DEVELOPMENT OF THE AUTOMATIC DATA MANAGEMENT AND THE ANALYSIS OF INTEGRATED DEFORMATION MEASUREMENTS

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November 1995

TECHNICAL REPORT NO. 176

PREFACE

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DEVELOPMENT OF THE AUTOMATIC DATA MANAGEMENT AND THE ANALYSIS OF INTEGRATED DEFORMATION MEASUREMENTS

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November 1995

PREFACE

This technical report is a reproduction of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Geodesy and Geomatics Engineering, November 1993. The research was supervised by Dr. Adam Chrzanowski and funding was provided partially by the Natural Sciences and Engineering Research Council of Canada, the New Brunswick Electric Power Commission, and the University of New Brunswick.

 The citation to this work should appear as follows:

Secord, J. M. (1995). *Development of the Automatic Data Management and the Analysis of Integrated Deformation Measurements*. Ph.D. dissertation, Department of Geodesy and Geomatics Engineering Technical Report No. 176, University of New Brunswick, Fredericton, New Brunswick, Canada, 237 pp.

ABSTRACT

The monitoring of deformations and the analysis of deformation measurements have recently evolved to the limit that technology can provide. Traditionally, geotechnical measurements have been performed and analysed separately from geodetic surveys (angles, distances, and height differences). It is now possible to deal with them together in an integrated analysis, largely due to the University of New Brunswick (UNB) Generalized Method for the analysis of deformation measurements. Current microcomputer technology allows for the collection and on-site analysis of measurements. The automation, or computer control, of data collection, processing, and analysis has decided advantages over manual methods, particularly concerning data integrity and the handling of large volumes of repeated measurements.

A system, "DAMADA", for the management of data for deformation analysis, from the time of sensing to the depiction of the deformation, was developed to facilitate the implementation of integrated analyses using the UNB Generalized Method. In doing so, it makes the collection, processing, and analysis of both geotechnical and geodetic data as automated as would be practical.

DAMADA has been successfully applied at a hydro-electric power generating station. The experiences of that application have led to several conclusions. The testing and calibration of instrumentation can improve the reliability and fidelity of the data, especially over long term repeated use in monitoring. DAMADA automatically accounts for routine testing and calibration as an integral part of the observation regimen. Three dimensional coordination of all observation points, geotechnical as well as geodetic, can facilitate the trend analysis, modelling, and depiction of the deformation of a structure. DAMADA can run on a modest microcomputer (80287) under DOS and is limited only by the storage capacity of the computer's hard drive. Although it currently considers horizontal and vertical geodetic observations separately, DAMADA is flexible enough that it could accommodate the simultaneous three dimensional monitoring of a structure.

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ACKNOWLEDGEMENTS

The research resulting in this thesis has had financial assistance from the Natural Sciences and Engineering Research Council of Canada, the New Brunswick Electric Power Commission (N.B. Power), and the University of New Brunswick. Technical assistance and support from N.B. Power (Mr. Gary Thompson, Manager, and Mr. Zbigniew Wroblewicz, Supervisor of Surveys, both of the Mactaquac Structures Investigation Project) has immensely aided the development of the system described in this thesis. Their co-operation over the several years of development is much appreciated. In the early stages of the development, some of the data collection programming was done by Mr. Frederick J. Wilkins, who was an M.Sc.E. candidate in the Department of Surveying Engineering at the time.

Dr. Chen Yong-qi, of the Wuhan Technical University of Surveying and Mapping, has been a close collaborator since 1982. His innovative suggestions, especially regarding the analysis of deformation measurements, have done much to advance the development of a system for the analysis of deformation measurements. His contributions are much appreciated.

Since 1981, Dr. Adam Chrzanowski has been a supervisor and colleague on various projects, many of which have been related to deformation measurements and their analysis. He has been particularly generous with his resources and time and with his thoughts, suggestions, and guidance. My gratitude to him is immeasurable.

1. INTRODUCTION

In the monitoring of deformations, a scheme must be devised to provide for the collection, processing, and analysis of data regarding the object, that is of interest in the monitoring, and of its surroundings. The objective of the scheme is to result in timely and responsible decisions concerning the object of interest, particularly if the conditions are critical and a warning must be given.

A monitoring scheme encompasses everything that happens to the data from the instant at which it is sensed to the time of analysis, when a warning may be issued. Four aspects of monitoring are of concern here: the time allowed for analysis, the volume or amount of data, the rate of sensing, and the amount of human involvement. Under ordinary circumstances, the interval of time between sensing and analysis may extend over several days or more. Under critical conditions, this may have to be nearly instantaneous in order to provide a warning, if necessary. The volume of data may consist of only several items, in the simplest routine investigation, or of hundreds or thousands of different data, in very complex or critical conditions. The rate of sensing may be annually, monthly, weekly, daily, hourly, or even more frequently. The amount of human involvement may range from total, in a purely manual system, to virtually none, in a fully automatic system. A manual system is labour intensive, prone to errors or blunders, and less flexible in the re-examination of data. As the time allowed for analysis lessens, as the volume of data increases, and as the rate of sensing becomes more frequent, an automatic system becomes more attractive.

Nonetheless, automation does have some limitations, as will be discussed in a subsequent section.

In some monitoring efforts, the scheme becomes more complicated as the deformation progresses. Initially, the problem may have appeared to be simple and straightforward enough that a manual system seemed to be adequate. As the deformation continues and more data are gathered, other aspects of the behaviour of the object may be revealed and the scheme becomes progressively more complicated. This may develope to the extent that the manual system can no longer cope with the demands of monitoring that have evolved. Consequently, an existing scheme will have to be automated, to some degree, in order to, at least adequately, meet these demands.

A monitoring scheme would likely consist of two major categories of data: geodetic, or surveying, and geotechnical. Geodetic measurements involve the observables of horizontal angle, or direction; spatial distance; and height difference. Geotechnical measurements consist of similar geometric quantities, but over a much smaller extent than for geodetic measurements (distances to a few metres rather than hundreds of metres), as well as measures of the physical or mechanical state of the object being monitored.

There has been a tradition, in most deformation monitoring efforts, that surveying measurements are performed and analysed independently from geotechnical monitoring efforts. However, as any quantity is repeatedly observed, the distinction between geodetic and geotechnical is unnecessary.

Also, computational mechanisms have been developed to allow an "integrated" analysis of deformations, in which any repeated observation of the state of the object, geometric or mechanical, can be utilized.

Therefore, this thesis will deal with the automation of existing monitoring schemes with the goal being to be able to perform an integrated analysis of the object undergoing the deformation. Further, in the context of a single site investigation, the scheme will be considered as involving the use of an on-site microcomputer rather than a mainframe or even minicomputer. In order to devise a monitoring scheme or to make an existing scheme in some degree automated, certain aspects of deformation monitoring must be regarded.

The process of monitoring can be undertaken in five stages: design of the scheme, repeated data capture and processing, data trend analysis, deformation modelling, and possible enhancement of the scheme. The initial stage of design relates the type, spatial distribution, and frequency of observation of the observables to the expected form of deformation. Following the design, the data are repeatedly captured and processed, or reduced, from a raw observed form into a suitable time series. Once they contain a sufficient amount of data, the various series are analysed for temporal, and possibly spatial, trends which would suggest several possible deformation models. The parameters of these models are then estimated with statistical assessment. The outcome of this assessment may lead to an enhancement of the scheme - a change in the type, number, location, or frequency of the observables. Each of the stages of monitoring is related to the others, to some extent, so that a change in one aspect must have regard for the others.

Most of these stages involve computations and would benefit from being automated, i.e., having the organizational and computational algorithms executed by computer, with virtually no human involvement. The speed and reliability of the data capture and processing are enhanced, especially if there is an appreciable volume of data. The data trend analysis can be performed more efficiently, with proper statistical assessment and illustrative graphical output. The deformation modelling is facilitated by statistical testing, graphical output and flexibility in being able to estimate the parameters of a variety of models.

For over a decade, the author has been involved in the development of a method for deformation analysis (e.g., Secord [1981]; Chrzanowski, Chen and Secord [1982a,b]; Chrzanowski, Chen and Secord [1983a,b,c]; Secord [1985]; Chrzanowski, Chen, Szostak-Chrzanowski, and Secord [1990]). The UNB Generalized Method for the Analysis of Deformations [Chen, 1983; Secord, 1985] has evolved and the analysis of deformations has reached its maturity. The author has been an active member of the Fédération Internationale des Géomètres (F.I.G.) *ad hoc* Committee on the Analysis of Deformation Measurements for several years [Kok et al., 1983; Chrzanowski and Secord, 1983a,b] and has been involved in consulting in a variety of deformation monitoring projects [Chrzanowski, Chen, and Secord, 1983a; Chrzanowski, Secord, and Rohde, 1985; Chrzanowski and Secord, 1987]. As evidenced by the *ad hoc* Committee, comparable approaches to the analysis of deformations have been established at other centres of research [Chrzanowski and Secord, 1983a,b]. However, the Generalized Method, particularly with its ability to provide for integrating all type of observables in the analysis (deformation modelling) has been unique. As a companion to the Generalized Method, a system for data management has been established by the author.

This thesis describes the system DAMADA (data management for deformation analysis) that the author developed in answer to the need of N.B. Power at its Mactaquac Generating Station, just upriver from Fredericton. A variety of instrumentation was being observed and recorded manually on field sheets. The data were entered into Lotus 1-2-3 worksheets for reduction and plotting of the series. As the volume and variety of data increased, the need for electronic data collection was recognised, not only for ease of gathering but also to ensure the reliability of the data. Chrzanowski and Secord [1987] revealed some instrumentation problems that could be easily overcome by altering the observation procedures and by introducing calibration measurements as a regular part of the observation regimen. Also, their solution would be facilitated by electronic data collection. Consequently, DAMADA was developed to make the data collection more efficient, with less opportunity for error and with more opportunities for checking consistency, to reduce the number of personnel required, and to make the processing and generation of plots and trend fittings automatic (since there were several hundred to do at a time). The system is presented here in general terms so that it could be applied to other forms of monitoring schemes.

A recent study for the United States Army Corps of Engineers by UNB (Chrzanowski et al., [1992]; see also Avella, [1992]) concludes that no single authority currently responsible for the monitoring of dams can serve as an example concerning all of the "three major aspects of dam monitoring, i.e., monitoring techniques, design of monitoring schemes, and analysis and management of the collected observations" [Chrzanowski et al., 1992]. This was incentive, beyond the needs of N.B. Power, for the author to devise a system for data management and analysis. Chrzanowski et al. [1992] also concluded that it is easy to neglect the calibration of instrumentation, critical to the long term reliability of instrumentation, particularly for *in situ* instrumentation which must have testing as a part of the observing procedure.

Chapter 2 outlines the requirements of a monitoring system and reviews some systems already in operation. There are several considerations to be made in devising a system, especially with regard for the design of observables, for the testing and calibration of instrumentation, and for data capture and processing. These are discussed in Chapter 3. Once sufficient data have been processed, it is necessary to analyse the trend of a series of repeated measurements (Chapter 4) in order to suggest possibilities for the modelling of the deformation (Chapter 5).

The deformation of a body is completely described in space and time if, for every particle of the body, the rigid body translation and rotation, strain tensor, and differential rotation components are defined in three dimensions over the period of time concerned. It is impossible to practically know the behaviour of every particle at every instant. Therefore, these characteristics are derived from a three dimensional displacement field resulting from measurements or "sampling" at selected points of the body at certain instants [Chen, 1983; Chrzanowski, Chen, and Secord, 1983c; Secord, 1985; Chrzanowski, Chen, and Secord, 1986]. While it is possible to observe three dimensional quantities, it has been traditional that two dimensional ("horizontal") precise geodetic surveys are performed separately from one dimensional ("vertical") precise geodetic surveys. This is a consequence of the nature of the instrumentation and observations and the type of monumentation (horizontal stability of monuments is controlled differently than vertical). As well, it is often more practical to show one or two dimensions on paper than to show a three dimensional view, particularly quantitatively and to scale. Consequently, discussion in this thesis separates one dimensional and two dimensional (i.e., in a plane but not necessarily horizontal) deformations. Nonetheless, the whole system can readily accommodate three dimensional data. It is really only the processes of campaign adjustment and spatial trend analysis that separate the vertical from the horizontal.

The overall consideration for the design of the scheme and the organization of the data, from capture to decision, is the concern of a system of data management. A system of data management for deformation analysis, "DAMADA", which has been developed by the author is presented in Chapter 6. The author's application of DAMADA to the monitoring of a hydro-electric power generating station is given as an example in Chapter 7. Conclusions and recommendations, resulting from the application of DAMADA, are made in Chapter 8.

2. MONITORING SCHEMES

The previous chapter established that, in most cases, a monitoring scheme would likely have to be automated to some extent during its lifetime. Automation of a system at its outset has become rather trivial because of the extent to which technology has made most of the relevant processes automated. Therefore, it is the automation of an existing manual system that is of concern in this thesis. This chapter will consider the requirements for data capture, processing, and analysis. Then, it will present several examples of existing systems and show why it is necessary to devise a new system, particularly for a monitoring scheme that is already in manual operation.

An automatic system is attractive when compared to a totally manual system but has some limitations. Although a "data acquisition system" strictly involves the gathering of data, the phrase has been used by many to mean the whole system of data management. Dunnicliff [1988] has weighed the advantages and limitations of an automatic data acquisition system and these points should be kept in mind when devising a system. Therefore, they are summarized in the following two lists. The advantages of an automatic data acquisition system are:

a) personnel costs for reading instruments and analyzing data are reduced;
b) more frequent readings are possible;
c) retrieval of data from remote or inaccessible locations is possible;
d) instantaneous transmission of data over long distances is

possible;
e) increased reading sensitivity and accuracy can be achieved;
f) increased flexibility in selecting required data can be provided;
g) measurement of rapid fluctuations, pulsations, and vibrations is possible;
h) recording errors are fewer and immediately recognizable; and
i) data can be stored electronically in a format suitable for direct computer analysis.

The limitations of an automatic system are:

a) a knowledgeable observer is replaced by hardware, i.e., less frequent "intelligent" visual inspections;
b) an excess of data could be generated, leading to a failure in timely response;
c) the data may be blindly accepted, possibly leading to a wrong conclusion;
d) there could be a high initial cost and, possibly, a high maintenance cost;
e) often requires site-specific or custom components that may be initially unproven;
f) complexity may require an initial stage of debugging;
g) specialized personnel may be required for regular field checks and maintenance;
h) a manual method is required as an alternative (backup);
i) a reliable and continuous source of power is required; and
j) the system may be susceptible to damage by weather or construction activity.

With an appropriate compromise between manual and automatic functions, a properly designed and working system can readily minimize the effects of the limitations mentioned above. Therefore, the advantages of an automatic (really "semi-automatic") system easily outweigh its disadvantages.

2.1 Examples of Existing Systems

In a variety of levels of sophistication, automated systems have become commonplace over the last decade or so, particularly in the monitoring of dams and hydro-electric power generating stations. Italy's ENEL (Ente Nazionale per l'Energia Elettrica) and ISMES (Istituto Sperimentale Modelli e Strutture) have been leaders in the philosophy [Fanelli, 1979] and in the creation of monitoring sytems [Anesa et al., 1981; Bonaldi et al., 1977; Bonaldi et al., 1980a,b]. Now, systems are well established in other countries [ICOLD, 1982; Chrzanowski et al., 1992], in particular: Austria [Hautzenberg, 1979; Ludescher, 1985]; Canada [Cartier and Hamelin, 1988]; Japan [Japanese National Committee on Large Dams, 1987]; Portugal [Florentino et al., 1985]; Switzerland [Swiss National Committee on Large Dams, 1985; Gilg et al., 1985]; and the United States [Bartholomew and Haverland, 1987; Bartholomew et al., 1987; Lytle, 1982; Walz, 1989].

Systems of data management have also been developed for other applications, especially regarding high precision metrology measurements [Friedsam et al., 1987; Quesnel, 1987; Ruland and Ruland, 1988; Missiaen, 1992]. They are restricted to handling only conventional geodetic observables and their primary purpose is for controlling the setting out of components rather than for deformation monitoring. Therefore, they will not be mentioned further here.

Any mention of data management systems in the literature has been usually by way of figures rather than any extensive verbal description and the emphasis has been on showing the communication aspects of a system.

Nonetheless, there are three existing systems which warrant mention here specifically. One is used at ENEL [Bonaldi et al., 1977; Anesa et al., 1981]. A second was developed by the U.S. Bureau of Reclamation (USBR) [Bartholomew et al., 1987]. Thirdly, activity in the U.S. Army Corps of Engineers (USACE) has been presented by Lytle [1982] and Walz [1989]. A brief description of these three systems is given below. Since current technology offers considerably more capacity and convenience, particularly with respect to computers, than even five years ago, the technological aspects of these examples should be kept in context. It would appear that the current trend is toward micrcomputers for on-site analysis and that communication to a central office via modem over a telephone line is fairly routine.

2.1.1 The ENEL system

In the ENEL system shown in Figure 2.1 [Bonaldi et al., 1977], there are two major subsystems: "Off-line" which serves as a central (remote) storage of all data; and "On-line" in which most of the activity takes place. It is the On-line or local (on-site) portion that is of interest. Two mini-computers are involved and are linked for the teletransmission of data. The remote virtually duplicates the functions of the local, except for the actual capture of data. The local provides data acquisition, validation, processing, storage, and transmission to other sites. Also, it issues a warning if the observed effect differs from the expected effect (derived from deterministic modelling) by more than an established tolerance.

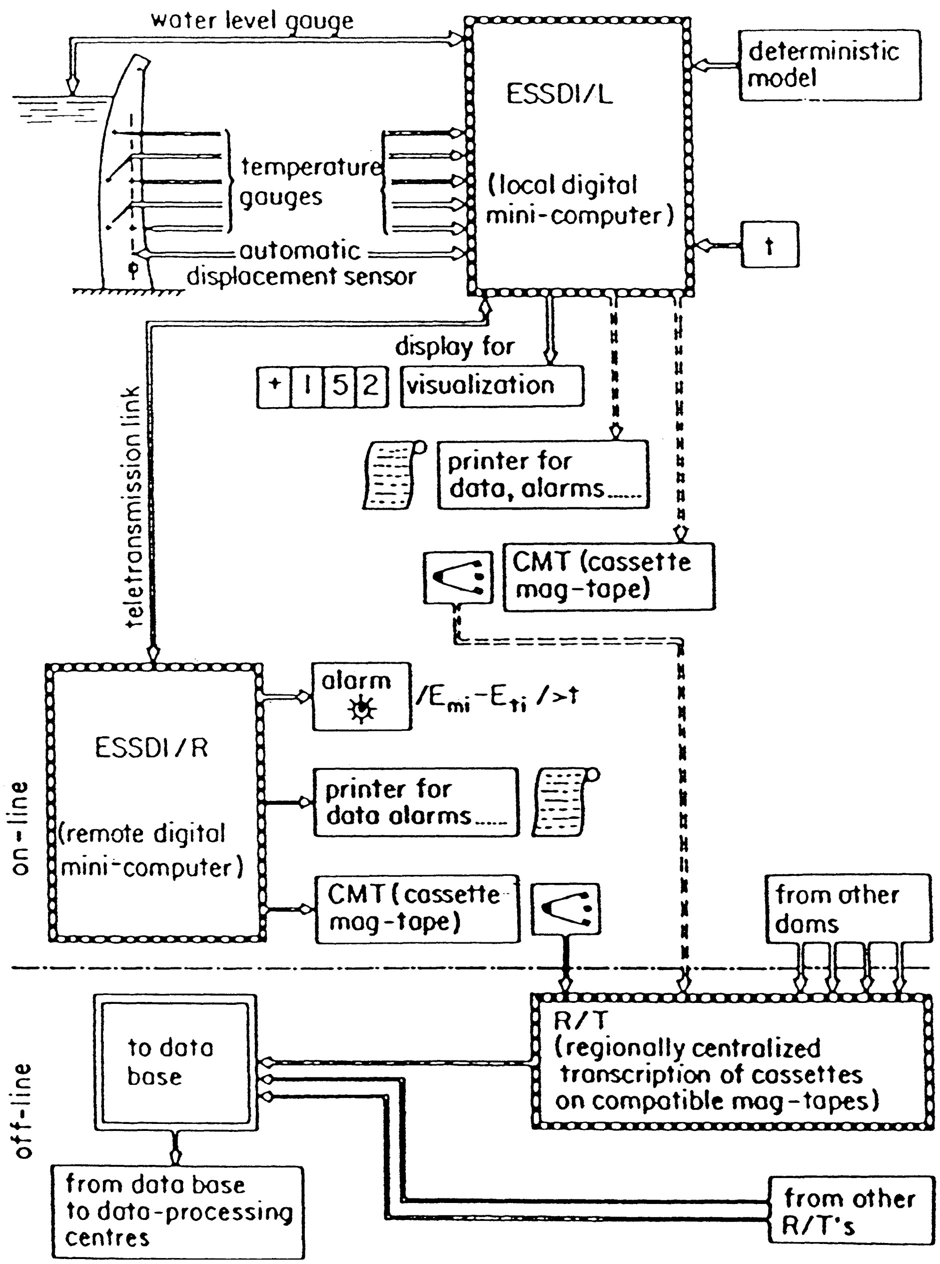


Figure 2.1. The ENEL System ("Hardware and schematic information flow for dam displacement control" [Bonaldi et al., 1977])

Deterministic modelling of the structure, based on its loading (e.g., hydrostatic) and temperature influences, yields theoretical displacements which are compared to the measured values [Bonaldi et al., 1977]. However, such a comparison is meaningful only if the deterministic model is based on substantial knowledge of the physical characteristics of the structure and the temperature distribution within it. This requires extensive two and three dimensional finite element modelling of the structure. The knowledge of the structure, its temperature distribution, and finite element modelling may not always be available or possible. Therefore, the comparison of theoretical and observed values of displacement is somewhat limited in its application.

A more recent view [Anesa et al., 1981] of the ENEL system is given in Figure 2.2. The on-line portion provides automatic control which is continuous in real-time. Automatic data collection follows a pre-established schedule and the observed values are compared with the predicted theorectical values. This system is main-frame based and the instrumentation is specific to each of the fifty, or so, sites involved.

In either of these descriptions, there is little mention of the data management component of the system, apart from the fact that specialized software is used on a mainframe. The ENEL system is certainly adequate in the context of automation at the outset of monitoring and of dealing with several sites as would be required in a national authority such as ENEL, where a mainframe would be available. This would be in contrast to the effort of this

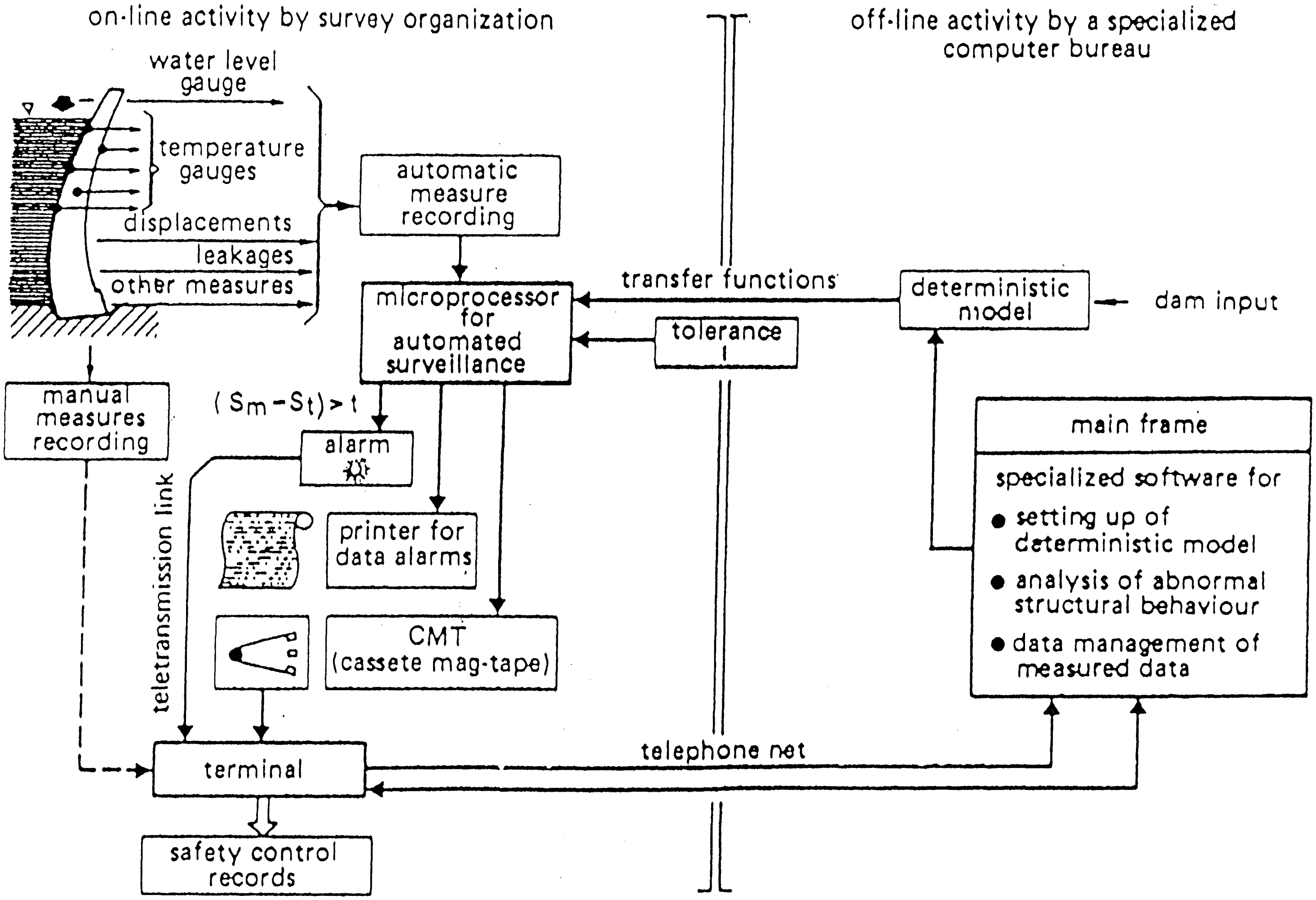


Figure 2.2. The ENEL System ("Microprocessor-aided monitoring system" [Anesa et al., 1981])

thesis - an on-site microcomputer based system.

2.1.2 The USBR system

The arrangement at the Calamus (embankment) Dam is managed by the USBR (Figure 2.3). The main aspect of this system is the means of communication by telephone line or satellite link from the dam to various locations in the country. Two appendices to Bartholomew et al. [1987] describe the data processing and automation of the Bureau's embankment dams. Bartholomew and Haverland [1987] discuss concrete dams but more detail, with respect to data management, is given in Bartholomew et al. [1987]. In both publications, there is a discussion regarding the different phases of data acquisition and processing - what is done by whom and in what sequence. Both also deal with different types of instrumentation and how the data time series from each could be represented graphically. It seems that action would be taken on anomalies that become apparent from a review of the series plots.

The same comments pertain to the USBR system as to the ENEL system. Although there is some discussion of data management, there is not enough to duplicate the system, especially if the system is to be installed on a microcomputer.

2.1.3 The USACE system

Lytle [1982] describes a system used by the St. Louis district of the

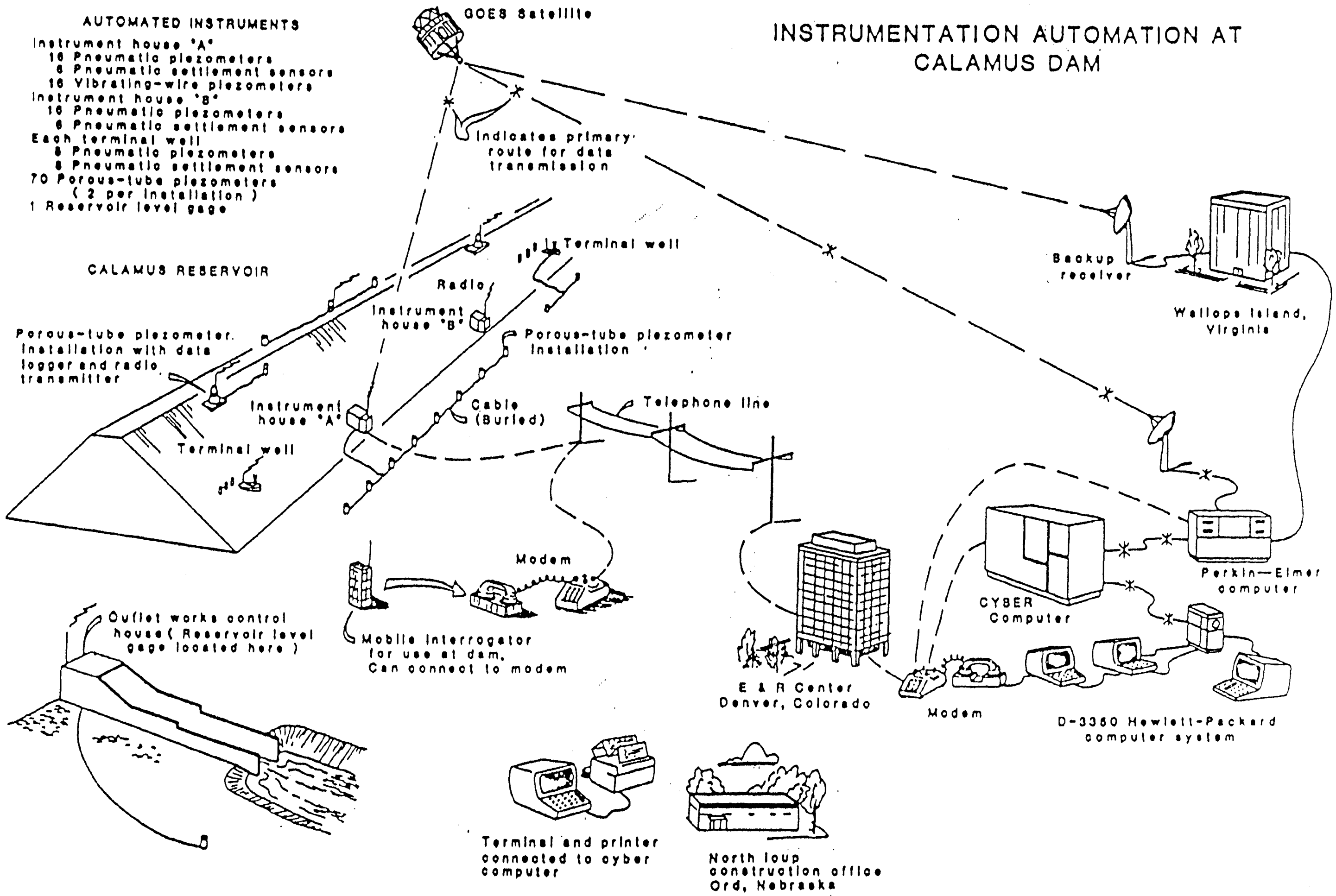


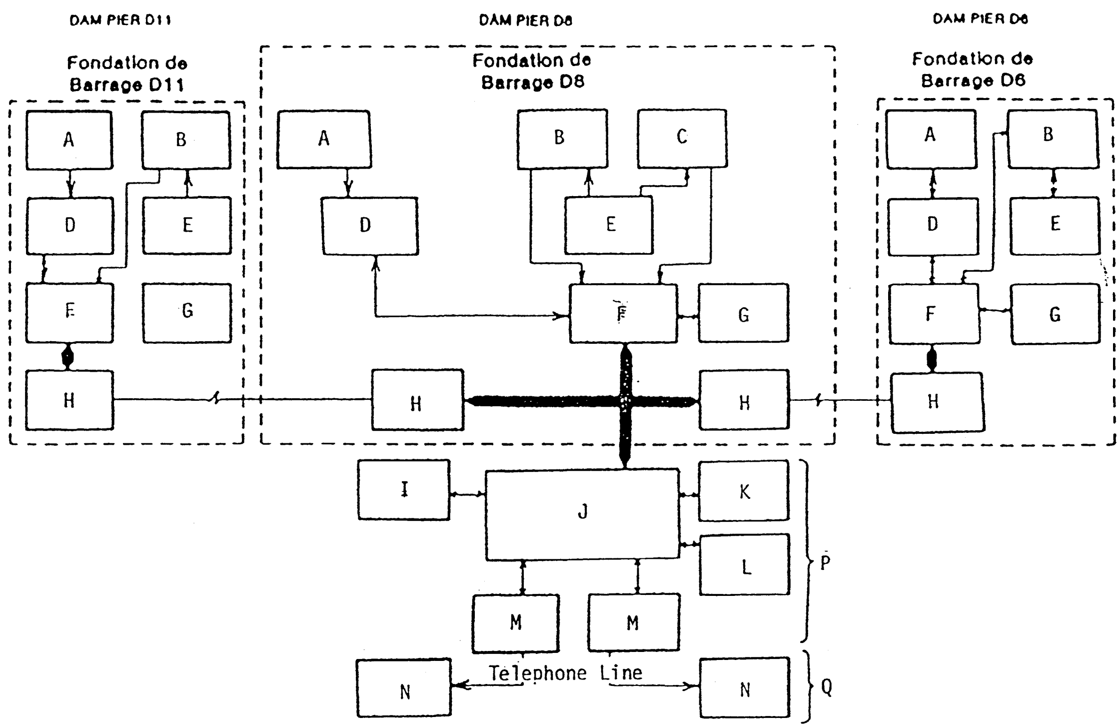
Figure 2.3. The USBR System ("Instrumentation automation at Calamus Dam" [Bartholomew, Murray, and Goins, 1987])

USACE, with respect to automated acquisition, processing, and plotting of data (Figure 2.4). An example of typical dialogue encountered in using the mini-computer based system is given. Walz [1989] discusses a system under development, initially to deal with totally automating piezometers in embankment dams, particularly with respect to local and district communication. The concepts of both authors are encompassed by the ENEL and USBR systems. The same comments can be made about the USACE system as for the other two.

2.2 Desirable Characteristics of a Data Mangement System

Together, the discussion and examples given above show the desirable characteristics of a data management system for deformation surveys (including both geotechnical and geodetic observables). These characteristics can be summarized as:

a) data integrity (offering checks in the field and later processing);
b) data security (automatic archiving and regular data file backup);
c) automation of acquisition, processing, and analysis;
d) compatibility and integration with other observables;
e) flexibility in access to the data for possible manual entry and editing;
f) data openness (useable by other software);
g) flexibility in the system to be easily modified to accommodate additional instrumentation or other forms of analysis;
h) on-site immediate access to data or any of the forms of analysis;
i) near-real time results of trend or other analyses; and



Block diagram of automated data acquisition.

(A) Vibrating wire piezometers.
(B) Biaxial tiltmeter.
(C) Electrical barometer.
(D) Exciter and switching unit.
(E) Dual DC power supply.
(F) Controler.
(G) Digital voltmeter.
(H) Extender.
(I) 20 M/byte disc.
(J) Computer with 64 K memory.
(K) Line printer.
(L) Graphics terminal.
(M) Modem.
(N) Off-site modem and terminal.
(P) On site data collection and reduction.
(Q) Off-site data collection.

Figure 2.4. The USACE System [Lytle, 1982]

j) testing and calibration is an integral component of the system.

Since the arrangement of instrumentation is site specific, a considerable effort would be required to adapt a system from another location that uses other forms of similar types of instrumentation. Although the ENEL system compares the outcome of deterministic modelling with the measured displacement, there is no integration of all possible types of observables in a deformation analysis. Because there does not appear to be any system that is readily adaptable to an on-site microcomputer environment, a system is proposed in Chapter 6 with regard for the desirable characteristics listed above. In order to lay the foundation for the proposal of a system, considerations to be made in the devising of a system, trend analysis, and deformation modelling are discussed in Chapters 3, 4, and 5, respectively.

To some extent, a system will have features that vary from location to location and from application to application. Therefore, the devising of a system and the aspects of a system are presented in the following chapters in a general manner. Since DAMADA was developed in direct response to the need at a hydro-electric power generating station, the references and example lean in that direction. Nonetheless, the author feels that the system is flexible to the extent that it can be applied to virtually any deformation monitoring task that would benefit from using both geodetic and geotechnical instrumentation.

3. CONSIDERATIONS IN DEVISING MONITORING SCHEMES

A monitoring scheme is created to obtain knowledge about the behaviour of the object of interest over time. This behaviour will have certain mechanical or physical characteristics and will be exhibited at a particular rate over time. In order to ensure that the scheme will be sampling at points on the object that will be reflective of the behaviour, the scheme must be designed with regard for the expected deformation, both in its physical nature and rate of progress. If a scheme is already in operation and it is necessary to modify the scheme to investigate other characteristics, other locations on the object, or at other rates of sampling, then the same considerations apply. Also, an existing scheme could be improved by making it more efficient, or economical, or by enhancing its precision or resolution of the deformation. Therefore, the design of a monitoring scheme must account for the relationship between the observables and the estimation of the parameters of the expected deformation - design for modelling.

An observable is a geometric or physical quantity that can be measured. The value of the observable that is measured is an observation or a measurement. The observation, as it is recorded from the sensing instrument, may have to be corrected or "reduced" for instrumental or atmospheric conditions and for transformation to a particular computational surface. An observation equation relates the observable to the quantities of interest, e.g., a distance measurement to the coordinates of the two points involved. Consequently, the design of a scheme, and the propogation of random errors, can be done without values for the observations so long as the geometry of the observables is known.

In all cases of monitoring efforts, the modelling or analysis is performed on a comparison of the most recent observations with a corresponding previous observation or series of observations. Consequently, it is essential that the variation in the values of the repeated measurements is due entirely to the physical variation between the sampling points involved. In order to ensure this, the testing and possible calibration of the instruments must be a regular component of the observation regimen.

To further ensure data fidelity, the procedure for data capture must be devised to introduce as much redundancy and assurance on the quality of the data as the observables will allow. Also, for security and additional assurance, the processing of the data must provide opportunities for checking the data and for applying the appropriate reductions. The successful capture and processing of the data are crucial in any monitoring effort because the observations are measuring the state of the object at the time of the campaign. If the data prove to be incorrect, the measurements cannot be re-observed and the information on the state of the object at that instant is lost.

3.1 Design Considerations for Modelling

If we consider monitoring in the general sense, that either geodetic or geotechnical observables or both are involved, then the design of a scheme, or an improvement to it, will involve considering:

a) the type of observables,
b) the location of the observation points,
c) the instrumentation involved,
d) the observing technique,
e) the duration of the observing campaign, and
f) the stability of the reference points.

The type of observable will depend on the nature of the phenomenon being investigated, as reflected in the deformation parameters that will be estimated from the measurements. The points involved in the observations will be located according to the shape of the structure as well as to the expected deformation. The instrumentation will be chosen according to the type of observable and required precision. The observation technique will depend on the instrumentation involved and the required precision. Also, the technique will be adopted that will minimize the effect of systematic errors that could vary from campaign to campaign, e.g., the effect of changes in ambient temperature. A campaign is a collection of observations which together would describe the state of the object at the instant associated with the campaign. Therefore, the observing campaign should be only as long as an instant would be, relative to the rate of deformation. In most configurations of measurements, the deformation is described with respect to points or anchors which are assumed to be stable. Since this stability is not so easy to predict, it is necessary to ensure that there is a sufficient number and suitable distribution of reference points that their relative stability can be assessed as part of the monitoring process.

A campaign of geodetic observables can be distinguished from a collection of geotechnical measurements mainly by the fact that geodetic observables are usually interrelated to form a network. As in the traditional use of geodetic measurements for positioning, these networks are arranged to provide geometric checks on the measurements of a campaign. Usually the configuration will allow an adjustment of the campaign to provide least squares estimates of the coordinates of the stations and a statistical assessment of the observations as well as of the results. In contrast, most geotechnical observables are located in isolation and the only check on an observation is an assessment of the immediate repetition of an observation. Therefore, there is a distinction here between geodetic observables, in observing campaigns, and geotechnical observables, in a series of repeated measurements. Nonetheless, as mentioned in the introduction, as soon as a geodetic observation has been repeated often enough, its time series can be treated in the same way as a geotechnical series.

3.1.1 Observing Campaigns

If the geodetic observables involved in a campaign can be considered in a network without a configuration defect, then the vector of observations, $\boldsymbol{\ell}$, can be related to the unknown coordinates, **x**, of the points or stations involved by

$$\boldsymbol{\ell} + \mathbf{v} = \mathbf{A}\mathbf{x} \tag{3.1}$$

through the design matrix, **A**. The least squares estimates (denoted by the underscore) of the coordinates are obtained by [Wells and Krakiwsky, 1971; Vanicek and Krakiwsky, 1986]

$$\underline{\mathbf{x}} = (\mathbf{A}^T\mathbf{P}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{P}\boldsymbol{\ell} \tag{3.2}$$

in which **P** is the weight matrix of the observables, the inverse of their covariance, **C**. The variance-covariance matrix, $\mathbf{C}_x = \sigma_o^2(\mathbf{A}^T\mathbf{P}\mathbf{A})^{-1}$, provides the knowledge of the accurcy of the coordinates corresponding to the combination of the choice of instrumentation and observation techniques, through the matrix **P**, and of the configuration of the network, through **A**. In most instances, σ_o^2 is taken as unity. In an actual adjustment, $\boldsymbol{\ell}$ in Equation (3.2) is the misclosure vector $\mathbf{w} = \mathbf{A}\mathbf{x} - \boldsymbol{\ell}$ since the normal equations are non-linear but this is not of consequence in the design or pre-analysis.

The design for deformation monitoring assumes that the same configuration and observables will be involved in the repetition of a campaign. Consequently, the process can be extended to consider a pair of campaigns.

The deformation can be described, in a displacement field, **dx**, as the difference in coordinates between the two campaigns, i.e., $\mathbf{dx} = \mathbf{x}_2 - \mathbf{x}_1$, with $\mathbf{C}_{dx} = \mathbf{C}_{x1} + \mathbf{C}_{x2}$, so $\mathbf{P}_{dx} = \mathbf{C}_{dx}^{-1}$, and campaign 2 following campaign 1. This displacement field would be the "observed" displacement field since it results from measurements and its displacement components are located only at points involved in the network of observables. The observed displacement field is related to the deformation model parameters, **c**, through

$$\mathbf{dx} + \mathbf{v} = \mathbf{Bc} \tag{3.3}$$

by the modelling design matrix, **B**. The least squares estimates of the deformation parameters are then obtained from

$$\underline{\mathbf{c}} = (\mathbf{B}^T\mathbf{P}_{dx}\mathbf{B})^{-1}\mathbf{B}^T\mathbf{P}_{dx}\mathbf{dx} \tag{3.4}$$

with the covariance matrix of the parameters, $\mathbf{C}_c = (\mathbf{B}^T\mathbf{P}_{dx}\mathbf{B})^{-1}$.

For design purposes, the covariance of the deformation parameters can be related directly to the covariance of the observables by combining the above to yield

$$\mathbf{C}_c = 2\,(\mathbf{B}^T\mathbf{A}^T\mathbf{C}^{-1}\mathbf{AB})^{-1}. \tag{3.5}$$

By specifying the type of instrumentation and the observation techniques, the elements of $\mathbf{C}^{-1}$ are defined ($\mathbf{C}^{-1} = \mathbf{P}$ in Equation (3.2)). These are usually only the diagonal variance components since the covariance between the observations is not known at this stage. The choice of observables and the location of the points involved result in the population of the design matrix, **A**, and the deformation model, relating the parameters to the points, defines the elements of the design matrix, **B**. Equation (3.5) is then evaluated with iterative changes (usually by "trial and error") in the elements of **A**, **B**, and **C** until the values of the elements of $\mathbf{C}_c$ are at the desired magnitude.

This approach to design can be rather laborious unless experience can guide in selecting the instrumentation, the observating techniques, the location of the points, and the deformation model. A more direct approach would be to follow Kuang [1991] who has developed a procedure for optimizing deformation monitoring schemes using a multi-objective optimization model. Of particular importance is the ability of the scheme to detect certain parameters (sensitivity) and to distinguish a statistically better model from another (separability). Both of these characteristics are discussed in Chen and Chrzanowski [1993].

Nonetheless, there must be some guidance in the choice of the variables involved. Usually, the nature of the structure and its behaviour dictate the deformation model and may limit the possible location of observation points. Choosing the optimal location for observation points can take advantage of the finite element method (FEM) which can predict points at which the maximum deformation may occur, given the physical nature and shape of the structure and the forces acting on it (see Szostak-Chrzanowski et al. [1993]).

3.1.2 Series of Repeated Isolated Measurements

Geotechnical observables are distinguished from geodetic ones by their often being located in isolation from other observables and, as a consequence, must be analysed as a time series for trend (Section 4.2). The same analysis can be performed for individual geodetic observables once they have been repeated a sufficient number of times.

The rate of deformation, particularly if there is to be a pattern such as cyclicity, will influence the frequency at which the observations are made. If a series has data at intervals of Δt, then analysis of that series cannot reveal any cyclicity with a period smaller than $2\Delta t$ [Kanasewich, 1981]. As the structure ages, the deformation activity will usually mature to a condition of relative stablity and the observations may be gathered less frequently. However, as discussed below and in Section 4.2, the density of data points with time will affect the trend fitting. The earlier data, more frequently gathered, will tend to dominate the fitting over the later less frequently observed data. It may be better to continue observations at the same rate, particularly if there is any likelihood of the deformation accelerating.

In the process of compiling input to the integrated analysis (Chapter 5), the time series of the relevant repeated observations are analysed for trend, with the separation of seasonal (effects of temperature change) and long term behaviour. In the absence of actual temperature information, the trend ("y", the change in the value of an observed or derived quantity) against time ("t", in years) is described by the following equation.

$$y = a_1 \sin\omega t + a_2 \cos\omega t + a_3 t + a_4 + a_5 \delta(t) + \ldots \qquad (3.6)$$

in which

ω is 2π since a period of 1 year is assumed,

a_3 is the "rate" or long term trend,

a_4 is a required "datum" slip so that the fitting is not unduly constrained (i.e., so that y is not necessarily zero when t is zero), and

$a_5\delta(t)$ ... are possible values of slips accounting for discontinuities in the data series ($\delta(t) = 0$ for $t < t_5$ and $\delta(t) = 1$ for $t \geq t_5$ with the slip occurring at t_5).

If a data series is continuous, then the minimum number of unknowns in the trend fitting is four, i.e., a_1, a_2, a_3, and a_4. If there are $n > 5$ data, then a least squares estimation of these unknowns can be done with the y values as the "observations". Since, as the independent variable in linear regression, the time values, t, are considered as errorless, then this is a linear parametric case. The design matrix, **A**, has elements

$s = \sin\omega t_i$ for a_1,

$c = \cos\omega t_i$ for a_2,

t_i for a_3, and

1 for a_4,

in a row for each y_i. If the actual time of the observation is "t'_i" in years, then $t_i = t'_i - t_o$ with t_o being the time of the very first observation in the series. Similarly, $y_i = y'_i - y_o$. If, as usually would be the case, the data are collected at regular intervals, Δt, then $t_j = t_{j-1} + \Delta t$.

Considering the form **y** + **v** = **Ax** with the a_i represented in **x** and **P** = **I** (the identity matrix) leads to the estimation of the a_i through

$$\underline{\mathbf{x}} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{y}. \tag{3.7}$$

From which, the residuals result via $\underline{\mathbf{v}} = \mathbf{A}\underline{\mathbf{x}} - \mathbf{y}$ and the estimated variance factor is $\underline{\sigma}_o^2 = \underline{\mathbf{v}}^T\underline{\mathbf{v}}/(n-u)$, with $u \geq 4$. Therefore, the variance-covariance matrix for the a_i is given by

$$\mathbf{C}_x = \underline{\sigma}_o^2\,(\mathbf{A}^T\mathbf{A})^{-1}. \tag{3.8}$$

In order to investigate the effect of the number of data points on the elements of $\mathbf{C}_x$, it is instructive to see that

$$\mathbf{A}^T\mathbf{A} = \begin{bmatrix} \sum_i^n s^2 & \sum_i^n sc & \sum_i^n st_i & \sum_i^n s \\ \text{sym} & \sum_i^n c^2 & \sum_i^n ct_i & \sum_i^n c \\ \text{sym} & \text{sym} & \sum_i^n t^2 & \sum_i^n t \\ \text{sym} & \text{sym} & \text{sym} & n \end{bmatrix}$$

Thus, the magnitudes of the elements of $\mathbf{A}^T\mathbf{A}$ increase as n increases, i.e., with the number of data points. Therefore, an improvement in $\mathbf{C}_x$ would be expected with an increase in n, i.e., with a shortening of the interval, Δt, between observations or samplings. Since it is rather tedious to show the values of the elements of $\mathbf{C}_x$ algebraically, Figures 3.1 and 3.2 have been generated.

Since the magnitude of $\underline{\sigma}_o^2$ is a consequence of the behaviour of the data and is specific to each series and since its value would be applied to all elements of $\mathbf{A}^T\mathbf{A}$, then the following discussion deals with the non-scaled standard deviations, i.e., the square roots of the elements of $\mathbf{Q}_x = (\mathbf{A}^T\mathbf{A})^{-1}$. In the interpretation of the trend, the values of a_1 and a_2 are not of as much interest as the amplitude, α, and phase, ϕ, of the sinusoid.

Equation (3.6) is really a decomposition of the expression $y = \alpha\sin(\omega t + \phi)$ with

$$\alpha = (a_1^2 + a_2^2)^{1/2} \text{ and} \tag{3.9}$$

$$\phi = \arctan\,(a_2/a_1), \text{ or, without ambiguity} \tag{3.10}$$

$$\phi = 2\arctan\,[a_1/(\alpha + a_2)]. \tag{3.11}$$

The phase is defined as being the value from $t = 0$, or $t = t_o$, forward to the value of t at which the sinusoid is zero and increasing from negative to positive. If the

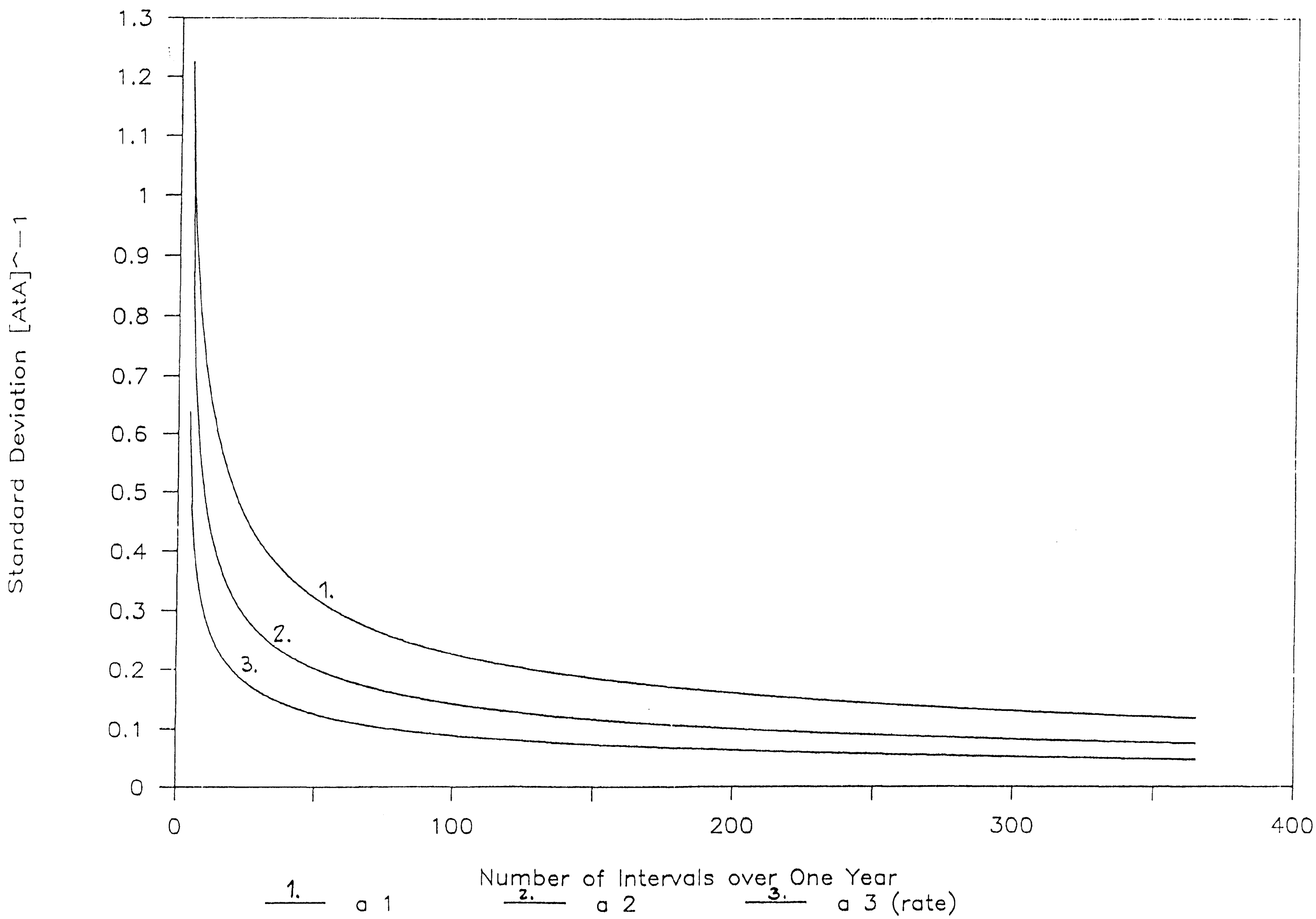


Figure 3.1. The behaviour of standard deviations with increased number of intervals per period

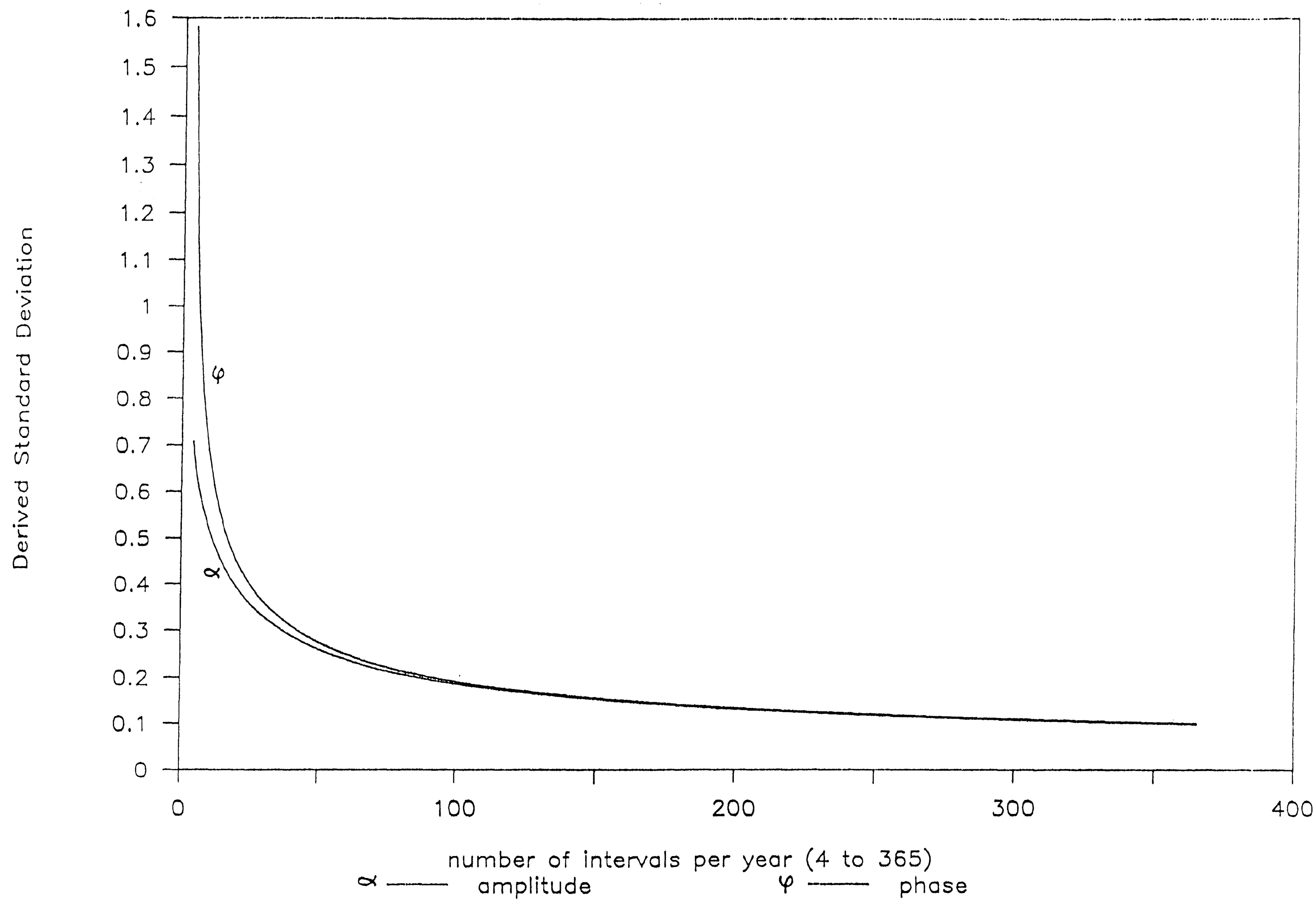


Figure 3.2. The behaviour of amplitude and phase standard deviations with increased number of intervals per period (amplitude of 1 unit, phase of $\pi/4$)

algorithm for calculating the arctangent in Equation (3.10) cannot recognize the signs of a_2 and a_1, then Equation (3.11) must be used to obtain a value for ϕ without an ambiguity of π or 180° [Steeves, 1981a]. The variance-covariance information concerning a_1 and a_2 from $\mathbf{Q}_x$ can be propogated into the knowledge of α and ϕ by

$$q_\alpha^2 = [a_1^2 q_1^2 + 2a_1 a_2 q_{12} + a_2^2 q_2^2]/\alpha^2 \text{ and} \tag{3.12}$$

$$q_\phi^2 = [a_2^2 q_1^2 - 2a_1 a_2 q_{12} + a_1^2 q_2^2]/\alpha^2. \tag{3.13}$$

In order to illustrate the outcome of Equations (3.12) and (3.13), consider the following cases in which $\alpha = 1$ unit:

i) $a_1 = 1$, $a_2 = 0$, so $y = \sin\omega t$ and $\phi = 0$;
ii) $a_1 = 0$, $a_2 = 1$, so $y = \cos\omega t$ and $\phi = \pi/2$ or 90°; and
iii) $a_1 = a_2 = (1/2)^{1/2}$ and $\phi = \pi/4$ or 45°.

In case i), the amplitude has the variance of a_1 and the phase, of a_2 (Figure 3.1). In case ii), the variances are reversed, i.e., that of a_2 for the amplitude and that of a_1 for the phase (also in Figure 3.1). Case iii) is not as simple and the expressions for variance are $q_\alpha^2 = (q_1^2 + 2q_{12} + q_2^2)/2$ and $q_\phi^2 = (q_1^2 - 2q_{12} + q_2^2)/2$ and behave as shown in Figure 3.2. In all three cases as well as for a_3, the standard deviation decreases as the number of data per period increases or the sampling rate increases or the regular sampling interval decreases. It would appear that the optimum would be between 50 and 100 samplings per period.

For example, if the period is one year, then the optimal would be weekly to twice weekly observations. Little improvement in the standard deviation of the rate (a_3), α, or ϕ is gained by increasing the frequency beyond 100 samplings per period.

The benefit of geometric redundancy and campaign statistical assessment usually found in geodetic campaigns is not available to geotechnical observables. Consequently, the testing and calibration of instrumentation and the reduction of observations are particularly important. This ensures that the data reflects the state of the object at the time of measurement and that any change in the reduced data is due to a change in the state of the object. Because of their importance, regular testing and calibration must be an integral component of the observation programme. Also, the schedule of observing should maximize the utilization of the testing and calibration (Section 3.2).

3.2 Testing and Calibration of Instrumentation

The testing of an instrument is the investigation of its behaviour under a variety of conditions, as would be encountered in the normal use of the instrument. Results of the testing would reveal the sensitivity of the instrument, its expected precision, and whether it exhibits any appreciable hysteresis. The sensitivity of an instrument is the rate at which its output changes in reaction to a change in its input. Since the testing is done under controlled conditions and with reasonable redundancy, then an outcome of the testing will be an estimate of the precision that can be expected in its performance. If an instrument response, for the same input value, when its input is decreasing is different from when the input was increasing, then the instrument is exhibiting hysteresis [Beckwith and Marangoni, 1990]. If the amount of hysteresis is significant, an observing technique would be adopted to lessen its effect to a negligible amount.

Calibration is the comparison of the output of an instrument to a known standard input. The result is a conversion factor or a constant that is applied to the instrument output to yield data in the required units. Similar to testing, the redundancy introduced in the calibration process yields a measure of the accuracy of the instrument, its linearity (in response to known input), and its sensitivity.

Together, testing and calibration provide information on an instrument that ensures its reliability in operation and fidelity in output. Dunnicliff [1988] suggests an acceptance test immediately when an instrument is received from its manufacturer and, even, that the client should be involved in the calibration of the instrument by the manufacturer. A distinction is made here between geodetic and geotechnical instrumentation because the redundancy and statistical assessment of a geodetic campaign is not available in geotechnical observations. This makes the testing and calibration of geotechnical instrumentation and of geodetic instrumentation, if observed in isolation, critically important in any monitoring effort.

3.2.1 Geodetic

The testing and calibration of levels, theodolites, and electro-optical distance measuring instruments (EODMI) is well known and routinely performed when such instruments are used in positioning (e.g., see Davis et al. [1981] and Rüeger [1990]). In deformation monitoring, it is likely that the precision of an instrument is more important than its accuracy, so long as its behaviour is consistent over time, since the concern is with the change in repeated measurements rather than with the absolute value. However, there must be some means of ensuring that this consistency is a regular aspect of the observing regimen. Therefore, testing and calibration of geodetic instruments for deformation monitoring are viewed slightly differently.

The current tendency is to provide a serial ASCII interface between the instrument and a computer. This allows for the data collection, in a very flexible form, from EODMI, electronic theodolites, and electronic levels. Consequently, the precision digital automatic level, NA3000 [Leica, 1991; Leica, 1992], is attractive for use, with invar staves, in deformation measurements. It is specified as providing a standard deviation of 0.4 mm per kilometre of double-run levelling [Leica, 1992]. However, recent experience [Greening, 1992] has shown that the compensator exhibits some systematic error when disturbed by cross-wind or by heating under direct exposure to the sun. Experiments

[Chrzanowski et al., 1985] toward trigonometric height traversing revealed that the compensator system of the Kern E2 also reacted to exposure to the sun. Therefore, it is necessary to test the behaviour of electronic levels and theodolites to determine their suitability and to develope observation procedures that will minimize the effect of influences that may be systematic during a campaign, but vary from campaign to campaign.

The use of precision EODMI in deformation measurements has become quite commonplace, even to the extent of replacing the more traditonal triangulation. Calibration becomes even more important when measuring isolated distances so that the EODMI is used as an electro-optical extensometer. Two characteristics of an EODMI system must be mentioned - additive constant and scale.

The additive constant, z_0, is defined as the amount that must be added to an EODMI output, d', to compensate for the combined eccentricity between the electro-optical centres of the instrument and reflector and their mechanical centres. So, $d = d' + z_0$. Sometimes, it is called the zero correction. Unfortunately, the phrase "zero error" has been used interchangeably; however, strictly speaking, it should have the opposite sign, i.e., $e_z = - z_0$. Therefore, care should be exercised to be sure of the sense in which it is being used. Following the concept of additive constant, the value of z_0 can be estimated by measuring all combinations of distances among a linear array of points, traditionally a "calibration baseline". Each point would have its unidimensional coordinate so that an observation equation can be formed as

$$[d + z_o] + v = x_j - x_i \quad \Rightarrow \quad d + v = x_j - x_i - z_o \tag{3.14}$$

in which d is the instrument output corrected for alignment and atmospheric conditions. The coordinates, except for that of the point at one end (say, $x_o = 0$), and the additive constant are the unknowns. So, if there are four or more points, redundancy is created and least squares estimates can be made in a linear parametric adjustment following Equations (3.1) and (3.2). A unique solution can be obtained with only three points but there is no statistical assessment. By contrast, an array of six points provides a redundancy of nine and the 15 observations can be made in, at most, five hours with the common precision EODMI. The value of z_o can be in excess of 80 mm (e.g., in the Tellurometer model MA200) and can vary among different combinations of reflector and EODMI. Usually, the value for the correction can be coded in the instrument but the value can be inadvertantly changed or cannot accommodate all reflectors being used. Therefore, the application of the additive constant should be done explicitly, with regard for the corresponding value for each reflector and in response to currently estimated values.

Rüeger [1990] offers an algorithm for solving for the additive constant and the baseline coordinates that is suitable for use on a calculator; however, it assumes all of the distances to have equal weight, i.e., $\mathbf{P} = \mathbf{I}$. This assumption is not valid, especially when there is a broad variation in magnitude in the distances. The linear array of points, whether a formal baseline or an *ad hoc* setting out of forced centering on tripods, should be arranged to involve a variety of distances, say from 50 m to 1000 m, as would be encountered in the use of the EODMI. It is well known that the variance of a distance, s, is given by

$$\sigma_s^2 = a^2 + b^2 s^2 \tag{3.15}$$

rather than "$(a + bs)^2$" as given in Rüeger [1990]. The constant component, a, is in the order of 0.3 mm to 0.5 mm and the proportional component, b, is 2 ppm for precision EODMI. Using 0.3 mm and 2 ppm, a 50 m distance would have a variance of 0.1×10^{-6} m^2 and a 1000 m distance, 4.1×10^{-6} m^2. The relative weights would differ by 40 times - certainly significant when the highest precision is sought.

For whatever reason, the value of z_o may change by an amount Δz_o between two campaigns. If the distances in a network are all of nearly the same magnitude, s, then the change may be misinterpreted as a change in scale, $\Delta z_o/s$, between the two campaigns.

Since the monitoring schedule would likely extend over several years with measurements at any time of the year, seasonal variations, particularly in temperature must be taken into account when using EODMI. This is normally the case when EODMI are used for "absolute" distance measurements in which true metres are desired. Even though the absolute value of a distance is not necessary in deformation monitoring since the differences are of interest, reduction of EODMI output for meteorological conditions is necessary in order to account for these seasonal variations and to allow campaign adjustments. Rüeger [1990] discusses the reduction and accuracy required for the measurement of wet and dry bulb temperature and atmospheric pressure.

For an EODMI using visible or near infrared radiation, it can be shown that the refractive index, n_L, which directly affects the scaling of the EODMI output, is affected by the dry bulb temperature, t, partial water vapour pressure, e, and atmospheric pressure, p, by the differential combination (following Rüeger [1990])

$$dn_L \, x10^6 = -0.886 \, dt \; -0.037 \, de \; +0.267 \, dp \tag{3.16}$$

at the conditions of t = 30°C, p = 1010 mb, and e = 26 mb. By following the same approach with the addition of the wet bulb temperature, t' = 24 °C, the partial water vapour pressure is related to the measurement of pressure and the two temperatures by the differential combination

$$de = -0.00397 \, dp \; -0.6686 \, dt \; +2.457 \, dt'. \tag{3.17}$$

In order to see how well the temperatures and pressure must be known, the coefficients of Equations (3.16) and (3.17) are squared in the expressions for the combination of variances as

$$\sigma_n^2 \, [ppm^2] = 0.0712 \, \sigma_p^2 \, [mb^2] + 0.7844 \; \sigma_t^2 \, [°C^2] + 0.00137 \; \sigma_e^2 \, [mb^2] \tag{3.18}$$

$$\sigma_e^2\,[mb^2] = 15.78x10\text{-}6\ \sigma_p^2\,[mb^2] + 0.4470\ \sigma_t^2\,[°C^2]$$

$$+\ 6.0377\ \sigma_{t'}^2\,[°C^2]. \tag{3.19}$$

If the contribution of these measurements to the variance of the refractive index is not to exceed 1 ppm, then, from Equation (3.18), the pressure can be measured to ±2.2 mb and the dry bulb temperature, to ±0.65 °C. Since the partial water vapour pressure can be known to ±15.6 mb, the wet bulb temperature is not as critical (±6.3 °C, as shown in Equation (3.19)). This means that the pressure and the temperature (dry bulb) must be known to 2.2 mb and 0.65 °C, respectively, along the whole of the path in order for the influence to be limited to 1 ppm. To do so would be quite challenging both in the execution of the measurements and in the computations. As a compromise, the temperatures and pressure should be measured at both the instrument and at the reflector and the mean value of the refractive index should be used in the reductions. Consequently, the value of the proportional component of the variance in Equation (3.15) is rarely less than 2 ppm. Having to know the temperature to 0.6 °C and the pressure to 2 mb requires the use of self-aspirating psychrometers and a barometer of appropriate resolution that is calibrated against an on-site stationary mercury barometer.

3.2.2 Geotechnical

Geotechnical instrumentation is a broad category that encompasses the measurement of physical and mechanical properties, as well as the geometric state, of an object. Generally, the contrast with geodetic instrumentation is a matter of extent, isolation, and localization of sensing. It is the isolation of geotechnical instrumentation and the consequence that there is little opportunity for redundancy, apart from repetition of readings which make their testing and calibration important. Hanna [1985], Bartholomew and Haverland [1987], Bartholomew et al. [1987], Dunnicliff [1988], and Beckwith and Marangoni [1990] discuss the installation and use of instrumentation. Dunnicliff [1988] stresses the importance of calibration but gives little detail since most procedures would be specific to a particular instrument. The same holds true here but several comments are appropriate.

The use of geotechnical observables in an integrated analysis requires the x,y,z coordinates of the points involved or, as in the case of extensometers, at least the separation, d, between anchor points. If the change, δd, in the separation is observed, then the strain, s, between the two points can be derived from $s = \delta d/d$, provided that the material can be considered homogeneous in the region between the two anchors. Then, it is necessary to stipulate how well the value of d must be known. Taking the parial derivatives and propagating variance results in the expression

$$\sigma_s^2 = [\delta d^2/d^4]\sigma_d^2 + \sigma_{\delta d}^2/d^2. \tag{3.20}$$

If the variances of both d and δd contribute equally, then the standard deviation for d can be obtained from

$$\sigma_d = \pm[d/\delta d]\,\sigma_{\delta d}. \tag{3.21}$$

With d = 10 m and $\sigma_{\delta d}$ = ±0.05 mm for example, σ_d will need to be ± 0.5 and 0.05 m for δd of 1.0 and 10.0 mm, respectively. If $\sigma_{\delta d}$ is ±0.1 mm instead, then the value of σ_d will be twice as much as well. Therefore, if the points have been coordinated (x,y,z known to the nearest centimetre), the three dimensional inverse can be used to obtain a value for d to be used in the calculation of the corresponding strain.

The value of the separation can be calculated the same way for either rod or tape (or wire) extensometers. However, the use of tape extensometers requires additional consideration. When not fully supported, the tape will hang in the shape of a catenary, the distance along which is longer than the straight line distance between the anchor points. The difference between the two lengths will vary according to the amount of tension that is applied along the tape. This difference is the "sag correction" applied in taping and is expressed by [Davis et al., 1981]

$$c_s = W^2L/(24P^2) \tag{3.22}$$

in which W [kg] is the mass of the portion, L [m], in suspension under a tension of P [kgf] (1 kgf = 9.80665 N). Equation (3.22) shows that the tension influences the amount of sag. In addition, the tension affects the actual length along the tape. If the tape is used under a tension of P when it is intended to be used under a tension of P_o, then the correction to be applied (added to L) is [Davis et al., 1981]

$$c_P = L(P - P_o)/(aE) \tag{3.23}$$

with a cross-sectional area, a, and with E being the modulus of elasticity of the material of the tape. It is obvious from Equations (3.22) and (3.23) that the tension must be the same for every measurement or that it is known for every measurement and a correction is applied.

Examining the corrections expressed by Equations (3.22) and (3.23) can reveal how well the tension must be known in using a tape or wire extensometer. Taking the partial derivatives of the two equations and combining them for an expression of the contribution of the tension results in

$$\sigma^2 = \{ [W^2L/(12P^3)]^2 + [L/aE]^2\} \sigma_P^2. \tag{3.24}$$

Considering the Kern Distometer ISETH [Kern Swiss, 1977] using a 1.0 mm diameter invar wire (E = 145 GPa, density of 8000 kgm^{-3}) under a tension of 8 kgf and over a length of 25 m in Equation (3.24) shows that knowing the tension to ±5 grams will affect the length by ±0.01 mm, the resolution of the dial gauge of the Distometer. In comparison, the Mk II Tape Extensometer [Soil Instruments Limited, 1983] uses a band of invar that is 13 mm by 0.2 mm under a tension of 12 kgf, resulting in a length change of ±0.05 mm (its resolution) from a change of ±50 grams in tension.

Tape or wire extensometers are designed to apply a known tension at each measurement usually by a coil spring as part of the apparatus, e.g., the Distometer ISETH [Kern Swiss, 1977] which uses invar wire and the Mk II Tape Extensometer [Soil Instruments Limited, 1983]. The problem is whether that tension is really known or at least constant for each use. The Distometer is accompanied by a calibration stand (invar, 0.74 m long) which allows setting of the tension to the designed 8 kgf as a regular part of its use. By contrast, the Mk II has a "1 m gauge" (anchors attached to an aluminium bar) [Soil Instruments Limited, 1983] but has no provision for checking the tension and has some history of its spring aging and therefore weakening [Chrzanowski and Secord, 1990]. Both the calibration stand and the gauge allow for the checking of the consistency of the instrument itself, without wire or tape. Other aging effects that involve the wire or tape as well as the instrument, such as gradual wearing of the index perforations of the tape (spaced every 25 mm), cannot be tested using the stand or gauge. The testing and calibration should be performed on the whole apparatus, i.e., including the assortment of possible wire lengths or the various lengths of tape, as used in the repeated measurements.

Consequently, it is necessary to provide a calibration area for the tape extensometer. Typically, the extensometer would be used to measure separations up to 25 m. A linear array of anchors can be set up at distances of 5, 10, 15, 20, and 25 m from the one end. The five separations can be monitored using invar rod extensometers at the same time as the calibration measurements so that the changes in the five separations are known and corrections can be applied to the tape extensometer readings. If the tape is at the same temperature as the rods, then no temperature correction is necessary.

If the ambient temperature at any of the rod, tape, or wire extensometer locations is not constant, a correction (or reduction) to a standard temperature will be necessary. If the standard temperature is t_o and the measurements have been made at a temperature of t, then the correction (added to L) is [Bomford, 1971]

$$c_t = \alpha L(t - t_o) + \beta L(t - t_o)^2 \tag{3.25}$$

with α being the coefficient of thermal expansion for invar (typically, 0.9 ppmK^{-1}). The term including the β coefficient is generally small enough to disregard for values of $(t - t_o)$ normally encountered [Kaye and Laby, 1966]. Sometimes, steel is used for the rods since it has the same coefficient of thermal expansion as concrete (10 to 15 ppmK^{-1}). Aluminium may be used for its light weight and less cost but it has a value of 23 ppmK^{-1} which makes its reaction to temperature the most dramatic.

It is possible to sense movement electronically, with output from the device as voltage or frequency and possibly conversion to linear units in the readout unit. An example of a voltage output device is a linear variable differential transformer (LVDT) [Beckwith and Marangoni, 1990]. LVDTs are convenient for attachment to rod extensometers and a readout unit is required to supply an input voltage. Frequency is the output when noncontact is desired, such as in the sensing of movement of a plumbline with respect to its reading table. When either voltage or frequency, rather than linear units, is being recorded, the testing and calibration of the sensor should be done with the sensor installed rather than separately before installation. Wroblewicz [1993] has found significant discrepancies (in the order of 1 mm) between both ways of calibrating LVDTs, likely a consequence of the length of connection between the sensor and its display unit. Even better would be the incorporation of the facility for occasional checking by direct mechanical means with the sensor in place and operating.

With switching among several devices, one readout unit can serve several locations. Even if the output is in linear units, it is good practice to compare the output with a direct measurement of displacement over the full range of the device. This should be done at the time of installation, especially if there is a considerable length of cable connecting the device to the output unit. It is advisable to make regular comparisons of the electronic output with the mechanical measurement of the same position. Therefore, the reading head (of an extensometer) or table (of a plumbline) should be designed to accommodate both styles of sensing. This would likely be possible if an already mechanical system is being automated.

In most cases, the manufacturer supplies a conversion factor or nomogram for each individual device or for all of the same model. As Dunnicliff [1988] emphasizes, it is necessary to calibrate a device, preferrably *in situ*, at the time of installation. This will provide a more appropriate conversion, ensuring whether it is a linear factor, and an indication of the range over which the conversion can be used. There should be sufficient data points to result in an acceptable statistical assessment, particularly if the factor is not really linear. Since the data will be collected either by direct interfacing or through keyboard input to a data collector, it is a simple matter to introduce conversion factors that are more complicated that a simple linear coefficient. Sometimes, it is enough to compare the unconverted readings with previous or predicted values in the field and to perform the actual conversion during the processing on the office microcomputer.

3.3 Data Capture and Processing

The value of an observable is observed or captured with possibly some immediate processing. Further processing reduces the information into a form which can be used with other observations in a campaign adjustment or can be appended to a data series. Because it is likely that some processing will occur immediately upon capturing the data, the two actions are being considered together. Nonetheless, processing occurs simultaneously with capture and subsequent to capture with different tasks at each time.

During capture, the points involved must be identified and ancillary observations, such as temperature, must be requested along with dealing with the observation. The observation would likely be repeated in order to obtain a mean and an estimate of its standard deviation and the mean would be compared with the predicted or most recent value as a check on consistency. Once the mean is acceptable, it is stored for further processing and another observable can be pursued.

Subsequent processing would further reduce the observation and place the data into the series file or campaign file following the structure of the data mangement system. The data would be immediately archived for security. Consistency would be checked either again for the observation or further for the reduced data.

Geodetic observations are traditionally combined into campaign adjustments which provide additional statistics on the quality of the data. In contrast, geotechnical observations are treated usually in isolation. As mentioned earlier, it is possible to consider geodetic obsevations individually as well. Therefore, a distinction is made below between observations by campaign and observations by individual measurement.

3.3.1 By Campaign

Geodetic observations can be combined together in several ways to allow campaign adjustments: horizontal or two dimensional (angles or directions only, "triangulation"; distances only, "trilateration"; angles, or directions, and distances together, "triangulateration"); vertical or one dimensional (height differences only, "levelling"); or a combination in three dimensions. Angular observations are normally done in at least two sets. The sets are combined together in a station adjustment to yield mean values and an estimate of the standard deviation. This allows screening at the time of observation to ensure that the means are acceptable and to lead to additional sets in order to achieve the required precision. A distance would be measured by precision EODMI and would also require sufficient remeasures to ensure an acceptable mean. In addition, the wet and dry bulb temperatures and pressure at the instrument and reflector would be required along with the heights in order to reduce the observation. The elevations of the stations would be used in the subsequent processing to reduce the observation to the appropriate computational surface. Zenith angles would not likely be used since precision EODMI are separate instruments and the accurcy of the reduction using zenith angles is inferior to using elevations. Also elevations, or at least height differences, would likely be known from the vertical component of the monitoring scheme. In addition to the actual observations, measurements on a calibration baseline would be done immediately at the beginning and at the end of a campaign. These measurements would follow the same processing route as the campaign observations, i.e., reduction to an appropriate computational surface. Levelling is usually checked at the time of observation by considering the misclosure between measurements in both directions along a route between two benchmarks and is later weighted according to the number of setups associated with the height difference measurement. Consistency can also be checked by comparing the current height difference with the most recent measurement, especially if the frequency of measurement is monthly or more often.

3.3.2 By Individual Measurement

When an observation is isolated, it is important to ensure its acceptable precision and consistency. The mean and associated standard deviation can indicate when enough repetitions have been made. Comparison with a predicted or most recent value will offer a check on its consistency. Some measurements may require the ancillary observation of temperature and the current observation may have to be corrected for the ambient temperature before it can be compared. Subsequent processing would convert or reduce the observation to the appropriate form of data for its series. This reduction may require measurements on a calibration base at the beginning and end of each campaign if not each day, e.g., for a tape or wire extensometer. The processing would have to recognize which calibration measurements would be used for particular observations.

4. TREND ANALYSIS

The intermediate link between the observations and the modelling is the trend analysis. The type and location of the observables have been based on the expected deformation or have been constrained, by topographic features or the shape of the structure, in possible locations or by observing procedures or by both. Once more than one campaign has been observed or once enough data are contained in a series, it is necessary to determine the tendency that is being exhibited in space or over time or both. The observed tendencies are then brought together to suggest possible forms of models, i.e., the choice of parameters to be estimated. The trend analysis acts as a filter by extracting the behaviour of interest, e.g., the annual trend or rate, from the time series, e.g., the noise being the seasonal cycle that is a reaction to the change in temperature. The extracted trends become the input or "observations" in the modelling and, therefore, it is necessary to have measures of variance associated with each trend. The spatial trend can be derived for one or two dimensional networks by considering the differences in coordinates estimated in the individual campaign adjustments, i.e., comparing campaigns. Spatial trend can also be derived vertically, for subsidence profiles, and horizontally, for plumbline or borehole profiles along or across the structure.

The author has contributed to the trend analysis by creating the graphical depiction of the temporal or spatial trend, by providing for the combination of series to create derived series. In addition, he has automated the fitting and integrated it within a data management system so that predicted values could be generated.

4.1 Campaign Comparison

In Section 3.1.1, there was some discussion concerning campaign comparison for the design of monitoring schemes. Here, the concern is with the comparison of campaigns once the measurements have been completed and the deformation is to be modelled. Basically, it would seem that the comparison is merely the differencing of coordinates. With the first campaign resulting in $\underline{\mathbf{x}}_1$ at t_1 with $\mathbf{C}_{x1} = \underline{\sigma}_{o1}{}^2\mathbf{Q}_{x1}$ and the second campaign giving $\underline{\mathbf{x}}_2$ at $t_2 > t_1$ with $\mathbf{C}_{x2} = \underline{\sigma}_{o2}{}^2\mathbf{Q}_{x2}$, the displacements are $\mathbf{dx} = \underline{\mathbf{x}}_2 - \underline{\mathbf{x}}_1$ with $\mathbf{C}_{dx} = \mathbf{C}_{x1} + \mathbf{C}_{x2}$. Unfortunately, it cannot be as straightforward as this for three major reasons. Firstly, it is rare in deformation monitoring that the coordinate system in which the adjustment is done has been absolutely defined. Consequently, the network suffers from one or more datum defects which must be removed by constraining the solution for the $\mathbf{x}_i$. Secondly, the values of $\underline{\mathbf{x}}_i$ and $\mathbf{Q}_{xi}$ will depend on the choice of constraints. The displacement field, $\mathbf{dx}$, is also dependent on the choice and cannot be created unless $\underline{\mathbf{x}}_1$ and $\underline{\mathbf{x}}_2$ have been estimated with the same constraints. Thirdly, in the context of this thesis, the network consists of reference stations and object points, the movements of which are described with respect to the reference stations. In order for this to be valid, the reference stations, or at least a majority of them, must be stable from campaign to campaign to preserve the reference. If the points that have been chosen to define the datum are not stable then the reference has been lost. Therefore, the comparison of campaigns must be concerned with the evaluation of individual campaigns and with the detection of unstable reference stations.

4.1.1 Evaluation of Individual Campaigns

If n_o observables are related to n_s stations, or points, in a network, then the coordinates of the stations are estimated following

$$\boldsymbol{\ell} + \mathbf{v} = \mathbf{A}\mathbf{x} \tag{4.1}$$

with $\mathbf{P}_{\ell} = (\sigma_o^2\mathbf{Q})^{-1}$. If the elements of $\mathbf{x}$ are elevations, their estimation is the linear parametric case. If two or three dimensional coordinates are to be estimated, the solution for $\mathbf{x}$ requires iterations in which the elements of $\mathbf{x}$ are corrections to the initial approximations since the parametric case is not linear and the elements of the design matrix, $\mathbf{A}$, must be updated. The following discussion is modified from Cooper [1987] and Chen et al. [1990b] and pertains to either case. It is presented here since it will also be needed in preparation for the discussion in Chapter 5 on deformation modelling.

The least squares solution to Equation (4.1) is obtained by solving

$$\mathbf{A}^T\mathbf{Q}^{-1}\mathbf{A}\mathbf{x} = \mathbf{A}^T\mathbf{Q}^{-1}\boldsymbol{\ell} \;\Rightarrow\; \mathbf{N}\mathbf{x} = \mathbf{u} \tag{4.2}$$

which requires the definition of the datum since **N** is singular as a result of the defects in the network. The datum can be defined by constraints, or a system of datum equations (one for each defect), in the form

$$\mathbf{D}^T\mathbf{x} = \mathbf{0}. \tag{4.3}$$

In the worst case, there could be a defect of four in defining the datum in two dimensions: translation in x, T_x; translation in y, T_y; rotation or orientation, ω; and scale, k. Triangulation would carry all four defects. Trilateration or triangulateration would have the scale defined and so there would be three defects. The use of satellite Global Positioning System (GPS) baseline components, projected onto the plane, would account for scale and orientation, so a defect of two results. A levelling network would have one defect, the elevation of one of the stations. If the coordinates, x_i and y_i, of a point are corrected by the amounts δx_i and δy_i and if the differences between coordinates for any two points are $\Delta x_{ij} = x_j - x_i$ and $\Delta y_{ij} = y_j - y_i$, the defects can be expressed for Equation (4.3) in the following manner. To define the scale, the distance, s_{ij}, between two stations remains invariant so $s_{ij}^2 = \Delta x_{ij}^2 + \Delta y_{ij}^2$. Taking the partial derivatives of this expression results in the scale constraint equation

$$- \Delta x_{ij}\,\delta x_i - \Delta y_{ij}\,\delta y_i + \Delta x_{ij}\,\delta x_j + \Delta y_{ij}\,\delta y_j = 0. \tag{4.4}$$

To define the orientation, the azimuth, α_{ij}, between two points does not change so that $\tan \alpha_{ij} = \Delta x_{ij}/\Delta y_{ij}$ and differentiation leads to the rotation constraint equation

$$- \Delta y_{ij}\, \delta x_i + \Delta x_{ij}\, \delta y_i + \Delta y_{ij}\, \delta x_j - \Delta x_{ij}\, \delta y_j = 0 \tag{4.5}$$

To counter the translation defect, the coordinates of one station are "fixed" (not changed during the adjustment) and the constraint equations are

$$\delta x_i = \delta y_i = 0. \tag{4.6}$$

Equations (4.4), (4.5), and (4.6) provide the coefficients for the **D** matrix with a row for each δx_i and δy_i and a column for each constraint component. With all defects in a horizontal network, **D** is populated as

$$
{}_{2ns}\mathbf{D}_4 = \begin{array}{c}
\\ \delta x_1 \\ \\ \delta x_k \\ \delta y_k \\ \\ \delta x_i \\ \delta y_i \\ \\ \delta x_j \\ \delta y_j \\ \\ \delta y_{ns}
\end{array}
\begin{array}{c}
\begin{array}{cccc} T_x & T_y & \omega & k \end{array} \\
\begin{bmatrix}
0 & 0 & 0 & 0 \\
. & . & . & . \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
. & . & . & . \\
0 & 0 & -\Delta y_{ij} & -\Delta x_{ij} \\
0 & 0 & +\Delta x_{ij} & -\Delta y_{ij} \\
. & . & . & . \\
0 & 0 & +\Delta y_{ij} & +\Delta x_{ij} \\
0 & 0 & -\Delta x_{ij} & +\Delta y_{ij} \\
. & . & . & . \\
0 & 0 & 0 & 0
\end{bmatrix}
\end{array} \tag{4.7}
$$

In the above version of **D**, the k^{th} station has been held fixed; the azimuth is from the i^{th} station to the j^{th} station; and the distance is between the i^{th} station and the j^{th} station. If the i^{th}, rather than the k^{th}, station had been held fixed, its coefficients for ω and k would be zero. These coefficients are equivalent to those in Chen et al. [1990b] apart from a factor of s_{ij} which has been eliminated. The form of **D** in Equation (4.7) would be used in triangulation. The fourth column, for k, would not be used for trilateration or triangulateration. Levelling would require **D** as a vector of n_s elements, all zero except for a one in the element corresponding to the station whose elevation is fixed to define the datum.

With an appropriately populated **D** matrix, Equation (4.2) can be solved by [Chen, 1983; Chen et al., 1990b]

$$\underline{\mathbf{x}} = (\mathbf{N} + \mathbf{D}\mathbf{D}^T)^{-1}\mathbf{u}. \tag{4.8}$$

However, the calculation of the cofactor matrix for $\underline{\mathbf{x}}$ is complicated by requiring a correction provided by using a matrix **H**, having the same rank as **D** and having elements such that $\mathbf{NH} = \mathbf{0}$. The elements of **H** are related to the centroid of the network, (x_o,y_o). The original coordinates, (x'_i,y'_i), are transformed so that

$$(x_i,y_i) = (x'_i, y'_i) - (x_o, y_o). \tag{4.9}$$

with

$$x_o = \frac{1}{n_s}\sum_{k}^{n_s} x'_k \text{ and } y_o = \frac{1}{n_s}\sum_{k}^{n_s} y'_k$$

There is a column in **H** for each defect and a row for each coordinate component, in contrast to the **D** matrix in which there are non-zero elements only for those stations involved in the constraints. So,

$$
{}_{2ns}\mathbf{H}_4 = \begin{array}{c} \\ \delta x_1 \\ \\ \\ \delta x_i \\ \delta y_i \\ \\ \\ \delta y_{ns} \end{array} \begin{array}{c} \begin{array}{cccc} T_x & T_y & \omega & k \end{array} \\ \begin{bmatrix} 1 & 0 & -y_1 & x_1 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 1 & 0 & -y_i & x_i \\ 0 & 1 & x_i & y_i \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 0 & 1 & -y_{ns} & x_{ns} \end{bmatrix} \end{array} . \tag{4.10}
$$

As for the **D** matrix, columns of the **H** matrix are discarded if there are fewer defects. In a levelling network, **H** becomes a vector of n_s elements, each of which is one. The cofactor matrix corresponding to $\underline{\mathbf{x}}$ in Equation (4.8) is obtained from [Chen et al., 1990b]

$$
\mathbf{Q}_{\underline{x}} = (\mathbf{N} + \mathbf{D}\mathbf{D}^T)^{-1} - \mathbf{H}(\mathbf{H}^T\mathbf{D}\mathbf{D}^T\mathbf{H})^{-1}\mathbf{H}^T. \tag{4.11}
$$

Both Equations (4.8) and (4.11) allow the use of regular inverses.

Some network adjustment programs, e.g., GEOPAN [Steeves, 1979], require the imposition of constraints in a different manner since they were written to adjust control surveys and densification. The translation components are compensated by fixing the coordinates of one station so the corresponding columns of the A matrix are discarded. The rotation or scale or both can be constrained by including ficticious observations with small standard deviations, e.g., ±0.01" and ±0.00001 m. Numerical problems may result from ill-conditioning of the **N** matrix if such an approach is followed on a small computer [Chen et al., 1990b].

A solution with respect to any other datum, $\underline{\mathbf{x}}_S$, can be transformed into the solution given by Equations (4.8) and (4.11) by the similarity transformation (see Chen [1983] and Chen et al. [1990b])

$$\underline{\mathbf{x}} = \mathbf{S}_o\underline{\mathbf{x}}_S \quad \text{and} \quad \mathbf{Q}_{\underline{x}} = \mathbf{S}_o\mathbf{Q}_{xS}\mathbf{S}_o{}^T \tag{4.12}$$

with

$$\begin{aligned} \mathbf{S}_o &= \mathbf{I} - \mathbf{H}(\mathbf{D}^T\mathbf{H})^{-1}\mathbf{D}^T \\ &= \mathbf{I} - \mathbf{H}(\mathbf{H}^T\mathbf{D}(\mathbf{D}^T\mathbf{D})^{-1}\mathbf{D}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{D}(\mathbf{D}^T\mathbf{D})^{-1}\mathbf{D}^T \\ &= \mathbf{I} - \mathbf{H}(\mathbf{H}^T\mathbf{W}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{W}. \end{aligned}$$

The **W** matrix acts as a form of weighting in matrix $\mathbf{S}_o$ and Equation (4.12) is called the "weighted similarity transformation". The inner constraints solution results if $\mathbf{W} = \mathbf{I}$ so that all of the stations together define the datum. If only certain stations are involved in the constraints, the elements of the diagonal **W** matrix are zero except for the stations involved in the constraints where they are one.

The *a posteriori* variance factor is estimated by

$$\underline{\sigma}_o{}^2 = \underline{\mathbf{v}}^T\mathbf{P}\underline{\mathbf{v}}/\nu \tag{4.13}$$

with $\underline{\mathbf{v}} = \mathbf{A}\underline{\mathbf{x}} - \boldsymbol{\ell}$ and $\nu = n_o - n_u + n_d$. The number of degrees of freedom, ν, is the combination of n_o, the number of observations; n_u, the number of unknowns; and n_d, the number of defects in the network. The χ^2 test on $\underline{\sigma}_o{}^2$ and the testing of residuals for outliers [Vanicek and Krakiwsky, 1986] would be performed to ensure that the outcome of the adjustment is acceptable.

4.1.2 Detection of Unstable Reference Stations

Since the $\underline{\mathbf{x}}_i$ can be transformed to the same datum, the displacement components with respect to a pair of campaigns can be determined from

$$\mathbf{dx} = \underline{\mathbf{x}}_2 - \underline{\mathbf{x}}_1 \quad \text{with} \quad \mathbf{Q}_{dx} = \mathbf{Q}_{\underline{x}1} + \mathbf{Q}_{\underline{x}2}. \tag{4.14}$$

Further, $\mathbf{C}_{dx} = \sigma_{op}^2\mathbf{Q}_{dx}$ with $\sigma_{op}^2 = (\nu_1\underline{\sigma}_{o1}^2 + \nu_2\underline{\sigma}_{o2}^2)/\nu_p$ and $\nu_p = \nu_1 + \nu_2$ provided that $\underline{\sigma}_{o1}^2$ and $\underline{\sigma}_{o2}^2$ are statistically compatible (see Chen [1983], Vanicek and Krakiwsky [1986]). If they are not compatible, the relative weighting between the two campaigns must be investigated for inconsistencies.

The **dx** has been created under the assumption that the reference stations are stable, i.e., that they have not changed position between the two campaigns. To ensure that this assumption is valid, it is necessry to transform the **dx** into a form that is independent of the choice of the datum in the estimation of the $\underline{\mathbf{x}}_i$ [Chen, 1983; Secord, 1985]. This is accomplished by the iterative weighted similarity transformation (sometimes called the "weighted projection") using a form similar to Equation (4.12). The coordinates of the reference stations and their cofactor elements are segregated by extracting them from **dx** and $\mathbf{Q}_{dx}$ to yield $\mathbf{dx}_r$ and $\mathbf{Q}_{dxr}$. The transformation is effected through

$$\underline{dx}_r = \mathbf{S}\mathbf{dx}_r \quad \text{and} \quad \mathbf{Q}_{\underline{dx}r} = \mathbf{S}\mathbf{Q}_{dxr}\mathbf{S}^T \tag{4.15}$$

with $\mathbf{S} = \mathbf{I} - \mathbf{H}(\mathbf{H}^T\mathbf{W}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{W}$ as in Equation (4.12) and matrix **H** being the same as in Equation (4.10), with a column to account for every defect involved in the two campaigns, i.e., the "union" of all defects [Chen et al., 1990] and with a row for each coordinate component of the reference stations. The elements of the weight matrix are functions of the displacement components in the transformation. Consequently, iteration in the transformation is necessary. Initially, $\mathbf{W} = \mathbf{I}$ and, in subsequent iterations, **W** is populated by the displacement components of the previous iteration. So, the i^{th} diagonal component at the k^{th} iteration is $w_{ii}^k = (|dx_{rii}^{k-1}| + \delta)^{-1}$. As the iterations occur, some of the dx_{rii} will become effectively zero. The δ is a small number, e.g., the convergence criterion in the iterations, which allows the w_{ii} to become very large as the corresponding displacement becomes very small, preventing possible numerical instabilities such as division by zero. Convergence is achieved once each of the displacement components is no different in magnitude from its value at the previous iteration by the amount δ and, by then, the **S** matrix has been created and the $\mathbf{Q}_{\underline{dx}r}$ can be transformed. The elements of $\mathbf{Q}_{\underline{dx}r}$ are then used in determining the significance of the displacement of each station, $d_i = (dx_{xi}^2 + dx_{yi}^2)^{1/2}$, compared to its $(1 - \alpha)$ confidence level (see, e.g., Chen [1983]; Secord [1985]; Vanicek and Krakiwsky [1986]). Two dimensional displacements are usually depicted as plots against their confidence ellipses, being significant when extending beyond the region of the ellipse. This is an illustration of the spatial trend over the time interval between the two campaigns.

The reference stations with significant displacement must then be considered as not being stable over the interval between the two campaigns. They must be segregated from the rest of the reference stations, as separate object points, during subsequent analyses (Chapter 5).

4.2 Time Series

A time series is created for each observable from the repeated observations y'_i at times t'_i which may not necessarily coincide with the times of other series. It is of interest to compare the behaviour of a series with other quantities and behaviour at other locations within the structure. Most structures change dimension in reaction to the changes in temperature experienced over the course of a year. It is not uncommon to see extremes of -35°C to +35°C, a change of 70°, over one year. The consequent cyclic nature of the behaviour may be of interest or the long term trend over several years may be considered more important. Details of cyclic trend analysis have been given in Section 3.1.2. Generally, a series may be described by

$$y = a_1 \sin \omega t + a_2 \cos \omega t + a_3 t + a_4 \; [+ \; a_5 \delta(t) + \ldots \qquad (4.16)$$

with $\omega = 2\pi$ for a period of one year if t is in years (see Equation 3.6). The sinusoid corresponding to the cyclic trend is described by the a_1 and a_2 terms. From them, the amplitude and phase can be derived (Section 3.1.2). The rate or long term trend is given by a_3. The constant a_4 is a required "datum" slip so that the fitting is not forced to be zero at time zero. Additional constants ($a_5\delta(t)$ etc.) may be required to account for gaps, slips, or discontinuities within the data series. An example of such a series is given in Chapter 7 (Figure 7.12). Least squares estimates of the values of the a_i and statistical assessment of their significance can be performed since there are usually many more data points than the number of unknowns (at least four, see Section 3.1.2).

A change in the interval over which the series is analysed may result in a different value for the rate. The frequency of data may be different for two intervals of data in a series. This would result if a monitoring effort were being phased down so that observations occur less often. The shape of the sinusoid in the interval with the more frequent data tends to dominate the characteristics of the whole series. An example covering both these aspects is discussed in Chapter 7 (Figures 7.15, 7.16, and 7.17).

Additional cycles of duration shorter than one year may be possible. Additional terms would be included in the same form as those for a_1 and a_2 but with other values of ω, e.g., 4π for a twice yearly cycle. From these additional pairs of terms, the corresponding amplitude and phase can be derived. If the smallest interval between data is Δt, the ω can be chosen only so that the corresponding period is no shorter than $2\Delta t$ [Kanasewich, 1981]. Therefore, it is important to have some idea of the expected cycles when initially devising the frequency of observation to ensure that the cycle would be resolved in the subsequent trend analysis.

4.2.1 Combined Measurements or Derived Series

Series trend analysis is not limted to strictly observed series. If the members of two series, y'_i and y''_i, have been observed at time t_i, or at least closely enough to be considered at the same time, they can be combined together to form a derived series, e.g., $y_i = y'_i + y''_i$, at t_i. Two examples of simple derived series are in multi-rod borehole extensometers and in several table readings along a plumbline. Series can also be derived, through a simple combination of height differences, to reveal vertical extension within a structure. A more complicated derivation of principal strain can be made from individual strain gauges installed in a rosette.

In the multi-rod extensometer, rods of various lengths are anchored within a borehole with each rod extending to the collar at the mouth of the borehole where readings are taken at each rod with respect to the collar. The original series would be r_1 for collar to anchor 1 at depth d_1, r_2 for collar to anchor 2 at depth $d_2 > d_1$, r_3 for collar to anchor 3 at depth $d_3 > d_2$, etc. These would show the change in length between the collar and each of the anchors. The change in length between any pair of anchors within the multi-rod cluster would be the derived series, e.g., anchor 2 to anchor 3 would be the series $r_3 - r_2$ over a distance of $d_3 - d_2$. The items in the derived series would have the same times, t_i, as in the original since all of the rods would have been measured at practically the same time.

If several reading tables are located along a plumbline, the original series would be the readings at each table. A derived series would be the difference between the table readings at two different elevations to reflect the relative horizontal movement between the two tables. It would be created in virtually the same manner as for the multi-rod extensometer.

Repeated geodetic horizontal or vertical campaigns can also lead to derived series. From the estimated two dimensional coordinates, distances can be derived and treated in the same manner as any other form of extensometer. Height differences can be obtained from estimated elevations. If the monumented points are coordinated so that horizontal distances are known or if they are measured, the height differences can be converted into tilts. The tilts arising from precision levelling (precision level with micrometer and invar staves) can easily rival any *in situ* tiltmeter in precision (± 0.05 mm over 1 m is

$\pm 10''$; over 5 m is 2"; over 10 m is 1"; over 30 m is 0.3") as well as being flexible enough to accommodate any base length.

If elevations are determined at several levels of a structure and if the levels are connected by invar wires, the vertical extension can be derived for any pair of points within the structure (Figure 4.1). Considering the campaigns at two different levels to have occurred at virtually the same time, relative to the expected deformation, allows the height difference between any two points, P_i and P_j, with the elevations of the zeroes, P_a and P_b, of the scales on the suspended invar plumblines or wires, to be expressed as $\Delta h_{ij} = E_j - E_i$ with $E_j = E_i + \Delta h_{ia} + \Delta h_{ab} + \Delta h_{bj}$. So, $\Delta h_{ij} = \Delta h_{ia} + \Delta h_{ab} + \Delta h_{bj}$ for which all elements can be considered at the k^{th} campaign, i.e., yielding $\Delta h_{ij}{}^k$ at t_k and creating the series. Because the scales, P_a and P_b, are attached to invar wire, Δh_{ab} can be considered as a constant, particularly if the temperature within the structure is reasonably consistent, even though the values of E_a and E_b might vary and Δh_{ab} may not really be known (each level is adjusted separately). The dependent variable in the series is really the change in Δh_{ij} from its initial value, i.e., $\delta(\Delta h_{ij}{}^k) = \Delta h_{ij}{}^k - \Delta h_{ij}{}^1 = [\Delta h_{ia} + \Delta h_{ab} + \Delta h_{bj}]^k - [\Delta h_{ia} + \Delta h_{ab} + \Delta h_{bj}]^1 = [\Delta h_{ia} + \Delta h_{bj}]^k - [\Delta h_{ia} + \Delta h_{bj}]^1$. The rate [mm/y] from the series can be converted into extension [mm/m/y or ppm/y] by dividing the rate by the vertical separation between P_i and P_j,

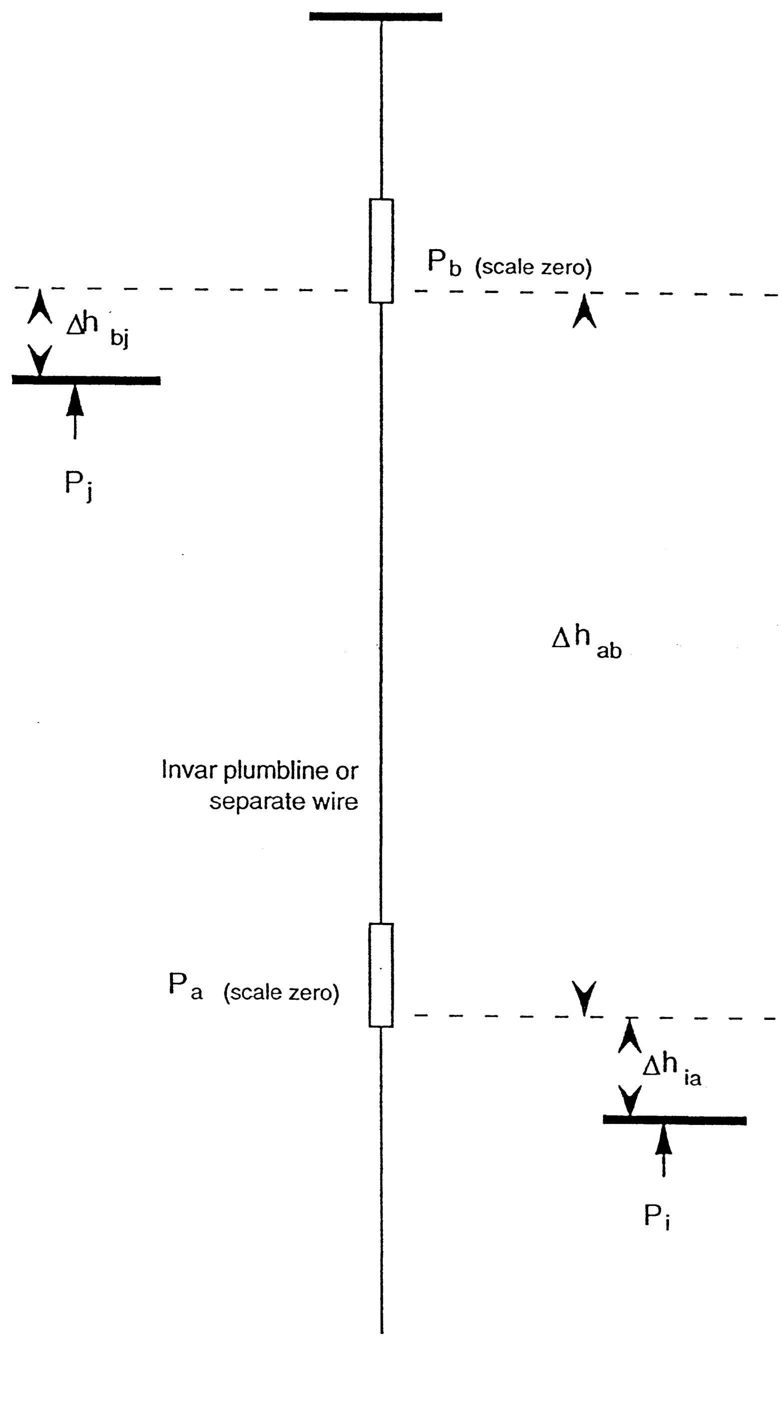


Figure 4.1. The derivation of changes in height differences
[Chrzanowski and Secord, 1991]

obtained as Δz_{ij} from the three dimensional coordinates of the observation points (benchmarks).

A derived series could easily be more complicated than the three examples given above. A set of strain gauges is often installed as a rosette. The individual gauge readings form the original series. The value of the principal strain and its orientation, with formulation depending on the rosette arrangement and orientation, can be calculated for the set of readings for each time of observation [Obert and Duvall, 1967]. The derived series would be of the principal strain and its orientation at that same time.

The units of a series may be changed after the fitting. If homogeneous strain is expected over the whole of the distance, extension between two anchor points, originally in millimetres, may be converted into strain, in millimetres per metre (10^{-3}) or in ppm (10^{-6}), by dividing by the distance between the two anchors. Relative movement between two reading tables, in millimetres, can be converted to tilt, in angular units, by dividing by the distance between the two tables.

4.2.2 Series Trend

In Equation (4.16), the long term trend was the rate, a_3, or the simple slope of the sinusoid. In some cases, this may not be enough to account for all of the long term behaviour. Particularly related to hydro-electric power and other dams, the approaches of several power authorities have been presented in the proceedings of various meetings of the International Congress on Large Dams (ICOLD) and in issues of Water Power and Dam Construction as well as independent publications by the authorities. Since there appears to be a general pattern in the style of modelling, i.e., the same types of parameters being considered, the approaches of four representative authors will be discussed here. In chronological order they are: Ente Nazionale per l'Energia Electrica (ENEL) [1980] from Italy; Guedes, Rosso, and Franco [1981] from Brazil; Silva Gomes and Silva Matos [1985] from Portugal; and Breitenstein, Köhler, and Widmann [1985] from Austria. Since the long term trend is modelled simultaneously with other trends, the whole model will be considered in each case.

The ENEL [1980] approach is to consider the displacement of a point "k" at a time "t" as being comprised of three components: a thermal component, $E_k(t)$; a water level component, $F_k(t)$; and an aperiodic, or drift, component, $G_k(t)$. Each component is a function of time and they combine together as a simple sum to form the resultant displacement: $\delta_k(t) = E_k(t) + F_k(t) + G_k(t)$. If temperatures, $I_i(t)$, have been measured at several locations, a simple polynomial is used to relate the n temperatures to the displacement at the point, so $E_k(t) = e_{k1}I_1(t) + e_{k2}I_2(t) = ... + e_{kn}I_n(t)$. If the temperatures have not been measured, sinusoids of up to p different periods, with $\omega = 2\pi$, are used to model the temperature effect: $E_k(t) = e_{11}\sin\omega t + e_{12}\cos\omega t + e_{21}\sin 2\omega t + e_{22}\cos 2\omega t + ... +$

$e_{p1}\sin p\omega t + e_{p2}\cos p\omega t$. In either way, the e_{ij} are the coefficients to be estimated. Since the effect of the water level is a function of time, i(t), then its component can be represented by the polynomial, $F_k(t) = a_0 + a_1 i(t) + a_2 i(t)^2 + a_3 i(t)^3 + ... + a_m i(t)^m$, with its a_i coefficients as unknowns. The long term trend is represented by the aperiodic (time dependent or irreversible) component and can take several forms, the most common of which is $G_k(t) = a_1 e^{-k_1} + a_2 e^{-k_2} + a_3 e^{-k_3} + ...$, with $k_j = (t - t_j)/T_j$ and the a_i to be estimated.

Guedes et al. [1981] present an approach similar to ENEL except for the expression for the long term drift which they call foundation or concrete creep. This time dependent displacement is expressed as $G(t) = c(1 - e^{-bt})$ in which "c" is the limit on the magnitude of the component and "b" is the rate at which the displacement tends toward that limit. For computation, this component is developed as a series with retention of the first four terms, so $G(t) = b_1 t - b_2 t^2 + b_3 t^3 - b_4 t^4$ with the b_i as unknowns.

Again, the approach by Silva Gomes and Silva Matos [1985] is similar to ENEL. They differ by considering the irreversible component as a simple third degree polynomial, i.e., $G(t) = a_1 t + a_2 t^2 + a_3 t^3$. This is virtually the same as Guedes et al. [1981].

Lastly, Breitenstein et al. [1985] differ in their treatment of the permanent deformation component by expressing it as $G(t) = a_1 t + a_2[\ln(1+ t/c_1)]^{1/c_2} + a_3[1 -$

e^{-t/c_3}] with the c_i as selected constants and the a_i to be estimated.

From the examples given above, it appears that the long term trend is described in exponential or logarithmic form. In all cases the result is depicted graphically and in most cases it is the combination that is shown. Therefore, a numerical or statistical assessment of its appropriateness is not available. Breitenstein et al. [1985] show a graph of the long term trend separately for the one structure used as an example. The period considered is ten years. It would be difficult to distinguish the curvature of their expression from a simple straight line, especially if the period were shorter than ten years. If a simple rate is used along with the expressions for the periodic behaviour, the pattern of the residuals with increased time would indicate whether a more sophisticated expression for the long term trend should be considered. Conversely, a polynomial to some reasonable order, say fourth as in Guedes et al. [1981], could be used initially with the elimination of statistically insignificant terms.

4.3 Spatial Series and Trend

Examining a series of repeated measurements is not restricted to considering their change on time. A series may also be related with respect to relative position in space. Either vertical profiles (subsidence or tilt) or horizontal profiles (change in relative position of points along a plumbline) can depict the relative deformation of points. The series is the ordered data with respect to position along a line. Thus, the independent variable is position along a line (unidimensional coordinate) rather than time. The profile is actually the relative change between the positions for points at two instances, i.e., between positions at two campaigns of measurement along the line.

4.3.1 Vertical Profiles

When the height differences are measured between pairs of vertical monuments (benchmarks) in succession along a line, the profile of the line can be described against progression along that line. The independent variable, x_k, would be the cumulative distance along the line as a sum of the distances between points or as calculated from the two dimensional coordinates of the points. The y_k, creating the profile of subsidence, is obtained from the height differences, Δh_{ij}, by $y_k = E''_k - E'_k$ with E'_k at t_1 and E''_k at $t_2 > t_1$. The E_k are the elevations of the k^{th} point during the campaign. In order to ensure a datum independence of the E_k, they are calculated from the successive height differences along the line as $E_k = \Sigma^k \Delta h_{ij}$, starting from the same stable point in both campaigns. The calculation of elevations may be rather arbitrary in each campaign if there is a simple single line of levelling so the profiles are based on the height differences rather than elevations. If a network of levelling can provide estimated elevations for a campaign, the height differences can be derived from them by $\Delta h_{ij} = E_j - E_i$. Thus, the plot of y_k against x_k shows a profile of the change in profiles between the two campaigns.

4.3.2 Horizontal Profiles

When the line of reference is vertical, the profile created is orthogonal to this line and is two dimensional horizontally. Sections, containing the vertical reference, are usually taken in mutually perpendicular directions, often corresponding to the x and y coordinate axes. Each of these sections contains a profile. Displacement from the vertical reference line can be determined in several ways, namely:

a) table readings (position of a plumbline with respect to table reference marks) at certain elevations;
b) shuttle readings (positioning of an inverted plumbline) at known elevations; and
c) tiltmeter measurements in series along a controlled route.

In a) and b), the reference line is mechanically the position of the plumbline. In c), the reference is created by gravity acting on a sensor within the tiltmeter. In b) and c), the shuttle and the tiltmeter are usually guided along the casing of a borehole. The three methods and their relationships are illustrated in Figure 4.2.

The vertical reference passes through the lowest point at depth d_A. This would be the anchor point of an inverted pendulum or the beginning reference of a series of tiltmeter measurements. The whole situation would be reversed, i.e., inverted, for a suspended pendulum - the anchor would be the suspension point at the top of the plumbline. For table readings, the horizontal distance from the plumbline to a reference mark is measured by a micrometer, or other

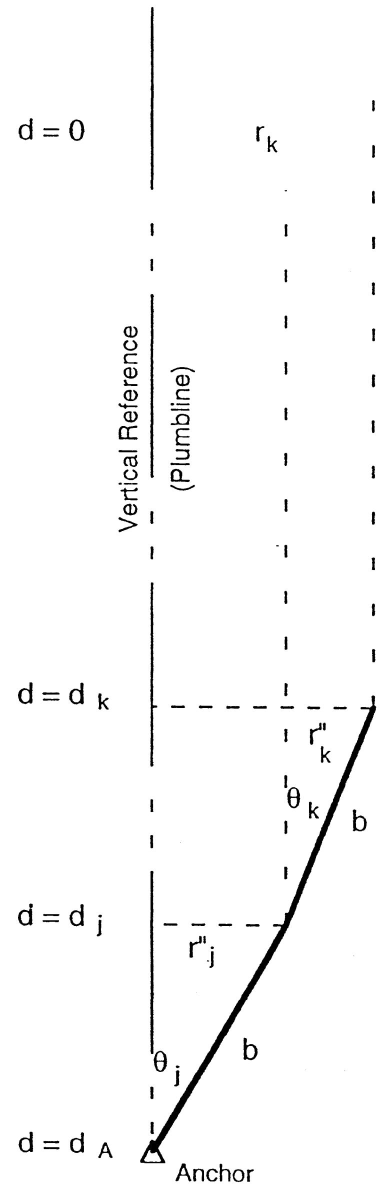


Figure 4.2. Obtaining profiles with respect to a vertical reference line

means, giving the reading r_k at depth d_k. For shuttle readings, the plumbline is anchored at the depth d_k and its position, r'_k, is measured at the top of the plumbline. The corresponding reduced reading is $r_k = r'_k - r_A$, with r_A being the reading without the shuttle, the position of the anchor read at the top. The progression along the reference line is $x_k = d_A - d_k$, from the anchor.

If a tiltmeter, having a base length of b, traverses upward from the bottom, then the series of tilts, θ_k, over the known base yields the increments of displacement, $r''_k = b \sin\theta_k$. Because the ends of the tiltmeter coincide in succesive positions, the displacement is cumulative, as $r_k = b \sin\theta_1 + b \sin\theta_2 + \ldots + b \sin\theta_{k-1} + b \sin\theta_k$, i.e., $r_k = b\, \Sigma^k \sin\theta_k$. Since the tilts are small, the progression along the reference line is an accumulation of tiltmeter base lengths, $x_k = kb$ from the bottom.

The profile at time t_1 is the r_{k1} versus the independent variable x_k. The profile is repeated with r_{k2} at $t_2 > t_1$ and having the same reference point as at t_1. The spatial series has $y_k = r_{k2} - r_{k1}$ so that it is a profile of the changes in the profile between the two campaigns. The slope of the profile of changes, m in $y_k = mx_k + y_o$, is the tilting of the profile between campaigns. The intercept, y_o, is included so that the line of tilt is not unduly constrained to pass through the lowest point or highest point.

5. DEFORMATION MODELLING

The modelling of deformations has been treated extensively regarding horizontal geodetic networks (see, e.g., Chrzanowski [1981], Reilly [1981], Schneider [1982], Chen [1983], Chrzanowski and Secord [1983a,b], Secord [1985], Chrzanowski and Chen [1986], Vanicek and Krakiwsky [1986], Kuang [1991]). It is only recently that there has been discussion, although not extensive, regarding analysis which involves all aspects of the deformation process or, at least non-geodetic observables, i.e., integrated analysis (Chen et al. [1985], Chrzanowski et al. [1985], Teskey [1985, 1987], Teskey and Porter [1988], Chrzanowski [1990], Chrzanowski et al. [1988, 1990, 1991]).

The "UNB Generalized Method for the Analysis of Deformations" has been devised (see Chen [1983], Secord [1985], Chen et al. [1990b]) to provide an approach to analysis that can be applied to virtually any style of deformation and any type of measurements. The Method has nine steps, namely (as modified from Secord [1985]),

1. design of the monitoring scheme [Chen et al., 1983; Kuang, 1991];
2. establishment of variances and possible correlations among observations within a single campaign of measurement or between campaigns [Chen and Chrzanowski, 1985; Chen et al., 1990a];
3. detection of outliers and systematic errors [Kavouras, 1982];
4. spatial or temporal trend or both (Chapter 4);
5. selection of possible deformation models;
6. estimation of parameters of the possible models (Chapter 5, Chen [1983], Secord [1985], Chen et al. [1990b]);
7. assessment of the models and choice of the "best" model [Chen, 1983; Secord, 1985; Chrzanowski et al., 1991];
8. computation of deformation characteristics, e.g., displacement field,

strain field (Chapter 5);

9. graphical depiction of the deformation.

These steps have been followed in a number of applications of the Method to the analysis of geodetic networks (e.g., Secord [1985] and Chen et al. [1990b]). However, as shown below, it is not limited to the repeated measurement of conventional geodetic networks.

In order to complete the discussion begun in Chapter 4, this chapter will deal with the inclusion of unstable reference stations in the analysis of a horizontal or vertical reference network. If all of the points involved in monitoring have been coordinated in the same three dimensional cartesian system, then it is possible to select a region of points for a section through the structure. The balance of this chapter will deal with the analysis of such a section integrating geotechnical and geodetic observables together. This is done to show the requirements of a data management system that would enable such an analysis.

5.1 Horizontal or Vertical Geodetic Networks

After the identification of unstable reference stations, the displacement vector, $\mathbf{dx}$, from Equation (4.12) is divided into three subvectors: $\mathbf{dx}_r$ (for n_r stable reference stations); $\mathbf{dx}_u$ (for n_u unstable reference stations); and $\mathbf{dx}_p$ (for n_p intended object points). The parameters of the deformation model, $\mathbf{c}$, are estimated following the relationship

$$\mathbf{dx} + \mathbf{v} = \mathbf{Bc}. \tag{5.1}$$

For each station or point there is a one (vertical) or two (horizontal) element subvector. The modelling for each classification of points is given as

a) stable reference station:

$$\begin{bmatrix} dx \\ dy \end{bmatrix}_r + \mathbf{v} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{5.2}$$

b) unstable reference station:

$$\begin{bmatrix} dx \\ dy \end{bmatrix}_u + \mathbf{v} = \begin{bmatrix} a_i \\ b_i \end{bmatrix} \text{ and} \tag{5.3}$$

c) object point:

$$\begin{bmatrix} dx \\ dy \end{bmatrix}_p + \mathbf{v} = \begin{bmatrix} a_k \\ b_k \end{bmatrix}. \tag{5.4}$$

There is an equation in the form of (5.2), (5.3), or (5.4) for each station or point in the network. The total number of unknowns will be $2(n_u + n_p)$ in a horizontal network or will be $(n_u + n_p)$ in a vertical network. There will be $2(n_u + n_p + n_r)$ or $(n_u + n_p + n_r)$ observations, respectively. The modelling of the object points as given in Equation (5.4) is of simple single point movement. Depending on their location and distribution it may be more appropriate to model them, or a group of them, together in a more complicated model (more parameters). The only restrictions are that as much redundancy should be allowed as possible and that the model makes physical or mechanical sense. As long as there are more observed displacements than parameters, the solution for the estimated parameters can be obtained from

$$\underline{\mathbf{c}} = (\mathbf{B}^T\mathbf{P}_{dx}\mathbf{B})^{-1}\mathbf{B}^T\mathbf{P}_{dx}\mathbf{dx} \quad \text{with} \quad \mathbf{Q}_{\underline{c}} = (\mathbf{B}^T\mathbf{P}_{dx}\mathbf{B})^{-1} \tag{5.5}$$

in which $\mathbf{P}_{dx} = \mathbf{C}_{dx}^{-1}$ provided that the original choice of datum was valid, i.e., it involved stable reference stations. Even so, it is likely that a singularity would arise in attempting to invert $\mathbf{C}_{dx}$ since it may have zero elements corresponding to the fixed station considered as the constraint in the original campaign adjustment. In addition, the **dx** would be datum dependent and the choice of parameters must account for this dependency (see, e.g., Chen [1983] and Secord [1985]); otherwise, the modelling will also be datum dependent. Even though the weighted similarity transformation provides a datum independent indication of trend, the modelling may not follow so easily from that trend if the $\mathbf{Q}_{dx}$ is used directly. Consequently, Chen et al. [1990b] suggest

$$\mathbf{P}_{dx} = [\mathbf{S}\,\mathbf{Q}_{dx}\,\mathbf{S}^T + \mathbf{H}\,(\mathbf{H}^T\mathbf{H})^{-1}\,\mathbf{H}^T]^{-1} - \mathbf{H}\,(\mathbf{H}^T\mathbf{H})^{-1}\,\mathbf{H}^T \tag{5.6}$$

with **S** as in Equation (4.12) and **H** as in Equation (4.15). Alternatively,

$$\mathbf{P}_{dx} = \mathbf{N}_1\,(\mathbf{N}_1 + \mathbf{N}_2 + \mathbf{H}\mathbf{H}^T)^{-1}\,\mathbf{N}_2. \tag{5.7}$$

In either Equation (5.6) or (5.7), the regular inverse can be used.

The advantage in modelling is that the redundancy created enhances the knowledge of the parameters. As well, the residuals corresponding to the displacements of the reference stations will reveal whether they can serve together as the stable reference against which the deformation of the object is described.

5.2 Integrated Modelling of Sections Through a Structure

The modelling of deformations which integrates geotechnical and geodetic observables extends the Generalized Method further to what was discussed in Chapter 4 and Section 5.1. Both Chen [1983] and Secord [1985] deal with the involvement of observables other than the traditional geodetic type and the model can be developed by considering two stages in the modelling process. The displacement field, **dx**, can be related to changes in observables, $\mathbf{d\ell}$, by

$$\mathbf{d\ell} + \mathbf{v} = \mathbf{Adx} \tag{5.8}$$

following Lazzarini [1974] as discussed in Secord [1985]. In this case, the design matrix, **A**, is populated by the same elements as if it were part of Equation (3.1). It relates the type of observable to the location of the points involved. Combining Equations (5.1) and (5.8) results in

$$\mathbf{d\ell} + \mathbf{v} = \mathbf{ABc} \tag{5.9}$$

which now relates the deformation model parameters directly to the observables. The elements of $\mathbf{d\ell}$ could be the changes in observations between two campaigns and the elements of **c** would be rates if divided by the interval of time over which the $\mathbf{d\ell}$ occurred. Or, the $\mathbf{d\ell}$ could be the rates of change resulting from trend analyses so that the **c** would be rates directly.

If the points involved in a selected section have x,y,z coordinates, their positions can be described in the plane of the section by transforming the x,y,z coordinates onto the plane. If the plane is parallel to one of the coordinate planes (xy, xz, or yz) then the transformation may be relatively simple. Often this is the case as the coordinate system is established with respect to the major axes of the structure (e.g., upstream/downstream and longitudinal, in a hydro-electric power dam). Consequently, the deformation modelling, i.e., creating the elements of the **B** matrix, becomes the same as for the analysis of a conventional horizontal network, already discussed in Chen [1983] and in Secord [1985].

Least squares estimates for the parameters are obtained from

$$\underline{\mathbf{c}} = (\mathbf{B}^T\mathbf{A}^T\mathbf{P}_{dl}\mathbf{AB})^{-1}\,\mathbf{B}^T\mathbf{A}^T\mathbf{P}_{dl}\mathbf{d}\boldsymbol{\ell} \quad \text{with} \quad \mathbf{Q}_c = (\mathbf{B}^T\mathbf{A}^T\mathbf{P}_{dl}\mathbf{AB})^{-1} \tag{5.9}$$

and with $\mathbf{P}_{d\ell}$ being the diagonal weight matrix having elements $p_{ii} = \sigma_{d\ell}^{-2}$. Once the parameters have been estimated, a field can be generated using $\mathbf{dx}_g = \mathbf{B}_g\underline{\mathbf{c}}$. Matrix $\mathbf{B}_g$ has elements similar to **B**, but the points, and their coordinates, are chosen in whatever distribution is desired but in the same system as used in **B**. The displacements $\mathbf{dx}_g$ constitute a displacement field that has been generated or derived from the parameters that had been estimated using only the points of observation.

Several possibilities exist for the modelling of the displacement field. Generally, the parameters may not have a mechanical meaning. It is merely necessary to describe the field that best fits all of the observations so that a denser, or at least regular, representation might be generated, as mentioned above. The complexity of the model will depend on the number and location of observation points and on the type of observables. Although a polynomial of higher order might be used, the illustration here has been limited to second order for simplicity. Considering a second order polynomial over a two dimentional section in x,y leads to the expressions for the two components of the displacement field at each observation point, k, as

$$dx_k = a_1x_k + a_2y_k + a_3x_ky_k + a_4x_k^2 + a_5y_k^2 \quad \text{and}$$

$$dy_k = b_1x_k + b_2y_k + b_3x_ky_k + b_4x_k^2 + b_5y_k^2. \tag{5.10}$$

Since the a_i and b_i, rather than the coordinates, are the unknowns, the solution of Equation (5.9) is the linear parametric case and can be obtained directly.

In Equation (5.10), it can be seen that the displacement field will be sensitive to the coordinate system and to the choice of origin. When x = 0 and y = 0, dx and dy must also be zero. This may not be desirable and the effect is obvious if a rotation parameter is involved. If a rotation, ω, is added to Equation (5.10) and is centered at (x_c,y_c), then

$$dx_k = a_1x_k + a_2y_k + a_3x_ky_k + a_4x_k^2 + a_5y_k^2 - \omega(y_k - y_c) \quad \text{and}$$

$$dy_k = b_1x_k + b_2y_k + b_3x_ky_k + b_4x_k^2 + b_5y_k^2 + \omega(x_k - x_c). \tag{5.11}$$

The best choice of origin for the displacement field may be obtained by considering the mechanical or physical properties of the behaviour of the structure. But this may not be so easy to interpret. However, there is some guidance from points in the modelling for which absolute displacements are the observables. Absolute displacements are displacements relative to points which are known to be beyond the influence of the mechanism effecting the deformation. Such points are the stable reference stations in a horizontal or vertical geodetic network or the deep anchor points of inverted pendula or borehole extensometers. The origin would be best located to minimize the discrepancies between the modelled displacements and the observed absolute values. Therefore, the best origin of the coordinate system can have its coordinates, (x_o,y_o), as part of the model. This would expand Equation (5.11) to be

$$dx_k = a_1(x_k - x_o) + a_2(y_k - y_o) + a_3(x_k - x_o)(y_k - y_o) + a_4(x_k - x_o)^2$$

$$+ a_5(y_k - y_o)^2 - \omega(y_k - y_c - y_o) \qquad \text{and}$$

$$dy_k = b_1(x_k - x_o) + b_2(y_k - y_o) + b_3(x_k - x_o)(y_k - y_o) + b_4(x_k - x_o)^2$$

$$+ b_5(y_k - y_o)^2 + \omega(x_k - x_c - x_o). \qquad (5.12)$$

Now, the unknowns are the a_i, b_i, ω, x_o, and y_o. The partial derivatives of Equation (5.12) reveal that the elements of the design matrix **B** would be functions of the unknowns. Therefore, the estimation process is no longer linear and would require iterations with initial values for the unknowns. Since the values of the parameters will likely range over several orders of magnitude, the criterion for convergence cannot be a single absolute number. It is suggested that the criterion should be a limit on the ratio of the most recent correction, say δx, to a parameter, say x, such that convergence has occurred if, for all x, $|\delta x/x| < \delta_{con}$. The value of δ_{con} would depend on the expected magnitude of the deformation (revealed by the amount of absolute movement) and could be in the order of 0.0001 (i.e., 0.01 % if millimetres of movement are expected). Otherwise, it would be necessary to already know the magnitudes of the parameters and to specify a separate δ_{con} for each one or for each group.

Expansion of Equation (5.12) and grouping of constant product terms (the combination of the a_i, b_i, x_o, y_o, or ω) leads to a simplification of the process of estimating the origin. By grouping the constant product terms together and redefining the meaning of the coefficients, the polynomial expressions of Equation (5.12) can be rewritten as

$$dx_k = a_o + a_1x_k + a_2y_k + a_3x_ky_k + a_4x_k^2 + a_5y_k^2 - \omega(y_k - y_c) \quad \text{and}$$

$$dy_k = b_o + b_1x_k + b_2y_k + b_3x_ky_k + b_4x_k^2 + b_5y_k^2 + \omega(x_k - x_c). \quad (5.13)$$

which is the same as Equation (5.11) with the addition of the constant terms a_o and b_o. These constant terms are the values of dx and dy at the origin (x = 0, y = 0) and can be considered as nuisance parameters (i.e., their values are not of interest) that allow the displacement field the freedom to best fit the absolute displacements. The estimation of the coefficients of Equation (5.13) is the same as for those of Equation (5.11) and there is no need for iteration as required for

Equation (5.12).

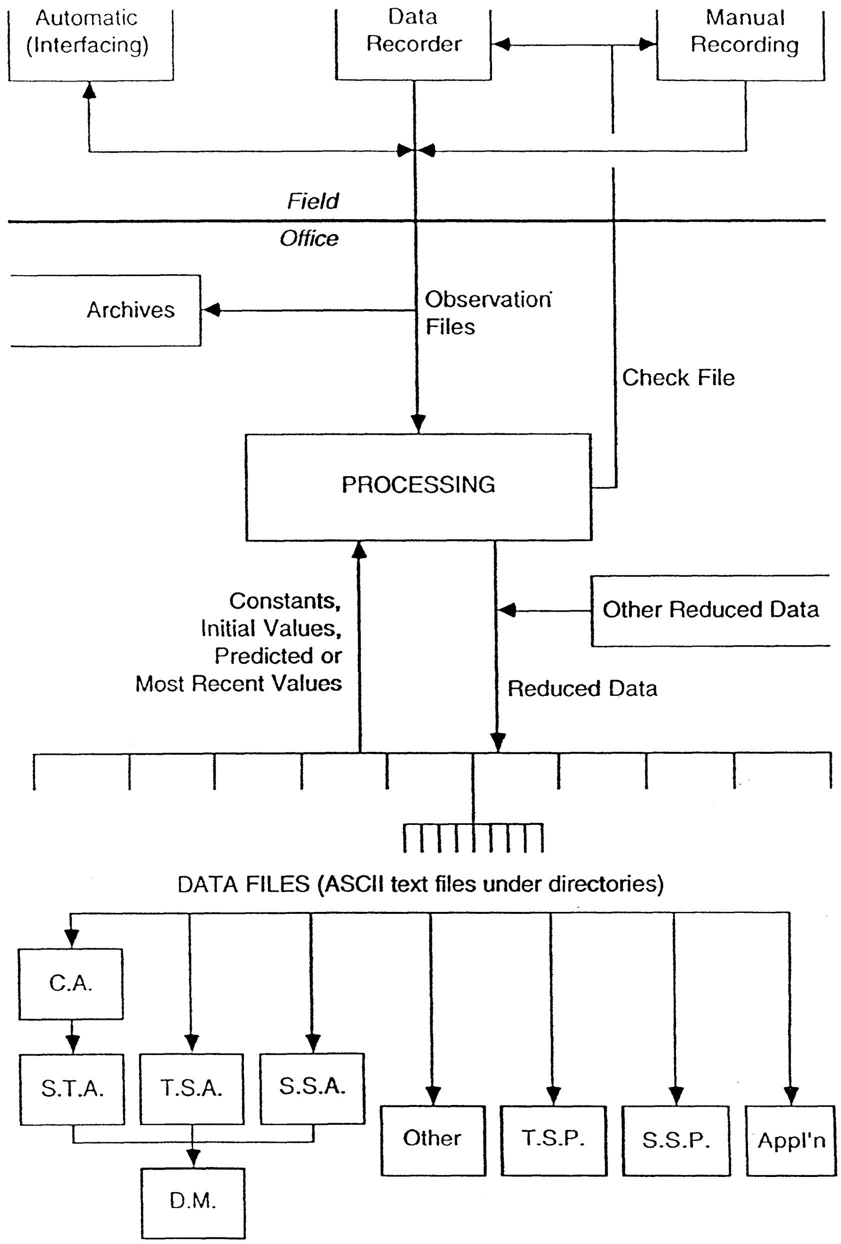
Once the parameters of the displacement field, **c**, have been estimated, a two dimensional strain field, ε_g, can be derived for the same array of points as for the generated displacement field, $\mathbf{dx}_g$. At any point, the strain field has three components: ε_x, ε_y, and ε_{xy} with $\varepsilon_x = \partial(dx)/\partial x$, $\varepsilon_y = \partial(dy)/\partial y$, and $\varepsilon_{xy} = [\partial(dy)/\partial x + \partial(dx)/\partial y)]/2$ and the dx and dy being the polynomial expressions of Equation (5.10), (5.11), or (5.12). If $\varepsilon_g = \mathbf{B}_\varepsilon \underline{\mathbf{c}}$, the elements of the $\mathbf{B}_\varepsilon$ matrix are the partial derivatives of the polynomials with respect to x or y (as opposed to being with respect to the coefficients as for **B** and $\mathbf{B}_g$). The two by two strain tensor for each point can be diagonalized to produce the maximum and minimum principal strains for the point which can be shown graphically [Obert and Duvall, 1967; Secord, 1985]. Since negative values are possible (compression), the magnitudes are represented by the scaled lengths of the axes of the ellipse with negative values plotted in a colour to contrast with positive values. Alternatively, the convention of outward arrows for extension (positive) and inward arrows for compression (negative) may be used.

6. "DAMADA", A SYSTEM OF DATA MANAGEMENT FOR DEFORMATION ANALYSIS

The preceding chapters have presented the various aspects of a monitoring scheme. With the accumulation of data and the facility for handling the data that is currently provided by on-site microcomputers, a system for the management of data used in the analysis of deformations has been devised by the author. Moreover, the system, "DAMADA" (data management for deformation analysis), allows for the conversion of an existing manual system and for the virtual automation of the gathering, processing, and analysis of the data and of the graphical depiction of the deformation.

An overview of DAMADA is given in Figure 6.1. Data flow in the directions indicated by the arrowed lines. The observations are made at the top of the figure and the final analyses and depictions are performed at the bottom.

There are two lines of flow between the field (locations of the observations) and the office (virtually, the microcomputer) - one entering and one returning. The observations can enter, or be uploaded to, the system in three possible ways: by direct interface to a measurement device or instrument; by keyboard entry on a data collector; or by manual recording on field sheets. Interfacing is also possible between the data collector and an instrument. In order to ensure integrity of the observation, the input value can be checked against the value predicted for the time of observation or against the most recent value. This is provided directly in the interfacing or by way of a check file



C.A.	Geodetic Campaign Adjustment	T.S.P.	Time Series Analysis and Plot
S.T.A.	Spatial Trend Analysis and Plot	S.S.P.	Spatial Series Analysis and Plot
T.S.A.	Time Series Trend Analysis and Plot	Other	Other and future programs of the system
S.S.A.	Spatial Series Analysis and Plot	Appl'n	other applications using the data
D.M.	Integrated Geometrical Deformation Analysis (Modelling)		

Figure 6.1. The data management system for deformation analysis, "DAMADA" (after Secord [1990] and Secord [1993])

that is either downloaded to the data collector or printed as a hardcopy for comparison when manually recording. Direct interfacing produces an observation. The data collector or manual recording produce observation files, i.e., a collection of observations taken during the workday. Since observation files would be more likely encountered, especially during the conversion from a manual system, further discussion will refer to observation files with the understanding that it pertains to individual observations from interfacing as well. Immediately on being uploaded, the observation file is archived for security. The contents of the observation file are processed to produce the appropriately reduced data that are then appended to their corresponding data files. The data files contain instrument constants, some calibration coefficients, and most recent values which are sometimes passed by way of the check file for comparison with the current value at the time of its observation.

Other data can be brought into the system so long as they are "reduced" or transformed to be compatible with the system. This data may be historic, i.e., gathered before the system was introduced. Or, the data may be from other sources, e.g., hydrological data or control survey data collected by another agency but involving the area about the structure.

There are two basic types of data files - campaign and series. The campaign data files result from the horizontal or vertical geodetic survey campaigns and serve as input to the campaign adjustment programs ("C.A." [this and subsequent acronyms refer to the labelling in Figure 6.1]). The series data files contain the various geotechnical observations in chronological order which are taken directly into the temporal trend or time series analysis ("T.S.P."). Time series can also be generated from repeated geodetic campaigns and analysed for trend ("T.S.A." which also includes geotechnical series analyses, the results of which are used in the deformation modelling, "D.M.").

Pairs of campaigns can be compared to investigate the stability of reference stations and to provide an indication of the spatial trend of deformation between the two campaigns in either one or two dimensions ("S.T.A."), the results of which would be used in the deformation modelling ("D.M."). Some geotechnical data, e.g., borehole profiles, lend themselves to spatial series, i.e., comparision of trend along a spatial reference according to the difference between two campaigns ("S.S.P."). Similar trends can be derived from a series of geodetic campaigns, e.g., subsidence profiles or tilts from levelling, and analysed ("S.S.A.") with the results being used in the modelling ("D.M."). As the culmination of the modelling, a graphical depiction of the deformation is presented.

The system would be operating on a microcomputer with a hard drive of sufficient capacity (the only limitation). All of the data and files are in simple ASCII text with uniform format for each type of file so that they can be accessed by any text editor and can be printed or serve as input to a variety of programs (the analysis mentioned above and "Other" programs as well) or applications ("Appl'n"). DAMADA will be further explained by describing the different types of files involved ("data organization"), the structure of each type of file ("data structure"), and the various computational modules used in the gathering, processing, and analysis of the data.

6.1 Data Organization and Structure

The system has six different main types of files: observation, data, check, calibration, coefficients, and coordinates. The first two, observation and data, are really the only ones encountered by the user of the system. The other three are internal to the system but are accessible to the user since they are also in ASCII text.

6.1.1 Observation Files

An observation file, including its name, is generated automatically by the data recorder or can be created, in the proper format, using any text editor. The name, "Dyymmdda", is based on the date, 19yy mm dd, from the operating system of the data collector. The last character of the name is the single letter (or character other than a period) label of the collector. Consequently, there can be up to 26, or more, different collectors operating on the same day. One file is created for every calendar day on each recorder. The observations from sessions of collecting after the first one, on any one day, are appended to the original observation file.

In the observation file (e.g., Appendix II.7), there is a record for each observation. Several data may be included in one observation, e.g., rod readings in a multi-rod extensometer, and are together in the same record. The beginning of the record contains a character code identifying the data file to which the data is to be processed. Usually the character code is identical to the name of the data file (up to eight characters, as allowed by the DOS system of a microcomputer). The code is generated by the data collector in response to prompts regarding the location of the observations. If the data collector can be equipped to read bar codes, labels could be situated at the observation location to facilitate input of the name and to guard against improper entry of a name. At the end of the record, after the observation data, the time, "hh:mm", is appended from the operating system of the data collector.

6.1.2 Data Files

A data file can be either of two types: campaign (input or outcome) or series. A campaign data file of either horizontal measurements (horizontal angles, or directions, or reduced distances or both) or of vertical measurements (height differences) serves primarily as input to a two or one dimensional adjustment program, respectively. The format of the campaign file (e.g., Appendix II.4) is compatible with whatever program is used in the adjustment. In the adjustment of a horizontal network, initial approximate coordinates are required. These are extracted from the coordinates file (see Section 6.1.5

below) as the campaign adjustment file is built. The results of a campaign adjustment (estimated coordinates, variance-covariance, estimated variance factor, and degrees of freedom) are kept in an outcome file with an ".XCX" extension (e.g., Appendix II.5) to the input file name which contains a code revealing the location of the network and the date of the campaign.

A series data file contains the time series of repeated observations, e.g., a geotechnical instrument, or the spatial series for a campaign, e.g., inverted pendulum shuttle readings. Time series or spatial series files can be created by extracting, in chronological order, the appropriate data from campaign files or from the outcome of the individual adjustments. Either type of series file is input to the trend analysis.

In some respects the content of a data series file will vary from one type of observable to the next (e.g., Appendices II.10, II.11, II.12). Generally the data series file contains an initial record for each data item that serves as a character string or descriptive title. The title is used by an assortment of programs when analysing or displaying the series as an identifier of the output. Following the descriptor records are any constants or coefficients used in the reduction of the observations to the data in the format kept by the series. In any one series file, there is a record for each observation or group observed at the same instant. Each record begins with the date and time of the observation and continues with the data item or items. With each data item is a single character flag that is either a blank, an asterisk, or the letter "s" (e.g., Appendix II.12). The asterisk indicates that a single item is to be ignored. This may happen if one of several data items was not observed at the same time as the others when normally they would be all in the same record. The letter "s" indicates that there is a slip or discontinuity in the data series between the date immediately before and the date immediately following.

6.1.3 Check File

The check file is updated during the processing of an observation file. It contains either the most recent value of an observation or its value predicted for the next time of measurement (e.g. Appendix II.8). The current version of the file is then downloaded to the data collector but can be provided as hardcopy for checking during manual recording. The data collection software uses the check file automatically while observations are being entered.

There is a record for each data item or items, in the same way as for the data file. The beginning of each record is a character identifier. This identifier is usually the same as the observation identifier or data series file name. The records are in alphabetical order by file name so that they can be found more easily on a printout.

6.1.4 Calibration Files

Calibration files are created from measurements by certain instruments, e.g., tape or wire extensometers or depth micrometers or EODMI, on calibration apparatus. The file contains data that are used in the corrections to observations as they are reduced or processed into the data files. These calibration files are arranged like any other series so that they provide a history of the behaviour of the instrument during its calibration measurements.

6.1.5 Coefficients File and Coordinates File

In order to predict the values to be placed in the check file, the temporal trend analysis will update the coefficients in the coefficients file (e.g., Appendix II.14). The time of the currently processed observation plus the interval between observations is the time of the next observation. This time is used with the coefficients of the fitting to the time series for that observable to predict the value of the observation that would be expected at the next measurement.

The coordinates file contains the three dimensional cartesian coordinates of all of the observation points within the structure and its surroundings. These coordinates are used during the reduction of distances to the computational surface used in the adjustment, in the input files for horizontal network adjustment, and as input to the modelling and to the plotting programs. Consequently, they do not have to be determined as accurately as if they were to be used for any direct comparison. Three dimensional traversing to centimetre accuracy would be sufficient for the non-geodetic points. The first campaign of measurements could provide the coordinates for the geodetic points. Elevations obtained from height difference measurements could be used for the "z" coordinates.

6.2 Computational Modules

Depending on the data type and on the stage of processing or analysis, there are several computational modules to be found in DAMADA. These are shown in Figure 6.2 with the same sense of progression as in Figure 6.1 - starting with the collection of data at the top and ending with depiction of the deformation at the bottom of the figure. There are six levels corresponding to the steps followed leading to a deformation analysis:

1. data gathering (THEOD, EODM, (A)LEV, GEOT, SSR),
2. data reduction or processing (DISR, ZERO, PROC),
3. campaign adjustment (PLANE, LEVEL),
4. trend analysis (WT2D, M2D, WT1D, FITPLT, SSPLT),
5. modelling (M2D, OBSMOD), and
6. depiction (PLOT, FITPLT, SSPLT, SIMPLT, SSSPLT).

6.2.1 Data Gathering

With a module for each type, there are five forms of data collection: from an electronic theodolite ("THEOD"), from an electronic distance measuring instrument ("EODM"), from an electronic automatic level or from conventional precise levelling ("(A)LEV"), from geotechnical instrumentation ("GEOT"), or from scanning or travelling instrumentation that creates a spatial series ("SSR"). Since directions are usually measured in several sets, THEOD retrieves the circle readings from the theodolite, performs a station adjustment, and allows for

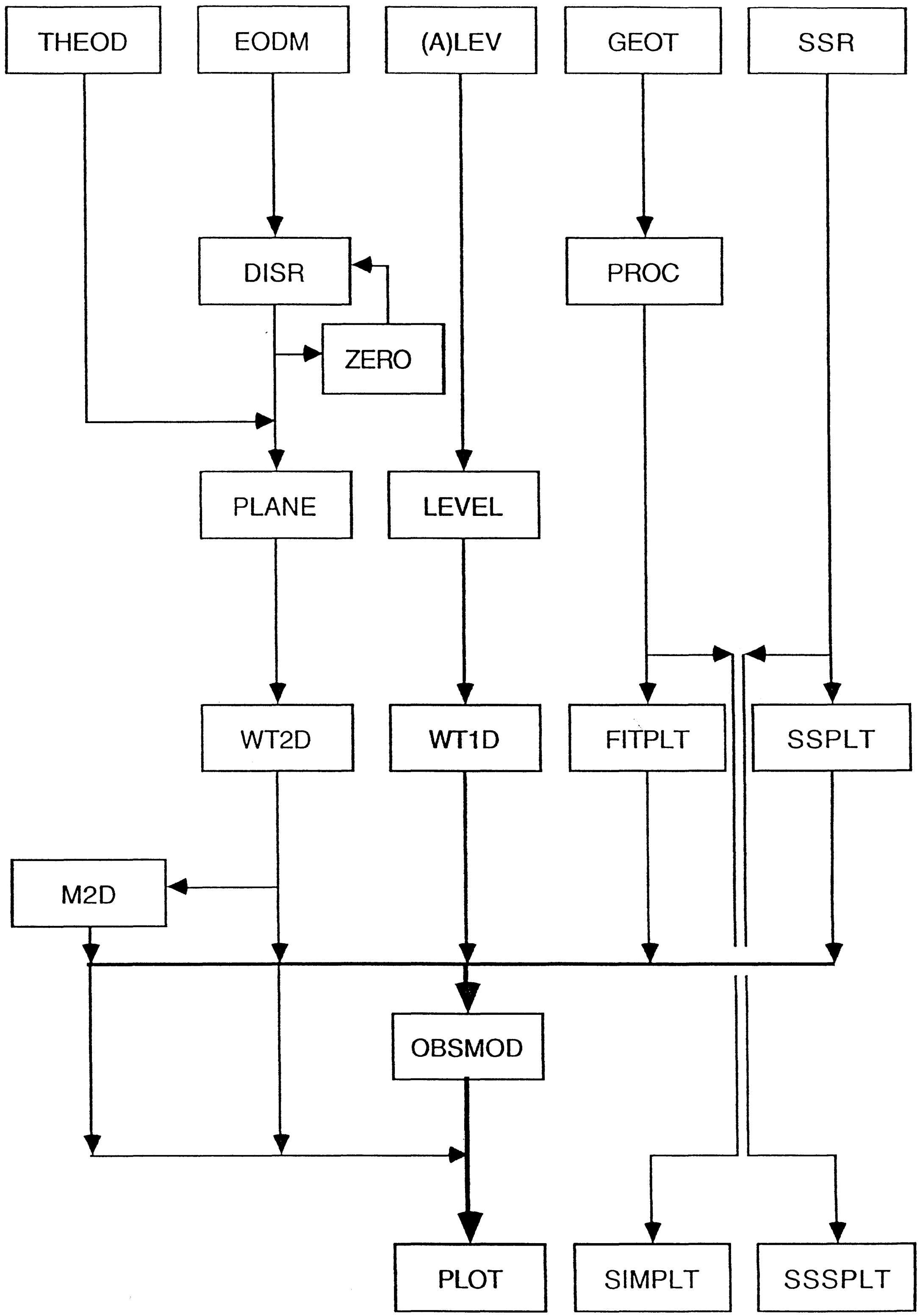


Figure 6.2. Computational Modules of DAMADA

the addition or deletion of a set so that the mean directions will have acceptable standard deviations. Its output is a summary listing and a file formatted for input to PLANE. EODM controls the operation of a precision EODMI with the accumulation of remeasurements until an acceptable standard deviation is achieved. It also controls the capture of the necessary ancillary observations of wet and dry bulb temperature and atmospheric pressure (at both instrument and reflector). Along with a summary listing, its observation file is created in a format readable by DISR (e.g., Appendix II.1). (A)LEV is really either a manual ("LEV") or an interfacing ("ALEV") version of data capture for precision levelling. LEV has keyboard input for micrometer observations on a pair of double-scaled invar staves while ALEV interfaces to a Leica NA3000 precision digital automatic level. Temperature at the instrument is recorded and the number of setups is calculated. The output from either LEV or ALEV is a summary listing and a file formatted as input to LEVEL. In THEOD, EODM, and (A)LEV, as soon as input is received from an instrument or the keyboard, it is copied to a logging file for security in case the capture session is interrupted.

GEOT controls the capture of all possible geotechnical observations. The generation of the observation identity code is done through location and instrument type prompts. The input value, which may be the mean of several measurements, is compared with the predicted value or the most recent value from the downloaded check file. The observation file from GEOT is input to PROC. SSR controls the observation of a spatial series campaign, e.g., inverted pendulum shuttle readings or a travelling tiltmeter. Along with the depth or distance along a reference line, the mean of readings, taken while the instrument is travelling in both directions (down and up or across and back), comprises the campaign observation file which is input to SSPLT.

6.2.2 Data Reduction or Processing

Data reduction or processing involves three modules: reduction of EODMI output ("DISR" and "ZERO") and processing of geotechnical data ("PROC"). DISR corrects the EODMI output for the meteorological conditions (wet and dry bulb temperatures and atmospheric pressure at both the instrument and the reflector) and applies the additive constant and possible scale factor. In addition, it applies the geometrical reduction of the distance to the plane and extracts the approximate coordinates, of the stations involved from the site coordinates file, in the format required for the adjustment by PLANE. ZERO estimates the value of the additive constant, used in DISR, from a set of baseline measurements and provides a check on the performance of the EODMI because of the ideal geometry and redundancy provided by the baseline.

PROC performs the reduction and organization of the items of the observation file into the appropriate data files. In doing so, it provides a second comparison between the current and most recent reduced data. Conversions, e.g., from frequency or voltage into millimetres, are done using the factors or coefficients kept in the data files. Calibration corrections, e.g., for tape extensometers, are applied automatically from the current calibration measurements and temperature corrections are made if they have not been done by GEOT.

6.2.3 Campaign Adjustment

Campaigns of geodetic observations are separately observed and adjusted in two dimensions ("PLANE") and in one dimension ("LEVEL"). Using the method of least squares, PLANE adjusts a horizontal campaign using the output from THEOD and DISR. The output is a summary listing and a coordinate-covariance file (with ".XCX" extension, e.g., Appendix II.5) which is input to WT2D or M2D. There is also a file as input to PLOT to show graphically the station or relative confidence ellipses of the campaign adjustment.

LEVEL provides an least squares parametric adjustment of a campaign of levelling (elevations estimated from height differences). Its output is a summary listing and an ".XCX" file for each campaign which is input to WT1D or is used by FITPLT to obtain tilts or vertical extension.

6.2.4 Trend Analysis

The trend can be analysed for the comparison of pairs of campaigns of geodetic observations by the weighted similarity transformation in either one ("WT1D") or two ("WT2D") dimensions and for a time series ("FITPLT") or spatial series ("SSPLT"). With the ".XCX" files for a pair of campaigns, WT1D or WT2D performs the weighted transformation in order to substantiate the stability of reference stations. Either WT1D or WT2D outputs a summary listing and a file as input to PLOT to show the spatial trend between any pair of campaigns. The trend from WT2D may be refined by modelling through M2D which would provide an opportunity to model any combination of behaviour, rather that just the single point movement resulting from WT2D.

FITPLT performs the time series analysis of any series of data either directly from a data file or derived from a combination. The series may also be derived from a chronological series of geodetic campaigns to obtain tilts, vertical extension, or change in an observable. As the comparison between two campaigns, a spatial series is analysed by SSPLT to provide, e.g., subsidence or the tilt of a borehole. Both FITPLT and SSPLT provide a full statistical assessment of the fitting, including significance of the parameters and examination of the residuals. Both also allow for interaction through on-screen display of the series and the possibility of restricting the time interval for the series (FITPLT) or changing the reference point or line (SSPLT).

6.2.5 Modelling

Modelling of the deformation can be done for geodetic campaigns in two dimensions ("M2D") or as an integrated analysis of a section through the structure ("OBSMOD"). M2D is used for modelling the deformation between a pair of horizontal network campaigns, based on the trend shown by WT2D. Many different models are possible with M2D and it provides a statistical assessment of the suitability of the model and its individual coefficients as well as the behaviour of the residuals. This aids the user in deciding on the best acceptable model. Along with a summary listing, M2D creates an input file to PLOT for a graphical depiction of the two dimensional deformation. Also, the outcome from M2D may be used in OBSMOD.

OBSMOD ("modelling from observations") can fit a displacement field to any type or arrangment of observables, geodetic or geotechnical, in a specified plane section (sample input and output are in Appendix III). A full statistical assessment of the modelling is provided. Based on the model, a displacement field, and its corresponding strain field, can be generated for any array of specified points in the plane. The observables, the displacement field, and the strain field can be plotted using PLOT.

6.2.6 Depiction

A graphical depiction is made of the results of the trend analysis ("FITPLT", "SSPLT") or of the deformation modelling ("PLOT"). Simple depiction of the change in a series of observations can be made without statistical assessment ("SIMPLT", "SSSPLT"). FITPLT plots the temporal series and its fitted trend in colour on imperial letter size paper (216 mm tall by 279 mm wide). SSPLT does the same for a spatial series. SIMPLT and SSSPLT plot up to six series (each a different colour), temporal or spatial respectively, simultaneously on one letter size page (279 mm tall by 216 mm wide) or half page (so that two plots per page are possible) but there is no fitting. FITPLT, SIMPLT, and SSSPLT can be run in a batch mode in which many plots can be done automatically in succession using a plotter with automatic paper feed, e.g., Hewlett-Packard HP7550. This can be repeated, monthly or quarterly for instance, by simply specifying the batch file which has already been created. PLOT provides the depiction in colour of the deformation from WT1D, WT2D, M2D, or OBSMOD on letter or ledger (279 mm tall by 432 mm wide) size paper. All of the plotting programs use HP-GL (Hewlett-Packard Graphics Language) and can therefore be used with any compatible plotter or can be readily adapted to other types of plotters.

7. APPLICATION OF DAMADA TO A GENERATING STATION

As mentioned during the introduction of Chapter 1, DAMADA was developed by the author in answer to the need for a system of data management that could accommodate a variety of levels of automation. This need arose at the Mactaquac Generating Station, owned and operated by N.B. Power (the New Brunswick Electric Power Commission) and located 16 km upriver from Fredericton. After four years of construction, the headpond was impounded in 1968, at which time three units were generating. By 1980, all six of the units were in operation. The Station consists of a main rockfill dam (518 m long with maximum height of 46 m), a diversion sluiceway, a spillway and intake, and the powerhouse which is connected to the intake by penstocks (see Figure 7.1). In the middle 1970s, the longitudinal vertical construction joint in the powerhouse exhibited increased opening (see Figure 7.2). By 1989, it was open by about 30 mm and was continuing expansion at a rate of 3 mm/y at the upper generator floor, decreasing to 1 mm/y at 12 m below [Chrzanowski et al., 1989; Hayward et al., 1991]. At the same time, leakage developed through the horizontal construction joints of the spillway, diversion sluiceway, and intake. By 1985, operation of the spillway gate adjacent to the intake was obstructed and cracking occurred in the spillway end pier [Hayward et al., 1991].

Several theories were offered in attempting to explain the unexpected behaviour, especially of the powerhouse and intake. Regional or local rock

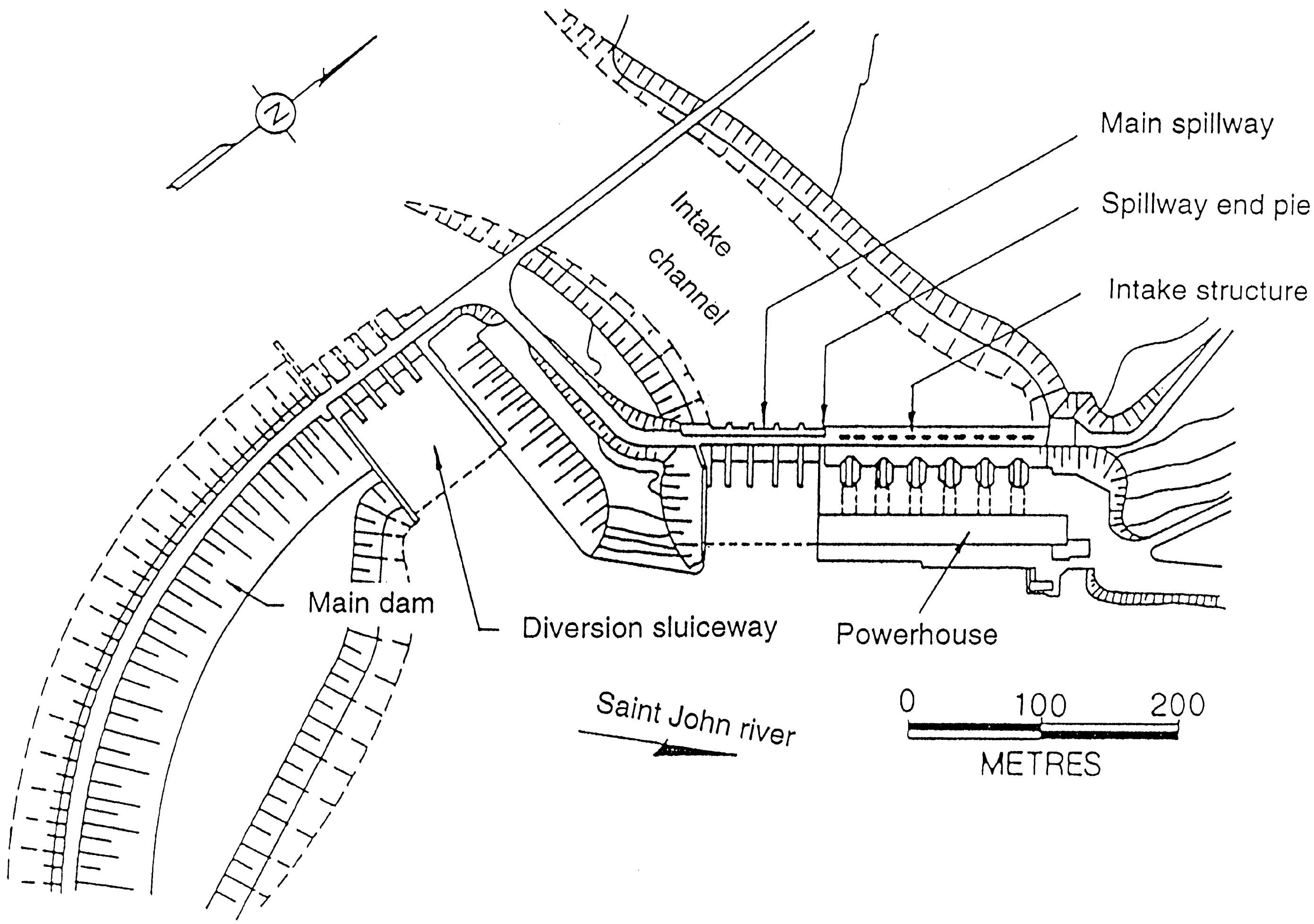


Figure 7.1. Plan view of the Mactaquac Generating Station
[Hayward et al., 1991]

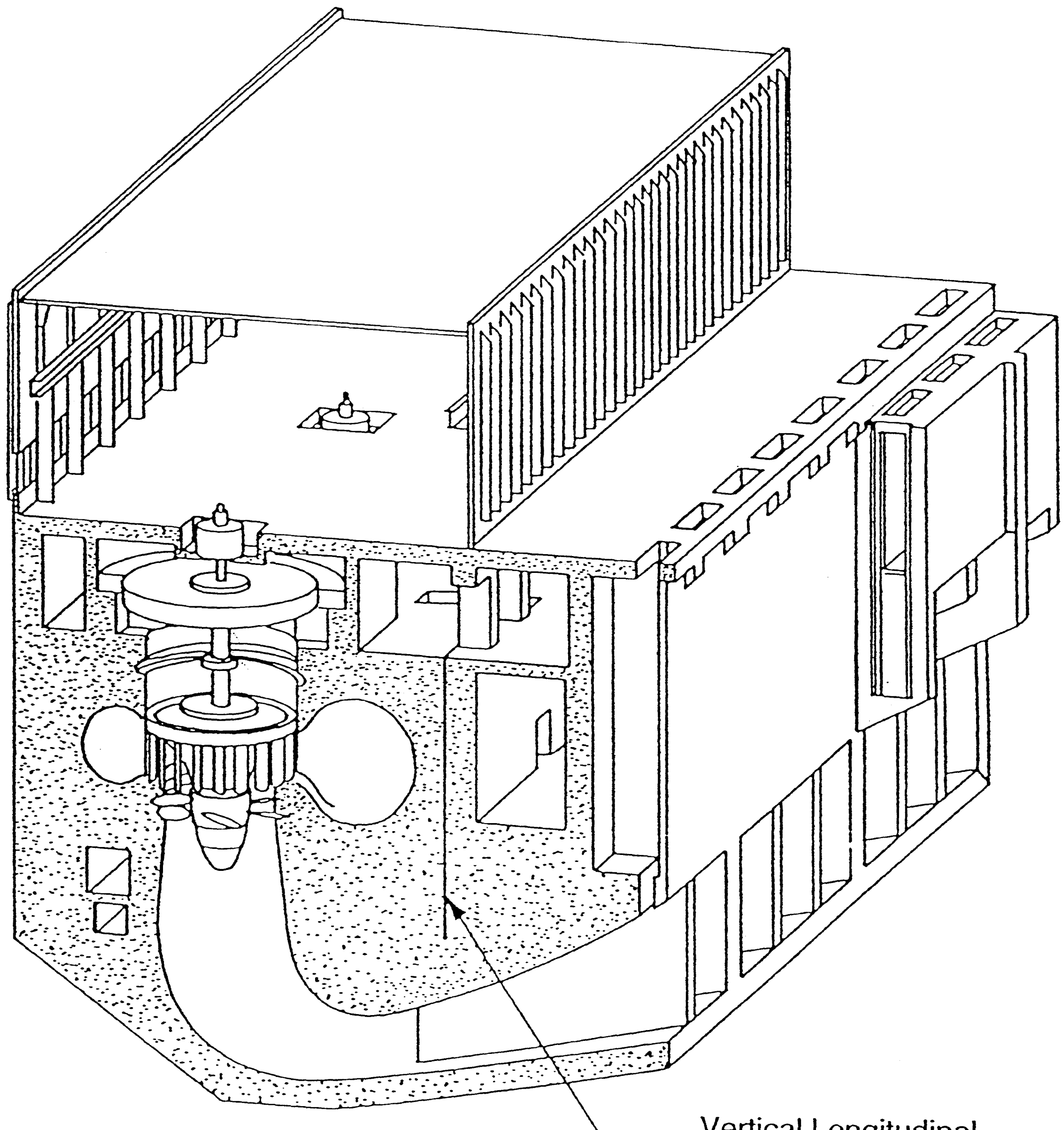


Figure 7.2. Section view of the powerhouse
[Hayward et al., 1991]

movement was suspected. The transfer of the water load to the powerhouse through the penstocks could also have been a cause. Also possible were residual stress and squeeze or rebound, or both, of the foundation or the effects of alkali-aggregate reactivity in the concrete [Chrzanowski et al., 1989; Hayward et al., 1991]. Over the years, an elaborate and extensive scheme of monitoring evolved in order to improve the understanding of the mechanisms and nature of the deformation of the structures. The scheme consists of a combination of geodetic and geotechnical observables, with frequencies of observation as listed in Table 7.1, most of which are used in the monitoring of the powerhouse and intake.

All of the stations or points involved in either geodetic or geotechnical observations have been coordinated by survey connections. The right handed coordinate system is oriented so that the "x" axis is parallel to the centreline of the units and the "y" axis is positive upstream. The "z" coordinates are really elevations and so are positive upward and are assumed to create a system that is x,y,z orthogonal Cartesian since the geodetic implications of using elevations for the "z" coordinate can be considered as negligible over the small area being investigated because of the low accuracy requirements. The three dimensional coordinates of every point are stored in one file called "MSXYZ" which is used by several programs in which the coordinates do not have to be known to an accuracy better than centimetres or so. Each station has a name of up to eight characters long that is uniformly used by all data collection,

Table 7.1. Geodetic and Geotechnical Observables at Mactaquac
[from Wroblewicz, 1991b,c]

Type	Number		(note below) Weeks
Multi-rod borehole extensometers	57	(196 rods)	2 or 3
Rod extensometers	67		2
Tape extensometer	66	anchor pairs	4
Four-pin gauges	19		2 or 3 or 4
Shear displacement gauges	4		2
Joint meters	8		1
Linear variable differential transformers	9		4
Telltales	20		12
Drains and weirs	16		2
Pressure relief wells	7		2
Piezometers	7		2
Inverted plumblines	18	tables	12
Suspended plumblines	66	(99 tables)	4
Tiltmeters (150 mm base)	2		2
Stress cells	23		2 or 4
Vibrating wire strain gauges	11		4
Concrete temperature probes	57		3
Thermocouples, thermistors	4		2 or 4
Precise vertical geodetic	212	stations or points	4
Precise horizontal geodetic	68	stations or points	4 or 12

"Weeks" is the interval of time, in weeks, between repeated measurements.

processing, analysis, and modelling software.

The application of DAMADA can be viewed in several components: geodetic campaigns (data capture, processing, adjustment, and trend), geotechnical instrumentation (data capture and trend), and modelling. Each of these three components will be presented with examples of the graphical product of each and with the corresponding data files in Appendix II. In the following discussion, the "modules" are the computational modules mentioned in Chapter 6 and shown in Figure 6.2.

Although DAMADA can accept manually recorded observations, it was developed in order to take advantage of electronic data collection. This would be particularly useful when using the geodetic instrumentation (electronic theodolite and EODMI and, potentially, a digital automatic precision level) since they now all allow for RS232 serial interfacing. Also, the observations are enhanced by several remeasurements and the operation of the instruments can be controlled from the data collector so that a better indication of the consistency of the observations can be obtained at the time of observation.

All data collection and interfacing is done using programs written in BASIC on CMT MC-V handheld computers [Corvallis Microtechnology, Inc., 1990]. The MC-V weighs 0.74 kg and is 240 mm long by 105 mm wide by 50 mm thick. It displays 8 lines of 21 characters or graphics of 64 by 128 pixels and has alpha (double function) and numeric keys, five function keys, cursor keys, and some special function keys. Its operating system is very similar to the DOS system found on personal computers and provides a real-time clock for date and time. Several directories can be created with a total of up to one megabyte of RAM. The MC-V is equipped with two RS232 serial interfacing connectors and the Kermit file transfer software is in ROM. Internal NiCad batteries provide power for up to nine hours between chargings. The whole MC-V is environmentally sealed.

7.1 Geodetic Campaigns

Traditionally, as mentioned in the introduction of Chapter 1, precision horizontal geodetic surveys have been performed separately from precision vertical surveys. This has also been the case at Mactaquac, particularly since the horizontal surveys have involved stations and points external to the structures and since precision spirit levelling has been carried out extensively within the structures, especially the powerhouse and intake. In both the horizontal and vertical campaigns, the date of the campaign, "yymmdd", is part of the campaign file naming. If several days of observations are involved, the name of the file that is input to the campaign adjustment (module PLANE or LEVEL) uses the date of the middle day of the campaign. The duration of the campaign (starting and ending dates) is incorporated in the title, or comment line, of a campaign file that appears in the printouts and plots.

7.1.1 Horizontal

The horizontal campaigns have consisted primarily of trilateration. Recently, the redesign of the surveys has added directions at several of the stations. The distances of a typical campaign are shown in Figure 7.3 and the directions, in Figure 7.4. From 1984 until 1988, annual measurements of the whole network were done by the Geodetic Survey of Canada using a Kern Mekometer ME3000 (Xenon flash; ±0.3 mm, ±2.0 ppm). In early 1990, the University of New Brunswick (UNB) and N.B. Power, together, purchased a Tellurometer model MA200 (laser; ±0.3 mm, ±2.0 ppm) which has been used exclusively since then for monthly measurements of a smaller portion connecting the powerhouse, intake/spillway, and diversion sluiceway. Near the Generating Station is a six pillar calibration baseline with an overall length of 1.6 km. All 15 distances are measured at the baseline with each retroreflector both at the beginning and at the end of a monthly or annual campaign. The estimation of the additive constant (by module ZERO after reduction by module DISR) in each case provides coordinates of the pillars that can be used by other agencies and reveals the behaviour of the instrument through the ideal geometry of the baseline. Appendices II.1, II.2, and II.3 contain sample files involved in a baseline measurement campaign. In all distance measurements, the MA200 is repeatedly repointed electronically 10 times so that its consistency can be seen and dry and wet bulb temperatures and atmospheric pressure at both the instrument and reflector are recorded at least three times throughout

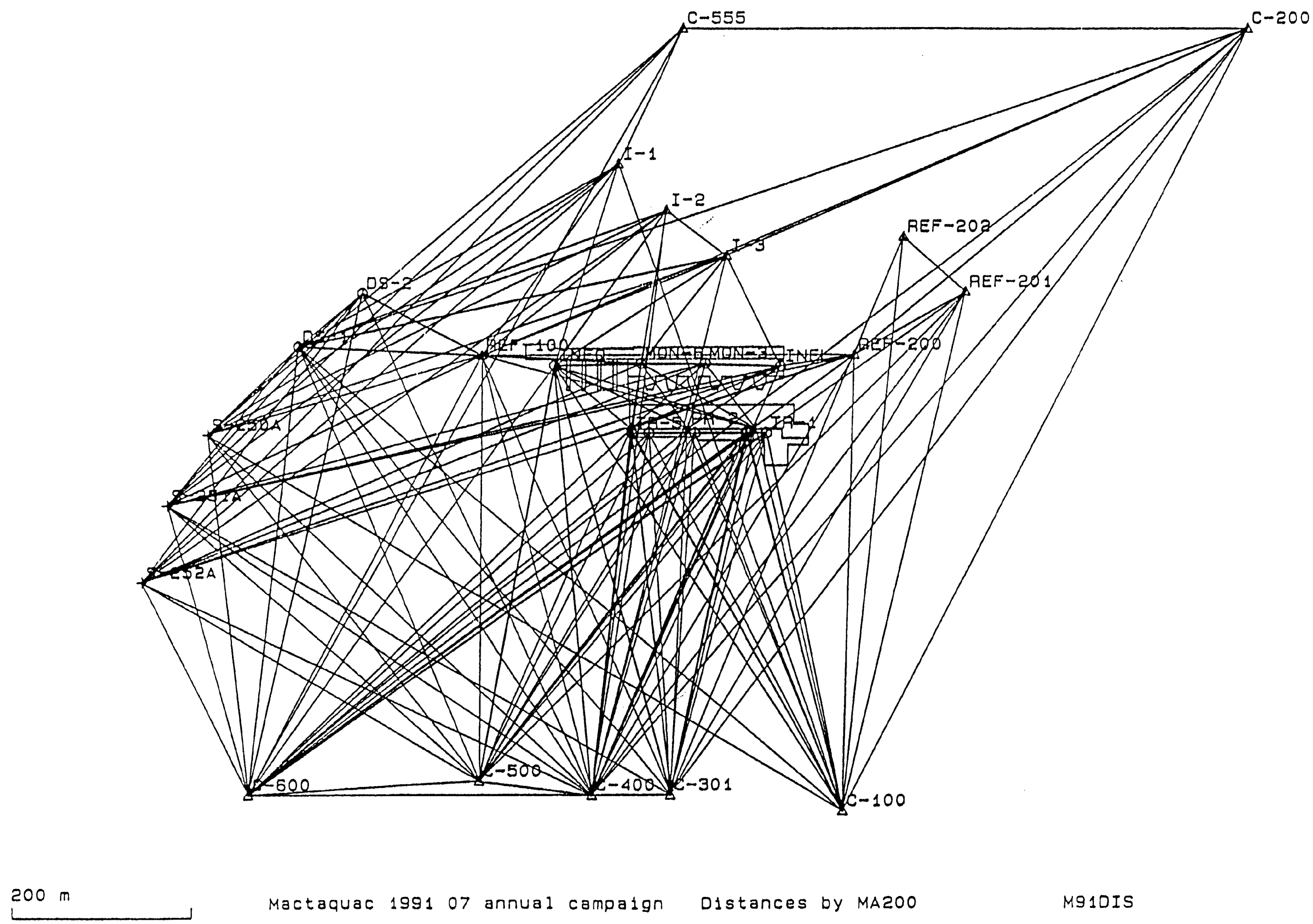


Figure 7.3. Typical horizontal geodetic campaign - distance observables
[Chrzanowski and Secord, 1992]

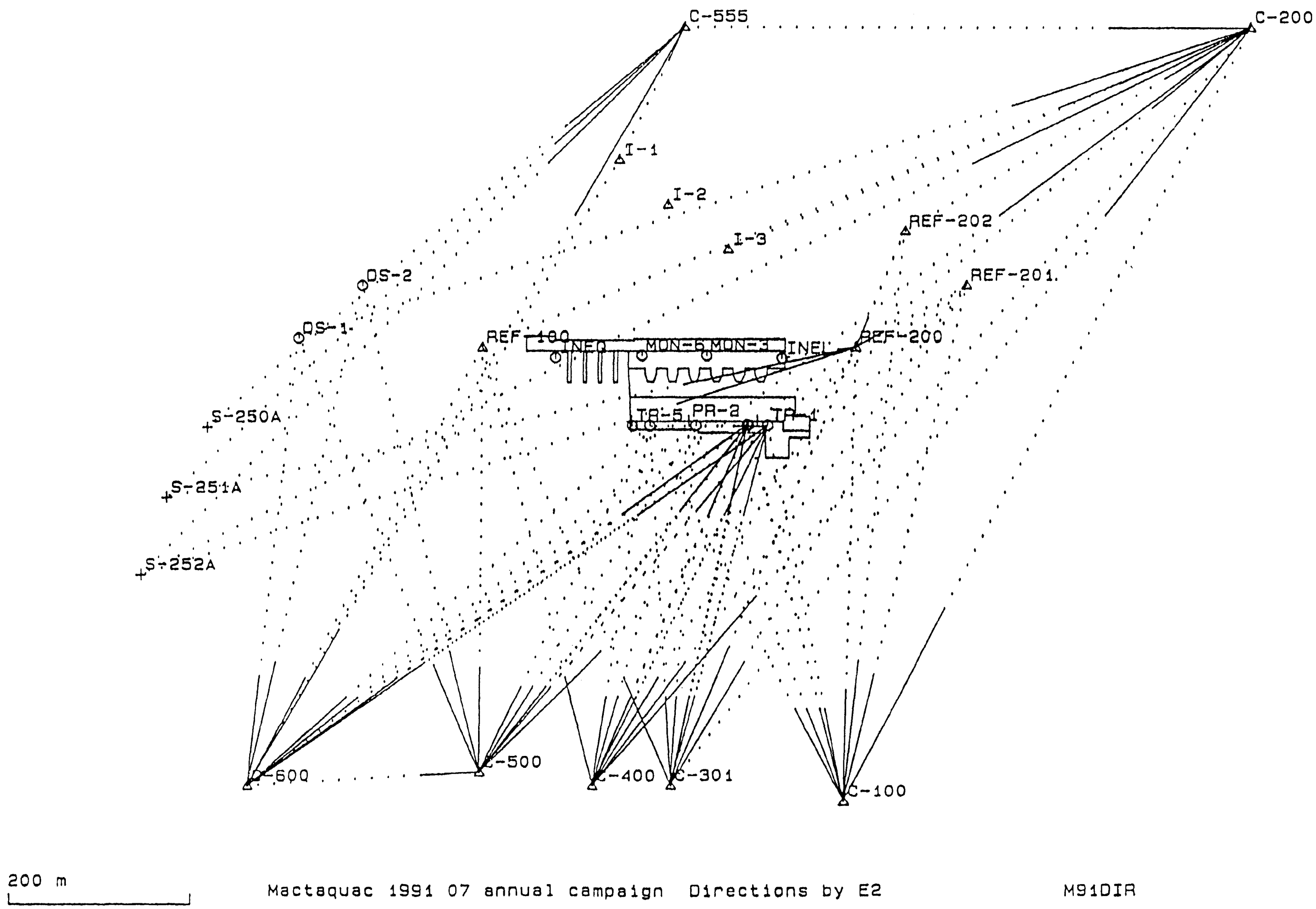


Figure 7.4. Typical horizontal geodetic campaign - direction observables [Chrzanowski and Secord, 1992]

the measurements. The data capture program on the MC-V (module EODM) controls the operation of the MA200 and automatically records its output and prompts for all of the keyboard input: station identification, instrumentation heights, and meteorological conditions. Two files are created for each day's measurements: raw input from the MA200 or keyboard, named "Gyymmdd", and input to the distance reduction program DISR, "MAyymmdd". The reduced distances are formatted for input to PLANE, or ZERO, in file "Myymmdd" with a summary of the reduction in "MAyymmdd.PRT".

Directions are measured in several sets with a Kern E2 precision electronic theodolite. The program on the MC-V (module THEOD) prompts for station names during the direct face pointings of the first set. Thereafter, the name is given with the prompt to control the order of capture (reverse order in reverse face or inverted position). After the second and subsequent sets, a station adjustment is performed to provide an estimate of the standard deviation of the mean values. Additional sets can be added or a set can be ignored in order to arrive at acceptable mean values. Three files are created during each day of observation: a log of all raw input from the E2 and keyboard ("Dyymmdd.RAW"), a summary of the reduced directions and station adjustments ("Dyymmdd.PRT"), and the means of each occupation formatted for input to the horizontal adjustment program ("Dyymmdd" merged into Myymmdd).

As a result, each campaign has a file, named ("Myymmdd"), as input to the horizontal adjustment program (module PLANE; sample in Appendix II.4). The program produces a print file ("Myymmdd.PRT"), a plot file ("Myymmdd.PLT" for plotting stations, observables, station ellipses, or relative ellipses, or both) and a file ("Myymmdd.XCX") containing the estimated coordinates, their variance-covariance matrix, and the estimated variance factor and its degrees of freedom (sample in Appendix II.5). The ".XCX" files are paired in campaign comparisons for the horizontal trend using the module WT2D which produces a print file ("??.PRT", "??" is a user specified eight character name, e.g., "M89A90F") and a plot file ("??.PLT") for plotting the displacements, and their ellipses at a chosen confidence level, resulting from a special solution, from inner constraints, or from the weighted transformation, e.g., Figure 7.5. The same ".XCX" files are used in the modelling of horizontal point movement and instability of reference stations (resulting from module WT2D; an example is shown in Figure 7.6) as a refinement of the trend from the weighted transformation.

Since a date is associated with each campaign and forms a part of the campaign file naming, a time series can be formed. The series can be of an observation extracted from the "Myymmdd" file or a quantity derived from coordinate pairs from its ".XCX" file. A file, e.g., "MXCX", can be created containing the file names in chronological order for the Myymmdd files by the DOS command "dir M??????.XCX |sort > MXCX". This file is then used to control the creation of the time series.

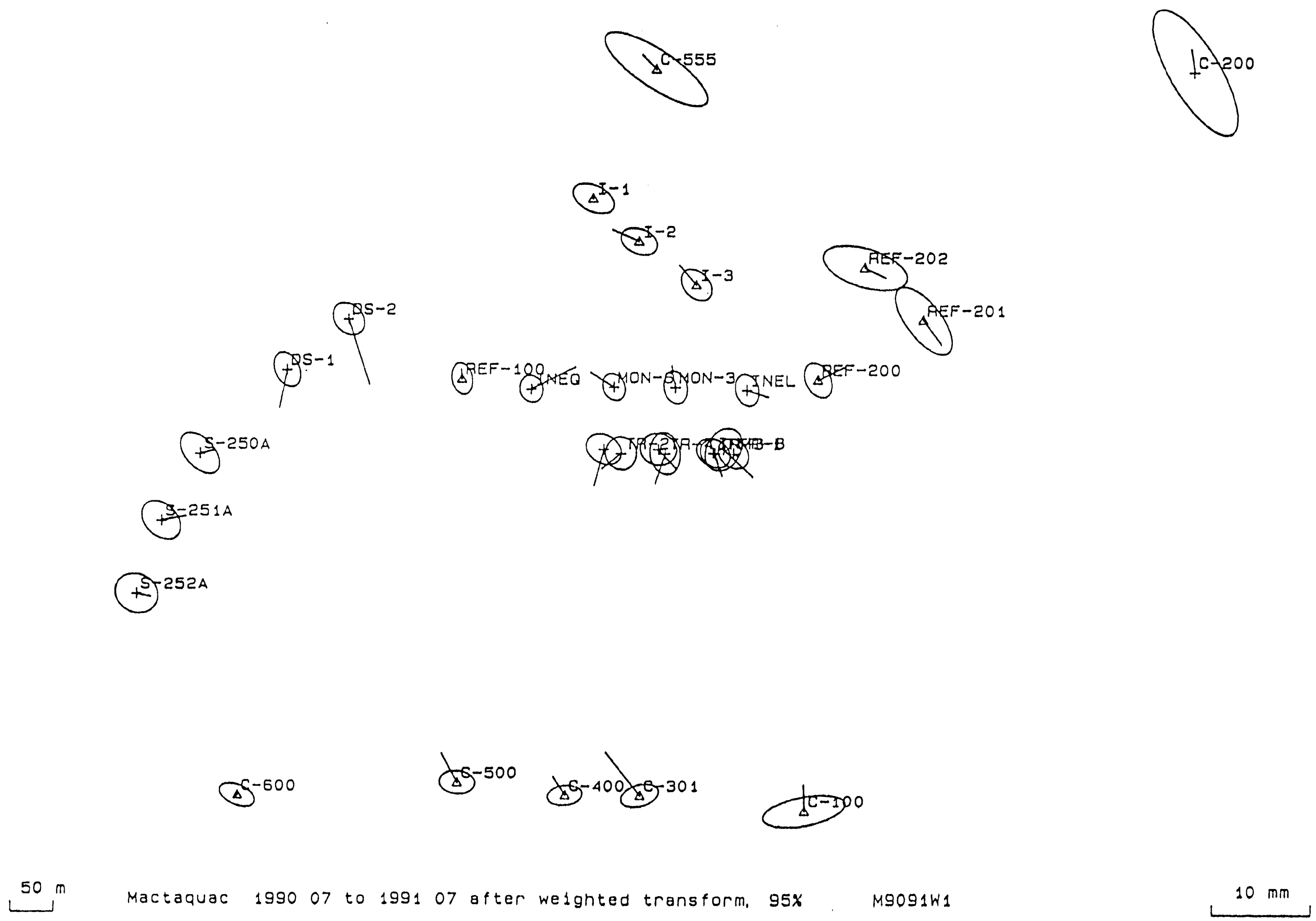


Figure 7.5. Horizontal campaign comparison - displacements and 95% ellipses after weighted transformation [Chrzanowski and Secord, 1992]

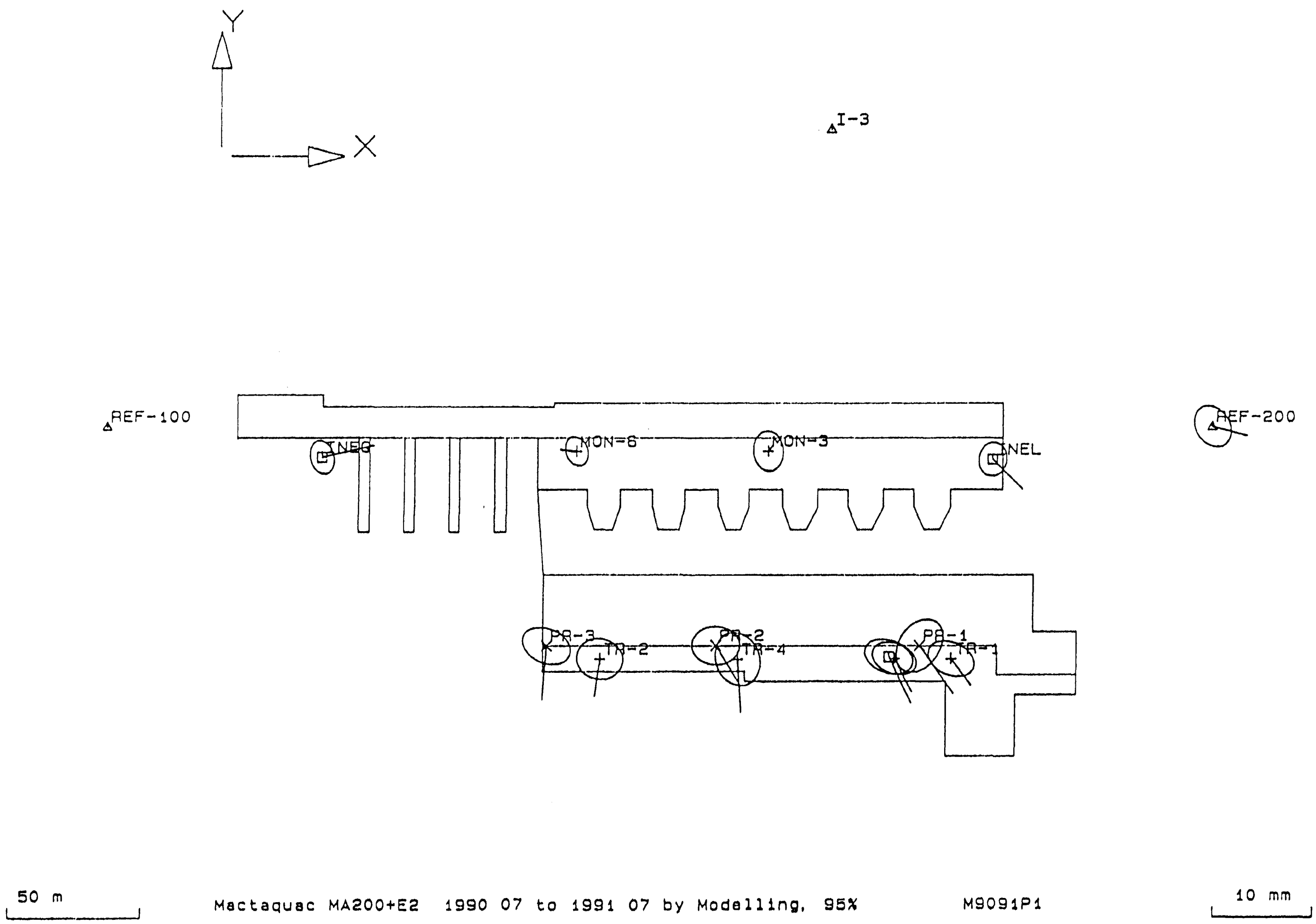


Figure 7.6. Horizontal campaign comparison - displacements and 95% ellipses after modelling [Chrzanowski and Secord, 1992]

7.1.2 Vertical

Precision levelling connects benchmarks located in every level of the intake and, extensively, of the powerhouse. Each level is adjusted separately but includes at least one zero of a scale mounted on an invar wire that is plumbed through a stairwell or vertical borehole. This allows connections between levels of a structure for the determination of vertical extension. As an example, the benchmarks of the four levels of the powerhouse (generator floor, turbine floor, -11 gallery, and -29 gallery) are shown in Figures 7.7 to 7.10. They have been plotted at the same scale and with respect to the same outline of the powerhouse. Transparent overlays of these plots facilitate orientation and the selection of points for vertical extension trends.

The observation files are named, in module (A)LEV, to identify the location and date of the campaign, e.g., "PGyymmdd" for the powerhouse ("P") generator floor ("G") level. The program (module LEVEL) estimating the elevations produces a print file ("PGyymmdd.PRT") and a ".XCX" file as done for the horizontal adjustment. Pairings of the ".XCX" files are used by the program WT1D to obtain the spatial trend. Since the ".XCX" files are named according to the location and date of the levelling, they can be used, in chronological order, to create time series in the same manner as for the horizontal campaigns.

A time series can be created for the tilt between any pair of points in the same level (module FITPLT). As an example, Figure 7.11 shows the tilt derived for the line from points "29 1" to "29 2" at the -29 gallery (shown in Figure 7.10).

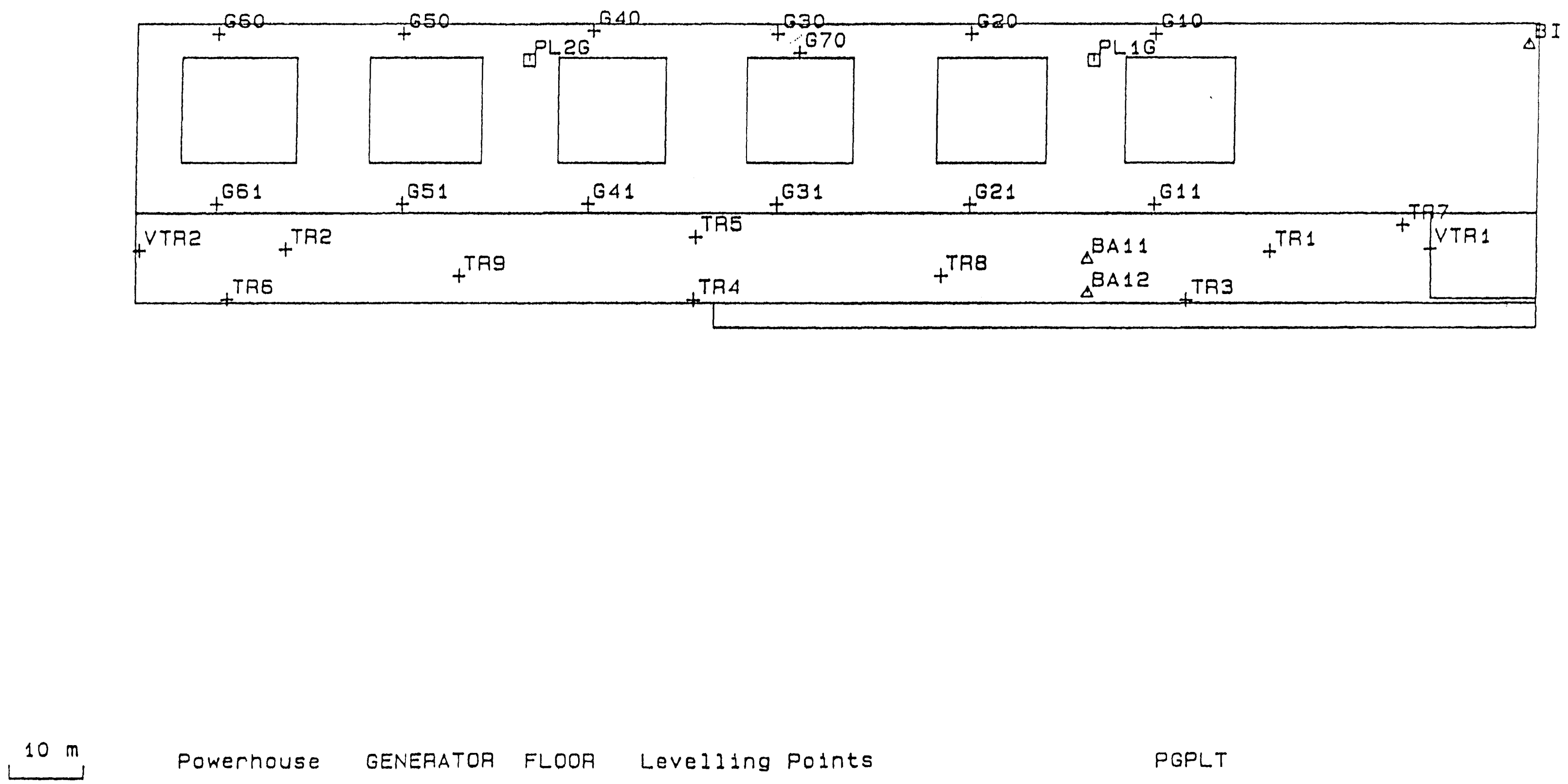


Figure 7.7. Powerhouse, Generator Floor, levelling points

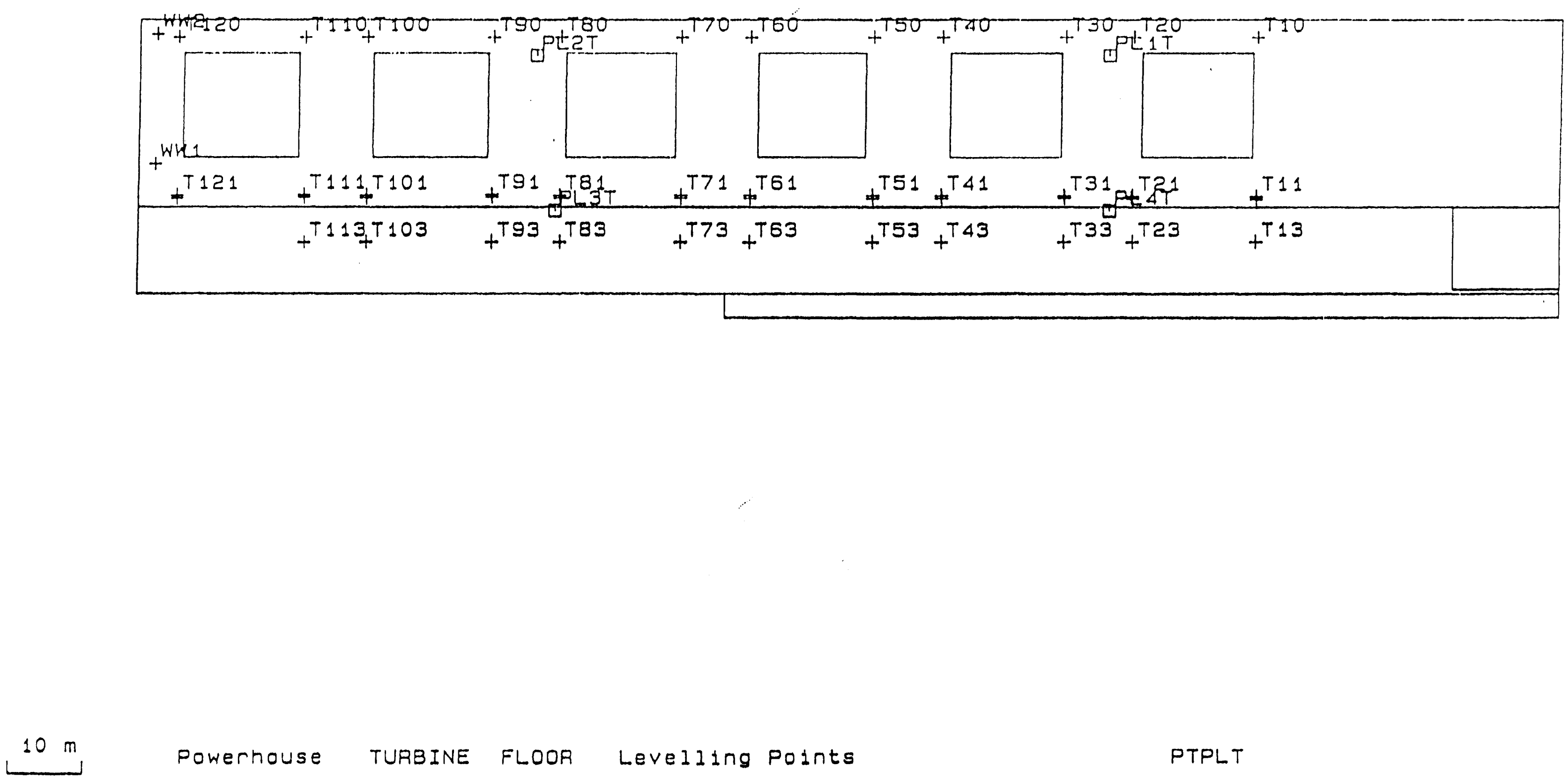


Figure 7.8. Powerhouse, Turbine Floor, levelling points

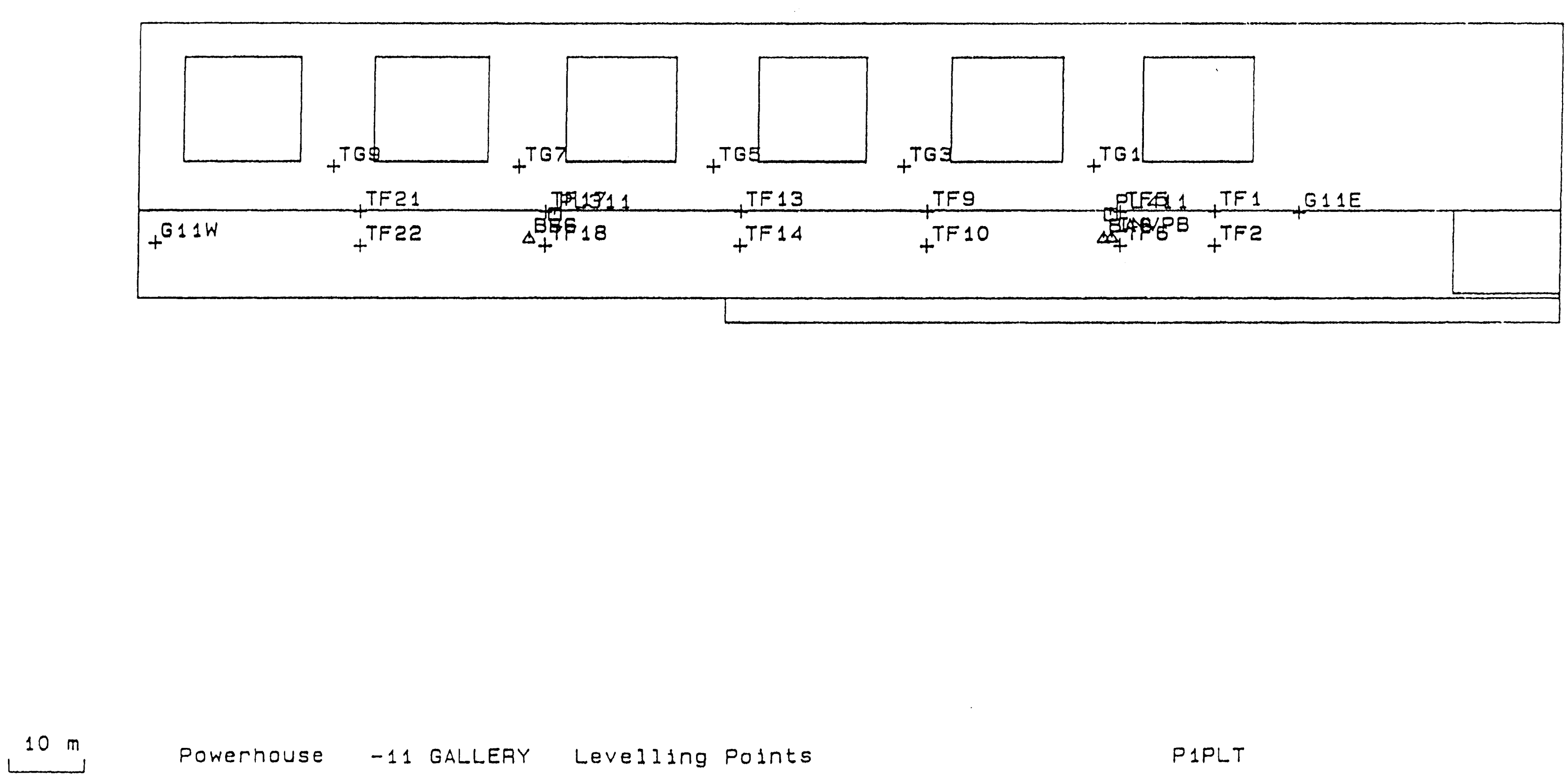


Figure 7.9. Powerhouse, -11 Gallery, levelling points

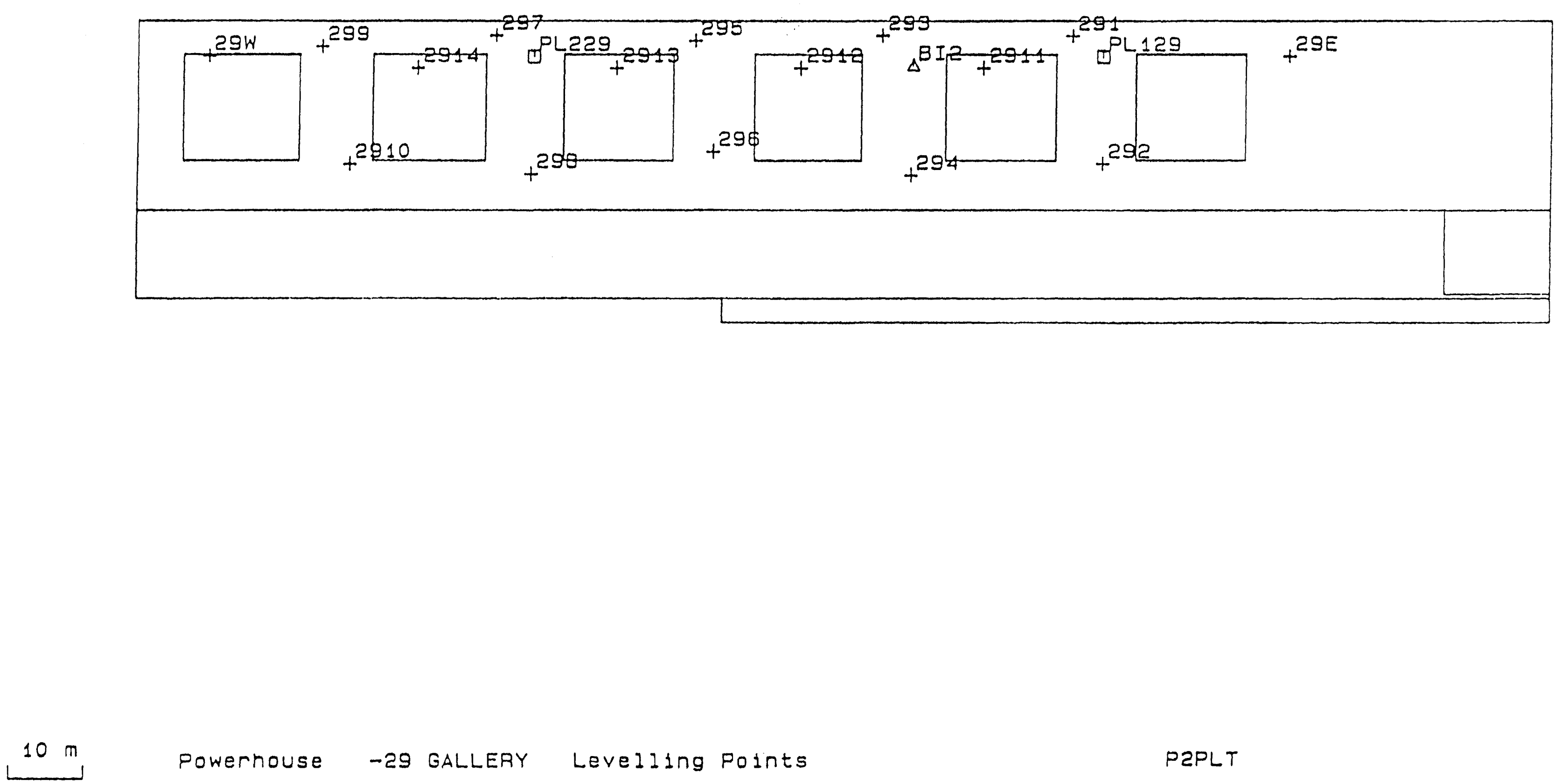


Figure 7.10. Powerhouse, -29 Gallery, levelling points

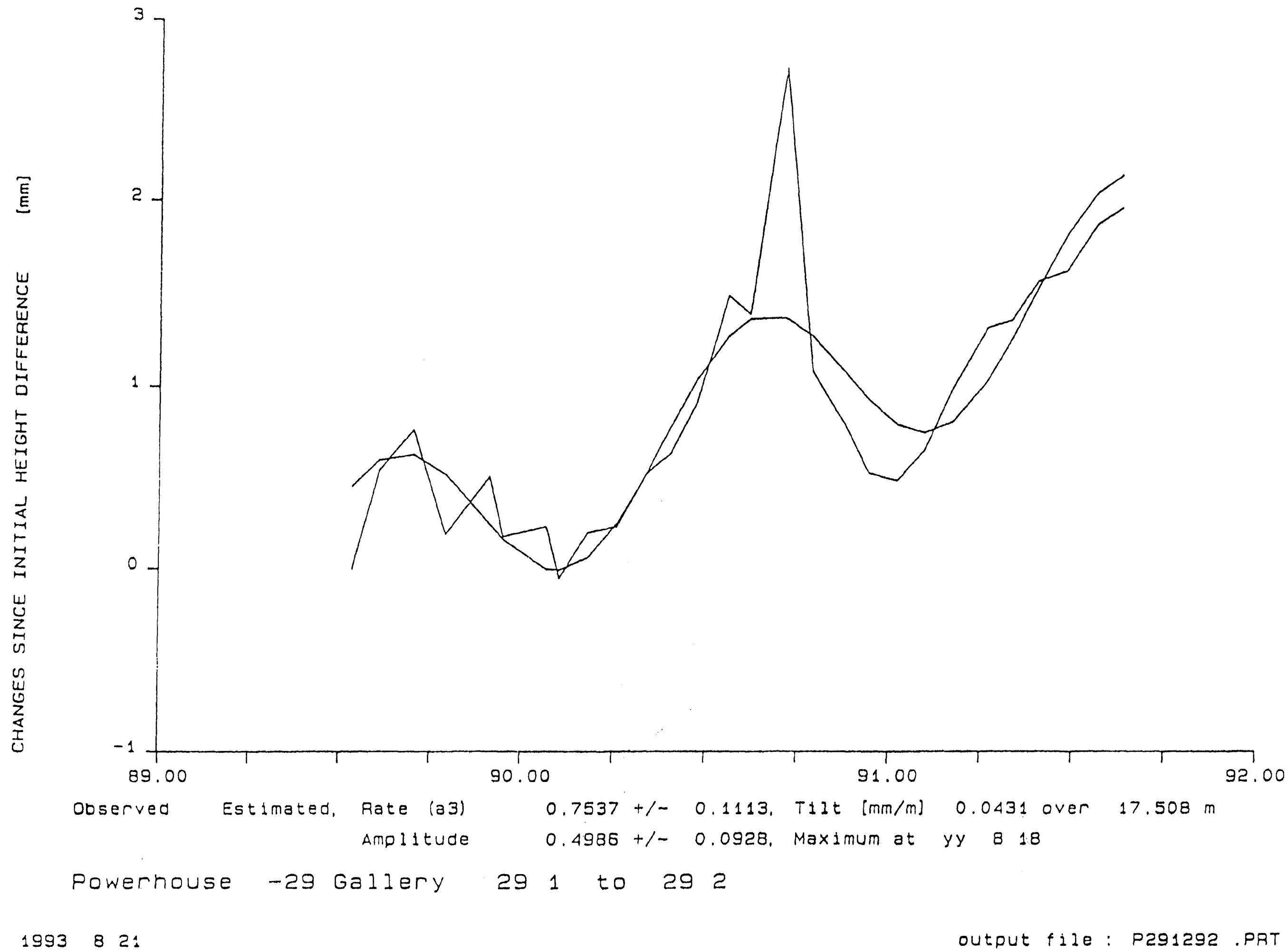


Figure 7.11. Time series of changes in height difference (tilt) derived from levelling (originally, "Observed" and "Estimated" are in different colours)

The rate of the series, +0.7537 mm/y, is the rate of change of the height difference between the two points. It is converted to a tilt rate of 0.0431 mm/m/y by dividing by the horizontal distance between the two points. This distance is calculated from the "x" and "y" coordinates of the two points in the MSXYZ file. The maximum of the sinusoid occurs on the 18th of August every year ("yy 08 18"). The numbers after the "+/-" are the standard deviations, of the estimated rate and amplitude of the sinusoid, scaled according to the behaviour of the residuals during the fitting. The output of the fitting by FITPLT is given in Appendix II.6.

The date of the plot corresponds to that of the operating system of the microcomputer. If a print file has been requested for the fitting in order to investigate details of the fitting, e.g., the residuals, its name would appear in the lower right corner. This is helpful when sorting out several fittings that have been done automatically in a batch.

Vertical extension can be represented in a time series for two points that are not on the same level, so long as the two levels are connected by scales on the same invar plumbline (Section 4.2.1). Plumbline "PL1", and similarly "PL2", extends from the generator floor to the -29 gallery with zero scales represented by "PL1G", "PL1T", and "PL129" at the generator floor, turbine floor, and -29 gallery respectively. In a similar manner, "PL3" and PL4" connect the turbine floor with the -11 gallery. Because of the plumbline connections, vertical extension between any point on any level can be calculated with respect to any other point. Since the deep vertical borehole extensometer, BI2, at the -29 gallery (Figure 7.10) has shown that it can provide a stable vertical reference, the vertical extension from BI2 to any other point can be considered to be the absolute vertical movement of the point. The height difference series is created following Section 4.2.1. The vertical extension rate [mm/m/y] is obtained by dividing the rate (in millimetres per year), from the series fitting, by the difference in "z" coordinates obtained from the MSXYZ file. The fitting and plot would be the same as in Figure 7.11 except that "tilt" is now "vertical extension".

7.2 Geotechnical Observations

Several data collectors are used in any one day. Each has a single letter identifier, "A", "B", etc., and this letter is suffixed to the observation file name, as "GyymmddA", for example (sample observation file in Appendix II.7). The program on the MC-V (module GEOT) will create a new file for each day and will append to a file if it has been already created. The observation name is constructed by the program in reaction to a series of prompts relating the type of observable and the location. If several readings are taken, the mean value is written to the observation record if its value agrees with the predicted or most recent value (provided in the "GEO.CHK" file downloaded to the MC-V at the beginning of each observing day) within the tolerance for the particular observable (a portion of a sample GEO.CHK file is given in Appendix II.8). If the difference between the values exceeds the tolerance, reobservations may be made or the currently observed value may be used, depending on the judgement of the observer.

At the end of an observing day, the observation file is uploaded into the "yymm" directory on the office microcomputer and immediately archived on a diskette. The processing can operate in a batch mode and the observations are extracted from the observation files, reduced, and appended to the appropriate data files. The data files reside in directories named for the type of observable, e.g., "EXB" for rod extensomenters, "EXT" for tape extensometers, "PEN" for suspended pendula, and "INV" for inverted pendula. The basis for the contents of the data files and their naming was the existing Lotus 1-2-3 worksheets. All of the historic data (created prior to the establishment of DAMADA) was transformed as text files from the worksheets so that no re-entry was necessary. The names of the data files were adopted with as little modification as possible because of the existing familiarity with the worksheet naming throughout N.B. Power and its consultants (a table of file naming convention is given in Appendix II.9).

There are over 66 observables by a "Mk II" tape extensometer [Soil Instruments Limited, 1983]. In an attempt to analyse the trend of several years of observations, many slips had to be introduced in the series in order to account for the discontinuities in the data produced by changes in the instrument (replacement of tapes, tension springs etc.). An example of such a series is given in Figure 7.12. Chrzanowski and Secord [1987] advised N.B. Power that the instrument would not produce an acceptable precision without calibration being a regular part of the observation regimen. In order to account for possible distances from less than five metres to up to 25 m, a horizontal calibration array was constructed in one of the galleries. Anchor points were mounted at intervals of 5 m over a total of 25 m. Invar rods, 6 mm in diameter, were suspended from the zero end to each of the anchors. Hence the array is a combination of tape extensometer anchors monitored by a multi-rod invar extensometer. Measurements are made at the beginning of each observation day.

The calibration correction, "c_t", for any particular measurement is derived from the difference between the appropriate calibration campaign at time "t" since 1988 02 10, the date of the base or initial campaign of calibration. A pair of anchors is related to its corresponding invar rod through a micrometer reading, "m_t", which was initially "m_o". The value of m_t increases as the anchors separate since the second anchor moves away from the end of the rod. Similarly, the tape extensometer reading would increase to "e_t" from its initial value of "e_o". Hence, at time "t", the correction is derived from $m_t - m_o = (e_t + c_t) - e_o$, making $c_t = (m_t - m_o) - (e_t - e_o)$. Since the tape and the rods are at the same temperature, no correction for thermal expansion is necessary. For each of the 5, 10, 15, 20, and 25 m separations, there are m_t values appended to file "B0" for each time of calibration. Similarly, the e_t values are in file "T0" and the c_t

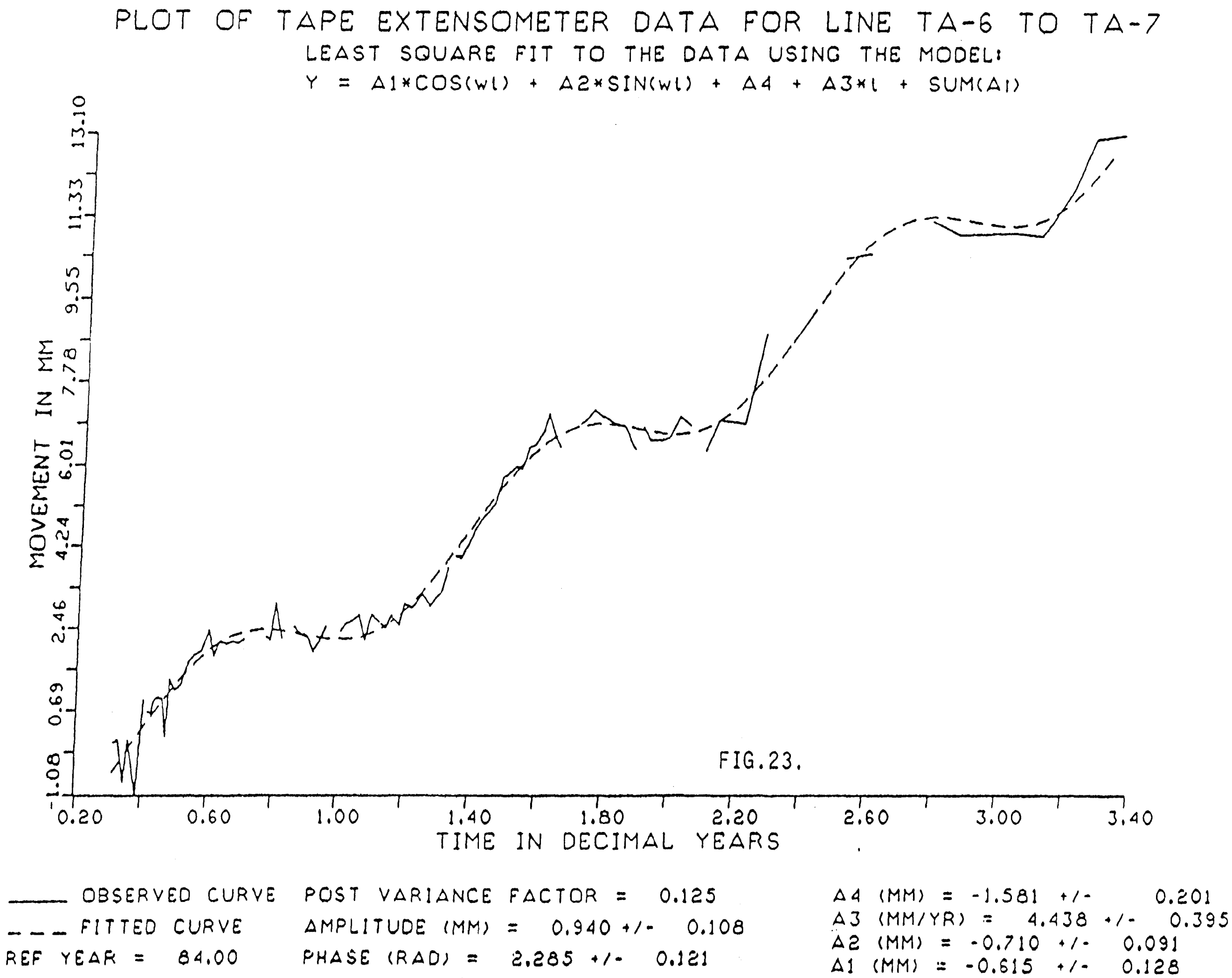


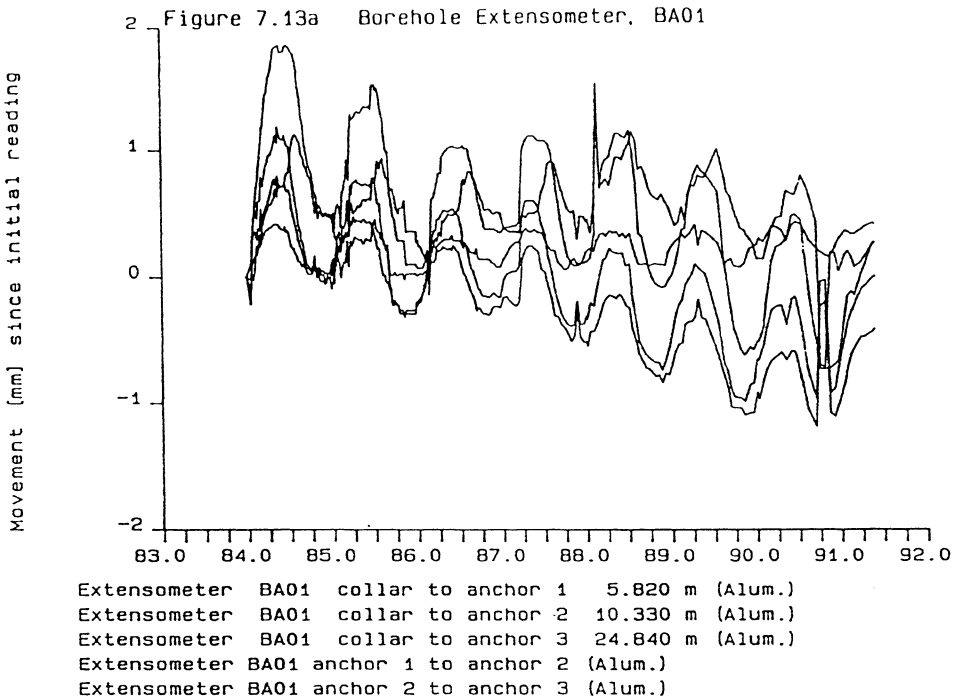
Figure 7.12. Historic tape extensometer series with many slips in the data [from Chrzanowski and Secord, 1987]

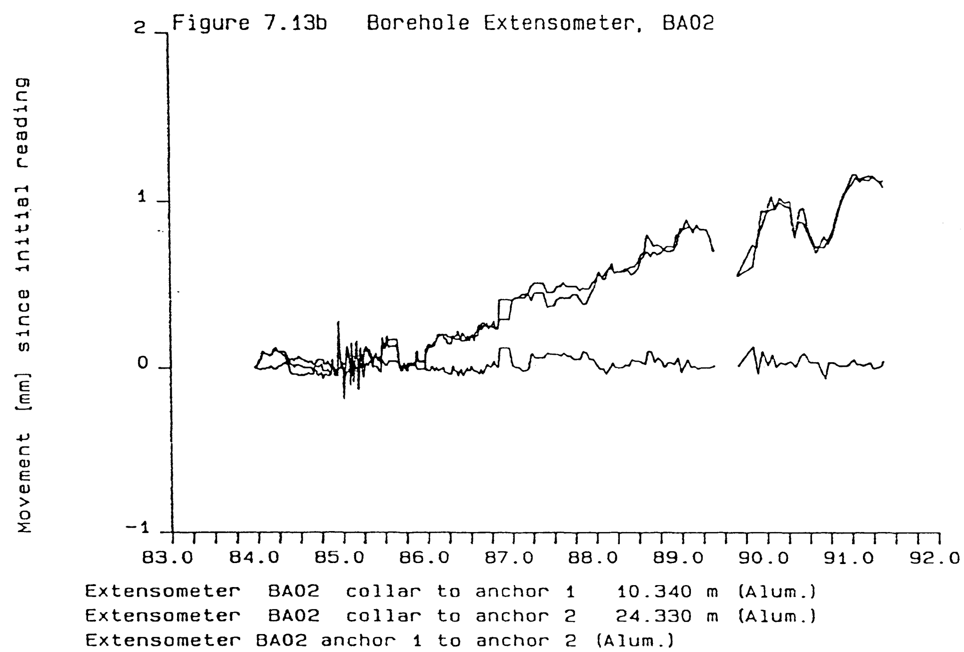
values, in "TAPCAL". It was found that it is sufficient to interpolate linearly for correction for tape extensometer observations that are not at the multiples of 5 m [Chrzanowski, Secord, and Szostak-Chrzanowski, 1989]. As a tape extensometer observation is processed, the T0, B0, and TAPCAL files must have been updated already for the observation day and the calibration correction is derived from the values in TAPCAL. Prior to calibration, the rates estimated from the series had standard deviations ranging from ±0.3 mm/y to ±0.8 mm/y, with most values around ±0.3 mm/y [Chrzanowski and Secord, 1987]. After calibration had been introduced, the rates were estimated with standard deviations mostly around ±0.1 mm/y (with some values to ±0.3 mm/y) [Chrzanowski and Secord, 1990]. As a consequence of the calibration effort, the tape extensometer has become a reliable instrument, with no slips in the data series and with improved standard deviations.

In addition to the series, the data files contain initial values and constants or coefficients used in the reduction of the data. Although many of the data files contain series that are direct reflections of the observations, some require rather elaborate organization of initial values and constants. There is a variety in the borehole extensometers and in the way in which temperature corrections are applied. Some use aluminium rods while others use invar. Some have different arrangements of thermistors for measuring temperatures at different depths of the borehole. Therefore there are codes in the data files to indicate what coefficient of thermal expansion is to be used and the depths at which thermistors are located (sample file in Appendix II.10). The reduction of other observations might depend on the orientation of the installation in order to resolve movement in the x or y directions so codes are imbedded in the data files. Initial values may change as the reference is changed, e.g., the relocation of a reading table for a pendulum as it displaces. A history of the intial values can also be included in the data file. Sensors used with inverted or suspended pendula may output frequency [Hz] which is converted to linear units [mm] using coefficients estimated in the fitting of data from calibration measurements. These values of these coefficients can be embedded in the data file (sample in Appendix II.11). Stress cells may require temperatures in the reduction of their readings. Thermistors can be part of the installation and may use a series of coefficients to convert their readings into temperatures. These coefficients and the organization of thermistor and stress cell can be part of the data file (sample in Appendix II.12).

7.2.1 Time Series

Several series can be viewed simultaneously on the same plot, each represented in a different colour (Figure 7.13 resulting from module SIMPLT). This would illustrate the trend and show several data together for comparison but without any analysis or statistics. Because there are many possible series (over 300 may be done routinely), the simultaneous plots are done at two per letter size page in a batch mode on a Hewlett-Packard HP7550A plotter with





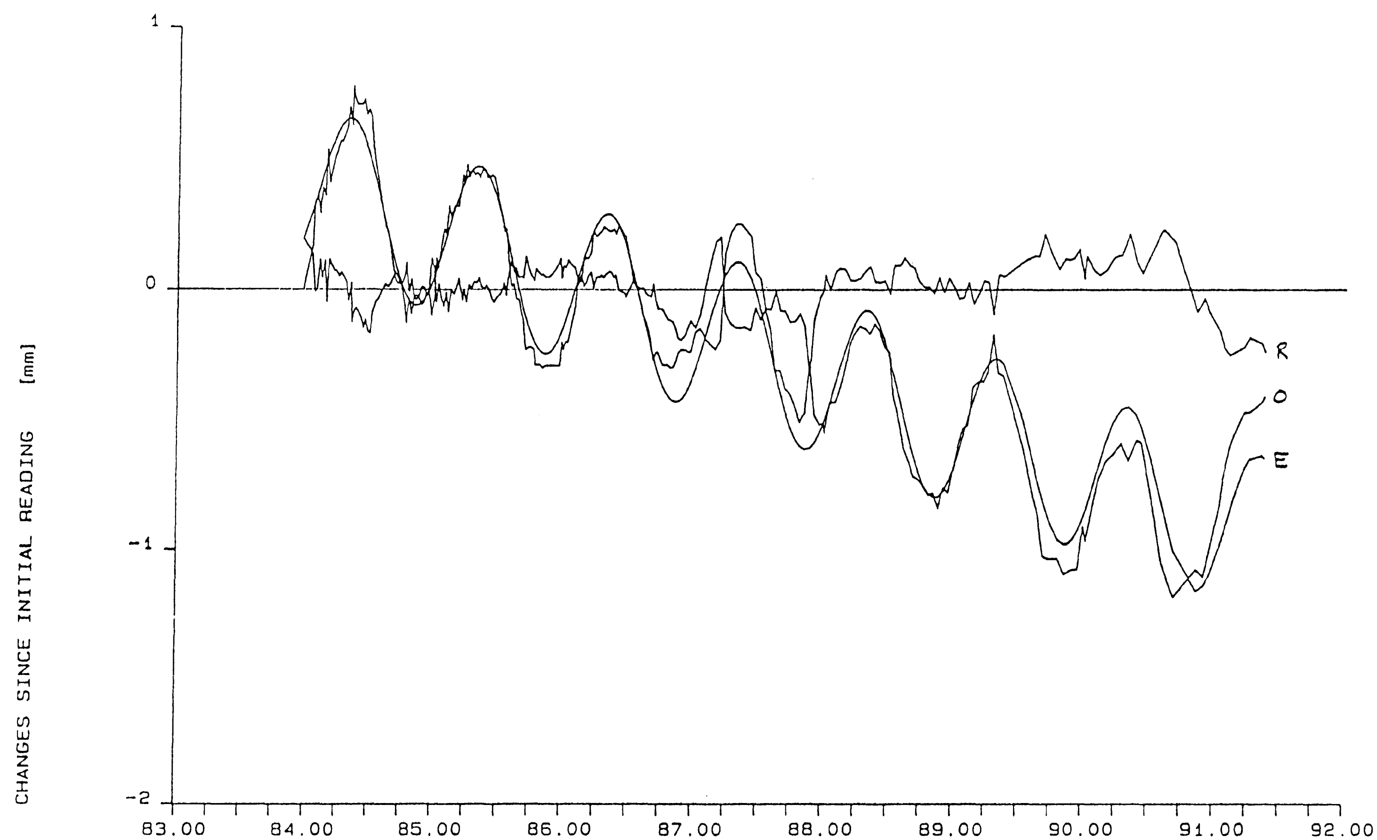
1993 8 23

Figure 7.13. Simultaneous plotting of several time series

(originally, each series and title combination is in a different colour) automatic paper feed (batch file, that created Figure 7.13, in Appendix II.13).

Temporal trend is performed on selected series, also in a batch mode (module FITPLT). The series is taken directly from a data file or may be derived from two or more quantities from the same file or from more than one file. The batch command file indicates the file name and column of data for each file and how they are to be combined. An example of a derived series fitting is given in Figure 7.14. In this case the print file was requested and was given the name "BA08.P21" which contains a statistical assessment of the fitting (file in Appendix II.14). Some housekeeping is shown in Figure 7.14: the date of the plot and the columns and file names where the data originated. The collar to anchor distance is extracted from the title and used in the calculation of the extension (0.1205 mm/m/y) which is the rate (1.5533 mm/y) divided by the anchor to anchor distance (12.890 m). The amplitude, time of the maximum in the cycle, and standard deviations are the same as in Figure 7.11. The fittings and plotting can be done together in a batch or individually with a screen display and interaction in order to choose the interval of time to be fitted.

The trend analysis cannot be entirely automatic since a change in the interval chosen for the analysis could result in a different value for the rate. Further, if the frequency of observation has changed, the fitting could be affected by the interval chosen since the denser portion of the series will tend to dominate the characteristics of the sinusoid and rate. As an illustration of this, a series of jointmeter data has been fitted in three ways. Figure 7.15 shows the



Observed Estimated, Rate (a3) -0.1840 +/- 0.0030, Extension -0.0408
Residuals Amplitude 0.3125 +/- 0.0086, Maximum at yy 5 6

Extensometer BA01 collar to anchor 2 10.330 m (Alum.)
minus Extensometer BA01 collar to anchor 1 5.820 m (Alum.)
1993 8 21 input from BA01 col 2 minus BA01 col 1, output file : BA01 .P21

Figure 7.14. Time series with sinusoid and rate fitting
(originally, "Observed", "Estimated", and "Residuals" are in different colours)

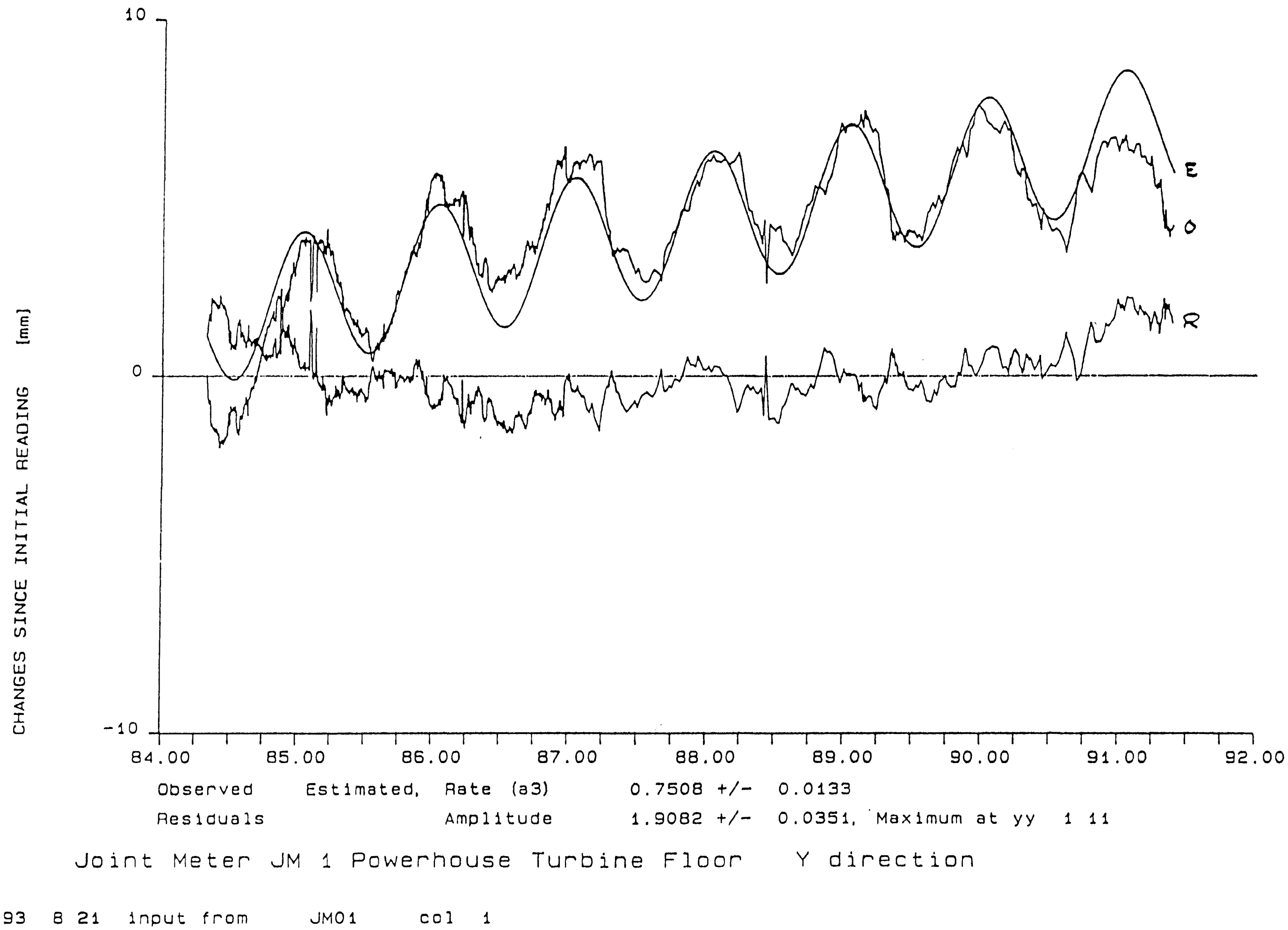


Figure 7.15. Time series with sinusoid and rate fitting, data from 1984 to 1991 (originally, "Observed", "Estimated", and "Residuals" are in different colours)

fitting over the interval including 1984 to 1991, with a rate of 0.75 ±0.01 mm/y and an amplitude of 1.92 ±0.04 mm. The fitting of the portion of the data from 1984 to the end of 1986 is shown in Figure 7.16 and results in a rate of 1.77 ±0.02 mm/y and an amplitude of 1.84 ±0.02 mm. In Figure 7.17, the latter portion, from the beginning of 1987 to 1991, yields a rate of 0.28 ±0.02 mm/y and an amplitude of 1.61 ±0.04 mm. The maxima of the three sinusoids occur within ten days of each other. The earlier, denser data (Figure 7.16) tends to dominate the fitting. The slope of the data is less for the later portion. Some change has occurred to lessen the rate of long term expansion. An automatic fitting of the whole series would not reveal this; however, visual inspection of the plot would suggest such a consideration. Obviously, this trend would not be revealed until a sufficient interval of time has transpired for the new rate to be defined. This illustrates the importance of human interaction in a monitoring system and the fact that a system cannot be fully or entirely automatic.

7.2.2 Spatial Series

Several of the inverted pendula extend through vertical boreholes. A shuttle centering mechanism [Boyer and Hamelin, 1985] is used to traverse these boreholes. The shuttle temporarily anchors the plumbline at the centre of the borehole making the plumbline vertically above it at the reading table. Table readings are taken with the plumbline extending freely (i.e., without the shuttle) as the reference and with the shuttle stopped at intervals of 1 m throughout the

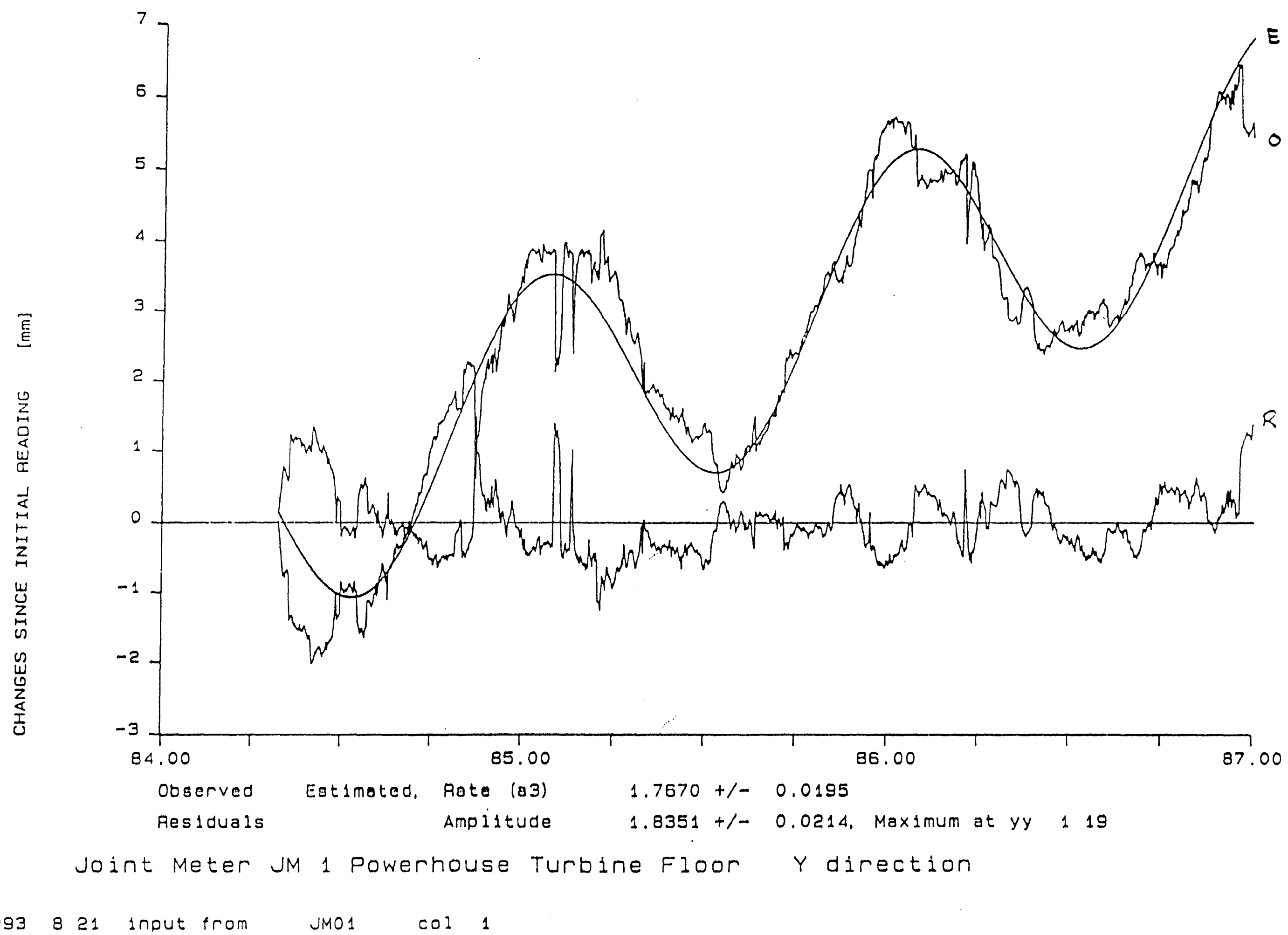


Figure 7.16. Time series with sinusoid and rate fitting, data from 1984 to 1986
(earlier portion of Figure 7.15; originally, "Observed", "Estimated", and "Residuals" are in different colours)

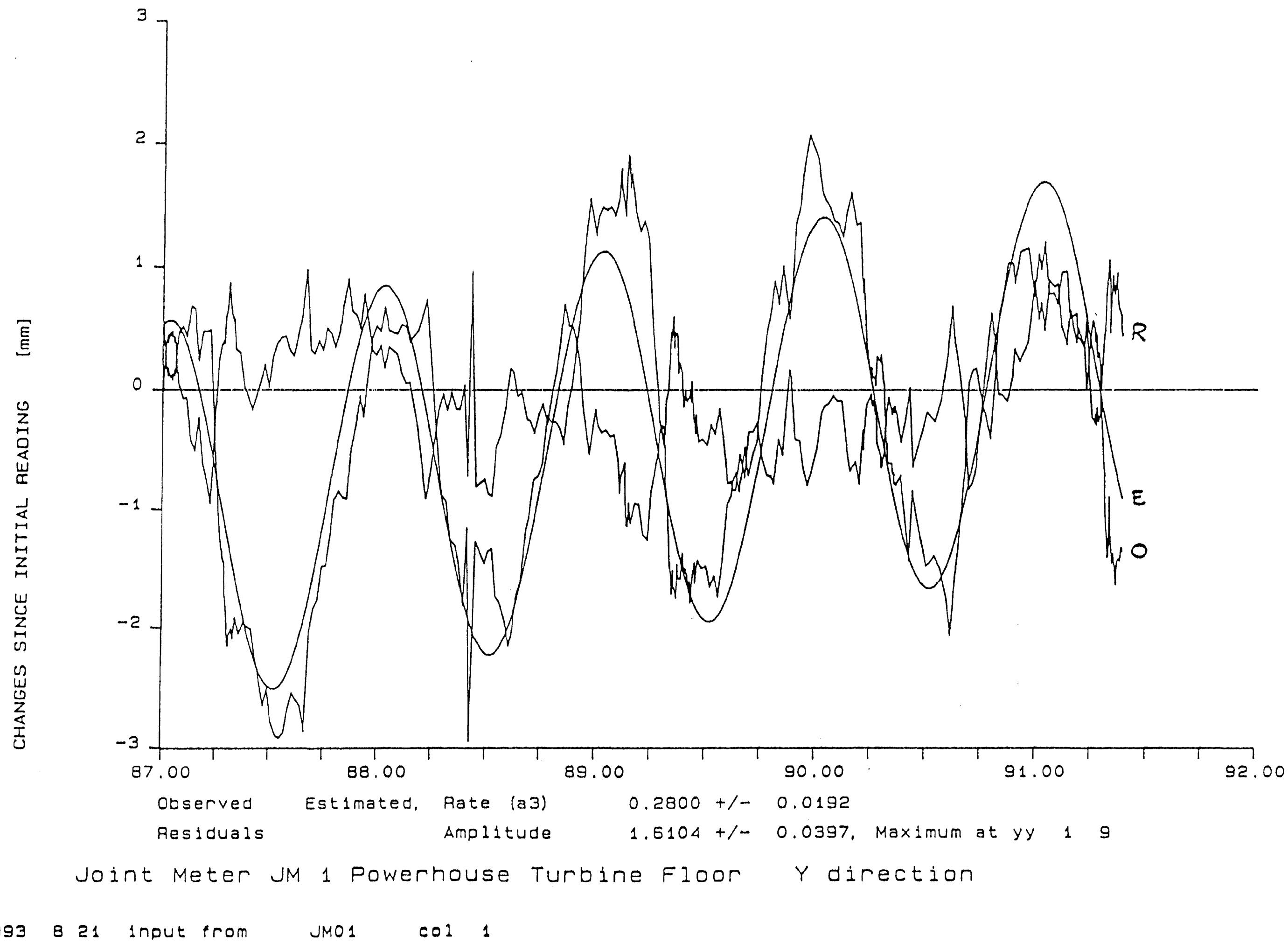
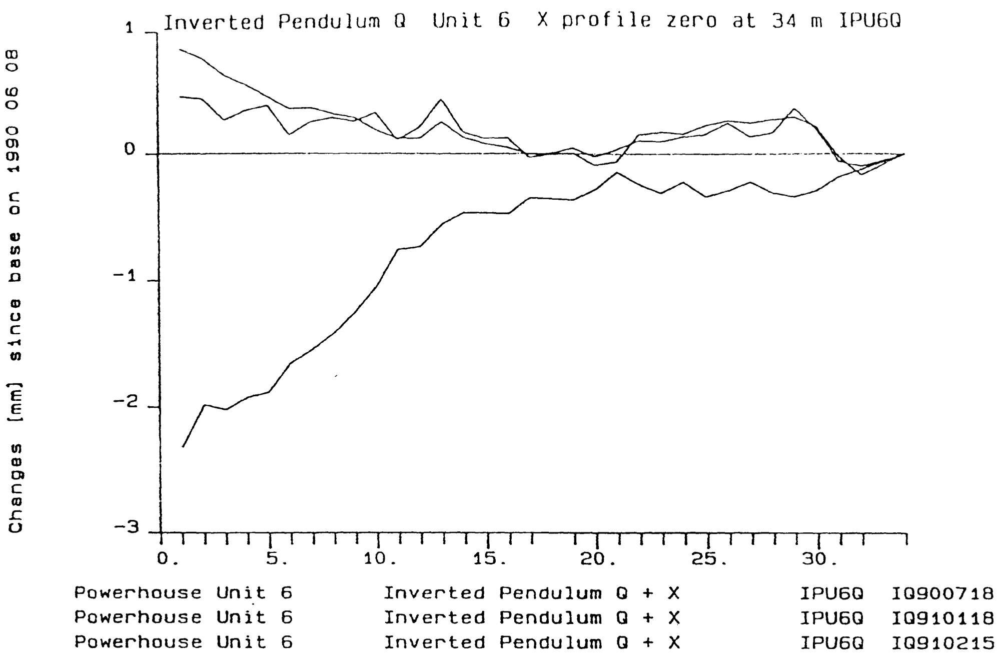


Figure 7.17. Time series with sinusoid and rate fitting, data from 1987 to 1991
(later portion of Figure 7.15; originally, "Observed", "Estimated", and "Residuals" are in different colours)

length of the borehole, traversing downward and then returning. The program on the MC-V (module SSR) controls the data gathering and creates the campaign file containing an average of the downward and upward traversing in the x and y directions for each depth. Each pendulum location is identified by a letter, e.g., "Q", so a campaign file is labelled as "IQyymmdd" ("I" for inverted pendulum, "Q" for that particular location). Profiles of a borehole can be plotted from several of these files simultaneously, as for the times series (Figure 7.13), except that the x axis of the plot is now depth (Figure 7.18 resulting from module SSSPLT, batch file creating Figure 7.18 in Appendix II.15).

Pairs of campaigns can be differenced to create a spatial series for fitting. This is done interactively with a screen display of the fitting in order to choose the zero or anchor depth or to remove a particular point. Figure 7.19 shows the plot from one such fitting (by module SSPLT). In this case, the change in the Y profile from 1990 06 08 to 1991 02 15 has been created. The slope of the profile difference (i.e., general tilting of the borehole) is 0.016 ±0.01 mm/m in the -Y or downstream direction with the shuttleless readings made common to each campaign. The difference at the 33 m depth has been flagged as an outlier. Figure 7.20 shows the same data except that the outlier has been excluded. Now, the tilt is 0.029 ±0.003 mm/m in the same sense. An interactive display has allowed for the changes in data and virtually immediate plots. A print file, "IQY.PRT" contains the details of both fittings, including the residuals and statistical assessment (Appendix II.16).



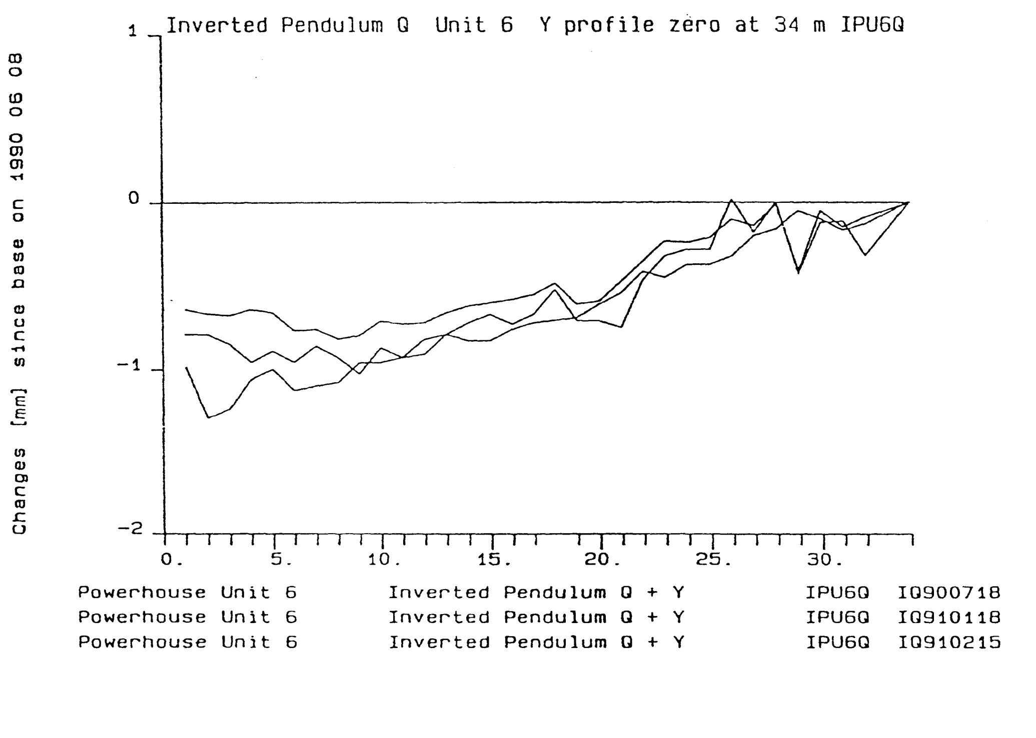


Figure 7.18. Simultaneous plotting of several spatial series (originally, each series and title is in a different colour)

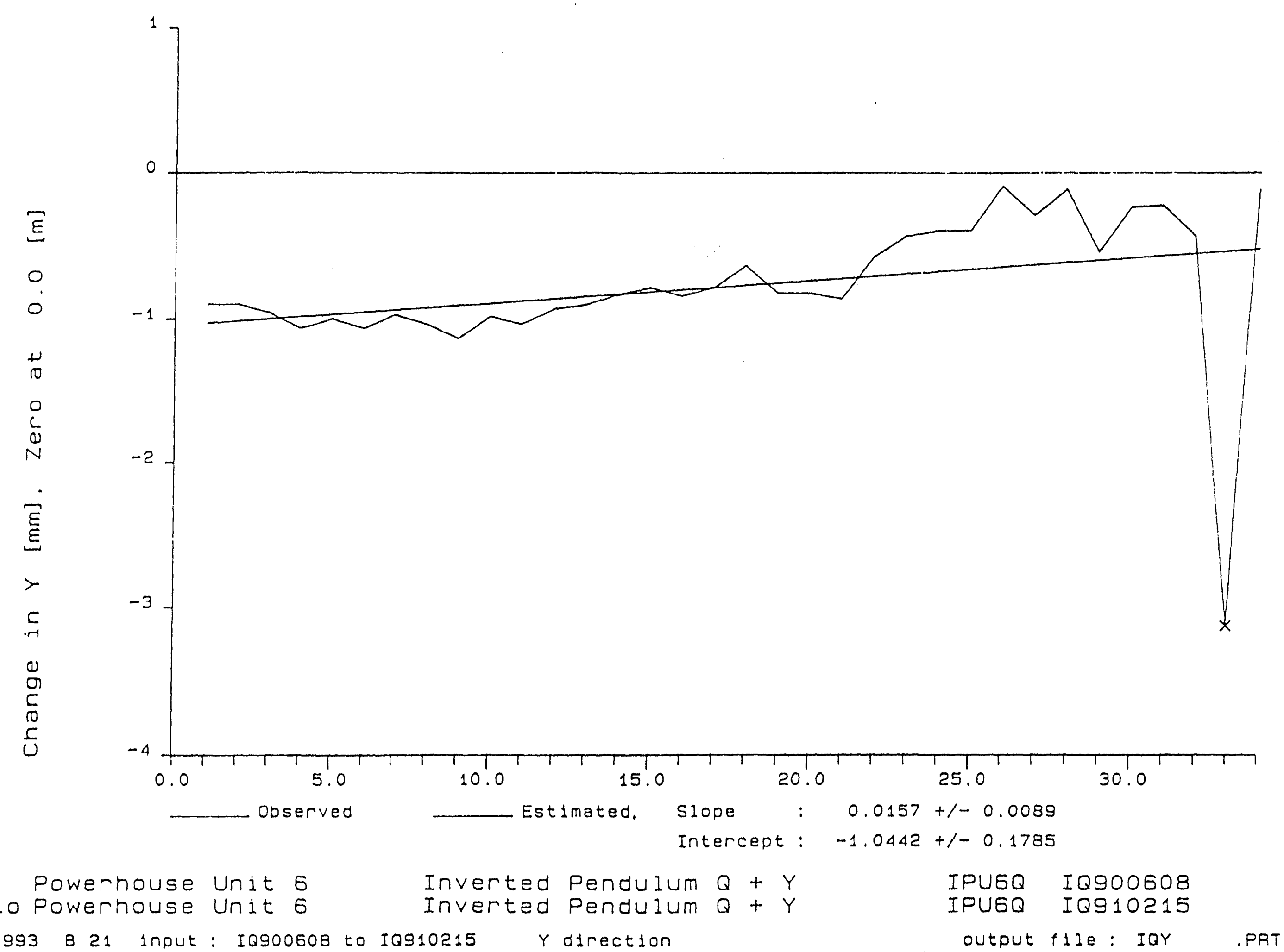


Figure 7.19. Spatial series, with fitting, from inverted pendulum shuttle readings

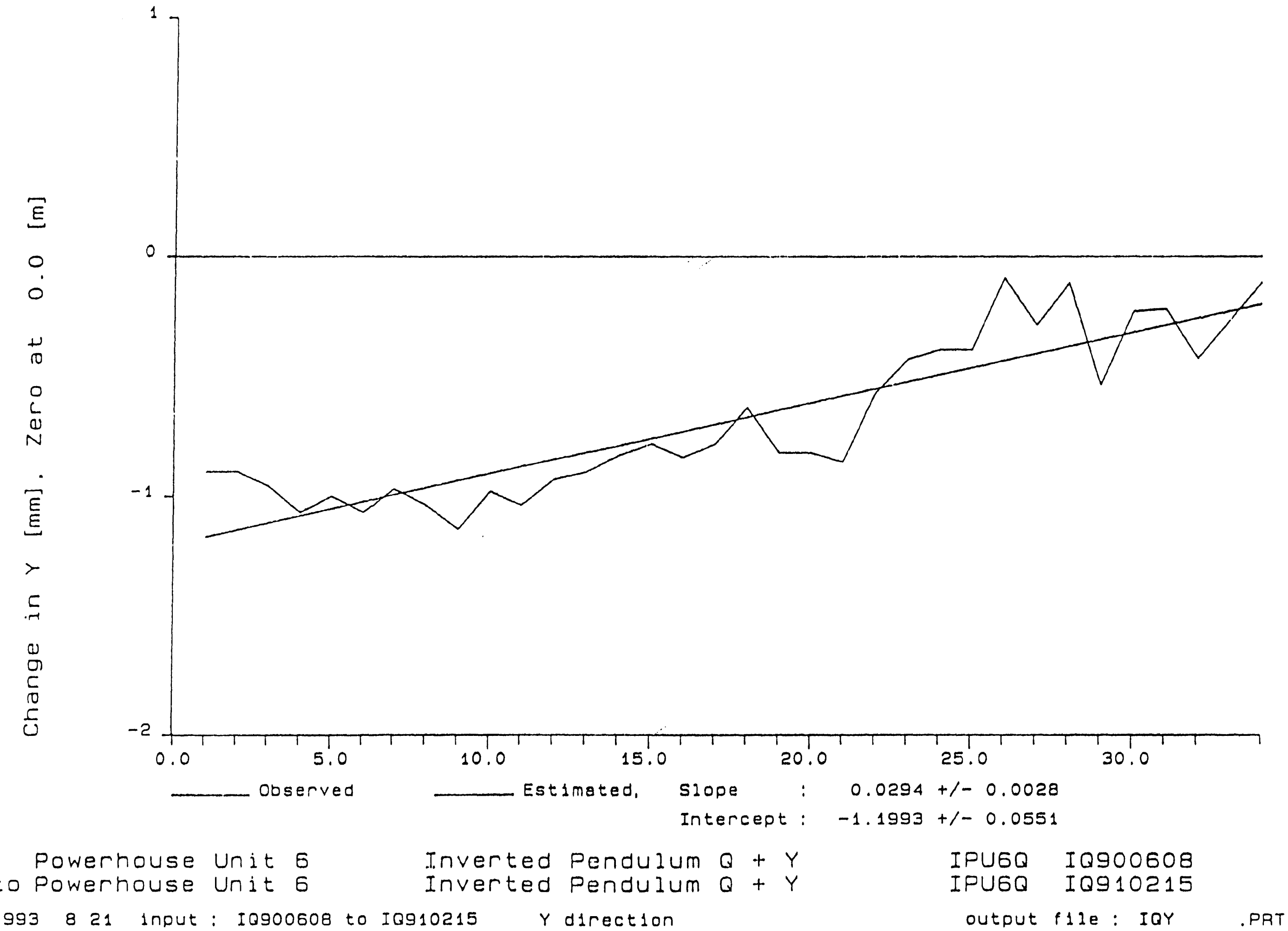


Figure 7.20. Spatial series, with fitting, from inverted pendulum shuttle readings (same data as Figure 7.19, with depth 33.0 removed)

7.3 Modelling

Since all observation points have been located in a common three dimensional coordinate system (file MSXYZ), any collection of points can be selected as a section through a structure. The dominant deformation in the powerhouse is in the upstream-downstream direction. This would be in the yz plane because of the orientation of the coordinate system. Therefore a vertical section through the powerhouse can be created by specifying the x and y, and possibly z, limits within which points could be considered. The observables in such a section are shown in Figure 7.21. In this case, they are borehole and rod extensometers, tape extensometers, pendula (relative horizontal movement), and horizontal and vertical displacements of points (absolute movement). The horizontal displacements are from either geodetic network campaigns or from deep inverted pendula. The observations into the modelling (module OBSMOD) are the rates from the fittings of the corresponding time series (file in Appendix III.1).

Taking the vertical section resolves the deformation into a two dimensional plane, that of the section. The coordinate system of the MSXYZ file would be y positive to the left (upstream) and z positive upwards in Figure 7.21. Since it is more conventional to think of a righthanded yz coordinate system, the MSXYZ coordinates were transformed into y positive to the right (downstream)

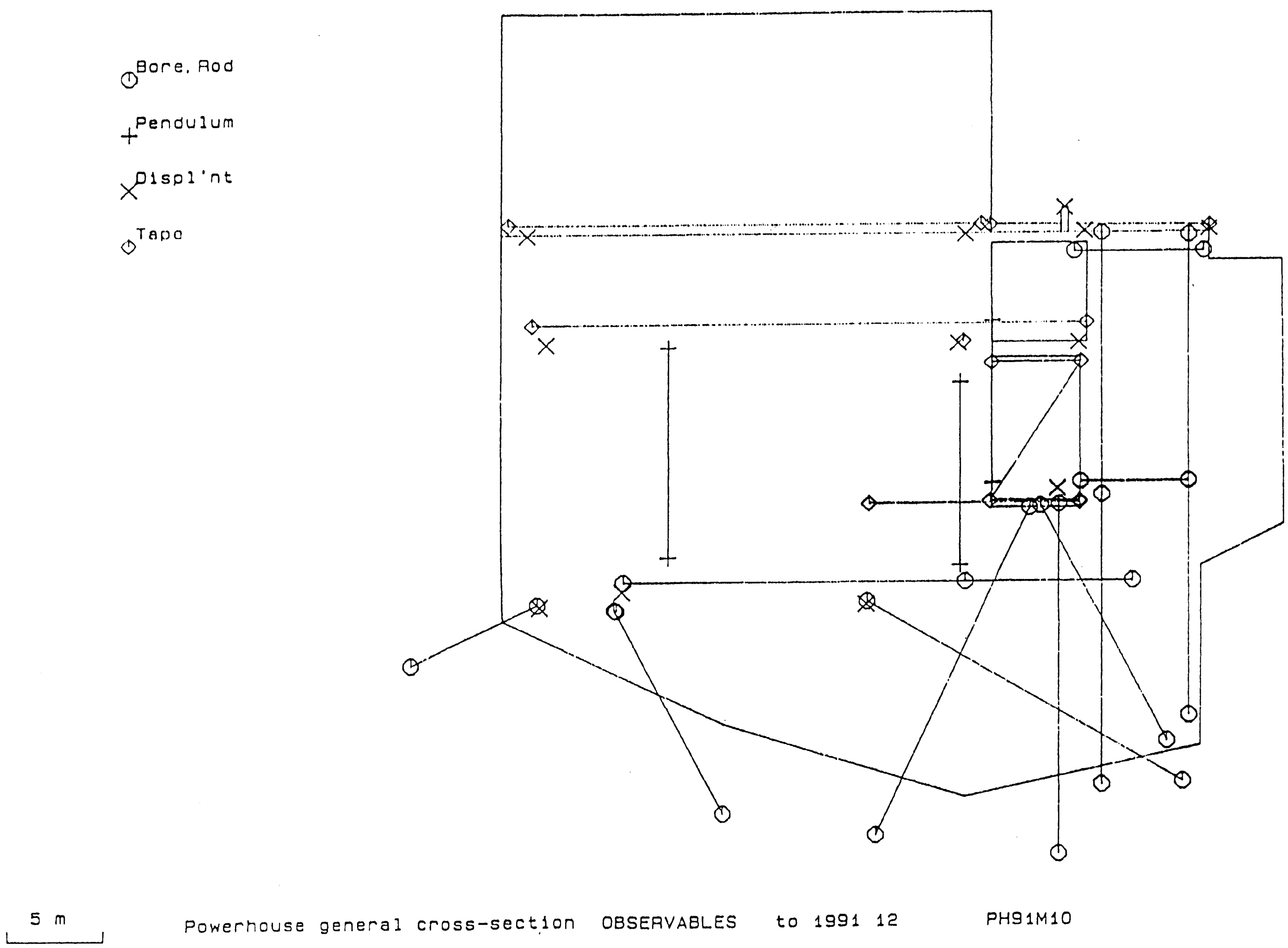


Figure 7.21. Powerhouse cross-section observables
[after Chrzanowski and Secord, 1992]

and z positive upward for the modelling. The modelling of a displacement field by a polynomial is sensitive to the choice of origin (Section 5.2). Therefore, the choice of the yz origin was part of the modelling input. Also, in order to have physical sense to the displacement field, stable anchors (of either inverted pendula or of deep boreholes) were held fixed (displacement component or components of zero, with high weight). A rotation, ω, about the "centre" point (y_c, z_c: bottom of the opening of the vertical construction joint in the powerhouse and, coincidentally, also the origin for the modelling) was modelled to account for the increase in opening with height. In the 1991 integrated analysis by Chrzanowski and Secord [1992], the displacement field [mm/y] was represented by the polynomials $dy = a_1y + a_3yz + a_4y^2 - \omega z$ and $dz = b_2z + \omega y$, with all of the coefficients being significant at 95% or more. Including the rotation parameter, which was only 12"/y or 0.06 mm/m/y, was only a minor improvement in the model, over not including it, so that there can be no strong conclusion that rotation of the downstream portion of the structure was occurring.

The displacement field [mm/y] described by the above polynomials was generated for a specified array of points (represented by small upright crosses) in the section and is shown in Figure 7.22. The corresponding strain field [ppm/y] is shown in Figure 7.23 (all values were positive except where noted as "-"). The modelling generates a print file (Appendix II.2), with a statistical assessment of the modelling, and the files to enable plotting of the fields.

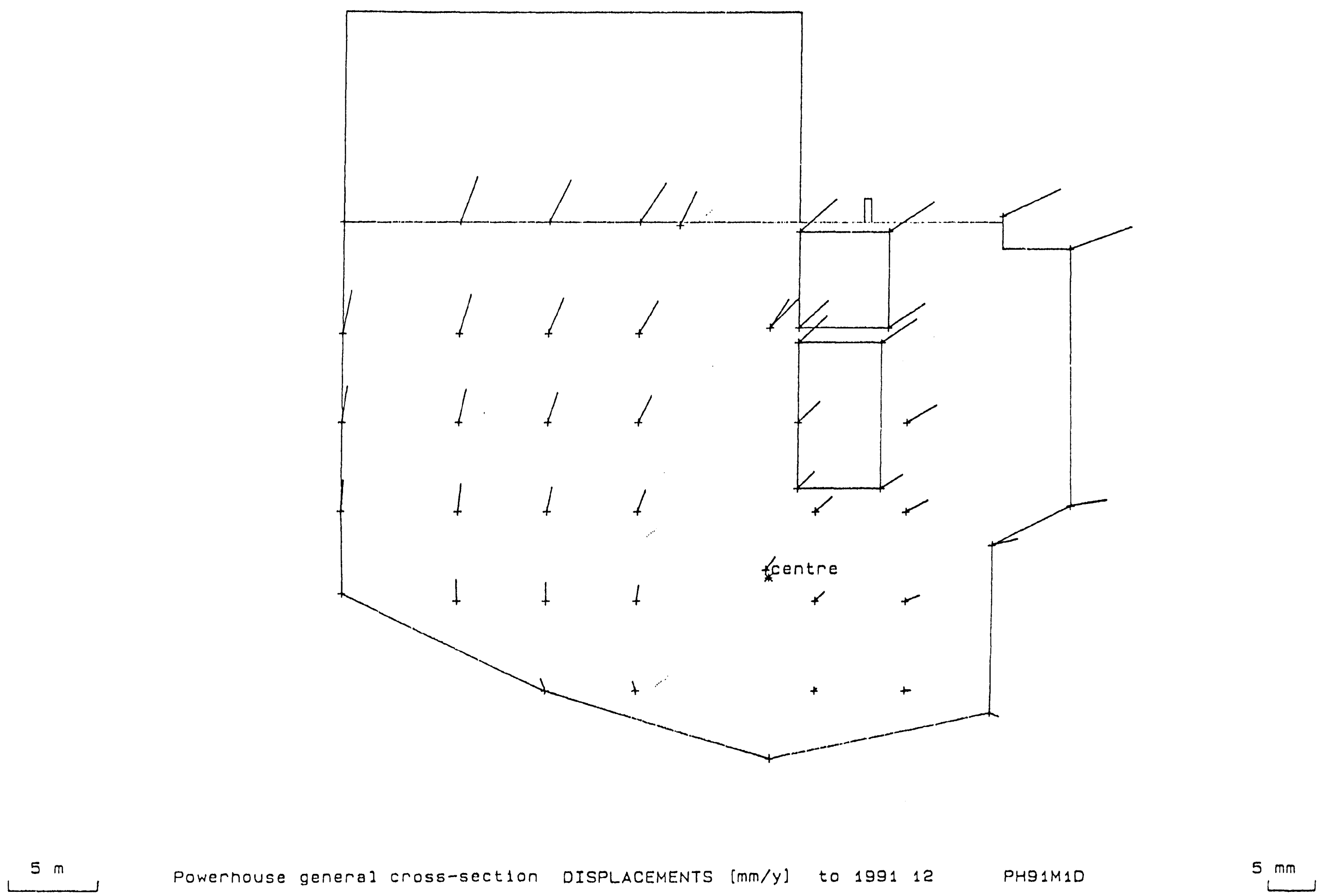


Figure 7.22. Powerhouse cross-section, displacement rate field generated by OBSMOD [Chrzanowski and Secord, 1992]

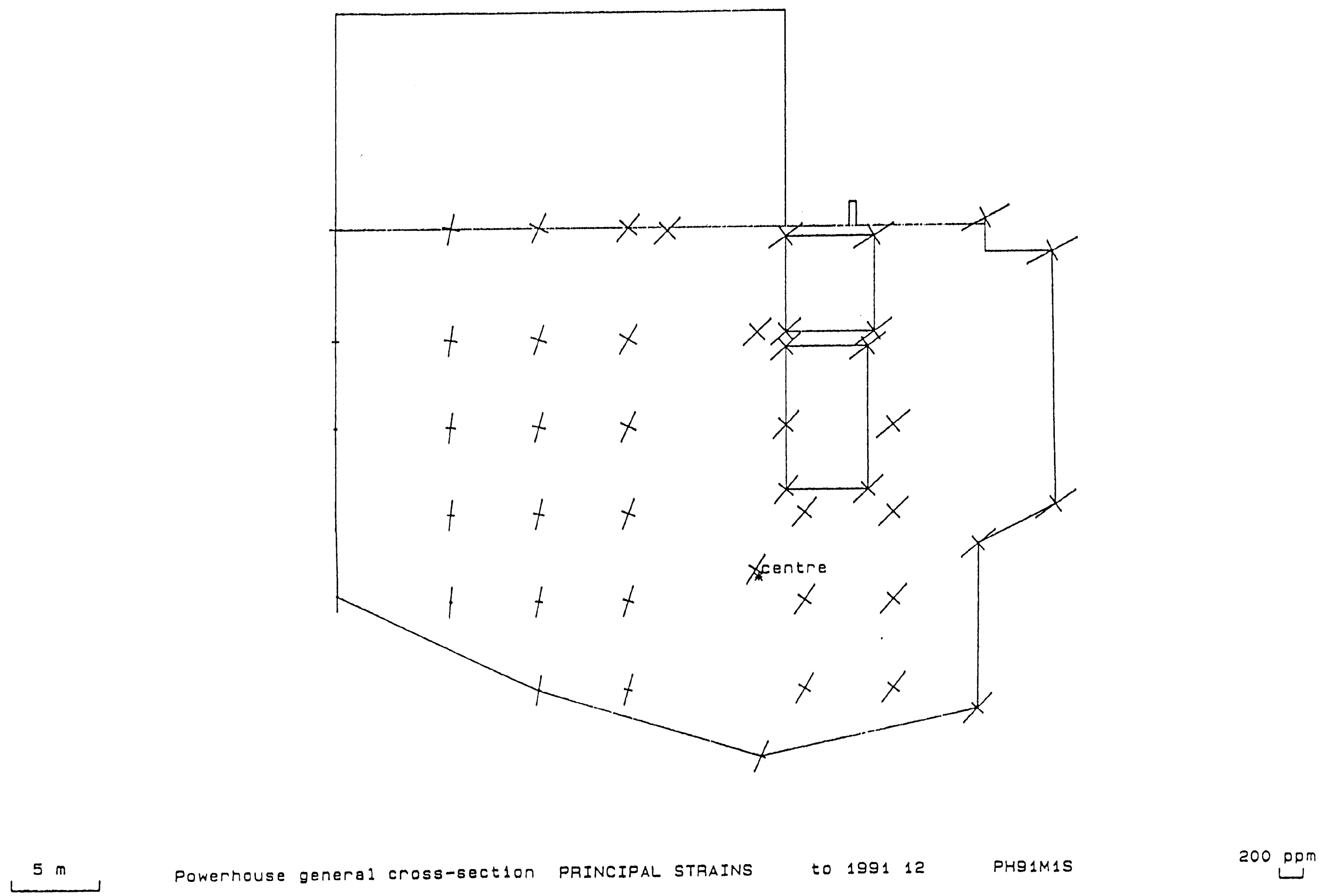


Figure 7.23. Powerhouse cross-section, principal strain rate field generated by OBSMOD [Chrzanowski and Secord, 1992]

8. CONCLUSIONS AND RECOMMENDATIONS

Systems for the automated monitoring of structures are well established; however, none has possessed all of the desirable characteristics of a data mangement system - from the gathering of the data to a depiction of the analysis of the structure. The system DAMADA, developed by the author, has been able to do this. DAMADA upholds data integrity; provides for data security; automates the acquisition, processing, and analysis of the data; allows for the integration of all types of observables; is flexible in access to the data (entry, editing, and use by other software); can accommodate additional types of instrumentation or other forms of analysis; can be accessed at the site; provides results in near-real time; and has both the testing and the calibration of instrumentation as an integral component of the system. In addition, DAMADA has complemented, and even facilited, the implementation of the UNB Generalized Method for the analysis of deformation measurements, particularly at the Mactaquac Generating Station.

DAMADA has been successfully applied to the monitoring of a hydro-electric power generating station. It has covered all aspects of the monitoring from data capture to the depiction of the deformation. In the application of DAMADA, a number of points arose concerning observations and instrumentation.

In the least squares fitting of a sinusoid and rate for the trend analysis, the standard deviation of the coefficients markedly improved with the increase in sampling rate. Little improvement is gained by a rate greater than 50 data per period. This was also reflected in the standard deviations of the amplitude and phase. For example, weekly observations would be the most statistically economical for an annual cycle.

The testing and calibration of instrumentation can improve the reliability and fidelity of data, especially over long term repeated use in monitoring. Routine testing and calibration present no additional burden if they are an integral part of the observation regimen and the system can automatically account for them, e.g., the calibration array for a tape extensometer. Maintaining the tension in a wire or tape extensomenter is critical (e.g., ±5 grams (±0.049 N) or ±50 grams (±0.49 N), respectively). A calibration array may be necessary in order to achieve this, e.g., with the tape extensometer. Sensors, such as LVDTs, should be calibrated *in situ* rather than in a laboratory or other location and it should be possible to calibrate occasionally along with the regular observations. The proportional part of the variance of an EODMI distance can rarely be smaller than 2 ppm, because of the limitations in sampling the meteorological conditions along the path. In order to achieve this for visible or near-infra-red wavelengths, the dry bulb temperature must be measured to ±0.6°C and the atmospheric pressure, to ±2 mb (±1.5 mm Hg) while the wet bulb temperature is not as crucial (±6°C). The additive constant for a particular EODMI-reflector combination can be appreciable and its change can be misinterpreted as deformation if it is undetected. If the additive constant is small, care must be exercised regarding the sign of its value and distinguisihing whether it is the zero "correction" or zero "error". Geodetic instrumentation, e.g., EODMI, can be used in isolation and can be treated in the same manner as traditional geotechnical instrumentation, with rivalling relative precision, but their testing and calibration and ancillary measurements of temperature and pressure become even more important in the maintenance of the reliability and fidelity of the data.

Several benefits follow from the three dimensional coordination (with precision at the level of several centimetres) of all observation points within a structure. The creation of input files, requiring approximate coordinates, and other processes can be automated if there is a single site-wide file of coordinates. Inverses from the coordinates can provide spatial distances used in calculating strain from change in dimension, tilt or vertical extension from change in height difference, or tilt from relative horizontal movement. Modelling is facilitated by specifying the range of coordinate values defining a section through a structure. Graphical depiction is similarly assisted, particularly if the structure outline has been digitized in the same coordinate system.

The transfer of change in height difference can be done through a structure to yield "absolute vertical movement". It is not necessary to know the actual heights or vertical distances between levels (i.e., actual elevations of the points) in the structure.

The integration of geodetic and geotechnical observations has allowed the modelling of selected sections of a structure. The estimated displacement field and derived strain field describe the behaviour of the structure as a result of the modelling that uses all possible observations together simultaneously.

The establishment of DAMADA at the Mactaquac Generating Station has been modest in its cost. The hardware requirements are a microcomputer (with at least an 80287 co-processor and sufficient hard drive capacity), a printer, a plotter, and several data collectors. All hardware, except for the data collectors, had already been in use in the monitoring programme. Savings have resulted from streamlining the amount of human involvement and the introduction of reliability checks during observation and the automation of most functions, especially the processing and plotting.

Although the development of DAMADA was based on vertical and horizontal geodetic surveys being separate, it would be straightforward to modify the system to accommodate a three dimensional adjustment program and, consequently, to analyse trend and to model in three dimensions. However, this would require repeated campaigns of precise three dimensional observations. Further work would be required to provide graphical depiction in three dimensions, e.g., an isometric view of a structure, the observables, and the deformation. However, it may be sufficient to resolve the deformation into its horizontal and vertical components for display (as is currently available).

There is one other aspect of DAMADA that has yet to be implemented. Direct connection to instrumentation has been done from a data collector.

Future work would involve the direct linking of instrumentation to the micro-computer for virtually continuous monitoring, provided that the operating system of the microcomputer had multi-tasking capabilities.

REFERENCES

Ahmadi, H. (1985). "Input determination in measuring instruments for dams." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 18, pp. 353-364.

Armenakis, C. and W. Faig (1990). "Optimal estimation of displacements by combining photogrammetric and dynamic models." Photogrammetric Engineering & Remote Sensing, v.54, n.8, August, pp. 1169-1173.

Anesa, F., P. Bonaldi, and G. Giuseppetti (1981). "Recent advances in monitoring dams." Water Power & Dam Construction, October, pp. 17-20.

Avella, S. (1992). "An Analysis of a Worldwide Status of Monitoring and Analysis of Dam Deformation." M.Eng. Report, Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B.

Barnett, R.H.W. and K.W. Funnell (1983). "Obtaining and processing surveillance data for large dams in Tasmania." Proceedings, Symposium, The Surveillance of Engineering Structures, Department of Surveying, University of Melbourne, November, 36 pp.

Bartholomew, C.L. and M.L. Haverland (1987). "Concrete Dam Instrumentation Manual." United States Department of the Interior, Bureau of Reclamation.

Bartholomew, C.L., B.C. Murray, and D.L. Goins (1987). "Embankment Dam Instrumentation Manual." United States Department of the Interior, Bureau of Reclamation.

Becek, K. and S. Cacon (1988). "Modelling of deformation processes for interpretations and prediction." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements. Fredericton, Canada. pp. 70-76.

Beckwith, T.G. and R.D. Marangoni (1990). Mechanical Measurements. Fourth Edition, Addison-Wesley Publishing Company, Don Mills.

Biacs, Z.F. and W.F. Teskey (1989) "A program package for adjustment, assessment and deformation analysis of precise engineering and monitoring networks." unpublished paper presented at the 82nd Annual Meeting of the Canadian Institute of Surveying and Mapping, Halifax, 1989 06 06-09.

Bomford, G. (1971). Geodesy. Third Edition, Oxford University Press, Oxford.

Bonaldi, P., M. Fanelli, and G. Giuseppetti (1977). "Displacement forecasting for concrete dams." Water Power & Dam Construction, September, pp. 42-50.

Bonaldi, P., M. Fanelli, G. Giuseppetti, R. Riccioni (1980a). "Automatic observation and instantaneous control of dam safety, Part two: A priori, deterministic models, and aposteriori models." ISMES Publication 133. Bergamo, Italy.

Bonaldi, P., M. Fanelli, G. Giuseppetti, and R. Riccioni (1980b). "Automated safety control procedures and management of surveillance for concrete dams in Italy." ISMES Publication 139. Bergamo, Italy.

Bonaldi, P., G. Ruggeri, G. Vallino, and G. Forzano (1985). "Examination of the behaviour of Corbara Dam via numerical simulation provided by mathematical models." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 77, pp. 1497-1528.

Boyer, B. and R. Hamelin (1985). "Auscultation topographique, progrès réalisés dans l'emploi des pendules inversés, amélioration de la fiabilité." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 4, pp. 79-108.

Breitenstein, F., W. Köhler, and R. Widmann (1985). "Safety control of the dams of the Glockner-Kaprun hydro-electric development." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 59, pp. 1121-1134.

Bury, K.V. and H. Kreuser (1986). "The assessment of risk for a gravity dam." Water Power & Dam Construction, v.38, n.12, December 1986, pp. 36-40.

Burstedde, I. (1988). "GEONET, A FORTRAN program system for the adjustment of geodetic networks." Stanford Linear Accelerator, Stanford University.

Burstedde, I. (n.d.). "Road Map to PC-GEONET, Standalone version 4.00." Stanford Linear Accelerator, Stanford University.

Cartier, R. and R. Hamelin (1988). "Data acquisition with HP-71B." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements. Fredericton, Canada. pp. 119-123.

Chen Y-q. (1983). "Analysis of Deformation Surveys - A Generalized Method." Department of Surveying Engineering Technical Report No. 94, University of New Brunswick, Fredericton, N.B., Canada.

Chen Y-q. (1988). "Deformation surveys in P.R. China." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements. Fredericton, Canada. pp. 136-141.

Chen Y-q. and A. Chrzanowski (1985). "Assessment of levelling measurements using the theory of MINQE." Third International Symposium on the North American Vertical Datum, Rockville, Maryland, U.S.A.

Chen Y-q. and A. Chrzanowski (1986). "An overview of the physical interpretation of deformation measurements." in Bock, Y. (ed.). Proceedings, Deformation Measurements Workshop, October/November, Boston, MIT Conference Services Office, Boston, Massachusetts, U.S.A., pp. 34-65.

Chen Y-q. and A. Chrzanowski (1993). "An approach to separability of deformation models." Zeitschrift für Vermessungswesen 8/1993, (in press)

Chen Y-q. and Du Z. (1990). "Analysis and management of deformation survey data of dams." F.I.G. XIX International Congress, Helsinki, Finland. Paper 604.4

Chen Y-q., A. Chrzanowski, and M. Kavouras (1990a). "Assessment of observations using minimum norm quadratic unbiased estimation (MINQUE)." CISM Journal ACSGC, v.44 n.4, Spring 1990, pp. 39-46.

Chen Y-q., A. Chrzanowski, and J.M. Secord (1985). "Generalized modelling of ground movements by integration of geodetic surveys with geotechnical measurements." I.S.M.S. IV International Congress, Harrogate, England.

Chen Y-q., A. Chrzanowski, and J.M. Secord (1990b). "A strategy for the analysis of the stability of reference points in deformation surveys." CISM Journal ACSGC v.44 n.2, Summer 1990, pp. 141-149.

Chen Y-q., M. Kavouras, and J.M. Secord (1983). "Design considerations in deformation monitoring." F.I.G. XVII International Congress, Sofia, Bulgaria. Paper 608.2

Chisholm, B.D. (1987). "Serial interface to Tellurometer model MA100." unpublished research report, Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada.

Chrzanowski, A. (1981). "A comparison of different approaches into the analysis of deformation measurements." F.I.G. XVI International Congress, Montreux, Switzerland. Paper 602.3

Chrzanowski, A. (1986). "Geotechnical and other non-geodetic methods in deformation measurements." in Bock, Y. (ed.). Proceedings, Deformation Measurements Workshop, October/November, Boston, MIT Conference Services Office, Boston, Massachusetts, U.S.A., pp. 112-153.

Chrzanowski, A. (1990). "Integrated monitoring and analysis of dam deformations: problems and solutions." Proceedings of Canadian Dam Safety Conference, September, Toronto, Canada, BiTech Publishers Ltd, Vancouver. pp. 1-17.

Chrzanowski, A. and Chen Y-q. (1986). "Report of the *ad hoc* committee on the analysis of deformation surveys." F.I.G. XVIII International Congress, Toronto, Canada. Paper 608.1

Chrzanowski, A. and Chen Y-q. (1992). "Evaluation and modelling of GPS errors in integrated deformation surveys: case studies." International Workshop on GPS Applications in the Geosciences, Crete, 1992 06 08-10.

Chrzanowski, A. and E.F. Hart (1983). "Role of the surveyor in North America in studies of ground movements in mining areas." Proceedings of the A.C.S.M. Annual Convention, Washington, pp. 262-271.

Chrzanowski, A. and J.M. Secord (1983a). "Report of the ad hoc committee on the analysis of deformation surveys." F.I.G. XVII International Congress, Sofia. Paper 605.2

Chrzanowski, A. and J.M. Secord (1983b). "Report on the deformation analysis of the monitoring network at the Lohmühle Dam." FIG Commission 6 Study Group C *ad hoc* Committee on Deformation Analysis.

Chrzanowski, A. and J.M. Secord (1985a). "Evaluation of the geodetic survey network at Mactaquac, Progress Report, Phase I." Contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric

Power Commission, Fredericton, N.B., Canada, January.

Chrzanowski, A. and J.M. Secord (1985b). "An evaluation of the geodetic survey network at Mactaquac." Final contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric Power Commission, Fredericton, N.B., Canada, March.

Chrzanowski, A. and J.M. Secord (1987). "An integrated analysis of deformation measurements at the Mactaquac Generating Station." Final contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric Power Commission, Fredericton, N.B., Canada, December.

Chrzanowski, A. and J.M. Secord (1990). "The 1989 integrated analysis of deformation measurements at the Mactaquac Generating Station." Final contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric Power Commission, Fredericton, N.B., Canada, May.

Chrzanowski, A. and J.M. Secord (1991). "The 1991 analysis of deformation measurements at the Mactaquac Generating Station." Interim contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric Power Commission, Fredericton, N.B., Canada, April.

Chrzanowski, A. and J.M. Secord (1992). "The 1991 analysis of deformation measurements at the Mactaquac Generating Station." Final contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric Power Commission, Fredericton, N.B., Canada, February.

Chrzanowski, A., Chen Y-q., and J.M. Secord (1982a). "A general approach to the interpretation of deformation measurements." Proceedings of the Centenial Convention of the Canadian Institute of Surveying, Ottawa, 1982 04 19-23, Canadian Institute of Surveying, Ottawa, v.2, pp. 247-266.

Chrzanowski, A., Chen Y-q., and J.M. Secord (1982b). "On the analysis of deformation surveys." Canadian Institute of Surveying, Proceedings of the Fourth Canadian Symposium on Mining Surveying and Deformation Measurements, Banff, Alberta, pp. 431-452.

Chrzanowski, A., Chen Y-q., and J.M. Secord (1983a). "On the strain analysis of tectonic movements using fault crossing geodetic surveys." in P. Vyskocil, A.M. Wassef and R. Green (editors), Recent Crustal Movements, 1982. Tectonophysics, 97: 297-315.

Chrzanowski, A., Chen Y-q., and J.M. Secord (1983b). "Analysis of the simulated monitoring network using the Fredericton Approach." in W. Welsch (edit) Deformationsanalysen '83, Hochschule der Bundeswehr München, Schriftenreihe, Heft 9, pp. 95-117.

Chrzanowski, A., Chen Y-q., and J.M. Secord (1983c). "A generalized approach to the geometric analysis of deformation surveys." in I. Joó and A. Detreköi (edit) Deformation Measurements, Deformationsmessungen, Akademiai Kiadó, Budapest, pp. 344-372.

Chrzanowski, A., Chen Y-q., and J.M. Secord (1986). "Geometrical Analysis of Deformation Surveys." in Bock, Y. (ed.). Proceedings, Deformation Measurements Workshop, October/November, Boston, MIT Conference Services Office, Boston, Massachusetts, U.S.A., pp. 170-206.

Chrzanowski, A., J.M. Secord, and M.W. Rohde (1985a). "Report on the pre-analysis of proposed monitoring surveys for the Ball Mountain Dam." Contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada for The BSC Group, Boston, Massachusetts, U.S.A.

Chrzanowski, A., J.M. Secord, and A. Szostak-Chrzanowski (1989). "The 1988 integrated analysis of deformation measurements at the Mactaquac Generating Station, Part 1: Deformation analysis and physical interpretation." Final contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric Power Commission, Fredericton, N.B., Canada, February.

Chrzanowski, A., S. Avella, Chen Y-q., and J.M. Secord (1992). "Report on Existing Resources, Standards, and Procedures for Precise Monitoring and Analysis of Structural Deformations." Contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the United States Army Corps of Engineers, U.S. Army Topographic Engineering Center, Fort Belvoir, Virginia, U.S.A., September

Chrzanowski, A., Chen Y-q., J.M. Secord, and A. Szostak-Chrzanowski (1991). "Problems and solutions in the integrated monitoring and analysis of dam deformations." CISM Journal ACSGC, V.45 n.4, Winter 1991, pp. 547-560.

Chrzanowski, A., Chen Y-q, A. Szostak-Chrzanowski, and J.M. Secord (1990). "Combination of geometrical analysis with physical interpretation for the enhancement of deformation modelling." F.I.G. XIX International Congress, Helsinki, Paper 612.3.

Chrzanowski, A., Chen Y-q., M.Y. Fisekci, J.M. Secord, and A. Szostak-Chrzanowski (1985b). "An integrated approach to the monitoring and modelling of ground movements." Proceedings of the 4th Conference on Ground Control in Mining, Morgantown, pp. 273-285.

Chrzanowski, A., Chen Y-q., J.M. Secord, G.A. Thompson, and Z. Wroblewicz (1988). "Integration of geotechnical and geodetic observations in the geometrical analysis of deformations at the Mactaquac generating station." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Fredericton, pp. 156-169.

Chrzanowski, A., T. Greening, W. Kornacki, J. Secord, S. Vamosi and Y.Q. Chen (1985c). "Applications and limitations of precise trigonometric height traversing." Proceedings of the Third International Symposium on the North American Vertical Datum (NAVD '85), Rockville, MD, U.S.A., 1985 04 21-26, pp. 81-93.

Cooper, M.A.R. (1987). Control Surveys for Civil Engineering. Nichols Publishing Company, New York.

Corvallis Microtechnology, Inc. (1990). "CMT MC-V Operator's Manual." Corvallis Microtechnology, Inc., Corvallis, Oregon, U.S.A.

Cross, P.A. and K. Thapa (1979). "The optimal design of levelling networks." Survey Review, v.XXV, n.192, pp. 68-79.

da Silveira, A.F. and J. de O. Pedro (1964). "Quantitative interpretation of results obtained in the observation of concrete dams." Huitième Congrès des Grandes Barrages, Edinborough, Q. 29, R. 43, pp. 791-809.

Davis, R.E., F.S. Foote, J.M. Anderson, and E.M. Mikhail (1981). Surveying: Theory and Practice. Sixth Edition, McGraw-Hill Book Company, Toronto.

Dearinger, J.A. (1974). "Structural and terrain movements." Journal of the

Surveying and Mapping Division, American Society of Civil Engineers. v.100, n.SU2, November, pp. 123-142.

Deumlich, F. (W. Faig, transl.) (1982). Surveying Instruments. Walter de Gruyter, New York.

Dietrich, C.F. (1991). Uncertainty, Calibration and Probability. 2nd Edition, Adam Hilger - IOP Publishing Ltd., New York.

Dungar, R. (1986). "Safety assessment of two concrete dams." Water Power & Dam Construction, v.38, n.12, December 1986, pp. 28-33.

Dunnicliff, J. (1988). Geotechnical Instrumentation for Monitoring Field Performance. John Wiley & Sons, Inc. Toronto.

Dunnicliff, J. (1990). "Twenty-five steps to successful perfomance monitoring of dams." Hydro Review, v.9, n.4, August 1990, pp. 48-62.

Enders, K. and W. Granson (1989). "Electronic data collector for engineering surveys" Automated Data Collection (workshop), Canadian Institute of Surveying and Mapping, Edmonton.

Ente Nazionale per l'Energia Elettrica (ENEL) (1980). "Behaviour of ENEL's Large Dams" ENEL, Rome

Fanelli, M. (1979). "Automatic observation for dam safety." Water Power & Dam Construction, Part One, Nov., pp.106-110, Part Two, Dec., pp. 41-48.

Fanelli, M. and G. Giuseppetti (1975). "Techniques to evaluate effects of internal temperatures in mass concrete." Water Power & Dam Construction, June/July, pp. 226-230.

Fanelli, M. and G. Giuseppetti (1980a). "Mathematical analysis of structures: usefulness and risks." I.A.B.S.E. XI Congress, Wien, pp. 637-646.

Fanelli, M. and G. Giuseppetti (1980b). "Two extreme cases of on-line control of structures." in H.H.E. Leipholz (ed.) Structural Control, North-Holland Publishing Company & SM Publications. pp. 255-268.

Fanelli, M. and G. Giuseppetti (1982). "Safety monitoring of concrete dams." Water Power & Dam Construction, November, pp. 31-33.

Florentino, C.A., M.E. Campos e Matos, A. Ferreira da Silva, and M.E. Monteiro da Rocha (1985). "Basic principles of dams observation [*sic*] in Portugal. The Aguieira Dam example." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 37, pp. 721-735.

Franklin, J. [edit] (1990). "Mine Monitoring Manual." Canadian Institute of Mining and Metallurgy, Special Volume 42.

Friedsam, H., R. Pushor, and R. Ruland (1987). "A realization of an automated data flow for data collecting, processing, storing and retrieving." Proceedings of the ASPRS/ACSM 1987 Fall Convention, Washington.

Geomation, Inc. (n.d.,a). "System 2300 overview." Equipment literature, Golden, Colorado, U.S.A.

Geomation, Inc. (n.d.,b). "System 2300 specifications and limitations." Equipment literature, Golden, Colorado, U.S.A.

Geomation, Inc. (n.d.,c). "System 2300 theory of operation." Equipment literature, Golden, Colorado, U.S.A.

Gicot, H. (1976). "Une methode d'analyse des deformations des barrages." Douzième Congrès des Grandes Barrages, Mexico City, v. IV, c. 1, pp. 787-790.

Gilg, B., W. Amberg, K. Egger, and Chr. Venzin [group of the Swiss National Committee on Large Dams] (1985). "Modern approach to dam monitoring in Switzerland." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 53, pp. 985-1004.

Grafarend, E. (1982). "Optimization of geodetic networks" I.U.G.G./I.A.G. International Symposium on Geodetic Network Computations, München, DGK C:258 III, pp. 69-81.

Greening, W.J.T. (1992). personal communication. Geodetic Engineer and Vice-President of Measurement Science Inc., consultant to The PB/MK Team at the Superconducting Supercollider Laboratory project, Texas.

Gründig, L. and J. Bahndorf (1985). "OPTUN - A program system for extended pre-analysis and adjustment." Papers for the Precise Engineering and Deformation Surveys Workshop, Canadian Institute of Surveying and University of Calgary, pp. 202-217.

Guedes, Q.M. and P.S.M. Coelho (1985). "Statistical behaviour model of dams."

Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 16, pp. 319-334.

Guedes, Q.M., J.A. Rosso, and H.C.deB. Franco (1981). "Analysing displacement measurements in gravity dams." Water Power & Dam Construction, October, pp. 43-46.

Guerreiro, M. and R. Del Hoyo (1985). "Bringing up-to-date monitoring systems on existing concrete dams." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 50, pp. 929-949.

Hanna, T.H. (1985). Field Instrumentation in Geotechnical Engineering. Volume 10 in Series on Rock and Soil Mechanics, Trans Tech Publications, Clausthal-Zellerfeld.

Hautzenberg, H. (1979). "Automatic supervision of Koelnbrein arch dam." Treizième Congrès des Grands Barrages, New Delhi, Q. 49, R. 18, pp. 267-275.

Hayward, D.G., G.A. Thompson, R.G. Charlwood, and R.R. Steele (1991). "Remedial measures at the Mactaquac Generating Station." Dix-septième Congrès des Grands Barrages, Vienne, Q. 65, R. 47, pp. 847-865.

Heck, B. (1985). "Monitoring dam deformations by means of geodetic control networks." in J. Laginha Serafim [edit] Safety of Dams. Addendum. [Proceedings of the International Conference on Safety of Dams, Coimbra, 1984 04 23-28]. A.A. Balkema, Rotterdam, pp. 455-466.

Hewlett-Packard Company (1986). "HP7550A Graphics Plotter, Interfacing and Programming Manual." Fourth Edition, Hewlett-Packard Company, San Diego.

ICOLD (1982). "Automated Observation for the Safety Control of Dams." Bulletin 41, International Committee on Large Dams (ICOLD), Paris, France.

ICOLD (1988). "Dam Monitoring, General Considerations." Bulletin 60, International Committee on Large Dams (ICOLD), Paris, France.

ICOLD (1989). "Monitoring of Dams and Their Foundations, State of the Art." Bulletin 68, International Committee on Large Dams (ICOLD), Paris, France.

Ingensand, H., W. Maurer, and W. Schauerte (1992). "Die Digitalnivellierfamilie

WILD NA2002/NA3000 und ihre Anwendungen in der Ingenieurvermessung." Beiträge zum XI. Internationalen Kurs für Ingenieurvermessung, Zürich, 1992 09 21-26, paper II 14.

Ingraham, T., G. Shyry, D.J. Sparks, and B. Dawson (1989). "Automated horizontal deformation surveys." Automated Data Collection (workshop), Canadian Institute of Surveying and Mapping, Edmonton.

Jankowski, W., J. Kloze, and T. Reszka (1985). "The automatization of the monitoring of Polish dams." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 14, pp. 281-285.

Japanese National Committee on Large Dams [JANCOLD] (1987). "Monitoring on dams and foundations in Japan." Japanese National Committee on Large Dams.

Kanasewich, E.R. (1981). Time Sequence Analysis in Geophysics. University of Alberta Press, Edmonton.

Kavouras, M. (1982). "On the Detection of Outliers and the Determination of Reliability in Geodetic Networks." Department of Surveying Engineering Technical Report No. 87, University of New Brunswick, Fredericton, N.B., Canada.

Kaye, G.W.C. and T.H. Laby (1966). Tables of Physical and Chemical Constants. 13th Edition, Longmans, Green, and Company, London.

Keane, D.F. (1974). "Precise dam surveys - Los Angeles County Flood Control District." Journal of the Surveying and Mapping Division, American Society of Civil Engineers, v.100, n.SU2, November, pp. 99-114.

Kern Swiss (1977). "Distometer ISETH, Instruction Manual." Equipment literature, Aarau, Switzerland.

Kern Swiss (1984a). "DM503, Instruction Manual." Equipment literature, Aarau, Switzerland.

Kern Swiss (1984b). "E2, Instruction Manual." Equipment literature, Aarau, Switzerland.

Kok, J., B. Heck, W. Welsch, R, Baumer, A. Chrzanowski, and J.M. Secord (1983). "Report of the FIG Working Group on the analysis of deformation measurements." in I. Joó and A. Detreköi (edit) Deformation

Measurements, Deformationsmessungen, Akademiai Kiadó, Budapest, pp. 373-416.

Krakiwsky, E.J. and A.P. Mackenzie (1985). "Network design." Papers for the Precise Engineering and Deformation Surveys Workshop, Canadian Institute of Surveying and University of Calgary, pp. 34-51.

Kreyszig, E. (1972). Advanced Engineering Mathematics. Third Edition. John Wiley and Sons, Inc., Toronto.

Kuang S-L. (1991). "Optimization and Design of Deformation Monitoring Schemes" Department of Surveying Engineering Technical Report No. 157, University of New Brunswick, Fredericton, N.B., Canada.

Larocque, G. (1977). "Pit Slope Manual Chapter 8 - Monitoring." Canada Centre for Mineral and Energy Technology (CANMET) Report 77-15.

Lazzarini, T. (1974). "Determination of displacements and deformation of structures and their environment by geodetic means." unpublished notes to lectures, Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada.

Leica Heerbrugg AG (1988). "Wild instruments on line." Equipment literature, Heerbrugg, Switzerland.

Leica Heerbrugg AG (1991). "Wild NA2000, User Manual." Equipment literature, Heerbrugg, Switzerland.

Leica Heerbrugg AG (1992). "Wild NA2002, NA3000." Equipment brochure, Heerbrugg, Switzerland.

Lotus Development Corporation (1986). "Lotus 1-2-3." Release 2.01. Lotus Development Corporation, Cambridge, Massachusetts.

Ludescher, H. (1985). "A modern instrumentation for the surveillance of the stability of the Kölnbrein Dam." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 42, pp. 797-812.

Lugiez, F., N. Beaujoint, and X. Hardy (1970). "L'auscultation des barrages en exploitation au service de la production hydraulique d'électricité de France, des principes aux résultats." Dixième Congrès des Grandes Barrages, Montréal, Q. 38, R. 33, pp. 577-600.

Lytle, J.D. (1982). "Dam safety instrumentation; automation of data observations, processing, and analysis." Quatorzième Congrès des Grandes Barrages, Rio de Janeiro, Q. 52, R. 30, pp. 493-511.

Lytle, J.D. (1985). "Dam safety monitoring: Instrumentation, observation and evaluation." in J. Laginha Serafim [edit] Safety of Dams. Addendum. [Proceedings of the International Conference on Safety of Dams, Coimbra, 1984 04 23-28]. A.A. Balkema, Rotterdam, pp. 425-439.

Marécos, J., M. Castanheta, and J.T. Trigo (1969). "Field observation of Tagus River suspension bridge." Journal of the Structural Division, American Society of Civil Engineers, April, pp. 555-583.

Meier, E. (1991). "A differential pressure tiltmeter for large-scale ground monitoring." Water Power & Dam Construction, January, pp. 38-40.

Missiaen, D. (1992). "The setting up of a database for a large engineering project, managing the alignment data of particle accelerators." Beiträge zum XI. Internationalen Kurs für Ingenieurvermessung, Zürich, 1992 09 21-26, paper III 2.

Mora Ramos, J. and J. Soares de Pinho (1985). "Delayed effects observed in concrete dams." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 38, pp. 737-747.

Niemeier, W., W.F. Teskey, and R.G. Lyall (1982). "Precision, reliability, and senstivity aspects of an open pit monitoring network." Proceedings of the 4th Canadian Symposium on Mining Surveying and Deformation Measurements, Banff, Canadian Institute of Surveying, pp. 409-430.

Nilsen, K.Y., E. DiBiagioi, and A. Andresen (1982). "Norwegian practice in instrumenting dams." Water Power & Dam Construction, November, pp. 34-38.

Obert, L. and W.I. Duvall (1967). Rock Mechanics and the Design of Structures in Rock. John Wiley and Sons, Inc., New York.

Oren, W., R. Pushor, and R. Ruland (1987). "Incorporation of the Kern ECDS-PC software into a project oriented software environment." Proceedings of the 1987 ASPRS/ACSM Annual Meeting, Baltimore, pp. 88-94.

Otnes, R.K. and L. Enochson (1978). Applied Time Series Analysis, Volume 1, Basic Techniques. John Wiley and Sons, Toronto.

Penman, A.D.M. and M.F. Kennard (1982). "Long-term monitoring of embankment dams in Britain." Water Power & Dam Construction, November, pp. 19-26.

Prescott, W.H. (1981). "The determination of displacement fields from geodetic data along a strike slip fault." Journal of Geophysical Research, v.86, n.B7, pp. 6067-6072.

Pürer, E. and N. Steiner (1986). "Application of statistical methods in monitoring dam behaviour." Water Power & Dam Construction, v.38, n.12, December, pp. 33-35.

Quesnel, J.-P. (1987). "Applied Metrology for LEP, Part II, Data Logging and Management of Geodetic Measurements with a Database." in S. Turner (edit) Proceedings of the CERN Accelerator School, Applied Geodesy for Particle Accelerators, Geneva, 1986 04 14-18, Organisation Européenne pour la Recherche Nucléaire (CERN), Geneva, Switzerland, pp. 248-254.

Reilly, W.I. (1981) "Complete determination of local crustal deformation from geodetic observations." Tectonophysics, 71(1981), pp. 111-123.

Richardus, P. (1984). Project Surveying, second edition, A. A. Balkema, Rotterdam.

Rocha, M., J.L. Serafim, and A.F. da Silveira (1958). "A method of quantitative interpretation of the results obtained in the observation of dams." Sixième Congrès des Grands Barrages, New York, Q. 21, R. 36, pp. 371-396.

Rohde, M.W. (1988). "Automated data acquisition for engineering and deformation surveys using electronic theodolites." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Fredericton, pp. 440-450.

Rop, G. and M. Bobik (1990). "Monitoring system for detecting movements of penstock supports." Water Power & Dam Construction, September, pp. 23-28.

Rossi Leidi, L. and E. Piancastelli (1964). "Analyse des deformations d'un barrage d'après les mesures des extensometres." Huitième Congrès des Grandes Barrages, Edinborough, Q. 29, R. 35, pp. 577-595.

Rossegger, Ch., H-B. Matthias, and K. Käfer (1990). "Computer-aided measurement system for hydro turbines." Water Power & Dam Construction, March, pp. 28-33.

Rüeger, J.M. (1990). Electronic Distance Measurement, An Introduction. Third Totally Revised Edition, Springer-Verlag, New York.

Ruland, R. and D. Ruland (1988). "Integrated database approach for geodetic applications." International Conference on Statistical and Scientific Database Management, Rome.

Savage, J.C, W.H. Prescott, M. Lisowski, and N.E. King (1979). "Geodetic measurements of deformation near Hollister, California, 1971-1978." Journal of Geophysical Research, v.84, n.B13, pp. 7599-7615.

Schaffrin, B. (1981). "Best invariant covariance component estimators and its [*sic*] application to the generalized multivariate adjustment of heterogeneous deformation observations." Bulletin Géodésique, 55(1981), pp. 73-85.

Schewe, L.D. (1987). "A monitoring programme for embankment dams." Water Power & Dam Construction, May, pp. 23-26.

Schneider, D. (1982). "Complex Crustal Strain Approximation" Department of Surveying Engineering Technical Report No. 91, University of New Brunswick, Fredericton, N.B., Canada.

Secord, J.M. (1981). "Implementing the Fredericton approach to deformation microgeodetic network analysis." Department of Surveying Engineering, unpublished BScE thesis, University of New Brunswick, Fredericton, N.B., Canada.

Secord, J.M. (1985). "Implementation of a Generalized Method for the Analysis of Deformation Surveys." Department of Surveying Engineering Technical Report No. 117, University of New Brunswick, Fredericton, N.B., Canada.

Secord, J.M. (1986). "Terrestrial survey methods for precision deformation measurements." in Bock, Y. (ed.). Proceedings, Deformation Measurements Workshop, October/November, Boston, MIT Conference Services Office, Boston, Massachusetts, U.S.A., pp. 34-65.

Secord, J. (1990). "The system of data management, processing, and deformation analysis devised for the Mactaquac Generating Station for

New Brunswick Power." Contract report prepared by the Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B., Canada, for the New Brunswick Electric Power Commission, Fredericton, N.B., Canada, June.

Secord, J. (1993). "Data management for deformation monitoring." Proceedings of the 1993 Canadian Society for Civil Engineering Annual Conference, Fredericton, N.B., 1993 06 08-11, Volume IV, pp. 469-478.

Silva Gomes, A.F. (1982). "Automated monitoring tasks in Portuguese dams, state of the art and prospects." Quatorzième Congrès des Grandes Barrages, Rio de Janeiro, Q. 52, R. 34, pp. 573-584.

Silva Gomes, A.F. and D. Silva Matos (1985). "Quantitative analysis of dam monitoring results. State of the art, applications and prospects." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 39, pp. 749-761.

Sjoberg, L.E. (1983). "Unbiased estimation of variance-covariance components in condition adjustment with unknowns - a MINQUE approach." Zeitschrift für Vermessungswesen, 9/1983, pp. 382-387.

Slobodnik, D. and E.F. Roof (1980). "Monitoring of dam movements using laser light." Transportation Engineering Journal, American Society of Civil Engineers, v.106, n.TE6, November, pp. 829-843.

Soil Instruments Limited (1983). "Tape Extensometer Mk II, User's Manual." Equipment literature, Uckfield, England.

Sousa Lima, V.M., J.F.A. Silveira, and J.C. Degaspare (1985). "Horizontal and vertical displacements of the Itaipu main dam, a study on field measurements and theoretical predictions." Quinzième Congrès des Grands Barrages, Lausanne, Q. 56, R. 10, pp. 223-247.

Steeves, R.R. (1979). "A User's Manual for Program GEOPAN, Geodetic Plane Adjustment and Analysis." Department of Surveying Engineering Technical Report No. 54, University of New Brunswick, Fredericton, N.B., Canada.

Steeves, R.R. (1981a). "Estimation of Gravity Tilt Response to Atmospheric Phenomena at the Fredericton Tiltmetric Station Using a Least Squares Response Method." Department of Surveying Engineering Technical Report No. 79, University of New Brunswick, Fredericton, N.B., Canada.

Steeves, R.R. (1981b). "A statistical test for significance of peaks in the least squares spectrum." Collected Papers, Geodetic Survey 1981. Surveys and Mapping Branch, Energy, Mines, and Resources Canada, Ottawa, Ontario, pp. 149-165.

Sterling, D.M. and G.L. Benwell (1989). "The status of the computerisation [sic] of dam monitoring data in Australia." Proceedings, Symposium on Surveillance and Monitoring Surveys, Department of Surveying and Land Information, The University of Melbourne, November, pp. 173-182.

Stevenson, R., D.E. Bowes, and J.P. Radochia (1986). "Finite element analysis of arch dams on a personal computer." Water Power & Dam Construction, December, pp. 19-22.

Swiss National Committee on Large Dams (1985). "Swiss Dams, Monitoring and Maintenance." [Edition for the 15th International Congress on Large Dams 1985 at Lausanne.] Comité national suisse des grands barrages, Zurich, Switzerland.

Swiss National Committee on Large Dams (1988). "Measuring installations for dam monitoring: concepts, reliability, redundancy." wasser, energie, luft - eau, énergie, air, v.80, n.1/2, pp. 11-20.

Szalay, K. (1980). "Performance monitoring for dam safety." Water Power & Dam Construction, September, pp. 21-26.

Szostak-Chrzanowski, A., A. Chrzanowski, A. Lambert, and M.K. Paul (1993). "Finite element analysis of surface uplift and gravity changes of tectonic origin." Proceedings of the 7th International (FIG) Symposium on Deformation Measurement and the 6th Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Banff, (9 pp., proceedings in preparation).

Tellumat Limited (1988). "Operator's handbook for Tellurometer MA200." Equipment literature, Surrey, England.

Teskey, W.F. (1985). "Determining deformation by combining measurement data with structural data." Papers of the Precise Engineering and Deformation Surveys Workshop, Canadian Institute of Surveying and University of Calgary, pp. 202-217.

Teskey, W.F. (1987). "Integrated Analysis of Geodetic, Geotechnical, and

Physical Model Data to Describe the Actual Deformation Behavior of Earthfill Dams under Static Loading." Universität Stuttgart, Institut für Anwendungen der Geodäsie im Bauwesen, translation of doctoral thesis, 147 pp.

Teskey, W.F. and T.R. Porter (1988). "An integrated method for monitoring the deformation behaviour of engineering structures." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Fredericton, pp. 536-547.

Vanicek, P. and E.J. Krakiwsky (1986) Geodesy: The Concepts. Second edition, North-Holland / Elsevier Science Publishers B.V., Amsterdam.

Walz, A.H. (1989). "Automated data management for dam safety evaluations." Water Power & Dam Construction, April, pp. 23-25.

Wells, D.E. and E.J. Krakiwsky (1971). "The Method of Least Squares." Department of Surveying Engineering Lecture Notes No. 18, University of New Brunswick, Fredericton, N.B., Canada.

Wells, D.E., P. Vanicek, and S. Pagiatakis (1985). "Least Squares Spectral Analysis Revisited." Department of Surveying Engineering Technical Report No. 84, University of New Brunswick, Fredericton, N.B., Canada.

Widmann, R. (1967). "Evaluation of deformation measurements performed at concrete dams." Neuvième Congrès des Grands Barrages, Istanbul, Q. 34, R. 38, pp. 671-676.

Wilkins, F.J., A. Chrzanowski, M.W. Rohde, H. Schmeing, and J.M. Secord (1988). "A three dimensional high precision coordinating system." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Fredericton, pp. 580-592.

Willm, G. and N. Beaupoint (1967). "Les méthodes de surveillance des barrages au service de la production hydraulique d'électricité de France, problèmes anciens et solutions nouvelles." Neuvième Congrès des Grands Barrages, Istanbul, Q. 34, R. 30, pp. 529-550.

Wilson, S.D. and P.E. Mikkelsen (1977). "Foundation Instrumentation Inclinometers, Reference Manual." United States Department of Transportation, Federal Highway Administration, Office of Development, Implementation Division.

Wroblewicz, Z., Z. Solymar, and G.A. Thompson (1988). "Deformation monitoring instrumentation at the Mactaquac generating station, New Brunswick, Canada." Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Fredericton, pp. 593-602.

Wroblewicz, Z. (1990). "Integrated monitoring of dam deformation - automated data acqusition systems at Mactaquac Generating Station, New Brunswick, Canada - A case study." International Symposium on Data Acquisition for the Investigation of Deformations, Katowice, Poland, April.

Wroblewicz, Z. (1991a). "CMT MC-V Operator's Guide." Revised Edition, Resources Development Division, New Brunswick Electric Power Commission, Fredericton, New Brunswick, April.

Wroblewicz, Z. (1991b). "Mactaquac Generating Station, Instrumentation Index." Resources Development Division, New Brunswick Electric Power Commission, Fredericton, New Brunswick, August.

Wroblewicz, Z. (1991c). "Mactaquac Generating Station, Instrumentation Manual." Preliminary Edition, Resources Development Division, New Brunswick Electric Power Commission, Fredericton, New Brunswick, August.

Wroblewicz, Z. (1993). personal communication. Supervisor of Surveys, Mactaquac Structures Investigation Project, Mactaquac Generating Station. New Brunswick Electric Power Commission, Fredericton, New Brunswick, August.

I. SYMBOLS AND ABBREVIATIONS

$\mathbf{A}$	matrix (bold upper case letter)
$\mathbf{a}$	vector (bold lower case letter)
$\underline{\mathbf{a}}$	least squares estimates (underlined letter - bold if vector, plain if scalar)
α	amplitude (Equation (3.9))
α	coefficient of thermal expansion (Equation (3.25))
β	second order coefficient of thermal expansion (Equation (3.25))
χ^2	the "chi-squared" distribution
δ	"small change in ..." or "small difference in ..."
∂	partial differential operator
ε	strain
Δ	"change in ..." or "difference in ..."
ϕ	phase (Equation (3.10) or (3.11))
$\boldsymbol{\ell}$	vector of observations
ν	number of degrees of freedom
σ_o^2	variance factor known *a priori*
$\underline{\sigma}_o^2$	variance factor known *a posteriori* (i.e., estimated)
Σ	summation
ω	frequency (Equation (3.6))
ω	rotation component or orientation (e.g., Equation (5.11), (5.12))
°C	degrees celsius

a	constant component of variance (Equation (3.15))
a_i	coefficients in trend fitting (Equation (3.6))
a_i	coefficients in modelling a displacement field (Equation (5.10) etc.)
b	proportional component of variance (Equation (3.15))
b_i	coefficients in modelling a displacement field (Equation (5.10) etc.)
$\mathbf{c}$	vector of model parameters
d	corrected distance, spatial distance
d	"infinitessimally small change in ..."
d'	EODMI output
$\mathbf{dx}$	vector of displacement components
e	2.718281828 ..., the base of natural logarithms
e_z	zero error
k	scale or scale factor
mb	millibar
n	number of observations
n	"number of ..."
n_L	refractive index (Equation (3.16))
ppm	parts per million (1 ppm = 1×10^{-6})
q_{ij}	element of $\mathbf{Q}$
s	spatial distance
t	dry bulb temperature
t	time argument
t'	wet bulb temperature
u	number of unknowns
$\mathbf{u}$	vector of constants (Equation (4.2))
$\mathbf{v}$	vector of residuals
$\mathbf{w}$	vector of misclosure components
y	coordinate component
$\mathbf{y}$	vector of changes since initial value (times series, Equation (3.7))

x	coordinate component
x	vector of unknowns
z	coordinate component
z_o	additive constant or zero correction
A	design matrix (e.g., Equation (3.1))
B	design matrix (e.g., Equation (3.3))
C	variance-covariance matrix
D	matrix of datum equation coefficients (Equation (4.3))
E	Young's modulus of elasticity (Equation (3.23))
H	defect matrix (Equation (4.10))
I	identity matrix
K	degrees kelvin
L	length (Equation (3.22) etc.)
N	matrix of normal equation coefficients (Equation (4.2))
P	tension or pull
P	weight matrix (e.g., Equation (3.2))
Q	cofactor matrix
S	similarity transformation matrix
T	translation component
W	mass or "weight" [kg] on earth (Equation (3.22) etc.)
W	"weight" matrix (Equation (4.12))
ASCII	American Standard Code for Information Interchange
C.A.	geodetic campaign adjustment
DAMADA	data management for deformation analysis
D.M.	integrated deformation modelling
ENEL	Ente Nationale per l'Enerigia Electrica, Rome, Italy
EODM	Electro-Optical Distance Measurement

EODMI	Electro-Optical Distance Measuring Instrument
GPS	satellite based Global Positioning System
ICOLD	International Committee (or Congress) on Large Dams
LVDT	linear variable differential transformer
S.S.A.	spatial series analysis and plot
S.S.P.	spatial series analysis and plot
S.T.A.	spatial trend analysis and plot
T.S.A.	time series analysis and plot
T.S.P.	time series analysis and plot
USACE	United States Army, Corps of Engineers
USBR	United States Bureau of Reclamation

II. SAMPLE FILES

```
Baseline by MA200 #216          + prism 1    1991 12 20        MB911220
6 7 2 3 0.0003 2.000 1.00000 0.0000 0.0000
PL-1
PL-1    PL-6      000 00 00.0
(a8,4f10.3)
PL-1        11.836  0000.000  0000.000    0.0000
PL-2        11.841   263.900  0000.000    0.0000
PL-3        11.704   503.810  0000.000    0.0000
PL-4        11.459   815.740  0000.000    0.0000
PL-5        11.340  1175.660  0000.000    0.0000
PL-6        11.096  1607.580  0000.000    0.0000
(2(a8,f7.3),f12.5,4f6.2,f8.3,i2)
PL-1     0.2790PL-2     0.2770  264.001900-15.25-15.25-12.95-13.751037.000 1 ##
PL-1     0.2790PL-3     0.2770  503.925900-14.00-14.50-12.00-12.751037.000 1
PL-1     0.2790PL-4     0.2770  815.866600-14.00-14.65-12.55-13.201037.000 1
PL-2     0.2790PL-3     0.2770  240.009000-14.00-14.50-12.50-12.651037.000 1
PL-2     0.2790PL-4     0.2770  551.950800-14.00-15.50-12.10-12.501038.000 1
PL-2     0.2790PL-5     0.2770  911.884400-13.00-13.70-11.20-11.651038.000 1
PL-3     0.2790PL-4     0.2770  312.027300-11.40-12.20-11.30-11.751038.000 1
PL-3     0.2790PL-5     0.2770  671.959500-11.00-11.55-11.00-11.601038.000 1
PL-3     0.2790PL-6     0.2770 1103.902000-12.00-12.60-12.45-12.801038.000 1
PL-4     0.2790PL-5     0.2770  360.018600-11.50-12.00-10.50-11.001036.000 1
PL-4     0.2790PL-6     0.2770  791.960400-11.75-12.25-11.35-11.851036.000 1
PL-5     0.2790PL-6     0.2770  432.027600-12.75-13.25-11.35-11.851036.000 1
```

Line marked "##" and below are file MA911220 from MC-V (module EODM)

```
Baseline by MA200 #216          + prism 1    1991 12 20          MZ911220
 0   1                        0 0       0      0       0              1 0
FIXED
PL-1
STATIONS
  PL-1              0.0000         0.0000    0.0000
  PL-2            263.9000         0.0000    0.0000
  PL-3            503.8100         0.0000    0.0000
  PL-4            815.7400         0.0000    0.0000
  PL-5           1175.6600         0.0000    0.0000
  PL-6           1607.5800         0.0000    0.0000
-9
OBSERVATIONS
    4     PL-1      PL-6              0.01           0.        0.       0.0
    1     PL-1      PL-2                  0.0003    2.0000   263.9911
    1     PL-1      PL-3                  0.0003    2.0000   503.9059
    1     PL-1      PL-4                  0.0003    2.0000   815.8338
    1     PL-2      PL-3                  0.0003    2.0000   239.9994
    1     PL-2      PL-4                  0.0003    2.0000   551.9285
    1     PL-2      PL-5                  0.0003    2.0000   911.8488
    1     PL-3      PL-4                  0.0003    2.0000   312.0153
    1     PL-3      PL-5                  0.0003    2.0000   671.9342
    1     PL-3      PL-6                  0.0003    2.0000  1103.8588
    1     PL-4      PL-5                  0.0003    2.0000   360.0053
    1     PL-4      PL-6                  0.0003    2.0000   791.9306
    1     PL-5      PL-6                  0.0003    2.0000   432.0110
```

Baseline by MA200 #216 + prism 1 1991 12 20 MZ911220

Observed Distances

From	To	Distance	a,	b,	Std Dev
PL-1	PL-2	263.991100	0.00030	2.00000	0.00061
PL-1	PL-3	503.905900	0.00030	2.00000	0.00105
PL-1	PL-4	815.833800	0.00030	2.00000	0.00166
PL-2	PL-3	239.999400	0.00030	2.00000	0.00057
PL-2	PL-4	551.928500	0.00030	2.00000	0.00114
PL-2	PL-5	911.848800	0.00030	2.00000	0.00185
PL-3	PL-4	312.015300	0.00030	2.00000	0.00069
PL-3	PL-5	671.934200	0.00030	2.00000	0.00138
PL-3	PL-6	1103.858800	0.00030	2.00000	0.00223
PL-4	PL-5	360.005300	0.00030	2.00000	0.00078
PL-4	PL-6	791.930600	0.00030	2.00000	0.00161
PL-5	PL-6	432.011000	0.00030	2.00000	0.00091

```
Baseline by MA200 #216          + prism 1    1991 12 20       MZ911220

Estimated Ordinates and Additive Constant with Scaled Standard Deviations

      263.90554  +/-   0.00035

      503.81932  +/-   0.00054

      815.74858  +/-   0.00072

     1175.66806  +/-   0.00093

     1607.59321  +/-   0.00119

       -0.08576  +/-   0.00033


Scaled Covariance Matrix

   1  1.2303E-07  1.6002E-07  2.0118E-07  2.5183E-07  3.0960E-07 -7.9089E-08
   2  1.6002E-07  2.9377E-07  3.5612E-07  4.4992E-07  5.6084E-07 -1.4884E-07
   3  2.0118E-07  3.5612E-07  5.1501E-07  6.2327E-07  7.7525E-07 -2.0557E-07
   4  2.5183E-07  4.4992E-07  6.2327E-07  8.6179E-07  1.0350E-06 -2.7128E-07
   5  3.0960E-07  5.6084E-07  7.7525E-07  1.0350E-06  1.4079E-06 -3.4973E-07
   6 -7.9089E-08 -1.4884E-07 -2.0557E-07 -2.7128E-07 -3.4973E-07  1.0649E-07


a posteriori Reference Variance     0.23670    or (    0.48652)**2
```

Baseline by MA200 #216 + prism 1 1991 12 20 MZ911220

Observed Distances, Standard Deviations, Actual Residuals

1	263.99110	0.00061	0.00020
2	503.90590	0.00105	-0.00081
3	815.83380	0.00166	0.00054
4	239.99940	0.00057	0.00015
5	551.92850	0.00114	0.00030
6	911.84880	0.00185	-0.00052
7	312.01530	0.00069	-0.00029
8	671.93420	0.00138	0.00029
9	1103.85880	0.00223	0.00085
10	360.00530	0.00078	-0.00006
11	791.93060	0.00161	-0.00020
12	432.01100	0.00091	-0.00008

Derived Interpillar Distances and Scaled Standard Deviations

263.90554	+/-	0.00035
239.91379	+/-	0.00031
311.92925	+/-	0.00031
359.91948	+/-	0.00036
431.92516	+/-	0.00045

Scaled Covariance Matrix

1	1.2303E-07	3.6991E-08	4.1164E-08	5.0647E-08	5.7770E-08
2	3.6991E-08	9.6757E-08	2.1190E-08	4.3148E-08	5.3156E-08
3	4.1164E-08	2.1190E-08	9.6538E-08	1.4467E-08	4.1052E-08
4	5.0647E-08	4.3148E-08	1.4467E-08	1.3025E-07	2.1217E-08
5	5.7770E-08	5.3156E-08	4.1052E-08	2.1217E-08	1.9968E-07

```
UNB/NBP MA200 + E2  1990 07  by Z.W.                                MAC9007
 0   1                       0 0       0      0       0               1 0
FIXED
C-400
STATIONS
  C-100        1143.2329        558.2815     0.0001
  C-301         951.4486        576.7600     0.0001
  C-400         864.5070        576.2640     0.0001
  C-500         739.6538        591.8794     0.0001
  C-600         481.3289        576.1220     0.0001
  REF-100       738.5273       1069.0475     0.0001
  REF-200      1152.0476       1068.9681     0.0001
  REF-201      1273.9424       1138.7980     0.0001
  REF-202      1204.6538       1200.8834     0.0001
  C-555         958.5834       1433.6263     0.0001
  DS-1          532.9884       1078.7907     0.0001
  I-1           887.8980       1282.6073     0.0001
  I-2           941.4170       1231.4819     0.0001
  I-3          1009.0727       1180.2421     0.0001
  TR-1         1055.0557        981.4781     0.0001
  TR-2          923.7953        981.4883     0.0001
  TR-3         1033.9318        981.5481     0.0001
  TR-4          975.3989        981.3615     0.0001
  S-250A        432.0433        979.6688     0.0001
  S-251A        388.2560        900.0802     0.0001
  S-252A        360.7655        813.8772     0.0001
  C-200        1584.2107       1431.5496     0.0001
  PR-1         1043.2890        986.3355     0.0005
  PR-2          967.1306        986.3848     0.0005
  PR-3          903.8628        986.2745     0.0005
  DS-2          604.0936       1138.2750     0.0001
  INVP-B       1031.8193        982.2177     0.0001
  INEQ          819.0562       1057.4615     0.0001
  INEL         1069.9984       1056.6677     0.0001
  MON-3         986.2621       1059.8171     0.0001
  MON-6         914.5641       1059.6864     0.0001
-9
OBSERVATIONS
    4     C-400     I-3                  0.01       13.       27.       39.0
    1     C-600     DS-2                     0.0003     3.0000   575.4000
    1     C-600     DS-1                     0.0003     3.0000   505.3170
    1     C-600     REF-100                  0.0003     3.0000   555.9926
    1     C-600     INEQ                     0.0003     3.0000   588.0051
    1     C-600     MON-6                    0.0003     3.0000   649.2537
    1     C-600     REF-200                  0.0003     3.0000   832.3171
    1     C-600     I-2                      0.0003     3.0000   800.7366
    1     C-600     INEL                     0.0003     3.0000   759.9071
    1     C-600     I-3                      0.0003     3.0000   802.1711
    1     C-600     MON-3                    0.0003     3.0000   699.2270
    1     C-600     S-252A                   0.0003     3.0000   266.5750
    1     C-600     REF-201                  0.0003     3.0000   972.0305
    1     C-600     S-251A                   0.0003     3.0000   337.0635
    1     C-600     TR-1                     0.0003     3.0000   702.4783
```

1	C-600	S-250A	0.0003	3.0000	406.5463
1	C-600	I-1	0.0003	3.0000	815.1174
1	C-600	TR-3	0.0003	3.0000	685.3761
1	C-600	PR-3	0.0003	3.0000	588.8622
1	C-600	INVP-B	0.0003	3.0000	684.0716
1	C-600	PR-2	0.0003	3.0000	635.8593
1	C-600	TR-4	0.0003	3.0000	639.0013
1	C-600	PR-1	0.0003	3.0000	695.7497
1	C-600	TR-2	0.0003	3.0000	600.0826
1	REF-200	REF-202	0.0003	3.0000	142.0177
1	REF-200	REF-201	0.0003	3.0000	140.4797
1	REF-200	INEL	0.0003	3.0000	82.9654
1	REF-200	PR-3	0.0003	3.0000	261.5947
1	REF-200	S-252A	0.0003	3.0000	831.3851
1	REF-200	S-251A	0.0003	3.0000	782.2412
1	MON-3	PR-1	0.0003	3.0000	93.0143
1	MON-3	PR-2	0.0003	3.0000	75.8836
1	MON-3	S-252A	0.0003	3.0000	672.1119
1	MON-3	PR-3	0.0003	3.0000	110.4421
1	MON-3	S-251A	0.0003	3.0000	618.9728
1	MON-3	MON-6	0.0003	3.0000	71.6958
1	REF-100	INEQ	0.0003	3.0000	81.3596
1	REF-100	REF-200	0.0003	3.0000	413.5195
1	REF-100	I-2	0.0003	3.0000	259.9022
1	REF-100	MON-6	0.0003	3.0000	176.2848
1	REF-100	PR-1	0.0003	3.0000	315.7846
1	REF-100	I-1	0.0003	3.0000	260.6138
1	REF-100	I-3	0.0003	3.0000	292.5060
1	REF-100	S-251A	0.0003	3.0000	388.8969
1	REF-100	S-250A	0.0003	3.0000	319.2502
1	C-555	C-600	0.0003	3.0000	981.3694
1	C-555	I-1	0.0003	3.0000	166.7427
1	C-555	S-252A	0.0003	3.0000	861.0924
1	C-555	S-251A	0.0003	3.0000	780.9899
1	C-555	S-250A	0.0003	3.0000	695.2135
1	TR-2	TR-4	0.0003	3.0000	51.6041
1	INEL	S-252A	0.0003	3.0000	749.6401
1	INEL	PR-3	0.0003	3.0000	180.4311
1	INEL	S-251A	0.0003	3.0000	699.4952
1	INEL	PR-2	0.0003	3.0000	124.5840
1	INEL	INEQ	0.0003	3.0000	250.9417
1	INEL	MON-6	0.0003	3.0000	155.4633
1	INEL	MON-3	0.0003	3.0000	83.7956
1	MON-6	INEQ	0.0003	3.0000	95.5329
1	MON-6	PR-3	0.0003	3.0000	74.1869
1	MON-6	PR-2	0.0003	3.0000	90.2019
1	MON-6	S-252A	0.0003	3.0000	605.9032
1	MON-6	PR-1	0.0003	3.0000	148.1578
1	INEQ	PR-1	0.0003	3.0000	235.2415
1	INEQ	MON-3	0.0003	3.0000	167.2206
1	INEQ	PR-2	0.0003	3.0000	164.2481
1	INEQ	PR-3	0.0003	3.0000	110.7234
1	I-1	INEQ	0.0003	3.0000	235.4349

1	I-1	S-252A	0.0003	3.0000	705.3948
1	I-1	MON-3	0.0003	3.0000	243.5374
1	I-1	S-251A	0.0003	3.0000	629.2632
1	I-1	I-2	0.0003	3.0000	74.0144
1	I-1	S-250A	0.0003	3.0000	547.3345
1	I-2	S-250A	0.0003	3.0000	568.2193
1	I-2	I-3	0.0003	3.0000	84.8697
1	I-2	INEL	0.0003	3.0000	217.0097
1	I-2	S-252A	0.0003	3.0000	715.2320
1	I-2	MON-3	0.0003	3.0000	177.4253
1	I-2	INEQ	0.0003	3.0000	212.7317
1	I-2	MON-6	0.0003	3.0000	173.8814
1	I-3	MON-6	0.0003	3.0000	153.1850
1	I-3	INEQ	0.0003	3.0000	226.2329
1	I-3	INEL	0.0003	3.0000	137.7765
1	I-3	S-250A	0.0003	3.0000	610.8952
1	C-200	C-555	0.0003	3.0000	625.6313
1	C-200	REF-202	0.0003	3.0000	444.1513
1	C-200	I-3	0.0003	3.0000	627.6457
1	C-200	REF-200	0.0003	3.0000	564.1191
1	C-200	REF-100	0.0003	3.0000	920.1020
1	C-200	DS-1	0.0003	3.0000	1108.8298
1	C-200	C-600	0.0003	3.0000	1395.7467
1	C-200	S-252A	0.0003	3.0000	1370.5224
1	C-200	C-301	0.0003	3.0000	1063.5107
1	TR-1	TR-3	0.0003	3.0000	21.1247
1	TR-1	TR-4	0.0003	3.0000	79.6566
1	TR-1	TR-2	0.0003	3.0000	131.2601
1	TR-1	TR-2	0.0003	3.0000	131.2601
1	TR-3	TR-4	0.0003	3.0000	58.5337
1	TR-3	TR-2	0.0003	3.0000	110.1369
1	TR-3	INVP-B	0.0003	3.0000	2.2159
1	C-400	INEL	0.0003	3.0000	522.5080
1	C-400	MON-3	0.0003	3.0000	498.6487
1	C-400	REF-200	0.0003	3.0000	570.4714
1	C-400	MON-6	0.0003	3.0000	486.0077
1	C-400	INEQ	0.0003	3.0000	483.3390
1	C-400	REF-100	0.0003	3.0000	508.6310
1	C-400	REF-201	0.0003	3.0000	695.7625
1	C-400	I-3	0.0003	3.0000	621.0393
1	C-400	I-2	0.0003	3.0000	659.7171
1	C-400	C-200	0.0003	3.0000	1117.8051
1	C-400	TR-1	0.0003	3.0000	447.7793
1	C-400	TR-3	0.0003	3.0000	439.2720
1	C-400	TR-4	0.0003	3.0000	420.0012
1	C-400	S-252A	0.0003	3.0000	556.9682
1	C-400	TR-2	0.0003	3.0000	409.5383
1	C-400	S-251A	0.0003	3.0000	575.9086
1	C-400	INVP-B	0.0003	3.0000	439.0801
1	C-400	S-250A	0.0003	3.0000	591.4042
1	C-400	PR-1	0.0003	3.0000	447.3447
1	C-400	DS-1	0.0003	3.0000	602.0265
1	C-400	PR-2	0.0003	3.0000	422.7637

1	C-400	DS-2	0.0003	3.0000	619.4108
1	C-400	PR-3	0.0003	3.0000	411.8913
1	C-400	C-500	0.0003	3.0000	125.8264
1	C-400	C-600	0.0003	3.0000	383.1781
1	DS-2	S-252A	0.0003	3.0000	405.5164
1	DS-2	S-251A	0.0003	3.0000	321.4371
1	DS-2	REF-100	0.0003	3.0000	151.2120
1	DS-2	S-250A	0.0003	3.0000	234.0017
1	DS-2	DS-1	0.0003	3.0000	92.7057
1	DS-1	I-1	0.0003	3.0000	409.2687
1	DS-1	I-2	0.0003	3.0000	436.0371
1	DS-1	S-251A	0.0003	3.0000	229.9679
1	DS-1	I-3	0.0003	3.0000	486.7729
1	DS-1	S-250A	0.0003	3.0000	141.4753
1	DS-1	REF-100	0.0003	3.0000	205.7697
1	C-301	C-400	0.0003	3.0000	86.9430
1	C-301	PR-3	0.0003	3.0000	412.2663
1	C-301	C-600	0.0003	3.0000	470.1211
1	C-301	PR-2	0.0003	3.0000	409.9246
1	C-301	PR-1	0.0003	3.0000	419.7428
1	C-301	S-251A	0.0003	3.0000	649.4022
1	C-301	TR-1	0.0003	3.0000	417.7694
1	C-301	TR-3	0.0003	3.0000	413.1076
1	C-301	DS-1	0.0003	3.0000	653.5622
1	C-301	DS-2	0.0003	3.0000	660.2683
1	C-301	INEQ	0.0003	3.0000	498.6011
1	C-301	TR-2	0.0003	3.0000	405.6714
1	C-301	TR-4	0.0003	3.0000	405.3097
1	C-301	INVP-B	0.0003	3.0000	413.3470
1	C-301	REF-100	0.0003	3.0000	536.3614
1	C-301	INEL	0.0003	3.0000	494.3364
1	C-301	I-2	0.0003	3.0000	654.8019
1	C-301	REF-200	0.0003	3.0000	531.5163
1	C-301	I-3	0.0003	3.0000	606.2306
1	C-301	MON-3	0.0003	3.0000	484.3123
1	C-301	MON-6	0.0003	3.0000	484.3348
1	C-301	REF-201	0.0003	3.0000	647.9890
1	C-301	REF-202	0.0003	3.0000	673.5317
1	C-100	TR-1	0.0003	3.0000	432.2847
1	C-100	I-2	0.0003	3.0000	702.8025
1	C-100	PR-3	0.0003	3.0000	490.3787
1	C-100	DS-1	0.0003	3.0000	802.0797
1	C-100	PR-2	0.0003	3.0000	462.9066
1	C-100	REF-202	0.0003	3.0000	645.5307
1	C-100	PR-1	0.0003	3.0000	439.5626
1	C-100	REF-201	0.0003	3.0000	595.0491
1	C-100	TR-3	0.0003	3.0000	437.1512
1	C-100	C-200	0.0003	3.0000	978.2932
1	C-100	INVP-B	0.0003	3.0000	438.3321
1	C-100	I-3	0.0003	3.0000	636.2681
1	C-100	TR-4	0.0003	3.0000	455.1534
1	C-100	I-1	0.0003	3.0000	768.0138
1	C-100	TR-2	0.0003	3.0000	476.7149

1	C-100	REF-200		0.0003	3.0000	510.7639
1	C-100	INEL		0.0003	3.0000	503.7404
1	C-100	MON-3		0.0003	3.0000	525.5278
1	C-100	INEQ		0.0003	3.0000	595.2073
1	C-500	PR-3		0.0003	3.0000	427.2117
1	C-500	C-600		0.0003	3.0000	258.8062
1	C-500	PR-2		0.0003	3.0000	455.3899
1	C-500	S-252A		0.0003	3.0000	439.1361
1	C-500	PR-1		0.0003	3.0000	497.7819
1	C-500	S-251A		0.0003	3.0000	467.4052
1	C-500	TR-1		0.0003	3.0000	501.2630
1	C-500	S-250A		0.0003	3.0000	494.9797
1	C-500	TR-3		0.0003	3.0000	488.3063
1	C-500	DS-1		0.0003	3.0000	528.9586
1	C-500	INVP-B		0.0003	3.0000	487.5710
1	C-500	DS-2		0.0003	3.0000	562.9636
1	C-500	TR-4		0.0003	3.0000	455.2723
1	C-500	REF-100		0.0003	3.0000	477.1700
1	C-500	TR-2		0.0003	3.0000	430.9341
1	C-500	I-1		0.0003	3.0000	706.4568
1	C-500	REF-201		0.0003	3.0000	764.5783
1	C-500	I-3		0.0003	3.0000	647.1160
1	C-500	INEL		0.0003	3.0000	570.2274
1	C-500	INEQ		0.0003	3.0000	472.3052
1	C-500	MON-3		0.0003	3.0000	528.9446
1	C-500	MON-6		0.0003	3.0000	499.4376
1	REF-202	REF-201		0.0003	3.0000	93.0350
1	REF-100	MON-6		0.0003	3.0000	176.2848
1	REF-100	I-1		0.0003	3.0000	260.6135
1	REF-100	DS-1		0.0003	3.0000	205.7699
1	REF-100	PR-1		0.0003	3.0000	315.7863
2	REF-200	C-600	0.80	0.	0.	0.0
2	REF-200	INEL	0.80	27.	46.	58.0
2	REF-200	REF-100	0.80	36.	19.	12.3
2	REF-200	C-301	0.80	328.	28.	54.5
-2	REF-200	C-400	0.80	336.	34.	36.3
2	TR-1	C-600	0.80	0.	0.	0.0
2	TR-1	TR-2	0.80	35.	14.	48.5
2	TR-1	TR-3	0.80	35.	25.	56.3
2	TR-1	C-301	0.80	319.	36.	6.7
2	TR-1	C-400	0.80	330.	25.	38.7
-2	TR-1	C-500	0.80	344.	14.	4.7
2	INVP-B	C-600	0.80	0.	0.	0.0
2	INVP-B	TR-3	0.80	234.	0.	6.8
2	INVP-B	C-301	0.80	317.	37.	41.8
2	INVP-B	C-400	0.80	328.	48.	54.3
-2	INVP-B	C-500	0.80	343.	13.	49.8
2	C-400	C-600	0.80	0.	0.	0.0
2	C-400	DS-1	0.80	56.	36.	31.2
2	C-400	DS-2	0.80	65.	9.	36.7
2	C-400	REF-100	0.80	75.	40.	51.8
2	C-400	I-2	0.80	96.	42.	57.8
2	C-400	TR-2	0.80	98.	20.	43.0

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     2     C-400     I-3                 0.80       103.       28.        55.8
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     2     C-400     TR-1                0.80       115.       12.        21.3
     2     C-400     REF-200             0.80       120.       17.        20.5
    -2     C-400     C-301               0.80       179.       41.        38.5
     2     C-301     C-600               0.80         0.        0.         0.0
     2     C-301     DS-1                0.80        50.       15.        55.9
     2     C-301     DS-2                0.80        58.       20.        11.9
     2     C-301     REF-100             0.80        66.       41.        18.5
     2     C-301     TR-2                0.80        86.       10.         8.5
     2     C-301     I-2                 0.80        89.       11.        59.0
     2     C-301     I-3                 0.80        95.       31.        55.4
     2     C-301     INVP-B              0.80       101.       17.        22.5
     2     C-301     TR-3                0.80       101.       35.        41.5
     2     C-301     TR-1                0.80       104.       26.        11.8
     2     C-301     REF-200             0.80       112.       15.         2.5
    -2     C-301     C-400               0.80       359.       45.         1.5
     2     C-500     REF-100             0.80         0.        0.         0.0
     2     C-500     I-1                 0.80        12.       14.        53.6
     2     C-500     I-3                 0.80        24.       44.        20.4
     2     C-500     TR-2                0.80        25.       25.        55.6
     2     C-500     INVP-B              0.80        36.       56.        59.5
     2     C-500     TR-3                0.80        37.       11.        44.0
     2     C-500     TR-1                0.80        39.        7.        37.4
     2     C-500     DS-1                0.80       337.        8.        12.3
    -2     C-500     DS-2                0.80       346.       12.         4.3
     2     C-600     REF-200             0.80         0.        0.         0.0
     2     C-600     TR-3                0.80         0.        2.        31.6
     2     C-600     TR-1                0.80         1.        3.        57.1
     2     C-600     C-500               0.80        32.       49.         2.4
     2     C-600     C-301               0.80        36.       13.        49.0
     2     C-600     C-400               0.80        36.       17.        15.1
     2     C-600     DS-1                0.80       312.       10.        33.6
     2     C-600     DS-2                0.80       318.       37.        37.9
     2     C-600     REF-100             0.80       333.       51.        45.4
     2     C-600     I-2                 0.80       341.       22.        40.6
     2     C-600     I-3                 0.80       347.       26.        51.4
     2     C-600     TR-2                0.80       353.       48.        48.6
    -2     C-600     INVP-B              0.80       359.       53.        30.5
-9
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C-500           739.65389927      591.87926940   1
C-600           481.32887270      576.12197229   1
REF-100         738.52740530     1069.04781221   1
REF-200        1152.04611020     1068.96938748  20
REF-201        1273.94119956     1138.79888341  21
REF-202        1204.65276964     1200.88448851  22
C-555           958.58250380     1433.62698868   1
DS-1            532.98832963     1078.79135576   2
I-1             887.89730487     1282.60796895   1
I-2             941.41654418     1231.48270217   1
I-3            1009.07302111     1180.24337654   1
TR-1           1055.05538142      981.47870060   3
TR-2            923.79492404      981.48853170   4
TR-3           1033.93148216      981.54866676   5
TR-4            975.39859428      981.36173741   6
S-250A          432.04341257      979.66881273   7
S-251A          388.25554768      900.08025389   8
S-252A          360.76415598      813.87488993   9
C-200          1584.21013777     1431.55031337   1
PR-1           1043.28716454      986.33305456  10
PR-2            967.13083462      986.38494069  11
PR-3            903.86514853      986.27435652  12
DS-2            604.09308273     1138.27520891  13
INVP-B         1031.81913258      982.21817199  14
INEQ            819.05754487     1057.46176931  15
INEL           1069.99759887     1056.66897709  16
MON-3           986.26078652     1059.81771815  17
MON-6           914.56426305     1059.68700558  18
C-400           864.50700000      576.26400000   1
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  0.6690371E-06 -0.6860751E-06  0.3597286E-06  0.1265812E-06 -0.1528482E-06
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  0.5739457E-07  0.7612499E-07 -0.3869179E-08  0.8519525E-07 -0.6532758E-07
  0.7612039E-07 -0.3745290E-08  0.8452231E-07 -0.1083532E-06  0.2960179E-07
 -0.4628737E-07  0.4303484E-07 -0.5361689E-07  0.5020629E-07 -0.4287753E-07
 -0.8936599E-06  0.1575639E-05  0.1221363E-06  0.8586933E-08  0.1931820E-06
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  0.7088852E-07 -0.2021620E-08  0.1216884E-06 -0.1235868E-06  0.9607361E-07
  0.1596063E-06  0.1003038E-06 -0.2144675E-08  0.1073723E-06 -0.4906978E-07
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  0.3551047E-07 -0.9280272E-08 -0.8940428E-08  0.2809330E-07 -0.2339691E-07
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  0.5456800E-07 -0.3279478E-07  0.5973740E-07  0.9058225E-08  0.7815256E-07
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  0.9832325E-07 -0.5623424E-07  0.6014107E-07 -0.9189884E-08 -0.1763515E-07
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  0.1367138E-06  0.9056708E-08  0.1969872E-07 -0.2021993E-08  0.3923426E-07
 -0.2148851E-07  0.1156117E-07 -0.1148786E-07  0.1169138E-07  0.2529035E-07
  0.2996129E-08  0.3928027E-07 -0.2381124E-08  0.3309097E-07 -0.1960380E-07
  0.8525429E-08  0.1137549E-07 -0.2148141E-07 -0.4125451E-08  0.6083910E-09
 -0.1460741E-08  0.4030773E-08  0.2368539E-08  0.9823699E-08  0.2215627E-07
  0.1451582E-07  0.2191352E-07  0.2891807E-08  0.2208568E-07  0.1283550E-07
  0.2186499E-07  0.4204749E-08  0.7659357E-08 -0.1696577E-07  0.2097397E-07
 -0.2824727E-07  0.1658991E-07 -0.2436994E-07 -0.2243003E-07  0.6809728E-07
  0.1727292E-07  0.1184204E-07  0.1787013E-07  0.5304429E-08  0.1874323E-07
 -0.3730843E-09  0.8512854E-08 -0.1786725E-07  0.2238530E-07  0.1266191E-07
  0.1251220E-07 -0.6059107E-08  0.1219444E-07  0.1600172E-07  0.1174897E-07
  0.7218705E-08  0.1201421E-07  0.1244441E-08
  0.5793854E-07  0.4175233E-08  0.1907197E-07  0.6801716E-08  0.4295474E-08
 -0.1095932E-07  0.2135675E-07 -0.1190034E-07  0.3400320E-07 -0.1626712E-07
  0.4186751E-07 -0.1844420E-07  0.3915572E-07 -0.2287254E-07  0.2649986E-07
 -0.1183137E-07  0.8636255E-08 -0.1311446E-07  0.2245570E-07 -0.8699746E-08
  0.2433745E-07  0.2984860E-08  0.2504357E-07 -0.2496191E-07  0.3855990E-07
 -0.2495416E-07  0.2888552E-07 -0.2497225E-07  0.3703126E-07 -0.2494925E-07
  0.3392979E-07 -0.4348371E-08  0.2470994E-08 -0.5006072E-08  0.3728064E-08
  0.4283513E-10  0.2488503E-08 -0.2109965E-07  0.4889542E-07 -0.8062057E-08
  0.3148943E-07 -0.1060207E-07  0.2847907E-07 -0.1040662E-07  0.2767003E-07
 -0.1689246E-07  0.1303777E-07 -0.2500544E-07  0.3687806E-07 -0.9787258E-08
  0.2608688E-07 -0.9592166E-08  0.2781498E-07 -0.9878584E-08  0.2723650E-07
 -0.9840419E-08  0.2836190E-07
  0.1614162E-06 -0.1663368E-07  0.8056163E-07 -0.3976739E-07  0.1787106E-07
 -0.7046211E-08  0.1805136E-07  0.2238951E-07  0.1496059E-07  0.2950610E-07
  0.9871061E-08  0.2422306E-07 -0.1100835E-07  0.9132738E-08  0.1610148E-07
 -0.3315948E-07 -0.3918131E-08  0.6661028E-08  0.1353299E-08  0.1142855E-07
  0.4807244E-08  0.1782586E-07  0.2378346E-07  0.1900578E-07  0.2414625E-07
  0.9591549E-08  0.2381888E-07  0.1722917E-07  0.2440940E-07  0.1543570E-07
  0.3319383E-07 -0.5140510E-07  0.3900650E-07 -0.5318406E-07  0.5509693E-07
 -0.6091534E-07 -0.6252812E-08  0.4443163E-07  0.2678561E-07  0.1981369E-07
  0.2765249E-07  0.1413184E-07  0.2634405E-07  0.9201077E-08  0.8650012E-08
 -0.2441436E-07  0.2315204E-07  0.1711256E-07  0.1934539E-07  0.3859441E-09
  0.1974925E-07  0.2122978E-07  0.1997068E-07  0.1601714E-07  0.1955251E-07
  0.8939117E-08
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.
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The upper-triangular portion of the variance-covariance matrix is stored by rows
The whole file is a total of 8 pages.

1993 8 21
Powerhouse -29 Gallery 29 1 to 29 2

Abcissa(x)	input, fit;		Ordinate(y) input, fit;		Group Code
89 7 14	89.53288	0.53288	115.56000	0.00000	1
89 8 10	89.60685	0.60685	116.10000	0.54000	1
89 9 14	89.70274	0.70274	116.32500	0.76500	1
89 10 16	89.79041	0.79041	115.74614	0.18614	1
89 11 29	89.91096	0.91096	116.06826	0.50826	1
89 12 13	89.94932	0.94932	115.73443	0.17443	1
90 1 25	90.06712	1.06712	115.79190	0.23190	1
90 2 7	90.10274	1.10274	115.50585	-0.05415	1
90 3 7	90.17945	1.17945	115.75975	0.19975	1
90 4 5	90.25890	1.25890	115.79146	0.23146	1
90 5 4	90.33836	1.33836	116.08526	0.52526	1
90 5 28	90.40411	1.40411	116.19334	0.63334	1
90 6 23	90.47534	1.47534	116.47200	0.91200	1
90 7 24	90.56027	1.56027	117.05226	1.49226	1
90 8 15	90.62055	1.62055	116.94934	1.38934	1
90 9 19	90.71644	1.71644	118.28595	2.72595	1
90 10 16	90.79041	1.79041	116.63686	1.07686	1
90 11 19	90.88356	1.88356	116.33350	0.77350	1
90 12 11	90.94384	1.94384	116.08400	0.52400	1
91 1 8	91.02055	2.02055	116.04200	0.48200	1
91 2 5	91.09726	2.09726	116.21357	0.65357	1
91 3 5	91.17397	2.17397	116.55040	0.99040	1
91 4 8	91.26712	2.26712	116.87934	1.31934	1
91 5 2	91.33288	2.33288	116.91905	1.35905	1
91 5 28	91.40411	2.40411	117.12940	1.56940	1
91 6 26	91.48356	2.48356	117.18525	1.62525	1
91 7 26	91.56575	2.56575	117.43326	1.87326	1
91 8 19	91.63151	2.63151	117.51706	1.95706	1

```
Powerhouse  -29 Gallery   29 1  to  29 2

Estimated Coefficients, Scaled Standard Deviations

  1   -0.336992      0.093398
  2    0.367485      0.100565
  3    0.753744      0.111295
  4   -0.350612      0.189519

       0.498607      0.092832 amplitude
       8 18                   mm,dd of Maximum
   0.0431 Tilt [mm/m] over    17.5078 m, horizontally


Powerhouse  -29 Gallery   29 1  to  29 2

i,   X,    Y,   Y Residual,   Standardized Y Residual

  1  89   7 14    0.532877    0.000000    0.456241     2.720502
  2  89   8 10    0.606849    0.540000    0.059248     0.384994
  3  89   9 14    0.702740    0.765000   -0.135919    -0.954538
  4  89  10 16    0.790411    0.186140    0.330070     2.405641
  5  89  11 29    0.910959    0.508260   -0.262820    -1.987327
  6  89  12 13    0.949315    0.174430   -0.014486    -0.110708
  7  90   1 25    1.067123    0.231900   -0.236069    -1.823950
  8  90   2  7    1.102740   -0.054150    0.044452     0.341598
  9  90   3  7    1.179452    0.199750   -0.137860    -1.041222
 10  90   4  5    1.258904    0.231460    0.018753     0.140922
 11  90   5  4    1.338356    0.525260   -0.001768    -0.013681
 12  90   5 28    1.404110    0.633340    0.143789     1.173671
 13  90   6 23    1.475343    0.912000    0.125669     1.101009
 14  90   7 24    1.560274    1.492260   -0.217843    -2.005387
 15  90   8 15    1.620548    1.389340   -0.021130    -0.191252
 16  90   9 19    1.716438    2.725950   -1.352924   -11.182202 Reject ?
 17  90  10 16    1.790411    1.076860    0.193095     1.489338
 18  90  11 19    1.883562    0.773500    0.290359     2.147185
 19  90  12 11    1.943836    0.524000    0.401326     2.968493
 20  91   1  8    2.020548    0.482000    0.308865     2.325390
 21  91   2  5    2.097260    0.653570    0.089762     0.687969
 22  91   3  5    2.173973    0.990400   -0.183666    -1.416275
 23  91   4  8    2.267123    1.319340   -0.290294    -2.232877
 24  91   5  2    2.332877    1.359050   -0.102389    -0.785822
 25  91   5 28    2.404110    1.569400   -0.038527    -0.293028
 26  91   6 26    2.483562    1.625250    0.193417     1.413577
 27  91   7 26    2.565753    1.873260    0.166230     1.111045
 28  91   8 19    2.631507    1.957060    0.174418     1.061363

Estimated variance factor .. (    0.35425 )**2
Number of data ..............          28
Number of parameters ........           4
Degrees of freedom ..........          24
```

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                                                                D930824Z
BA12       18.14 22.00 24.49 26.36 27.00 28.92 21.3  0.0  0.0  0.0  0.0  0.008:56
BB11        0.06  0.00  0.12  0.17  0.17  0.17 26.1  0.0  0.0  0.0  0.0  0.015:51
BY01       91.03  0.00  0.00  0.00  0.00  0.00 21.3 20.5 20.5 20.5 20.3  0.012:43
BZ06       92.34  0.00  0.00  0.00  0.00  0.00 27.6 23.3 23.2 20.9 19.4 21.911:14
BZ07        0.06 -0.00  0.00  0.00  0.00  0.00 22.5 21.5  0.0  0.0  0.0  0.011:46
CTBA012     18.3333 09:00
DI41         107.69    115.29    112.25     17.16 09:20
DS02          1.04     -0.54 09:26
FW1         195.5369    7.1250 14:54
HPTEMP       22.60      25.00 16:02
HPTEMP       21.00      21.50 10:35
IPU6QT       935.00     590.00 10:51
IIMOCT        -3.00      -1.00 11:02
IIEEAT        1.70      4.96     57.95 11:27
JM00         58.7300    0.0000    0.0000    0.0000 13:09
JM02          0.0000  104.5000  107.4500    0.0000 09:13
JM21          0.0000   88.9800    0.0000    0.0000 09:16
L080        -4.1570 13:15
M020          -1.48      5.65      0.23 09:05
PPG14UT      -0.41      6.58 10:20
PPH052        87.870    80.256    74.476   251.730 08:26
PIS01       158.5600  116.3601    0.0000    0.0000 10:59
PIS02       151.0100  116.6901    0.0000    0.0000 11:31
PIS03       154.8400  115.5300    0.0000    0.0000 11:36
PIS04       111.7800   94.1200    0.0000    0.0000 11:40
PPS011        72.053   116.104    43.882    45.542 08:27
PPTR02        1.39      0.56 11:37
PPTR03        2.25      4.16 14:55
PPTR01        1.17     -3.50 15:12
RBH40        15.30    15.10    15.20    17.10    19.30    21.10 11:17
SBH063     9030    6.950 3020.  9031    6.320 2792.     0    0.000     0.  15:17
SOCG05     9359    5.100 3550.  9365    4.950 3540.     0    0.000     0.  15:37
T0           5.00479  10.00093  14.99888  20.00021  25.00011 10:38
B0          63.54001  63.18001  63.74400  64.15001  63.93001 10:38
TAPCAL       0.00060   0.00126   0.00182   0.00310   0.00334 10:38
TK01-08     14.11136  23.00000 11:28
TK08-09     14.08030  23.00000 11:29
UPRH175       0.00       0.00 14:49
VWSG09    3322.0000 10:30
WLTR        10.5500 08:38
WLHP       132.4401 08:39
XT29         90.4875   93.6625   92.0750    0.0000 10:25
ZP01         1.4800 15:47
```

The time of observation is given at the end of each record. Normally, these would increase chronologically downward in the file. This file was assembled from several other observation files in order to show the variety in the type of observation. Consequently, the times do not increase downward.

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CHECK FILE FOR GEOTECHNICAL INSTRUMENTATION                        GEO.CHK
BA01     3 57.42 60.78 57.48
BA01   T 0
BA01   C 0
BA06     2 76.36 63.10   .00   .00   .00   .00 1833 3434    0    0    0    0
BA06   T 2 100000 110000      0      0      0      019003500
BA06   C 2   26.0    1.6
BA09     5   .00 70.96 74.31 75.36 74.24   .00 1082 1953 3048 3817 5281    0
BA09   T 5 100000 110000 111000 111100 111110      010671829304836595183
BA09   C 5   26.0   26.0   26.0   26.0    1.6
BZ05     1 75.21   .00   .00   .00   .00   .00 3602    0    0    0    0    0
BZ05   T 5 111110                                   01001000190028003600
BZ05   C 1    1.6
BZ06     1 92.00   .00   .00   .00   .00   .00 3371    0    0    0    0    0
BZ06   T 5 111110                                   01001000190028003370
BZ06   C 1    1.6
BZ07     2  -.21  -.09   .00   .00   .00   .00  862   38    0    0    0    0
BZ07   T 1 100000                                   0075
BZ07   C 1    1.6
CTBA001      17.22
CTBA002      10.00
CTBA003       6.11
CTBA004      15.00
CTBA005      15.56
DI06        106.17    106.90    101.90      8.67
DI07        104.63    102.73    109.32     15.75
DI08        106.33    107.86    106.16     20.70
DI13        107.03    106.63    105.59     16.25
DS01          .15       .06             160.84    159.94
DS02         1.04      -.54             161.47    159.73
DS03         -.21      -.31             160.66    160.80
DS04         -.19       .00             160.46    160.89
FW1       148.0700    6.3750 10:25
FW2       137.4214    6.1875 10:26
FW3         0.2551    0.5000 10:26
FW4         1.9371    1.1250 10:27
HPTEMP       21.00
IIEEAT       1.660     5.110    58.071    78.350    78.350
IPU2BT      10.280    19.110    68.731    78.350    78.350
IIMOCT      10.000    -3.000    10.000  -108.000
IIM3DT      10.000    75.340    10.000    73.810
IIM5ET      10.000    74.150    10.000    69.140
IIU6FT      10.000  -801.000    10.000  -235.000
IIU6GT      10.000    45.200    10.000    49.440
IPU1HT      10.000    74.510    10.000   -78.090
IPU2IT      10.000    70.870    10.000   -69.080
IPU3JT      10.000    65.770    10.000   -77.860
IPU5KT      10.000    70.260    10.000   -73.830
IIM4MT      10.000    76.370    10.000    72.580
IIU5NT      10.000  -248.000    10.000  -264.000
IIU3OT      10.000  -583.000    10.000  -163.000
IIM2PT      10.000    62.070    10.000    69.080
IPU6QT      10.000   935.000    10.000   590.000
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IIEERT       10.000  -900.000     10.000  -900.000
IIEEST       10.000  -167.000     10.000  -464.000
IDSHTT       10.000    92.750     10.000    54.560
IDSLTT       10.000    68.020     10.000    62.340
JM00      1 X      58.7300      .0000      .0000      .0000
JM01      1  YZ      .0000  113.5431  108.4442      .0000
JM02      1  YZ      .0000  106.0549  108.8967      .0000
JM03      1  YZ      .0000   99.5388  111.9205      .0000
JM21      1  Y       .0000   89.5242      .0000      .0000
L010     -3976.7874
L020      8286.8132
L030        95.0953
L031      2110.4862
M010           .000    10.000      -.340    10.000
M020         -1.480    10.000      5.650    10.000
PDSEQ         11.70       .96                76.87     76.82
PDS01     1 XY      131.20     130.81
PDS02     1 XY      133.50     128.81
PDS03     1 XY      137.90     130.02
PDS04     1 XY      144.13     128.08
PDS05     1 XY      148.64     125.75
PDS06     1 XY      146.97     123.25
PIE01     1 XY      131.42     131.57
PIE02     1 XY      137.64     125.68
PIE03     1 XY      140.25     123.60
PIE04     1 XY      140.86     122.30
PIE05     1 XY      141.66     122.07
PIE06     1 XY      140.15     118.74
PIP01     1 XY      132.27     131.95
PIP02     1 XY      132.65     140.20
PIS01     1 XY      158.77     116.55
PIS02     1 XY      152.70     115.35
PIS03     1 XY      156.57     114.80
PIS04     1 XY      113.60      94.00
PPTR01         1.98      4.17                78.03     77.96
PPTR02         1.31      1.03                77.60     77.82
PPTR03         1.08     -3.14                77.89     78.21
PPG06U         -.94      4.06                69.37     69.24
PPG06D          .39     -6.57                69.39     69.32
PPG07U          .90      1.92                69.42     69.42
PPG07UT         .78      2.68                69.59     69.62
PPG07D         3.49      1.18                69.35     69.39
PPG07DT       -1.10      -.20                69.35     69.35
PPG08U         -.13      3.15                69.38     69.36
PPG08D         -.51     -3.70                69.30     69.28
PPG11U         -.32     10.04                69.29     69.29
PPG11D         -.34     -6.92                69.32     69.28
PPH011      260.050   152.031    135.474   260.550
PPH012       94.120    79.798     74.700   232.420
PPH021      246.180   151.715    134.779   240.970
PPH022       85.830    78.925     74.410   217.720
PPS052       68.140   118.240     43.313    45.664
PPT08     2  Y          .00     234.45  Y        .00     265.95
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PPT10     2  Y        .00     219.23  Y        .00     253.07
PPT0141   2 XY     131.44     130.50 XY     132.00     120.33
PPT14     2  Y       0.00     241.17  Y       0.00     300.00
PPT18     2  Y        .00     249.42  Y        .00     295.41
PPT22     2  Y        .00     217.48  Y        .00     236.60
PPT26     2  Y        .00     230.72  Y        .00     267.07
RBA09     6              14.2     12.0     12.5     8.9      9.4      9.9
RBH40     6              12.9     16.4     17.5    19.1     21.1     24.9
RBH41     6              15.4     18.3     19.6    20.2     21.3     24.3
RBH42     6              15.5     17.3     19.0    20.9     22.4     24.7
SBH050    3 8155  4.160  5430. 8164  4.450  4270. 8172  3.530  4270.
SBH051    3 8154  3.990  6300. 8167  3.210  4710. 8171  3.500  4710.
SOCG01    2 8153  4.650  4260. 8163  4.240  4260.    0   .000     0.
SOCG02    2 8157  6.080  4440. 8165  5.710  4410.    0   .000     0.
SOCG03    3 8160   .000     0. 8169  3.430  4510. 8175  5.180  5500.
SOCG04    2 9363  6.700  3960. 9360  5.560  3870.    0   .000     0.
SOCG05    2 9359  6.740  3940. 9365  5.980  3910.    0   .000     0.
SOCG06    2 9362  6.360  3950. 9361  5.570  4400.    0   .000     0.
SOCG07    2 9366  5.740  4070. 9364  6.060  4460.    0   .000     0.
B0              63.500   63.060   63.590   63.910   63.752
T0           5.00529  10.00113  14.99930  20.00084  25.00001
TAPCAL        .00006    .00094    .00125    .00222    .00325
TA04-05    24.11031
TA06-07    10.82895
TA08-09    28.38301
TS11-12    13.00200
UPRH172         .00       .00
UPRH173        3.00      2.96
UPRH174        2.00      1.76
UPRH175         .00       .00
VWSG01    2656.0000
VWSG02    2637.0000
VWSG03    2591.0000
WLHP         128.57
WLTR          19.69
XT01      1 XYZ   53.9750  107.9500   80.9625     .0000
XT03      1 XYZ  130.1751  133.3500  123.8250     .0000
XT11      1  Y      .0000   69.8500     .0000     .0000
XT12      1  Y      .0000   57.1500     .0000     .0000
XT13      1 XYZ   77.7875   63.5000   22.2250     .0000
XT14      1  YZ     .0000  120.6500   82.5500     .0000
XT15      1  YZ    0.0000  120.6500   58.7375    0.0000
ZP01           .899
ZP02           .985
ZP03          1.646
ZP04           .616
ZP05          1.935
ZP09           .000
ZP10           .000
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This is only a selection of records from a full GEO.CHK file which would be a total of 13 pages.

Name	Directory	
A		
Ba	EXB	borehole extensometers
BX	PSTAB	Distometer (pillar stability)
BY	EXB	invar wire extensometers ('vertical deflection')
BZ	EXB	invar rod extensometers
B0	EXB	with T0, as calibration apparatus measurements
C	TEM	concrete temperature probes
D	DDD	4 pin displacement gauges
DS	DDD	shear displacement gauges
E		
F	FFF	drains; weirs
G	STR	gauges, strain
H	TEM	head pond temperature
I...S	PEN	inverted pendula, shuttle readings
I...T	PEN	inverted pendula, table readings
J	DDD	jointmeters
K	PSTAB	E2 angles, levelling (pillar stability)
L	DDD	LVDTs (linear variable differential transformer)
M	STR	tiltmeters
N		
O		
Paaaa	PEN	suspended pendula; plumblines
PPa0i	PEN	a=H,S suspended pendula with A,B,C,D components
PPTR0i	PEN	suspended pendula with +y,+x,-y,-x readings; QX,QY
Q		
R	TEM	thermocouples; thermistors
S	STR	Interfels stress cells
T	EXT	Solinst tape extensometer
T0	EXT	with B0, as calibration apparatus measurements
U	FFF	pressure relief wells
V	STR	VWSGs (vibrating wire strain gauges)
W	FFF	water level: tailrace, head pond
X	DDD	telltales
Y		
Z	FFF	piezometers

```
0 5 111110 6  0.000 10.670 18.290 30.480 36.590 51.830           BA09
Extensometer BA09 collar to anchor 1  10.820 m (Alum.)
26.0 000000
Extensometer BA09 collar to anchor 2  19.530 m (Alum.)
26.0 000000
Extensometer BA09 collar to anchor 3  30.480 m (Alum.)
26.0 000000
Extensometer BA09 collar to anchor 4  38.180 m (Alum.)
26.0 000000
Extensometer BA09 collar to anchor 5  52.810 m (Alum/Invar)
 1.6 000000
(I2,2I3,2x,5(F9.4,A1))                                                 was
91 10 31      69.21     56.12     56.01     56.85     61.45           54.24
86 08 11       0.00      0.00      0.00      0.00      0.00           55.83
86 08 18       0.00     -0.01      0.00      0.01     -0.21           54.91
86 08 25       0.01     -0.24     -0.06     -0.08     -0.21           55.84
86 09 02       0.00     -0.35     -0.18     -0.19     -0.22           61.57
86 09 08       0.00     -0.43     -0.24     -0.20     -0.21
86 09 15       0.01     -0.41     -0.24     -0.19     -0.22           54.70
86 09 22       0.01     -0.43     -0.26     -0.19     -0.22           55.93
86 09 29       0.02     -0.43     -0.27     -0.19     -0.21           55.98
86 10 06       0.02     -0.41     -0.25     -0.18     -0.21           56.79
86 10 14       0.02     -0.36     -0.23     -0.18     -0.21           61.43
86 10 20       0.02     -0.34     -0.20     -0.16     -0.21
86 10 27       0.02     -0.34     -0.19     -0.13     -0.19
86 11 03       0.02     -0.34     -0.19     -0.12     -0.18
86 11 10       0.02     -0.34     -0.19     -0.12     -0.18
86 11 17       0.01     -0.14     -0.05      0.04     -0.18
86 11 24       0.02      0.07      0.09      0.25     -0.18
86 12 01       0.04      0.35      0.36      0.44     -0.17
86 12 08       0.04      0.63      0.57      0.75     -0.16
86 12 15       0.04      0.92      0.92      1.01     -0.16
86 12 22       0.07      1.16      1.03      1.21     -0.15
87 01 05       1.21      1.74      1.77      1.84      0.88
87 01 19       1.20      2.05      2.15      2.12      0.88
87 02 03       1.20      2.26      2.33      2.31      1.35
87 02 16       1.21      2.52      2.62      2.59      1.39
87 03 02       1.21      2.76      2.83      2.86      1.45
87 03 16       1.21      2.99      3.29      3.16      1.35
87 03 30       2.06      3.38      3.78      3.76      2.59
87 04 13       2.09      3.52      4.01      3.91      2.60
87 04 27       2.11      3.79      4.49      4.40      3.22
87 05 11       2.08      3.56      4.41      4.47      2.96
87 05 22       2.11      3.43      4.40      4.45      3.25
87 06 08       2.04      3.13      4.26      4.36      3.16
87 06 22       2.07      3.06      4.33      4.36      3.16
87 07 06       2.07      3.10      4.33      4.36      3.18
87 07 20       2.07      2.67      4.27      4.36      3.16
87 08 04       2.03      2.22      3.98      4.29      3.16
87 08 17       2.06      1.93      3.74      4.17      3.05
87 08 31       2.06      1.34      3.15      3.71      3.01
87 09 14       1.22      0.99      2.80      3.40      3.03
87 09 28       1.33      0.92      2.60      3.29      3.12
87 10 13       1.22      0.95      2.62      3.29      3.13
```

87 10 26	1.22	1.01	2.63	3.30	3.15
87 11 09	1.21	1.22	2.70	3.34	3.16
87 11 23	1.21	1.76	2.84	3.54	3.18
87 12 06	1.25	2.28	3.24	3.97	3.18
87 12 21	1.44	2.94	3.77	4.44	3.22
88 01 04	1.79	3.52	4.28	4.95	3.83
88 01 18	2.05	3.97	4.76	5.36	4.36
88 02 03	2.01	3.89	4.71	5.26	3.77
88 02 15	2.51	4.55	5.39	5.89	4.88
88 02 29	2.73	4.87	5.74	6.30	5.40
88 03 14	2.95	5.05	5.99	6.43	5.61
88 03 25	2.91	5.24	6.28	6.64	5.81
88 04 11	3.01	5.52	6.63	6.94	6.19
88 04 25	2.92	5.53	6.78	7.02	6.39
88 05 09	3.27	5.70	7.09	7.15	6.67
88 05 24	3.28	5.79	7.38	7.43	7.00
88 06 06	3.28	5.51	7.49	7.52	7.07
88 06 20	3.27	5.10	7.27	7.38	7.07
88 07 05	3.28	4.40	6.86	6.95	7.07
88 07 18	3.36	4.25	6.73	6.85	7.09
88 08 03	3.28	3.74	6.40	6.51	7.05
88 08 15	3.28	3.31	6.10	6.22	7.05
88 08 29	3.29	2.96	5.81	5.97	6.48
88 09 12	3.25	2.85	5.70	5.91	6.46
88 09 26	3.26	2.83	5.70	5.86	6.46
88 10 11	3.25	2.85	5.70	5.86	6.45
88 10 21	3.27	2.92	5.76	5.89	6.45
88 10 22	3.28	2.93	5.77	5.91	6.47
88 10 24	3.27	2.96	5.77	5.93	6.46
88 10 25	3.27	3.00	5.79	5.92	6.46
88 10 26	3.25	3.00	5.78	5.92	6.46
88 10 27	3.24	3.05	5.79	5.89	6.47
88 10 28	3.35	3.07	5.82	5.95	6.45
88 10 29	3.25	3.04	5.81	5.93	6.46
88 10 30	3.25	3.08	5.84	5.94	6.45
88 10 31	3.26	3.09	5.83	5.95	6.47
88 11 01	3.26	3.11	5.83	5.96	6.46
88 11 02	3.25	3.16	5.82	5.97	6.45
88 11 03	3.24	3.17	5.83	5.97	6.45
88 11 04	3.26	3.23	5.84	5.97	6.46
88 11 05	3.25	3.29	5.86	5.98	6.47
88 11 07	3.27	3.39	5.93	6.08	6.46
88 11 21	3.28	3.94	6.11	6.45	6.50
88 12 05	3.28	4.53	6.51	6.96	6.57
88 12 19	3.47	5.24	6.97	7.60	7.21
89 01 03	3.84	5.87	7.53	8.16	7.83
89 01 16	4.08	6.38	7.97	8.71	8.40
89 01 30	4.30	6.75	8.23	9.02	8.82
89 02 13	4.37	6.95	8.43	9.13	9.01
89 02 27	4.43	7.21	8.63	9.33	9.27
89 03 14	4.47	7.46	8.82	9.70	9.61
89 03 28	4.69	7.66	8.97	9.88	9.73
89 04 10	4.76	7.84	9.18	10.02	9.86
89 04 24	4.77	7.86	9.40	10.08	10.26

89	05	08	4.91	8.13	9.94	10.41	10.83
89	05	23	4.86	8.07	10.13	10.38	10.92
89	06	12	4.86	7.19	9.91	10.10	10.92
89	07	04	4.86	6.54	9.60	9.69	10.87
89	07	24	4.76	5.93	9.36	9.39	10.45
89	8	15	4.7500	5.3400	8.9500	8.8800	9.9000
89	8	16	4.5800	5.3400	8.9800	8.8800	9.9600
89	8	26	4.6000	5.1500	8.9500	8.9100	9.9500
89	8	28	4.5800	4.9900	8.7600	8.6800	9.6000
89	9	2	4.6100	4.9500	8.7500	8.6800	9.6400
89	9	5	4.6200	4.9600	8.7500	8.6800	9.6300
89	9	14	4.5800	4.9400	8.7600	8.6700	9.6100
89	9	21	4.5300	4.8800	8.6900	8.5800	9.5200
89	9	25	4.6200	4.9700	8.6700	8.6500	9.6400
89	10	1	4.5200	4.8600	8.6200	8.5700	9.5200
89	10	7	4.5200	4.9300	8.6500	8.5900	9.5200
89	10	13	4.5700	5.0500	8.7600	8.7000	9.5600
89	10	17	4.5700	5.2300	8.8100	8.7500	9.6100
89	10	27	4.5600	5.5400	8.8800	8.8000	9.5600
89	10	29	4.5500	5.5800	8.9000	8.8000	9.5400
89	10	30	4.5500	5.6400	8.9000	8.8100	9.5500
89	10	31	4.5400	5.6800	8.9400	8.8300	9.5800
89	11	1	4.5600	5.7900	8.9600	8.8900	9.5600
89	11	2	4.5900	5.8400	8.9600	8.9200	9.5600
89	11	3	4.5600	5.8400	8.9700	8.8900	9.5600
89	11	4	4.5600	5.8500	8.9900	8.9300	9.5500
89	11	5	4.5500	5.8400	8.9700	8.9000	9.5400
89	11	6	4.5500	5.8600	8.9900	8.9100	9.5700
89	11	7	4.5600	5.8500	8.9900	8.8900	9.5400
89	11	14	4.5900	6.1400	9.1100	9.0800	9.5900
89	11	27	4.7800	6.4600	9.2600	9.2200	9.6000
89	12	18	5.1800	7.6700	9.7500	10.3900	10.1500
90	1	9	5.5800	8.6200	10.4500	11.2000	11.3100
90	1	31	5.8700	9.3100	10.9200	11.8300	12.1100
90	2	13	5.9800	9.5200	11.0300	12.0300	12.4000
90	3	5	6.1100	9.7700	11.3300	12.2300	12.6700
90	3	26	6.1700	10.0300	11.5800	12.5600	13.1500
90	4	17	6.2200	10.1000	11.6200	12.6600	13.3300
90	4	23	6.2000	10.1600	11.6700	12.6600	13.3400
90	5	7	6.2000	10.1600	11.6700	12.6600	13.3400
90	5	30	6.4100	9.8500	11.7900	12.7700	14.3000
90	6	14	6.4000	9.3700	11.6300	12.5400	15.1200
90	7	9	5.7100	8.1000	11.1400	11.6800	15.8200
90	8	7	5.6900	7.2400	10.7900	11.1600	17.7600
90	8	13	5.7300	7.1600	10.7800	11.1300	18.1400
90	8	20	5.7400	7.1200	10.7600	11.1000	18.3700
90	8	28	5.7300	7.0700	10.7700	11.1000	18.5900
90	9	18	6.4200	7.0000	11.5400	11.5900	17.6700
90	9	18	6.4200	7.0000	11.5400	11.5900	17.6700
90	9	26	6.4100	7.0100	11.5400	11.5800	17.5800
90	10	1	6.4300	7.0500	11.5800	11.6300	17.6300
90	10	22	6.4500	7.6100	11.8000	11.7600	17.4700
90	11	16	6.4400	8.6800	12.0600	12.0900	16.6200
90	12	4	6.9200	9.5300	12.4800	12.6000	16.0800

90	12	20	6.9100	10.2300	12.7500	13.3900	15.7000	
91	1	14	6.9800	11.2200	13.4200	14.1800	15.3400	
91	1	29	7.5100	11.3800	13.5700	14.4400	15.1900	
91	1	29	7.5100	11.3800	13.5700	14.4400	15.1900	
91	2	11	7.5000	11.5700	13.6200	14.4500	15.2500	
91	2	26	7.4900	11.7200	13.6900	14.5100	15.2400	
91	3	27	7.4800	12.1400	13.8400	14.7200	15.2800	
91	4	9	7.4800	12.2200	13.8900	14.7900	15.3900	
91	5	15	7.4900	12.5600	14.0100	14.9200	16.1300	
91	5	22	7.4900	12.5600	14.0200	14.9300	16.1400	
91	6	18	7.5400	11.7200	13.9300	14.9100	17.6400	
91	7	10	7.5200	10.9400	13.7100	14.5900	18.6700	
91	7	30	7.5200	10.8700	13.5900	14.3400	19.9400	
91	8	15	7.5100	9.9900	13.3700	14.1600	20.3700	
91	9	9	7.5000	9.6200	13.3200	14.0200	20.8700	
91	9	23	7.5400	9.5700	13.4000	14.0400	20.9600	
91	10	22	7.5100	9.7600	13.4000	14.0100	21.2600	
91	10	31	7.4900	9.7500	13.5000	14.0600	20.6200	
91	10	31	7.4900	9.7500	13.5000	14.0600	20.6200	HEAD REMOVE
91	11	4	-69.2100*	9.7800*	13.4900	14.0600	20.6300	
91	12	3	-69.2100*	10.9800*	13.8200	14.4100	20.1700	
91	12	17	-69.2100*	11.9700*	14.1500	14.8300	19.6700	

```
0 1                                                    IIU3OT
Inverted Pendulum O Intake Unit 3, table displacement X direction
Inverted Pendulum O Intake Unit 3, table displacement Y direction
x    -0.1026934743  0.0169257669  -0.0000001463  -0.0000000039
   1.6738658e-14  7.3257064e-16
y    -0.0189587193  0.0165559336   0.0000010095  -0.0000000038
   3.5129042e-13  7.6658480e-16 -2.7063599e-21
(i2,2i3,2x,2(f9.4,a1))
89  6 12     0.1511    0.3789
89  6 12     0.0000    0.0000
89  6 19     0.0338    0.2322
89  6 26    -1.0973    0.2322
89  7  5     0.1861    0.9100
89  7 10     0.2369    1.1569
89  7 18     0.2708    1.2227
89  7 24     0.2877    1.5505
89  8  1     0.3046    1.8281
89  8 17     0.3554    1.9746
89  8 26     2.7662    1.9746
89  8 28     5.0809    1.3048
89  8 30     6.8508    0.9924
89  8 30     7.0027    0.9759
89  8 30     7.1237    0.9430
89  8 30     7.2891    0.8111
89  8 31     8.0856    0.5964
89  9 11     9.4594    0.7946
89  9 18     9.2828    0.4972
89  9 25     9.2691    0.3813
89 10  2     8.7705    0.3151
89 10 17     6.4982    0.7946
00  0  0           s         s
90 12 20    -2.6830   -3.1882
91  3 12     3.0289    3.4844
```

Readings [Hz] in the x and y directions from the observation file are converted to linear units [mm] in module PROC by the polynomial with the six coefficients given in lines 4 and 6

```
0 4                                                                    SOCG05
Thermistor in OCG-5/1 near stress cell 9359       Draft Tube Unit 2
Stress Cell 9359 in OCG-5 / 1                     Draft Tube Unit 2
Thermistor in OCG-5/2 near stress cell 9365       Draft Tube Unit 2
Stress Cell 9365 in OCG-5 / 2                     Draft Tube Unit 2
60.2946386 -0.0175534905 0.0000024263 -1.8368653e-10 5.5949189e-15
9359 9359  1.000 3.53  362.6 20.671  14.6  1     0.0 89 09 11
9365 9365  1.000 3.49  362.6 20.793  15.3  1     0.0 89 09 11
                         9359                9365
(i2,2i3,2x,2(f9.4,a1,f9.0,a1))
89  8 16    20.6710      1393.   20.7930     1315.
89  8 18          *          *   20.9170     1323
89  8 21    21.1650      1422.   21.2910     1340.
89  8 28    20.7320      1356.   20.4280     1286.
89  9  5    19.6560      1318.   18.9120     1270.
89  9 11    18.5780      1315.   18.3030     1197.
89  9 25    17.9790      1331.   17.8190     1199.
89 10 11    14.3730      1085.   14.7220     1266.
89 11  6    10.9590      1147.   10.5260     1087.
89 11 21     8.0000      1101.    7.2390     1126.
89 11 29     5.1170      1130.    4.4300     1171.
00  0  0          s          s         s          s
89 12  4     3.1740       956.    2.3670      972.
89 12 19     0.9390       839.    0.7340      826.
90  1  2     0.5930       826.    0.9350      820.
90  1 10     0.4740       833.    0.3560      831.
90  1 31     0.3367       802.    0.2020      821.
90  2 13     0.1450       789.   -0.0048      811.
90  2 26     0.0137       777.   -0.0968      814.
90  3 26     0.0137       778.   -0.0968      798.
90  4  9    -0.0602       778.   -0.1514      806.
90  4 23     0.5132       831.    0.6933      838.
90  5  7     6.1075      1070.    6.5063     1082.
90  5 22     8.9235      1147.    9.0217     1155.
90  6  6    11.5154      1229.   11.8196     1250.
90  6 15    13.5931      1279.   14.1966     1269.
90  7  4    18.7444      1321.   18.8561     1324.
90  7 16    19.8317      1302.   19.8317     1285.
90  8  2    21.1028      1288.   20.8548     1222.
90  8 20    21.7995      1253.   21.4168     1162.
90  8 28    21.4168      1251.   21.3536     1123.
90  9 12    20.0681      1155.   19.7730     1013.
90  9 26    17.9253       895.   17.6069     1097.
90 10  9    14.8665       916.   14.0221      789.
90 10 23    11.3279       804.   10.9953      658.
90 11  5     6.2206       617.    5.6612      842.
90 11 23     2.2060       552.    1.5129      386.
90 12  4     1.1693       499.    0.9804      394.
90 12 18     0.1830       470.   -0.0233      370.
91  1  4    -0.0602       477.   -0.2056      379.
```

91	1	14	-0.1151	463.	-0.2235	354.
91	1	29	-0.0968	477.	-0.2056	379.
91	2	11	-0.1151	488.	-0.2056	372.
91	2	25	-0.1151	492.	-0.2414	409.
91	3	11	-0.0785	488.	-0.1876	401.
91	3	25	-0.0602	495.	-0.1695	408.
91	4	9	-0.0968	495.	-0.2056	416.
91	4	22	-0.2414	385.	-0.1514	527.
91	4	22	-0.1514	496.	-0.2414	416.
91	5	7	5.3056	721.	5.4689	633.
91	5	21	9.1203	883.	9.5543	777.
91	6	3	12.4441	983.	12.6037	871.
91	6	17	15.4208	1077.	15.3740	953.
91	7	10	18.1404	1173.	18.0864	1034.
91	7	15	18.0864	1147.	17.8186	1021.
91	7	30	19.5400	1217.	19.3095	1042.
91	8	12	20.0681	1213.	19.8905	1015.

Line 6: coefficients used in the conversion of thermistor readings into temperature [°C] by module PROC
Lines 7 and 8: correlation between thermistors and cells and coefficients for the conversion of cell readings into pressure [psi] by module PROC

```
Figure 7.13a   Borehole Extensometer, BA01
Movement [mm] since initial reading
BA01     1  BA01     2  BA01     3  BA01     2- BA01     3-
                                    BA01     1  BA01     2
Extensometer BA01 anchor 1 to anchor 2 (Alum.)
Extensometer BA01 anchor 2 to anchor 3 (Alum.)

Figure 7.13b   Borehole Extensometer, BA02
Movement [mm] since initial reading
BA02     1  BA02     2  BA02     2-
                        BA02     1
Extensometer BA02 anchor 1 to anchor 2 (Alum.)
********
********
```

Line 1: title for plot of several series
Line 2: label for y axis
Lines 3 and 4: code to indicate file and column of data, entry in line 4 when derived
(in this example, the first three series are columns from file BA01, series 4 and 5 are differences as indicated by their titles)
Lines 5 and 6: titles for derived series
Line 7: blank line separating plots (see Lines 13 and 14)
Lines 8 to 12: information for second plot
Line 13: asterisks to indicate new page
Line 14: asterisks to indicate end of plots

1993 8 21 input file: BA01

Extensometer BA01 collar to anchor 2 10.330 m (Alum.)

Abcissa(x) input, fit; Ordinate(y) input, fit; Group Code

83 12 22	83.97397	0.97397	0.00000	0.00000	1
84 1 18	84.04781	1.04781	0.17000	0.17000	1
84 1 24	84.06421	1.06421	0.34000	0.34000	1
84 1 31	84.08333	1.08333	0.36000	0.36000	1
84 2 8	84.10519	1.10519	0.29000	0.29000	1
84 2 14	84.12158	1.12158	0.39000	0.39000	1
84 2 22	84.14344	1.14344	0.36000	0.36000	1
84 2 27	84.15710	1.15710	0.54000	0.54000	1
84 3 6	84.17896	1.17896	0.41000	0.41000	1
84 3 12	84.19536	1.19536	0.46000	0.46000	1
84 3 20	84.21721	1.21721	0.51000	0.51000	1
84 3 26	84.23361	1.23361	0.53000	0.53000	1
84 4 2	84.25273	1.25273	0.57000	0.57000	1
84 4 9	84.27186	1.27186	0.57000	0.57000	1
84 4 25	84.31557	1.31557	0.63000	0.63000	1
84 4 30	84.32923	1.32923	0.70000	0.70000	1
84 5 8	84.35109	1.35109	0.63000	0.63000	1
84 5 10	84.35656	1.35656	0.78000	0.78000	1
84 5 16	84.37295	1.37295	0.73000	0.73000	1
84 5 21	84.38661	1.38661	0.71000	0.71000	1
84 5 28	84.40574	1.40574	0.71000	0.71000	1
84 6 5	84.42760	1.42760	0.71000	0.71000	1
84 6 8	84.43579	1.43579	0.72000	0.72000	1
84 6 11	84.44399	1.44399	0.73000	0.73000	1
84 6 18	84.46311	1.46311	0.67000	0.67000	1
84 6 21	84.47131	1.47131	0.68000	0.68000	1
84 6 25	84.48224	1.48224	0.69000	0.69000	1
84 7 2	84.50137	1.50137	0.66000	0.66000	1
84 7 9	84.52049	1.52049	0.54000	0.54000	1
84 7 16	84.53962	1.53962	0.47000	0.47000	1
84 7 24	84.56148	1.56148	0.41000	0.41000	1
84 7 30	84.57787	1.57787	0.36000	0.36000	1
84 8 7	84.59973	1.59973	0.29000	0.29000	1
84 8 13	84.61612	1.61612	0.24000	0.24000	1
84 8 20	84.63525	1.63525	0.21000	0.21000	1
84 8 27	84.65437	1.65437	0.16000	0.16000	1
84 9 4	84.67623	1.67623	0.09000	0.09000	1
84 9 10	84.69262	1.69262	0.04000	0.04000	1
84 9 17	84.71175	1.71175	0.02000	0.02000	1
84 10 1	84.75000	1.75000	0.02000	0.02000	1
84 10 9	84.77186	1.77186	0.05000	0.05000	1
84 10 15	84.78825	1.78825	0.10000	0.10000	1
84 10 22	84.80738	1.80738	-0.01000	-0.01000	1
84 10 29	84.82650	1.82650	0.04000	0.04000	1
84 11 5	84.84563	1.84563	-0.03000	-0.03000	1
84 11 11	84.86202	1.86202	-0.04000	-0.04000	1
84 11 19	84.88388	1.88388	-0.03000	-0.03000	1
84 11 27	84.90574	1.90574	-0.06000	-0.06000	1
84 12 3	84.92213	1.92213	-0.05000	-0.05000	1
84 12 10	84.94126	1.94126	0.00000	0.00000	1
84 12 17	84.96038	1.96038	0.00000	0.00000	1
84 12 25	84.98224	1.98224	-0.10000	-0.10000	1

1993 8 21 input file: BA01
Extensometer BA01 collar to anchor 2 10.330 m (Alum.)
Abcissa(x) input, fit; Ordinate(y) input, fit; Group Code

85	1	2	85.00411	2.00411	-0.03000	-0.03000	1
85	1	7	85.01781	2.01781	0.12000	0.12000	1
85	1	14	85.03699	2.03699	0.08000	0.08000	1
85	1	21	85.05616	2.05616	0.17000	0.17000	1
85	1	28	85.07534	2.07534	0.23000	0.23000	1
85	2	4	85.09452	2.09452	0.21000	0.21000	1
85	2	11	85.11370	2.11370	0.32000	0.32000	1
85	2	18	85.13288	2.13288	0.27000	0.27000	1
85	2	25	85.15205	2.15205	0.32000	0.32000	1
85	3	5	85.17397	2.17397	0.32000	0.32000	1
85	3	11	85.19041	2.19041	0.32000	0.32000	1
85	3	21	85.21781	2.21781	0.44000	0.44000	1
85	3	25	85.22877	2.22877	0.41000	0.41000	1
85	4	1	85.24795	2.24795	0.48000	0.48000	1
85	4	8	85.26712	2.26712	0.43000	0.43000	1
85	4	15	85.28630	2.28630	0.46000	0.46000	1
85	4	22	85.30548	2.30548	0.44000	0.44000	1
85	4	29	85.32466	2.32466	0.45000	0.45000	1
85	5	6	85.34384	2.34384	0.43000	0.43000	1
85	5	13	85.36301	2.36301	0.46000	0.46000	1
85	5	20	85.38219	2.38219	0.46000	0.46000	1
85	5	27	85.40137	2.40137	0.43000	0.43000	1
85	6	3	85.42055	2.42055	0.43000	0.43000	1
85	6	10	85.43973	2.43973	0.44000	0.44000	1
85	6	17	85.45890	2.45890	0.43000	0.43000	1
85	6	24	85.47808	2.47808	0.38000	0.38000	1
85	7	4	85.50548	2.50548	0.32000	0.32000	1
85	7	8	85.51644	2.51644	0.29000	0.29000	1
85	7	15	85.53562	2.53562	0.22000	0.22000	1
85	7	22	85.55479	2.55479	0.23000	0.23000	1
85	7	29	85.57397	2.57397	0.10000	0.10000	1
85	8	6	85.59589	2.59589	0.01000	0.01000	1
85	8	12	85.61233	2.61233	0.02000	0.02000	1
85	8	19	85.63151	2.63151	-0.04000	-0.04000	1
85	8	26	85.65068	2.65068	-0.04000	-0.04000	1
85	9	3	85.67260	2.67260	-0.09000	-0.09000	1
85	9	10	85.69178	2.69178	-0.12000	-0.12000	1
85	9	16	85.70822	2.70822	-0.23000	-0.23000	1
85	9	24	85.73014	2.73014	-0.22000	-0.22000	1
85	10	1	85.74932	2.74932	-0.22000	-0.22000	1
85	10	10	85.77397	2.77397	-0.23000	-0.23000	1
85	10	15	85.78767	2.78767	-0.29000	-0.29000	1
85	10	21	85.80411	2.80411	-0.29000	-0.29000	1
85	10	28	85.82329	2.82329	-0.29000	-0.29000	1
85	11	4	85.84247	2.84247	-0.30000	-0.30000	1
85	11	12	85.86438	2.86438	-0.29000	-0.29000	1
85	11	18	85.88082	2.88082	-0.29000	-0.29000	1
85	11	25	85.90000	2.90000	-0.29000	-0.29000	1
85	12	2	85.91918	2.91918	-0.29000	-0.29000	1
85	12	9	85.93836	2.93836	-0.29000	-0.29000	1
85	12	16	85.95753	2.95753	-0.29000	-0.29000	1

1993 8 21 input file: BA01

Extensometer BA01 collar to anchor 2 10.330 m (Alum.)

Abcissa(x) input, fit; Ordinate(y) input, fit; Group Code

85 12 23	85.97671	2.97671	-0.29000	-0.29000	1
85 12 27	85.98767	2.98767	-0.20000	-0.20000	1
86 1 1	86.00137	3.00137	-0.23000	-0.23000	1
86 1 6	86.01507	3.01507	-0.20000	-0.20000	1
86 1 13	86.03425	3.03425	-0.20000	-0.20000	1
86 1 22	86.05890	3.05890	-0.14000	-0.14000	1
86 2 1	86.08630	3.08630	-0.08000	-0.08000	1
86 2 10	86.11096	3.11096	0.03000	0.03000	1
86 2 18	86.13288	3.13288	0.03000	0.03000	1
86 2 26	86.15479	3.15479	0.11000	0.11000	1
86 3 3	86.16849	3.16849	0.12000	0.12000	1
86 3 11	86.19041	3.19041	0.12000	0.12000	1
86 3 18	86.20959	3.20959	0.14000	0.14000	1
86 3 24	86.22603	3.22603	0.22000	0.22000	1
86 4 1	86.24795	3.24795	0.20000	0.20000	1
86 4 11	86.27534	3.27534	0.22000	0.22000	1
86 4 14	86.28356	3.28356	0.22000	0.22000	1
86 4 21	86.30274	3.30274	0.24000	0.24000	1
86 4 28	86.32192	3.32192	0.23000	0.23000	1
86 5 7	86.34658	3.34658	0.22000	0.22000	1
86 5 12	86.36027	3.36027	0.22000	0.22000	1
86 5 20	86.38219	3.38219	0.23000	0.23000	1
86 5 26	86.39863	3.39863	0.21000	0.21000	1
86 6 2	86.41781	3.41781	0.25000	0.25000	1
86 6 20	86.46712	3.46712	0.20000	0.20000	1
86 6 23	86.47534	3.47534	0.20000	0.20000	1
86 7 2	86.50000	3.50000	0.13000	0.13000	1
86 7 7	86.51370	3.51370	0.09000	0.09000	1
86 7 14	86.53288	3.53288	0.03000	0.03000	1
86 7 21	86.55205	3.55205	0.02000	0.02000	1
86 7 28	86.57123	3.57123	-0.02000	-0.02000	1
86 8 5	86.59315	3.59315	-0.06000	-0.06000	1
86 8 11	86.60959	3.60959	-0.10000	-0.10000	1
86 8 18	86.62877	3.62877	-0.12000	-0.12000	1
86 8 25	86.64795	3.64795	-0.15000	-0.15000	1
86 9 2	86.66986	3.66986	-0.19000	-0.19000	1
86 9 8	86.68630	3.68630	-0.27000	-0.27000	1
86 9 15	86.70548	3.70548	-0.24000	-0.24000	1
86 9 22	86.72466	3.72466	-0.24000	-0.24000	1
86 9 29	86.74384	3.74384	-0.27000	-0.27000	1
86 10 6	86.76301	3.76301	-0.29000	-0.29000	1
86 10 14	86.78493	3.78493	-0.29000	-0.29000	1
86 10 20	86.80137	3.80137	-0.29000	-0.29000	1
86 10 27	86.82055	3.82055	-0.30000	-0.30000	1
86 11 3	86.83973	3.83973	-0.30000	-0.30000	1
86 11 10	86.85890	3.85890	-0.28000	-0.28000	1
86 11 17	86.87808	3.87808	-0.24000	-0.24000	1
86 11 24	86.89726	3.89726	-0.23000	-0.23000	1
86 12 1	86.91644	3.91644	-0.23000	-0.23000	1
86 12 8	86.93562	3.93562	-0.23000	-0.23000	1
86 12 15	86.95479	3.95479	-0.24000	-0.24000	1
86 12 22	86.97397	3.97397	-0.24000	-0.24000	1

1993 8 21 input file: BA01
Extensometer BA01 collar to anchor 2 10.330 m (Alum.)
Abcissa(x) input, fit; Ordinate(y) input, fit; Group Code

87	1	5	87.01233	4.01233	-0.16000	-0.16000	1
87	1	19	87.05068	4.05068	-0.15000	-0.15000	1
87	2	3	87.09178	4.09178	-0.19000	-0.19000	1
87	2	16	87.12740	4.12740	-0.21000	-0.21000	1
87	3	2	87.16575	4.16575	-0.23000	-0.23000	1
87	3	16	87.20411	4.20411	-0.19000	-0.19000	1
87	3	30	87.24247	4.24247	0.15000	0.15000	1
87	4	13	87.28082	4.28082	0.22000	0.22000	1
87	4	27	87.31918	4.31918	0.25000	0.25000	1
87	5	11	87.35753	4.35753	0.25000	0.25000	1
87	5	22	87.38767	4.38767	0.23000	0.23000	1
87	6	8	87.43425	4.43425	0.20000	0.20000	1
87	6	22	87.47260	4.47260	0.06000	0.06000	1
87	7	6	87.51096	4.51096	0.04000	0.04000	1
87	7	20	87.54932	4.54932	-0.08000	-0.08000	1
87	8	4	87.59041	4.59041	-0.16000	-0.16000	1
87	8	17	87.62603	4.62603	-0.31000	-0.31000	1
87	8	31	87.66438	4.66438	-0.31000	-0.31000	1
87	9	14	87.70274	4.70274	-0.38000	-0.38000	1
87	9	28	87.74110	4.74110	-0.40000	-0.40000	1
87	10	12	87.77945	4.77945	-0.45000	-0.45000	1
87	10	26	87.81781	4.81781	-0.51000	-0.51000	1
87	11	9	87.85616	4.85616	-0.47000	-0.47000	1
87	11	23	87.89452	4.89452	-0.28000	-0.28000	1
87	12	6	87.93014	4.93014	-0.48000	-0.48000	1
87	12	21	87.97123	4.97123	-0.52000	-0.52000	1
87	12	31	87.99863	4.99863	-0.51000	-0.51000	1
87	12	31	87.99863	4.99863	-0.51000	-0.51000	1
88	1	4	88.00956	5.00956	-0.55000	-0.55000	1
88	1	18	88.04781	5.04781	-0.43000	-0.43000	1
88	2	3	88.09153	5.09153	-0.43000	-0.43000	1
88	2	15	88.12432	5.12432	-0.38000	-0.38000	1
88	2	29	88.16257	5.16257	-0.31000	-0.31000	1
88	3	14	88.20082	5.20082	-0.21000	-0.21000	1
88	3	25	88.23087	5.23087	-0.17000	-0.17000	1
88	4	11	88.27732	5.27732	-0.14000	-0.14000	1
88	4	25	88.31557	5.31557	-0.15000	-0.15000	1
88	5	9	88.35383	5.35383	-0.17000	-0.17000	1
88	5	24	88.39481	5.39481	-0.13000	-0.13000	1
88	6	6	88.43033	5.43033	-0.16000	-0.16000	1
88	6	20	88.46858	5.46858	-0.22000	-0.22000	1
88	7	5	88.50956	5.50956	-0.24000	-0.24000	1
88	7	18	88.54508	5.54508	-0.42000	-0.42000	1
88	8	3	88.58880	5.58880	-0.51000	-0.51000	1
88	8	15	88.62158	5.62158	-0.61000	-0.61000	1
88	8	29	88.65984	5.65984	-0.66000	-0.66000	1
88	9	12	88.69809	5.69809	-0.72000	-0.72000	1
88	9	26	88.73634	5.73634	-0.73000	-0.73000	1
88	10	11	88.77732	5.77732	-0.76000	-0.76000	1
88	10	24	88.81284	5.81284	-0.79000	-0.79000	1
88	11	7	88.85109	5.85109	-0.78000	-0.78000	1
88	11	21	88.88934	5.88934	-0.84000	-0.84000	1

1993 8 21 input file: BA01

Extensometer BA01 collar to anchor 2 10.330 m (Alum.)

Abcissa(x) input, fit; Ordinate(y) input, fit; Group Code

88 12 5	88.92760	5.92760	-0.76000	-0.76000	1
88 12 19	88.96585	5.96585	-0.78000	-0.78000	1
89 1 3	89.00685	6.00685	-0.69000	-0.69000	1
89 1 16	89.04247	6.04247	-0.59000	-0.59000	1
89 1 30	89.08082	6.08082	-0.53000	-0.53000	1
89 2 13	89.11918	6.11918	-0.52000	-0.52000	1
89 2 27	89.15753	6.15753	-0.37000	-0.37000	1
89 3 14	89.19863	6.19863	-0.35000	-0.35000	1
89 3 28	89.23699	6.23699	-0.35000	-0.35000	1
89 4 10	89.27260	6.27260	-0.31000	-0.31000	1
89 4 24	89.31096	6.31096	-0.17000	-0.17000	1
89 5 8	89.34932	6.34932	-0.32000	-0.32000	1
89 5 23	89.39041	6.39041	-0.33000	-0.33000	1
89 7 17	89.54110	6.54110	-0.61000	-0.61000	1
89 8 15	89.62055	6.62055	-0.80000	-0.80000	1
89 8 28	89.65616	6.65616	-0.87000	-0.87000	1
89 9 11	89.69452	6.69452	-1.03000	-1.03000	1
89 9 25	89.73288	6.73288	-1.04000	-1.04000	1
89 10 23	89.80959	6.80959	-1.04000	-1.04000	1
89 11 9	89.85616	6.85616	-1.10000	-1.10000	1
89 11 20	89.88630	6.88630	-1.09000	-1.09000	1
89 12 4	89.92466	6.92466	-1.08000	-1.08000	1
89 12 18	89.96301	6.96301	-1.08000	-1.08000	1
90 1 2	90.00411	7.00411	-0.91000	-0.91000	1
90 1 9	90.02329	7.02329	-0.97000	-0.97000	1
90 1 29	90.07808	7.07808	-0.82000	-0.82000	1
90 2 13	90.11918	7.11918	-0.73000	-0.73000	1
90 3 5	90.17397	7.17397	-0.66000	-0.66000	1
90 3 26	90.23151	7.23151	-0.63000	-0.63000	1
90 4 17	90.29178	7.29178	-0.59000	-0.59000	1
90 5 7	90.34658	7.34658	-0.66000	-0.66000	1
90 5 30	90.40959	7.40959	-0.58000	-0.58000	1
90 6 14	90.45068	7.45068	-0.59000	-0.59000	1
90 7 9	90.51918	7.51918	-0.78000	-0.78000	1
90 8 8	90.60137	7.60137	-1.04000	-1.04000	1
90 8 13	90.61507	7.61507	-1.07000	-1.07000	1
90 9 13	90.70000	7.70000	-1.19000	-1.19000	1
90 11 14	90.86986	7.86986	-1.08000	-1.08000	1
90 12 4	90.92466	7.92466	-1.11000	-1.11000	1
90 12 20	90.96849	7.96849	-1.01000	-1.01000	1
91 1 17	91.04521	8.04521	-0.83000	-0.83000	1
91 1 29	91.07808	8.07808	-0.71000	-0.71000	1
91 1 29	91.07808	8.07808	-0.71000	-0.71000	1
91 2 13	91.11918	8.11918	-0.61000	-0.61000	1
91 2 26	91.15479	8.15479	-0.56000	-0.56000	1
91 3 27	91.23425	8.23425	-0.47000	-0.47000	1
91 4 10	91.27260	8.27260	-0.47000	-0.47000	1
91 5 14	91.36575	8.36575	-0.43000	-0.43000	1
91 5 22	91.38767	8.38767	-0.41000	-0.41000	1

Estimated Coefficients, Scaled Standard Deviations

1	-0.180703	0.008497
2	-0.254965	0.008584
3	-0.183966	0.003018
4	0.591484	0.013131

0.312507	0.008567	amplitude
5 6		mm,dd of Maximum

i,	X,	Y,		Y Residual,	Standardized Y Residual			
1	83	12	22	0.973973	0.000000	0.192504	13.778261	Reject ?
2	84	1	18	1.047814	0.170000	0.131563	9.611606	Reject ?
3	84	1	24	1.064208	0.340000	-0.010398	-0.763410	
4	84	1	31	1.083333	0.360000	0.003177	0.234601	
5	84	2	8	1.105191	0.290000	0.112028	8.330811	Reject ?
6	84	2	14	1.121585	0.390000	0.041039	3.067726	Reject ?
7	84	2	22	1.143443	0.360000	0.108907	8.197640	Reject ?
8	84	2	27	1.157104	0.540000	-0.048217	-3.645186	Reject ?
9	84	3	6	1.178962	0.410000	0.116577	8.874191	Reject ?
10	84	3	12	1.195355	0.460000	0.090832	6.949893	Reject ?
11	84	3	20	1.217213	0.510000	0.070169	5.405063	Reject ?
12	84	3	26	1.233607	0.530000	0.069576	5.385828	Reject ?
13	84	4	2	1.252732	0.570000	0.049053	3.818447	Reject ?
14	84	4	9	1.271858	0.570000	0.064809	5.072142	Reject ?
15	84	4	25	1.315574	0.630000	0.025455	2.014829	
16	84	4	30	1.329235	0.700000	-0.042743	-3.394033	Reject ?
17	84	5	8	1.351093	0.630000	0.025382	2.024922	
18	84	5	10	1.356557	0.780000	-0.126008	-10.063773	Reject ?
19	84	5	16	1.372951	0.730000	-0.082378	-6.599324	Reject ?
20	84	5	21	1.386612	0.710000	-0.070190	-5.635683	Reject ?
21	84	5	28	1.405738	0.710000	-0.084867	-6.832958	Reject ?
22	84	6	5	1.427596	0.710000	-0.106790	-8.619694	Reject ?
23	84	6	8	1.435792	0.720000	-0.126365	-10.207426	Reject ?
24	84	6	11	1.443989	0.730000	-0.146645	-11.853457	Reject ?
25	84	6	18	1.463115	0.670000	-0.113246	-9.164259	Reject ?
26	84	6	21	1.471312	0.680000	-0.135702	-10.985098	Reject ?
27	84	6	25	1.482240	0.690000	-0.163228	-13.217010	Reject ?
28	84	7	2	1.501366	0.660000	-0.166209	-13.459674	Reject ?
29	84	7	9	1.520492	0.540000	-0.081765	-6.618816	Reject ?
30	84	7	16	1.539618	0.470000	-0.049434	-3.998364	Reject ?
31	84	7	24	1.561475	0.410000	-0.034438	-2.781589	
32	84	7	30	1.577869	0.360000	-0.019116	-1.542017	
33	84	8	7	1.599727	0.290000	0.004051	0.326176	
34	84	8	13	1.616120	0.240000	0.018922	1.520975	
35	84	8	20	1.635246	0.210000	0.008433	0.676586	
36	84	8	27	1.654372	0.160000	0.018985	1.520556	
37	84	9	4	1.676230	0.090000	0.045842	3.664711	Reject ?
38	84	9	10	1.692623	0.040000	0.065266	5.211308	Reject ?
39	84	9	17	1.711749	0.020000	0.051956	4.144009	Reject ?
40	84	10	1	1.750000	0.020000	-0.005422	-0.432054	
41	84	10	9	1.771858	0.050000	-0.061782	-4.924262	Reject ?
42	84	10	15	1.788251	0.100000	-0.128144	-10.220348	Reject ?

```
i,   X,    Y,    Y Residual,   Standardized Y Residual

 43  84 10 22    1.807377   -0.010000   -0.033331   -2.661765
 44  84 10 29    1.826503    0.040000   -0.094158   -7.533009  Reject ?
 45  84 11  5    1.845628   -0.030000   -0.030518   -2.447367
 46  84 11 11    1.862022   -0.040000   -0.022383   -1.799356
 47  84 11 19    1.883880   -0.030000   -0.029743   -2.400205
 48  84 11 27    1.905738   -0.060000    0.008635    0.699917
 49  84 12  3    1.922131   -0.050000    0.008546    0.695302
 50  84 12 10    1.941257    0.000000   -0.026159   -2.138056
 51  84 12 17    1.960383    0.000000   -0.007107   -0.583740
 52  84 12 25    1.982240   -0.100000    0.118848    9.819605  Reject ?
 53  85  1  2    2.004110   -0.030000    0.078736    6.545477  Reject ?
 54  85  1  7    2.017808    0.120000   -0.050828   -4.242067  Reject ?
 55  85  1 14    2.036986    0.080000    0.019622    1.646728
 56  85  1 21    2.056164    0.170000   -0.038229   -3.226143  Reject ?
 57  85  1 28    2.075343    0.230000   -0.064899   -5.507061  Reject ?
 58  85  2  4    2.094521    0.210000   -0.010922   -0.931864
 59  85  2 11    2.113699    0.320000   -0.086843   -7.448665  Reject ?
 60  85  2 18    2.132877    0.270000   -0.003206   -0.276407
 61  85  2 25    2.152055    0.320000   -0.020551   -1.780662
 62  85  3  5    2.173973    0.320000    0.014895    1.297692
 63  85  3 11    2.190411    0.320000    0.039738    3.475575  Reject ?
 64  85  3 21    2.217808    0.440000   -0.043052   -3.788705  Reject ?
 65  85  3 25    2.228767    0.410000    0.000130    0.011432
 66  85  4  1    2.247945    0.480000   -0.049451   -4.378839  Reject ?
 67  85  4  8    2.267123    0.430000    0.017305    1.537857
 68  85  4 15    2.286301    0.460000    0.000103    0.009210
 69  85  4 22    2.305480    0.440000    0.028707    2.567231
 70  85  4 29    2.324658    0.450000    0.022941    2.056986
 71  85  5  6    2.343836    0.430000    0.042691    3.836730  Reject ?
 72  85  5 13    2.363014    0.460000    0.007911    0.712334
 73  85  5 20    2.382192    0.460000   -0.001382   -0.124585
 74  85  5 27    2.401370    0.430000    0.014897    1.344914
 75  85  6  3    2.420548    0.430000   -0.003105   -0.280482
 76  85  6 10    2.439726    0.440000   -0.035178   -3.178603  Reject ?
 77  85  6 17    2.458904    0.430000   -0.051053   -4.612053  Reject ?
 78  85  6 24    2.478082    0.380000   -0.030406   -2.745121
 79  85  7  4    2.505480    0.320000   -0.017620   -1.588299
 80  85  7  8    2.516438    0.290000   -0.008003   -0.720835
 81  85  7 15    2.535616    0.220000    0.024631    2.214766
 82  85  7 22    2.554795    0.230000   -0.024470   -2.196172
 83  85  7 29    2.573973    0.100000    0.065211    5.840794  Reject ?
 84  85  8  6    2.595890    0.010000    0.108324    9.679138  Reject ?
 85  85  8 12    2.612329    0.020000    0.063059    5.624594  Reject ?
.
.
.
```

Continues for the full 256 observations (total of 10 pages)

```
Estimated variance factor .. (     0.09634 )**2
Number of data ...............        256
Number of parameters .........          4
Degrees of freedom ...........        252
```

```
Inverted Pendulum Q  Unit 6  X profile zero at 34 m IPU6Q
Changes [mm] since base on 1990 06 08
X         34.00     IQ900608
IQ900718  IQ910118  IQ910215

Inverted Pendulum Q  Unit 6  Y profile zero at 34 m IPU6Q
Changes [mm] since base on 1990 06 08
Y         34.00     IQ900608
IQ900718  IQ910118  IQ910215
********
********
```

Line 1: title for plot of several series
Line 2: label for y axis
Line 3: choice of profile direction, depth for zero, base campaign
Line 4: subsequent campaigns for simultaneous plotting of differences in profiles with respect to base profile
Line 5: blank line separating plots (see lines 10 and 11)
Lines 6 to 9: information for second plot
Line 10: asterisks to indicate new page
Line 11: asterisks to indicate end of plots

```
Depth, profiles for
Powerhouse Unit 6       Inverted Pendulum Q + X         IPU6Q  IQ900608
Powerhouse Unit 6       Inverted Pendulum Q + Y         IPU6Q  IQ900608
```

0.00	3.48	1.32
1.00	0.37	-6.96
2.00	-2.14	-4.83
3.00	-4.79	-1.59
4.00	-5.15	-1.68
5.00	-4.13	-3.08
6.00	-1.97	-2.41
7.00	-1.57	-0.74
8.00	-0.48	-0.14
9.00	1.07	-1.03
10.00	2.92	-2.04
11.00	4.08	-2.37
12.00	3.54	-4.44
13.00	5.55	-5.48
14.00	7.82	-6.06
15.00	8.70	-5.20
16.00	10.16	-7.08
17.00	10.00	-9.22
18.00	8.60	-6.81
19.00	7.54	-5.70
20.00	6.24	-6.65
21.00	3.68	-7.29
22.00	2.39	-7.96
23.00	2.90	-6.83
24.00	2.56	-5.29
25.00	2.79	-4.09
26.00	3.33	-3.22
27.00	3.21	-3.76
28.00	3.65	-3.01
29.00	3.24	-1.15
30.00	5.98	-0.86
31.00	6.64	0.00
32.00	3.87	0.93
33.00	0.98*	4.16*
34.00	4.42	1.87

Depth, profiles for
Powerhouse Unit 6 Inverted Pendulum Q + X IPU6Q IQ910215
Powerhouse Unit 6 Inverted Pendulum Q + Y IPU6Q IQ910215

0.00	2.87	1.90
1.00	-0.07	-7.28
2.00	-2.60	-5.15
3.00	-5.42	-1.97
4.00	-5.70	-2.17
5.00	-4.64	-3.50
6.00	-2.72	-2.90
7.00	-2.21	-1.13
8.00	-1.09	-0.60
9.00	0.43	-1.59
10.00	2.35	-2.44
11.00	3.29	-2.83
12.00	2.85	-4.79
13.00	5.09	-5.80
14.00	7.09	-6.31
15.00	7.92	-5.40
16.00	9.39	-7.34
17.00	9.07	-9.42
18.00	7.70	-6.86
19.00	6.65	-5.94
20.00	5.25	-6.89
21.00	2.72	-7.57
22.00	1.65	-7.95
23.00	2.18	-6.68
24.00	1.82	-5.10
25.00	2.12	-3.90
26.00	2.70	-2.73
27.00	2.56	-3.47
28.00	3.03	-2.54
29.00	2.64	-1.11
30.00	5.30	-0.51
31.00	5.72	0.36
32.00	2.80	1.08
33.00	3.22	1.61
34.00	3.52	2.34

```
Profile Change from
Powerhouse Unit 6       Inverted Pendulum Q + Y        IPU6Q  IQ900608
to
Powerhouse Unit 6       Inverted Pendulum Q + Y        IPU6Q  IQ910215


 1   0.00   0.00
 2   1.00  -0.90
 3   2.00  -0.90
 4   3.00  -0.96
 5   4.00  -1.07
 6   5.00  -1.00
 7   6.00  -1.07
 8   7.00  -0.97
 9   8.00  -1.04
10   9.00  -1.14
11  10.00  -0.98
12  11.00  -1.04
13  12.00  -0.93
14  13.00  -0.90
15  14.00  -0.83
16  15.00  -0.78
17  16.00  -0.84
18  17.00  -0.78
19  18.00  -0.63
20  19.00  -0.82
21  20.00  -0.82
22  21.00  -0.86
23  22.00  -0.57
24  23.00  -0.43
25  24.00  -0.39
26  25.00  -0.39
27  26.00  -0.09
28  27.00  -0.29
29  28.00  -0.11
30  29.00  -0.54
31  30.00  -0.23
32  31.00  -0.22
33  32.00  -0.43
34  33.00  -3.13
35  34.00  -0.11
```

```
Profile Change from
Powerhouse Unit 6        Inverted Pendulum Q + Y        IPU6Q   IQ900608
to
Powerhouse Unit 6        Inverted Pendulum Q + Y        IPU6Q   IQ910215


 1    1.00  -0.90
 2    2.00  -0.90
 3    3.00  -0.96
 4    4.00  -1.07
 5    5.00  -1.00
 6    6.00  -1.07
 7    7.00  -0.97
 8    8.00  -1.04
 9    9.00  -1.14
10   10.00  -0.98
11   11.00  -1.04
12   12.00  -0.93
13   13.00  -0.90
14   14.00  -0.83
15   15.00  -0.78
16   16.00  -0.84
17   17.00  -0.78
18   18.00  -0.63
19   19.00  -0.82
20   20.00  -0.82
21   21.00  -0.86
22   22.00  -0.57
23   23.00  -0.43
24   24.00  -0.39
25   25.00  -0.39
26   26.00  -0.09
27   27.00  -0.29
28   28.00  -0.11
29   29.00  -0.54
30   30.00  -0.23
31   31.00  -0.22
32   32.00  -0.43
33   33.00  -3.13
34   34.00  -0.11
```

```
Estimated Coefficients, Scaled Standard Deviations

slope          0.015650 +/-     0.008899
intercept     -1.044171 +/-     0.178531



i       Xi        Fitted Yi   Residual

  1     1.000000   -0.900000   -0.128521
  2     2.000000   -0.900000   -0.112871
  3     3.000000   -0.960000   -0.037221
  4     4.000000   -1.070000    0.088429
  5     5.000000   -1.000000    0.034079
  6     6.000000   -1.070000    0.119729
  7     7.000000   -0.970000    0.035380
  8     8.000000   -1.040000    0.121030
  9     9.000000   -1.140000    0.236680
 10    10.000000   -0.980000    0.092330
 11    11.000000   -1.040000    0.167980
 12    12.000000   -0.930000    0.073630
 13    13.000000   -0.900000    0.059280
 14    14.000000   -0.830000    0.004930
 15    15.000000   -0.780000   -0.029419
 16    16.000000   -0.840000    0.046231
 17    17.000000   -0.780000    0.001881
 18    18.000000   -0.630000   -0.132469
 19    19.000000   -0.820000    0.073181
 20    20.000000   -0.820000    0.088831
 21    21.000000   -0.860000    0.144481
 22    22.000000   -0.570000   -0.129869
 23    23.000000   -0.430000   -0.254219
 24    24.000000   -0.390000   -0.278568
 25    25.000000   -0.390000   -0.262918
 26    26.000000   -0.090000   -0.547268
 27    27.000000   -0.290000   -0.331618
 28    28.000000   -0.110000   -0.495968
 29    29.000000   -0.540000   -0.050318
 30    30.000000   -0.230000   -0.344668
 31    31.000000   -0.220000   -0.339018
 32    32.000000   -0.430000   -0.113367
 33    33.000000   -3.130000    2.602283
 34    34.000000   -0.110000   -0.402067

Estimated variance factor .. (     0.50906 )**2,  (assumed to be 1.000 a
priori)
Number of data ...............          34
Number of parameters .........           2
Degrees of freedom ...........          32
```

```
Profile Change from
Powerhouse Unit 6       Inverted Pendulum Q + Y       IPU6Q  IQ900608
to
Powerhouse Unit 6       Inverted Pendulum Q + Y       IPU6Q  IQ910215
```

1	0.00	0.00
2	1.00	-0.90
3	2.00	-0.90
4	3.00	-0.96
5	4.00	-1.07
6	5.00	-1.00
7	6.00	-1.07
8	7.00	-0.97
9	8.00	-1.04
10	9.00	-1.14
11	10.00	-0.98
12	11.00	-1.04
13	12.00	-0.93
14	13.00	-0.90
15	14.00	-0.83
16	15.00	-0.78
17	16.00	-0.84
18	17.00	-0.78
19	18.00	-0.63
20	19.00	-0.82
21	20.00	-0.82
22	21.00	-0.86
23	22.00	-0.57
24	23.00	-0.43
25	24.00	-0.39
26	25.00	-0.39
27	26.00	-0.09
28	27.00	-0.29
29	28.00	-0.11
30	29.00	-0.54
31	30.00	-0.23
32	31.00	-0.22
33	32.00	-0.43
35	34.00	-0.11

Data point number 34, at depth 33.00, has been excluded

```
Profile Change from
Powerhouse Unit 6       Inverted Pendulum Q + Y         IPU6Q  IQ900608
to
Powerhouse Unit 6       Inverted Pendulum Q + Y         IPU6Q  IQ910215


 1   1.00  -0.90
 2   2.00  -0.90
 3   3.00  -0.96
 4   4.00  -1.07
 5   5.00  -1.00
 6   6.00  -1.07
 7   7.00  -0.97
 8   8.00  -1.04
 9   9.00  -1.14
10  10.00  -0.98
11  11.00  -1.04
12  12.00  -0.93
13  13.00  -0.90
14  14.00  -0.83
15  15.00  -0.78
16  16.00  -0.84
17  17.00  -0.78
18  18.00  -0.63
19  19.00  -0.82
20  20.00  -0.82
21  21.00  -0.86
22  22.00  -0.57
23  23.00  -0.43
24  24.00  -0.39
25  25.00  -0.39
26  26.00  -0.09
27  27.00  -0.29
28  28.00  -0.11
29  29.00  -0.54
30  30.00  -0.23
31  31.00  -0.22
32  32.00  -0.43
33  34.00  -0.11
```

```
Estimated Coefficients, Scaled Standard Deviations

slope          0.029388 +/-     0.002818
intercept     -1.199280 +/-     0.055052


i       Xi        Fitted Yi   Residual

  1    1.000000   -0.900000   -0.269892
  2    2.000000   -0.900000   -0.240503
  3    3.000000   -0.960000   -0.151115
  4    4.000000   -1.070000   -0.011727
  5    5.000000   -1.000000   -0.052338
  6    6.000000   -1.070000    0.047050
  7    7.000000   -0.970000   -0.023562
  8    8.000000   -1.040000    0.075827
  9    9.000000   -1.140000    0.205215
 10   10.000000   -0.980000    0.074603
 11   11.000000   -1.040000    0.163992
 12   12.000000   -0.930000    0.083380
 13   13.000000   -0.900000    0.082768
 14   14.000000   -0.830000    0.042157
 15   15.000000   -0.780000    0.021545
 16   16.000000   -0.840000    0.110933
 17   17.000000   -0.780000    0.080321
 18   18.000000   -0.630000   -0.040290
 19   19.000000   -0.820000    0.179098
 20   20.000000   -0.820000    0.208486
 21   21.000000   -0.860000    0.277875
 22   22.000000   -0.570000    0.017263
 23   23.000000   -0.430000   -0.093349
 24   24.000000   -0.390000   -0.103960
 25   25.000000   -0.390000   -0.074572
 26   26.000000   -0.090000   -0.345184
 27   27.000000   -0.290000   -0.115795
 28   28.000000   -0.110000   -0.266407
 29   29.000000   -0.540000    0.192981
 30   30.000000   -0.230000   -0.087630
 31   31.000000   -0.220000   -0.068242
 32   32.000000   -0.430000    0.171146
 33   34.000000   -0.110000   -0.090077

Estimated variance factor .. (    0.15498 )**2,  (assumed to be 1.000 a
priori)
Number of data ..............          33
Number of parameters .........          2
Degrees of freedom ...........         31
```

III. DEFORMATION MODELLING EXAMPLE USING OBSMOD

```
POWERHOUSE GENERAL CROSS-SECTION WITH ROTATION,    TO 1991 12        PH91M1
Y Z  3  5 1 1 0.050 0
1113142296
 0 0 0 0 0
 1 1 1 1 0
 1 1 1 1 1
X Y Z
(I5,A10,F15.8,F15.8,F15.8,2X,I3)
     TA-4       1029.928        1011.218          11.819      2        #
     TA-5       1029.852         986.585          11.815      3
     TA-6       1029.358         986.115          11.756      3
     TA-7       1029.329         974.767          11.652      3
     TA-8       1030.759        1009.988           6.337      2
     TA-9       1030.763         981.081           6.404      3
     TF-1       1045.200         986.130          -3.340      3
     TF-2       1045.220         981.460          -3.350      3
     TF-3       1045.220         986.040           4.230      3
     TF-4       1045.180         981.390           4.270      3
     TG-1       1029.402         992.402          -3.441      2
     TG-2       1029.459         981.439          -3.440      3
     JM-2.2     1015.798         987.540           5.406      2
     JM-2.3     1015.798         987.530           5.406      3
     PPT08:T    1045.31          986.00            6.54       3
     PPT08:B    1045.31          986.00           -2.33       3
     PPH-C:T    1031.490        1002.89            5.120      3
     PPH-C:B    1031.490        1002.89           -6.30       3
     PPS-C:T    1030.000         987.68            3.20       3
     PPS-C:B    1030.000         987.68           -6.76       3
     PPTR0      1031.794        982.244           12.650      3
     BA-4:C     1026.71         1009.67           -8.78       2
     BA-4:1     1026.71         1016.33          -11.886      2
     BA-5:C     1027.095        1005.666          -9.077      2
     BA-5:1     1027.095        1000.032         -19.672      1
     BA-6:C     1030.741         982.533          -3.529      3
     BA-6:1     1030.741         982.533         -21.870      2
     BA-7:C     1031.833         992.483          -8.651      2
     BA-7:2     1031.833         976.113         -18.101      2
     BA-8:C     1030.121         984.065          -3.718      3
     BA-8:2     1030.121         992.055         -20.838      2
     BA-11:C    1030.87          980.30           11.27       3
     BA-11:2    1030.87          980.30           -3.03       3
     BA-11:5    1030.87          980.30          -18.23       2
     BA-12:C    1030.87          975.80           11.13       3
     BA-12:4    1030.87          975.80          -14.67       2
     BA-13:C    1031.05          981.74           10.27       3
     BA-13:2    1031.05          975.04           10.27       3
     BA-15:C    1014.40          983.50           -3.62       3
     BA-15:4    1014.40          976.93          -15.98       2
     BA-16:C    1010.00         1005.20           -7.62       2
     BA-16:4    1010.00          987.40           -7.62       3
```

```
      BA-16:6     1010.00           978.70            -7.62      3
      BA-17:C     1030.55           981.41            -2.28      3
      BA-17:1     1030.55           975.81            -2.28      3
      BI-2:C      1006.48          1005.56            -9.115     2
      G20         1015.23          1010.25            11.23      2
      G21         1015.23           987.41            11.24      3
      T40         1009.65          1009.24             5.28      2
      T41         1009.67           987.79             5.30      2
      T43         1009.66           981.49             5.31      3
      TR1         1055.04           981.20            11.37      3
      TR4          978.52           974.77            11.46      3
      2901        1027.37          1009.56            -8.91      2
      2902        1031.39           992.52            -8.80      2
      2911        1015.70          1005.28            -8.12      2
      INVPB       1031.77           982.62            -2.68      3
      CTRAUX      1030.121          987.60            -8.70      0
      CTR         1030.0           1012.70           -19.10      0
      ORIGIN      1030.            1012.70           -19.10      0
-9
(I5,2X,3(A10,1X),2F10.6)
   11  BA-5:1                             0.00020   0.00000        ##
   12  BA-5:1                             0.00020   0.00000
   12  BI-2:C                             0.00020   0.00140
   11  BA-4:C                             0.00020   0.00000
   11  INVPB                              0.00020   0.00240
   12  INVPB                              0.00020   0.00220
   12  G20                                0.00020   0.00320
   12  G21                                0.00020   0.00300
   12  T40                                0.00020   0.00280
   12  T41                                0.00020   0.00280
   12  T43                                0.00020   0.00300
   11  TR1                                0.00060   0.00320
   12  TR1                                0.00020   0.00360
   11  TR4                                0.00070   0.00430
   12  TR4                                0.00020   0.00210
   12  TG-1                               0.00020   0.00200
   12  TF-1                               0.00020   0.00200
   12  TF-2                               0.00020   0.00160
   12  2901                               0.00020   0.00070
   12  2902                               0.00020   0.00150
   12  2911                               0.00020   0.00180
   11  PPTR0                              0.00040   0.00370
   21  TA-4       TA-5                    0.00020   0.00370
   21  TA-6       TA-7                    0.00020   0.00290
   21  TA-8       TA-9                    0.00020   0.00390
   21  TG-1       TG-2                    0.00020   0.00140
   21  TF-1       TF-4                    0.00020   0.00130
   21  TF-3       TF-4                    0.00020   0.00030
   21  TF-1       TF-2                    0.00020   0.00050
   21  JM-2.2     JM-2.3                  0.00020   0.00140
```

```
   31  PPH-C:T    PPH-C:B                   0.00030   0.00040
   31  PPS-C:T    PPS-C:B                   0.00030   0.00140
   31  PPT08:T    PPT08:B                   0.00030   0.00150
   22  BA-4:C     BA-4:1                    0.00020   0.00040
   22  BA-5:C     BA-5:1                    0.00020   0.00090
   22  BA-6:C     BA-6:1                    0.00020   0.00140
   22  BA-7:C     BA-7:2                    0.00020   0.00080
   22  BA-8:C     BA-8:2                    0.00020   0.00220
   22  BA-11:C    BA-11:2                   0.00020   0.00180
   22  BA-11:2    BA-11:5                   0.00020   0.00140
   22  BA-12:C    BA-12:4                   0.00030   0.00230
   22  BA-13:C    BA-13:2                   0.00020   0.00110
   22  BA-15:C    BA-15:4                   0.00030   0.00110
   22  BA-16:C    BA-16:4                   0.00020   0.00110
   22  BA-16:4    BA-16:6                   0.00020   0.00070
   22  BA-17:C    BA-17:1                   0.00020   0.00050
-9
(I5,A10,F15.8,F15.8,F15.8,2X,I3)
     DP1        1030.0          974.77          11.65      3      ###
     DP2        1030.0          971.0            9.75      3
     DP3        1030.0          970.85          -4.7       3
     DP4        1030.0          975.2           -6.9       3
     DP5        1030.0          975.25         -16.25      3
     DP6        1030.0          987.45         -18.85      3
     DP7        1030.0         1011.5           -9.6       2
     DP8        1030.0         1011.6           11.3       2
     DP9        1030.0          992.75          11.1       2
     DP10A      1030.0          987.80           5.33      2
     DP10B      1030.0          987.80           5.33      3
     DP11A      1030.0          987.80          -8.28      2
     DP11B      1030.0          987.80          -8.28      3
     DP12       1030.0          980.00         -15.00      3
     DP13       1030.0          980.00         -10.00      3
     DP14       1030.0          980.00          -5.00      3
     DP15       1030.0          980.00           0.00      3
     DP16       1030.0          981.08           5.33      3
     DP17       1030.0          981.08          10.75      3
     DP18       1030.0          986.05          10.75      3
     DP19       1030.0          986.05           5.33      3
     DP20       1030.0          986.05           0.00      3
     DP21       1030.0          985.00          -5.00      3
     DP22       1030.0          985.00         -10.00      3
     DP23       1030.0          985.00         -15.00      3
     DP24       1030.0          995.00         -15.00      3
     DP25       1030.0          995.00         -10.00      3
     DP26       1030.0          995.00          -5.00      3
     DP27       1030.0          995.00           0.00      3
     DP28       1030.0          995.00           5.00      3
     DP29       1030.0          995.00          11.30      3
     DP30       1030.0         1000.00          11.30      3
```

```
       DP31       1030.0          1000.00          5.00       3
       DP32       1030.0          1000.00          0.00       3
       DP33       1030.0          1000.00         -5.00       3
       DP34       1030.0          1000.00        -10.00       3
       DP35       1030.0          1000.00        -15.00       3
       DP36       1030.0          1005.00        -10.00       3
       DP37       1030.0          1005.00         -5.00       3
       DP38       1030.0          1005.00          0.00       3
       DP39       1030.0          1005.00          5.00       3
       DP40       1030.0          1005.00         11.30       3
       DP41       1030.0          1011.6          -5.00       3
       DP42       1030.0          1011.6           0.00       3
       DP43       1030.0          1011.6           5.00       3
       DP44       1030.0           986.05          4.50       3
       DP45       1030.0           981.42          4.50       3
       DP46       1030.0           981.42         -3.72       3
       DP47       1030.0           986.05         -3.72       3
-9
//
```

Lines 3 to 6: model choice
line 3: parameter codes: 11:"a_1x", 13:"a_3xy", 14:"a_4x^2", 22:"b_2y", 96:"$-\omega(y-y_c)$" and "$\omega(x-x_c)$"
line 4: zone 1 ("stable" points)
line 5: zone 2
line 6: zone 3 (with rotation about point CTR (x_c,y_c))
Parameters can be added or removed by altering the contents of these lines. Many other choices for the coefficients of the dx and dy expressions are possible with OBSMOD

Line with # at end to line containing "-9"
Stations with x,y,z from MSXYZ file and zone code

Line with ## at end to line containing "-9"
Observations with code, names of stations involved, standard deviation, value of observation
Code 11: absolute horizontal displacement
Code 12: absolute vertical displacement
Code 21: tape extensometer
Code 22: borehole or rod extensometer
Code 31: relative horizontal table movement (suspended pendulum)

Line with ### at end to line containing "-9"
Points creating the array for which the displacement and strain fields are generated with coordinates in the same system as MCXYZ

1992 02 11 08:26:07
POWERHOUSE GENERAL CROSS-SECTION WITH ROTATION, TO 1991 12 PH91M1

DEFORMATION MODEL WITH 3 ZONES AND 5 PARAMETERS
WITH 1 AUXILIARY CENTRES OF ROTATION

TESTING AT ALPHA LEVEL OF 0.05000

	11	13	14	22	96
1	0	0	0	0	0
2	1	1	1	1	0
3	1	1	1	1	1

STATIONS, X, Y, Z, ZONE CODE

TA-4	1029.9280	1011.2180	11.8190	2
TA-5	1029.8520	986.5850	11.8150	3
TA-6	1029.3580	986.1150	11.7560	3
TA-7	1029.3290	974.7670	11.6520	3
TA-8	1030.7590	1009.9880	6.3370	2
TA-9	1030.7630	981.0810	6.4040	3
TF-1	1045.2000	986.1300	-3.3400	3
TF-2	1045.2200	981.4600	-3.3500	3
TF-3	1045.2200	986.0400	4.2300	3
TF-4	1045.1800	981.3900	4.2700	3
TG-1	1029.4020	992.4020	-3.4410	2
TG-2	1029.4590	981.4390	-3.4400	3
JM-2.2	1015.7980	987.5400	5.4060	2
JM-2.3	1015.7980	987.5300	5.4060	3
PPT08:T	1045.3100	986.0000	6.5400	3
PPT08:B	1045.3100	986.0000	-2.3300	3
PPH-C:T	1031.4900	1002.8900	5.1200	3
PPH-C:B	1031.4900	1002.8900	-6.3000	3
PPS-C:T	1030.0000	987.6800	3.2000	3
PPS-C:B	1030.0000	987.6800	-6.7600	3
PPTR0	1031.7940	982.2440	12.6500	3
BA-4:C	1026.7100	1009.6700	-8.7800	2
BA-4:1	1026.7100	1016.3300	-11.8860	2
BA-5:C	1027.0950	1005.6660	-9.0770	2
BA-5:1	1027.0950	1000.0320	-19.6720	1
BA-6:C	1030.7410	982.5330	-3.5290	3
BA-6:1	1030.7410	982.5330	-21.8700	2
BA-7:C	1031.8330	992.4830	-8.6510	2
BA-7:2	1031.8330	976.1130	-18.1010	2
BA-8:C	1030.1210	984.0650	-3.7180	3
BA-8:2	1030.1210	992.0550	-20.8380	2
BA-11:C	1030.8700	980.3000	11.2700	3

BA-11:2	1030.8700	980.3000	-3.0300	3
BA-11:5	1030.8700	980.3000	-18.2300	2
BA-12:C	1030.8700	975.8000	11.1300	3
BA-12:4	1030.8700	975.8000	-14.6700	2
BA-13:C	1031.0500	981.7400	10.2700	3
BA-13:2	1031.0500	975.0400	10.2700	3
BA-15:C	1014.4000	983.5000	-3.6200	3
BA-15:4	1014.4000	976.9300	-15.9800	2
BA-16:C	1010.0000	1005.2000	-7.6200	2
BA-16:4	1010.0000	987.4000	-7.6200	3
BA-16:6	1010.0000	978.7000	-7.6200	3
BA-17:C	1030.5500	981.4100	-2.2800	3
BA-17:1	1030.5500	975.8100	-2.2800	3
BI-2:C	1006.4800	1005.5600	-9.1150	2
G20	1015.2300	1010.2500	11.2300	2
G21	1015.2300	987.4100	11.2400	3
T40	1009.6500	1009.2400	5.2800	2
T41	1009.6700	987.7900	5.3000	2
T43	1009.6600	981.4900	5.3100	3
TR1	1055.0400	981.2000	11.3700	3
TR4	978.5200	974.7700	11.4600	3
2901	1027.3700	1009.5600	-8.9100	2
2902	1031.3900	992.5200	-8.8000	2
2911	1015.7000	1005.2800	-8.1200	2
INVPB	1031.7700	982.6200	-2.6800	3
CTRAUX	1030.1210	987.6000	-8.7000	0
CTR	1030.0000	1012.7000	-19.1000	0
ORIGIN	1030.0000	1012.7000	-19.1000	0

STATIONS, Y AS X, Z AS Y, ZONE CODE

TA-4	1.482000	30.919000	2
TA-5	26.115000	30.915000	3
TA-6	26.585000	30.856000	3
TA-7	37.933000	30.752000	3
TA-8	2.712000	25.437000	2
TA-9	31.619000	25.504000	3
TF-1	26.570000	15.760000	3
TF-2	31.240000	15.750000	3
TF-3	26.660000	23.330000	3
TF-4	31.310000	23.370000	3
TG-1	20.298000	15.659000	2
TG-2	31.261000	15.660000	3
JM-2.2	25.160000	24.506000	2
JM-2.3	25.170000	24.506000	3
PPT08:T	26.700000	25.640000	3
PPT08:B	26.700000	16.770000	3

PPH-C:T	9.810000	24.220000	3
PPH-C:B	9.810000	12.800000	3
PPS-C:T	25.020000	22.300000	3
PPS-C:B	25.020000	12.340000	3
PPTR0	30.456000	31.750000	3
BA-4:C	3.030000	10.320000	2
BA-4:1	-3.630000	7.214000	2
BA-5:C	7.034000	10.023000	2
BA-5:1	12.668000	-0.572000	1
BA-6:C	30.167000	15.571000	3
BA-6:1	30.167000	-2.770000	2
BA-7:C	20.217000	10.449000	2
BA-7:2	36.587000	0.999000	2
BA-8:C	28.635000	15.382000	3
BA-8:2	20.645000	-1.738000	2
BA-11:C	32.400000	30.370000	3
BA-11:2	32.400000	16.070000	3
BA-11:5	32.400000	0.870000	2
BA-12:C	36.900000	30.230000	3
BA-12:4	36.900000	4.430000	2
BA-13:C	30.960000	29.370000	3
BA-13:2	37.660000	29.370000	3
BA-15:C	29.200000	15.480000	3
BA-15:4	35.770000	3.120000	2
BA-16:C	7.500000	11.480000	2
BA-16:4	25.300000	11.480000	3
BA-16:6	34.000000	11.480000	3
BA-17:C	31.290000	16.820000	3
BA-17:1	36.890000	16.820000	3
BI-2:C	7.140000	9.985000	2
G20	2.450000	30.330000	2
G21	25.290000	30.340000	3
T40	3.460000	24.380000	2
T41	24.910000	24.400000	2
T43	31.210000	24.410000	3
TR1	31.500000	30.470000	3
TR4	37.930000	30.560000	3
2901	3.140000	10.190000	2
2902	20.180000	10.300000	2
2911	7.420000	10.980000	2
INVPB	30.080000	16.420000	3
CTRAUX	25.100000	10.400000	0

The x,y,z coordinates from MCXYZ have been transformed into x,y in the plane of the section so that y is positive upward and x is positive to the right.

OBSERVATION CODE, STATIONS, STANDARD DEVIATION, OBSERVATION

11	BA-5:1		0.000200	0.000000
12	BA-5:1		0.000200	0.000000
12	BI-2:C		0.000200	0.001400
11	BA-4:C		0.000200	0.000000
11	INVPB		0.000200	0.002400
12	INVPB		0.000200	0.002200
12	G20		0.000200	0.003200
12	G21		0.000200	0.003000
12	T40		0.000200	0.002800
12	T41		0.000200	0.002800
12	T43		0.000200	0.003000
11	TR1		0.000600	0.003200
12	TR1		0.000200	0.003600
11	TR4		0.000700	0.004300
12	TR4		0.000200	0.002100
12	TG-1		0.000200	0.002000
12	TF-1		0.000200	0.002000
12	TF-2		0.000200	0.001600
12	2901		0.000200	0.000700
12	2902		0.000200	0.001500
12	2911		0.000200	0.001800
11	PPTR0		0.000400	0.003700
21	TA-4	TA-5	0.000200	0.003700
21	TA-6	TA-7	0.000200	0.002900
21	TA-8	TA-9	0.000200	0.003900
21	TG-1	TG-2	0.000200	0.001400
21	TF-1	TF-4	0.000200	0.001300
21	TF-3	TF-4	0.000200	0.000300
21	TF-1	TF-2	0.000200	0.000500
21	JM-2.2	JM-2.3	0.000200	0.001400
31	PPH-C:T	PPH-C:B	0.000300	0.000400
31	PPS-C:T	PPS-C:B	0.000300	0.001400
31	PPT08:T	PPT08:B	0.000300	0.001500
22	BA-4:C	BA-4:1	0.000200	0.000400
22	BA-5:C	BA-5:1	0.000200	0.000900
22	BA-6:C	BA-6:1	0.000200	0.001400
22	BA-7:C	BA-7:2	0.000200	0.000800
22	BA-8:C	BA-8:2	0.000200	0.002200
22	BA-11:C	BA-11:2	0.000200	0.001800
22	BA-11:2	BA-11:5	0.000200	0.001400
22	BA-12:C	BA-12:4	0.000300	0.002300
22	BA-13:C	BA-13:2	0.000200	0.001100
22	BA-15:C	BA-15:4	0.000300	0.001100
22	BA-16:C	BA-16:4	0.000200	0.001100
22	BA-16:4	BA-16:6	0.000200	0.000700
22	BA-17:C	BA-17:1	0.000200	0.000500

ESTIMATED DEFORMATION COMPONENTS, UNSCALED STD. DEV. AND STANDARDIZED PARAMETERS

```
2       A1      -0.4011332380D-04   +/-  0.1187791571D-04          1.8914

3       A1      -0.4011332380D-04   +/-  0.1187791571D-04          1.8914

2       A3       0.2730961701D-05   +/-  0.3300405079D-06          4.6344

3       A3       0.2730961701D-05   +/-  0.3300405079D-06          4.6344

2       A4       0.1912473689D-05   +/-  0.2634030189D-06          4.0665

3       A4       0.1912473689D-05   +/-  0.2634030189D-06          4.0665

2       B2       0.1157862243D-03   +/-  0.2546275172D-05         25.4679

3       B2       0.1157862243D-03   +/-  0.2546275172D-05         25.4679

3       OMEGA2  -0.6191920230D-04   +/-  0.8169028197D-05          4.2452
```

VARIANCE-COVARIANCE MATRIX FOR ESTIMATED DEFORMATION COMPONENTS (NOT MULTIPLIED BY 3.1879936967)

```
    1  1.4108D-10 -1.9778D-12 -2.6122D-12 -3.3580D-13  7.9962D-12
    2 -1.9778D-12  1.0893D-13  6.7924D-15 -2.0970D-13  1.2788D-12
    3 -2.6122D-12  6.7924D-15  6.9381D-14  1.7196D-14 -2.8997D-13
    4 -3.3580D-13 -2.0970D-13  1.7196D-14  6.4835D-12 -1.0734D-11
    5  7.9962D-12  1.2788D-12 -2.8997D-13 -1.0734D-11  6.6733D-11
```

Parameters are repeated for each zone in which they are considered.
"OMEGA2" ("ω") is only in zone 3. The other parameters are in both zones 2 and 3.
Zone 1 contains the stable points and therefore does not have any parameters since $dx = 0$ and $dy = 0$ comprise its model.

```
CODE, STATIONS, OBSERVATION RESIDUAL,  SCALED STANDARDIZED RESIDUAL
ESTIMATED VARIANCE FACTOR     3.1879936967
VARIANCE FACTOR  A PRIORI     1.0000000000

  11  BA-5:1                          0.000000      0.000000
  12  BA-5:1                          0.000000      0.000000
  12  BI-2:C                         -0.000244     -0.677480
  11  BA-4:C                         -0.000019     -0.051485
  11  INVPB                          -0.000155     -0.382542
  12  INVPB                          -0.000607     -1.666253
  12  G20                             0.000312      0.814520
  12  G21                             0.000501      1.310957
  12  T40                             0.000023      0.061160
  12  T41                             0.000025      0.067349
  12  T43                            -0.000552     -1.488213
  11  TR1                             0.001298      1.182798
  12  TR1                            -0.000468     -1.242341
  11  TR4                             0.001344      1.045177
  12  TR4                             0.000644      1.635730
  12  TG-1                           -0.000187     -0.513293
  12  TF-1                           -0.000266     -0.734089
  12  TF-2                           -0.000157     -0.427587
  12  2901                            0.000480      1.332610
  12  2902                           -0.000307     -0.853524
  12  2911                           -0.000529     -1.466193
  11  PPTR0                           0.000815      1.078244
  21  TA-4      TA-5                 -0.000038     -0.091421
  21  TA-6      TA-7                 -0.001009     -2.457898
  21  TA-8      TA-9                 -0.000213     -0.536453
  21  TG-1      TG-2                  0.000036      0.095442
  21  TF-1      TF-4                  0.000077      0.209645
  21  TF-3      TF-4                  0.000329      0.906557
  21  TF-1      TF-2                  0.000029      0.080530
  21  JM-2.2    JM-2.3               -0.000525     -1.274770
  31  PPH-C:T   PPH-C:B              -0.000118     -0.213551
  31  PPS-C:T   PPS-C:B              -0.000243     -0.420663
  31  PPT08:T   PPT08:B               0.000410      0.723237
  22  BA-4:C    BA-4:1               -0.000355     -0.944401
  22  BA-5:C    BA-5:1                0.000122      0.336204
  22  BA-6:C    BA-6:1                0.000410      1.121518
  22  BA-7:C    BA-7:2                0.000305      0.678272
  22  BA-8:C    BA-8:2                0.000261      0.703601
  22  BA-11:C   BA-11:2              -0.000144     -0.397436
  22  BA-11:2   BA-11:5              -0.000092     -0.249597
  22  BA-12:C   BA-12:4              -0.000043     -0.077948
  22  BA-13:C   BA-13:2               0.000048      0.126283
  22  BA-15:C   BA-15:4              -0.000385     -0.699984
  22  BA-16:C   BA-16:4              -0.000073     -0.190573
  22  BA-16:4   BA-16:6               0.000210      0.561577
  22  BA-17:C   BA-17:1               0.000263      0.711971
```

```
TAU (0.05) : 1.9491          TAU (0.01) : 2.5175
TAU MAX (0.05) : 3.1094          TAU MAX (0.01) : 3.4621


THE QUADRATIC FORM        :   130.7077415653

ESTIMATED VARIANCE FACTOR :     3.1879936967
1.0 / ESTIMATED VARIANCE FACTOR :    0.3136769063
TO BE COMPARED TO LOWER AND UPPER BOUNDS

DEGREES OF FREEDOM        :    41
```

STATIONS, X, Y, Z, ZONE CODE

DP1	1030.0000	974.7700	11.6500	3
DP2	1030.0000	971.0000	9.7500	3
DP3	1030.0000	970.8500	-4.7000	3
DP4	1030.0000	975.2000	-6.9000	3
DP5	1030.0000	975.2500	-16.2500	3
DP6	1030.0000	987.4500	-18.8500	3
DP7	1030.0000	1011.5000	-9.6000	2
DP8	1030.0000	1011.6000	11.3000	2
DP9	1030.0000	992.7500	11.1000	2
DP10A	1030.0000	987.8000	5.3300	2
DP10B	1030.0000	987.8000	5.3300	3
DP11A	1030.0000	987.8000	-8.2800	2
DP11B	1030.0000	987.8000	-8.2800	3
DP12	1030.0000	980.0000	-15.0000	3
DP13	1030.0000	980.0000	-10.0000	3
DP14	1030.0000	980.0000	-5.0000	3
DP15	1030.0000	980.0000	0.0000	3
DP16	1030.0000	981.0800	5.3300	3
DP17	1030.0000	981.0800	10.7500	3
DP18	1030.0000	986.0500	10.7500	3
DP19	1030.0000	986.0500	5.3300	3
DP20	1030.0000	986.0500	0.0000	3
DP21	1030.0000	985.0000	-5.0000	3
DP22	1030.0000	985.0000	-10.0000	3
DP23	1030.0000	985.0000	-15.0000	3
DP24	1030.0000	995.0000	-15.0000	3
DP25	1030.0000	995.0000	-10.0000	3
DP26	1030.0000	995.0000	-5.0000	3
DP27	1030.0000	995.0000	0.0000	3
DP28	1030.0000	995.0000	5.0000	3
DP29	1030.0000	995.0000	11.3000	3
DP30	1030.0000	1000.0000	11.3000	3
DP31	1030.0000	1000.0000	5.0000	3
DP32	1030.0000	1000.0000	0.0000	3
DP33	1030.0000	1000.0000	-5.0000	3
DP34	1030.0000	1000.0000	-10.0000	3
DP35	1030.0000	1000.0000	-15.0000	3
DP36	1030.0000	1005.0000	-10.0000	3
DP37	1030.0000	1005.0000	-5.0000	3
DP38	1030.0000	1005.0000	0.0000	3
DP39	1030.0000	1005.0000	5.0000	3
DP40	1030.0000	1005.0000	11.3000	3
DP41	1030.0000	1011.6000	-5.0000	3
DP42	1030.0000	1011.6000	0.0000	3
DP43	1030.0000	1011.6000	5.0000	3
DP44	1030.0000	986.0500	4.5000	3
DP45	1030.0000	981.4200	4.5000	3
DP46	1030.0000	981.4200	-3.7200	3

DP47	1030.0000	986.0500	-3.7200	3

STATIONS, Y AS X, Z AS Y, ZONE CODE

DP1	37.930000	30.750000	3
DP2	41.700000	28.850000	3
DP3	41.850000	14.400000	3
DP4	37.500000	12.200000	3
DP5	37.450000	2.850000	3
DP6	25.250000	0.250000	3
DP7	1.200000	9.500000	2
DP8	1.100000	30.400000	2
DP9	19.950000	30.200000	2
DP10A	24.900000	24.430000	2
DP10B	24.900000	24.430000	3
DP11A	24.900000	10.820000	2
DP11B	24.900000	10.820000	3
DP12	32.700000	4.100000	3
DP13	32.700000	9.100000	3
DP14	32.700000	14.100000	3
DP15	32.700000	19.100000	3
DP16	31.620000	24.430000	3
DP17	31.620000	29.850000	3
DP18	26.650000	29.850000	3
DP19	26.650000	24.430000	3
DP20	26.650000	19.100000	3
DP21	27.700000	14.100000	3
DP22	27.700000	9.100000	3
DP23	27.700000	4.100000	3
DP24	17.700000	4.100000	3
DP25	17.700000	9.100000	3
DP26	17.700000	14.100000	3
DP27	17.700000	19.100000	3
DP28	17.700000	24.100000	3
DP29	17.700000	30.400000	3
DP30	12.700000	30.400000	3
DP31	12.700000	24.100000	3
DP32	12.700000	19.100000	3
DP33	12.700000	14.100000	3
DP34	12.700000	9.100000	3
DP35	12.700000	4.100000	3
DP36	7.700000	9.100000	3
DP37	7.700000	14.100000	3
DP38	7.700000	19.100000	3
DP39	7.700000	24.100000	3
DP40	7.700000	30.400000	3
DP41	1.100000	14.100000	3
DP42	1.100000	19.100000	3

DP43	1.100000	24.100000	3
DP44	26.650000	23.600000	3
DP45	31.280000	23.600000	3
DP46	31.280000	15.380000	3
DP47	26.650000	15.380000	3

The x,y,z coordinates from the MCXYZ system have been transformed into x,y in the plane of the section so that y is positive upward and x is positive to the right.

DERIVED DISPLACEMENTS :

STATION	DX/DY	DY/DZ	A,	B, AT	0.05,	AZ	A
DP1	0.00568	0.00277	0.00030	0.00017	270	30	53
DP2	0.00608	0.00231	0.00034	0.00021	87	4	52
DP3	0.00356	0.00063	0.00030	0.00021	71	57	22
DP4	0.00255	0.00064	0.00027	0.00015	76	31	37
DP5	0.00100	-0.00043	0.00041	0.00017	81	39	21
DP6	-0.00040	0.00002	0.00036	0.00000	89	53	24
DP7	-0.00001	0.00110	0.00004	0.00002	356	31	2
DP8	0.00005	0.00352	0.00014	0.00002	357	48	46
DP9	0.00161	0.00350	0.00026	0.00013	283	28	12
DP10A	0.00185	0.00283	0.00025	0.00010	281	0	31
DP10B	0.00272	0.00284	0.00018	0.00011	83	42	22
DP11A	0.00092	0.00125	0.00023	0.00005	272	2	56
DP11B	0.00095	0.00127	0.00023	0.00005	272	9	28
DP12	0.00071	0.00000	0.00035	0.00010	83	55	23
DP13	0.00147	0.00058	0.00028	0.00009	83	10	55
DP14	0.00222	0.00116	0.00022	0.00009	82	42	1
DP15	0.00298	0.00174	0.00018	0.00010	84	23	47
DP16	0.00362	0.00242	0.00018	0.00010	270	10	54
DP17	0.00443	0.00305	0.00023	0.00012	271	27	28
DP18	0.00367	0.00336	0.00022	0.00012	84	29	26
DP19	0.00294	0.00273	0.00018	0.00010	87	35	16
DP20	0.00222	0.00212	0.00017	0.00008	270	33	16
DP21	0.00165	0.00147	0.00020	0.00006	89	27	55
DP22	0.00096	0.00089	0.00026	0.00004	88	37	58
DP23	0.00028	0.00031	0.00032	0.00003	88	2	17
DP24	-0.00030	0.00093	0.00027	0.00010	283	23	42
DP25	0.00025	0.00151	0.00023	0.00012	286	10	2
DP26	0.00080	0.00209	0.00019	0.00015	286	22	23
DP27	0.00135	0.00267	0.00018	0.00016	43	7	50
DP28	0.00190	0.00325	0.00021	0.00015	40	14	40
DP29	0.00260	0.00398	0.00027	0.00015	46	38	37
DP30	0.00209	0.00429	0.00033	0.00014	36	51	20
DP31	0.00148	0.00356	0.00028	0.00013	27	36	42
DP32	0.00100	0.00298	0.00024	0.00014	16	48	46
DP33	0.00052	0.00240	0.00022	0.00016	356	42	7

DP34	0.00003	0.00182	0.00023	0.00016	324	49	26
DP35	-0.00045	0.00124	0.00026	0.00014	306	23	14
DP36	-0.00008	0.00213	0.00028	0.00012	348	17	13
DP37	0.00033	0.00271	0.00029	0.00011	3	17	56
DP38	0.00074	0.00329	0.00032	0.00010	15	16	18
DP39	0.00116	0.00387	0.00035	0.00010	24	26	41
DP40	0.00168	0.00460	0.00041	0.00011	33	14	10
DP41	0.00023	0.00312	0.00039	0.00002	7	0	5
DP42	0.00055	0.00370	0.00042	0.00003	16	20	14
DP43	0.00088	0.00428	0.00046	0.00004	24	13	18
DP44	0.00282	0.00264	0.00017	0.00010	88	12	7
DP45	0.00345	0.00235	0.00018	0.00010	89	48	59
DP46	0.00224	0.00140	0.00020	0.00008	85	4	40
DP47	0.00172	0.00168	0.00019	0.00006	270	46	1

PRINCIPAL STRAINS :

STATION	EMAX	EMIN	AZ EMAX		
DP1	0.0002163602	0.0000911010	62	6	20
DP2	0.0002278342	0.0000888582	62	29	9
DP3	0.0001995742	0.0000782296	54	48	57
DP4	0.0001795797	0.0000755775	50	1	3
DP5	0.0001659941	0.0000634373	42	52	27
DP6	0.0001339880	0.0000416785	24	9	58
DP7	0.0001185381	-0.0000096002	0	43	57
DP8	0.0001185488	0.0000470838	1	12	16
DP9	0.0001458348	0.0000913519	45	4	48
DP10A	0.0001542224	0.0000861401	46	24	3
DP10B	0.0001542224	0.0000861401	46	24	3
DP11A	0.0001395750	0.0000636191	31	46	17
DP11B	0.0001395750	0.0000636191	31	46	17
DP12	0.0001533676	0.0000613090	37	58	19
DP13	0.0001590285	0.0000693029	42	13	0
DP14	0.0001657129	0.0000762733	46	35	12
DP15	0.0001734306	0.0000822104	50	53	5
DP16	0.0001785843	0.0000874817	54	17	28
DP17	0.0001888546	0.0000920133	58	27	22
DP18	0.0001693775	0.0000924804	54	24	59
DP19	0.0001602615	0.0000867946	48	55	12
DP20	0.0001527107	0.0000797894	43	13	3
DP21	0.0001499127	0.0000729488	39	41	39
DP22	0.0001449051	0.0000643015	34	54	6
DP23	0.0001409134	0.0000546385	30	37	50
DP24	0.0001252713	0.0000320310	15	36	47
DP25	0.0001264138	0.0000445434	18	5	36

DP26	0.0001279594	0.0000566526	21	20	21
DP27	0.0001301152	0.0000681516	25	38	6
DP28	0.0001331969	0.0000787247	31	16	24
DP29	0.0001390536	0.0000900730	40	21	16
DP30	0.0001269878	0.0000830142	26	2	0
DP31	0.0001245048	0.0000682920	19	2	55
DP32	0.0001233143	0.0000558277	15	27	46
DP33	0.0001224989	0.0000429884	12	55	52
DP34	0.0001219116	0.0000299209	11	4	29
DP35	0.0001214710	0.0000167066	9	39	59
DP36	0.0001195663	0.0000131414	5	41	52
DP37	0.0001197204	0.0000266421	6	31	42
DP38	0.0001199268	0.0000400906	7	38	8
DP39	0.0001202163	0.0000534558	9	10	47
DP40	0.0001207994	0.0000700778	12	14	47
DP41	0.0001185366	0.0000025812	0	44	32
DP42	0.0001185392	0.0000162334	0	50	28
DP43	0.0001185426	0.0000298848	0	58	15
DP44	0.0001589908	0.0000857986	48	2	27
DP45	0.0001758190	0.0000866799	53	17	58
DP46	0.0001627641	0.0000772863	46	0	39
DP47	0.0001482947	0.0000740462	39	17	34

IV. COMPUTATIONAL MODULES: SOURCE CODE SIZE

The following is a list of the computational modules of DAMADA as shown in Figure 6.2, giving the number of lines of source code for each module. The programs on the data collector were written in MC-BASIC which is compatible with GW-BASIC that is available on most microcomputers running under DOS. All of the other programs were written in FORTRAN using the Watcom WATFOR87 compiler and Watcom GKS for screen graphics.

Modules in BASIC

ALEV	425
EODM	386
GEOT	1055
LEV	381
SSR	646
THEOD	560

Modules in FORTRAN

DISR	440	FITPLT	1626
LEVEL	1477	M2D	1170
OBSMOD	1475	PLANE	1100
PLOT	707	PROC	2374
SIMPLT	1226	SSPLT	1082
SSSPLT	750	WT1D	1266
WT2D	1618	ZERO	321

VITA

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	Barrie District North Collegiate	1963 - 1967	
Universities attended:	University of Windsor	1976 - 1978	
	University of New Brunswick	1978 - 1982	B.Sc.E.
	University of New Brunswick	1982 - 1985	M.Sc.E.
	University of New Brunswick	1985 -	

Publications:

Secord, J.M. (1993). "Data management for deformation monitoring." Proceedings of the 1993 Annual Conference of the Canadian Society for Civil Engineering, Fredericton, 1993 06 09 - 11, Volume IV, p. 469-478.

Chrzanowski, A., Chen Y-q., J.M. Secord, A. Szostak-Chrzanowski (1991). "Problems and solutions in the integrated monitoring and analysis of dam deformations." CISM Journal ACSGC, Winter 1991, v.45 n.4, p. 547-560.

Chen Y-q, A. Chrzanowski, J.M. Secord (1990). "A strategy for the analysis of the stability of reference points in deformation surveys." CISM Journal ACSGC, Summer 1990, v.44 n.2, p. 39-46.

Chrzanowski, A., Chen Y-q., A. Szostak-Chrzanowski, J.M. Secord (1990). "Combination of geometrical analysis with physical interpretation for the enhancement of deformation monitoring." Fédération Internationale des Géomètres, XIX International Congress, Helsinki, Finland, paper 612.3, 15 pp.

Chrzanowski, A., Chen Y-q., J.M. Secord, A. Szostak-Chrzanowski, D.G. Hayward, G.A. Thompson, Z. Wroblewicz (1989). "Integrated analysis of deformation surveys at Mactaquac." International Water Power and Dam Construction, August 1988, p. 17-22.

Chrzanowski, A., Chen Y-q., J.M. Secord, G.A. Thompson, Z. Wroblewicz

(1988). "Integration of geotechnical and geodetic observations in the geometrical analysis of deformation at the Mactaquac Generating Station." in Chrzanowski, A. and W. Wells (edit) Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurement, Fredericton, NB, 1988 06 06-09, p. 156-169

Wilkins, F.J., A. Chrzanowski, M.W. Rohde, H. Schmeing, J.M. Secord (1988). "A three dimensional high precision coordinating system." in Chrzanowski, A. and W. Wells (edit) Proceedings of the 5th International (FIG) Symposium on Deformation Measurement and the 5th Canadian Symposium on Mining Surveying and Rock Deformation Measurement, Fredericton, NB, 1988 06 06-09, p. 156-169

Chrzanowski, A., Chen Y-q., J.M. Secord (1987). "Geometrical analysis of deformation surveys." Papers of the Deformation Measurements Workshop, Boston, 31 October - 1 November 1986, p. 369-383

Secord, J.M. (1987). "Terrestrial survey methods for precision deformation measurements." Papers of the Deformation Measurements Workshop, Boston, 31 October-1 November 1986, p. 34-65

Chen Y-q., A. Chrzanowski and J. Secord (1985). "Generalized modelling of ground movements by integrating geodetic surveys with geotechnical measurements." Proceedings of the 6th International Congress of ISM, Harrogate, England, 9-13 September, p. 912-920.

Chrzanowski, A., Chen Y-q., P. Romero and J.M. Secord (1986). "Integration of geodetic and geotechnical deformation surveys in the geosciences." in H.G. Henneberg (edit) "Recent Crustal Movements 1985", Tectonophysics, 130: 369-383.

Chrzanowski, A., Chen Y-q., M.Y. Fisekci, J. Secord and A. Szostak-Chrzanowski (1985). "An integrated approach to the monitoring and modelling of ground movements." in S.S. Peng, J.H. Kelley (edit) Proceedings of the 4th Conference on Ground Control in Mining, Morgantown, WV, 22-24 July, p. 273-285.

Chrzanowski, A., T. Greening, W. Kornacki, J. Secord, S. Vamosi and Chen Y-q. (1985). "Applications and limitations of precise trigonometric height traversing." Proceedings of the Third International Symposium on the North American Vertical Datum (NAVD '85), Rockville, MD, 21-26 April, p. 81-93.

Secord, J.M. (1984). "Implementation of a Generalized Method for the Analysis of Deformation Surveys." M.Sc.E. Thesis 1984 12, 161 pp., University of New Brunswick, Dept. of Surveying Engineering, Technical Report 117 , 1985 10.

Chrzanowski, A., Chen Y-q., J.M. Secord (1983). "On the strain analysis of tectonic movements using fault crossing geodetic surveys." In P.Vyskocil, A.M. Wassef, R. Green (edit) Recent Crustal Movements 1982, Tectonophysics, 97: 297-315.

Chrzanowski, A., J.M. Secord (compile) (1983). "Report of the *ad hoc* committee on the analysis of deformation surveys." FIG XVII International Congress, Sofia, Bulgaria, paper 605.2, 15 pp.

Chrzanowski, A., J.M. Secord (1983). "Report on the deformation analysis of the monitoring network at the Lohmühle Dam." FIG Commission 6 Study Group C *ad hoc* Committee on Deformation Analysis, 18 pp.

Chen Y-q., M. Kavouras, J.M. Secord (1983). "Design considerations in deformation monitoring." FIG XVII International Congress, Sofia, Bulgaria, paper 603.2, 14 pp.

Chrzanowski, A., Chen Y-q., J.M. Secord (1983). "Analysis of the simulated monitoring network using the Fredericton approach." in W. Welsch (edit) Deformationsanalysen '83, Hochschule der Bundeswehr München, Schriftenreihe, Heft 9, p. 95-117

Chrzanowski, A., Chen Y-q., J.M. Secord (1983). "A generalized approach to the geometric analysis of deformation surveys." in I. Joó, A. Detreköi (edit) Deformation Measurements / Deformationsmessungen, Akadémiai Kiadó, Budapest, p. 344-372

Kok, J., B. Heck, W. Welsch, R. Baumer, A. Chrzanowski, Chen Y-q., J. Secord (1983). "Report of the FIG Working Group on the analysis of deformation measurements." in I. Joó, A. Detreköi (edit) Deformation Measurements / Deformationsmessungen, Akadémiai Kiadó, Budapest, p. 373-416

Chrzanowski, A., Chen Y-q., J.M. Secord (1982). "On the analysis of deformation surveys." Canadian Institute of Surveying, Proceedings of the Fourth Canadian Symposium on Deformation Measurements, Banff, Alberta. p. 431-452

Chrzanowski, A., Y.Q. Chen, J.M. Secord (1982). "A general approach to the interpretation of deformation measurements." Canadian Institute of Surveying, Proceedings of the Centennial Convention, Ottawa, Ontario. v.2, p. 247-266