Calibrating Antenna Phase Centers

A Tale of Two Methods

Boussaad Akrour, Rock Santerre, and Alain Geiger

OFTEN OVERLOOKED, THE ANTENNA IS A VITAL COMPONENT OF ANY GPS RECEIVER. WITHOUT IT, A receiver simply would not work. The job of the antenna is to convert the miniscule energy in electromagnetic waves received from GPS satellites into an electrical current that can be processed by the receiver. The receiver then determines the coordinates of the antenna – or, more precisely, it determines the coordinates of the electrical phase center of the antenna. Typically, the phase center is near the physical center of the antenna and for many low-accuracy GPS applications, the exact location of the phase center is immaterial. However, for demanding applications such as monitoring the deformation of the Earth's crust, assessing the stability of bridges and buildings, for machine control, and for attitude determination, the relationship between the electrical phase center and the physical structure of the antenna is crucial – it should be known to the millimeter level.

But try as they might, antenna designers have yet to create an antenna whose phase center is absolutely stable with respect to the physical structure of the antenna – there is always some movement of the phase center as the elevation angle and azimuth of an arriving electromagnetic wave changes. The movement can amount to millimeters or more. Such variation will contribute an error to positions computed using low-noise carrier-phase measurements. However, with the appropriate set-up, it is possible to measure the phase-center variation and calibrate an antenna. The mean phase center and its variation can then be used in software used to process collected carrier-phase data.

In this month's column, we investigate two techniques for calibrating GPS antennas and examine how well they agree. — R.B.L.

The calibration of GPS antennas is of the utmost importance in GPS baseline determination, especially when millimeter precision is required for applications such as the monitoring of engineering structures or for GPS attitude determination. For these applications, even correcting for the mean phase center is not enough. To fully meet the precision requirements of these applications, the phase-center variation must also be taken into account.

In relative GPS positioning, both antennas are set up and centered on the two ends of the baseline that is to be measured. The geometric center of each antenna is used to determine the offset in relation to the geodetic point above which the antenna is installed. However, a GPS receiver determines the coordinates of the antenna's electrical phase center. The phase center is defined as being the point where the satellite signal is collected. The offset between the mean phase center and the geometric center of an antenna can range from a few millimeters to several centimeters.

The observation error due to the offset between the instantaneous and the geometric phase centers is represented by the amount of two projections on the antenna-satellite vector (see **Figure 1**): (1) the mean phase-center error ($\epsilon\Phi_m$), and (2) the phase-center variation ($\epsilon\Phi_r$) that is the difference between the mean phase center and the instantaneous phase center.

This article presents two methods for the calibration of GPS antenna phase centers. The first one is carried out in the field in a relative mode using an antenna-support calibration beam. The second method relies on observations made in an anechoic chamber. A comparison of both methods in relative mode was performed with regard to the components of the mean phase center and the phase-center variations. The results show that the differences between the two methods do not exceed 2 millimeters, even though they use completely different approaches.

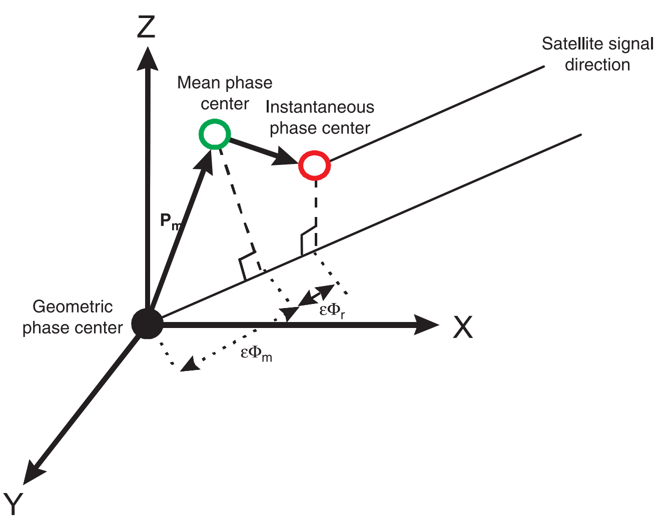


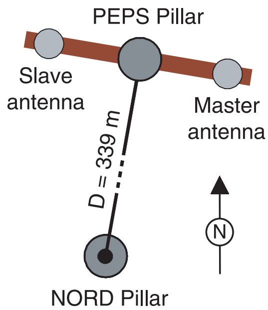
FIGURE 1 Geometry of GPS antenna phase center

Calibration Beam

The first GPS antenna calibration method investigated in our study has been carried out in relative mode using a calibration beam on which a pair of antennas is mounted. That is to say that a slave antenna is calibrated with reference to another one considered as the reference (master) antenna.

The calibration beam was built by the metrology-geodesy laboratory of Université Laval. It is made of aluminum, with an approximate length of one meter, and it has two antenna mounts with forced-centering bolts. The distance between the centers of the two mounts was accurately measured in the laboratory using an interferometer. A theodolite is permanently installed at the center of the beam in order to define its orientation with a back-sight toward another geodetic point. The sighting axis of the theodolite is perpendicular to the axis formed by the

▲ Calibration beam set up on a pillar



▲ **FIGURE 2** Calibration beam installation

forced-centering bolts of both antenna mounts. To ensure the beam is level in both longitudinal and transversal directions, two tubular bubble levels are perpendicularly mounted on the beam.

The main advantage of the calibration beam over a baseline formed by two arbitrary geodetic reference points is convenience while maintaining a high accuracy in determining the beam azimuth.

The calibration of both antennas, in relative mode, is carried out by using two geodetic points, as follows. The calibration beam was installed on a pillar (PEPS) on the Université Laval campus and oriented perpendicularly to the direction to another pillar (NORD) by means of the beam's theodolite. **Figure 2** illustrates the calibration beam installation on the PEPS pillar.

The length of the calibration beam (L_B) is known from laboratory measurements and the beam is leveled and oriented in the field so that the three-dimensional baseline components ΔN_B, ΔE_B, and Δh_B, are known.

Temperature Compensation. The length of the beam was measured in the laboratory at a temperature of 20°C. During an antenna calibration session, the beam length gets shorter or longer depending on the ambient temperature. If the ambient temperature exceeds 20°C, the nominal length of the beam is longer than when calibrated in the laboratory. When the temperature is below 20°C, the nominal length is shorter. Knowing the thermal expansion coefficient of aluminum (23 parts per million per °C), the beam length variation and its corrected length are given by the following equations:

$$\Delta L_B = 23 \times 10^{-6} \times L_B \times \Delta t \qquad (1)$$

$$L_{Bc} = L_B + \Delta L_B \qquad (2)$$

where

ΔL_B is the beam-length variation resulting from aluminum thermal expansion (meters);

Δt is the difference between the field and calibration temperatures — field minus laboratory (°C);

L_B is the beam length during laboratory calibration (meters);

L_{Bc} is the beam length corrected for thermal expansion (meters).

For example, for an outside operating temperature of -20°C, the beam length would be shorter than that in the laboratory by almost 1 millimeter.

What Is Antenna Phase Center?

The electrical phase center of an antenna is the apparent source of electromagnetic radiation when the antenna is used for transmitting. If the source is an ideal point source, the phase center is the center of the radiating spherical wavefronts (of equal phase). According to the reciprocity theorem, the spatial response of an antenna is exactly equivalent to its radiation pattern. So, when the antenna is used for receiving, the phase center is the effective collecting point of the radiation – the point at which electromagnetic wave energy is transferred to the antenna. For a GPS receiving antenna, the phase center is the point to which the receiver's phase measurements actually refer. Since a real antenna is not an ideal point source, its equiphase contours will not be perfectly spherical, and hence the center of curvature may vary with the azimuth and elevation angle of an arriving signal.—R.B.L.

Antenna Tests. We have tested our relative calibration technique on two antennas. The first one was a conventional geodetic L1/L2 dual-frequency antenna. We use one of these antennas as the reference antenna in all of our investigations. The second antenna was a choke-ring type. We calibrated one of the geodetic antennas and a choke-ring antenna twice; once in 1995 and again in 2000 using the calibration beam. They were also calibrated in an anechoic chamber in 1999. These calibration tests were part of a wider research effort related to monitoring of engineering structures with single-frequency receivers. Accordingly, the antennas were calibrated only at the L1 frequency.

We carried out two observation sessions of 24 hours each for both of the antennas. These sessions were performed during two consecutive days but delayed by 4 minutes per day, since the satellite sky distribution is repeated with a period close to a sidereal day (23 hours, 56 minutes). During the first observation day, both antennas were oriented so that a physical mark on the antenna pointed to magnetic north. The second day, they were turned to magnetic south. This scenario covers all parts of the superior hemisphere of the antennas. Indeed, for mid-latitude sites, the inclination of the GPS satellite orbits causes a "shadow" area in the sky where it is not possible to make GPS observations.

The sampling interval was 1 minute, and no mask angle was used. Yet, the post-processing was carried out with an imposed elevation mask angle of 15°. Two geodetic-class receivers were used for the calibrations and, to compensate for the beam-length variations, temperature measurements were taken automatically with an electronic thermometer.

We processed the data collected by the receiver in between-receiver, single-difference mode using the DETECSAT2 software developed at the Centre for Research in Geomatics at Université Laval. This processing approach allows us to calculate the relative mean phase-center components of the antennas. These components are obtained by averaging the results of the two GPS observation sessions (antenna orientations to magnetic north and south). The components of the relative mean phase center (ΔN, ΔE, Δh) in the local geodetic reference frame are given by these

TABLE 1 Comparison of the L1 relative mean phase-center components (conventional geodetic and choke-ring antennas) for an elevation mask angle of 15°

	Phase-center components		
(mm)	ΔE	ΔN	Δh
Beam (September 1995)	-1.5	0.5	29.6
Beam (January 2000)	-0.9	1.0	30.4
Anechoic Chamber (Aug 1999)	-3.1	0.4	30.9

TABLE 2 Size and shape of the confidence ellipsoids (with a probability level of 95%) of the relative mean phase centers resulting from the two calibration methods (for an elevation mask angle of 15°)

Calibration method	Beam			Anechoic chamber		
Semi-axis	a	b	c	a	b	c
Length (mm)	1.3	0.9	2.5	0.6	0.6	1.2
Azimuth (°)	175	85	178	0	90	180
Elevation (°)	0	0	90	0	0	90

equations:

$$\Delta N = \Delta N_B - \Delta N_{GPS} \quad (3)$$

$$\Delta E = \Delta E_B - \Delta E_{GPS} \quad (4)$$

$$\Delta h = \Delta h_B - \Delta h_{GPS} \quad (5)$$

The components ΔN_B, ΔE_B, Δh_B and ΔN_{GPS}, ΔE_{GPS}, Δh_{GPS} are the known north, east, and vertical components of the calibration-beam baseline, and those determined by the GPS observations, respectively. As the length of the calibration beam is very short (about one meter), the relative errors in the GPS results due to tropospheric and ionospheric refraction and errors in the satellite ephemerides are completely eliminated in the single-difference processing.

For each GPS observation epoch and for each satellite, the single-difference residuals are also calculated. These residuals contain information about the relative phase-center variation with respect to the relative mean phase-center values. The GPS observation residuals also absorb the observation noise and any multipath errors. The calibration site was selected in order to minimize multipath effects.

Anechoic Chamber Calibration

The second GPS antenna calibration method presented in this article is based on the measurements taken in an anechoic chamber using a GPS signal simulator. An anechoic chamber is an enclosure ranging in size from a few meters to tens of meters on a side used for the testing of antennas and other radio-frequency (RF) devices. The interior walls of the chamber are covered with RF-absorbing material that reduces signal reflections or "echoes" to a minimum. This method is performed in absolute mode; that is, each antenna is calibrated separately. The calibration of our antennas was carried out in the anechoic chamber of the Department of Electrical Engineering, University of New Brunswick, in August 1999.

During this calibration, the antenna undergoes two rotations (variations of the "azimuth" and the elevation angle) per step of 5° each. At each antenna position, the "azimuth," the elevation angle, the gain of the antenna and the signal phase are measured and recorded by a computer, which manages the whole calibration process. For each antenna, a total of 1387 observations are recorded.

The observed phase measurements are reported in a coordinate reference frame centered at the antenna rotation point during calibration. X and Y axes are directed respectively towards the "north" and "east" marks on the antenna. The Z axis is perpendicular to the antenna ground plane. The coordinates (x_i, y_i, z_i) of a point defined by the phase measurement (converted into millimeters) are given by these equations:

$$x_i = r_i \cos E_i \cos\alpha_i = r_i \sin\zeta_i \cos\alpha_i \quad (6)$$

$$y_i = r_i \cos E_i \sin\alpha_i = r_i \sin\zeta_i \sin\alpha_i \quad (7)$$

$$z_i = r_i \sin E_i = r_i \cos\zeta_i \quad (8)$$

where

E_i is the elevation angle (measured during calibration);

ζ_i is the zenith angle (90° - E_i);

α_i is the "azimuth" of the phase measurement counted from the antenna N mark (measured during calibration);

r_i is the phase measurement converted into millimeters.

The problem amounts to a sphere resolution, which means finding the radius and the center coordinates from all the points (x_i, y_i, z_i). The sphere is named "best-fit sphere." The general equation of a sphere in Cartesian coordinates is given by:

$$(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - R_0^2 = 0 \quad (9)$$

The parameters x_0, y_0, z_0, R_0 represent the mean phase-center coordinates and the radius of the best-fit sphere. These parameters and their respective precisions are determined by a least-squares adjustment. The observation residuals obtained from this process contain information about the phase-center variations.

Phase-Center Variations

For the beam calibration, since the observation (satellite) sky distribution is non-homogenous, the phase-center variations' dependence on azimuth and elevation angle is described with a spherical harmonics development using the following formulation:

$$\varepsilon\Phi_r(\alpha,\zeta) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \left(a_{n,m}\cos m\alpha + b_{n,m}\sin m\alpha\right) p_{n,m}(\cos\zeta)$$

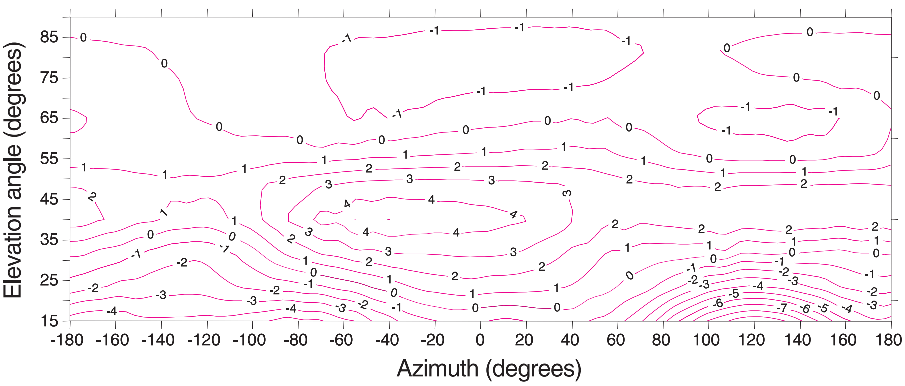
$$\varepsilon\Phi_r(\alpha,\zeta) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \left(a_{n,m} y_{n,m} + b_{n,m} y^{*}_{n,m}\right)$$

(10) and (11)

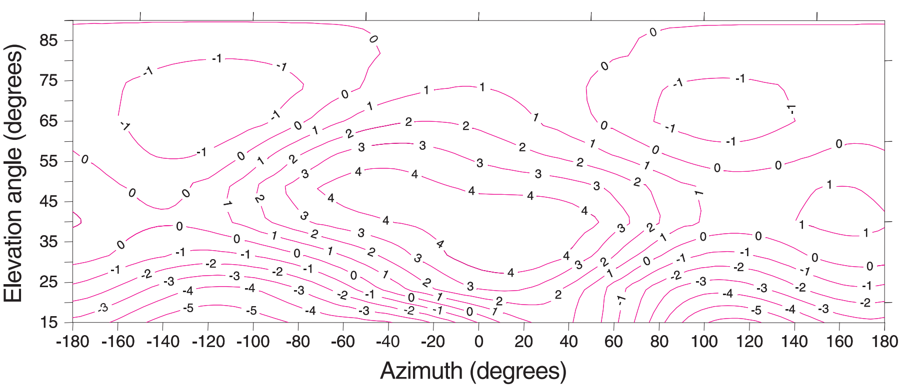
where

- $\epsilon\Phi_r$ is the phase-center variation (least-squares residual) in a given direction (input for spherical harmonics modeling);
- α and ζ are the azimuth and zenith angle of the residual;
- $p_{n,m}$ is the standardized Legendre polynomial of the first kind;
- $y_{n,m}$ and $y^*_{n,m}$ are the standardized spherical harmonics;
- $a_{n,m}$ and $b_{n,m}$ are the standardized spherical harmonic coefficients (parameters to be determined);
- n and m are the spherical harmonic degree and order.

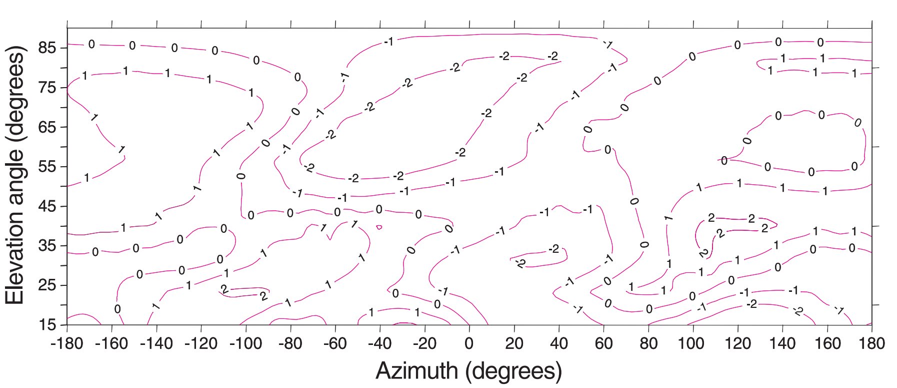
The $a_{n,m}$ and $b_{n,m}$ coefficients are then estimated from the "observables" $\epsilon\Phi_r(\alpha,\zeta)$ with equations (10) and (11). These coefficients



▲ **FIGURE 3** L1 phase-center variations (in millimeters) with respect to the relative mean phase center of conventional geodetic and choke-ring antennas resulting from the anechoic chamber calibration for an elevation mask angle of 15°



▲ **FIGURE 4** L1 phase-center variations (in millimeters) with respect to the relative mean phase center of conventional geodetic and choke-ring antennas resulting from the beam calibration (September 1995) and modeled with spherical harmonics (n=6, m=4) for an elevation mask angle of 15°



▲ **FIGURE 5** Difference (in millimeters) of the relative L1 phase-center variations resulting from the beam calibration and anechoic chamber techniques for an elevation mask angle of 15°

allow us subsequently to take into account the phase-center variations, with respect to the mean phase center, as required for precise GPS applications.

Comparing The Two Methods

Comparison of calibration results via the calibration beam method and the anechoic chamber method was performed in relative mode. It was carried out on components of the relative mean phase center as well as on relative phase-center variations.

Mean Phase Center. The calibration of the summer 1995 and winter 2000 sessions on the beam show a high repeatability of the results, even though the observed weather conditions differed significantly (respectively 27°C and -17°C). The respective components resulting from the calibration method on the beam and in the anechoic chamber agree within 2 millimeters even though both methods use completely different approaches (see Table 1). Table 2 shows the precision of calibration results of the relative mean phase center determination of the two calibration methods.

Phase-Center Variations. The comparison of the phase-center variations resulting from the two calibration methods is performed by the relative residual patterns. These patterns depend on the direction (azimuth and elevation angle) of the observations carried out during the calibration.

Figure 3 illustrates the curves of the isovalues (in millimeters) of the relative phase center variations of the geodetic and choke-ring antennas from the adjustment of anechoic chamber observations for an elevation mask angle of 15°.

To compare with the pattern of the phase-center residuals resulting from the observations in the anechoic chamber, the beam calibration residuals are initially modeled with a development in spherical harmonics, as described earlier. Then, a regular grid is generated with the determined model, every 5° in azimuth and elevation angle (same grid as for the anechoic chamber results).

Figure 4 shows the curves of the isovalues of the relative phase-center variations for the two antennas, from the beam calibration (September 1995) for an elevation mask angle of 15°. The curves are plotted from the relative residuals model developed with the spherical harmonics of degree 6 and order 4 (a total of 43 coefficients).

A comparison of the curves of Figures 3 and 4 reveals a general similarity of the two patterns. The figures show two hollows centered at the azimuths -120° and 120° and 15° elevation angle. They present also a peak of 4 millimeters centered at the azimuth -20° and 40° elevation angle. Figure 5 shows that the difference between both sets of curves is less than two millimeters in all directions.

Synergy. The calibration of GPS antenna phase-center variation in an anechoic chamber is expensive, not widely available, and must be performed by an electrical engineering specialist. While this technique provides absolute calibration of GPS antenna phase-center variation, the relative calibration procedure using a calibration beam, as presented here, is much less expensive and can be performed by GPS users themselves. With this method, information about phase-center variation is relative to a master GPS antenna. However, if the master antenna has been calibrated in absolute mode in an anechoic chamber, the absolute phase-center calibration of the second (slave) GPS antenna can then be inferred.

Conclusions

We have compared two methods for the calibration of relative GPS antenna phase center: on a calibration beam and in an anechoic chamber. The relative mean phase centers and the phase-center variations have been evaluated with the two calibration methods for a pair of geodetic antennas. The results show that the differences between the two methods do not exceed 2 millimeters, though they use completely different approaches.

The plots of the relative antenna phase center variations determined by the two methods of calibration also show a great similarity. The values of the relative phase centers varying between -7 millimeters and 5 millimeters. The magnitutde of the variations shows the need to take them into account when correcting GPS phase measurements in high-precision works such as the monitoring of engineering structures and for GPS attitude determination.

Acknowledgments

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Manufacturers

The conventional geodetic antenna was an **Ashtech** (now **Thales Navigation**, Santa Clara, California) *700228A*; the choke-ring antenna was an Ashtech *700936C*, manufactured by **Dorne and Margolin Company** (now **Edo Corporation**, New York, New York). Two Ashtech *Z-XII* geodetic-class receivers were used for the calibrations.

Further Reading

Previous *GPS World* articles on antennas and antenna calibration:

"A Primer on GPS Antennas" by R.B. Langley, *GPS World*, July 1998, pp. 50-54.
"Characterizing the Behavior of Geodetic GPS Antennas" by B.R. Schupler and T.A. Clark, *GPS World*, February 2001, pp. 48-55.
"Calibrating Antenna Phase Centers : The Block IIA Satellite" by G.L. Mader and F.M. Czopek, *GPS World*, May 2002, pp. 40-46.

Further information on the spherical harmonics approach in characterizing antenna phase-center variations:

"Determination of Antenna Phase Center Variations Using GPS Data" by M. Rothacher, S. Schaer, L. Mervart, and G. Beutler in *Proceedings of the IGS Workshop, Special Topics and New Directions*, Potsdam, Germany, May 15-18, 1995, pp. 205-220.

"A New Approach for Field Calibration of Absolute Antenna Phase Center Variations" by G. Wübbena, F. Menge, M. Schmitz, G. Seeber, and C. Völksen in *Proceedings of ION GPS-96*, the 9th International Technical Meeting of the Satellite Division of The Institute of Navigation, Kansas City, Missouri, September 17-20, 1996, pp. 1205-1214.

Information on the effects of antenna phase-center variations on GPS measurements:

"Influence of Phase Center Variations on the Combination of Different Antenna Types" by A. Geiger in *Proceedings of GPS'90*, the Second International Symposium on Precise Positioning with the Global Positioning System, Ottawa, Canada, September 3-7, 1990, pp. 466-476.

"Étude des effets de la variation des centres de phase des antennes GPS" by M. Bourassa, Master's thesis, Département des sciences géomatiques, Université Laval, Québec, Canada, 105 pp.

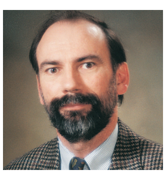
Further information on the anechoic chamber calibration procedure:

"GPS Antenna Design Characteristics for High Precision Applications" by J.M. Tranquilla and B.G. Colpitts, presented at the American Society of Civil Engineers Specialty Conference GPS 88, Engineering Applications of GPS Satellite Surveying Technology, Nashville, Tennessee, May 11-14, 1988 and published in *Journal of Surveying Engineering*, Vol. 115, No. 1, February 1989, pp. 2-14.

BOUSSAAD AKROUR holds an engineer diploma in geodetic sciences from the National Center of Space Techniques of Algeria (1990), as well as M.Sc. (1998) and Ph.D. (2002) degrees in geomatics sciences from Université Laval in Quebec City, Canada. He has twelve years' experience in the fields of monitoring engineering structures and GPS. He is currently working in GPS applications and research at the Canadian Coast Guard in Quebec City.

ROCK SANTERRE is a professor of geodesy and GPS in the Department of Geomatics Sciences, and a member of the Centre for Research in Geomatics at Université Laval. He holds a Ph.D. in geodesy from the University of New Brunswick. He has twenty years' experience in GPS positioning, and holds two patents related to GPS equipment.

ALAIN GEIGER is a professor at the Swiss Federal Institute of Technology (ETH) in Zürich. He lectures on satellite geodesy and navigation in ETH's Institute of Geodesy and Photogrammetry. He is a member of the Swiss Geodetic Commission and the International Association of Geodesy, president of the Swiss Institute of Navigation, and professeur associé at Université Laval.



The "Innovation" column features discussions about advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by **RICHARD LANGLEY** of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates your comments and topic suggestions. To contact him, see the "Columnists" section on page 2 of this issue.