Recent Advances in Geodetic Science and Perspectives for the Near Future

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Geomatics Atlantic, Delta Hotel, Fredericton, NB

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Topics

- Why is GGE so special?
- Geodesy stronger than ever
- The three pillars of Geodesy
- Gravity Field
- Positioning
- Earth Rotation and Orientation

UNB UNIVERSITY OF NEW BRUNSWICK

50 YEARS GEODESY AND GEOMATICS ENGINEERING UNB

Why is GGE so special?

- GGE has the best program
- GGE has the best students
- GGE has the most clever profs
- GGE has the best supporting staff
- GGE has the most efficient secretaries
- GGE is num … g
- GGE has wo

GEODESY

GEODESY AND GEOMATICS ENGINEERING

Geodesy stronger than ever

- Ten years ago there were some who thought that Geodesy was dead
  - Just press a button and voilà!
- Past 10 years has seen a tremendous growth in Geodetic Science
  - Instrumentation
  - 'New' satellite systems for positioning and Earth sensing
  - Massive amount of data
  - Advances in theoretical aspects
  - Increasing importance for understanding the Earth System
  - Advances in applications
    - ✓ "Environmental Geodesy"

The three pillars of Geodesy

Positioning and Kinematics

Gravity Field

Earth Orientation and Rotation

and their temporal variations

The three pillars of Geodesy

- Presentation divided into the three pillars
- Focus on:
  - Major advances in the past 10 years (snapshots)
  - Focus on UNB's contribution (snapshots)
- Challenges and perspective for the next 10 years
- (we do not have time to discuss details, only to present the main ideas)

Geodetic Research Laboratory

Prof. Langley

Assoc. Prof. Dare

Prof. Santos

Prof. Emeritus Vaníček

Adjunct Prof. Kim

Santos, 2010
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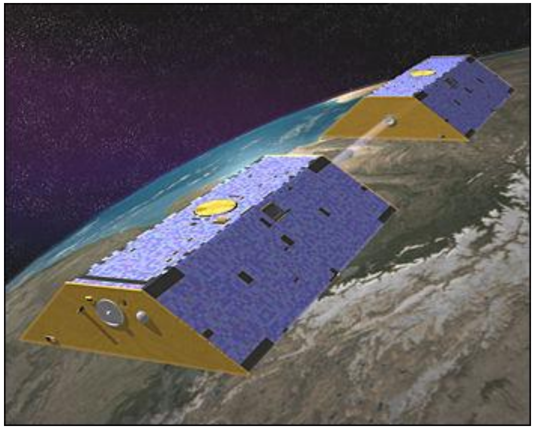
- Advances in the past 10 years
  - Satellite gravity missions (CHAMP, GRACE and GOCE) and its wide spectrum of applications; temporal variations of mass distribution (next slides)
    - Other missions (laser altimetry, Earth observation possible due to POD)
  - Advances in regional and global geoid modeling
  - Geoid as the vertical reference (Canada and US)
  - Unification of vertical frames
  - New EGM model (EGM2008)

CHAMP

- Launched on 15 July 2000; Re-entered Earth's atmosphere on Sept. 20, 2010.
- Objective: observe long-term temporal variations primarily in the magnetic field, in the gravity field and within the atmosphere.

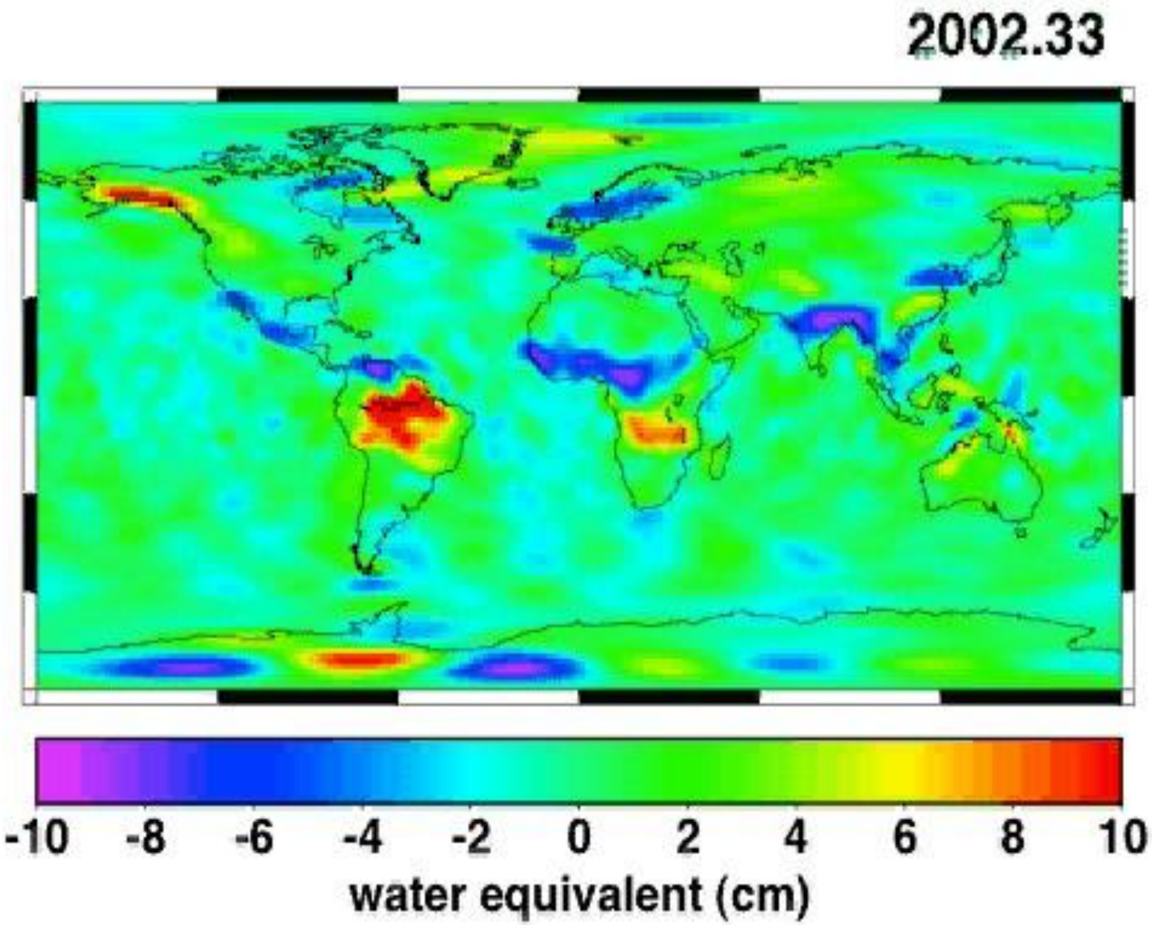
Gravimetric Satellite Missions

- GRACE (A and B)
  - Launched on Mar 17, 2002. Originally planned for 5 years. NASA and DLR agreed to extend mission through the end of its on-orbit life, which is expected in 2015.
  - Objective: map the Earth's gravity field providing information about the distribution and flow of mass within the Earth (geoid and temporal variation).



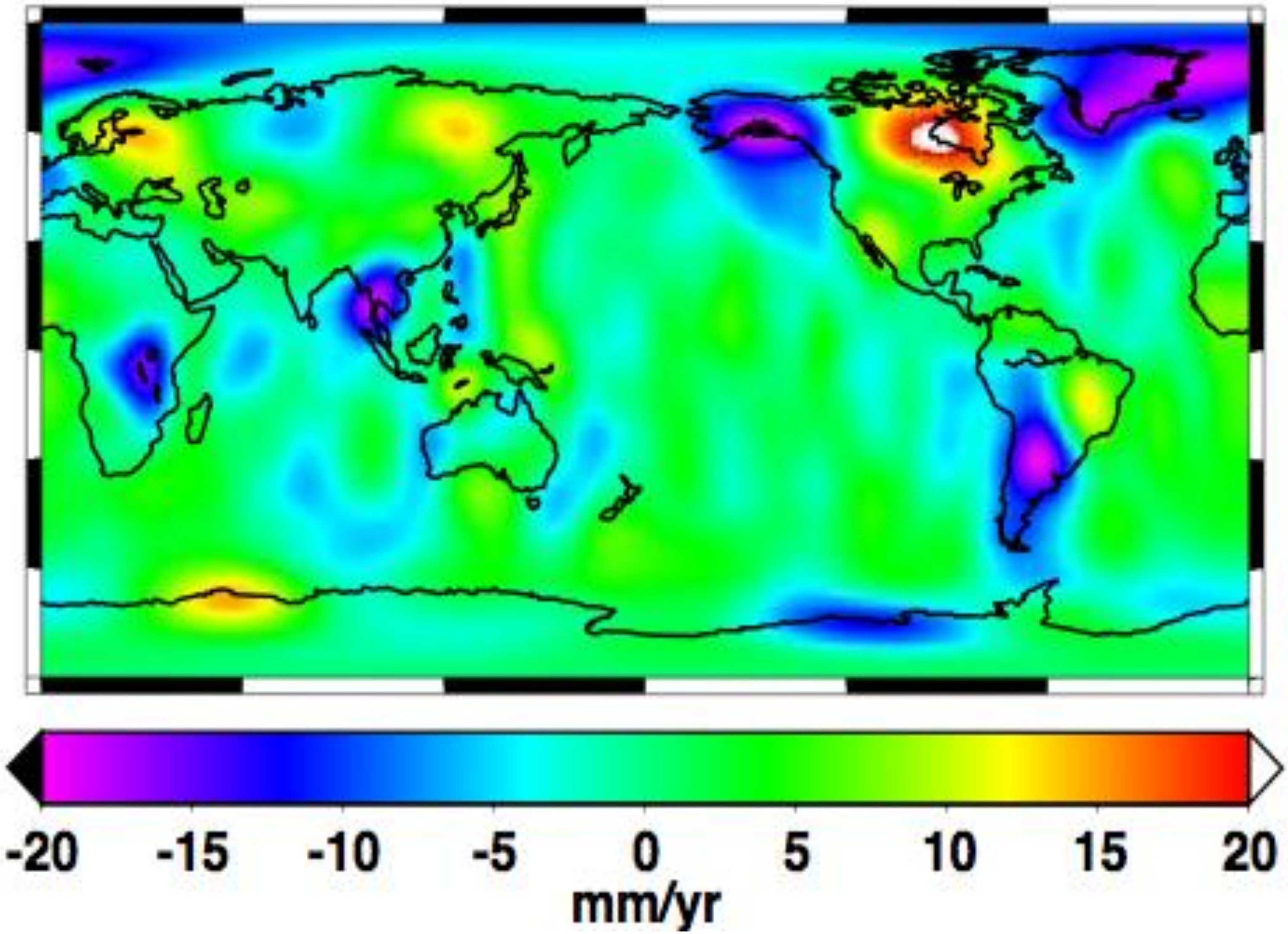
Measuring Water Storage in the Amazon

GRACE Surface Water Mass Variations



Swenson, Leuliette, Nerem, 2005

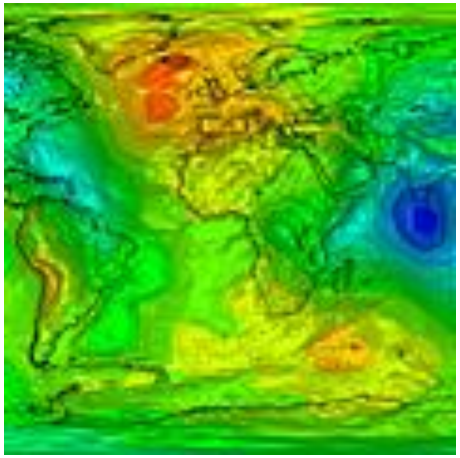
GRACE Geoid Change Trend: 2002-2005



Nerem, 2005

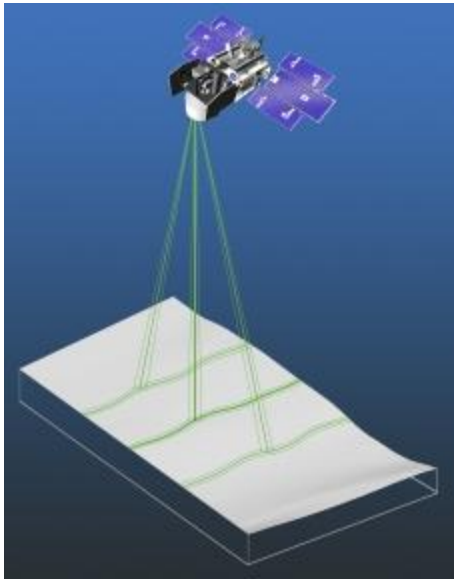
Gravimetric Satellite Missions

- GOCE
  - Launched on 17 March 2009.
- Objective:
  - To determine the gravity-field anomalies with an accuracy of 1 mGal (where 1 mGal = 10-5 m/s2)
  - To determine the geoid with an accuracy of 1-2 cm
  - To achieve the above at a spatial resolution better than 100 km
  - GOCE's 1st gravity model ➔



ICESat

- Ice, Cloud, and land Elevation Satellite (ICESat)
- 13-Jan-03 ➔ Oct 2009
- Geoscience Laser Altimeter System (GLAS).



ICESat-2 coming in 2015

Many more missions to observe the Earth system
⇒ Precise Orbit Determination

Geoid modelling at UNB

- SHGeo: Stokes-Helmert approach for the precise Geoid determination
- Developed over the past 25+ years at UNB (and over the last centuries by Stokes and Helmert)
  - Used for geoid computations of several countries
    - Mexico, Brazil, Iran, Sweden, Slovakia, Canada, and Israel
- Currently, package is being tested against the synthetic gravity field over Australia (see next slide)
  - RMS at 0.5 mm; RMS of 26 cm.

Santos, 2010
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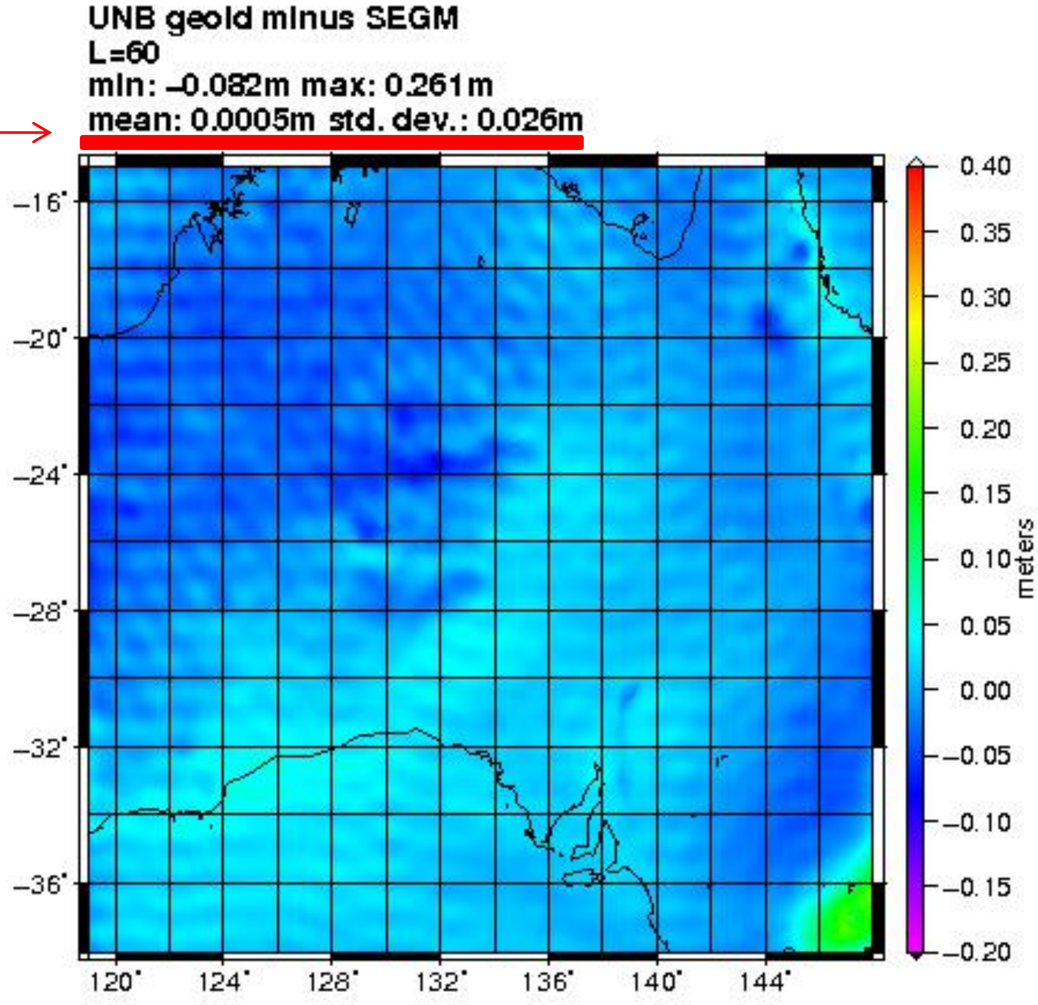
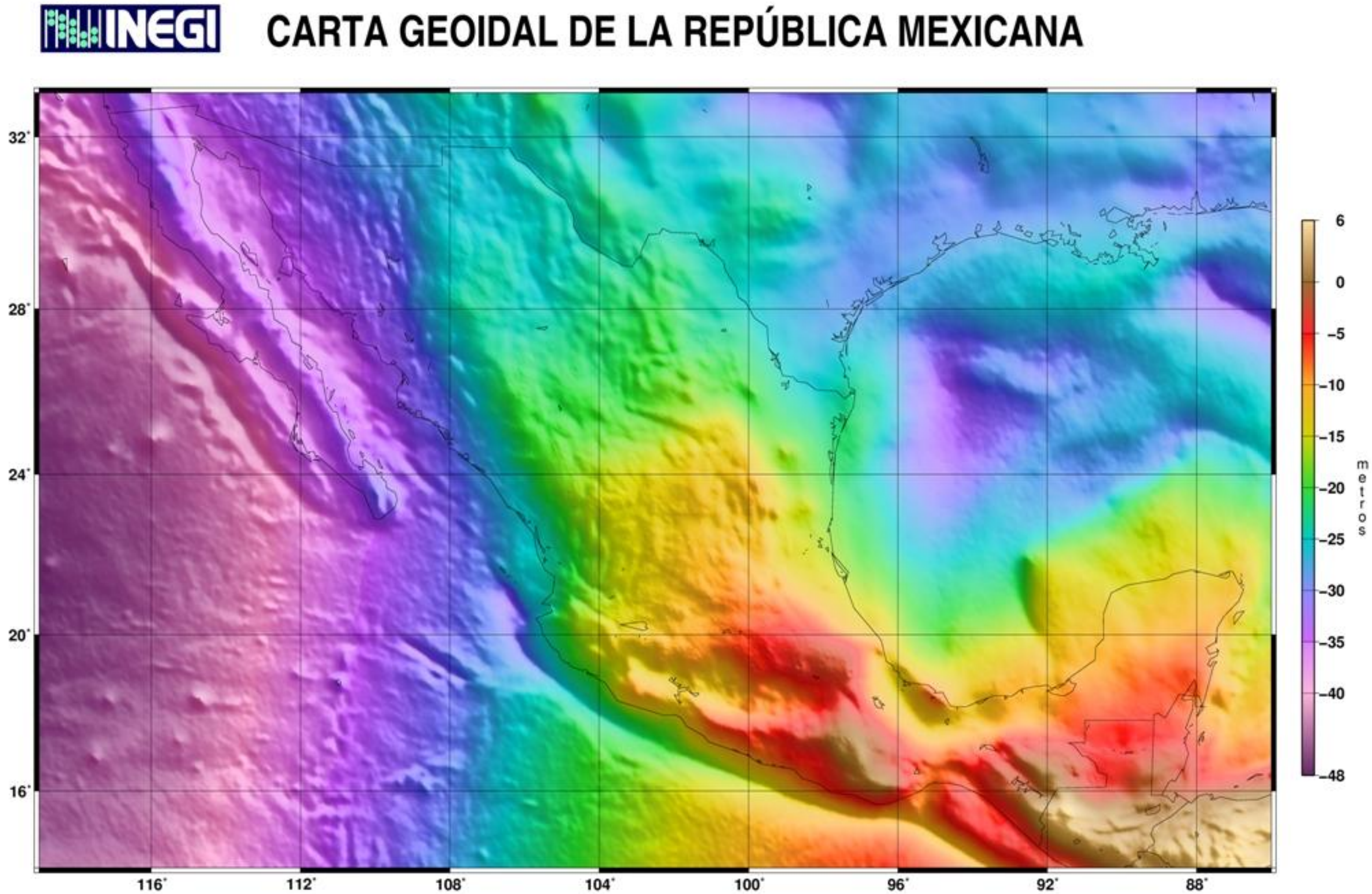
SHGeo accuracy over Australia

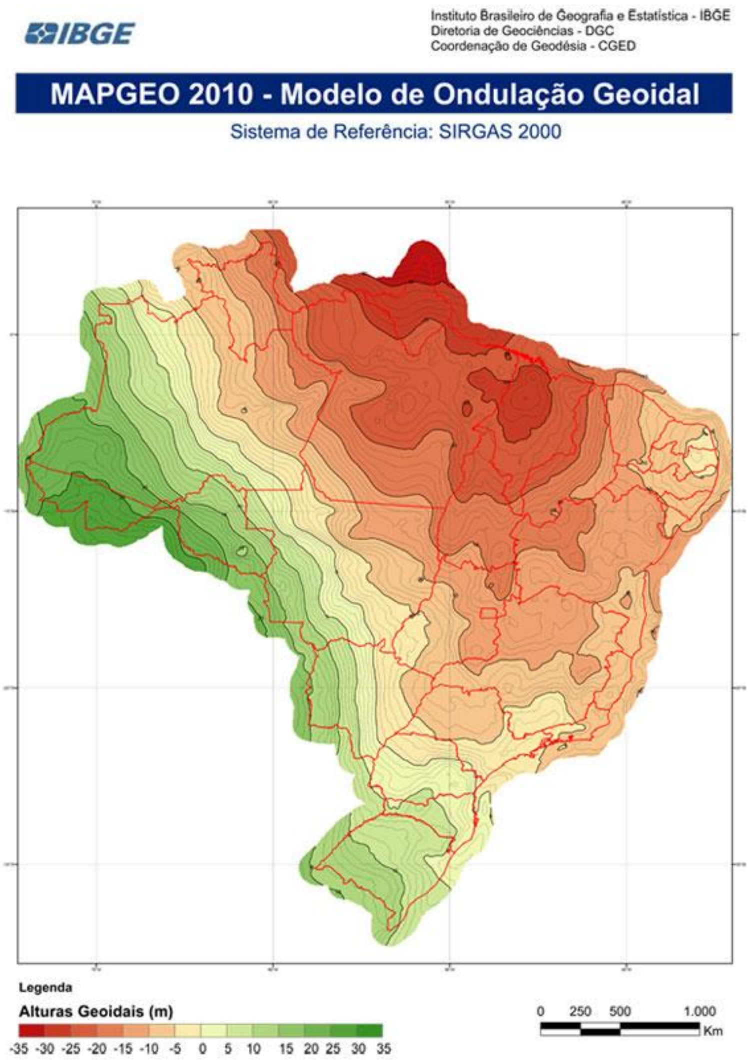


Kingdon, Vanicek and Santos (2010). "Testing Stokes integration with geopotential models." CGU/CMOS Assembly.

SHGeo: Mexican Geoid



SHGeo: Brazilian Geoid



Possible via the *National Geospatial Framework Project*

Rigorous Orthometric Heights

- Our contribution to Heights System Unification
- Rigorous evaluation of the mean value of the Earth's gravity acceleration along the plumbline within the topography
- Rigorous orthometric heights can be obtained from Helmert's. orthometric heights.

Table 2 Descriptive statistics of corrections to Helmert's orthometric height from the profile shown in Fig. 2

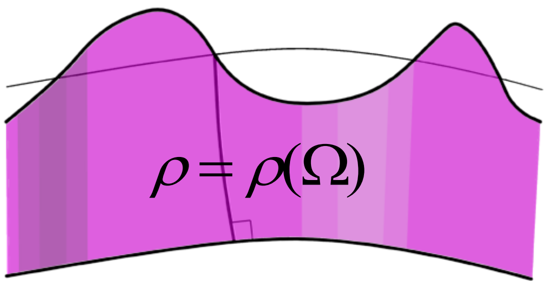
Values in centimetres, rounded to the nearest millimetres

	Correction due to gravity disturbance	Correction due to terrain-roughness	Correction due to lateral variation of density	Correction due for 2nd-order normal gravity	Correction due for 2nd-order Bouguer shell
Mean	6.0	−1.4	0.2	−0.0	−0.0
STD	3.3	2.5	1.1	0.0	0.0
Minimum	0.0	−11.5	−1.9	0.0	0.0
Maximum	15.4	2.5	5.2	−0.1	−0.0

(Vaníček, Santos, Tenzer, Kingdon, Ellmann, Martin, Featherstone, Kuhn, 2004-2006)

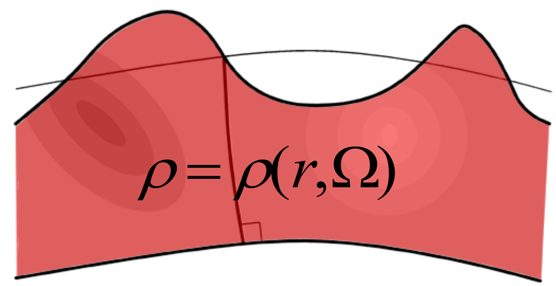
Orthometric Heights ‘vs’ Normal Heights

- Geoid ‘vs’ Quasi-geoid
- Modelling topographical density for geoid determination
- How much 2D or 3D density affect the geoid (and as consequence orthometric heights)?



2D Density Model

vs

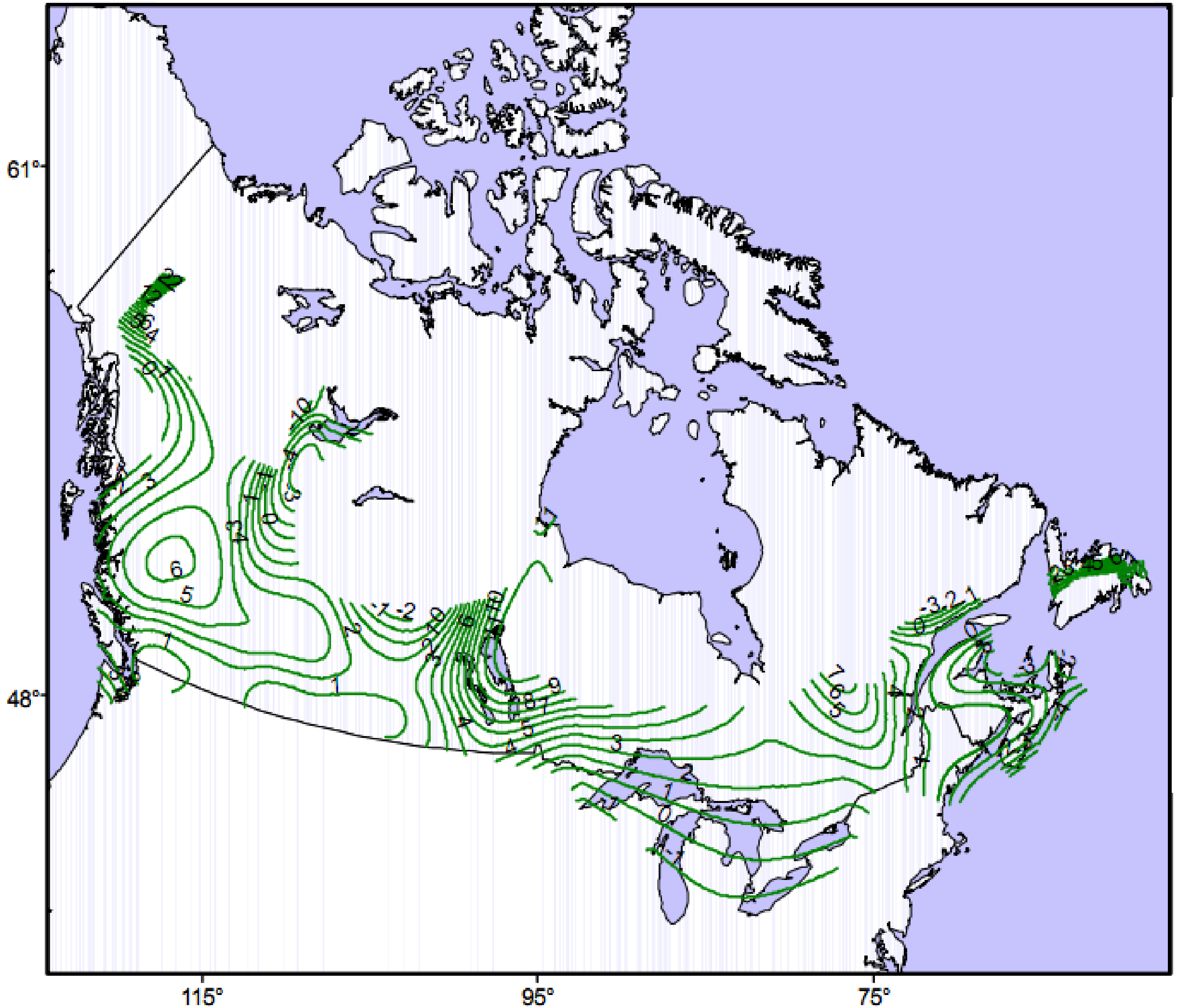


3D Density Model

(Kingdon, Vaníček, Santos, 2008-10)

Pattern of vertical crustal motion in Canada

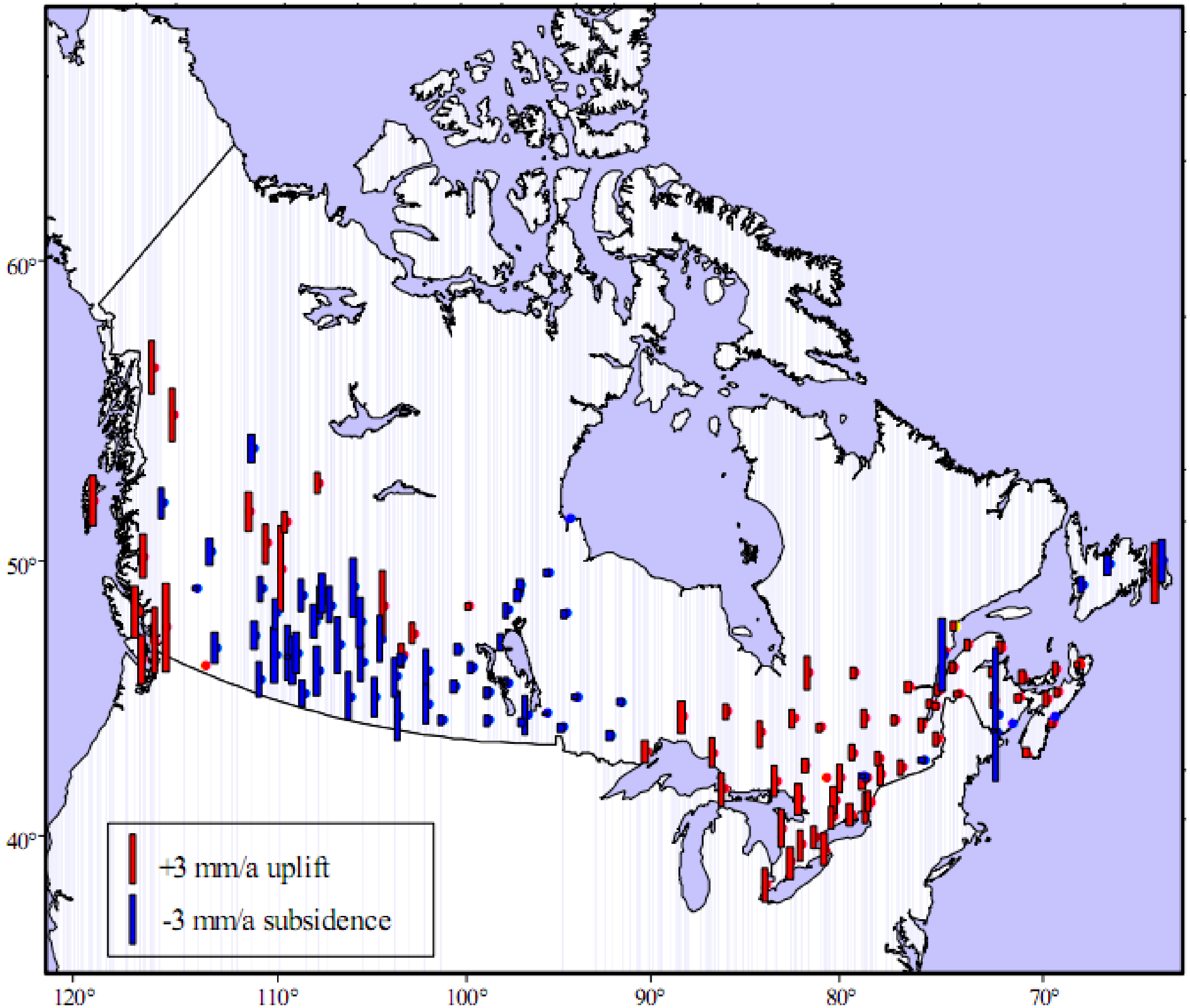
- mm/year



Koohzare, Vaníček, Santos, 2008)

Rate of geoidal changes

- mm/year

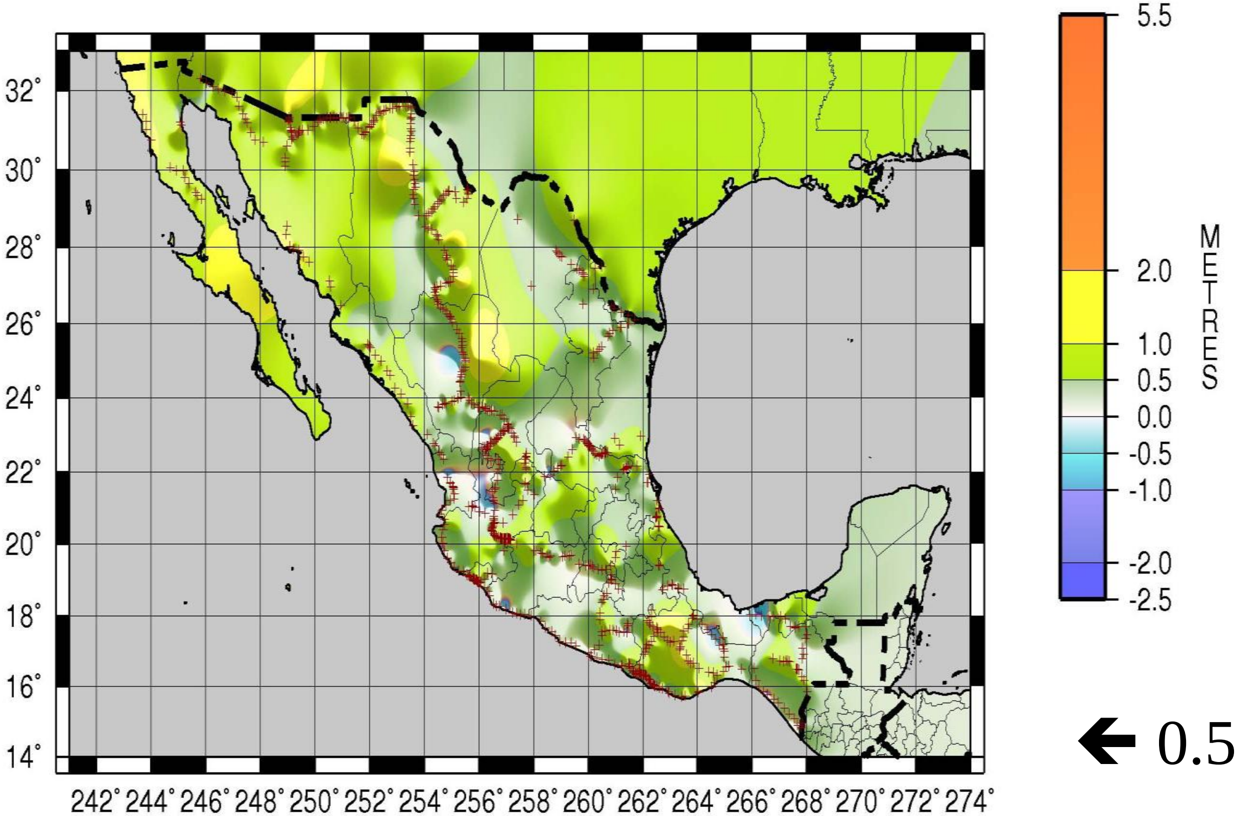


Koohzare, Vaníček, Santos, 2008)

New EGM 2008 Model

- UNB participated in the evaluation of the new EGM08
- Test areas: Mexico and New Brunswick

Santos M. C., D. Avalos, G. Baker and P. Vaníček (2008). "Evaluation of the *beta* EGM08 Geopotential Model based on Mexican Data." Gravity, Geoid and Earth Observation – GGEO 2008 Symposium – 23-27 June, 2008 – Chania, Crete, Greece.



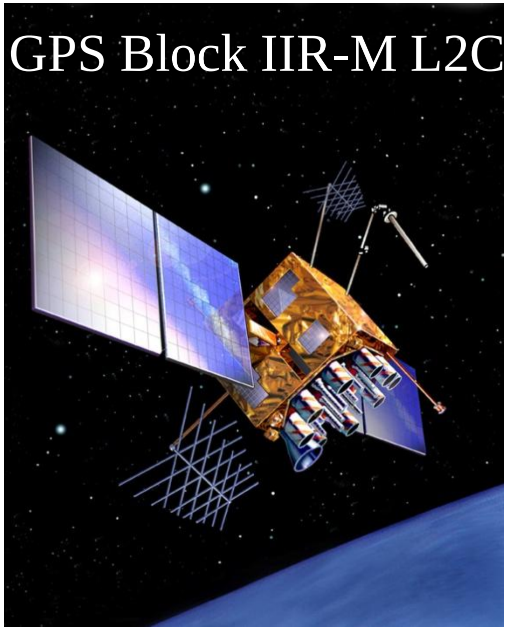
	Geoid Undulation	
	Diff EGM08	Diff EGM96
Mean	0.598	0.787
Maximum	0.701	1.044
Minimum	0.462	0.608
Median	0.614	0.808
Std. Deviation	0.070	0.117

← 0.5 m RMS

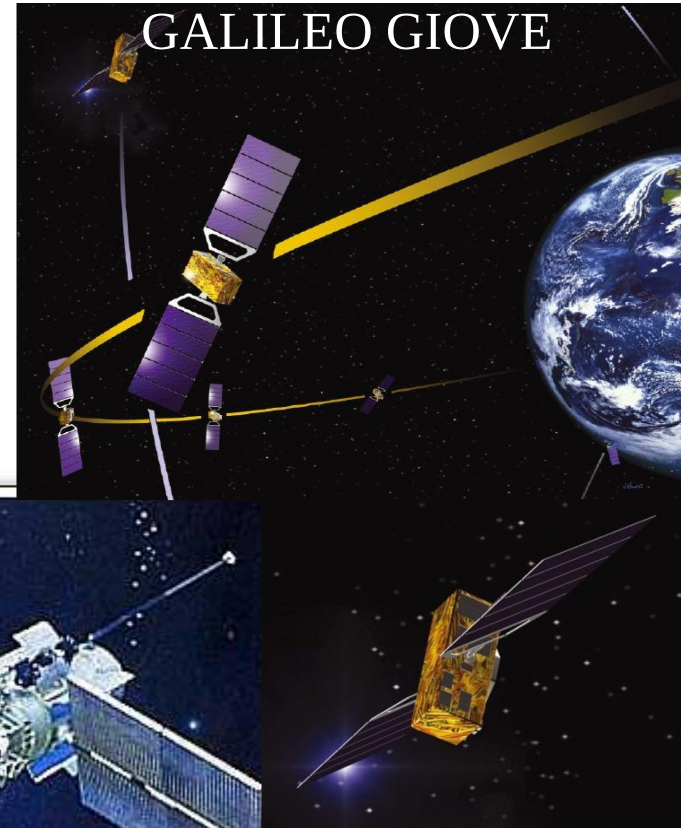
Positioning and Kinematics

- Advancements in the past 10 years
  - Modernization of GPS (new satellites and new signals), the revamping of GLONASS and the emergence of new systems
  - Geodetic networks for Earth monitoring, deformation monitoring, ionosphere, troposphere, WADGPS
  - Application of GPS in scientific satellites (POD)
  - Improvements in modelling neutral-atmospheric (a.k.a. tropospheric)
    - ✓ Numerical Weather information
  - Advances in modelling GPS observations for RTK and Precise Point Positioning

GNSS


GPS Block IIR-M L2C


GPS Block IIF L5


GALILEO GIOVE


Compass


GLONASS


QZSS
Michibiki

Number of active satellites

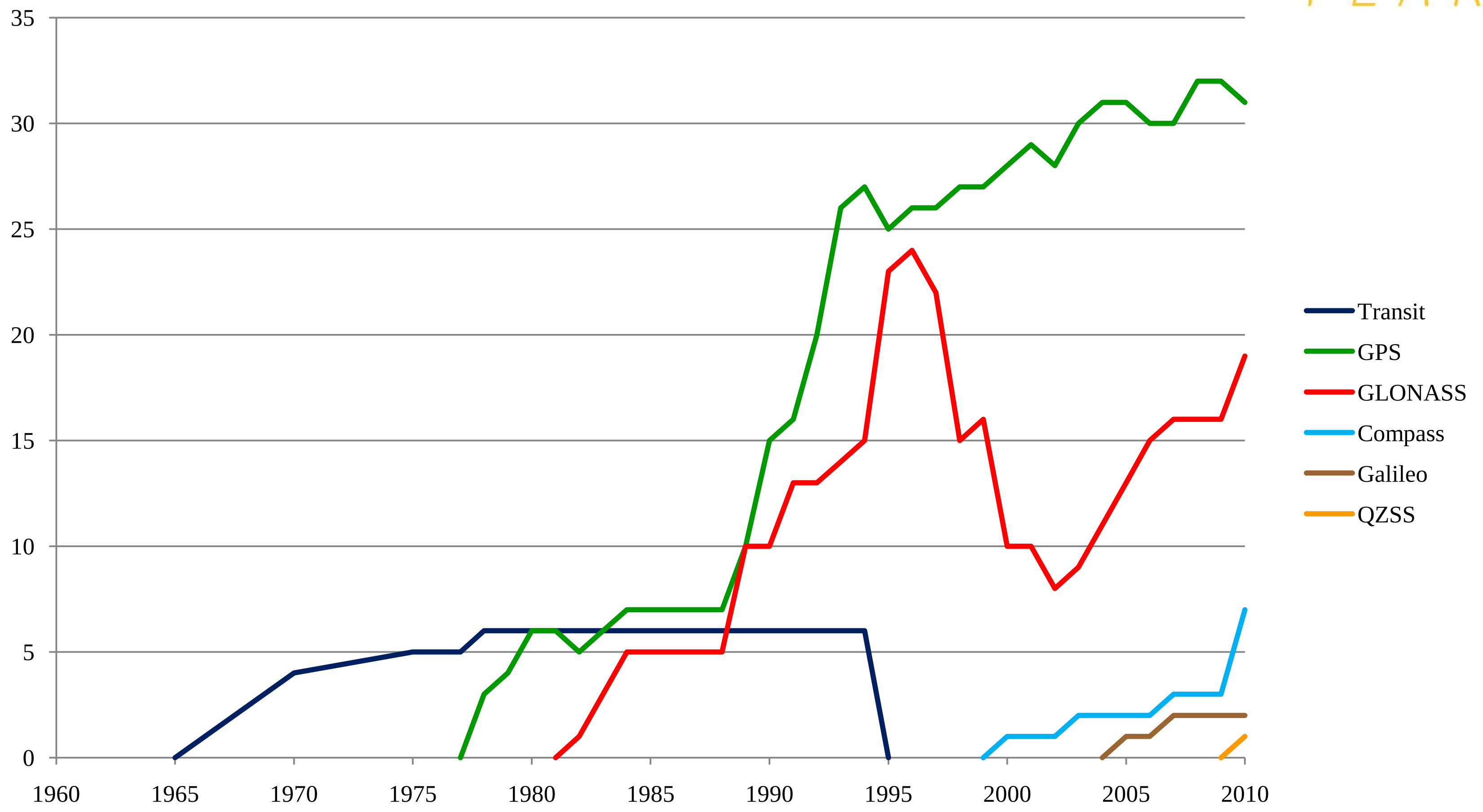
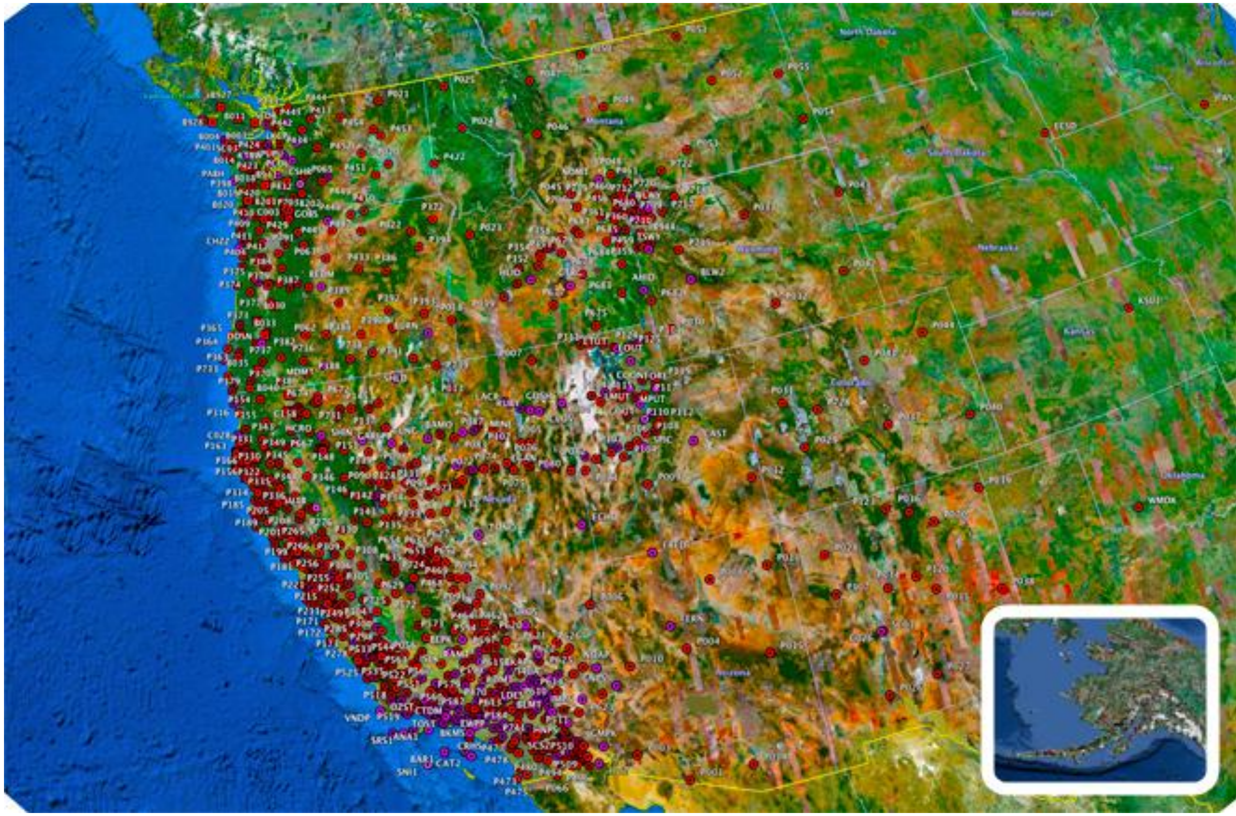


Plate Boundary Observatory (PBO)

- geodetic component of *EarthScope* project
- 1100 permanent GPS stations; 78 Borehole Seismometers, 74 Borehole Strainmeters, 26 Tiltmeters and 6 Laser Strainmeters (LSM)
- collecting data on a real-time to near-real-time basis.

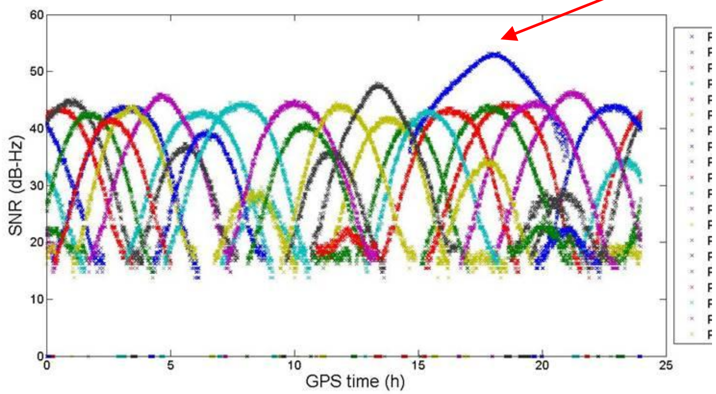


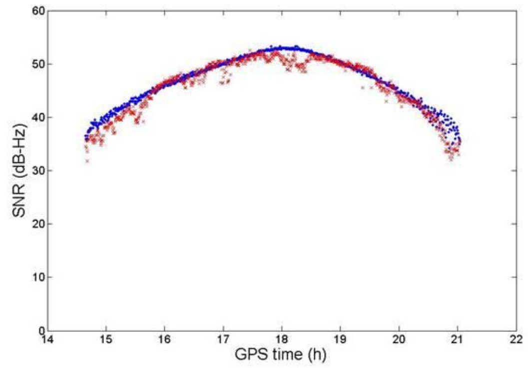
Other networks around the world: IGS, volcanoes, tsunami, atmosphere, etc)

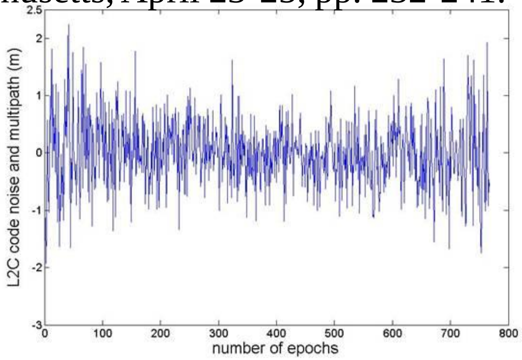
L2C – New 'Civil' GPS Signal

- Study of the new open civil signal, called <u>L2C</u>.

Sükeová, L, M. C. Santos, R. B. Langley, R. F. Leandro, O. Nnani, F.G. Nievinski (2007). "GPS L2C Signal Quality Analysis." *Proceedings of the ION 63rd Annual Meeting*, Cambridge, Massachusetts, April 23-25, pp. 232-241.







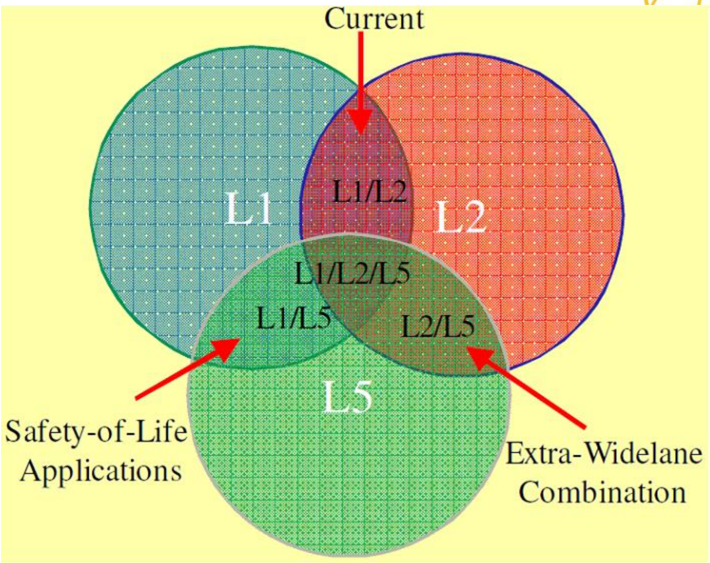
- First determination of bias between P2 and L2C signals

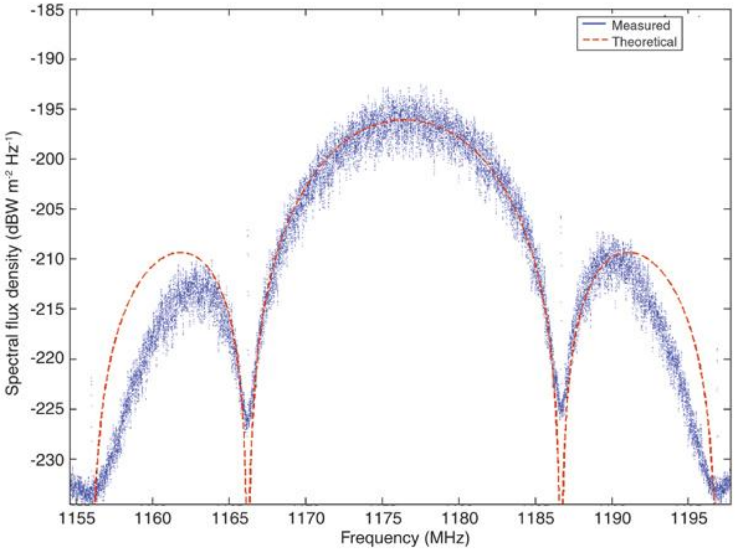
Leandro, R. F., R.B. Langley, and M.C. Santos (2007). "Estimation of P2-C2 Biases by Means of Precise Point Positioning." *Proceedings of the ION 63rd Annual Meeting*, Cambridge, Massachusetts, April 23-25, pp. 225-231.

L5 – GPS now 'triple frequency'

- Triple Frequency ambiguity resolution possible

Urquhart, L and M. C. Santos (2008). "An analysis of multi-frequency carrier phase linear combinations for GNSS." 37th COSPAR Scientific Assembly, 13-20 July, 2008, Montreal

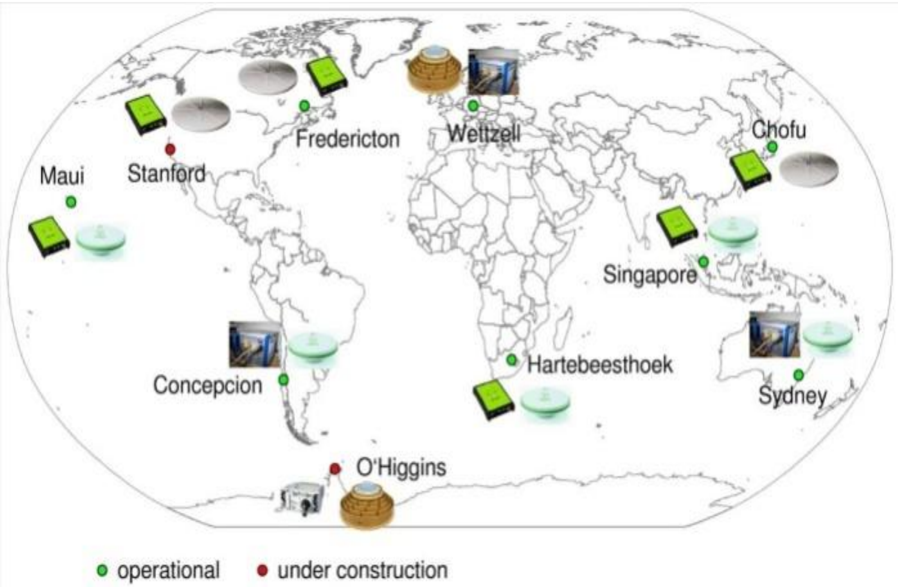


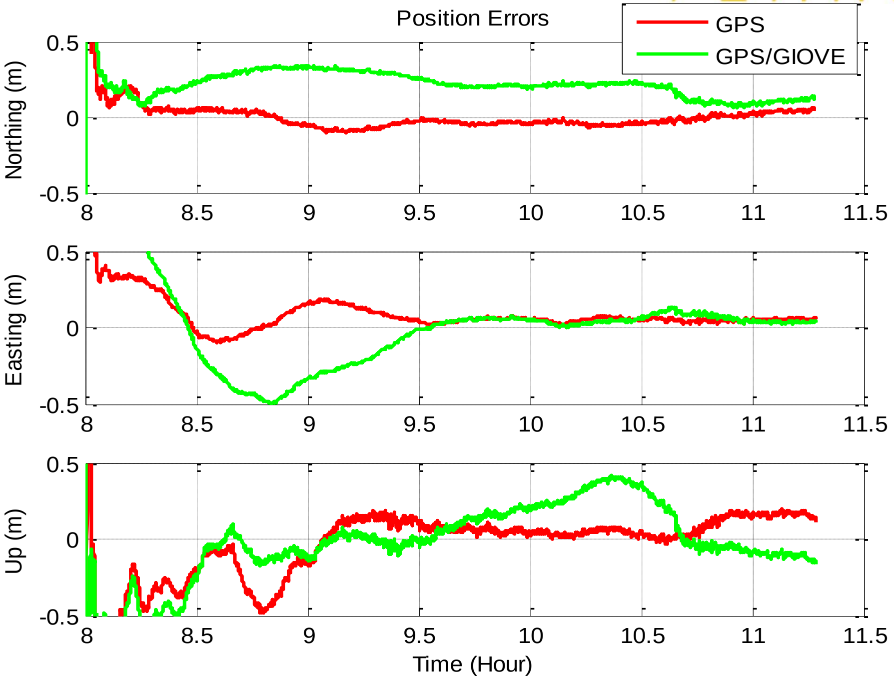


- SVN49 Anomaly

PPP including GIOVE (Galileo) data

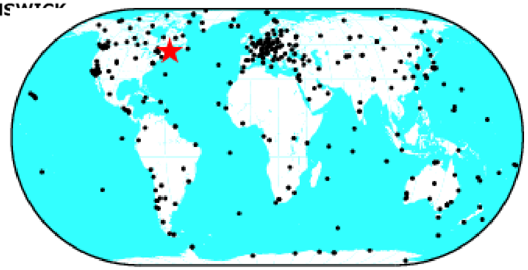
- CONGO network





- Cao, Hauschild, Steigenberger, Langley, Urquhart, Santos, and Montenbruck (2010). Performance Evaluation of Integrated GPS/GIOVE Precise Point Positioning. ION NTM.

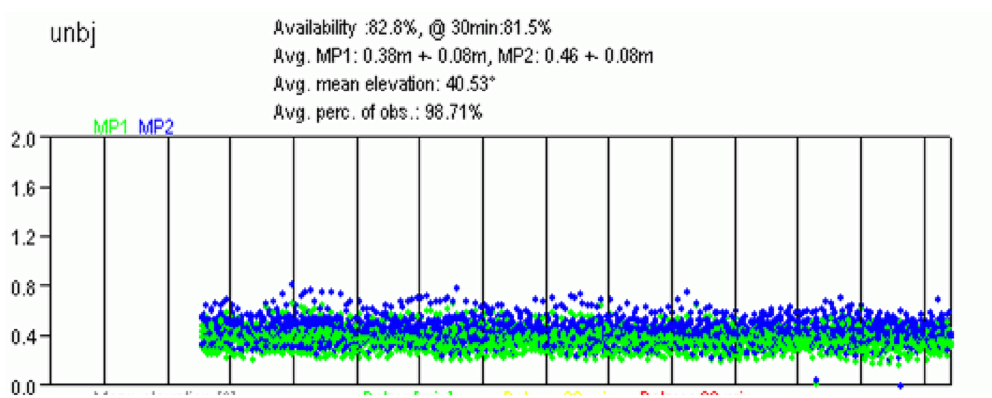
UNBJ – UNB's IGS station



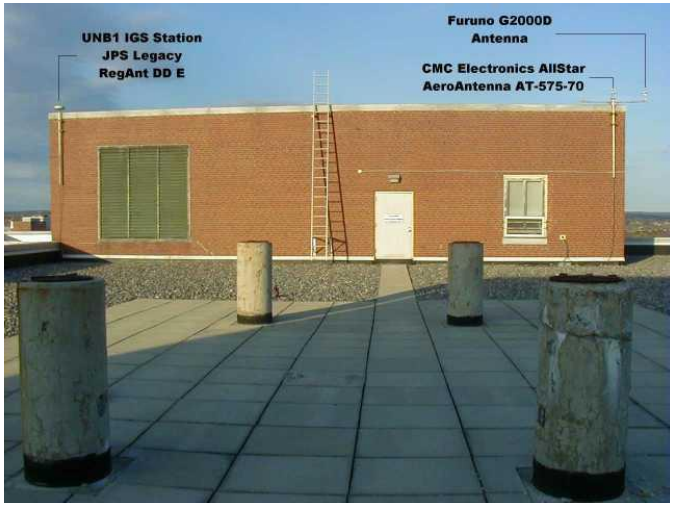
http://igscb.jpl.nasa.gov

The International GNSS Service (IGS) is a voluntary federation of more than 200 worldwide agencies that pool resources and permanent GPS & GLONASS station data to generate precise GPS & GLONASS products, such as precise satellite positions.

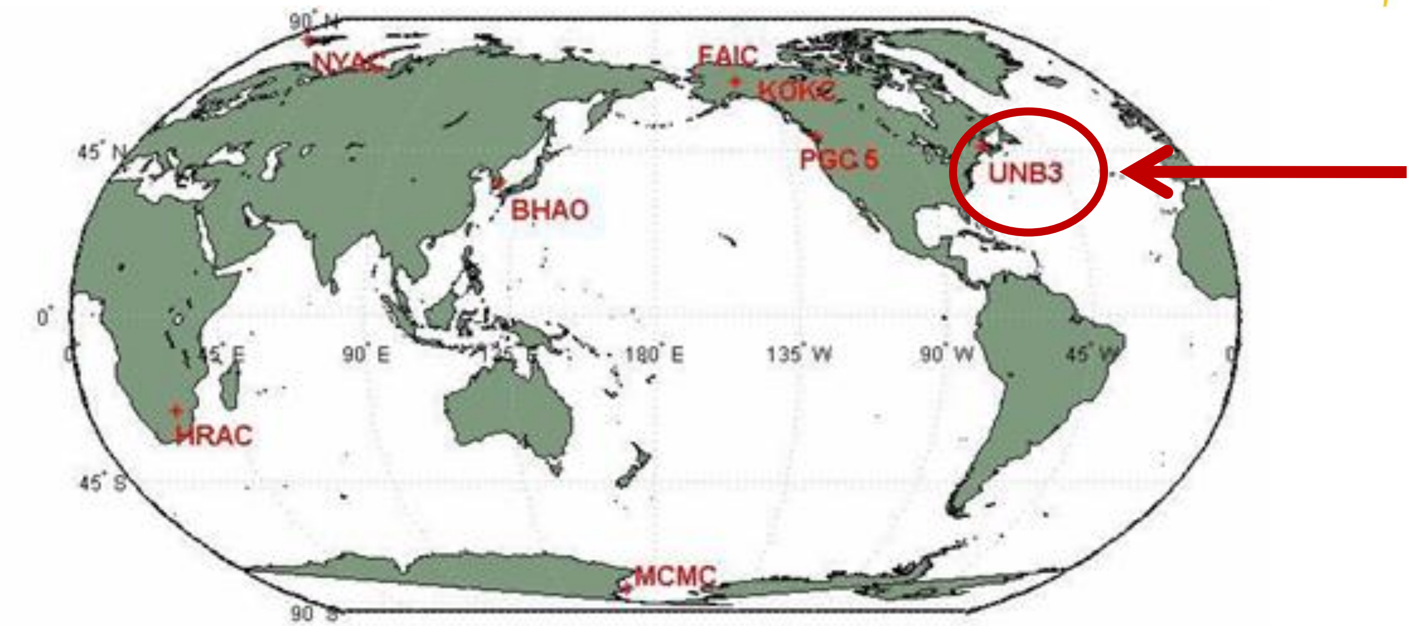
The University of New Brunswick runs a continuously operating GPS/GLONASS receiver situated on the roof of the Head Hall building, on the UNB Fredericton campus. Data have been continuously archived since 15 July 2001.



http://www.gfz-potsdam.de



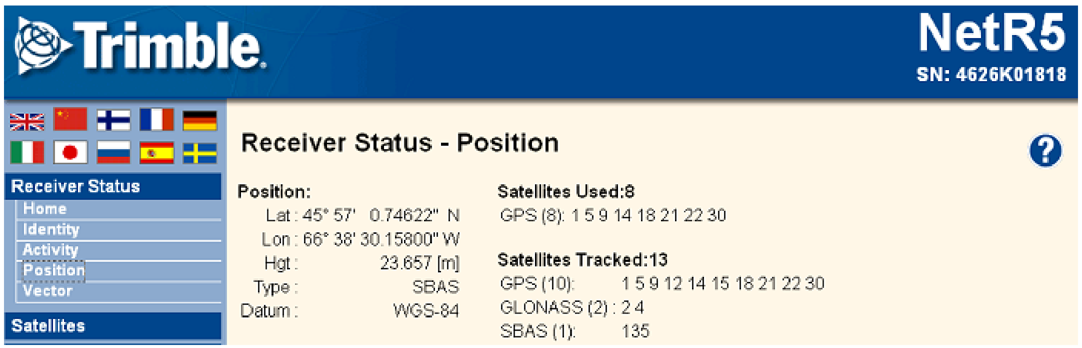
UNB3 Station L2C Signal

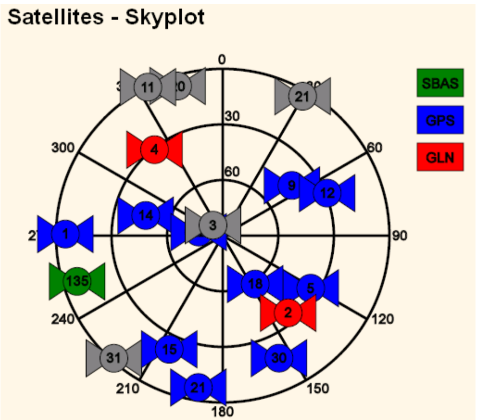


IGS has organized a network of L2C capable GPS receivers which have been established in different places. One of these stations is UNB3, operated by UNB. The role of this project is to analyze the quality of the new signal, as well as the impact of its use for positioning and navigation.

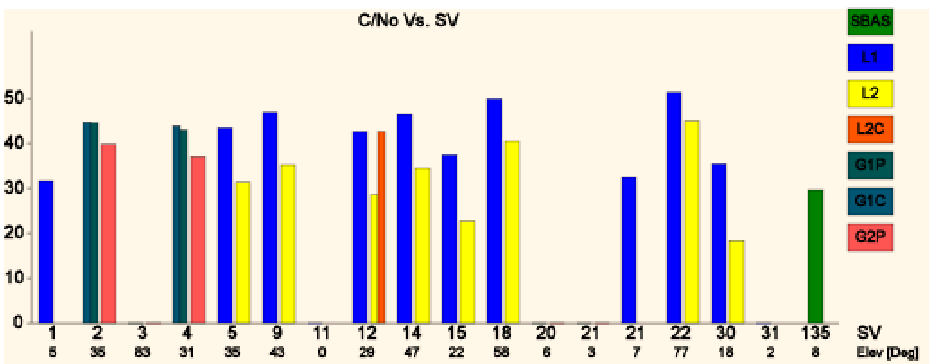
UNB3 Station – Trimble NetR5 Receiver

GPS station UNB3 is operated with a Trimble NetR5 receiver. This receiver was donated by Trimble to UNB. In compensation for this donation, the members of the GNSS Group provide feedback to Trimble with respect to performance of the receiver and its related utilities.



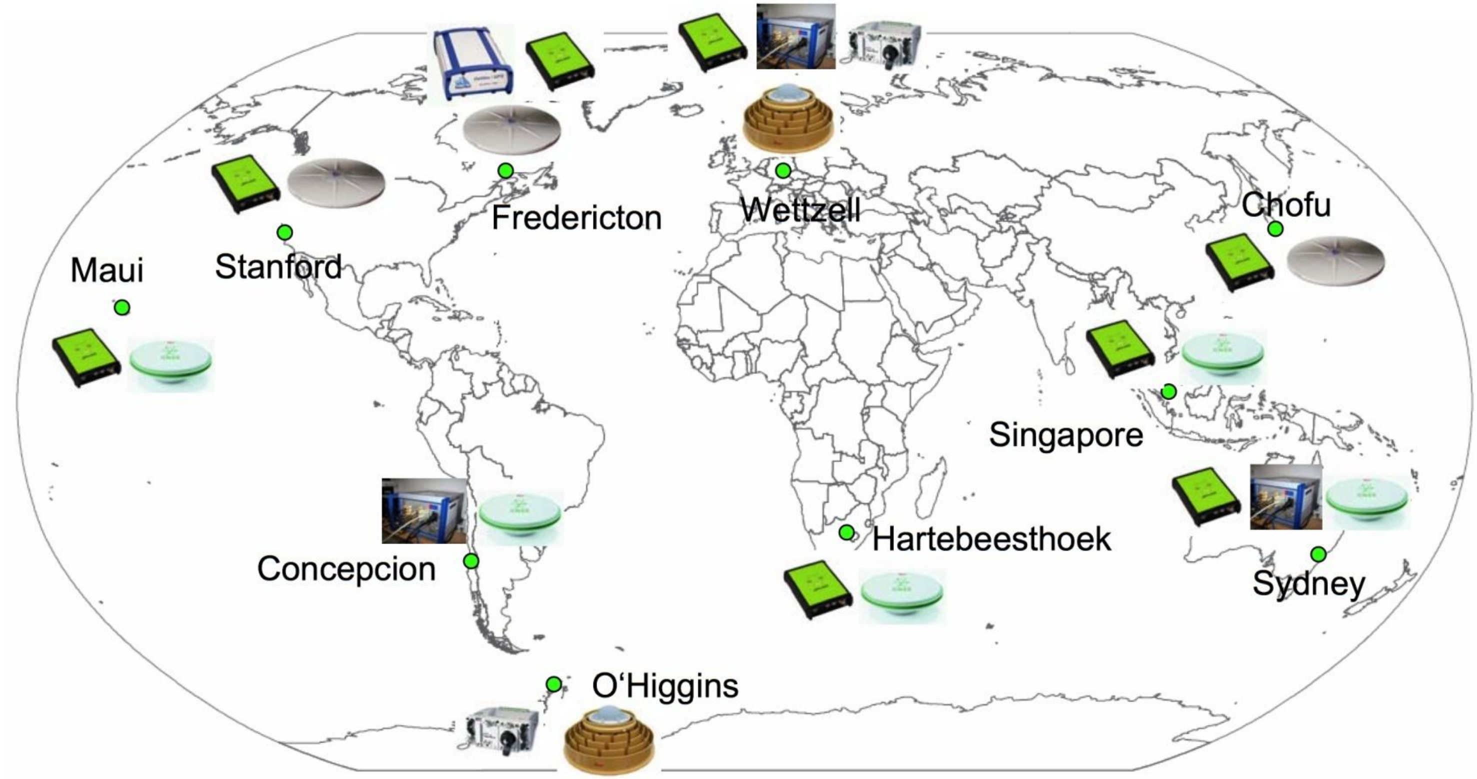


http://trimble.com



CONGO Network

The UNB GNSS Research Group hosts receivers of the Cooperative Network for GIOVE Observation (CONGO). This global real-time network, established by the German Aerospace Center (DLR) and the German Federal Agency for Cartography and Geodesy (BKG), tracks GPS and GIOVE satellite signals on three frequencies.

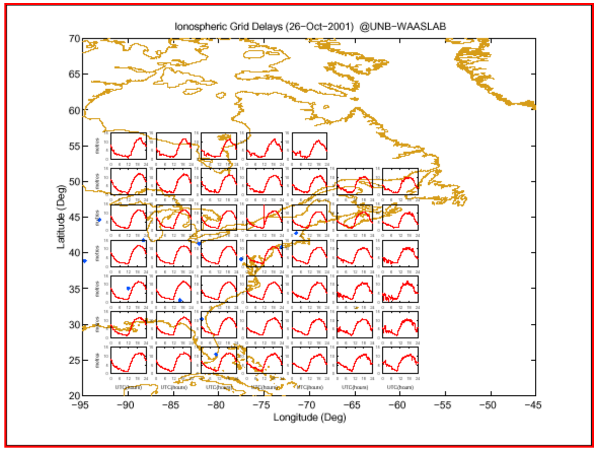


UNB WAAS Monitoring Station

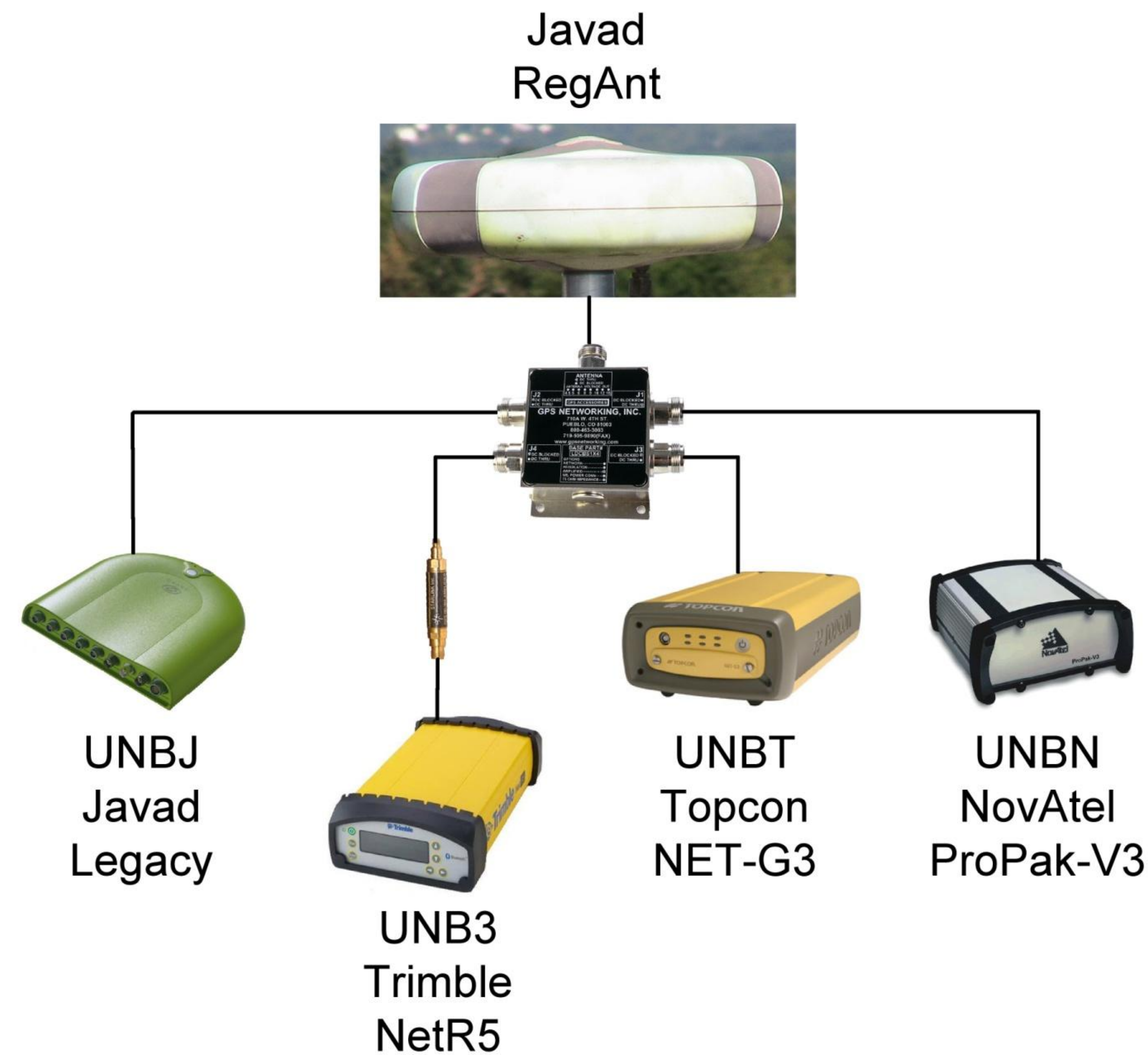
http://gps.faa.gov

WAAS (Wide Area Augmentation System) is a system developed to allow the use of GPS as a primary means of navigation in the U.S. National Airspace System. It is designed to provide accurate, continuous, and all-weather coverage to satisfy today's aviation needs. In this system, geostationary satellites send messages with information used to improve navigation accuracy and reliability.

The University of New Brunswick runs a continuously operating GPS receiver with WAAS capability. The goal of this work is to access and test the WAAS messages.



Some Other UNB 24/7 Receivers



Receivers have also been donated to UNB by NovAtel and Topcon in return for receiver performance feedback.

Additional 24/7 receivers monitor WAAS and the Canadian DGPS Service signals.

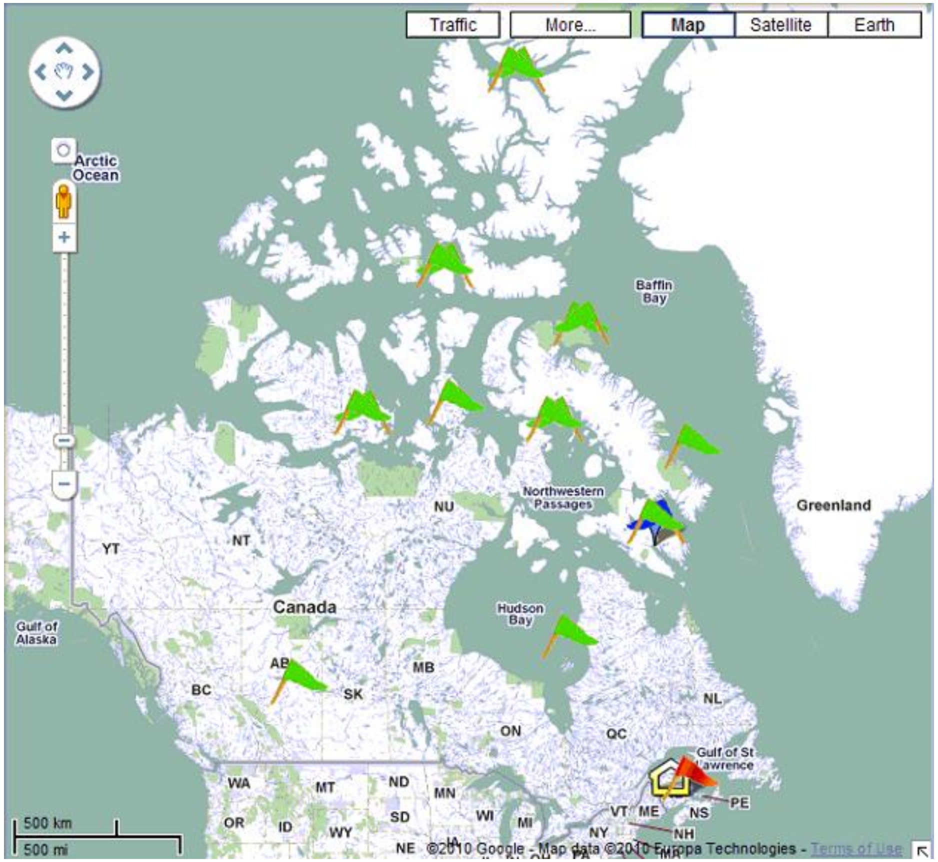
UNB2 - UNB's GPS-based Weather Station

UNB runs a continuously operating GPS receiver dedicated to meteorology. The receiver is part of SuomiNet which is a network of GPS receivers at universities and other locations providing real-time atmospheric precipitable water vapour measurements and other geodetic and meteorological information. The data is being used operationally by meteorologists to improve short term weather forecasts.

The GPS receiver is supplemented by accurate electronic weather sensors and a water vapour radiometer.

Canadian High Arctic Ionospheric Network (CHAIN)

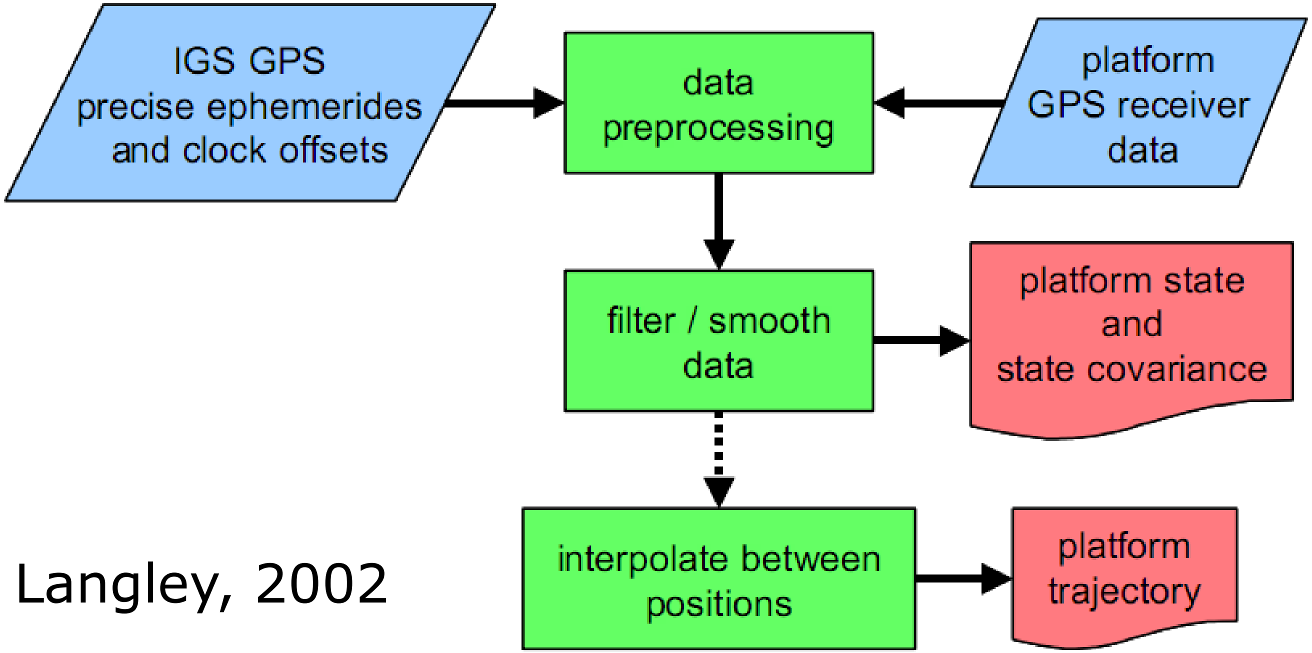
- Network of Canadian Advanced Digital Ionosondes (CADI) and (scintillation) GPS Receivers



Jayachandran, P. T., R. B. Langley, J. W. MacDougall, S. C. Mushini, D. Pokhotelov, A. M. Hamza, I. R. Mann, D. K. Milling, Z. C. Kale, R. Chadwick, T. Kelly, D. W. Danskin, and C. S. Carrano (2009). "The Canadian high arctic ionospheric network (CHAIN)." *Radio Science*., 44, RS0A03 doi:10.1029/2008 RS004046.

POD

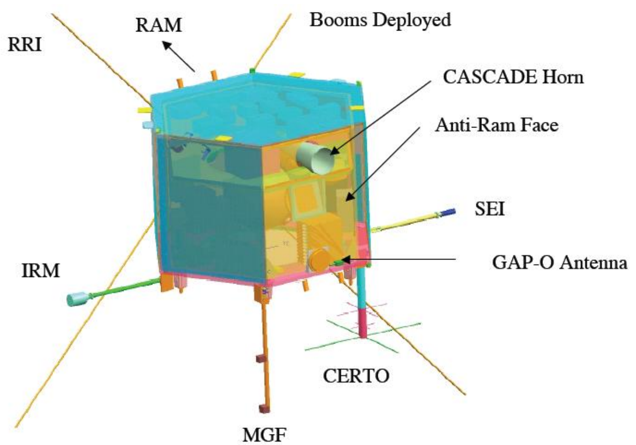
- On-board GPS receivers determining the orbit of low Earth orbiting satellites.
- CHAMP Orbit Determination with GPS Phase-Connected, Precise Point Positioning.

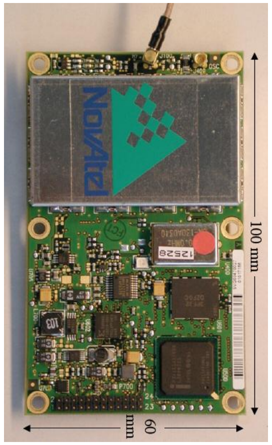


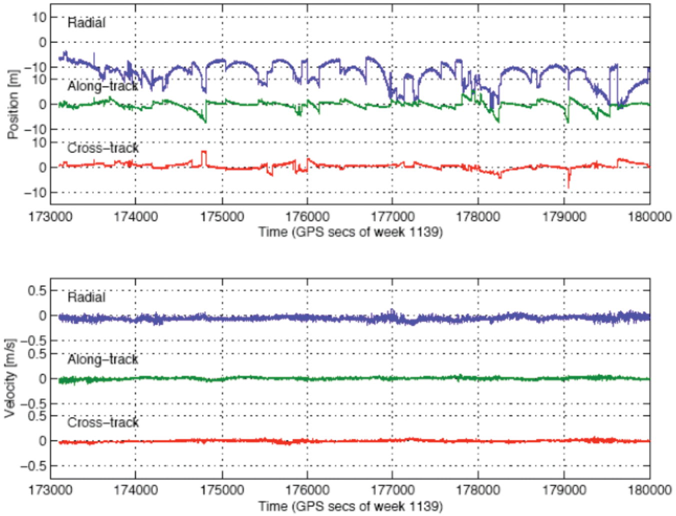
Bisnath, Langley, 2002

Qualification of GPS Receivers for Spacecraft

CASSIOPE is a Canadian satellite scheduled for launch in 2007 and its mission is designed for a wide range of tasks. Once in orbit the satellite position and velocity will be determined by means of onboard GPS receivers. This satellite will carry a device called GAP which consists of 5 NovAtel OEM4-G2L GPS receivers. UNB is responsible for GAP design and testing.

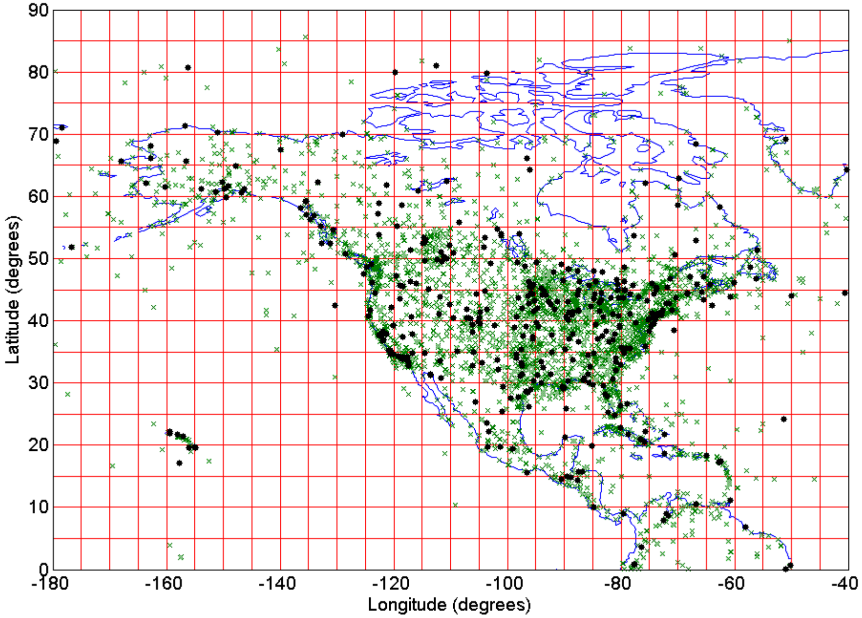


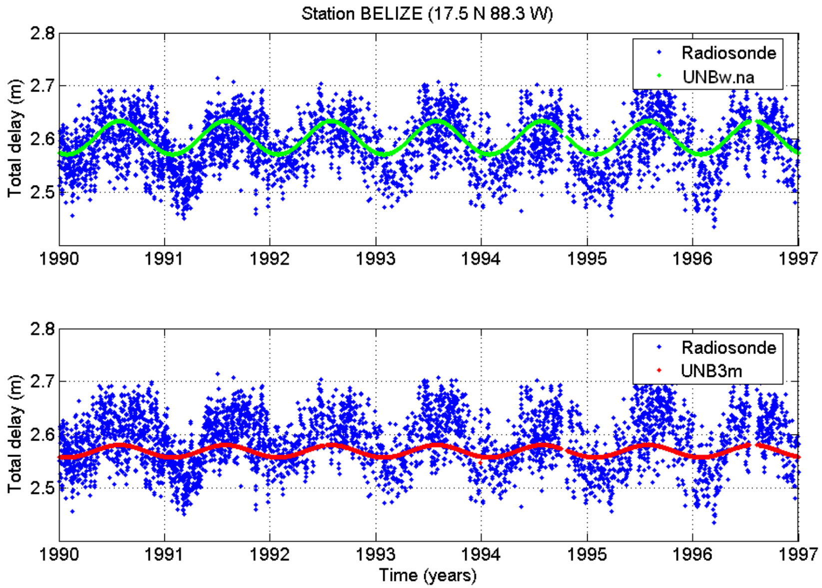




An extensive series of tests has been conducted to assess the suitability of the use of this GPS receiver in this application. These include GPS signal simulator tests to validate the signal acquisition and tracking performance, as well as environmental tests to demonstrate the survivability of the receiver hardware under space conditions.

UNB3 Neutral-Atmosphere model

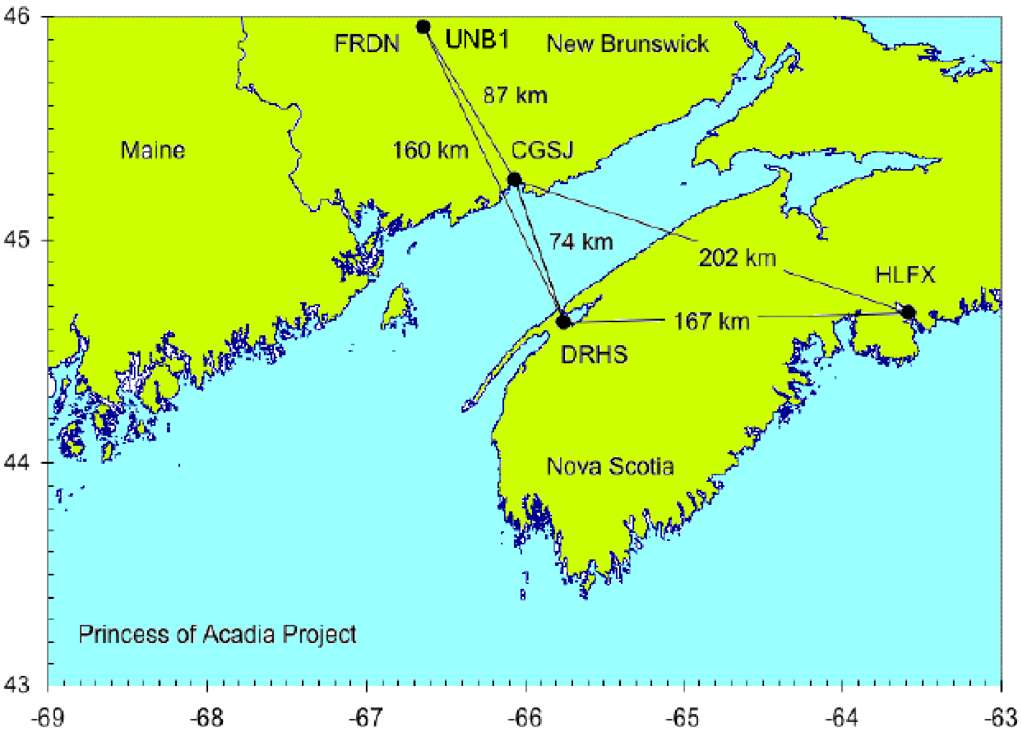




- Leandro, Langley and Santos (2008). "UNB3_pack: A neutral atmosphere delay package for radiometric space techniques." *GPS Solutions*, Vol. 12, No. 1, pp. 65-70.
- Leandro, Santos and Langley (2009). "A North America Wide Area neutral atmosphere model for GNSS applications." *Navigation*, Vol. 56, No. 1, pp. 57-71.

Numerical Weather Model

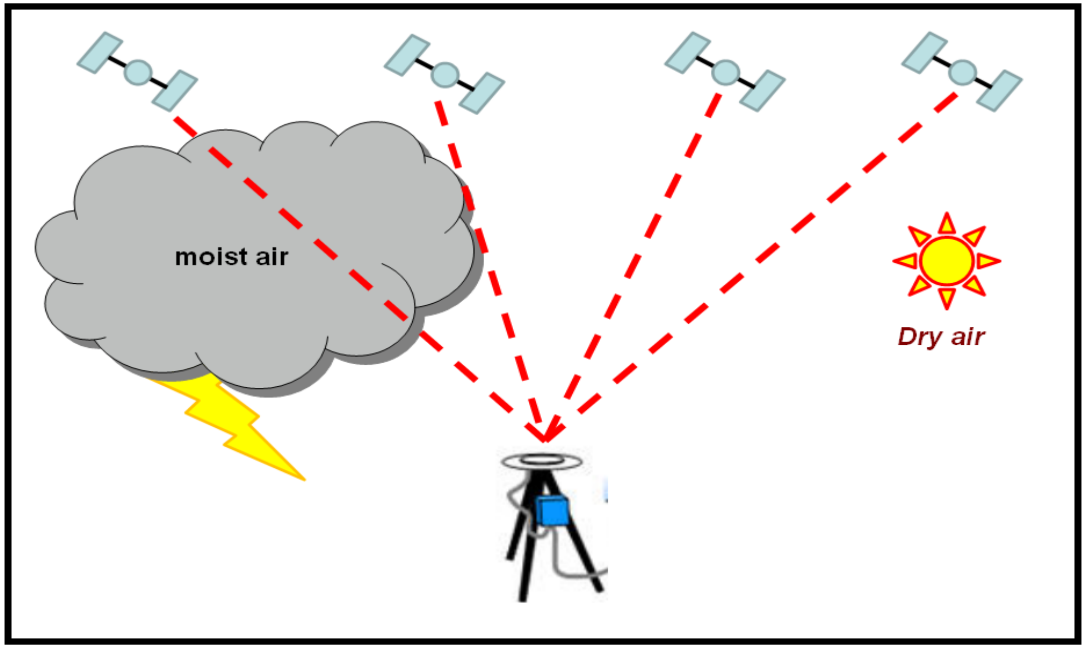
- Princess of Acadia Project
  - Differential troposphere ➔ use Numerical Weather Prediction models

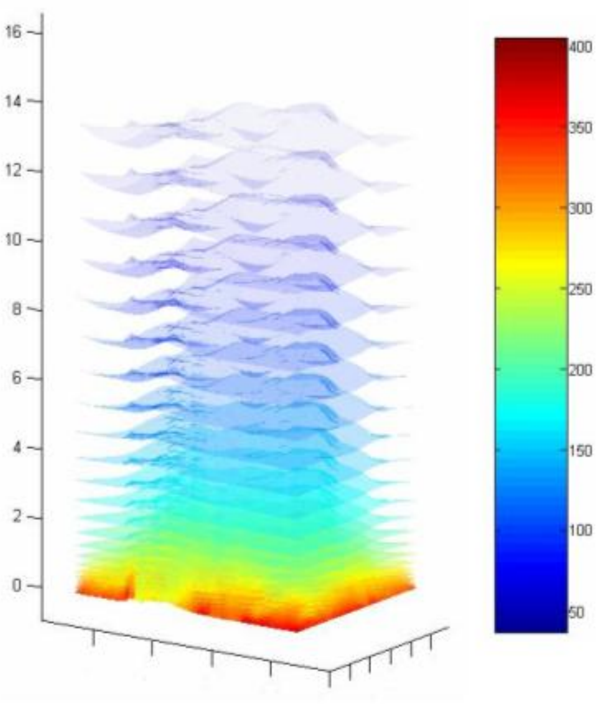


Azimuthal Asymmetry

- Elevation angle dependence
- Azimuth angle dependence

Azimuthal asymmetry



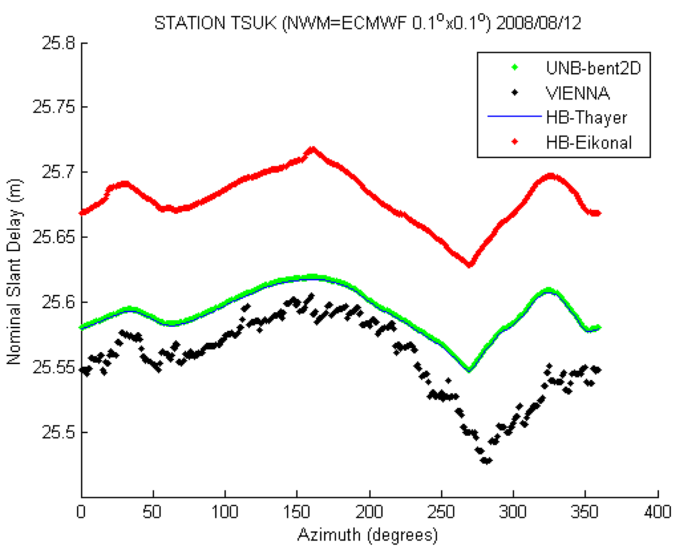


- Current research:
  - Validation and comparison of ray-tracing algorithms (under IAG Working Group): UNB, IGG, NiCT, GS Toulouse and GFZ (slide 20).
  - Incorporate info from NWM into closed-form mapping functions to better represent asymmetry of the Earth's neutral-atmosphere by means of gradients, spherical harmonics, etc.

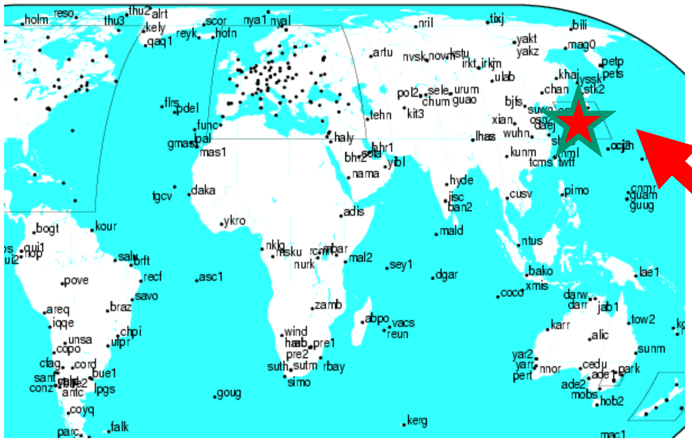
    - ✓ Urquhart, Nievinski, Santos (2009)." Fitting of NWM Ray-tracing to Closed-form Tropospheric Model Expressions." IAG2009 (Accepted);
    - ✓ Urquhart, Nievinski, Santos (2010). "Evaluation of different strategies for mitigating azimuthally asymmetric tropospheric delays." EGU2010.

Weather Models for GPS

The use of numerical weather models (NWM) for the reduction of space geodetic observations is very complex. UNB has been actively participating in the *IAG Working Group 4.3.3: NWM for Positioning* whose responsibility is to assess the technical aspects of using NWM for modeling the atmospheric delay in space geodetic techniques.



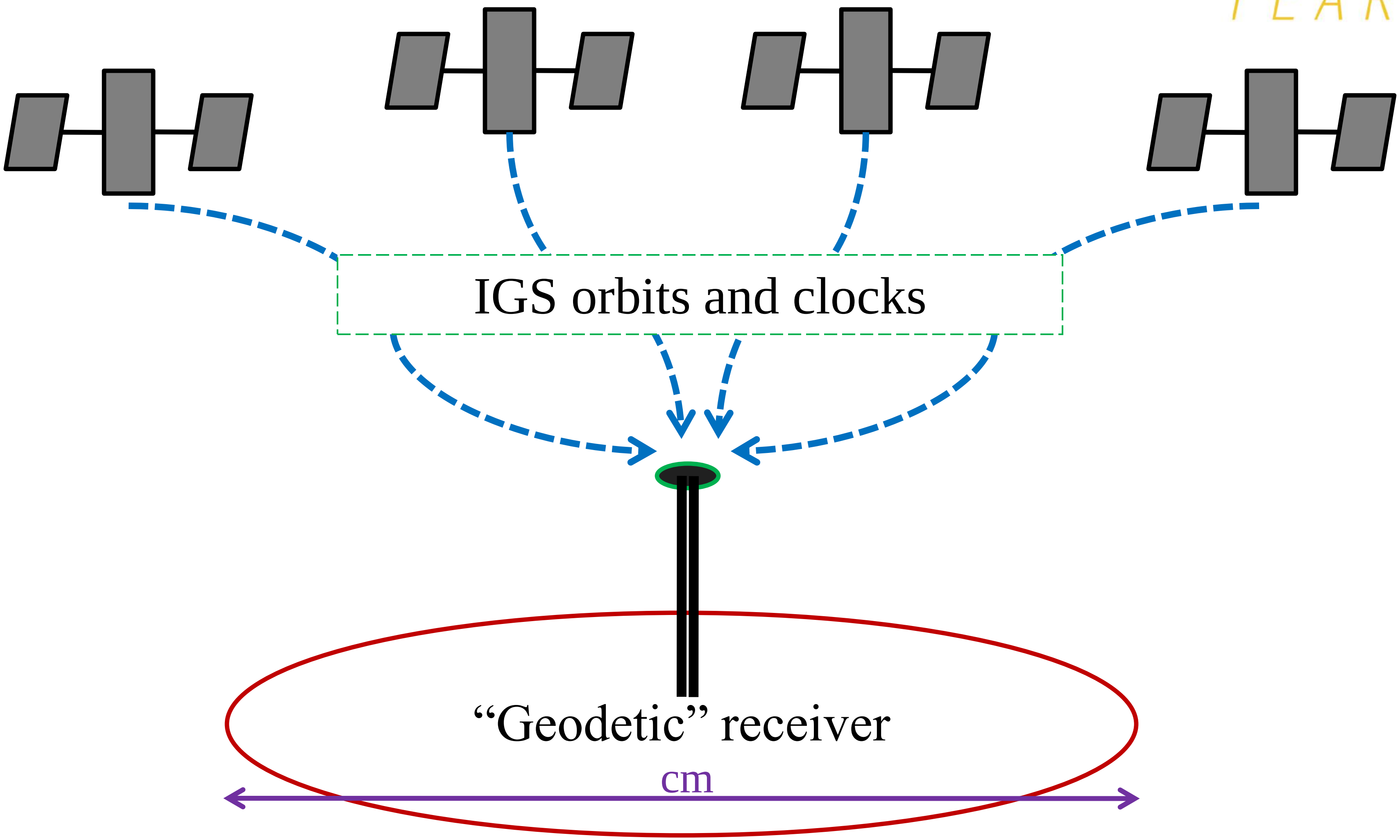
Slant delay at 5° elevation angle for various ray-tracing algorithms



http://igscb.jpl.nasa.gov

The working group has recently undertaken a ray-tracing benchmark campaign to assess and compare the various techniques and algorithms being used throughout the world.

Precise Point Positioning



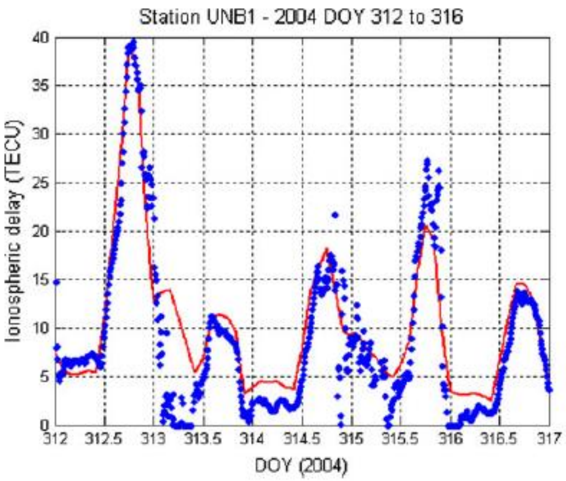
PPP

- GAPS: In-house UNB PPP package
- On-line version gaps.gge.unb.ca (over 3,000 hits this year, until yesterday)
- PPP processing plus data analysis:
  - (pseudo-)satellite clock;
  - ionospheric delay (iono maps);
  - code biases;
  - code multipath and noise.
    - ✓ Leandro (2009). "Precise Point Positioning with GPS, a new approach for positioning, atmospheric studies, and signal analysis." TR 267 (Ph.D. Thesis).
    - ✓ Leandro, Santos, Langley (2010). "Analyzing GNSS data in PPP software." *GPS Solutions* (online first; in press)

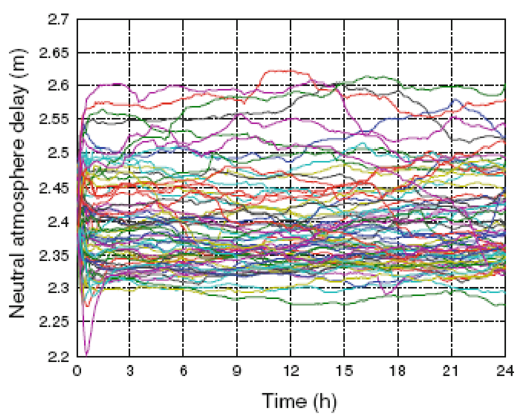
Precise GPS Point Positioning

Upload your RINEX observation files to: <http://gaps.gge.unb.ca>

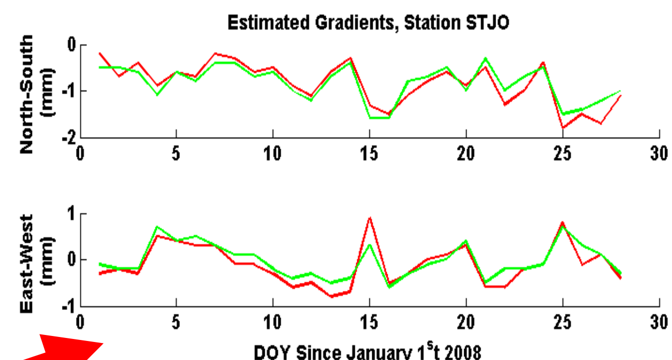
Obtain not only an accurate station position, but also many useful atmospheric parameters.



Ionospheric delay



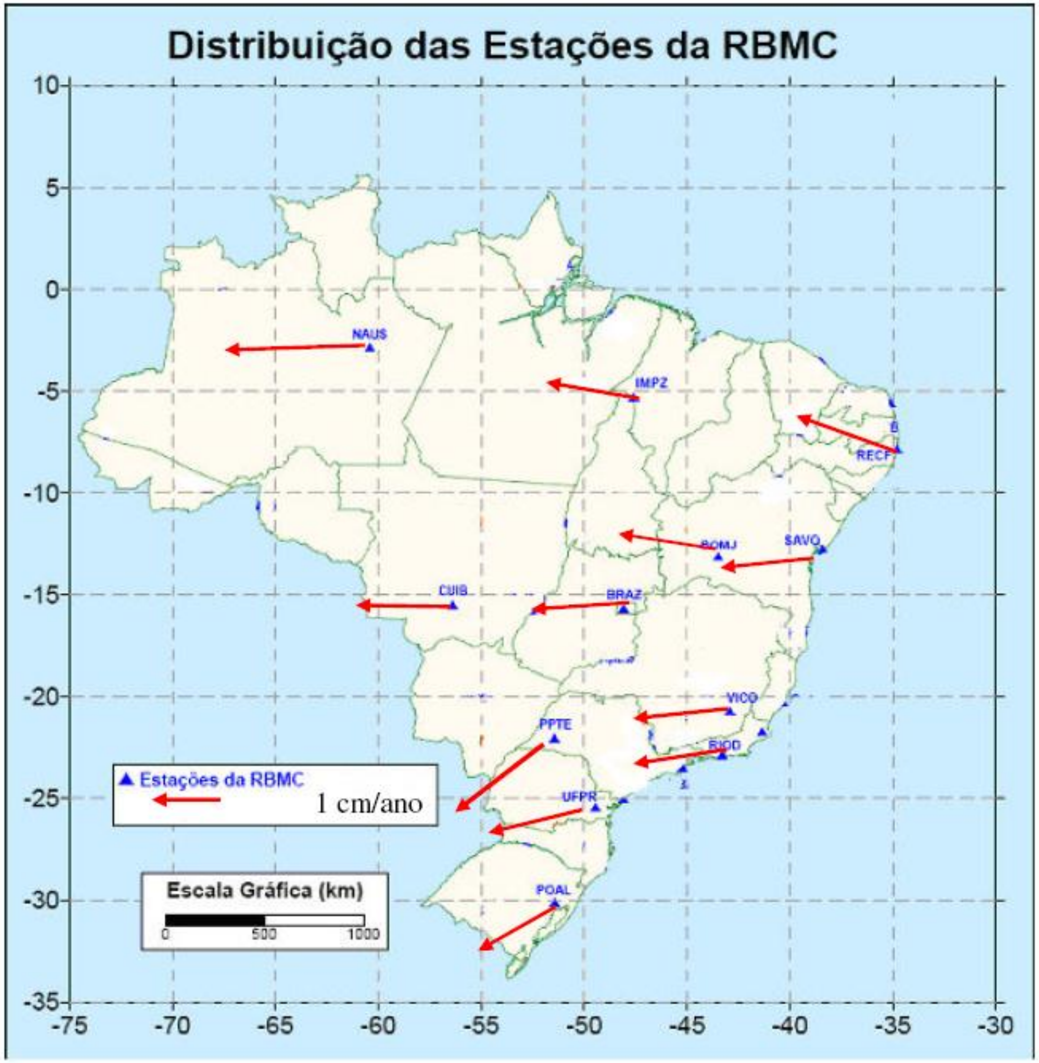
Zenith Tropospheric delay



(Coming Soon!)

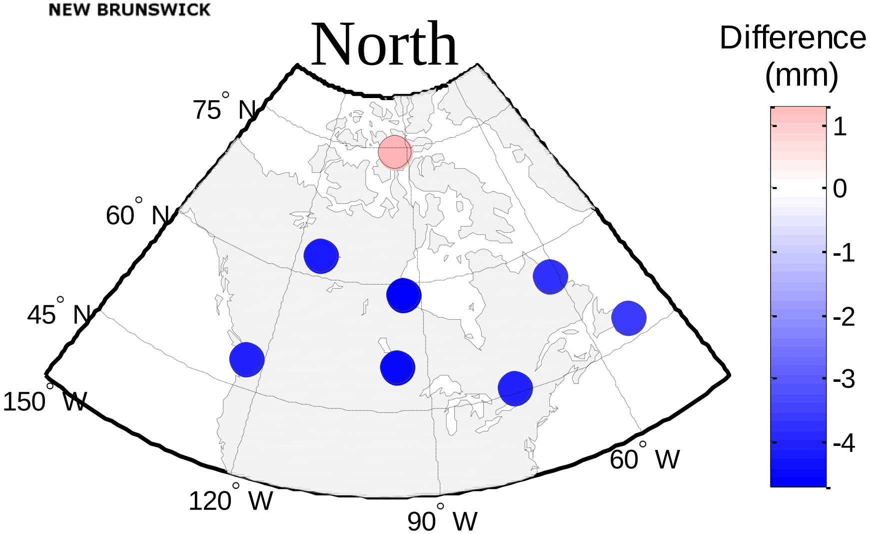
Tropospheric gradients

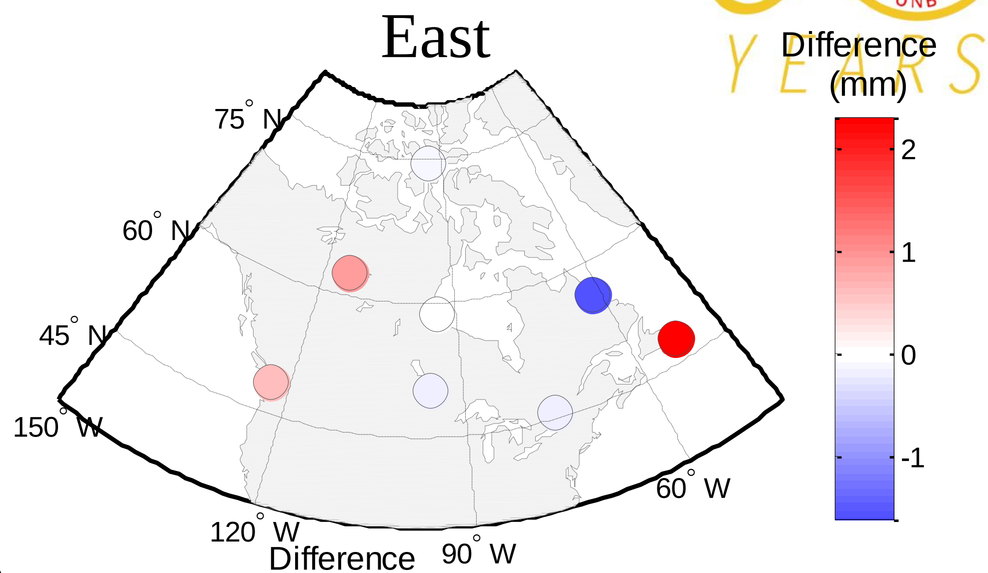
Horizontal and vertical time series analysis

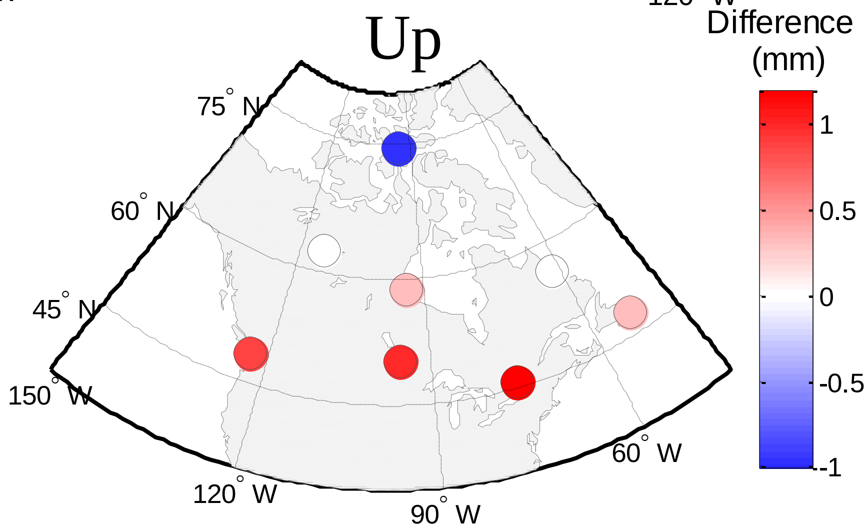


Similar analysis in Mexico (horizontal and vertical)

Geocentric Correction







Difference between the RMS of GAPS when Geocenter correction IS APPLIED

Negative values indicate a reduction in RMS

A new navigation algorithm

- A purely mathematical approach based on the laws of mechanics (e.g., Hamilton's principle), applied in a statistical space.
- licence sold to a private company.
  - Used by the British Navy.

Table 1: comparative results of KF and NNA tests – speed vs. accuracy

Test results from	Time needed for processing	Max. position error	Average position error
Kalman filter	0.02 sec	8 m	3 m
New Navigation Algorithm	0.11, 0.23 sec	2 m	1 m

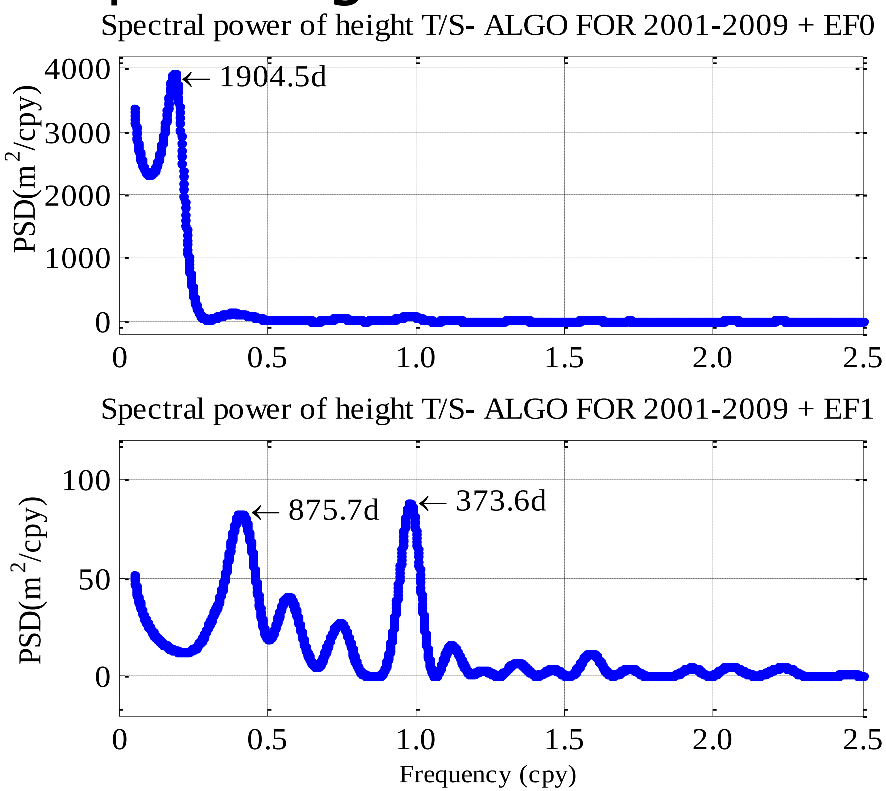
- Advancements in the past 10 years
  - Enhancement of Reference Frames
  - IGS Reprocessing Campaign
    - ✓ Consistent set of GPS orbits and clocks
    - ✓ Consistent set of Earth Orientation Parameters
  - VLBI around the world
    - ✓ not so much in Canada

Analysis of REPRO1 at frequency domain

- Newly reprocessed and consistent IGS time series to be released in the next weeks ➔ REPRO1
  - E.g., incorporates absolute PCV among other model improvements (IERS Conventions)
- How better is it?
- Most importantly: How better can it become?
  - REPRO2 on the horizon
- Objectives:
  - detect remaining periodicities in coordinate and residual time series, at frequency domain;
  - Look for their sources (geophysical; longer, unmodelled terms).

Testing with Canadian stations

- Proof-of-concept using a few CACS stations



- Mtamakaya, Santos and Craymer (2010). "Detection of Vertical Temporal Behaviour of IGS Stations in Canada Using Least Squares Spectral Analysis." *IAG 2009 Proceedings* (accepted)

A Challenging Future

- Challenges and opportunities
  - Centimetre geoid determination for height system modernization
  - Unification of vertical datum worldwide
  - GNSS as an ubiquitous positioning system
  - GGOS
  - Need to integrate and assimilate heterogeneous space-borne airborne and terrestrial data
    - Development in theory and models (and intrumentation)
  - Monitoring the Earth System
    - Climate (*always*) change (not global warming) and natural hazards
    - "Environmental" Geodesy
  - Continue with cooperation with other geosciences in describing dynamic properties of the Earth.

Acknowledgments

- The following former GGE Graduate students are acknowledged for their *hint*'s on future trends in Geodesy:
  - Azadeh Koohzare
  - Jianliang Huang
  - Rock Santerre
  - Spiros Pagiatakis
  - Felipe Nievinski
  - Attila Komjathy
  - Paul Collins
  - Pavel Novak

University of New Brunswick

Making a Significant Difference

UNB
UNIVERSITY OF NEW BRUNSWICK

GNSS-based Time Transfer

- C/A, P3 time transfer techniques
- PPP being tested in the past years
- It requires processing of concatenated, longer time series
- Few issues:
  - Transition among daily data files
  - Better modelling of tropo (NWM) and iono (high-order)
  - Tidal effects still?
  - PPP ambiguity resolution
  - Galileo contribution to Time Transfer

PPP ambiguity resolution?

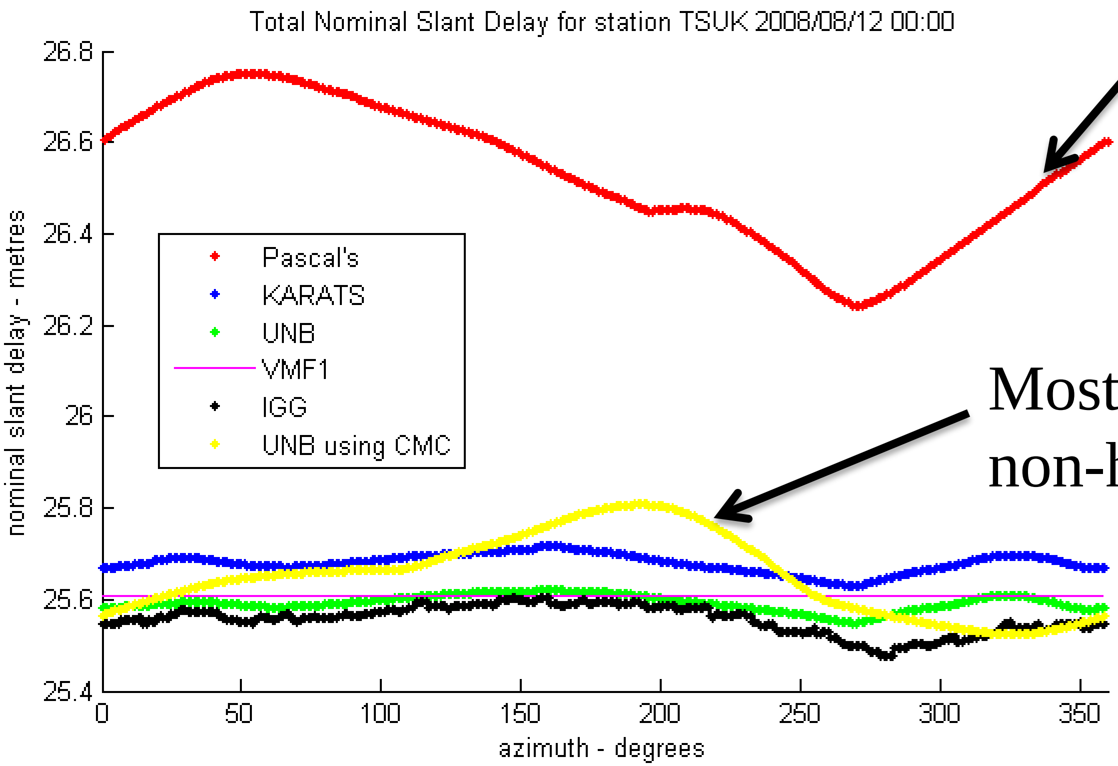
- Only possible if supported by a network.
- CNES and GFZ have generated "new product" that if applied may provide PPP ambiguity resolution at user level.
  - CNES: "integer clocks" (not a good name, actually)
  - GFZ: "fractional phase"
  - JPL: --check that --JG
- "Products" need 3rd party testing
- If it works ⇒ PPP time transfer using carrier-phase!

Numerical Weather Model

- Increasing use of Numerical Weather Models (NWM) helps enhancing the prediction models.
- Has also become a source of neutral atmospheric delay that can be directly applied in GNSS processing, including PPP.
- NWMs contain a more realistic temporal representation of the delay than prediction models ... BUT ...
- the extraction of this information requires ray-tracing through the neutral atmosphere, a time consuming task if done properly.
- A few issues:
  - Need of fast and accurate ray-tracing algorithms;
  - Practical use vis-à-vis computational cost 'vs' accuracy;
  - Necessary to extract all information contained in a NWM to obtain a more accurate delay than that provided by prediction models
  - Verhangen, Santos plus others (2010). "Positioning and Applications for Planet Earth." *IAG Symposia*, Springer (accepted)

Comparison #1

Slant factors multiplied by nominal total zenith delay of 2.520m for all azimuth's at 5 degree elevation angle.

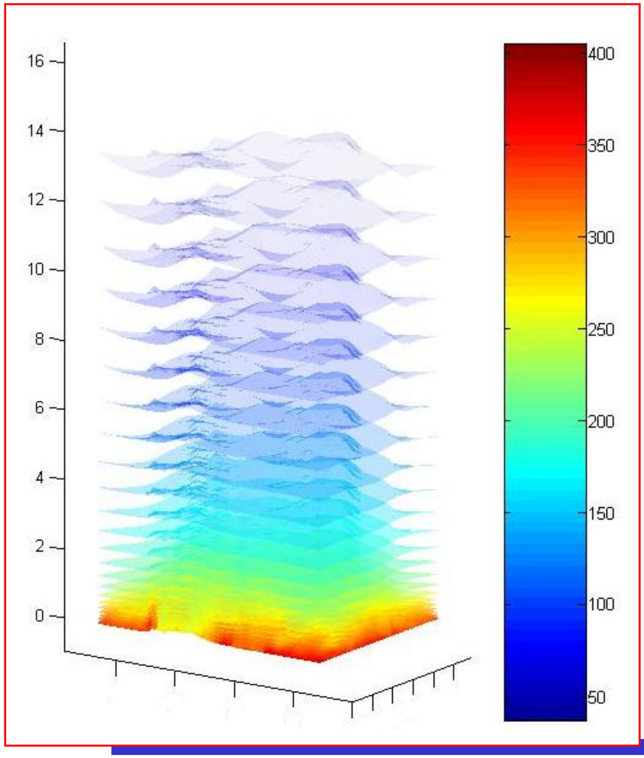


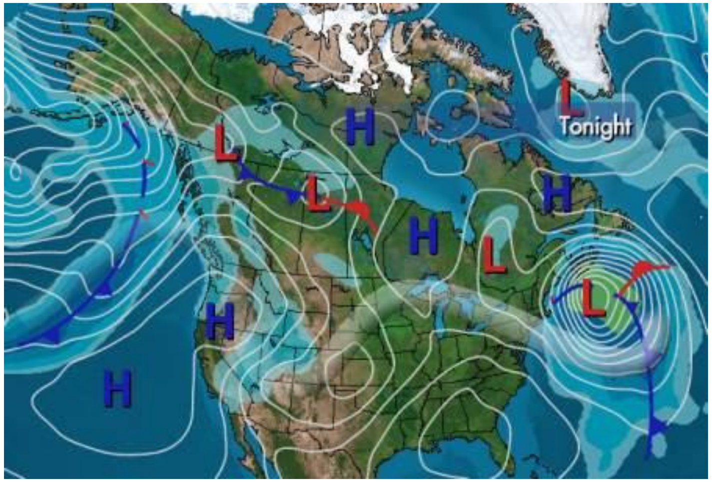
Suspected to have used an initial elevation angle of 5 degrees

Most of this difference is due to non-hydrostatic delay.

Weather Models for GPS

Before GPS receivers can pick-up the satellite signals, the signals pass through the atmosphere and suffer changes in their speed, resulting in erroneous measurements. UNB researchers have investigated the applicability of weather forecast models to reduce the impact of the atmosphere in high precision GPS positioning.





These models are useful because the effect of the atmosphere on GPS depends on weather parameters. The models are made available by the weather forecasting agencies as three-dimensional grids with values of pressure, temperature, and relative humidity.