GPS Error Sources and Mitigation

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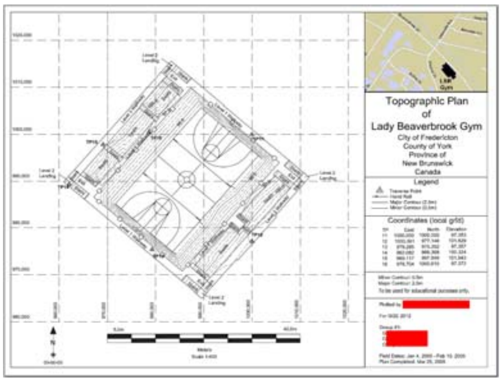
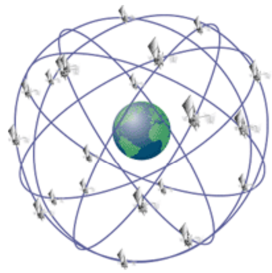
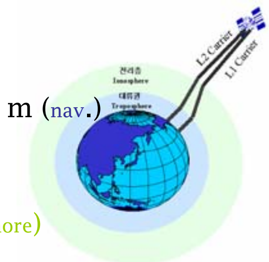




GPS Error Budget

◆ Error Budget (1σ)

- Satellite Clock Error ~ 2.1 m
- SV Ephemeris Error 0.05 (precise) - 2 m (nav.)
- Ionospheric Refraction ~ 4 m
- Tropospheric Refraction ~ 0.7 m
- Selective Availability (N/A) ~ 70 m (not anymore)
- Receiver Noise ~ 0.5 m
- Multipath ~ 1.4 m (maximum; different for a correlator tech.; code and phase are diff.; e.g. phase=1/4 wavelength = 5 cm on L1 for a narrow correlator)
- Dilution Of Precision : Above * 1 ~ 6 (lower the better)



Total Error without SA : ~ 30m (without major error correction, e.g. troposphere, but no multipath)

Total Error without SA, error mitigation: 3~10m (code point positioning)

Biases

Two classes of biases

Effect on baseline length (scale)

Common bias on both end points of a baseline

Example: Bias in absolute tropospheric delay

Neglecting the ionospheric delay

Wrong height of fixed reference stations

Effect on relative station (height)

Different bias on both end points of a baseline

Example: Bias in relative tropospheric delay

Wrong horizontal position of fixed reference stations

Satellite orbit, Antenna phase center differences, multipath

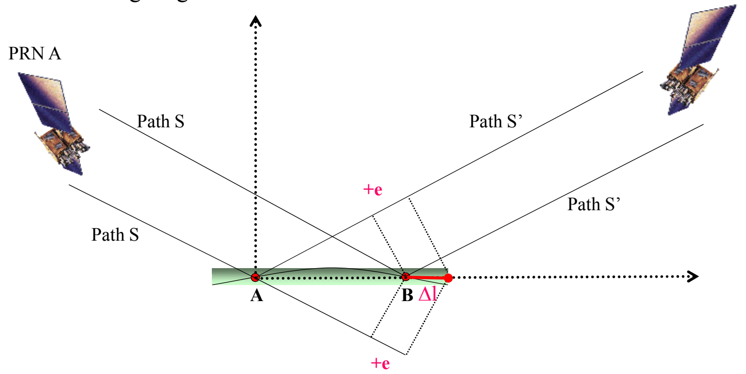
Errors in Scale

Errors in scale

Common bias on both end points of a baseline

Example: Bias in absolute tropospheric delay, Neglecting the ionospheric delay

Wrong height of fixed reference stations

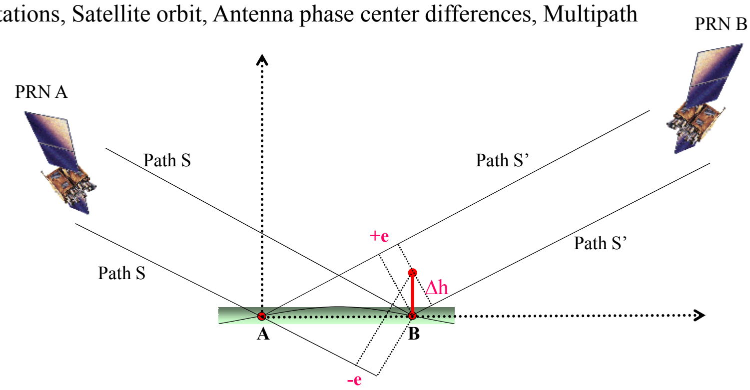


Errors in Height

◆ Errors in height

Different bias on both end points of a baseline

Example: Bias in relative tropospheric delay, Wrong horizontal position of fixed ref. stations, Satellite orbit, Antenna phase center differences, Multipath



Satellite Orbits

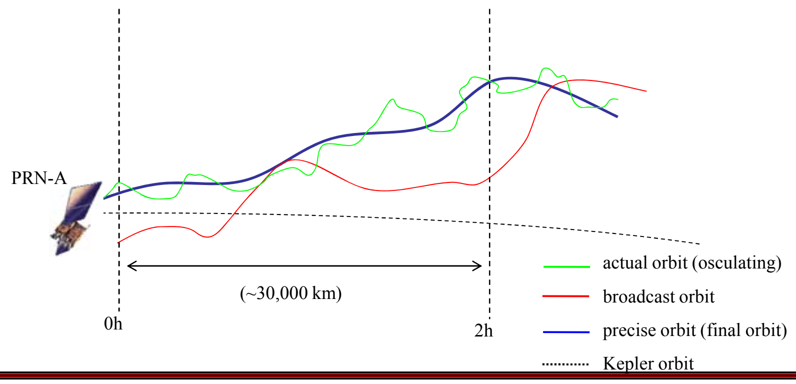
◆ GPS broadcast, precise, and osculating orbit

Broadcast orbit : based on pseudorange (uncertainties ~ 2 m)

Final precise orbit : based on phase observables (uncertainties ~ 0.05 m)

Orbital residual error : important for long baseline (over 500 km)

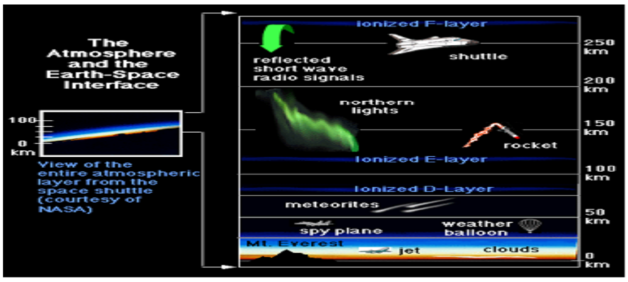
Note: the figure below is much exaggerated for explanation



Ionosphere

Overview

- The ionosphere is a major source of range and range-rate error for GPS positioning
  - Located in the region between 70 km and 1000 km
  - Formed by the UV ionizing radiation from the Sun
  - weekly ionized plasma, or gas, which can affect radio wave propagation in various ways
  - Variability is much larger than the troposphere
  - Change rapidly in absolute value & difficult to model
  - A dispersive medium → frequency dependent



Ionosphere

Mitigation

- **Single-Frequency Case (Klobuchar Model)**
  - A simple algorithm for the single-frequency user to correct for approximately 50% of the ionospheric error.
  - Navigation message provides only eight coefficients to describe the worldwide behavior of the ionosphere
  - Only need to compute user's position from ephemeris
  - The half cosine form is used to represent the diurnal variation of TEC

$$T_{iono} = F \times \{DC + A \cos[2\pi (t - \phi)/P]\}$$

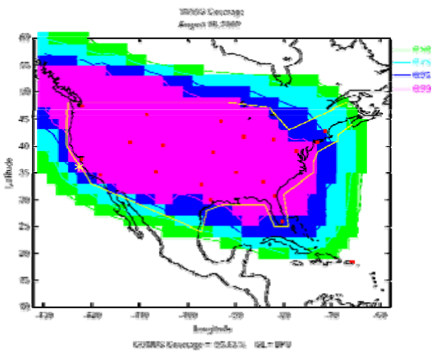
where, A = Amplitude, P = period,
DC = offset term, ϕ = local noon

- **Dual-Frequency Case: Combination**
  - Frequency dependent ionosphere can be eliminated by using a combination, called ionosphere-free linear combination for the first order ionosphere effect. The second order effect is much smaller, a few millimeter or a cm, and can not be mitigated using dual-frequency.

WAAS

Mitigation (not for Geodetic Level)

- FAA's WAAS (Wide-Area Augmentation System) is a multi-reference-station Differential GPS that provides vector of corrections to users having *WAAS compliant receivers.*
- This vector contains ionospheric, clock and ephemeris corrections that are sent down to the user via geostationary satellites.
- Figure depicts the WAAS coverage over continental USA (CONUS) and southern parts of Canada.
- UNB WASS lab. (link)



WAAS

Mitigation (not for Geodetic Level)

- The WAAS was initially developed for precise aircraft navigation and is currently in commission serving that purpose and many other high-precision applications.
- Aviation accuracy requirement is <7.6 m 95% of the time in horizontal and vertical.
- WAAS testing done in September 2002 produced accuracy performance of 1-2 m horizontal and 2-3 m vertical.
- WAAS benefits:
  - Primary means of navigation
  - More direct routes
  - Precision approach capability
  - Simplified equipment on-board the aircraft
  - Decommission of older and expensive ground equipment
  - Improved accuracy and integrity

WAAS

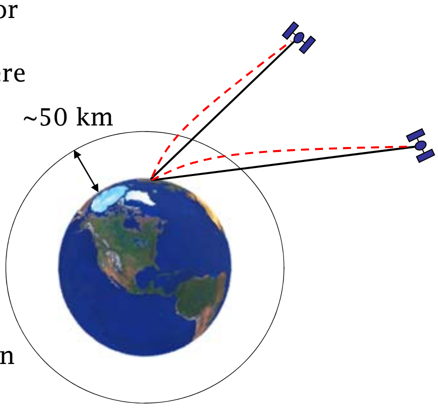
Mitigation (not for Geodetic Level)

- Several real-time ionospheric algorithms have been developed, and these are implemented using various engineering concepts.
- We can put them into two categories:
- Grid-based algorithms
- Mathematical fitting methods
- The issues to be considered are accuracy, complexity, the amount of information to be transmitted, etc.

Troposphere

Overview

- The troposphere is an important source of range and range-rate error for GPS positioning
  - The lower part of the atmosphere
  - Consist of dry gases(N_2, O_2, Ar, etc.) & water vapor
  - Non-dispersive medium for frequencies up to 15GHz
  - The phase and group velocities on both L1 & L2 are equally delayed w.r.t. free-space propagation
  - Tropospheric delay is a function of the refractive index & height
  - Refractive index is dependent on the local temperature, pressure, and relative humidity



Effects of the Troposphere

Range Delay

- Typically, total delay exceed 2.5 m in zenith direction;
- Dry delay component is stable and predictable, consists of 90% of total delay based on model (e.g. UNB3m etc.).
- The rest 10% of the part, wet delay component, is highly variable and there contains 99% of the water vapor in the atmosphere in the boundary from 0 to 10 km MSL.
- 1 mm at pole to up to 40 mm in tropics.
- Vary by 3 cm/hour in case of weather front.
- Problems are much complicated due to the high correlation between the troposphere delay and height.

Tropospheric refractivity

- When radio signals traverse the earth's atmosphere, they bend significantly by variability of the refractive index of the lower layer of troposphere.
- At every point, the refractive index of a parcel of air can be expressed as a function of pressure, temperature, and humidity.
- Greater than unity and causes an excess path delay.
- The tropospheric delay can be divided:

  Hydrostatic delay (Dry delay), and

  Non-Hydrostatic delay (Wet delay)

Tropospheric refractivity

- Hydrostatic (Dry) delay: 2.3 m and accounts for about 90% of the total delay at the zenith and for a sea-level location.

  - Determined from surface pressure measurement and can get better than 1.00 mm, for given pressure to 0.3 mb and better [Bevis et al., 1993].

- Non-Hydrostatic (Wet) delay: Typically around 0.2m. Very large spatial and temporal variability.
- Asymmetric distribution of charge in the water molecule causes permanent dipole moment and causes retardation of propagation of electromagnetic radiation through the atmosphere.

Troposphere Model

Assumption of models

- Homogeneous troposphere: Dry atmosphere; Concentric layers of equal thickness, each of these layers will equally contribute to the total pressure at the earth's surface.
- Isothermal troposphere: A dry atmosphere of constant temperature.
- Constant-lapse-rate troposphere: The temperature varies linearly with height.

$$T = T_o - \alpha z$$

- Standard troposphere: Provides P,T and moisture height profiles, as well as information on latitudinal and seasonal variations of these parameters.

Troposphere Model

Mitigation Model (all zenith direction)

Hydrostatic (dry) part

- Hopfield and modified Hopfield model
- Saastamoinen model
- Davis et al.
- Baby et al. and many more…

Non-hydrostatic (wet) part

- Hopfield model
- Saastamoinen model
- Chao model
- Callahan model
- Baby et al. and many more

Troposphere Model

Mitigation Model

Mapping function

- Cosecant function
- Dry Niell
- Wet Niell
- Hopfield

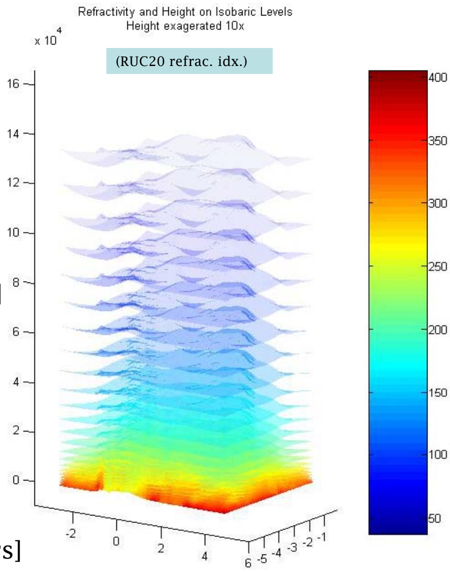
Recent Mitigation Model

Numerical Weather Prediction Model (NWP); e.g. US (RUC13) or Canadian (CMC)

Tropospheric Error Mitigation → Many research papers (inc. Y.W.Ahn, navleader website)

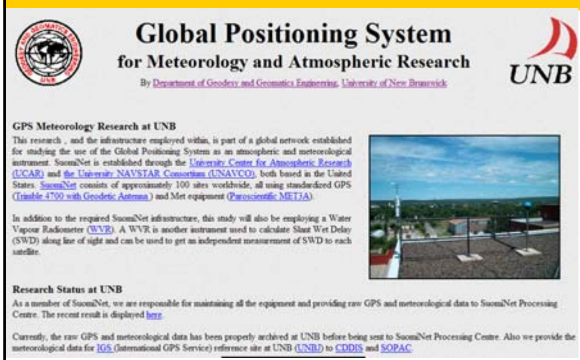
Summary: Mitigating Approach

1. **Estimating trop. parameters *with using* GNSS observations**
2. **Modeling tropo. refraction *without using* GNSS observations** (e.g. standard atmosphere, *meteorological measurements*, *water vapor radiometers*, met sensors, local meteorological models: *(theoretical & empirical models e.g. UNB3, **UNB3m**, Saastamoinen*
3. **NWP model (GNSS observations + others)**



[e.g. Ahn(2005) ~ Ahn (2009), ION papers]

Evaluations



Global Positioning System
for Meteorology and Atmospheric Research
By Department of Geodesy and Geomatics Engineering, University of New Brunswick

UNB

GPS Meteorology Research at UNB

This research , and the infrastructure employed within, is part of a global network established for studying the use of the Global Positioning System as an atmospheric and meteorological instrument. SuomiNet is established through the University Center for Atmospheric Research (UCAR) and the University NAVSTAR Consortium (UNAVCO), both based in the United States. SuomiNet consists of approximately 100 sites worldwide, all using standardized GPS (Trimble 4700 with Geodetic Antenna) and Met equipment (Paroscientific MET3A).

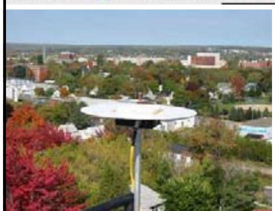
In addition to the required SuomiNet infrastructure, this study will also be employing a Water Vapour Radiometer (WVR). A WVR is another instrument used to calculate Slant Wet Delay (SWD) along line of sight and can be used to get an independent measurement of SWD to each satellite.

Research Status at UNB

As a member of SuomiNet, we are responsible for maintaining all the equipment and providing raw GPS and meteorological data to SuomiNet Processing Centre. The recent result is displayed here.

Currently, the raw GPS and meteorological data has been properly archived at UNB before being sent to SuomiNet Processing Centre. Also we provide the meteorological data for IGS (International GPS Service) reference site at UNB (UNBJ) to CDDIS and SOPAC.

Paroscientific MET3A



UNB2

http://kepler.gge.unb.ca

Radiometric WVR-1000

Multipath

Mitigation Model

- Multipath
  - A signal arrives at the receiver via multiple paths due to reflections from the Earth & nearby objects
    - Distort the PRN code & navigation data
    - Distort the phase of the carrier
    - Can cause the receiver tracking loop to lose lock
  - Multipath mitigation techniques for GPS
    - Elevation mask(cutoff) angle & Antenna sitting place
    - Ground plane to increase free-space antenna gain at low elevation angles
    - Choke ring antenna attenuate multipath signal incident on the antenna at the horizon and negative elevation angles

Phase Center Variation

Mitigation Model

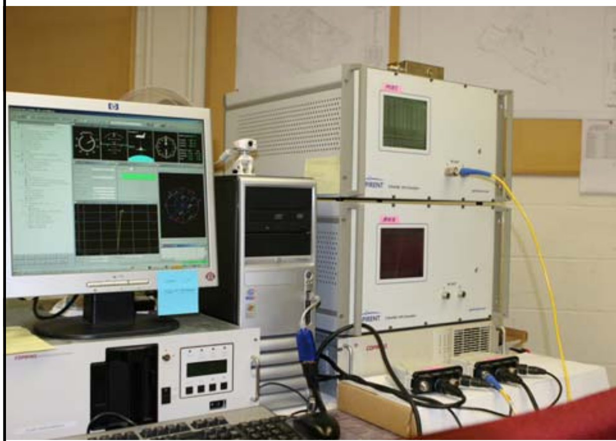
- The phase center of a GPS antenna is neither a physical point nor a stable point. For any given GPS antenna, the phase center will change with the changing direction of the signal from a satellite.

- Ideally, most of this PCV depends on satellite elevation. Azimuthal effects are only introduced by the local environment around each individual antenna site.

- These phase center variations affect the antenna offsets that are needed to connect GPS measurements to physical monuments.
  : If this variation is ignored, the measured baseline will be between the average phase centers of the two antennas.
  : These average phase center locations are a weighted average of all the individual phase centers for each of the measurements included in the solution.

Advanced Analysis

◇ **SPIRENTS™ STR4760; GPS L1,L2,L2C Dual Simulator**



❑**SimGEN™ Platform**

- Models Applicable

: Atmosphere
  - troposphere
  - ionosphere

: Multipath

: Satellite orbit

: Clock error (on sat.)

: Antenna attenuation, etc.

- **Models Applied, e.g.**

: Residual Troposphere or Multipath, etc.

(GNSS simulation and system integration lab. at UNB)

(Gillin Hall: E112)

APPLICATION & Knowledge

One of A Few of Interesting GNSS Projects;

Gantry Crane Auto Steering

(Dr.Kim and Prof.Langley)

Broaden Your Knowledge;

Where are you living in our Space?

APPLICATION & Knowledge

Blank

Closing Remarks

- **From** Surveying Basics, Various measuring methods, etc. **To** GNSS, an advanced positioning methods (high-precision geodetic level)
- **Highlights**: EDM, 3-D Terrestrial Laser Scanners, DEM fundamental concepts, GNSS positioning principles and practice. GNSS error sources and possible mitigation methods. Many Newer technologies (Laser Scanner, Upcoming GNSS,
- **Many newer technologies**; Laser scanner, Upcoming GNSS, Newer GNSS signal generators, Evaluation method of the tropospheric errors