High Precision Realization and Applications of GPS

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OVERVIEW

• Current state:
  – GPS is routinely used to make daily, sub-millimeter horizontal and 2-3 mm vertical position measurements accuracy position measurements
  – GPS satellite orbits are determined to a few centimeters and clocks to 100-ps (ps=10^{-12} sec)

• In this talk we:
  – Review some of the history starting in 1979
  – Early geophysical applications (mid-1980s)
  – Development of the International GPS service (IGS) in 1992
  – Current application of these results Earth sciences through a series of examples.
History

- Prior to GPS, very long baseline interferometry (VLBI) was developed (late 1960s) for making astronomical and geodetic measurements.
- For geodetic measurements, this system used cross-correlation of (high-bandwidth) recordings of signals from extra-galactic radio sources to determine time delays between signals arriving at different radio telescopes located around the world.
- The system is expensive but demonstrated that sub-centimeter, global positioning was possible.
- In the late 1970s when GPS satellites were launched, it was clear that a similar technique could be used with to measure the travel time differences between the satellites and ground receivers.

Early GPS History

- While both extra-galactic radio sources and GPS radiated radio signals that could be used interferometrically, GPS had several major advantages and some disadvantages.
- Advantages of GPS:
  - GPS satellites are much closer to the ground and their radio signals (although weak by most standards) are much stronger than extra-galactic radio sources: Thus small antennas could be used
  - To some level, the signal structure of GPS is known and therefore rather than correlating between signals received at different locations, correlation could be done with a replica of the transmitted signal
GPS Advantages

- Small antennas and direct correlation of signals (within the receiver) are major advantages of GPS over VLBI.
- Small antennas means they can be omni-directional and thus able to track satellites simultaneously: eliminates the need for an accurate clock ($300K hydrogen maser in VLBI, $1M antenna).
- Simultaneous tracking also means that carrier phase measurements can be used yielding a thousand-fold improvement in data noise over ranges measurements.
- Direct correlation of signals removes need for large recording devices ($200K in VLBI because of bandwidth needed).
- Result: $10K GPS receiver can produce position estimates of similar quality to $2M VLBI system.

GPS Disadvantages

- Small omni-directional antennas are sensitive to reflections of GPS signals corrupting measurements (multipath).
- Because the GPS antenna is fixed, the precise determination of the point that the phase is being measured to is complex (and not unique). In VLBI, the antenna moves and the position is determined to a geometric location related to the axes of the antenna.
- The satellite transmission phase pattern is not easily determined. VLBI has a similar problem with "source structure" but since VLBI uses true interferometers, the sources can be mapped.
- GPS satellites are in Earth orbit and so positioning depends on the dynamics of the satellites (solar radiation pressure is largest uncertainty). VLBI extra-galactic radio sources are basically "fixed" in inertial space and there are 100s of them choose from. Only 27-28 GPS satellites that go through systematic generation changes.
Contrast between GPS and VLBI

Summary of VLBI versus GPS

- GPS is “cheap” with similar precision to VLBI (and in certain applications more precise)
- Far less expensive to operate (government agencies versus counties and universities)
- Earth orbiting satellites provides GPS with sensitivity to center of mass of Earth system
- However, on global scale and at levels of tens of millimeters of position, GPS has systematic errors due to phase center variations and possibly dynamics of satellite orbits.
GPS in the 1980s

- The early days of civilian GPS were plagued by uncertainty about how much of the codes written on the GPS signals would be publicly available. VLBI also had shown that even if knew just one of the codes, the signals could be tracked.
- Largest uncertainty was the availability of P-code on the L2 frequency which is critical for high precision.
- As a result, “codeless” and “code-limited” tracking receivers were developed. Texas Instruments also released a fully code tracking receiver.
- First full codeless receiver (Macrometer) tested in 1979. Only assumed that the code was bi-phase modulated. Used Doppler to separate signals from different satellites, needed a high quality clock (<1 microsecond drift per session) and external ephemeris information. (Jeep included with receiver)

GPS in 1980s

- Geophysics community starting using GPS (mainly TI 4100) for studying deformation in California in the mid-1980s. Despite problems with the TI4100 receiver and antenna, horizontal positions precise to a few millimeters for 8-24 hours sessions were obtained.
- National geodetic communities around the world also started using GPS for control surveys. Mix of TI4100 and Macrometer commercial receivers.
- Availability of accurate satellite orbits was a major problem. For a survey in California, additional receivers in other parts of the north hemisphere needed to be deployed for tracking.
GPS late 1980s

- GPS high precision results actually degraded between the mid-1980s and early 1990s (worse year was 1990)
- Major reasons for degradation:
  - Uncertainty about the availability of GPS signal codes, lead to the development of many semi-codeless receivers (assumed only that the CA code would be available on L1 only: cross correlation of L1 with L2 to obtain ionospheric delay and phase. (Trimble Ashtech were some of the companies).
  - Increasing ionospheric activity made L2 tracking difficult
  - Move away from the TI4100 to codeless receivers in global tracking network lead to poor orbit determinations: e.g., Cooperative International GPS Network (CIGNET)).

GPS Early 1990s

- Major change at the beginning of the 1990s.
- Jet Propulsion Laboratory (JPL) released the Rogue GPS receiver which combined full code tracking (when P-code was available) with codeless tracking when Anti-spoofing (AS) was turned on (testing of AS started in 1992). Also used the Dome-Margolian antennas with choke-rings.
- Turning point was the 1991 "GPS for IERS and Geodynamics" experiment (GIG) that demonstrated a global deployment of 40 GPS receivers with rapid download of data.
Start of IGS

- Based on success of GIG91, plans developed to deploy a global network of Rogue tracking receivers that return data in near-real-time (daily downloads).
- Near-real-time processing of the data (several day delay).
- Plan to develop a international service that would provide accurate GPS orbit information (initially) and other derived GPS products.
- The International GPS service (IGS) pilot project started in June 1992. Pilot was so successful that it transitioned directly into the service.

Organization of IGS

- Over 200 contributing organizations in 75 countries, many more users
- Recognized as an international scientific service
- Advocates an open data policy
- Network of over 300 permanent precision geodetic receivers produce GPS data on a continuous basis, ~100 report hourly, subset for a real-time network demonstration
  - Member of Federation of Astronomical and Geophysical Data Analysis Services, 1996 (FAGS)
- IUGG and ICSU recognition
  - International Union of Geodesy and Geophysics
  - International Council of Scientific Unions
Operations of the IGS

- Operational Data Centers
  - Retrieve data from receivers
  - Validate data and monitor station status
  - Translate raw GPS data into RINEX (Receiver Independent Exchange)
  - Forwards appropriate files to Global Data Centers or Regional Data Centers
- Global Data Centers organize the files on the basis of site and time, and provide Internet data access to users and analysts
- IGS Analysis Centers pick up the data from the Global Data Centers, and estimate precise orbits, Earth Rotation parameters (ERP), clocks, etc.
- Analysis Center results are collected by the Analysis Coordinator and combined into the official IGS products
  - orbits in SP3 format
  - results in SINEX - Solution Independent Exchange format
  - ancillary product files
1991-92 network

2002 Network (over 300 stations)

Orbital uncertainty

Projects and Working groups in IGS

- Reference Frame Densification
  - Generate a robust and homogeneous reference system, relating scientific results anywhere in the world
  - Plot network time series, position and velocities support plate motion and crustal deformation studies
- Precise Time & Frequency Project
  - Exploit GPS measurements for improved accurate time and frequency comparisons worldwide, sub nanosecond
  - Joint with the BIPM in France
- Low Earth Orbiter (LEO) Project
  - Generate precise orbits for LEO satellites, Gravity (CHAMP, SAC-C, GRACE, JASON, etc.)
  - Support occultation measurements for atmospheric profiling
- GLONASS Service Pilot Project IGLOS-PP
  - Flexible GNSS model - ‘classic’ products from Russian GLONASS system
- Tropospheric Working Group
  - Derive total zenith path delay or precipitable water vapor for GPS observations
  - Ground-based meteorology, weather forecasting (severe storms), climate
Projects (continued)

• Ionospheric Working Group
  – Use dual frequency GPS data to determine Total Electron Content (TEC) including its temporal and spatial variations
  – Daily measurements and maps of the Ionosphere

• Sea Level Project - TIGA
  – Measuring long-term motion of Tide-gauge Benchmarks
    • decouple crustal deformation or subsidence signatures at coastal areas from long-term sea-level changes, ocean loading effects
  – Support altimeter calibration at specific sites and inter-mission calibrations, TOPEX, JASON, etc.

• Real-time Working Group
  – Develop international standards for cooperation of real-time data exchanges
  – Evaluate IGS involvement in real-time applications

• AFREF Initiative - African Reference System
  – Develop a continental reference system based on sustainable technology for the African continent
  – Establish the geodetic base for all development within Africa

Examples of Applications of GPS

• Global tectonic motions: Provides boundary conditions for understanding seismic risk and fundamental properties of the Earth

• Tectonic studies in California
  – Comparison of analyses by different groups and analysis programs and methods (one group uses satellite clock estimates and orbits to “point-position” using phase.
  – Time series after earthquakes
  – Effects of atmospheric pressure and ground water loading effects on GPS.
Global Plate motion 190
sites <2 mm/yr Horizontal

GPS Networks (Data and Results freely available from Internet)

- The International GPS service (IGS) uses about 140 stations to determine GPS satellite orbits
- Southern California Integrated GPS Network has 250 stations
- The National Geodetic Survey CORS network has currently 260 sites
- Japanese network >1000 stations
- Plate Boundary Observatory (PBO) could add 875 sites across Western US and Alaska in next 6 years.
190 stations around LA.
Red SIO
Black JPL
RMS diff
~0.7 mm/yr

Detailed view of LA Basin
Detailed View of Time Series

- Example of time series:
  - After the Hector Mine November 1999 in eastern California.
  - Analysis of these time series reveals information about the crustal properties and the behavior of faults after earthquakes.
  - Time series from site in Canada that shows some non-tectonic reasons for position non-secular changes in positions. This type of analysis reveals information about large scale fluid movements on the Earth’s surface and subsurface.

Example of Post-seismic Deformation (LDES latitude)

![Graph showing post-seismic deformation](image)
Height Changes at Penticton, Canada

Penticton Height Changes with Atmospheric load
Penticton Zoom in Winter Months

Water storage load displacement (NCEP)
Reasons for Improved Quality

• Why has the quality of GPS positioning improved so much?
  – Improvements in instrumentation: To some degree, phase noise has not improved that much since 1980s but antennas and reliability have improved.
  – Global network for tracking satellites: Major reason for improvement
  – Analysis models: Significant improvements especially in propagation effects and data cleaning
  – Satellite improvements: Not so much in signal generation but certainly in satellite behavior during eclipses.
  – Remaining problem: Transmission characteristics (>1 m difference between Block IIR reported and “measured” phase center position.

Conclusions

• Although GPS was designed a “few-meter” global positioning system, it is now routinely used for few mm-level global positioning in post-analysis, and tens of centimeter real-time positioning. For “regional” positioning sub-millimeter positioning (1-day averages) is possible.
• Many reasons for this improvement but one of the major ones is the availability of data and analysis products from several hundred globally distributed GPS receivers operated under the auspices of the International GPS service (IGS).
• Algorithm and analysis procedures (driven partly by IGS needs) also have lead to significant improvements.
• There is still more improvement to be expected as signals and noise are separated in current analyses.
Web Resources

- IGS: http://igscb.jpl.nasa.gov/
- Global GPS analyses:
  http://www-gpsg.mit.edu/~fresh/MIT_IGS_AAC.html
- 250-station California Array (SCIGN):
  http://www.scign.org
- University GPS consortium (UNAVCO):
  http://www.unavco.org
- This presentation:
  http://www-gpsg.mit.edu/~tah/ION03.html