Montserrat GAMIT/GLOBK/Track Workshop
Introduction

Thomas Herring, MIT

tah@mit.edu

Workshop Overview

- Web site
  http://geoweb.mit.edu/~simon/gtgk/Montserrat12/
  Lectures and Tutorials: Day 1:
  1. Introduction to GPS data processing and how processing is treated in gamit/globk
  2. GAMIT Lecture: Overview of standard processing in GAMIT; daily session processing
  3. GLOBK Lecture: Overview of the way GLOBK is used to analyze and combine results from GAMIT processing
  4. Tutorial session: Salton Sea data analysis around time of Magnitude 5.8 aftershock to El Major Cucapah April 4, 2010 Mw 7.2 earthquake. Demonstrates short session and globk combined processing.

Workshop Overview

- Lectures and Tutorials Day 2
  1. Modeling details, atmospheric delays, loading
  2. Treatment of earthquakes, equipment changes and other effects
  3. Statistics of time series and determination of error models for velocity estimates
  4. Analysis of Salton Sea data over a longer period of time using time series.

Workshop overview

- Lectures and Tutorial Day 3
  1. Introduction to Track kinematic processing
  2. Tuning in track: Configurations and how to assess quality of solution. Analysis of long and short baseline results.
  3. TrackRT Installation and setup. Real-time version of track using the BKG BNC caster protocol
  4. Tutorial session looking at track results: Earthquake surface wave analysis and kinematic trajectory.

Workshop Overview

- Lectures and Tutorial Day 4
  1. GAMIT/GLOBK utility scripts and programs
  2. GLOBK prototyping tools for large analyses. Treatment of break in time series and earthquake effects.
  3. GPS meteorological applications.
  4. Tutorial session using the tsview, tscon and tsfit

Workshop Overview

- Lectures and tutorials Day 5
  1. Review of discussions and issues raised during the first four days. Opportunity to revisit issues that were not clear when first presented. The contents in this lecture will depend on questions raised during short course.
  2. Remainder of the day will be spent finishing the tutorial exercises and discussing issued raised by participants data sets

Workshop Overview

- Asking questions during the workshop is critical for getting the most from this course.
- Each participant is expected to ask questions and during the first 4-days to submit questions and/or issues which will be addressed in the Friday morning session.
- Each participant will submit questions/issues in email to tah@mit.edu and these will be addressed on Friday morning.
- Questions so far?
- General question: Interest in real-time data processing?

GPS overview

- For GPS processing, the critical information needed is range and phase data from a receiver collecting data from multiple GPS satellites and information about the orbits of the satellites (earth-fixed frame) and some information about clocks in satellites.
- In GAMIT, only crude clock information needed due to double-differencing.
- To integrate GPS orbits, information needed about rotation between earth-fixed and inertial space.
- For the most accurate GPS results, other ancillary information needed (e.g., atmospheric models, ocean tides, antenna and receiver biases).
- Program *track* (kinematic processing) can use just RINEX data files and SP3 GPS orbit files but GAMIT needs a full suite of additional files (track also can use some of these file). The main GAMIT processing script *sh_gamit* handles getting all these files.

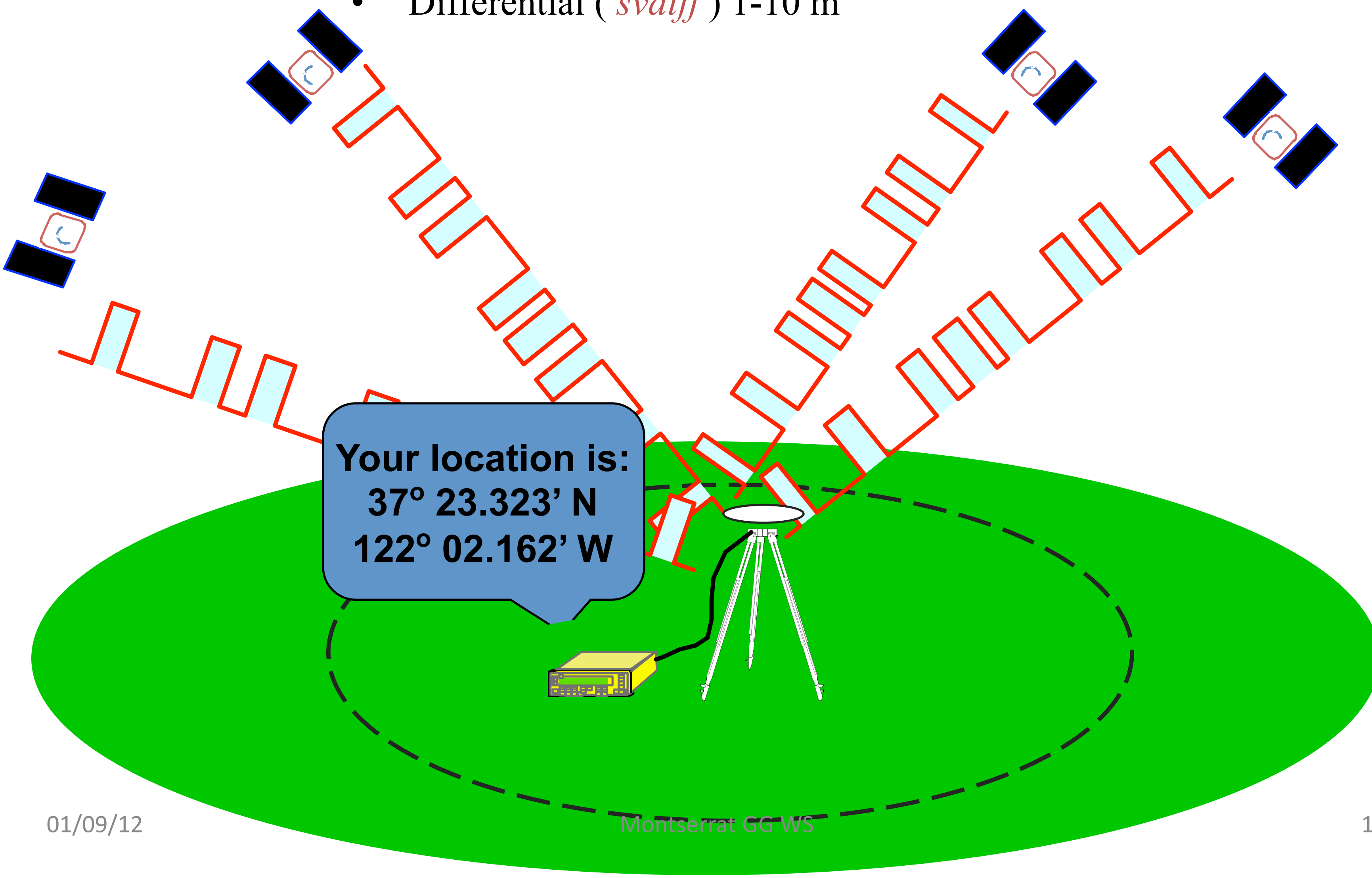
GPS overview

- GAMIT processes GPS phase and range data files (RINEX format) usually for 24-hour sessions of data. For newer data collection (post 1996), orbits do not need to be estimated because IGS has very good combined orbits available.
- GLOBK combines together results from daily GPS processing and is used to generate velocity estimates and time-series products.
- After discussing some general GPS processing issues in the rest of this lecture, we then discuss GAMIT and GLOBK operations.

Instantaneous Positioning with GPS Pseudoranges

Receiver solution or *sh_rx2apr*

- Point position (*svpos*) 5-100 m
- Differential (*svdiff*) 1-10 m



Observables in Data Processing

Fundamental observations

L1 phase = f1 x range (19 cm) L2 phase = f2 x range (24 cm)

C1 or P1 pseudorange used separately to get receiver clock offset (time)

To estimate parameters use doubly differenced

LC = 2.55 L1 - 1.98 L2 "Ionosphere-free phase combination" L1-cycles

PC = 2.55 P1 - 1.55 P2 "Ionosphere-free range combination" Meters

Double differencing (DD) removes clock fluctuations; LC removes almost all of ionosphere. Both DD and LC amplify noise (use L1, L2 directly for baselines < 1 km)

Auxiliary combinations for data editing and ambiguity resolution

"Geometry-free combination (LG)" or "Extra wide-lane" (EX-WL)

LG = L2 - f2/f1 L1 used in GAMIT

EX-WL = L1 - f1/f2 L2 used in TRACK

Removes all frequency-independent effects (geometric & atmosphere) but not multipath or ionosphere

Melbourne-Wubbena wide-Lane (MW-WL): phase/pseudorange combination that removes geometry and ionosphere; dominated by pseudorange noise

MW-WL = (L1-L2)-(ΔF/ΣF)(P1+P2) = (L1-L2)-0.12 (P1+P2)

Modeling the observations

I. Conceptual/Quantitative

- Motion of the satellites
  - Earth's gravity field (flattening 10 km; higher harmonics 100 m)
  - Attraction of Moon and Sun (100 m)
  - Solar radiation pressure (20 m)
- Motion of the Earth
  - Irregular rotation of the Earth (5 m)
  - Luni-solar solid-Earth tides (30 cm)
  - Loading due to the oceans, atmosphere, and surface water and ice (10 mm)
- Propagation of the signal
  - Neutral atmosphere (dry 6 m; wet 1 m)
  - Ionosphere (10 m but LC corrects to a few mm most of the time)
  - Variations in the phase centers of the ground and satellite antennas (10 cm)

* incompletely modeled

Modeling the observations
II. Software structure

- Satellite orbit
  - IGS tabulated ephemeris (Earth-fixed SP3 file) [track]
  - GAMIT tabulated ephemeris (t-file): numerical integration by arc in inertial space, fit to SP3 file, may be represented by its initial conditions (ICs) and radiation-pressure parameters; requires tabulated positions of Sun and Moon
- Motion of the Earth in inertial space [model or track]
  - Analytical models for precession and nutation (tabulated); IERS observed values for pole position (wobble), and axial rotation (UT1)
  - Analytical model of solid-Earth tides; global grids of ocean and atmospheric tidal loading
- Propagation of the signal [model or track]
  - Zenith hydrostatic (dry) delay (ZHD) from pressure (met-file, VMF1, or GPT)
  - Zenith wet delay (ZWD) [crudely modeled and estimated in solve or track]
  - ZHD and ZWD mapped to line-of-sight with mapping functions (VMF1 grid or GMT)
  - Variations in the phase centers of the ground and satellite antennas (ANTEX file)

Parameter Estimation

- Phase observations [solve or track]
  - Form double difference LC combination of L1 and L2 to cancel clocks & ionosphere
  - Apply a priori constraints
  - Estimate the coordinates, ZTD, and real-valued ambiguities
  - Form M-W WL and/or phase WL with ionospheric constraints to estimate and resolve the WL (L2-L1) integer ambiguities [autcln, solve, track]
  - Estimate and resolve the narrow-lane (NL) ambiguities
  - Estimate the coordinates and ZTD with WL and NL ambiguities fixed

  --- Estimation can be batch least squares [solve] or sequential (Kalman filter [track]
- Quasi-observations from phase solution (h-file) [globk]
  - Sequential (Kalman filter)
  - Epoch-by-epoch test of compatibility (chi2 increment) but batch output

Limits of GPS Accuracy

- Signal propagation effects
  - Signal scattering (antenna phase center / multipath)
  - Atmospheric delay (mainly water vapor)
  - Ionospheric effects
  - Receiver noise
- Unmodeled motions of the station
  - Monument instability
  - Loading of the crust by atmosphere, oceans, and surface water
- Unmodeled motions of the satellites
- Reference frame

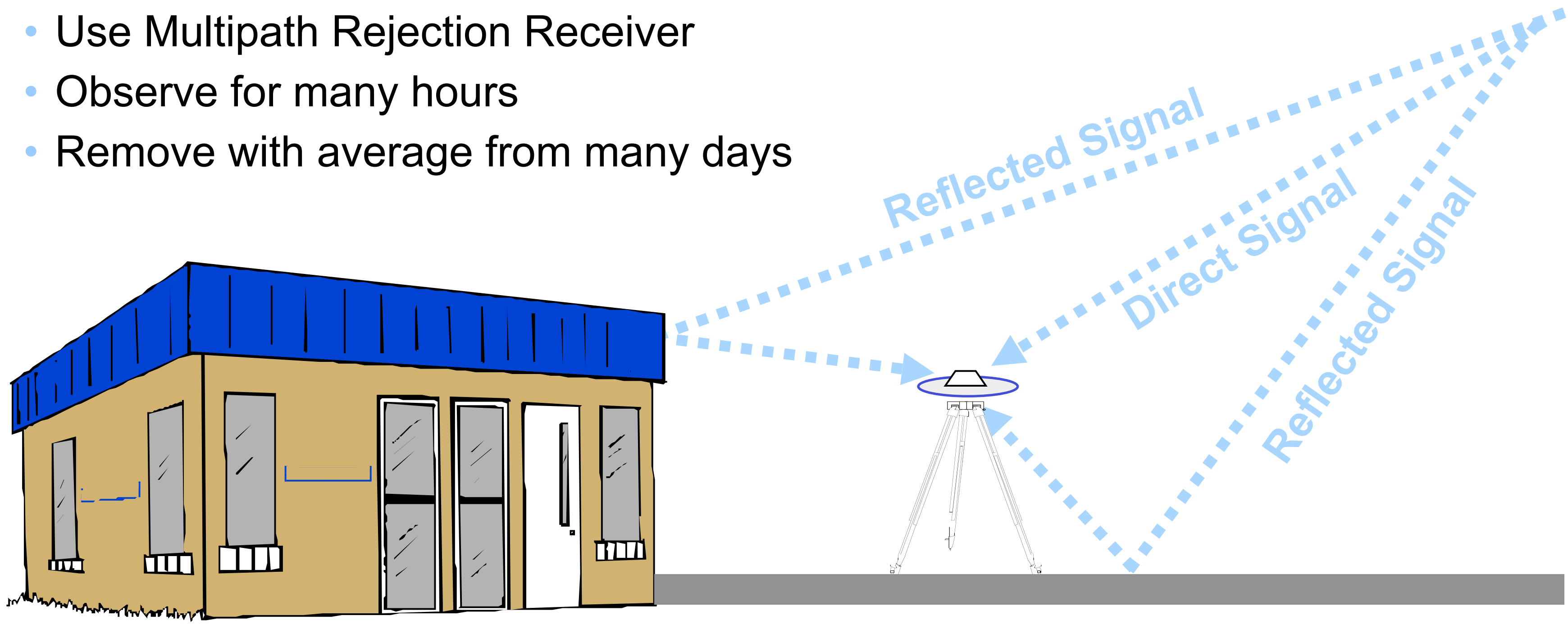
Limits of GPS Accuracy

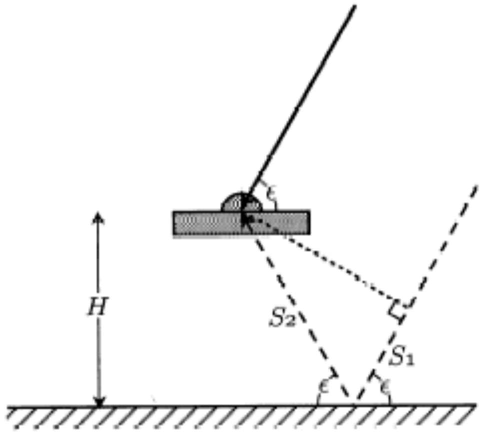
- Signal propagation effects
  - Signal scattering (antenna phase center / multipath)
  - Atmospheric delay (mainly water vapor)
  - Ionospheric effects
  - Receiver noise
- Unmodeled motions of the station
  - Monument instability
  - Loading of the crust by atmosphere, oceans, and surface water
- Unmodeled motions of the satellites
- Reference frame

Multipath is interference between the direct and a far-field reflected signal (geometric optics apply)

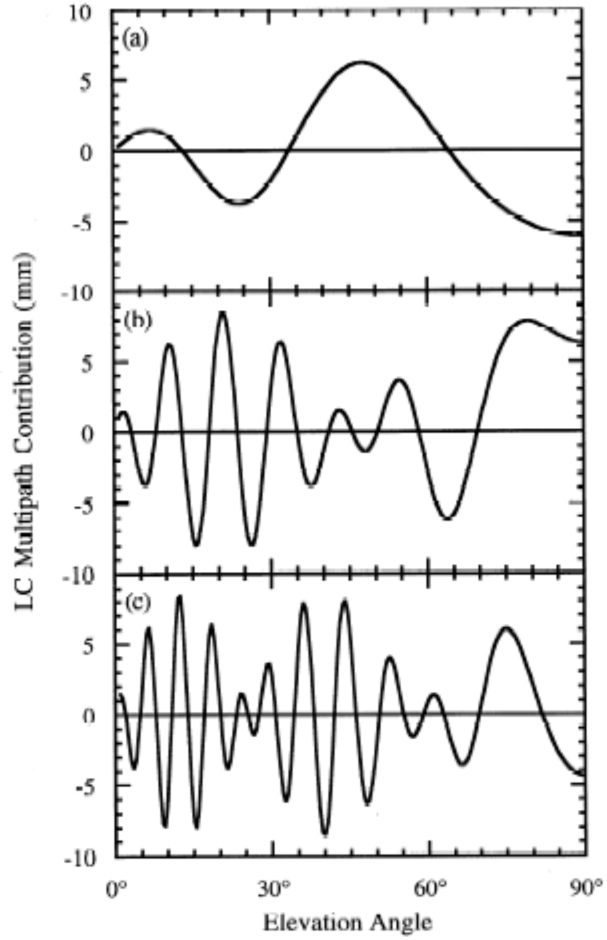
To mitigate the effects:

- Avoid Reflective Surfaces
- Use a Ground Plane Antenna
- Use Multipath Rejection Receiver
- Observe for many hours
- Remove with average from many days





Simple geometry for incidence of a direct and reflected signal



Antenna Ht

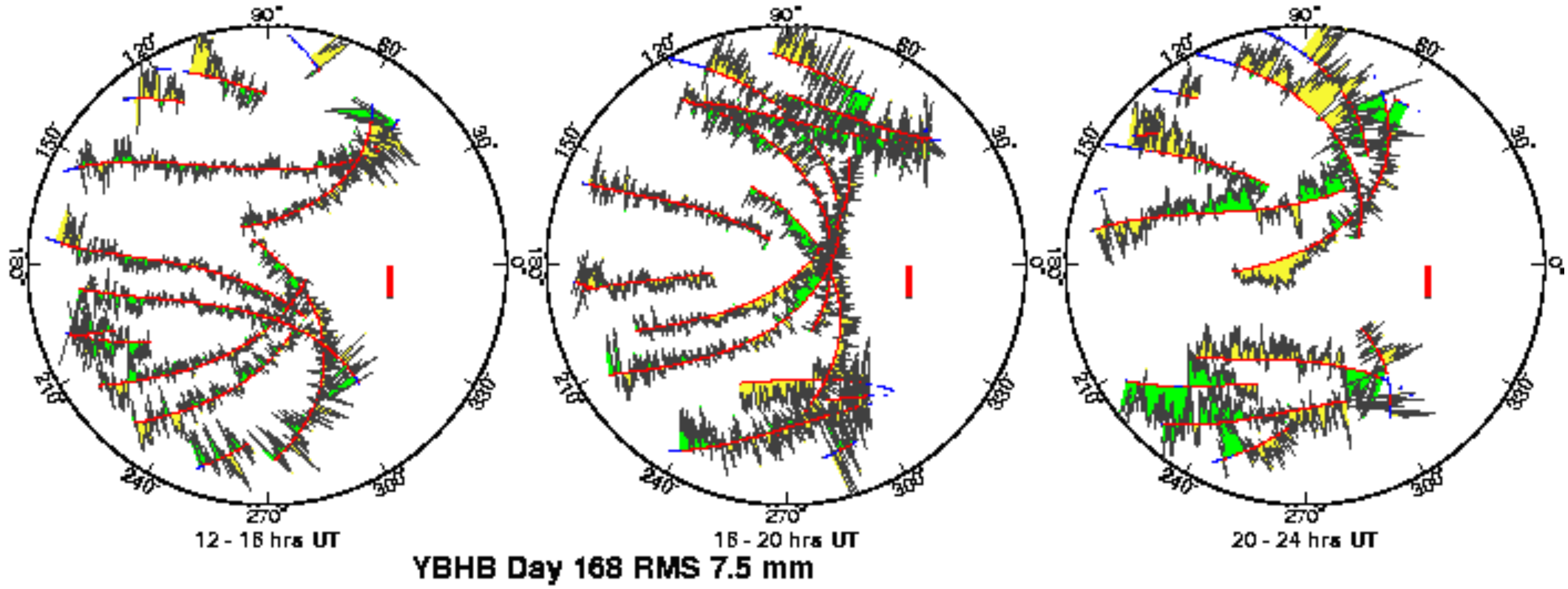
0.15 m

0.6 m

1 m

Multipath contributions to observed phase for three different antenna heights [From *Elosegui et al*, 1995]

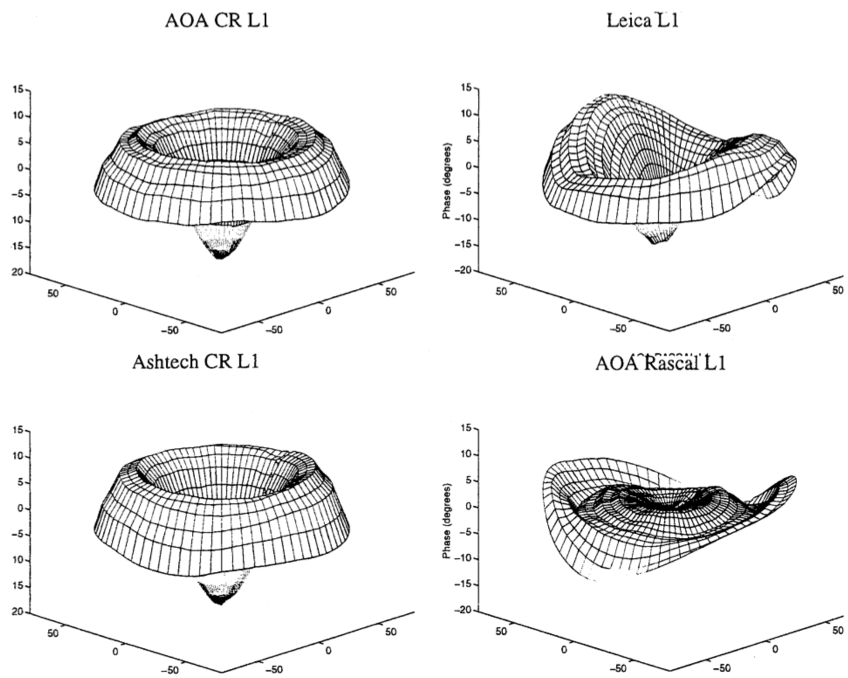
Multipath and Water Vapor Effects in the Observations



One-way (undifferenced) LC phase residuals projected onto the sky in 4-hr snapshots. Spatially repeatable noise is multipath; time-varying noise is water vapor.

Red is satellite track. Yellow and green positive and negative residuals purely for visual effect. Red bar is scale (10 mm).

More dangerous are near-field signal interactions that change the effective antenna phase center with the elevation and azimuth of the incoming signal



Left: Examples of the antenna phase patterns determined in an anechoic chamber…BUT the actual pattern in the field is affected by the antenna mount

To avoid height and ZTD errors of centimeters, we must use at least a nominal model for the phase-center variations (PCVs) for each antenna type

Figures courtesy of UNAVCO

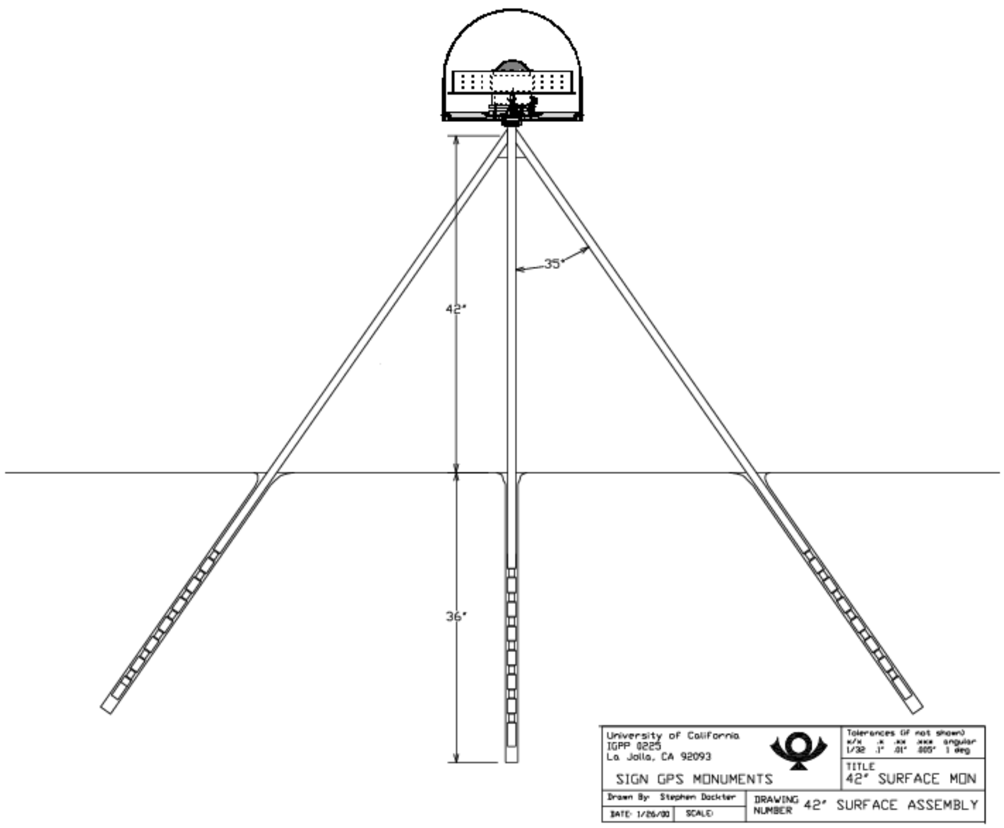
Antenna Phase Patterns

Limits of GPS Accuracy

- Signal propagation effects
  - Signal scattering (antenna phase center / multipath)
  - Atmospheric delay (mainly water vapor)
  - Ionospheric effects
  - Receiver noise
- Unmodeled motions of the station
  - Monument instability
  - Loading of the crust by atmosphere, oceans, and surface water
- Unmodeled motions of the satellites
- Reference frame

Monuments Anchored to Bedrock are Critical for Tectonic Studies

(not so much for atmospheric studies)



Good anchoring:

Pin in solid rock

Drill-braced (left) in fractured rock

Low building with deep foundation

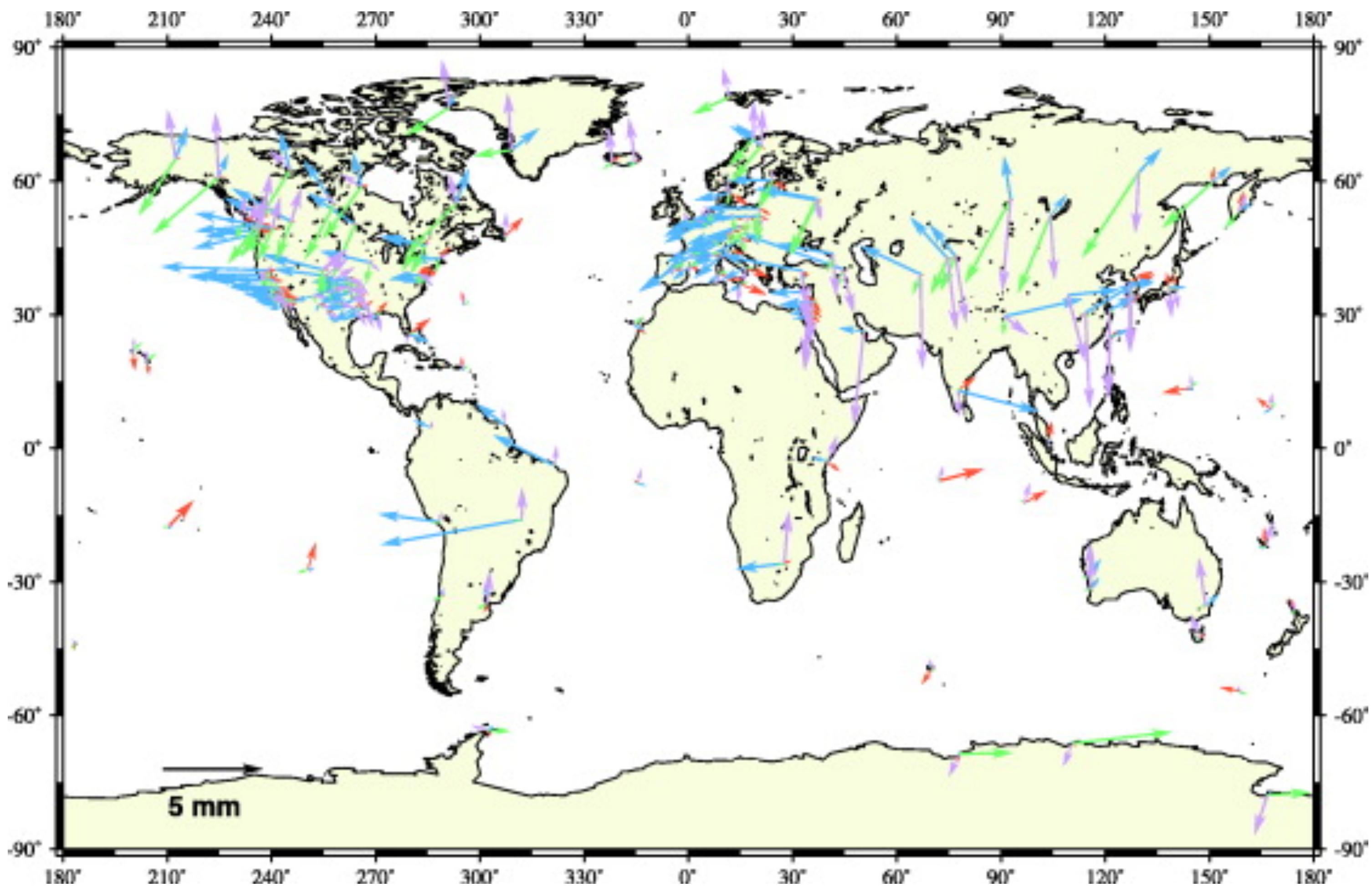
Not-so-good anchoring:

Vertical rods

Buildings with shallow foundation

Towers or tall building (thermal effects)

Annual Component of Vertical Loading



Atmosphere (purple) 2-5 mm

Water/snow (blue/green) 2-10 mm

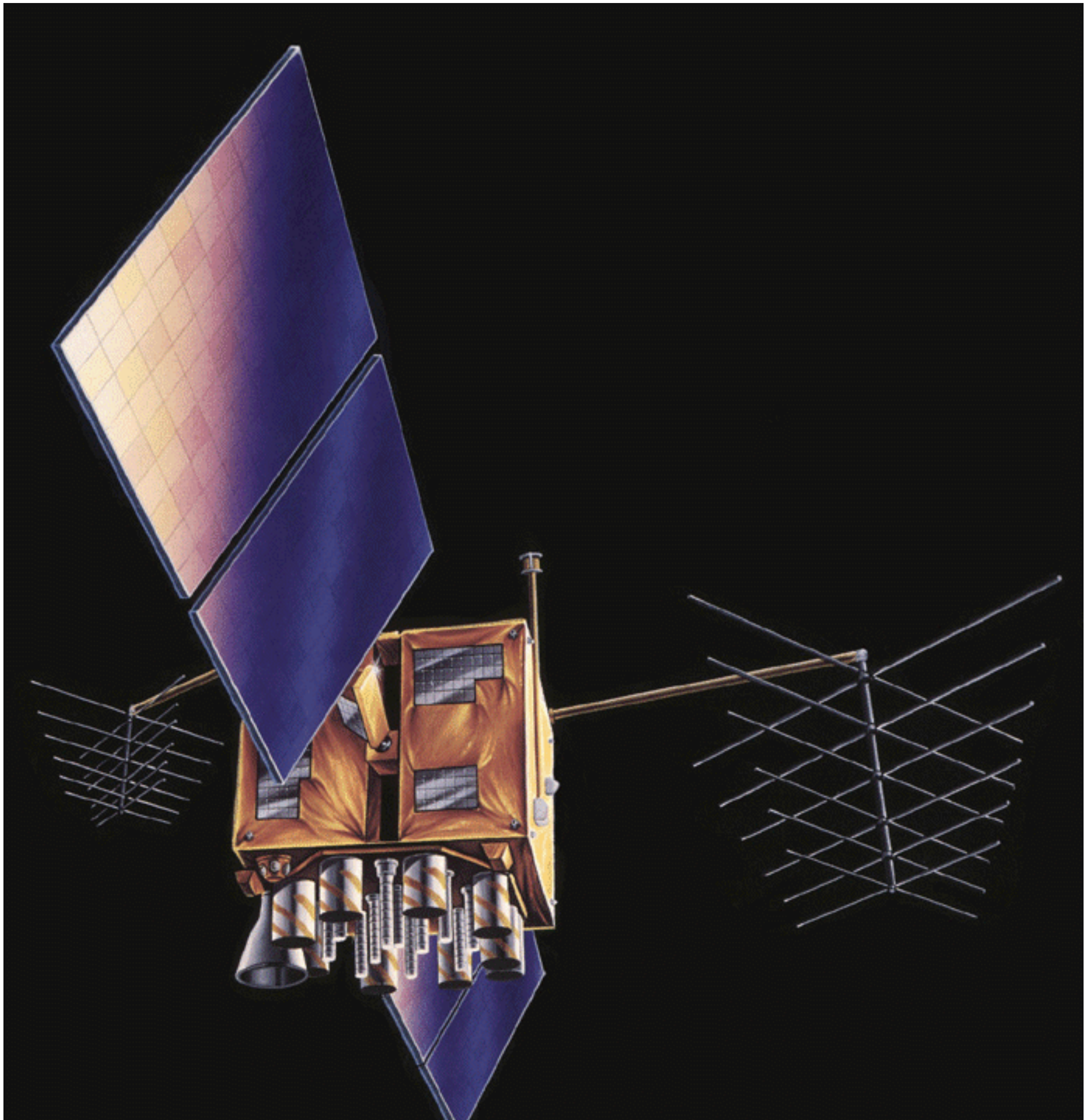
Nontidal ocean (red) 2-3 mm

From Dong et al. J. *Geophys. Res., 107*, 2075, 2002

Limits of GPS Accuracy

- Signal propagation effects
  - Signal scattering (antenna phase center / multipath)
  - Atmospheric delay (mainly water vapor)
  - Ionospheric effects
  - Receiver noise

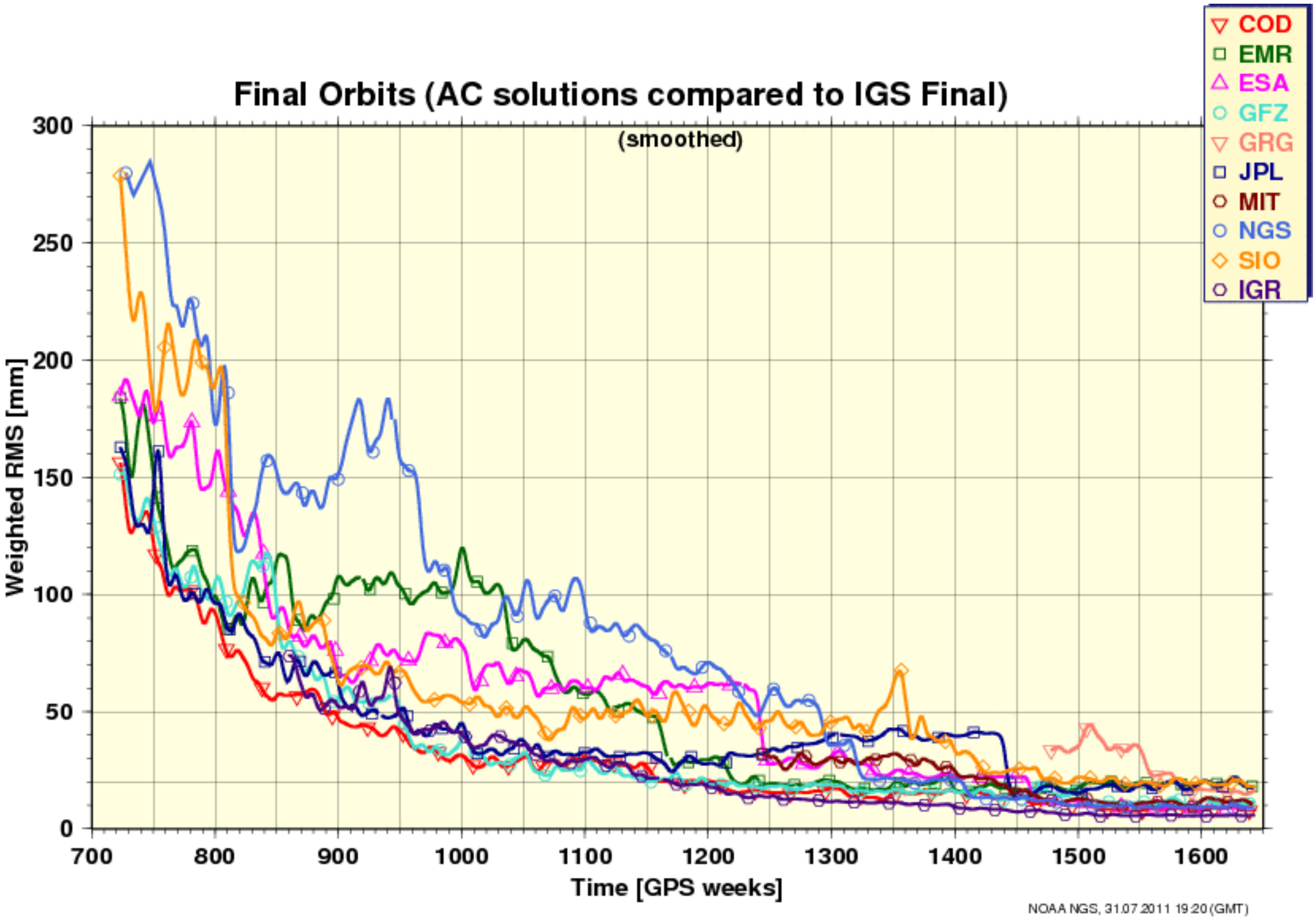
  - Monument instability
  - Loading of the crust by atmosphere, oceans, and surface water
- Unmodeled motions of the satellites
- Reference frame



GPS Satellite

Limits to model are non-gravitational accelerations due to solar and albedo radiation, unbalanced thrusts, and outgassing; and non-spherical antenna pattern

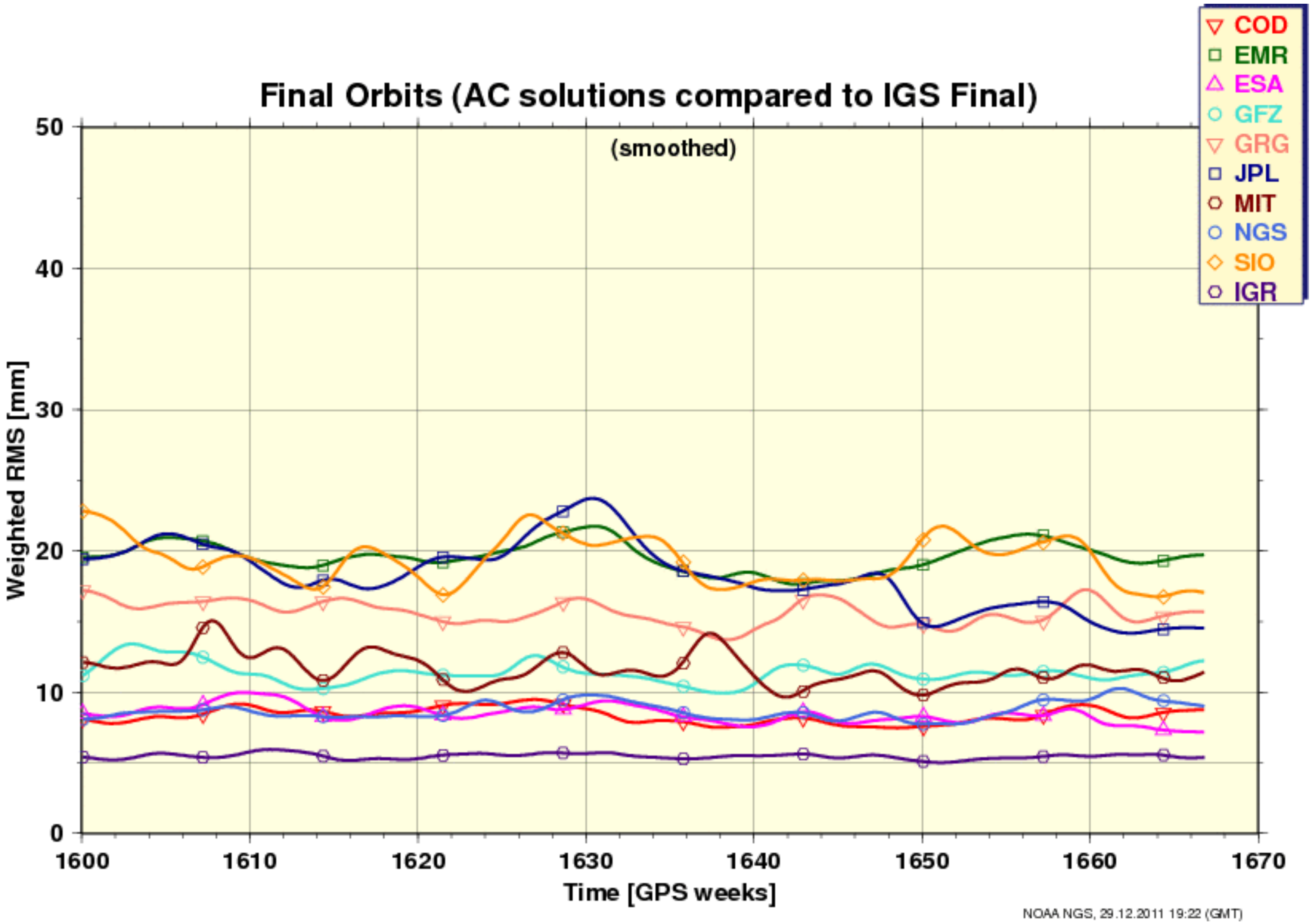
Modeling of these effects has improved, but for global analyses remain a problem



Quality of IGS Final Orbits 1994-2011/07

20 mm = 1 ppb

Source: http://acc.igs.org



Quality of IGS Final Orbits Last Year 2010/12-2011/12

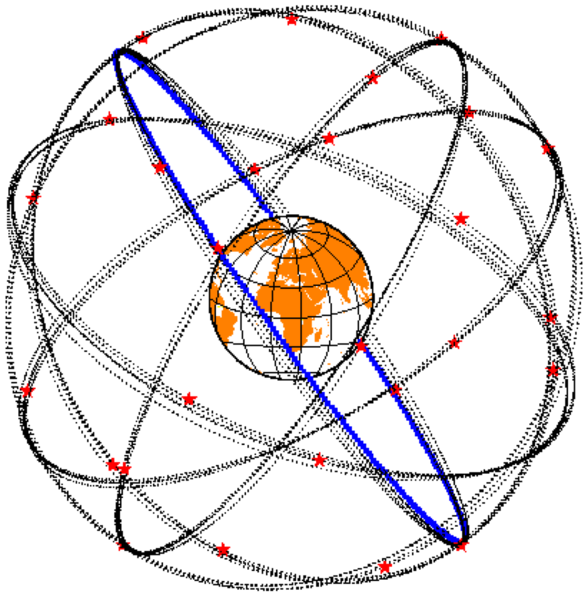
20 mm = 1 ppb

Source: http://acc.igs.org

Limits of GPS Accuracy

- Signal propagation effects
  - Signal scattering (antenna phase center / multipath)
  - Atmospheric delay (mainly water vapor)
  - Ionospheric effects
  - Receiver noise
- Unmodeled motions of the station
  - Monument instability
  - Loading of the crust by atmosphere, oceans, and surface water
- Unmodeled motions of the satellites
- Reference frame

Reference Frames



Global Reference Frame quality:

Center of Mass <10 mm

ITRF ~ 2 mm, < 1 mm/yr

Continental scale networks (e.g. PBO)

< 1 mm/yr horiz., 2 mm/yr vert.

Local scale (100-200 km) depends on how “realized” and available stable sites (IGS sites in region)

Effect of Orbital and Geocentric Position Error/ Uncertainty

High-precision GPS is essentially relative !

Baseline error/uncertainty ~ $\frac{\text{Baseline distance}}{\text{SV altitude}}$ x geocentric SV or position error

SV errors reduced by averaging:
Baseline errors are ~ 0.2 • orbital error / 20,000 km
e.g. 20 mm orbital error = 1 ppb or 1 mm on 1000 km baseline

Network ("absolute") position errors less important for small networks
e.g. 5 mm position error ~ 1 ppb or 1 mm on 1000 km baseline
10 cm position error ~ 20 ppb or 1 mm on 50 km baseline

* But SV and position errors are magnified for short sessions

Summary

- High precision GPS (mm and better positioning) requires external information in additional to just the data and orbit information.
- Larger site separations and mixed equipment types require more care in the data analysis than short baseline, homogeneous system data collection.
- All of the external information needed is available and the GAMIT processing system gathers most of this information automatically. There is some information that users need to keep up to date (discussed later).
- The next two lectures examine running GAMIT and GLOBK. The final session today will be tutorial looking at an earthquake effected data set.