GPS and volcano monitoring

PASI workshop: January 20, 2011

Chuck DeMets

Univ. of Wisconsin-Madison

8:30 to 10 AM – GPS on a volcano

1. Absolute and differential measurements
2. Practical issues
3. Data processing and interpretation

10 to 10:45 - Break

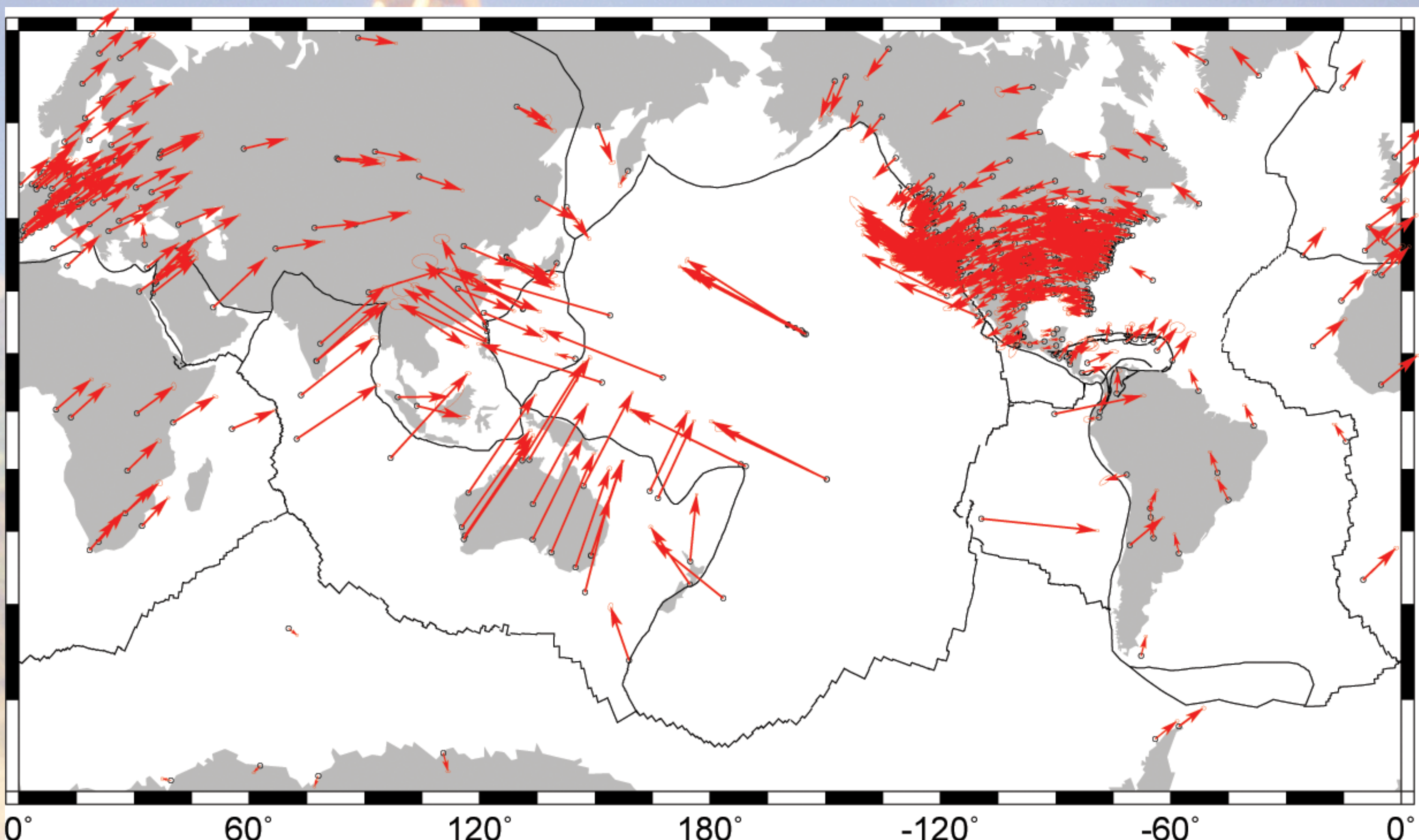
10:45 to 12 – Examples

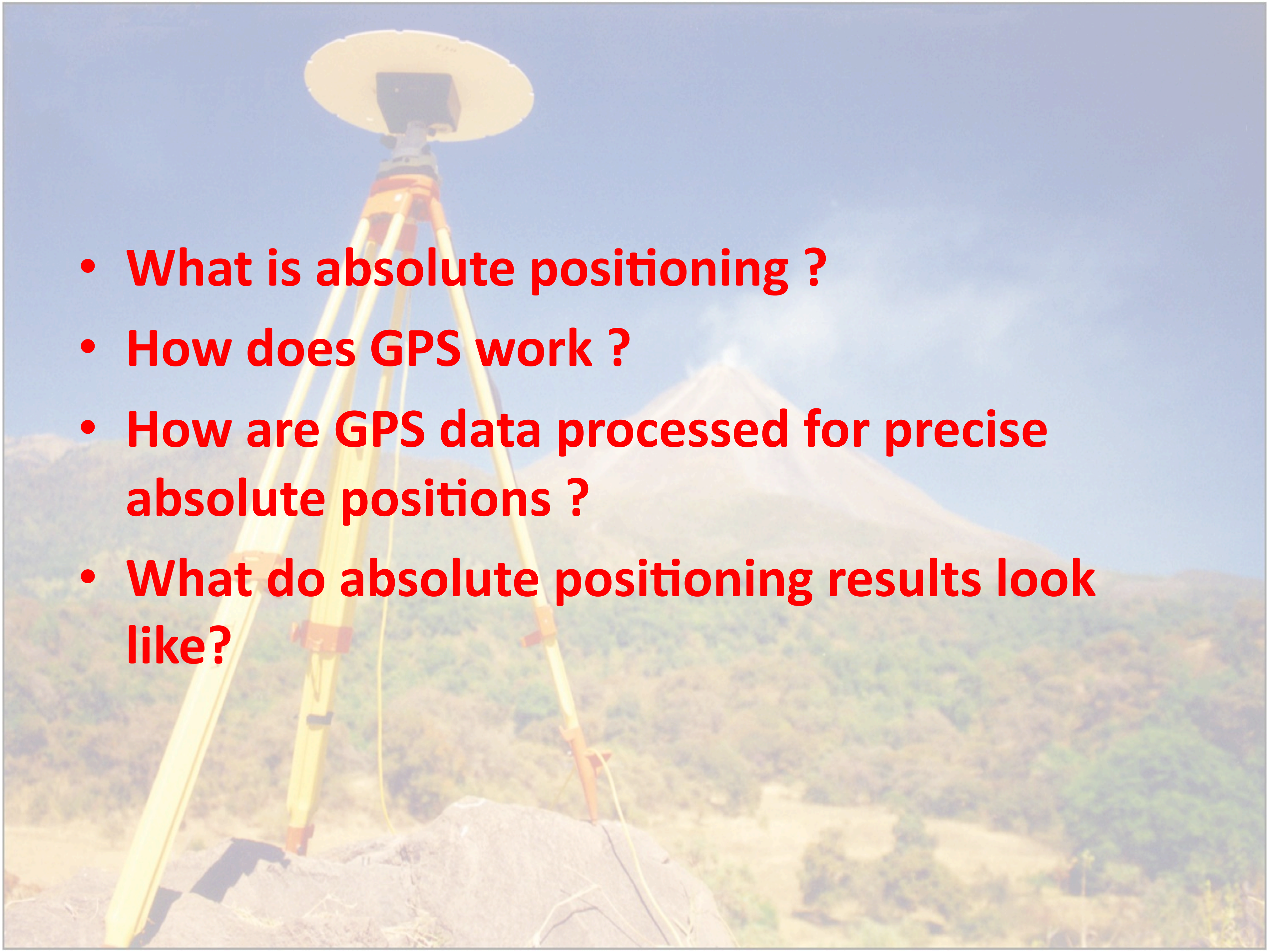
1. Peru – Edu Taipe; INGEMMET
2. Colombia - Milton Ordonez; INGEOMINAS
3. Nicaragua - Armando Saballos; Univ. South Florida
4. El Salvador - DeMets; Univ. Wisconsin-Madison

12:15 to 1:45 - Lunch break

1:45 to finish – GPS processing exercise – from raw data to tectonic interpretation

Absolute positioning with GPS



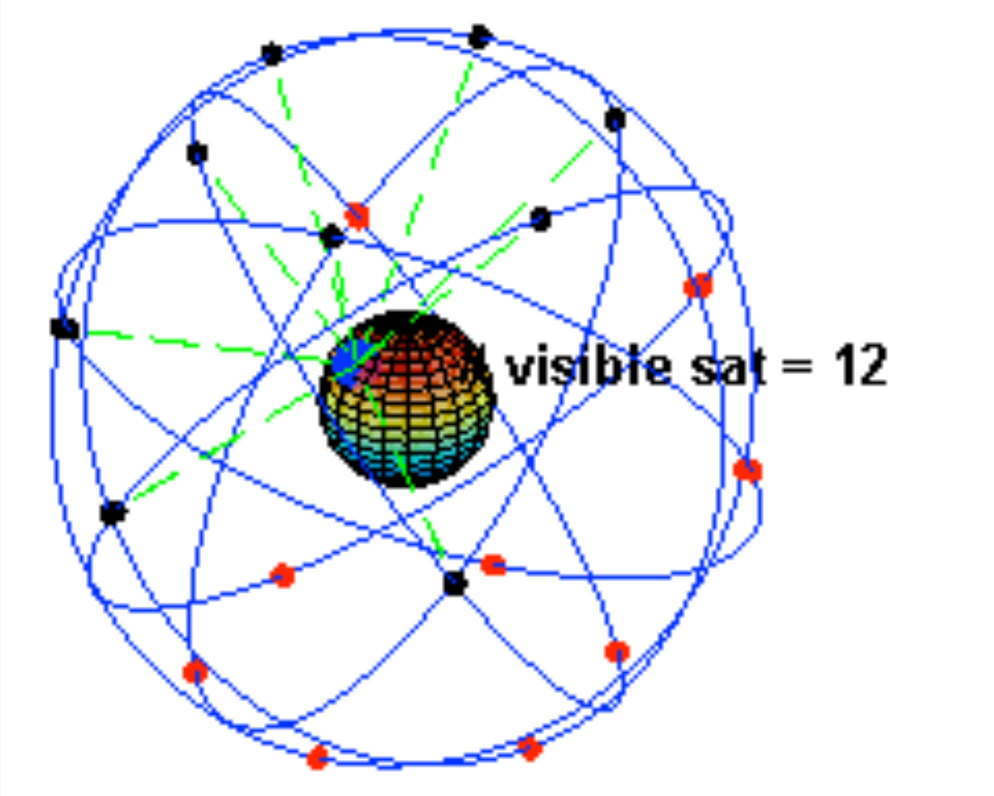


- What is absolute positioning ?
- How does GPS work ?
- How are GPS data processed for precise absolute positions ?
- What do absolute positioning results look like?

Absolute positioning is the method of measuring on a stationary GPS mark to find the site **latitude, longitude, and elevation**.

How does GPS work?

- Principle of triangulation
- GPS satellite signal
- GPS data file



How does GPS work (triangulation) ?

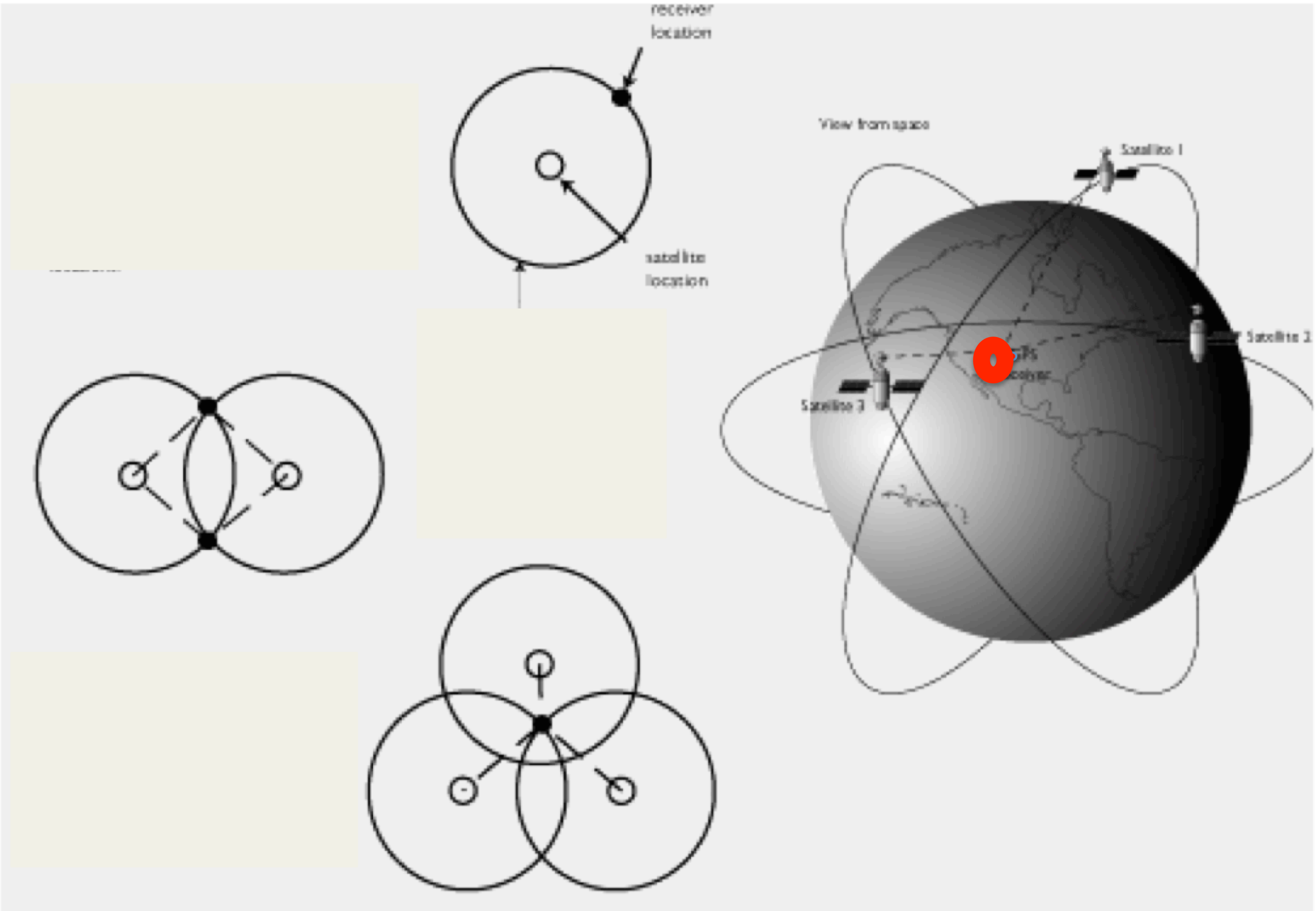
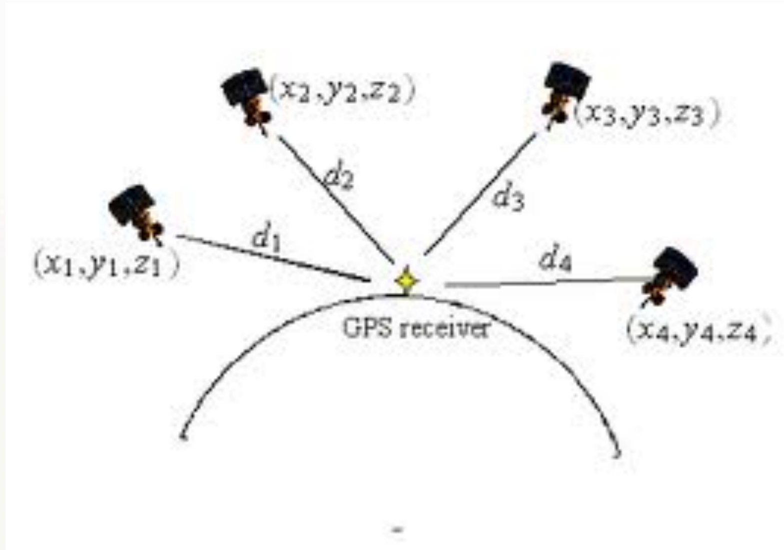


Figure 3.1. How does a GPS work?



- Let (x_o y_o z_o) be receiver position
- Let (x_n y_n z_n) be position of *nth* GPS satellite
- *Distance (range) from GPS receiver to nth GPS satellite is*

$$d_n = \text{sqrt}\,[\,(x_n - x_o)^2 + (y_n - y_o)^2 + (z_n - z_o)^2\,]$$

$d_n = \text{sqrt} [(x_n - x_o)^2 + (y_n - y_o)^2 + (z_n - z_o)^2]$

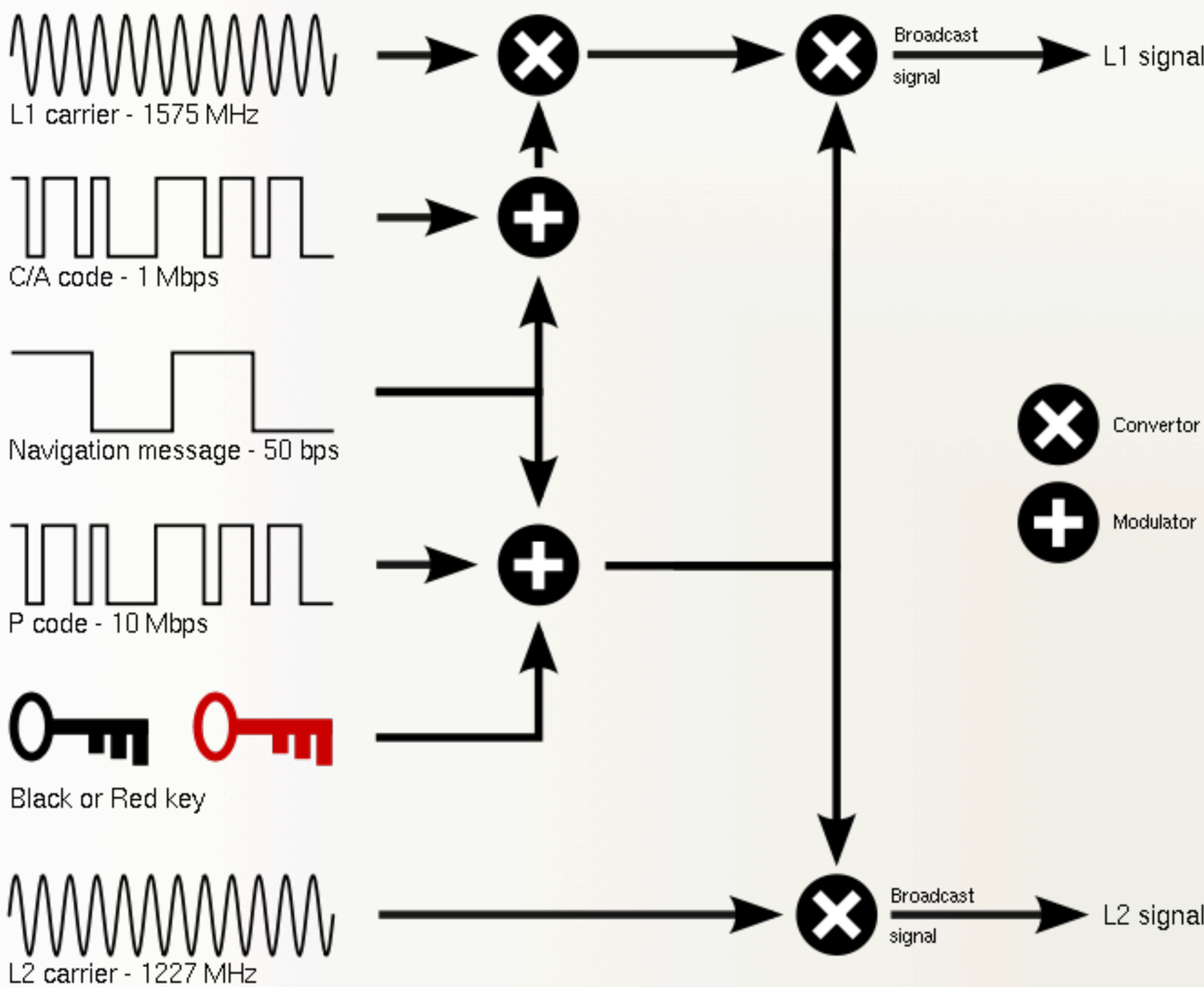
Known: Satellite positions x_n y_n z_n (change during day)

Measured: Distances d_n (change during day)

Want to estimate: Receiver position x_o y_o z_o

Position may remain constant (static) or may change (kinematic)

How is distance (range) from receiver to satellite determined ?



Satellites send two frequency signals each with four parts.

C/A and P-codes and high-frequency carriers.

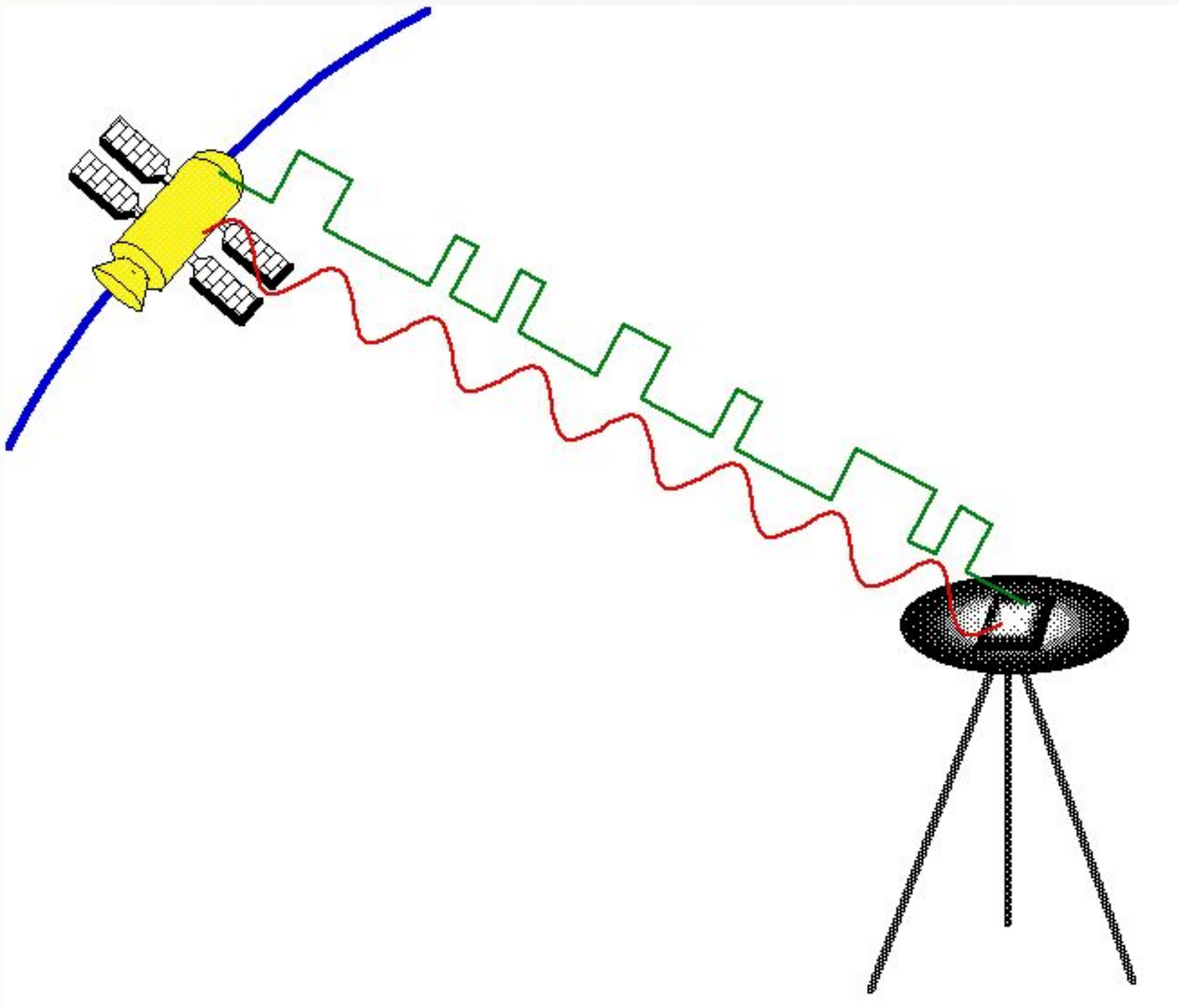
GPS receivers take apart and record the signals

EXAMPLE GPS DATA FILE

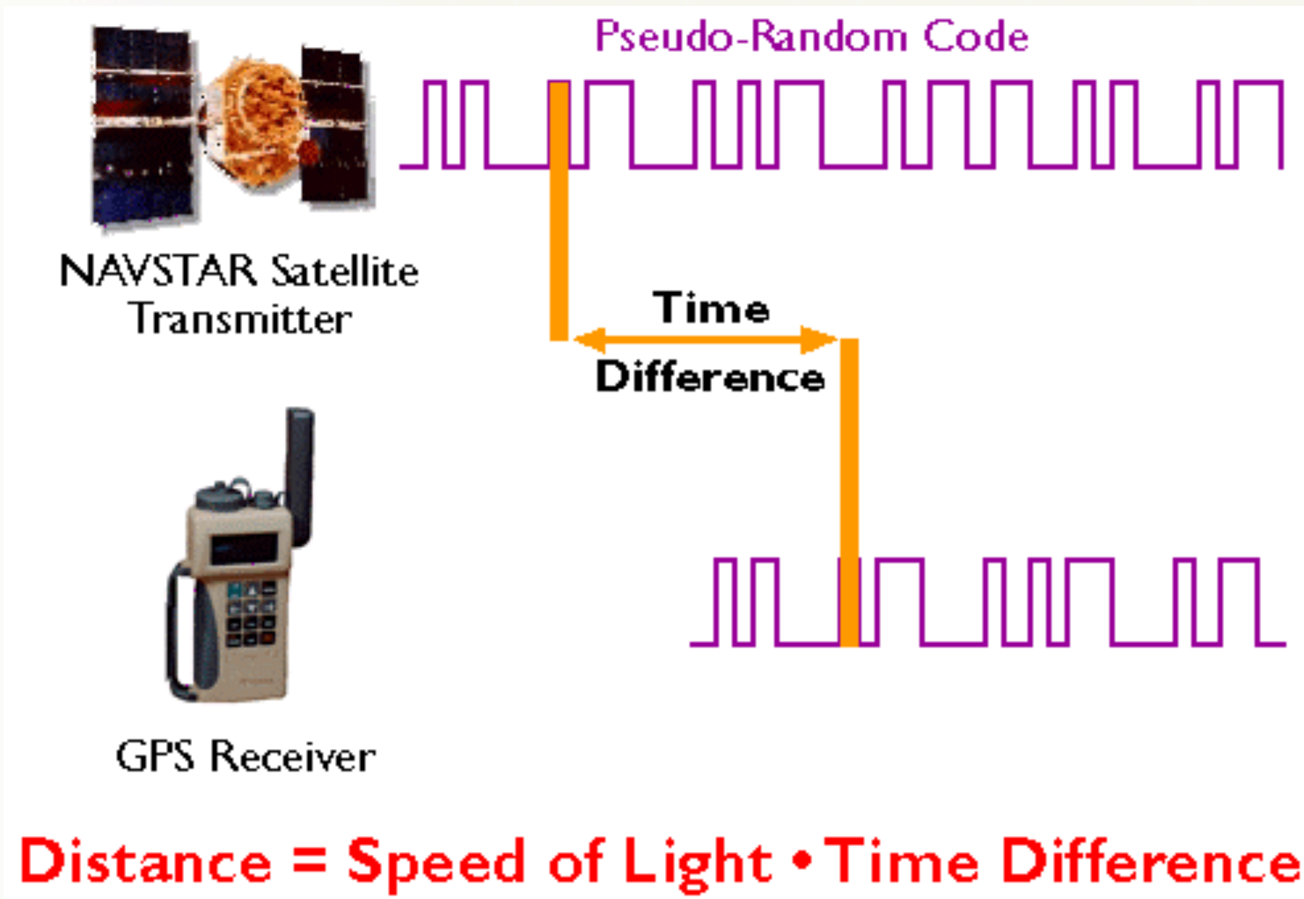
```
     2.11           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
teqc  2010Mar17                         20101020 07:34:50UTCPGM / RUN BY / DATE
1140                                                        MARKER NAME
GSI, JAPAN          GEOSPATIAL INFORMATION AUTHORITY OF JAPAOBSERVER / AGENCY
00000               TRIMBLE NETRS                           REC # / TYPE / VERS
                    TRM39105.00     GSI                     ANT # / TYPE
 -4307239.9528  4147691.6838  2211925.7447                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     6    L1    C1    L2    P2    S1    S2                  # / TYPES OF OBSERV
    30.0000                                                 INTERVAL
  2010     9    28     0     0    0.0000000     GPS         TIME OF FIRST OBS
 10  9 28  0  0  0.0000000  0  7G03G06G14G16G21G29G31
 -10465271.871 6  23186899.125 6  -8108106.77047  23186897.56247        43.750
        29.5004
 -16251262.332 7  21703027.883 7 -12749183.04548  21703025.42248        49.500

 YR MO DY HR MN SEC             SATELLITE INFO
 10  9 28  0  0  0.0000000  0  7G03G06G14G16G21G29G31
```

SAT #	L1 (phase)	C1 (range in m)	L2 (phase)	P2 (range in m)
03	-10465271.871	23186899.125	-8108106.77047	23186897.56247
06	-16251262.332	21703027.883	-12749183.04548	21703025.42248

Finding sat-to-receiver distance from C/A or P-code



- Each GPS **satellite** has OWN unique C/A & P-code
- Each GPS receiver knows C/A and P-codes for ALL GPS satellites.



How precise are ranges found with CA and P codes ?

- CA code “chips” 1.023 million times per second
- P code chips 10.23 million times per second
- Average “chip” has wavelength of 300 meters for CA code and 30 m for P code.
- Receiver can “line up” edges of the CA and P “chips” to about 1%, or 3 meters for CA and 30 cm for P.

Historical note

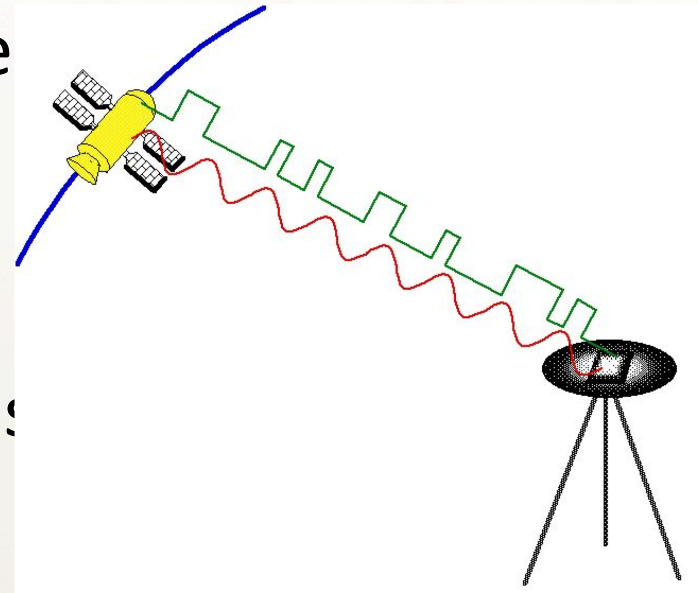
US Dept of Defense originally envisioned civilian access to only CA code for meter-level positioning. Planned to reserve P-code for military precise positioning (cm-level).

Academic community discovered how to estimate ranges from high-frequency L1 and L2 carrier signals instead of the coded signals.

Allows millimeter-level positioning accuracy.

Millimeter-level GPS: Absolute positioning

L1 & L2 carriers are sine waves.
Cannot cross-correlate to estimate range like P-code because every cycle looks same



Range to satellite = number of L1 or L2 cycles counted by receiver times L1 (19 cm) or L2 (24 cm) wavelengths.

GPS receiver COUNTS cycles (phase).

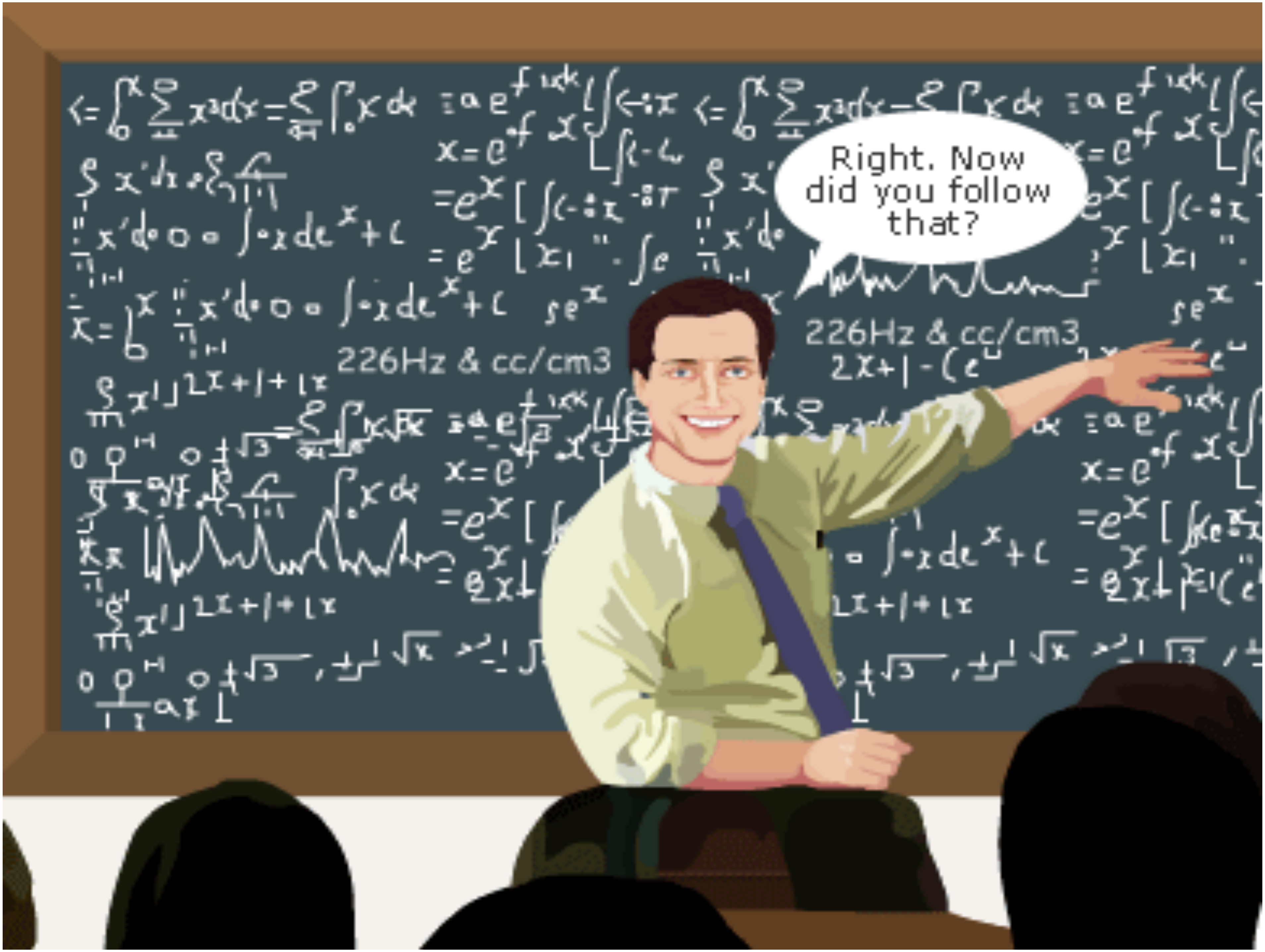
```
YR MO DY HR MN SEC                SATELLITE INFO
10  9 28  0  0  0.0000000  0  7G03G06G14G16G21G29G31

SAT #      L1 (phase)     C1 (range in m)  L2 (phase)      P2 (range in m)
03       -10465271.871    23186899.125    -8108106.77047  23186897.56247
06       -16251262.332    21703027.883   -12749183.04548  21703025.42248
```

Millimeter-level GPS: Absolute positioning

$$d(L1) = d_{sat\text{-}to\text{-}GPS} + \lambda_1 N_1 + c*(dT_{sat} - dT_{rec}) + d_{trop} - d_{ion} + d_{multipath}$$

Errors in d(L1) range measurement caused by:

- $\lambda_1 N_1$ is "bias" due to unknown number of cycles when receiver first detects satellite.
- dT_{sat} & dT_{GPS} are satellite and GPS receiver clock errors
- d_{trop} , d_{ion}, $d_{multipath}$ are GPS signal delays from water vapor in the atmosphere, free electrons in the ionosphere, and multipath near the GPS antenna.


Right. Now did you follow that?
226Hz & cc/cm3
226Hz & cc/cm3

Millimeter-level GPS: Absolute positioning

I have GPS Rinex files that I want to process to estimate absolute station coordinates. How can I do it?

Answer: Three software packages are freely available: BERNESE, GAMIT, and GIPSY. All three are FREE. ~1000 institutions worldwide use these (I use GIPSY).

Drawback: Obtaining and learning this software can require months and significant computer expertise.

FREE Web-based automated processing of GPS RINEX files - Absolute positioning

apps.gdgps.net – NASA Jet Propulsion Laboratory automated processing w/GIPSY (static & kinematic)

ga.gov.au/geodesy/sgc/wwwgps - AUSPOS – Australian Geoscience (static only)

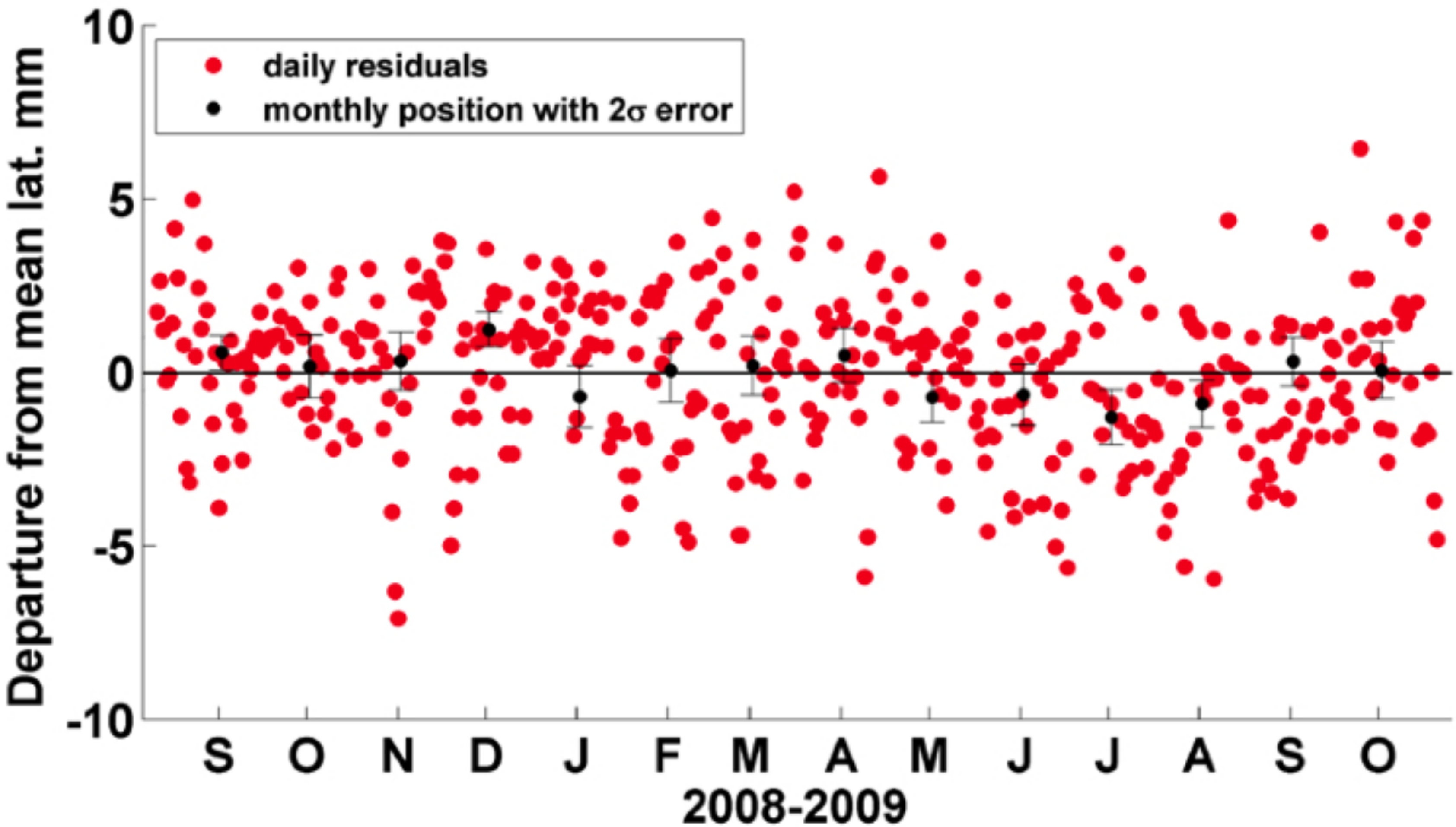
sopac.ucsd.edu/processing – Scripps SOPAC SCOUT software w/GAMIT (static only)

ngs.noaa.gov/OPUS – National Geodetic Survey (static only)

Millimeter-level GPS: Does it work?

Volcano reference station – El Salvador

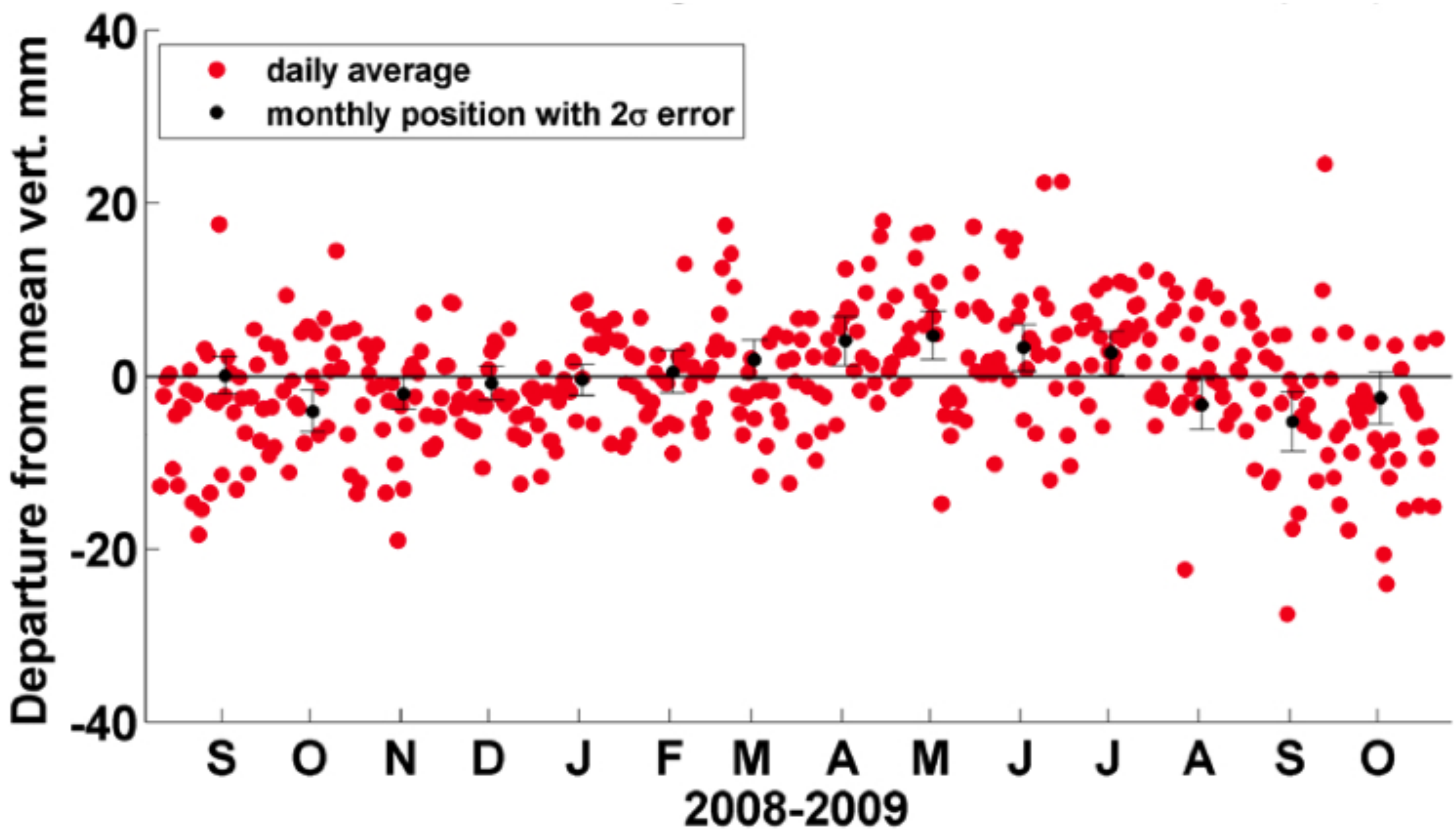
Daily Latitude estimates – GIPSY – 365 days



Millimeter-level GPS: Does it work?

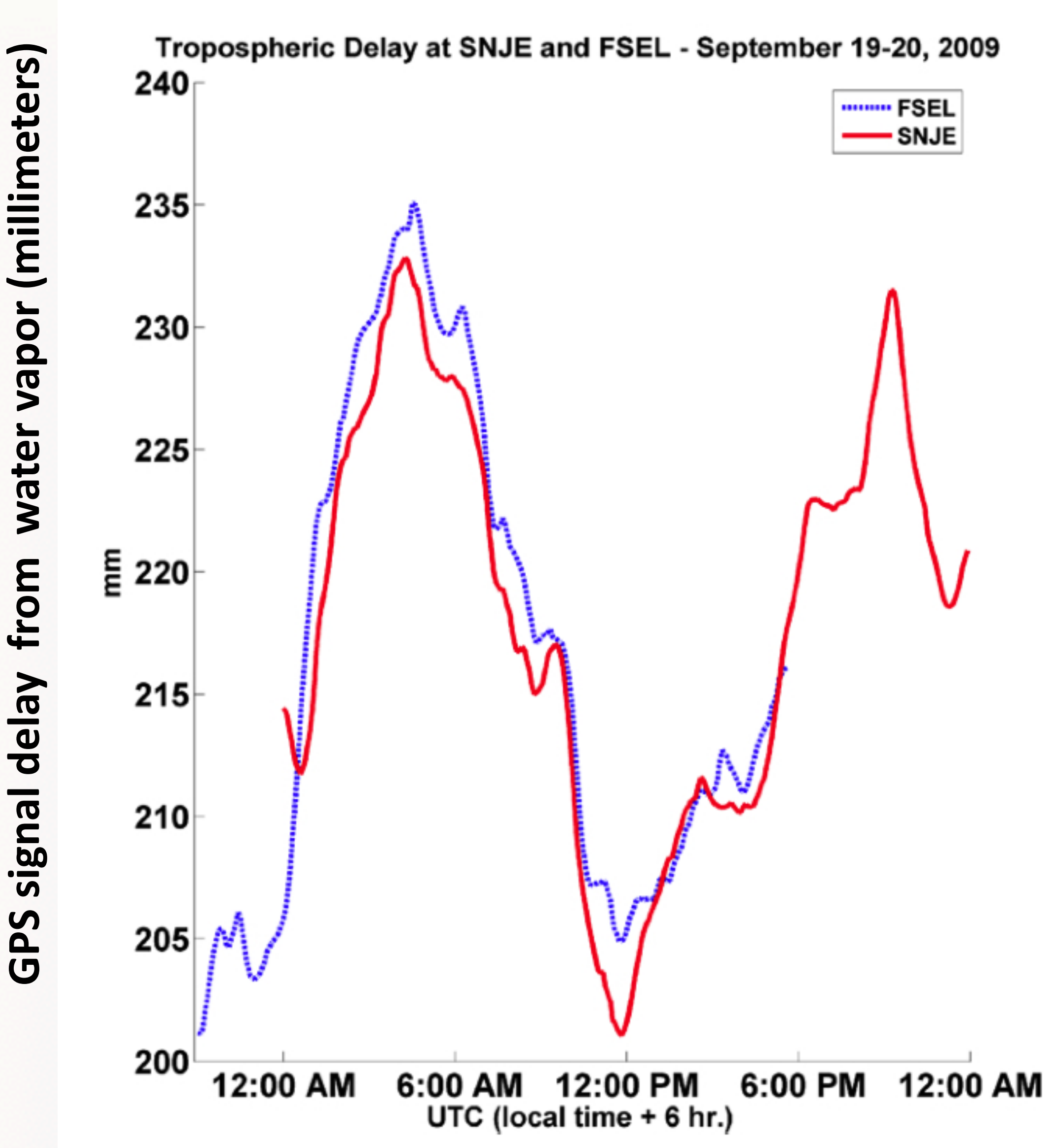
Volcano reference station – El Salvador

Daily Elevation estimates – GIPSY – 365 days



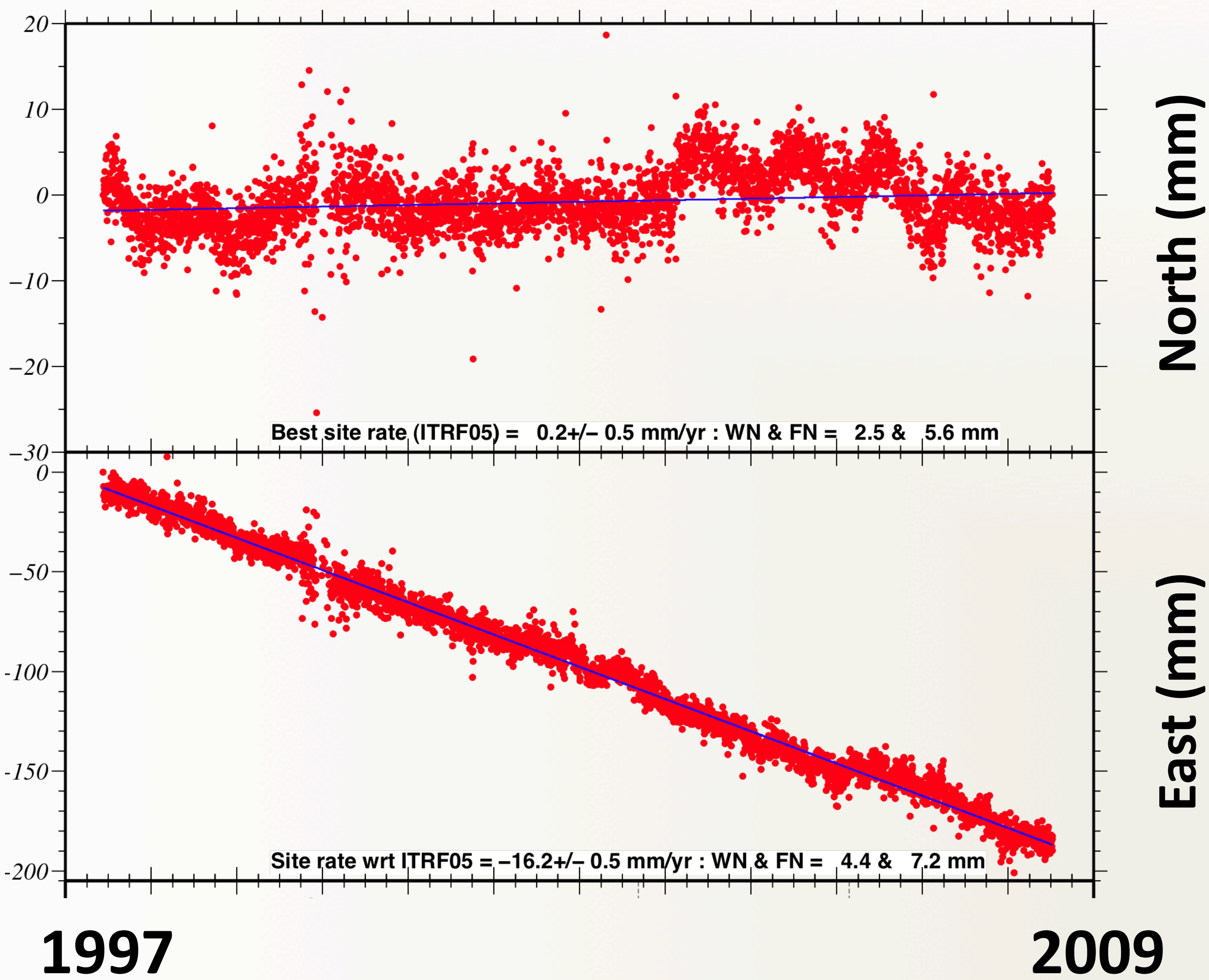
Tropospheric water vapor delay

(GIPSY estimates parameters other than site location)

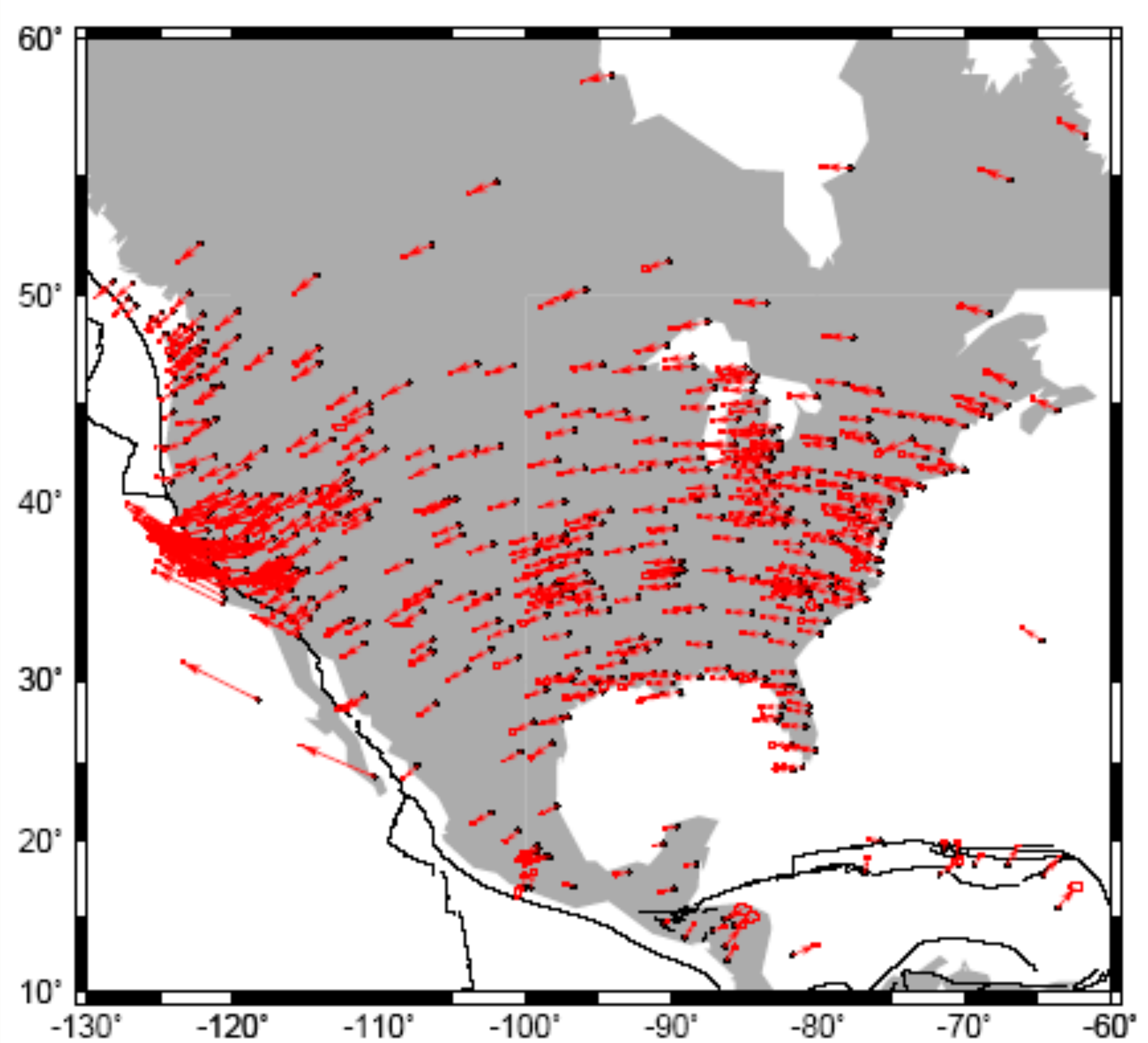


Millimeter-level GPS: Absolute positioning

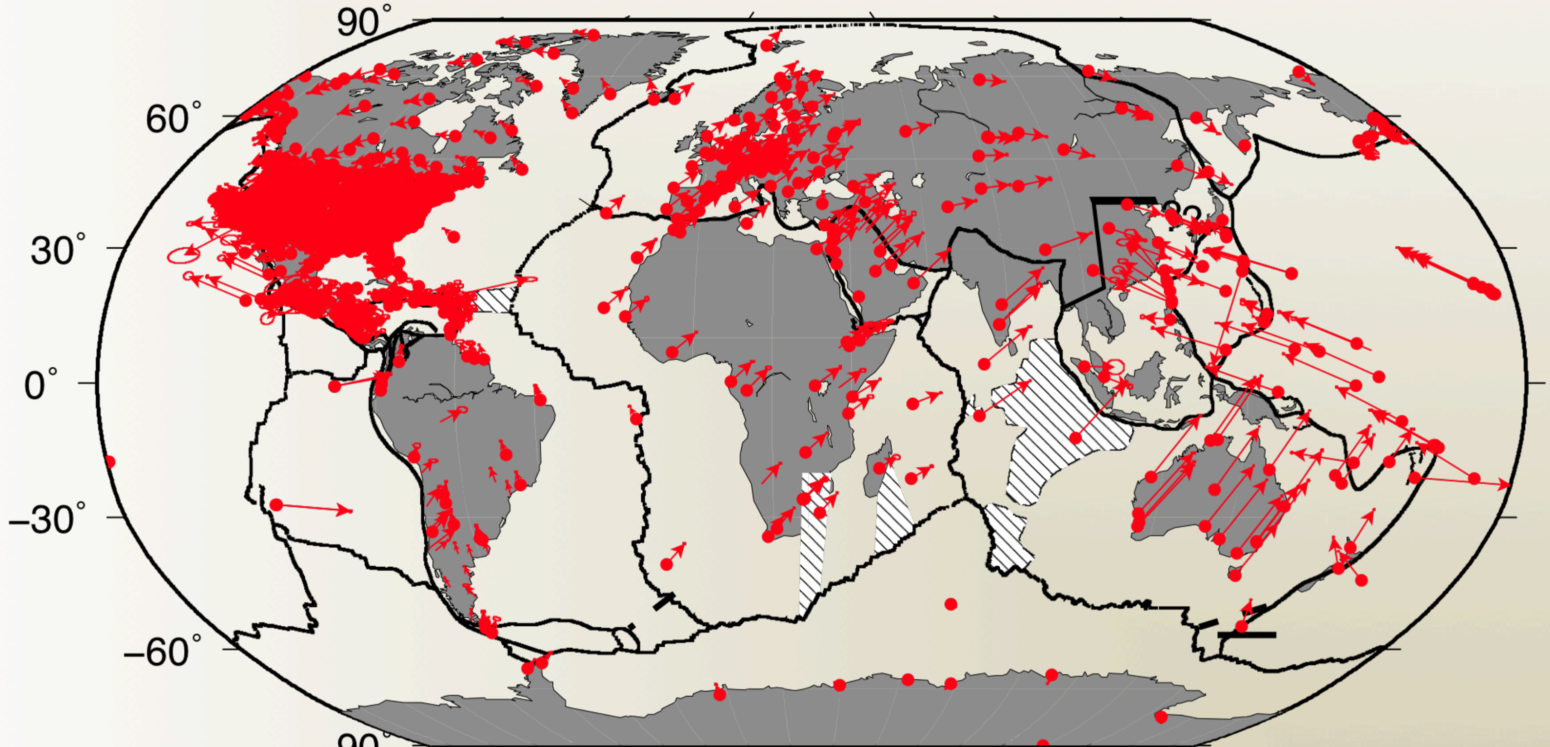
STB1 site motion (44.796N 272.686E) – Uses ITRF05



Millimeter-level GPS: North American continuous GPS



Global plate motions – UW-Madison solution – 2/2009

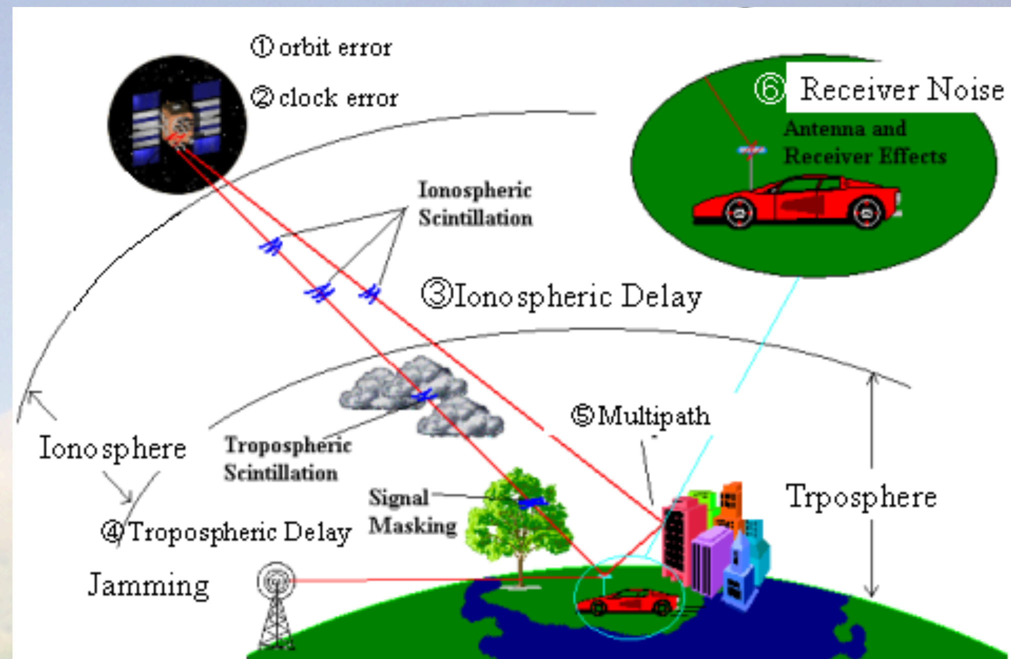


GPS station locations for which daily and campaign data are GIPSY–processed at UW–Madison


Short break

Differential GPS positioning

Why use differential GPS instead of precise absolute positioning?



1. Several sources of positioning error cancel (or nearly so) over short distances (iono, tropo, orbit). Can get precise ***relative*** position estimates for occupation times as short as 30 minutes.
2. Can occupy more sites, but limited to distances less than 10 km.
3. Requires two receivers instead of one.

Differential GPS: Field strategy

Field strategy:

***Reference site*: no sky obstruction, 1-2 km from volcano, stable geodetic mark with good access and security**

***Volcano sites:* minimize sky obstr., closer than 5 km to reference site, closer to summit is better (larger signal)**

***Network*: If volcanic network > ~5 km, need > 1 reference site. Can use long (24+ hr) occupations of reference sites to TEST stability of reference sites. Use absolute positioning to process their data.**

CRITICAL: Differential GPS REQUIRES that reference site receiver operate at same times that "roving" receiver occupies volcano sites.

Differential GPS: Equipment

2 – L1/L2 P-code GPS receiver and antennas ($4,000 to 7,000 US each)
2 – antenna tripods/tribrachs or fixed-height spike mounts (~$500-$1000 each)
2 – battery or solar panels ($100-$1000)
1 – rock drill plus epoxy glue and steel pins (~$1,000)
1 – Field notes to relocate geodetic marks
(NOTE: can buy used GPS on eBay !)

Differential GPS: Data processing

Commercial dGPS software:

Trimble GPSurvey (out of date)

Trimble Geomatics Office (current, ~$5,000)

Others ?

Free dGPS software:

VECSOL

XRapS

Others ?

Trimble Geomatics Office Output

Baseline Processing Report

Project : TSBL

User name	hnlechne	**Date & Time**	9:35:51 AM 11/3/2010
Coordinate System	UTM	**Zone**	16 North
Project Datum	WGS 1984		
Vertical Datum		**Geoid Model**	EGM96 (Global)
Coordinate Units	Meters		
Distance Units	Meters		
Height Units	Meters		

Processing Summary

ID	From	To	Baseline Length	Solution Type	Ratio	Reference Variance	RMS
B1	SNJE	TSBL	4591.0009m	Iono free fixed	10.5	1.215	0.012m
B2	SNJE	TSBL	4591.0087m	Iono free fixed	115.9	1.274	0.010m
B3	SNJE	TSBL	4590.9954m	Iono free fixed	70.5	1.095	0.014m
B4	SNJE	TSBL	4591.0000m	Iono free fixed	94.4	1.211	0.010m
B5	SNJE	TSBL	4591.0085m	Iono free fixed	3.2	1.895	0.015m
B6	SNJE	TSBL	4591.0041m	Iono free fixed	105.4	1.091	0.011m
B7	SNJE	TSBL	4591.0076m	Iono free fixed	16.2	2.436	0.020m
B8	SNJE	TSBL	4591.0078m	Iono free fixed	46.8	2.427	0.017m

Trimble Geomatics Office Output

Back to Processing Summary

Baseline Summary

Baseline Components

- Standard Errors
- Covariance Matrix

Occupations

Tracking Summary

Residuals

Processing Style

- Static
- Kinematic
- Global
- Quality
- Tropo
- Iono
- Events
- OTF Search

Highlight in Trimble Geomatics

Baseline Components (Mark to Mark)

From:	SNJE				
Grid		Local		WGS 84	
Northing	1534685.0479m	Latitude	13°52'05.68930"N	Latitude	13°52'05.68930"N
Easting	218903.9564m	Longitude	89°36'02.49129"W	Longitude	89°36'02.49129"W
Elevation	1659.0238m	Height	1660.1910m	Height	1660.1910m

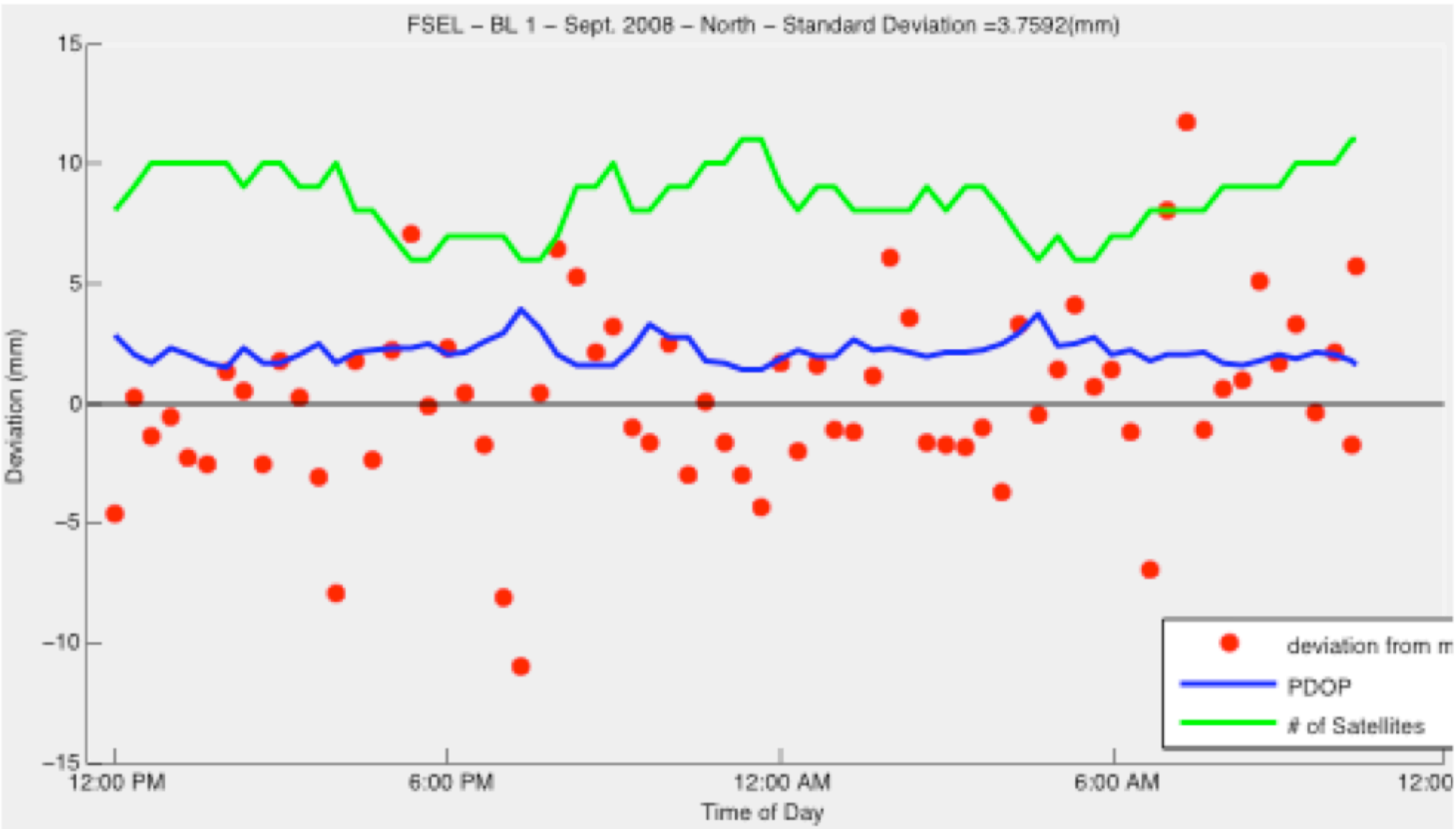
To:	TSBL				
Grid		Local		WGS 84	
Northing	1531174.1933m	Latitude	13°50'10.47539"N	Latitude	13°50'10.47539"N
Easting	215950.9501m	Longitude	89°37'39.49047"W	Longitude	89°37'39.49047"W
Elevation	1868.9929m	Height	1869.9222m	Height	1869.9222m

Baseline:					
Δ Northing	-3510.8546m	NS Fwd Azimuth	219°26'40"	Δ X	-2906.3997m
Δ Easting	-2953.0063m	Ell. Distance	4584.9346m	Δ Y	-1071.2080m
Δ Elevation	209.9693m	Δ Height	209.7312m	Δ Z	-3388.6050m

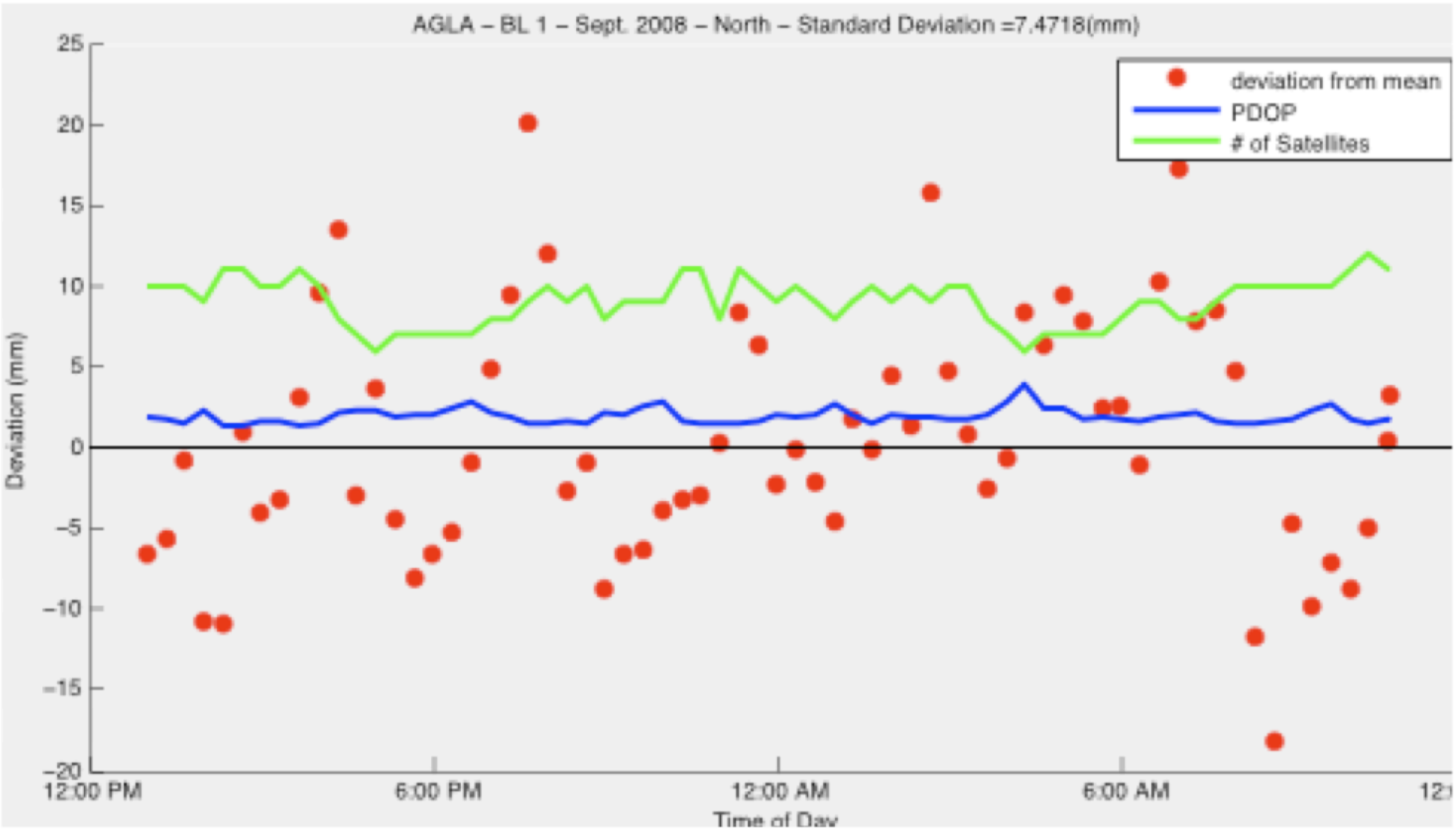
Standard Errors

Baseline Errors:					
σ Δ Northing	0.0008m	σ NS Fwd Azimuth	0.045 seconds	σ Δ X	0.0011m
σ Δ Easting	0.0011m	σ Ell.Distance	0.0009m	σ Δ Y	0.0029m
σ Δ Elevation	0.0029m	σ Δ Height	0.0029m	σ Δ Z	0.0010m

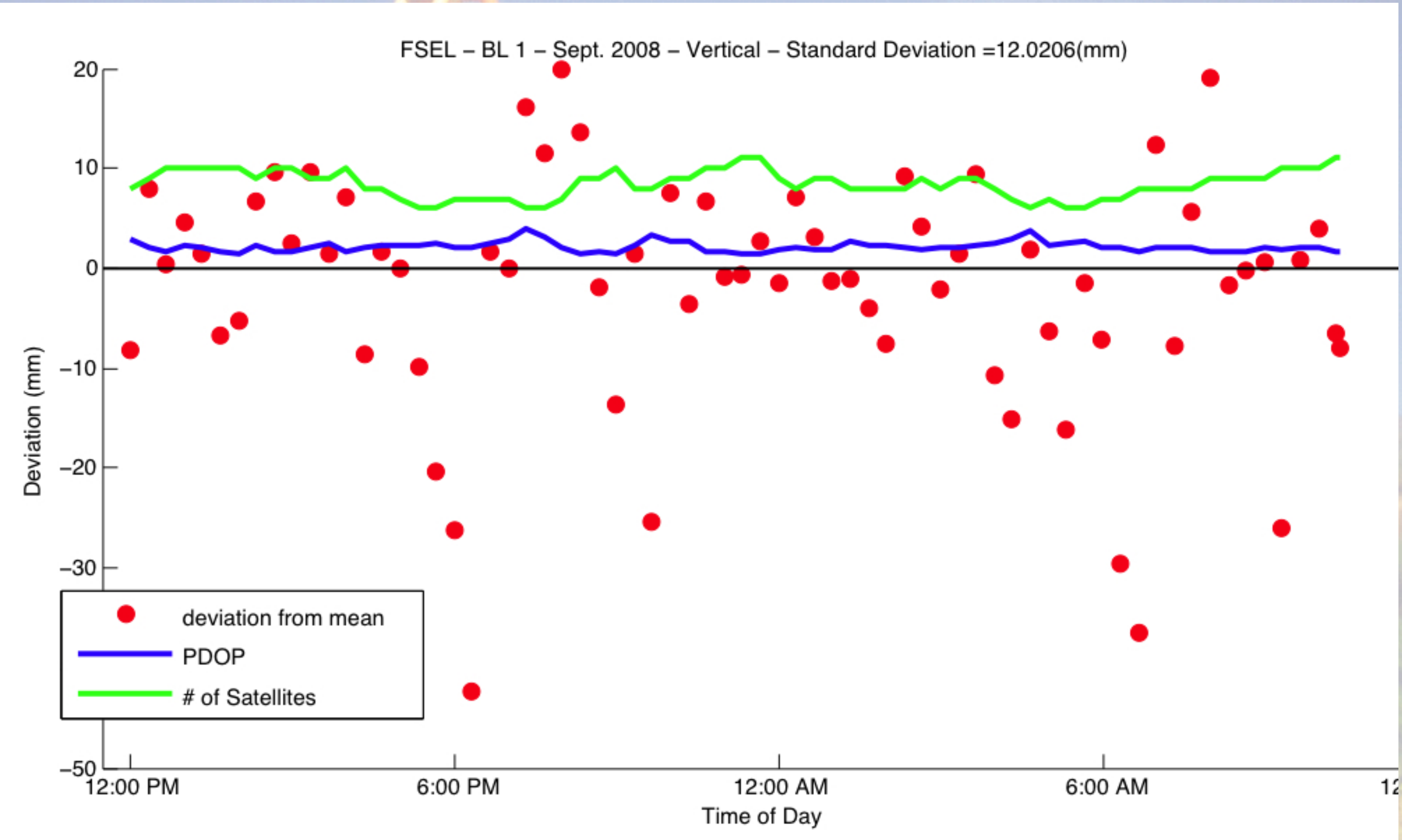
1-km-baseline – 20-minute sessions – N baseline length repeatable to ±3.8 mm



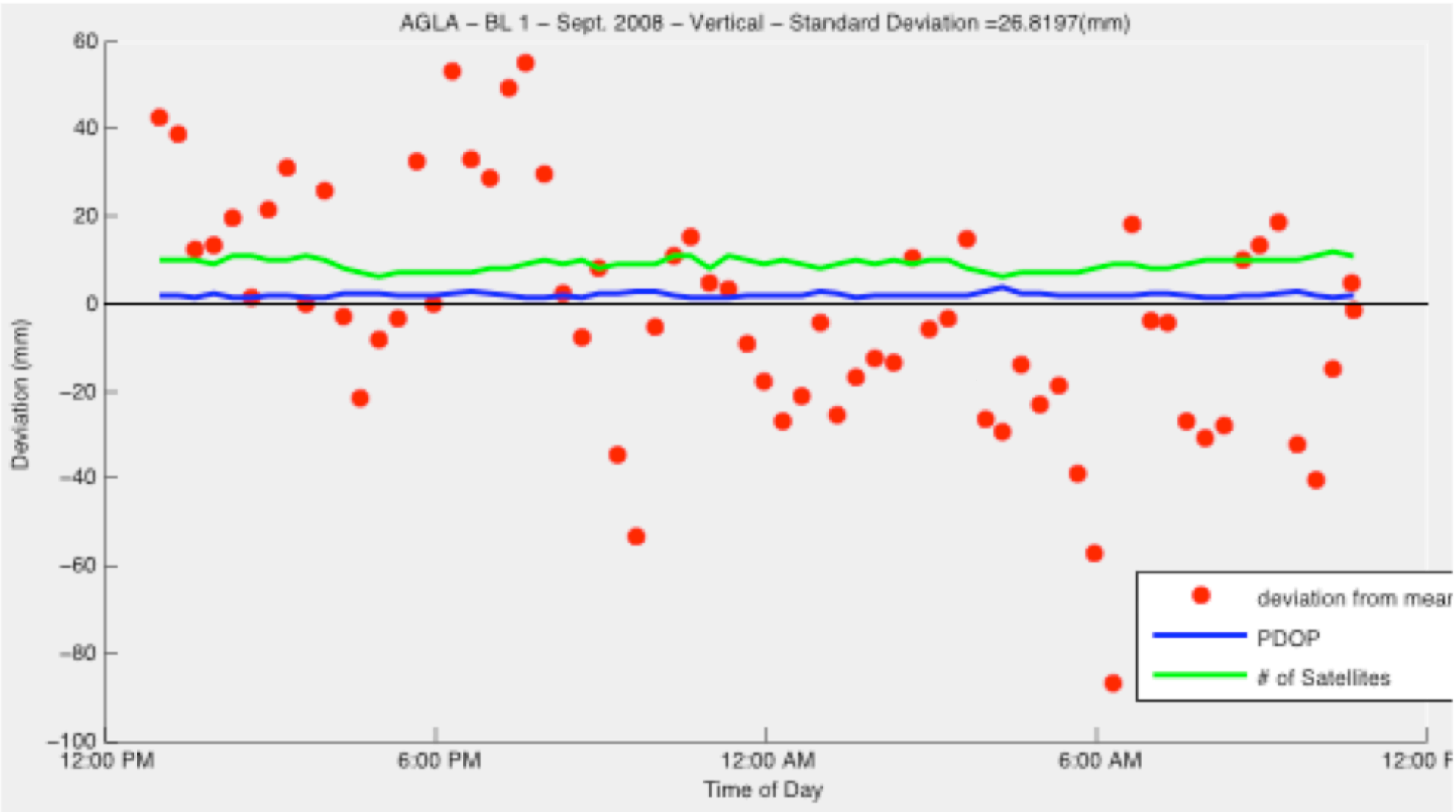
10-km-baseline – 20-minute sessions – N baseline length repeatable to ±7.5 mm



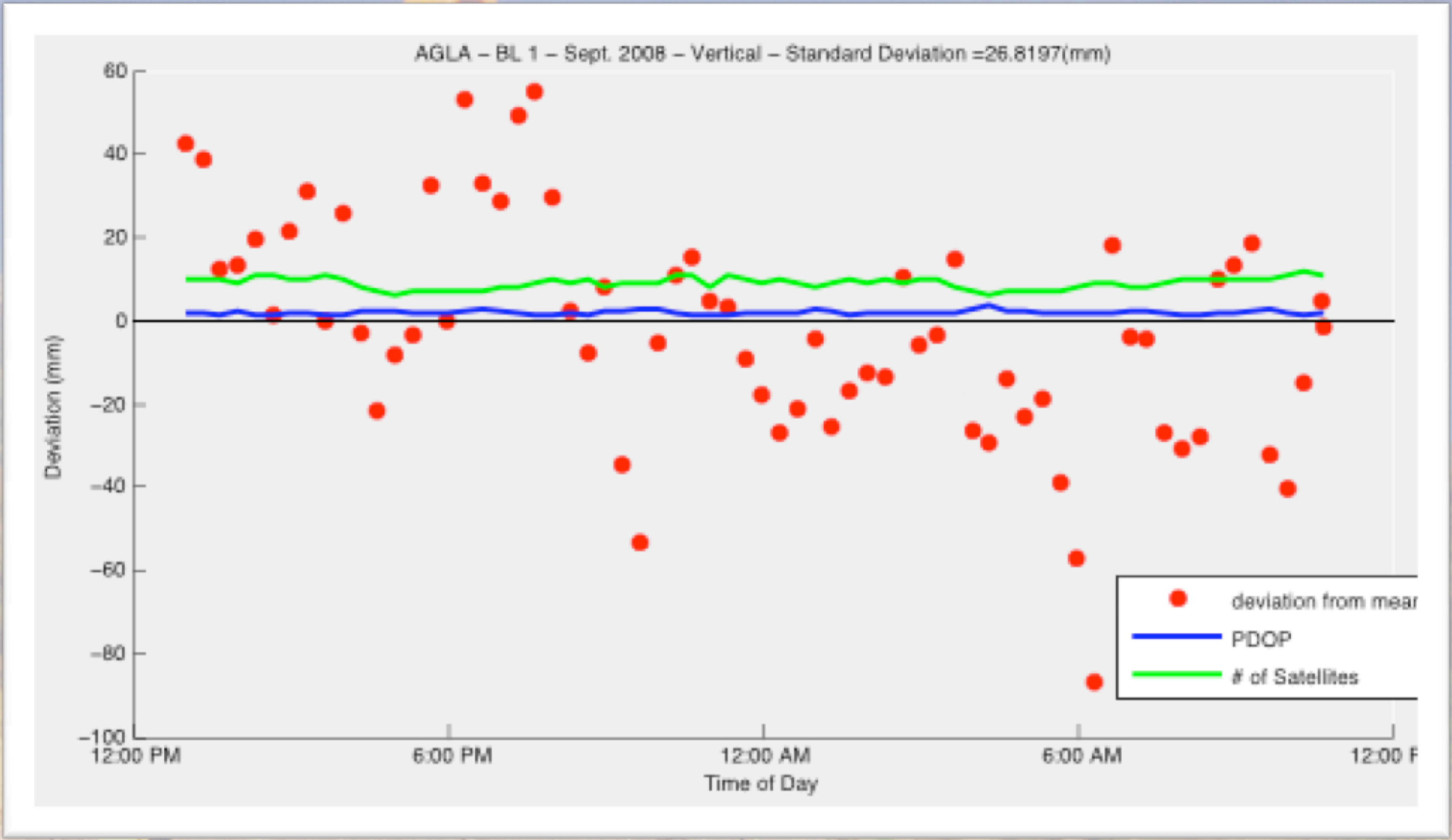
1-km-baseline – 20-minute sessions – V baseline length repeatable to ±12 mm



10-km-baseline – 20-minute sessions – V baseline length repeatable to ±27 mm



10-km-baseline – 20-minute sessions – V baseline length repeatable to ±27 mm



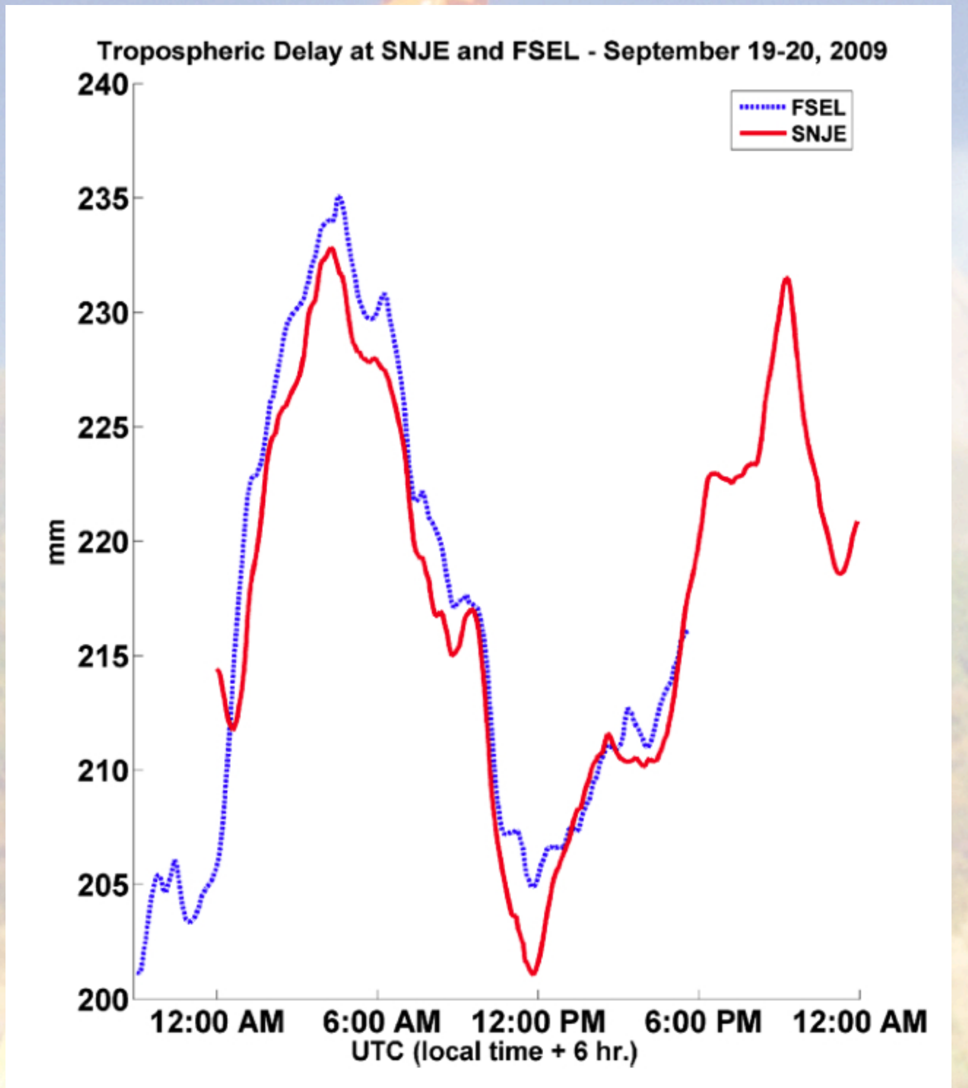
Differential GPS: Results and reliability

- CONCLUSIONS FOR NOW:
- ~1-km inter-station distance & 20-minute session: Repeatable to ±4 mm for N & E and ±10-15 mm VERTICAL.
- ~10-km distance & 20-minute sessions: Repeatable to ±8 mm for N & E and ±25 mm VERTICAL.
- LATER: More results from above data

Tropospheric water vapor delay

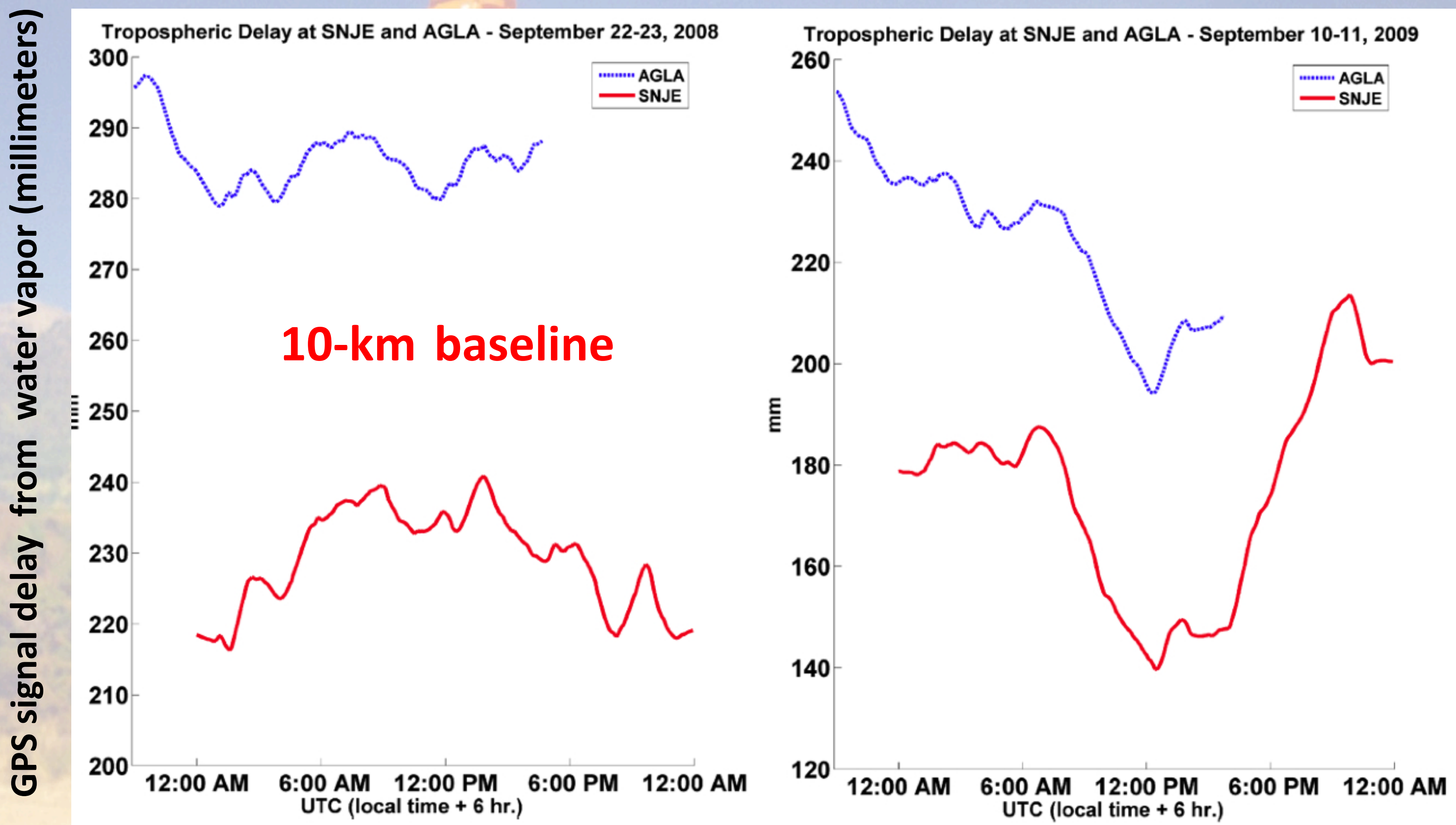
1-km baseline: Delays similar, so effects cancel at two sites

GPS signal delay from water vapor (millimeters)



SNJE to FSEL

Tropospheric delays differ, so error in relative locations is added (mostly elevation)



Differential GPS: Limitations

- Common troposphere assumption source of error
- Short sessions may amplify multipath error
- Assumes no deformation at reference site (a testable assumption)
- ALTERNATIVE – 3-hr sessions and APPS absolute positioning will give 5/5/10 mm precisions.