UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN | COLLEGE OF ENGINEERING

Using GPS Receivers to Study the Upper Atmosphere

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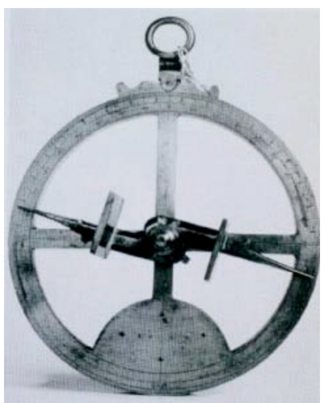
With a big THANKS to Anthea Coster for providing some very useful slides!

Overview

- Overview of the Global Positioning System
- GPS Observables and the Navigation Solution
- Inverting GPS measurements to study the atmosphere
  - Ionospheric electron density and scintillations
  - Examples from recent experiments
- The future of GPS in studying the upper atmosphere

The History of GPS in 7 minutes…

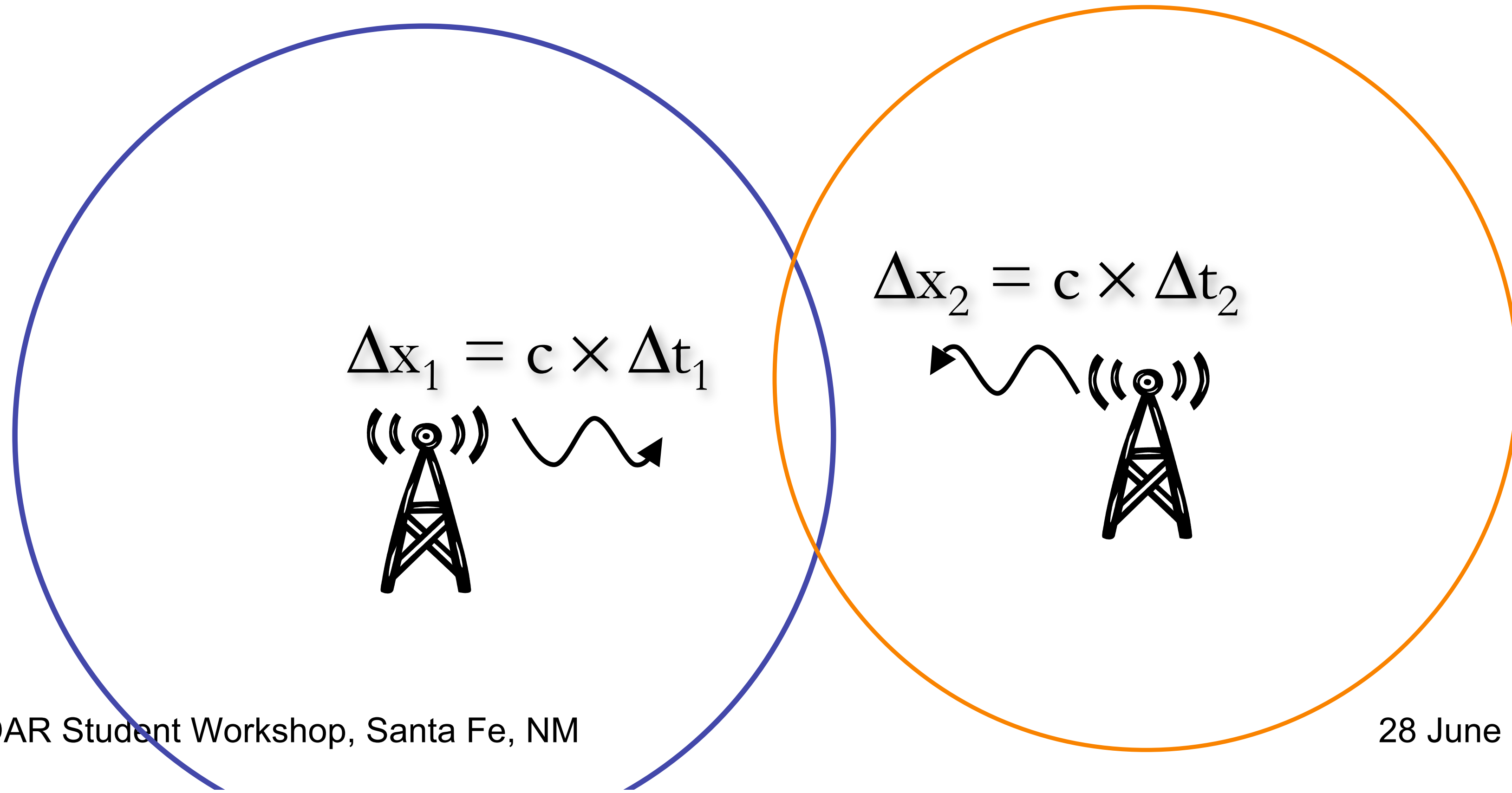
- At its most basic level, navigation consists of knowing *where* and *when* you are.
- In the hunter-gather days, navigation was quite simple as most societies were only aware of the world within walking distance.
- As our societies grew and intermingled, better ways to communicate distances and directions were needed.



  - This required a sophisticated and consistent way to describe position and time.
  - Several societies developed new instrumentation and techniques (magnetic compass, celestial navigation, etc).
  - These “traditional” methods required training and practice to master.

Radio-Based Navigation Systems

- In the early 20th century, new navigation systems based on radio wave propagation were created.
  - Operated on the basic idea of measuring the time difference in the received signal from two (or more) synchronized ground stations.



Radio-Based Navigation Systems

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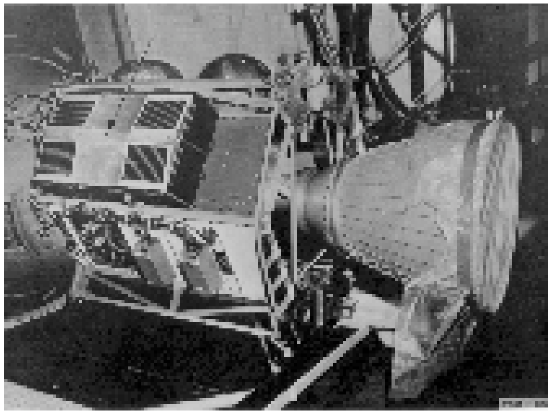
  - Operated on the basic idea of measuring the time difference in the received signal from two (or more) synchronized ground stations.
- The Long-Range Navigation system (LORAN) is an early example of this type of system.
  - Requires a network of transmitting ground stations
  - Positional accuracy of ~250 m
  - Primarily 2D solution
- LORAN is still in use today, with compatible systems operated around the world.

LORAN transmitting station, Malone, FL

The Dawn of the Space Age

- After the launch of Sputnik 1 in 1957, it was quickly realized that space-based transmitters held great advantages over the ground-based LORAN systems.
- The five-satellite Transit constellation was launched by the US Navy in the 1960s to demonstrate the utility of satellite-based timing signals for navigation.
- Improved clock accuracy demonstrated by the Timation satellite, launched by the Naval Research Laboratory in 1967.



Timation satellite.

Air Force Program 621B

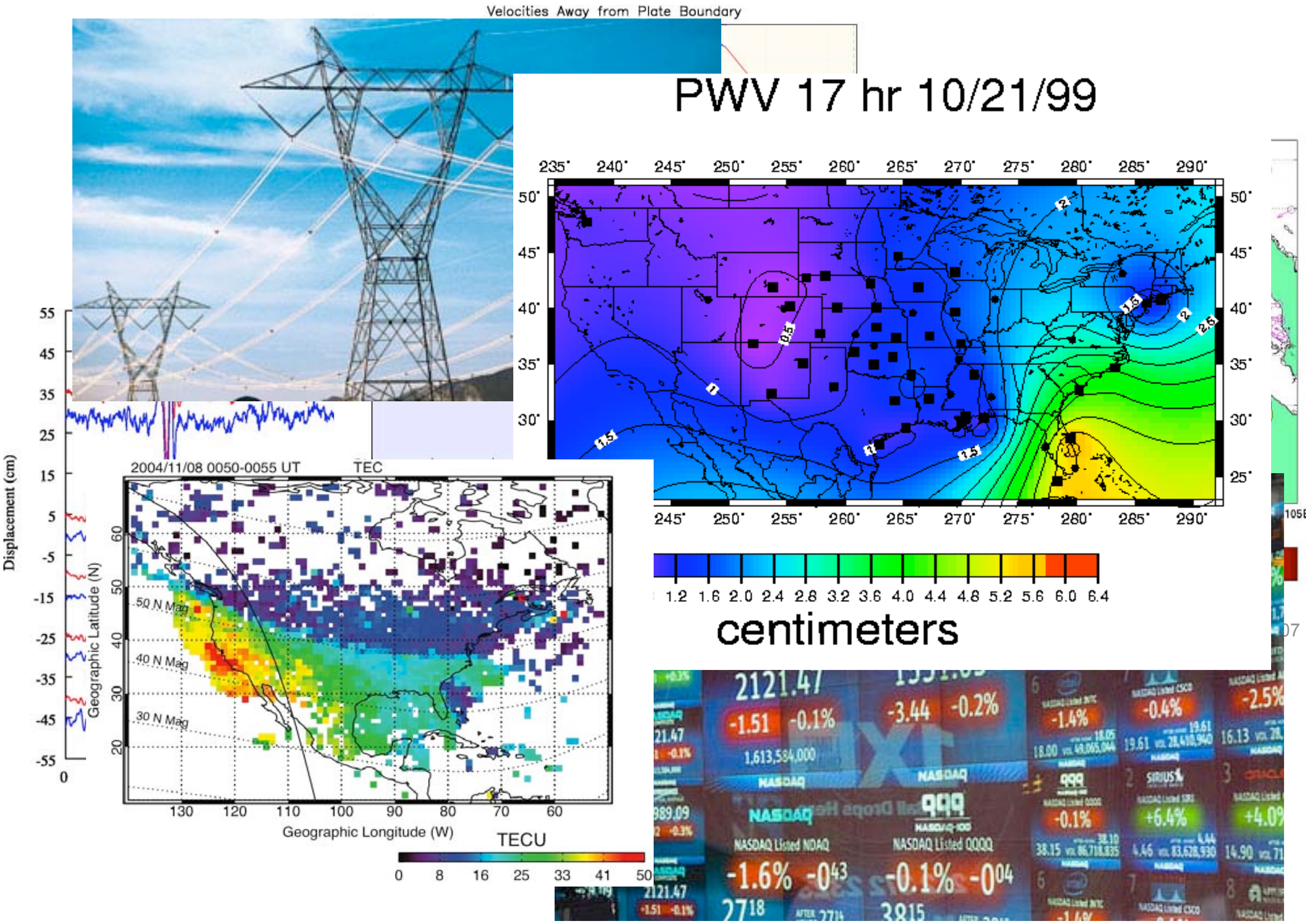
- “To the Navy, navigation is essentially a two-dimensional problem, but the Air Force was definitely interested in the third dimension” (Bradford W. Parkinson, “Co-Inventor” of GPS)
- 621B was an Air Force project and was the first satellite-based navigation system to provide accurate altitude information.
  - Timation could provide altitude with enough satellites.

The Birth of GPS

- In 1973, Parkinson and his colleagues met to create a new system combining the strengths of Transit, Timation, and 621B
- Resulted in the Global Positioning System/ NAVSTAR, approved on Dec 17, 1973.

- The first GPS satellite was launched in February 1978.
  - Additional satellites, with improvements, were steadily launched until the constellation reached 24 satellites and the system was declared “operational” in December 1993.

Not Just for Navigation



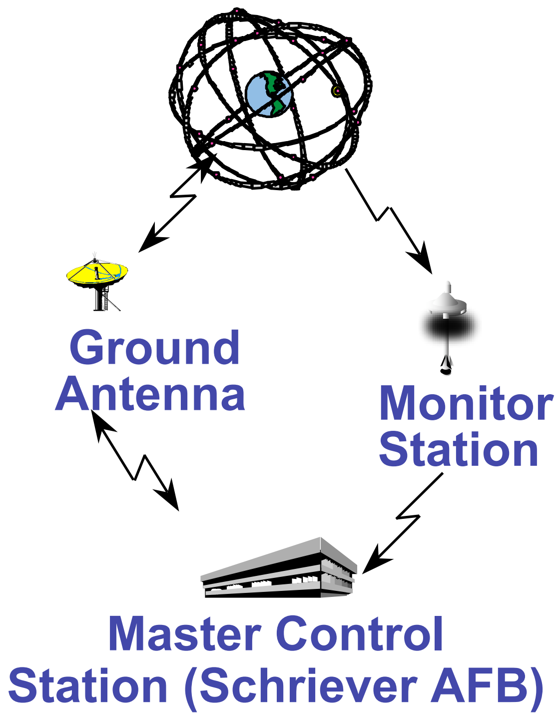
Why GPS is so Popular

- Low cost
  - Application dependent, but receivers range from <$100 to $10K
  - Allows for many systems to be deployed into arrays for relatively low cost
- Easy to install and operate
  - Can run autonomously
  - Data are (relatively) easy to analyze
- Operates rain or shine

The Global Positioning System

- GPS consists of three distinct segments:
  - The GPS Control Segment
  - The GPS Space Segment
  - The GPS User Segment
- We are primarily concerned with the space segment (where the satellites are and what they are transmitting) and the user segment (where we are and what information we are receiving).

GPS Control Segment



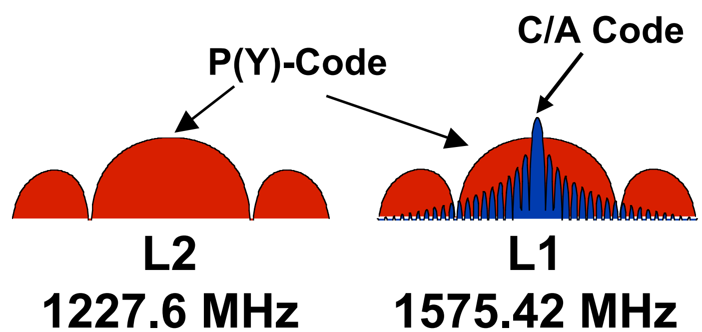
- ***Master Control Station (MCS):*** Satellite control, System operations
- ***Alternate Master Control Station:*** Training, Back-up
- ***Monitor Station (MS):*** L-band; Collect range data, Monitor navigation signal
- ***Ground Antenna (GA):*** S-band; Transmit data/commands, Collect telemetry

GPS Space Segment

- The space segment consists of the satellites:
  - 6 orbital planes
    - 12-hour inclined (55°) circular orbits
    - Altitude of ~20,200 km
    - At least 4 satellites per orbital plane
  - The current constellation consists of 31 satellites
    - Different "revisions" are in use (IIA, IIR, IIR-M)
    - Last launch in March 2009; Next scheduled for Aug 2009
    - ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt
  - Satellites identified by:
    - *Satellite Vehicle Number (SV)*: Unique to the particular satellite. Increases with each new satellite (currently up to 61)
    - *Pseudo Random Number (PRN)*: Unique to a particular active satellite, but reused as satellites are decommissioned (01-32)

GPS Space Segment

- Each satellite transmits on two frequencies*:
  - L1 is 1.57542 GHz
    - Carries coarse acquisition code (C/A) as well as the precision(encrypted) code (P(Y)); encrypted for military use.
  - L2 is 1.2276 GHz
    - Carries the P(Y) code
- Signals are encoded using code-division multiple access (CDMA) spread spectrum technology
  - Encoded using a pseudorandom code based upon the satellite's PRN



*GPS is undergoing modernization; this Information pertains to the current satellites.

GPS User Segment

- The bulk of the GPS industry is focused on the user (civilian) segment
  - Receivers vary in cost and abilities
  - Most common are L1 C/A code receivers
  - In our field, we use dual-frequency receivers which use semi-codeless tracking to track the encoded L2 signal in addition to high-rate single frequency scintillation receivers
- The primary task of the receiver is to acquire, track, and decode the transmitted signals in order to calculate a 4D navigation solution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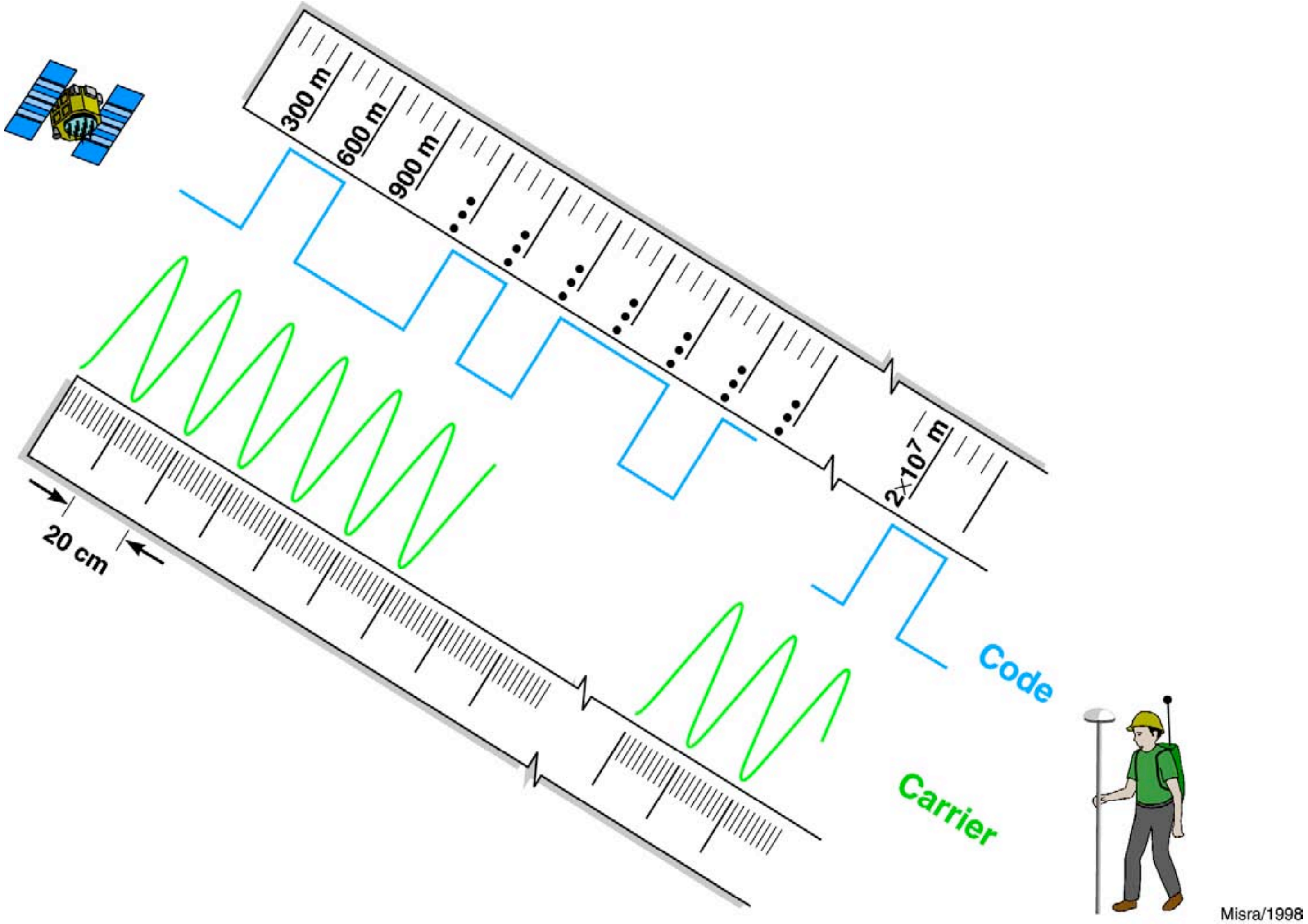
GPS Observables

- The GPS signals contain:
  - GPS satellite ephemeris
    - Coarse information on entire constellation (*almanac*)
    - Precise information on the transmitting satellite
  - Clock information
  - Satellite health status
- The observables at the receiver are:
  - *Pseudorange*: based on the time offset between transmit time and received time
    - Contains offset in time between satellite clock, receiver clock, and GPS time
  - *Integrated phase*: based on counting cycles of carrier phase
    - Contains an integer ambiguity due to relative nature of phase

GPS Observables

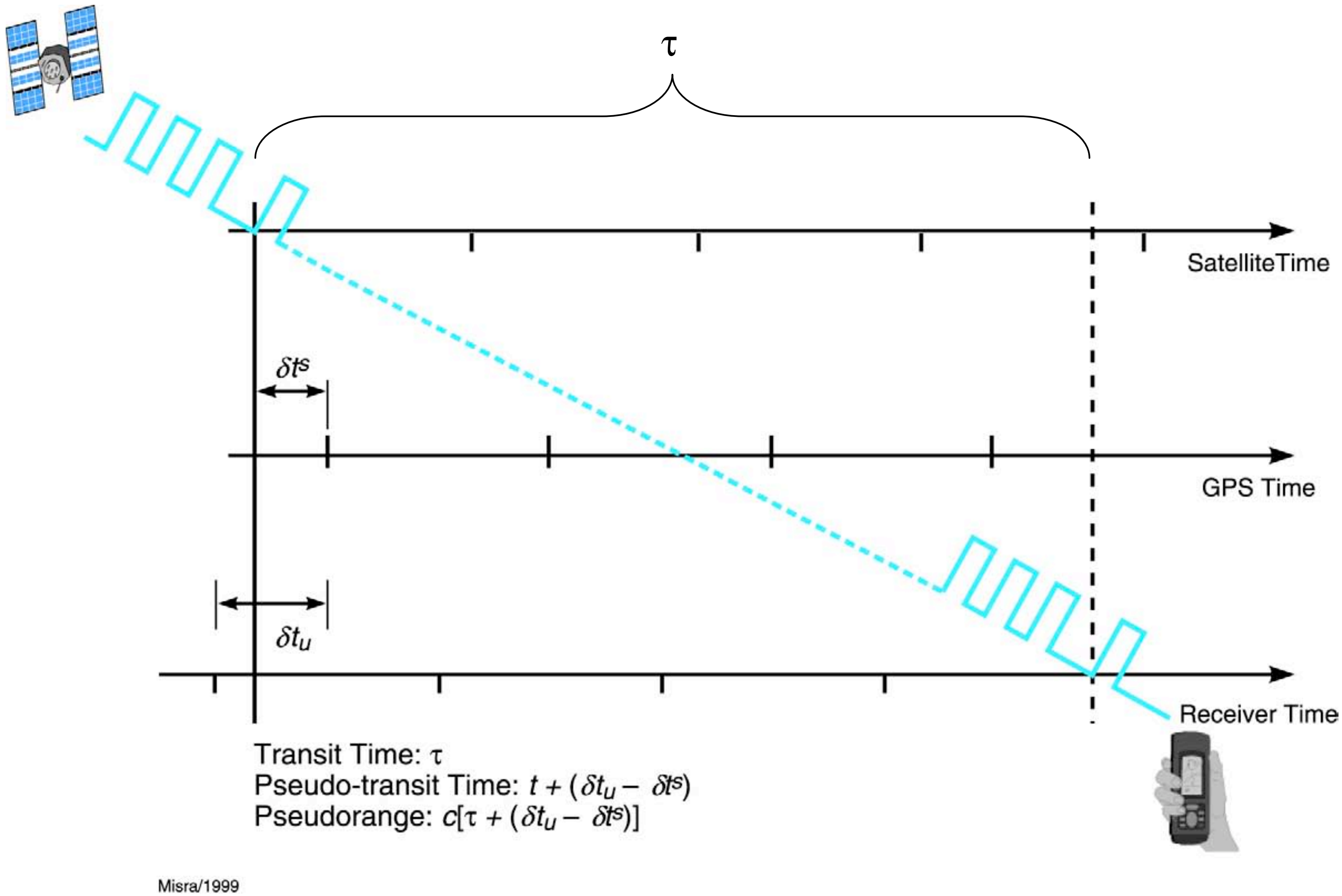


GPS Time

- GPS uses its own time reference, which is maintained by the GPS control segment
  - GPS time differs from UTC by an integer number leap seconds (currently GPS = UTC+15)
- GPS seconds are referenced to Sat/Sun midnight (0 to 604800 s)
  - 20 bits in satellite message ($2^{20} = 1048576$)
- GPS days range from 0 (Sunday) to 6 (Saturday)
- GPS weeks count the number of weeks since 05/06 Jan 1980
  - 10 bits in satellite message ($2^{10} = 1024$)
  - Creates a rollover problem every 1024 weeks (~20 years)
  - Last occurred on 21/22 Aug 1999

- This information is needed in downloading the correct data files from GPS data repositories:
  - For example: igs15333.sp3 contain satellite locations for week 1533, day 3 (Wednesday of the week beginning on Sunday, May 24, 2009… that is, Wed, May 27, 2009)

GPS Observables



GPS Navigation Solution

- The pseudorange, ρ(t), is one of the primary observables measured by a GPS receiver

$$\rho(t) = P(t) + c\left(\delta t_u(t) - \delta t^s(t-\tau)\right)$$

- If the satellite clock offset is known (it is), we can then solve for the four unknowns (ρ contains the 3D location, and the receiver clock offset)
  - Requires four measurements to solve for the four unknowns

We're done, right? How does all of this help us study the ionosphere?

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Atmospheric Effects on GPS

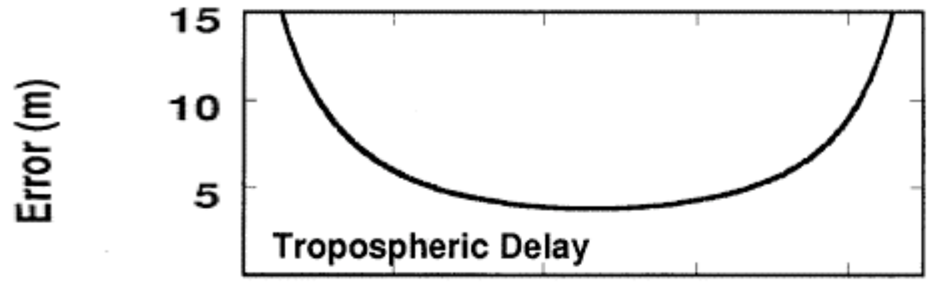
- We have assumed that the signal is propagating in a vacuum at the speed of light
- Because there is an atmosphere between us and the satellites, this is not the case
  - The signal will propagate at a velocity less than *c*
  - The signal will bend slightly due to changing index of refraction in the atmosphere (small effect)
- These effects can be lumped into an extra delay term (also should include an error term for other sources):

$$\rho(t) = P(t) + c\left(\delta t_u(t) - \delta t^s(t-\tau)\right) + c\delta t^{D,s}(t) + \varepsilon(t)$$

  - Delay term can be separated into tropospheric and ionospheric delays

Tropospheric Effects on GPS

- The troposphere (below ~16 km) causes delay on the GPS signal
  - Characterized by a varying index of refraction
  - Delay (at zenith) can be on the order of 2.5 m

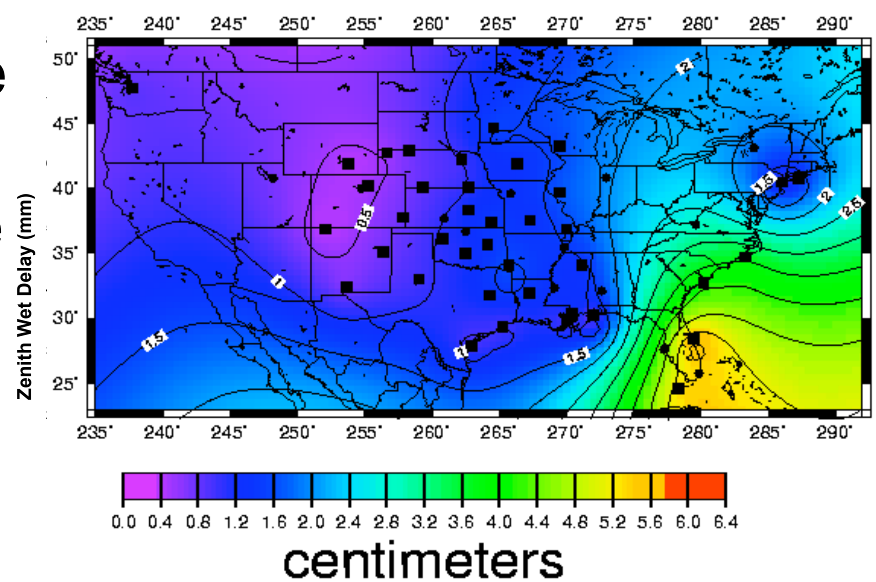


  - Delay can be largely removed using differential GPS techniques
  - Identical on both GPS frequencies
- The tropospheric delay can be separated into two parts:
  - *Hydrostatic delay (dry)*: Accounts for 80-90% of the total delay and can be modeled to a high degree of accuracy
  - *Wet delay*: A highly variable function of temperature and water vapor content, not easily modeled

Tropospheric Effects on GPS

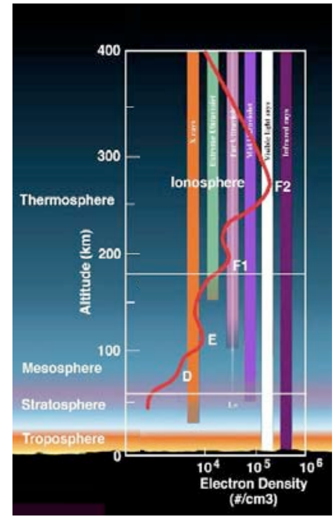
- The wet portion of the tropospheric delay can be measured using a dual-frequency receiver (to remove the ionosphere) located at a well-surveyed site (so we know what the true range to each satellite it)
- This has been shown to be as accurate as other methods for measuring the water vapor content (e.g., radiosondes, water vapor radiometers)

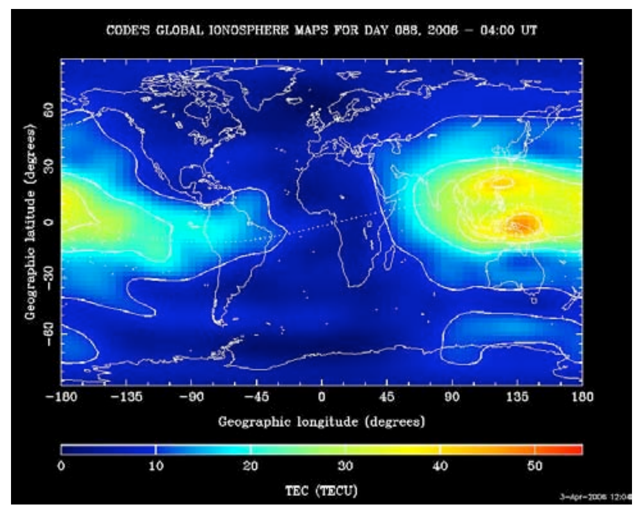
PWV 17 hr 10/21/99



Ionospheric Effects on GPS

- The ionosphere (between ~100 and 1000 km) also causes delay on the GPS signal
  - Characterized by the number density of electrons encountered along the signal path
  - Delay (at zenith) can be 15 m or more (up to ~40 m during solar maximum or storms)
  - Traditionally modeled using the Kobuchar model
  - Delay is frequency dependent, that is the ionosphere is *dispersive* in nature





Ionospheric Dispersion

- Starting from Maxwell's equations, we can derive a *dispersion relationship* for an electromagnetic wave in a plasma:

$$\frac{k^2}{\omega^2} = \frac{1}{c^2}\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right) \text{ where } \omega_{pe} = \sqrt{\frac{ne^2}{\varepsilon m}}$$

- From this, we can derive the phase and group velocities of an EM wave in a plasma:

$$v_\phi = \frac{\omega}{k} = \left(\sqrt{\frac{1}{c^2}\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)}\right)^{-1}$$

$$v_g = \frac{d\omega}{dk} = c\sqrt{1 - \frac{\omega_{pe}^2}{\omega^2}}$$

Ionospheric Delay

- The ionospheric delay can be quantified by considering two equivalent paths, one with an ionosphere and one in vacuum.
- Propagation time is given by:

$$t_{vacuum} = \int_{vacuum} \frac{dP}{v_g} = \int_{vacuum} \frac{1}{c} dP$$

$$t_{ionosphere} = \int_{ionosphere} \frac{1}{c\sqrt{1-\frac{\omega_{pe}^2}{\omega^2}}} dP$$

$$\delta t^{iono} = t_{ionosphere} - t_{vacuum}$$

$$= \frac{1}{c} \int_P \frac{\omega_{pe}^2}{2\omega^2} dP$$

$$= \frac{40.3}{cf^2} \underbrace{\int_P n \, dP}_{\text{TEC}}$$

Using GPS to Measure TEC

- The *total electron content* (TEC) has become a very popular and useful measurement of the state of the ionosphere
- Because of the frequency dependence, we can measure the relative delay between the signals on L1 and L2 and solve for the TEC

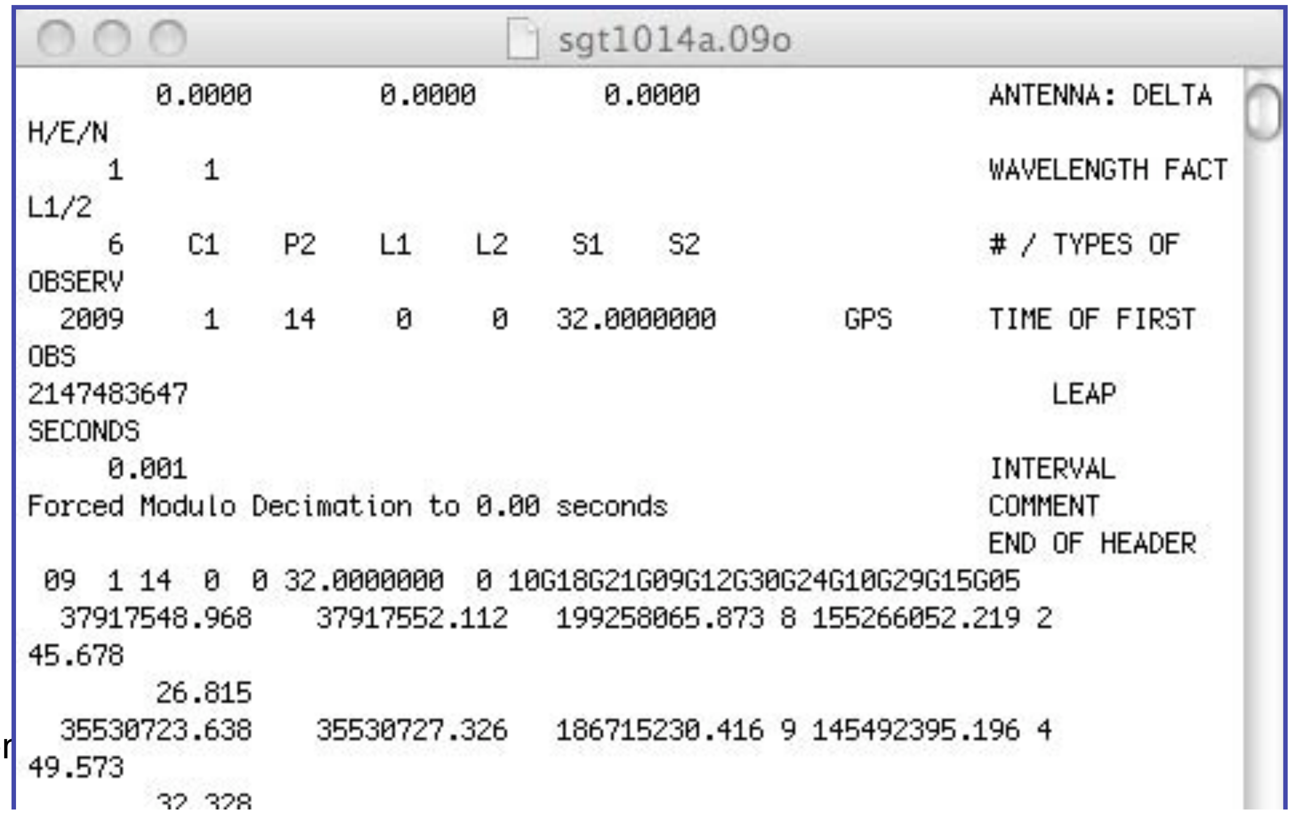
$$\Delta\left(\delta t^{iono}\right) = \frac{40.3}{c} TEC \left(\frac{f_{L1}^2 - f_{L2}^2}{f_{L1}^2 f_{L2}^2} \right)$$

$$TEC = \frac{\Delta\rho}{c}\left(\frac{f_{L1}^2 f_{L2}^2}{f_{L1}^2 - f_{L2}^2} \right) + \varepsilon \quad \text{or} \quad TEC = \frac{-\Delta L}{c}\left(\frac{f_{L1}^2 f_{L2}^2}{f_{L1}^2 - f_{L2}^2} \right) + \varepsilon$$

How TEC is Calculated

- RINEX* is the most common format for saving and transferring dual-frequency GPS data
- Software exists (or can easily be written) to read RINEX files and calculate TEC

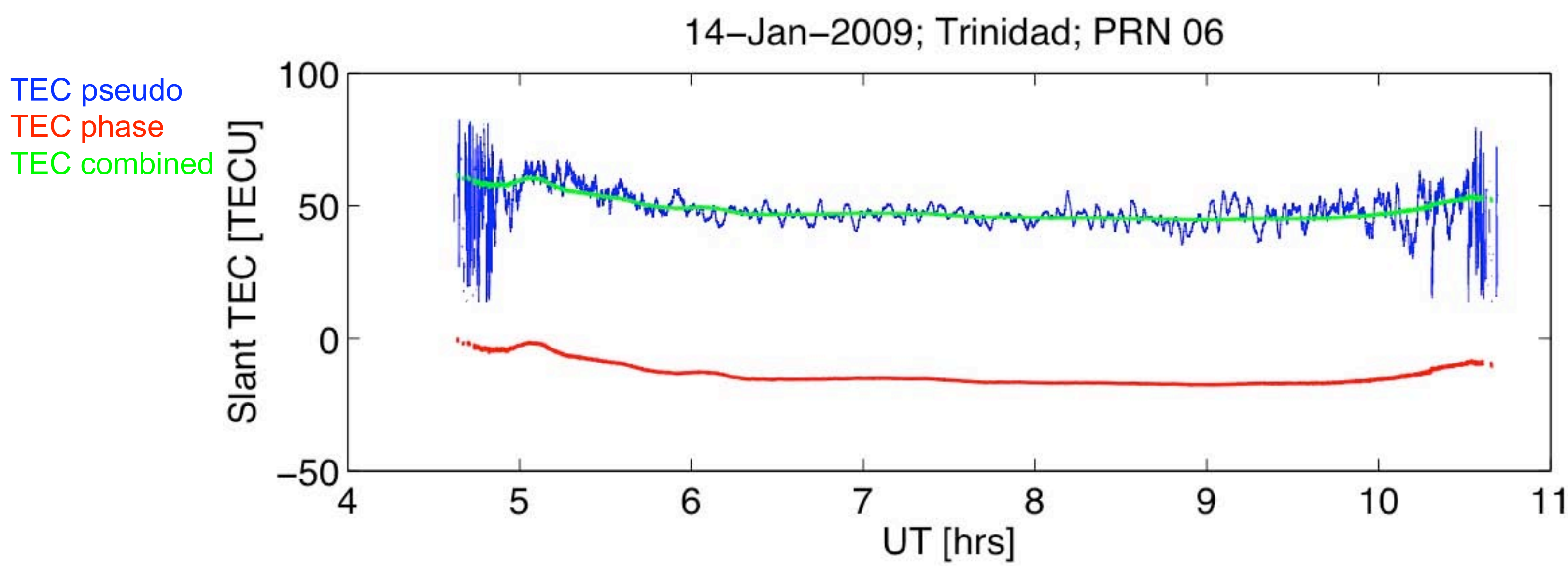
*http://www.ngs.noaa.gov/CORS/instructions2/



```
sgt1014a.09o
        0.0000          0.0000          0.0000                      ANTENNA: DELTA
H/E/N
     1     1                                                        WAVELENGTH FACT
L1/2
     6     C1     P2     L1     L2     S1     S2                    # / TYPES OF
OBSERV
  2009     1     14     0     0     32.0000000       GPS            TIME OF FIRST
OBS
2147483647                                                              LEAP
SECONDS
     0.001                                                          INTERVAL
Forced Modulo Decimation to 0.00 seconds                            COMMENT
                                                                    END OF HEADER
 09  1 14  0  0 32.0000000  0 10G18G21G09G12G30G24G10G29G15G05
  37917548.968    37917552.112   199258065.873 8 155266052.219 2
45.678
        26.815
  35530723.638    35530727.326   186715230.416 9 145492395.196 4
49.573
        32.328
```

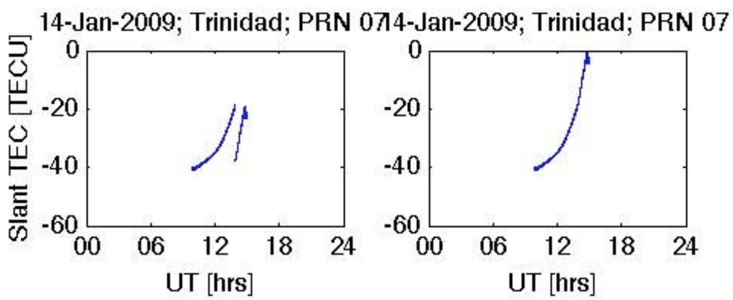
GPS-Derived TEC

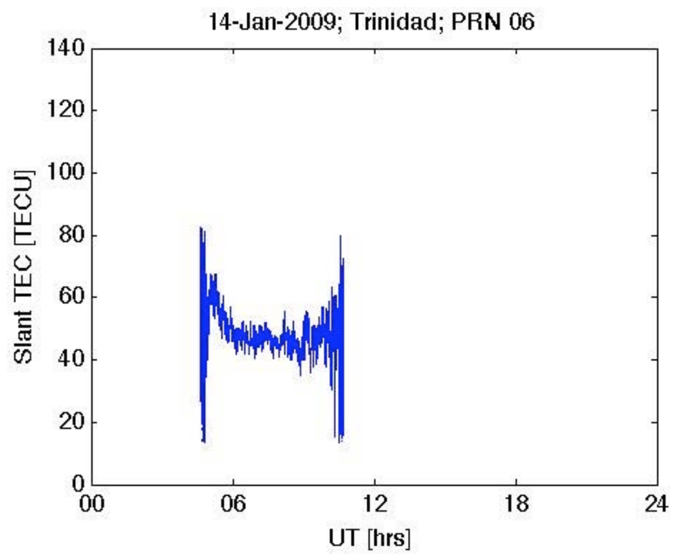
- TEC derived from the pseudorange is an *unambiguous* measurement, but it is noisy, especially at low elevations
- TEC derived from the phase range is less noisy, but has an *inherent ambiguity* from a lack of reference in counting phases
- Combining the two gives the best of both worlds



Error Sources in GPS-TEC

- *Cycle-slips* occur when a receiver temporarily loses lock on a satellite
  - Resets phase counter and so the phase TEC is no longer continuous
- Most modern receivers are fairly robust to cycle-slips under normal conditions
- Techniques exists to re-level phase arcs after a cycle slip
- *Multipath* can increase variance of TEC at low elevation angles
  - Mitigated by good antenna installation practices, as well as receiver and antenna type





Satellite and Receiver Biases

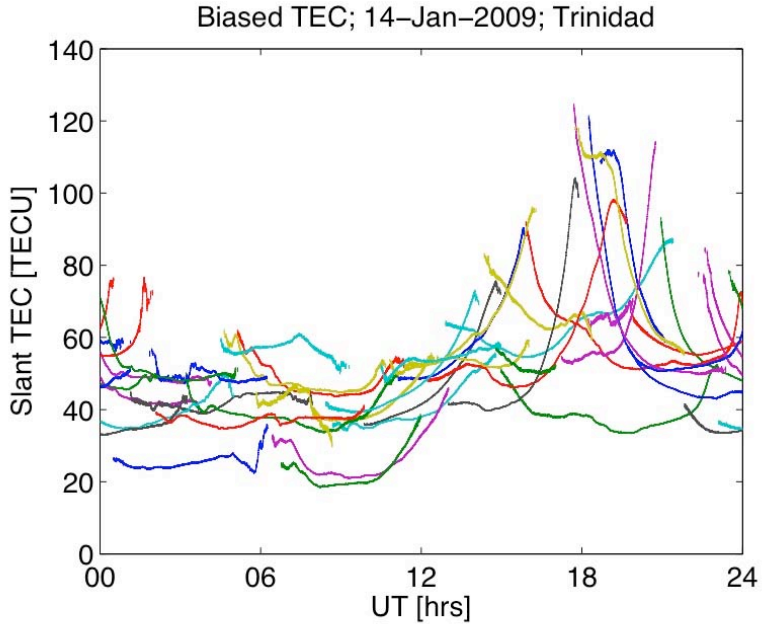
- The combination of the phase and code TEC gives us a smooth (phase) curve at an absolute (code) level… with a caveat

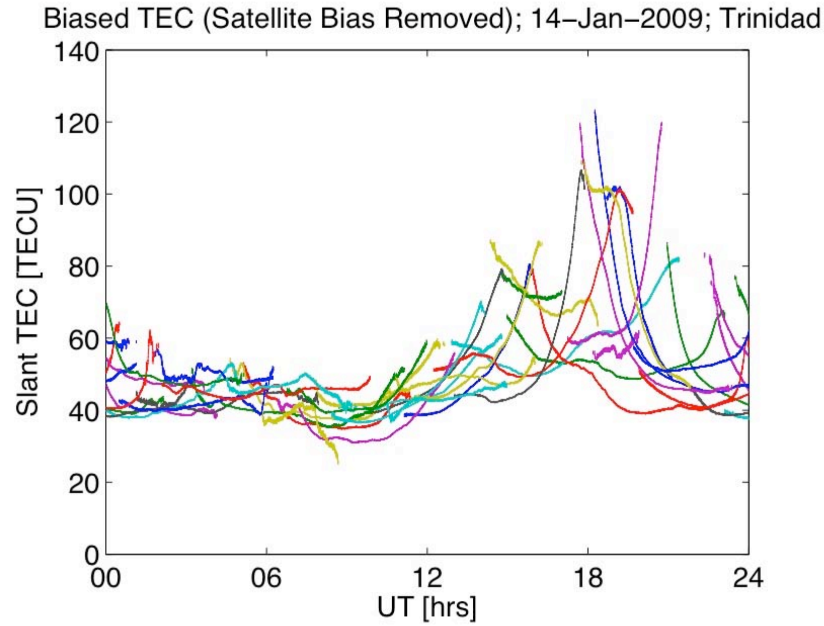
$$TEC = \frac{\Delta\rho}{c}\left(\frac{f_{L1}^2 f_{L2}^2}{f_{L1}^2 - f_{L2}^2}\right) + \varepsilon$$

- ε represents both receiver noise and *inter-frequency biases* in the satellite and receiver hardware
  - Biases must be properly accounted for to study absolute TEC (but not necessarily for relative studies)

Satellite Biases

- *Satellite biases* are common to data collected by any receiver
  - Estimates are calculated by various groups and can be obtained through the web (e.g., in *ionex* files)
  - Each group's methods vary slightly, as do the results





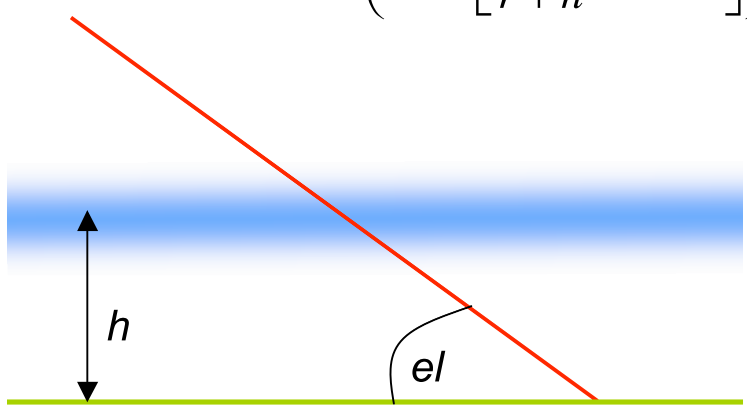
Receiver Biases

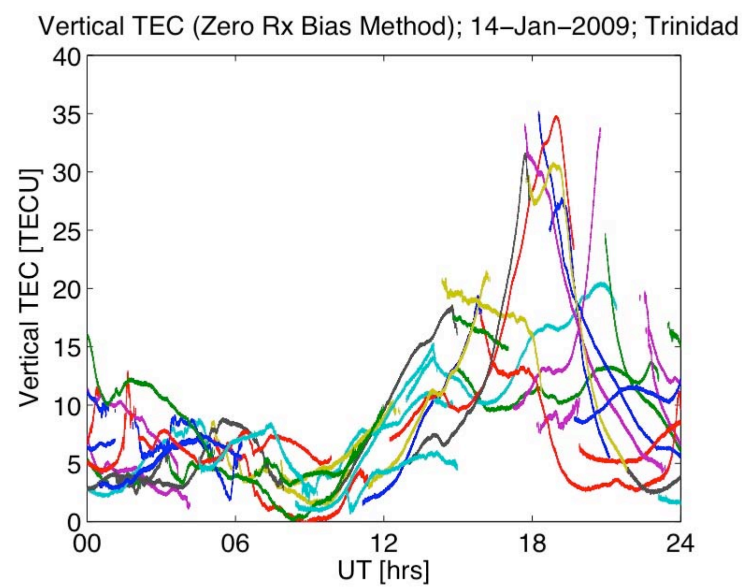
- What remains is the *receiver bias*, which is much more difficult to quantify
  - Each receiver is different
  - Bias can be a function of time and temperature (and therefore may not be constant for a given day)
- Several techniques exist to solve for the receiver bias, each with pros and cons
  - Minimum scalloping (assumes temporal stability of ionosphere)
  - Least squares (requires multiple receivers and only solves for the differential bias between receivers)
  - Zero TEC method (assumes minimum value of 0 TECU each day)

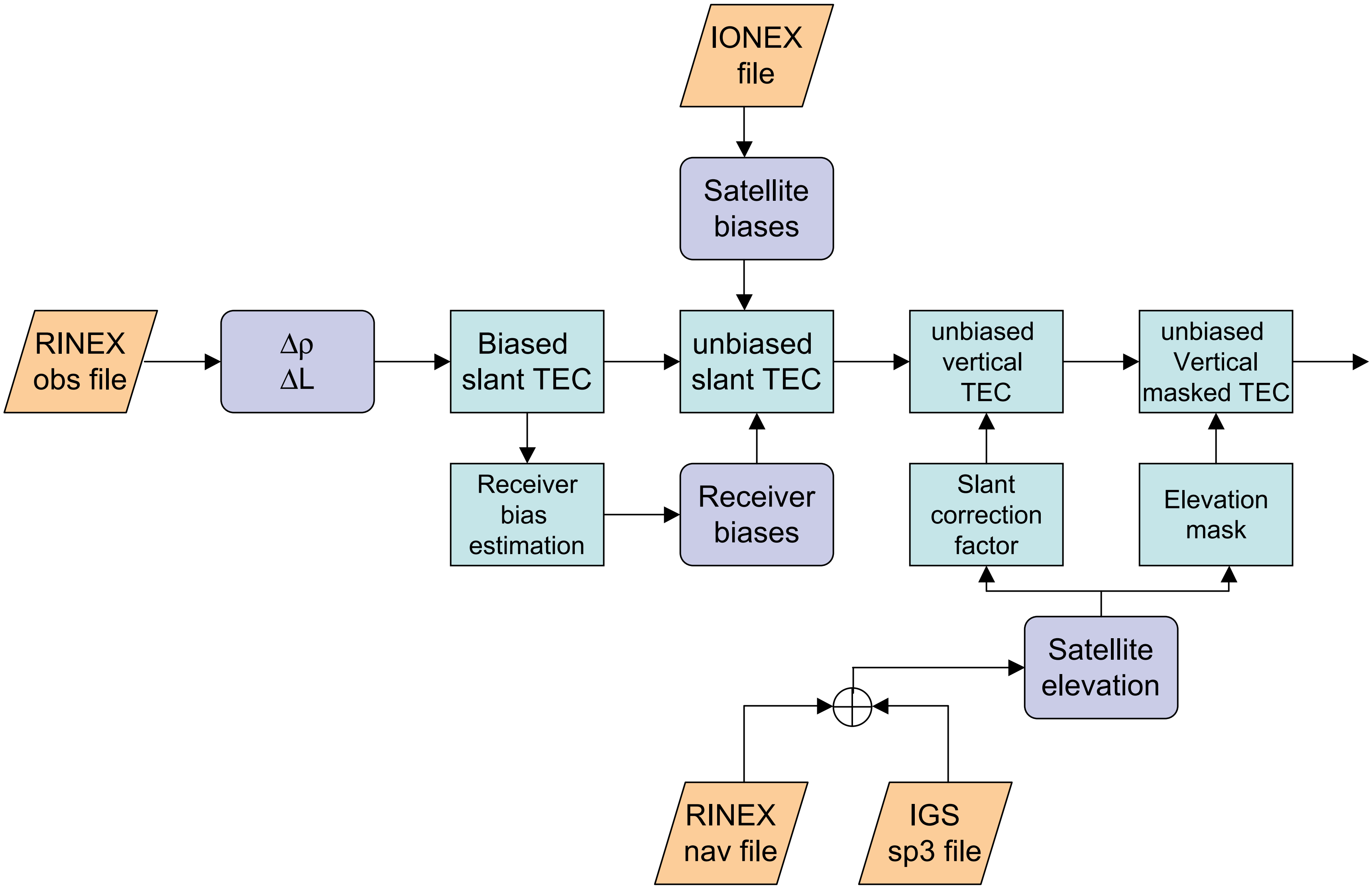
Slant to Vertical Correction

- At this point, we have an estimate of the unbiased *slant* TEC
- An estimate of the *vertical* TEC can be obtained through the use of a mapping function (many exist)

$$S(el) = \frac{1}{\cos\left(\sin^{-1}\left[\frac{r}{r+h}\cos(el)\right]\right)}$$

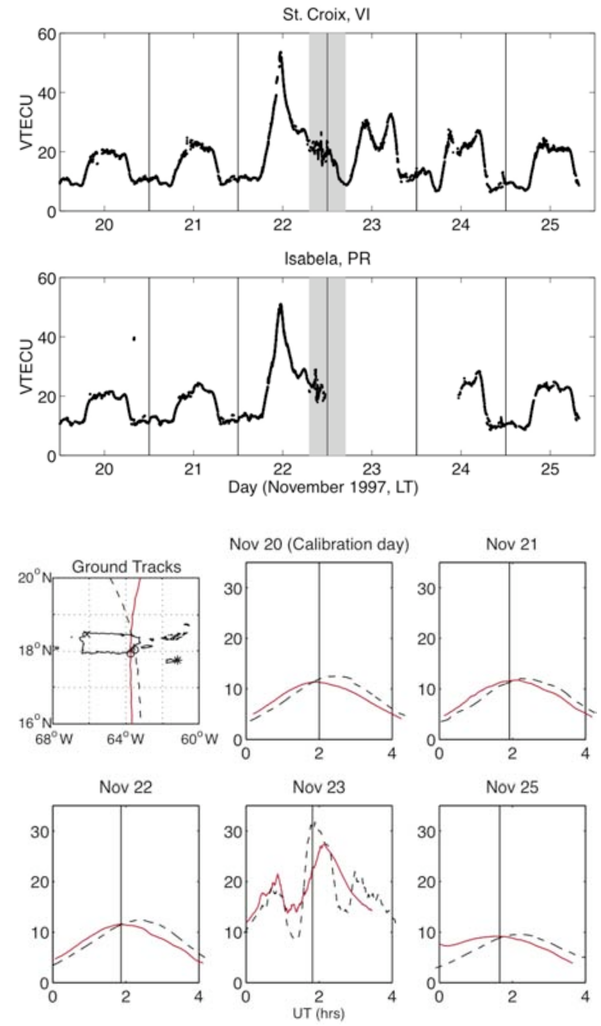


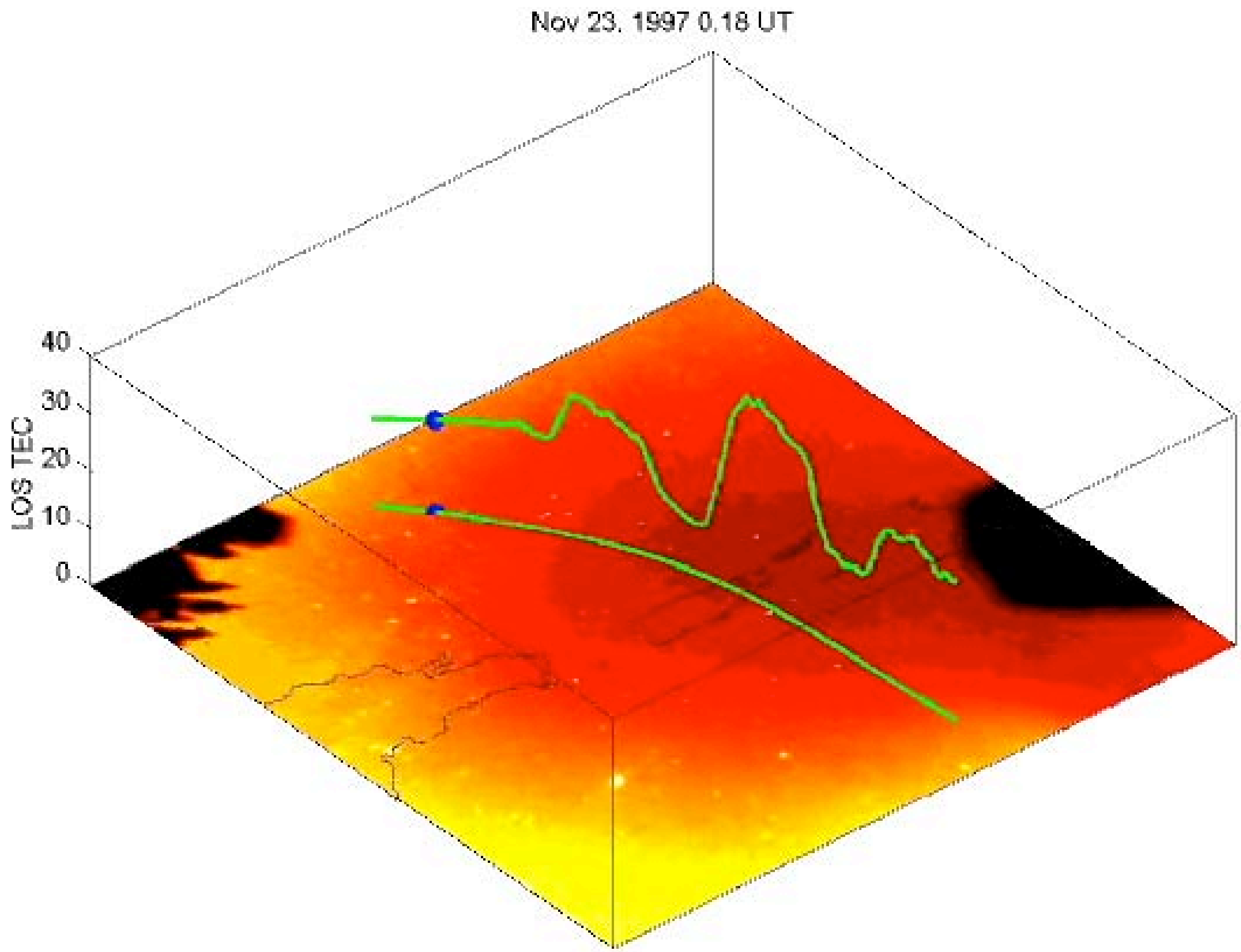



IONEX file
Satellite biases
RINEX obs file
Δρ ΔL
Biased slant TEC
unbiased slant TEC
unbiased vertical TEC
unbiased Vertical masked TEC
Receiver bias estimation
Receiver biases
Slant correction factor
Elevation mask
Satellite elevation
RINEX nav file
IGS sp3 file

Single Site GPS-TEC

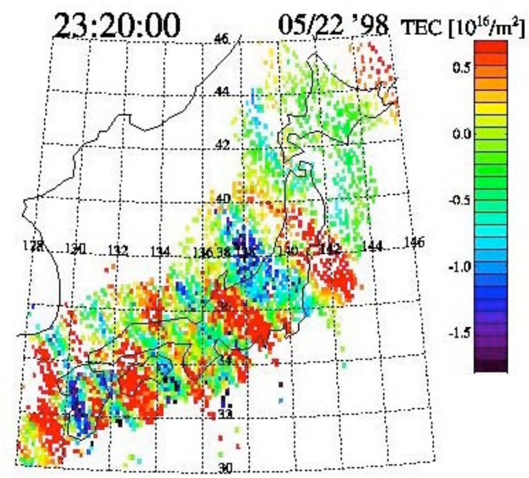
- Processing GPS data from a single site is fairly straightforward and provides useful information on the state of the ionosphere
  - Can study the day-to-day variability of electron density and structure
  - Limited by coverage and convolution of temporal and spatial dynamics

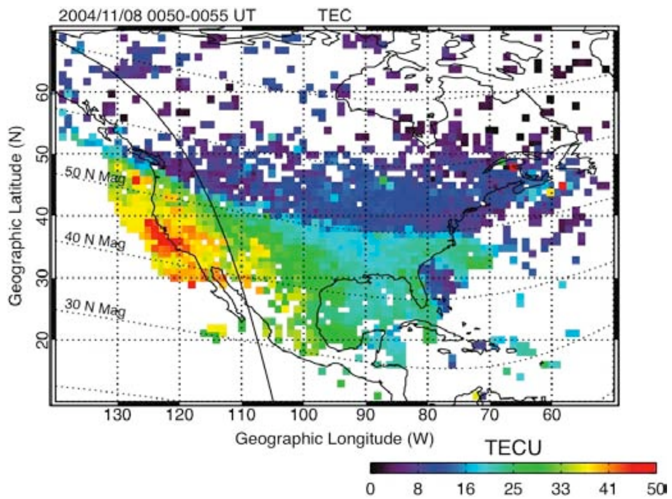



Nov 23, 1997 0.18 UT
LOS TEC
40
30
20
10
0

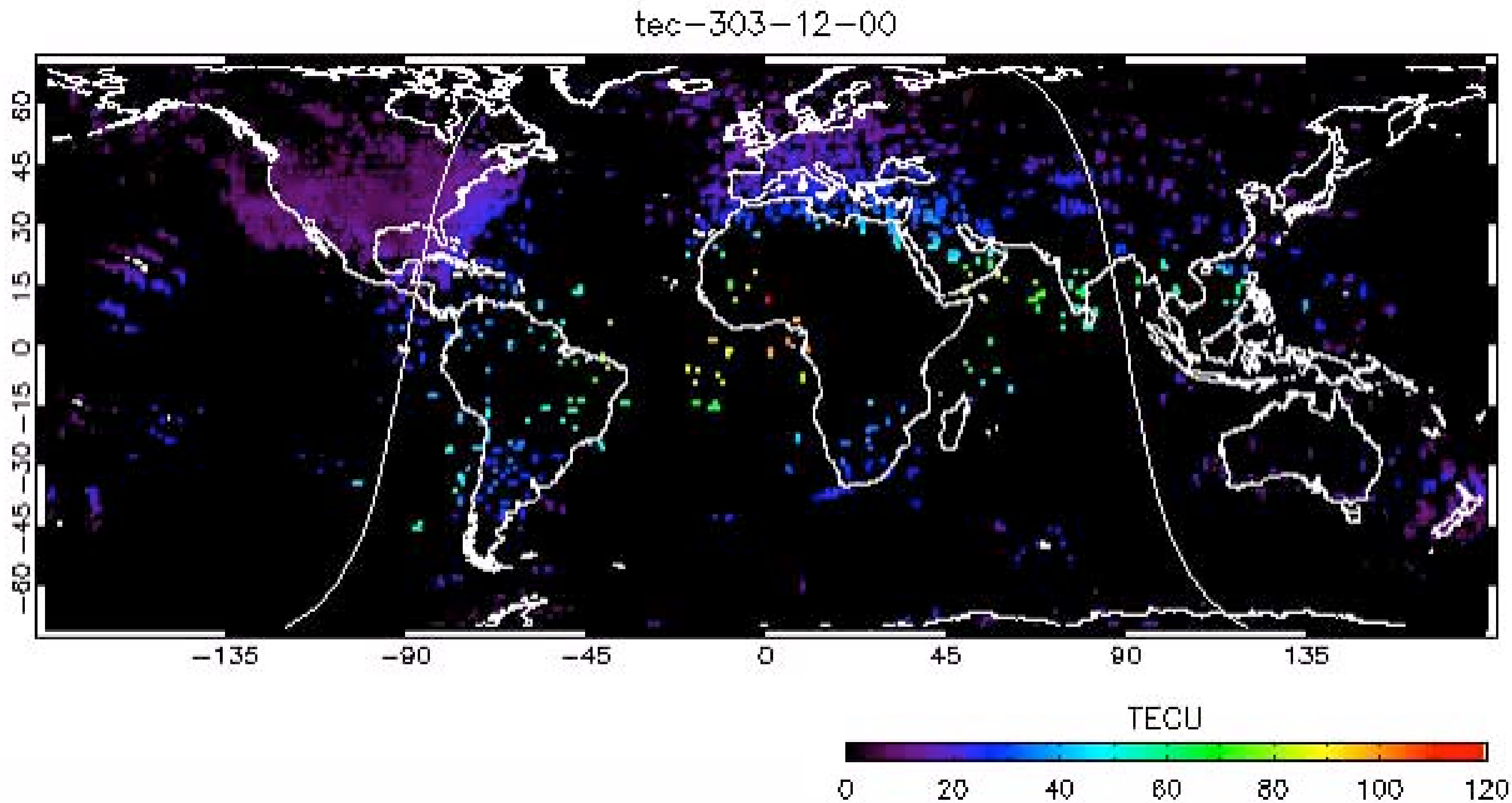
GPS-TEC in Networks

- Thousands of dual-frequency GPS receivers have been deployed to support a variety of research
- Combining data from these different networks gives a much larger picture of the ionosphere





Global TEC Movies



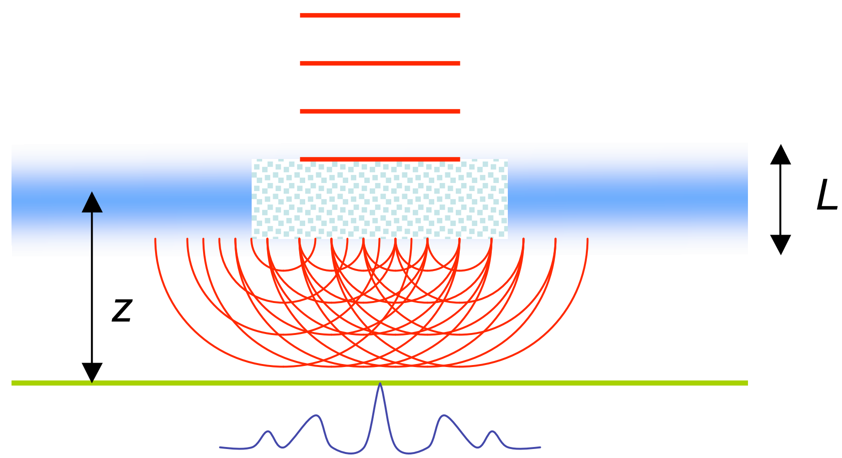
Scintillations

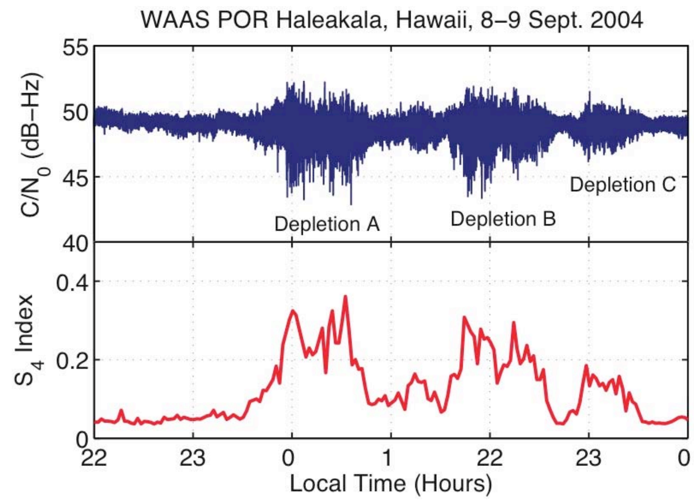
- A second effect of the ionosphere on radio waves is scintillation
- Caused as a radio wave propagates through a region with structure at the *Fresnel scale*

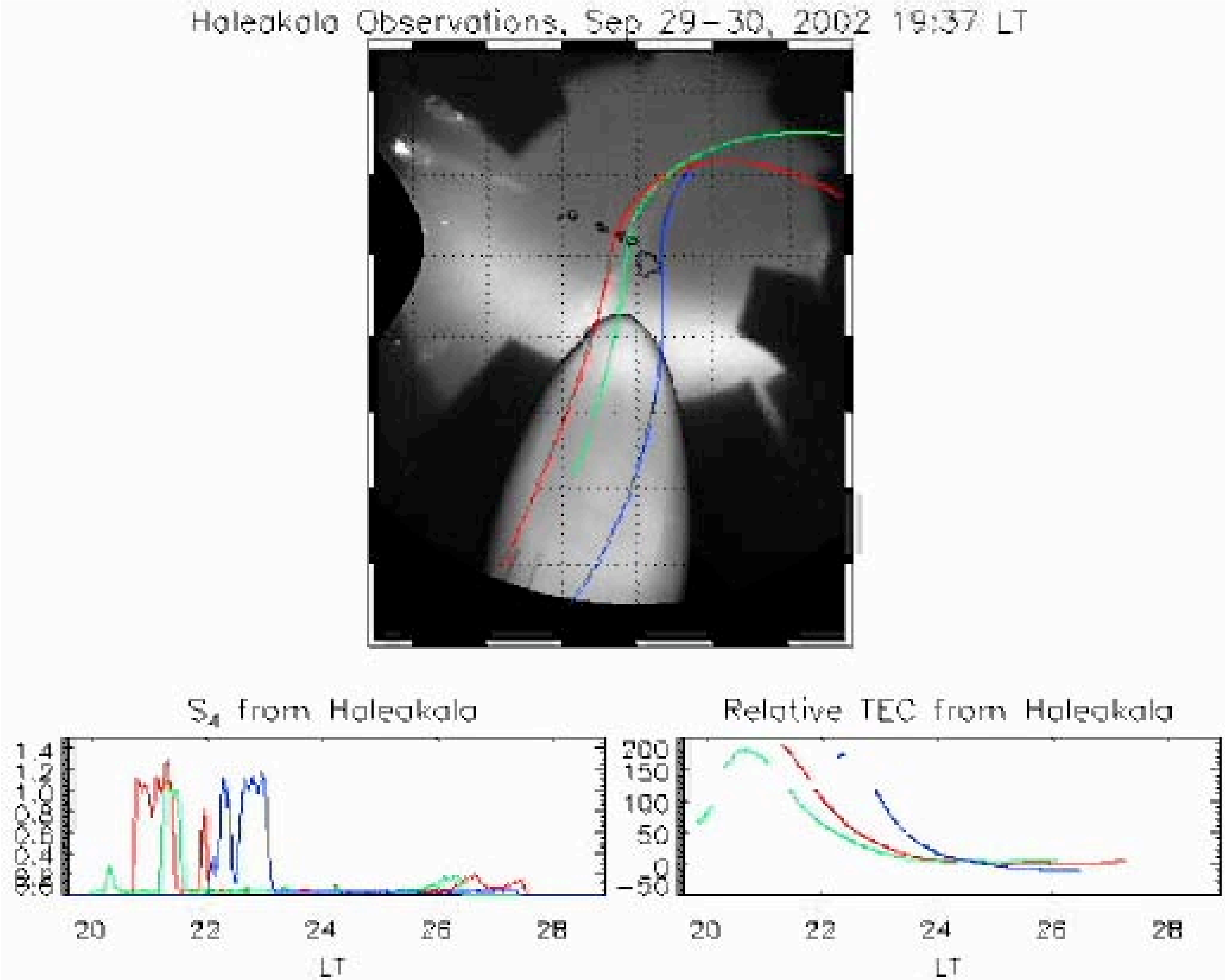
$$d_F = \sqrt{\lambda\left(z - \frac{L}{2}\right)}$$

- Results in rapid power fluctuations in the received signal
- Quantified by the S_4 index

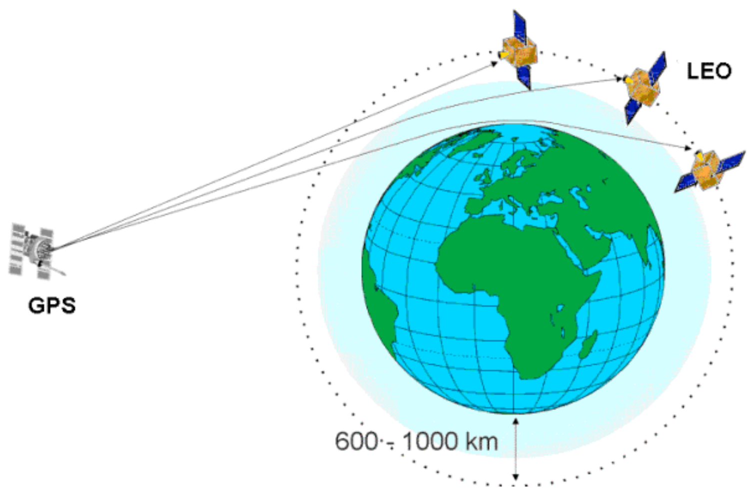
$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$



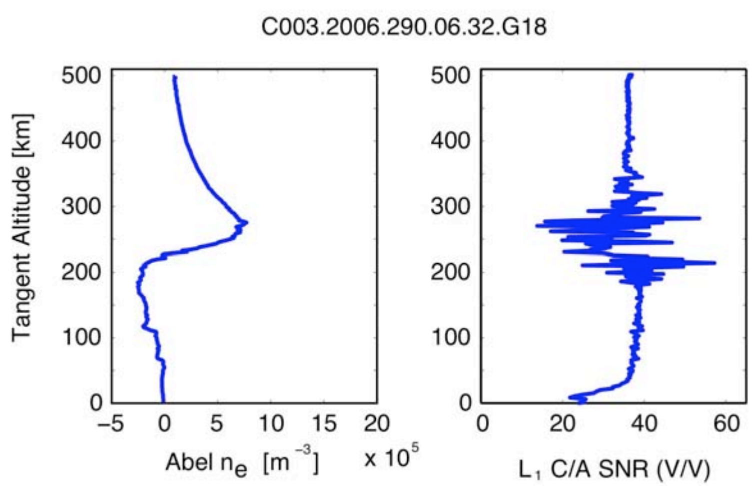



Haleakala Observations, Sep 29–30, 2002 19:37 LT
S4 from Haleakala
Relative TEC from Haleakala
LT
LT

Space Based Receivers



http://geodaf.mt.asi.it/html_old/GPSAtmo/space.html



- GPS receivers do not need to be confined to the ground
- Using satellite-based receivers, *occultation measurements* can be used to derive vertical profiles of the ionosphere or the topside integrated content

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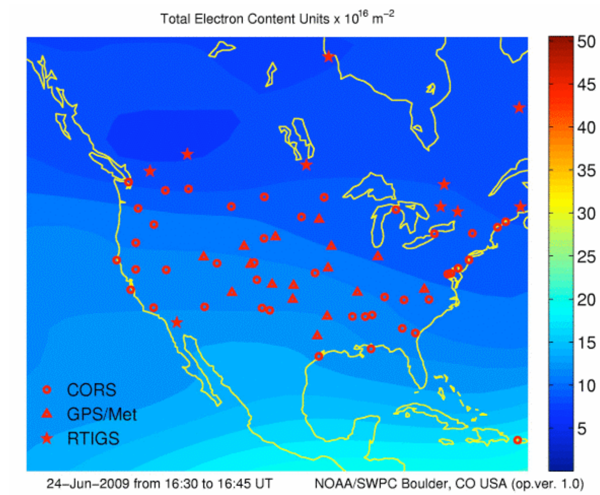
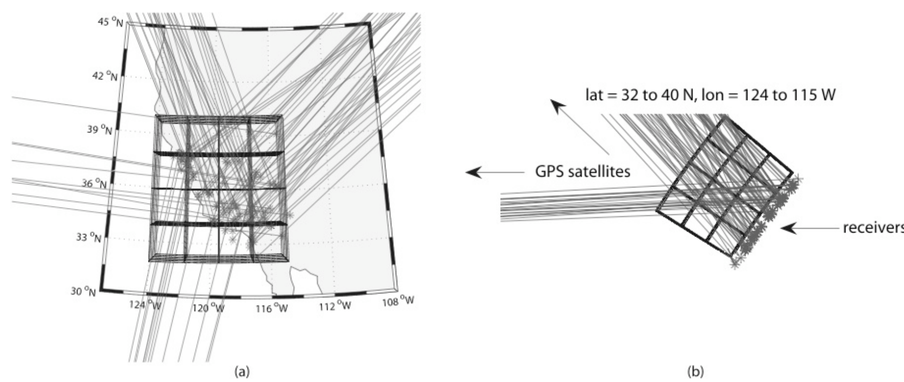
- Inverting GPS measurements to study the atmosphere
  - Ionospheric electron density and scintillations
  - Examples from recent experiments
- The future of GPS in studying the upper atmosphere

What the Future Holds

- GPS data are routinely integrated into cutting edge *assimilative models* for real-time monitoring of the ionosphere
- Networks are becoming denser, allowing for studying 3D structure through *tomographic methods*
- GPS modernization will provide additional signals for more robust measurements

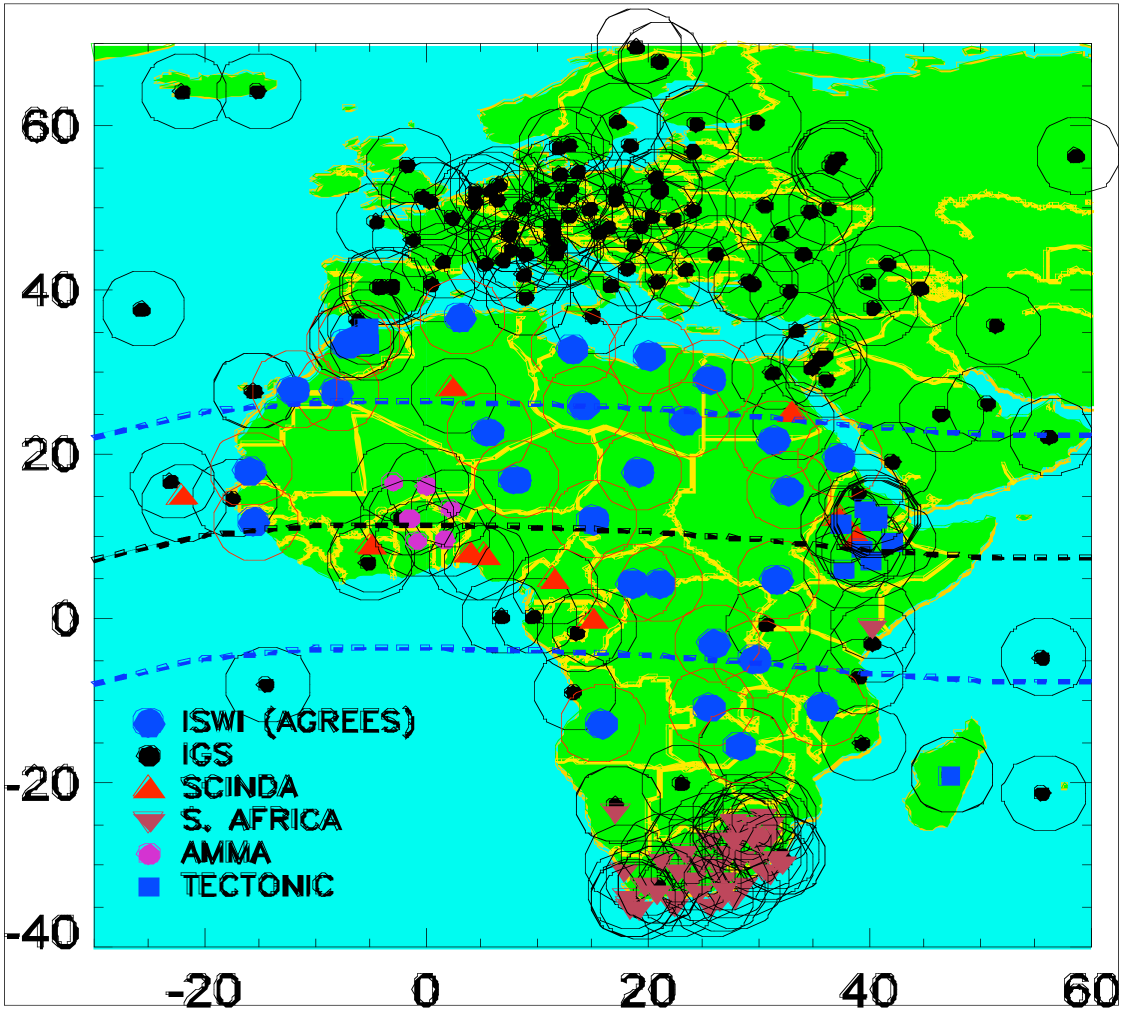


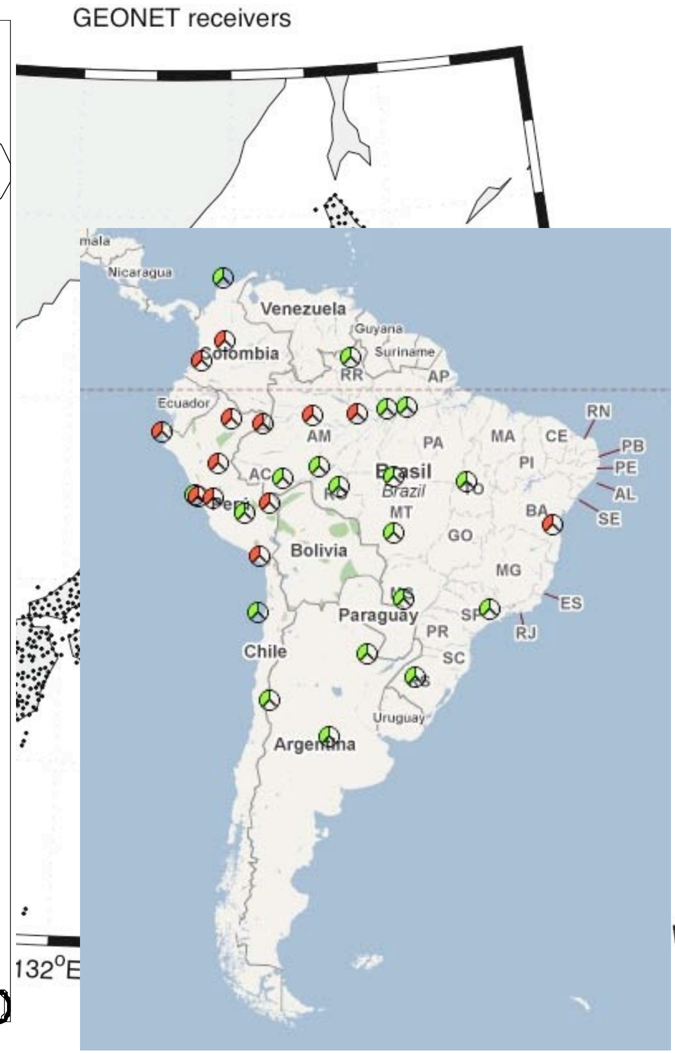
http://www.swpc.noaa.gov/ustec/



Lee et al., 2007

Increasing GPS Coverage





What the Future Holds

- Large gaps in coverage on land are rapidly being filled
  - Oceans are more difficult, but are covered by satellite programs, to some extent
  - New ways (buoys?) to cover oceans?
  - Both global coverage and locally dense coverage have their benefits
- With new GNSS signals coming on line in the near future, coverage will increase (both in the sky and in frequency)
  - Opportunities for new, flexible receiver design
- Clustering of GPS and other instruments will increase the scientific output
  - Low-power designs will be a must to allow for off-grid deployments
- New analysis algorithms required to optimally utilize all information gathered at such sites

Summary

- The GPS has become a powerful tool, not just for navigation, but for a plethora of scientific pursuits.
- GPS data are readily available from public databases.
- GPS data analysis for ionospheric studies is (relatively) straightforward, with a few caveats.
- GPS measurements are poised to form the backbone of ionospheric monitoring networks over the coming decades.

A Partial List of GPS Resources

Background, History, and General Information:
http://www.aero.org/education/primers/gps/gpstimeline.html
http://www.thespacereview.com/article/626/1
http://www.gpsworld.com/
http://www.springerlink.com/content/109380/
RINEX information:
http://www.ngs.noaa.gov/CORS/instructions2/
GPS Calendar:
http://www.ngs.noaa.gov/CORS/instructions3/
Satellite Information:
ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt
http://igscb.jpl.nasa.gov/components/prods_cb.html
ftp://ftp.unibe.ch.aiub/CODE/

Network Data Sites:
http://www.ngs.noaa.gov/CORS/
http://sopac.ucsd.edu/
http://igscb.jpl.nasa.gov/
http://stegps.kugi.kyoto-u.ac.jp/
ftp://cddis.gsfc.nasa.gov/gps/data/

TEC Maps:
http://madrigal.haystack.mit.edu/madrigal/
http://www.swpc.noaa.gov/ustec/
http://iono.jpl.nasa.gov/gaim/rtgaim.html
http://www.suominet.ucar.edu/map_plot.html