LORAAS Based Ionospheric Measurements and Their Application to The Navy Space Surveillance Fence

Brian Davis

Agenda

- The Ionosphere: An Overview
- The Navy Space Surveillance Fence
- Correcting NAVSPASUR Measurements with Ionospheric Scan Data
- Correction Results
- Conclusions

The Ionosphere:

An Overview

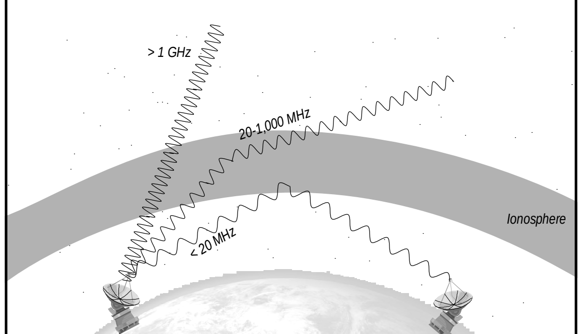
The Ionosphere

- The ionosphere is a dispersive medium that exists above the Earth from (approximately) 90km to 2000km.
- Ions of O, N_2, and O_2 exist (mostly resulting from ultraviolet radiation) in varying concentrations and can be quantified in terms of a Total Electron Count (TEC) for any given ionospheric region.
- Daytime TEC values are typically higher than nighttime TEC values, as solar activity is directly proportional to the TEC.

The Ionosphere

- The ionosphere acts as a refractive medium to signals
  - Lower frequencies (below about 20 MHz) are entirely reflected by the ionosphere
  - Frequencies between 20-1,000 MHz are refracted, or bent, by the ionosphere
  - Above 1 GHz, ionospheric refraction is negligible
- Refraction (and therefore, delay) amount (i.e. the index of refraction *n*) varies linearly with the TEC
- Refracted/delayed radar returns from an object can cause an error in range/elevation measurements

Ionospheric Refraction



Determining the TEC

- If the TEC is known, then *n* is known
- A few methods to determine the TEC
  - Model (International Reference Ionosphere)
  - Ionosondes (Ground base sensors)
  - Dual-frequency GPS (GIMs)
  - Space based sensors (LORAAS/SSULI, TOPEX)

Determining the TEC

The IRI

- The International Reference Ionosphere (IRI) is a model in FORTRAN that has been around since about 1978
- Updates are made every few years by a Working Group from the URSI/COSPAR*
- Model behaves much like many climatological models, with an error of around 25%

* URSI - International Union of Radio Science
COSPAR - Committee on Space Research

Determining the TEC

Ionosondes

- Ionosondes are ground based sensors that have been employed for decades to detect the ionospheric height (for signal reflections).
- They can not "see" the topside of the ionosphere very well

Determining the TEC

Dual-Frequency GPS

- GPS uses two frequencies to transmit information:
  1575.42 MHz and 1227.60 MHz
- By determining phase delays in both frequencies (using embedded signal data) the amount of ionospheric delay can be determined (thus yielding the TEC along the signal path).
- Numerous fixed GPS receivers exist around the world. The TEC around these sites is regularly smoothed into Global Ionosphere Maps (GIMs).

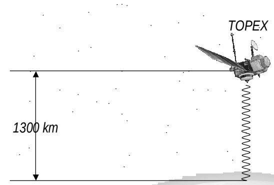
Determining the TEC

Space Based Sensors

- Sensors can either be designed primarily to measure the ionosphere, or can measure it inadvertently (much like GPS does)
- TOPEX measures the ionosphere indirectly through the use of a dual-frequency altimeter and phase differencing (but only when directly over the water)
- LORAAS (a prototype sensor on ARGOS) measures the ionosphere directly using an ultraviolet (λ = 80 to 180 nm) airglow sensor

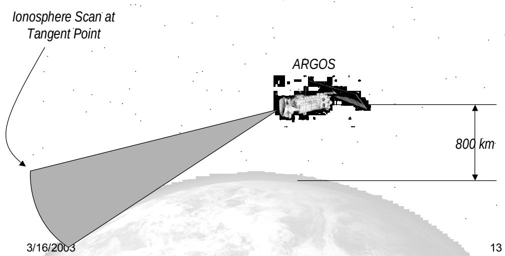
Determining the TEC

Space Based Sensors



Determining the TEC

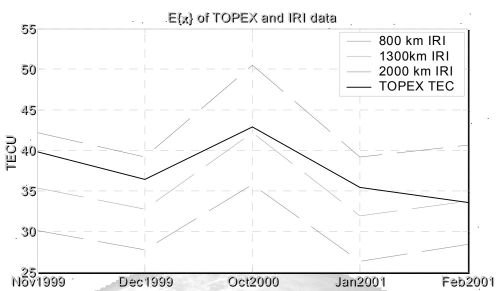
Space Based Sensors



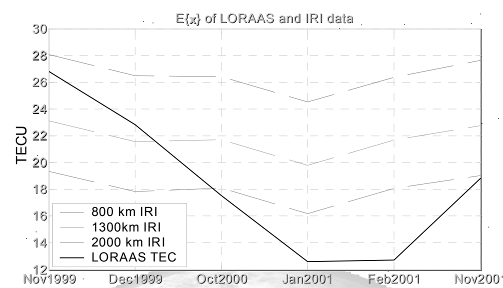
Validating the LORAAS Data

- Prior to using data from the prototype LORAAS sensor, extensive validation was done to verify reported TEC values.
- LORAAS TECs were compared against:
  - TOPEX
  - Ground-based GPS receivers (through RINEX files and GIMs)
  - Space-based GPS receivers (CHAMP & SAC-C)
  - IRI
- The available LORAAS TEC data (nightside, 2:00am-3:00am LT) compared as expected to well known TEC measurements *(with the exception of November and December, 1999)*

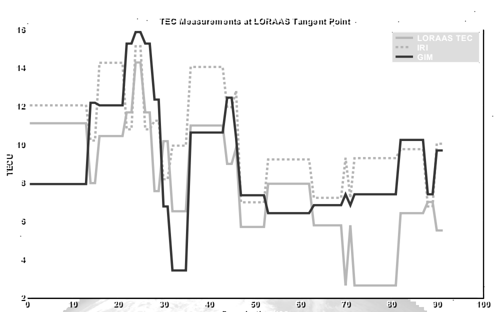
TOPEX vs. IRI



LORAAS vs. IRI



Comparing TEC Values

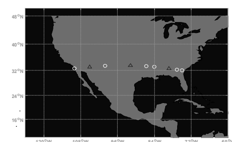


The Navy Space Surveillance Fence

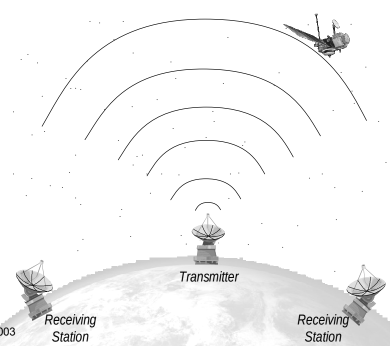
The Navy Space Surveillance Fence

- Built in 1958, in response to the launch of Sputnik
- Utilizes 3 transmitters, 6 receivers located on the Great Circle at 33°N Lat.
- Transmits a continuous wave (CW) signal at 216.9 MHz in a thin, fan beam pattern

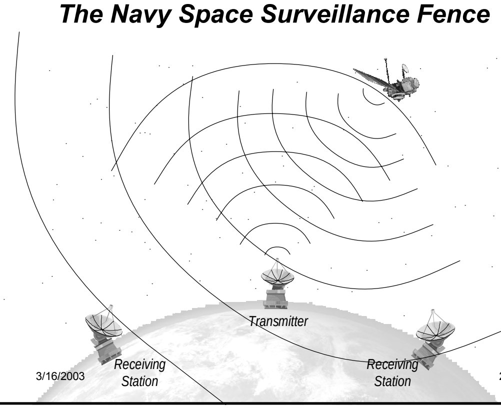
The Navy Space Surveillance Fence



The Navy Space Surveillance Fence

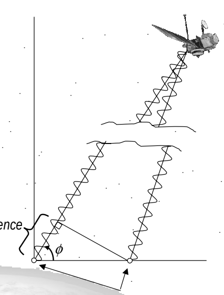


The Navy Space Surveillance Fence

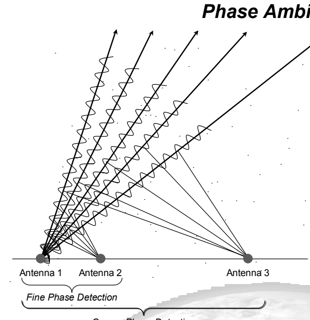


Fence Detection Method

- Interferometery techniques are used to obtain observation angle
- Multiple antenna spacings allow various degrees of phase discrimination



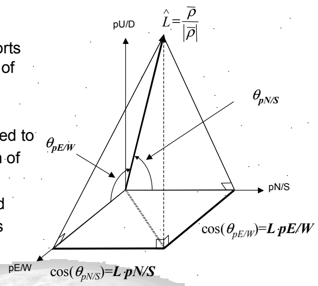
Fence Detection Method:
Phase Ambiguity



- (No data (such as a PRBS) is present on the radar signal so phase discrimination is limited to 360º only.
- A detected phase of 65º between two elements of the array could really be $360n^{o} + 65^{o}$
- Separate elements (12 in all) at various spacings (relative to the wavelength λ) allow coarse and fine phase discrimination.

Direction Cosines

- The Navy Space Surveillance Fence reports its observations in units of direction cosines
- $\theta_{pN/S}$ and $\theta_{pE/W}$ can be used to determine the projection of the $\boldsymbol{L}$ vector onto the psuedo-North/South and psuedo-East/West basis respectively.



Direction Cosines → ECEF

$$L_{pENU} = [e \quad n \quad u]\rho$$

where

$$e = \bar{L} \cdot \overline{pE/W} = \cos(\theta_{pE/W})$$
$$n = \bar{L} \cdot \overline{pN/S} = \cos(\theta_{pN/S})$$
$$u = \sqrt{1 - n^2 - e^2}$$

ρ = Slant range

Basis Rotation Matrices:

$$R_1(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_2(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}$$

$$R_3(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The coordinate transform is as follows:

$$L_{xyz} = R_3(-90° - \lambda) R_1(\phi - 90°) R_3(A) L_{pENU}$$

A = azimuthal rotation of the antenna array
λ = receiver east longitude
ϕ = receiver north latitude

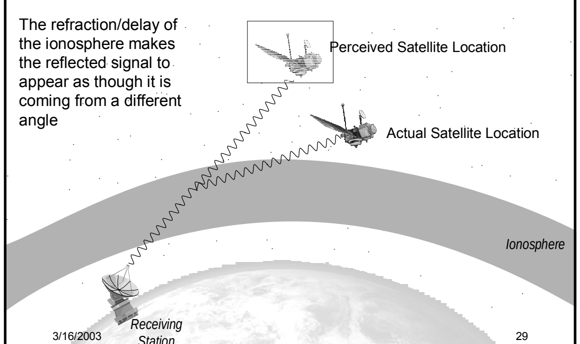
The Navy Space Surveillance Fence

- Despite its age, the "NAVSPASUR" Fence is a workhorse
  - Reports thousands of observations per day
  - In use by NORAD to track most objects orbiting the Earth
- Contract for a major upgrade has recently been awarded

Ionospheric Corrections to NAVSPASUR Observations

Effects of the Ionosphere on The NAVSPASUR Fence

The refraction/delay of the ionosphere makes the reflected signal to appear as though it is coming from a different angle



But if the ionospheric error is that small…

If the ionospheric error is that small (on the order of a few hundred meters at most), why do we care about it?

- When using The Fence to determine orbits, multiple "passes" of the satellite must be used. Ionospheric errors, which are correctable, can contribute to an incorrect orbit of the observation if not removed.
- Other elements in the space surveillance network have much lower errors, and so the NAVSPASUR fence data is routinely discarded due to its poor quality.

Step One: Coordinate Transformations

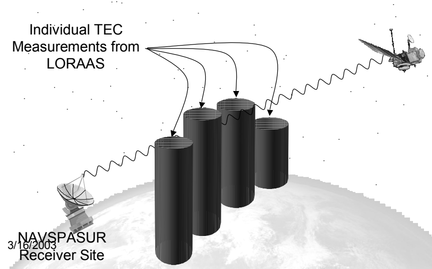
- The primary challenge in ionospheric correction is matching up the ionospheric measurements to the radar or signal error you wish to correct.
- To match a TEC measurement with a specific observation, it is easiest to consider both within the same coordinate system.
- Measurements or observations can be reported in any number of methods:
  - Direction Cosines (as in the NAVSPASUR obs)
  - East North Up (ENU) / Azimuth, Elevation, Range
  - Earth-Centered, Earth-Fixed (ECEF or ECF)
  - Latitude, Longitude, Altitude
  - etc…

Step Two: Matching TEC & Obs

- Now that all the coordinates are in the same basis, how does one match a TEC measurement to a particular observation in the fence?
  - The ionosphere is a dynamic medium, such that a TEC measurement may only be valid for a radius of 250 km, and within +/- 2 hours.
- Certain TEC measurement types suffer limitations
  - Space based TEC observations (such as those from LORAAS) may be sparse in data points (so matching up TEC & Ob may not be easy)
  - GPS based GIMs must be interpolated to the desired point
  - IRI TEC values are modeled, not measured

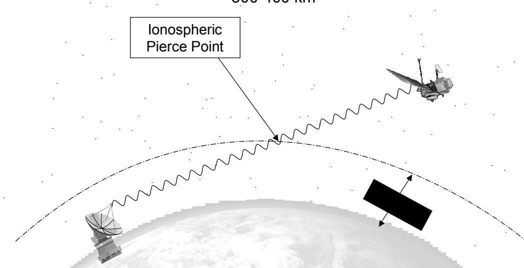
Step Two: Matching TEC & Obs

In the case of Space based TEC measurements, data observations may be limited. How does one utilize such a localized measurement to such a long signal path?



Step Two: Matching TEC & Obs

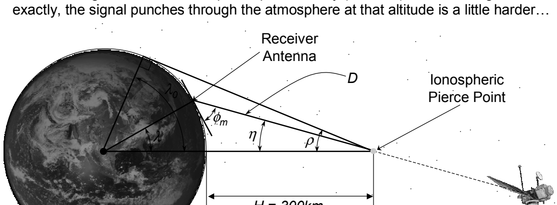
First, one must determine the "pierce point" of the ionosphere, or where the ionosphere is the densest. This is commonly considered to be around 300-400 km



Step Two And a Half:

Determining the Pierce Point

Determining the altitude of the pierce point is easy (~300km)…determining where, exactly, the signal punches through the atmosphere at that altitude is a little harder…



Known values:

η = angle between the the receiving antenna and the subsatellite point
λ = angle from target to subsatellite point
ϕ_m = spacecraft elevation angle

Step Two And a Half:

Determining the Pierce Point

- To match up ionosphere scans to pierce points, the coordinates must be in the same basis (ECEF), which requires the slant range *D* to be determined.
- To do this, the following equation must be used:

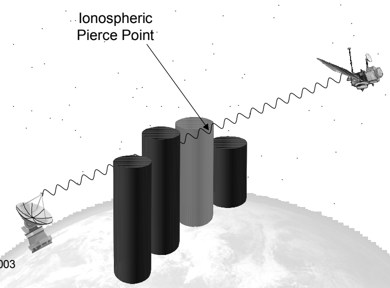
$$D = R_{\oplus}\left(\frac{\sin\lambda}{\sin\eta}\right)$$

which, expands into this:

$$D = R_{\oplus}\frac{\cos\left(\phi_m + \sin^{-1}\left[\frac{R_{\oplus}\cos\phi_m}{R_{\oplus}+H}\right]\right)}{\cos(\phi_m)\left[\frac{R_{\oplus}\cos\phi_m}{R_{\oplus}+H}\right]}$$

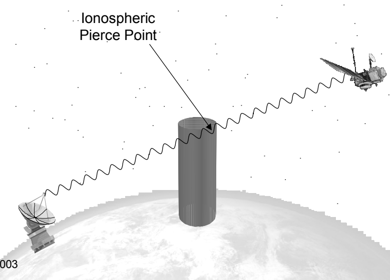
Step Two: Matching TEC & Obs

Then, choose the TEC measurement closest to the pierce point (in both time *and* distance)



Step Two: Matching TEC & Obs

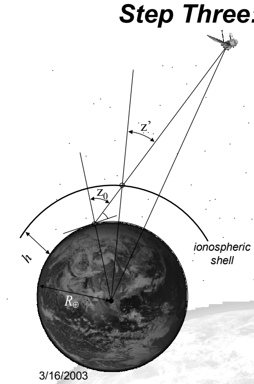
Then, choose the TEC measurement closest to the pierce point (in both time *and* distance)



Step Three: Ob Correction

- Once the closest TEC to the pierce point has been found (if it exists), a correction for TEC can be done using the following equations:

Step Three: Ob Correction



Ionospheric delay (in meters):

$$\Delta r_{iono} = \frac{1}{\cos z'} \frac{40.3}{f^2} VTEC$$

Determination of pierce angle z':

$$\sin z' = \frac{R_\oplus}{R_\oplus + h} \sin z_0$$

$$= \frac{R_\oplus}{R_\oplus + h} \cos\phi$$

Delay equation becomes:

$$\Delta r_{iono} = \frac{40.3 \cdot VTEC}{\cos\left[\sin^{-1}\left(\frac{R_\oplus}{R_\oplus + h}\cos\phi\right)\right] f^2}$$

Step Three: Ob Correction

Determine the ionosphere range delay Δr_{iono} with:

$$\Delta r_{iono} \approx \frac{40.3 \cdot VTEC}{\cos\left[\sin^{-1}\left(\frac{R_\oplus}{R_\oplus + h} e\right)\right] f^2}$$

which is then used to calculate the difference in the East-West Direction Cosine:

$$\Delta e_{iono} \approx -\frac{\left(r_{sat} + R_\oplus\sqrt{1-n^2-e^2}\right)e}{h(2R_\oplus + h) + R_\oplus\left(1-n^2-e^2\right)} \cdot \frac{\Delta r_{iono}}{r_{sat}}\sqrt{1-n^2-e^2}$$

r_{sat} = satellite range
$R_\oplus$ = Earth radius
n = pN/S Direction Cosine
h = ionosphere shell height
$VTEC$ = vertical total electron count
e = pE/W Direction Cosine
f = signal frequency

Step Three: Ob Correction

- Note that there is not correction to Δn_{iono} the pN/S direction cosine. The amount of correction in the plane of the fence is negligible.
- Because satellite ranges from the fence are triangulated from multiple sites (based off of the measured angles), final corrections to the fence can only be measured in terms of direction cosines.

Results

Available Data: LORAAS

- Limited data was available from the LORAAS sensor:
  - November & December 1999
  - October 2000
  - January, February, November, December 2001
- These data sets span both a period of high solar activity (implying high TEC values) and low solar activity (lower TEC values)
- All data sets cover 2:00-3:00 am local time (nightside), which is when the ionosphere is typically fairly "calm" (low TECs, moderate changes)
- In total, about 470 scans were available in the vicinity of the NAVSPASUR fence

LORAAS Data Preparation

- LORAAS Data provided in terms of an electron density profile, with 9.9 km sample increments.
- To determine the VTEC (vertical total electron count) at the tangent point, one must use a midpoint Riemann sum:

$$VTEC = \sum_i \left[\frac{(d_i + d_{i+1})}{2} \cdot S_i \right]$$

where d_i is the electron density for the region i, and S_i is the path length through the region i. In this case, we consider $\boldsymbol{S}_i = \boldsymbol{S} = 9.9$ km

Available Data: NAVSPASUR

- Two satellite (TOPEX and WestPac) observations were provided from the NAVSPASUR fence in the same months as available LORAAS data.
- Both TOPEX's and WestPac's orbits are known very precisely, so a "truth" position could be obtained (to compare against where NAVSPASUR "thinks" the satellites are).
- In total, about 15,000 observations were available from the fence, 12,000 of which were of TOPEX (our primary verification satellite).

Aligning the data

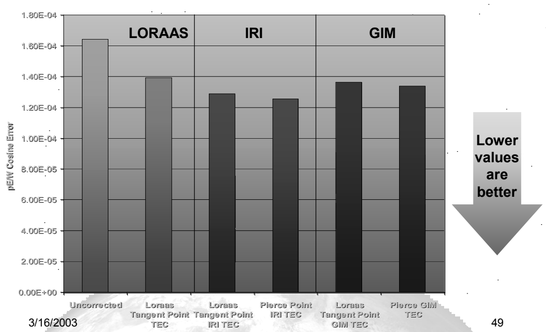
- Essentially, we had to have a scan from LORAAS align with an orbit of TOPEX or WestPac to obtain a TEC scan relevant for a particular observation.
- Ideally, a scan should be within ± 2 hours, and within a radius of 250km of the ionosphere pierce point of the observed satellite.
- Unfortunately, the average distance of the *closest* overlapping scans/points was about 272 km, and an average of 2.5 hours away. And, only 91 (out of ~12,000) observations were inside any sort of overlap window (Not an ideal scenario).

Additional Benchmarks

- In addition to the corrections made with LORAAS data, each data point (in the 91 obs nearby to a LORAAS scan) was "corrected" using TEC generated from the IRI and a GIM.
- Because the IRI and GIM can be used to determine the TEC at *any* point, two data points were used:
  - IRI & GIM at the scan point of LORAAS
  - IRI & GIM at the actual ionospheric pierce point

Correction Results

(mean values)



Correction Results Explained

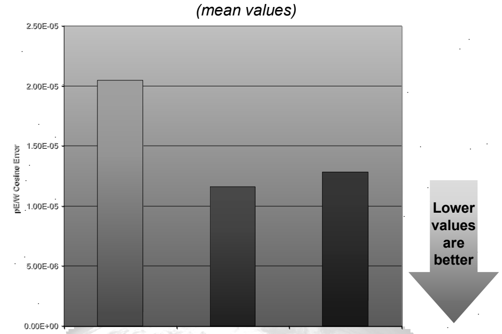
- As the previous slide indicated, the LORAAS correction eliminated about 15% of the error, but both the GIM and IRI TEC measurements eliminated over 18% and 23% respectively.
- Why? Here are a few speculations:
  - LORAAS sensor measurements were too far away (in both time and distance) to provide valid TEC measurements
  - Night side ionosphere is fairly "stable", so models such as the IRI provide a more realistic estimate than dayside estimates
  - IRI & GIM may actually be "overcorrecting" because of incorrect TEC values
  - LORAAS sensor may not be calibrated correctly (recall that this is still a prototype)

Further IRI & GIM Testing

- Because the LORAAS TEC corrections yielded less than spectacular results, we tried correcting *all* 12,000 NAVSPASUR TOPEX obs with GIM & IRI TEC values to see what effects that would have…

GIM & IRI Correction Results

(mean values)



GIM & IRI Correction Results Explained

- It appears that any type of ionospheric correction will indeed reduce the NAVSPASUR Fence errors, allowing more precision observations
- Additional atmospheric corrections still need to be taken into account, as well as bias removal, etc.

Conclusions

Conclusions

- LORAAS TEC values do indeed aid in the improvement of NAVSPASUR, but:
  - Data density is extremely sparse
  - Sensor accuracy still a question
- Other methods (IRI or GIM) seem to yield more of an overall improvement, and are easier to implement.

3/16/2003 55