**Annex A**

# Brazilian Test Bed
# Ionosphere Analysis

**Rio de Janeiro October 9-17, 2001**
**Prepared byThomas Dehel, Maj Corbelli**

The primary purpose of the trip to Rio de Janeiro was to work with members of the Brazilian Testbed Team, and to set up receivers (with their help) to collect additional ionospheric data (the October flight test to Brazil had been postponed due to concerns after the September attack). Senhor Corbelli of the BTB and myself also met with two of the ionospheric experts from Brazil (INPE). We discussed ionospheric features, particularly the equatorial anomaly and plasma bubbles and I provided a brief introduction for how the WAAS models the ionosphere and bounds the errors with GIVEs. The Ionospeheric experts from Brazil were of great help, and provided many papers covering their research into plasma bubbles. A list of the papers is given below.

**Problem Summary:**

The ionosphere near the geomagnetic equator has physical process and features that rarely, if ever, affect CONUS; these include the geomagnetic anomaly, plasma bubbles, and scintillation. These features occur primarily due to the interaction of the earths magnetic field and the field of the plasma from the Sun, the layers of the ionosphere, and various currents and other fields that change during the course of a day. The most severe effect occurs near sunset, where a current in the atmosphere creates a field which lifts the ionospheric plasma from the area near the geomagnetic equator, propels the plasma up, until it can no longer be lifted and slides generally down magnetic field lines, where an excess of plasma is built up. This buildup occurs roughly 15-20 degrees in latitude both North and South of the geomagnetic equator. (I call this problem #1, since it results in a non-planar ionosphere).

Sometimes (over 80% of the evenings in Brazils summer at all points in the solar cycle, according to paper [9]), the uplift force is strong enough to cause (through an instability process) a void, which propagates along the magnetic field lines and creates a hole in the ionospheric plasma. This tube (oriented North-South, along the Earth's magnetic field lines), can be roughly 100-200 kilometers wide, and the delay gradient at the edges can be large, (but was still to be determined). The feature can appear to move north or south, as it is lifted higher, but general moves from west to east at speeds of about 100 meters per second. (Bubbles: Problem #2)

On many nights that the bubbles are formed, the same instability process creates smaller bubbles in the walls of the tube; this process continues until features of a scale size which cause L band scintillation are formed. This moving tubular scintillation structure continues to move west to east, until nighttime recombination ultimately eliminates it. (Scintillation: Problem #3). Scintillation has been known to affect communications and GPS lock for some time; one area that needs more data is to collect GEO message loss data during scintillation from a moving aircraft, since an aircraft moving west-to-east will nearly match the speed of the pattern, resulting in longer fade durations and potentially higher loss due to scintillation.

**October Trip Data Collection Summary**

With great help from several members of the Brazilian Testbed team, (including Carlos Scheafer amd Ten. Eng. Ulisses Guinaraes, and the Brazilian DEPV which provided a van and Brazilian Air Force personnel), we set up two additional data collection sites in the mountainous Rio area: Rio-North site was located approximately 80 km North, and the Rio-West site, which was locate 95 km West. One of the Brazilian 5 testbed sites is located in Rio de Janeiro. By some luck, the hotel I was in was almost nearly 20 km south, so I collected additional data on the roof of the hotel in the evening (called Rio-South).

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The additional receivers set up temporarily included two Milleniums (Rio-North and Rio-West), an Ashtech Z-Extreme (Rio-South), and an Ionospheric Scintillation Monitor (Rio-TRS). Some limited data was even logged from the Garmin "GPSMAP 76" handheld at the Rio-South location.

Technical problems with the remote Milleniums limited the amount of useful data; however (again with some luck), complete data sets were collected of the key ionospheric features and will be shown in this summary. (Note: Change of UTC day happened in the evening, when the interesting iono features were also occurring. The table is broken into columns indicating the UTC evenings).

**Data Overview**

| Data / evening | Oct 10/11 | Oct 11/12 | Oct 12/13 | Oct 13/14 | Oct 14/15 | Oct 15/16 |
|---|---|---|---|---|---|---|
| Brazil Testbed (5 sites) | Oct 10 | (Oct 11 tape in shipment) | X | X | X | X |
| Rio-West (Mill) | X | (partial) | | | | |
| Rio-North (Mill) | | X | X | | | |
| Rio-South (Ashtech) | | | X | X | X | X |
| Rio TRS (ISM) | X* | X* | X | X | | X |
| Iono features: | Bubbles, Scintillation | Rio-Quiet (TBV) | Eq. Anom. only | Bubbles and Scint. | Rio - Quiet | Bubbles and Scintillation |

* ISM data still on ISM hard drive – not yet downloaded

**List of Papers provided by Brazilian Iono researchers:**


1. Some Characteristics Of Spread F at magnetic Equatorial Station Fortaleza, M.A. Abdu et al, (Institueo de Pesquisas Espacais paper, 1980, accepted in the Journal of Geophysical Research)
2. Association Between Plasma Bubble Irregularities and Airglow Disturbances Over Brazilian Low Latitudes, M.A. Abdu et al, (Geophysical Research Letters, Vol 7, No. 11, Pages 980-982, 1980.
3. Magnetic Declination Control of the Equatorial F-Region Dynamo Electric Field Development and Spread-F, M.A. Abdu et al, (Institueo de Pesquisas Espacais paper 1980, published in the Journal of Geophysical Research, Vol 86, page 11443, 1981.
4. Equatorial F-Region Vertical Plasma Drifts: Seasonal and Longitudinal Asymmetries in the American Sector, M.A. Abdu et al, Journal of Geophysical Research, Vol 91, page 12055, 1986.
5. Magnetic Activity effects on range type spread-F and vertical plasma drifts at Fortaleza and Huancayo as studied through ionosonde measurements and theoretical modeling, M.A. Abdu et al, Annales Geophysicae, 1990.
6. Rocket Observations of Equatorial Plasma Bubbles Over Natal, Brazil, Using a High-Frequency Capacitance probe, M.A. Abdu et al, Journal of Geophysical Research, Vol 96, page 7689, 1991.
7. Ionospheric Scintillation Effects on DGPS Positioning, E.R. de Paula, P.M. Kintner, M.A. Abdu, et al, presented to the SBGf meeting at Rio de Janeiro, 1999.
8. Equatorial Spread F Statistics in the American Longitudes: Some Problems relevant to ESF Description in the IRI Scheme, M.A. Abdu et al, Adv. Space Res., Vol 25 No 1, pp 113-124, 2000.
9. Ionospheric Plasma Bubble Climatology Over Brazil Based on 22 Years (1977-1998) of 630NM Airglow Observations, M.A. Abdu, E.R. DePaula, et al, Accepted to JASTP, 2001
10. Fading Timescales associated with GPS signals and potential consequences, Paul Kitner, Hyosub Kil, E.R. de Paula, et al, Accepted to Radio Science, 2001
11. Ionospheric irregiularity zonal velocities over Cachoeira Paulista, E.R. de Paula, P.M. Kintner, et al, Accepted for JASTP, 2001.


Several unpublished first drafts were also provided for information.

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**Data Exampl es**

Figure one shows the slant delay to the GEO (using code-carrier, adjusted by dividing by two), for the four days which cover Oct 12 – Oct 16th). The data is shown for both for Rio de Janeiro and Brasilia; Rio is expected to lie closer to the peak of the Equatorial Anomaly crest feature, and Brasilia lies closer to the geomagnetic equator. Figure one shows the simultaneous rise of the Rio delay and fall of the Brasilia delay, as expected during the anomaly, during the evening of Oct 12/13 (beginning at time 500000 on the x axis). The following night shows the drastic decline in the Brasilia delay as the Rio TRS shows signs of dropouts due to scintillation (about time 600000). The next night (which has been counted in seconds extending the previous week, for display purposes), shows no equatorial anomaly or scintillation at Rio, but may show evidence of smaller features at Brasilia. The final day shows the beginning of another evening of bubbles and scintillation in Rio.

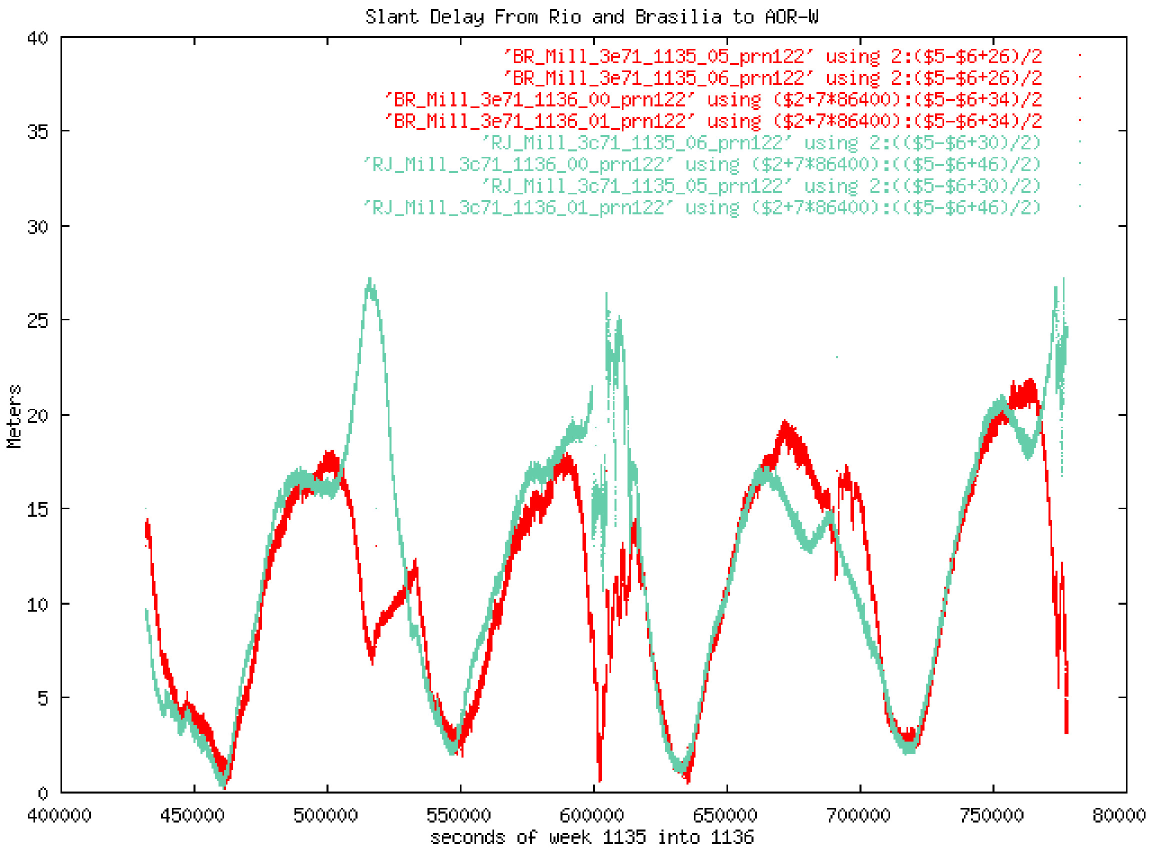


Figure 1. Four days of Iono Slant delay to AOR-W

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Figure two shows the slant delay from the Rio TRS, Rio-North, and Brasilia, for the day of Oct 12/13. The key feature interesting in this plot is that Rio-North is closer to Brasilia, but has a higher delay than Rio, implying that the peak of the anomaly crest lies closer to Brasilia. The initial estimate is about 21 meters over the Rio-North –Brasilia distance of 830 km which gives a gradient of increase of at least 2.5 meters per 100 km, followed be a decline of about 1 meter over the 80 km from Rio-North to Rio. A planar surface would provide a poor fit (planar deviation > 3 meters) over distances as small as a few hundred kilometers.

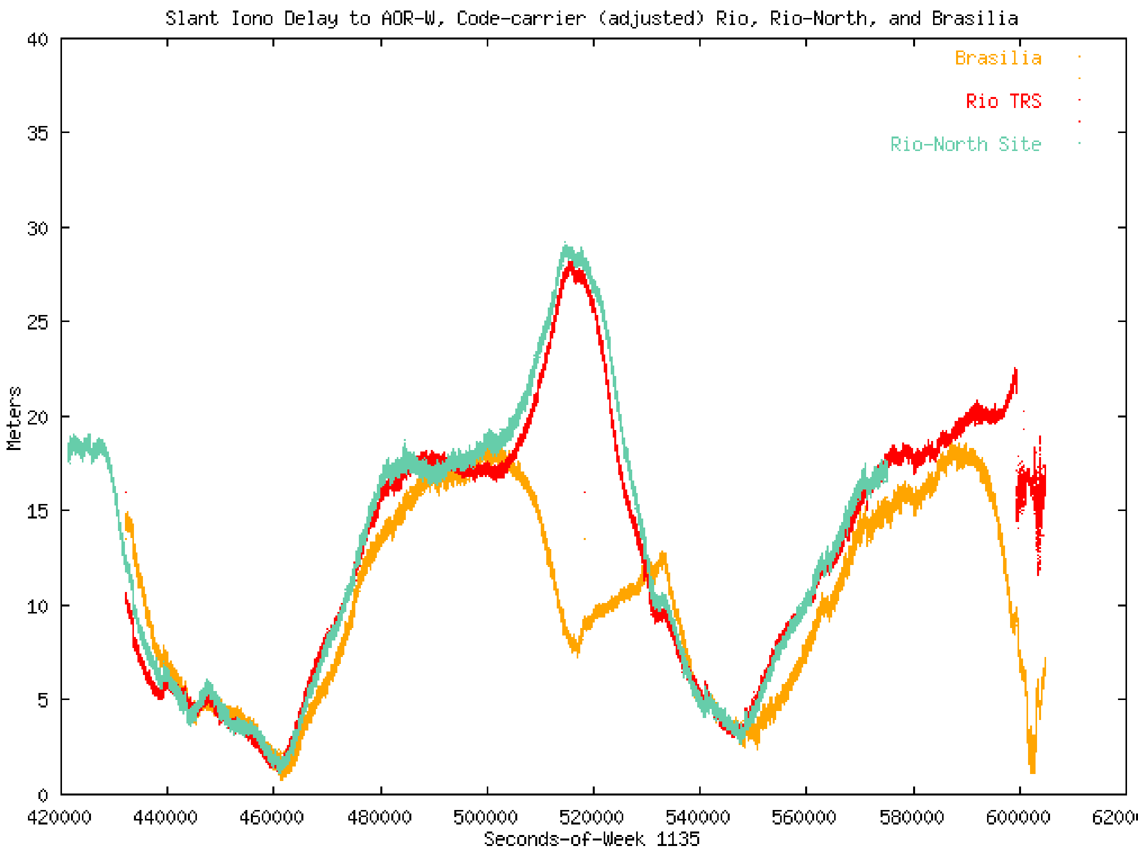


Figure 2: Slant Iono Delay to AOR-W from Rio, Rio-North, and Brasilia

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Figure 3 shows slant iono delay (carrier-carrier) to PRN 25 from the Rio-West site and the Rio TRS on Oct 10/11. The plots shows the similar shape offset in time, demonstrating the west-to-east drift of the ionosphere during these events. The apparent speed is the result of the satellite motion and the motion of the ionosphere (as discussed extensively in paper [10]), but shows the expected direction and proper range of speed (~600s/95 km = 158 m/s). This is a smaller scale event (only a few meters), and the carrier locks were lost where the plots terminate, on each receiver. The plots may show some apparent evolution of the bubbles as they drift, which may be due to bubble growth or satellite look angle change. The exact cause may not matter, but the issue will be that the shape of the feature can seem to change as they move, which would hamper any efforts to model the ionosphere as a “frozen” but moving feature.

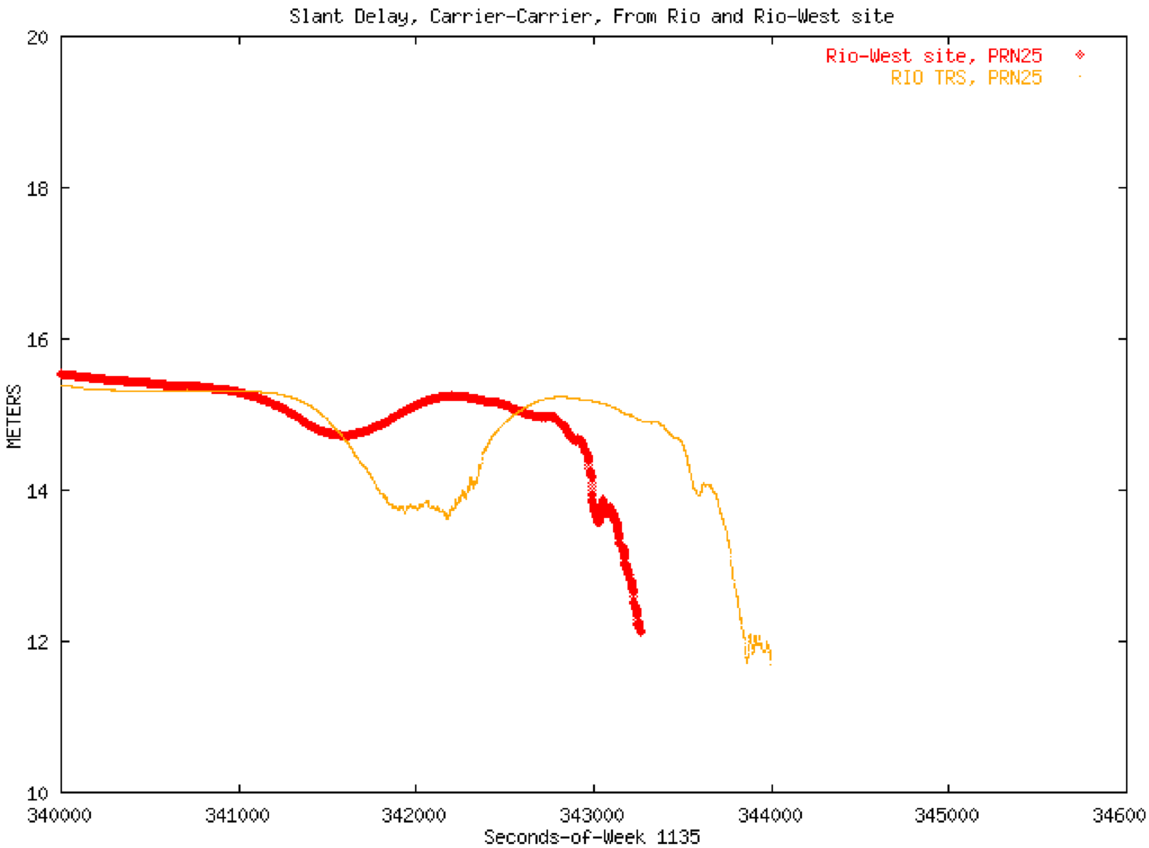


Figure 3: PRN 25 from Rio and Rio-West

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Figure 4 shows a much larger feature from both Rio and Rio-West, on the evening of October 10/11. (However, the majority of the feature from the Rio TRS site is expected to be on a tape which is being shipped to me). The plots show code-code, adjust to L1 delay, and shows many instances where the receivers dropped out due to scintillation (which, as described earlier, has a physical relationship with the bubbles). This is a slant delay to PRN 11, which was at an elevation angle of about 60 degrees. At time 345000, a feature is visible in the Rio West line of site that has not yet moved to the Rio TRS site. (Believe me, I really want to see this data!) By the time it should be visible at Rio TRS, the UTC day changed, and the data is on the tape I don't have yet. What is most interesting from the data shown is that the feature at 345000, visible in Rio-West as a delay change of almost 10 meters down and back, was not visible 95 km away. A 10 meters change over 50 km implies a gradient of at least 2 meters in 10 km can exist in these bubbles. The data (only available from Rio-West at the moment) shows total magnitudes approaching 20 meters. The most frustrating part of this effort is that, since the bubbles are physically related to scintillation, there can be some doubt as to whether or not the data is legitimate. However, since the cause is an accepted physical feature of the ionosphere, and multiple receivers tend to corroborate the data, I'm tending to believe the numbers.

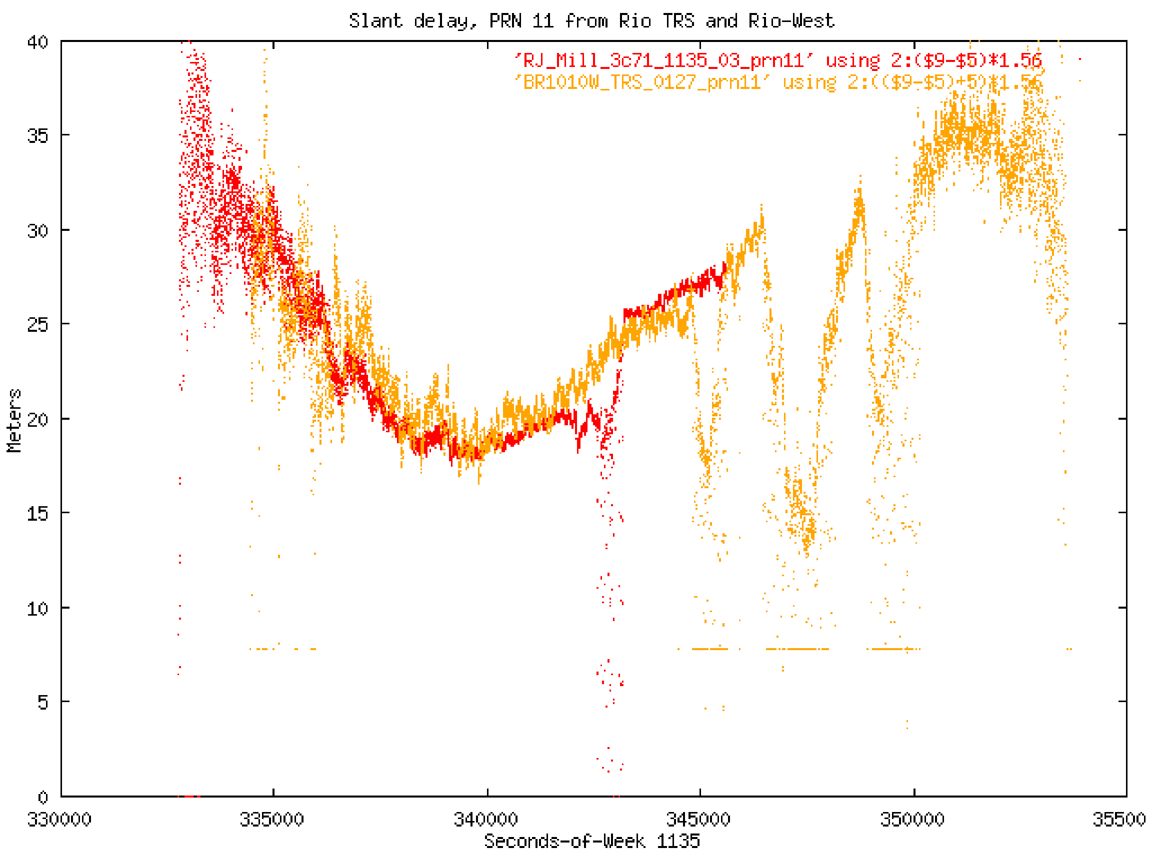


Figure 4: Slant Iono Delay: PRN 11 from Rio and Rio-West

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Figure 5 shows another example of a bubble, also to PRN 11 on the evening of October 13/14, from both the Rio TRS and Rio-South. The Ashtech (shown in green, L1 (code-carrier)/2) seemed to loose lock more easily, so I only have a limited portion of the bubble. However, the shape shows a very good agreement to the Rio-TRS data (in red) (which is 20 km north). This data also shows the lack of north-south motion, which is generally the case (but not guaranteed, as the vertical lift may appear like a north south motion on some satellite ray path). The magnitude of this bubble reaches approximately 20 meters.

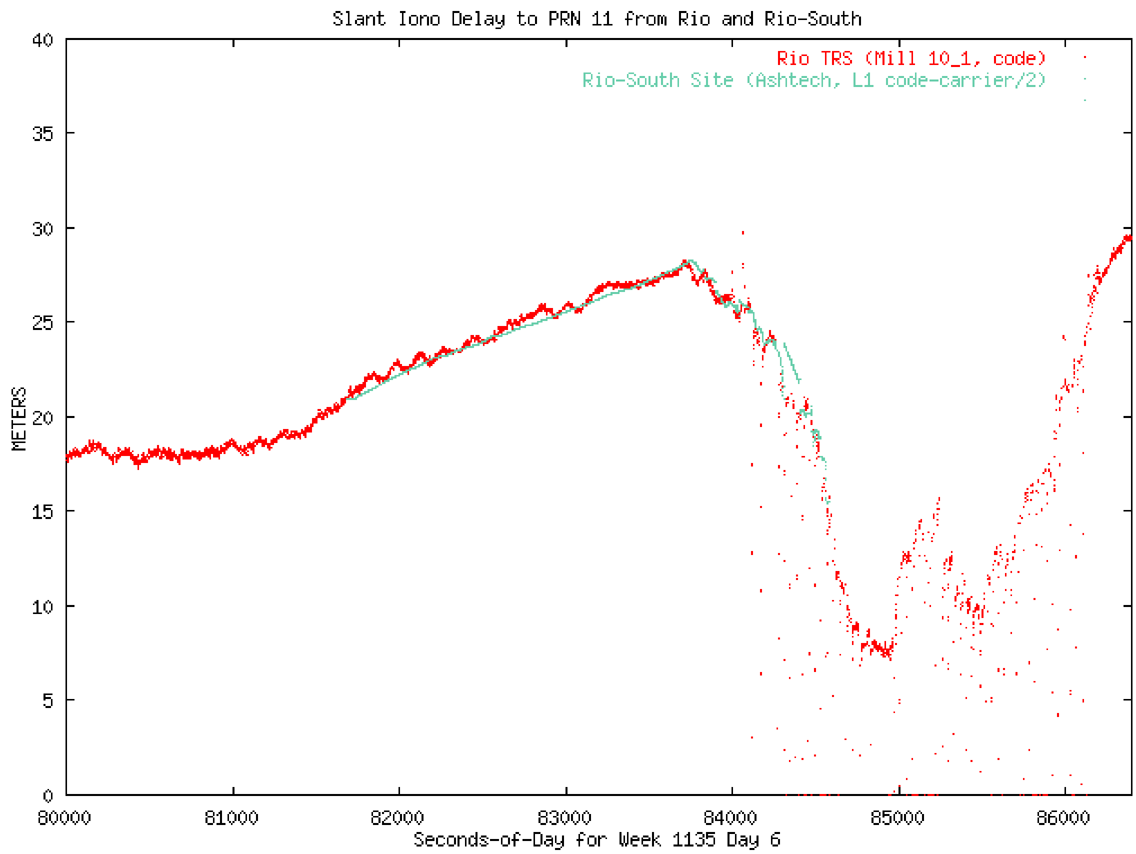


Figure 5: PRN 11 Iono Slant Delay from Rio TRS and Rio-South site

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Scintillation is evident in most of the plots shown. One specific indicator of scintillation of importance is the loss of the GEO message resulting from scintillation. Data from the 3 southern Brazilian TRS sites showing loss of GEO messages is summarized in the following table:

Geo messages lost

| Week/Day | 1135_5 | 1135_6 | 1136_0 | 1136_1 |
|---|---|---|---|---|
| Rio de Janeiro | 2 | 1783 | 783 | 1197 |
| Curitiba | 0 | 967 | 2033 | 1029 |
| Brasilia | 3 | 1 | 0 | 0 |

A slight difficulty in understanding this table is caused by the fact that the scintillation event occurs in the evening, usually straddling two UTC days; so a more detailed mapping of the losses to the specific scintillation times will be done. However, from my observation of the data, the GEO message losses occur at the times of the scintillation events, and that generally the losses are grouped in bunches (up to 10-20 messages in a row, at least one case over 100 messages lost in a row).

**Conclusions/Recommendations**

The ionosphere over Brazil and all along the geomagnetic equator contains features which appear very detrimental to WAAS. The Equatorial Anomaly, documented and supported in physics, exists regularly after sunset, causes a non-planar ionosphere on a routine basis, and would therefore seem to prevent the application of the CONUS safety case (of constantly checking for a planar ionosphere). In addition, the non-planar Equatorial Anomaly features my also contain voids or bubbles (also supported by physics) which are spatially small but have a very high delay gradient, to a total delay change of 20 meters or more. These bubbles also may or may not cause sufficient scintillation which will cause the receiver to lose lock; in addition, the characteristics of a moving aircraft receiver losing lock will likely differ from a stationary receiver losing lock. This would seem to force the use of GIVEs (easily) in excess of 6 meters to protect the user who may be locked onto satellites through these potentially undetected but very common features. GIVEs in excess of 6 meters (15 or 45 meters) will prevent the use of LNAV/VNAV. There may be times of the year where bubbles are less likely, or times in the solar cycle where the gradients should be less severe, but since the features may be enhanced by intense geomagnetic storms at any time, it would seem difficult to take advantage of that fact. The fundamental difference to the US case is that here the very irregular features are normal, not the very rare exception. This should be considered by persons responsible for safety approval of the proposed SBAS systems in areas near the geomagnetic equator, and considered as a very large program risk area by those developing SBAS systems for precision approach or vertical guidance.

Even for an NPA type WAAS system, scintillation to GPS satellites and the GEO will still cause a significant difficulty. At the very least, I recommend that we go forward with the Brazilian flight test postponed from October, and fly for 5 or 6 nights in January, 2002, and determine airborne GPS dropout and GEO message loss rates in comparison with stationary receivers. The Brazilians provided significant explanation as to why January is even worse than October in their longitude [3]. We can also use it as an opportunity to collect additional bubble observations, if there are any questions raised from the data presented here.

There has been discussion of an extended LAAS type of architecture, but the existence of the large delay gradients in the bubbles (generally, but not necessarily east-west gradients) should be considered when analyzing the safety of this architecture.