INTERNATIONAL CIVIL AVIATION ORGANIZATION

RLA/00/009 PROJECT SECOND COORDINATION MEETING ON GNSS AUGMENTATION TRIALS

(Río de Janeiro, Brazil, 28 to 30 August 2002)

Agenda Item 4: **Review of activities foreseen in the project document and reformulation of same**

(Presented by Brazil)

Summary

This working paper presents review information on the project document.

References:

- RLA/00/009 Project Document; and
- **C**onclusion 7/9 of the Seventh Meeting of Civil Aviation Authorities (RAAC/7).

1. **Background**

1.1 The preliminary results of BTB operation, from October 1st on, have exposed significant ionospheric features along of the geomagnetic equator; these include geomagnetic anomalies, plasma bubbles, and scintillation, with damage to the use of ionosphere models conceived from the environmental characteristics of North Hemisphere. Those preliminary results have caused the need to data collecting during flight (**Apendix A**) which was performed by a FAA B-727 aircraft, entirely equipped (January 2002). Based on these results and reviewing the conclusion 7/9 of the Seventh Meeting of Civil Aviation Authorities (RAAC/7), the project document shall be modified in order to accomplish these modifications.

2. **Project Plan suggested modifications**

2.1 **Modifications suggest by items**

2.1.1 B. Project Justification:

Add Item 1.3.3 with the following text:
1.3.3 The data obtained with the test bed will be necessary to model the ionosphere in the geomagnetic equator area as well as to establish the impact on service availability and continuity during the occurrence of ionospheric disturbances.

Add one phase before phase 1:

Phase 0 Develop the Geomagnetic Equator Ionospheric Model

2.1.2 D Immediate Objective, Outputs and Activities:

Add a new immediate objective dealing with ionospheric modelling according to the following title:
Develop and evaluate a new version of the TMS software based on one ionospheric model adequate to the geomagnetic equator.

2.2 Issues for general discussion

The group should analyse if the precision approach references throughout the project document has to be maintained or changed to a more realistic requirement.

3 **Action suggested**

3.1 The Meeting is invited to take note of the contents in this working paper, and incorporate the changes on the document.

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APPENDIX A

FAA/Brazil January 2002 Flight Test
Initial Test Report (Feb 8, 2002)
T. Dehel

Introduction

The FAA and the DEPV of Brazil are both investigating the potential applications of GPS and augmentations of GPS to meet air navigation and aircraft precision guidance requirements. Under formal agreements between the two countries, the FAA has provided technical assistance to Brazil for the purchase and installation of the Brazilian testbed. The Brazil Testbed is currently used to collect GPS data/SBAS data at five locations in Brazil. The most critical difference between the performance of GPS and GPS augmentation in the continental United States (CONUS) and Brazil is that Brazil is situated along the geomagnetic equator, and there are ionospheric features near the geomagnetic equator, which are very different than features found over CONUS. This flight test was to collect additional data on the effects of these features on GPS and WAAS/SBAS, in order to evaluate global applicability or limitations of satellite navigation to aviation. This is the initial test report; the report expected to be completed by April, 2002. For more specific information about the Ionopsheric conditions in Brazil, see the flight test plan (to be attached).

Flight Test Overview

The Flight Test Plan called for three nights of flying with scintillation structure present, and one without. With some luck, there were strong scintillation structures present on the three of the nights flown, and one night with weak or no scintillation present. A more exact comparison of the level of the scintillation present with the range of scintillation usually experienced will be done after consultation with Brazilian Ionospheric experts. Figure one shows the level of GEO (AOR-W) carrier fluctuations observed from the Rio Testbed Reference Station (TRS), and also the Brasilia TRS (located approximately 900 km North of Rio). The times when the S/N fluctuates significantly correspond to the scintillation structures desired and are in the evenings; Saturday evening (around second-of-week 600,000), shows no scintillation in the Rio area (at least in the view to the GEO, which is at an elevation angle of 60 degrees and slightly Northwest from Rio), while Brasilia, further North, shows what may be a small level of scintillation. Flights were flown Thursday evening (approx second-of week 430,000), Friday evening (approx 520000), Saturday (600000), and Monday (in the next week, but on this plot it shows as time 780000).

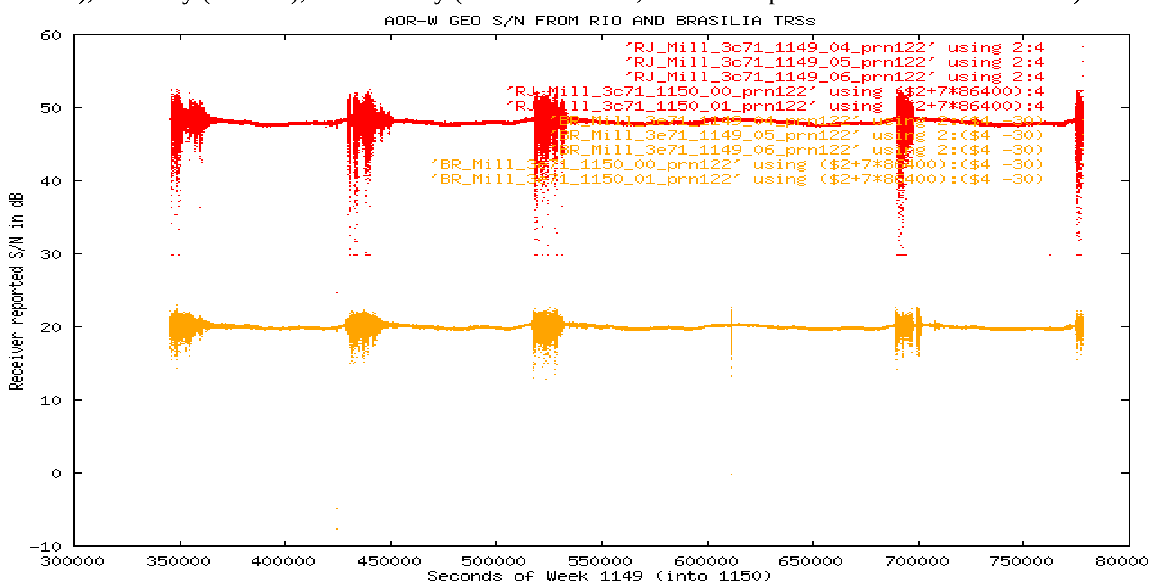

Figure 1. GEO (AOR-W) S/N for Jan 16-21, 2002

The flight test plan called for a large, square box pattern, and the final airspace provided consisted of an east-west rectangle, 50 miles by 30 miles, located over the South Atlantic Ocean just South of Rio de Janeiro, off the coast of Brazil. The aircraft was flown at lower altitudes to accommodate the range of speeds used in the test.

Goals of the Flight Test

The general goals of the flight test using the FAA B-727 were to collect flight data (while substantial ground data was also collected) to measure the effect of the voids/scintillation structures, focusing primarily on the effect of scintillation on GPS dropouts, GEO message dropout from multiple GEOs, and comparing dropouts of multiple stationary and airborne receivers. As no method to set the GIVEs which can support LNAV/VNAV has yet been proposed and proved as safe, additional iono delay data was collected to support analysis of this effort (should Brazil or others decide to undertake it).

The specific goals of the test were to collect enough data during peak-of-sunspot-cycle, routinely-bad, daily ionospheric conditions, to answer the following questions:

1) Are there interruptions in GPS-only enroute and NPA applications (i.e., does the aircraft receive enough satellites with a sufficient HDOP to permit continuous NPA operations)?

2) Are there interruptions in SBAS-NPA (i.e., does the aircraft receive at least 4 GPS satellites and a small enough message loss rate from 1 GEO, or both combined, to permit continuous SBAS NPA operations)?

3) Is there any evidence that GPS dropouts due to scintillation differ between moving and airborne receivers, or between airborne receivers when flying with, perpendicular, or against the motion of the ionosphere (expected to be approximately 100 m/s, west-to-east)?

4) Is there any evidence that GEO message loss due to scintillation differ between moving and airborne receivers, or between airborne receivers when flying with, perpendicular, or against the motion of the ionosphere (expected to be approximately 100 m/s, west-to-east)?

5) Are two GEOs (separated as are AOR-W and AOR-E, north-east and north-west from Rio de Janeiro) sufficient to insure a continuous SBAS data message?

6) Is there additional evidence of voids/bubbles? What is the highest gradient (N-S and E-W)? Is there any difference between direction or speed in the probability of maintaining lock and measuring the voids (similar to (4), but this requires L1/L2 or L1 code with uninterrupted carrier lock)?

The questions will be answered with a combination of data collection by multiple receivers and post-processing. For example, as neither an operational or prototype SBAS-NPA service is available in Brazil *from a GEO*, the data will be post-processed to determine whether the GEO message loss rate (from one or both GEOs) would have been sufficient to support NPA while at least 4 satellites were available with range.

Questions 1,2, 5 and 6 will be addressed in this initial report. Questions 3 and 4 will required more careful analysis than time allowed for this report.

Question 1: Are there interruptions in GPS-only enroute and NPA applications (i.e., does the aircraft receive enough satellites with a sufficient HDOP to permit continuous NPA operations)?

For this question we use data from the certified aircraft receiver, the GPS-1000 card, which is part of the certified Universal FMS on the FAA B-727 (N-40). The Horizontal Integrity Level (HIL) is required to remain below 0.3 nautical miles to permit NPA. Figure 2 shows the comparison of the HIL word output by the receiver on the evening flights of January 17th (with high scintillation) and Saturday , January 19th (Low/No Scintillation). Figure 2 shows that, on Saturday, during low/no scintillation, the HIL generally remained below 0.3, while on the 17th, several values in excess of 0.3 were output. Figure 3 shows a similar results when comparing January 18th to January 19th.

A probable explanation for the increase in the HIL word is the degradation of HDOP which would occur if one or more GPS satellites were lost by the receiver due to scintillation. Figures four and five compare the number of satellites tracked on these days.

It is seen in these figures that, in this certified aircraft receiver, that fewer satellites are tracked continuously on the nights with higher levels of scintillation in the Rio area. Since the number of GPS satellites varies over time (as the satellites move in their orbits), and the number tracked by the aircraft may be affected by flight (e.g. turning away from a low satellite may drop it temporarily), these figures show a comparison of two different nights. On different nights at about the same local time, approximately the same number of satellites should be tracked (the satellite locations are similar every (approx.) 24 hours) by an aircraft doing similar turns in the same airspace. The number of satellites tracked varies but never dropped below 6. With the limited data collection possible on this receiver, however, it is not known yet whether track on several satellites was lost and returned quickly (thereby avoiding a net accumulation of lost satellites), or whether track on just a few satellites was lost for longer periods of time. [This issue will become more important later in this report].

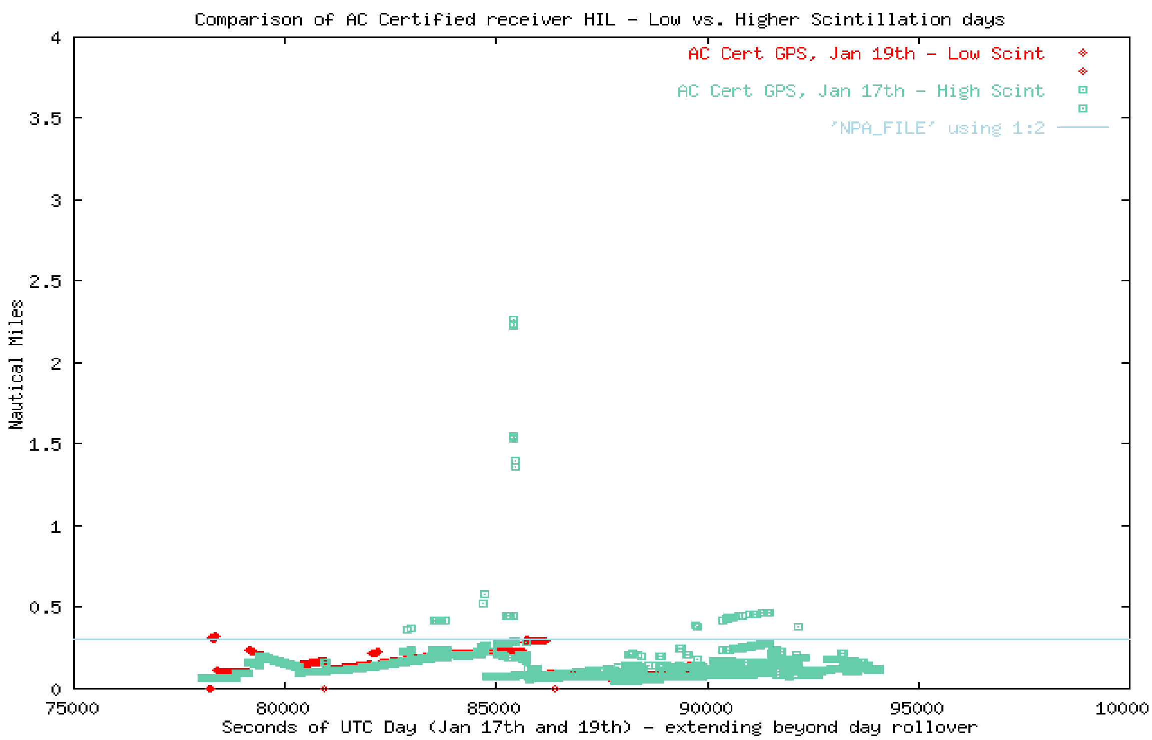

Figure 2. HIL Output, 17th and 19th January

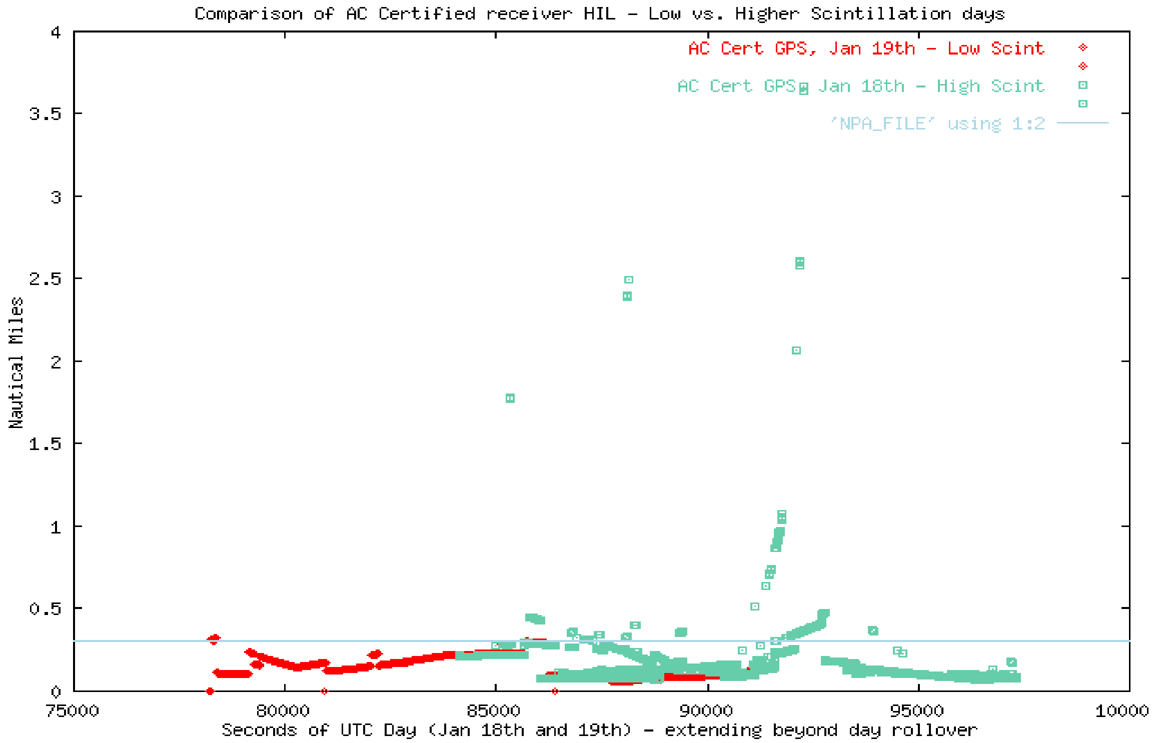

Figure 3. HIL Output, 18th and 19th January

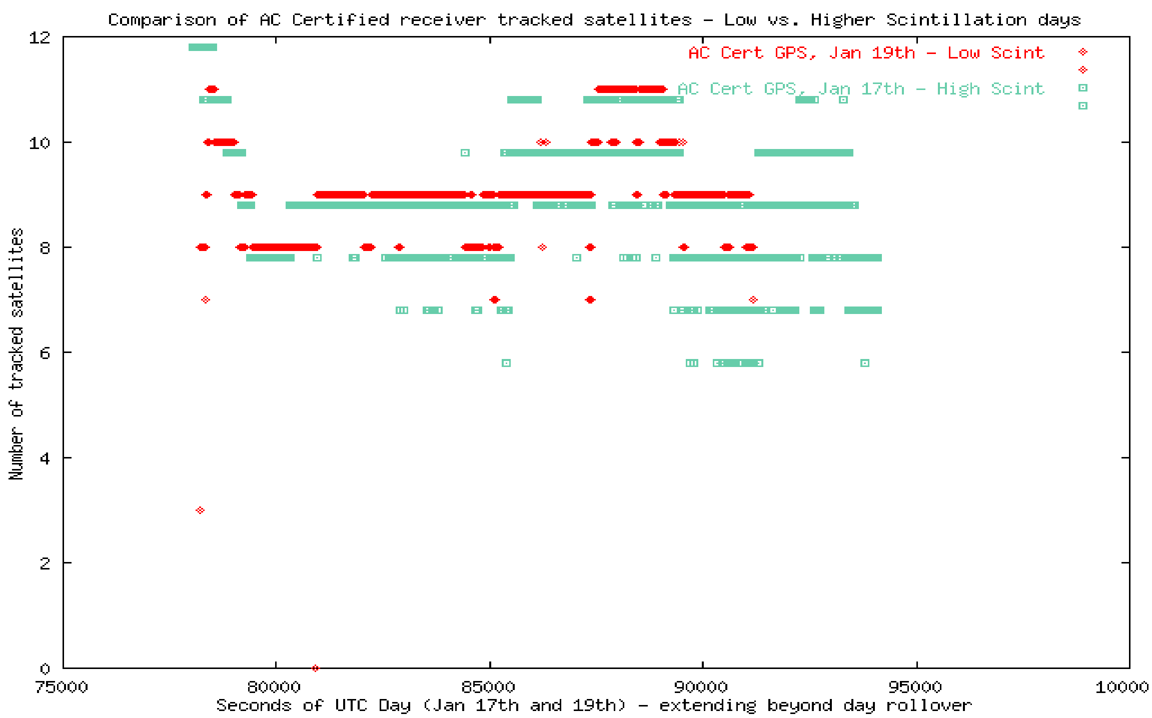

Figure 4: Comparison of Tracked Satellites, Jan. 17th and 19th.

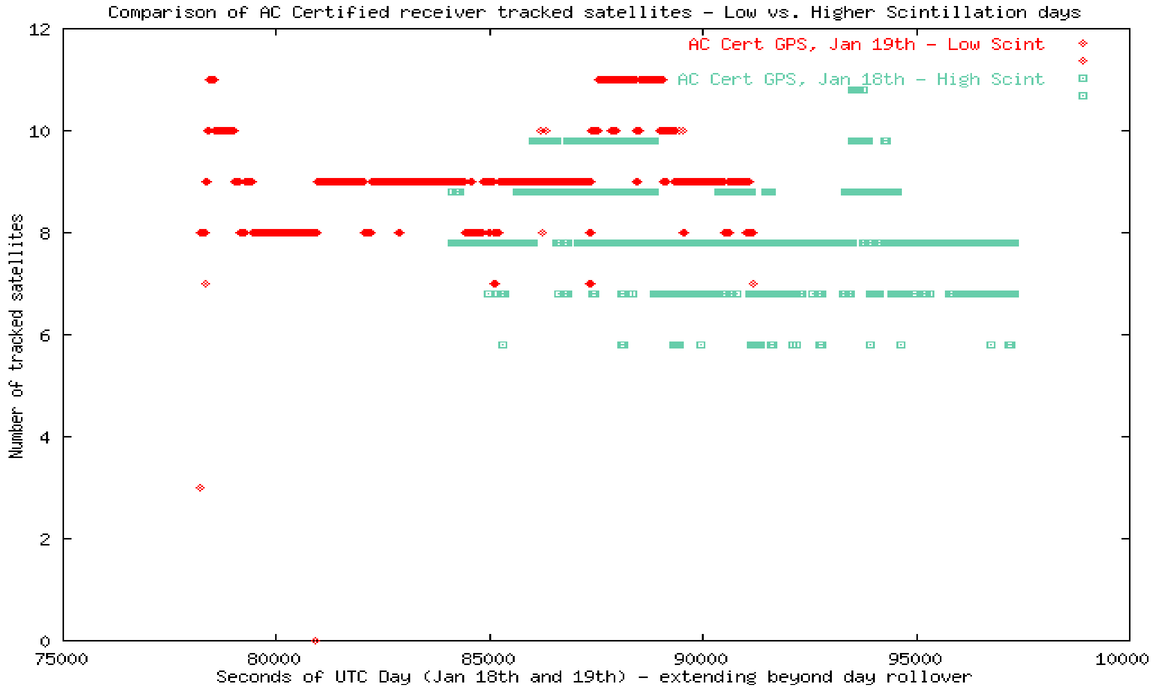

Figure 4: Comparison of Tracked Satellites, Jan. 18th and 19th.

Quest ion 1 Conclusion: During this test, there appear to be effects during strong scintillation conditions sufficient enough to affect the availability of GPS NPA using RAIM for integrity (at least in this implementation of RAIM).

Question 2: Are there interruptions in SBAS-NPA (i.e., does the aircraft receive at least 4 GPS satellites and a small enough message loss rate from 1 GEO, or both combined, to permit continuous SBAS NPA operations)?

Question 2 part 1a: Does the aircraft receive at least 4 GPS satellites continuously.
Figure six shows the number of satellites used in the position solution on Jan 18th, both from the Rio TRS (Millenium 10-1 receiver) and the B-727 (Novatel OEM-4 receiver). Again, all satellites are assumed to be monitored and have a UDRE or 23 meters. The plots also show a valid position computation was made (which generally corresponds to times of 4 or more satellites). The aircraft receiver shows a period of time (at approximately 520000) where less than four satellites were available on which to make a position computation. The period lasts for under 1000 seconds – about 15 minutes.

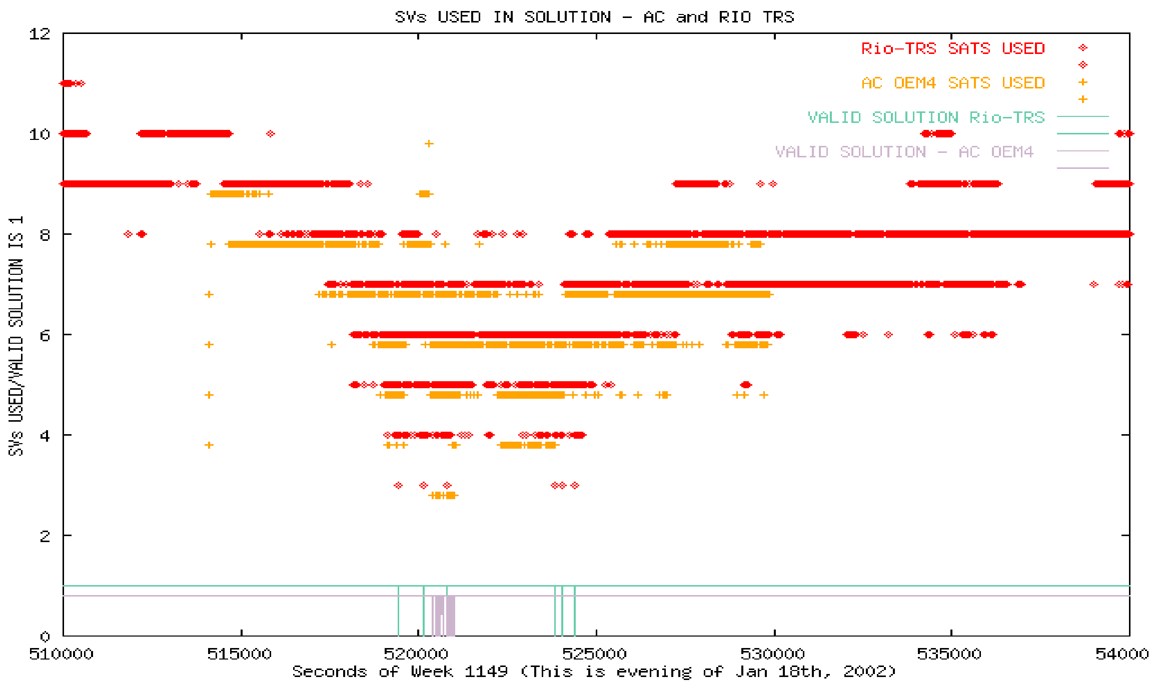

Figure 6: SVs used; Aircraft and Rio TRS, Jan 18th.

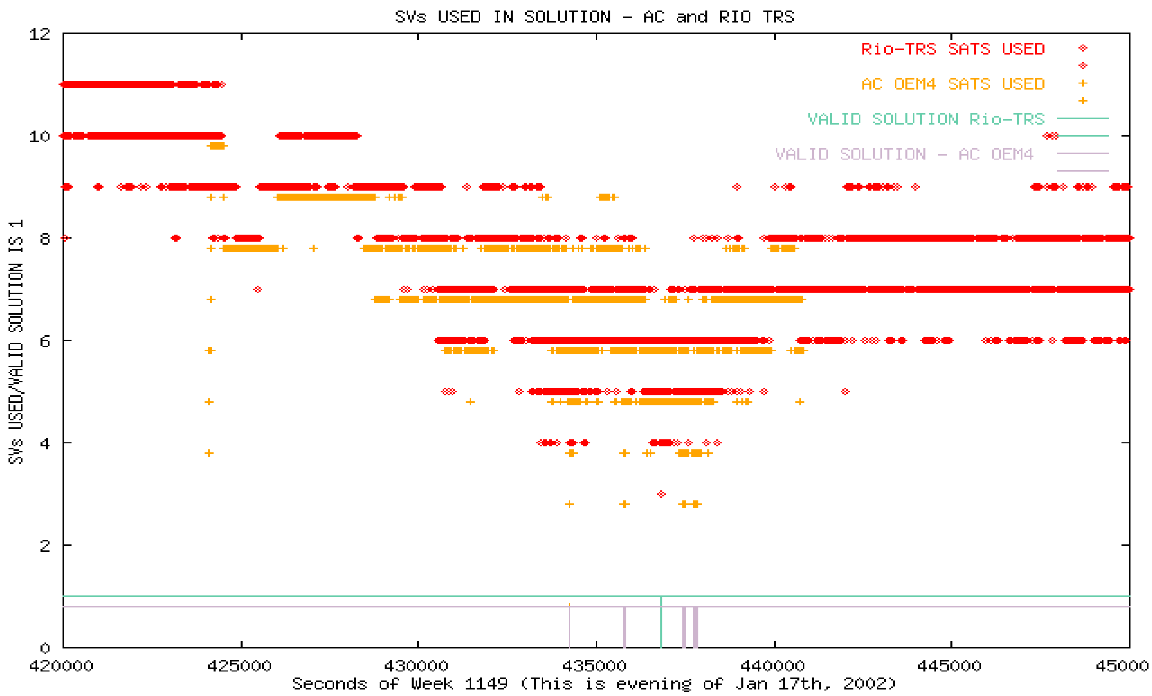

Figure 7: SVs used; Aircraft and Rio TRS, Jan 17th.

Figure 8 shows similar data for Jan 17th. But the degradation to less than 4 SVs is, in total, less. Figure 8 shows the results for Jan 19th, which does not show any periods of under 4 SVs for the aircraft.

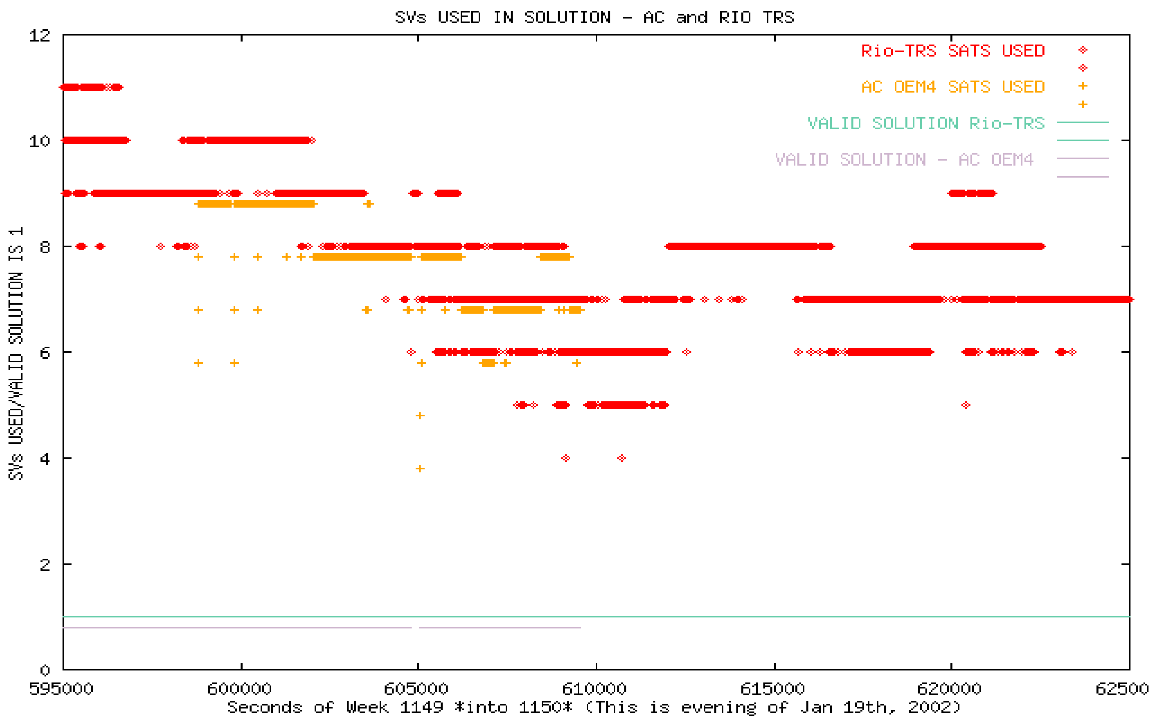

Figure 8: SVs used; Aircraft and Rio TRS, Jan 19th.

Figure 8 also shows that the aircraft generally remained at 6 or more SVs during this flight. Figure 9 shows the following, and last, evening flight, on a night of stronger scintillation (January 21st).

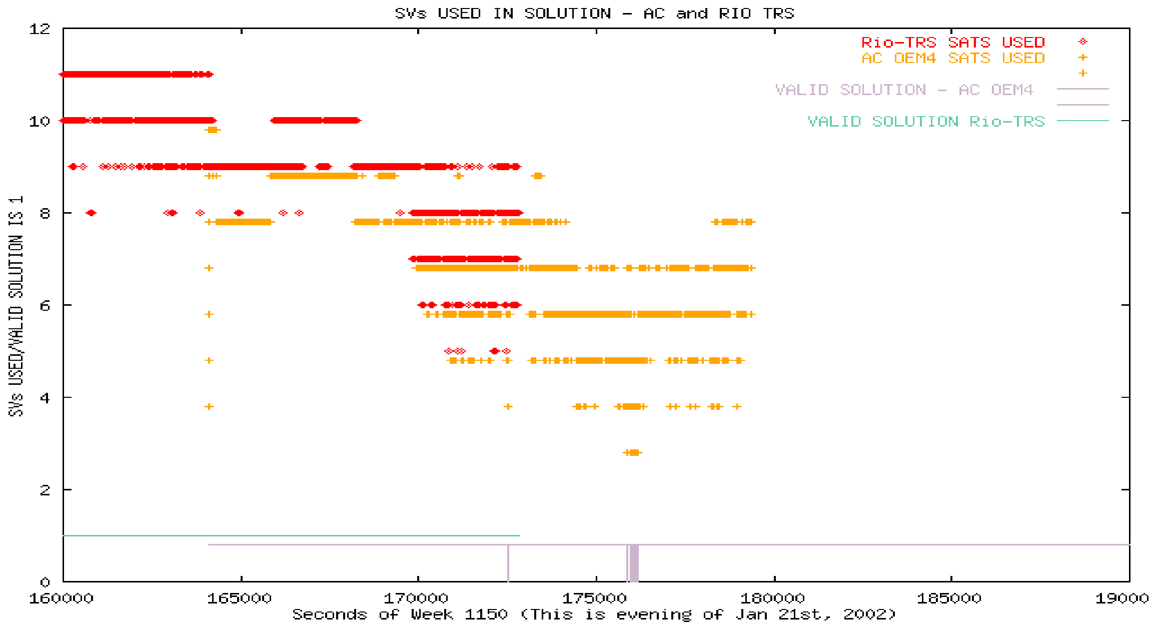

Figure 9: SVs used; Aircraft and Rio TRS, Jan 19th

Figure 9 shows again that the number of SVs used in the position solution dropped below 4 for a period of under 1000 seconds (less than 15 minutes). (Note: the Rio TRS data for day 1150_02 was not yet appended after the day rollover).

The previous four plots also show data for the Rio TRS; in this computation, the AOR-W GEO was included, giving the ground station and extra satellite to possibly include in the position computation. Even with this advantage, the ground station still had instants of less than four satellites visible in the Jan 17th and 18th. Data.

Even though the total time affected (time where under 4 SVs were useable in the solution) was low (under 15 minutes per evening of strong scintillation), there is still the discrepancy in number of satellites used by the certified aircraft receiver versus the experimental receivers. The certified receiver always used 6 or more SVs (and was not able to track either GEO). The possible explanations are:

a) Different installations/antennas
b) Different receiver tracking internals or position solution algorithms/rules.

Reason (a) remains a possible contributor, but there are some definite reasons where (b) could have affected the number of satellite used. One example is that, in a "WAAS MOPS" receiver, in PA mode, there is a requirement to reduce the range noise on a GPS satellite (Section XXXX). In our implementation, we use code carrier smoothing for 10 seconds after the satellite is re-acquired following an outage or cycle slip (as permitted in the WAAS MOPS, section XXXXX). However, the smoothing, and subsequent need for continuous carrier lock, are not a requirement for NPA mode (so the aircraft certified receiver may not implement these), while these rules were implemented in the experimental WAAS position solution. There area where these could impact the performance is that, as individual satellites are lost due to short, strong scintillation, they are not returned to the position solution computation as quickly, and as other satellites are also affected, there would be a more likely accumulation of unused satellites. As partial demonstration of this point, Figure 10 shows the total number of SVs tracked (including the two GEOs, when available) versus the number used in the solution. At the time that only three satellites were available for the position solution, a total of 8 satellites were tracked. Even if the two GEOs made up part of this total, the number of satellites tracked at this time was six.

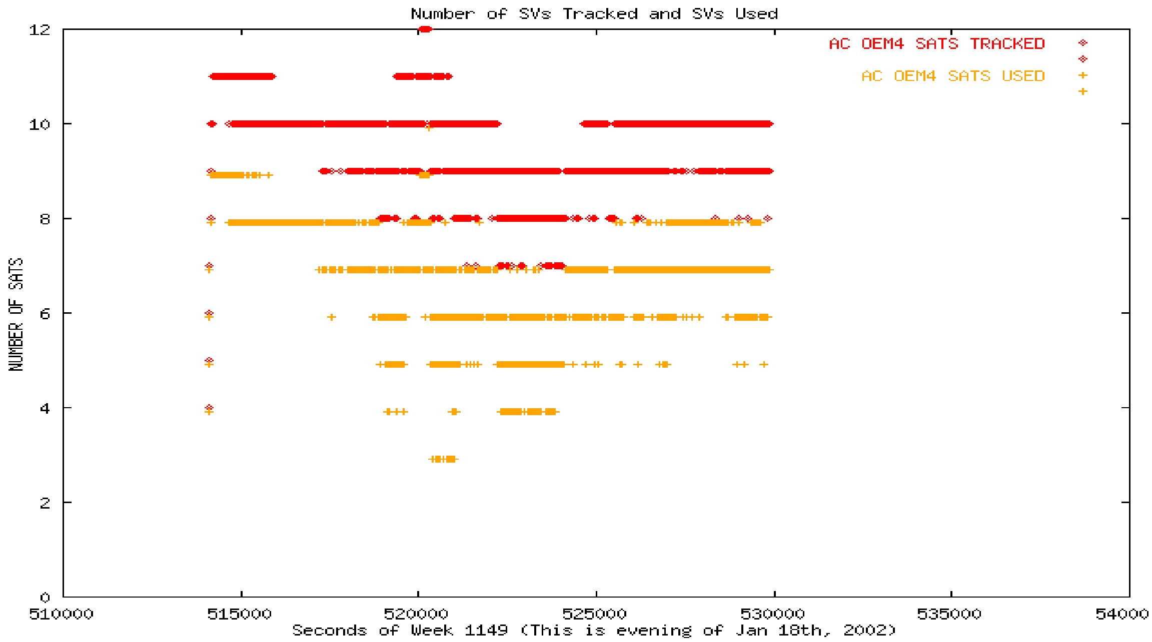

Figure 10: SVs Tracked vs. Used, Aircraft OEM-4 receiver

Conclusion, Question 2-1a – although flight and ground tests should short periods of time (under 15 minutes total per night) where the effects of scintillation resulted in under 4 SVs available for the position solution, a detailed examination of the implementation and the receiver/position solution rules should yield a higher minimum number of satellites. Also note a minimum of 6 satellites was actually observed during this test in the certified aircraft receiver (which is able to support NPA). Therefore this concept is for NPA (which should not require carrier smoothing/continuous carrier lock) but may not be extendable to PA modes (where lower pseudorange noise is a MOPS requirement).

Question 2-1b(added) - Although 4 is the minimum number of ranging sources necessary to develop a position solution, NPA operations has a further requirement that the Horizontal Protection Level be at 556 meters or less; so, to answer this question, it is necessary to also confirm that the HPL remains below 556 meters.

As stated in the test plan, neither an operational nor prototype SBAS-NPA service is available in Brazil *from a GEO.* In order to investigate this question, we "simulated" a South American WAAS. During the flights we ran the position solution software in SPS mode with a "simulated" UDRE of 23 meters, which falls in between the WAAS UDREis of 11 (corresponding to 15 meters) and 12 (corresponding to 45 meters). Since the focus of the test is on NPA mode, with SA off, the accuracy achieved without corrections easily meets NPA requirements. The UDRE of 23 meters corresponds to a standard deviation of GPS range error of 7 meters, which has been observed in the US since SA has been turned off. A UDRE of less than 15 meters should easily be achievable by an SBAS in South America (US WAAS UDREs are typically under 4 meters). The ionospheric variance defined in the RTCA DO-229 WAAS MOPS was used.

Figure 11 shows the HPL and horizontal error for the Rio TRS at times when at least 4 satellites were available. Notice, that under the simulated UDREs used, that the HPL did exceed the Horizontal Alert Limit of 556 meters for short durations (again under 15 minutes total).

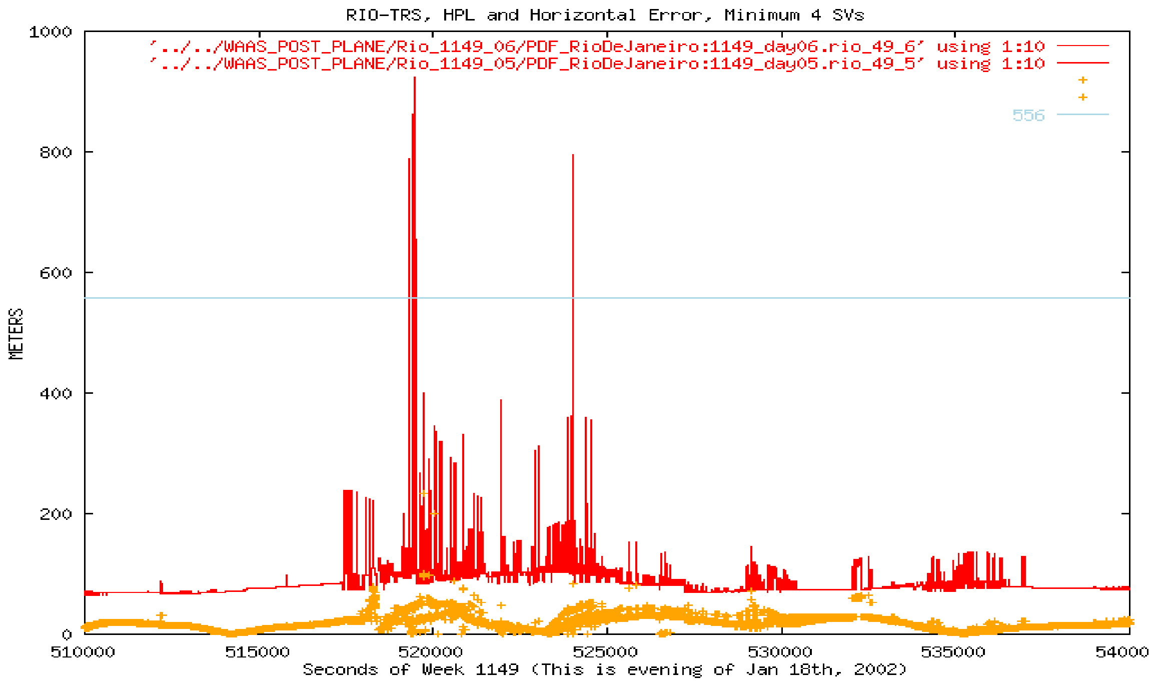

Figure 11: HAL and Horizontal error, minimum 4 SVs, RIO TRS, January 18th.
Red (top) line is HPL and bottom marks are horoizontal error (no corrections)

The data was replotted using the HPL generated when at least 6 SVs were available on the same evening and the data is shown in Figure 12.

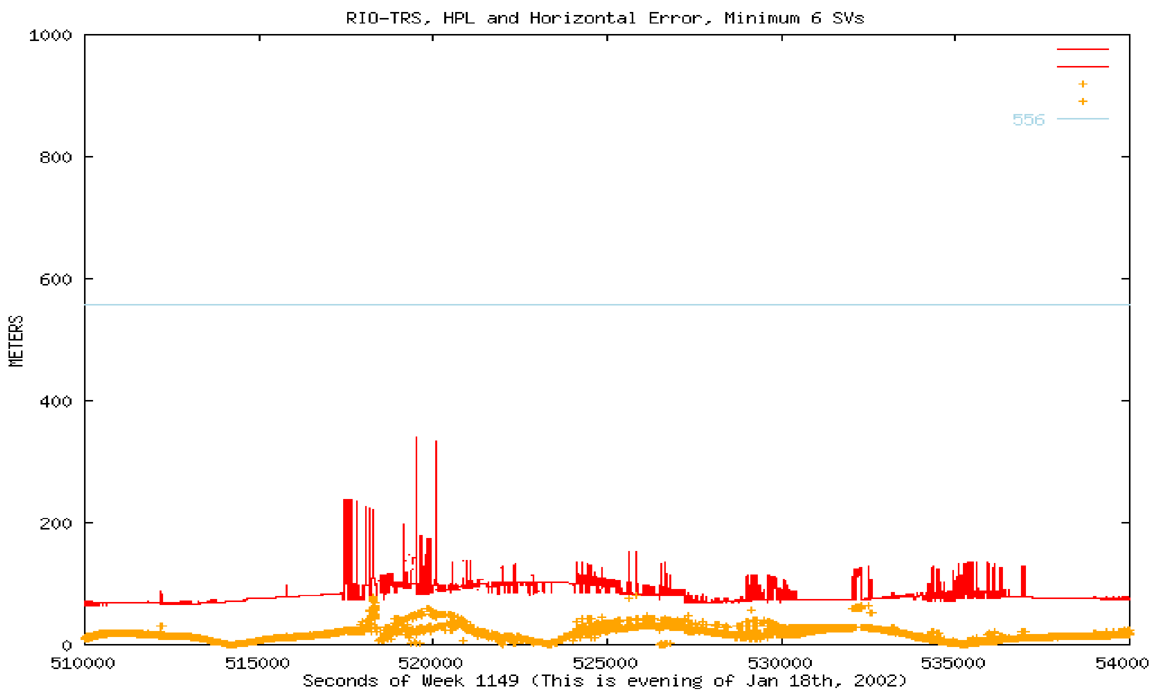

Figure 12: HAL and Horizontal error, minimum 6 SVs, RIO TRS, January 18th.
Red (top) line is HPL and bottom marks are horoizontal error (no corrections)

Conclusion, Question 2-1b: Although the testing showed that the HPL may exceed the HAL for a short time (15 minites during an evening of strong scintillation), an aircraft receiver that performs at least as well as the certified aircraft receiver should track sufficient satellites to provide uninterrupted NPA service (HAL under 556 meters) during the level of scintillation observed. In addition, *even with no corrections at all* provided to GPS, the accuracy remained well with the requirement.

Question 2-2: Is the GEO message loss rate small enough message loss rate from 1 GEO, or both combined, to permit continuous SBAS NPA operations)? (The MOPS receiver requirement for NPA mode is 1 loss per 10,000 messages; in PA it is 1 in 1000).

Figures 13 –15 show the cumulative GEO messages lost from both AOR-W and AOR-E for the three nights of scintillation (using the aircraft OEM4 receiver). It is seen that the most dramatic losses occur in bunches during the scintillation structures; also very evident is the fact that the losses to AOR-E are consistently much smaller than the losses to AOR-W. This difference may be due to pierce point location; for example, the line of sight to AOR-W may have been directly up a "bubble tube" while the line of site to AOR-E may have been more across the same tube as it traveled by. Other possibilities exist and should be investigated. The net result is that the message losses did not occur simultaneously, so that the likelihood of continuous integrity provided by the combination of the GEOs for NPA operations in South America has been demonstrated during these nights of strong scintillation. The message losses from both GEOs during the quiet night (Saturday, January 19th), was zero (Figure 16).

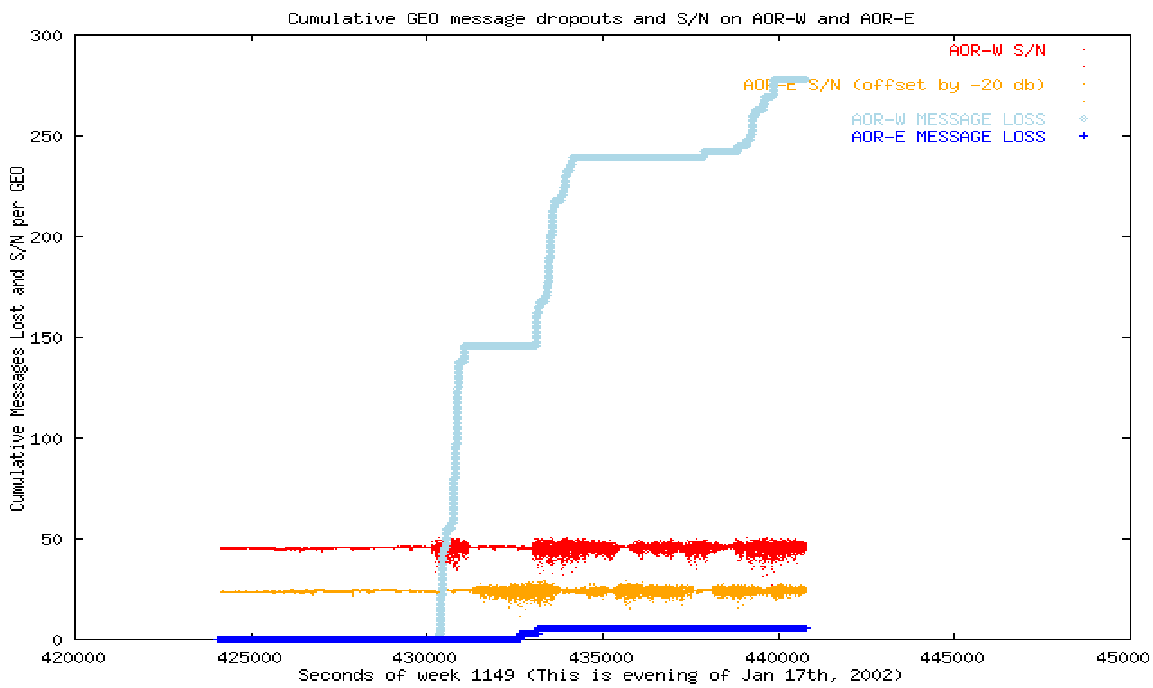

Figure 13: Aircraft GEO Message Loss, Jan. 17, 2002

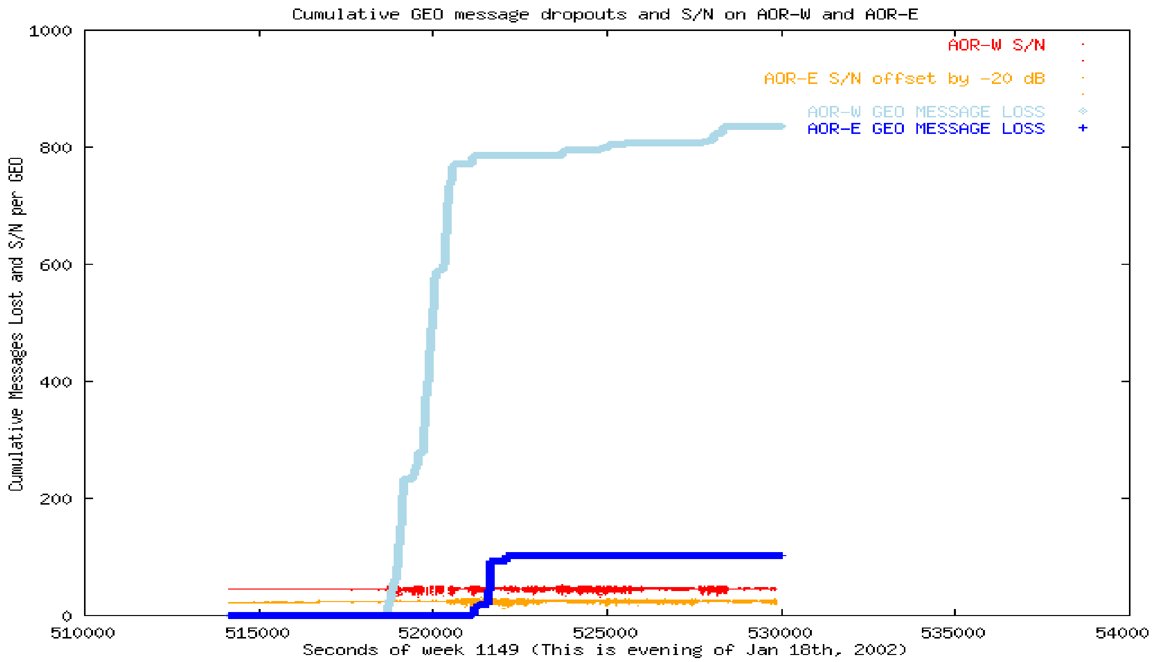

Figure 14: Aircraft GEO Message Loss, Jan. 18, 2002

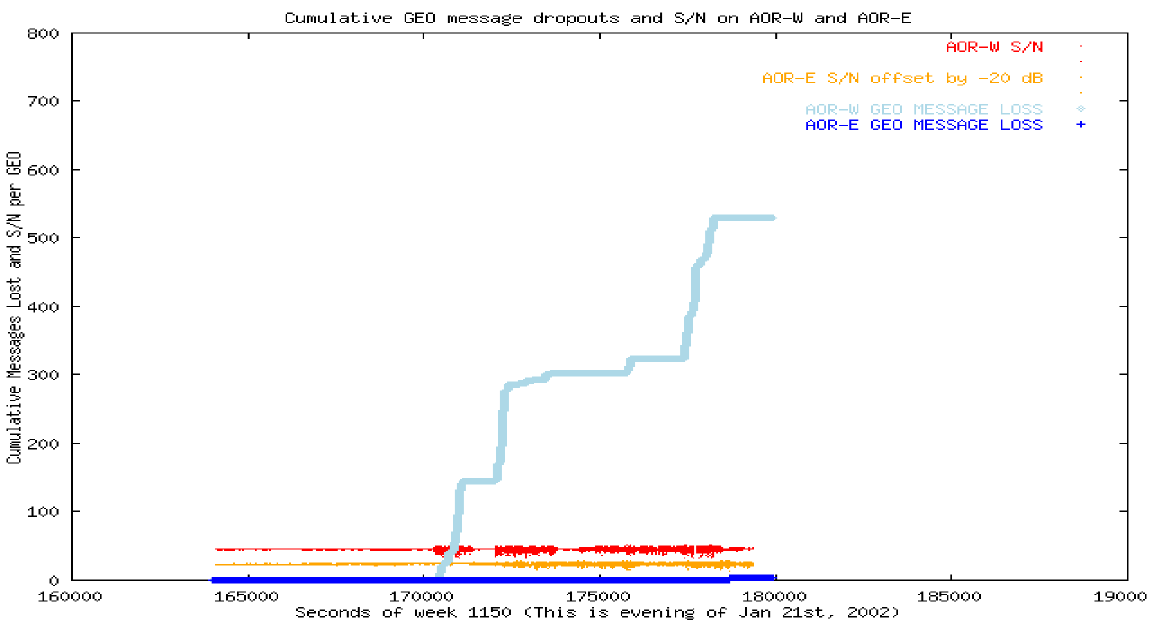

Figure 15: Aircraft GEO Message Loss, Jan. 21, 2002

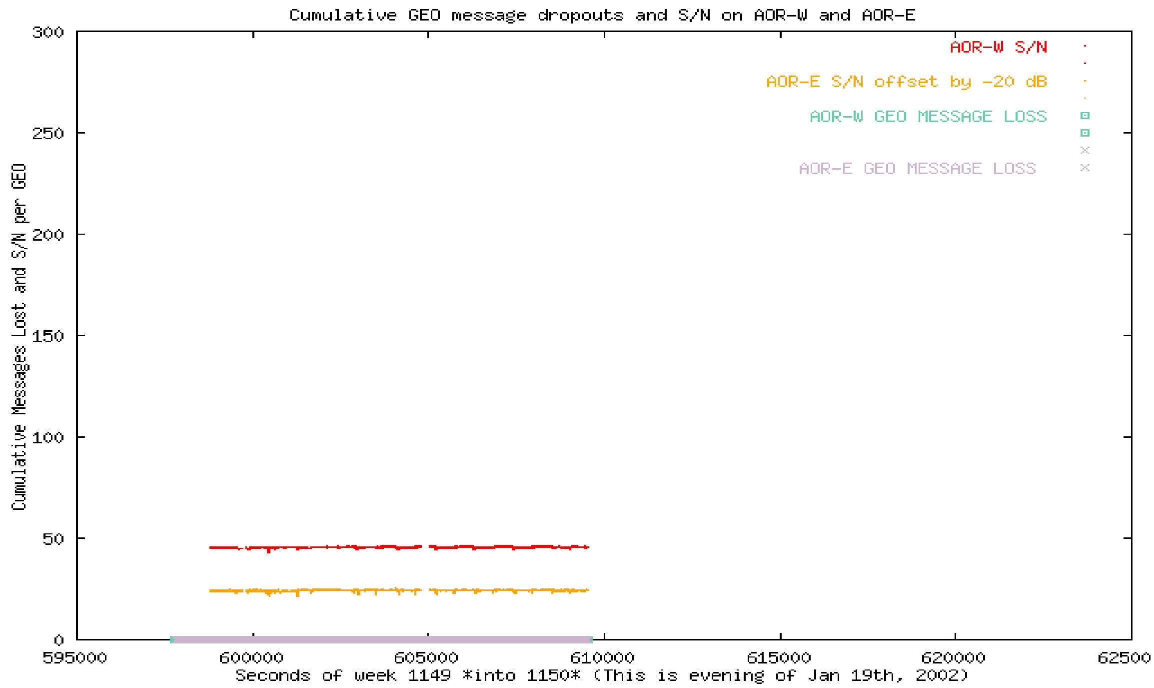

Figure 16: Aircraft GEO Message Loss, Jan. 19, 2002
(This is the quiet, low scintillation night in Rio, show no geo message losses)

Conclusion, Question 2-2: Even though AOR-W showed hundreds of GEO messages lost during periods of strong scintillation, the low loss rate from AOR-E (or some other well located GEO) would yield a GEO message stream which would be able to support SBAS operations. The reasons for the dramatic differences should be investigated to help determine optimal GEO placement for South America.

Question 2 overall conclusion: Sufficient satellites for ranging sources and sufficient GEO messages from dual well placed GEOs should be sufficient to support continuous NPA operations even in strong conditions of scintillation observed during this flight test.

Questions 3: Is there any evidence that GPS dropouts due to scintillation differ between moving and airborne receivers, or between airborne receivers when flying with, perpendicular, or against the motion of the ionosphere (expected to be approximately 100 m/s, west-to-east)? - will be examined in a later report.

Question 4: Is there any evidence that GEO message loss due to scintillation differ between moving and airborne receivers, or between airborne receivers when flying with, perpendicular, or against the motion of the ionosphere (expected to be approximately 100 m/s, west-to-east)? - will be examined in a later report.

Question 5 (regarding GEO placement) has been answered in Question 2-2.

Question 6: Is there additional evidence of voids/bubbles? What is the highest gradient (N-S and E-W)? Is there any difference between direction or speed in the probability of maintaining lock and measuring the voids (similar to (4), but this requires L1/L2 or L1 code with uninterrupted carrier lock)?

Figure 17 shows a "bubble" which passed into view at the aircraft and the Rio TRS in the line of sight to PRN7 on Jan 18th. Other data was collected at a point 13 km east of Rio, but this data has not yet been examined. The gradients of the bubbles observed will be determined in the later report.

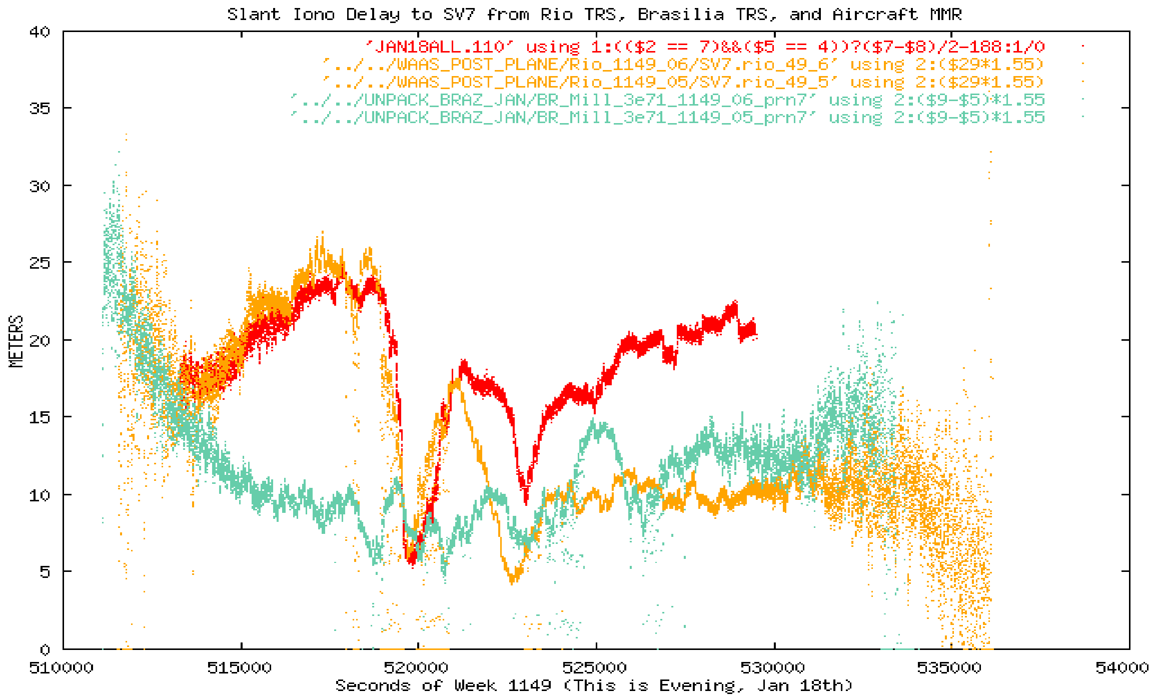

Figure 17: Change in ionospheric delay due to bubble.
(Bubble visible at Rio TRS and aircraft, not obvious at Brasilia TRS)

Data was collected from the evening of January 17th from the Rio TRS and a temporary receiver location approximately 15.7 km West (A military base/airfield called Camp Alfonsos). Data was also collected on the aircraft which was flying a “box” pattern just south of Rio de Janeiro. Figure 6-1 shows the overall map for the area, and the aircraft pattern (RIO_PT is the Rio TRS location, CAMPOE-PT is the location of the temporary receiver at Camp Alfonsos, and the square shows the aircraft pattern.

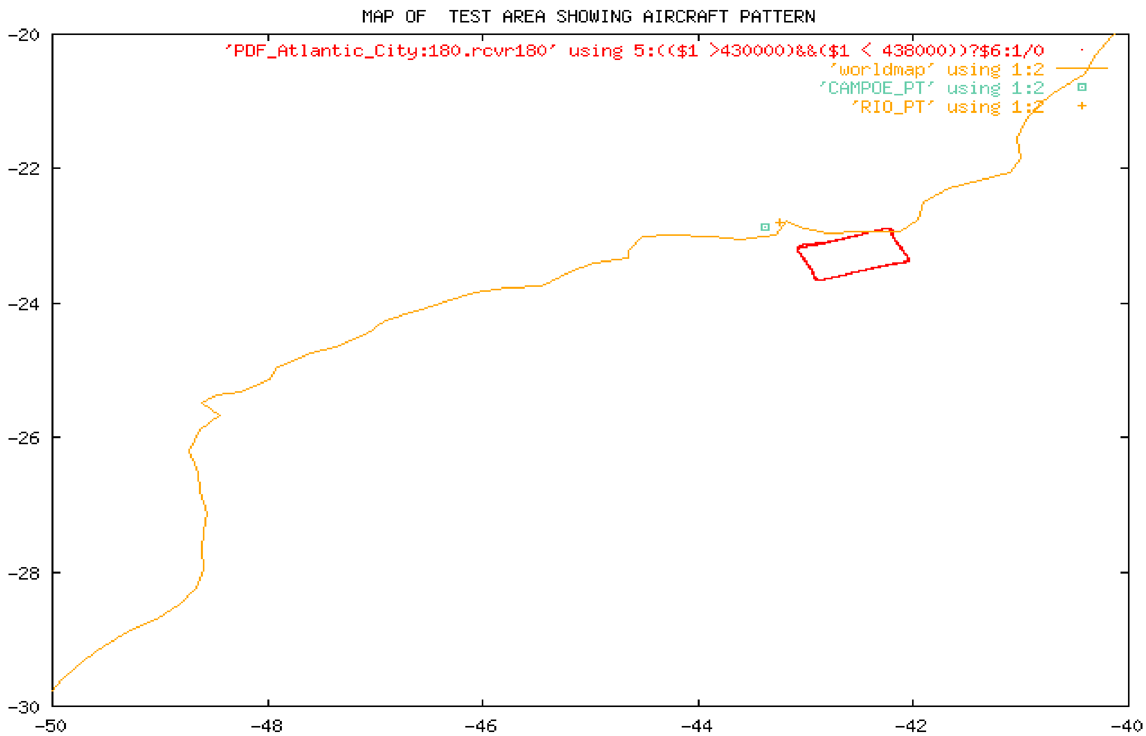

Figure 6-1: Area Map

All receiver were tracking the AOR-W GEO, and the passing of a “wall” of one of the bubbles was observed at all three locations. This allows the computation of a spatial gradient and speed. Figure 6-2 shows the code-carrier (divided by two) measurement by each receiver, and the large (over 8 meter) drop in iono delay is evident as the “wall” passes each receiver.

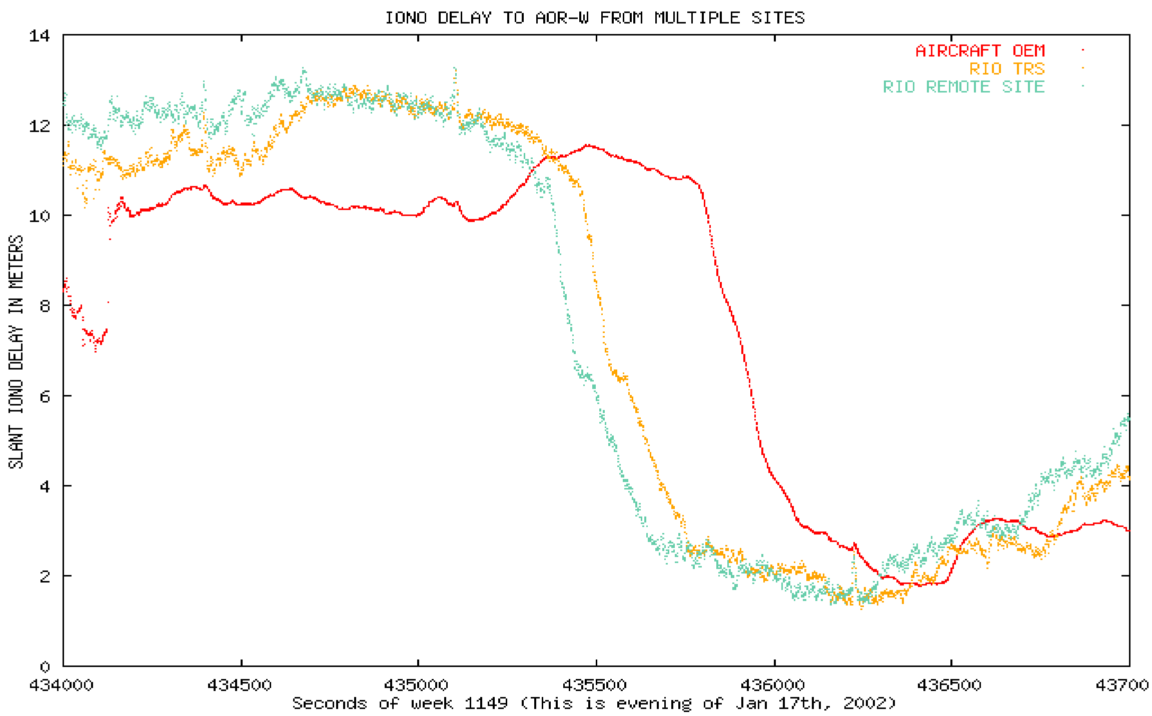

Figure 6-2: "Bubble Wall" passes each receiver

Figure 6-3 shows and enlargement of the map, which shows the location of the aircraft during the timeframe. The location of the large marks on the aircraft line shows the position of the aircraft when the bubble wall was first encountered. The aircraft was flying west at the time (while the bubble was moving east). The initial estimate of the along-geomagnetic equator distance and speed of the bubble wall were derived from Figures 6-3 and Figure 6-4 which shows an enlargement of Figure 6-2.

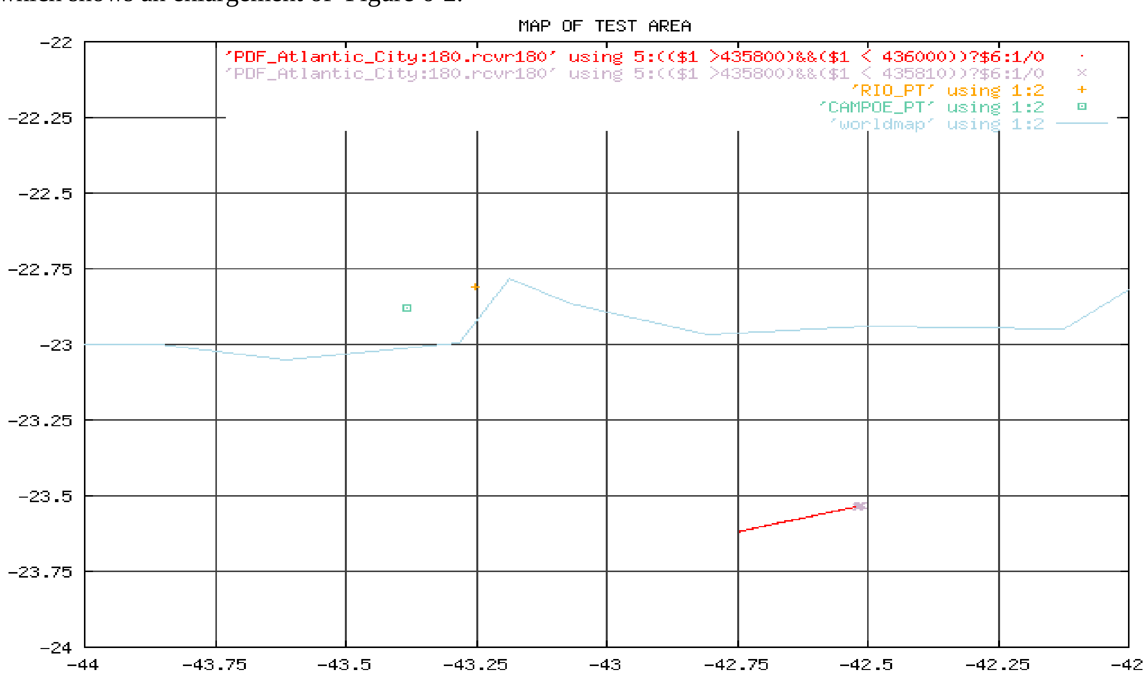

Figure 6-3: Enlargement showing aircraft location and direction

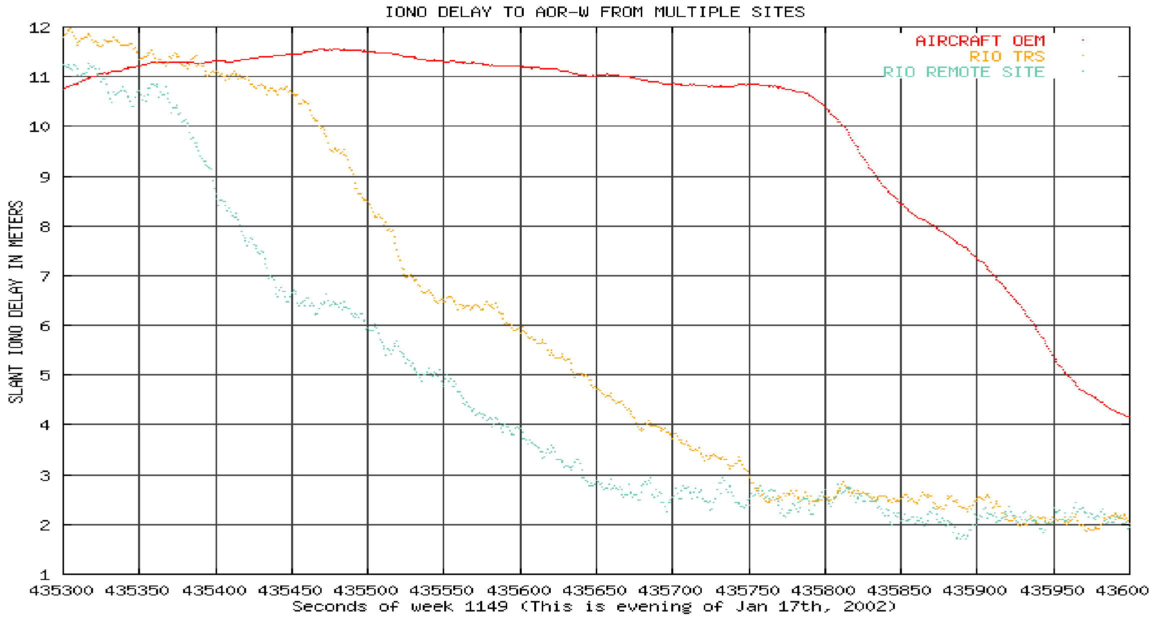

Figure 6-4: Enlargement showing more detail on wall crossing times

Inspection of Figure 6-4 shows that a typical 2 meter gradient exists between the Camp Alfonsos receiver (called the Rio-Remote Site in this plot) and the Rio TRS located 15.7 km away, during the wall passage; and that the maximum spatial gradient is approximately 4 meters over the 15.7 km distance (at about time 435450). (Giving a maximum gradient of about 2.5 meters/10 km). Also note that the entire bubble wall had passed the Rio TRS before it was visible on the aircraft (at about 435800), meaning the gradient on the larger scale was somewhat lower (about 1.6 meters/10 km). Note that these are slant measurements, not adjusted for obliguity (which at the 60 degree elevation angle of the GEO results in a decrease of roughly 20% adjusting to the vertical delay).

Using a approximations that the Ionospheric pierce points were spaced as the receivers, and that the direction of motion of the "wall" is straight magnetic east (approximately the line from Camp Alfonsos to the Rio TRS), and that the wall is straight and aligned North-South, perpendicular to the geomagnetic equator, we compute three estimates of the wall speed:

From Camp Alfonsos to Rio TRS: 174 meters/second
From Camp Alfonsos to Aircraft: 147 meters/second
From Rio TRS to Aircraft: 146 meters/second

All three estimates are significantly higher than the 100 m/s range that we initially expected to see.

Conclusion, Question 6: Additional evidence exists for voids/bubbles in the data collected during the Flight Test in Rio, and the east-west gradient maximums have been observed to exceed 2 meters in 10 km in receivers spaced only 15.7 km apart.

Overall Conclusion: SBAS NPA should work in South America even during strong scintillation but care needs to be taken in receiver requirements and GEO placement. Poor implementation of receiver rules (for example, requiring code/carrier smoothing if the accuracy requirements of NPA do not call for it), or poor GEO placement may result in a system that suffers availability degradation during strong scintillation. This conclusion also assumes that the SBAS reference stations will be placed to insure continuous monitoring of GPS satellites during severe localized scintillation, and that severe localized scintillation will not cause false integrity alerts.

Recommendation: Additional MOPS requirements should be developed and substituted for the MOPS note on performance in scintillation (section XXXX) to assure performance at least as "good" as the certified receiver in N-40 and to assure that PA requirements which could degrade performance in NPA mode during scintillation are not needlessly used in NPA mode.

- END -