A Look at GPS Positioning in Solar Cycle 24

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ABSTRACT

Positioning errors in GPS receivers can be impacted by Equatorial Spread-*F* (ESF) scintillations. We have carried out a survey of GPS positioning errors from our receivers at seven stations at a range of magnetic latitudes around the equator. The magnetic latitude is important because scintillations at GPS frequencies vary considerably with this parameter. We report case studies of the typical errors observed during scintillation and we find that errors in excess of 30 meters are relatively common. We then look at the errors statistically in order to compare the error levels from these stations as a function of magnetic latitude. Through this analysis, we are able to show the latitude dependence of the positioning errors which are strongest around 20^{o} magnetic and are virtually absent at the magnetic equator and poleward of the anomaly crest.

1. INTRODUCTION

Scintillations near the magnetic equator arise from large scale regions of plasma depletion in the *F*-region of the ionosphere. These regions rise up post-sunset from the magnetic equator and follow magnetic field lines, extending as far as 25^{o} poleward. These macroscopic regions of plasma depletion are characterized by smaller scale variations in plasma density causing perturbations in the signal amplitude and phase of radio waves that pass through the ionosphere. Scintillations can affect GPS positioning accuracy through errors in the range and in the carrier phase along each satellite link. When scintillations become intense, they can lead to a loss of lock on a specific satellite, further degrading the accuracy of the solution. Scintillations can even lead to loss of positioning service when fewer than four satellites are available [*Carrano et al.*, 2005]. The effects of ESF scintillations on GPS positioning are of interest to many users, but to date, the characteristics of these errors have been largely unknown.

Recently, several receivers have been installed at strategic locations which measure both the ESF scintillations and the concurrent degradation in the position solution. These receivers serve as detectors of scintillation serving the Scintillation Network Decision Aid [*Bishop et al.*, 2004] which is a system designed for forecasting scintillation effects on operational communications systems. In this study, we examined position errors and scintillation levels from 6 stations located in South America as well as a station in the Atlantic, as shown in Figure 1. One of the objectives of this study is to characterize the magnitude of the positioning errors that arise from scintillation. Also, since scintillations at the GPS L1 frequency (1,575 MHz) are strongly dependent on the magnetic latitude, we also investigate the range of magnetic latitudes where errors related to scintillation might be expected to be significant. Therefore, these results can be useful to operators in gauging the potential for errors at a given receiver location.

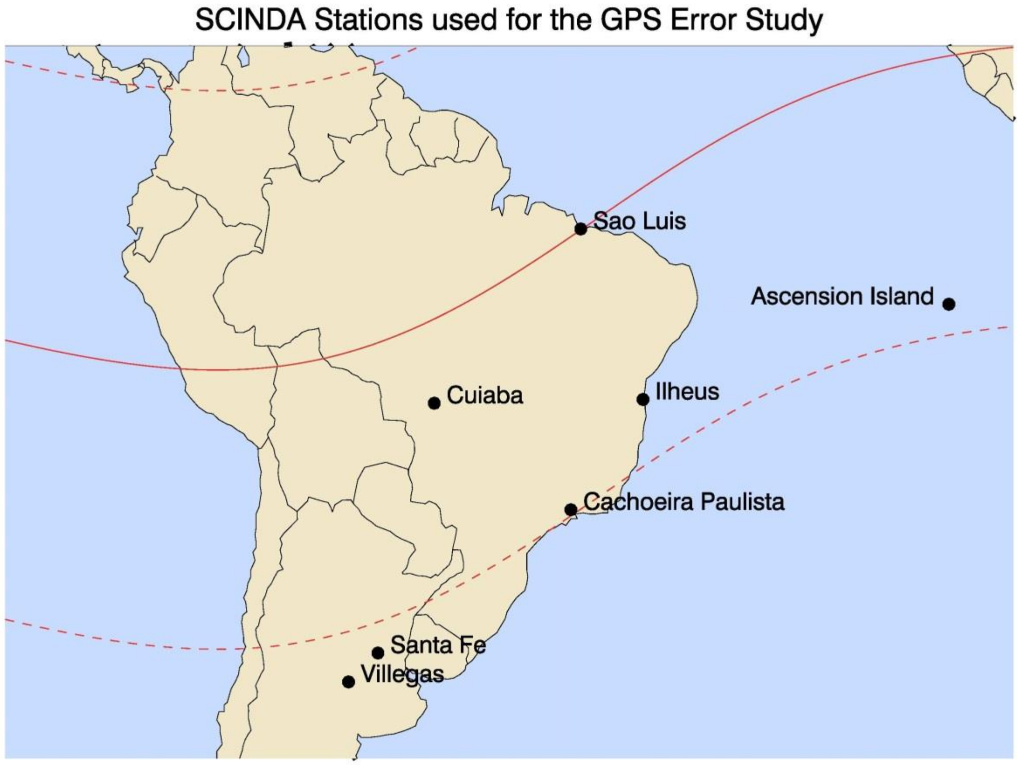

Figure 1. The stations we examined in characterizing the errors in GPS positioning. The solid red line is the geomagnetic equator and the dashed line represents 20^o to the North and South of the equator which defines the band in which scintillation is expected.

2. CHARACTERISTICS OF ESF SCINTILLATIONS

In order to better understand these results, it is helpful to review some of the characteristics of ESF scintillations [*Basu et al.*, 1988]. Scintillations can disrupt radio signals at frequencies from 100 MHz up to a few GHz. However, solar cycle and local time variability of the scintillations are strongly dependent on the frequency. The scintillations that impact the GHz signals employed by GPS receivers are present almost exclusively around solar maximum. This is because the relative density fluctuations will not cause scintillation if the background electron density is too low [*Groves et al.*, 2012]. In this study, we look only at months during the solar maximum of the present solar cycle. The scintillations are entirely a nighttime phenomenon, beginning shortly after 300 km sunset. The GHz scintillations remain strong for 3-4 hours and die away almost completely by local midnight. At the L1 frequency, the scintillation is limited to a band beginning at about 8^o and extending poleward to about 18^o based on our data. This region corresponds roughly to what is often termed the crest of the equatorial anomaly. There is also a seasonal dependence of the scintillation, which maximizes when the solar terminator is parallel to the magnetic field lines, or generally at equinox [*e.g. Tsunoda*, 2010].

3. DATA ANALYSIS

The processing of the GPS position data is straightforward. The positions are recorded as the latitude, longitude and altitude at a frequency of 1 Hz. First, a "truth" value is obtained for the geocentric position using a 24 hour period on a quiet night in which there is no scintillation. This "truth" position is then used to calculate the 1 second differences in altitude and in horizontal position. The latter of these is calculated from the difference in angle between the vector given by the "truth" and the instantaneously reported position. We report errors here as horizontal, from the latitude and longitude, and errors in altitude. The quiet night positioning errors vary from station to station because they depend on the type of GPS receiver deployed there. Therefore, some stations exhibit a higher noise level. Although it is not the purpose of this report to evaluate the performance of the various receivers, it is important to know the position errors in the absence of scintillation. We can estimate the accuracy by taking the 95th percentile errors obtained from the quiet nights used to calculate the "truth" position. We find a range of 1.9-3.1 meters horizontal error and a range of 5.3-8.4 meters in the altitude error.

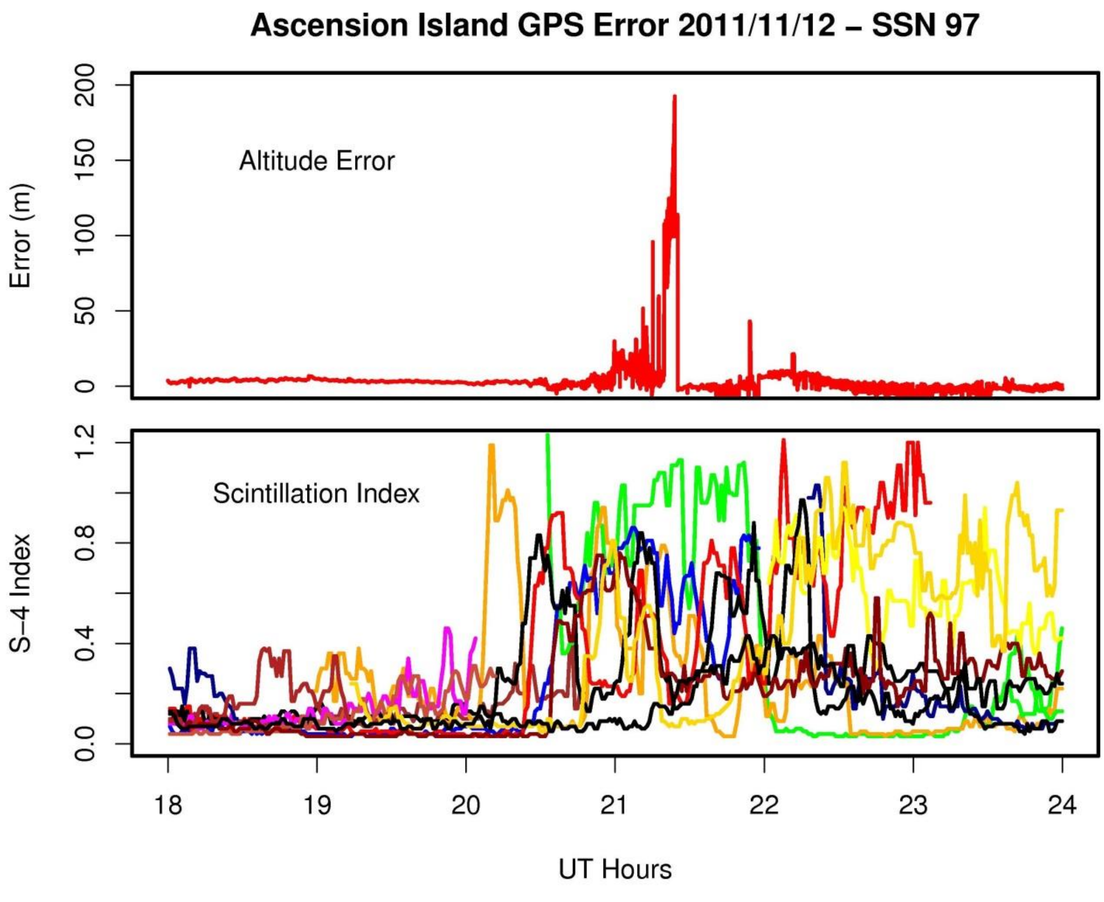

Figure 2. The error in altitude (top) and the scintillation index S-4 (bottom) measured at Ascension Island on 2011 November 12. The various colors in the bottom panel represent the S-4 measured on the several satellite links. The monthly sunspot number here is 97.

4. CASE STUDIES OF POSITIONING ERRORS

In this section, we look at some of the errors we have encountered from the several stations. Figure 2 shows one night of data taken at Ascension Island. The top panel shows the altitude error and the bottom panel shows the scintillation index S-4, which is a measure of the fluctuations in the amplitude of the signal from the station to the various satellites. We see that the period of increased error begins with a large increase in the noise level. This is followed by an excursion of the error in a positive direction which exceeds about 75 meters and persists for several minutes. Looking at the scintillation index, we can see that the largest errors correspond to periods when almost all the links are experiencing heavy scintillation.

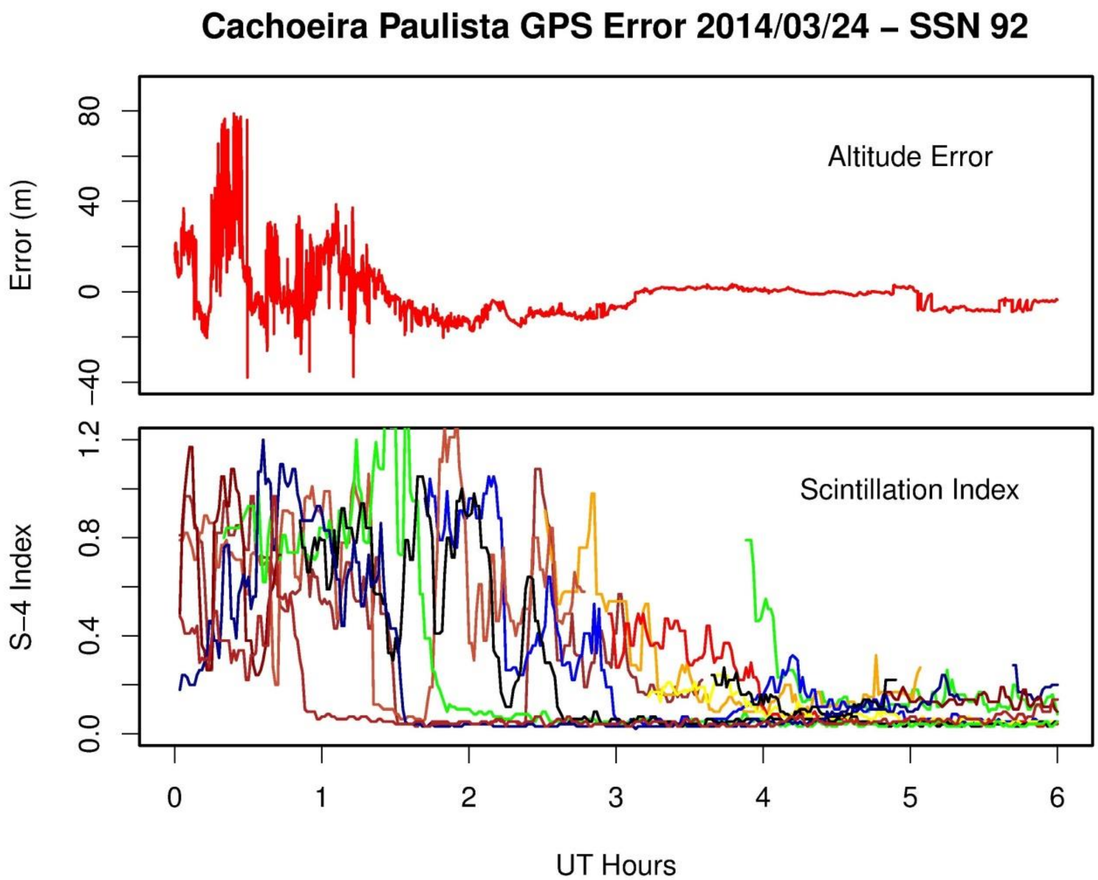

Figure 3. Same as Figure 2 except for Cachoeira Paulista on 2014 March 24 where the monthly sunspot number was 92.

Another case of relatively large altitude error is shown in Figure 3. This data is from Cachoeira Paulista which is close to the same magnetic latitude as Ascension. We see here that there is a large random component to the error, with the computed altitude fluctuating by around 60 meters between successive 1 second computed values. This sort of error might be even worse than the constant offset in Figure 2 for some applications if successive values are differenced. These cases are some of those we have come across in the data and we have not performed an exhaustive survey looking for worst case errors. This sort of study might be valuable.

5. STATISTICS OF POSITIONING ERRORS

We have also looked at the errors in a statistical way by generating histograms of the errors obtained from a complete month in the hour where we expect the maximum scintillation to occur. One such histogram for Ilheus is shown in Figure 4. Ilheus is at about 15^{o} magnetic which we expect is directly under the crest of the equatorial anomaly. Histograms like Figure 4 show the errors due to scintillation by comparing the result in the daytime (red bars) where we do not get scintillation to the result at the hour where peak scintillation occurs (blue bars). So the red bars indicate the noise in the system. The difference between the red and blue bars thus provides a measure of the errors induced by scintillation. In order to assess the effect of magnetic latitude on the errors we have generated similar histograms for all 7 stations.

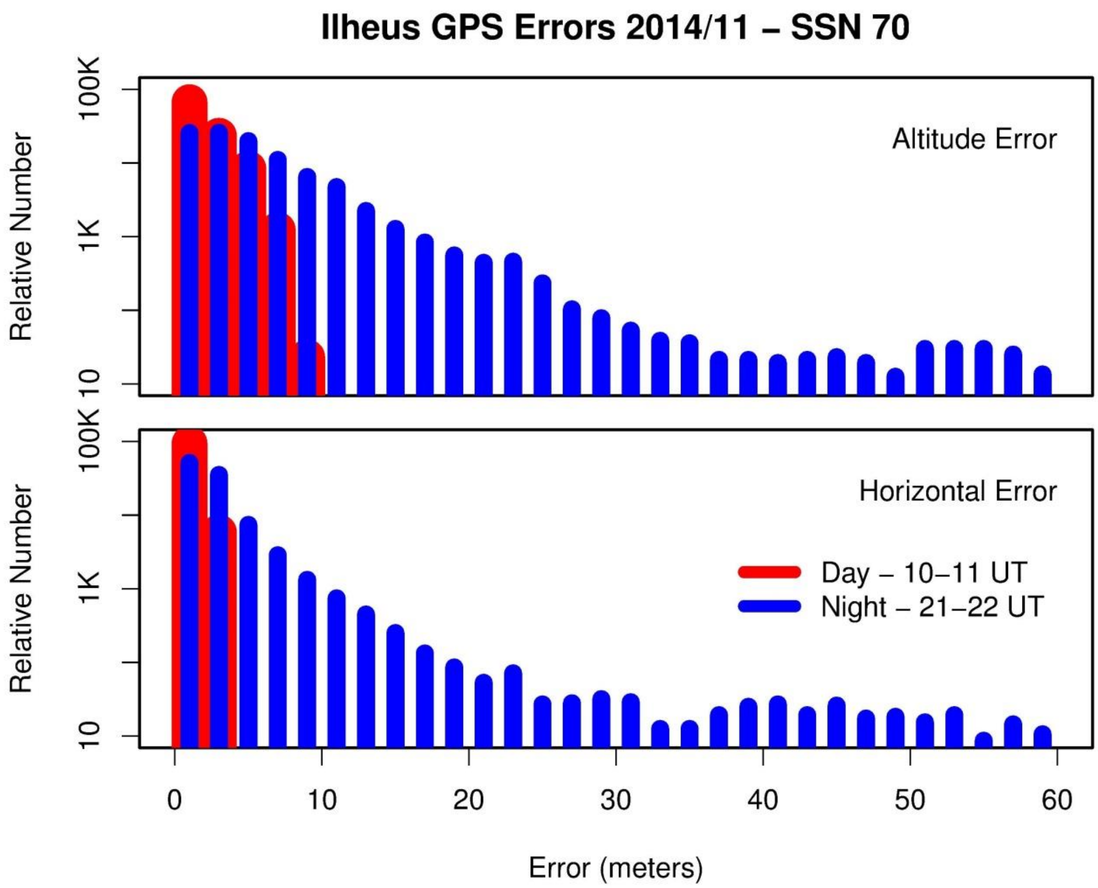

Figure 4. Histograms of the occurrence probability of errors from November of 2014 at Ilheus. The red bars are taken from a daytime hour when scintillation is not expected and the blue bars are taken from the hour when the scintillation peaks.

Note that we have used a log scale on the ordinate. This is because errors in excess of 30 meters are relatively rare. For reference, there are 408 seconds in the case of Figure 4 where the errors exceeded 30 meters. This amounts to 0.39% of the time. Even so, these errors might impact operational systems. This depends to a large extent on the application.

6. THE EFFECT OF MAGNETIC LATITUDE

As mentioned in the Section 2, the occurrence of scintillation at the L1 frequency is confined to a limited range of magnetic latitude. The stations used in this study were chosen because they span the range of magnetic latitudes where we expect scintillation to occur. Therefore, we can use histograms like Figure 4 to judge qualitatively where we expect positioning errors to be substantial. This should be of considerable importance to GPS users.

Table 1. The magnetic latitudes of the stations considered in this study along with the qualitative degree of positioning error found

Station	Magnetic Latitude	GPS Errors
Sao Luis	0.1°	None
Cuiaba	6.5°	Weak
Ilheus	15.2°	Strong
Ascension Island	17.8°	Strong
Cachoeira Paulista	19.6°	Strong
Santa Fe	22.2°	Weak
Villegas	23.6°	None

Table 1 shows the variability of GPS positioning errors found along with the magnetic latitudes of the stations. To arrive at a degree of error we have defined three qualitative thresholds. The stations labeled "None" show no difference in the day and night occurrence probabilities from histograms like Figure 4. The stations labeled "Weak" show differences but those errors are for the most part below 30 meters. The stations labeled "Strong" show a substantial number of errors in excess of 30 meters. We see that the strong errors occur in the region of the anomaly crest around 15° magnetic. Once we get to about 6° on the equator side and 22° on the pole side, the errors are probably not operationally significant. It is interesting, though, that the region of large errors is somewhat broader than that of the scintillation region itself, especially on poleward side. It may be that obscuration of the sky on the north side is more detrimental to the positioning calculation. This deserves further investigation.

7. CONCLUSIONS

We have carried out a survey of positioning errors for several stations in Brazil and Argentina as well as one in the Atlantic sector. These stations span the range of magnetic latitude where ESF scintillation is expected to occur. Case studies of the errors on several days have shown errors in excess of 30 meters in both the horizontal and the altitude at stations in the scintillation band across the equatorial anomaly. We looked at the errors statistically and found basically the same behavior of the stations under the anomaly crest with the errors tailing off both poleward and equatorward. This allows us to characterize the locations where positioning errors would be significant to operators. We do not find significant errors equatorward of about 6° or poleward of about 22°. This band is somewhat wider than that of the scintillation itself, indicating perhaps that significant errors occur when only part of the sky is obscured by scintillation.

The operational significance of the errors found here will of course depend on the application. However, we have found references to the impact on aviation in Seo *et al.*[2010]. These authors say that the alert limits of the LPV-200 approach procedure are 40 meters in the horizontal and 35 meters in altitude. Therefore, it would seem that the errors found in this study would be significant for aviation. It should be noted these larger errors are relatively rare, occurring less than 1% of the time. However, we have found sustained errors for several minutes which exceed this threshold. In any case, we can conclude that GPS positioning errors caused by scintillation can have operational impact at a relatively large expanse of latitudes surrounding the equator.

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