Passive detection of sporadic $E$ using GPS phase measurements

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Abstract
A passive sporadic $E$ detection technique based on a Global Positioning System (GPS) receiving system has been developed and tested in a midlatitude environment. This system detects the small-scale total electron content (TEC) variations believed to be produced by electron density structures associated with sporadic $E$. The current GPS detection technique was able to detect ionosonde-detected sporadic $E$ conditions for 73% of the cases at high-elevation look angles in a set of midlatitude summer observations. Several approaches have been identified that may significantly improve this detection ratio. These approaches include reducing GPS phase multipath, implementing time and space averaging, and investigating the use of high-speed GPS TEC measurements. This technique provides a basic sporadic $E$ detection functionality for applications where an ionosonde is not available. It also provides complementary ionospheric information in regions outside the ionosonde viewing area for applications where an ionosonde is available.
Introduction

Sporadic E has historically been detected from ionogram traces which are returns from vertically transmitted, swept frequency pulses in the 1-30 MHz range [Hansucker, 1991; Smith and Matsushita, 1962]. Although this technique produces an accurate indication of overhead sporadic E under most conditions, it is often desirable to know whether sporadic E is present in the regions outside of the overhead region but within the field of view of a ground station. In addition, there are certain communication applications which prohibit the use of an active transmitter. These factors lead us to investigate the possibility of detecting sporadic E by using signals from Global Positioning System (GPS) satellites [Hofmann-Wellenhof et al., 1992] tracked with a passive receiver.

GPS satellites transmit two L band frequencies that can be combined to produce a measure of the integrated total electron content (TEC) of the ionosphere. GPS TEC measurements have been used over the past decade in a variety of applications and environments [Klobuchar et al., 1985; Last and Roth, 1988; Coster et al., 1993; Wilson et al., 1993]. The GPS pseudo-range observations can be used to produce absolute (unbiased) TEC measurements with accuracy levels of \( \sigma \approx 1 \) TECU (where 1 TECU = \( 10^{16} \) e/m^2) [Sardon et al., 1994; Klobuchar and Basu, 1993; Coster et al., 1991; Bishop et al., 1985] for data rates of about 1 Hz. However, GPS phase observations can provide relative (biased) TEC measurements at much higher levels of relative accuracy (\( \sigma \approx 0.01 \) TECU). This bias, which is simply an unknown constant in the TEC measurement that changes when a receiver loses lock on the satellite signal, does not need to be known if one is only interested in changes in the TEC rather than the absolute value. The small-scale changes in these biased GPS TEC measurements have been investigated as a means to detect sporadic E in a midlatitude environment.

Several caveats should be noted at this point. This GPS sporadic E detection technique is based on a statistical correlation between the sporadic E conditions, as detected by an ionosonde, and the TEC fluctuations measured by GPS. It is important to note that the ionosonde observations do not provide an actual map of the electron density structures in the regions sampled by GPS but provide an indirect indication of the presence of these structures. We hypothesize that these electron density structures, which are related to the ionosonde detected sporadic E conditions, will produce fluctuations in the GPS TEC measurements. If this is true, then in order for this technique to be practical, these E region TEC fluctuations must be distinguished from F region (and intermediate layer) TEC fluctuations. We recognize that these assumptions will not hold in all ionospheric environments, especially those where the F region has significant small-scale fluctuations.

In a recent set of observations this GPS sporadic E technique was able to detect sporadic E conditions for 73% of the cases at high-elevation look angles (greater than 70°) in a midlatitude set of summer observations using a standard GPS receiving system and a relatively simple detection algorithm. Because one of the main limitations of this technique is the phase multipath error in the biased TEC measurement, this sporadic E detection rate may be improved significantly by implementing multipath mitigation techniques that are currently under investigation in the GPS community [Ardal et al., 1994]. If the phase multipath can be reduced, then this may improve the reliability of this passive technique of detecting sporadic E and other anomalous ionospheric conditions.

Observations

These observations were conducted during three months of the summer of 1994 in Austin, Texas (30.4°N, 202.3°E), using dual-frequency, phase measurements from a geodetic quality GPS receiver (Ashtech Z-12) and ionograms from a digital ionosonde (KEL Aerospace). Ionograms were recorded at 15-min intervals and then visually inspected to identify 55 sporadic E “events.” These events were defined as time periods (0.5–3 hours) when the \( f_0E_s \) value was above 7 MHz throughout the entire time period [Smith and Matsushita, 1962]. A corresponding number of control events were identified for times when sporadic E was clearly absent (\( f_0E_s \) less than 4 MHz) for the entire period. The majority of the selected events were from the local night period. The event time periods were selected so that the control events covered the same GPS satellite viewing geometry as the corresponding sporadic E events. Since the GPS satellites repeat their orbital tracks once each sidereal day, the same viewing geometry occurs at the same time each day with an approximate 4-min per day offset. This observational condition is important because the phase multipath errors are strongly dependent upon the satellite viewing geometry. It should be noted that the ionosonde basically detects sporadic E
conditions nearly overhead the station (greater than 40°). It is possible that sporadic E conditions could be outside the viewing angle of the ionosonde but could still be visible to the GPS receiver. This aspect is discussed further in the discussion section below.

The GPS receiver collected data continuously during the observations using a laboratory rooftop antenna site and a data collection interval of 30 s. This data is not from an optimum location in terms of multipath considerations; however, it was decided that the long time span of data available from the station outweighed multipath considerations. There were typically eight or more GPS satellites simultaneously in view during the observations, and each satellite remained in view for 4–6 hours at a time. The GPS data were processed through a cycle slip correction program to ensure that all the phase data were continuous or flagged otherwise [Cocoa et al., 1993]. The biased TEC was calculated from the GPS data by differencing the two phase measurements and scaling the output to units of TECU [Hofmann-Wellenhof et al., 1992]. This biased TEC measurement represents the integrated number of electrons along the station-satellite path with an unknown constant offset.

The biased TEC measurements change as a function of time due to the slowly changing viewing angle and the actual spatial and temporal variations of the TEC in the ionosphere. The data were filtered using a third-order Butterworth high-pass filter with a cutoff frequency corresponding to 10 min. This filtering removes the slow variations of the TEC, which are due to viewing angle changes and diurnal changes in the ionosphere, and leaves the rapid variations, which were hypothesized to be associated with sporadic E conditions. The filter design and the cutoff frequency were selected using an semiempirical approach. A comparison of the sporadic E detection percentages from several different cutoff frequencies in the 4–30-min range showed that the 10 min value gave optimum results. After removing filter initialization effects, the standard deviations of the filtered TEC values were calculated over 20-min time periods. This parameter, labeled the sporadic E detection parameter, $\sigma_{E_s}$, was used to distinguish between the sporadic E and control events. Initial investigations showed that the $\sigma_{E_s}$ values depended on both the elevation angle of the observation and the sporadic E conditions. The elevation angle dependence is most likely due to the effects of phase multipath, which is known to increase at lower elevation angles. The $\sigma_{E_s}$ histograms for the sporadic E and control event cases are shown in Figure 1 for observations with elevation angles greater than 55°, where multipath effects are smallest. It is clear that the sporadic E values are spread out over a much wider range than the control values.

Because these two distributions are clearly non-Gaussian, a comparison of the means of these two populations would not be appropriate. To avoid this problem, a comparison of the median and upper/lower quartile levels for each population was performed. To isolate the elevation angle effects, the data were separated into 15° elevation angle bins. The results of this comparison are shown in Figure 2. The separation of the sporadic E and control populations are statistically significant at the high-elevation angles but not at the low-elevation angles.

A paired observation comparison was also performed on the sporadic E and control populations to generate detection statistics for all elevation angles while minimizing the effects of multipath. In this comparison each individual $\sigma_{E_s}$ observation from the sporadic E population was paired with a corresponding $\sigma_{E_s}$ observation from the control population. The observations were paired so that they had the same elevation and azimuth angles but were taken from different days. (Phase multipath depends on both the elevation and azimuth angle due to reflections from nearby structures.) This approach ensures that the two observations will have similar multipath error contributions.

After the data were paired, the sporadic E detection ratio $N_c/N_l$ was calculated using the same 15° elevation angle bins as before. $N_c$ is the number of cases when $\sigma_{E_s}$ (sporadic E) is greater than $\sigma_{E_s}$ (control), and $N_l$ is the total number of cases. A $N_c/N_l$ value of 0.50 would be expected if the sporadic E and control populations had identical $\sigma_{E_s}$ distributions. The calculated $N_c/N_l$ values range from 0.63 to 0.73 with the values generally increasing with elevation angle. This detection ratio represents the fraction of observations from the sporadic E population that could be identified as sporadic E when the effect of the multipath contribution is mitigated by pairing the sporadic E and control observations. This implies that the technique was able to identify 73% of the sporadic E cases for high-elevation look angles with a somewhat smaller percentage at lower-elevation angles.
Discussion

Sporadic $E$ is produced by thin structures of electron density enhancements in the altitude range between 90 and 130 km [Smith and Matsushita, 1962; Whitehead, 1970, 1989]. These structures typically extend several hundred kilometers horizontally but only a few kilometers in the vertical direction. The structures move through the background ionosphere with a typical horizontal velocity of about 150 m/s, which is comparable to the velocity of the $E$ region intercept of the GPS line of sight. There are also smaller irregularities within the larger sporadic $E$ structures. Given this physical picture of sporadic $E$, it was hypothesized that there would be significant variation in the integrated TEC as the GPS line of sight passes across the edges of these discrete structures.

A typical value for the integrated TEC of a sporadic $E$ layer is on the order of $1 \times 10^{-2}$ TECU [Mathews et al., 1993], which is roughly equivalent to the precision of an overhead GPS TEC measurement. If the GPS line of sight were to pass across the edges of several sporadic $E$ structures of this magnitude, then a distinctive signature might be evident in the TEC measurements. This implies that it might be possible to detect sporadic $E$ TEC variations using GPS if the appropriate detection algorithm were identified. However, it was unknown whether these sporadic $E$ TEC variations would be dominated by $F$ region TEC variations, since the bulk of the electron density is contained in the $F$ region rather than the $E$ region for a typical midlatitude ionosphere. The results of these observations imply that the short-timescale sporadic $E$ TEC variations are larger than the nominal $F$ region variations, at least for certain ionospheric conditions, that is, midlatitude summer near the minimum of the solar cycle.

There are several potential limitations to this type of observation that should be pointed out. First, it is very likely that the sporadic $E$ and control populations were not identified perfectly from the ionosonde data. Because the ionosonde only provided a single measure of sporadic $E$ conditions overhead (elevation angle greater than 40°) once every 15 min, it is possible that sporadic $E$ conditions were not present throughout the entire GPS viewing region (greater than 10°) during this time. For the same reasons, the control population could have contained isolated sporadic $E$ structures that were not detected by the ionosonde but did affect the GPS observations. These population contamination effects would reduce the true separation of the two distributions and lower the sporadic $E$ detection ratio.

Another more fundamental limitation to this type of observation is related to the sporadic $E$ structures themselves. The underlying assumption is that all sporadic $E$ events are associated with structures which increase the $\sigma_{E_s}$ values. The $\sigma_{E_s}$ parameter, however, is only sensitive to a limited range of structures, depending on their size, velocity, and the magnitude of their density enhancements and gradients. If the structure is outside this range, then the $\sigma_{E_s}$ value will not increase. This limitation could be avoided by performing an set of observations in which the structures themselves are detected rather than the sporadic $E$ condition. This could be accomplished using an incoherent scatter radar to map the $E$ region structures [Miller and Smith, 1975; Mathews et al., 1993] while the GPS system is measuring the TEC variations. A direct comparison of the actual structures and the TEC variations would allow one to develop a more sophisticated sporadic $E$ detection parameter which would be more successful in detecting sporadic $E$ conditions.

There are several approaches that can be taken to improve the sporadic $E$ detection ratio based on the results of these observations. One approach would be to reduce the GPS system noise contribution to the $\sigma_{E_s}$ parameter. The control curve in Figure 2 is composed of noise contributions from the GPS receiver, phase multipath, and ionospheric TEC variations from non-sporadic $E$ conditions. It has been shown in experiments at Applied Research Laboratories, The University of Texas at Austin (ARL:UT) that the GPS receiver noise makes only a small contribution to this curve (approximately 0.002 TECU). However, it is not well understood whether the remaining noise is due mainly to multipath or TEC variations.

Results from a recent multipath mitigation experiment at ARL:UT suggest that multipath makes a larger contribution than the TEC variations from non-sporadic $E$ conditions, and that the multipath contribution can be reduced significantly with appropriate multipath mitigation techniques. In this experiment, when the data from an experimental GPS antenna, placed in a very low-multipath environment (slightly below ground level in an open field), was compared to data from a standard antenna on a nearby laboratory rooftop, the low multipath $\sigma_{E_s}$ values were a factor of 2–5 smaller than those from the rooftop environment. Phase multipath may be
able to be mitigated by other means also. Axelrad et al. [1994] report that multipath can be significantly reduced by modeling the multipath signature using the signal-to-noise value measured by the receiver and subtracting this model from the phase measurements.

A second approach for improving the detection ratio would be to use time and space averaging on the \( \sigma_{E_1} \) observations. The GPS technique provides an average of 10 independent \( \sigma_{E_1} \) observations during each 1-hour time frame, when observations above 10\(^{\circ}\) elevation are used. Since the sporadic \( E \) events typically have a correlation time of about 1 hour and a correlation distance of several hundred kilometers [Smith and Matsushita, 1992], there may be many \( \sigma_{E_1} \) observations for a single correlated event. If all of the \( \sigma_{E_1} \) observations for a given time frame and ionospheric region are combined (simple averaging may not be the optimal method), this may provide a more reliable indication of the sporadic \( E \) conditions during this time frame for a given region.

A third approach would be to investigate the correlation of small-scale TEC variations and sporadic \( E \) structures. A number of studies have shown a correlation between sporadic \( E \) and amplitude scintillation [Whitehead, 1989]. In addition, sporadic \( E \) structures have been associated with quasi-periodic amplitude scintillations which display ringing patterns with periods ranging from 10 seconds to several minutes [Maruyama, 1991]. Although current GPS receivers are not capable of measuring amplitude scintillation due to accuracy and data rate limitations, GPS manufacturers are developing new receivers that will be capable of outputting phase measurements at rates of 20 Hz or higher [Van Dierendonck et al., 1993]. When these receivers become available, it will be possible to measure TEC variations at much smaller scale sizes than is currently possible. The GPS line of sight intercept in the \( E \) region moves at velocities ranging from 20 m/s overhead to 200 m/s at 10\(^{\circ}\) elevation. Thus the smallest scale size that can be detected is at the kilometer level when a 30 second sampling rate is used, but can be extended down to the meter level if a 20-Hz data rate were available. The information from these smaller-scale TEC variations may improve our capability of detecting sporadic \( E \) structures.

Conclusions

A passive sporadic \( E \) detection technique based on a GPS receiving system has been developed and tested in a midlatitude environment. This system detects the small-scale TEC variations produced by sporadic \( E \) electron density structures. The current GPS detection technique was able to detect sporadic \( E \) conditions for 73% of the cases at high-elevation look angles in a set of midlatitude summer observations. The detection ratio for this technique will vary in different ionospheric environments due to the different relative contributions of the \( E \) and \( F \) regions to the TEC fluctuations, multipath, and other factors.

Several approaches have been identified that may significantly improve this detection ratio. These approaches include reducing GPS phase multipath, implementing time and space averaging, and investigating the use of high-speed GPS TEC measurements. This technique provides a basic sporadic \( E \) detection functionality for applications where an ionosonde is not available. It also provides complementary ionospheric information in regions outside the ionosonde viewing area for applications where an ionosonde is available.
References


This preprint was prepared with the AGU LATEX macros v3.1. File sporrogps-internal formatted 1995 October 10.
Figure 1. The top histogram shows the distribution of $\sigma_{E_4}$ values derived from TEC measurements during the sporadic $E$ time periods, while the lower histogram is from non-sporadic $E$ periods.
Figure 2. Median values of $\sigma_{E_s}$ as a function of elevation angle. The error bars indicate the upper and lower quartiles of the distribution.