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Comparison of GPS and Incoherent Scatter Measurements of the Total Electron Content

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ABSTRACT

GPS and incoherent scatter (IS) measurements of the total electron content (TEC) taken during 1-3 March 1989 are compared. During this period, four different GPS satellites, SV nos. 6, 9, 11, and 12, were observed. The TI4100 GPS receiver at Millstone monitored these satellites continuously while they were in view. At the same time, the Millstone UHF radar was sequentially pointed in the direction of several of these satellites taking incoherent scatter measurements. The incoherent scatter measurements produce profiles of the electron density distribution. The IS profiles are then integrated to produce TEC measurements up to 800 km. The combined pseudo-range and phase data of the GPS system measure the group delay at both the L1 (1575.42 MHz) and L2 (1227.6 MHz) frequencies. This information is converted to TEC measurements along the line of sight to the satellite at 19000 km. The comparison of the GPS and incoherent scatter data gives us a new technique for estimating the number of electrons above 800 km. Our results were surprising. The 1-3 March time period was associated with interesting geophysical conditions. The experiment began during quiet geomagnetic conditions and at a time when the daily 10.7 cm solar flux values were moderate (162). On 1 March, a large electron content, sometimes greater than 30 TEC units was observed in the ionosophere or plasmasphere above 800 km. This large TEC value is surprisingly high when compared to previous studies, taken during solar minimum conditions, which found only 2-6 TEC units of plasmaspheric content above 2000 km (Klobuchar, et al., 1978). During the middle of the experiment, the geomagnetic activity increased. An electron density trough was then observed to form towards the north and propagate southward. In addition, the total number of measured electrons above 800 km fell dramatically.

INTRODUCTION

At Lincoln Laboratory a transportable device is being developed which uses the Global Positioning System (GPS) to determine real-time ionospheric path delays. We are using a TI4100 GPS receiver which is capable of receiving the dual L-band frequencies (1227.6 and 1575.42 MHz) broadcast by each satellite. Up to 21 different GPS satellites will eventually be on station in near-circular, semi-synchronous orbits at altitudes of approximately 19000 km. The plan is that at least 4 satellites will be in view at any place, 24 hours a day (Spilker,1978).

Because our GPS receiver is located at the Millstone Radar site, we have the advantage that the GPS data can be compared directly with incoherent scatter (IS) measurements of the ionosphere. Incoherent scatter measurements are taken routinely with the UHF radar at Millstone Hill. During the period 1-3 March 1989, the UHF radar was sequentially pointed in the direction of several GPS satellites taking incoherent scatter measurements. The IS data was then processed to give an alternative determination of the total electron content (TEC) along the line of sight to each GPS satellite (Buonsanto,1989). The IS data is carefully calibrated at the beginning and end of each run using foF2 data from a colocated Digisonde operated by the University of Lowell. The IS radar provides electron density profiles from approximately 100 km to 1000 km or higher. Because of the decreasing signal-to-noise ratio, however, data at the greatest heights are not always reliable. For the present experiment, the TEC is derived by integrating the electron density profiles from 100 km to 800 km in height.

In principle, it should be possible to obtain the ionospheric path delay directly from the GPS group delay measurements at the two L-band frequencies. The delay introduced by the ionosphere is a function of both the TEC and frequency. However, although the GPS range data is accurate enough for the majority of user needs, the ionospheric correction cannot be determined directly from this data. This is primarily because of multipath effects and the L1/L2 biases.

Multipath effects in the group delay data account for approximately 6 ns of increase in the noise level. For comparison, a 2 ns increase in group delay amounts to an error in the path delay at L-band of 1 meter. At Millstone, the multipath effects have been reduced by use of absorbing material under the antenna and can be further reduced by data averaging (Sciegienny, private communication). The multipath problem is not as severe in the GPS phase advance measurements. The GPS phase data show an increase in the noise level on the order of only 50 ps (Dahlke et al.,1988). The trouble with the phase advance data is that they contain an unknown bias due to the integer cycle ambiguity of phase measurements, i.e. the number of full phase cycles between the satellite and receiver is not known. By combining the GPS phase data with the group delay data we may overcome the difficulties inherent with both data types.

Before going any further, we would like to illustrate these three different types of data. Figure 1 shows the GPS phase data, the GPS group delay data, and the Millstone UHF incoherent scatter data plotted as a function of time for one satellite. The increased noise level in the group delay data is apparent. To account for the unknown cycle ambiguity and bias, the mean value of the phase data is set to be the mean value of the group delay data. The IS data represents the integrated TEC up to an altitude of approximately 800 km along the line of sight to the satellite.

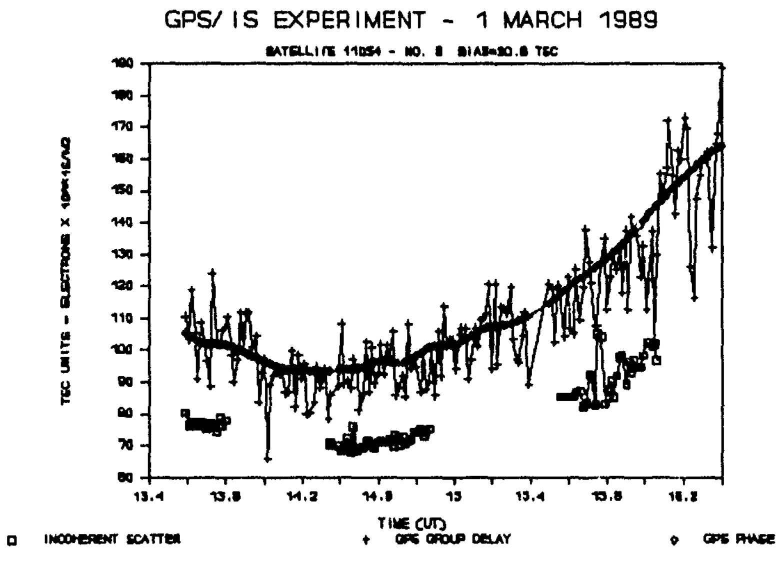


Figure 1. Illustration of Incoherent Scatter and GPS Phase and Group Delay Data.

The IS derived TEC should be less than that derived from the GPS system which measures out to 19000 km. Note that a total bias of 30.6 TEC units is evident between the GPS data and the IS data. This bias, which we will refer to as the IS bias, can be attributed to additional ionosphere above 800 km and to the combined satellite and receiver bias.

The combined satellite and receiver biases are known as the L1/L2 biases. The L1/L2 biases correspond to the additional differential delay between the two frequencies introduced by the satellite and receiver hardware. These biases must be measured (or estimated) and removed from the GPS group delay data in order to accurately determine the ionospheric path delay. These biases have been studied extensively (Lanyi, et al.,1987, Dahlke, et al., 1988, Coster and Gaposchkin,1989) and the results of those studies will be presented in the next section.

In this paper we are going to discuss the comparisons of the GPS and incoherent scatter measurements of TEC taken during 1-3 March 1989. During this period we observed 4 different GPS satellites, SV nos. 6, 9, 11, and 12 (corresponding to SSC nos. 11054, 11783, 14189, and 15271). The GPS observing schedule from Millstone for these satellites is given in Table I. There is a 5 hour difference between local time at Millstone and universal time, so that the daytime experiments started at 8:30 am and the nighttime experiments started at 11:15 pm.

TABLE I. Experiment Times.

SV #.	Day (UT) 1 March	Day (UT) 2 March	Night (UT) 2 March	Night (UT) 3 March
6	13:35-16:23	13:28-16:19	4:17-7:28	4:13-7:24
9	13:35-18:08	13:28-16:19	4:17-9:45	4:13-9:41
11			4:17-9:45	4:13-9:41
12	15:30-18:08	15:24-18:03	5:39-9:45	5:37-9:41

Interesting geophysical conditions occurred during the 1-3 March time period. Although 1989 is generally associated with high solar flux conditions, the daily solar flux values during this time were only at moderate levels. The 90 day mean F10.7 cm flux value was 213 throughout, while the daily F10.7 cm flux values were, respectively, 169, 174, and 169. Prior to 2 March, the geomagnetic activity had been quiet for a period of about a week. The highest Kp value on 1 March was 3+, with the average Kp for that day being 3-. On 2 March, however, the Kp went from a 3+ value between 0-3 hours UT to a value of 6- between 3-6 hours UT. The Kp then fell to 4- from 6-9 hours UT. This means that during our nighttime pass on 2 March moderate geomagnetic storm conditions existed. The Kp was again moderately high during our daytime pass on 2 March with the Kp values being 3+ and 4. Finally, during the nighttime observations on 3 March, the Kp was 5 between 3-6 UT and 6- between 6-9 UT. Geophysical data for this period is summarized in Table II.

Table II. Geophysical Parameters.

DATE	F10.7(daily)	F10.7(avg)	Kp (3 Hour Values)
1 March 89	169	213	3+3 2 3-3+3-2 2+
2 March 89	174	213	3+6-4-3+4 3+3 3+
3 March 89	169	213	3 4 6-5-5-5 4 3

L1/L2 BIASES

To use the GPS group delay data accurately, one must first estimate the satellite (SV) and receiver L1/L2 biases. Coco et al.(1990) have shown that although the TI4100 receiver bias varies from unit to unit, the change over time in the bias is quite small. They found the day-to-day variation of the TI 4100 receiver bias over a 5 week period to be less than 0.5 ns. In this paper, we are going to assume that our receiver bias is neglible. Regardless of our assumption, however, the receiver bias should be common to all satellites observed, and it should be a stable value.

Pre-launch calibration values of the satellite, or SV (space vehicle) L1/L2 biases were measured by Rockwell. Since then, other studies have developed techniques for determining the SV biases using a multistation system of receivers (Dahlke, et al.,1988, Lanyi, et al.,1987) At Millstone, we estimate the SV biases using a single receiver at one site (Coster and Gaposchkin,1989). The estimated SV biases are listed in Table III. The ARL values are from Coco et al.(1990). The standard deviations are given in parenthesis. The ARL SV biases all have an associated standard deviation of 0.5 ns.

It is important to notice that the biases ARL determined remained fairly constant from the year 1987 to 1989. Our technique for determining the SV biases produced similar results, with the exception of satellite no. 6, which has a large standard deviation. Our method for determining these satellite biases does not properly account for the difference in electron content above

TABLE III. Satellite (SV) L1/L2 Biases in Nanoseconds of Differential Delay between L2 and L1.

SV PRN	Pre-Launch	ARL 87	ARL 89	MIT LL 89
3	-0.24	1.06	1.11	
6	2.33		0.25	4.41(1.79)
8	1.53			
9	-0.34	-0.34	-0.34	0.40(0.63)
11	3.05	3.16	3.16	2.94(0.54)
12	0.02	2.96	2.95	2.17(1.21)
13	1.62	1.79	2.36	

800 km as a function of location, and thus we assume that it is our estimate of the no. 6 bias that is in error. We are going to adopt the recovered 1989 ARL SV biases for our discussion here.

It is useful to present our adopted SV biases in units of TEC since those are the units that the IS Biases are reported in. The conversion between ns of differential delay and TEC units (equal to number of electrons x 10**16 m-2) is given below (Dahlke, 1986):

$$TEC = 2.85 * TDD, \text{ where} \quad 1)$$

TDD = TTL2 - TTL1 (transit time of L2 - transit time of L1 in ns)

The 1989 ARL SV biases, given in TEC units, are listed in Table IV.

Table IV. SV Biases in TEC Units.

SV No.	ARL '89
6	0.83
9	-0.97
11	9.01
12	8.41

SATELLITE NO. 9.

We begin our discussion with satellite no. 9 since it has consistently been shown to have a small SV bias (-0.97 TEC), and a small standard deviation (0.61 TEC). Figure 2 shows the Millstone viewing geometry for this satellite in azimuth and elevation during 1-3 March 1989. The start of the nighttime pass is delimited by a small square and the start of the daytime pass by a small oval. During the night, the satellite moves from the northwest to the southwest and during the day it moves from the southeast to the northeast. Figures 3a-d show the combined incoherent scatter and GPS phase and group delay data for this satellite during the experiment. Note that on 1 March there is an IS bias of 33 TEC units (34 TEC units if we account for the SV bias). Recall that the IS biases include the bias due to the additional ionosphere above 800 km plus the satellite and receiver bias. In our discussion we will give the total measured IS bias followed by, in parenthesis, the IS bias minus the estimated SV bias. It is this second value which reflects our estimate of the number of electrons above 800 km. On 1 March, when the IS data measures 60-110 TEC units, the GPS system measures 90-140 TEC units. The implication of this is that as much as one-third of the TEC on 1 March is above 800 km, or that 5.4 m of delay at L1 can be attributed to electrons above 800 km. On the following day, 2 March, after the geomagnetic storm had begun, an IS bias of only 3.73 TEC units (4.7 TEC), or 0.61 m of delay at L1, is measured.

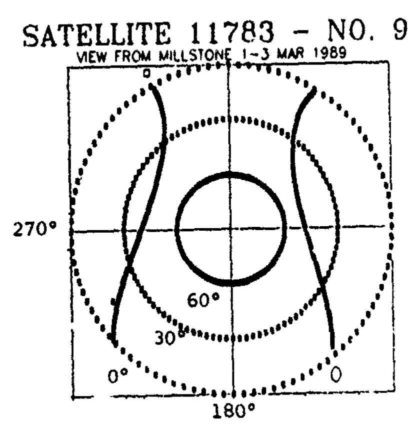


Figure 2. Geometry for SV # 9 from Millstone in Azimuth and Elevation.

On the night of 2 March, during the initial geomagnetic disturbance, the measured IS bias of satellite no. 9 was 8.14 TEC units (9.1 TEC). Smaller biases are expected at night due

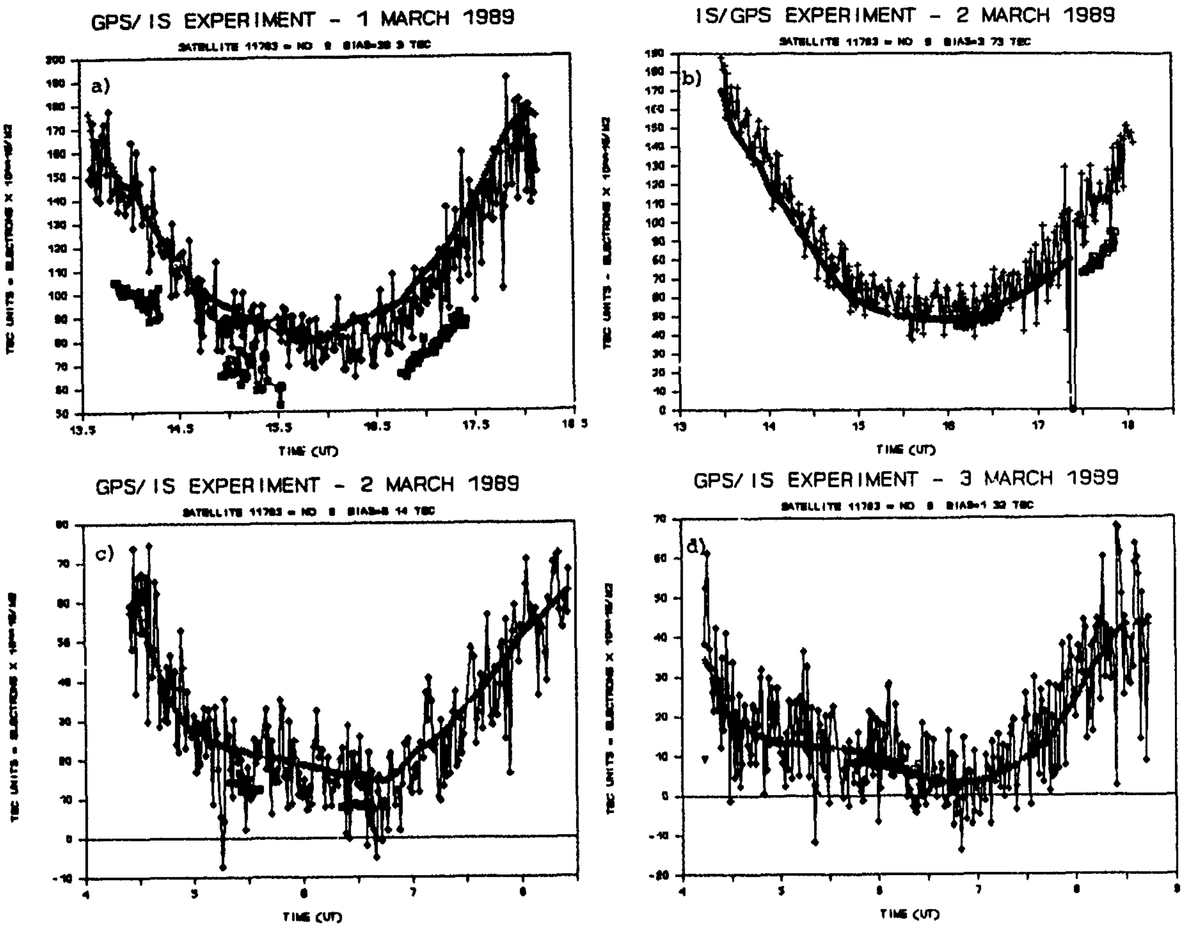
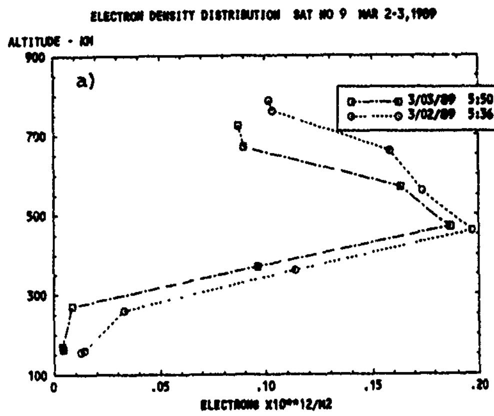


Fig. 3a-d. Comparison of GPS and Incoherent Scatter TEC Data for SV no. 9 on 1-3 March 1989. The IS data are demarked by a square, the GPS phase data by a cross, and the GPS group delay data by a diamond. Figs. 3a and b show the daytime data, while Figs. 3c and d refer to the nighttime data.

to the smaller electron content. Nevertheless, the total TEC measured by the GPS system, during the time for which we have GPS observations, varied between 16-25 TEC units, indicating that as much as half of the ionosphere on this night was above 800 km. The 3 March nighttime data, which was also taken during storm conditions, shows a bias of only 1.32 TEC (2.29 TEC) units. In fact, if the beginning and end of the IS data are compared on this day, we see that initially there was a bias of nearly 3 TEC units, while by the end of the pass, the IS bias is almost 0. This observation is confirmed by the associated IS profiles of the ionosphere shown in Figs. 4a-b. At the beginning of the pass, shown in Fig. 4a, a standard electron density distribution can be observed on both days. However, in Fig 4b by the 6:30 UT, the IS data on 3 March shows a very depleted electron density distribution. Note also that it is at this time that the smallest bias between the GPS and the IS data is measured. This suggests that what we are seeing a real ionospheric or plasmaspheric effect, such as an ionospheric trough, rather than a calibration or other type of problem.



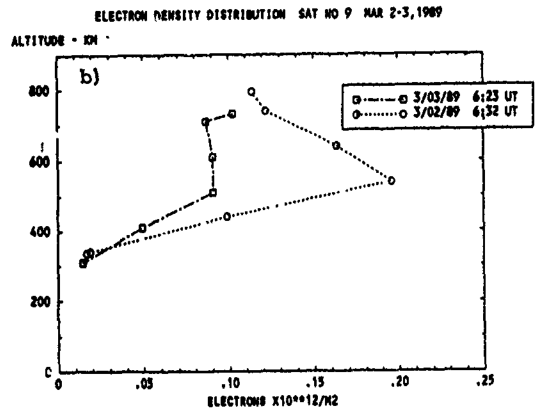


Figure 4a. **Figure 4b.**
IS Determined Electron Density Distribution as a Function of Altitude.

SATELLITE NO. 12.

On 1-3 March 1989, satellite no. 12 was observed to follow a path from the northwest to the southwest during the night and from the southeast to northeast during the day, see Figure 5. For this satellite, the estimated SV bias is approximately 6.73 TEC units. As can be seen in Fig. 6a, the measured IS bias was 27.4 TEC units on 1 March during the daytime. Subtracting the assumed satellite bias, we are left with 20.7 TEC units that can be attributed to the ionosphere above 800 km. The IS bias drops to 19.9 TEC (or 13.2 TEC once we subtract the satellite bias) on 2 March. In addition, we observe that the peak electron density is observed to about 118 TEC units on 1 March while on 2 March the peak is only 98 TEC units.

The ionospheric structure looks very smooth during both sets of daytime passes. This is in contrast to the nighttime data on 2 or 3 March. Both sets of nighttime data show disturbed ionospheric structure. On 2 March the observed IS bias was 25.3 TEC units (18.6 TEC). At approximately 8.2 UT, a bump in the GPS phase data can be observed followed by a rapid rise in the estimated TEC content. This is partly due to a change in elevation, although the associated elevation was only 23.5 degrees at this time. On 3 March, the GPS satellite is

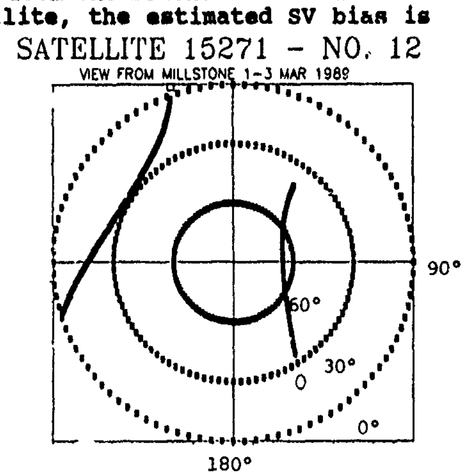
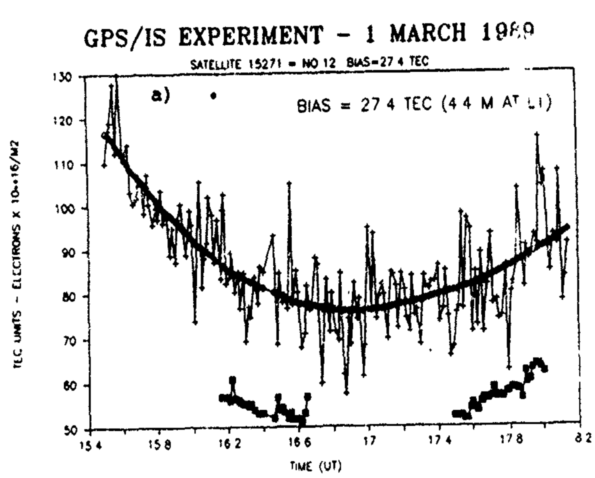
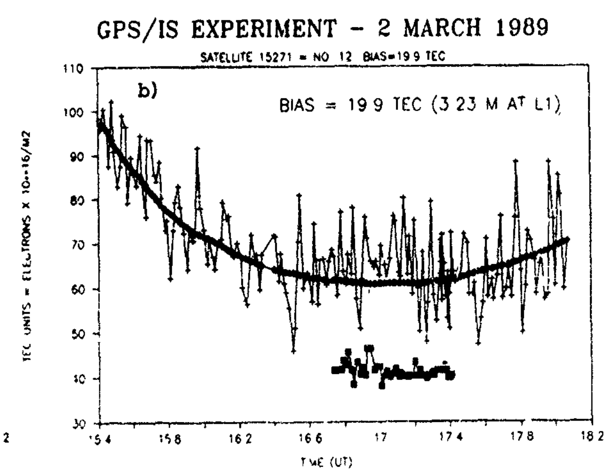


Figure 5. Geometry for SV # 12 from Millstone in Azimuth and Elevation.





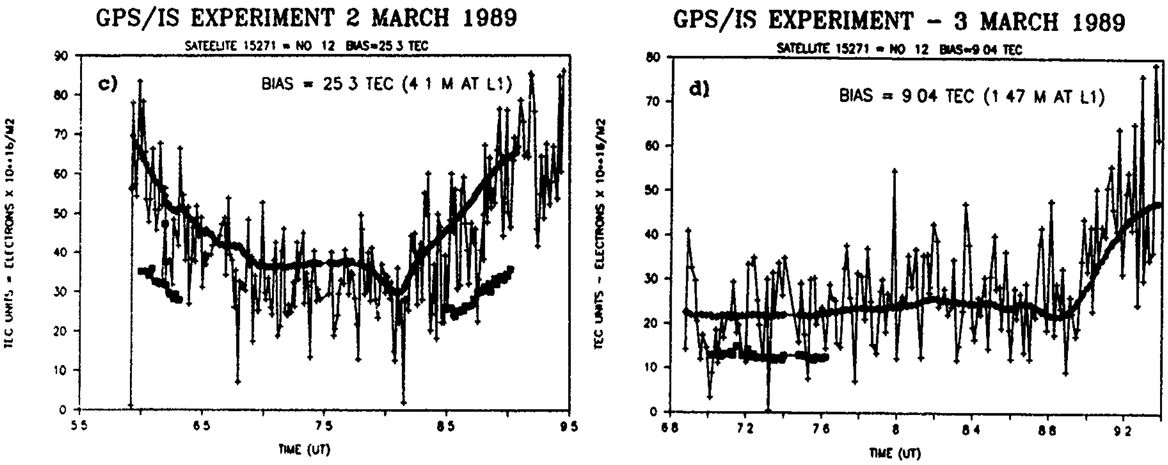


Fig. 6a-d. Comparison of GPS and Incoherent Scatter TEC Data for SV no. 12 on 1-3 March 1989. The IS data are demarked by a square, the GPS phase data by a cross, and the GPS group delay data by a diamond. Figs. 6a and b show the daytime data, while Figs. 6c and d refer to the nighttime data.

following the same observing geometry as on 2 March, except that it is viewed 4 minutes earlier. Nevertheless, the bump is not observed until approximately 8.9 UT, with an associated elevation of 10.4 degrees. In addition, on 3 March, the measured IS bias is only 9.04 TEC units (2.31 TEC). Recall that during the night, this satellite moves from the north to the south. We think that we are observing an electron density depletion or trough that was generated by the 2-3 March geomagnetic storm. The trough propagated southward from 2 March to 3 March.

SATELLITE NO. 6.

Satellite no. 6 travels from the northwest to the southwest during the night and remains at a fairly high elevation throughout the pass (see Fig. 7). During the daytime, the satellite travels from the southeast to the northeast. As can be viewed in Figs. 8a and b, the daytime bias changes relatively little from the 1st to 2nd of March. A bias of 30.6 TEC units (29.8 accounting for the satellite bias of .83 TEC) is seen on the 1 March. This bias drops to 26.4 TEC (25.6 TEC) during the day on 2 March. The bias satellite no. 6 sees on 1 March is somewhat misleading. If one looks only at the section of the pass that is repeated on the 2 March, the bias on 1 march is 38.5 TEC (37.7 TEC). The maximum TEC dropped from 170 on 1 March to 140 on 2 March.

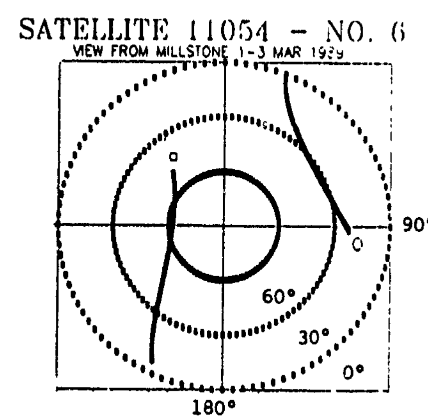


Figure 7. Geometry for SV # 6.

At night, the measured IS bias dropped from 12.6 TEC (11.8 TEC) on 2 March to 3.3 TEC (2.47 TEC) on 3 March. Again, the measured IS bias on 2 March is somewhat misleading. The earlier IS data taking during the 2 March nighttime pass has a bias of only 5.5 TEC. It is looking towards the south where the bias gets larger. This is vet another indication that the electron density increases looking towards the south. It is also interesting to observe the flat slope of the 3 March data from 4.2 to 5.8 UT, and compare this shape to the 2 March data. During this time period, the TEC data remains less than 10 TEC (9.2 TEC), indicating the presence of a trough.

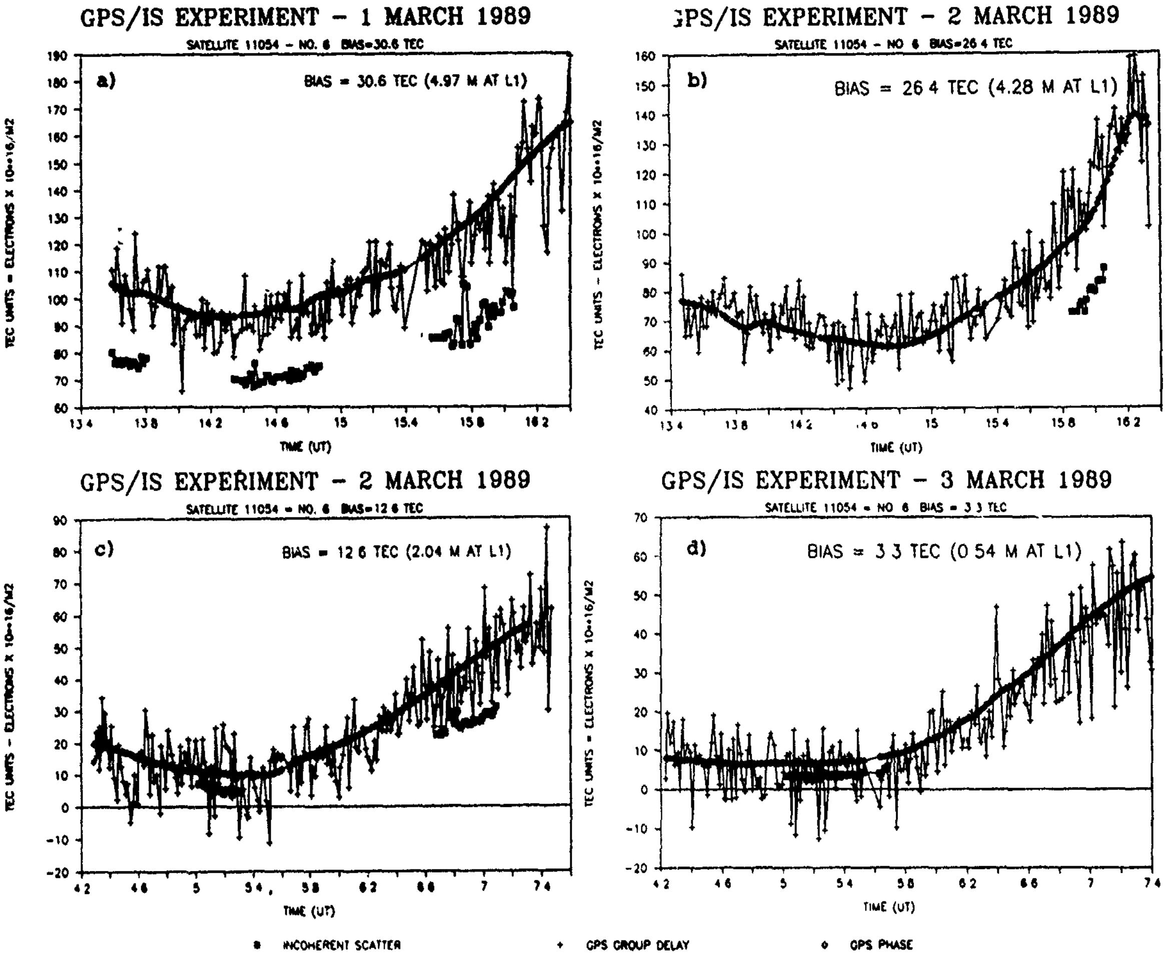


Fig. 8a-d. Comparison of GPS and Incoherent Scatter TEC Data for SV no. 6 on 1-3 March 1989. The IS data are demarked by a square, the GPS phase data by a cross, and the GPS group delay data by a diamond. Figs. 8a and b show the daytime data, while Figs. 8c and d refer to the nighttime data.

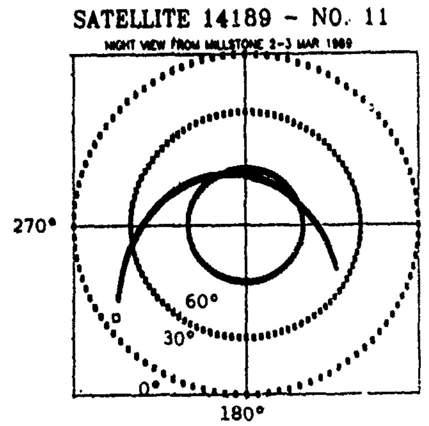
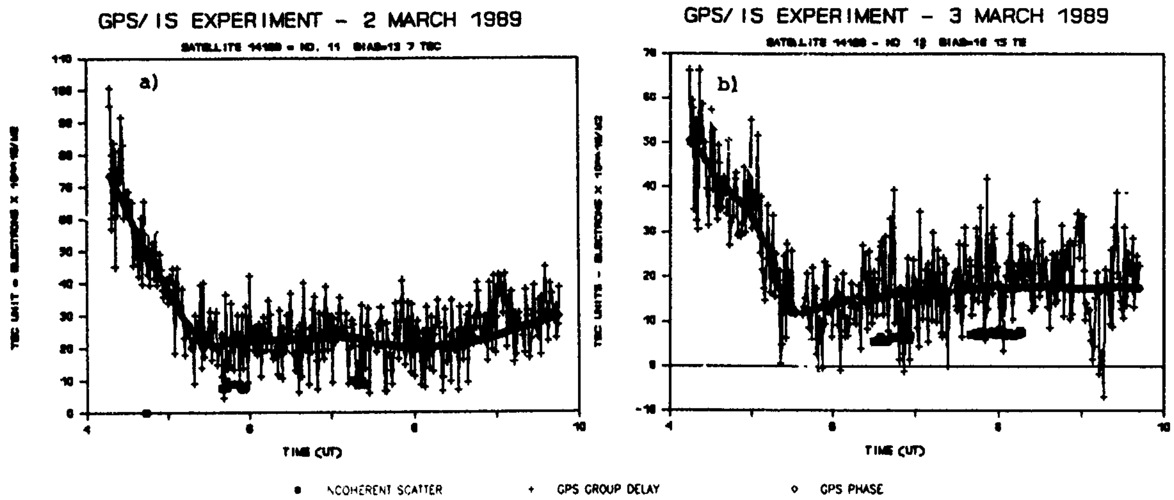
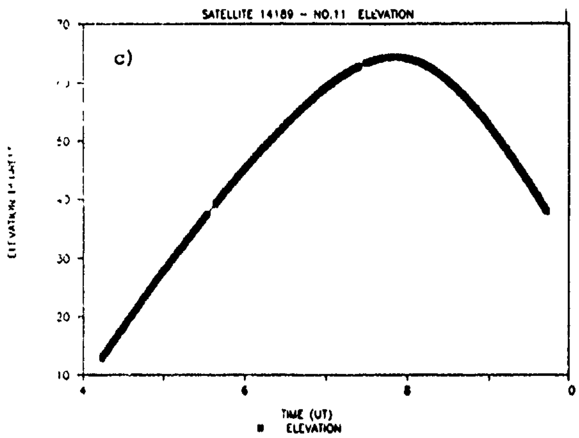


Figure 9. Geometry for SV # 11

SATELLITE NO. 11.

Satellite no. 11 was only viewed during the night observing sessions from Millstone. Nevertheless, it has some of the more interesting geometry as is indicated in Fig. 9. This satellite starts in the southwest, moves over head, and then heads towards the southeast. The measured SV bias for this satellite is 9.01 TEC. On 2 March a bias of 13.7 TEC (4.7 TEC) is seen in Fig 10a and on 3 March a bias of 10.15 TEC (1.15 TEC) is seen in Fig. 10b. Note the precipitous decline in the TEC observed in both sets of data. On both days the TEC flattens out at about 5.20 UT. Yet, on both days, the elevation is greater than 20 degrees by 4.6 UT and greater than 30 degrees by 5.20. We think this structure is yet another indication of the greater electron density towards the southwest.





Figs. 10a-c. Comparison of GPS and Incoherent Scatter TEC Data for SV no. 11 on 1-3 March 1989. The IS data are demarked by a square, the GPS phase data by a cross, and the GPS group delay data by a diamond. Figs. 10a and b show nighttime data. Fig. 10c shows the corresponding elevation to SV no. 11 from Millstone during the pass.

SUMMARY AND CONCLUSIONS

A new technique for estimating the number of electrons above 800 km has been validated through the comparison of the IS and GPS TEC data. The number of electrons that are detected to be above 800 km, sometimes as great as 30 TEC units, is surprisingly high when compared to previous studies of the plasmasphere which showed only 2-6 TEC units above 2000 km. (Klobuchar, et al., 1978). The previous studies were all taken during minimum solar flux conditions. Our estimates of the additional TEC above 800 km are given in Table V. All of the satellites estimate a smaller TEC above 800 km on 3 March than on 1 March, a decrease which varies from 18 to 32 TEC units.

Table V. Summary of Estimated TEC above 800 Km

	DAY (UT)		NIGHT (UT)	
	1 March	2 March	2 March	3 March
SV #				
6	29.8	25.6	11.8	2.5
9	34.3	4.7	9.1	2.3
11			4.7	1.6
12	20.7	13.2	18.6	2.3

The data for satellite no. 9 is slightly anamolous because it shows a large decrease in TEC during the day on 2 March. This is interesting because the observation was taken looking to the northeast at approximately 16.1-16.6 UT with an azimuth of 291 degrees and an elevation between 38 and 47 degrees. A second incoherent scatter observation of this satellite, also measuring a small IS bias, was taken at 17.5 UT with an azimuth of 299 degrees and an elevation of 6.2 degrees. If we consider the geometry of this measurement, it is approximately 1.5 hours after satellite no. 6 observes approximately the same location (295 azimuth and 8 degrees elevation). In addition, satellite no. 12 looks at a similar part of the sky at a slightly higher elevation (azimuth 290 and elevation 60) directly after the first set of IS measurements of satellite no. 9. Neither satellite no. 6 nor satellite no. 12 observed a small IS bias on this day. Either we are observing the propagation of an electron density trough during the daytime, or we are observing changing satellite biases for at least one of the satellites. However, recall that satellite no. 9 had the smallest SV bias measured. The change in the measured IS bias is 10 nanoseconds, far greater than the estimated SV bias fforthis satellite. We therefore believe that an electron density trough is being observed moving southward during the day.

In conclusion, using the combination of our GPS receiver and Incoherent Scatter radar, we think that we observe a large electron content in the ionosphere and plasmasphere prior to the geomagnetic storm. As the result of the geomagnetic storm, this excess plasma is blown away and, during the following two day period, the electron density trough that is generated propagates southward. We think that the combination of the GPS and incoherent scatter data offers an exciting new technique for measuring the total electron content above 800 km.

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