# Study of Global Ionospheric Total Electron Content (TEC) and Plasmaspheric Density Changes Due to Interplanetary Pressure and Magnetic Field Changes

B. T. Tsurutani, A. J. Mannucci, G. A. Hajj, B. Dasgupta and J. K. Arballo

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

## 1. Introduction

It has recently been shown (Huang and Foster, 2001) that either interplanetary ram pressure changes or northward turnings of the interplanetary magnetic field (IMF) can directly influence the midlatitude dayside ionosphere. Huang and Foster reported a clear case where a decreased ram pressure pulse (incorrectly reported as due to interplanetary [reverse] shock) or a northward turning of the IMF ($B_N > 0$) turning led to a decrease in the ionospheric total electron content (TEC) by 23% and a decrease in the dayside ionospheric F region plasma density (over 37° and 44° geographic latitudes) by 25 – 30%.

Changes of this magnitude represent significant space weather effects, but the physical connection between solar wind changes and the ionosphere is not fully understood. The decreases in TEC were measured by the Millstone Hill radar located at 55° invariant latitude and the delays of the density decrease was ~1.5 hours after the interplanetary event impinged upon the magnetosphere. Huang and Foster (2001) presented two separate scenarios of physical mechanisms for these ionospheric changes, but because of the near similarity of the interplanetary phenomena, they could not distinguish between the two.

In this paper we describe our plans to better understand this phenomenon using TEC measurements from ground and space-borne GPS receivers. We will: 1) develop a data analysis test using simultaneous Advanced Composition Explorer (ACE) interplanetary data and a quasi-constellation of newly launched satellites carrying JPL-designed Global Positioning System (GPS) receivers in addition to a global network of GPS ground receivers. The satellites carrying the GPS receivers are located at different altitudes and these differences will be used to distinguish between the two mechanisms proposed by Huang and Foster (2001). In addition to being able to distinguish between two mechanisms, we will 2) perform a systematic study to empirically determine the amount of ionospheric density decrease as a function of local time (simultaneous multipoint measurements rather than a one point measurement) and as a function of the strength of solar wind pressure changes (both increases and decreases) and strong interplanetary magnetic field $B_Z$ changes. Finally, 3) we will also study the effects that these ionospheric changes have on the plasmaspheric electron densities.

Because ionospheric plasma density changes (both increases and decreases) are largest during magnetic storms and are also the least understood of all storm phenomena, we will focus our analyses efforts on magnetic storm related events.

Interplanetary fast forward shocks are the largest abrupt ram pressure pulses detected in the interplanetary medium. The onsets of low beta magnetic clouds (Klein and Burlaga 1982) are the largest abrupt decreases in ram pressure pulses. Shocks and the onsets of magnetic clouds also have the largest southward ($B_S$) and northward ($B_N$) magnetic field changes in the interplanetary medium (Tsurutani and Gonzalez, 1999). We will focus on these interplanetary events to study ionospheric and plasmaspheric responses.

## 2. Global Measurements of Rapid Ionospheric Density Decreases and Possible Plasmaspheric Density Increases

Huang and Foster (2001) have suggested two possible mechanisms to explain the TEC and F-peak electron density decreases due to interplanetary changes. The first mechanism (a) is an expansion of the entire magnetosphere (including the plasmaspheric magnetic field lines) due to the ram pressure decreases. The idea is that with the extension of plasmaspheric magnetic field lines, the plasma in the ionosphere would expand into the low-density outer regions of the plasmasphere until a new pressure equilibrium is reached. In the interim, the ionosphere densities will be decreased. Huang and Foster (2001) mention that short-term effects can have time scales of 2-3 hours while it typically takes days to reach a final equilibrium. The second mechanism they propose (b) involves a penetration of the interplanetary $B_N$ fields into the magnetosphere/plasmasphere where a westward convection electric field brings the ionospheric plasma to lower latitudes. The authors suggest that the latter effect could lead to enhanced recombination rate and thus a plasma density reduction.

In summary, the first mechanism, a), has no reduction in free electrons (and ions) and only allows a diffusion of these thermal plasma particles to higher altitudes. The second mechanism, b), leads to a direct reduction of the plasma electrons and ions.

These two mechanisms can be distinguished by using GPS data (combined with ACE solar wind plasma and magnetic field data). Both large-scale solar wind ram pressure decreases as well as increases will be examined (the plasmaspheric effects of pressure increases should be similar but reversed from the pressure decreases). Large magnetic field $B_N$ and $B_S$ turnings will also be studied (mechanism b) to determine if these do indeed cause ionospheric electron density decreases for $B_N$ turning alone (IMF $B_S$ turning would not be expected to have reverse effects).

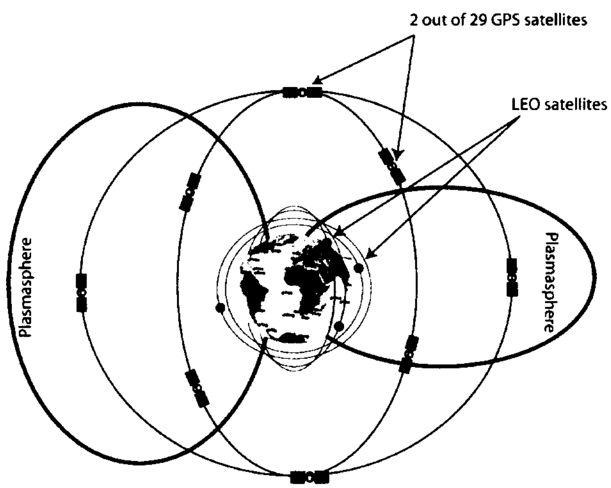


**Figure 1** A depiction of the GPS observation system with a subset of 8 GPS receivers, 4 low-Earth orbiters at different altitudes and orbital planes, and a sub-set of the global GPS ground network. Each GPS receiver on the ground or in space continuously track 8-12 GPS satellites simultaneously and provide absolute measurements of TEC along the transmitter-receiver links.

## 3. GPS Observations

The GPS observation system consists of 3 main components that will be utilized for our study: (1) the GPS transmitters, (2) a quasi-constellation of low-Earth orbit (LEO) satellites, (3) a network of 100+ ground GPS receivers. These three components and the observational geometry are depicted in Figure 1 and explained in more detail below.

*The GPS Transmitters*

The GPS transmitters consists of 24 satellites (+5 spares) distributed in 6 orbital planes, each orbiting the Earth at a radius of ~26,000 km with a period of ~12 hrs and 55° inclination. Each GPS satellite transmits two right-handed circularly polarized signals at L-band carrier frequencies: L1 at 1575.42 MHz (19 cm) and L2 at 1227.6 MHz (24.4 cm), modulated by a pseudo-random precision code (P-code). By a simple procedure of combining the L1 and L2 measurements, it is possible to obtain the Total Electron Content (TEC: the integrated electron density along transmitter-receiver line-of-sight) with a precision of 0.01 TECU and accuracy of 1-2 TECU (1 TECU = $10^{16}$ e/cm$^2$, Mannucci et al., 1998).

*GPS Receivers in Low-Earth Orbits*

Four space missions carrying a new-generation of JPL-designed GPS receivers were recently launched into low-Earth orbits. Table 1 summarizes these missions. The new-generation GPS receivers carried by these missions provide high-quality L1 and L2 (and therefore TEC) measurements even when the GPS signal encryption activated by the Department of Defense (DoD) is turned on. For the purpose of our investigation, we distinguish between two types of measurements, (1) zenith measurements and (2) occultation measurements.

*Zenith Measurements* are collected by the GPS antennas looking upward at a rate of 1 measurement every 10 seconds. Each antenna tracks 8-12 GPS satellites simultaneously, therefore, providing a total of ~0.5 million daily TEC measurements taken in all directions above the LEO satellites. Furthermore, because of the range of altitudes that these satellites are distributed, (over 300-1340 km), combining these measurements will allow us to separate the contribution to TEC from different altitudes and to get the vertical distribution of electron density in the topside ionosphere and the plasmasphere.

*Occultation Measurements* are collected by a limb-viewing antenna (pointing in the fore-, or aft- direction of the satellite). One occultation constitutes the set of measurements obtained while a GPS satellite is setting or rising behind the ionosphere as viewed by the LEO satellite, and therefore provides a profile of electron density below the satellite's height (Hajj and Romans, 1998). The number of daily ionospheric occultations from CHAMP, SAC-C and GRACE (Jason-1 has no occultation antenna) will exceed 1200 per day. Typical daily occultation coverage from these satellites is shown in Figure 2.

| Mission | Launch date | Altitude, km | Inclination | Antennas | Life time |
|---|---|---|---|---|---|
| CHAMP | July, 2000 | 470 | 83° | Up/Fore | 5 yrs |
| SAC-C | Nov., 2000 | 702 | 97° | Up/Fore/Aft | 3 yrs |
| Jason-1 | Dec., 2001 | 1340 | 63° | Up | 5 yrs |
| GRACE-1 | Mar., 2002 | 300-500 | 89° | Up/Fore | 5 yrs |
| GRACE-2 | Mar., 2002 | 300-500 | 89° | Up/Aft | 5 yrs |

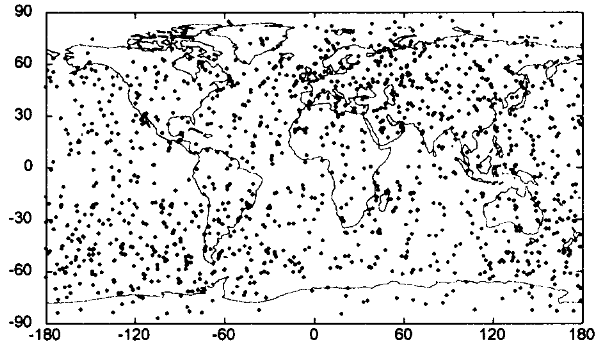


**Figure 2.** Representative one-day occultation coverage from CHAMP, SAC-C and GRACE (a total of ~1250 occultations). Each occultation yields a profile of electron density below the LEO height.

*GPS Ground Network*

Data obtained every 30 seconds from a network of 100+ ground GPS receivers distributed globally (Figure 3) are routinely processed at JPL and half-hourly global vertical TEC maps are obtained (Mannucci et al., 1998). These maps are formed by interpolating line-of-sight TEC measurements over a simplified ionospheric "shell structure" without invoking any physical model. The instrumental biases that affect ground-based GPS observations are estimated simultaneously with the interpolated TEC structure. The global TEC data set and maps are useful tools for examining the ionospheric response to magnetic storms on synoptic scales (Ho et al., 1998).

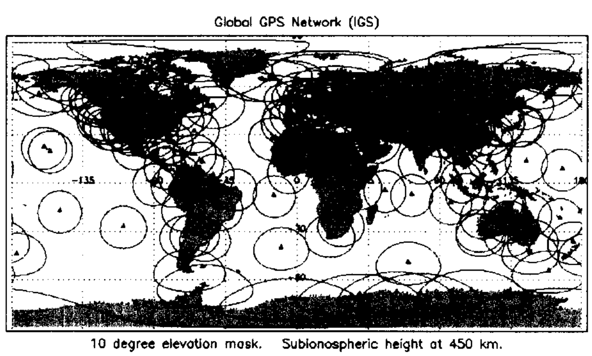


**Figure 3.** A map showing the distribution of selected stations of the continually operational global GPS network processed daily at JPL. Circles around the stations enclose projection areas at 450-km altitude, assuming an elevation cutoff of 10 degrees.

*GPS Data Analysis and Ionospheric Specification*

Extracting information from GPS TEC data can be done in many different ways with various levels of sophistication. We will pursue at least the following two ways of using GPS TEC data: 1) direct examination of enhancement and reduction of line-of-sight TEC as they probe different regions in the ionosphere and the plasmasphere from different altitude vantage points; 2) the use of a Global Assimilative Ionospheric Model (GAIM) where data and physics are combined (in a manner similar to numerical weather prediction—NWP) to estimate the evolution of the three-dimensional distribution of electron density in time (Wang et al., 2002; Hajj et al., 2002).

The method used in analyzing the TEC data will be determined based on the specific event under investigation, its geophysical location and the alignment of the various TEC links at that time. Incorporating the more sophisticated degree of processing using GAIM will be introduced only if necessary to uniquely specify the mechanism causing the enhancement, reduction or redistribution of the TEC or electron density.

## 4. Analysis Method

The ACE plasma and magnetic field data will be used to first identify fast forward and fast reverse shocks occurring in 2001 and 2002. Since fewer reverse shocks are present than forward shocks, the reverse shock events will be supplemented by ram pressure decrease events associated with tangential discontinuities (such as at the sunward boundary of magnetic clouds) discussed previously. The ram pressure prior to each event and after each event will be recorded as well as the shock normal directions and discontinuity normals, using techniques that are well established in the literature. The importance of the normals will be to establish at which local time the planar shock/discontinuity first impinges on the magnetosphere.

Sharp interplanetary magnetic field $B_N$ and $B_S$ turnings or intensifications detected at ACE will also be identified in the data. Our choice for this part of the study will be to search for large-scale discontinuities such as fast forward shocks and tangential discontinuities at the onset of magnetic clouds. Sharp discontinuities also have the advantage that the timing of impingement on the magnetopause nose can be calculated to ~1 min accuracy. Both IMF $B_N$ and $B_S$ turnings from these events will be identified and the normal direction categorized. There may be ram pressure changes associated with these events, so both pieces of information will be identified and recorded. It should be noted that many of the sharp turnings that cause substorms are Alfvénic in nature and have small spatial scale sizes. The size of the Alfvén waves can be even smaller than the size of the magnetosphere, thus these $B_Z$ events will not be suitable for a study of this type and will be avoided.

The ionospheric electron densities will be measured at a variety of ionospheric heights by use of the various LEO satellites listed in Table 1 (and described in the *GPS Receivers in Low-Earth Orbits* section) and the ground network (see the *GPS Ground Network* section).

The effect of the solar wind ram pressure pulses will be monitored from the initial sudden impulse at the magnetospheric tangent point of the shock/discontinuity and will be followed as the shock/discontinuity propagates into the downtail direction. One would expect to detect ionospheric disturbances "propagating" in local time, a feature that was not possible in the previous Huang and Foster (2001) study.

*Ionosphere/Plasmasphere Modeling*

Magnetospheric and plasmaspheric modeling will be applied and compared to the measured total electron content and density profiles. The measured solar wind ram pressure variations and magnetic field $B_Z$ turnings will be used as inputs to the latest Tsyganenko (2002a,b) magnetospheric model to estimate the plasmaspheric magnetic field expansion and compressional effects. These results in turn will be used as inputs to the plasmaspherical/ionospheric model. The model predictions for the plasmaspheric/ionospheric density changes will be compared to the GPS measurements, allowing closure to the process.

The authors of this paper have access and are well familiar with the Global Assimilative Ionosphere Model or GAIM (Hajj et al., 2000; Pi et al., 2002). GAIM solves the continuity and momentum equations on a fixed Eulerian frame using finite elements defined by intersecting geomagnetic field lines and magnetic geopotential lines and it is built with the capacity to assimilate TEC data. Currently the geomagnetic field used by GAIM is that of a magnetic dipole. However, we intend to modify the code such that a time-dependent magnetic field based on the Tsyganenko magnetosphere can be used. Moreover, the data assimilation capability of GAIM is very attractive for this study because it allows the use of TEC data described earlier and its assimilation into an ionospheric/plasmaspheric model to obtain an optimal solution to the distribution of plasma.

## 5. Summary

In this paper we have discussed a method of studying a significant ionospheric space weather event that is closely correlated with changes to the solar wind ram pressure on the magnetosphere. Huang and Foster (2001) have suggested two physical mechanisms that may account for the observed TEC decreases, and we describe here an integrated observational and modeling study to determine the physical cause. The ionospheric data will consist primarily of TEC measurements derived from ground and space-borne GPS receivers orbiting at several altitudes between 300 and 1340 km. The solar wind changes will be inferred using data from the ACE spacecraft, which measures in-situ plasma densities and magnetic field lines.

## 6. Acknowledgements

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

**References:**

Hajj, G. A., and L. J. Romans, 1998: Ionospheric electron density profiles obtained with the Global Positioning System: Results from the GPS/MET experiment, *Radio Sci.*, **33**, 175-190.

Hajj G. A., L. C. Lee, X. Pi, L. J. Romans, W. S. Schreiner, P. R. Straus, and C. Wang, 2000: COSMIC GPS ionospheric sensing and space weather, *Terr. Atmos. Oceanic Sci.*, **11**, 235-272.

Hajj, G. A., B. D. Wilson, C. Wang, and Xiaoqing Pi, 2002: Ionospheric data assimilation by use of the Kalman filter, *Proc. 10th International Ionospheric Effects Symposium*, Alexandria, Virginia, May 7-9.

Ho, C. M., A. J. Mannucci, U. J. Lindqwister, X. Pi, B. T. Tsurutani, L. Sparks, B. A. Iijima, B. D. Wilson, I. Harris, and M. J. Reyes, 1998: Global ionospheric TEC variations during January 10, 1997 storm, *Geophys. Res. Lett.*, **25**, 2589.

Huang, C. S., and J. C. Foster, 2001: Variations of mid-latitude ionospheric plasma density in response to an interplanetary shock, *Geophys. Res. Lett.*, **28**, 4425.

Klein, L. W., and L. F. Burlaga, 1982: Interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, **87**, 613.

Mannucci, A. J., B. Wilson, D. Yuan, U. Lindqwister, and T. Runge 1998: A global mapping technique for GPS-derived ionospheric total electron content measurements, *Radio Sci.*, **33**, 565-582.

Pi, X., C. Wang, G. A. Hajj, G. Rosen, and B. D. Wilson, 2002: Estimate E×B drift using a global assimilative ionospheric model: An observation system simulation experiment, *J. Geophys. Res.*, to appear on 2002.

Tsurutani, B. T., and W. D. Gonzalez, 1999: The interplanetary causes of magnetic storms: A review, in *Magnetic Storms*, ed. B. T. Tsurutani, W. D. Gonzalez, Y. Kamide, and J. K. Arballo, Amer. Geophys. Un. Press, Washington D.C. **98**, 77.

Tsyganenko, N. A., 2000a: A model of the near magnetosphere with a dawn-dusk asymmetry, 1. Mathematical structure, submitted to *J. Geophys. Res.*.

Tsyganenko, N. A., 2002b: A model of the new magnetosphere with a dawn-dusk asymmetry, 2. Parameterization and fitting to observations, submitted *to J. Geophys. Res.*

Wang, C., G. Hajj, X. Pi, I. G. Rosen, and B. Wilson, 2001: A review of the development of a global assimilative ionospheric model, *Proc. Beacon Symposium*, Boston, Massachusetts, June.