Sporadic \( E \) morphology from GPS-CHAMP radio occultation

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[1] The scintillations of phase and amplitude in terms of signal-to-noise ratio (SNR) of the GPS radio occultation signal are caused by thin ionization layers. These thin irregular electron density layers in the \( E \) region ionosphere are often called sporadic \( E (E_s) \). For a one-month retrieval of \( E_s \) morphology we use the variances of the phase and SNR fluctuations of worldwide \( \sim 6000 \) GPS/CHAMP occultations in the \( E \) region. The \( E_s \) morphology is studied globally with the SNR and phase variances in terms of monthly zonal means, seasonal maps, and diurnal and long-term variations. The zonal mean variances reveal strong, extended \( E_s \) activities at summertime midlatitudes but weak, confined activities in wintertime high latitudes, peaking at \( \sim 105 \) km. Global maps at 105-km altitude show clear dependence of \( E_s \) activities on the geomagnetic dip angle, where the summertime midlatitude \( E_s \) occurs mostly at dip angles of \( 30^\circ \)–\( 60^\circ \) and the wintertime high-latitude enhancement occurs mostly at dip angles >\( 80^\circ \). The midlatitude \( E_s \) variances exhibit a strong semidiurnal variation with peak hours near 0800–1000 and 2000 local solar time, respectively. The peak hours are delayed slightly with decreasing height, suggesting influences from the semidiurnal tide. To provide more insights on the observed SNR and phase variances, we model radio wave propagation for the CHAMP observing geometry under several perturbed cases in the \( E \) region ionosphere. The model simulations indicate that the SNR variance has the maximum response to \( E_s \) perturbations at vertical wavelengths of \( \sim 1.2 \) km, whereas the phase response maximizes at \( \sim 2 \) km (for the 1-s variance analysis). The characteristic scale depends little on the truncation time used in the SNR variance analysis, but it increases with the truncation time for the phase variances. Initial studies show that reasonable global \( E_s \) morphology can be produced on a monthly and seasonal basis with the CHAMP one-antenna occultations. Better results from other existing and upcoming GPS occultation missions are anticipated in future studies, and they will significantly improve our understanding of this important phenomenon.


1. Introduction

[2] Sporadic \( E (E_s) \) is known as a transient phenomenon where high-density ion layers form in a narrow-altitude region in the \( E \) region ionosphere. Knowledge of global \( E_s \) properties and effects is of great interest to radio communications and navigations. Advances in solar terrestrial physics and atmospheric dynamics require a better understanding of the electric conductivity and its variability in the \( E \) region. Detailed physical and statistical descriptions of the \( E_s \) processes, especially from a global perspective, are essential for understanding their formation and variations and ultimately for improving numerical forecast of space weather.

[3] Observations of \( E_s \) in the past were mostly from ground-based remote sensing, sometimes in situ techniques, and only recently from satellite sensors [e.g., Farley, 1985; Whitehead, 1989; Kelly, 1989; Mathews, 1998; Hocke et al., 2001, and references therein]. As reported from ionosonde and incoherent scatter radar data (i.e., electron density, electric field, etc.), \( E_s \) layers usually occur around 90–110 km altitudes with thickness of 0.5–5 km and a horizontal extent of 10–1000 km. The thin and patchy layers of enhanced electron density, sometimes also called \( E_s \) clouds, may last from minutes to hours causing radio signal interruption or frequency drift. Strong local time and seasonal variations of midlatitude \( E_s \) have been observed, showing the maximums in daytime hours and during summer months. \( E_s \) observations remain limited to a few geographical locations, and theories (including the well-known wind shear theory) still have difficulties quantitatively explaining \( E_s \) formation and variability in many situations.

[4] \( E_s \) variabilities exist over broad temporal and spatial scales, which are believed to be related to other atmospheric and ionospheric processes. For instance, radar...

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observations show strong short-period field-aligned structures imbedded in long-period \( E_s \) irregularities, which are consistent with gravity wave characteristics in that region [Tsunoda et al., 1994; Fukao et al., 1998]. Pancheva et al. [2003] reported significant correlation between radar wind measurements and \( E_s \) irregularities near 100 km, which was attributed to planetary and tidal wave modulations. \( E_s \) occurrences are also influenced by solar activities [Baggaley, 1984; Maksyutin et al., 2001] and convective systems in the troposphere [Shrestha, 1971; Datta, 1972]. Hocke et al. [2001] studied \( E_s \) irregularities using GPS/Meteorology (GPS/MET) phase measurements and found that strong activities occur mostly at heights between 95 and 105 km at summertime midlatitudes. These \( E_s \) irregularities appear to correlate with deep convective and topography-induced processes in the troposphere [Hocke and Tsuda, 2001; Hocke et al., 2002]. In addition, linkage of \( E_s \) to other ionospheric phenomena, including spread F and traveling ionospheric disturbance, has also been investigated [Tsunoda and Cosgrove, 2001].

[5] Techniques for \( E_s \) observations have been advanced remarkably in recent years. Satellite-to-satellite radio communications, such as Global Positioning System-Low Earth Orbiter (GPS-LEO) occultations, provide an ideal geometry for observing layered structures like \( E_s \), with many advantages over GPS-ground links. In order to observe \( E_s \) layers, ground-based GPS receivers need to make overhorizon measurements [Coco et al., 1995], which are often contaminated by large multipath errors. The satellite-to-satellite links normally do not have multipath problems with the surrounding environment, provided that the high-rate (50 Hz and 100 Hz) vertical sampling with advanced GPS receivers can accurately resolve thin-layered structures. For satellite-to-satellite links, \( E_s \) signals are much stronger than those received during ground-to-satellite links, and contaminations from \( F \) region fluctuations can be effectively minimized. More importantly, GPS-ground measurements are regional, whereas GPS-LEO occultations are global with \(~200–250\) daily profiles on a single antenna.

[6] The GPS constellation consists of \(~29\) satellites (canonically 24 plus a few spares) that are distributed roughly in six circular orbital planes with \(~55^\circ\) inclination at \(20,200\)-km altitude. Each GPS satellite continuously broadcasts at two L-band frequencies: 1.6 (L1) and 1.2 GHz (L2) [Spilker, 1980]. Precise measurements of time delay between GPS transmitters and LEO receivers can be used to obtain profiles of atmospheric pressure, temperature, and water vapor [e.g., Kursinski et al., 1997] or electron density [Hajj and Romans, 1998]. These profiles generally have good vertical resolution, benefiting from very high sampling rates (e.g., 50 and 100 Hz) in the occultation measurements. Remote sensing of Earth’s atmosphere with the GPS occultation technique was first demonstrated in GPS/MET mission during 1995–1997 [Ware et al., 1996]. The recent missions, such as the German Challenging Minisatellite Payload (CHAMP) [Wickert et al., 2001], the Argentinean Satelite de Aplicaciones Cientificas-C (SAC-C) [Hajj et al., 2004], and the Department of Defense Ionospheric Experiment [Straus et al., 2003] are producing a total of \(~600\) occultations per day. Future GPS occultation missions, such as Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and Communications/Navigation Outage Forecasting System, will provide over \(~3000\) profiles per day with dense geographical and local time coverage.

[7] This paper describes a novel variance analysis method for extracting \( E_s \) information from the signal fluctuations in satellite radio occultations and compiles a climatology of \( E_s \) with recent measurements from GPS/CHAMP. The paper is organized as follows: Section 2 describes GPS/CHAMP data collected during 2001–2003 and the analysis method. Section 3 presents the global \( E_s \) morphology to show its geographical, vertical, and local time variations. These initial results reveal many interesting features and open the door for further modeling and theoretical investigations. In section 4 we model radio wave propagation through a perturbed ionosphere to characterize the sensitivity of occultation measurements to perturbation vertical and horizontal scales. A conclusion is given in section 5.

2. Data and Analysis

[8] In most applications, high-frequency oscillations in the signal’s amplitude (measured by signal-to-noise ratio (SNR)) and phase data are usually treated as measurement noise for its fussy nature and potential degradation to communication quality. This “noise,” however, contains valuable information on physical and statistical properties and variabilities about \( E_s \), which can be used to study and understand their occurrences.

[9] The SNR and phase scintillations in satellite-to-satellite links can be directly related to electron density fluctuations associated with \( E_s \). The atmosphere/ionosphere interacts with radio wave propagation through atmospheric refractivity, \( N = (n − 1)10^6 \), for the index of refraction \( n \). The refractivity depends on atmospheric temperature \( T \), total and water vapor pressure \((P \text{ and } P_w)\), electron density \( n_e \), and radio frequency \( f \); namely,

\[
N = 77.6 \frac{P}{T} + 3.73 \times 10^6 \frac{P_w}{T^2} - 4.03 \times 10^7 \frac{n_e}{f^2},
\]

where \( P \) and \( P_w \) are in hectopascals, \( T \) is in kelvins, \( n_e \) is in \( m^{-3} \), and \( f \) is in hertz. Important atmospheric/ionospheric effects on the GPS occultation measurements are summarized by Hajji et al. [2002] as follows:

2.1. Bending Effect

[10] Atmospheric refraction introduces bending to radio wave propagation from GPS to LEO, causing an excess phase delay. The bending effect increases with air, water vapor, and electron densities. Because of this bending, the signal can be received even when the transmitter is slightly behind the Earth. The bending contributions from air/water are generally small at tangent heights above \(~50\) km, compared to electron density effects.

2.2. Defocusing/Focusing Effect

[11] Vertical gradients of the bending angle cause the transmitted beam to diverge or converge, which reduces/increases signal power at the area-constant receiver antenna. The defocusing/focusing effect increases with air pressure as the vertical gradient increases, causing the receiver power to decrease gradually with pressure at tangent heights below
~30 km. Sharp vertical structures, such as ones near the planetary boundary layer, can even cause a temporary loss of signal.

2.3. Diffraction Effect

Diffraction occurs when the transmitted signal encounters the irregularities of scales near or less than the Fresnel diameter which depends on the transmitted radio wavelength, the transmitter-receiver distance, and the refractivity vertical gradient. For typical GPS-LEO occultation applications (at an 800-km orbit) the Fresnel diameter is ~1.5 km in the \( E \) region and hundreds of meters in the troposphere.

2.4. Multipath Effect

Very sharp and thin vertical structures in the atmosphere/ionosphere may cause strong differential bending among the transmitted rays. As a result the signals may reach the receiver from different paths. In this case, interference among the rays from different paths must be considered.

2.5. SNR and Phase Fluctuations

Figure 1 (top) shows the 50-Hz SNR, L1, and L2 phase measurements during a CHAMP occultation in January 2002. Starting from a tangent height of ~140 km, this occultation scans through the \( E \) region at a descending rate of ~2.2 km/s. In this case the SNR is close to ~800, the free-space value (SNR\(_{\text{0}}\)), until the tangent height is below
~40 km. The defocusing effect of the neutral atmosphere begins to play a major role in the lower heights and causes an overall attenuation of the SNR until it vanishes near the Earth’s surface. Since the raw data contain phase and SNR as functions of time rather than tangent height, the mapping between time and tangent height was done from knowledge of the satellite ephemeris, assuming the straight line propagation in the ionosphere and upper stratosphere, and using the Abel inversion for bending angle in the lower stratosphere and troposphere.

[16] The SNR fluctuates slightly about SNR$_0$ above ~50 km for normal quiet ionospheric conditions, but the SNR$_0$ can vary substantially from occultation to occultation, depending on the viewing angle of the GPS satellite with respect to the LEO antenna. In the normal cases the L1 and L2 excess delays (corrected for satellite motions and clocks) vary gradually at tangent heights above ~40 km due to the weak bending by the ionosphere but increase exponentially below ~40 km due to the strong bending of the neutral atmosphere. In this example (Figure 1), the excess delays and the SNR exhibit abrupt variations at tangent heights between 80 and 120 km, which are indicative of sharp structures in that region.

[17] To extract short-scale SNR and phase perturbations, we first detrend the data with an N-point running window. This detrending method outputs the difference between the data sequence and the N-point smoothed sequence as a filtered result. It is an equivalent high-passed filtering process where slowly varying or large-scale components are removed. Because the phase measurements vary exponentially with height, this filtering process is applied twice when detrending the phase data.

[18] The detrended data are shown Figure 1 (bottom), where the SNR perturbations are normalized by SNR$_{an}$. In this case, large oscillations due to $E_s$ are clearly evident in SNR/SNR$_{an}$ and phase perturbations at tangent heights of 80–120 km. The SNR perturbations reach as high as 50%, while L1 and L2 phase perturbations show maxima of 5 and 8 cm, respectively. Both SNR and phase fluctuations reduce substantially at tangent heights between 30 and 70 km, where they are mostly dominated by the measurement noise. In the enhanced $E_s$ region, fluctuations can be much greater than the instrument noise. At tangent heights below ~40 km, fluctuations are dominated by neutral atmospheric variabilities in temperature, pressure, and water vapor, and they are outside the scope of this paper and will be investigated in a separate study.

[19] $E_s$-induced fluctuations in the SNR, L1, and L2 phase measurements exhibit great coherency in most parts of the $E_s$ event (Figure 2). The correlations between L1 SNR and phase fluctuations are sometimes complicated by the detailed $E_s$ structure, but the L1-L2 phase correlations generally obey the frequency dependence described in equation (1) for electron density perturbations. As shown in Figure 2 (right), the L1 and L2 phase fluctuations are linearly correlated with a slope close to $(f_1/f_2)^2$, where $f_1$ and $f_2$ correspond to the L1 and L2 frequencies, respectively. An interesting scenario appears at 103–107 km altitudes where L2 phase oscillations lag L1 by ~150 m. This lag manifests itself as the circular pattern in the L1 and L2 phase correlation (Figure 2 (middle right)), which is likely caused by the frequency-dependent bending associated with sharp vertical structures of these $E_s$ layers. The bending separation between L1 and L2 phase measurements (typically 100–500 m) depends on the vertical gradient of electron density [Hajj and Romans, 1998]. Because $E_s$ layers are often thin, large vertical gradients in electron density are readily present over a few kilometers and cause a noticeable separation in the high-rate measurements. By carefully modeling radio waves propagation through highly structured media, it is possible to reconstruct a high-resolution vertical profile of $E_s$ layers from the 50-Hz SNR and phase measurements [Igarashi et al., 2002; Gorbunov, 2002; Ao et al., 2003].

2.6. Sampling and Coverage

[20] To cover the typical height range of $E_s$ phenomena (80–120 km), GPS receivers need to start tracking at a tangent height above $E_s$ layers. During the early CHAMP operation in 2001–2002, occultations did not start sufficiently high to sample the entire $E_s$ region. Figure 3 shows that the high-rate occultations were only as high as ~100–110 km before February 2002, which was later raised to 140–150 km specifically for $E_s$ studies.

[21] Normal CHAMP operation produces 200–250 daily occultations, but the number of profiles in the level 2 data is significantly less than that in the level 1 data because of tighter quality controls needed for the level 2 retrievals (i.e., density and temperature profiles in the stratosphere and troposphere). This study uses the SNR and phase data released in the level 2 files, which appear to have a sufficient number of profiles for monthly and seasonal climatologies. In future studies the algorithm will be modified to directly use the level 1 data and hence increase the number of daily occultations.

[22] CHAMP orbit precesses in local time with a rate of ~5.6 min/d at the equator, sampling a complete 24-hour cycle every ~130 days with both ascending and descending nodes. However, this revisit period is not exactly 130 days since occultations are spread by ~2 hours for each node (Figure 4). This spreading is caused by the nature of the GPS-LEO occultation geometry and the broad antenna field of view (~70°) that allows the receiver to view occultations from many directions where GPS satellites may appear. The spreading in local time is more discrete at the equator than at middle and high latitudes. This spread time coverage causes the effective repeat period (for covering 24-hour local time) to be ~108 days and therefore helps slightly to reduce aliasing between diurnal and seasonal variations.

2.7. Variance Analysis and Noise Removal

[23] The SNR and phase fluctuations contain not only $E_s$ perturbations but also instrument/measurement noise and other ionospheric variations at higher altitudes. The instrument/measurement noise sometimes shows up as spikes in SNR and phase perturbations and can vary from occultation to occultation. The deduced variances from SNR and phase measurements, $\sigma^2$, can be written as a sum of these sources:

$$\sigma^2 = \sigma^2_{E_s} + \sigma^2_{e} + \sigma^2_{F},$$

where $\sigma^2_{E_s}$, $\sigma^2_{e}$, and $\sigma^2_{F}$ are respectively $E_s$ noise, and $F$ region variances. The noise, including instrument radiometric and clock errors, may not completely behave as a
random and stationary sequence. Because these errors vary from occultation to occultation, we must remove them on a profile-by-profile basis. The clock error tends to generate small periodic spikes in the phase data, contributing significant spectral power at high frequencies (>10 Hz). To remove these clock spikes, we apply the three-point high-pass filter to the phase data and subtract the three-point filtered sequence from the N-point filtered one. We refer to this process as the (N, 3) band-pass filtering. As shown in Figure 5, the (N, 3) band filter can significantly reduce the noise power at frequencies >10 Hz, and removing the noise is particularly important for the phase variances where $E_s$ amplitudes are weak.

As the standard variance products, we process the 50-Hz SNR and phase data with several band-pass filters: (401, 3), (201, 3), (101, 3), (51, 3), and (21, 3) to study $E_s$ variabilities at different vertical scales. The noise removal with the three-point filter also helps to eliminate possible F region contaminations [Straus et al., 2003]. F region fluctuations can generate very noisy measurements over a broad range of tangent heights, extending above and below the $E_s$ region. Profiles are discarded if the averaged three-point variance is 20 times greater than its monthly mean at tangent heights above 120 km or between 40 and 80 km. Furthermore, L1 and L2 phase measurements are analyzed between 40 and 60 km. Because the L2 phase measure-

**Figure 2.** Correlations for (left) SNR phase and (right) L1-L2 phase fluctuations at (top) 75–103, (middle) 103–107, and (bottom) 107–120 km. Dots represents the phase measurements, and the slope is the ratio of L1 and L2 frequencies.

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Figure 3. Summary of CHAMP height coverage.

Figure 4. Summary of CHAMP local time coverage at ±45° and at the equator.
ments are noisier than L1, a looser tolerance is applied for L2 quality control.

For CHAMP occultations the 51-point truncation corresponds to a vertical scale of ~2.2 km. The vertical scale used by Hocke et al. [2001] is equivalent to the 201-point (or 4 s) truncation. However, there are three key differences between our approach and the one used by Hocke et al. [2001]: (1) They did not analyze the SNR data but the horizontal total electron content deduced from L1-L2 phase differences. (2) They chose to measure the average rather than the variance of the fluctuations, which may significantly change the \( E_s \) strength and morphology. (3) They did not consider measurement noise or calibration errors in their analysis.

3. Results

3.1. Zonal Means

Monthly mean variances in June 2002 (Figure 6) and January 2003 (Figure 7) show clearly that \( E_s \) features dominate the summer hemisphere. The maxima in the SNR and phases fluctuations are aligned with the \( E_s \) layers and represent approximately the vertical distribution of \( E_s \) variability. The summertime \( E_s \) is dominated by activities at altitudes of 80–120 km with the peak at ~105 km near 45°S in January and at ~102 km near 45°N in June. The \( E_s \) variances in the summer hemisphere correlate well with the mean zonal wind, which reaches ~40 m/s in the Committee on Space Research (COSPAR) International Reference Atmosphere 1986 climatology. The \( E_s \) variances in June appear slightly greater in amplitude than those in January and occur in a broader height range. The \( E_s \) variances are much weaker in the winter hemisphere but remain significant in CHAMP phase data. Equatorial \( E_s \) variances are generally weak, confined in a narrow altitude region around 100 km, and may be more prominent in June than in January. Besides, large variances at lower altitudes (<20 km) reflect sharp variations of atmospheric refractivity associated with temperature and water vapor changes in the troposphere.

3.2. Seasonal Variations

Figure 8 shows the daily averages of CHAMP SNR and phase variances for an annual cycle using data collected between May 2001 and July 2003. Both ascending and descending samples are used for averaging so as to reduce the aliasing effects from diurnal variations. However, semi-diurnal and seasonal variations can still alias to each other, which could explain the periodical (~65 days) modulations seen in the seasonal variations.

As shown in Figure 8, the \( E_s \) variances exhibit strong seasonal variations at all latitudes and have slightly different morphologies at 95, 105, and 112 km. Near 95 km, midlatitude \( E_s \) activities in the Northern Hemisphere (NH) last 6 months from April to October, and the largest
variance appears in late May and early June. The peak variance moves in latitude from \(~20^\circ\text{N}\) in April to \(~40^\circ\text{N}\) in June and back to \(~20^\circ\text{N}\) in August before shifting to \(~40^\circ\text{N}\) again in September. The NH high-latitude (around \(75^\circ\text{N}\)) activity prevails in almost all seasons except for the short break in March. The midlatitude \(E_s\) activities in the Southern Hemisphere (SH) occur mostly in October and November with many weaker enhancements spread over other periods (January–February, April, and September). The SH high-latitude (around \(60^\circ\text{S}\)) variances are spread between October and February with the most active ones in December and January.

At 105 km, where the \(E_s\) variances are strongest, the NH midlatitude \(E_s\) shows greater enhancements during May–August and peaks in mid-June. At the NH high latitudes, \(E_s\) activity appears mainly in the off-summer months (October–March), and the summertime activity is diminished compared to the one at 95 km. In the SH the middle and high-latitude activities are blurred together during the October–March period, and weak variances are present near \(\sim 60^\circ\text{S}\) for the rest of the period. Equatorial \(E_s\) activities are significant for the January–February, May–June, and August–October periods.

At 112 km the seasonal variation of the NH midlatitude \(E_s\) varies not only with time but also with latitude as the maximum shifts from \(30^\circ\text{N}\) in May to \(\sim 50^\circ\text{N}\) in late July. The strongest variance here occurs in late July and early August, further delayed from the peak times at the lower heights. The NH high-latitude activity becomes weaker but remains significant over the period from October to March. The SH \(E_s\) activities are split into two periods (November–December and January–February) with the stronger one in the first period. The equatorial \(E_s\) in late January and early February remain more prominent than those during the transition (equinoctial) periods.

### 3.3. \(E_s\) Variance Maps

The GPS-LEO occultation technique can provide global maps of \(E_s\) variances, which are important for studying the dependence of \(E_s\) on the horizontal winds.
and the geomagnetic field. Figure 9 shows the 105-km maps of L1 SNR/SNR₀ and phase variances during (a) June–August 2002 (JJA) and (b) December 2002 to February 2003 (DJF) when the summertime Es are maximized. These maps reflect the stationary component of Es at planetary scales that may be related to the geomagnetic field. Because CHAMP satellite drifts slowly in local time as shown in Figure 4, the 3-month averages can be contaminated somewhat by fast-traveling planetary waves.

[32] In JJA (Figure 9a), Es irregularities appear strongly in the summer hemisphere, mostly over China, northwestern Pacific, western United States, northern Atlantic, and southern Europe. However, they mostly fall into the latitude band where the geomagnetic field dip angles are between 30° and 70°. This dip angle dependence is quite striking for the summertime activities as they move north and south in latitude following the dip angle changes. The strong longitudinal variations in the 30°–70° dip angle band can not be simply related to the geomagnetic field. Other variabilities, such as horizontal winds and ion sources, must be taken into account. The wintertime Es activities in JJA are weak and coincide mostly with the dip angles >80°, the southern polar cap with open geomagnetic field lines. Patchy Es activities are evident in the phase variance at dip angles >80° in the summer pole. Equatorial Es activities are generally weak and patchy, not showing any dependence on the geomagnetic equator.

[33] In DJF (Figure 9b) the strongest summertime Es activity is over southern Pacific with variances as high as ~(150%)² in SNR/SNR₀ and ~1.6 cm² in L1 phase. Other active regions are over the southern Andes and the east and west Australian coasts. In the region south to Indian Ocean and South Africa (between 30° and 60°S), there is a weak but significant Es appearance. Also showing the strong dip angle dependence, the enhanced variances are basically confined to the 20°–60° latitude band, whereas the weak variances occur almost everywhere in the summer hemisphere. In the winter hemisphere, again, Es activities become weak and mostly restricted to the region of dip angles >80°.

3.4. Diurnal Cycle

[34] To study the local time variation of Es activity, we use 3 months of CHAMP data and average them into each hourly bin. Latitudinal and height dependence of Es diurnal cycle is of particular interest for studying potential tidal influences because of unique neutral wind shears associated with the tides. During the JJA season the summer midlatitude Es exhibits a strong semidiurnal variation at 105 km with peaks around 1000 and 2000 local solar time (LST)
Figure 8. Latitude-dependent seasonal variations of (a) CHAMP SNR/SNR$_0$ and (b) phase variances at 95, 105, and 112 km with a 2-km bin. The 51-point variances from the period of May 2001 to July 2003 are used to average out sampling gaps and short-term variability. A 15-day smoothing is applied to the daily averages. Contour scales are (\%)$^2$ for the SNR/SNR$_0$ variance and cm$^2$ for the L1 and L2 phase variances.
Figure 9. L1 Maps of SNR/SNR\(_0\) and phase variances at 100–110 km for (a) June–August 2002 and (b) December 2002 to February 2003. Map has a grid box size of 5\(^\circ\) \times 10\(^\circ\) in latitude by longitude and is smoothed with a three-point averaging. White contours, in degrees, are plotted to show the variations of geomagnetic field dip angle at 105 km.
The semidiurnal variation in the CHAMP variances is generally consistent with ground-based observations from a number of sites in the NH \cite{Whitehead, 1989}. Figure 10 also shows a downward progression with height at 45°C176N in both SNR and phase variances at 70–115 km. Equatorial Es and the wintertime activities, on the other hand, are dominated by a diurnal variation, showing the peak time between 1400 and 1800 LST. In DJF (Figure 11) the diurnal variation dominates summertime Es activities with the maximum enhancement around 2000 LST. In the winter hemisphere, Es activity is still dominated by a semidiurnal variation with maximums around 0800 and 2000 LST. Equatorial Es is weak with a diurnal variation and peaks around 1800 LST. The time-height relation at 45°C176S reveals only slight downward progression for the enhancement near 2000 LST.

4. Simulation of E Region Radio Occultation Scintillations

To better understand the SNR and phase variances, we carry out a series of radio wave propagation calculations using a multiple phase screen model to simulate the SNR and phase fluctuations under observing conditions similar to those in GPS-CHAMP occultations. The simulated SNR and phase fluctuations are analyzed with the same variance method to study the sensitivity of GPS occultation to layered ionospheric structures.

4.1. Multiple Phase Screen (MPS) Model

The MPS model in this study uses an effective approach for solving the propagation properties of radio waves through the atmosphere \cite{Levy, 2000}. It divides the atmosphere into a series of “phase screens” where the propagating signal is delayed subsequently by an amount determined from the index of refraction at those locations. From one phase screen to the next, the wave propagates as if in vacuum. Computational parameters, including the distance between phase screens as well as the spacing between discretization points in each phase screen, are adjustable according to the needs for model resolution.

The MPS model can compute diffraction effects from sub-Fresnel-scale structures and produce accurate amplitude and phase in the presence of atmospheric multipath structures. It has been widely used for wave scintillation calculations through atmospheric turbulence \cite{Martin and Flatté, 1988} and is the de facto standard for simulating GPS occultations. The model and geometric parameters are cho-
4.2. Simulations of SNR and Phase Fluctuations

[39] In simulating $E_s$-induced scintillations, we insert wave-like refractivity perturbations near the 100-km altitude and compute signal SNR and phase sequences along the sampling path similar to the CHAMP instrument. We then calculate the SNR and phase variances using the same method as described in section 2 for the real data. The SNR and phase variances are studied against various input perturbation parameters. Most important is the variance dependence on the vertical and horizontal perturbation scales. This property is critical for interpreting the $E_s$ variances observed by CHAMP. In the presence of both horizontally and vertically varying structures, the long line of sight (LOS) path associated with GPS occultation may impose strong smoothing on the $E_s$ layers, making small-scale and localized layers indistinguishable. Similarly, altitude and orientation of thin $E_s$ layers with respect to the LOS direction can change the variance substantially, all of which can be investigated in detail with the MPS model.

[40] In the first set of simulations (Figure 12a) a packet of perturbing layers (with a Gaussian envelop) in terms of refractivity are inserted near the ~100-km altitude. All the perturbing layers are parallel spherical shells with the same horizontal lengths centered at the tangent point. Three horizontal lengths (200, 400, and 1000 km) and seven vertical wavelengths (0.1, 0.2, 0.5, 1, 2, 4, and 8 km) are used for the sensitivity study, and as an example, the results for 200 km are shown in Figure 13. For short vertical wavelengths (0.1 and 0.2 km) the MPS model produces some fuzzy SNR and phase fluctuations at subkilometer scales. Note that these fluctuations are confined mostly in the height region where the perturbation is inserted with a broader spread in the cases of shorter vertical wavelengths (0.1 and 0.2 km). In fact, the SNR and phase responses to the $E_s$-like perturbations depend largely on the vertical wavelength of the layers inserted. Such scale dependence in SNR and phase variances, which we call the “observational filter,” is an important property to characterize the sensitivity of occultation techniques to layered perturbations. For the cases of horizontal scales of 400 and 1000 km (not shown) the SNR and phase fluctuations are evident at lower tangent heights due to the extension of thin layers, which reside quite far away from the tangent point. When $E_s$ layers extend uniformly over several hundred kilometers, spherical symmetry can be applied to retrieve sub-Fresnel structures of the refractivity perturbations using methods...
influence of the far-side layers when tangent heights are below 100 km. However, heights below 100 km as the LOS still intersects with these holography \[ \text{like the canonical transform} \] Gorbunov radiative transfer calculation.

Between the transmitter and the receiver, are used in the from the tangent point. Multiple phase screens, spaced near the tangent point and (b) symmetric but far away (a) near the tangent point and (b) symmetric but far away from the tangent point. Multiple phase screens, spaced between the transmitter and the receiver, are used in the radiative transfer calculation.

like the canonical transform [Gorbunov, 2002] or radio holography [Igarashi et al., 2002]. However, the reality is associated with nonuniform layers with patchy distribution in between. The next set of simulations illustrates the effects of horizontally inhomogeneous layers.

In the second group of simulations (Figure 12b) we split the perturbing layers into two parts and place them symmetrically about the tangent point with a gap (~1000 km) in between. Like the first set of simulations the packet of perturbations is placed near 100-km altitude. Now the simulated $E_s$ fluctuations appear at the tangent heights below 100 km as the LOS still intersects with these layers when tangent heights are below 100 km. However, influence of the far-side $E_s$ layers on SNR and phase decreases rapidly as the tangent height descends because the LOS is intersecting these layers at increasing angles (in other words, causing less diffraction). These simulation results imply that the SNR and phase variances must be treated with caution as the ambiguity arises from small-scale inhomogeneous horizontal and vertical structures.

4.3. Observational Filters

Observational filters also point out limitations associated with the radio occultation technique in terms of resolving vertical and horizontal scales of $E_s$ layers. Compared to ground-based techniques, which offer good vertical resolution and time coverage, GPS occultation technique can provide a comparable vertical resolution but coarse horizontal resolution. To quantify the sensitivity of the SNR and phase measurements to ionospheric fluctuations, we define the “observational filter” as the variance response to perturbations of different vertical or horizontal scales and compute these filter functions from the simulations with the MPS model.

Figure 12 shows the “1-s observational filters” of CHAMP SNR and phase variances as a function of perturbation vertical wavelength. Because the other input perturbations are held constant, the variance responses in Figure 14 depict mainly effects of the perturbation vertical wavelength on the SNR and phase variances. Each of these filter functions has a characteristic vertical scale where the variance maximizes. In the SNR case the variance response maximizes for perturbations at a vertical wavelength of ~1.2 km, whereas in the phase case it is ~2 km. It is interesting to note that the characteristic scale of 1.2 km in the SNR response is insensitive to the truncation length used (i.e., 51 points), which is very different from the phase variance response. The characteristic scale of the phase response shifts to a greater vertical wavelength for larger truncation lengths. Hence the phase variances can be used to infer the vertical wavelength spectrum of $E_s$ power, which would be an interesting study in the future.

The characteristic scale of observational filter is determined by the method used to compute the variance and by the physical processes (such as focusing/defocusing, refraction, and diffraction effects) affecting radio wave propagation. At small scales the SNR and phase variances are controlled by the diffraction effect of the perturbing layers, which tend to spread the perturbation power to a broader height (or angular) range in the observing plane, causing both reduced SNR and phase variances. Such spreading effect can be seen in the 0.2-km case of Figure 13. At large scales the phase variance is tapered by the truncation length used in the variance analysis. The characteristic scale of the phase variance is a result of the filtering at both large and small scales, but it increases with the truncation length as more power is allowed from long wavelengths. On the other hand, the SNR variances at large scales are determined primarily by the vertical gradient of refractivity perturbations [Karayel and Hinson, 1997] and depend weakly on the truncation length used. As a result the SNR variance decreases with vertical wavelength (~$\lambda^{-2}$ if horizontal $E_s$ scales are held constant) to yield the unique characteristic scale of ~1.2 km.

5. Discussions

The preliminary $E_s$ climatology from CHAMP ratio occultation is generally consistent with reports from ground-based observations. Global $E_s$ variance maps from CHAMP exhibit clear dependence on the geomagnetic dip angle and the horizontal winds. Most of the midlatitude $E_s$ variances can be qualitatively explained within the framework of the classical wind shear theory [Whitehead, 1961], whereas the high-latitude variances remain to be investigated thoroughly. More physical modeling work is needed to make realistic comparisons between the observed and modeled $E_s$ morphologies in the midlatitudes. In addition to the horizontal winds, impacts from other ionospheric and atmospheric variables must be considered, including magnetic field orientations, ion-neutral collision, electric field,
and ion sources. A simple model for $E_s$ layer generation [Mathews, 1998], which is based on the wind shear theory but neglecting electric and eastward magnetic fields, expresses the ion vertical velocity in the form as follows:

$$w_z = \frac{1}{1 + \gamma^2} (V \cos I \sin I + \gamma U \cos I),\quad (3)$$

where $\gamma$ is the ratio of ion-neutral collision frequency to ion gyrofrequency, $I$ is the geomagnetic dip angle, $U$ and $V$ are the zonal and meridional winds. It is generally believed that the zonal (meridional) wind is more efficient to affect ion motions at altitudes below (above) 130 km as the ratio $\gamma$ becomes greater (smaller) than unity. Nevertheless, $\gamma$ can vary largely with height at 100–150 km altitudes as well as with latitude. Such transition is evident in global model simulations with realistic horizontal winds [Carter and Forbes, 1999].

[46] The dip angle-dependent $E_s$ variances from CHAMP suggest that the influence of the meridional wind might extend far below 130 km. As seen in both DJF and JJA seasons, the $E_s$ variances appear to maximize near $|I| = 45^\circ$, which agrees with the maximum produced from the first term in (3). In other words, the geomagnetic field-controlled conductivity may play a dominant role in the formation of $E_s$ layers. In addition, the local time variation of these variances seems also consistent with the strong influence of the meridional wind. The 1000 and 2000 LST peaks are in phase with the semidiurnal nodes of the meridional wind at 105 km [Zhang et al., 2003], suggesting that the semidiurnal tide might play a direct role in modulating the $E_s$ layers at 100 km. However, the global model simulations [Carter and Forbes, 1999] did not show the extended influence of the semidiurnal tide at 100 km where only a diurnal variation is present. Clearly, the CHAMP observations can be used as strong constraints on these physical models to refine the mechanisms that control $E_s$. Our speculation about the semidiurnal tidal modulation in the $E_s$ variances is a simplistic explanation and does not consider potential influences from other variables, such as electric field and eastward component of the geomagnetic field.

[47] Above ~110 km the $E_s$ variances from CHAMP reduce sharply at summertime midlatitudes, implying a lack of layered electron density structures at 110–140 km (the nominal top of occultation profiles). A question imme-

**Figure 13.** MPS model simulations for the perturbation setting described in Figure 12, where (top) refractive index profiles are shown. L1 (middle) SNR perturbations and (bottom) phase perturbations were detrended in the same way with the 1-s filter as aforementioned for CHAMP data. Three perturbation cases with vertical wavelength (left) 0.2, (middle) 1, and (right) 4 km, are shown. Instrument/calibration noise is not considered in these simulations.
Immediately arises regarding the so-called intermediate layer, a descending ion layer from the bottom F region and often observed in Arecibo and other radar data [e.g., Mathews et al., 1993]. Some numerical models have reproduced these descending layers by imposing tidal-like modulations in the horizontal winds [Earle et al., 1998; Carter and Forbes, 1999]. However, the signatures of these descending ion layers are absent in CHAMP Es variances. One explanation is that these intermediate layers might be transient, lacking stability and coherency (over tens to hundreds of kilometers) to produce scintillations in the CHAMP data. As indicated in radar observations, these intermediate layers exhibit various stabilities and tend to fluctuate frequently over a much shorter timescale while descending. Thus the occultation technique may not be suitable for observing electron density fluctuations associated with these intermediate layers.

For the similar reason, small-scale field-aligned perturbations, like those due to gravity wave perturbations, are difficult for the GPS occultation technique to detect. As observed in ground-based radar echoes, these field-aligned oscillations are often embedded in Es layers and have horizontal scales of tens of kilometers and temporal scales of minutes. The long LOS path of GPS occultation will likely smear out most fluctuations of these kinds.

The CHAMP orbit is not ideal for sampling diurnal variations because of the long revisiting period (108 days). The CHAMP sampling can hardly resolve the aliasing between seasonal and diurnal/semidiurnal variations. In studying the diurnal variation, we carefully chose a period when the Es variances are large and relatively stable over a 3-month period. This allowed us to deduce the semidiurnal variation without being significantly influenced by the seasonal variation. However, the strong diurnal/semidiurnal variations become a problem when studying the seasonal variations, causing an artificial modulation in the latter due to the CHAMP sampling cycle (Figure 8). Combining the measurements from ascending and descending orbits helps reduce impacts of the diurnal variation, but the seasonal variation remains aliased to the semidiurnal variation (the dominant component of Es). Multiyear averaging may remove some of the semidiurnal influence on the seasonal variation by taking advantages of uncorrelated semidiurnal phases from year to year. An effective way to improve local time sampling is to combine existing SAC/C (Sun-synchronous) and CHAMP measurements. Complete removal of the aliasing between the seasonal and semidiurnal variations requires a better sampling which will become available with future missions such as COSMIC (six receiver satellites) or Equator Atmosphere Research Satellite in a low-inclination rapid precession orbit.

Finally, CHAMP Es variances in the enhanced regions are often significantly greater than the instrument/measurement noise. However, the noise treatment with the
(51, 3) truncation in the variance analysis is proven useful in detecting weak $E_\alpha$ variances. By removing large spikes from clock errors, the $E_\alpha$ variance maps have showed fewer patchy spots and more consistent patterns between the SNR and phase results.

6. Summary and Future Work

In this paper we described a novel variance analysis on the 50-Hz SNR and phase measurements from satellite radio occultation. The method is applied to GPS/CHAMP data and produces new information on global $E_\alpha$ morphology. The important results are summarized as follows:

1. The 51-point (or 1-s) variances from CHAMP SNR and phase data reveal strong $E_\alpha$ enhancements at summertime midlatitudes. The maximum $E_\alpha$ variance appears at $\Delta V = 105$ km near 45°S in January 2003 and $\Delta V = 102$ km near 45°N in June 2002.

2. The seasonal variation of the $E_\alpha$ variances shows a height-dependent morphology. The variance in the NH midlatitude summer peaks slightly later in time at higher altitudes.

3. Global $E_\alpha$ variance maps show strong dependence on the $E_\alpha$ strength on the geomagnetic dip angle at 105 km. The summertime midlatitude $E_\alpha$ variance.$\vert y \vert = 30^\circ - 60^\circ$, while the wintertime polar $E_\alpha$ variance.$\vert y \vert > 80^\circ$.

4. CHAMP also observes a strong semidiurnal variation in the midlatitude $E_\alpha$ variances with peak hours around 0800–1000 and 2000 LST at 100 km for the JJA season. The peak hours are delayed as height decreases and the 2000 LST variance maximum extends to a slightly lower height. For the DJF season the summertime $E_\alpha$ enhancement is dominated by a diurnal variation with the peak hour near 2000 LST.

5. Simulations using a radio wave propagation model suggest that the SNR and phase variances have different characteristics in the “observational filter” for $E_\alpha$-induced perturbations. The SNR variance has the maximum response at a vertical scale of $\sim 1.2$ km, and this characteristic scale is nearly independent of the truncation length used. On the other hand, the characteristic vertical scale of the phase variance increases with the truncation length, varying from 2 km in 51-point truncation to 8 km in 201-point truncation.

The initial results from GPS/CHAMP occultation reveal great potentials for observing global $E_\alpha$ phenomena. We anticipate more exciting results from other existing and upcoming GPS occultation missions, including SAC-C, Gravity Recovery and Climate Experiment, and COSMIC. With the improved global coverage and sampling (~250 occultations/antenna), the seasonal and diurnal variations of $E_\alpha$ can be fully resolved, along with the dependence on geomagnetic field, dynamic wind shear, metastable ions, solar radiation, and particle precipitation. Studies similar to this variance analysis can be readily extended to other GPS occultation measurements, and the joint analysis with the recent wind measurements from Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics satellite will be very useful for understanding the role of the horizontal winds. Global $E_\alpha$ observations from GPS radio occultation have raised some challenging issues for current $E_\alpha$ theory and models, and reliable statistics of global $E_\alpha$ morphology will add strong constraints on the underlying physical mechanisms in $E_\alpha$ generation and variation.

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