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PRELIMINARY INVESTIGATION OF LONGITUDINAL DIFFERENCES IN TEC AND SCINTILLATION AT TRANSITION LATITUDES

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The intensity of the two L-band signals transmitted from satellites of the Global Positioning System and the differential carrier phase (DCP) and differential group delay (DGD) between them have been recorded at two locations on opposite sides of the North Atlantic -- Hanscom AFB, MA, and Lerwick, Shetland Islands, UK. Recordings, at 20 samples per sec, were initiated in September 1989, with some 6790 hours of data being collected at Hanscom and some 3700 hours at Lerwick by the end of November 1990. The DCP records, calibrated by means of DGD, have been converted to measurements of ionospheric total electron content (TEC), with the intensity records being used to identify times of radiowave scintillation produced by relative fine structure therein. Substantially greater occurrence of sharp TEC gradients and scintillation was documented at Lerwick than at Hanscom, with clear evidence of geomagnetic control. The two stations are well separated in longitude, and their fields of view overlap substantially in latitude, although centered some five degrees apart geomagnetically. The large difference in TEC/scintillation activity may result from the latter difference or from other factors. Samples of the activity are provided herein, and recommendations are made for analyses designed to isolate the likely factors.

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PRELIMINARY INVESTIGATION OF LONGITUDINAL DIFFERENCES IN TEC AND SCINTILLATION AT TRANSITION LATITUDES

I. INTRODUCTION AND OBJECTIVES

The F layer of the earth's ionosphere behaves rather differently in three latitudinal regions. The simplest -- produced almost entirely by solar ultraviolet (uv) radiation and controlled largely by diffusion -- is the mid-latitude region, between about 20 and 50 deg geomagnetic latitude. The equatorial F layer, at lower geomagnetic latitudes, also is produced primarily by solar uv, but it is substantially more dynamic and structured on the night side of the earth than is its mid-latitude neighbor. Specifically, its plasma there is subject to convective-interchange instabilities analogous to the Rayleigh-Taylor instability, well-known in neutral fluid dynamics. Such instabilities result in substantial spatial variation in plasma density and its path integral, Total Electron Content (TEC). At sufficiently small scales, these structures produce random fluctuations -- "scintillations" -- in the phase, polarization, and intensity of radio signals received via transionospheric channels.

Poleward of the mid-latitude ionospheric lies another structured and still more dynamic region. The high-latitude ionosphere is produced, not only by solar uv, but also by energetic particles (primarily electrons with many kev of energy) that precipitate into it from the magnetosphere. In addition to providing a "storage bin" for these particles (also ultimately of solar origin), the magnetosphere -- and its interaction with the streaming plasma and imbedded magnetic field of the solar wind -- largely control the high-latitude F layer dynamically. Not only do plasma-interchange instabilities produce density and TEC structures there, but the primary force that drives them -- the **E** x **B** force, where **E** and **B** respectively denote the local electric and magnetic fields -- dictates convective motion of the F-layer plasma and its structures.

The high-latitude ionosphere may be divided further into the auroral and polar subregions, dominated respectively by particle and convective effects. Our interest in this report is in plasma structures and dynamics in the transition region between the mid-latitude and auroral ionospheres. Generally, the transition region lies between about 50 and 65 deg geomagnetic latitude, but the definition is not a static one. By transition latitudes, we mean the region of the ionosphere extending from the plasmapause (the poleward terminus of the mid-latitude ionosphere) through the scintillation boundary that lies near the equatorward edge of the auroral oval (the region of diffuse aurora). It includes the main plasma trough that separates the uv-derived, diffusively driven mid-latitude F layer and the particle-influenced, convecting high-latitude F layer. It lies more equatorward on the night side of the earth than on the day side and migrates progressively equatorward with increasing geomagnetic disturbance. In the North Atlantic, the transition region lies between geographic latitudes of about 45 and 70 deg, somewhat more southerly on the American side and northerly in the European sector.

Northwest Research Associates (NWRA) has conducted a preliminary investigation of L-band group delay, dispersion, and scintillation produced by the ionosphere on opposite sides of the North Atlantic. The project entailed the recording of differential group delay (DGD), differential carrier phase (DCP), and amplitude of the two L-band signals received from satellites of the Global Positioning System (GPS), using receivers owned by the Geophysics Laboratory (GL) of Air Force Systems Command (now an element of Phillips Laboratory). Measurements were conducted at GL, located at Hanscom AFB, MA, and at Lerwick, in the Shetland Islands, UK. While about 70 deg apart in longitude and almost 20 deg in geographic latitude, these two stations lie closer to one another in geomagnetic latitude, being respectively near 55 and 60 deg invariant. The DGD and DCP data were processed to identify dominant changes in group delay and dispersion, respectively. In addition, the signal-strength records were processed to evaluate L-band scintillation in terms of the fractional standard deviation, S_4, of received signal intensity (power).

The objectives of the project were (1) to determine differences between the parameters measured in the two different longitude sectors and (2) to interpret observed differences in terms of ionospheric total electron content (TEC) and intermediate-scale density structures near the two stations. The ultimate aim of the research is to understand the TEC and structural differences within the context of high-latitude ionospheric and magnetospheric dynamics. From the outset, however, the study was viewed as preliminary. It has been limited to identification of whatever differences might arise between the databases from the two stations. Systematically categorizing those differences will require separation of individual records in terms of the time and location of their line-of-sight intersections with the ionosphere.

II. RECEIVER INSTALLATION AND DATA COLLECTION

The first major task performed under the contract was to identify and arrange for use of an appropriate field site in the UK and to deploy a GPS receiver there. Lerwick was chosen because of its location in the transition region between geomagnetically middle and high latitudes (beneath the main ion trough and just equatorward of the usual location of the auroral oval) and because it would facilitate comparison with ionospheric data collected in that region by others (L. Kersely, private communication). Permission to install and operate the equipment at the Lerwick Observatory was obtained from the UK Meteorological Office in August 1989. The primary receiver (a Stanford Telecommunications Model STEL-5010) deployed to the Shetlands station previously had operated at Thule, Greenland. It was calibrated and its operation monitored for two weeks early in the first quarter of the project, and it was shipped to the UK on 4 September 1989. It arrived at Lerwick on 12 September and, after recalibration, was placed in service on 15 September. It has operated there since, with some interruptions due to various equipment and operational problems. A similar receiver (STEL-5010) began operation for this project at Hanscom on 25 September 1989, and it continues in similar operation for related purposes. In late March and early April 1990, NWRA configured and installed a backup receiver (a Texas Instruments Model TI-4100) at Lerwick.

Each STEL receiver records the intensity of the two signals (L1 at 1575.4 MHz, and L2 at 1227.6 MHz) transmitted from a single GPS satellite during any given observing period, along with the DCP and DGD between them. A satellite is doppler tracked typically for a few hours, and then the receiver selects another satellite based on the elevation of its forthcoming track across the sky. The raw measurements are recorded at 20 samples per sec (sps), the DCP and DGD data being smoothed and decimated later to 10 samples per min (spm) for processing. The TI 4100 receiver at Lerwick is capable of recording data from four satellites simultaneously.

An example of raw data from the STEL receiver at Lerwick is contained in Fig. 1, in the form of a strip chart run in the field for diagnostic and quick-look purposes. The two lower panels show the L1 (bottom) and L2 signal strengths, including some intensity scintillation -- in particular, three patches measuring $\pm$ several dB and lasting a few minutes. The top panel shows the DCP, subject to a many-π ambiguity. When the 2π crossovers are connected, the DCP provides a high-resolution record of relative TEC, subject to some fine-scale distortion at times of scintillation. The absolute value of TEC is provided, with far coarser resolution, by the DGD, shown (on an inverted scale) in the remaining panel in TEC units of 10^{16} el/m^2.

Early in the project, we laid out and implemented a spreadsheet routine to provide a catalogue and quick-look synopsis of activity levels from Lerwick and Hanscom. An example is shown in Fig. 2, which contains the spreadsheet output from Lerwick for the month in which the record shown in Fig. 1 was collected (on its last day). In the main field of Fig. 2 and of the spreadsheet outputs from other months, the single-digit entries, 1 through 6, refer to six levels of TEC variability, as determined from the DCP records. (A 0 entry denotes an hour in which no data were collected.) This TEC activity scale originally was developed from visual inspection of similar records from Thule, Greenland. It is quantified in the table on page 5, in terms of TEC change measured in TEC units per unit time. (See the reference* for sample records that defined the scale originally.) Single asterisks in the spreadsheet outputs denote times that intensity scintillation was detected on one (usually, the lower) or both of the two GPS frequencies. The threshold of detectability for scintillation is approximately $S_4 = 0.05$.

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*Klein, M.J., C.C. Andreasen, and J.M. Lansinger, 1988, "Transionospheric Scintillation and TEC Studies," *Final Technical Report GL-TR-90-0273*, Contract No. F19628-87-C-0003, Northwest Research Associates, Inc., ADA232836.

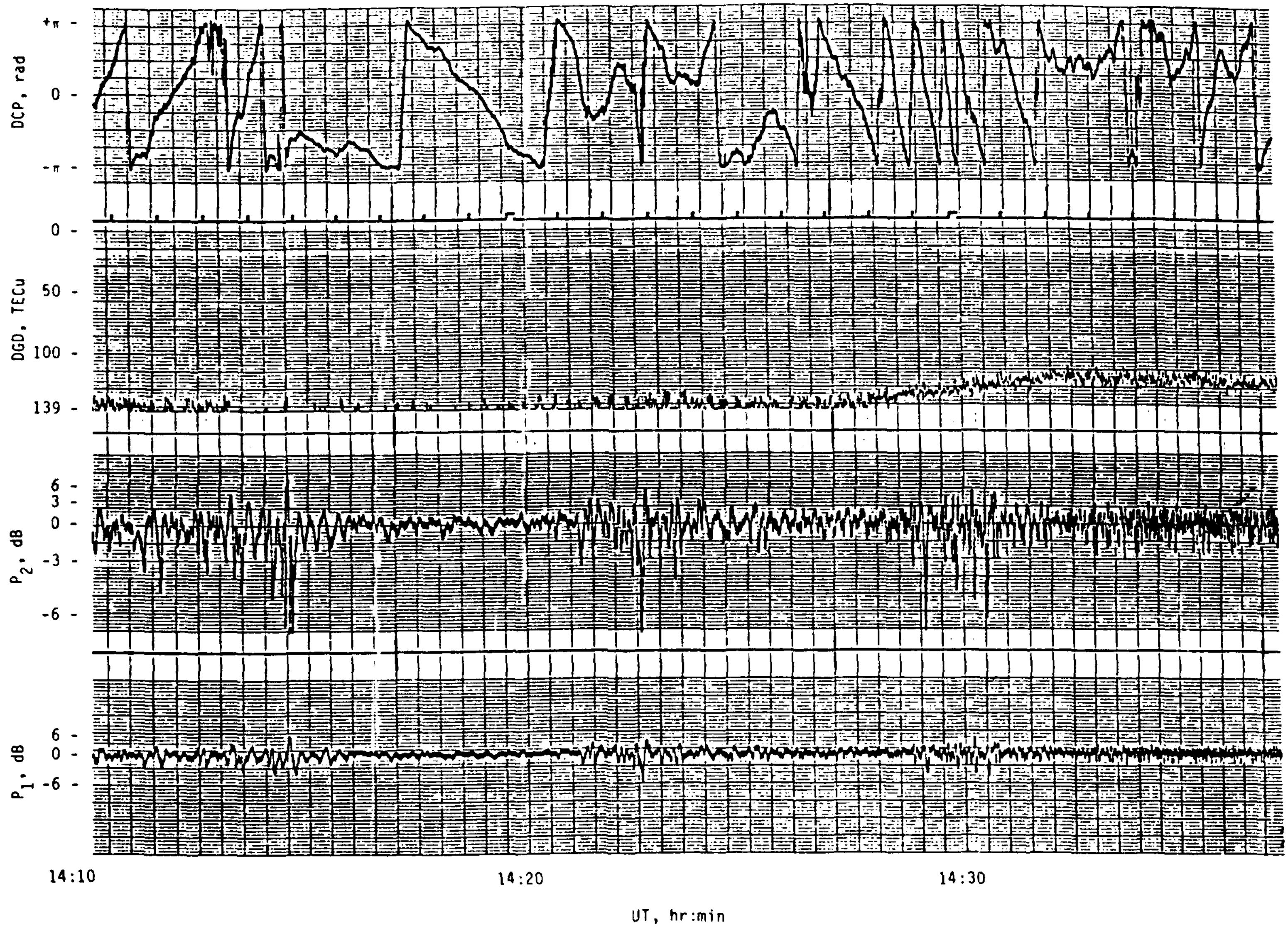

Figure 1. Sample strip chart of raw data output in the field for equipment diagnosis and quick-look data assessment. Panels, from top to bottom, show differential carrier phase (DCP) between L1 (1575.4 MHz) and L2 (1227.6 MHz), differential group delay (DGD) between the same two signals, and their received intensities (P_2 and P_1 for L2 and L1, respectively) in dB relative approximately to their means over the 26 minutes shown. Note the inversion (0 on top) of the DGD scale. Data recorded at Lerwick on 31 December 1989.

PLACE: SHETLAND MONTH: DECEMBER YEAR: 1989 ACTIVITY REPORT FOR STI 5010 GPS RECEIVER.

DAYS	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	DATA TAPE #	DAILY TOTAL HOUR'S ON AIR	DAILY ACTIVITY LEVEL 2 AND UP	DAILY ACTIVITY LEVEL 3 AND UP	ADDITIONAL COMMENT'S ON OCCURING PROBLEMS
01	2	1	0	0	0	0	0	0	0	0	0	0	0	0	F1	1	0	0	0	0	2	0	0	0	34-35	5	2	0	W
02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	1	35	7	0	0	W
03	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	A0	F0	1	0	0	0	0	35-36	4	0	0	W
04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	2	0	0	0	36	4	1	0	W
05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	A1	F0	0	1	E1	1	0	1	1	36-37	7	0	0	W
06	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	37	7	0	0	W
07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	A0	F1	E1	1	E1	0	0	37-38	6	0	0	W
08	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	A1	F1	0	1	1	1	E1	1	1	38-39	11	0	0	W
09	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	39	5	0	0	W
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	A0	F0	1	1	0	0	0	0	39-40	2	0	0	W
11	1	E1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	E1	1	0	1	1	40	11	0	0	W
12	0	0	0	0	0	0	0	0	0	0	0	0	A0	F0	1	1	0	0	0	0	1	1	2	0	40-41	5	1	0	W
13	1	1	1	1	0	0	0	0	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	41	17	0	0	
14	2	1	1	1	0	0	0	0	1	1	0	0	0	0	1	1	A1	F1	2	2	2	2	2	1	41-42	16	6	0	
15	C1	2	2	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	42	19	2	0	
16	1	1	1	1	0	0	0	0	1	2	2	1	1	1	1	1	1	1	A1	F1	1	1	1	1	42-43	20	2	0	
17	1	1	1	1	0	0	0	0	0	1	0	0	0	A0	F2	2	0	1	1	1	1	1	1	1	43-44	14	2	0	
18	1	1	1	1	0	0	0	0	1	E1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	44	20	1	0	
19	1	1	1	1	0	0	0	0	1	1	1	1	1	1	A1	F1	1	1	1	1	1	1	1	1	44-45	20	0	0	
20	1	1	1	1	0	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	1	1	1	1	45	12	0	0	
21	1	1	2	1	0	0	0	0	0	1	0	0	0	2	A1	F1	1	1	1	1	1	1	1	1	45-46	15	2	0	
22	1	1	1	1	0	0	0	0	1	1	0	0	0	2	3	1	0	1	2	2	1	1	1	1	46	16	4	1	
23	1	1	1	0	0	0	0	1	1	1	0	0	0	0	1	1	1	0	1	1	1	1	1	1	46	15	0	0	
24	1	1	1	0	0	0	A0	1	1	1	1	1	2	2	2	F1	0	1	2	2	2	2	4	4	46-47	19	9	2	
25	4	3	2	2	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	47	18	4	2	
26	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	A0	F0	1	1	2	2	2	2	2	47-48	9	6	0	
27	*3	*3	*2	2	0	0	0	0	2	2	0	1	1	1	1	2	1	1	2	4	*3	*3	*3	*3	48	19	13	7	
28	4	1	1	0	0	0	0	1	1	0	1	1	1	1	1	A1	F2	1	1	1	1	1	1	1	48-49	19	2	1	
29	*1	*1	*2	0	0	0	0	2	2	0	0	0	0	*4	*4	0	0	0	0	*2	*4	*2	*2	*3	49	12	10	4	
30	*3	*3	*2	0	0	0	0	0	2	0	0	0	0	3	2	A0	F1	*4	2	2	1	2	2	2	49-50	14	12	4	
31	*4	*4	*4	0	0	0	0	3	2	0	1	1	1	*3	*3	3	1	1	1	1	1	1	1	1	50	19	8	7	

COMMENT'S:

A: TAPE STOP.
B: GPS SYSTEM OFF THE AIR.
C: NEW SATELITE WINDOWS INSERTED.
D: SOME DATA ON CHART NOT RECORDED ON TAPE.
E: SOME DATA BROKEN UP.
F: TAPE CHANGE.
TOTAL HOURS OF ACTIVITY LEVEL 1:300
TOTAL HOURS OF ACTIVITY LEVEL 2:59
TOTAL HOURS OF ACTIVITY LEVEL 3:16
TOTAL HOURS OF ACTIVITY LEVEL 4:12
TOTAL HOURS OF ACTIVITY LEVEL 5:0
TOTAL HOURS OF ACTIVITY LEVEL 6:0

TOTAL HOURS OF ACTIVITY LEVEL 2 AND ABOVE: 87
TOTAL HOURS OF ACTIVITY LEVEL 3 AND ABOVE: 28

ADDITIONAL COMMENT'S.

* = L1/L2 SCINTILLATION.
** = NO ABSOLUTE TEC.
T = TAPEDRIVE PROBLEM.
H = HPIB INTERFASE PROBLEM.
V = FLOPPY DISK/DRIVE PROBLEM.
W = WRONG SATELITE WINDOWS.
P = POWER FAILURE.
Q = ANTENNA PROBLEM.

Figure 2. Example of spreadsheet catalogue and quick-look synopsis of TEC and scintillation activity, showing data for the month in which the record shown in Fig. 1 was collected.

Table. TEC variability levels.

	Level	Variability	Comment
1	Quiet	< 0.5 TEC u/10 min	No detectable activity.
2	Small	< 0.5 TEC u/ 5 min	Detectable TEC variation, detectable scintillation.
3	Moderate	< 1.0 TEC u/ 5 min	Smooth rolling structures.
4	Disturbed	< 1.0 TEC u/30 sec	Sharp, short gradients.
5	Very Disturbed	> 1.0 TEC u/30 sec	Very sharp, sustained gradients.
6	Extremely Disturbed	> > 1.0 TEC u/30 sec	Extremely large gradients.

The catalog resulting from the spreadsheets shows that, from September 1989 through November 1990, some 3700 hours of data were collected at Lerwick and approximately 6790 hours of data were collected at Hanscom. The main interruption in data continuity occurred at Lerwick between mid-June and mid-September 1990. There was no extended interruption at Hanscom. Data interruptions at Lerwick stemmed from several instrument problems, as well as en-route delays in shipping of blank tapes to the site. The former included temporary loss of an antenna during a severe windstorm in the Shetland Islands. Some problems did not result in total loss of data, since some data were recorded on strip charts and floppy disks, as well as on the primary magnetic-tape medium.

Certain problems degraded data in such a way that the degradation could be overcome in subsequent processing. One example involved calibration of the DCP records by means of DGD to permit measurement of absolute TEC. The DGD measurement is obtained from the relative time delay between coded messages (the so-called P code) telemetered on the two frequencies by the GPS satellites. The receiver produced telemetry inputs to the DGD measurement unit over a voltage range (-5 to +5 volts) that was twice that expected (0 to 5 volts) by the unit. A hardware modification in the field corrected the problem, and a software modification permitted recalibration of the erroneous data. The procedure was to convert the erroneous DGD values back to voltages and then to recompute the correct DGD and the corresponding TEC. The DGD unit was able to tolerate some negative voltage, although not as much as -5 volts. Thus, the original DGD values were correct except at certain voltage levels. The recalibrated TEC values still were somewhat unreliable near those levels, but we were able to refine them by means of the DCP measurements. To do so, we obtained reference points for absolute TEC from the reliable portions of the DGD records and connected them by means of the (relative, but highly precise) DCP records.

III. DATA PROCESSING

The data illustrated in Fig. 1 were recorded on magnetic tape for later calibration refinement, including linearization, and further processing. Regarding signal fluctuations, for instance, the intensity scintillation index was computed as follows:

$$S_4 = \langle (P - \langle P \rangle)^2 \rangle^{1/2} / \langle P^2 \rangle^{1/2} , \qquad (1)$$

where <> represents averaging over 1 min. These indices are shown in the top and bottom panels of Fig. 3 for, respectively, the L2 and L1 data illustrated in Fig. 1. The faithful manner in which the two indices track, that for the lower frequency being consistently larger than that for the higher, is an indication of high data quality. The obvious departure in this tracking fidelity at the end of the record, when the receiver was about to be switched to another satellite, gives ready indication that the extreme S_4 value for L2 (well in excess of unity) at that time is faulty. The (valid) L2 value of S_4 approaching 0.9, near the middle of the time span, is rare for L-band scintillation at high latitudes, although it is encountered more frequently near the geomagnetic equator, especially near solar maximum.

While scintillation is measured at each of the two frequencies, TEC is determined from the DCP and DGD between them, as follows. The TEC is related to the phase-path detect, ϕ_i, on each of the two frequencies, f_i, by

$$TEC = f_i \phi_i / c r_e , \qquad (2)$$

where c is the speed of light, and r_e is the classical electron radius. To measure the signal phase, one needs a phase reference from the satellite. To provide such a reference is the reason for receiving both L1 and L2, which are coherent harmonics of a common oscillator. The receiver produces a baseband signal whose phase is a scaled difference between ϕ_1 and ϕ_2. The two frequencies are sufficiently close together that their phase variations are correlated under most mid-latitude and high-latitude conditions. In this circumstance, the phase (in radians) obtained from the baseband signal and output from the receiver is

$$DCP = [1 - (f_2/f_1)^2] \, \phi_2 . \qquad (3)$$

Combining Equations (2) and (3), with the former evaluated at f_2, yields

$$TEC = 0.37 \, DCP , \qquad (4)$$

in TEC units.

The DCP is free of effects due to (the time integral of) geometrical doppler and phase instability in the transmitter and receiver (other than differential ones between the two carrier channels). Its time history yields, via Eq. (4), a very accurate measure of the time history of TEC variations along the radio propagation path. For typical values of TEC (which range globally from a few units to the order of 100 units), however, the DCP usually is ambiguous by several factors of 2π. The ambiguity is resolved by means of the DGD, which, when measured in nsec, is related to TEC by

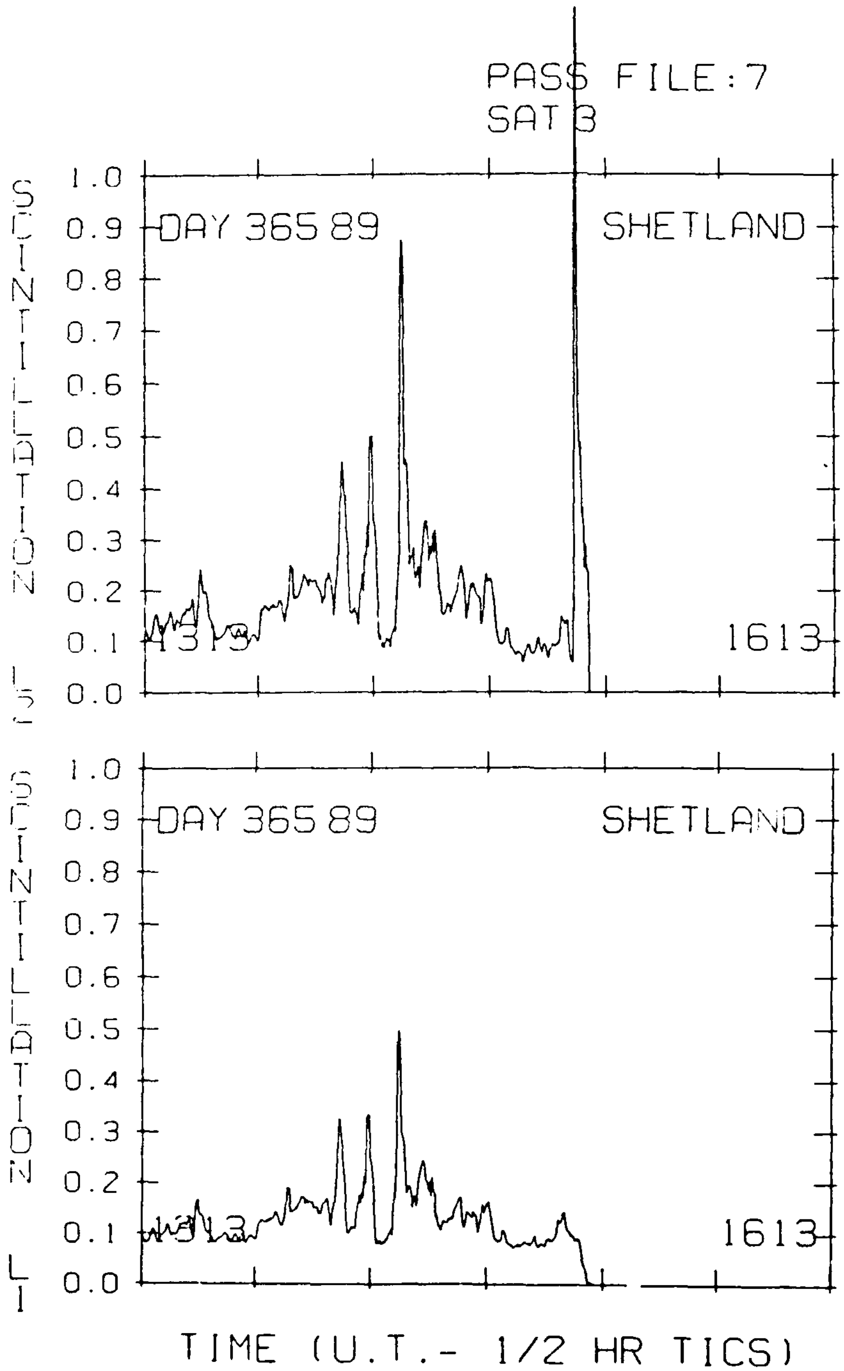

Figure 3. Intensity scintillation indices, S_4, computed for L2 (top) and L1 (bottom) from the raw data illustrated, in part, in the bottom two panels of Fig. 1. Time span is 13:13 through 16:13 UT. The three spikes in S_4 correspond to the three patches of scintillation in Fig. 1. The large spike in the L2 value occurred later than the end of Fig. 1 and is an obvious artifact.

$$\text{TEC} = 2.86 \text{ DGD} \tag{5}$$

units. Thus, DGD provides only a very coarse measure of TEC, but it is not ambiguous unless the TEC level reaches 279 units. The combination of DCP and DGD yields an estimate of absolute TEC and a precise record of its variations.

The TEC values recorded by the foregoing means during the satellite pass that yielded the intensity scintillation indices shown in Fig. 3 are presented in Fig. 4, along with the azimuth and elevation angles of the satellite as viewed from Lerwick. The double trace at the top shows the TEC measured on the slant path, the smoother one being obtained from the DGD and used to set the absolute level of the more finely structured one, which is derived from the DCP. The latter has been divided by the secant of the ray-path incidence angle on the ionosphere to convert the slant-path TEC to an equivalent vertical TEC, which is shown by the single curve plotted beneath the double trace. The azimuth and elevation are shown respectively by the x and + traces.

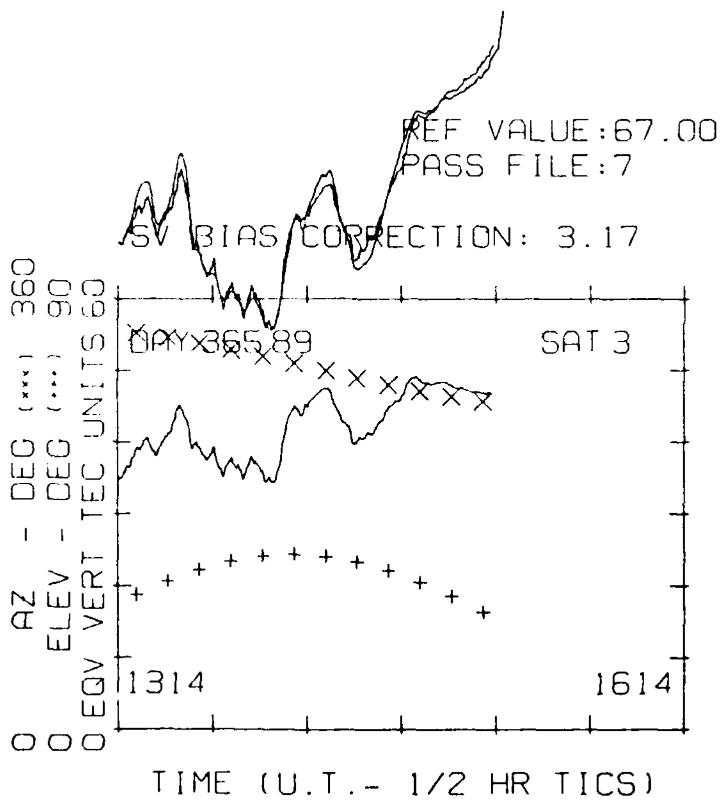

Figure 4. TEC values corresponding to S_4 records shown in Fig. 3, derived from the DGD (smoother of the two overlapping traces at the top) and DCP (more finely structured trace) measurements shown, in part, in Fig. 1. Lower solid trace is equivalent vertical TEC derived from DCP by removing effect of changing slant path-length. X and + indicate satellite azimuth and elevation, respectively. Time span is 13:14 through 16:14 UT.

Figure 5 contains a synopsis of TEC data obtained at Lerwick over the 24-hour period in which the GPS track that produced the data shown in Figs. 1, 3, and 4 occurred, along with satellite-location information. The solid traces show the equivalent vertical TEC derived from DCP and calibrated by means of DGD during eight separate satellite tracks of the type illustrated in Fig. 4. The sub-ionospheric latitudes and longitudes of the satellite tracks (location of point where raypath penetrates 350 km altitude) are shown respectively by the x and + traces. Individual track durations range from about an hour to about three hours, the two-hour (approximately 13 to 15 hours UT in Fig. 5) track shown in Figs. 3 and 4 being of typical duration.

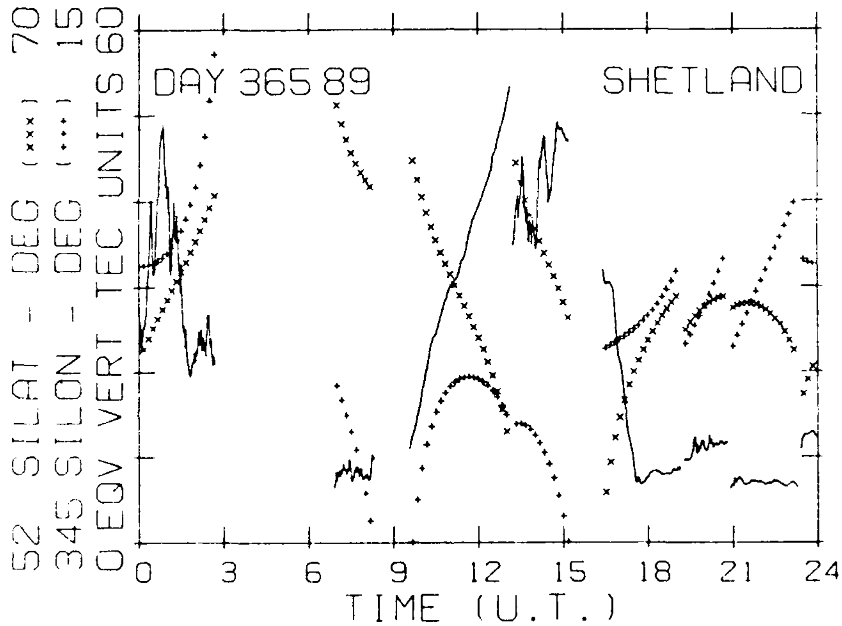

Figure 5. Synoptic chart of equivalent vertical TEC values (solid curves) derived from DCP and calibrated by means of DGD from measurements at Lerwick over the 24-hour period (31 December 1989, UT) in which the satellite track producing the data in Figs. 1, 3, and 4 occurred. x and + indicate satellite latitude and longitude, respectively.

IV. RESULTS

A single day's data from a single station contains a mix of information about TEC and scintillation in relation to several variables of interest, a point illustrated for TEC in Fig. 5 and in Fig. 6. In both, we see generally higher values of TEC in the middle UT hours (which also is midday in local time at Lerwick) than at night. This general behavior, more consistently portrayed in Fig. 6 than in Fig. 5, stems from the dominance of solar ultraviolet radiation in producing the ionosphere. This diurnal variation is convolved with any true longitudinal variation during a single track as the satellite drifts eastward (*e.g.*, the track through 03 UT in

Fig. 6) or westward (track through 18 UT). As the satellite drifts, so does the radio ray-path and its intersection with the ionosphere, which thus drifts to later or earlier times of day, respectively. Similarly, the satellite's northward or southward motion causes the intersection to move in geographic and geomagnetic latitude.

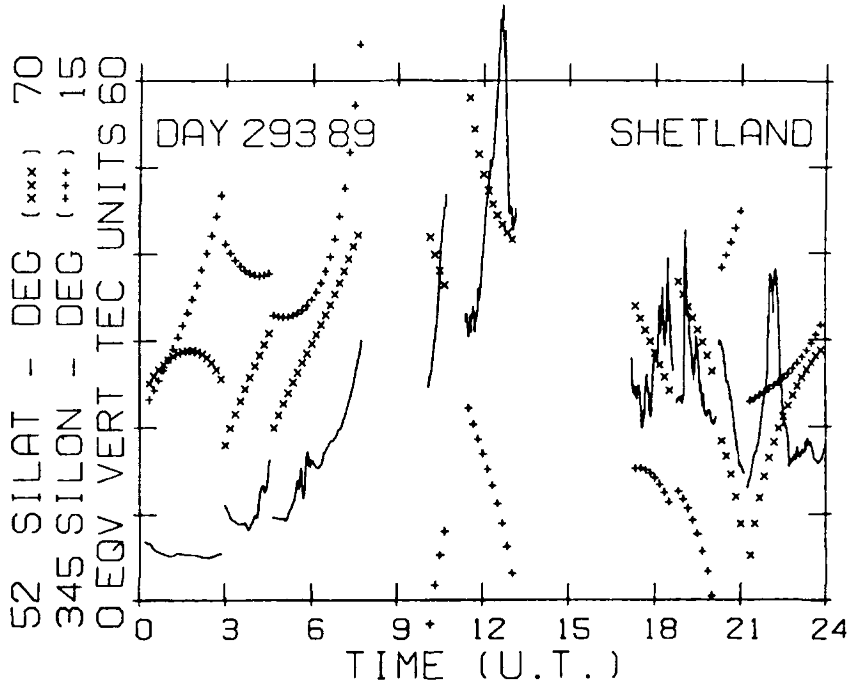

Figure 6. Synoptic chart of equivalent vertical TEC and satellite latitude and longitude for 24-hour period of 20 October 1989, UT.

Superposed on the drift of the penetration point in latitude and longitude is the drift of the ionospheric plasma itself. For instance, in the second half of the day shown in Fig. 6, considerable structure may be seen in the TEC records. This very likely is the signature of plasma-density structures convecting in the dusk sector of the auroral and sub-auroral F layer. The day shown (20 October 1989) was the first day of a major magnetic storm that lasted through the next day and on into 23 October. The storm's sudden commencement occurred at 09:17 UT on the 20th, and K_p reached 8+ for the period 18 to 21 UT. The day shown in Fig. 5 (31 December 1989) also was magnetically disturbed, especially in its early hours.

Clearly, detailed analysis of TEC and scintillation data within the context of ionospheric dynamics requires separation of the temporal and spatial behaviors described above. Such detailed analysis was beyond the scope of this preliminary investigation, but we were able to identify events of interest for such analysis in the future. For example, Fig. 7 contains the quick-look spreadsheet output from Lerwick for the month of September 1989 (the month in which observations started). We note four days in which substantial signal fluctuations, characterized by TEC activity at level 3 or above and/or by scintillation, took place. Three of these days -- the

PLACE: SHETLAND MONTH:SEPTEMBER YEAR:1989 ACTIVITY REPORT FOR STI 5010 GPS RECEIVER.

HOURS

DAYS	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	DATA TAPE #	DAILY TOTAL HOUR'S ON AIR	DAILY ACTIVITY LEVEL 2 AND UP	DAILY ACTIVITY LEVEL 3 AND UP	ADDITIONAL COMMENT'S ON OCCURING PROBLEMS
01																													
02																													
03																													
04																													
05																													
06																													
07																													
08																													
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10																													
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12																													
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14																													
15																F1	1	1	1	1	0	0	0	0	1	5	0	0	
16	*3	*2	2	0	0	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	19	3	1	
17	1	1	1	1	1	1	1	1	1	1	0	A1	F1	0	1	1	1	1	1	1	1	1	1	1	1-2	20	0	0	
18	1	1	1	1	1	1	1	1	1	A1	##	##	##	##	F1	1	1	1	1	*3	*3	2	1	2	2-3	20	4	2	
19	*2	*3	*3	2	*4	*4	*4	1	1	1	0	0	0	0	F1	1	1	1	1	1	1	1	1	1	3	20	7	5	
20	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	3	21	0	0	
21	1	1	1	1	1	A1	F1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	1	3-4	20	0	0	
22	1	1	1	1	1	1	1	1	1	1	0	0	0	1	*1	*1	1	1	1	1	1	1	0	1	4	20	0	0	
23	1	1	1	1	1	1	1	1	1	A1	0	0	F1	1	1	1	1	1	1	1	1	1	1	1	4-5	22	0	0	
24	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	1	5	20	0	0	
25	1	1	1	1	1	1	1	1	1	1	0	0	0	1	A1	F1	1	1	1	1	1	1	1	1	5-6	20	0	0	
26	1	1	1	1	1	1	1	1	1	1	0	0	0	*1	1	1	1	3	*3	1	*4	2	0	0	6	19	4	3	
27	0	1	1	1	1	1	1	1	1	1	0	0	0	A1	F1	1	1	1	1	1	1	1	0	1	6-7	19	0	0	
28	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	1	7	20	0	0	
29	1	1	1	1	1	1	1	1	1	0	0	0	0	1	A1	F1	1	0	1	1	1	1	0	1	7-8	18	0	0	
30	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	8	20	0	0	
31																													

COMMENT'S:

A: TAPE STOP
B: GPS SYSTEM OFF THE AIR.
C: NEW SATELITE WINDOWS INSERTED.
D: SOME DATA ON CHART NOT RECORDED ON TAPE.
E: SOME DATA BROKEN UP.
F: TAPE CHANGE.
TOTAL HOURS OF ACTIVITY LEVEL 1:285
TOTAL HOURS OF ACTIVITY LEVEL 2:7
TOTAL HOURS OF ACTIVITY LEVEL 3:7
TOTAL HOURS OF ACTIVITY LEVEL 4:4
TOTAL HOURS OF ACTIVITY LEVEL 5:0
TOTAL HOURS OF ACTIVITY LEVEL 6:0

TOTAL HOURS OF ACTIVITY LEVEL 2 AND ABOVE: 18
TOTAL HOURS OF ACTIVITY LEVEL 3 AND ABOVE: 11

ADDITIONAL COMMENT'S.

* = L1/L2 SCINTILLATION.
**= NO ABSOLUTE TEC.
T = TAPE DRIVE BROKEN.
H = HPIB INTERFASE PROBLEM.
V = FLOPPY DRIVE/DISK PROBLEM.
W = WRONG SATELITE WINDOWS.
P = POWER FAILURE.
X = ANTENNA BLOWN AWAY.
##= SYSTEM CALIBRATED.

Figure 7. Quick-look spreadsheet output from Lerwick for September 1989, indicating scintillation and/or elevated TEC activity on UT dates 16, 18, 19, 22, and 26, all of which were geomagnetically disturbed days.

18th, 19th, and 26th -- were the three most disturbed days of the month magnetically (K_p sum = 36+, 38-, and 35+, respectively). The remaining one -- the 22nd -- was the next most disturbed day magnetically (K_p sum = 28+) in the half of the month for which we have full GPS data from Lerwick, and the sixth most disturbed in the month. (The fourth most disturbed day of the month, with K_p sum = 35, was the 15th. The greatest magnetic activity on that day occurred in its closing hours, when the GPS receiver was not operating, as indicated by the 0s in Fig. 7. The fifth most disturbed day was the 4th, with K_p sum = 29-, prior to commencement of observations.) We present here a preliminary discussion of signal perturbations on 22 September, during which scintillation occurred with only modest TEC activity (level 1), and on 26 September, during which scintillation occurred with TEC activity as high as level 4.

Figure 8 contains the synoptic TEC chart from 22 September. Although classified as having only level-1 TEC activity, the first GPS track after noon UT clearly was the most disturbed of the 24-hour period shown. It was during the latter half of this track that the scintillation indicated in Fig. 7 occurred. We have performed further analysis of the data from this period. The latitude and longitude tracks (x and +, respectively) indicate that the satellite was moving slowly equatorward and eastward across the arctic circle east of Iceland, being the highest-latitude track of the day. The ionospheric penetration point scanned over the Norwegian Sea, in the general vicinity of the Faroe Islands northwest of the Shetlands. The southernmost segment of this latitude span had been sampled somewhat farther to the east (and, therefore, at a slightly lower geomagnetic latitude) on the last track before noon UT (several hours earlier), with generally quiet ionospheric conditions being encountered there and to the south.

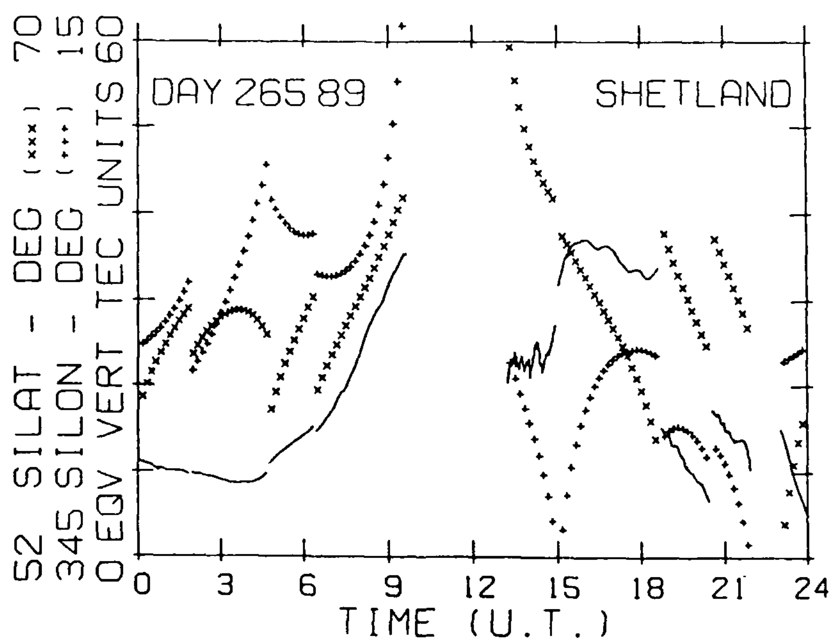

Figure 8. Synoptic chart of equivalent vertical TEC and satellite latitude and longitude for 24-hour period of 22 September 1989, UT. Scintillation occurred during UT hours 14 and 15, in the presence of level-1 TEC activity.

It happens that one of the "Transit" satellites of the Navy Navigation Satellite System (NNSS) was tracked from Lerwick near the time of both of the foregoing final forenoon and first afternoon GPS tracks (L. Kersley and G. Bishop, private communication, 1991). The Transit receiver output the dispersive phase (DCP) between 150-MHz and 400-MHz carriers, which are broadcast from all the NNSS satellites. Since the Transit satellites are in polar (90-deg inclination) orbits above (1000 km) the ionospheric F layer, their dispersive-phase records provide a latitudinal scan of relative TEC in the vicinity of the receiving station. By means not known to us, the Transit records are calibrated to an absolute level of TEC, our interest here being only in TEC gradients.

The latitudinal TEC scans from Transit most nearly coincident with the final forenoon and first afternoon GPS tracks on 22 September 1989 are reproduced in Fig. 9. We note that the transition region between the midlatitude (higher TEC) and subauroral (lower TEC) ionosphere is characterized by a steeper gradient in the afternoon pass than in the morning pass. All other conditions being equal, the afternoon period (steeper gradient) would have been more susceptible to development of plasma structures at transition latitudes by means of convective-interchange instabilities than would the morning period.

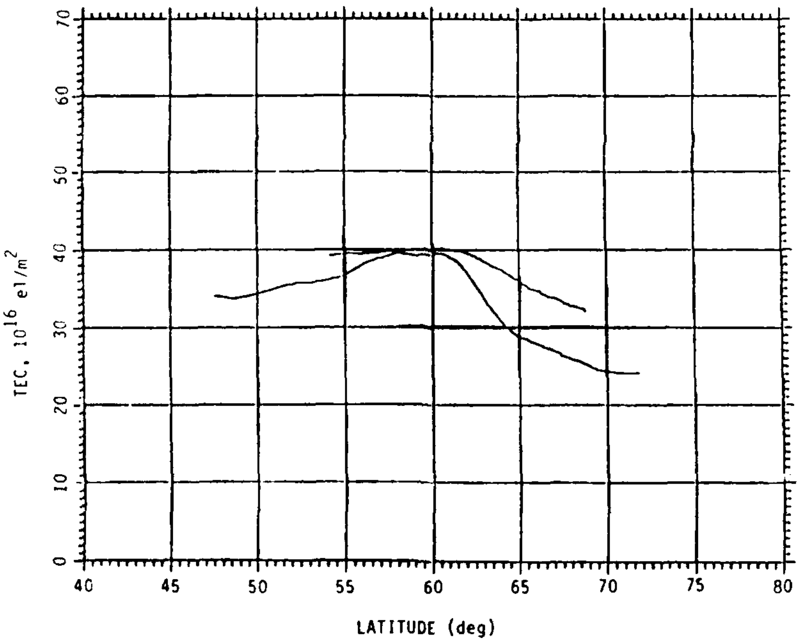

Figure 9. Latitudinal scans of TEC observed at Lerwick by means of polar-orbiting "Transit" satellites between 0906 and 0918 UT (shallow curve) and between 1518 and 1529 UT (steeper curve) on 22 September 1989. The former was approximately along the 353-deg meridian, and the latter approximately along the 4-deg meridian. (Data provided by L. Kersley via G. Bishop.)

The afternoon GPS track encompassed a latitude span some ten or so degrees higher, geomagnetically, than did the morning track. Thus, it would be expected generally to have sampled a more dynamic ionospheric region. On 22 September, the three-hour planetary geomagnetic activity index, K_p, developed as follows: 2, 3, 4-, 5-, 4+, 4+, 4-, 3-. Thus, the last morning GPS track occurred in a developing stage (3rd three-hour period) of geomagnetic activity, and the first afternoon pass occurred in a well-developed stage (5th period). By the latter time, the auroral and subauroral regions presumably had expanded equatorward from their quiescent, quiet-time locations.

In contrast to the single disturbed GPS track on 22 September, all post-noon passes on 26 September were disturbed, primarily in terms of TEC fluctuation. Scintillation was encountered also. The persistence of the post-noon TEC activity is evident in Fig. 10, which contains the synoptic TEC chart for the day. Noting that the track pattern in latitude and longitude is virtually identical to that of four days earlier (Fig. 8), we see that the TEC structures extended more equatorward on the 26th than on the 22nd.

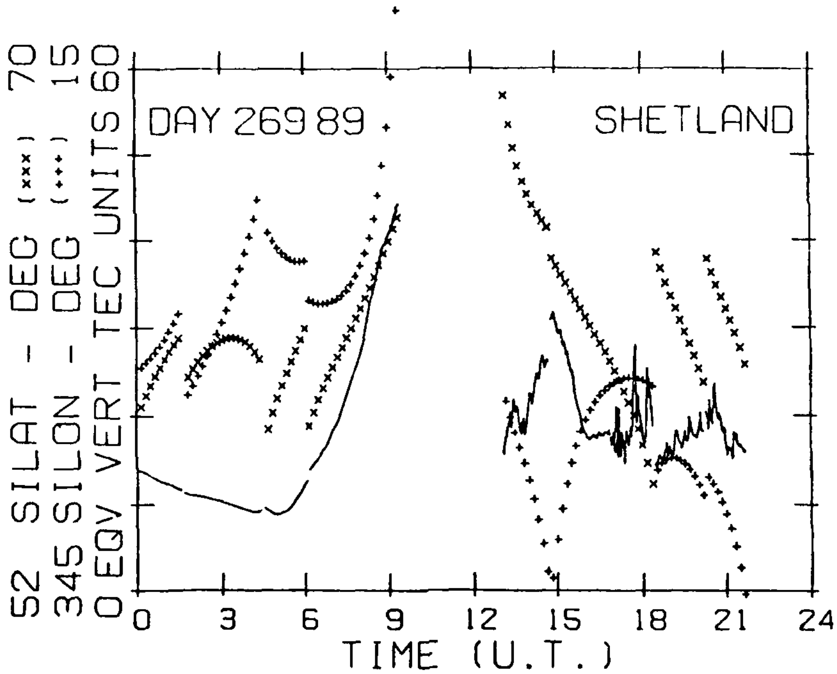

Figure 10. Synoptic chart of equivalent vertical TEC and satellite latitude and longitude for 24-hour period of 26 September 1989, UT.

Thorough investigation of signal behavior during disturbed conditions would employ a combination of the routinely processed data and the raw data, recorded at 20 sps. Spectral analysis of the raw DCP data also should be interpretable in terms of the spatial spectrum of relative fine structure in TEC and of the plasma-density irregularities responsible for it. Such spectral analysis has been performed on data from 26 September to demonstrate utility of the database collected under this contract for the purpose. Full accounting for the effects of diffraction would be somewhat complicated in the event of strong scintillation ($S_4 > 0.5$, say). Such events are rare in the database collected under this contract, so interpretation in terms of the spatial spectra of plasma structures should be feasible in future research. In this preliminary investigation we confined our efforts to the routinely processed data.

Figures 11 and 12 respectively contain the TEC and scintillation-index plots for the first afternoon pass on 22 September. We see that scintillation occurred in three patches. The first was coincident with some evident fine structure in TEC and the second with a local TEC enhancement encountered near 1413 UT. The third occurred during increasing TEC near the end of the pass. The presence of intensity scintillation means that the individual phases of the two GPS signals observed at the ground would not perfectly track the variations in TEC imposed by the line-of-sight integral of plasma density directly. The scintillation is sufficiently weak, however, that the effects of propagation on the phases of signals so closely spaced in frequency probably were correlated, a conjecture that can be tested by means of the individual (raw) intensity records. If so, the DCP record still should be interpretable in terms of TEC, and its spectrum in terms of the spatial spectrum of plasma structures.

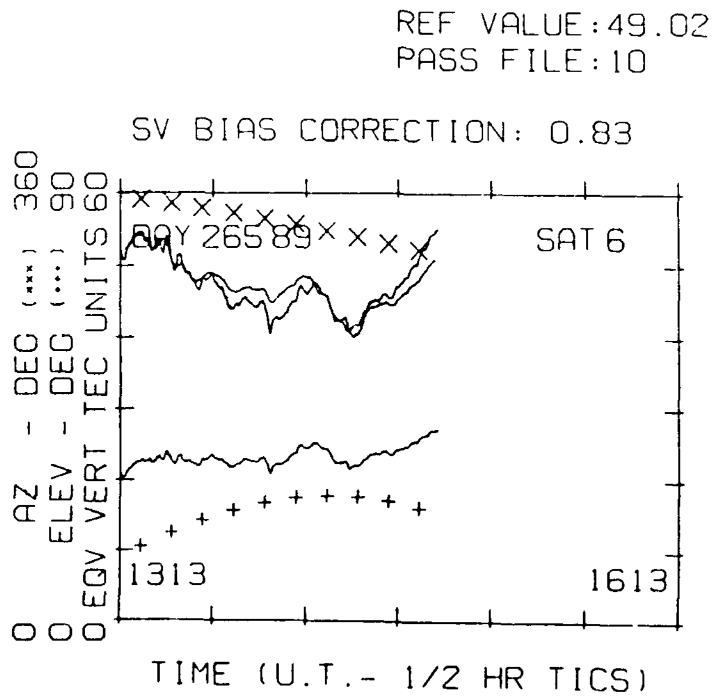

Figure 11. TEC measured during the first afternoon GPS track in Fig. 8.

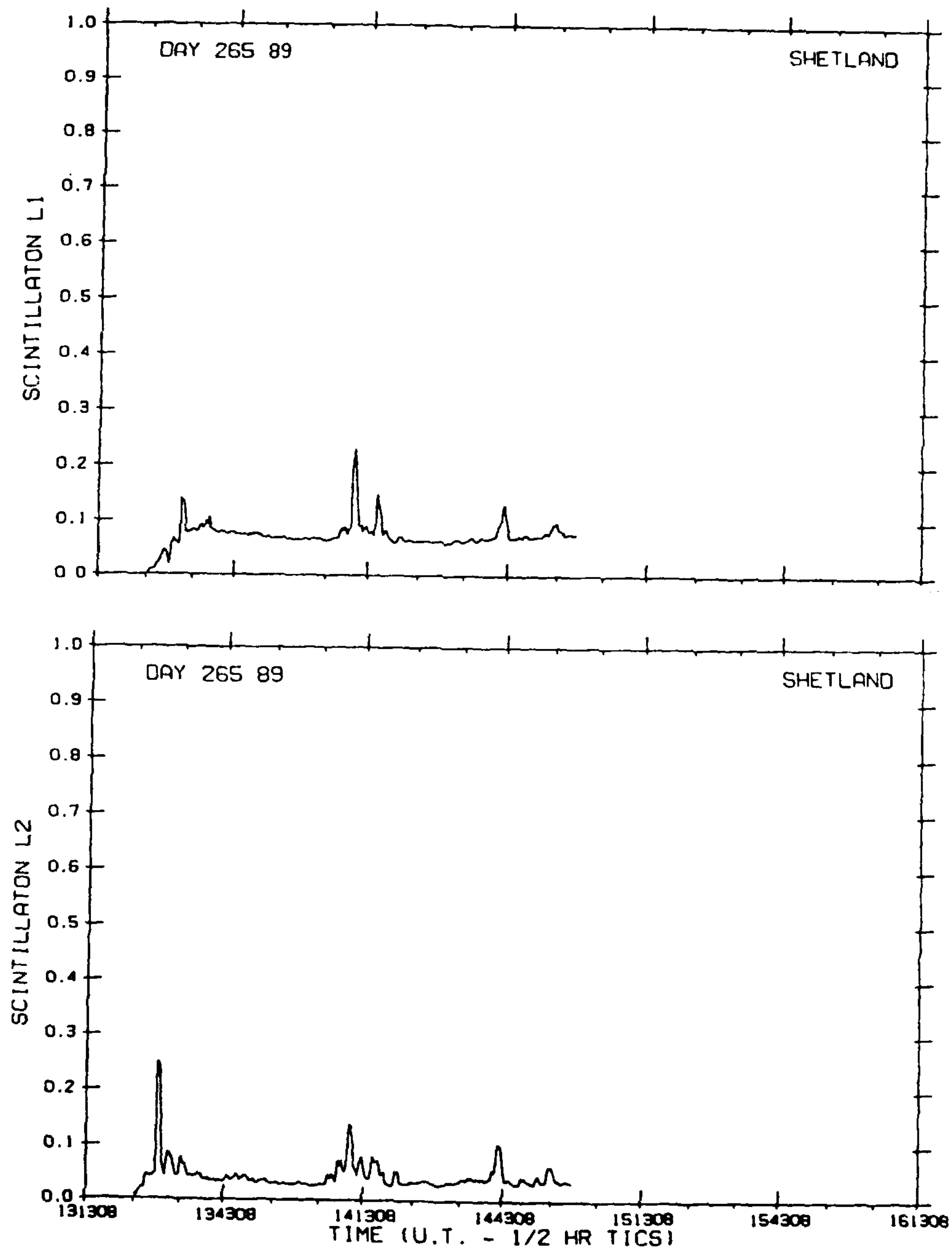

Figure 12. Intensity scintillation indices, S_4, measured during the first afternoon GPS track in Fig. 8.

Equally interesting features appear in the TEC records from the afternoon of 26 September, when the line of sight to four sequentially observed GPS satellites scanned first the highest-latitude region observable from Lerwick and then, thrice, lower transitional latitudes. The TEC record from the first (and longest) of the transitional scans is shown in Fig. 13. Of particular interest is the ten-minute-or-so period centered on about 17:27 UT, when strong quasi-period TEC variations were recorded. These variations could be the signature of a passing gravity wave launched from the auroral oval under geomagnetically disturbed conditions characterized by $K_p = 6+$.

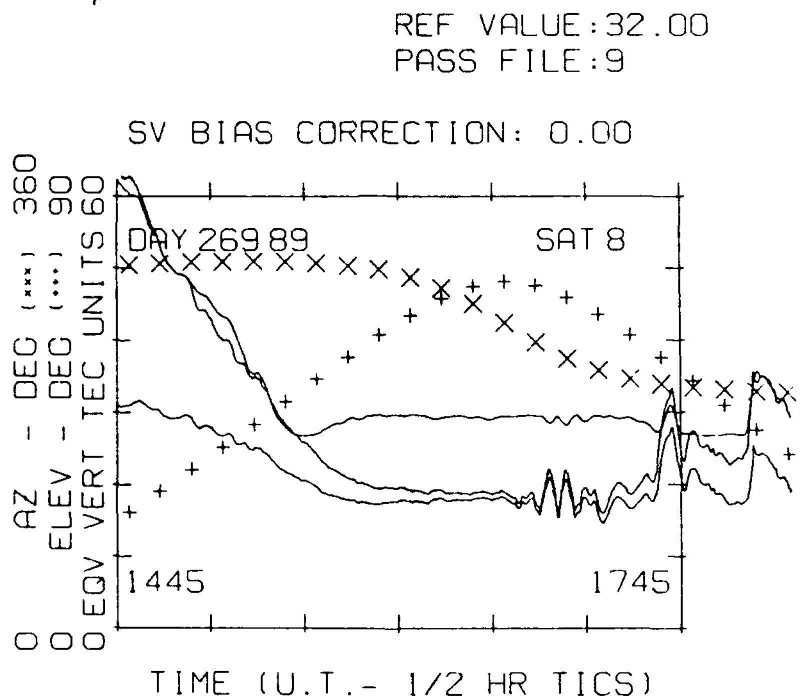

Figure 13. TEC measured during the second afternoon GPS track in Fig. 10. Note strong quasi-periodic signature centered on about 17:27 UT.

V. CONCLUSION AND DISCUSSION

In this preliminary investigation, we have found decidedly more variation in DCP, DGD, and L-band signal intensity in the database from the Shetland Islands than in that from Hanscom Field. This behavior discloses a far greater incidence of sharp TEC gradients and scintillation resulting therefrom in the ionospheric region viewed from Lerwick than in that viewed from Hanscom. New studies that have been proposed -- one employing routinely processed TEC and scintillation data of the type displayed in this report and one employing the raw (20-sps) data collected under this contract -- should disclose the nature of the ionospheric processes responsible for this observed difference.

The fields of view of the aforesaid two databases are well separated in longitude and largely overlapping in latitude. Still, their center points are separated in geomagnetic latitude by about five degrees, and this could be enough to account for the substantially greater degree of activity seen at Lerwick than at Hanscom. To test this possibility and to assess any residual effect due to longitude, each routinely processed data segment needs to be placed in a location/time bin. The bin should be defined by the latitude and longitude of the penetration point of the radio line of sight in the F layer (at 350 km, say) and the local time at that point. This is a simple matter of geometry. The local time and season then should be used to locate the penetration point relative to the solar terminator, so that gradients associated therewith can be identified.

Each location/time would correspond to a particular geomagnetic latitude and longitude/time, which also should be identified using a standard model of the geomagnetic field (preferably, the International Geomagnetic Reference Field). Given the clear evidence in the Lerwick database of geomagnetic control over the TEC and scintillation activity observed there, the data segments also should be placed into K_p bins. It may be that another index of geomagnetic activity, such as the auroral electrojet index, would parameterize the activity more systematically. This preliminary analysis disclosed an unusually clear relationship between the activity and K_p, however, so the latter would provide a useful starting point.

Detailed analysis of selected portions of the raw data would provide additional information on signal behavior and the underlying plasma structures that cause it. As a first step, the selected intensity and DCP measurements should be plotted for visual inspection at full (20-sps) resolution. Such inspection of the DCP records may yield identifiable signatures of TEC fine structure due to particular dynamical processes, analogous to that identified, at coarser resolution, in Fig. 13 as possibly due to a passing gravity wave. Inspection of the corresponding intensity records would disclose propagation effects that might have to be accounted for in interpretations. Useful in this regard would be inspection of both the L1 and L2 records, performing a "correlation by inspection" to ferret out any instances in which DCP may be altered by decorrelation of propagation effects on the two frequencies. We believe that such instances have been rare. Whether such propagation effects are absent or are to be dealt with, the DCP records should be interpreted either deterministically or statistically, depending upon the character of a particular event. In the latter case, spectral analysis should be used to interpret the DCP records in terms of the spatial spectrum of plasma-density structures, and we have proven its feasibility with the database collected under this contract.

It is recommended that the database described herein be incorporated into a more extensive one containing TEC and scintillation data from Hanscom Field; the Shetland Islands; and Thule, Greenland. We further recommend analysis of the contents of the combined database to form conclusions about the solar-maximum behavior of TEC and its fluctuations at trough-edge, auroral, and polar-cap latitudes. The results of such an analysis would contribute to software intended to characterize the transionospheric radio propagation channel employed for communication and surveillance purposes.