AFRL-VS-HA-TR-98-0037

# FURTHER INVESTIGATONS OF IONOSPHERIC TOTAL ELECTRON CONTENT AND SCINTILLATION EFFECTS ON TRANSIONOSPHERIC RADIOWAVE PROPAGATION

C.C. Andreasen
E.J. Fremouw
A.J. Mazzella, Jr
G.S. Rao
J.A. Secan

NorthWest Research Associates, Inc
PO Box 3027
Bellevue, WA 98009-3027

12 February 1998

Scientific Report No. 3

19980608 051

**AIR FORCE RESEARCH LABORATORY**
Space Vehicles Directorate
29 Randolph Road
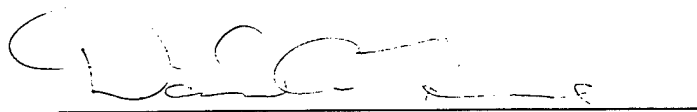**AIR FORCE MATERIEL COMMAND**
**HANSCOM AFB, MA 01731-3010**

"This technical report has been reviewed and is approved for publication"


GREGORY J. BISHOP
Contract Manager

ROBERT A. MORRIS
Acting Branch Chief


DAVID A. HARDY
Acting Chief


This report has been reviewed by the ESC Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies form the Defense Technical Information Center (DTIC). All others should apply to the National Technical Information Service (NTIS).

If your address has changed, if you wish to be removed from the mailing list, if the addressee is no longer employed by your organization, please notify AFRL/VSOS-IM, 29 Randolph Road, Hanscom AFB, MA 01731-3010. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

# REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or another aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE<br>12 February 1998 | 3. REPORT TYPE AND DATES COVERED<br>Scientific No. 3 |
|---|---|---|

**4. TITLE AND SUBTITLE**

Further Investigations of Ionospheric Total Electron Content and Scintillation Effects on Transionospheric Radiowave Propagation

**6. AUTHOR(S)**

C. Charley Andreasen, Edward J. Fremouw, Andrew J. Mazzella Jr., G.-S. Rao, James A. Secan

**5. FUNDING NUMBERS**

F19628-94-C-0067
PE 62601F
PR DMSP
TA GH
WU AA

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Northwest Research Associates, Inc.
14508 NE 20th Street
P.O. Box 3027
Bellevue, WA 98009-3027

**8. PERFORMING ORGANIZATION REPORT NUMBER**

NWRA-CR-98-R177

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010
Contract Manager: Greg Bishop / VSBP

**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

AFRL-VS-HA-TR-98-0037

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release - distribution unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** (Maximum 200 words)

The effects of the ionosphere on numerous communication, navigation, and surveillance systems continue to be of Air Force concern. In this project, Northwest Research Associates (NWRA) is collaborating with researchers from Air Force Research Laboratory at Hanscom AFB and others to address these concerns in three broad areas. In the most advanced effort, operational code for running a gridded version of the WBMOD ionospheric scintillation model, called WBMGRID, with the full Scintillation Decision Aid (SCINDA) system was delivered to the 50th Weather Squadron (now the 55th Space Weather Squadron). The most extensive of the NWRA efforts involved careful use of two-frequency GPS receivers to measure ionospheric total electron content (TEC), which introduces range errors on operational GPS links. Central tasks in this effort included utilization of receivers at four operational sites of the Ionospheric Measuring System (IMS), continued development and refinement of the IMS employing a fifth receiver located at Hanscom, and assessment and analysis of the resulting data. The newest of the efforts goes beyond passive observation of ionospheric effects on radiowave systems to preparation for active experiments in the High Frequency Active Auroral Research Program (HAARP).

**14. SUBJECT TERMS**

Global Positioning System (GPS), High Frequency Active Auroral Research Program (HAARP), ionosphere, radiowave scintillation, space weather, total electron content (TEC)

**15. NUMBER OF PAGES**
42

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT<br>Unclassified | 18. SECURITY CLASSIFICATION OF THIS PAGE<br>Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT<br>Unclassified | 20. LIMITATION OF ABSTRACT<br>SAR |
|---|---|---|---|

# Contents

# Further Investigations of Ionospheric Total Electron Content and Scintillation Effects on Transionospheric Radiowave Propagation

## 1. Introduction

The overall objective of the various tasks that make up this project is to improve our understanding of ionospheric effects on transionospheric radiowave propagation. The phenomena being studied cover the full range of scale sizes from tens of meters (scintillation effects) to thousands of kilometers (large-scale TEC effects). The twelve tasks outlined in the proposal for this work [Fremouw et al, 1994] can be grouped into the following six study areas. (The tasks in the proposal corresponding to these study areas are indicated in parentheses.)

1.  Investigate the logarithmic slope of the phase-scintillation power-density spectrum (PDS) at large scales in the equatorial region. Develop a model for a two-regime power-law PDS based on the results of the investigation and implement it in WBMOD. (Tasks 1 and 2)

2.  Investigate the magnitude and behavior of small-scale phase gradients using the equatorial scintillation data sets built in the first study. Develop algorithms for including the effects of small-scale phase gradients on transionospheric propagation and implement them in the WBMOD ionospheric scintillation model. (Tasks 3 and 4)

3.  Develop models consistent with the current propagation algorithm in WBMOD for individual intermediate-scale ionospheric features associated with enhanced scintillation (equatorial plumes, polar patches, auroral boundary blobs). Implement these in WBMOD. (Tasks 5 and 6)

4.  Develop techniques for producing short-term forecasts of scintillation effects over large spatial areas, implementing and demonstrating these techniques in computer programs. (Task 7)

5.  Deploy, operate, and maintain satellite receiver instrumentation on a long-term basis at local and remote sites to collect databases of ionospheric Total Electron Content (TEC) and scintillation observations. Use these data to (a) analyze performance of ionospheric monitors, (b) validate models of ionospheric behavior, and (c) develop/formulate algorithms to improve the performance of both ionospheric monitors and models. (Tasks 8 and 9)

6.  Deploy, operate, and maintain satellite receiver instrumentation on a short-term basis at local and remote sites where unique opportunities exist for enhancement of test data sets, particularly where other instruments have been deployed to collect other ionospheric measurements. Collect these data, and ancillary data from other instrumentation, into documented data sets that can be used as outlined in the previous study description. (Tasks 8, 9, and 12)

[Note: Task 11 is not explicitly included in the above listing as it includes support to all of the various tasks described in the proposal.]

In response to a memorandum from the Contracting Officer dated 6 June 1996, Northwest Research Associates (NWRA) has shifted emphasis from study areas 1 through 4, above, to study areas 5 and 6. As regards study area 6, especially, NWRA is participating in the High-frequency Active Auroral Research Program (HAARP) managed by Phillips Laboratory at Hanscom (PLH, now part of the Air Force Research Laboratory) and the Office of Naval Research (ONR). This report summarizes progress during the period 1 July 1996 through 30 June 1997. HAARP activities are reported in a separate subsection.

## 2. WBMGRID Algorithm and Code Development

A meeting took place on 25 July 1996 between NWRA personnel and representatives of PLH/GPIA and RADEX to discuss the WBMGRID codes delivered on 10 June 1996. The following changes to these codes were requested:

1. Calculate the longitude variation of $log(C_kL)$ written to file latfun.dat for the local time at the longitude specified for the real-time inputs (program IRRGRID).

2. Permit the use of real-time inputs to modify the climatology without generating a section within which only the non-plume $log(C_kL)$ value is output to the grid (program IRRGRID).

3. Permit input of latitude boundaries for the real-time analysis section as well as the longitude boundaries (program IRRGRID).

Version 0.01 of the WBMGRID codes incorporating these changes was delivered via ftp to RADEX on 2 August. The WBMGRID User's Manual was updated on 2 August to reflect changes to the inputs and outputs of the various codes, and a copy was provided to PLH/GPIA at that time.

After discussions with RADEX and PLH/GPIA personnel, a further modification was made to the IRRGRID program to decouple the maximum values within the equatorial region and at the equatorial crests, and Version 0.02 of program IRRGRID was delivered via ftp on 5 August. During further testing of the WBMGRID codes, RADEX personnel found a logic error in the way that the LLGRID program processed inputs of the longitude range for the analysis. This was corrected, and a new version of subroutine LATBYLON for program LLGRID was ftp'd to RADEX on 22 August. None of these changes required modification of the User's Manual. No further modifications or changes have been made to the code.

Work on this task during the report period was focused on the formal delivery and initial installation of WBMGRID with the full SCINDA system at 50th Weather Squadron [50WS, now 55th Space Weather Squadron (55SWXS)]. No problems with the WBMGRID software were identified to NWRA during or subsequent to the test/implementation period. No further changes to the code have been requested.

While at 50WS, we were asked if it would be possible for us to implement SCINDA at NWRA to aid in developing updates. After some discussion, it was determined that the SCINDA code would require a platform that supports the OpenGL graphics engine, and that we should look into two options (Windows/NT and Linux) for implementation at NWRA. A small effort was begun investigating these two options, an effort that was abandoned when the decision was made not to release the SCINDA code.

3

## 3. SSIES Data

The decision was made by PLH/GPIA to discontinue our efforts to obtain a sample of SSIES data from 50WS in order to assess the performance of the current SSIES processor and the quality of the data that would be available for P. Sultan's SSIES analysis package. It is our understanding that responsibility for this assessment has been passed to PLH/GPSG (Dr. Fred Rich). We have, therefore, dropped all work in this area pending further guidance from PLH/GPIA.

## 4. Ionospheric Measurements

### 4.1 Operations

Data files continue to be processed, reviewed, and archived to tape at each of the deployed Ionospheric Measuring System (IMS) sites at Eareckson Air Force Station, Shemya, Alaska (following its initial validation period at Hanscom); Thule Air Base, Greenland; Croughton, United Kingdom; and Otis Air National Guard Base, Massachusetts. Data processing, review, and archiving for the fifth IMS commenced at Hanscom in March 1997, when this system was delivered from the Charles Stark Draper Laboratory (CSDL). The 15-Minute TEC data reported by the IMS are plotted for each day at each site, to monitor the calibrations, data anomalies, and changes in the active GPS constellation. Tapes are catalogued for content and indexed for local storage upon arrival at PLH each month.

GPS ephemeris files are retrieved from Holloman AFB on a weekly basis, for use in determining the apparent sky positions of GPS satellites and the associated Ionospheric Penetration Point (IPP) coordinates, which are used by the bias-determination process. An auxiliary program was developed to plot the GPS satellite coverage versus time, using these sky-position files, to facilitate comparisons of predicted to actual coverage.

A summary log is being maintained for the Otis IMS, the Croughton IMS, the Thule IMS, and the Shemya IMS, primarily to monitor the duration of operations for each of the two UNIX computer systems in each IMS. The cause of the system shutdown is also recorded in this log. Utilization of a script previously developed to process the status-report files from the IMS, in conjunction with a processor identification report to the on-site system log, has greatly facilitated this log maintenance. A histogram of system operating-time durations, by month, is included in this summary log for each IMS, and a summary table displaying the total percentage of operating time for each month and the number of occurrences of various outage causes also has been developed. A sample table is included as Table 1.

Table 1: Summary performance table for the IMS sites.

| | Percent Uptime | awn main | dms main | mps main | rcv main | All main | Sync fail | Time diff | Temp <10C | Temp >30C | Cmd | Total | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aug 1996** | | | | | | | | | | | | | |
| Otis | 99.7 | | | | 7 | | | | | | | 7 | |
| Croughton | 99.8 | | | 8 | 5 | | | | | | 2 | 15 | |
| Thule | 95.8 | | 1 | 1 | 5 | 1 | | 2 | | | | 10 | |
| **Sep 1996** | | | | | | | | | | | | | |
| Otis | 99.4 | | | | 10 | | | | | | 4 | 14 | |
| Croughton | 99.6 | | | 6 | 7 | | | | | | 4 | 17 | |
| Thule | 99.8 | | | | 4 | | | | | | 1 | 5 | |
| Shemya | 99.8 | | | | | | | | | | | | Deployed 20-Sep |
| **Oct 1996** | | | | | | | | | | | | | |
| Otis | 96.5 | 1 | | 1 | 5 | | | | | | 2 | 9 | Maint visit: 31-Oct; Outage:7-Oct |
| Croughton | 99.8 | | | | 3 | 1 | 5 | | | | | 9 | |
| Thule | 99.9 | | | 1 | 5 | 2 | | | | | | 8 | |
| Shemya | 99.5 | | | | 5 | | | | | | | 5 | |
| **Nov 1996** | | | | | | | | | | | | | |
| Otis | 99.5 | 1 | | 5 | 4 | | | 1 | | | 3 | 14 | |
| Croughton | 99.4 | | | | 6 | | 6 | | | | | 12 | |
| Thule | 83 | 1 | 3 | | 3 | | | | 5 | | | 12 | |
| Shemya | 99.7 | | | | 5 | | | | | | 4 | 9 | |
| **Dec 1996** | | | | | | | | | | | | | |
| Otis | 99.6 | 1 | | 1 | 9 | | | | | | | 11 | |
| Croughton | 99.8 | | | | 5 | | 5 | | | | | 10 | |
| Thule | 71.5 | | 5 | 1 | 3 | | | | 5 | 2 | | 16 | |
| Shemya | 94.2 | | 1 | | 6 | | | | | | | 7 | Outage: 6-Dec |

The hard disk for the local PC used to monitor the remote IMS sites displayed preliminary indications of failure mode in the period just prior to the IMS installation visit for Shemya, in September 1996, and finally failed shortly after the commencement of the Shemya visit, while an order for replacement drives was still being processed. IMS support efforts were shifted to utilize a second PC normally dedicated to data analysis and processing development. This PC then experienced a power supply failure, while the Shemya site visit was still in progress. Support efforts were then shifted to the PC that had been remotely monitoring the Real-Time Monitor (RTM) system at Shemya, and continued there until the power supply in the second system was replaced on 26 September 1996. A new hard drive was acquired soon after the completion of the Shemya installation trip, and this drive was installed in the IMS monitoring system and configured for use. A new video monitor was subsequently added to this system.

To facilitate utilization of the IMS companion PCs by CSDL during their system configuration surveys, separate user accounts were established on the companion PCs for remote access by either NWRA or PLH personnel based at PLH or personnel at CSDL. NWRA personnel also conducted a tutorial session at CSDL demonstrating the techniques for proper remote connection to the companion PCs or directly to the IMS.

The spare IMS companion PC was configured for use with Windows/NT 4.0, using one of the spare hard disks that were acquired after the Shemya installation trip. The required application software and existing IMS processing software were being installed on the system, in preparation for simulation testing as an IMS companion PC, but the system chassis was required for shipment to Croughton, and its replacement from Croughton was subsequently shipped to Shemya, so this development effort was suspended. It is expected that Windows/NT 4.0 will

provide more stable operations than Windows 95, with the additional advantage of matching the operating system in use on PCs at PLH.

The lingering demise of PRN 20 over the period August 1996 to December 1996 posed a problem for the IMS 15-Minute TEC reports, in that the Differential Carrier Phase (DCP) increased linearly with time, so that the phase-averaging produced a completely unrepresentative slant TEC and the resulting equivalent vertical TEC could range as high as 300 TEC units. A health-status indicator is incorporated in the IMS Automated Weather Network (AWN) transmissions to 50WS, but the data processing there did not filter the data based on this indicator. A provisional method of excluding the data from consideration by 50WS was implemented based on the recognition that negative equivalent vertical TEC values are not reported in the AWN transmissions. Consequently, a large bias value was set for PRN 20 in the IMS bias configuration table, sufficient to keep all TEC values negative. A similar technique was applied to PRN 10 and PRN 30 when these satellites were initially activated for the GPS constellation, but had not attained a normal health status and had not been calibrated. This bias assignment is now the default value used in the IMS configuration files for all uncalibrated satellites.

In conjunction with the suppression of TEC values reported to 50WS from unhealthy or uncalibrated GPS satellites, a description was prepared of a possible extension to the IMS bias configuration table to facilitate this process while maintaining clarity within the configuration table. This description was distributed to personnel from PLH, McClellan AFB, 50WS, and CSDL for further comment and possible implementation.

NWRA personnel participated in a status meeting on 9 January 1997 that was conducted with personnel from PLH, McClellan AFB, and CSDL to present the current status of the IMS developments and to coordinate efforts for the transfer of the fifth IMS and the Software Development system to PLH. These systems were received at PLH in early March, and assistance was provided to PLH personnel in re-assembling the fifth IMS. On-line documentation for the IMS was stored on one of the pair of PCs being returned to PLH by CSDL, and these files were retrieved and stored on the IMS monitoring PC for general access. This documentation has been surveyed and indexed, with reference to available documentation lists, and is also being reviewed for completeness and information regarding IMS operations and functionality.

The Software Development system for the IMS was assembled and configured for operational use, with local network connections established to the fifth IMS, for testing purposes. The local network connections between the Development System and the IMS were interrupted temporarily by a reconfiguration of the laboratory workspace due to repair work.

The elevation-threshold setting applied by the IMS software for the selection of data to be processed was changed in October 1996 from its provisional value of 25 degrees back to its original value of 15 degrees, to improve the degree of spatial coverage. The threshold of 25 degrees had been instituted in late 1995 in conjunction with investigations of anomalous data samples at low elevations, but this problem was also addressed by changes in the Matlab scripts on the IMS, so it was not apparent that the 25-degree threshold should be retained. The threshold

7

was reduced by successive steps for the Otis IMS, with examination of the data at each step, until the 15-degree threshold was attained, without an accentuation of low-elevation data sample anomalies. The 15-degree threshold was then instituted at Shemya, also without a consequent accentuation of low-elevation data sample anomalies. The elevation thresholds had never been modified for either the Croughton IMS or the Thule IMS, and these values were left unchanged. The software elevation threshold was not reduced below 15 degrees because the setting for the receiver for GPS satellite acquisitions is 15 degrees.

All of the deployed IMS units reported missing data for the construction of TEC and Scintillation (TELSI) messages to be transmitted on the AWN, beginning at 00:00 Universal Time (UT) on 24 February 1997. This condition persisted until the IMS processing software was stopped on each running processor and then restarted. Only the raw Two-Hz data were found in the archive files generated by the IMS, with no One-Minute data or 15-Minute data present. Investigation of potential causes for this condition is continuing.

All of the operating IMS units reported time problems during the transition to Daylight Time on 6 April 1997. Several system swaps occurred, but the situation eventually resolved itself, without operator action. Investigation of potential causes for this condition is continuing.

The companion PC returned by CSDL was refurbished and configured as a spare companion PC. Because the processor for this system is only a 90 MHz CPU, in contrast to the 120 MHz CPU for the standard companion PC, this system will be only a secondary spare.

Two procedures were implemented to facilitate local and remote diagnostics for the IMS. One procedure allows operator interaction with the Uninterruptible Power Supply (UPS) through the UNIX processors, avoiding the previous practice of connecting a spare terminal directly to the UPS, a practice that could not be performed remotely. The other procedure simulates normal processing activity for the system power controller, so that diagnostic and configuration activities can be performed that require stopping the normal IMS software operations.

Discussions were conducted with PLH personnel to develop a plan for network data transmissions to succeed the current AWN transmissions, scheduled to be terminated on December 31, 1997. The proposed method will minimize software changes to the IMS and will be compatible with the network intended to support the Digital Ionospheric Sounding System.

The PC system utilized to monitor the remote IMS units and their companion PCs experienced a sudden disk failure in early June, and operations were transferred to an alternative PC for about three weeks. A PC chassis that became available when its power supply and system board were damaged by a power outage was refurbished with a new power supply, system board, and hard drives, and configured with Windows NT as the new IMS monitoring system. The former monitoring system was reconfigured as a spare IMS companion PC, already having the same type of chassis and system board as the other companion PCs, with a new hard drive and other standard components. The failure of its hard drive was as unexpected as it was sudden, because the manufacturer was different from that of previous hard drives in the monitoring and companion PCs.

8

A 200-MHz Pentium Pro PC system was assembled and configured for writing CDs, for archival and distribution purposes. This system was used to create several CDs of GPS data from Thule, originally recorded in 1989 and currently being transcribed from reel tapes to PC files by PLH personnel.

### 4.1.1 Procedural Developments

Previous evaluations of the multipath effect on the 15-Minute TEC data reports from the Croughton IMS had been conducted by calculating the cumulative phase-averaging as the satellite pass progressed, rather than only at the end of the satellite pass. Because of the long-period multipath, the cumulative phase-averaging adjustment approaches its final value only asymptotically, and can differ from this value by 2 to 5 TEC units over much of the satellite pass. This difference then appears as a bias error for most of the 15-Minute TEC reports, mimicking a poor calibration. A preliminary test was conducted in which the bias value for a single GPS satellite was shifted to compensate partially for this error, utilizing the mean value of the cumulative phase-averaging adjustment. The equivalent vertical TEC profile for this satellite noticeably improved in the 15-Minute data plots. The process of calculating and implementing these bias shifts has since been incorporated into the bias-calibration procedures automatically.

Procedures were developed and installed for each of the IMS sites to perform automatically a daily provisional estimate of the required bias-calibration corrections, utilizing the approximate azimuth and elevation stored with the IMS TEC data instead of a refined almanac. This procedure incorporates programs developed previously which eliminate extreme outliers for the Differential Group Delay (DGD) data and correct discontinuities in the DCP data prior to phase-averaging. The resulting tables of bias-correction estimates are used in conjunction with the daily plots of 15-Minute IMS equivalent vertical TEC data to assess the need for a calibration update. These calculations still are subject to some bias errors due to data anomalies, so operator judgment is required in evaluating the results.

The daily procedures that run automatically on each IMS companion PC were also augmented to generate the tables of 15-Minute IMS TEC data, so that these are immediately available for download at the beginning of each day. A communications script was also developed to facilitate the download of files from the IMS companion PCs.

Previous automated procedures for removal of outdated files on the IMS companion PCs were significantly upgraded. The period for which data files of various types are kept on-line can be specified, and provisions also were incorporated to verify the tape-archive status of the IMS data-archive files before deleting these.

Two programs that are regularly used to process IMS data were revised to allow for the extension and processing of pass files beyond midnight (UT). The first program concatenates short (nominally 15 minutes) pass-file segments extracted from the IMS archive files into full pass files, and was revised to appropriately adjust the time tags to retain continuity when a date transition occurs. This program subsequently was revised and extended to handle consecutive segment files that straddle a year rollover. The second program processes the full pass files to generate IPP databases, which are used for the bias calibrations, and was modified to make the

9

appropriate association between the pass-file times and the times recorded for the azimuth and elevation data when a day transition occurs. These revised programs were installed on each deployed IMS companion PC, and a number of other processing procedure changes were incorporated to allow full pass files to be generated always, without regard for date transitions, although some passes may become fragmented if the data collection process is interrupted. The generation of full passes minimizes the distorting effects of multipath on phase averaging, and leads to more accurate results for the bias calibrations.

The plotting program that had been developed to display the 15-Minute interval values for TEC was augmented to display the satellite coverage as a function of local time at the Ionospheric Penetration Point. This capability facilitates the investigation of anomalies observed for the 15-Minute IMS reports.

A separate procedure was developed to plot satellite coverage in Universal Time from the 15-Minute data files retrieved daily from each IMS, to facilitate detection of brief system outages. Because carrier phase lock must be re-established after a system outage, data sets spanning an outage are less suitable for performing calibrations than continuous data sets. Unless a critical need for calibration is present, calibrations are generally postponed from days on which an outage occurs.

Provisions for selection of data by longitude were incorporated into the program that plots data from the databases used by the bias-calculation program. Use of a longitude restriction when plotting TEC data against local time imposes a time-difference restriction on different measurements tagged by the same local time, allowing some discernment between temporal and spatial variations for the ionosphere. This technique was applied to a day of data from the Croughton IMS, yielding a perceptible, but inconclusive, display of a temporal variation in the ionosphere, with significant limitations arising from the degree of GPS coverage.

The program that performs the bias calculations was augmented to incorporate an additional weighting factor based on the difference in Universal Time between TEC measurements that were being correlated to determine bias values. This version of the program was tested on a day of data from the Croughton IMS that appeared to display some ionospheric dynamical effects, and produced a more consistent diurnal profile, after some adjustment of the weighting parameters. This version was also applied to a day of data from the Thule IMS, but did not produce a significant improvement even with some further adjustments of the weighting parameters. An additional provision was incorporated into the bias-calculation program to report values associated with the error estimates for the biases.

The program that performs the bias calculations was further augmented to incorporate provisions to utilize previous TEC measurements with associated known biases as reference values for determining unknown biases. (See Appendix A for technical details.) This version of the program was tested using data from the Otis IMS that previously had been examined thoroughly and calibrated on a full-day basis using the earlier version of the bias-calculation program. The first set of tests utilized two successive days of January 1995 data and involved calibrations over successive six-hour periods, each referenced by the immediately prior interval. A distinct improvement was obtained in comparison to unreferenced bias calculations over the

10

same six-hour intervals, in that equivalent vertical TEC values did not rise sharply at the endpoints of the intervals. The second set of tests utilized two successive days of April 1997 data and involved calibrations performed one satellite pass at a time, using all previously completed passes as references. Despite the active ionospheric conditions occurring later in the day, the overall agreement with the full-day calibration was good, with significant variations of about 5 TEC units occurring only for the shorter passes.

An additional feature that was included in the bias calculation was an elevation-dependent weighting function that could be applied to the IPP conjunctions. This extension allows a lower elevation threshold to be invoked in selecting IPP conjunctions, which allows better coverage over GPS satellites that only appear at low elevations, while diminishing the error resulting from the slant TEC conversion factor when the same satellite is viewed at both high and low elevations.

As part of the evaluation for elevation threshold values and elevation weighting for IPP conjunctions, the slant TEC conversion factor was evaluated against true slant TEC to vertical TEC ratios using a basic representation of the ionosphere derived from the *Handbook of Geophysics and the Space Environment* (Jursa, 1985). Daytime and nighttime conditions for solar minimum and solar maximum were considered. Earlier evaluations using a simple Chapman model with a peak ionospheric density at 350 km had indicated a discrepancy between the simple slant conversion formula and the actual slant-to-vertical conversion below 35 degrees elevation, but the more recent evaluation using the Handbook results produced a closer correspondence at all elevation angles and for ionospheric profiles typical of different times of day. This conclusion is only valid for mid-latitude ionospheric profiles, however. Determination of an appropriate slant factor will allow extension of the bias calculation to lower elevations, reducing the number of satellites that may be undetermined due to lack of conjunctions in IPP latitude and local time, and could also improve the representative accuracy of the equivalent vertical TEC values reported by the IMS.

### 4.1.2 Calibrations

Data files are retrieved from the IMS sites and are used to evaluate the performance of the current bias definitions for the IMS and to calculate revised bias values for installation on the IMS. These data also are reviewed for anomalous and spurious TEC measurements, as part of the continued assessment of the IMS performance. Calibrations were performed for each of the sites using data from the dates listed in Table 2.

11

Table 2: Calibration Data Dates: IMS Sites

| Otis | Croughton | Thule | Shemya |
|------|-----------|-------|--------|
| 28-Jul-1996 | 24-Jul-1996 | 10-Feb-1997 | 19-Sep-1996 |
| 29-Sep-1996 | 12-Sep-1996 | 28-Apr-1997 | 15-Oct-1996 |
| 16-Dec-1996 | 31-Oct-1996 | 12-May-1997 | 15-Dec-1996 |
| 18-Dec-1996 | 25-Nov-1996 | 27-May-1997 | 20-Jan-1997 |
| 29-Jan-1997 | 13-Jan-1997 | 09-Jun-1997 | 26-Jan-1997 |
| 19-Feb-1997 | 18-Feb-1997 | 23-Jun-1997 | 16-Feb-1997 |
| 25-Mar-1997 | 23-Mar-1997 | | 19-Feb-1997 |
| 20-Apr-1997 | 26-Mar-1997 | | 03-Mar-1997 |
| 04-May-1997 | 14-Apr-1997 | | 26-Mar-1997 |
| 21-May-1997 | 27-Apr-1997 | | 08-Apr-1997 |
| 02-Jun-1997 | 14-May-1997 | | 23-Apr-1997 |
| 16-Jun-1997 | 28-May-1997 | | 07-May-1997 |
| 29-Jun-1997 | 01-Jun-1997 | | 18-May-1997 |
| | 11-Jun-1997 | | 03-Jun-1997 |
| | 29-Jun-1997 | | 22-Jun-1997 |

The Croughton calibration for 12 September 1996 was performed with PLH personnel, as a preview for the calibration to be performed on-site during the Shemya IMS installation. Data files for 17 November 1996 were retrieved from the IMS being tested at CSDL and were used for a general examination of data quality and to calculate bias values. The results were good, especially considering the multipath level expected from the urban location of the antenna. The 18 December 1996 calibration for Otis was performed to include an additional GPS satellite, missing from the 16 December 1996 calibration. Most of the calibrations that were performed at Shemya for the period January 1997 to March 1997 primarily were to obtain correct bias values after each of the antenna changes at that site. The 26 March 1997 calibration for Croughton was performed to correct a pass-truncation problem that had occurred for the previous calibration.

Preliminary notification was received in March 1997 from 55SWXS that the IMS data soon would be utilized for model applications. Consequently, a regular schedule of calibrations was established, so that the individual sites were re-calibrated no less often than once every two weeks, and sooner if circumstances or data results indicated a need. Operational status for the IMS data utilization was declared by 20 June 1997, with the data being applied for PRISM model calculations by 55SWXS.

### 4.1.3 Site-specific Activities

### 4.1.3.1 Otis

Examination of the log files for the Otis IMS indicated that it was using only one processor beginning in July 1996, but that its System-A processor was not even reporting initialization attempts, and it appeared to be failing in a hardware mode before log reports could be initiated. A trip to Otis on 31 October 1996 was accomplished to diagnose the problem with this processor. It was determined that the processor network component was causing a communication problem.

CSDL configured a spare processor to fix this problem, using IMS processing software re-compiled by CSDL, and this system was installed in January 1997 by PLH and CSDL personnel. Problems with the communications parameter settings, which had defaulted to those for the overseas IMS systems, were resolved by NWRA personnel, enabling automated data transmissions to 50WS. This system has been monitored by NWRA personnel since its installation and has been performing normally.

A complete failure of the companion PC at Otis ANGB, MA, occurred on 3 December 1996. The site technician was unable to bring the system back up, and a trip to the site was accomplished on 4 December 1996. The power supply cooling fan was defective; the power supply was replaced and the system brought back on line.

The companion PC at Otis ANGB encountered further problems in early February 1997, and was exchanged for the companion PC obtained from Shemya. The problem with the PC obtained from Otis was determined to be the hard disk drive, which was replaced. This system was then configured as the spare companion PC.

### 4.1.3.2 Croughton

The System-A processor for the Croughton IMS had failed to initialize consistently since the site visit in May 1996, reporting an error through the IMS software initialization procedure. NWRA personnel investigated both the suggestion that there was a license expiration for the Matlab software, which was not indicated by the information in the license file, or that the Matlab software was not operational, which was also found to not be the case. The problem with this processor was ultimately determined by NWRA personnel to be an improper protection setting for some of the executable files, and was corrected in January 1997.

During the Shemya installation visit in September 1996, sporadic problems were encountered with the companion PC at Croughton, UK, in that the system would sometimes halt operation and not reboot, even with intervention from local technicians. A complete failure occurred on 30 September 1996. A hard disk problem was again suspected, and a disk replacement was initiated. A new hard disk was configured for use and shipped to Croughton in early October, where it was installed in the companion PC by a member of the local technical staff. The disk that was replaced was then shipped back to PLH. The companion PC performed well for about a week, but similar problems then recurred. A spare PC chassis was then configured as a replacement, with the inclusion of additional memory, and was shipped to Croughton, in exchange for the PC there. The PC that was returned to PLH was examined upon its arrival, and was determined to have a defective processor cooling fan, which was then replaced.

Remote support was provided for a diagnostic and maintenance visit by PLH personnel to the Croughton IMS site in February 1997. Although both processors at that site appeared to be functioning normally, TELSI messages were only being received sporadically by 50WS. The problem appeared to be in the connections for a communications junction box within the IMS, and was circumvented by bypassing the junction box, thus establishing a link to only one IMS processor. The other IMS processor was then shut down. PLH personnel arranged for new

13

connector cables to be sent to Croughton for installation in the IMS, after which both processors were activated.

### 4.1.3.3 Thule

The companion PC at Thule AFB began displaying frequent outages in February 1997, requiring action by on-site personnel to re-establish remote connections. Discussions and diagnostic sessions were also conducted with on-site personnel, and, based on the symptoms, a likely processor fan failure was diagnosed, without excluding other possible problems. The companion PC obtained from Otis was shipped to Thule in mid-March 1997. This PC was installed by on-site personnel, with further diagnostics and configuration performed by NWRA personnel during a maintenance visit in April 1997. The previous companion PC at Thule was subsequently shipped back to PLH, where a preliminary examination has not detected any problems. Minimal changes will be implemented to adapt the returned PC as the companion PC for the fifth IMS at Hanscom, and further checking will be performed in an operational environment.

Activities were coordinated with PLH and 55SWXS, as well as with remote site personnel, to implement a faster transmission speed for the AWN connection to the Thule IMS, and follow-up actions were conducted to assure continued proper IMS operations and successful data transmission to 55SWXS.

### 4.1.3.4 Shemya

A site visit to Eareckson AFS, Shemya, Alaska, was performed in mid-September 1996 to install the fourth IMS and its companion PC. During this visit, the installation and system initialization were performed solely by one staff member from NWRA and one staff member from PLH, rather than the full IMS installation team, with some assistance from the on-site technical staff, including the prior installation of the mounting pole for the GPS antenna. A physical connection between the IMS and the AWN was also established by the visiting installation staff, but the system addresses did not appear to be active at that time, so data reports from the IMS were not received initially at 50WS.

On-site PLH personnel at Shemya and NWRA personnel at PLH collaborated in performing the initial bias calibration of the Shemya IMS, utilizing data for 19 September 1996, with the data review being performed at Shemya using the IMS companion PC. Software updates for the calibration processing, which were instituted while the IMS and companion PC were in transit to Shemya, were installed on the companion PC using dialup connections.

During the later stages of the Shemya site visit, after the calibration of the IMS, the head actuator for the hard drive of the IMS companion PC failed. A new hard drive was ordered for overnight delivery to PLH, where NWRA personnel installed it in a spare PC chassis, loaded the operating system and required application software, configured it for IMS support, and shipped it to Shemya, where it was installed by a local technician. The operational status of the companion PC was then verified by NWRA personnel, by remote dialup from PLH. This was the fifth hard drive of this type to have failed, although in this case, the mode of failure was different. A set of

spare replacement drives had been on order through PLH, in anticipation of a replacement contingency, but had not yet arrived.

The companion PC at Shemya began displaying problems on 22 November 1996, and quickly deteriorated to an unusable status. A PC chassis that had been shipped from Croughton for analysis and repairs was reconfigured as the Shemya companion PC and shipped to Shemya, where it arrived on 5 December 1996 and was installed by a member of the local technical staff. Remote access to the PC was established, and proper connections to the IMS also were verified, with the IMS requiring a restart due to an earlier power outage. The Scale Factor Generator was also restarted on the companion PC. The PC that was replaced was shipped back to PLH, arriving in early January. An examination of this PC indicated that its power supply fan had failed, so the fan was replaced. The system was then updated for the current processing software and configured as a spare companion PC, pending the arrival of the fifth IMS system from CSDL.

The same IMS software installed on the replacement Otis System-A IMS processor in January 1997 was also installed on the Shemya System-A IMS processor, to test its performance for the alternative AWN protocol used outside the continental United States. This system also has been monitored since its installation and has been performing normally.

The IMS at Shemya, AK, experienced a loss of GPS signals in mid-January 1997, a condition that was traced back to the antenna, which was mounted in a specially designed housing located on the roof of the radar building. To maintain IMS operations, the cable to this antenna was switched to a similar GPS antenna mounted nearby on the roof, but without any protective housing. The latter antenna had been used by the RTM system for investigations prior to the IMS installation and comparative tests after the IMS installation. The former RTM antenna was utilized in this manner for almost a month, until a visit to the site by NWRA personnel in February permitted an examination of the original IMS antenna. No problems were detected with the IMS antenna or housing during the visit, so the cable connections were re-established to this antenna. Operations in this mode continued for about five weeks, until 20 March 1997, at which time the GPS signals were again unavailable for the IMS. A number of diagnostics were conducted with on-site personnel, but the cable could not be switched to the RTM antenna for several days because of extreme weather conditions. The cable was finally re-. connected to the RTM antenna on 25 March 1997, and nominal operation of the IMS was restored soon afterwards, with a system calibration appropriate to the changed antenna.

### 4.1.3.5 IMS #5

The companion PC being utilized with the fifth IMS at CSDL for development efforts was reported to be having some file and device-driver problems in late 1996. This PC was examined after delivery to PLH, with indications that some disk problems and file loss had occurred. The necessary files were restored after hard-disk diagnostic and repair programs were run, and the PC was returned to CSDL.

In March 1997, the fifth IMS, its companion PC, an auxiliary monitoring PC, and the IMS Software Development system were transferred from CSDL to PLH.

15

## 4.2 Anomalous Biases

Close daily monitoring of the IMS data has revealed a phenomenon in which a single satellite that had been calibrated previously appears to have a bias value significantly different from its normal value for an entire satellite pass. This condition has been dubbed "anomalous biases", and has been observed for each of the IMS sites, but only with relative rarity (typically twice per month per site, over all active GPS satellites).

A number of investigations have been conducted to determine the source of the "anomalous bias" problem, which poses a distinct obstacle to the routine utilization of the IMS data reports, because the magnitude of the anomaly is typically on the order of 100 TEC units. The possibility of a true satellite problem has been excluded by simultaneous observations of a single satellite from two distinct IMS sites, with an "anomalous bias" being observed from only one of these sites. The anomaly also appears in the earliest available data stored by the IMS, before the bias corrections are implemented, and therefore cannot arise from an error in acquiring the bias configuration table. The pattern of the multipath in the DGD is also unchanged when an "anomalous bias" occurs, nor is the problem associated with a particular receiver channel. The occurrence of the problem does not appear to be associated with an excessive number of visible GPS satellites, nor with a particular direction in the sky.

A specialized hardware configuration implemented on the IMS at Otis was utilized in a further investigation of the "anomalous bias" problem, commencing on 12 September 1996. The output data from the IMS receiver were routed to a separate data-recording program, in addition to the normal routing to the IMS processing software. The subset of raw output values recorded in this manner was expected to allow the determination of whether the "anomalous bias" occurs as a consequence of some anomaly in one of the individual GPS transmission frequencies or as a consequence of the differencing between frequencies that occurs in the initial stages of the IMS processing software. These recorded receiver output values can be analyzed once an "anomalous bias" condition has been encountered at Otis. The utilization of this data recording at Otis required close monitoring for this IMS, because the recorded files are quite large for a single day. After more than one month of monitoring the data at Otis, one "anomalous bias" event was captured on 21 October 1996 at approximately midnight (UT). Pseudo-ranges from the captured data for the two GPS frequencies were converted to TEC values, for comparison to the results of the IMS processing. Captured receiver data, one-minute-averaged data from the IMS, Two-Hertz data, and the sky map generated by Global Satellite Software (GSS) were extensively studied to investigate the cause of TEC anomalies. The conclusion, based on the captured receiver data, is that there is a flaw in the Ashtech receiver or antenna.

The anomalous bias problem has been discussed by PLH and the receiver manufacturer, Ashtech, and has been attributed to the early version of the firmware in the IMS receivers. PLH arranged for a firmware upgrade and shipped three of the spare Ashtech receivers to be upgraded. Although the upgraded receivers were operational with the RTM software, the utilization of these receivers in the IMS produced data-acquisition errors. A special diagnostic configuration was invoked for the fifth IMS at Hanscom, and examination of the resulting data indicated that the data-quality flag bits being generated by the upgraded Ashtech firmware were different from the flag bits generated by the older firmware. The data-selection processing was traced to one of the

16

Matlab scripts invoked by the IMS, so this script was redesigned and rewritten to select data based on the settings of only certain specified flag bits. The revised script was installed on the IMS at Hanscom with one of the upgraded receivers, and normal data-collection operations were resumed. The anomalous bias occurrences are still being tabulated and will continue to be monitored throughout installation of the upgraded receivers. As of 30 June 1997, after approximately six weeks of operation, no anomalous bias cases had occurred for the IMS at Hanscom with the upgraded receiver.

## 4.3 Ghost Satellites

The presence of the specialized hardware configuration at Otis was a consequence of the earlier investigations into the "ghost" satellites that were sporadically reported in the IMS data. This problem has been considered resolved since the change from the original Micropulse antennas deployed with the IMS to the Ashtech antennas acquired with the spare IMS receivers, as no "ghosts" have been detected with the use of the Ashtech antennas. Recent discussions between PLH personnel and Ashtech staff have indicated that the "ghosts" arise with high gain levels on the antenna input to the receiver. This association confirms an earlier conjecture by NWRA personnel that the "ghosts" may be associated with antenna gain, because the sources for "ghosts" from the Micropulse antenna were traced to high-elevation satellites, where the antenna gain is higher, and the Ashtech antenna was found to have overall less gain than the Micropulse antenna.

## 4.4 RTM/Shemya

During the Shemya IMS installation visit in September 1996, the operating system and tape-archiving software for the RTM PC previously deployed there were upgraded, and operation of this PC was reactivated, following some disk file-system problems in the period just prior to the site visit. This system was monitored on a nearly daily basis, with the data being retrieved manually and reviewed for further occurrences of the interference effects that were detected by this system in the period following the site survey in April 1996. The interference effects were determined to be no problem for the IMS output, due to the data averaging performed by that system.

The RTM system at Shemya was operated until 3 December 1996, when a receiver lock-up condition would have necessitated a complete manual power reset. By this date, it was apparent that the phase-lock loss problem was recurring at a significant frequency, so that the data would be usable only with some difficulty, and it was decided to forego resetting the system. Operations were resumed briefly from 12 December 1996 to 20 December 1996, to collect data for a possible comparison to the IMS.

## 4.5 Scale Factor Generator

The Scale Factor Generator (SFG) program, originally developed in 1992 for use with the RTM to support the Cobra Dane radar at Shemya, was adapted to utilize the 15-Minute data from the Shemya IMS to perform the same role. The SFG program was determined to be compatible with the Windows-95 operating system currently in use on the IMS companion PCs, and was

subsequently tested in a data processing and display mode on the Otis IMS companion PC, although the parameters of the data processing are not suitable for that site. The revised software and associated support were installed on the Shemya IMS companion PC during the IMS installation site visit by the visiting staff, but the subsequent failure of the hard drive on the companion PC precluded any commencement of SFG operations or evaluation. The SFG software was also installed on the replacement hard drive, so that operations could commence in October. The SFG program operation was reinitiated for the replacement PC installation in early December.

Range correction tables are retrieved monthly from the 50WS/55SWXS bulletin board and used to determine the appropriate sunspot number for the ionosphere model incorporated into the SFG program.

The TEC and Scale Factor log files for the periods 12 October 1996 to 24 November 1996 and 10 December 1996 to 29 December 1996 were reviewed, and data for 23 November and 17 December were selected for further analysis. The TEC and Scale Factor log files for the period 29 December 1996 to 20 March 1997 were reviewed, and a summary report characterizing the entire period of performance of the SFG was prepared. Further review of the TEC and Scale Factor log files for the period 21 March 1997 to 25 June 1997 was performed.

### 4.6 Campaigns

Several days of data were collected at PLH in early September 1996 using a single-frequency Trimble Pathfinder receiver, with its associated software, and a dual-frequency Ashtech receiver, with RTM software, in preparation for the Chile campaign scheduled for late September 1996. The data-collection process was reviewed and streamlined for each system, and documentation was prepared for personnel attending the campaign, in collaboration with PLH personnel. These data sets were processed and reviewed to evaluate the instrument performances and the quality of the data. The Trimble data appeared typical for this instrument, with the usual jitter in the 1-second sampling interval, so the data are useful for scintillation measurements but probably no better than past data sets for TEC measurements. The campaign was postponed for at least a month, to October 1996, just after packing efforts were completed for these two systems. These campaign plans were eventually cancelled, and a campaign to Ascension Island was conducted instead.

Programs were also developed to expedite the processing for another Trimble receiver planned for use as a timing reference. While the signal-strength parameter appears to be of the same resolution as the signal parameter for the Trimble Pathfinder receiver, the signal level appears to be significantly lower, and the reported precision for the Doppler and pseudo-range detrimentally affects the ability to use the timing receiver for TEC measurements.

An RTM/Ashtech system intended for deployment in Peru was also examined during a preliminary testing period at Hanscom. It provided good satellite coverage, and, when calibrated, a reasonable diurnal TEC profile.

A collaborative effort is being conducted with Boston College personnel to process data from their RTM system at Ancon, Peru, using the calibration method originally developed for the IMS. Some loss of DCP values has been encountered, but not as badly as for the RTM system temporarily deployed at HAARP and subsequently at Ascension Island. A number of programs, some with recent enhancements, were utilized from the distribution system being maintained at PLH, and some specific revisions were incorporated into the processing procedures to process the data optimally. The derived bias values have tended to be high, producing equivalent vertical TEC diurnal profiles that have negative excursions of about five TEC units, but the profiles are otherwise acceptable.

Data collected by the RTM/Ashtech and Trimble Pathfinder receivers during the March 1997 Ascension Island campaign were transferred from the collection systems to local computers, and processing of the RTM data for TEC values was performed. The DCP data loss problem was again severe for the RTM, and, despite a number of experimental trials and parametric adjustments, only relatively poor bias calibrations and diurnal TEC profiles were obtained.

The program that performs a sliding average to smooth DGD values was revised to improve the treatment at the endpoints of the satellite pass. This program was applied to data obtained using the RTM program, for satellite passes where the DCP was not recoverable, but only marginal improvement was obtained in calibrating the TEC data by incorporating the satellite passes available only as DGD.

Coordinated efforts are being conducted with the Applied Research Laboratory at the University of Texas at Austin and PLH personnel to determine the causes of DCP data losses encountered by a number of distinct RTM systems deployed to various locations. Some diagnostic data-collection sessions have been conducted and will be processed and reviewed to determine specific time intervals and satellites for which the problem occurs.

## 4.7 Network Data Sources

Due to significant changes in the distribution-center file systems, procedures were revised that earlier had been developed to retrieve TEC data files from either the Jet Propulsion Laboratory (JPL) distribution center or the National Oceanic and Atmospheric Administration (NOAA) Continuously Operating Reference Station (CORS) network, which is managed by the National Geodetic Survey (NGS). Supplementary procedures were developed to process the CORS files using networked PCs, because the distributed data decompression program does not work under the Windows-NT operating system, so a DOS PC is employed for this step.

The revised data-acquisition and processing procedures for the CORS data files were utilized to process four consecutive days of data for Gaithersburg, MD, commencing with 28 January 1996. A number of particular features of this data set required special attention and processing, including circumvention of Anti-Spoofing effects and date anomalies from recording system re-starts, but a diurnal vertical TEC profile for a narrow overhead latitude band was corroborated by calibrated measurements by the Otis IMS for the same latitude band, and day-to-day transitions were also consistent. This processing included the first extensive use of elevation-weighted

19

phase-averaging, to reduce the effect of large multipath amplitudes at low elevations. The results of these calculations were summarized in line-of-sight (slant) TEC tables, for use by other investigators at PLH.

Programs previously developed to eliminate extreme outliers for the DGD data and correct discontinuities in the DCP data prior to phase-averaging were adapted to include the capability of processing the abbreviated "standard" pass-file format in addition to the extended IMS data format for which they were originally developed. The revised programs are therefore suitable for use on the pass files derived from either the JPL distribution center data or the NOAA CORS data.

The program that generates IPP databases for the bias calibrations was modified to handle the abbreviated pass-file format properly. Provisions to accommodate this format had been implemented previously, but a deficiency in the format specification resulted in alternate data samples being omitted. This omission was generally not a problem for the bias calculation, which is tolerant of a reasonable degree of decimation, but did have a detrimental effect on the phase-averaging. The program that corrects for phase discontinuities also was modified to handle this abbreviated pass file-format.

To enhance the capabilities for processing general data in RINEX format, a program was developed to translate a general RINEX file into an extended form of the usual TEC tabulation, with a separate file for each satellite. In conjunction with available plotting routines, this new program allows for detailed examination of the source carrier and group delay data used to derive the DCP and DGD.

A sample set of data was acquired from Falcon Air Force Base, in order to evaluate the quality of the data collected by the GPS Monitor stations and the suitability of a data exchange format defined earlier. A program was developed to convert these data files into a format similar to that used for standard GPS data processing, after which plots were generated for DGD, DCP, and signal strength. The DGD data appeared to be distinctly quantized in the plots (see Figure 1), but to a greater degree than would be indicated by the displayed precision of the delivered data, while the DCP data appeared normal. The signal strength displayed an unusual "banded" structure, but distinct from a quantization (see Figure 2). Only a portion of a single day of data was acquired, but these data appear suitable for the standard bias-calibration process. Arrangements were made to have a full day of data, from all five GPS Monitor stations, delivered on 'tar' 8mm tapes.

Two days of data were acquired on an 8mm 'tar' tape from Falcon Air Force Base, in order to process the data collected by the GPS Monitor stations and determine the suitability of these data for accurate ionospheric measurements. After many attempts to read the data from the tape, a successful data transfer was achieved by connecting and configuring a spare 8mm tape drive on the IMS Software Development system. A data-decimation program was developed to facilitate processing of the data, which originated as four samples every six seconds, for each site. Three of the ten sets of data were processed to calibrate TEC values, producing diurnal TEC profiles that were slightly low, as evidenced by negative TEC excursions, but were otherwise reasonable.
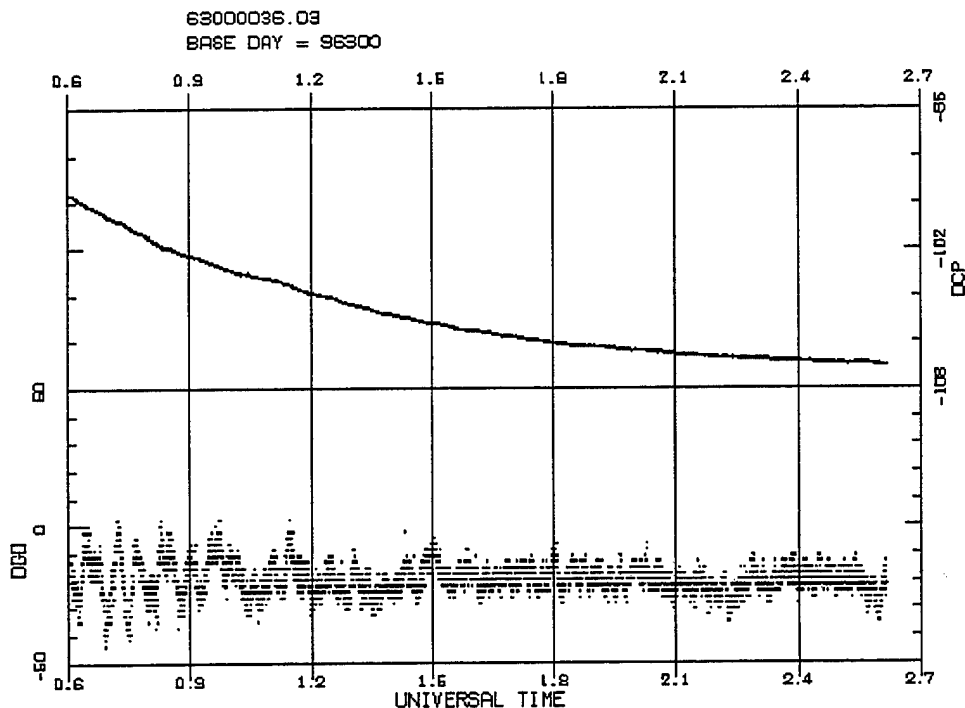
20

Figure 1. Sample GPS data from Falcon AFB, displaying quantization in the Differential Group Delay (lower plot) but smooth variation for the Differential Carrier Phase (upper plot).
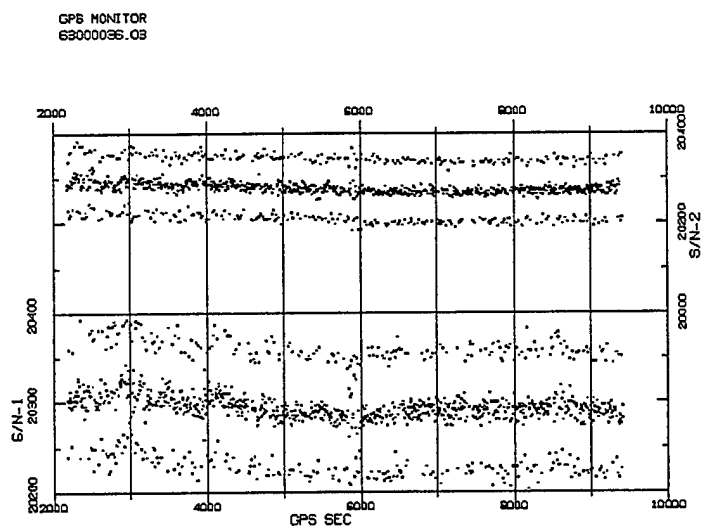


Figure 2. Sample GPS signal strength data from Falcon AFB, for the two GPS frequencies (L1, lower plot; L2, upper plot), displaying the "banded" structure.

A test version of the AltaVista "Tunnel" software package was acquired for use in transferring processed and calibrated data in a secure manner over the Internet back to Falcon Air Force Base.

A sample set of hourly data being provided to 50WS by JPL was also transmitted to PLH for evaluation. This set consisted of data from multiple sites and dates, and a considerable amount of processing was required to select subsets of the data corresponding to desired sites and dates. For some of these subsets, matching sites and dates of raw TEC data were obtained from the JPL network distribution system, processed, and calibrated, to obtain diurnal profiles of equivalent vertical TEC. The hourly TEC values appeared to be distinctly different from the processed raw values, without any appearance of a normal diurnal profile. Furthermore, the range of coverage of the hourly data appeared to be inordinately large, including ionospheric regions not visible from the site of the observing station. Based on a suggestion by PLH personnel, the coordinates labeled as IPP coordinates were treated as sub-satellite coordinates, and the appropriate translation to IPP coordinates was performed. The resulting diurnal profiles of equivalent vertical TEC then more closely matched the profiles derived from the raw data. Subsequent contacts with personnel from JPL indicated that the sample set was only provided as a format sample, and could not be regarded as containing any valid coordinate data. The major contributor to the improvement in the diurnal profile for the hourly data could then only have been the clustering of the data into the vicinity of the observing station.

GPS data collection was performed using one of the single-frequency NovAtel receivers recently acquired by PLH, and attempts were made to process these data using the software that was supplied with the NovAtel receivers by a third party. This software would not generate translated files of the source binary data, and was abandoned in favor of a program developed by one of the researchers from Boston College. The latter program functioned according to its specifications, but did not acquire all of the data types desired for analysis, nor did it translate the data into one of our standard processing formats. Following an initial attempt to modify the Boston College program, a completely new program was written to perform the data translation into a format similar to our processing format for the Trimble Pathfinder receiver, and some sample plots of the data were generated. This NovAtel receiver was used at HAARP during a campaign in February 1997, with a Pentium Windows/NT PC configured for data collection and display operations for this receiver. Data collection and review operations have continued following the campaign, without any indications of significant scintillation.

## 4.8 Analyses

Data, reference files, and software that are utilized in the processing for GPS satellite and receiver bias calibrations previously had been consolidated from several systems onto the DEC Alpha-150 PC. These files were augmented by recompiled programs suitable for DOS PCs, while the previous software had been principally for Windows-95 or Windows-NT PCs. These items were provided to other researchers by individual arrangements.

Contour plots and 3-D surface-fitted plots were generated for IMS calibrated data. Resulting plots show expected diurnal profiles and latitudinal gradients, even for solar minimum data where the daily peak is on the order of 10 TEC units. This means that accuracy of 2 TEC units or better must be maintained throughout or else the variations will not be resolvable.

Calibrated IMS data were interpolated on uniform grids and used for Bent model comparisons. The differences between the model and the real data were obtained. Model

calculations failed to show the latitudinal variations and resulted in up to 4 TEC units of error even for solar minimum days. Model calculations for solar maximum conditions were also made and compared to scaled IMS data, with consequent errors from the model of up to 50 TEC units in some areas.

## 4.9 Scintillation Simulation

A statistical simulation of scintillation effects was developed for use by the Wright Laboratory at Wright-Patterson AFB with their Antenna Wavefront Simulator (AWFS), to provide realistic scenarios of sustained scintillation levels more severe than those experienced for the current solar-minimum conditions. The basis for the simulation is the "six sigma" model (Fremouw et al, 1980), with the cross-correlation standard deviations currently being defined as zero. (See Appendix B for technical details.) Reasonable simulation results have been obtained for the scintillation scattering component, and the structure for the geometric optics component of the scintillation also has been developed. Further analysis was performed to define the parameters for the geometric optics component. The resulting scintillation spectrum, intensity variations, and phase variations were evaluated, and displayed a reasonably good correspondence to actual L-band scintillation occurrences. Seven sets of simulated data were transmitted to Wright Laboratory for testing of four GPS receivers during the last week of June 1997.

## 4.10 Automated Calibrations

Preliminary stages were developed in utilizing real-time slant TEC measurements from the RTM to generate IPP databases that can support near-real-time bias calibrations for a GPS receiver. The slant TEC measurements are reported every five minutes in a file originally designed for the SFG, and these samples are organized by satellite into databases containing the IPP latitude and local time in addition to the elevation and (uncorrected) slant TEC measurement. Time-interval checks also are performed to determine whether individual satellite passes have been concluded, and associated lists are maintained of databases that are active or concluded. These lists and the associated databases then can be used by the augmented bias-calculation program to evaluate composite satellite and receiver biases for satellite passes that are currently in progress, using concluded passes and their previously calculated bias values to provide reference TEC values. Some further effort is required to develop and test the calibration controller software, but the real-time IPP database generation has been tested; the resulting slant TEC profiles are substantially in agreement with slant TEC profiles derived by the standard post-processing methods.

23

## 5. HAARP Activities

Under HAARP, a world-class observatory is being constructed in Gakona, AK, to conduct upper-atmospheric, ionospheric, and radio-propagation research. In addition to a high-power HF transmitter being installed by Advanced Power Technologies, Inc. (APTI), NWRA is coordinating installation of an array of geophysical diagnostic instruments. In September 1996, we conducted a site visit to evaluate the requirements and suitability of Gakona for deployment of radio receivers for monitoring and scintillation. NWRA's other activities involving HAARP diagnostics during this report year are reported in Subsection 5.1.

The first major research campaign involving HAARP was conducted between 24 February and 14 March 1997, and much of our activity involving diagnostics was associated with the planning and conduct of the campaign. The campaign was primarily concerned with ULF/ELF/VLF experiments during active ionospheric conditions and Stimulated Electromagnetic Emissions (SEE) experiments during quiet periods.

The next major HAARP campaign is scheduled tentatively for September 1998, at which time the HF transmitter should be operating at 960 kW. In addition, an expanded Operations Center will be available, and a diagnostics road and pads should be in place.

### 5.1 Development of HAARP Diagnostics

*30-MHz Riometer:* Departure of the riometer principal investigator (P.I.), Jens Ostergaard of Boston College, created a problem with interpretation and control of data quality. NWRA assumed responsibility for operation of the instrument, with PLH handling quality control. NWRA intends to engage Mr. Ostergaard as a consultant to analyze the riometer data.

Processing programs were reviewed, and a backlog of data from the period January through October 1996 was processed. Some progress was attained in automating the data processing, but many of the responses to program queries must be supplied manually because the standard DOS input redirection is incompatible with these programs. Initially, printed copies of the plots also had to be generated manually, using special keyboard commands and a memory-resident utility. To overcome this impediment, we developed a new program to generate printed copies of the plots automatically. This development required an upgrade for the software device drivers to support the color printer being used. The programs were all installed and tested on the Windows/NT PC that was configured for use at the HAARP site. Some difficulties with the video display for the plotting programs were encountered and overcome.

*Imaging Riometer:* The imaging riometer operated by the University of Maryland (UM) was reinstalled at Gakona. Funding was provided by PLH to upgrade the system for on-site calculation of quiet-day curves and for improved data display. Researchers at UM developed software to calculate the quiet-day curve on site and to provide absorption displays in real time. Previously, the local display had represented the total riometer output, and absorption values had not been determined until the data were returned to Maryland. The new software was delivered and installed by Alan Weatherwax during the HAARP's 1997 research campaign. A review of

the Imaging Riometer operation and data was held on 17 June at UM with Ted Rosenberg and Alan Weatherwax.

*Scintillation Monitor:* Operation and display software for the HAARP Scintillation Monitor was demonstrated at SRI International on 28 January, including a remote display at Hanscom. Following the demonstration, it was decided to install the system at HAARP for the March HIPAS/HAARP campaign. Bob Livingston, then of SRI International, installed this eight-antenna system on site during the campaign. Data collection was limited due to computer problems.

*Magnetometer:* The fluxgate-magnetometer's computer display failed after a series of power outages at Gakona. Prof. John Olson, of the University of Alaska at Fairbanks (UAF), was contacted, and the display was repaired by means of a replacement monitor from APTI.

*Ionosonde:* The configuration, installation, and price of an appropriate antenna for the HF Ionosonde was discussed with the University of Massachusetts at Lowell's Center for Atmospheric Research (UMLCAR). A substantial variety of antennas are available for consideration.

*GPS and Scintillation Receivers:* NWRA installed PLH's Novatel receiver at Gakona for measurement of TEC and amplitude scintillation. The Novatel, which receives an L-band signal transmitted from GPS satellites, provides samples along a few slowly moving lines of sight through the Alaskan ionosphere. NWRA developed software to convert the Novatel data to netCDF format and archive it in the HAARP database.

Procedures were developed by NWRA to process and display current Novatel data on-site, in preparation for a site visit in late June of 1997 by Mr. Arthur Money, from the office of the Secretary of the Air Force (SAF). Some enhancements were incorporated in the on-site computer to support these extended processing capabilities. NWRA Consultant John Rasmussen supported the June visit to the HAARP site by Mr. Money of SAF/AQ, including preparation of data displays and presentation of the diagnostic area. NWRA Consultant Lee Snyder, coordinated Mr. Money's activities in the Fairbanks area, including visits to UAF and its Poker Flat Research Range, in addition to Clear Air Station and the Navy's High Power Auroral Stimulation Facility. The UAF tour included visits to the Geophysical Institute and the Arctic Region Supercomputing Center.

Novatel data may be accessed from the HAARP site on the World Wide Web or directly via 'http://www.nwra.com/nwra/haarp/'. Time-series plots of the intensity scintillation index, $S_4$, and several phase-scintillation parameters may be accessed. For phase, the spectral strength, T, at a fluctuation frequency of one Hz and the spectral index, p, are available, in addition to several other parameters provided by the Novatel receiver. The phase data from this single-frequency GPS receiver are of uncertain significance until we learn more about the receiver.

Future installation of an NWRA ITS10S receiver at Gakona will permit reception of phase-locked VHF/UHF signals transmitted by the Transit satellites of the Navy Ionospheric Measuring System (NIMS). The latter will augment the quasi-continuous GPS sky samples with quasi-snapshots in the form of detailed latitudinal scans of TEC and of amplitude and phase scintillation during passes of several Transits. NIMS was formed upon decommissioning of the

Navy Navigation Satellite System at the end of CY 96, with the transmitters being left on for purposes of ionospheric research.

*ULF/ELF/VLF/LF Receivers:* HAARP has two primary ELF/VLF receivers, which are located at Gilmore Creek and Delta Junction, AK. They were provided as government-furnished equipment to the ONR/UCLA contract under which HIPAS is operated, and ONR requested that they be transferred to the Air Force's UAF contract. For the March campaign, a third receiver was located close to Gakona for ELF experiments scheduled there. The additional receiver was assembled by Dave Sentman, of UAF, and Mike McCarrick, of APTI, using spare parts and a set of new sensing coils. Dave Sentman conducted noise measurements and selected a location approximately seven miles west of the HAARP site.

Temperature problems associated with the new coils made operation of the third receiver intermittent; however, it operated well enough to provide the first measurements of ionospherically generated ELF using the HAARP HF transmitter. It appears that the receiver at Delta Junction will need to be moved due to noise associated with the Loran transmitter in Tok, AK.

The upgraded ULF/ELF/VLF/LF Radiometer, developed for HAARP by Stanford University, was operated at Stanford during the March campaign. It does not appear that any signals were detected.

The HAARP SEE receiver was operated at the ELF receiver site near Gakona by Keith Groves, John Quinn, and Lt. Shinn, of PLH, for both SEE and Artificial Plasma Inhomogeneity Generation (API) experiments.

*Optical Imager and Instrument Shelter:* Under a subcontract from NWRA, UAF developed the HAARP Optical Instrument Shelter (OIS), and it was installed during February. Charley Andreasen, of NWRA, installed an optical fiber link between the OIS and the HAARP Operations Center, and NWRA arranged for regular telephone service to the OIS and to the ELF site at Delta Junction. The HAARP optical imager was installed in the OIS and operated during the campaign by Peter Ning, of Keo Consultants, and Lt. Bongiolatti, of PLH. The installation and operation went very well, although the aurora was observed only to the north of the site.

*Other Diagnostic Activities:* In addition to the foregoing, NWRA consultants coordinated operational efforts and development of data displays for (a) SRI International's Scintillation Monitor and (b) the magnetometer and ELF/VLF receivers operated by the UAF. Consultants John Rasmussen and Lee Snyder continued to represent diagnostic interests in development of infrastructure at the HAARP site, including questions related to the operations center, the road, and instrument pads. Establishment of an access road for on-site diagnostics in 1997-98, including pads, power, and data/telephone lines would encourage permanent placement of useful diagnostic instruments at the site. Based on a design review, Dr. Snyder also recommended revisions in plans for the Operations Center to better serve the needs of HAARP scientists.

## 5.2 Facilitation of HAARP Operations and Broader Scientific Collaborations

NWRA Consultant Lee Snyder, together with Frederick M. Robinson, of Dynamics Research Corporation, worked with the ONR Contracting Office to define acquisition approaches for completion of the HAARP ionospheric research instrument. Dr. Snyder also drafted a white paper regarding mitigation of HAARP radio-frequency interference. The purpose of the paper is to summarize actions taken in response to the direction provided in the HAARP environmental Record of Decision. The paper was provided to Mr. Edward J. Kennedy, of Naval Research Laboratory (NRL), to accompany the request for a frequency allocation for the next stage in the construction of the HAARP transmit array.

At the request of the National Science Foundation (NSF), Dr. Snyder and NWRA Consultant Professor William E. Gordon drafted a charter for an Incoherent Scatter Radar (ISR) Design Panel. The main purpose of the Design Panel is to identify approaches for meeting the science requirements defined in the final report of the NSF/HAARP ISR Requirements Panel. Subsequently, Dr. Snyder drafted, coordinated, and finalized the ISR Design Panel's report. The report was distributed only to the Panel sponsors (NSF, ONR, and PLH), as it contains information that may be source-selection sensitive. It reviews various design approaches and weighs the issues for developing an ISR to support performance requirements for the NSF Resolute Bay Polar Cap Observatory and the HAARP Gakona, AK, site. A mechanical approach was developed for a 110-meter-diameter, planar, receive-only array. The mechanical approach was made available for HAARP site planning.

Together with other members of the research community, Dr. Snyder and Professor Gordon completed a white paper entitled *On Opportunities for Collaborative Research with Incoherent Scatter Radars at Gakona, Alaska and Resolute Bay, Canada.* The purpose of the paper is to summarize the research opportunities that could result from cooperative operation of the existing and proposed Arctic ISRs. This paper was provided to NSF, ONR, PLH, and all attendees at the meeting of the aforementioned ISR Requirements Panel held last April in Santa Fe.

NWRA organized the 1997 RF Ionospheric Interactions Workshop, which is held annually to develop coordinated research campaigns for the HAARP, HIPAS, and Arecibo facilities. This workshop, which is sponsored by NSF, PLH, and ONR, is aimed at making the most effective use of available resources, including diagnostic instruments. The 1997 workshop was held during the period 27 through 30 April in Santa Fe, NM. In the absence of Prof. Gordon, NWRA Consultant John Evans summarized the ISR Design Panel's report at the workshop.

NWRA continues to present, monitor, and resolve issues associated with diagnostics and research campaigns at the Program Management Review meetings held each month with the transmitter contractor, APTI. Dr. Snyder drafted changes to the HAARP transmitter Statement of Work and Specification to be consistent with the programmatic decision to extend the definition of the Demonstration Prototype to be a fully active 6x8 antenna array with a combined transmitter power of 960 kW.

Mr. Rasmussen and Dr. Snyder continue to present, monitor, and resolve issues associated with diagnostics and research campaigns at the Program Management Review meetings held

each month with the transmitter contractor, APTI. Dr. Snyder also participated, with representatives of Continental Electronics Co. (CEC), in reviews directed at resolving contract issues and establishing plans for and progress on development and production of sixty 10-kW transmitters needed to power the full, existing six-by-eight HAARP antenna array.

Dr. Snyder also participated in the 65% Design Review held on 9 May at the USKH architect's facility in Anchorage, AK. In conjunction with this review, coordination and support was provided for visits by PLH personnel to the HAARP site at Gakona, the Copper Valley Electric Association (CVEA) in Glennallen, and Detroit Diesel in Anchorage. CVEA has a contract with APTI for upgrading commercial electric service to the HAARP site at Gakona, and Detroit Diesel has a contract for storage and refurbishment of diesel-electric generators for HAARP use.

During the same trip, coordination with FAA personnel in Anchorage resulted in definition of the HAARP transmitter power level above which the Aircraft Alert Radar must be operated. NWRA consultant Snyder has established contractor communications regarding the Lear Astronautics UPS-3 transportable radar and has obtained performance specifications for it. This short-range Doppler radar may be suitable to upgrade HAARP's capability for detecting general-aviation aircraft at low altitude in the presence of ground clutter.

In addition to the foregoing, NWRA supported program planning and implementation of the workshop on Longwave Electromagnetic Imaging of Underground Structures held at PLH on 6 and 7 May 1997.

## 5.3 Public Relations

A two-day open house was held at the Gakona facility. This second annual event, which attracted over 200 attendees, featured presentations on the status of the HAARP Ionospheric Research Observatory, including transmitter construction, diagnostics, spectrum monitoring, and environmental compliance. NWRA participated by providing the consulting services of Professors William Gordon of Rice University and Michael Kelley of Cornell University to answer questions about the ionosphere and to address public concerns about the facility. In addition, presentations were provided on the available diagnostics systems.

Additional support regarding public relations was provided via preparation of regular announcements of HAARP activity that appear in the Copper River Country Journal and in developing an educational outreach program between the Glennallen High School and the UAF's Geophysical Institute.

An open lecture entitled "An Introduction to Ionospheric Research and HAARP" was presented on Friday night, 28 February, in the Glennallen High School auditorium featuring Professor Syun Akasofu, Director, Geophysical Institute, UAF; and Edward Kennedy of the NRL. The following day a short, half-credit course on "Ionospheric Research and Tour of the HAARP Facility" was given by members of the Geophysical Institute, visiting scientists, and the HAARP staff. Three groups of high school students from Glennallen High School and Kenny Lake High School visited the site.

Dr. Snyder supported Government briefings to the National Telecommunications and Information Agency (NTIA) and the Voice of America (VOA), both in Washington, DC. The purpose of the briefing to the NTIA was to update the Agency on HAARP testing and development plans. The purpose of the discussion with VOA was to acquaint them with the objective and characteristics of the HAARP transmitter facility.

Dr. Snyder also drafted responses to public and Pentagon inquiries. These included response drafts to a public inquiry regarding the ISR and to a Pentagon inquiry as to the program plans for operation and maintenance of the completed HAARP facility. He also coordinated development of a response to a Pentagon request for information on procedures to preclude unauthorized, remote operation of the HAARP transmitters.

NWRA also drafted result summaries, suitable for lay persons, for one experiment conducted during the February-March HAARP Research Campaign and diagnostic data for a January space-weather event. The experiment was HAARP modulation of the auroral electrojet to transmit extremely low frequencies, and the diagnostic data summary was for the January halo-type coronal-mass ejection and subsequent geomagnetic storm that coincided with failure of an AT&T communications satellite.

## 6. Publications

Lunt, N., L. Kersley, G. Bishop, A. Mazzella, "Protonospheric Electron Contents From GPS/NNSS Observations," International Beacon Satellite Symposium, 1997.

Bishop, G.J., D.S. Coco, N. Lunt, C. Coker, A.J. Mazzella, L. Kersley, "Application of SCORE to Extract Protonospheric Electron Content from GPS/NNSS Observations," Institute of Navigation GPS-97, 1997.

C.E. Valladares, R. Sheehan, A. Mazzella, G. Bishop, S. Basu, K. Groves, "Observations of Equatorial Plasma Irregularities using GPS Receivers and UHF Spaced Antennas," presentation at IAGA, Upsala, Sweden, Feb 1997.

G. Bishop, A. Mazzella, S. Rao, A. Batchelor, P. Fleming, N. Lunt, L. Kersley, "Validations of the SCORE Process," Institute of Navigation NTM-97, Mar 1997.

## References

Fremouw, E. J., C. C. Andreasen, and J. A. Secan, "Investigations of ionospheric total electron content and scintillation effects on transionospheric radiowave propagation," *NWRA–CR–94–P223*, Northwest Research Associates, Inc., Bellevue, WA, 1994.

Jursa, A. S., editor, "Handbook of Geophysics and the Space Environment," *AFGL-TR-85-0315, ADA167000*, Air Force Geophysics Laboratory, 1985.

Fremouw, E. J., R. C. Livingston, and D. A. Miller, "On the statistics of scintillation signals," *Journal of Atmospheric and Terrestrial Physics. 42*, 717-731, 1980.

## Acronyms and Initials

| | |
|---|---|
| 50WS | 50th Weather Squadron |
| 55SWXS | 55th Space Weather Squadron |
| AFRL | Air Force Research Laboratory |
| API | Artificial Plasma Inhomogeneity Generation |
| APTI | Advanced Power Technology, Inc. |
| AWN | Automated Weather Network |
| CEC | Continental Electronics Co. |
| CORS | Continuously Operating Reference Station |
| CSDL | Charles Stark Draper Laboratory |
| CVEA | Copper Valley Electric Association |
| DCP | Differential Carrier Phase |
| DGD | Differential Group Delay |
| GPS | Global Positioning System |
| HAARP | High-frequency Active Auroral Research Program |
| IMS | Ionospheric Measuring System |

| | |
|---|---|
| IPP | Ionospheric Penetration Point |
| ISR | Incoherent Scatter Radar |
| NGS | National Geodetic Survey |
| NIMS | Navy Ionospheric Measuring System |
| NNSS | Navy Navigation Satellite System |
| NOAA | National Oceanic and Atmospheric Administration |
| NRL | Naval Research Laboratory |
| NSF | National Science Foundation |
| NTIA | National Telecommunications and Information Agency |
| NWRA | NorthWest Research Associates |
| OIS | Optical Instrument Shelter |
| ONR | Office of Naval Research |
| PLH | Phillips Laboratory at Hanscom |
| RINEX | Receiver Independent Exchange (data format) |
| RTM | Real-Time Monitor |
| SAF | Secretary of the Air Force |
| SEE | Stimulated Electromagnetic Emissions |
| SFG | Scale Factor Generator |
| TEC | Total Electron Content |
| TELSI | TEC and Scintillation (message format) |
| UAF | University of Alaska at Fairbanks |
| UCLA | University of California, Los Angeles |
| UM | University of Maryland |
| UMLCAR | University of Massachusetts Lowell's Center for Atmospheric Research |
| UT | Universal Time |
| VOA | Voice of America |

## Appendix A: GPS Bias Calibrations

The GPS receiver and satellite calibration process is based on minimization of correlated ionospheric measurement discrepancies performed by one receiver over multiple satellites, using data collection periods of eight hours to 24 hours (or longer). The quantity being minimized is defined as [Bishop et al, 1994]:

**1)** $E = \dfrac{1}{2}\sum_{\alpha}\sum_{i}^{I\alpha}\sum_{\beta\neq\alpha}\sum_{j}^{J\beta} W_{\alpha i,\beta j} \times (T_{\alpha i} - T_{\beta j})^2$

where

        $\alpha i$ denotes satellite $\alpha$, sample $i$

        $W_{\alpha i,\beta j}$ = weighting factor between samples $\alpha i$ and $\beta j$;

        $T_{\gamma k}$ = calculated equivalent vertical TEC for sample $\gamma k$.

The equivalent vertical TEC is calculated from the measured slant TEC ($S_{\gamma k}$) using a scaling factor based on the elevation angle ($\varepsilon_{\gamma k}$), with a prior adjustment for the combined satellite and receiver bias:

        $T_{\alpha i} = (S_{\alpha i} - B_{\alpha}) \times \cos(\arcsin(\mu\cos(\varepsilon_{\alpha i})))$

**2)**    $\mu = R_e \big/ (R_e + H_{IPP})$

where

        $S_{\alpha i}$ = (uncorrected) slant TEC for the data sample;

        $B_{\alpha}$ = combined receiver and satellite bias, in TEC units, for satellite $\alpha$;

        $\varepsilon_{\alpha i}$ = elevation angle for data sample;

        $R_e$ = radius of the earth;

        $H_{IPP}$ = altitude for the assumed ionosphere layer.

The summations for E in Equation 1 can be partitioned into sets for which the satellite biases are unknown and sets for which the satellite biases (or associated vertical TEC values) are known. The resulting definition then has the form:

**3)**
$$E = \frac{1}{2}\sum_{\alpha}'\sum_{i}^{I\alpha}\sum_{\beta\neq\alpha}'\sum_{j}^{J\beta} W_{\alpha i,\beta j} \times (T_{\alpha i} - T_{\beta j})^2 + \frac{1}{2}\sum_{\alpha}'\sum_{i}^{I\alpha}\sum_{\beta}''\sum_{j}^{J\beta} W_{\alpha i,\beta j} \times (T_{\alpha i} - T_{\beta j})^2 +$$
$$\frac{1}{2}\sum_{\alpha}''\sum_{i}^{I\alpha}\sum_{\beta}'\sum_{j}^{J\beta} W_{\alpha i,\beta j} \times (T_{\alpha i} - T_{\beta j})^2 + \frac{1}{2}\sum_{\alpha}''\sum_{i}^{I\alpha}\sum_{\beta\neq\alpha}''\sum_{j}^{J\beta} W_{\alpha i,\beta j} \times (T_{\alpha i} - T_{\beta j})^2$$

where summations with a single prime are over satellites (or individual satellite passes) for which the bias values are unknown, and summations with a double prime are over satellites with known bias values (or other known vertical TEC measurements). The last such partitioned set of summations contains no unknown bias values, and may be omitted, defining a new composite discrepancy E' by the remaining three sets. This quantity can be minimized by solving the set of linear equations determined by taking the partial derivative of E' with respect to all of the unknown bias values.

The weighting factor $W_{\alpha i,\beta j}$ for each correlated pair of TEC measurements can be formulated to emphasize subsets of the pairwise correlations or to impose constraints on the data selection for correlations, by the use of step functions of the observation parameters (latitude, longitude, elevation, etc.). Apart from selection domains for latitude and longitude of the Ionospheric Penetration Point (IPP) for the line-of-sight to the satellite and a threshold elevation for the line-of-sight to the satellite, the weighting factor is currently defined as:

$$4) \quad W_{\alpha i,\beta j} = \exp(-\frac{1}{2}(\frac{\theta_{\alpha i} - \theta_{\beta j}}{\theta_0})^2) \times \exp(-\frac{1}{2}(\frac{\lambda_{\alpha i} - \lambda_{\beta j}}{\lambda_0})^2) \times \exp(-\frac{1}{2}(\frac{\tau_{\alpha i} - \tau_{\beta j}}{\tau_0})^2) \times \sin^N(\varepsilon_{\alpha i}) \times \sin^N(\varepsilon_{\beta j})$$

where

$\theta_{\alpha i}$ = IPP latitude for data sample;

$\lambda_{\alpha i}$ = IPP local time (and day) for data sample;

$\tau_{\alpha i}$ = Universal time (and day) for data sample;

$\theta_0$ = reference latitude difference, for scaling;

$\lambda_0$ = reference local time difference, for scaling;

$\tau_0$ = reference Universal time difference, for scaling;

$N$ = exponent for elevation weighting.

## Alternative Formulation

In circumstances where only the satellite biases (or relative satellite biases) are known, it is possible to reformulate the original minimization condition to determine the unknown receiver bias. Let each combined satellite and receiver bias $B_\alpha$ be decomposed into a receiver bias $B_R$ and a satellite bias $\Delta B_\alpha$:

$$B_\alpha = B_R + \Delta B_\alpha$$

The minimization condition for E then depends on a single unknown value $B_R$, and the derivative condition minimizing E becomes a single linear equation in one unknown variable. This method has not yet been implemented, but it is not expected to be much faster in operation than the multiple-bias method, because the data acquisition process for calculating the coefficients of the equation is not significantly changed and remains the most time-consuming portion of the calculation by a significant margin. However, it may prove to be a useful method for initializing a receiver bias value using a relatively short duration of data collection and for maintaining a receiver calibration.

## REFERENCE

Bishop, G., D. Walsh, P. Daly, A. Mazzella, and E. Holland, "Analysis of the Temporal Stability of GPS and GLONASS Group Delay Correction Terms Seen in Various Sets of Ionospheric Delay Data", *Proceedings of ION GPS-94*, The Institute of Navigation, Washington, D.C., September 1994.

## Appendix B: Implementation of Scintillation Simulation

The need to evaluate scintillation effects on GPS receivers at a time near solar minimum has required development of models characterizing scintillation and implementation of methods to generate realistic time sequences of intensity and phase based on these models. For this particular application, the two-component, six-sigma model was utilized, with a number of simplifying assumptions.

In this model of scintillation, the complex scintillation signal is represented as the product of a refractive (focus) component and a diffractive (scatter) component:

$$S = \exp(\chi_f + j\phi_f)(x_s + j\, y_s)$$

where $\chi_f$, $\phi_f$, $x_s$, and $y_s$ are all normally distributed stochastic variables. The required parameter values describing these distributions are:

$\mu_{\chi f}$ = mean value for the focus logarithmic amplitude;

$\sigma_{\chi f}$ = standard deviation for the focus logarithmic amplitude;

$\sigma_{\phi f}$ = standard deviation for the focus phase;

$\sigma_{\chi f\phi f} = \sqrt{(\rho_{\chi f\phi f}\sigma_{\chi f}\sigma_{\phi f})}$ = square root of the correlation covariance between the focus amplitude and phase;

$\mu_{xs}$ = mean value for the scattering x-component;

$\sigma_{xs}$ = standard deviation for the scattering x-component;

$\sigma_{ys}$ = standard deviation for the scattering y-component;

$\sigma_{xsys} = \sqrt{(\rho_{xsys}\sigma_{xs}\sigma_{ys})}$ = square root of the correlation covariance between the scattering rectangular components.

The mean values for the focus phase and imaginary scattering component are defined to be zero.

For the current implementation, the correlation coefficients, $\rho_{\chi f\phi f}$ and $\rho_{xsys}$, are assumed to be zero, reducing the model to four sigmas. Of these, $\sigma_{xs}$ and $\sigma_{ys}$ are assumed equal, and are defined by:

$$\sigma_{ys} = \sigma_{xs} = \sqrt{(1 - \sqrt{(1 - S_{4s}^2)})}$$

where $S_{4s}$ is the scintillation index assigned to the scattering component. (Conversely, $S_{4s} = \sqrt{(2\sigma_s^2 - \sigma_s^4)}$ .) The remaining two (focus) sigmas are defined independently of the scattering sigmas. Polar plots of the focus component seem to indicate a relationship of approximately

$$\sigma_{\phi f} = 2\pi\sigma_{\chi f}$$

but for this implementation, a simplification was imposed by defining only $\sigma_{\phi f}$ and setting $\sigma_{\chi f}$ to zero.

Scattering Component Simulation

The real (x) and imaginary (y) parts of the scattering component were produced by initially generating two Gaussian pseudo-random number time sequences with the specified means ($\mu_{xs}$,

$\mu_{ys}$) and standard deviations ($\sigma_{xs}$, $\sigma_{ys}$). Each of these sequences was then filtered (in the frequency domain) by the same filter, having the following frequency characteristics:

$$F(f) = \sqrt{N_A} f^{-\frac{p}{2}} \sin\left(f \middle/ f_F\right) \qquad \text{for } f \leq \left(\pi \middle/ 2\right) f_F$$

$$F(f) = \sqrt{N_A} f^{-\frac{p}{2}} \qquad \text{for } f > \left(\pi \middle/ 2\right) f_F$$

where

    $p$ = power spectral index;

    $f_F$ = Fresnel frequency;

    $N_A$ = normalization factor, determined (in the discrete frequency domain) by

$$\frac{N}{2} = N_A \sum_{n=1}^{N/2} F(nf_0)^2$$

for N data samples, and a fundamental frequency $f_0 = 1/(N\Delta t)$, with a sampling interval $\Delta t$. This definition for the normalization is intended to preserve the standard deviations for the real and imaginary parts of the scattering components, in conjunction with the following definitions for the zero-order terms for the Fourier transforms of the scattering components:

$$\tilde{x}_0 = \sqrt{N - \left[\tilde{x}_{N/2} + 2\sum_{n=1}^{N/2-1} \tilde{x}_n\right] - \left[\tilde{y}_{N/2} + 2\sum_{n=1}^{N/2-1} \tilde{y}_n\right]}$$

$$\tilde{y}_0 = 0$$


Focus Component Simulation

The focus component phases ($\phi_f$) were similarly produced by initially generating a Gaussian pseudo-random number time sequence, with zero mean and a standard deviation $\sigma_{\phi f}$, and then applying a filter of the form:

$$F_\varphi(f) = \sqrt{N_\phi} f^{-\frac{q}{2}} \qquad \text{for } f < \pi f_F$$

where

    $q$ = power spectral index;

    $N_\phi$ = normalization factor, determined (in the discrete frequency domain) by

$$\frac{N}{2} = N_\phi \sum_{n=1}^{N/2} F_\phi(nf_0)^2$$

35

Note that there is a sudden high-frequency cutoff for the focus phase power spectrum.

## Composite Scintillation

The composition of the scattering and focus components is performed by first determining the amplitude and phase of the scattering component:

$$A_s = \sqrt{x_s^2 + y_s^2}$$

$$\cos(\phi_s) = \frac{x_s}{A_s}$$

$$\sin(\phi_s) = \frac{y_s}{A_s}$$

The composite phase is then defined as the sum of the scattering and focus phase values. Thus, the total phase excursions can exceed $2\pi$.

## Fresnel Frequency

The Fresnel frequency governing the spectral characteristics of the scintillation is given by

$$f_F = \frac{V_{IPP}}{L_F}$$

where

$V_{IPP}$ = transverse line-of-sight velocity of the Ionospheric Penetration Point;

$L_F$ = Fresnel length.

The Fresnel length is proportional to

$$\sqrt{\frac{(d_{sat} - d_{IPP})d_{IPP}/d_{sat}}{v}}$$

for

$d_{sat}$ = distance to satellite;

$d_{IPP}$ = distance to Ionospheric Penetration Point;

$v$ = transmission frequency;

and the implemented values were scaled to GPS conditions from Wideband results, using a Fresnel length of 700 m, a satellite altitude of 1000 km, and a transmission frequency of 138 MHz.

## Scintillation Simulation Evaluation

36

After generating the random-number sequence and performing the filtering to create a simulated scintillation signal, calculation of the $S_4$ values for the scattering and focus components (separately) produces values distinctly different from those used to generate the simulation. The method used to calculate $S_4$ is implemented in the form

$$S_4 = \text{standard deviation } (A^2)/\text{mean } (A^2)$$

The $S_4$ values were also observed to vary when calculated over partial segments (30 seconds long) of the time sequence, so the simulation is not stationary. Similar features were noted for the $\sigma_\phi$ values derived from the simulation.

The power spectra for the simulated amplitudes and phases were also determined; they reasonably matched the required spectral indices, but did not exactly reproduce the specified indices. The low-frequency domain for the amplitudes displays a less steep spectral index, as desired, but the phase spectral index also tends to be less steep at low frequencies.