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INVESTIGATIONS OF THE NATURE AND BEHAVIOR OF PLASMA-DENSITY DISTURBANCES THAT MAY IMPACT GPS AND OTHER TRANSIONOSPHERIC SYSTEMS

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14. ABSTRACT

This report summarizes research during a contract for investigating (a) natural variations in ionospheric total electron content (TEC) and (b) plasma and electromagnetic effects produced by transmitting high-powered HF waves into the ionosphere. Ongoing efforts to maintain and utilize data from the Air Force Ionospheric Measuring Systems are being conducted. Initial efforts in upgrading these systems for enhanced data collection and reporting capabilities also are being conducted. Preliminary scintillation capabilities at the GPS L1 and L2 frequencies were established, with additional arrangements for incorporating UHF scintillation measurements also being accomplished. An array of diagnostic instruments is being maintained and enhanced in association with the High-frequency Active Auroral Research Program (HAARP). In addition to a classic riometer and a GPS Total Electron Content (TEC) sensor previously operating at the HAARP site, NWRA also operates a set of Transit receivers for measurements of TEC and scintillation at VHF and UHF, supplementing the receiver at HAARP with a receiver north of the site and an additional receiver installed south of the HAARP site.

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Preface

This report summarizes work completed during the period from 10 September 1997 through 30 September 2002 on a project to investigate effects of the earth's ionosphere on transionospheric systems.

In addition to the authors, other contributors to the efforts described herein were NWRA staff members Charley Andreasen, John Begenisich, J. Francis Smith, and Tong Xu and NWRA consultants Jens Ostergaard, Sanghun Lee, John Rasmussen, and A. Lee Snyder. We express our appreciation to Randy Hopkins of Raytheon for his on-site support of the IMS at Eareckson Air Force Station, Shemya, Alaska; to Carlton Curtis (formerly of Boston College) for his collaboration in support of IMS operations; to Todd Pedersen of AFRL for his assistance in retrieving operating parameters from the Thule IMS; and to Cpl. John Cooper for his on-site support of the RTM at Unst, Shetland Islands.

List of Symbols, Abbreviations, and Acronyms

55 SWXS	55th Space Weather Squadron
AFRL	Air Force Research Laboratory
AFWA	Air Force Weather Agency
APTI	Advanced Power Technology, Inc.
CESR	Contingency Equipment Status Report
CORS	Continuously Operating Reference Station
DCP	Differential Carrier Phase
DGD	Differential Group Delay
ELF	Extremely Low Frequency
FTP	File Transfer Protocol
GPS	Global Positioning System
HAARP	High-frequency Active Auroral Research Program
HF	High Frequency
HP	Hewlett Packard
IMS	Ionospheric Measuring System
IPP	Ionospheric Penetration Point
ITS	Ionospheric Tomography System
MUF	Maximum Usable Frequency
NetCDF	Network Common Data Format
NIMS	Navy Ionospheric Measuring System
NNSS	Navy Navigational Satellite System
NRL	Naval Research Laboratory
NWRA	NorthWest Research Associates
ONR	Office of Naval Research
OpSEND	Operational Space Environment Network Display
PCA	Polar Cap Absorption
PDR	Powerful Diagnostic Radar
PRISM	Parameterized Real-time Ionospheric Specification Model
PRN	Pseudo-Random Noise (GPS identification signature)
RINEX	Receiver Independent Exchange (data format)

rms	root mean square
RTM	Real-Time Monitor
SAO	Standard Archiving Output
SBIR	Small-Business Innovation Research
SCORE	Self-Calibration of Range Errors
SCION	SCION Associates, Inc.
SEE	Stimulated Electromagnetic Emission
SFG	Scale Factor Generator
sps	samples per second
SWN	Space Weather Network
TEC	Total Electron Content
TELSI	TEC and Scintillation (message format)
UHF	Ultra-High Frequency
VHF	Very High Frequency
VLF	Very Low Frequency

1. PROJECT OBJECTIVES

The ionosphere can both disrupt and enhance the operation of military communication, navigation, and surveillance systems. For instance, the integral of plasma density along ray paths through the ionosphere (the "total electron content," or TEC) imposes range errors on signals received from satellites in the Global Positioning System (GPS). Indeed, GPS transmits two frequencies specifically for the purpose of correcting such errors. The correction depends on reliable measurement of frequency-differential "pseudorange." Such corrections can be applied also to nearby or remote single-frequency receivers, a procedure that can be degraded by temporal changes and spatial gradients in TEC.

An objective of this project is to characterize the temporal changes and gradients in TEC as measured by means of both GPS pseudorange and more precise measurements of Frequency-Differential carrier phase as the Sun advances in its eleven-year activity cycle. To meet this objective, Northwest Research Associates (NWRA) is (a) operating, calibrating, and maintaining GPS-based equipment, including the Air Force Ionospheric Measuring System (IMS, AN/GMQ-35), at various locations and (b) processing and analyzing data obtained thereby. Developments for GPS-related topics are reported in Section 2.

It may be possible to enhance operation of some low-data-rate but high-priority communication systems by exercising a degree of control over ionospheric disturbance by means being investigated in the High-frequency Active Auroral Research Program (HAARP). Under HAARP, the Air Force Research Laboratory (AFRL) and the Office of Naval Research (ONR) are developing a facility in Alaska for upper-atmospheric, ionospheric, and solar-terrestrial research. An objective of this project is to contribute to characterizing processes triggered in the upper atmosphere and ionosphere by high-power radio waves transmitted from the HAARP facility, specifically as those processes relate to large-scale and km-scale irregularities in ionospheric plasma density and to radiowave absorption. No developments for HAARP topics took place under this contract during the final year of the project. Section 3 provides a synopsis of the work completed during the first four years.

2. GPS TOPICS

In this section we provide a detailed summary of work completed in the final year covering the period 1 September 2001 through 30 September 2002. Details for the work completed in the first four years can be found in Annual Report #1 (AR1) [*Fremouw et al.,* 1998], Annual Report #2 (AR2) [*Andreasen et al.,* 1999], Annual Report #3 (AR3) [*Fremouw et al.,* 2000], and Annual Report #4 (AR4) [*Fremouw et al.,* 2001].

2.1 Standard Operations

Data files were processed, reviewed, and archived to tape at each of the deployed IMS sites at Eareckson Air Force Station, Shemya, Alaska, and Thule Air Base, Greenland. Tapes were catalogued for content and indexed for local storage upon arrival at AFRL each month. The 15-minute TEC data from Shemya were reported by the IMS to AFRL by means of the Space Weather Network (SWN). The data can be plotted for each day to monitor the calibrations, data anomalies, and recent changes in the active GPS constellation. Such monitoring is conducted at a low level of effort following the decision in September 1998 to deactivate the IMS units at Otis, Croughton, and Thule, and the decision in February 2000 to exclude support funding for Ascension Island.

A quick bias calibration is performed automatically on the Companion PC at the active sites, to facilitate detection of bias variations requiring re-calibration. These calculations are subject to some bias errors due to data anomalies, so operator judgment is required in evaluating the results. Because of IMS data utilization by the COBRA DANE radar at Shemya, a regular schedule of calibrations is performed for that site, so that the IMS is re-calibrated no less often than once every two weeks, and sooner if circumstances or data results indicate a need.

GPS ephemeris files were 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 coordinates, which are used by the bias-determination process.

A summary log was 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 system shutdown also is recorded in this log. A histogram of system operating-time durations, by month, is included in this summary log for each IMS. 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 included.

2.2 Site-specific Activities

2.2.1 Ascension Island

An attempt in March 2001 to reinstate operations for the Ascension Island IMS by AFRL personnel at the site for a campaign was unsuccessful, with an apparent electrical failure for one of the UNIX computers and serious difficulties in starting the other UNIX computer. The UNIX computer with the possible electrical failure was returned to Hanscom for examination, and was found to have a failed power supply, which has been replaced. This computer was reinstalled in the IMS at Ascension Island during the September 2001 installation of a new IMS rack, which is not yet operational, at that site. Complete operation of the original IMS unit at Ascension Island was verified, and additional procedures to overcome the expiration of the system clock batteries were installed and activated.

In March 2002, two Hewlett Packard (HP) Apollo computers were configured at Nashua, tested, and sent to Ascension Island to replace the Apollo computers for the original IMS unit at that site, which were reported to have failed during attempted utilization for a campaign. AFRL personnel who had traveled to Ascension Island were unable to achieve operational status for these replacement computers. Other duties of the AFRL personnel prevented them from doing an in-depth analysis of the cause of the operating problems.

The two HP Apollo computers that were returned from Ascension Island have been tested at NWRA Nashua. One unit was found to have a faulty on/off switch and the other failed due to a dead power supply. Both of these problems were fixed, but the network portion of the motherboard on both computers is inoperable.

2.2.2 *Thule*

A trip to Thule was started on May 16 to assist with the installation of the original IMS rack on the network. Due to the apparent failure of both the HP Apollo processors in the original IMS, the new IMS rack was installed instead, and the accreditation documents were rewritten to reflect this change. A new IMS rack description and schematic was sent to Air Force Weather Agency (AFWA) personnel to expedite the paperwork.

During the brief period of accessibility for the Thule IMS on the network, the GPS satellite coverage and sky tracks for Thule were examined to determine appropriate satellite exclusion criteria and avoid conflicts that were detrimental to IMS operation.

2.3 Maintenance

One of the large-capacity server systems obtained for evaluation as a possible field site server for the upgraded IMS units has been converted for use as a monitoring system for data transmissions from the remote IMS sites, after the failure of the system previously performing this role. Further developments were conducted for this configuration effort, including the reinstatement of automated tasks for data retrieval. The content of these data reports was reviewed with Boston College personnel at AFRL, in conjunction with IMS data display activities.

Some problems were encountered with bias calibrations occurring immediately after the year transition from 2001 to 2002. These were traced to problems associated with the calculation of azimuth and elevation values from the first almanac file retrieved after the year transition. A subsequent almanac retrieval remedied this situation.

Information was retrieved from the sites to support the accreditation of the IMS units to be migrated to the SWN. AFRL personnel provided some assistance in this effort, because dial-up access to the Thule IMS was hampered by technical difficulties. As part of this effort, the source code for the IMS, including that operating on the Companion PC, was surveyed to provide the Air Force Weather Agency with a scope of the categories and extent of the code base for the IMS.

Efforts were coordinated with Boston College personnel at Hanscom to re-establish usage of the DropBox File Transfer Protocol (FTP) server, following a change of computer domain assignments and the invalidation of passwords at AFRL in March 2002. This was replaced by a new FTP server established at the NWRA Nashua facilities to receive file transmissions from the IMS field units eliminating the automated retrieval and post-processing on one of the AFRL computers. The data retrieval, concatenation, and display capabilities were established on one of the NWRA Nashua computers, with a data monitor display to report recent outages in data transmissions.

Two new hard drives for the HP Apollo computers from the Otis IMS rack, were successfully duplicated and installed, replacing drives that had failed. Parts required for the refurbishment of the old IMS racks were ordered, and some of these have been received. Disassembly of the Croughton rack was begun.

A stand-alone development system was assembled during this period. Some parts are still needed to complete the system.

The program that generates TELSI messages was modified to ensure that exponents for TEC values were restricted to the required range (10^{15} to 10^{19} electrons/m^2), and a field-overflow problem also was addressed.

The processing for FTP TELSI transmissions on the SWN was modified to incorporate site-specific prefixes for the file names, to allow AFWA to distinguish messages arriving from both Shemya and Thule. In conjunction with this revision, FTP TELSI transmissions to the 55th Space Weather Squadron (55 SWXS) were discontinued. Some problems were encountered by AFWA in decoding the TELSI messages from Thule, which contain statistical scintillation parameters not present in the Shemya TELSI messages. These problems were addressed at AFWA and were reported to be resolved, although no new TELSI transmissions have been generated in this format to verify the resolution.

Review of the Shemya IMS performance history in mid-August 2002 indicated that one of the Unix processors had not conducted data collection activities since early June 2002, even with several swap restarts having occurred during this period. This situation is still under investigation.

2.4 Scale Factor Generator (SFG)

Range correction tables are acquired monthly by special arrangements with COBRA DANE personnel. These tables are used to determine the appropriate effective sunspot number for the ionosphere model incorporated into the SFG program. An identical version of the SFG program currently is operating on a computer for the operators there, as well as on the IMS-Net PC. Arrangements were made with the radar operators at Shemya to record scale factors determined from radar measurements into the TEC and Scale Factor log files, and these values also are reviewed. The radar scale factors can be compared directly to the SFG scale factors. Daily predictions of the hourly scale factors previously had been retrieved from the 55 SWXS bulletin board, for future inclusion with these comparisons. For technical reasons, these scale factors have been unavailable since 9 November 1998.

The TEC and Scale Factor log files from the SFG program at Shemya for the period April 2001 to mid-December 2001 were reviewed.

2.5 Additional Developments

Discussions were conducted with Boston College personnel concerning the initial processing steps required to prepare Receiver Independent Exchange (RINEX) data for use by the bias determination program and possible methods for circumventing residual Year-2000 problems. New software provided by the Applied Research Laboratories of the University of Texas at Austin was investigated for applicability in resolving some of these problems.

Because there is no Internet access to some of the IMS sites, it is difficult or impossible to monitor IMS operations by retrieving the log files from the two Unix systems. A set of programs was developed and tested at Nashua to send the IMS activity log file to the Companion PC. This log file is then archived to the data tape, which is sent to AFRL each month.

Cost estimates for several maintenance options were developed, accounting for the deployments to new sites and the retention of an original IMS unit at Shemya, as well as incorporating the facilitated maintenance capabilities arising from the ongoing IMS modification developments, especially the automated calibrations. Related costs were provided for partial hardware replacements for components in an original IMS unit, if this is not to be supplanted by a new IMS unit.

2.6 IMS Modifications

A program of upgrades for the IMS units to implement their specified operational capabilities was initiated. The two major aspects of the upgrades are adaptation and improvement of the communications capabilities to use the Internet-protocol SWN instead of the modem-based Automated Weather Network, and incorporation of scintillation measurement capabilities.

The Contingency Equipment Status Report (CESR) is generated by the UNIX computer in the IMS and sent to the Windows PC. A program was written to decode the CESR and create a text file equivalent on the Windows PC. A process to detect the receipt of a CESR and send the text equivalent in an E-mail notification was developed and tested. This process continues to be monitored to ensure that all possible conditions for CESR generation are correctly reported. It was proposed that three categories be added to the subject line so that the operator could determine whether the CESR is indicating a critical failure, a warning of a potential problem, or reporting the status of IMS operations. A simplified CESR message body was also proposed.

Materials were prepared to describe the automated calibration process and validation of the calibration. A schematic of the process is displayed in Figure 1.

Discussions of the TEC multipath mitigation were conducted, including the description of an algorithm establishing consistency among multipath measurements for the different satellite passes, in a manner similar to the bias calibrations. This algorithm is sketched in the Appendix.

2.7 Alternative Data Evaluations

A Real-Time Monitor (RTM) system was maintained at Hanscom for development of data collection and processing methods, with particular application to the data-collection systems deployed at the Shetland Islands, HAARP, and Qaanaaq. Various software and script revisions and additions were tested on this system before use on the deployed field systems.

2.8 GPS Positioning Error Evaluations

A joint effort with AFRL and Boston College was conducted for the evaluation of the GPS positioning error maps generated by the Operational Space Environment Network Display (OpSEND) program. Position determinations reported by single-frequency GPS receivers were compared to their known locations, and the positioning errors were compared to results derived either from TEC values calculated using the Parameterized Real-time Ionospheric Specification Model (PRISM) or directly-measured TEC values at the receiver location. NWRA was responsible for recording the single-frequency GPS positions for the receivers located at Hanscom and HAARP (Gakona, AK) and providing the corresponding dual- frequency GPS

TEC measurements, while Boston College and AFRL performed the PRISM evaluations and generated the OpSEND results.

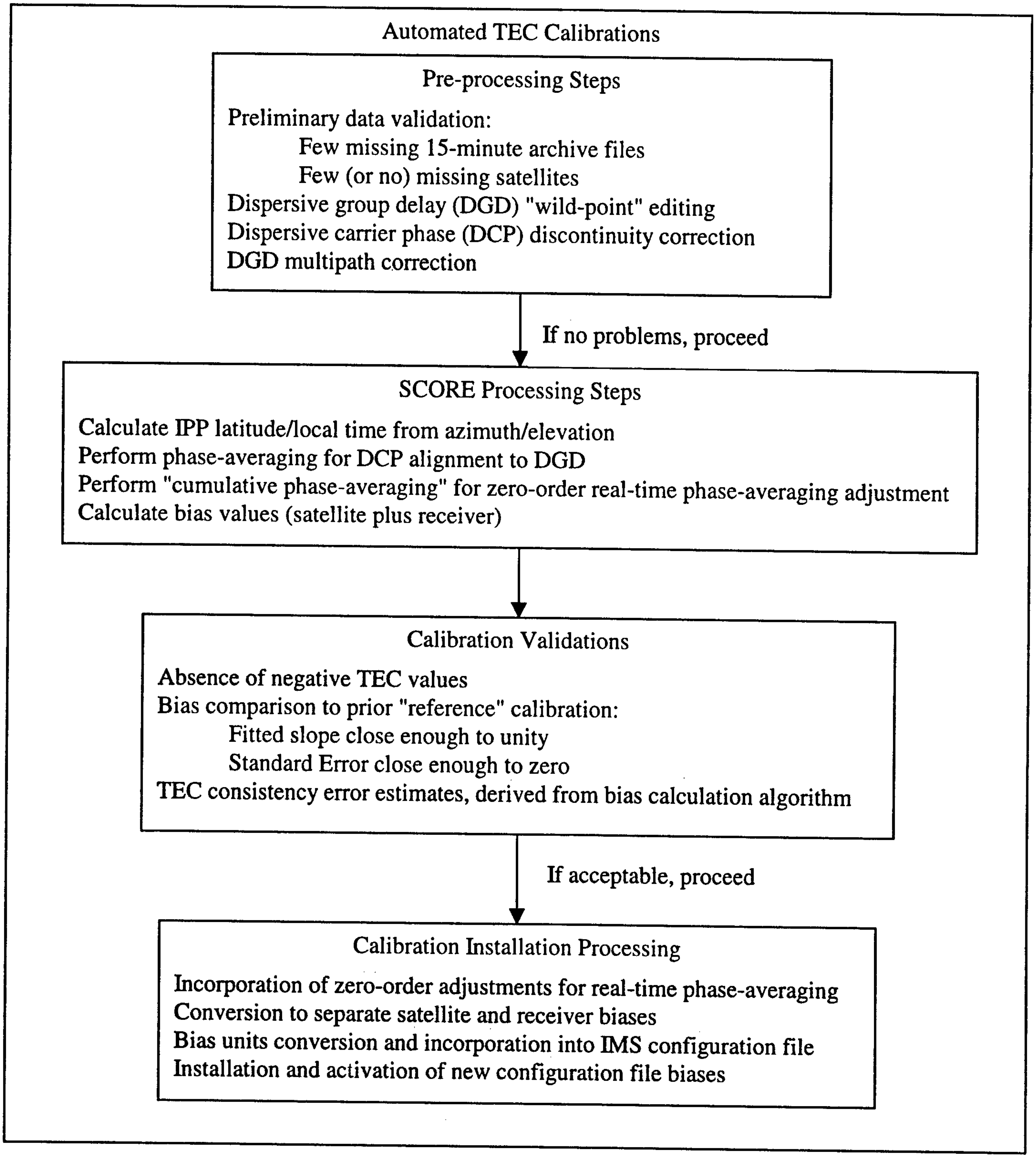

Figure 1: Schematic outline for automated bias calibration. Items not yet automated are shaded. The "cumulative phase-averaging" step, and the associated "zero-order adjustments," can be eliminated after the multipath mitigation is implemented.

An Excel spreadsheet with supplementary macros was augmented to facilitate the acquisition and plotting of these tabulations in the desired format, with further extensions to include the larger number of satellites visible at Gakona, AK. All of the designated days of single-frequency data were processed, but only about two-thirds of the designated days of dual-frequency data were processed, which proved sufficient for the preliminary analysis and report.

2.9 International Collaborations

An RTM data-collection system continued operations at Unst, in the Shetland Islands, with occasional dial-up connections from AFRL. This system experienced a failure and stopped working during the second quarter of the report period. Previously archived data, received on tape at Hanscom, are available for processing for calibrated TEC diurnal variations.

3. HAARP TOPICS

Under HAARP, a major observatory is being constructed at Gakona, AK, to conduct upper-atmospheric, ionospheric, and radio-propagation research. At Gakona, a high-power HF transmitter is being installed in increasingly powerful stages by Advanced Power Technologies, Inc. (APTI). Along with other research organizations, NWRA is participating in and coordinating installation of an array of geophysical diagnostic instruments. Under this contract NWRA has prepared instruments for measurement of transionospheric radio-propagation effects and facilitated installation of other diagnostics.

Our efforts involving development of HAARP diagnostics are reported in Subsection 3.1. We summarize other HAARP activities in Subsections 3.2 and 3.3.

3.1 Development of HAARP Diagnostics

NWRA's activities related to development of HAARP diagnostics included participation in or coordination/facilitation of the installation and/or operation of several instruments, as summarized in the following subsections.

3.1.1 Digisonde

The HAARP Digisonde performs a sounding of the ionosphere every 15 minutes and records the data in Standard Archiving Output (SAO) files. It also creates a GIF file that puts the data in a graphic image, the latest of which can always be found on the HAARP web site. Tyler Wellman, an entering freshman at Brown University, worked at Gakona during the summer of 1999 as an NWRA Student Intern. With guidance from Dr. Helio Zwi, of APTI, Mr. Wellman created a C program that converts the SAO files into network Common Data Format (netCDF) files.

3.1.2 30-MHz Classic Riometer

A riometer measures the average amplitude of galactic radio noise within the instrument's antenna beam, as received through the absorbing region of the lower ionosphere. Ionospheric absorption during particle-precipitation events can be deduced by subtracting measurements performed during quiet ionospheric periods from measurements made during disturbed periods. The measurement performed during quiet ionospheric conditions produces a "quiet-day curve."

Traditionally, riometer data analysis has been performed well after the fact, when a considerable body of data (e.g., a month's worth) is available. A quiet-day curve then can be determined by various techniques, such as mass plots, the inflection method, etc., as described in the literature. At HAARP, where the riometer is used to gauge the instantaneous level of absorption during modification experiments, this approach is not suitable. Rather, a method is needed to determine the level of absorption in real time.

The quiet-day curve is linked to sidereal time rather than solar time (which differ by about four minutes per day) because the radio noise being measured originates from the stars of our galaxy, notably those close to the ecliptic plane. Even here, the radio-noise sources are not evenly distributed, so quiet-day curves depend on the latitude of the riometer antenna, as well as on azimuth and elevation. Thus, derivation of universally applicable quiet-day curves is not possible; each riometer has its own. Also, the curve is displaced due to the difference between solar and sidereal time.

Ionization in the lower ionosphere is produced by a number of sources. Background absorption is linked to the solar zenith angle and the regular solar flux. Particle precipitation causes additional auroral and polar-cap absorption (PCA). The background contribution to the absorption measurement varies with season at a given riometer site. A quiet-day curve determined in late December will represent the galactic noise seen through the diurnal variation of the background absorption during a period when the solar zenith angle is largest. Thus, this curve should represent a lowest baseline of background absorption and may be used as a universal quiet-day curve. Such an approach currently is used with the HAARP classic riometer.

Two problems arise from use of a universal quiet-day curve. First, increased background absorption during the summer will be a dominating feature of the diurnal absorption measurement. The background absorption usually is not of interest to experimenters, and it should be suppressed to isolate the auroral and/or PCA components of the total absorption. Furthermore, a quiet-day curve derived during late December will include periods when the ionosphere above the station is sunlit. In the summer time, these periods may be in darkness due to the difference between solar and sidereal time. This difference can lead to negative absorption values apparently being measured during parts of the night.

Adaptive corrections of the quiet-day curve are possible at high-latitude stations where auroral absorption events are rare or absent and where, consequently, most days are quiet days. At auroral latitudes, however, there may be no quiet days at all during a month, and adjustment of the quiet-day curve will not lead to usable results. The HAARP riometer is situated at such a latitude.

The seasonal variation of background absorption is quite regular. Quiet-day curves derived for particular days of the year are almost identical on consecutive years, leading to the suggestion that a seasonally adjusted quiet-day curve can be derived for universal use at a particular station. NWRA consultant Jens Ostergaard developed a seasonally adjustable quiet-day curve for the HAARP classic riometer.

During a visit to Gakona, Mr. Ostergaard installed new data-acquisition and storage software, including code for computing seasonally adjusted quiet-day curves for all days of the year. The software derives two sets of quiet-day curves and the associated absorptions. One set is based on the quiet-day curve for 27 December, which represents the lowest level of absorption throughout the year. The other set is based on the seasonally adjusted quiet-day curves. Both sets are stored on the data server at Gakona for on-line presentation on the HAARP web site. An option has been implemented to switch displays between the two sets of curves on the riometer data-acquisition computer at Gakona.

A new, armored cable was laid between the operations center and the riometer pad. New power supplies were installed for both the riometer and its GPS timing receiver. In addition, new memory and batteries were installed in the GPS clock, enabling it to operate reliably through an extended power failure. The riometer was calibrated with a noise source, and a high-pass filter was inserted in the antenna cable to eliminate RF interference experienced when the HAARP transmitter operates. The antenna system also was checked and all guy wires adjusted and secured, to render the antennas truly vertical. Calibration software was rewritten in C and placed on the riometer computer at Gakona. The software is employed to determine the gain and linearity of the riometer, for use by the data-acquisition program. A quality-assurance parameter now is included in the data files as an indicator of invalid or questionable operation.

An example of data from the classic riometer, as routinely displayed on the HAARP web site, appears in Figure 2. The smooth green line represents the seasonally adjusted quiet-day curve, and the blue line indicates, for comparison, the riometer's detector output, which is proportional to received galactic noise. Bursts (including some above the quiet-day curve) are caused by local or ionospherically propagated radio interference. The difference between the quiet-day curve and the detector output represents ionospheric absorption and is indicated in dB by means of the red curve. During the 36-hour period displayed, absorption abruptly increased from about one dB or less to about five dB at approximately 1700 UTC on 6 April, coincident with onset of major geomagnetic disturbance. Episodes of lesser absorption occurred approximately 24 hours later.

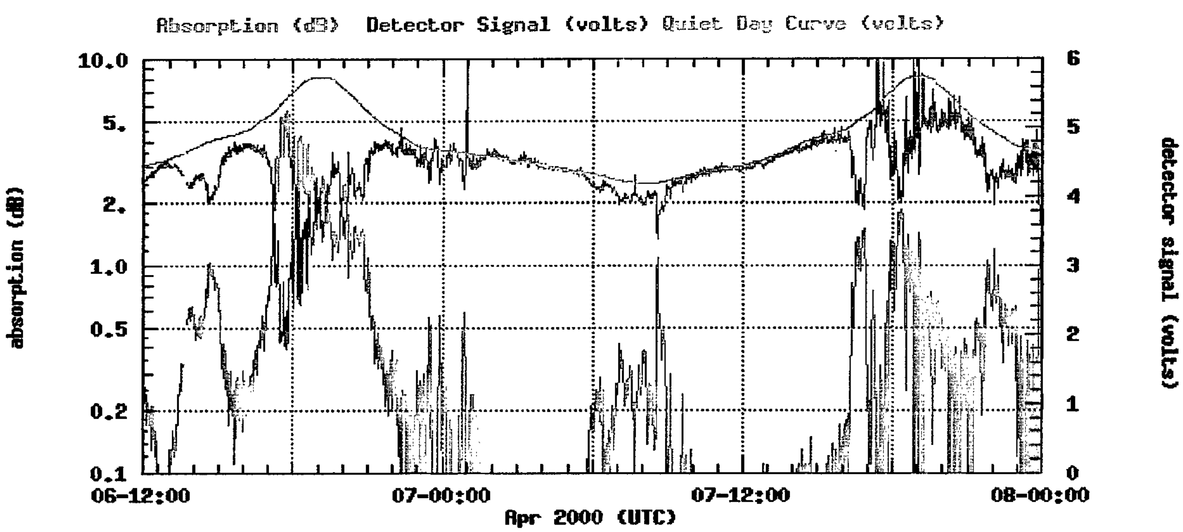

Figure 2: Display, from the classic-riometer page on the HAARP web site, of ionospheric absorption (red) in dB, along with the galactic radio noise (blue) and comparative quiet-day curve (green) from which it is derived. Near the beginning of the 36-hour period displayed, a major ionospheric/geomagnetic disturbance began at about 1700 UTC on 6 April.

During this contract period, the riometer experienced an increase in propagated interference under current (solar-maximum) ionospheric conditions, in which the maximum useable frequency (MUF) often is at or slightly above 30 MHz. With propagated interference being a common problem for riometry, several remedies have been devised. The most obvious is use of a frequency consistently higher than the MUF on possible propagation paths, but frequency extrapolation is problematic at high latitudes due to the patchiness of absorption. A preferred approach would be to employ an IF bandwidth substantially narrower than that used in the HAARP riometer (200 kHz), together with a frequency sweep and minimum-strength detector. Such modification was beyond the scope of this contract, and a new riometer is being developed under a separate contract. Meanwhile, the operating frequency of the existing riometer was shifted to a relatively "clean" portion of the band, and its bandwidth was narrowed to 30 kHz. These steps have reduced the effect of propagated interference substantially.

3.1.3 GPS Receiver for Measuring Absolute TEC and Estimating Location

Early in this contract period, NWRA operated HAARP's Novatel single-frequency GPS receiver at Gakona and archived data from it until the trailer housing the receiver was relocated near the end of March 1998. Participants in the RF Ionospheric Interactions Workshop held in April of that year discussed the utility of installing a two-frequency GPS receiver at Gakona having a sufficiently high sample rate that intensity and differential phase scintillation could be recorded (at least 10 Hz, and preferably 20 Hz). NWRA was tasked with investigating such a receiver.

Based on a survey of 429 receivers from 70 manufacturers in the January 1998 issue of *GPS World*, NWRA Senior Research Scientist Edward Fremouw conferred with Santimay Basu (AFRL), Gregory Bishop (AFRL), Clayton Coker (the Applied Research Laboratory (ARL) at the University of Texas at Austin), Anthea Coster (Lincoln Lab), Keith Groves (AFRL), Robert Livingston (Scion Associates), Andrew Mazzella (NWRA), and James Secan (NWRA). The upshot was that (1) operation of the single-frequency Novatel receiver at Gakona was taken over by AFRL to monitor whatever L-band scintillation might be encountered there, and (2) NWRA was directed to concentrate its GPS activities in HAARP on TEC measurements.

To measure absolute TEC, NWRA purchased an Ashtech Z-FX Continuously Operating Reference Station (CORS), consisting of a 12-channel GPS receiver and a choke-ring antenna, and installed it at HAARP. Data acquisition from the Z-FX CORS is performed by the RTM program, including high-rate (one-Hz) intensity and phase from both GPS frequencies and low-rate (one sample/minute) differential group delay and differential carrier phase, with S_4 scintillation indices being computed once per minute.

Stored as RINEX files, the Group Delay and Carrier Phase data are used for determining bias calibrations in post-processing, using the SCORE (Self-Calibration of Range Errors) technique. As a by-product of our TEC measurements, the S_4 values are available for surveys of scintillation occurrence. The RTM data collection is supplemented by a real-time process to convert one-minute reports from the RTM program into ionospheric penetration-point (IPP) databases, which become the source of calibrated measurements of absolute TEC displayed on the HAARP Web site and stored there in Network Common Data Format (netCDF).

An example of the principal display is given in Figure 3, which spans the same time interval as the riometer data shown in Figure 2. Nearly simultaneously with the abrupt increase in absorption near 1700 UT on 6 April, TEC dropped rapidly. The drop was followed by a sharp increase near 2100 UT, spanning about five hours during which geomagnetic activity continued. The lesser episodes of absorption near the end of Figure 2 were not accompanied by any significant change in TEC or resumption of geomagnetic activity.

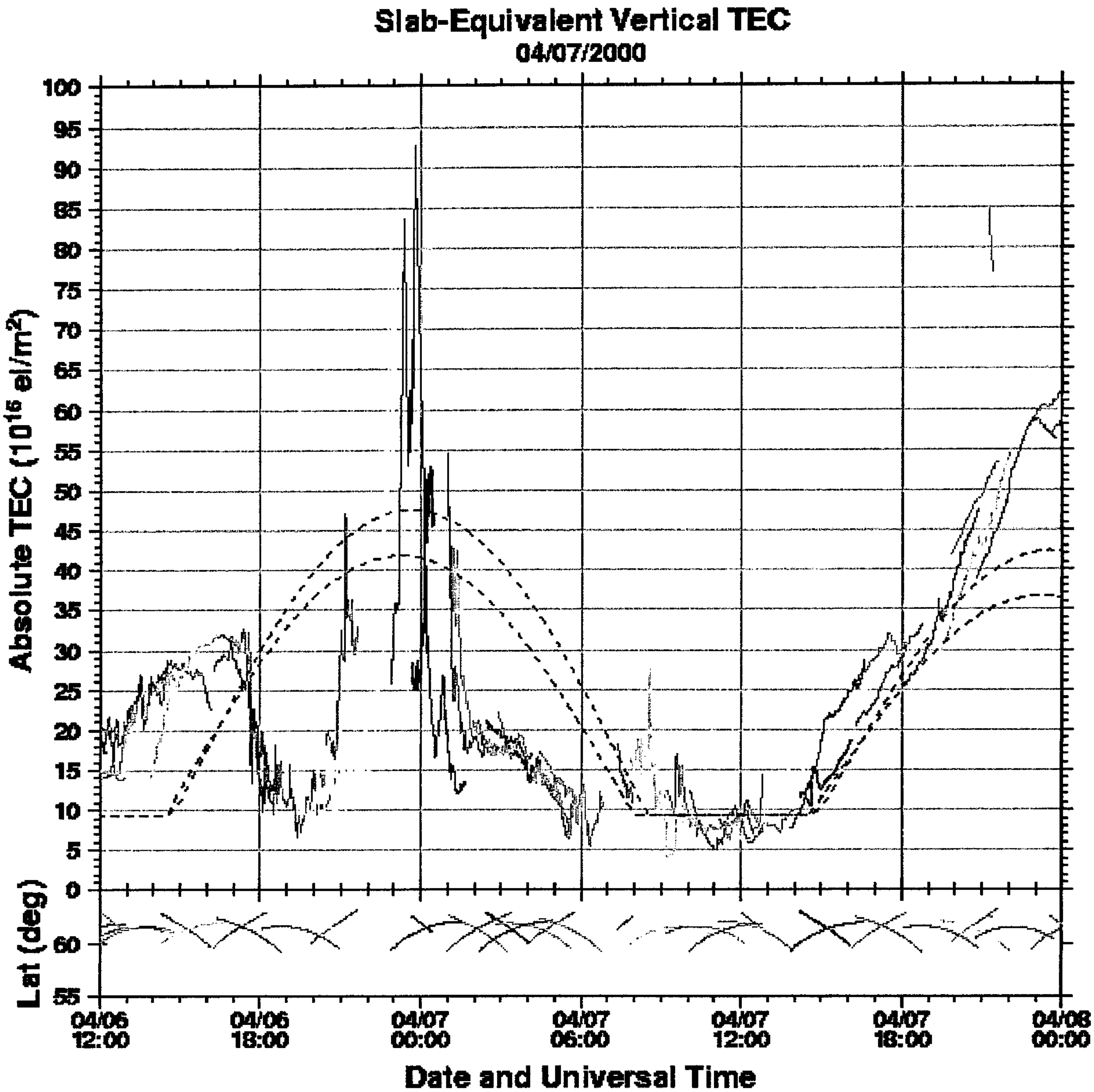

Figure 3: Time history of vertical TEC near Gakona during the same 36 hours for which riometer data are displayed in Figure 2. The decrease starting near 1700 UT on 6 April and subsequent abrupt increase ending near 0200 UT coincided with substantial geomagnetic activity at Gakona.

For each UTC day, slant TEC also is shown in a collection of 24-hour time-series plots, one plot for each GPS satellite (PRN#), along with the elevation angle of that satellite as viewed from

Gakona. An example of the multi-satellite plots appears in Figure 7a of *Andreasen et al* [1999]. Beneath the time-series panels, a polar-coordinates plot shows the azimuth and elevation of all GPS tracks observed from Gakona during the day, as illustrated in Figure 7b of the same report.

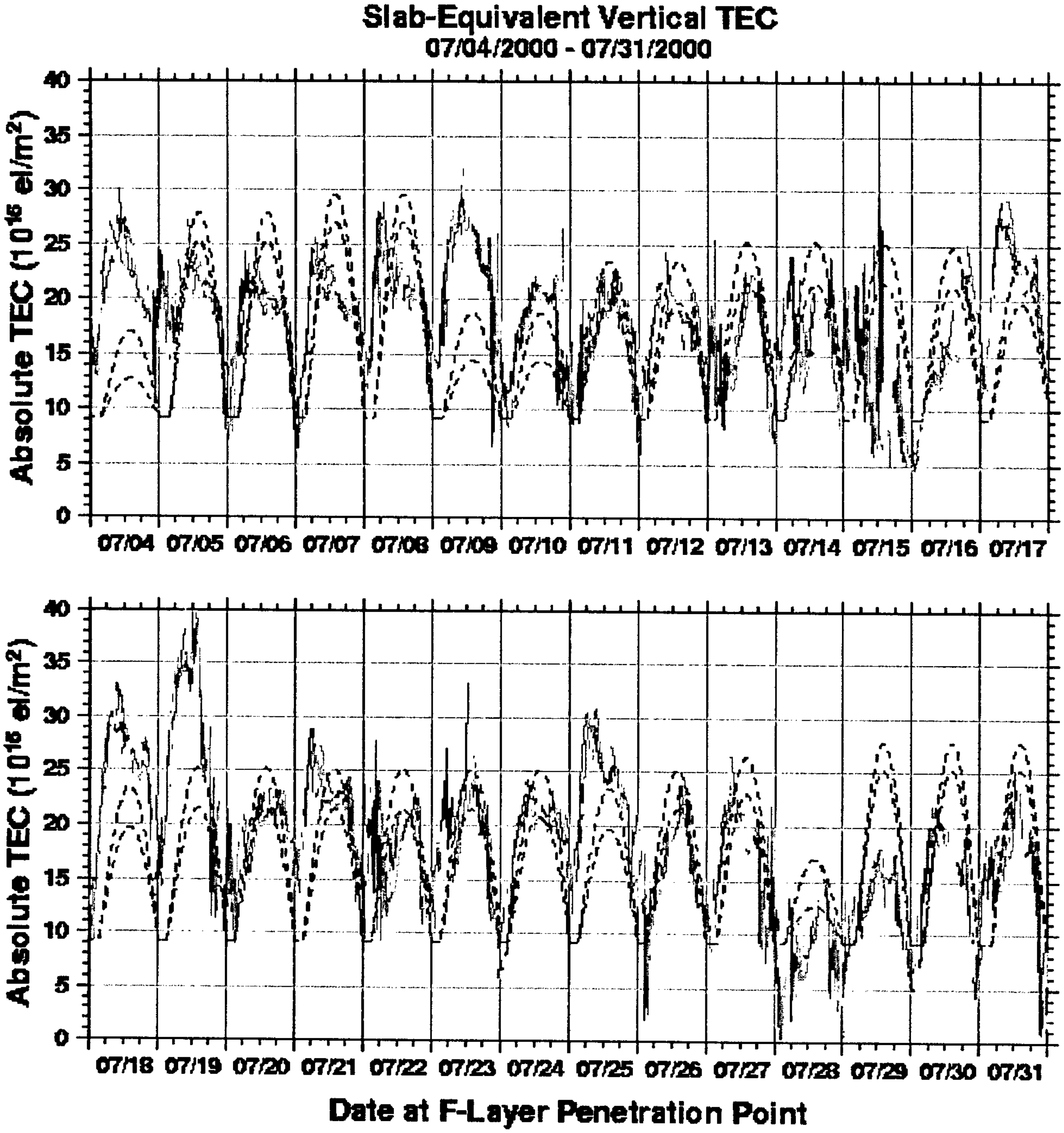

Figure 4: Example of web display showing 28-day time series of absolute TEC compared with model values (broken curves) computed from coefficients broadcast by GPS satellites. Displays of seven-day spans also are available.

Note that GPS satellites can be viewed to the south from Gakona up to elevation angles of about 80° and low to the north (over the pole) up to an elevation angle of about 20°. The orbital inclination of GPS precludes measuring TEC in the region overhead and immediately northward of Gakona.

In addition, a visitor to the HAARP Web site may view seven-day and 28-day spans of absolute TEC variation. An example of the 28-day plots (showing essentially the month of July 2000) appears in Figure 4. In this and all such displays (36-hour, seven-day, and 28-day), the colored traces show absolute TEC as determined from the CORS two-frequency measurements, and the dashed curves show values calculated from a model using coefficients transmitted by GPS satellites for estimation of TEC by single-frequency users. The latter may be thought of as "quiet-day curves" updated for currently anticipated ionospheric conditions.

3.1.4 Transit Receivers for Recording Latitude Scans of Relative TEC

Under a Small-Business Innovation Research (SBIR) contract, NWRA developed an ionospheric tomography system (ITS) capable of producing two-dimensional images of ionospheric plasma-density structures on scales from tens to thousands of km. The SBIR system included a coherent receiving subsystem (the NWRA ITS10 receiver) for measuring relative TEC by recording the differential (dispersive) phase between VHF and UHF signals transmitted from the U.S. Navy's Transit satellites.

Subsequently NWRA augmented the ITS10 to permit measurement of intensity scintillation at both VHF and UHF (the scintillation-capable receiver being designated the ITS10S), as well as phase fluctuations corresponding to TEC variations on scales down to somewhat less than a kilometer. The ITS10S records intensity and differential phase at 50 samples per sec (sps) during satellite passes of approximately 15 minutes duration. The dispersive phase is converted to relative TEC, smoothed to one sps, and referenced to the minimum value recorded during the pass.

Originally, the ITS10S was designed to receive signals in the "operational" band employed by the Transit satellites in the now-decommissioned Navy Navigational Satellite System (NNSS). It was capable also of receiving signals from the NNSS "maintenance" band (the two bands being slightly offset in opposite senses from the nominal frequencies of 150 and 400 MHz), but switching from one band to the other required manual re-tuning. Since de-commissioning of the NNSS, the Transit satellites have been operated as the Navy Ionospheric Monitoring System (NIMS). In NIMS operation, the individual Transits are switched from time to time between the two bands. To increase the number of signal sources readily available to the ITS10S, NWRA Research Engineer J. Francis Smith developed a frequency-agile sweep circuit that permits reception of signals in both bands, as well as in bands employed by Russian and other U.S. coherent-beacon satellites, without manual re-tuning.

Under this contract, NWRA installed and has operated three modified ITS10S receivers in Alaska, one at Gakona, one near Delta Junction to the north, and one at Cordova to the south. The dispersive phase recorded at these stations constitutes offset latitude scans of relative TEC and its small-scale gradients in the auroral zone (night-side oval) and sub-auroral trough. The offset scans provide measurements at different angles through a given IPP, permitting tomographic inversion to resolve the ambiguity in measured TEC and to produce two-dimensional (altitude/latitude) images of plasma density. Although three stations (and the resulting three look angles through a particular feature) offer only a minimal tomographic capability, three-station images can reveal major ionospheric features. An example of such a rudimentary F-layer image was presented as Figure 8 by *Fremouw et al* [2000].

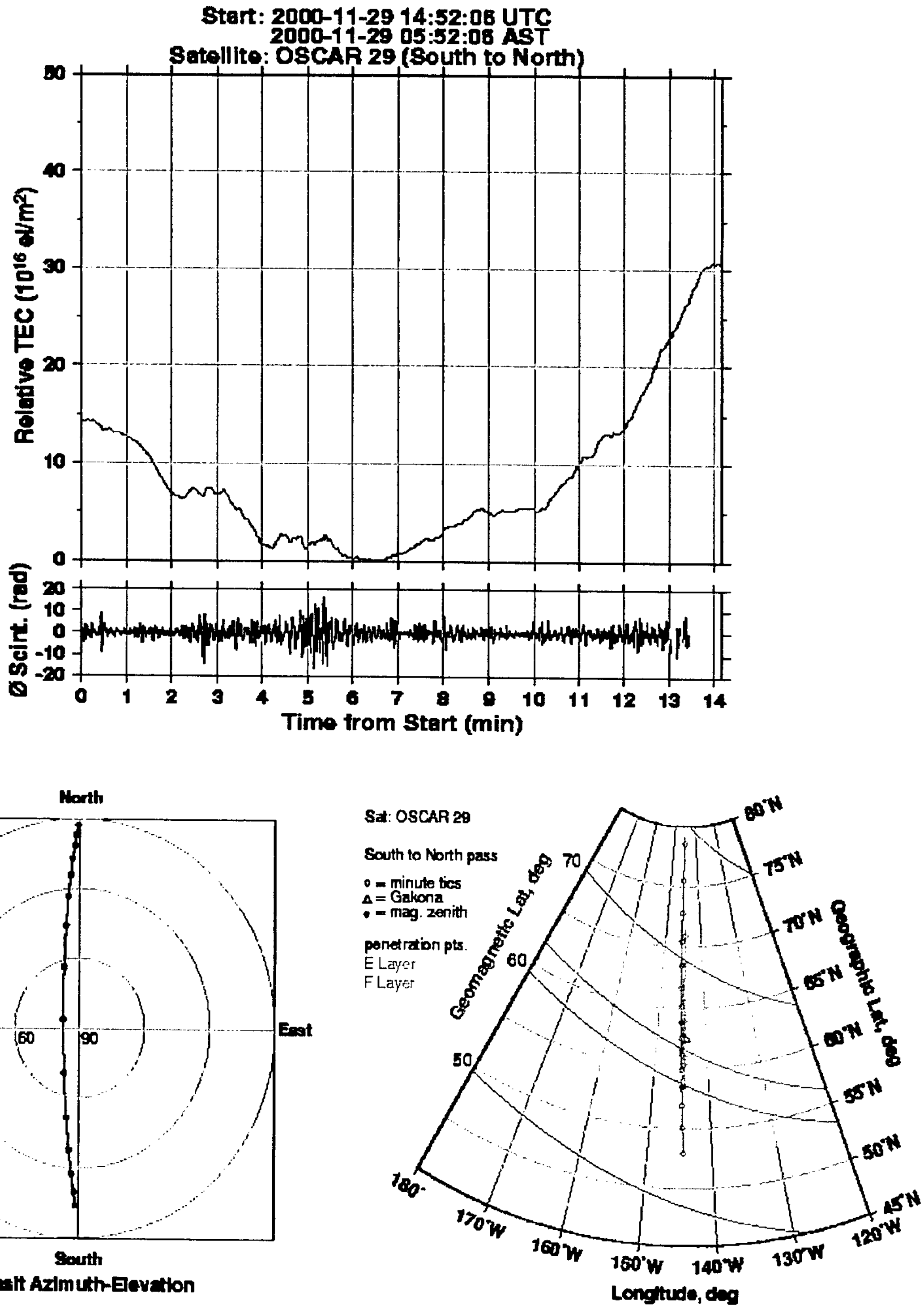

Figure 5: Example of HAARP web display showing dispersive-phase scintillation along with relative TEC (upper plot), during pass of a Transit satellite over Gakona (lower two plots).

The Transits radiate by means of circularly polarized antennas. Because of inconsistencies in polarization sense between different classes of Transits, the ITS10S originally employed a linearly polarized receiving antenna. Only one class of Transit, the Oscar class, remains, and we have converted the ITS10S antennas to circular polarization. This permits recording signals from other coherent-beacon satellites, some of which transmit with linear polarization, without encountering deep signal fades due to Faraday rotation. Accordingly, all ITS10S receivers have been outfitted with simple turnstile antennas matching the circular polarization sense transmitted by the Oscar-class Transits.

The 50-sps data rate of the ITS10S receivers provides a capability for recording radiowave scintillation, given sufficient signal strength to obviate the need for smoothing. As deployed for HAARP, the receivers are outfitted with very simple, fixed antennas (as described in the preceding paragraph) directed toward the zenith. Even with such low-gain receiving antennas, the signals received from the Transit satellites and some other Transit-like satellites are sufficiently strong to record scintillation during at least high-elevation portions of their passes (typically above 20 deg or so for the Transits). Accordingly, we implemented recording of dispersive-phase scintillation at both Gakona and Delta.

An example of a combined TEC and phase-scintillation record posted on the HAARP web site is shown in Figure 5, along with the pass geometry. The lower strip in the upper panel displays 50-sps phase residuals obtained after detrending by subtraction of the output from a low-pass filter having a sharp cutoff at 0.1 Hz (i.e., after removal of trends with periods greater than ten sec). The residual trace is displayed when the average signal-to-noise ratio over a running ten-sec window exceeds 14 dB on both VHF and UHF. As a quantitative measure of scintillation, the rms value of phase fluctuation also is calculated during ten-second periods in which at least 250 acceptable residual values are recorded. The results are included at the end of ASCII and netCDF files posted on the HAARP web site.

The data illustrated in Figure 5 are from a pass of a Transit satellite that occurred near the end of a period of geomagnetic activity. It revealed scintillation-producing irregularities even to the south of Gakona. The scintillation enhancement that occurred just after five minutes from the pass start, as the line of sight scanned near Gakona's magnetic zenith, is a geometrical effect due to field alignment of the irregularities.

Conversion from relative slant-path to absolute vertical TEC may be performed most reliably by integrating vertically through tomographic images of plasma density. Given a sequence of such measurements from a single station, an approximate conversion can be made under sufficiently simple ionospheric conditions. Such approximate conversion relies on an ad hoc assumption, usually that of a slab-like ionosphere devoid of horizontal gradients. Even with such an ad hoc assumption, one needs additional information to account for the unknown offset inherent in records of relative TEC (stemming from the $n\pi$ ambiguity in the dispersive phase actually measured). We have implemented a hybrid method of calibrating Transit passes for different sites against each other and against GPS TEC measurements as a means of deriving such information.

3.1.5 Spaced-antenna Scintillation Monitor

Under a separate contract from AFRL, Scion Associates has installed a spaced array of antennas and associated receiving equipment for recording signals from slow-moving satellites (near their apogee in highly eccentric orbits). Scintillation analysis of the received signals is expected to yield information on the structure (spatial spectrum) and motion of km-scale plasma-density irregularities produced by HAARP heating and by natural causes. Under this contract, NWRA Consultant John Rasmussen coordinated efforts to achieve real-time transfer of these data to the HAARP Operations Center and to integrate them onto the HAARP web site.

3.1.6 All-sky Imaging Camera

During June and July of 2000, Mr. Wellman returned as an NWRA Student Intern to work with AFRL personnel at Hanscom AFB. His principal project for the summer was to create a Java applet to display false-color images from the All-Sky Imaging camera in real time. The research of AFRL Scientist Todd Pederson, who previously had developed a program to produce such images, is facilitated by the portability afforded by the Java applet.

Mr. Wellman first modified the control code of the All-Sky Imager to produce condensed JPEG files containing eight kilobytes of data for Internet display and/or real-time download over a narrowband connection. He then developed the applet to provide a capability to display the JPEG files on the web. The files contain such information as the latitude and longitude of the camera, the wavelength of the filter (red, green, blue, or infrared) employed, and the time of data recording. The Java applet reads the data stored in the JPEG file and displays the image via a web browser with the time, location, and wavelength written over it. It also displays the stored image in red, green, blue, or gray, depending on the filter employed.

3.1.7 Coherent Backscatter Radar

During this report period, HAARP acquired a 139-MHz radar for measuring coherent backscatter from fine-scale ionospheric irregularities. NWRA Consultant John Rasmussen collaborated with experimenters who intend to employ the radar as a diagnostic on placement of its antenna array and instrument shelter. Mr. Rasmussen coordinated construction, by Ahtna Construction, of the support structure for the antenna array. Following laying of a foundation for the instrument shelter, the shelter was erected. Under Mr. Rasmussen's supervision, NWRA Student Intern David Bruington installed instrument racks and cabinets.

3.1.8 Powerful Diagnostic Radar

A panel, including five NWRA consultants, formulated recommendations for a powerful diagnostic radar (PDR) at Gakona. Following an organizational meeting of co-chairs Brenton Watkins and William Gordon in San Francisco in December 1999, the expert panel of radar engineers and scientists was convened to work out a recommended approach to acquisition of a PDR and to estimate the associated cost. In addition to Drs. Watkins and Gordon and with NWRA Consultant A. Lee Snyder serving as its executive, the panel consisted of radar engineers David K. Barton and Allan Schell and radio scientists Frank T. Djuth and Michael C. Kelley. The panel's report was completed and delivered to the HAARP Program Managers, Paul Kossey of AFRL and Ed Kennedy of ONR/NRL, in August 2000. Dr. Snyder also prepared a brief description of the PDR as it might be acquired for use at Gakona, for inclusion in the *HAARP Diagnostics Brochure* prepared by Mr. Rasmussen.

3.2 Other Diagnostic Activities

Brett Isham, Associate Professor at Interamerican University of Puerto Rico, spent the summer of 1999 as an NWRA consultant working with the HAARP group in the Ionospheric Hazards Branch of AFRL at Hanscom. Dr. Isham has extensive expertise in radar observations of the ionosphere, particularly in high-power HF wave-interaction experiments, for which HAARP is an ideal instrument. In early July, Dr. Isham joined Keith Groves and engineer Jake Quinn, both of AFRL, for the first test experiments of the newly expanded, one-MW HAARP antenna array. For that experiment Dr. Isham reconfigured the HAARP Digisonde, which is a low-power HF radar, to take X-mode radar spectra of the irregularities created during HAARP O-mode transmissions. These measurements supplemented spectra of stimulated electromagnetic emission (SEE) and ionospheric scintillation recorded by Dr. Groves and Mr. Quinn. SEE is sensitive to irregularities in the scale-size range of one to ten meters, and scintillation is sensitive to the hundred-meter irregularity range. The X-mode observations are intended to bridge the gap, as they should be sensitive primarily to structures on a scale of tens of meters.

Dr. Isham devoted additional time to furthering the analysis of data taken in collaboration with Groves, Quinn, and others in northern Scandinavia in 1998, and to publishing the results of earlier experiments devoted to Langmuir turbulence and transition to the irregularity regime. These results show for the first time that cavitating Langmuir turbulence, known to occur in mid-latitude HF experiments at Arecibo, also occurs in high-latitude experiments. This is important for improving understanding of the processes of irregularity generation during HF experiments at facilities such as EISCAT and HAARP.

3.3 Scientific Collaborations

Dr. Spencer Kuo, of the Department of Electrical Engineering at Polytechnic University in Farmingdale, NY, also spent the summer of 1999 at Hanscom as an NWRA consultant. He collaborated with Dr. Groves and Drs. Paul Kossey and John Heckscher of AFRL and with Prof. M.C. Lee, of the Massachusetts Institute of Technology, in a theoretical study of Extremely Low Frequency (ELF) and Very Low Frequency (VLF) wave generation in the heating-wave-modulated polar electrojet. An amplitude-modulated heating wave is known to modulate the ionospheric conductivity and, therefore, the electrojet current, effectively producing an ELF/VLF antenna.

The work indicated that a stimulated thermal instability also is excited and that this instability introduces an electron-temperature modulation more effectively than does the passive Ohmic-heating process. The thermal instability is expected to improve considerably the intrinsic efficiency of ELF and VLF wave generation by the amplitude-modulated HF heating wave. The generation efficiency and signal quality depend on the HF-wave modulation scheme. Four amplitude-modulation schemes were examined and compared.

Subsequently Sanghum Lee, a student of Prof. Kuo at Polytechnic University, worked as an NWRA consultant to extend the foregoing analysis into the non-linear regime. He conducted a numerical study of ELF/VLF generation by electrojet modulation via an X-mode HF heating wave. In the numerical study, Mr. Lee examined four amplitude-modulation schemes that had been investigated in the linear analysis: (1) rectangular wave, (2) beat wave, (3) rectified half wave, and (4) triangular wave. Specifically, he assessed the dependencies of the ELF/VLF radiation intensity on the power, modulation frequency, and modulation scheme of the HF heating wave.

Mr. Lee's results indicated that ELF radiation intensity (at 100 Hz) increases abruptly when the power of the heating wave exceeds a critical level. The critical level, p_c, varies with the modulation scheme and increases with frequency. He investigated the relative efficacy of the four modulation schemes in the range from 100 to 5000 Hz by comparing the spectral intensities of the fundamental and the second and third harmonics of the generated ELF/VLF radiation. In accord with the linear analysis, the numerical results indicated that the rectified half-wave is the most efficient modulation, while the beat wave generates the signal of highest quality (i.e., having the least harmonic content).

4. PUBLICATIONS AND PRESENTATIONS

The following publications and presentations resulted, in part, from research carried out under this contract.

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Fremouw, E.J., Latitudinal Scans of Total Electron Content during the Campaign, RF Ionospheric Interactions Workshop, Santa Fe, NM, April 1999.

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Appendix: Multipath Consistency Algorithm

For operational purposes, the multipath will be considered to be the sample-by-sample difference of the dispersive group delay (DGD) and the dispersive carrier phase (DCP), with the phase offset ambiguity for DCP removed by phase-averaging (weighted or unweighted) over an entire pass. For passes confined to relatively small regions of the sky, this presents the possibility of a residual multipath component offsetting the entire pass. The method described here is intended to eliminate this residual component for individual passes, by imposing consistency conditions between passes at common sky coordinates.

$$M_{\alpha_i} = \mathrm{DGD}_{\alpha_i} - \mathrm{DCP}_{\alpha_i}$$

M_{α_i} : multipath (in TEC units), pass α, sample i

DGD_{α_i} : dispersive group delay, pass α, sample i

DCP_{α_i} : dispersive carrier phase, pass α, sample i, after phase-averaging

As with the TEC bias calibration, each pass is associated with a multipath bias m_α, derived from a consistency condition over all passes. At each sky conjunction, the adjusted multipath values for the two passes should be equal. Thus, $M_{\alpha_i} - m_\alpha = M_{\beta_j} - m_\beta$ if the samples α_i and β_j correspond to the same sky location. Globally, over all passes, this can be imposed as a minimization condition on E, defined by:

$$E = \sum_{\alpha} \sum_{i} \sum_{(\beta \neq \alpha)} \sum_{j} W_{\alpha_i \beta_j} \left[\left(M_{\alpha_i} - m_\alpha \right) - \left(M_{\beta_j} - m\beta \right) \right]^2$$

with a supplementary condition $\sum_{\alpha} m_\alpha = 0$ (required because only the difference $m_\alpha - m_\beta$ appear in the minimization.

The quantity $W_{\alpha_i \beta_j}$ is a weight function, specified to select the sky conjunctions for the paired passes. For a spatially symmetric weighting, this can be defined as a function of the angular distance between two measurements:

$$\delta_{\alpha_i} = \arccos\left\{ \sin\left(\varepsilon_{\alpha_i}\right) \sin\left(\varepsilon_{\beta_j}\right) + \left[\cos\left(\varepsilon_{\alpha_i}\right) \cos\left(\varepsilon_{\beta_j}\right) \cos\left(\phi_{\alpha_i} - \phi_{\beta_j}\right) \right] \right\}$$

for elevations ε and azimuths ϕ.

The conditions for minimizing E can be obtained from the partial derivatives of E with respect to the unknown multipath biases. For N passes, the first N-1 equations ($\gamma = 1, \ldots, N-1$) for the multipath biases are:

$$\sum_{j} \sum_{(\alpha \neq \gamma)} \sum_{i} \left(W_{\alpha_i \gamma_j} + W_{\gamma_j \alpha_i} \right) \left[\left(M_{\alpha_i} - m_\alpha \right) - \left(M_{\gamma_j} - m_\gamma \right) \right] = 0$$

and the last equation is the supplementary condition: $\sum_{\alpha} m_\alpha = 0$.

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