CASES: A Novel Low-Cost Ground-based Dual-Frequency GPS Software Receiver and Space Weather Monitor

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BIOGRAPHIES

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Steven Powell is a Senior Engineer with the GPS and Ionospheric Studies Research Group in the Department of Electrical and Computer Engineering at Cornell University. He has been involved with the design, fabrication, testing, and launch activities of many scientific experiments that have flown on high altitude balloons, sounding rockets, and small satellites. He has designed ground-based and space-based custom GPS receiving systems primarily for scientific applications. He has M.S. and B.S. degrees in Electrical Engineering from Cornell University.

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ABSTRACT

GPS receivers can be used for monitoring space weather events such as TEC variations and scintillation. This paper describes the new GPS sensor developed by ASTRA, Cornell and UT Austin. The receiver is called "Connected Autonomous Space Environment Sensor (CASE)", and represents a revolutionary advance in dual frequency GPS space-weather monitoring. CASES is a paperback-novel-sized dual-frequency GPS software receiver with robust dual-frequency tracking performance, stand-alone capability, and complete software upgradability. The receiver tracks L1 and L2 civilian signals (specifically L1 C/A, L2 CL and L2 CM).

The sensor measures and calculates TEC with a relative accuracy of a few 0.01 TECU at a cadence of up to 1 Hz (post-processing up to 100 Hz). It measures amplitude and phase at up to 100 Hz on both L1 and L2-C, for up to 14 satellites in view. It calculates the standard scintillation severity indicators S_4, τ_0, and σ_Φ, and a new index, the Scintillation Power Ration (SPR), all at a cadence that is user defined. It is able to track through scintillation with {S4, τ_0, amplitude} combinations as severe as {0.8, 0.8 seconds, 43 dB-Hz (nominal)} (i.e., commensurate with vigorous post-sunset equatorial scintillation) with a mean time between cycle slips of 480 seconds and with a mean time between frequency-unlock greater than 1 hour.

Other capabilities and options include: Various data interface solutions; In-receiver and network-wide calibration of biases, and detection and mitigation of multipath; Network-wide automated remote configuration of receivers, quality control, re-processing, archiving and redistribution of data in real-time; Software products for data-processing and visualization.

CASES has been designed and developed by the ionosphere community rather than adapting a commercial receiver. The low price of the sensor means that many more instruments can be purchased on a fixed budget, which will lead to new kinds of opportunities for monitoring and scientific study, including networked applications. Other potential uses for CASES receivers include geodetic and seismic monitoring, measurement of precipitable water vapor in the troposphere at meso-scale resolution, and educational outreach.

I. INTRODUCTION

Ionospheric weather includes gradients and irregularities that affect transionospheric UHF and L-band line-of-sight propagation (scintillation) and VHF/HF sky-wave and scatter propagation. Such disturbances lead to communication and navigation outages with operational impacts. These disruptive phenomena occur frequently in the tropics, less frequently in the polar region, and even less frequently at mid-latitudes, but they occur everywhere with serious consequences. Mitigating these impacts through ionospheric specification, now-casting, and forecasting is a goal now within reach. While assimilative models have been developed that utilize ionospheric data, there is insufficient ionospheric data to adequately specify the global ionosphere. The main reasons are: (1) existing instruments are inadequate; (2) existing instruments are too expensive; (3) 70% of the earth is covered in water, making instrument deployment difficult. The development of tools to enable "actionable" ionospheric weather forecasts and specification of irregularities is the ultimate goal of ASTRA LLC, and development of the CASES GPS receiver is part of the strategy.

Section II of this paper contains a description of the need for a hardware platform like CASES, and a brief history of its development. Section III describes the six salient features that make this new receiver so popular. Section IV describes some of the post-processing and user-interface options available with CASES, and additional data services available from ASTRA, and Section V contains conclusions.

II. THE NEED

Space weather refers to conditions in space (the Sun, solar wind, magnetosphere, ionosphere, or thermosphere) that can influence the performance and reliability of space-borne and ground-based technological systems. Ionospheric irregularities at equatorial, auroral, and middle latitudes constitute a major category of space weather effects that need to be better characterized and understood.

Figure 1 shows a mosaic of ultraviolet images from the nightside ionosphere obtained by the Global Ultra Violet Imager (GUVI) on NASA's Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. The image illustrates many important ionospheric features. The geographic equator is in the center of the figure, with the north pole at the top. The magnetic equator is not aligned with the geographic equator, and is shown as the wavy green line at low latitudes. The brightest portions of the UV image occur on either side of the magnetic equator, and are caused by the large electron density in the Appleton Anomalies. The brightness of the images falls off towards the equator and middle latitudes because the electron concentrations are lower. Brighter UV emissions are observed in both polar regions, due to the effects of auroral particle precipitation.

At low latitudes, each image shows extended airglow depletions with braided irregularities. The airglow depletion corresponds with depletions of ionospheric electron density, and GPS signals have many times confirmed the existence of corresponding TEC depletions. The scale sizes of the gradients in the ionospheric depletions vary from several hundred km to the image resolution of about 10 km, or smaller.

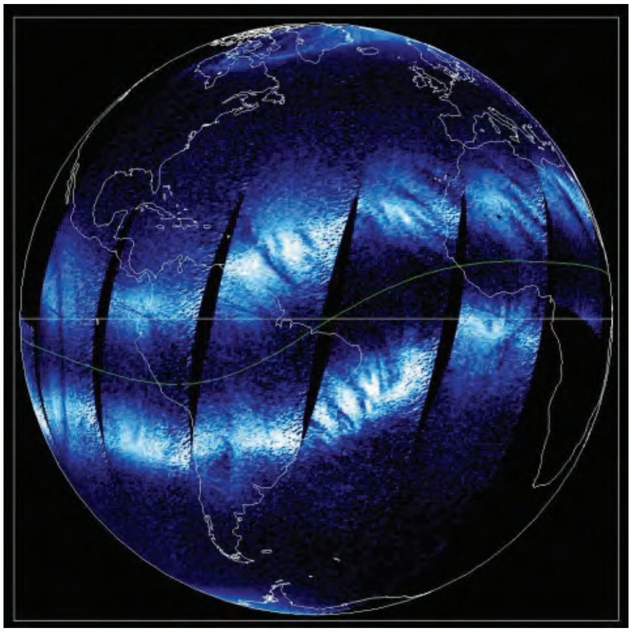

Figure 1. Mosaic of ultraviolet images of the ionosphere from the GUVI instrument on NASA's TIMED satellite (image courtesy of Larry Paxton, APL).

Gradients of 30 TECU over 10 km scale lengths occur at all latitudes, and even at midlatitudes gradients of 300 TECU over 100 km scale lengths have been reported during ionospheric storms. These severe ionospheric gradients tend to occur in the mid-Atlantic region of the United States, producing rapidly changing ranging errors (as a function of time) to a single GPS satellite. Such TEC variations during a mid-latitude ionospheric storm led to severe impacts on the FAA augmentation of GPS called WAAS[1]. The storm's effects can last for nearly a full day. This inability to resolve the ionosphere at these scales required WAAS to be broadly unavailable for up to 15 hours across the United States during large ionospheric storms in 2003 and 2004.

Associated with these gradients are ionospheric irregularities and scintillations that can cause GPS receivers to lose signal tracking[2]. Given the widespread introduction of GPS into the modern world's technical infrastructure in the past five years, the increased reliance on GPS for PNT (Positioning, Navigation, and Timing), and the upcoming solar maximum in 2013, there will be a sudden demand for GPS diagnostic systems when high-end users discover that their technologies are vulnerable.

That vulnerability is greatest in the tropics, where severe scintillations can occur on a daily basis. Here, fades at L-band can exceed 30 dB and are more severe at lower frequencies. Figure 2 compares the carrier-to-noise ratio of scintillating and non-scintillating signals recorded simultaneously from two GPS satellites. The received power of the scintillating signal varied by more than 40 dB. These fades cause loss of GPS receiver tracking lock, increased occurrence of cycle slips, lengthen acquisition times, decrease PNT accuracy, and in severe cases cause loss of navigation[3]. For GPS receivers, tracking normally fails below 26 dB-Hz. At UHF frequencies scintillations are even more severe and can interfere with MILSAT communication networks. Thus, understanding, specifying, and predicting ionospheric irregularities/scintillation are a top priority.

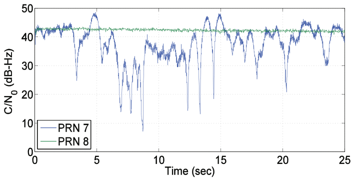

Fig 2. Comparison of scintillating and non-scintillating signals using data taken in Brazil.

A recent report[4] identifies "inadequate spatial distribution of ground-based measurements" as "one of the most serious obstacles to progress in understanding and predicting the space physics environment." The report recommends deploying arrays of small space-weather sensors connected by a modern communications infrastructure to enable fine-scale spatial and temporal resolution of space weather phenomena. Such arrays could provide an "actionable" ionospheric specification at the regional scale and smaller.

With this in mind, the late Paul Kintner, and colleagues at Cornell University, began the development of a software-based GPS receiver that could continuously monitor the ionosphere and space weather, even through severe scintillation. In 2007, Kintner approached ASTRA LLC about helping commercialize such a receiver, the outcome of which is the CASES receiver described here.

The design goal when building the CASES receiver was to provide a capable platform with many peripheral options while remaining inexpensive, relatively small, and consuming a small amount of power. The final configuration has three main components: a custom-built dual-frequency front end, a Digital Signal Processor board, and a Single Board Computer featuring an ARM microcontroller running Linux. Further details of the CASES hardware and software are provided in an accompanying paper in this issue[5].

Table 1 depicts the performance of the CASES receiver, including the scintillation parameters computed onboard and their cadence.

Feature		**CASES Receiver**
L1C/A & L2-C carrier phase and amplitude data		Yes, 14 channels each, at 100 Hz (e.g. I's and Q's)
L1 C/A & L2-C pseudorange data		Yes, 14 channels each, up to 1 Hz
TEC Output		Yes, up to 1 Hz (relative accuracy ~0.01 TECU)
Scintillating parameter output		S_4, s_ϕ, τ_o, Scint. Power Ratio, (50 sec, 100 sec)
Tracking robustness	Mean time between cycle slips for $\{S_4 = 0.8, \tau_o = 0.8$ sec, C/No = 43 dB-Hz$\}$	480 seconds
	L2-C tracking threshold	25 dB-Hz (expected)
Reconfigurability		Complete sensor reconfigurability downstream of ADC: correlation/accumulation, tracking loops, computation of observables
Stream digitized RF front-end samples to disk		Yes
Communication Ports		Ethernet, WiFi, RS-232 USB host (e.g hard drive)
Push data to external FTP site		Yes
Single Board Computer peripherals		Variety of ports and protocols can accept external sensor data/integration (e.g. magnetometer, humidity, etc)

Table 1. Performance characteristics of the CASES space weather monitor

III. SIX SALIENT FEATURES OF THE CASES RECEIVER

The CASES space weather sensor is a low-cost, open-architecture, science-grade, dual-frequency GPS receiver. It lies at the heart of the ionospheric monitoring system being developed by ASTRA. The new CASES sensor combines several radical innovations that make it well suited for space weather diagnosis and provide advantages over competing GPS sensors:

Feature #1: Software Radio Technology. Whereas traditional GPS receivers depend on one or more special-purpose ASIC chips, the CASES sensor implements all digital signal processing functions (i.e., those downstream of its analog RF front end) -- from correlation to navigation solution -- in a general-purpose DSP. The fourfold benefits of the software radio approach are:

- flexibility to accommodate specialized signal processing schemes like the scintillation-robust tracking loops discussed below;
- remote reconfigurability; i.e., an entirely new receiver personality can be downloaded from a remote location;
- full control over receiver behavior, products, and cadences; and
- reduced cost, because the receiver uses a mass-produced COTS DSP chip in place of special-purpose GPS chips used by other manufacturers.

Feature #2: Use of the new L2C signal. The sensor is capable of receiving and processing not only the usual C/A-code signal on the GPS L1 frequency, but also the new CM (civil medium length) and CL (civil long length) codes now being broadcast on the GPS L2 frequency. The new signals, known jointly as L2C, are the first of a new set of signals that the GPS Wing of the U.S. Air Force plans to roll out as part of a larger GPS modernization effort. The new L2C signals on Block IIR-M and IIF satellites make possible the creation of more robust, less complex, and yet more precise GPS Total Electron Content receivers and scintillation monitors. Since the L2C signal began broadcasting, several L2C-capable GPS receivers have emerged in the marketplace, but these are expensive (> $10k) and are not particularly well suited for space weather monitoring. The continued development of GPS software receivers at Cornell, together with Cornell's recent demonstration of software receivers operating on DSP chips[6], have opened the door for inexpensive GPS software receivers that rapidly exploit the new signals and that are easily configured in networks.

GPS receivers such as the CASES sensor that are capable of tracking the new L2C signal enjoy three advantages compared with traditional dual-frequency civilian receivers:

- First, the absence of data bit modulation on the L2 CL code permits tracking with a non-squaring-type phase-locked loop (PLL) instead of the standard squaring-type PLL used to recover carrier phase in the presence of zero-mean binary phase modulation. This leads to a significant 6-dB improvement in the receiver's tracking threshold. The full 6-dB benefit relative to L1 C/A tracking will not be immediately realized because the native L2 signal power is 3 dB lower than that of L1, but it is likely that the L2 signal power will be increased as part of the GPS modernization effort.
- The second advantage of tracking the new L2C signal also leads to an improvement in the tracking threshold, but for a different reason. Until recently only an encrypted military signal was available on L2, and the only option for extracting dual-frequency observables in a civilian receiver was to employ one of several proprietary signal processing techniques to recover the L2 carrier. Such techniques, while impressive in their ingenuity, pay a severe price in squaring loss for their lack of knowledge of the encrypted military code. For example, the state-of-the-art technique for L2 carrier recovery suffers a squaring loss of 11 dB at a nominal carrier-to-noise ratio (C/N0) of 39 dB-Hz and a loss of 19-dB at C/N0 = 30 dB-Hz. Such a degraded tracking threshold makes traditional civilian tracking on L2 extremely fragile, leading to repeated cycle slips and even frequency-unlock during weak signal tracking or strong ionospheric scintillation. In contrast, L2C-capable GPS receivers can, when tracking the L2CL code, avoid both data-bit- and encryption-induced squaring losses, with a better than 11-dB improvement in signal tracking threshold.
- The third advantage of an L2C-capable GPS receiver is cost, as discussed below.

Feature #3: Tracking Through Weak Signals. The third feature of the CASES sensor that sets it apart from standard dual-frequency GPS receivers is the incorporation of specialized tracking loops designed for operation in both weak-signal and scintillating environments. Over the past few years, several of the CASES partners have been engaged in a focused research effort to study PLL behavior in weak signal and scintillating conditions[7,8,9]. The research has identified tracking loop architectures and parameters suited for weak-signal tracking and others suited for tracking during scintillation. Tracking techniques that adapt to the signal conditions and use data-bit or parity aiding (when tracking data-bit-modulated signals) offer the most promise[9]. The CASES team has developed a laboratory facility for testing GPS receivers under realistic scintillation conditions[10]. This facility, combined with the CASES sensor's flexible open software architecture, has permitted tracking loop strategies to be tested and tuned for robustness.

Other commercial receivers, while effective in avoiding total loss of lock (frequency unlock) because of their use of a frequency-lock-loop backup to the phase-lock loop, are not well suited for small-scale array-based ionospheric tomography because they do not provide continuous phase measurements during moderate to severe scintillation (i.e., there are measurement gaps in their data output). They respond by re-initializing the phase time history and transitioning to a frequency-lock-loop to avoid frequency unlock. Once power returns to near nominal levels (after a few seconds), phase lock is regained. Meanwhile, no valid amplitude or phase data are produced by the receiver. The effect of sharp canonical fades causing initial phase unlock on other commercial receivers is described in more detail by an accompanying paper[5]. In contrast, the CASES sensor is designed to track phase continuously with a greatly extended mean time between cycle slips. In summary, the CASES sensor's L2C capability offers greatly improved L2 tracking robustness and significantly reduces the cost of tracking this signal.

Feature #4: Low Cost. The CASES sensor's low cost is due in part to a design that eliminates two expensive features not required for ionospheric monitoring or precise carrier-phase-based positioning applications. The first of these features, P(Y)-code tracking on L2, is unnecessary because the CASES sensor directly tracks the new L2C signal. The availability of the L2C signal eliminates the need for complicated proprietary techniques for recovering the L2 carrier, the licensing fees for which contribute significantly to the cost of traditional dual-frequency civilian receivers.

The second expensive feature common in other receivers is the inclusion of an expensive oven-controlled crystal oscillator (OCXO), meant to ensure that oscillator phase jitter is not confused for scintillation. The CASES sensor arrives at nearly the same benefit with a less-expensive temperature-compensated crystal oscillator (TCXO) by exploiting a non-scintillating carrier signal as a phase reference, a technique referred to as CDGPS-based phase referencing (where CDGPS refers to carrier phase differential GPS). Moreover, in dense-array applications, one CASES sensor can be anchored to an OCXO while the other sensors in the array – each with an inexpensive TCXO -- are phase synchronized to the anchor sensor in a relative sense via carrier-phase differential techniques. This technique, which greatly reduces the cost per array, is referred to as CDGPS-based array-wide phase synchronization[11].

Avoiding these two costs is crucial to the CASES sensor's low price tag. The low price of the sensor means that many more instruments can be purchased on a fixed budget. In turn this will lead to new kinds of opportunities for monitoring and scientific study, including Diffraction Tomography and the deployment of large regional arrays of CASES receivers for ionospheric specification.

Feature #5: Connectivity. The ultimate question asked by GPS users is "How do I get access to my data?" Historically, GPS receivers have had very limited connectivity and access. The CASES receiver was designed with the user in mind, and provides almost unlimited connectivity via a large number of options as illustrated in Figure 3. The client's computer can access the CASES data directly via an RS232 connection, or indirectly via local or remote network connections. The Internet can be accessed via Ethernet cable or WiFi. CASES data can also be forwarded from the client's computer to other users (not shown), or it can be stored directly from the receiver locally on an SD card, external hard drive, or even a memory stick.

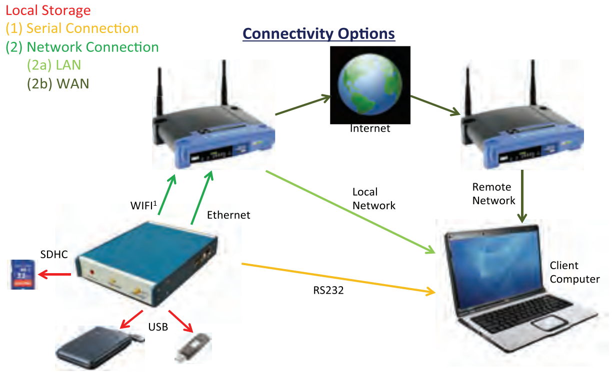

Fig 3. Connectivity options for CASES include RS232, Ethernet, and WiFi, together with local storage options via USB.

Feature #6: Licensable Software. The CASES software is driven by a configuration file that is easily modified by the user to change the set of recorded parameters, or their cadence. However, there are some modifications that can not be made using the configuration file, and then the user will want access to the CASES software source code. While the contents of most commercial GPS receiver manufacturer's software is a closely guarded secret, the CASES software is licensable from ASTRA, for those users that are interested in making their own modifications.

Several techniques used in the CASES receiver are described in detail in an accompanying paper[5], and include: Removal of local clock effects; An advanced triggering mechanism for determining the onset of scintillation; Data buffering; Data bit prediction. Many of these techniques require access to the source code to make any significant modifications.

IV. VALIDATION, POST-PROCESSING AND USER-INTERFACE OPTIONS

The testing and validation of the CASES receiver is described in detail in an accompanying paper in this issue[5]. The receiver has been tested and validated using both real and simulated data in an effort to confirm the expected performance, including the precision with which it can produce observables such as phase and pseudorange. Tests indicate the CASES onboard processing delivers an RMS error for a single receiver of 0.35 meters in pseudorange.

In the laboratory, the data bit prediction tracking algorithms were tested using data from a Spirent simulator for cases of strong scintillation. Figure 4 depicts the phase error measured by CASES without the use of data bit prediction, and Figure 5 shows the result when the algorithm was used. Both tests were performed under simulated heavy scintillation defined by $S_4 = 0.8$, $\tau_0 = 0.8$ sec, C/N0 = 43 dB-Hz. Using the data bit prediction algorithm, the mean time between cycle slips was 480 sec. This level of performance exceeded the design requirements of CASES by a factor of two. These results are discussed in more detail in an accompanying paper[5].

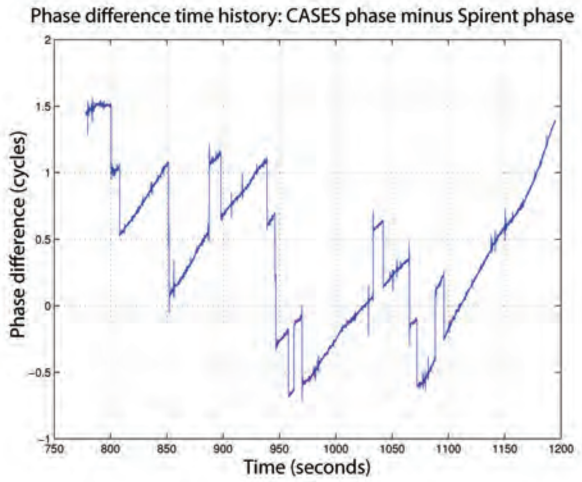

Fig 4. Phase error measured by CASES without the data bit tracking algorithm

CASES receivers have operated reliably for many months at ASTRA's headquarters in Boulder, CO, in laboratory environments in Austin, TX, and at Cornell. CASES receivers have also operated successfully under harsher conditions in a number of geophysically interesting locations during several field campaigns. A receiver has operated reliably in Jicamarca, Peru for almost a year, and seven receivers operated reliably in Peru during a campaign lasting several weeks. Two CASES receivers operated reliably for several months at South Pole, Antarctica, and two more will be deployed in Antarctica this year.

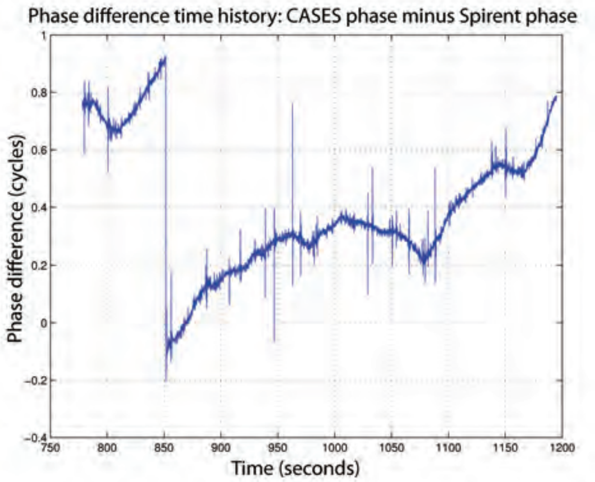

Fig 5. Phase error measured by CASES with the data bit tracking algorithm activated

In addition to the on-board processing, ASTRA has also developed a suite of post-processing software and services that can be made available to the user. Table 2 indicates some of the post-processing options available with CASES. These range from a simple user interface, to a sophisticated system that integrates data from multiple nearby receivers and applies various quality control algorithms to the data. ASTRA also has the ability to ingest multiple ionospheric data sets into an ionospheric assimilation algorithm known as IDA4D (Ionospheric Data Assimilation in 4-D)[12,13,14], and to produce HF propagation maps from the resultant regional and global ionospheric specification.

The user interface developed by ASTRA means that the CASES receiver is useful 'straight out of the box'. The user interface software includes plotting options like maps to indicate where various CASES receivers are located, and options to plot various parameters being computed locally by the receiver. For example, Figure 6 depicts the variation of the S_4 index computed from GPS signal collected from several different GPS satellites over a period of several hours by a CASES receiver in Austin, TX. At low elevations, multipath masquerades as scintillation and raises the S_4 level, and the user should activate an elevation mask to remove these erroneous S_4 values. The particular antenna used, and the multipath environment, are both significant factors in obtaining high accuracy with any GPS receiver.

Post-Processing Module	Task
User Interface	Provides user with a graphical interface to control and update a network of receivers, and visualize data
Single Unit QC	Cycle slip correction, phase debiasing, TEC debiasing
Multi Unit QC	Compare data from multiple nearby receivers to remove outliers
Scintillation	Compute scintillation parameters (S4, Sigma Phi, ROTI)
System Integration	Combine user interface with QC and scintillation modules
HF Propagation	Predicts line of sight RF propagation using model ionosphere

Table 2. Postprocessing software options available with CASES receiver

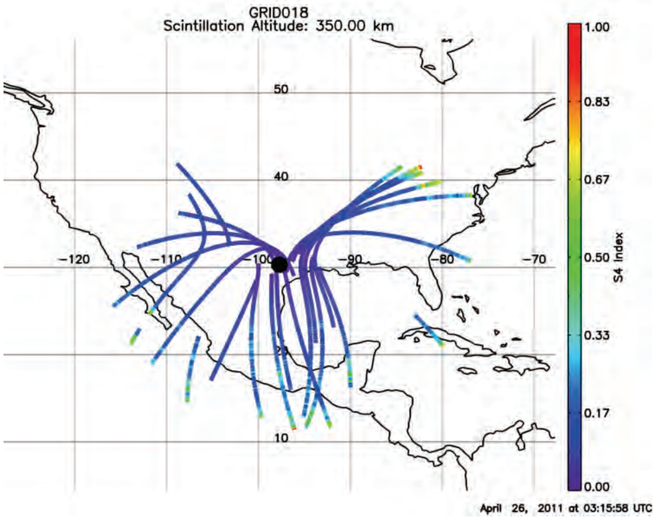

Fig 6. ASTRA's User Interface software includes plotting routines that provide immediate visualization of the data coming from the CASES receiver, together with a number of receiver control options, and the ability to upload new software or configuration controls to the receiver.

The amount of data being produced by the CASES receiver can be quite large, especially when being recorded at 100 Hz. CASES data rates can vary widely depending on how the user sets the flags in the configuration file.

The low rate data requires approximately 63 bytes per sample. If the user streams low rate data at 1 second per sample, that comes out to 63 B/s per channel. Typical satellite coverage gives about 12 channels in use at any given time, which gives a total requirement of 750 B/s, or about 65 MB/day. Lowering the data rate to 5 seconds per sample will drop this to 150 B/s and 13 MB/day. The user can also set a limit on the number of channels that can be tracked at any given time, anywhere from 1 channel to the default of 22 channels. Our system in Antarctica is set up to track a maximum of 4 channels at any given time, and send data at 15 seconds per sample, giving it a typical daily requirement of around 1 MB, depending on satellite coverage.

The high rate data uses the most bandwidth, as it requires approximately 25 bytes per sample and is sent at 100 Hz, giving a bandwidth requirement of about 2.5 kB/s per channel. For typical 12 channel coverage, this gives a total requirement of 30 kB/s, or about 2.6 GB/day. Again, this can be trimmed by setting a limit on the number of channels that send high rate data, and/or activating a scintillation monitor to selectively send high rate data depending on measured scintillation activity. Our system in Antarctica is set to send high rate data for a maximum of 4 channels at any given time, using the scintillation monitor with a scintillation power ratio threshold of -20 dB. This produces roughly 5 MB/day in high rate data.

It should be noted that the typical 12 channel requirement is based on the current L2C coverage and about 10 satellites in view (10 satellites in view, 2 of which are broadcasting L2C, giving 10 L1 + 2 L2C = 12 channels total). As the L2C coverage grows, so the CASES bandwidth requirements will grow. The accompanying paper by O'Hanlon et al[5]. describes a triggering technique to reduce the amount of unwanted data.

In order to help our customers deal with these challenges, ASTRA offers three different levels of service with the CASES receiver, as shown in Table 3. These range from Level-1, where the user is completely independent, manages their own data, and uses only the data extraction software developed by ASTRA; to Level-3, where ASTRA manages the user's data, including archiving, processing and quality control, and the user accesses their data through the ASTRA computer network. In between, at Level-2, the user is licensed to use ASTRA's post-processing and visualization software but remains somewhat independent.

Product Options	Includes
Level 1	CASES Receiver, ASCII data extraction software
Level 2	Level 1 + ASTRA post-processing and data visualization software
Level 3	Level 1 + Access to ASTRA generated quality controlled, post-processed data and visualization for customer’s CASES receivers

Table 3. CASES service options available from ASTRA

V. CONCLUSIONS

The CASES software-defined dual-frequency GPS receiver has been developed as a space weather monitor. In addition to the navigation solution obtained by other GPS receivers, the CASES receiver also measures ionospheric TEC and scintillation with high accuracy and reliability. The receiver outputs phase and amplitude information, together with timing and ephemeris on a 100 Hz cadence. In addition, the receiver computes ionospheric TEC and scintillation parameters on a cadence that is user selectable (typically 30 – 60 sec). The scintillation parameters delivered by CASES include S_4, τ_0, σ_ϕ, and the Scintillation Power Ratio. The software receiver uses a number of novel algorithms for on-board processing of the GPS signals on L1C/A and L2C. In addition, post-processing of the 100 Hz data provides additional opportunities for quality control

The CASES receiver is being commercialized by ASTRA LLC (www.astraspace.net) of Boulder, CO and is available off-the-shelf at short notice, in two different form factors, as shown in Figure 7. The original CASES receiver is approximately the size of a large paperback book with a volume of 130 cubic inches. However, a second form factor is available, a modified stack having a volume of only 40 cubic inches. This smaller form factor is less than 4” on each side, making it suitable for use in a Cubesat. The approximate mass of the three boards in CASES are 50 grams, 60 grams, and 75 grams for the RFE, DSP, and SBC boards, respectively. A space-based receiver will utilize only the RFE and DSP boards (110 grams total, approx). The current version of CASES consumes about 6.5W of power, however a lower-power version is under development at ASTRA.

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Fig 7. Two different form factors are available for the CASES receiver. The smaller one (top) is designed to fit inside a Cubesat.

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