Evolved Tiny Ionospheric Photometer (ETIP): A Sensor for Ionospheric Specification

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THEME: Atmosphere-Ionosphere-Magnetosphere Interactions

EXECUTIVE SUMMARY

We describe a nadir-viewing far-ultraviolet (FUV) photometer concept as a complementary sensor to GPS radio occultation (GPSRO) techniques to meet space weather monitoring objectives for total electron content (TEC). The Evolved Tiny Ionospheric Photometer (ETIP) addresses the need for compact spaceflight sensors that contribute to ionospheric density profile specification and data assimilation. Photometric measurements of oxygen nightglow at 135.6 nm are operationally equivalent to TEC measurements for the purpose of ionospheric specification and forecasting. FUV nadir photometry is a powerful technique to accurately measure ionospheric structures in the presence of large gradients—a problematic measurement scenario for GPSRO methods.

The ETIP sensor design enhances reliability, performance, lifetime, and manufacturability of the flight-proven Tiny Ionospheric Photometer (TIP) sensor, in operation for over four years on the COSMIC mission. We incorporate innovative design elements from a new low size, weight, and power ionospheric photometer, developed by SRI International (SRI) for NRL's Space Weather CubeSat mission, to achieve an evolved design which provides improved duty cycle, signal-to-noise, sensitivity, and redundancy. The ETIP measures the naturally-occurring 135.6 nm radiant emission produced by electron-ion recombination processes to characterize horizontal ionospheric gradients that can compromise GPS occultation retrievals, to identify the presence of ionospheric depletions, and to improve the fidelity of global ionospheric specification. ETIP collects ionospheric measurements on the nightside (where horizontal gradients are strongest and spread-F depletions occur), and accumulates noise characterization and diagnostic data on the dayside.

The innovative ETIP sensor design consists of identical paired nadir-viewing far-ultraviolet photometers, which together occupy less volume and footprint than the heritage TIP photometer design and mitigates a long-wavelength contamination issue affecting previous TIP sensors. ETIP operates with a fast off-axis parabolic telescope feeding a heated SrF_2 optical blue-cut filter to eliminate undesirable short wavelength emission; a compact CsI photocathode photomultiplier tube, selected for insensitivity to unwanted long wavelength emissions, collects the 135.6 nm emission with extremely high sensitivity (500 counts s^{-1} Rayleigh^{-1}). By using twin photometers, one unit can monitor ionospheric emission with 100% duty cycle while the other monitors dark counts and/or any residual long-wavelength contaminating (red-leak) emission. When red-leak is negligible, both photometers can collect 135.6 nm emissions, doubling the effective sensitivity to an unprecedented 1000 counts s^{-1} Rayleigh^{-1}. This sensor design provides uniquely high sensitivity, operational redundancy, and graceful degradation at sensor end-of-life.

SENSOR DESCRIPTION

Though the need for space environment monitoring is growing and operational space weather models are becoming increasingly sophisticated and data-hungry, DoD and other agencies face the prospect of a shortfall in our space-based assets capable of monitoring the ionosphere-thermosphere system as the DMSP, C/NOFS, and COSMIC missions wind down. In this resource-limited environment, providing data to current and future (full-physics) versions of the global assimilative ionospheric models (GAIM) [e.g. *Schunk et al.*, 2004; Komjathy et al. 2010] requires not simply generating a greater volume of homogeneous measurements (e.g. TEC from ground-based GPS and GPSRO), but providing GAIM with heterogeneous data sets which provide complementary gauges for global ionospheric specification. UV photometers measure ionospheric structure without regard to a preferred transmitter-receiver geometry and can provide early detection of ESF bubbles at nadir well before scintillation effects manifest at spacecraft altitudes. Nadir photometry integrates vertically to characterize horizontal ionospheric morphology and local gradients, while GPSRO integrates horizontally to reveal vertical structure. GPS-based TEC and photometer-based 135.6 nm UV radiance thus represent a heterogeneous data pair, and their mutual assimilation into GAIM significantly enhances the quantitative fidelity of the convergent ionospheric solution.

UV Remote Sensing and Nadir Photometry Method

Operational Utility of 135.6 nm Radiance

Naturally occurring ultraviolet and visible emissions from the night sky have been used since the late 1960's as a means of determining the number densities of electrons and O^+ ions in the F-region ionosphere. The emissions are produced by radiative recombination of O^+ ions and electrons to produce atomic oxygen in an excited state which subsequently decays by emitting a photon. The use of the nighttime O emissions to remotely sense the F–region electron density is described by *Tinsley and Bittencourt* [1975], *Chandra et al.* [1975], *Dymond et al.,* [1996, 1997], and *Meier* [1991]. The far-ultraviolet (FUV) emissions are of the most interest for space-based ionospheric sensing, because the Earth's lower atmosphere strongly absorbs FUV radiation. Thus, there is no FUV background.

The workhorse among the UV emissions is the atomic oxygen emission line at 135.6 nm. In the nighttime F-region ionosphere the optically thin 135.6 nm emission doublet arises from the recombination of atomic oxygen ions,

$$O^{+}+e^{-}\rightarrow O(^{5}P)+h\nu_{135.6} \tag{1}$$

with a photon volume emission rate proportional to 7.3×10^{-13} cm^3 s^{-1} (α_{1356}) times the square of ionospheric density ($n_e * n_{O+}$) in CGS units [*Melendez-Alvira* et al., 1999]. If height-integrated to yield observed nightglow brightness ($4\pi I$), we see that the result is proportional to the path integral of ionospheric density squared (due to charge neutrality with $n_e = n_{O+}$):

$$4\pi I = 10^{-6}\int_{0}^{\infty} \gamma\, \alpha_{1356}\, n_e(z)\, n_{O^+}(z)\, dz \tag{2}$$

Because this 135.6 nm radiance integral is similar to the TEC integral (line of sight path integral of n_e) both share assimilative value to ionospheric models such as GAIM and IDA4D [*Bust et al.*, 2004]. The 135.6 nm radiance, with an integrand proportional to the *square* of ionospheric density, is much more sensitive to ionospheric gradients than is TEC, making it more useful in assimilation programs to accurately reproduce ionospheric morphology.

Current State of the Art: COSMIC/TIP

The six TIP sensors [*Kalmanson et al.*, 2004] on the COSMIC satellites [*Rocken et al.*, 2000] were designed in large measure to address this critical role of measuring ionospheric gradients. The COSMIC/TIP sensors have been operating on-orbit continuously since mid-May 2006. The sensors were designed to be simple to operate, low maintenance, inexpensive, and of very high sensitivity. To make measurements with high enough precision to complement the GPSRO measurements, the signal-to-noise ratio of the TIP measurements had to be as high as possible within the size and spatial resolution constraints. The photometer sensor heads of the TIPs were designed to fit into 15×15×7.5 cm^3 volumes. The spatial resolution was desired to be better than 50 km. The TIP fields-of-view were 3.8° diameter, leading to a ~30 km footprint at an ionospheric altitude of 350 km when viewed from 800 km.

The heart of the TIP sensor is a heated SrF_2 window, which serves as a blue-cut filter (Figure 1). By heating the window to 100° C, the cutoff wavelength shifts longward to eliminate an unwanted oxygen emission line at 130.4 nm, yet passes 135.6 nm emission nearly unattenuated. This allows TIP to maintain high sensitivity by avoiding low-throughput interference filters and inefficient diffraction gratings. The TIP sensitivities ranged from ~400-700 counts s^{-1} $Rayleigh^{-1}$ [Budzien et al. 2009; Dymond et al. 2009a]; the exposure times are nominally 1.14 s. For comparison, the GUVI instrument on NASA's TIMED satellite had a sensitivity of 28 counts s^{-1} $Rayleigh^{-1}$, but over a 12°×0.4° field-of-view and with an exposure time of 0.03 s. When the instruments are compared at the same spatial resolution (~30 km), the GUVI sensitivity-dwell time product is 2.7 counts $Rayleigh^{-1}$, while the TIPs are ~450-800 counts $Rayleigh^{-1}$: the TIPs are effectively 150–270 times the sensitivity of the GUVI at the same spatial resolution. This sensitivity difference reflects how TIP is highly-optimized for nighttime sensitivity in a narrow track along the spacecraft nadir, whereas GUVI was designed for mapping broad swaths of bright atmosphere.

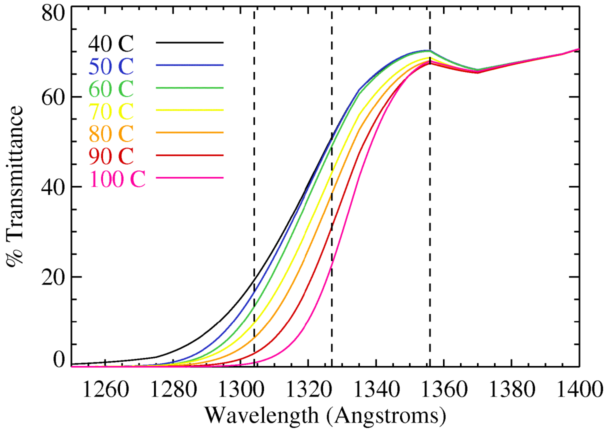

Figure 1: The transmittance of a heated SrF_2 window eliminates 130.4 nm at 100° C but passes 135.6 nm virtually unattenuated [Budzien et al., 2009]

A significant problem of photometer "red-leak" (unwanted visible and near-UV sensitivity) became evident upon initial TIP operations. The CsI photocathode of the TIP photomultiplier tube (PMT) detectors is normally "solar-blind", exhibiting sensitivity which sharply drops by many orders of magnitude at wavelengths longward of 200 nm. A rapid flight unit development cycle (6 months!) and a constricted budget limited the time available for full detector photometric characterization. The detectors were not screened for sensitivity at wavelengths outside the FUV expected passband. Consequently, TIP is sensitive to lights from bright urban areas, scattered moonlight, and terminator glints from COSMIC beacon antennas, which collectively reduce the volume of the highest-quality ionospheric photometry data.

Therefore, to advance the state-of-the-art a primary design goal for ETIP is to characterize TIP-era red leak in the laboratory, to procure enhanced red roll-off PMTs to reduce red-sensitivity, and to monitor any residual red-leak on-orbit using a dedicated red-leak background filter.

Vertical TEC from Optical Remote Sensing

The vertical total electron content can be directly computed from ETIP measurements of the oxygen 135.6 nm radiance. The radiance integral (Equation 2) can be evaluated directly when a Chapman layer approximation [*Chamberlain and Hunten*, 1987] is assumed for the electron (and ion) density distribution. The Chapman layer closely approximates the O^+ ion distribution at night and upon integration radiance in Rayleighs becomes:

$$4\pi I = 0.212(NmF2/10^6)^2 H_{km} \tag{5}$$

where *NmF2* is the peak electron density in units of cm^{-3} and H_{km} is the scale height in kilometers. The comparable total electron content integral yields:

$$VTEC = 0.33\, NmF2/10^6\, H_{km} \tag{6}$$

where *VTEC* indicates the vertically integrated electron density (vertical total electron content, VTEC) in TECU (10^{12} cm^{-2}). Because 135.6 nm radiance is proportional to the product of the vertical total electron content and peak electron density, it provides a more sensitive detection of ESF bubbles and other small-scale ionospheric structures than does TEC. Equations 5 and 6 allow VTEC to be derived from radiance:

$$VTEC = 0.717\sqrt{4\pi I H_{km}} \tag{7}$$

where the value of H_{km} can be extracted from an assimilative model or derived from analysis of GPS occultations. Table 1 casts the ETIP sensitivity in VTEC units with governing assumptions on SNR and layer scale height.

Table 1. ETIP Measurement Sensitivity

Measurement Output	Output Range	Accuracy	Cadence	Comment
Vertical TEC observable	0.5—250 TECU	0.5—0.25 TECU rel. sensitivity; 15% abs. accuracy	1 Hz	Horizontal Resolution 30 km @ 800km orbit 16 km @ 500km orbit Scale height from GPS occultation or GAIM
Electron Density Peak	NmF2 of 2×10^4—1×10^7 cm^{-3}			

Relevance to Space Weather Sensing Objectives

The ETIP concept is motivated by DoD space environment monitoring requirements and flow-down from those requirements to provide a large quantity of high quality measurements of ionospheric gradients, especially at night where the gradients are larger and more problematic. *Dymond et al.* [2009b] used the TIP instruments on the COSMIC constellation to show that high sensitivity photometric measurements could be used in a tomographic inversion scheme to complement the very high precision GPSRO measurements made by those satellites and provide a more accurate and complete picture of the electron density distribution in the night-side ionosphere. The TIP sensors significantly "raised the bar" for photometric measurements of the nighttime ionosphere. The combination of high spatial resolution and high sensitivity produced high precision ionospheric measurements even at mid-latitudes, during the early morning hours, at solar minimum conditions where the ionospheric densities are known to be extremely small.

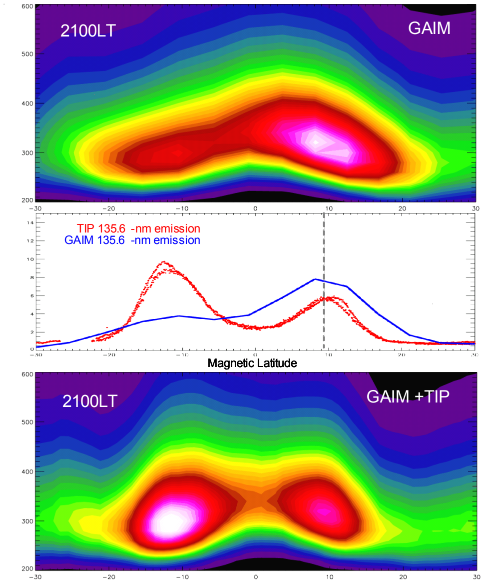

Figure 2: GAIM EDP specification without (top) and with TIP data (bottom). The middle panel show two TIP passes (red) and the initial GAIM predicted brightness (blue).

Improving GAIM Results with ETIP

The ETIP UV radiance and TEC measurements will significantly improve the quality of electron density profile (EDP) specifications produced by ionospheric assimilation models like GAIM. The top panel of Figure 2 shows electron density profiles produced by GAIM at 2100 local time (LT) as a function of magnetic latitude and altitude when ingesting only ground-based GPS measurements. The middle panel shows measurements of the 135.6 nm radiance at this local time by two different COSMIC/TIP sensors (red traces) as compared to the 135.6 nm radiance that GAIM would produce using the EDP shown above (blue trace). The GAIM output clearly does not match the TIP observations as the relative intensities of the northern and southern ionization crests are opposite of what is actually measured. When the TIP observations are ingested into GAIM, the electron density profile produced by the model more accurately specifies the anomaly crests and the trough (Figure 3, bottom panel). This demonstrates how nadir-viewing UV photometer data such as those provided by ETIP can drive the GAIM model toward an electron density profile specification that is much more consistent with the real ionosphere.

Moreover, ETIP provides data with a constant, simple viewing geometry and uniformly high quality over land and ocean, which facilitates both ingestion and error correlation analysis, which are critical aspects of assimilative modeling. The dependence of the UV signal upon the square of electron density places a very strong constraint upon the electron density and TEC predicted by GAIM. Assimilation of nadir photometer data can even improve vertical accuracy of ionospheric specifications, despite the fact that ETIP itself provides no vertical information. This surprising capability arises from the aliasing of horizontal and vertical signal along the many long slant TEC lines-of-sight from other data sources feeding GAIM. By improving GAIM's horizontal ionospheric specification, ETIP data allow GAIM to more accurately render TEC, NmF2, and even hmF2 derived largely from complementary assimilated datasets The improvements to ionospheric specification from such heterogenous data are particularly important in the highly structured nightside ionosphere.

ETIP Design

Design Philosophy

The core ETIP design philosophy embraces two main principles: 1) reliance on TIP design heritage to the greatest extent possible (while addressing performance limitations and reliability) and 2) incorporation of innovative CubeSat Tiny Ionospheric Photometer (CTIP) [*Noto et al.*, 2009] subsystems to drive down size, weight, and power (SwaP) and enhance performance. The TIP sensors on all six COSMIC satellites have operated in orbit for four years and four weeks with no operational failures. The new design addresses red-leak issues by procuring new PMTs specially-selected for enhanced roll-off longward of 135.6 nm, and providing ETIP with a dedicated full-aperture BaF$_2$ filter capable of providing red-leak background monitoring.

Optical Design

The notional ETIP is envisioned as a dual modular photometer with two identical optical chains. The twin channels provide one channel dedicated to 100% duty cycle nightside monitoring of 135.6 nm ionospheric airglow to improve duty cycle over TIP, while the alternate channel provides simultaneous measurement of red-leak or dark counts (Figure 3). Each optical chain incorporates scattered light baffles, a first-surface F/1 off-axis parabolic (OAP) mirror, a heated SrF$_2$ blue-cut filter, solenoid actuated red-pass BaF$_2$ filter, solenoid shutter, and up-rated Hamamatsu PMT —all elements designed for the volume and power constrained CTIP program. The combination of a 50.8 mm focal length OAP mirror and 3.4 mm PMT photocathode illumination was selected to yield an instrumental FOV of 3.8° to match the specification of TIP. In order for these optics to comply with the CubeSat standard, significant light-weighting and power optimization was required. For example, the third generation heated SrF$_2$ filter subassembly, which removes strong OI emission at 130.4 nm, maintains the crystal at 100° C with 1.5 W despite -30° to + 50° C thermal forcing. The photometric response of PMTs, BaF$_2$ and SrF$_2$ crystals in each of the two optical chains will be optimally matched during ETIP assembly so that each path serves a redundant function. The ETIP thus provides operational features heretofore

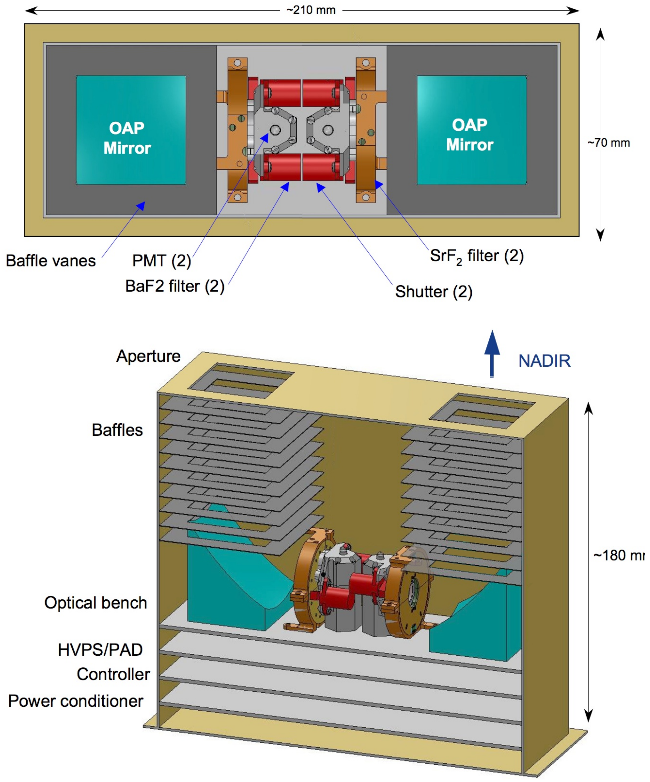

Figure 3: ETIP design - top and interior views.

unavailable in the TIP and CTIP designs. In addition to allowing uninterrupted 135.6 nm coverage during acquisition of red-leak and dark samples, the ETIP can also command both chains to acquire 135.6 nm photocounts so as to double on-band sensitivity.

Table 3. TIP and ETIP Comparison

Parameter	TIP	ETIP
Sensitivity (cnts/R-s)	500	500*
Red-leak Background Samples	None	Continuous
Max 135.6 nm Duty Cycle	93%	100%
Field of View	3.8°	3.8°
Volume	3000 cm^3	2700 cm^3
Mounting Footprint	300 cm^2	150 cm ^{2}
Weight	2300 g	2000 g
Average Power	7.6 W	10 W
Filter Cycles	1,600,000	24,000,000

*Sensitivity doubling to 1000 possible at the expense of background monitoring and 3 W additional power

Mechanical Design

Figure 3 outlines a notional ETIP layout with a vertical stack of electronic boards underneath an optical bench. The ETIP housing, supporting all internal subsystems and providing a light-tight barrier, will be designed along the lines of the TIP-era TICE electronics enclosure to allow individual access to EMI-shielded electronic boards during integration and testing. Because the ETIP optical paths are essentially clones, judicious layout of the electronic boards will allow an optional housing to be envisioned with a square mounting footprint as opposed to the rectangular footprint shown in Figure 3.

Optional Improvement: Additional Off-Nadir Pointing

The modularity and small footprint of the ETIP enables additional operational capabilities including off-nadir pointing. In addition to the baseline nadir oriented ETIP, this scenario envisions a second ETIP unit configured with a base wedge or front-end periscope so that its optical chain is oriented at a fixed off-nadir angle (ONA) in-track. Such in-track ONA measurements, in conjunction with nadir measurements, yields a measurement set with intersecting ray paths suitable for ionospheric tomographic imaging. ETIP configurations using mounting wedge versus periscope implementation allow sensor packaging options customizing vertical form factor, horizontal footprint, and photometric throughput.

SUMMARY

ETIP is part of a new generation of space weather sensors with low size, weight, and power suitable for deployment on buses ranging from small to large satellites. To produce the initial two sensors, including development, risk reduction, operationalization, and extensive testing costs approximately $4M. After the design program is complete, additional flight sensors could be procured for missions at a rough order of magnitude estimated cost of $950k each, when produced singly. The ETIP design addresses the requirements for space weather sensors, and includes adequate flexibility for accommodation on a range of future flight opportunities, including microsatellite constellations. Such modularity and configurability are crucial to satisfy NRL's mission to transition innovative sensor concepts out of the laboratory and into the military, civilian, and commercial sectors.

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