Improving Ionospheric Specification and Forecasting: Making the Next Steps

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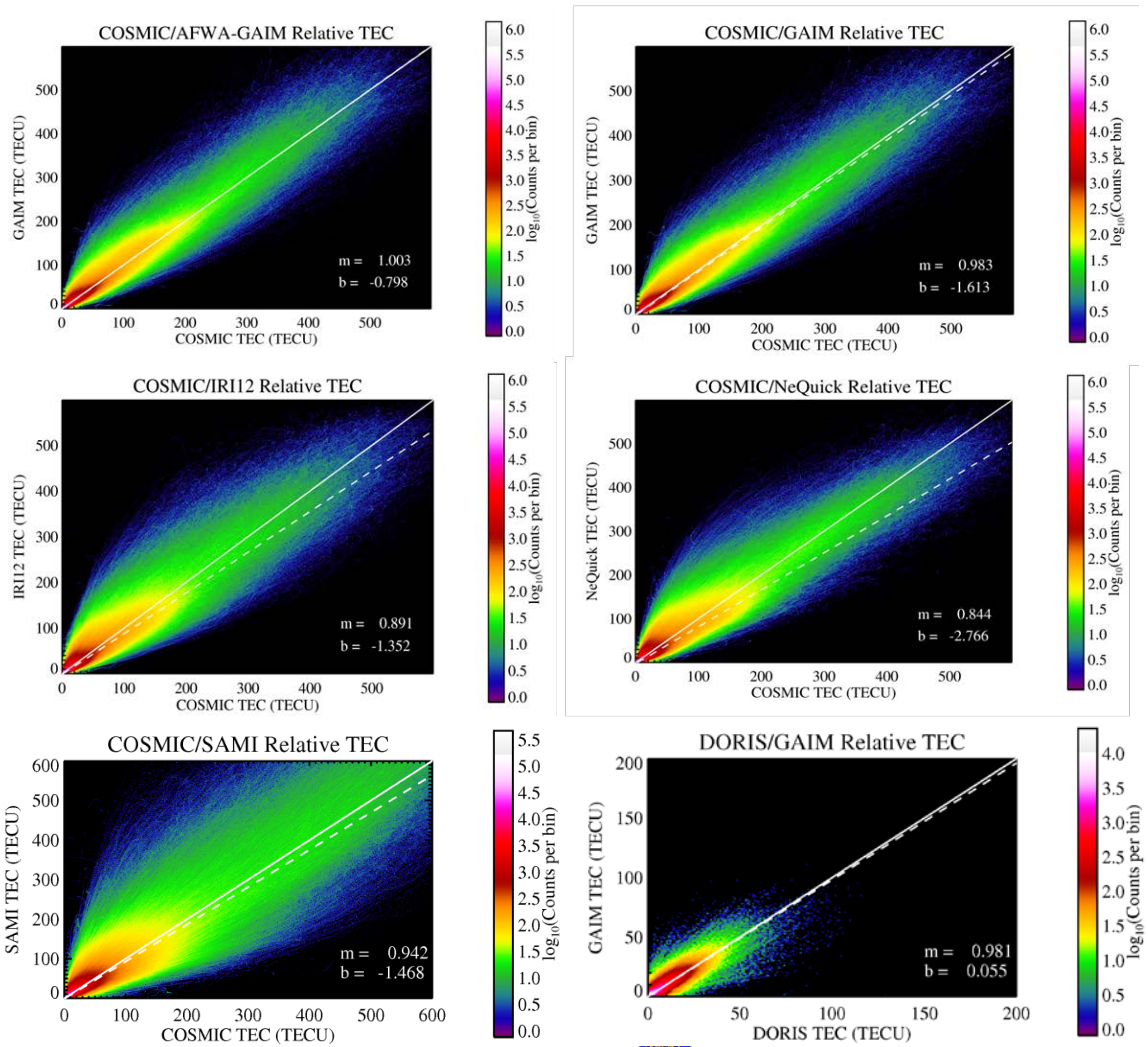
Introduction

- The big picture:
  - *The DoD has stated requirements for ionospheric specification and forecasting accuracy, however, while great deal of progress has been made, specification and forecasting accuracy still does not meet the those requirements.*
- What is the specific problem?
  - *Ionospheric specification and forecasting have benefitted from data assimilation models, but the <u>types and geographic availability of data available</u> are insufficient to allow the models to meet the DoD requirements.*
  - *Current ionospheric specification relies heavily on ionospheric sensing based on the GPS constellation*
  - *However, this approach limits model forecasting and specification accuracy*
    - RO lacks measurement persistence but has good global coverage, Ground based GPS has measurement persistence but lacks global coverage
    - Provides specification but no information on physical drivers
    - No information regarding the neutral thermosphere, which affects ionospheric production, loss, and transport
- What can we do to improve ionospheric specification and forecasting?

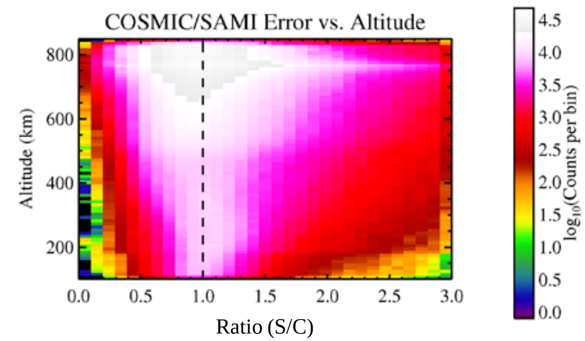
Model Accuracy Assessment

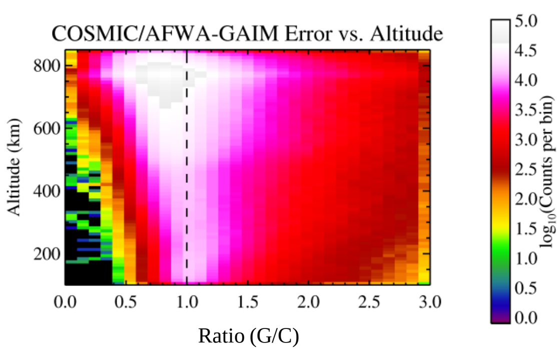
- Study used GPS RO from the COSMIC-1 constellation to evaluate ionospheric specification
- Reasonable correlation is seen from all models
  - *USU GAIM-GM showed the best performance*
- The scatter is the problem
  - *Specification only good to ~15% (GAIM)*
  - *Specification from other models is poorer*

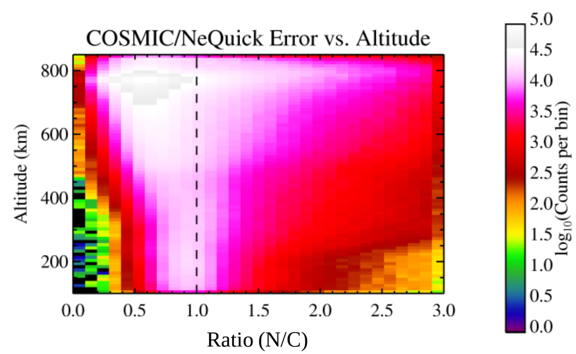


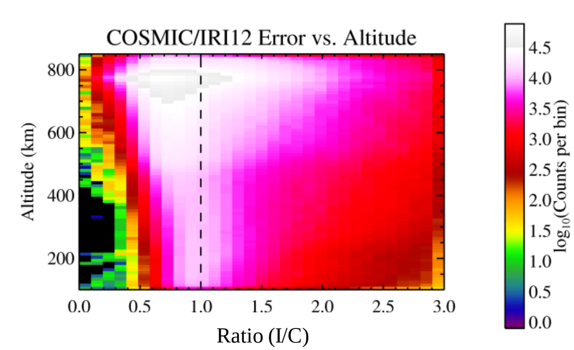
Topside and TEC Error

- All models underestimating topside sTEC
  - *GAIM: -15%*
  - *SAMI-3: -5%*
  - *IRI 2007 & 2012: -25%*
  - *NeQuick: -40%*
- Underestimation of scale-height should cause underestimate of vTEC





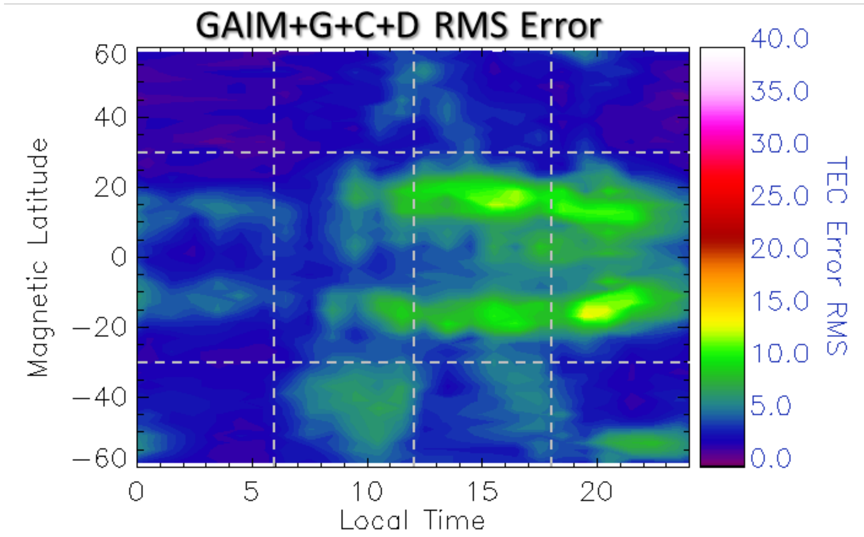




Low scale heights suggests that the overall thermodynamic state and plasma transport mechanisms of the ionosphere/thermosphere system are not adequately captured

USU-GAIM vs. Jason vTEC

- Assessed GAIM Modeling Accuracy against vertical TEC data from JASON radar altimeter
  - *Average vertical TEC ~45 TECU*
- Problems:
  - *GAIM specification error largest just poleward of Equatorial Ionization Anomaly crests → lack of ground-based TEC*
  - *Scatter: Even if biases are removed there is ~ ±6 TECU RMS (1 σ) scatter out of mean of 45 TECU (~13 %)*
  - *Consistent with COSMIC/model study above*



Global Impact

OSE Option	OO	Global TEC RMS Error	Global Relative Error
Ground+COSMIC+DMSP	1	5.3	23.4%
Ground+DMSP	3a	5.5	24.5%
Ground+COSMIC	3b	5.5	24.5%
Ground	2	5.7	25.5%
Climatology	4	9.6	42.7%

Error Improvement (%) over GAIM+ground

		0-6 LT	6-12 LT	12-18 LT	18-24 LT
Northern Mid Lats	30N to 60N	**4**	1	**7**	**7**
Low Latitudes	30S to 30N	**10**	**8**	**5**	**10**
Southern Mid Lats	60S to 30S	**8**	**6**	**15**	**10**

Importance of Neutral Specification

- The neutral thermosphere drives the plasma content and distribution
  - *O & N_2 densities drive production and loss*
  - *Winds & temperature drive plasma transport*
- Recent work used TIEGCM and Ensemble Kalman Filter to assess the importance of "unobserved" state variables to the forecast
  - *Observable: e^- density from RO*
  - *Densities: O^+, O, O_2, and N_2 (by mixing ratio)*
  - *Winds: zonal and meridional*
  - *Neutral Temperature*

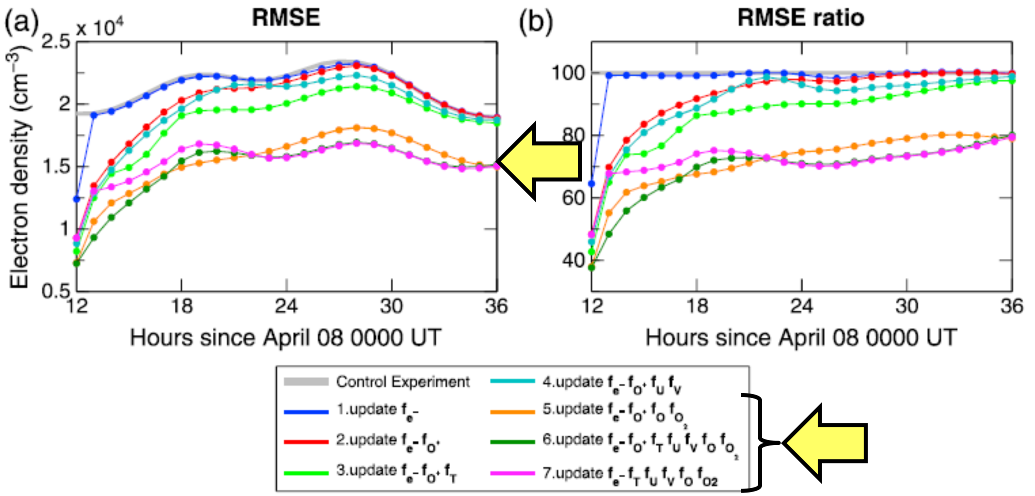


Figure 3. The global mean (a) RMSEs and (b) RMSE ratios of the electron density during the 24 h ensemble forecast period (from 1200 UT of 8 April to 1200 UT of 9 April 2008).

<u>Reference:</u>

Hsu et al.(2014), Effects of inferring unobserved thermospheric and ionospheric state variables by using an Ensemble Kalman Filter on global ionospheric specification and forecasting, J. Geophys. Res. Space Physics, 119, 9256–9267, doi: 10.1002 /2014JA020390.

Study showed that knowledge of the neutral atmosphere, O, N_2 and O_2, was the most important factor in improving ionospheric forecasting

The Way Forward

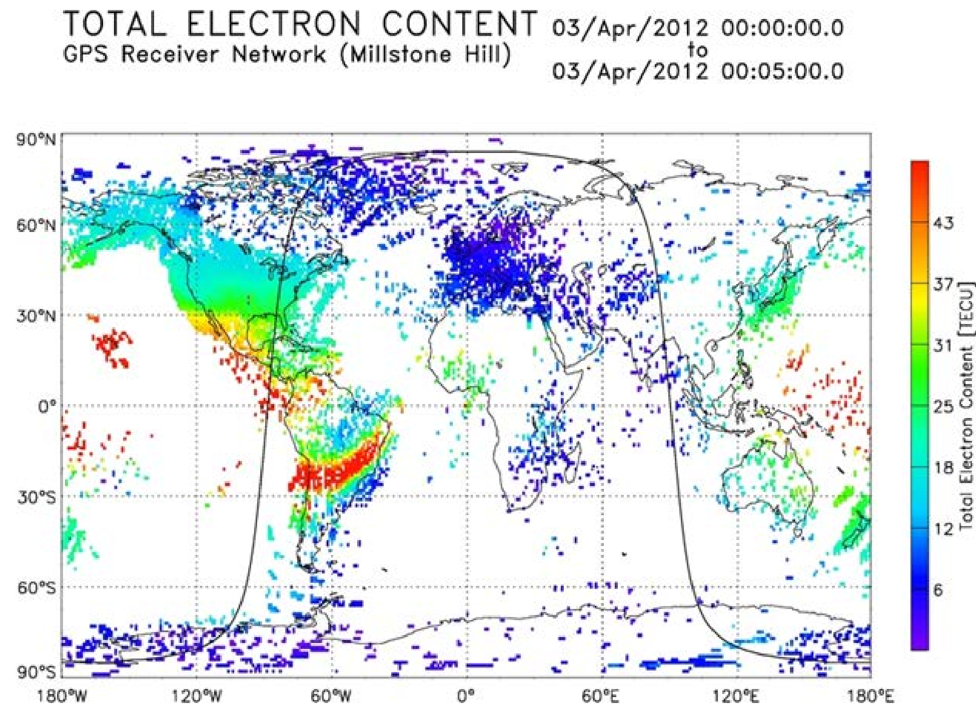
- Improve physics in the models: GAIM-FP
  - ☑ *Include full physics*
  - ☑ *Include neutral thermosphere*
  - ☑ *Improve spatial resolution*
- Add more data into the assimilations
  - *Additional sources with better coverage in space and time*
    - ☑ GPS sensing, ground and space
    - – Heterogeneous sources
      - ✓ Additional ground-based measurements
      - ✓ Additional space-based measurements
  - *Altitude coverage is critical*
    - – Helps specify the drivers
    - – Helps infer the overall thermodynamic state
- Improve measurement persistence
  - *Geosynchronous imagery*

SPECIFICATION

Ground-based Sensing

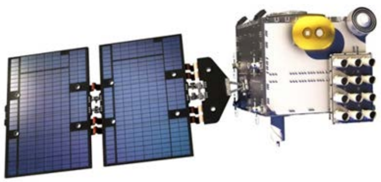
- There is a large number of ground-based GPS receivers
  - *Provide spatially dense, high-persistence measurements*
- Ionosonde and incoherent scatter radars also provide high quality measurements
  - *Again these measurements are sparse*
  - *These sites sometimes have limited persistence*
- However, 70% of the Earth's surface is covered by water – there are few measurements over open ocean

Ground-based GPS Data Available from Va. Tech. DaVIT



LEO TEC (Electrons)
-COSMIC-2-

COSMIC-2

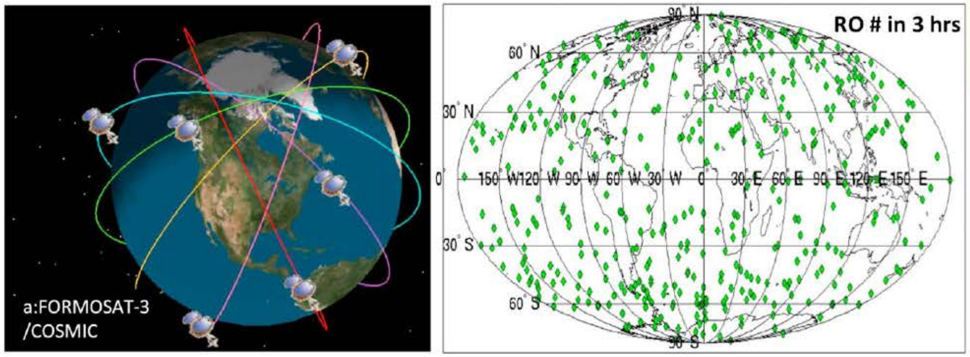


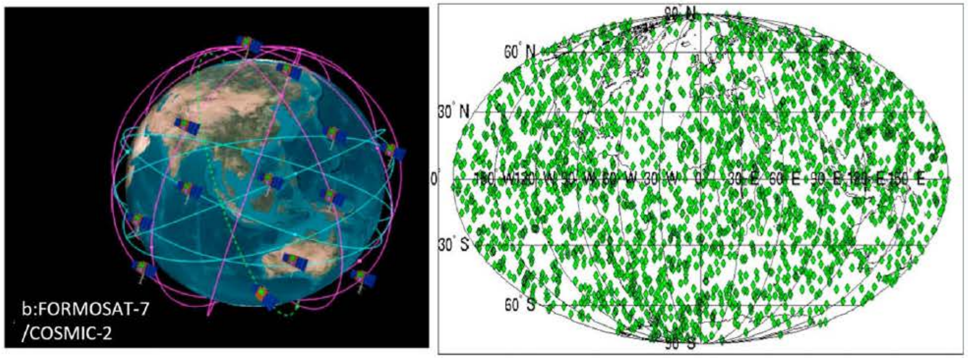
http://www.sstl.co.uk/Missions/FORMOSAT-7

Table 1. Space Weather Products and Accuracy Requirement for COSMIC-2

Instrument	Parameter	Observation Range	Accuracy
TGRS	Relative TEC	0–2000 TECU	0.3 TECU
	Absolute TEC	0–2000 TECU	3 TECU
	Electron density profile	3×10^{10}–10^{13} el · m^{-3}	Less than the greater of 10^{11} el · m^{-3} and 20%
	Amplitude scintillation (S4)	0.1 to 1.5	0.1
	Phase scintillation (σ_φ)	0.1 to 20 rad	0.1 rad
IVM	Ion density	10^{9}–5×10^{12} m^{-3}	5%
	Ion composition	0–1	5%
	Ion velocity	Cross track: ±1000 m/s; In track: ±1000 m/s	Cross track: ±5 m/s; In track: ±10 m/s
RF Beacon	Amplitude scintillation (S4)	0.1 to 1.5	0.1
	Phase scintillation (σ_φ)	0.1 to 20 rad	0.1 rad

Yue, X., W. S. Schreiner, N. Pedatella, R. A. Anthes, A. J. Mannucci, P. R. Straus, and J.-Y. Liu (2014), Space Weather Observations by GNSS Radio Occultation: From FORMOSAT-3/COSMIC to FORMOSAT-7/COSMIC-2, *Space Weather*, 12, 616–621, doi:10.1002/2014SW001133.

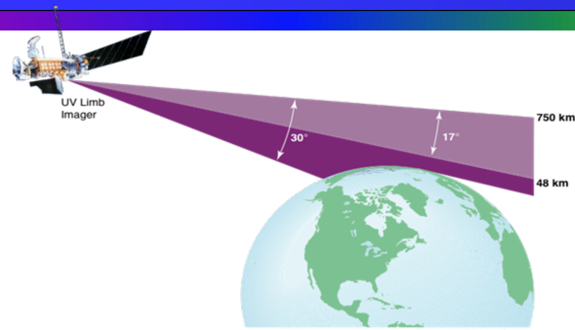




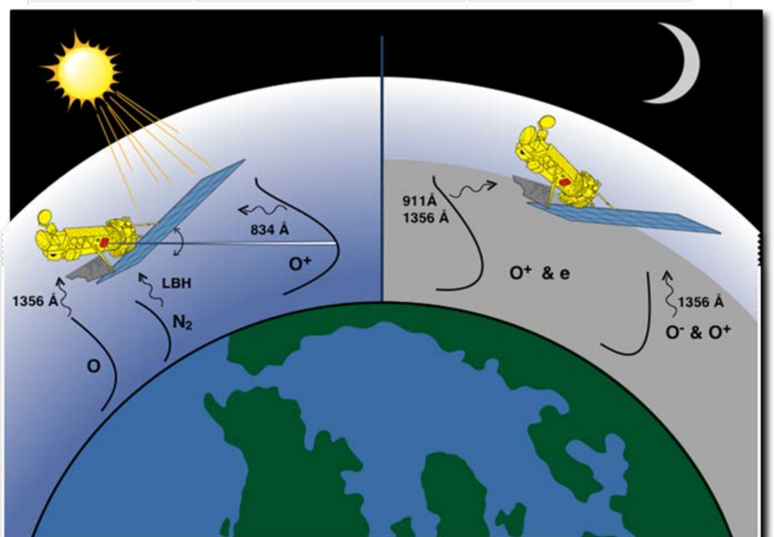
RO Payload	Satellite	Space Weather Payload
IGOR GPS ~2,000 per day	6 LEO satellites ~72° inclination ~800 km altitude ~61 kg >0.68 for 2 years launched 2006	TIP TBB
TriG GPS+ GLONASS >8,000 tropo per day >12,000 iono per day	First Launch	
	6 LEO satellites ~24° inclination ~520 km altitude ~215 kg >0.66 for 5 years ~launch 2016	IVM RF Beacon
	Second Launch	
	6 LEO satellites ~72° inclination ~720 km altitude ~215 kg >0.66 for 5 years ~launch 2019	TBD

ADDITIONAL DATA SOURCES

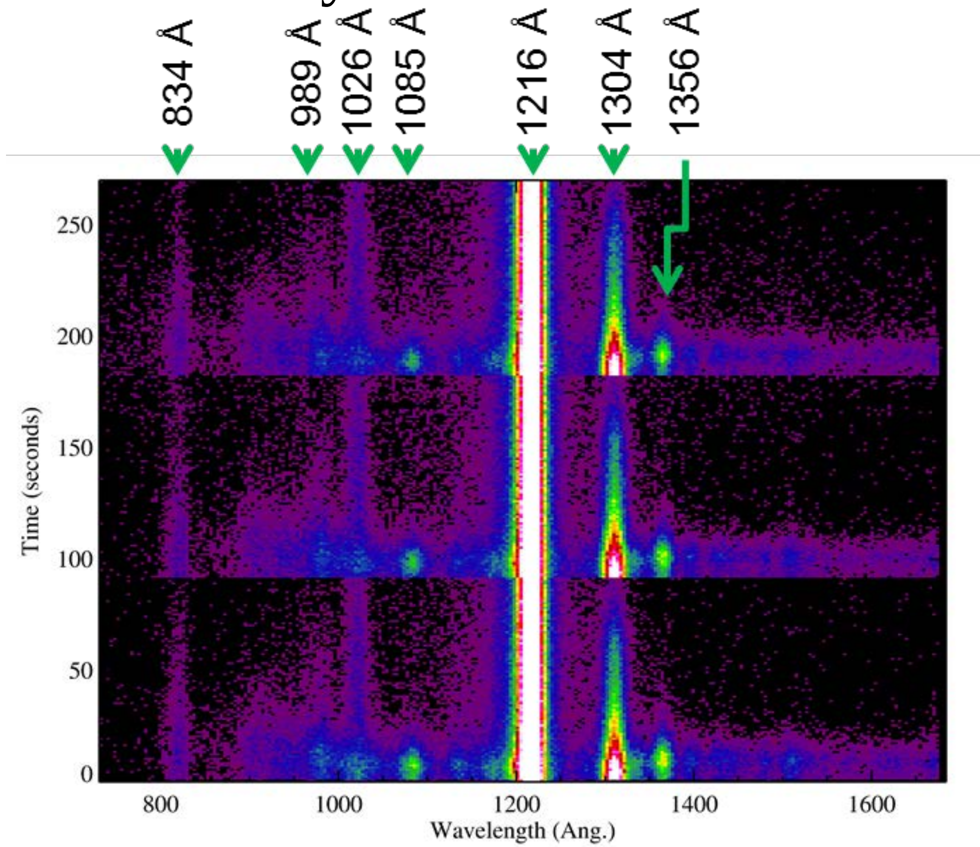
Limb Sounders (Neutrals and Ions)
-Special Sensor Ultraviolet limb Imager-



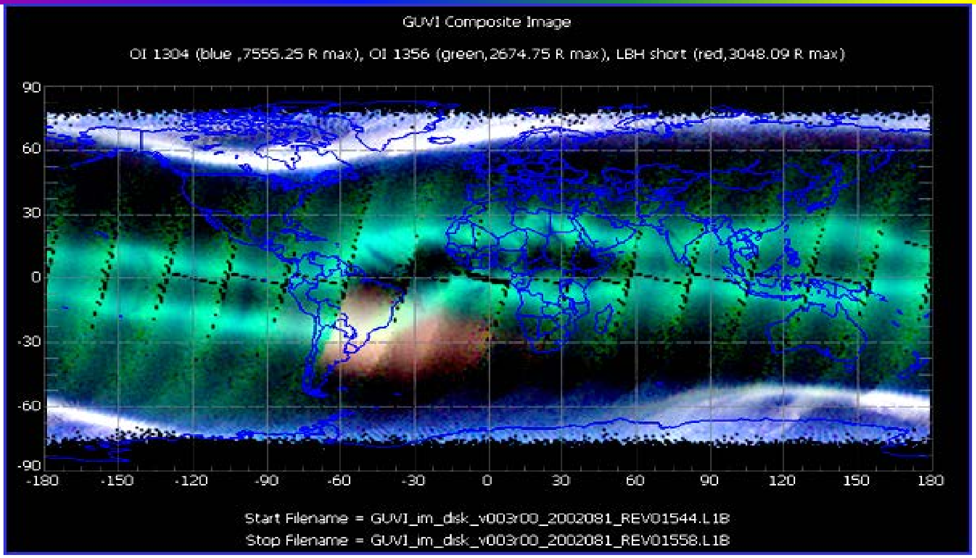
SSULI Processing Algorithm and Data Products		
Solar Zenith Angle	**Algorithm**	**EDR Data Products**
SZA < 85°	Dayside Ionosphere Algorithm (Requires 834 SDRs)	O+ Density Profile. hmF2, nmF2
SZA >= 108°	Nightside Ionosphere Algorithm (Required 1356 and 911 SDRs)	O+, O Density Profiles, hmF2, nmF2
SZA < 85°	Dayside Neutral Density Algorithm (Requires 1356 and LBH SDRs)	O, N_2, O_2 Density Profiles. Temperature Profile.

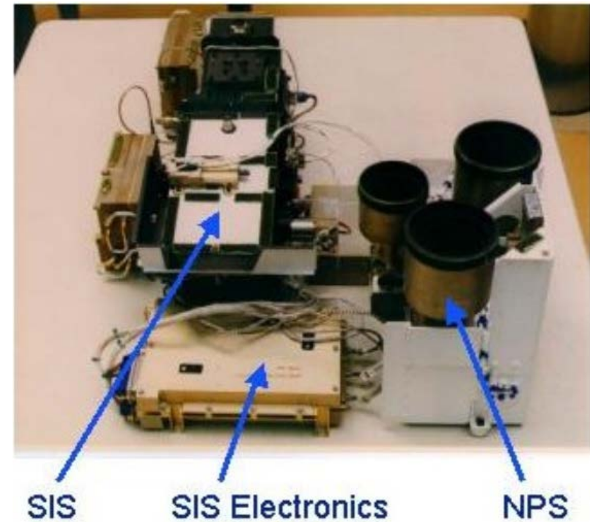


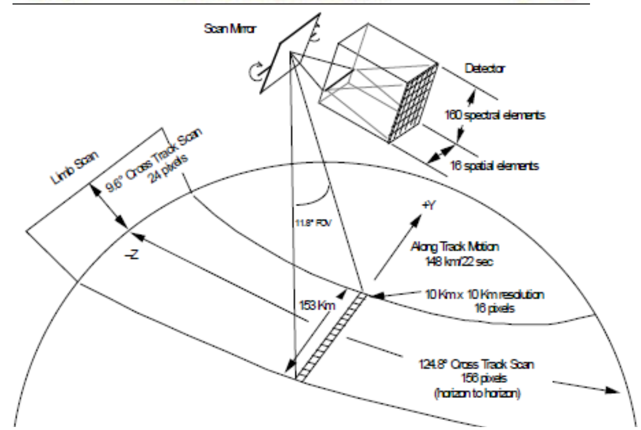
3 Daytime Limb Scans



Nadir Imager (Neutrals and Ions)
-Special Sensor Ultraviolet Spectrographic Imager (SSUSI)-



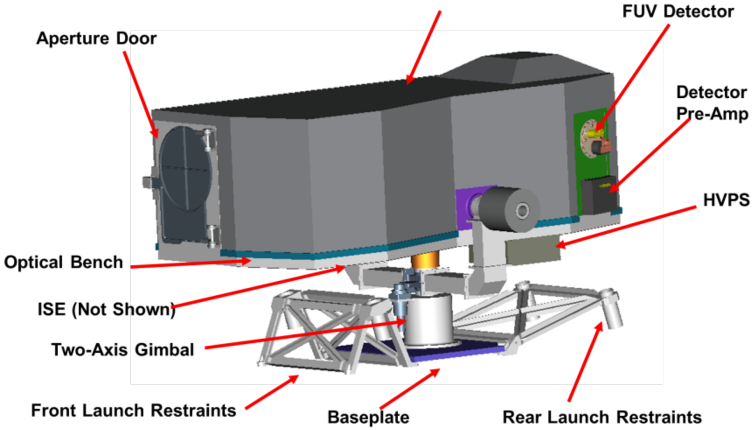


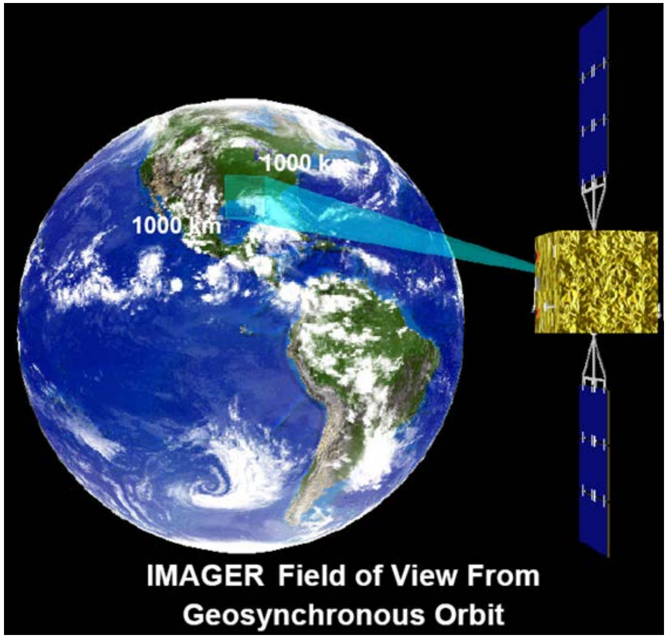


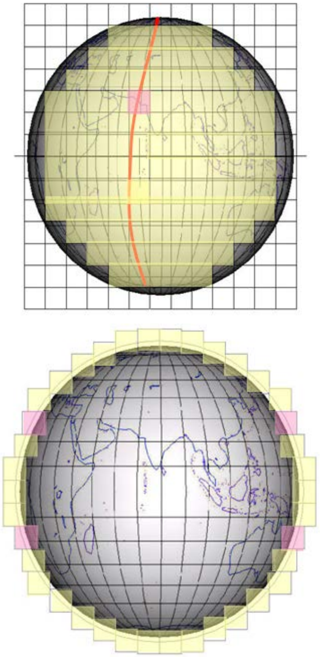
SSUSI Concept of Operations

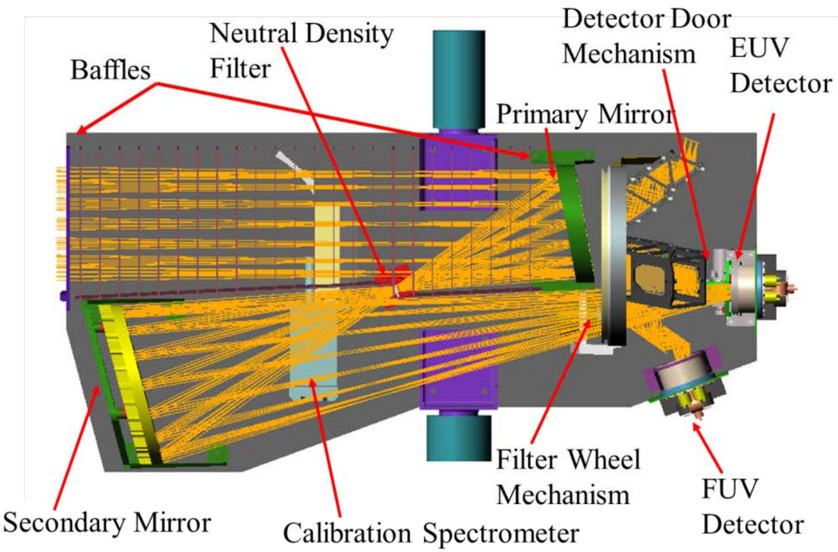
- Cross-track scanner from LEO
  - *Electron density at night*
  - *Daytime neutral atmosphere observations*
  - *Position of auroral oval day/night*

Geosynchronous Imagery









IMAGER: Ionospheric Mapping and Geocoronal Experiment

- *Ionospheric Imaging from Geostationary Orbit in near Real-time (~100 sec)*
- *Study Spatial & Temporal Evolution of Mesoscale Ionospheric Irregularities*

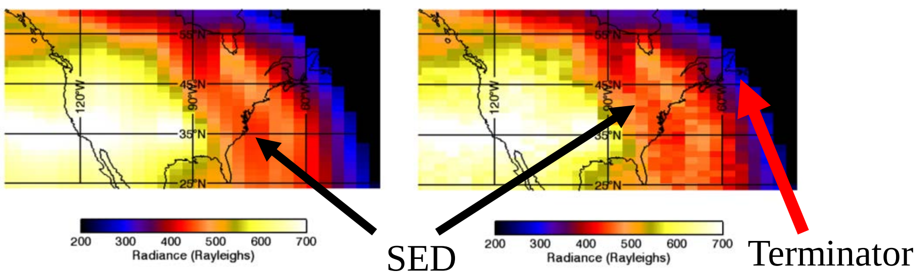
Geosynchronous Ionospheric Sensing

Simulations for the IMAGER instrument

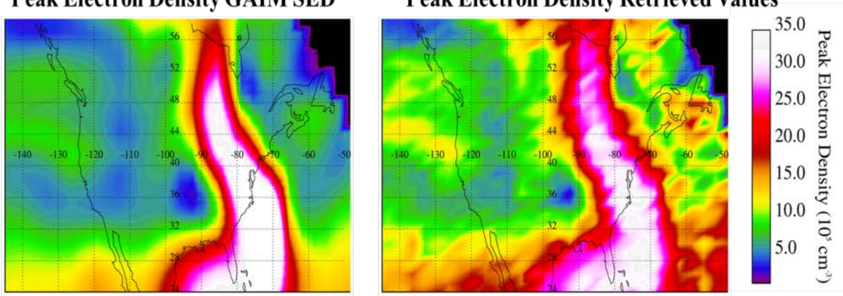
- *Non-linear inversions*
- *Realistic instrument noise*

Daytime Simulations

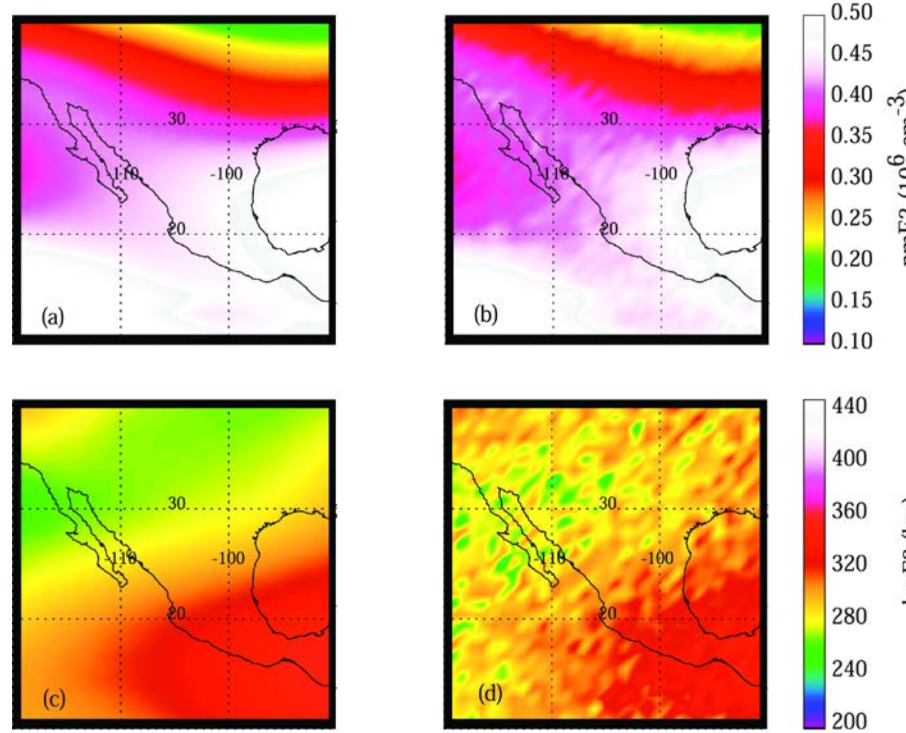
SED 83.4 nm Radiance Without Noise | **SED 83.4 nm Radiance With Shot Noise**



Peak Electron Density GAIM SED | **Peak Electron Density Retrieved Values**

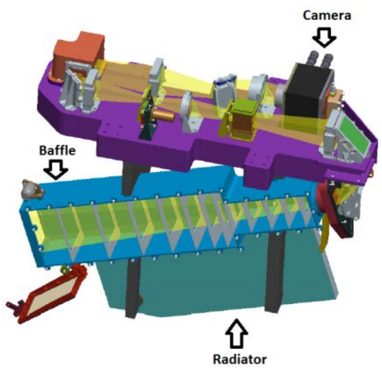


Nighttime Simulations



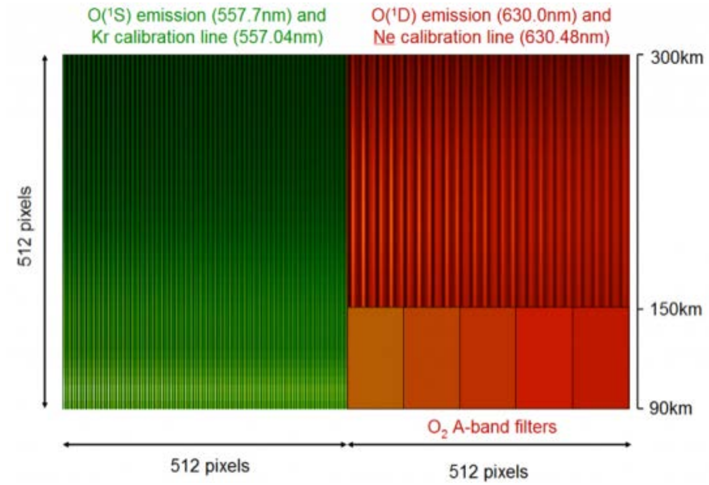
Thermospheric Winds
-MIGHTI on ICON-

Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI)



Two orthogonal fields of view allow the retrieval of the wind vector from the Ionospheric Connection Explorer (ICON) spacecraft. (http://icon.ssl.berkeley.edu/)

Nighttime limb imaging in visible wavelengths from the ISS (October 29, 2011) reveals the target emissions of the ICON MIGHTI instrument. The 762 nm O_2 band emission (false color in image above) provides temperatures, while Doppler shift of the 557.7 nm (green) and 630.0 nm (red) OI emission lines provides wind profiles.



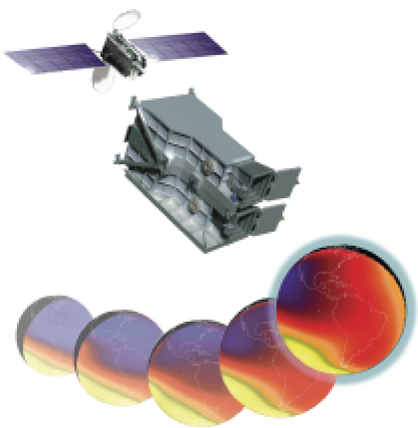
Side by side imaging of all emissions on one CCD

MIGHTI performance requirements:

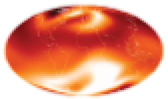
Altitude range [km]	Orbit Day	Orbit Night	Vertical resolution [km]	Horizontal resolution [km]	Precision [m/s]
90-105	Y	Y	5	500	8.7
105-170	Y	N	5	500	10
170-210	Y	N	30	500	10
210-300	Y	Y	30	500	8.7

Geosynchronous Imagery
-Global-scale Observations of the Limb and Disk (GOLD)-

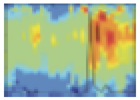
GOLD



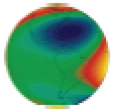
- GOLD Mission of Opportunity will study how space around Earth responds to the Sun and the lower atmosphere.
- GOLD will make unprecedented images of Earth's response.
- GOLD will fly as a hosted payload on a commercial communications satellite owned and operated by SES-GS
- GOLD's ultraviolet imaging spectrograph will be built by LASP at the University of Colorado
- GOLD's science data will be processed and distributed by the Florida Space Institute at the University of Central Florida, the lead institution for the mission



1. How do geomagnetic storms alter the temperature and composition structure of the thermosphere?



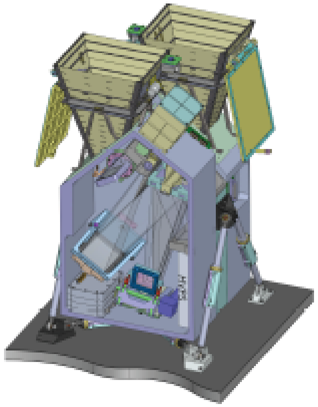
2. What is the global-scale response of the thermosphere to solar extreme-ultraviolet variability?



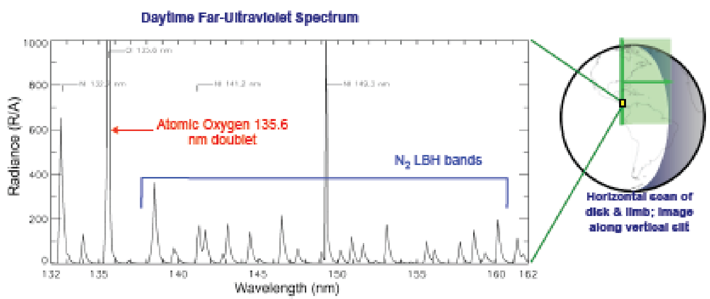
3. How significant are the effects of atmospheric waves and tides propagating from below on thermospheric temperature structure?

4. How does the nighttime equatorial ionosphere influence the formation and evolution of equatorial plasma density irregularities?

Instrument Concept



- Two identical channels
- Each channel fully independently in all observing modes
  - disk images and limb scans
    - dayside: T and O/N_2
    - nightside: O^+ density
  - stellar occultations
  - full disk maps and limb scans with 30 minute cadence
  - limiting resolution is ~50 km
- A single channel can perform all measurements with reduced cadence or reduced spatial resolution

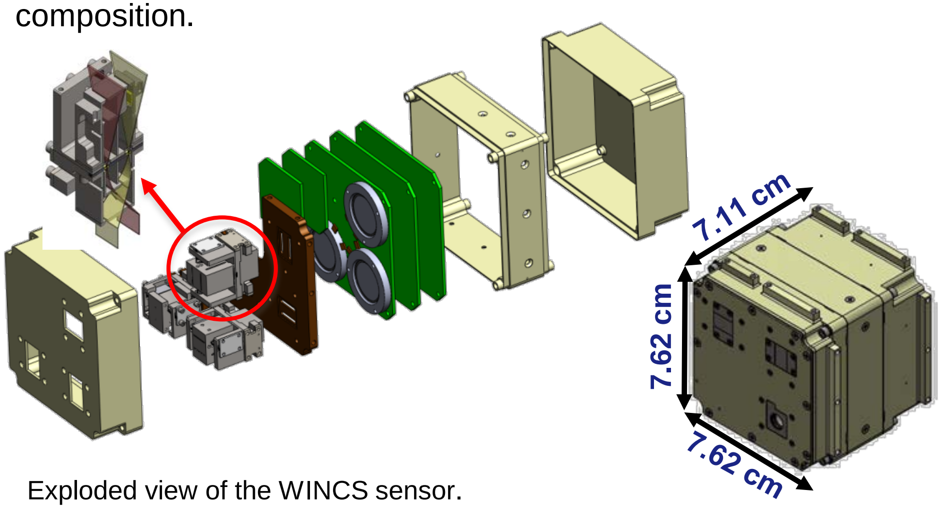


- Temperature obtained on disk from rotational shape of N_2 LBH bands
- O/N_2 composition measured using ratio of 135.6 doublet to LBH bands
- Temperature on limb determined by slope of emission altitude profile
- O^+ at night observed using 135.6 recombination emission
- O_2 profile on limb from stellar occultations

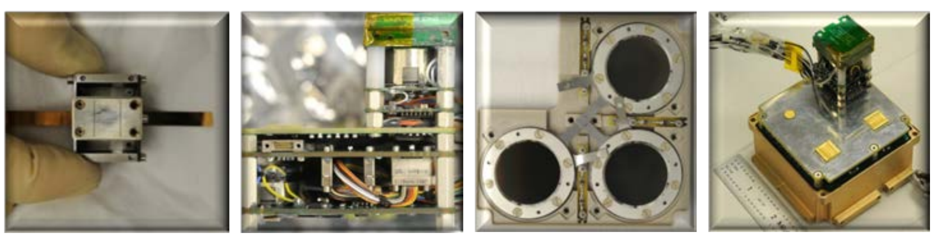
Winds Ions Neutrals Composition Suite (WINCS)

Description

Low size, weight and power (SWaP) in-situ instrument suite capable of measuring neutral winds, neutral temperature, neutral composition, ion drifts, ion temperature and ion composition.



Exploded view of the WINCS sensor.



Flight Hardware for the WINCS instrument, from left to right: spectrometer body, flight electronics, focal plane array, anodes and HV power supply

Measurements Capabilities

Instrument	Parameter	Range	Resolution	
WTS	Density	10^3-10^{10} cm^{-3}	<3%	Neutrals
WTS	Temperature	1000-4000 K	<1%	
WTS	Wind	+/- 2000 m/s	16 m/s	
NMS	Composition	10^3-10^{10} cm^{-3}	<3%	
IDTS	Density	10^3-10^7 cm^{-3}	<3%	Ions
IDTS	Temperature	1000 - 4000 K	<1%	
IDTS	Drift	+/- 2000 m/s	16 m/s	
IMS	Composition	10^3-10^7 cm^{-3}	<3%	

Value

- NRL has developed a low SWaP in-situ sensor.

  Volume: 7.62 x 7.62 x 7.11 cm

  Mass: 875 g

  Power: 1 W + interface card to s/c
- Provide operational utility of data set from CubeSat and other small satellite busses.
- Ideal for an operational constellation of 30-50 sensors, as secondary payloads to larger satellites or primary instrument on CubeSats.

Summary

- With the upcoming retirement of the DMSP satellites and no replacement on the horizon, we propose an approach for improved ionospheric specification and forecasting

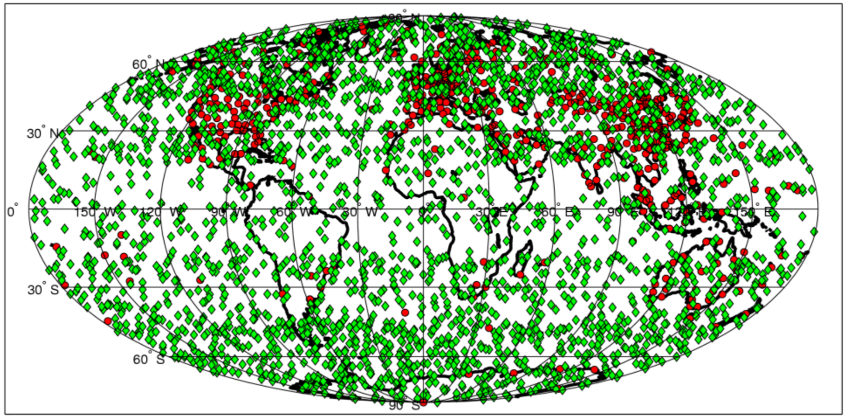
- Our approach entails
  - *Adding heterogeneous data sources – in addition to GPS-based specification*
  - *Geosynchronous imagery*
  - *LEO sensing of the neutral density and temperature*

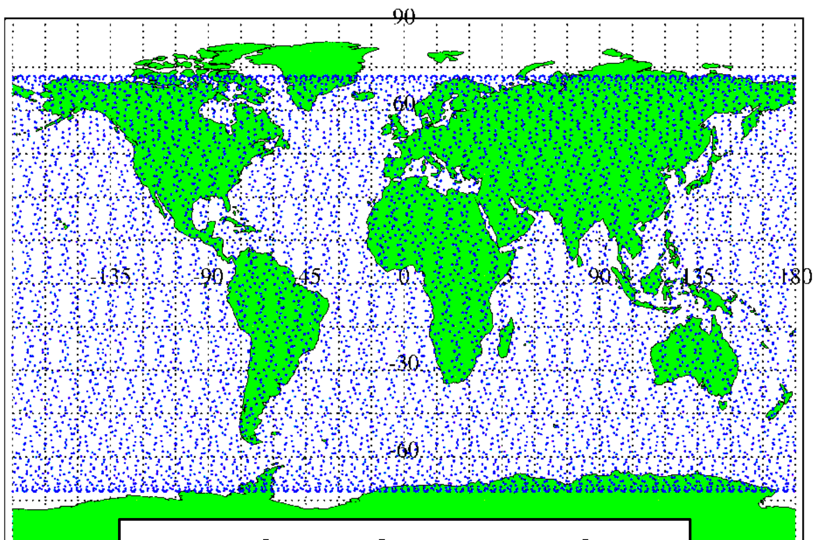
- Advantages of our approach:
  - *Provides specification of the neutral density – needed for improved forecasting*
  - *Improved spatial and temporal coverage*
  - *Could be accomplished by ride-sharing opportunities on both LEO and GEO satellites – reducing program costs*

Acknowledgements: The Chief of Naval Research also supported this work through the Naval Research Laboratory (NRL) 6.1 Base Program.

Limb Sounding/RO Sampling Comparison
-COSMIC-1-

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs





UV Limb Sounder, 6 S/C, 24 hours

- The COSMIC-1 constellation of six satellites produced ~2500 occultations per day (~400 occultations per satellite)
  - *Sampling is sparser in the equatorial region*
- A modern limb sensor gathers a limb scan roughly every 90 seconds for ~960 limb scans per day
  - *A constellation of 6 satellites would produce 5760 limb scans per day – >2× the number of occultations produced by the COSMIC constellation*
  - *12 satellites ➔ 11520 > number produced by COSMIC-2 (~10,000)*
  - *Ionosphere + neutral density*