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 types and geographic availability of data available 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?
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
  - Scattering: 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

<table>
<thead>
<tr>
<th>Error Improvement (%) over GAIM+ground</th>
<th>0-6 LT</th>
<th>6-12 LT</th>
<th>12-18 LT</th>
<th>18-24 LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Mid Lats 30N to 60N</td>
<td>4</td>
<td>1</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Low Latitudes 30S to 30N</td>
<td>10</td>
<td>8</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Southern Mid Lats 60S to 30S</td>
<td>8</td>
<td>6</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

Global Impact

<table>
<thead>
<tr>
<th>OSE Option</th>
<th>Ground RMS Error</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground+GAIM</td>
<td>5</td>
<td>23.4%</td>
</tr>
<tr>
<td>Ground+DMSP</td>
<td>5.5</td>
<td>24.5%</td>
</tr>
<tr>
<td>Ground+COSMIC</td>
<td>5.5</td>
<td>24.5%</td>
</tr>
<tr>
<td>Climatology</td>
<td>9.6</td>
<td>42.7%</td>
</tr>
</tbody>
</table>

5/22/2015
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

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

Reference:
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
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

**TOTAL ELECTRON CONTENT**
03/Apr/2012 00:00:00.0

GPS Receiver Network (Millstone Hill)
03/Apr/2012 00:05:00.0
### Table 1. Space Weather Products and Accuracy Requirement for COSMIC-2

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Parameter</th>
<th>Observation Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGRS</td>
<td>Relative TEC</td>
<td>0–2000 TECU</td>
<td>0.3 TECU</td>
</tr>
<tr>
<td></td>
<td>Absolute TEC</td>
<td>0–2000 TECU</td>
<td>3 TECU</td>
</tr>
<tr>
<td></td>
<td>Electron density profile</td>
<td>$3 \times 10^{-16}$ to $10^{18}$ el·m$^{-3}$</td>
<td>Less than the greater of $10^{15}$ el·m$^{-3}$ and 20%</td>
</tr>
<tr>
<td></td>
<td>Amplitude scintillation ($\sigma_P$)</td>
<td>0.1 to 1.5</td>
<td>0.1 rad</td>
</tr>
<tr>
<td></td>
<td>Phase scintillation ($\phi_P$)</td>
<td>0.1 to 20 rad</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Ion density</td>
<td>$10^{-5}$ to $10^{-2}$ m$^{-3}$</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Ion composition</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Ion velocity</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>RF Beacon</td>
<td>Amplitude scintillation ($\sigma_P$)</td>
<td>0.1 to 1.5</td>
<td>0.1 rad</td>
</tr>
<tr>
<td></td>
<td>Phase scintillation ($\phi_P$)</td>
<td>0.1 to 20 rad</td>
<td>0.1 rad</td>
</tr>
<tr>
<td></td>
<td>Cross track: ±1000 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>In track: ±1000 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cross track: ±5 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>In track: ±10 m/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Image Descriptions

- **a:** FORMOSAT-3/COSMIC
- **b:** FORMOSAT-7/COSMIC-2

### Diagrams

- **RO Payload**
  - IGOR GPS
    - ~2,000 per day
  - ~63 kg
  - ~72° inclination
  - ~800 km altitude
  - 0.68 for 2 years launched 2006
  - **Satellite:** TIP
  - **Space Weather Payload:** TBD

- **TrIG GPS+GLONASS**
  - ~6,000 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
    - 2016
  - **Satellite:** IVIM RF Beacon
  - **Space Weather Payload:** TBD

- **Second Launch**
  - 6 LEO satellites
    - ~72° inclination
    - ~720 km altitude
    - ~215 kg
    - >0.66 for 5 years
    - 2019
  - **Satellite:** TBD
ADDITIONAL DATA SOURCES
Limb Sounders (Neutrals and Ions)
-Special Sensor Ultraviolet limb Imager-

SSULI Processing Algorithm and Data Products

<table>
<thead>
<tr>
<th>Solar Zenith Angle</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SZA &lt; 85°</td>
<td>Dayside Ionosphere Algorithm (Requires 034 SDRs)</td>
</tr>
<tr>
<td></td>
<td>Nightside Ionosphere Algorithm (Requires 1356 and 911 SDRs)</td>
</tr>
<tr>
<td>SZA &lt; 85°</td>
<td>Dayside Neutral Density Algorithm (Requires 1356 and LBH SDRs)</td>
</tr>
</tbody>
</table>

EDR Data Products

- O+ Density Profile, hmF2, nmF2
- O+, O Density Profiles, hmF2, nmF2
- O, N2, O2 Density Profiles, Temperature Profile

3 Daytime Limb Scans

Wavelength (Ang.)

- 834 Å
- 989 Å
- 1026 Å
- 1085 Å
- 1216 Å
- 1304 Å
- 1356 Å

Time (seconds)
Cross-track scanner from LEO

- Electron density at night
- Daytime neutral atmosphere observations
- Position of auroral oval day/night

SSUSI Concept of Operations
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

Nighttime Simulations

(a) SED
(b) Terminator

(c) Peak Electron Density GAIM SED
(d) Peak Electron Density Retrieved Values
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.

Nighttime limb imaging in visible wavelengths from the ISS (October 29, 2011) reveals the target emissions of the ICON MIGHTI instrument. The 762 nm O₂ 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.

MIGHTI performance requirements:

<table>
<thead>
<tr>
<th>Altitude range [km]</th>
<th>Orbit Day</th>
<th>Orbit Night</th>
<th>Vertical resolution [km]</th>
<th>Horizontal resolution [km]</th>
<th>Precision [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-105</td>
<td>Y</td>
<td>Y</td>
<td>5</td>
<td>500</td>
<td>8.7</td>
</tr>
<tr>
<td>105-170</td>
<td>Y</td>
<td>N</td>
<td>5</td>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>170-210</td>
<td>Y</td>
<td>N</td>
<td>30</td>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>210-300</td>
<td>Y</td>
<td>Y</td>
<td>30</td>
<td>500</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Geosynchronous Imagery
-Global-scale Observations of the Limb and Disk (GOLD)-

Instrument Concept

- Two identical channels
- Each channel fully independently in all observing modes
  - disk images and limb scans
    - dayside: T and O/N\textsubscript{2}
    - nightside: O\textsuperscript{*} 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

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?

Daytime far-ultraviolet spectrum

- Temperature obtained on disk from rotational shape of N\textsubscript{2} LBH bands
- O/N\textsubscript{2} composition measured using ratio of 135.6 doublet to LBH bands
- Temperature on limb determined by slope of emission altitude profile
- O\textsuperscript{*} night observed using 135.8 recombination emission
- O\textsubscript{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.

Measurements Capabilities

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Parameter</th>
<th>Range</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTS</td>
<td>Density</td>
<td>$10^3$-$10^{10}$ cm$^{-3}$</td>
<td>3%</td>
</tr>
<tr>
<td>WTS</td>
<td>Temperature</td>
<td>1000-4000 K</td>
<td>1%</td>
</tr>
<tr>
<td>WTS</td>
<td>Wind</td>
<td>+/- 2000 m/s</td>
<td>16 m/s</td>
</tr>
<tr>
<td>NMS</td>
<td>Composition</td>
<td>$10^3$-$10^{10}$ cm$^{-3}$</td>
<td>3%</td>
</tr>
<tr>
<td>IDTS</td>
<td>Density</td>
<td>$10^3$-$10^7$ cm$^{-3}$</td>
<td>3%</td>
</tr>
<tr>
<td>IDTS</td>
<td>Temperature</td>
<td>1000 - 4000 K</td>
<td>1%</td>
</tr>
<tr>
<td>IDTS</td>
<td>Drift</td>
<td>+/- 2000 m/s</td>
<td>16 m/s</td>
</tr>
<tr>
<td>IMS</td>
<td>Composition</td>
<td>$10^3$-$10^7$ cm$^{-3}$</td>
<td>3%</td>
</tr>
</tbody>
</table>

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.
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