Filling a Data Gap in the Ionosphere

Dave Rainwater$^1$, B. Barnum$^2$

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$^1$ The University of Texas at Austin
   Applied Research Laboratories
   Austin, TX 78758

$^2$ The Johns Hopkins University
   Applied Physics Laboratory
   Laurel, MD 20723

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The Upper Atmosphere Science Problem

Our current understanding of the upper atmosphere (ionosphere, plasmasphere, magnetosphere) is informed only by very short, intense studies of extremely localized regions, and a sparse synoptic picture.

- Very little is understood from first principles.
- The connection to the lower atmosphere is tenuous.
- Dynamics are only vaguely understood, even at the synoptic scale.

The 3 Big Questions:

1. What is the mesoscale (10’s to 100’s of km) picture and dynamics of the ionosphere? How does this differ from and influence the global dynamics?
2. What are the mesoscale dynamics that emerge from the auroral zones and propagate to lower latitudes?
3. Where is the division between large-scale structure and turbulent structure? (E.g., that could be characterized by a power law distribution.)

We have no global data sets, and very little real-time data of sufficient quality.
- There is a compelling need for an evolution in ionospheric data.
The Practical Solution

- We can’t measure the state variables directly, so do the next best thing.
- Dynamic observation of electron density allows state variable reconstruction.
- Scintillation maps give picture of turbulent behavior.

- Ionosphere specification is a 2-D or 3-D map of the free electron content (3-D necessary for almost all modern science and applications).
- State of the art is 3DVAR/“4DVAR” data assimilation onto climatology.
- ARL:UT performs ionosphere specification for the U.S. Government: TRIPL-DA →
Our Goals

GEOScan Goal:
“Image the Earth’s radiation belt and plasma environment with an unprecedented temporal and spatial resolution that provides the details of the governing physical processes for large-scale global reconfigurations that drive space weather events and resultant societal effects.”

Concise Goal:
Image Earth’s plasma environment globally in real-time at the mesoscale.

Detailed Goals:
- 3-D iono. specification at 50-100 km horiz. × 1-2 km vert. resolution.
- Map scintillation.
  - globally
  - persistent
  - real-time
  - highly accurate data
  - well-characterized error, including model errors
## Ionospheric Data Types

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Type</th>
<th>Meas’m’t</th>
<th>Probe Region</th>
<th>Utility</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS Overhead</td>
<td>ray (MEO→LEO)</td>
<td>TEC</td>
<td>topside</td>
<td>mixed</td>
<td>Y</td>
</tr>
<tr>
<td>GNSS Occultation</td>
<td>ray (MEO→LEO)</td>
<td>TEC</td>
<td>bulk</td>
<td>vert. structure</td>
<td>Y</td>
</tr>
<tr>
<td>GNSS Ground</td>
<td>ray (MEO→Gnd)</td>
<td>TEC</td>
<td>bulk</td>
<td>horiz. structure</td>
<td>Y</td>
</tr>
<tr>
<td>LEO Beacon</td>
<td>ray (LEO→Gnd)</td>
<td>TEC</td>
<td>bulk</td>
<td>horiz. structure</td>
<td>N</td>
</tr>
<tr>
<td>Ground Beacon</td>
<td>ray (Gnd→LEO)</td>
<td>TEC</td>
<td>bulk</td>
<td>horiz. structure</td>
<td>Y</td>
</tr>
<tr>
<td>Insitu</td>
<td>point</td>
<td>$n_e$</td>
<td>varies</td>
<td>normalization</td>
<td>N</td>
</tr>
<tr>
<td>Ionosonde/Sounder</td>
<td>point</td>
<td>$n_{F_2}, h_{F_2}$</td>
<td>$F_2$</td>
<td>normalization</td>
<td>N</td>
</tr>
<tr>
<td>Optical</td>
<td>various</td>
<td>$n_e$</td>
<td>$F$</td>
<td>normalization</td>
<td>Y</td>
</tr>
</tbody>
</table>

- Current data sets (mostly GNSS) are incomplete:
  - far from global
  - mixed accuracy
  - poor horiz. resolution, or suffers spatio-temporal mixing

- Ground–LEO ray TEC data provides the best horizontal bulk resolution without spatio-temporal mixing

- The optimal data set would contain an abundance of all data types!
Existing Data Sources

- IGS GNSS live streaming stations (e.g. via JPL)
  Mostly just populated land masses, not all stations high-quality
- Ionosondes
  Global, but very few real-time and persistent
- DMSP – LIMB UV, In-situ electron density
- COSMIC 1 – GPS occultation and overhead, In-situ
  Data latency several hours
- Envisat, SPOT 5 – DORIS LEO
  Data latency is weeks; only 2 sats
- C/NOFS – LEO beacon (normally off)

Conclusion: These data sets leave huge gaps in our needs.

Even the future GNSS data from COSMIC 2 won’t fill the gaps: bulk horizontal resolution globally is unaddressed.
DORIS from LEO Fills the Gap

- **Important characteristics:**
  - ~60 stations with **global coverage** (incl. ocean coverage)
  - dual-band, 401 and 2036 MHz, phase-coherent
  - Need only a passive receiver to use
  - 25× better freq. diversity than GNSS
  - Better coverage than GNSS

- CNES has demonstrated strong commitment to maintaining/upgrading system
  - 53 stations already upgraded to v3.0 (geodesy-grade)
  - DORIS signals in LEO used for precision iono. content & scint., troposphere water vapor, Earth orientation, absolute station position, reference frame ties, ...

- If DORIS didn’t exist, we’d propose a system exactly like it!
Orbit Simulations

- Orbit simulations of DORIS from LEO show excellent data value, and synergy with other datasets.
  - 100 km ionosphere grid (horiz.) assumed (state of the art is 400 km)

Goals:
- Understand size & characteristics of potential data set
- Specify instrument requirements
- Compare with other data sets for 3DVAR benefits

Conclusions:
- DORIS from LEO would provide unprecedented amounts of data
  - >10× more than any existing live streaming source
- Truly global coverage
- Truly persistent coverage
- Excellent synergy with other data sets (especially GNSS-RO)
DIRGO Proposal

- DIRGO is the DORIS Ionospheric Realtime Global Observatory
- ARL:UT & JHU/APL propose to fly on LEO platforms of opportunity.

1. GEOScan
   - Broad geoscience collaboration proposal to NSF
   - Atmospheric, Ocean, Earth science components
   - Would fly several instrument packages on Iridium NEXT unspecified platform
   - DIRGO is a potential ionospheric Hosted Sensor

2. USAF
   - Interested in flying a suite of space weather instruments
   - DIRGO was considered for Iridium, but Iridium space no longer available
   - Specific platforms not yet identified

→ In either case, the intention is for data to be public and immediately available.
DIRGO Science

DIRGO instruments will report phase (Doppler is derivable) and scintillation.

**DIRGO primary mission** is bulk ionosphere specification:
- $<100$ km $\times$ 2 km,
- 0.2 TECu (relative) accuracy

**DIRGO secondary mission** is scintillation mapping at two length scales:
- 401 and 2036 MHz independently
- S4 (amplitude and phase) to $<0.1$
- $\sigma_\Phi$ to $<0.1$ rad

**DIRGO tertiary mission** (desired) is atmospheric water vapor.

Requires JHU/APL’s precise oscillator option on Frontier.
Orbit determination process extracts water vapor content (TWV).
→ U. Texas Center for Space Research has expertise in DORIS O.D.
→ DORIS-derived TWV has demonstrated same precision as GPS data.

Frontier Radio - Multi-Band SDR Development for DORIS

**Highlights:**
- Small size (16 cm x 11 cm x 5 cm, receive-only)
- Low mass (2.1 kg)
- Low power receive mode (<2.5 W using low voltage bus)
- UHF and S-Band receiver (401.25 or 2036 MHz)
- Space mission design heritage: TIMED, CONTOUR, and New Horizons missions; just launched on RBSP
- SDR S/Ka- and X/Ka-band versions qualified to TRL-9

**Flight Readiness Status**
- S/Ka- and X/Ka-band versions of SDR qualified to TRL-9
- Select design and hardware heritage from prior space missions
- Single-band (S) flight unit is on the RBSP mission (30 Aug 2012 launch) – extremely harsh radiation environment
- Multiple-band DORIS receiver slice now under development with UT-ARL
Frontier-DORIS Antenna Design

- 40 cm QFH antenna can’t be used on most future platforms.

→ ARL:UT is designing a compact dual-layer patch antenna for DORIS.

  - Req’ts: RCP, good impedance match
  - 4 probe feeds
  - Substrate $\epsilon_r = 10$ to reduce size
  - Mass $\sim 2$ kg

- Initial EM studies with HFSS:
  - free-space
  - primitive hosted payload box model

→ Can meet all science objectives.
Payload Burdens

SWaP is excellent for this type of instrument.

- \(~2~W~power\)
- \(~3~kg~mass~incl.~antenna\)
- \(<1~U~(1000~cm^3)~volume~(not~incl.~antenna)\)
- \(~20-30~Kbps~data~output\)

→ This would be the most compact, low-power DORIS Rx in the world.

- Designed for a 15-year lifetime.
Summary

- **Our Science Goals**
  - Persistent global mesoscale observation of the ionosphere
    - 3D electron density specification
    - scintillation maps
  - If desired, tropospheric water vapor as well

- **ARL+APL Sensor Technology**
  - JHU/APL flight-heritage proven design (Frontier radio)
  - ARL:UT compact DORIS antenna for arbitrary platforms

- **The Path Forward**
  - Pursuing multiple flight opportunities in polar LEO
  - USAF very interested, but no funding yet
BACKUP
Dear Dave Rainwater,

With respect of your request concerning the proposal to fly DORIS receivers on Iridium NEXT and the CNES / French commitment to maintaining the DORIS system, we are able to inform you that in terms of both quality and longevity, the system can be considered available over the next decade.

Recently, a reflexion has been made internally in CNES with respect of the DORIS system and the conclusions are that the program is useful for a set of planned missions. Currently, the DORIS program has to be maintained until at least 2024. At this time, beside missions in operations, some other ones are under different levels of development, as the following ones, indicated with their possible dates to be launched/ended: SARAL (2012-2017), Jason-3 (2014-2024), Sentinel 3a/b (2014/2021 – 2017/2024), Jason-CS-A (2018/2024).

Yours Sincerely,

Mioara Mandea
Solid Earth Programme Manager
Programmes and Strategy Directorate
DORIS Constellation Summary

- **Past missions**
  - HY-2A, C, D
  - HY-2B, C, D
  - HY-2C

- **Current missions, agreed life time**
  - Sentinel-3A
  - CryoSat-2
  - Jason CS
  - GRASP

- **Future missions pending approval**
  - Sentinel 3B

- **Future missions, nominal life time**
  - Sentinel-3A

- **Current missions, agreed life time**
  - Sentinel-3A
  - CryoSat-2
  - Jason CS
  - GRASP

- **Future missions pending approval**
  - Sentinel 3B
ARL:UT is the Applied Research Laboratories at the University of Texas
- Ionospheric science and space weather
- Data assimilative methods
- EM signals propagation (ray tracing)
- Software-defined receivers
- Digital signal processing
- GPS precision applications and data analysis

JHU/APL is the Johns Hopkins University Applied Physics Laboratory
- Space program has built & operated 64 spacecraft
- Near-earth and deep space missions
- UV sensors, particle measurements
- Transceivers and software-defined radios, precision oscillators
- Recent missions include New Horizons (Pluto), Messenger (Mercury), Radiation Belt Storm Probe (launched Aug 2012)

Both are UARCs – University-Affiliated Research Centers (non-profit):
→ Scientists working primarily on science in applications settings.
Occultation v. Trans-Iono Rays

- GNSS occultation data can’t resolve horizontal structure

- Bernhardt (2005) demonstrated this clearly with a simulated equatorial bubble

  - GPS occ. data can’t see it:

  - DORIS LEO data can