DORIS Observations from Future LEO Constellations

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Introduction

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.

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?

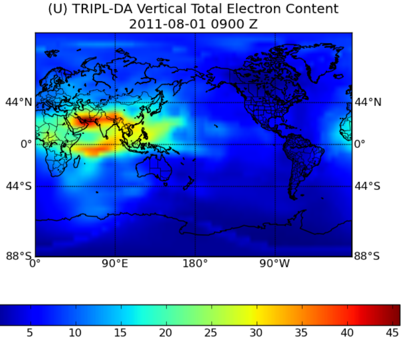
③ Where is the division between large-scale structure and turbulent structure? (E.g., that could be characterized by a power law distribution.)

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.
- Ionosphere specification is a 2-D or 3-D map of the free electron content.
- Dynamical observation of electron density allows reconstruction of the state variables.
- State of the art is 3DVAR/"4DVAR" data assimilation onto climatology.



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.

Ionospheric Data Types

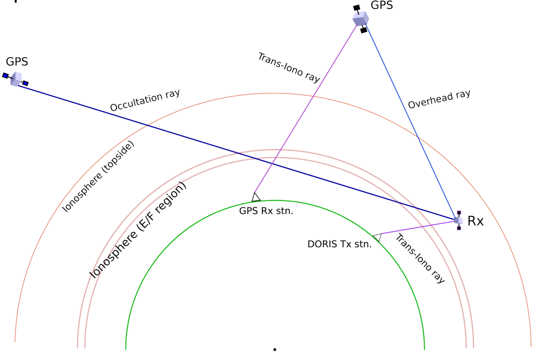
Data Source	Type	Meas'mt	Utility/Character	Global	3DVAR Value
GNSS Overhead	ray (MEO→LEO)	TEC	topside	Y	low
GNSS Occultation	ray (MEO→LEO)	TEC	vertical structure	Y	med†
GNSS Ground	ray (MEO→Gnd)	TEC	bulk, horiz. resolution	N	high
LEO Beacon	ray (LEO→Gnd)	TEC	bulk, horiz. resolution	N	very high
Ground Beacon	ray (Gnd→LEO)	TEC	bulk, horiz. resolution	Y	very high
Insitu	point	n_e	normalization	N	low
Ionosonde/Sounder	point	n_{F_2}, h_{F_2}	normalization	N	high
Optical	various	n_e^2	n_{F_2}, h_{F_2}	Y	low

† Useful for bulk specification only in combination with trans-ionospheric ray data

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

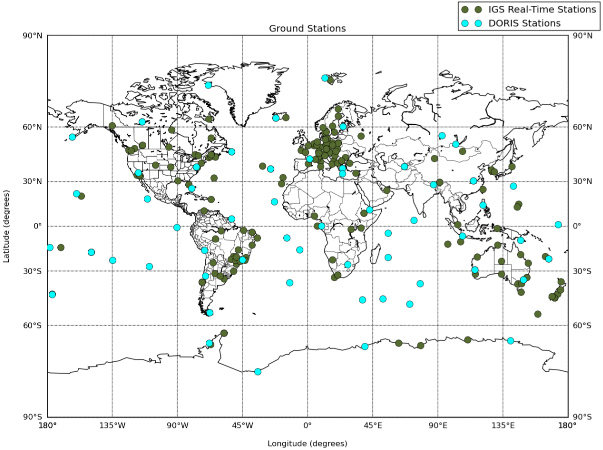
- Ground–LEO ray TEC data provides the best horizontal bulk resolution without spatio-temporal mixing

- The optimal data set would contain an abundance of all data types



Suitability of DORIS

- 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, ...

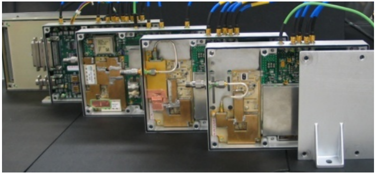


- If DORIS didn't exist, we'd propose a system exactly like it!

Frontier Radio - Multi-Band SDR Development for DORIS

Dual-Band SDR Configuration

Prototype Slices



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
- RBSP mission begun Aug 2012 – harsh radiation belt environment during solar maximum.
- 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

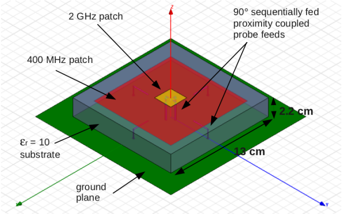
APL

Frontier-DORIS Antenna Design

- Large 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 ~ 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.

- ◦ < 5 W power (expect $\sim$2 W)
- ◦ < 5 kg mass incl. antenna (expect 3 kg)
- ◦ < 1 U (1000 cm^3) volume (not incl. ext. antenna)
- ◦ $\sim$ 10 kbps data output

$\rightarrow$ This would be the most compact, low-power DORIS Rx in the world.

- Designed for a 15-year lifetime.

DIRGO Science

DIRGO instruments will report phase (Doppler is derivable).

DIRGO primary mission is ionosphere specification:
→ high-resolution bulk electron density specification.

DIRGO secondary mission is scintillation mapping at two length scales.

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.

(cf. Flouzat et al., *Geophys. J. Int.* **178** 1246-1259, 2009)

DIRGO Proposal

- DIRGO is the DORIS Ionospheric Realtime Global Observatory
  → DORIS dual-band Tx network ID'd as best signal of opportunity.
- ARL:UT & JHU/APL proposal to fly DORIS Rx's on Iridium NEXT.
  → Iridium NEXT ID'd as best platform 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 has been included for consideration
  - Evaluation in late 2012 / early 2013
  - Specific platforms not yet identified

→ In either case, the data would have been public and immediately available.

▸ Iridium NEXT is no longer a possibility.

Hosted payload space will instead be used for air traffic control.

Other Opportunities

- Numerous other opportunities to fly are on the horizon.

Possibilities include:

- COSMIC II polar (2016-2018?)
- Cubesats (several U.S. Government programs)
- Air Force weather satellites
- Government funding for commercial sat hosted payloads

- ARL:UT & JHU/APL are pursuing funding for all flight opportunities.

Meanwhile, we are being given the chance to demonstrate our technology on the ground in a lab setting.

Future Considerations

1. Reassure USAF that the DORIS system will be around long-term.

- Thanks to CNES for providing official letter of commitment.

2. Confirm to USAF that DORIS signals can support scintillation.

Need to answer question about phase stability in 0.1-300 Hz regime.
We look forward to discussions with CNES engineers about this.

Summary

- Our Science Goals
  - Persistent global mesoscale observation of the ionosphere
    - 3D electron density specification
    - scintillation maps
  - If possible, 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
  - upcoming presentation at COSMIC workshop (Oct. 31)

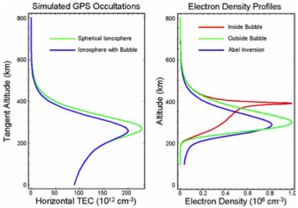
$\boxed{\text{BACKUP}}$

GPS as Ionosphere Probe

- GPS is also dual-band, but isn't ideal:
  ① GPS ground stations cover only certain land masses – not global
  ② GPS ground data has representativeness & spatio-temporal issues
  ③ GPS occultation data cannot resolve horizontal structure

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

  · GPS occ. data can't see it:



  · DORIS LEO data can ⟶