Case Study on Potential Impact to Weather Forecasting and Environmental Monitoring if GPS Radio Occultation is Denied

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(viewgraphs borrowed from Larry Young, Tom Meehan, Jeff Tien, Dave Ector, Tom Yunck, Tony Mannucci, and more)

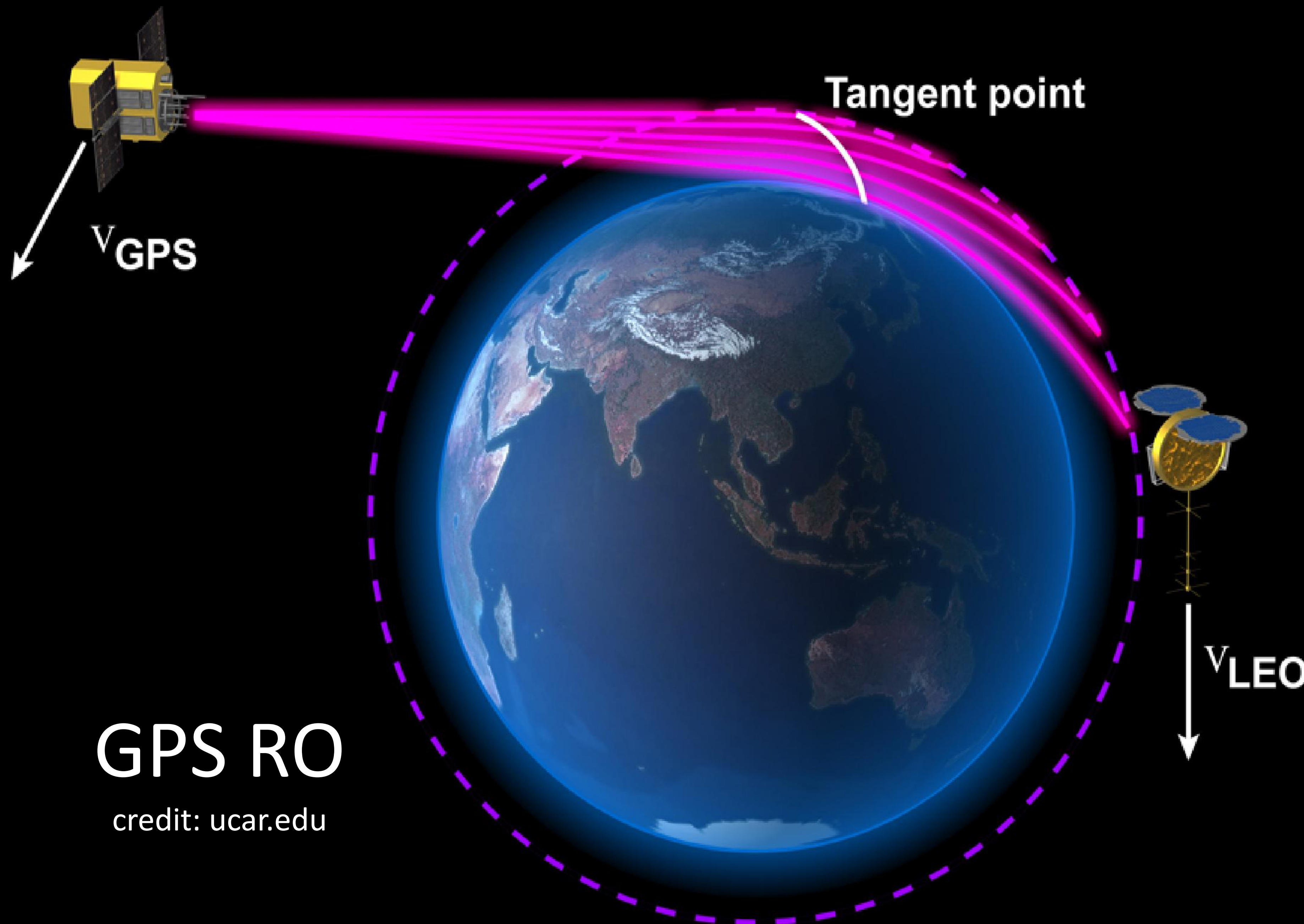
Synopsis

- Radio Occultation (RO) is critical for modern accurate weather forecasting, climate change science, and space weather
- Direct customers include NOAA, USAF, NASA, NSF, Taiwan Space Agency, Korean Space Agency, ESA. We are all indirect customers.
- Unplanned changes to spectrum will cause severe disruption to RO
- Addition of high power transmissions in L-Band with adequate notice causes performance degradation and raises cost. We need signal details to quantify these effects.

History

- Radio Occultation (RO) was developed by scientists at Caltech's Jet Propulsion Laboratory (JPL) and at Stanford in the early 1970s
- RO quantified the refractivity of planetary atmospheres by observing the doppler shifts of downlinks from occulting spacecraft
- GPS RO was proposed as an instrument (GGI) for NASA's Earth Observation System by a team at JPL lead by Tom Yunck circa 1989

- Shortly after, a proposal from the University Corporation for Atmospheric Research (UCAR) was successful, resulting in GPS/MET launching in 1995 with a JPL-developed RO instrument on an OSC Microlab satellite with a Pegasus launch



GPS RO

credit: ucar.edu

The RO Measurement at a Glance (glossing over "details")

- As the ray from the GPS satellite cuts down through the atmosphere, it is refracted.
- The additional range compared to the straight-line distance increases as the ray comes through denser atmosphere at lower heights
- Over the 100 seconds of an occultation event, this accumulates to about 1 km of additional delay.
- This delay is a function of density (n/V), which is related to temperature by the ideal gas law, P*V = n*R*T
- Given sub-mm measurement precision, RO can determine atmospheric temperature profiles to 0.1 – 0.5 K accuracy in the lower atmosphere
- RFI is a problem because the signal is defocussed by tens of dB at low ray heights, and SNR is marginal (in fact, tracking loops cannot be closed, and the data are captured running open loop.)

Why is RO Data so Valuable?

- Temperature – much better measurement uncertainty than other satellite data – no calibration is needed
  - COSMIC ~0.1 - 0.5 degrees
  - AMSU, IASI, AIRS ~1-2 degrees
- Much higher vertical resolution (*not so good horizontal*)
  - COSMIC – 0.1-0.2km
  - AMSU, IASI, AIRS ~ 1-2km
- COSMIC Soundings track to the surface ~80% *limited by SNR*
- Extremely low temperature bias
  - COSMIC – order of magnitude lower bias than other satellite instruments
- Daily "gold standard" for worldwide temperature profiles (oceans and land) – not impacted by clouds
- Low-cost instrument

TriG GNSS Receiver for COSMIC-2

COSMIC-2 Mission Objective:

- Providing operational global GNSSRO-based Earth observations (including refractivity, temperature, moisture, and electron content and density profiles of the troposphere, stratosphere, and ionosphere)

Partnership *with NASA*: NOAA/USAF (SSAEM)/NSPO (Taiwan)

Orbits: 500km equatorial (24°); 800km polar

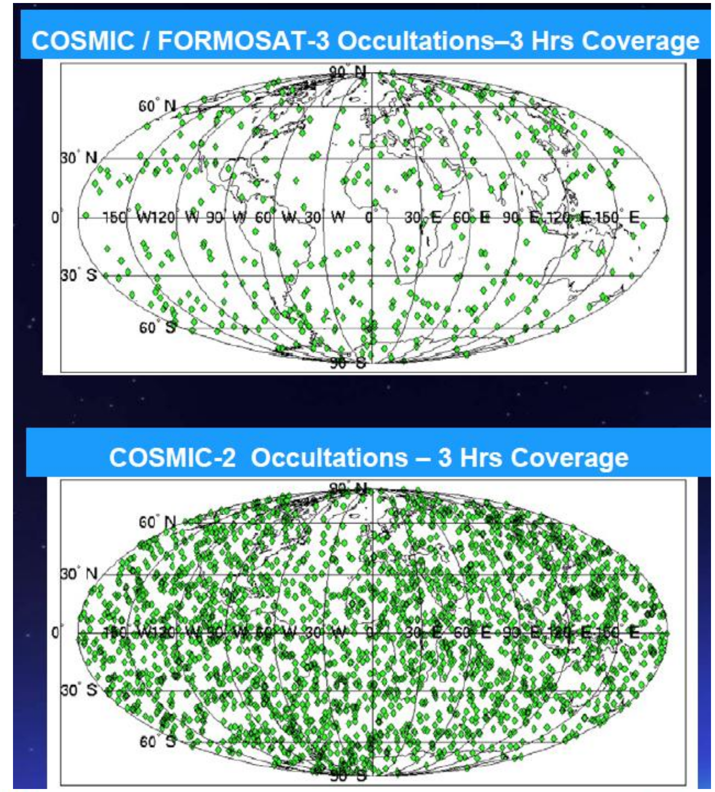
Number of S/C: 12

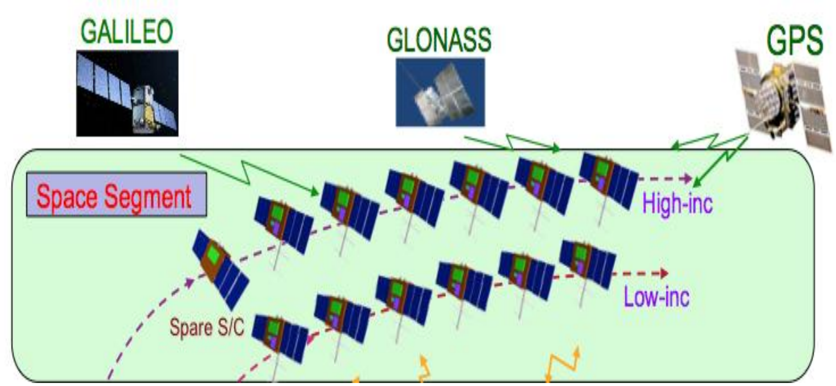
Launch: 6 S/C on 2015; 6 S/C on 2017

Mission Life: 5 years

Key GNSS Receiver Requirements:

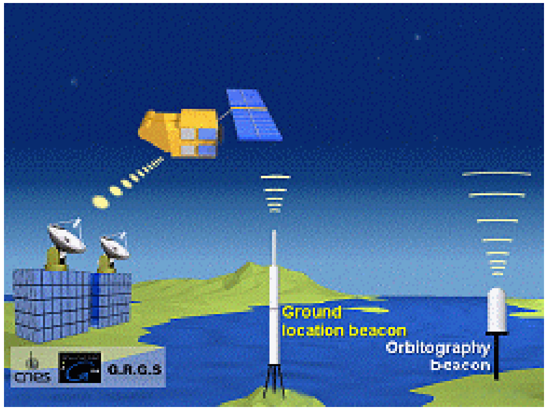
- GPS/Glonass FDMA (Threshold) / Galileo (Objective)
- Neutral Atmospheric Soundings / day / payload:
  - 1125 (Threshold) / 1600 (Objective)
- Ionospheric Soundings & Arc / day / payload:
  - 1125 (Threshold) / 2250 (Objective)
- Ionosphere Scintillation





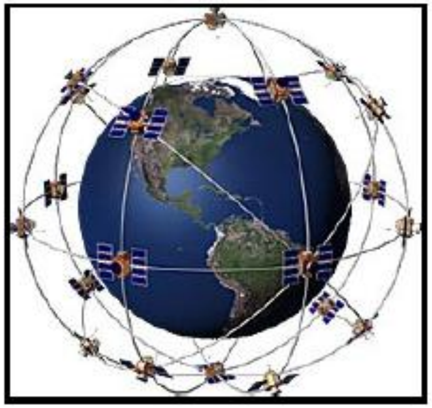
Why Does TriG Have Wide Filters? To Receive All GNSS+ Signals

- Wide bandwidth RF Downconverter capable of receiving all GNSS signals, plus other:
  - GPS, Galileo, GLONASS, Compass
  - Other navigation signals (QZSS, DORIS, GEO augmentations at MSS or S-band, etc)
- TriG will track both legacy and new GPS signals
  - Provide uninterrupted multi-frequency GPS tracking service through 2020 retirement of semi-codeless
- Tracking more GNSS signals will improve both POD and the quality and quantity of the measurements from RO and surface reflection observations.

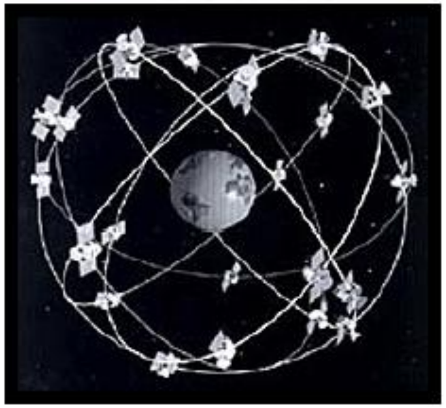


DORIS Transmitting Station

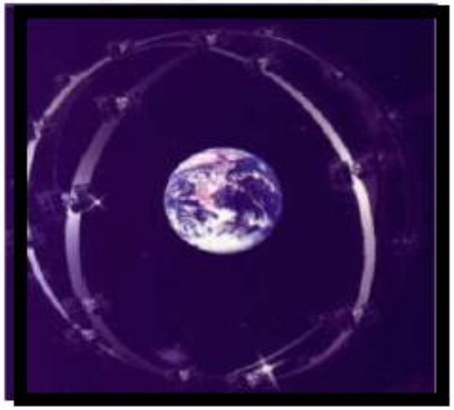
GPS



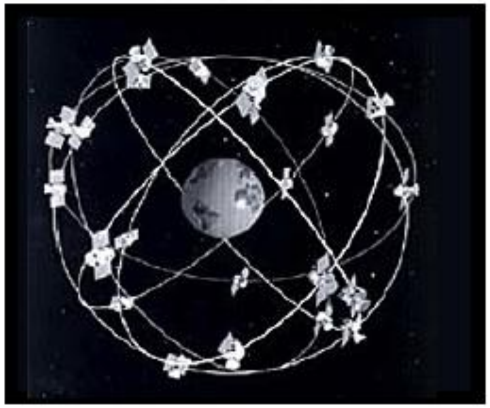
Galileo



GLONASS



Compass



Why Does TriG Have Wide Filters? (contd)

- Allows flexible use of spectrum, including augmentation signals not specified at launch
- Design avoids narrow filters because
  - Narrow filters degrade performance
    - Insertion loss-> lower SNR
    - Phase and delay distortion across signal band
    - Phase and delay variation vs temperature
    - All these get worse with sharper cutoff and if cutoff is closer to the GNSS frequencies
  - Additional development cost and time
  - Cost for additional pre-flight testing
  - Additional size and mass of flight instrument
  - Cost of filters themselves

Summary

- RO needed for:
  - Weather forecasting - forecast errors cost lives, NOAA customer
  - Climate change science, USG customers (NSF, NASA, …)
  - Space Weather now-casting, USAF customer
- Unplanned changes to spectrum will cause severe disruption to RO
- Addition of high power transmissions in L-Band with adequate notice causes performance degradation and raises cost. We need signal details to quantify these effects.
- Propose standardized conducted test setup to measure degradation in performance of any proposed mitigation solution

Questions?

How RFI and RFI Rejection Techniques affect RO Soundings

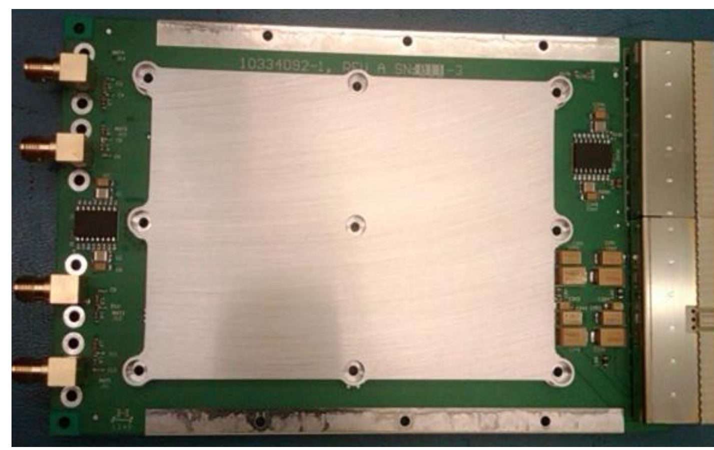
- In certain geographic areas such as the continental US SNRs will be lower, leading to more random noise in the carrier phase measurements and therefore greater refractivity errors.
- Lower SNRs means there will be a reduction in the % of occultations that persist to low heights above the surface, affecting recovery of water vapor.
- Addition of more restrictive filters with sharp cutoffs will cause phase and delay variations vs. frequency, and these will change as a function of instrument temperature. This could produce significant systematic errors.

Flexible Architecture with Large Reconfigurable Resources

- Software and signal processing firmware are fully reconfigurable post-launch.
- Programmable LO in the RFDC allows each (*of 32)* RF channel to down-convert signals from any GNSS frequency within the front-end bandwidth
- Individual RF channels are disabled as needed to reduce power consumption
- Large reconfigurable signal processing logic resources with up to 300 reconfigurable satellite signal processing channels.

Reconfigurable Digital Processor

Wideband RF Downconverter



Javad's Filter Solution

(taken from ex parte to FCC
6 OCT 2011)

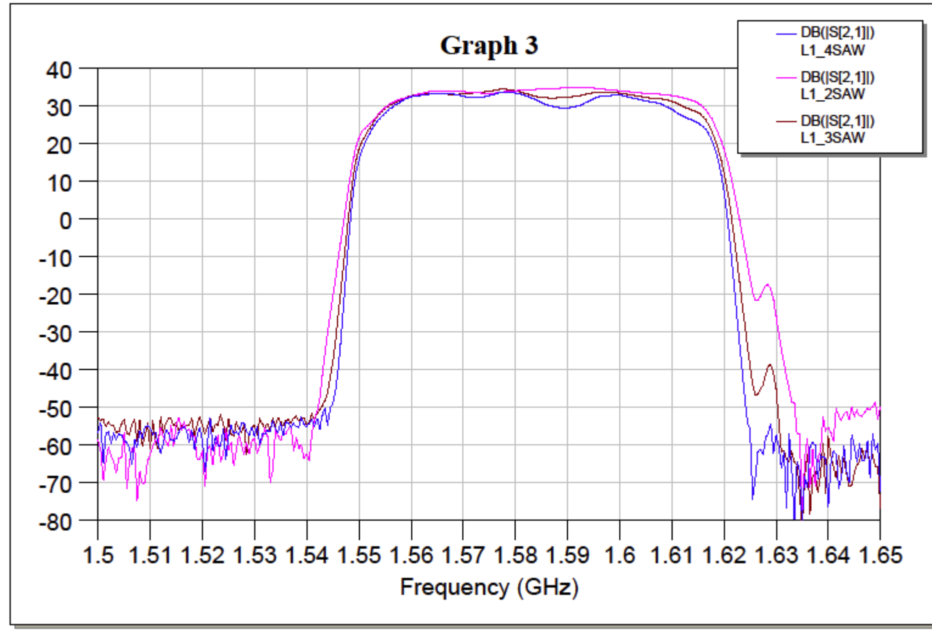
This example demonstrates how a filter with sharp cutoffs introduces severe variations in phase and delay in the signal bandpass.

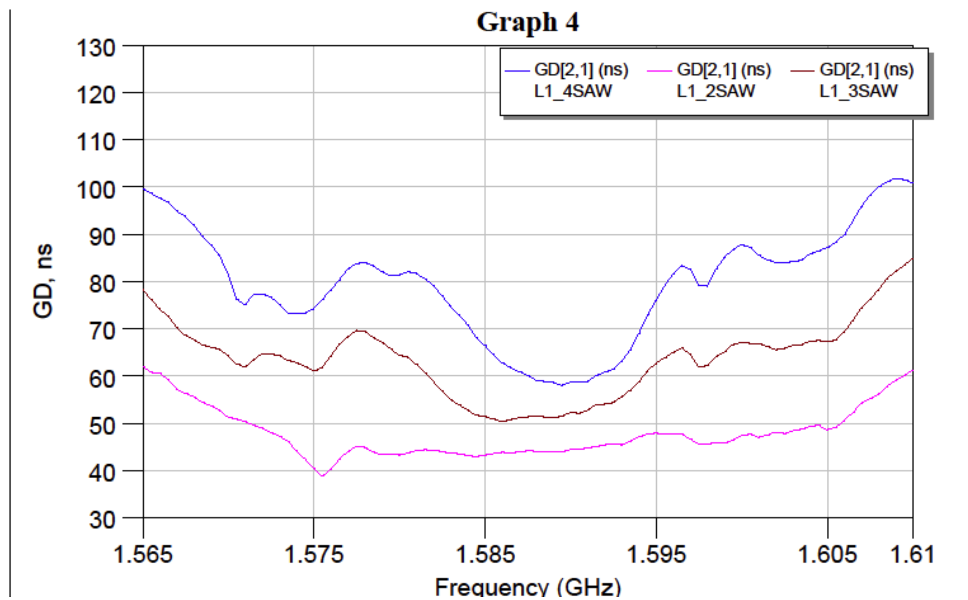
Graph 3 shows the amplitude cutoff in dB. Graph 4 shows the in-band delay vs frequency.

Note the 4 SAW filter delay varies from 60 to 100 ns. *Not acceptable*

These curves will all change as a function of temperature. *Estimated change not acceptable*

Max insertion loss 2.84 dB. Causes 3.9 dB SNR degradation. *Not acceptable*



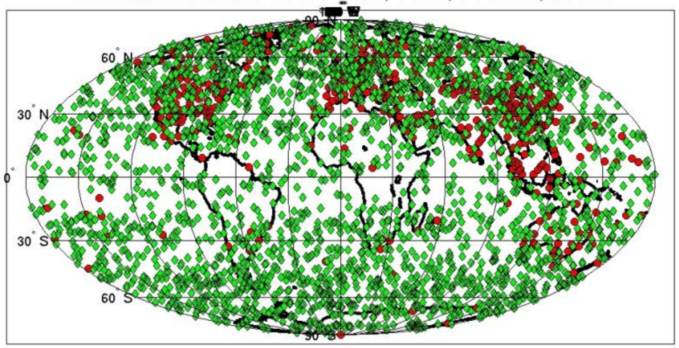


Suggested References for Material supporting the need for RO data

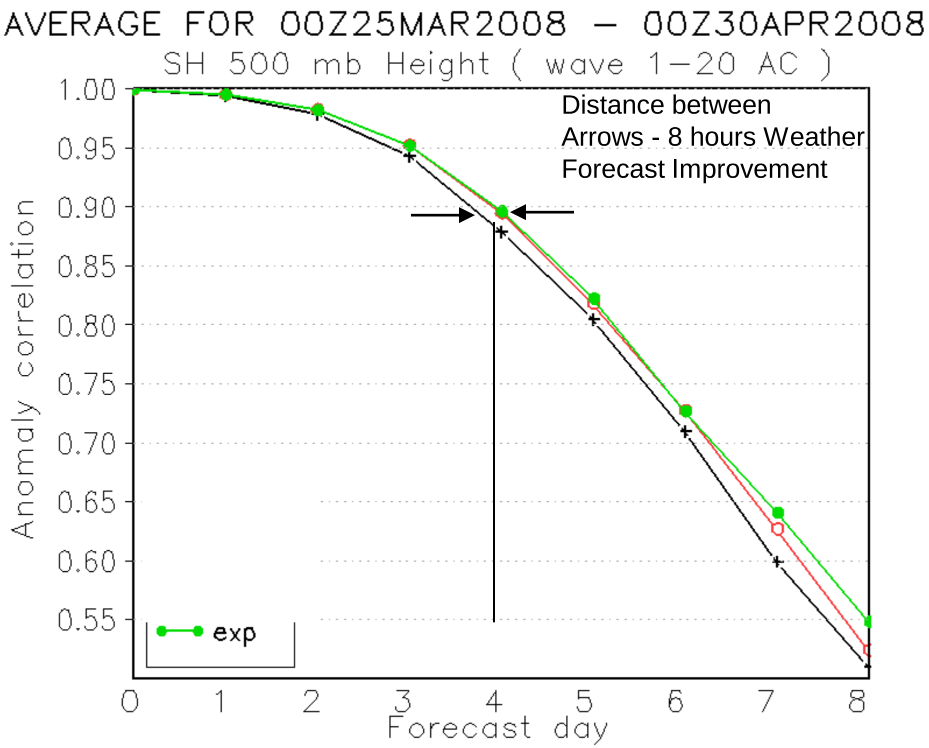
- Benefits from RO to weather prediction (extreme weather events) and climate science (reliable global warming benchmarks)
  - Dr. Bill Kuo, NCAR
  - Dr. Lidia Cucurall, NOAA
- Benefits to space weather (as required for warfighter communications)
  - Dr. Paul Straus, Aerospace/USAF SSAEM

6 COSMIC satellites -> Significant Impact to Better Weather Service Forecast

- Proven significant forecast accuracy improvement
- 40-day experiments:
  - **Black line - No COSMIC**
  - **Red line - COSMIC Initial Operations**
  - **Green line -** Current COSMIC

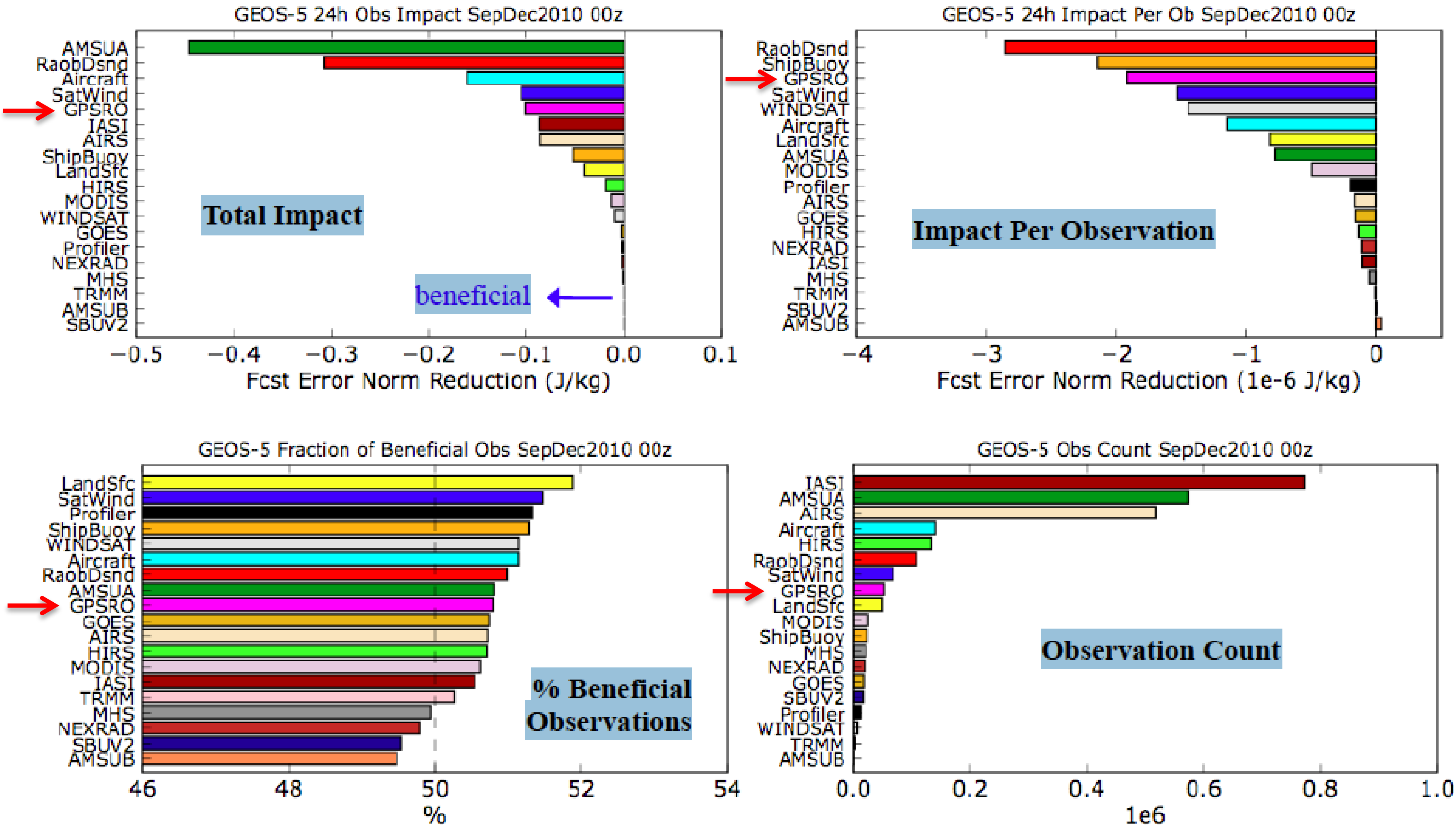


Daily - COSMIC vs Radiosondes



-COSMIC provides 8 hours of improvement in Weather forecast skill at day 4 and over 15 hours in day 7
- Particularly significant improvement over the oceans
- Analysis – COSMIC satellite loss causes significant NOAA forecast skill loss

Operational Impact

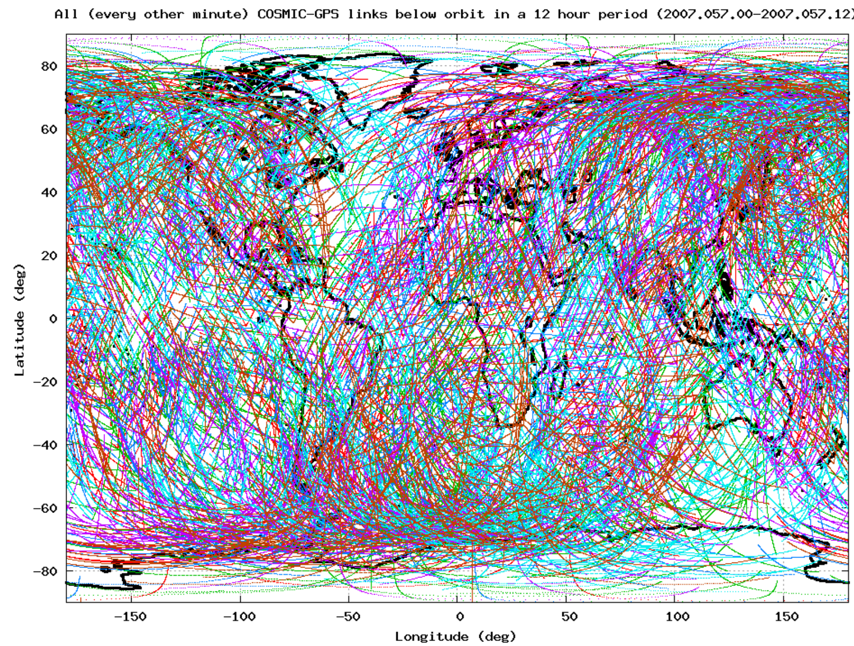


Ron Gelaro, NASA/GMAO

From Ector et al. presentation AMS Annual Meeting, January 2012

Space Weather Needed by USAF Sponsor

- GNSSRO tracks profiles through Ionosphere – very accurate Space Weather instrument
  - TECU uncertainty – 0.001
  - S4 index uncertainty – 0.1
- Fully supports coupled ionosphere/troposphere model
  - Single profile from surface to space



COSMIC Observed TEC rays in 12 hours