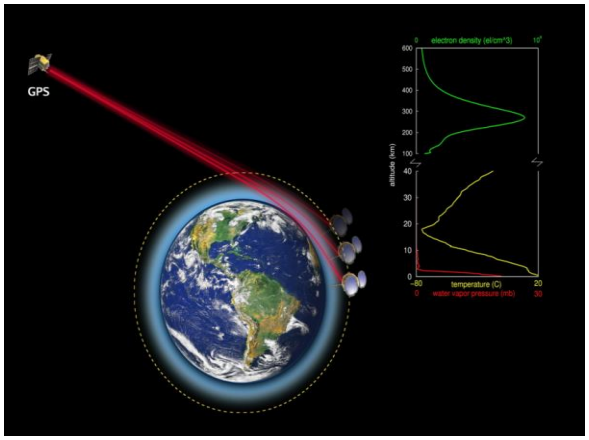
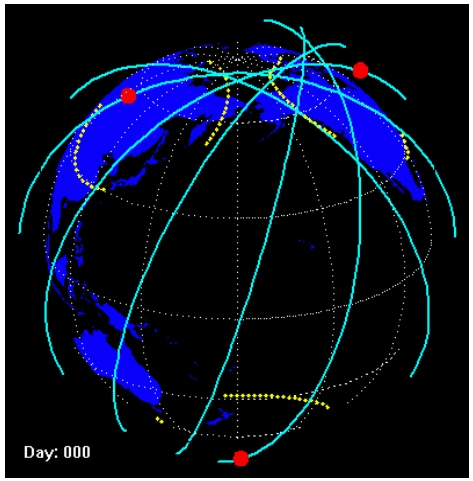
Follow-On Radio Occultation Constellations for Meteorology, Ionosphere and Climate: Overview of Currently Planned Missions, Data Quality and Coverage, and Potential Science Applications

Bill Schreiner, C. Rocken, X. Yue, B. Kuo
COSMIC Program Office, UCAR, Boulder CO
www.cosmic.ucar.edu

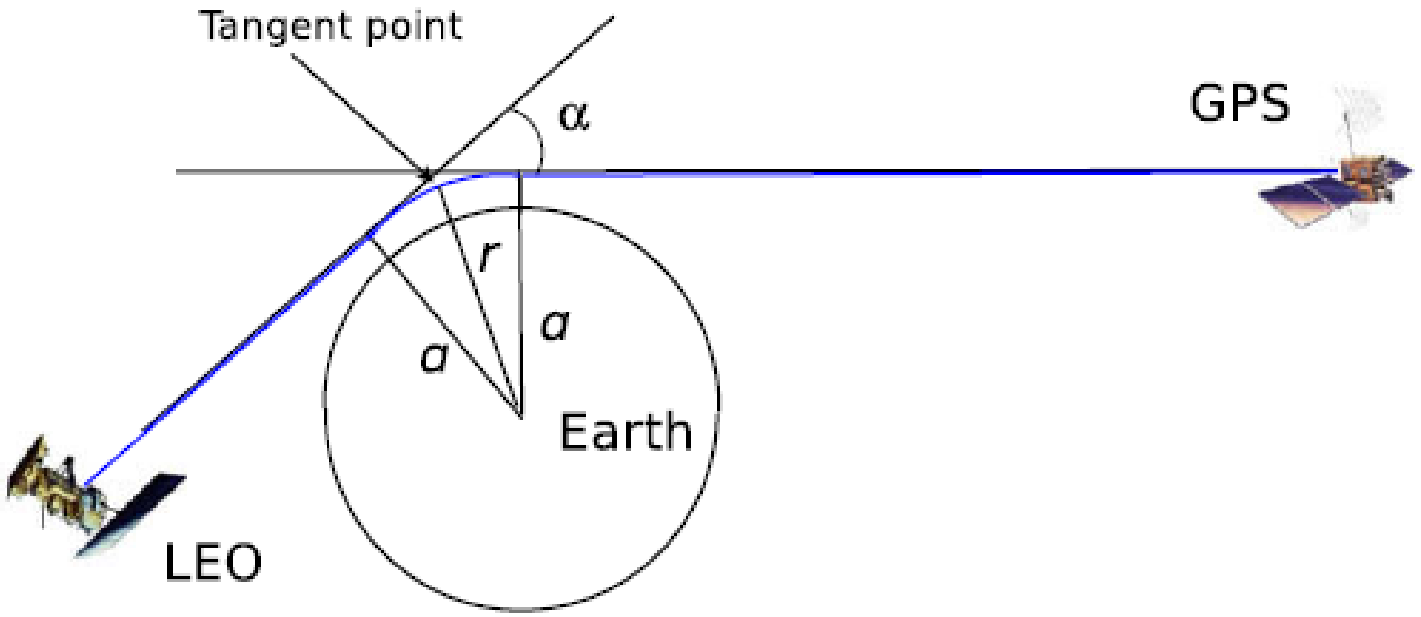
P. Wilczynski, D. Ector, R. Fulton
NOAA/NESDIS Office of Systems Development, Silver Springs, MD





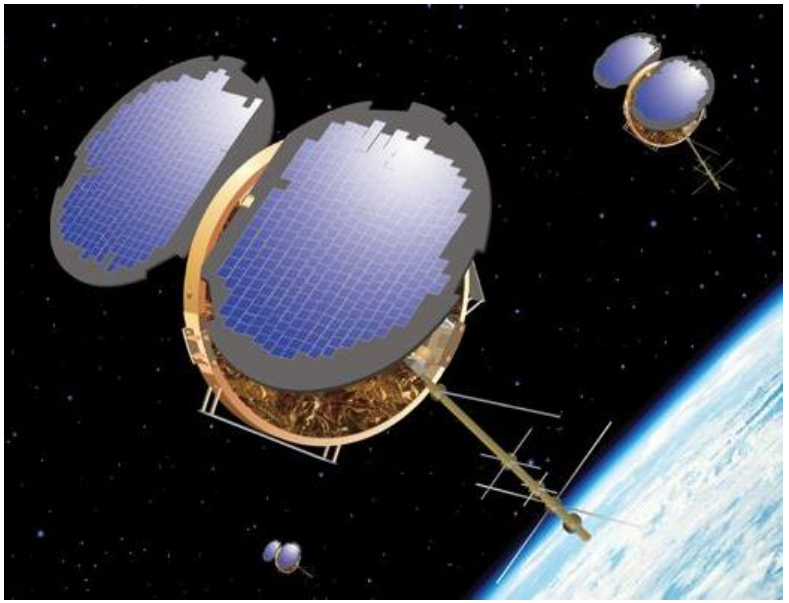
Outline

- COSMIC and RO Overview
- Future RO Missions
- Summary



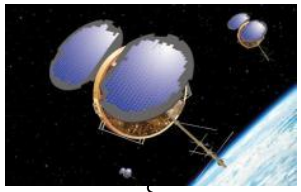
COSMIC

(Constellation Observing System for Meteorology, Ionosphere and Climate)



- Joint Taiwan and US project
- NSF is U.S. lead agency
  - NOAA, NASA, Air Force, Navy
- 6 Satellites launched April 14, 2006
- **GPS Radio Occultation Receiver**
  - Refractivity
  - Pressure, Temperature, Humidity
  - **Absolute Total Electron Content (TEC)**
  - **Electron Density Profiles (EDP)**
  - **Ionospheric Scintillation (S4 amplitude)**
- Tiny Ionospheric Photometer (TIP) – UV Radiances
- CERTO Tri-Band Beacon Transmitter
- Complete global and diurnal sampling
- Demonstrated forecast value of GPS radio occultation soundings in near-real time
- Total cost ~$100M; Taiwan paid for 80% of costs
- Mission on time, within budget, and exceeding expectations

COSMIC Operational Processing



RTSs:
Alaska
Norway
Antarctica/McMurdo

Input Data
- COSMIC data
- GPS ground data
- GPS NDM Bits
- GFS Forecast
- IGS/IGU ORB/CLK
- Bernese Config files

TACC

CDAAC

Science & Archive

UCAR/Unidata's LDM

WGET

Research Community

1500-2000 WMO BUFR Files per day with Latency ~ 75-90min

SFTP

AFWA

NESDIS

GTS

JCSDA

NCEP

ECMWF

CWB

UKMO

JMA

Canada Met.

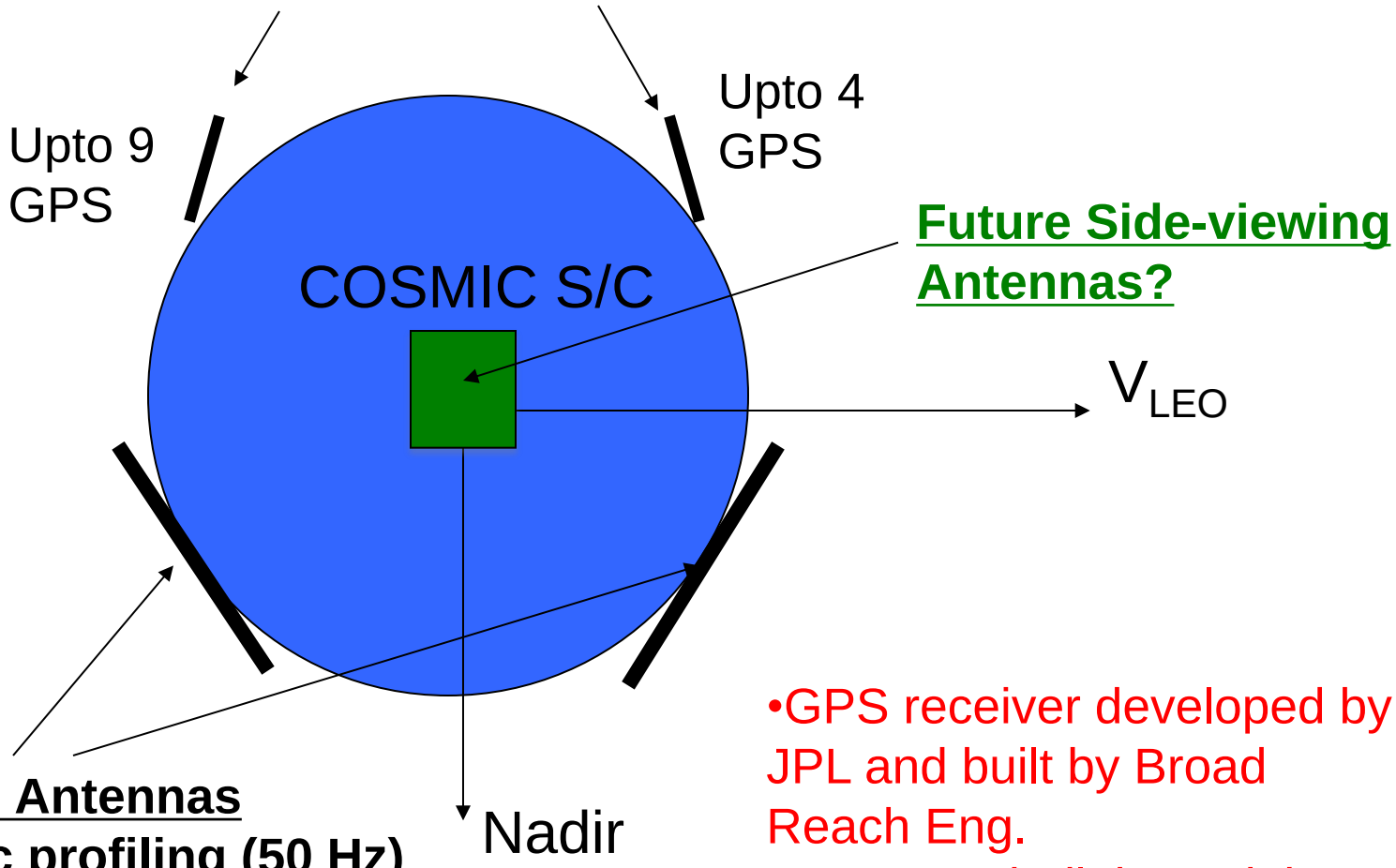
Meteo France

Boulder, CO

Providing data to > 1,250 registered users from 54 countries

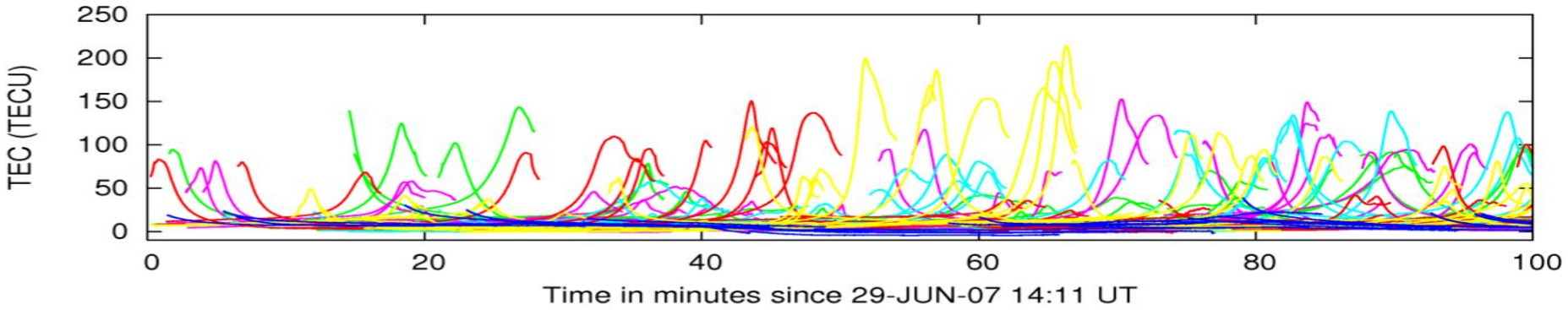
Apr 27-30, 2010

GPS Antennas on COSMIC Satellites



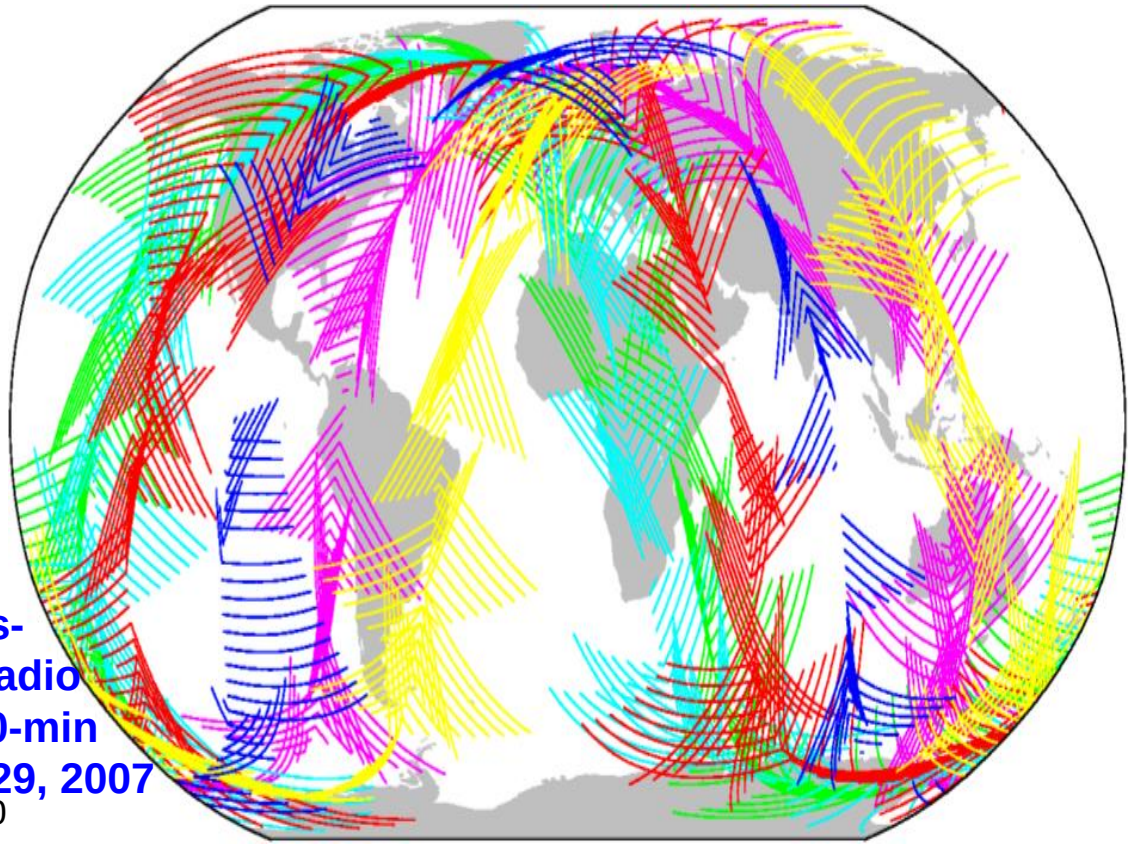
- GPS receiver developed by JPL and built by Broad Reach Eng.
- Antennas built by Haigh-Farr

GPS Absolute TEC



- Absolute TEC good to ~ 3 TECU
- Relative TEC

  ~ 0.001 TECU
- Actual COSMIC reference link data ~ 0.0024 TECU at 1-Hz (2009.001-004)

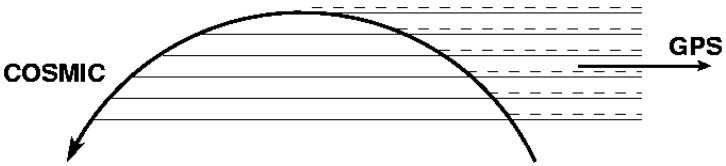


COSMIC trans-ionospheric radio links for a 100-min period, June 29, 2007

COSMIC GPS Radio Occultation

GPS Satellite

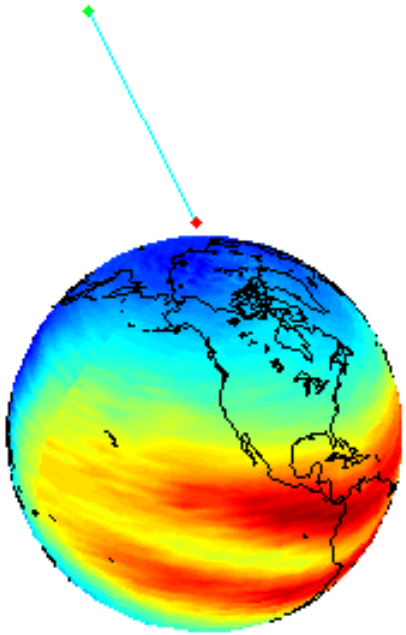
COSMIC LEO Satellite



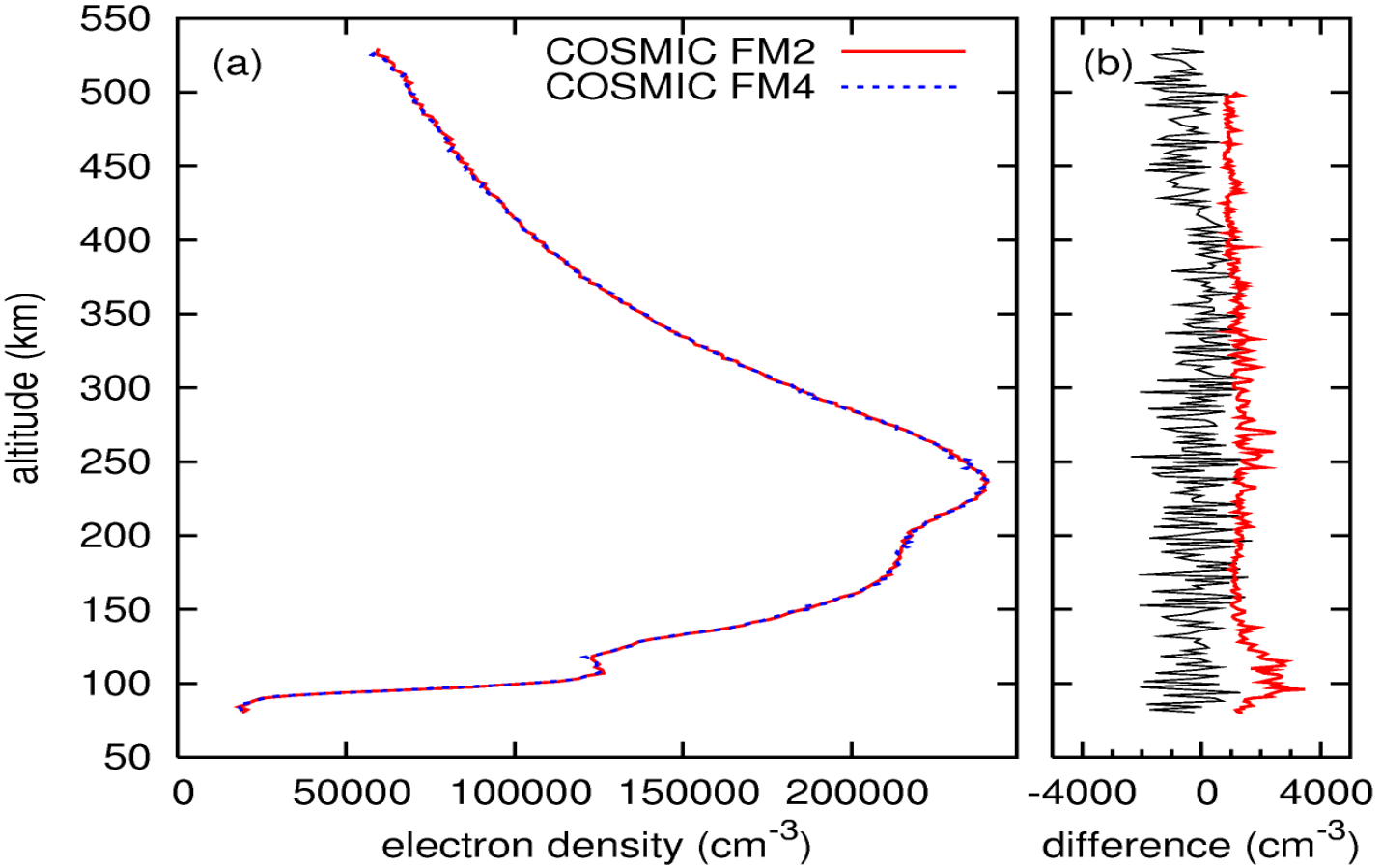
ΔTEC = solid - dashed
[Schreiner et al., 1999]

$$N(r) = -\frac{1}{\pi}\int_{r}^{r_{\mathrm{LEO}}} \frac{d\tilde{T}/dp}{\sqrt{p^2 - r^2}}\,dp\,.$$

- Inverted via onion-peeling approach to obtain electron density N(r)
- Assumption of spherical symmetry



EDP Precision from Collocated Soundings

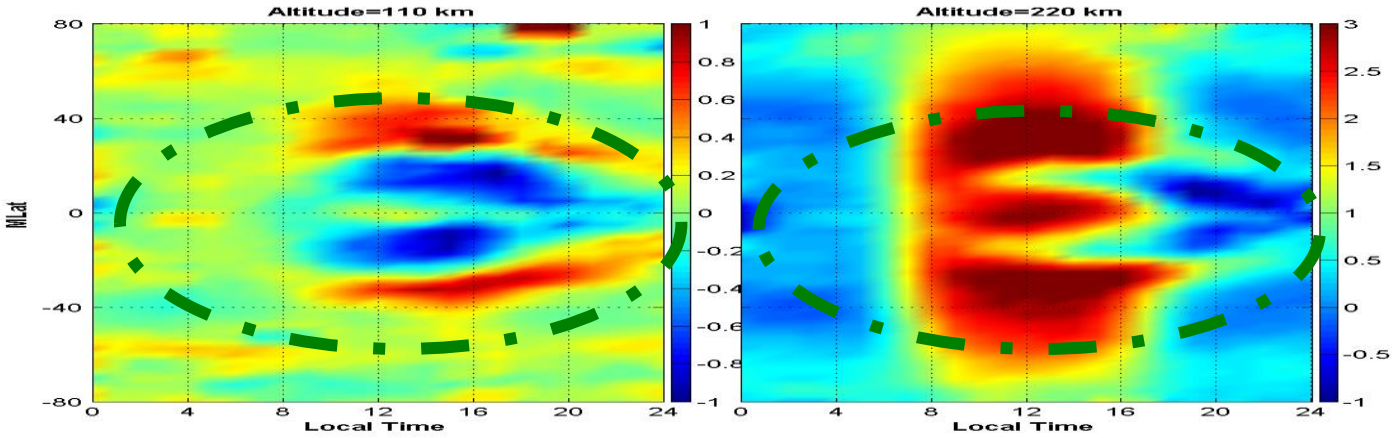


[Schreiner et al., 2007]

COSMIC EDP Retrieval Errors

- COSMIC EDP retrieval assumes spherical symmetry (Abel inversion)
- Simulation Performed by UCAR/COSMIC :
  - small errors at F-layer and above
  - Larger errors below F-layer (shown below for real obs and error simulation)
- EDP Retrieval improvements are under investigation at UCAR

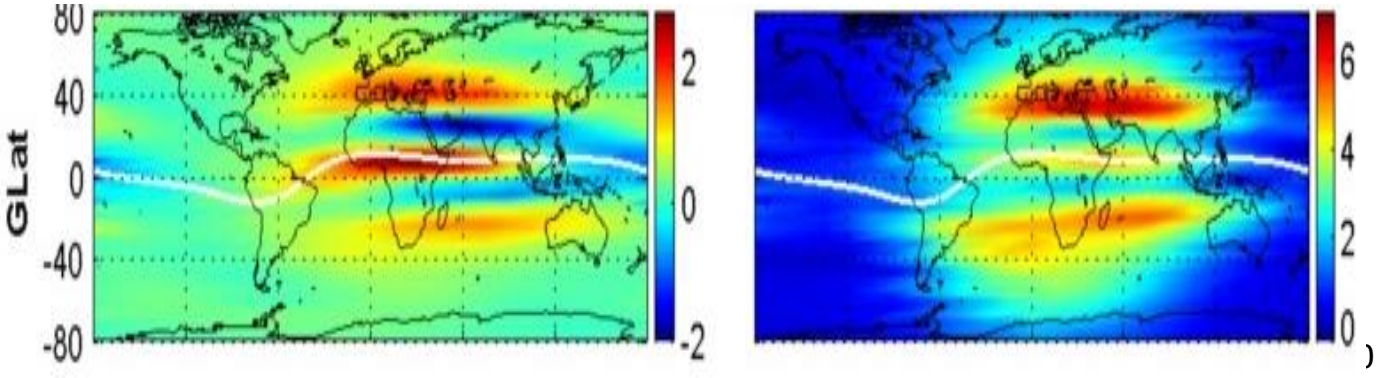
COSMIC Observations



110 km altitude **220 km altitude**

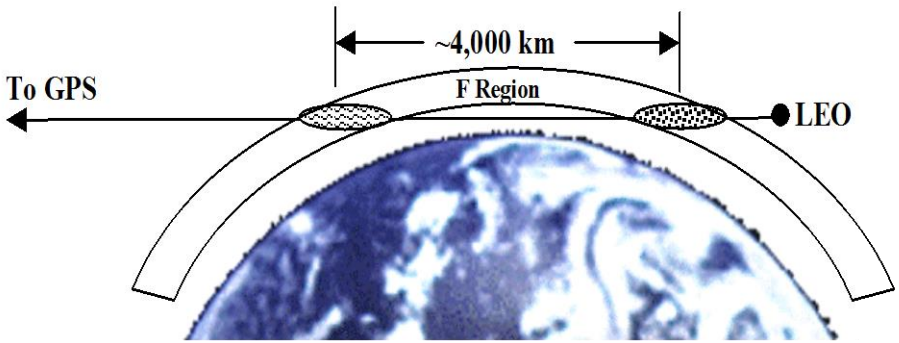
[Yue et al., 2010]

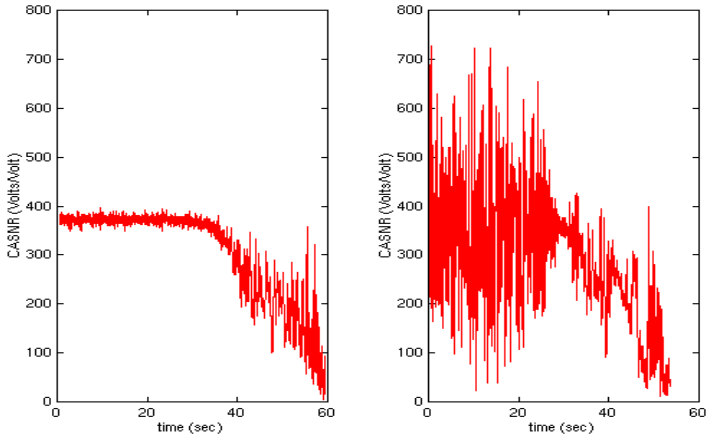
Abel retrieval Error from Simulation



Unit: $1 \times 10^{11}/m^3$

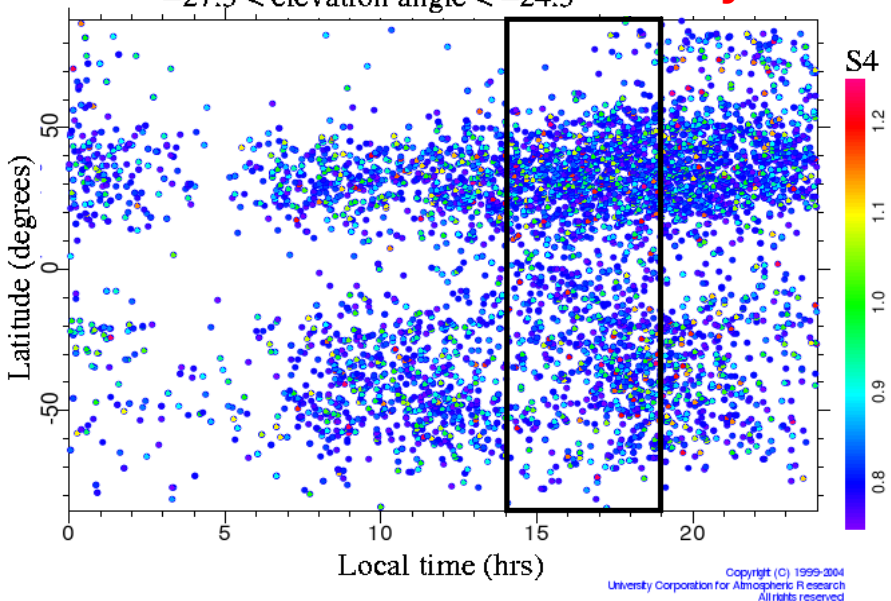
GPS L-band Scintillation



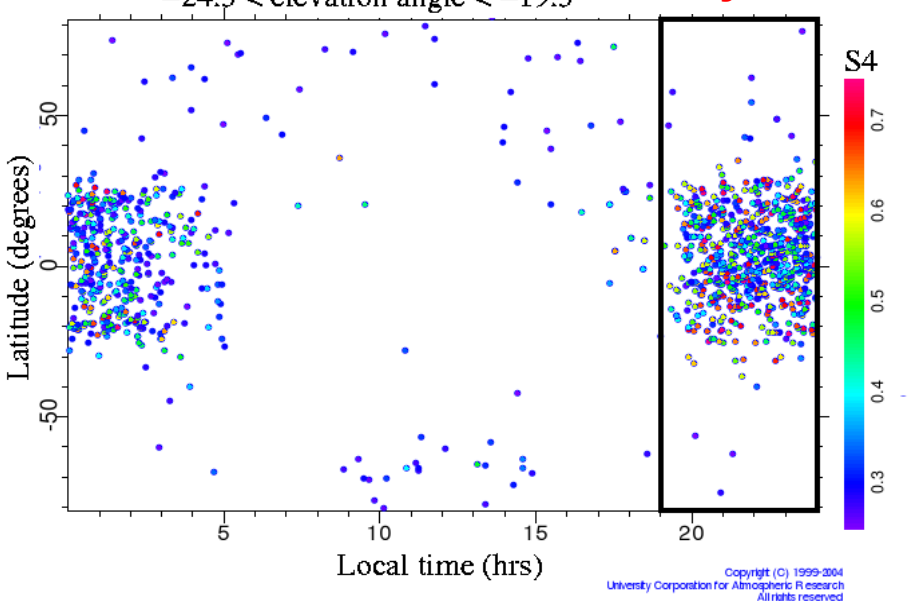


Where is the source region of the scintillation?
Localize irregularities: [see Sokolovskiy et al., 2002]

E layer



F layer



Recent Ionosphere and Space Weather Studies Performed with COSMIC Data

- COSMIC EDPs used for verification of IRI and TIEGCM models (Lei et al., 2007)
- COSMIC EDPs used to estimate ionosphere High Transition Heights (HTH) and agree well with C/NOFS data (Yue et al., AGU, 2009)
- COSMIC EDP inversion errors quantified in E and F layers of ionosphere (Yue et al., 2010)
- COSMIC used to study ionospheric response to Sudden Stratospheric Warming event (Yue et al., 2010)
- By using COSMIC NmF2 and hmF2, HAO/NCAR reported that the Weddell Sea Anomaly phenomena can be explained by conjugate effects (Burns et al., 2009)
- Mid-latitude summer nighttime anomaly (MSNA) of the ionosphere observed by COSMIC EDPs (Lin et al., 2009)
- Plasma depletion bays observed by COSMIC EDPs (Liu et al., 2009)
- COSMIC S4 Scintillation indices used in validation with C/NOFS data (Strauss, 2009) and to map irregularity regions (Gouthu et al., 2009)
- Sporadic E layer climatology produced with COSMIC data (Wang, 2009)
- COSMIC EDPs and TIP data used to study the ionosphere disturbance during 15 Dec 2006 geomagnetic storm and found a long lasting positive storm effect in ionosphere (Pedatella et al., 2009)
- TIP data used to map the post-sunset equatorial anomaly and F-region depletions (Coker et al., 2009)
- JPL did many observation system simulation experiments (OSSE) and found that COSMIC 2 can advance the assimilation performance because of much more GPS TEC observations than current COSMIC (Pi et al., 2009)

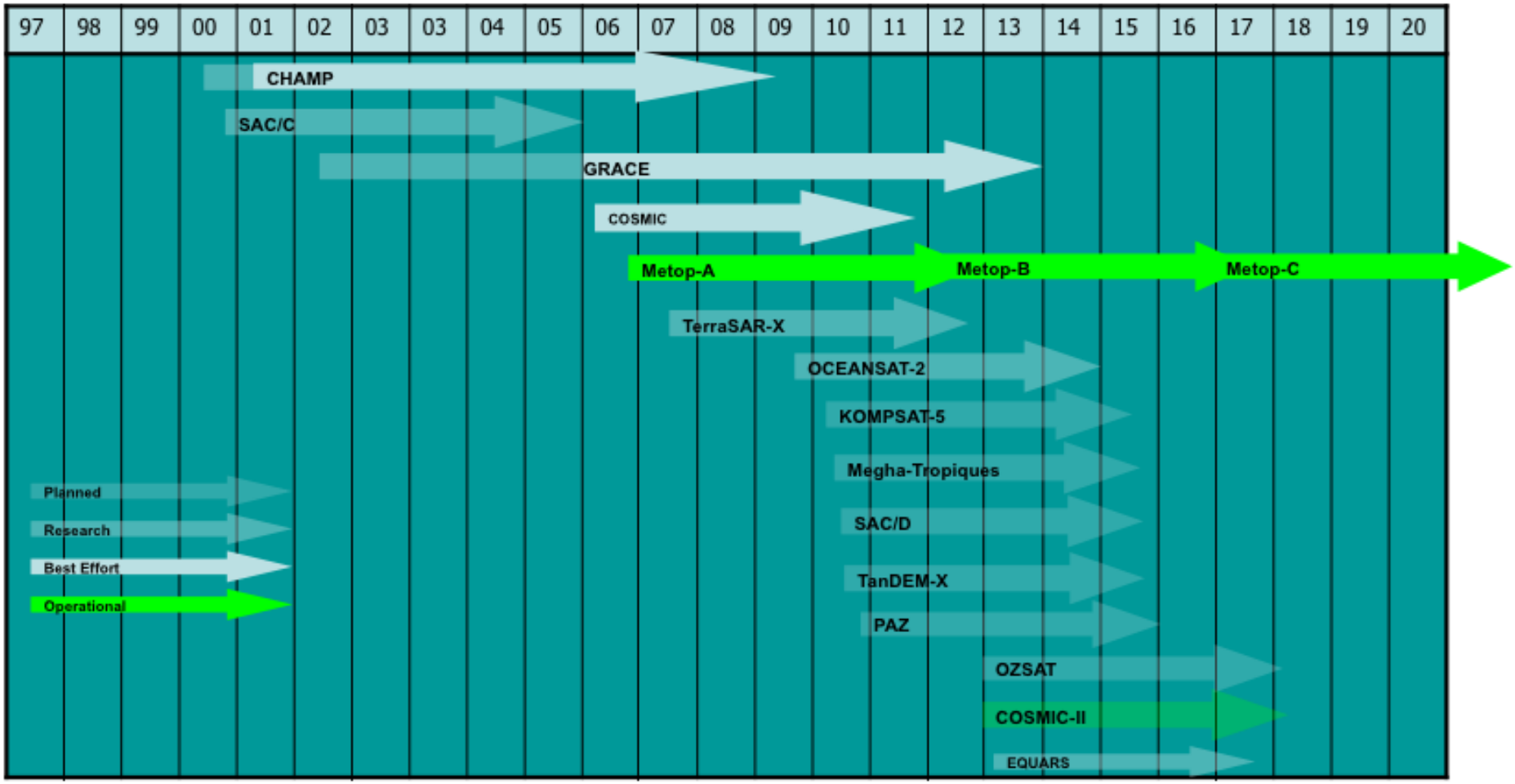
GNSS Radio Occultation Follow-On Plans at NOAA

- NOAA Operational ROFollow-On mission funded in President's FY2011 budget.
- NASA has funded JPL to develop advanced GNSS RO payload.
- UCAR working with NOAA and Taiwan on the planning of a COSMIC-II Mission.
- Preliminary design calls for 12 low Earth orbiting satellites, tracking GPS, GALILEO and possibly GLONASS.
- Will produce more than 8,000 soundings per day.
- Data Latency being studied
- Expected launch in 2014-15
- NOAA also considering RO Data Purchase

Constellation Requirements

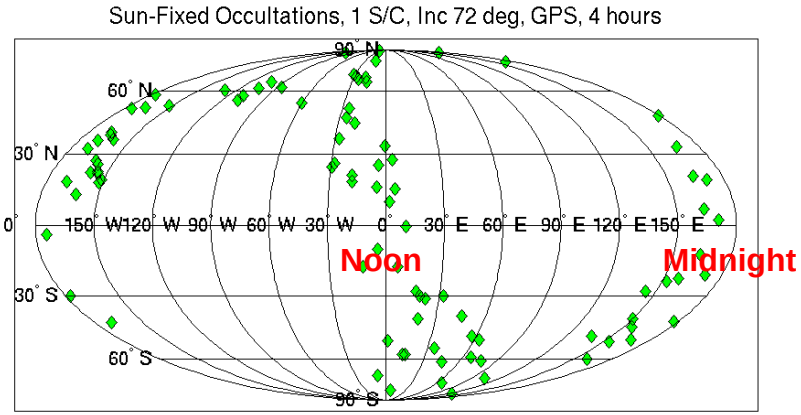
- Uniform RO global sampling
- Uniform RO local time sampling
- Minimize RO data latency
- Minimize deployment time
- Maximize GPS tracking data

GNSSRO Possible Missions

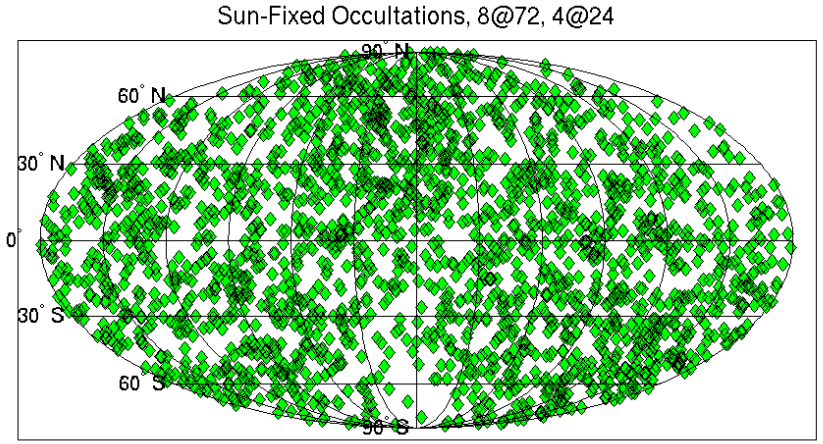


EDP Local Time Coverage in 4 hrs

1 S/C
GPS
4 hrs

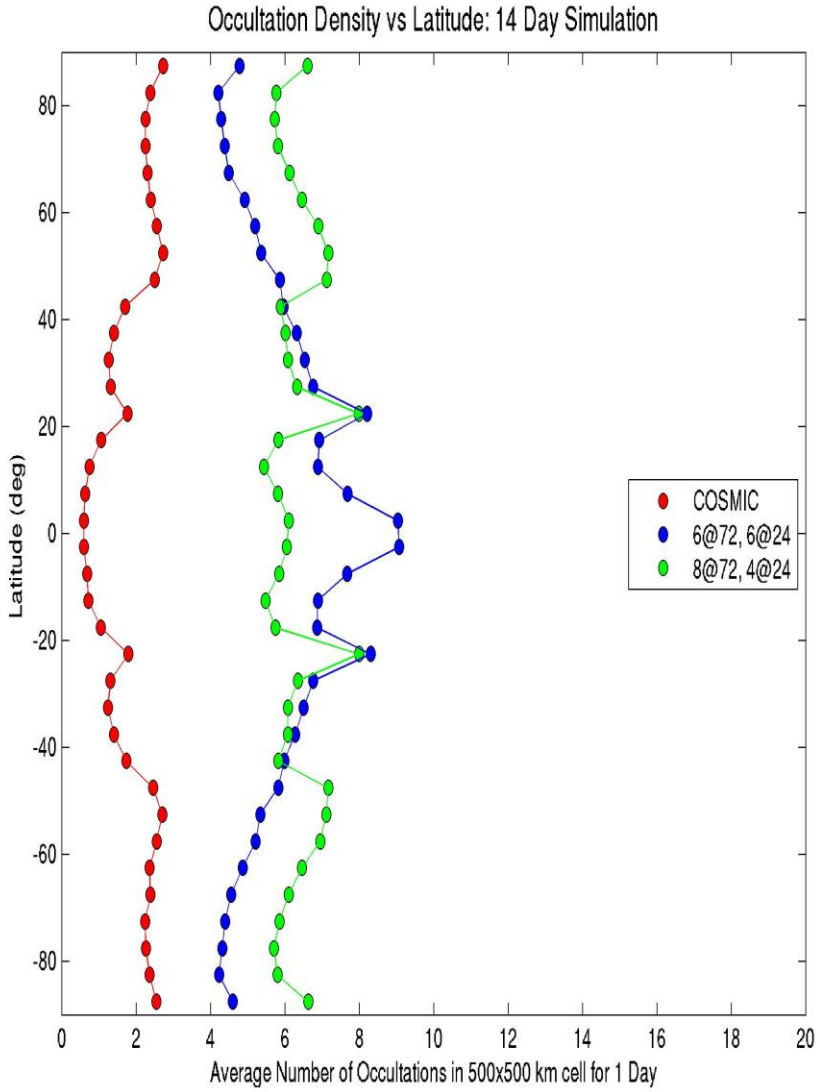


12 S/C,
GPS+Galileo
4 hrs

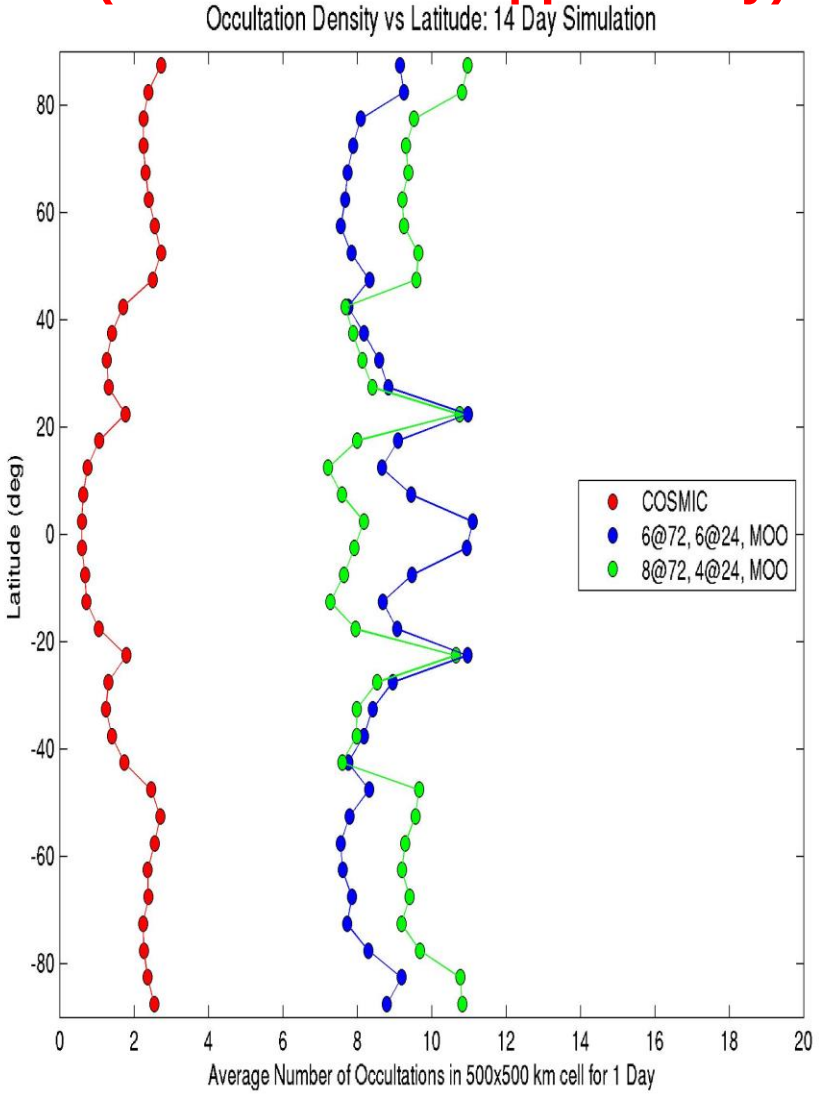


Occultation Density vs. Constellation Options

12 S/C with GPS+Galileo



Add 8 MOOs with GPS (+ Missions of Opportunity)



Average Data Latency with Ground Stations

- **Worst-Case**: Current COSMIC
  - 15 deg elevation cutoff
  - Data to CDAAC = LOS + 4 min
  - CDAAC processing time = 7.5 min
- **Best-Case**: Realistic COSMIC-II
  - 5 deg elevation cutoff
  - Data to CDAAC = AOS + 3 min
  - CDAAC processing time = 5 min

15 sites:
Fairbanks, Tromso, McMurdo, TrollSat, Guam, Hawaii, Vandenberg, Colorado, NewHampshire, DiegoGarcia, England, Thule, Bangalore, Mauritius, Taiwan

Network	LEO Inclination (deg)	Worst-Case Average Latency (min)	Best-Case Average Latency (min)
COSMIC (Fairbanks, Tromso)	72	68	**57**
COSMIC+McMurdo	72	58	**43**
COSMIC+McMurdo+TrollSat	72	44	**32**
15 Stations	72	31	**21**
15 Stations	24	48	**37**

- Satellite-Satellite Comm (TDRSS, InmarSat) Option being considered: ~5-15 min latency

Summary

- COSMIC Space Weather Data Products
  - > 3 Million Absolute TEC data arcs
  - > 2.3 Million EDPs
  - Large amount of scintillation data
  - ~90% available within 3 hrs, ~50% in 1 hr, and ~10% in ½ hr
  - Positive impact on ionospheric and space weather studies
- NOAA moving ahead with GNSS RO Follow-On planning
- NOAA collaboration with Taiwan, 12 satellites launched ~ 2014-15
- ~ 8,000 RO's per day with near uniform geographic and LT sampling
- Data Latency TBD: Ground Stations (~ 30 min ave) vs Sat-Sat Comm (5-15 min)
- NOAA considering RO data purchase

Acknowledgments

- NSF
- Taiwan's NSPO
- NASA/JPL, NOAA, USAF, ONR, NRL
- Broad Reach Engineering

UCAR NSF NASA USAF NOAA NSPO ONR