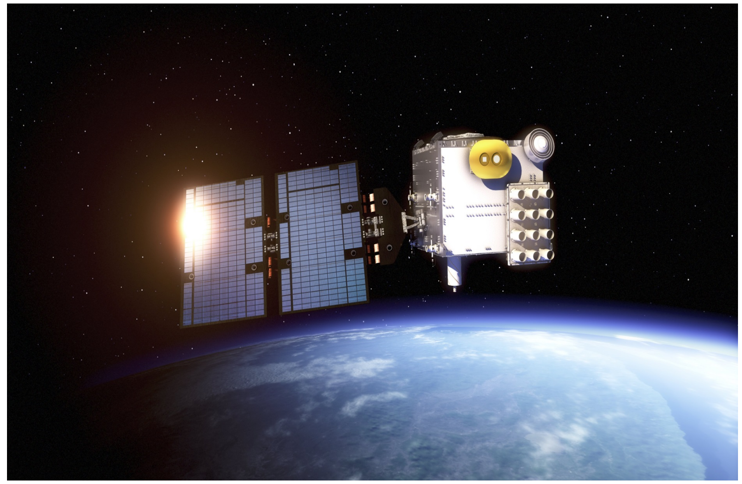


GNSS Radio Occultation Science and Applications

Jan Weiss, Rick Anthes, John Braun, Bill Kuo,
Bill Schreiner, Sergey Sokolovskiy
UCAR COSMIC Program

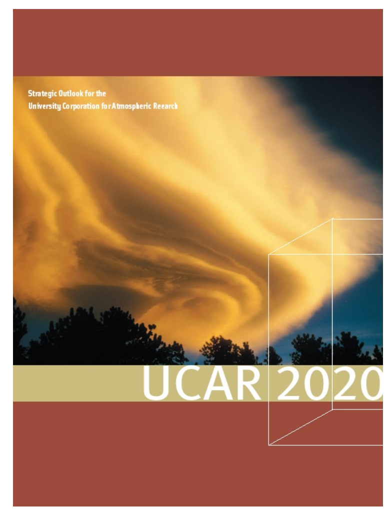
IGS Workshop
February 10, 2016

Outline

- UCAR organization
- GNSS radio occultation overview
- Radio occultation missions
- Impacts on weather prediction
- COSMIC-2
- Interfaces to IGS

UCAR Organization

- University Corporation for Atmospheric Research
- A consortium of 100 North American universities
- Founded in 1960 to create, operate, and manage National Center for Atmospheric Research (NCAR) on behalf of National Science Foundation and the universities
- ~1500 staff including ~800 scientists and engineers
- Science, computational and observational facilities, huge data sets, high-end numerical models of the sun, atmosphere, oceans, coupled climate system
- COSMIC Program
  - ~25 scientists, engineers, programmers, IT, support staff
  - Expertise in ground and space GNSS processing, radio occultation, spacecraft integration/testing, atmospheric, space weather, and climate science



Radio Occultation

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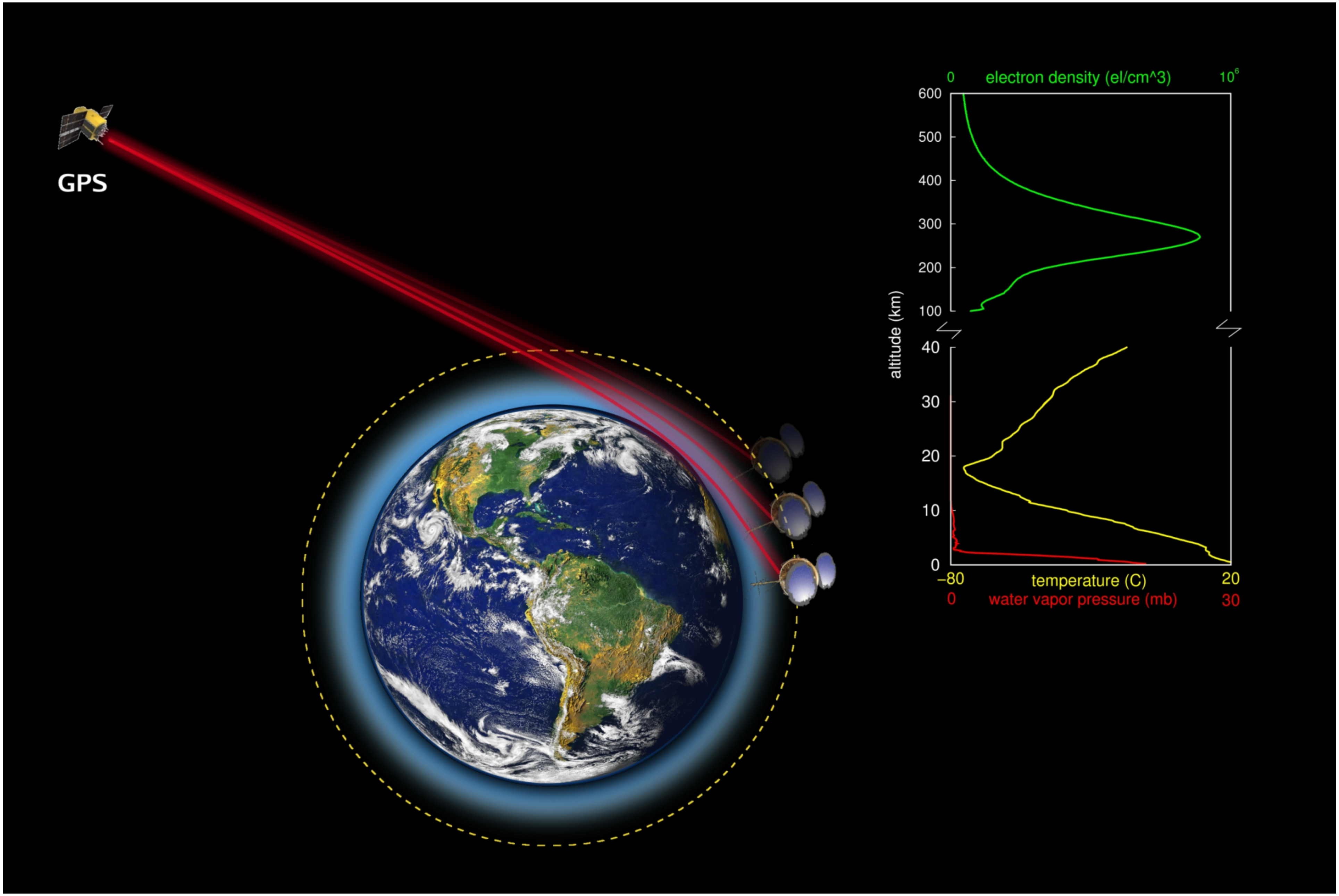
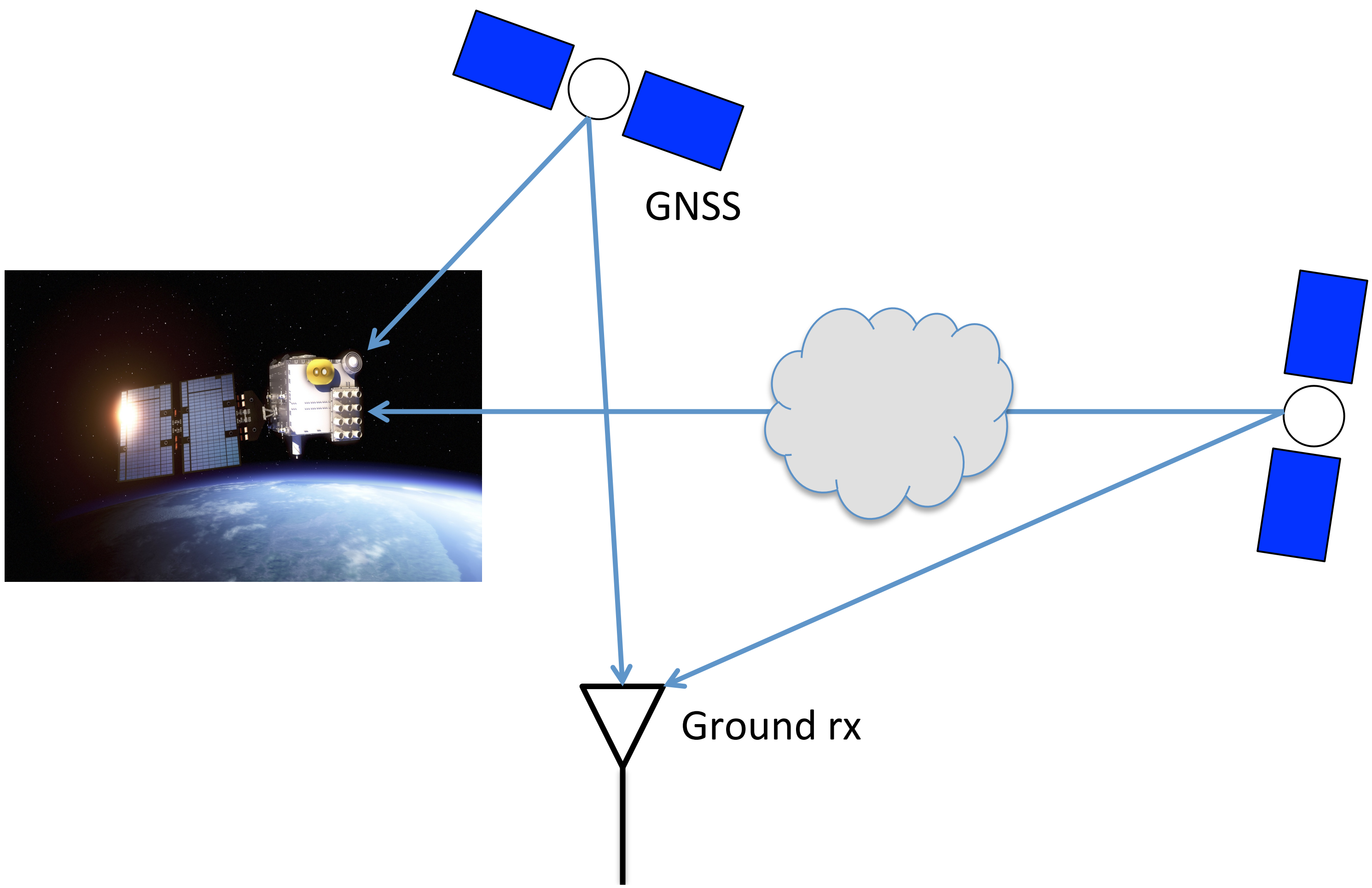
- Radio occultation (RO) technique looks at bending of radio waves traversing an atmosphere
- First applied to planetary atmospheres by teams at Stanford University and JPL with Mariner IV spacecraft (1965)

GNSS Radio Occultation



LEO RO Tracking Configuration

- Upward looking antennas for POD, ionosphere
  - Dual frequency range and phase at 1 Hz
- Fore/aft limb-viewing RO antennas, neutral atmosphere
  - Open loop tracking at 50-100 Hz, contains navigation message bits



Characteristics of RO Data (1/2)

- Limb sounding geometry complementary to ground and space based nadir viewing instruments
- Global coverage
- Profiles ionosphere, stratosphere and troposphere
- High accuracy (equivalent to < 0.5 K; average accuracy < 0.1 K)
- High precision (0.02-0.05 K)
- High vertical resolution (0.1 km near surface – 1 km tropopause)
- Only system from space to profile atmospheric boundary layer (ABL)
- All weather: minimally affected by aerosols, clouds or precipitation

Characteristics of RO Data (2/2)

- Absolute TEC accuracy < 1-3 TECU
- Relative TEC accuracy < 0.3 TECU
- Independent height and pressure
- Requires no first guess sounding
- No calibration required
- Climate benchmark quality – tied to SI standards
- Independent of processing center
- Independent of mission
- No instrument drift
- No satellite-to-satellite bias
- Compact sensor, low power, low cost

Scientific Uses of RO Data

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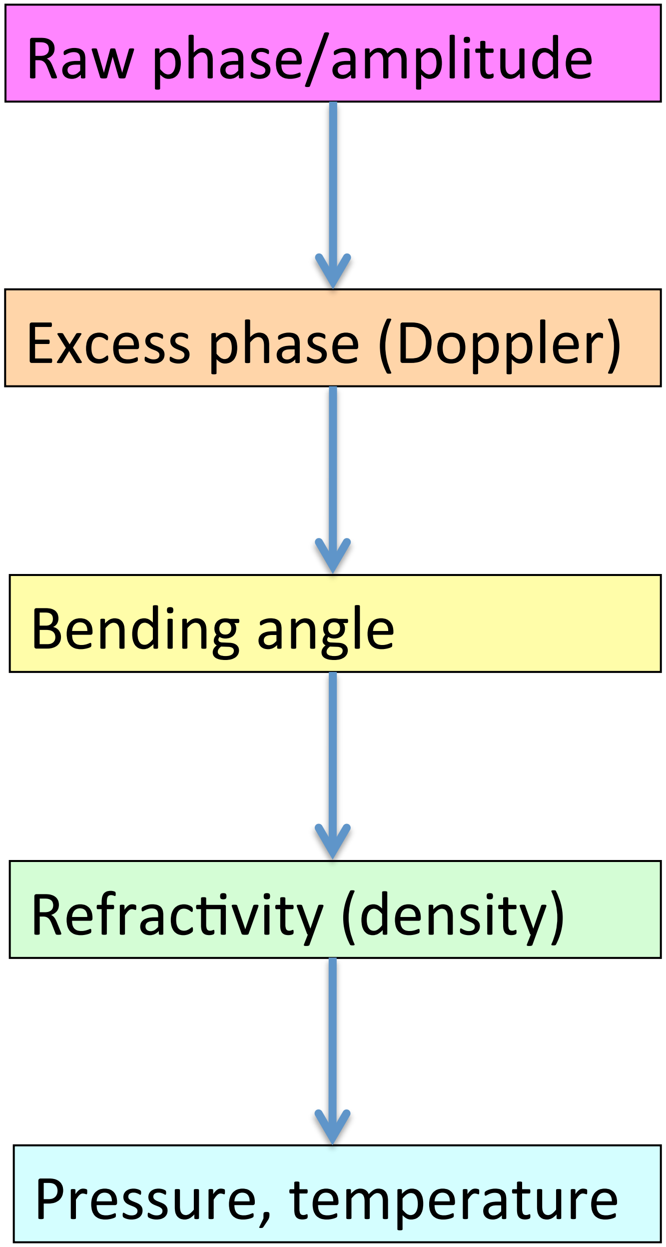
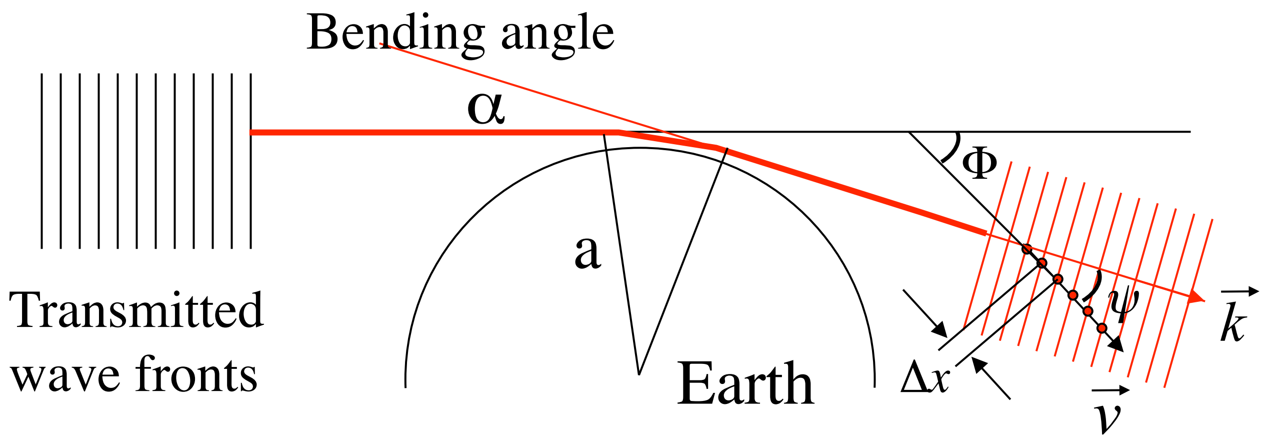
- Weather
  - Improve global weather analyses, particularly over data sparse regions such as the oceans, tropics, and polar regions
  - Increase accuracy of numerical weather forecasts
  - Improve understanding of tropical, mid-latitude and polar weather systems and their interactions
- Ionosphere and Space Weather
  - Observe global electronic density distribution
  - Improve the analysis and prediction of space weather
  - Improve monitoring/prediction of scintillation (e.g. equatorial plasma bubbles, sporadic E clouds)
- Climate
  - Monitor climate change and variability with unprecedented accuracy – world's most accurate, precise, and stable thermometer from space!
  - Evaluate global climate models and analyses
  - Calibrate infrared and microwave sensors and retrieval algorithms

Radio Occultation Processing



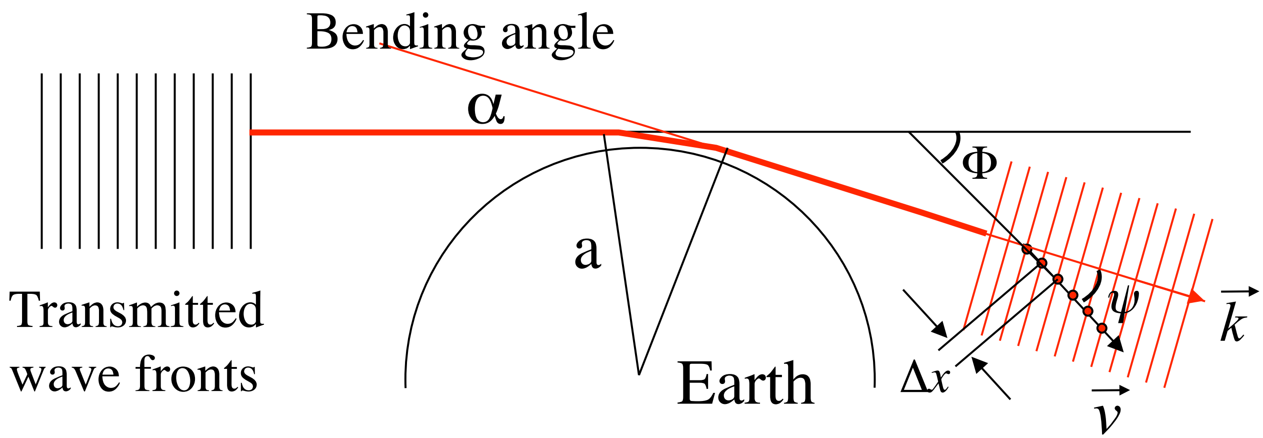
- Precise orbit determination, excess phase computation (extra path length)
- Local transform, no error propagation
- Non-local transform, error propagation downward
- Non-local transform (hydrostatic integration), error propagation downward

Bending Angle from Geometric Optics



- Geometric optics (GO) method uses carrier phase
  - Needs single path propagation
  - Provides accurate solutions in the upper troposphere and above, does not work in lower troposphere
- Requires knowledge of transmitter and receiver position/velocity from precise orbit determination (POD)

Bending Angle from Geometric Optics



- From POD we know the location of source and receiver orbit $\vec{v}$, thus we know Φ
- Measure Doppler shift:

$$f_d = \frac{1}{\Delta t} = \frac{v}{\Delta x} = \frac{v}{\lambda}\cos\psi = f_T \frac{v}{c}\cos\psi$$

- Thus we know ψ and compute the bending angle:

$$\alpha = \Phi - \psi$$

Atmospheric Refractivity

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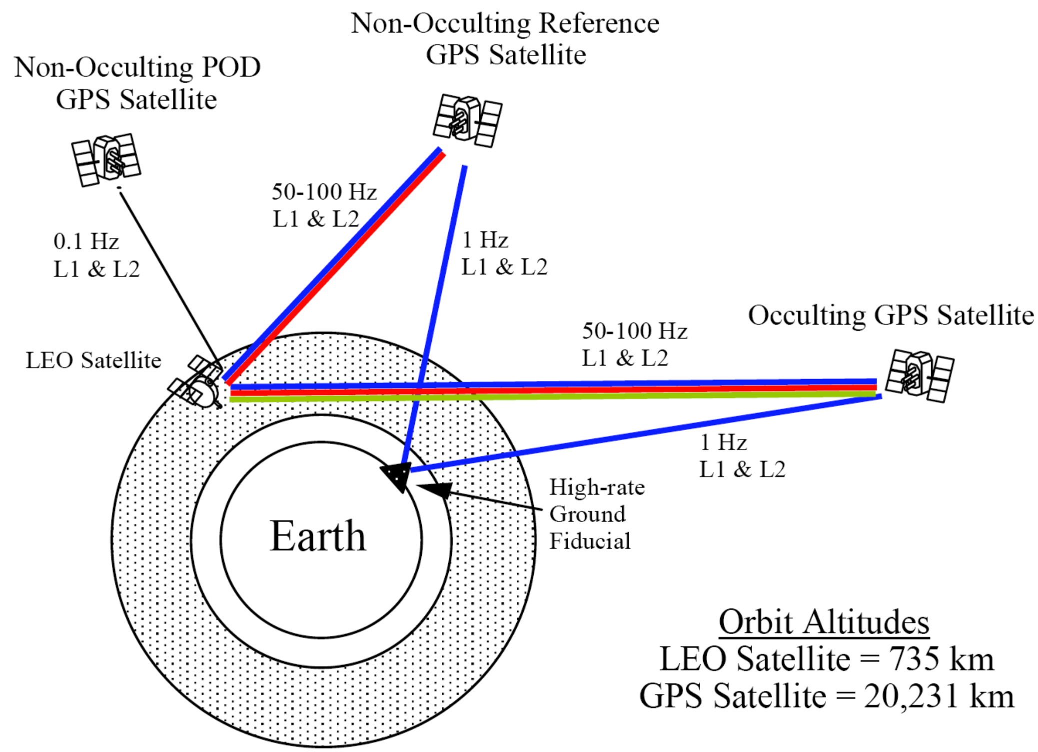
- Function of
  - Pressure (P)
  - Temperature (T)
  - Water vapor (P_W)
  - Electron density (n_e)

$$N = 77.6\frac{P}{T} + 3.73\times10^{-5}\frac{P_w}{T^2} - 4.03\times10^{7}\frac{n_e}{f^2}$$

  - Ionosphere free combinations processed to remove n_e
- Operational weather models ingest bending angles and compute their own N, P, T, P_W

Dealing with Clock Parameters

- Undifferenced
  - Assumes perfect knowledge of LEO clock
  - Use estimated GNSS clocks
  - Lowest noise
- Single difference
  - LEO clock removed
  - Use estimated GNSS clocks
  - Noise from reference link
- Double difference
  - Removes all clocks
  - Highest noise: atmosphere, thermal noise, multipath
- We typically use single difference approach



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UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

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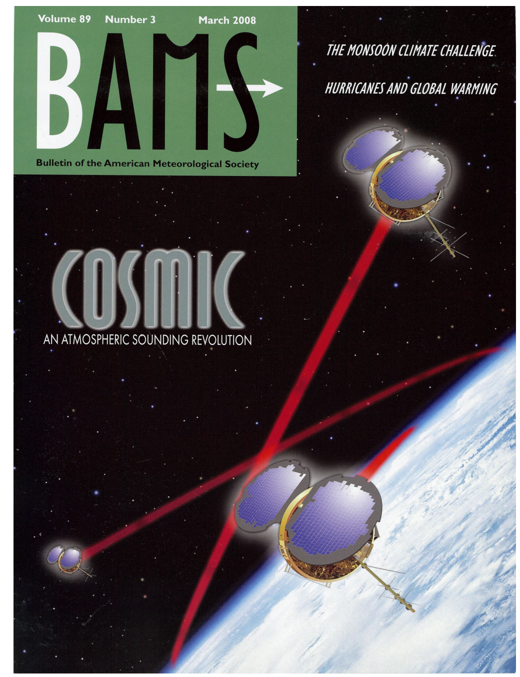
- COSMIC-2
- Interfaces to IGS

COSMIC-1

- Six spacecraft launched April 14, 2006
- Three instruments
  - JPL/BRE Blackjack GPS receiver
  - Tiny Ionosphere Photometer
  - Tri-band beacon (for ionosphere, not used due to interference)
- Global observations of
  - Refractivity
  - Pressure, temperature, humidity
  - Ionospheric electron density
  - Ionospheric scintillation
- Two year mission planned
  - Two satellites still operating (~10 years)

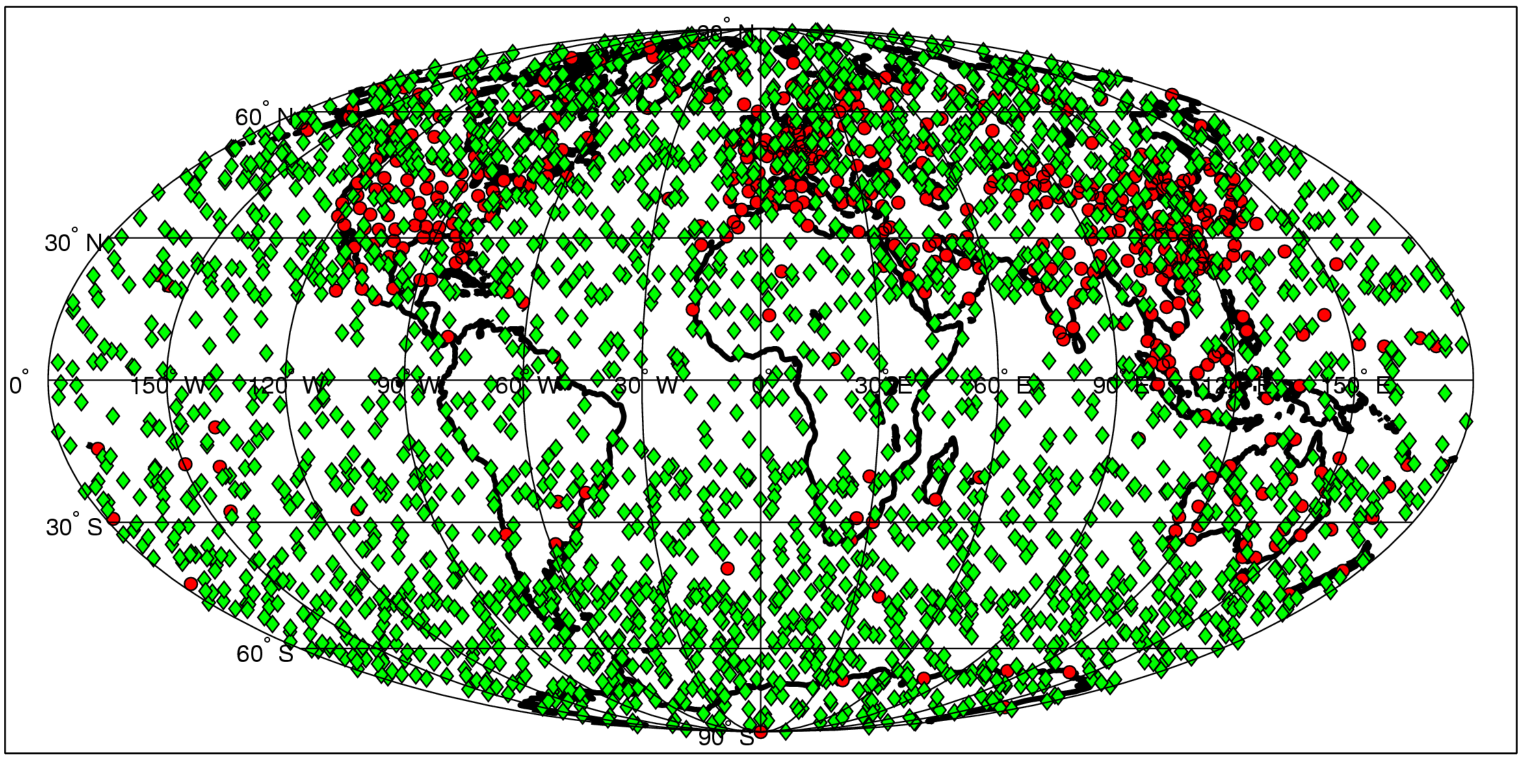


[BAMS March 2008]

COSMIC-1

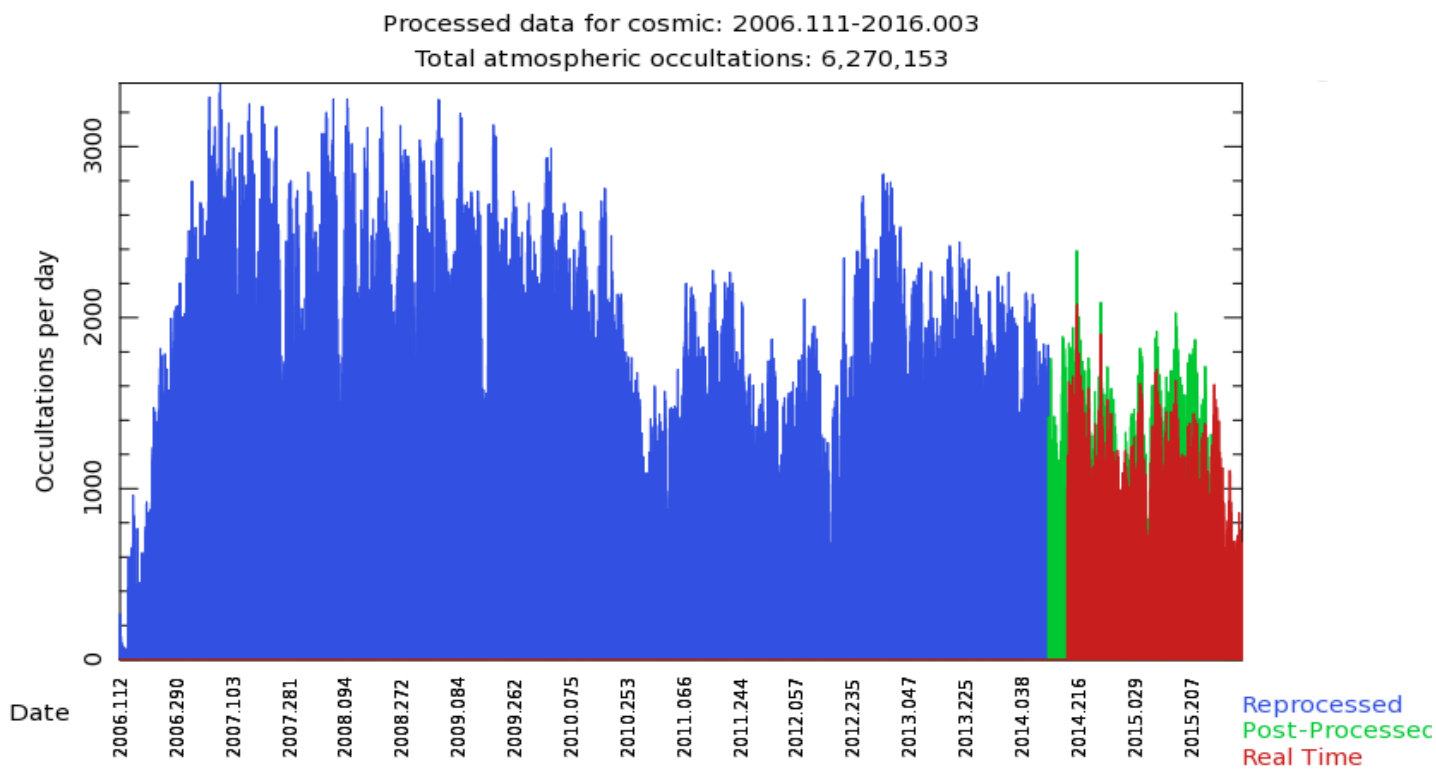
- Spacecraft in 800 km, 72 deg inclination circular orbit
- Occultation (green) and radiosonde (red) locations

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs



COSMIC-1

- > 6 million profiles since 2006



- Two of six satellites still operating nearly 10 years after launch

All RO Missions Processed at UCAR

Mission	Total Atmospheric Occultations	Total Ionospheric Occultations
CHAMP	443911	306416
C/NOFS	150772	0
COSMIC-1 (6 s/c)	6321617	4274341
GPSMET	5002	0
GPSMETAS	4666	0
GRACE	380198	183028
KOMPSAT-5	20974	0
METOP-A	1399120	0
METOP-B	529319	0
SAC-C	353756	0
TerraSAR-X	470326	0
Total	**10079661**	**4763785**

[Status February 4, 2016]

CDAAC

- COSMIC Data Analysis and Archive Center
  - Processing and analysis system for near real-time, post-processing, and reprocessing of GNSS and RO data
    - Data collection, level 0 to level 3 processing, quality control, operations and product monitoring, product delivery, data archiving
  - Developed since late 1990s, initial capabilities in 2002, quasi-operational since 2006 (delivering to global weather centers, 99.7% availability)
  - Research community data and product access via FTP and website
    - > 3300 users from 86 countries

CDAAC Operations Diagram

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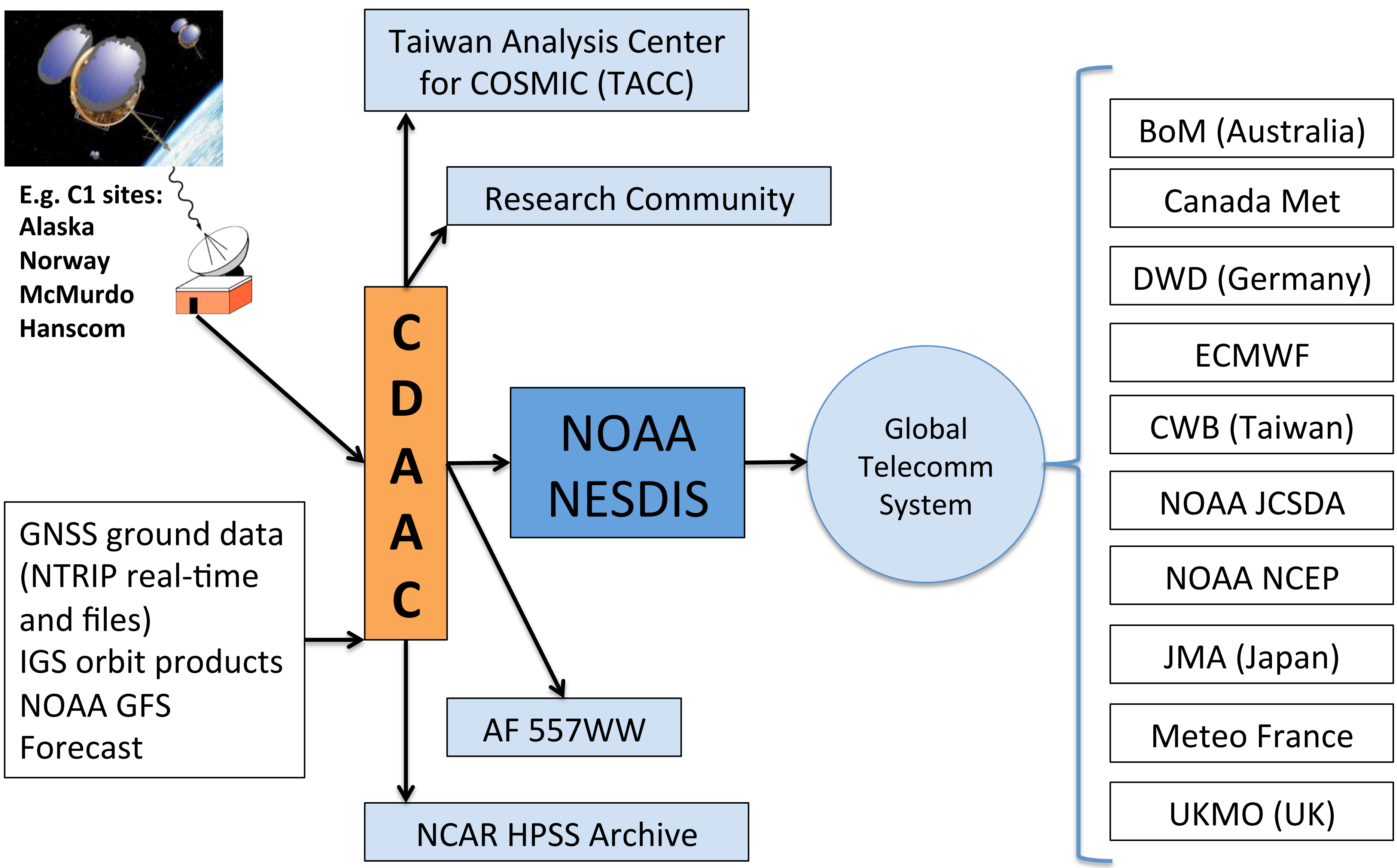

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ECMWF Implementation of GPS RO

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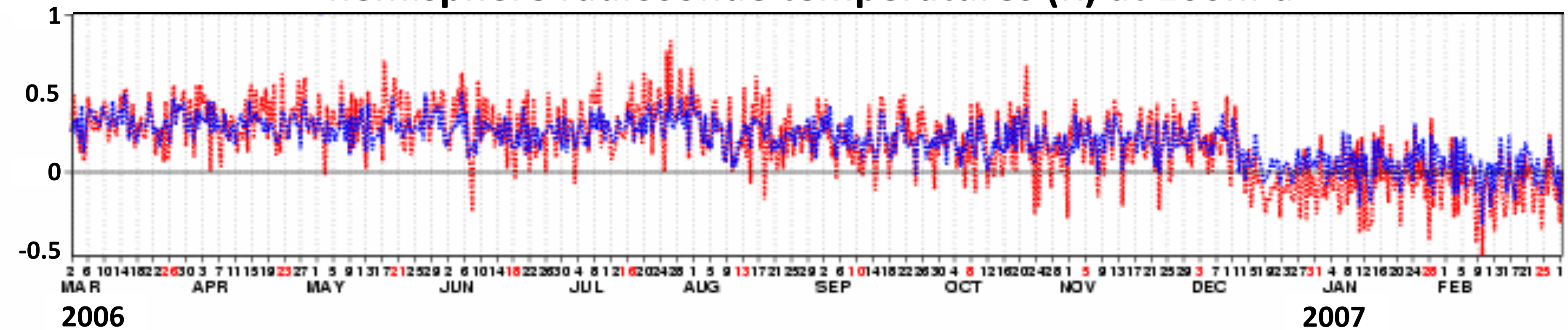
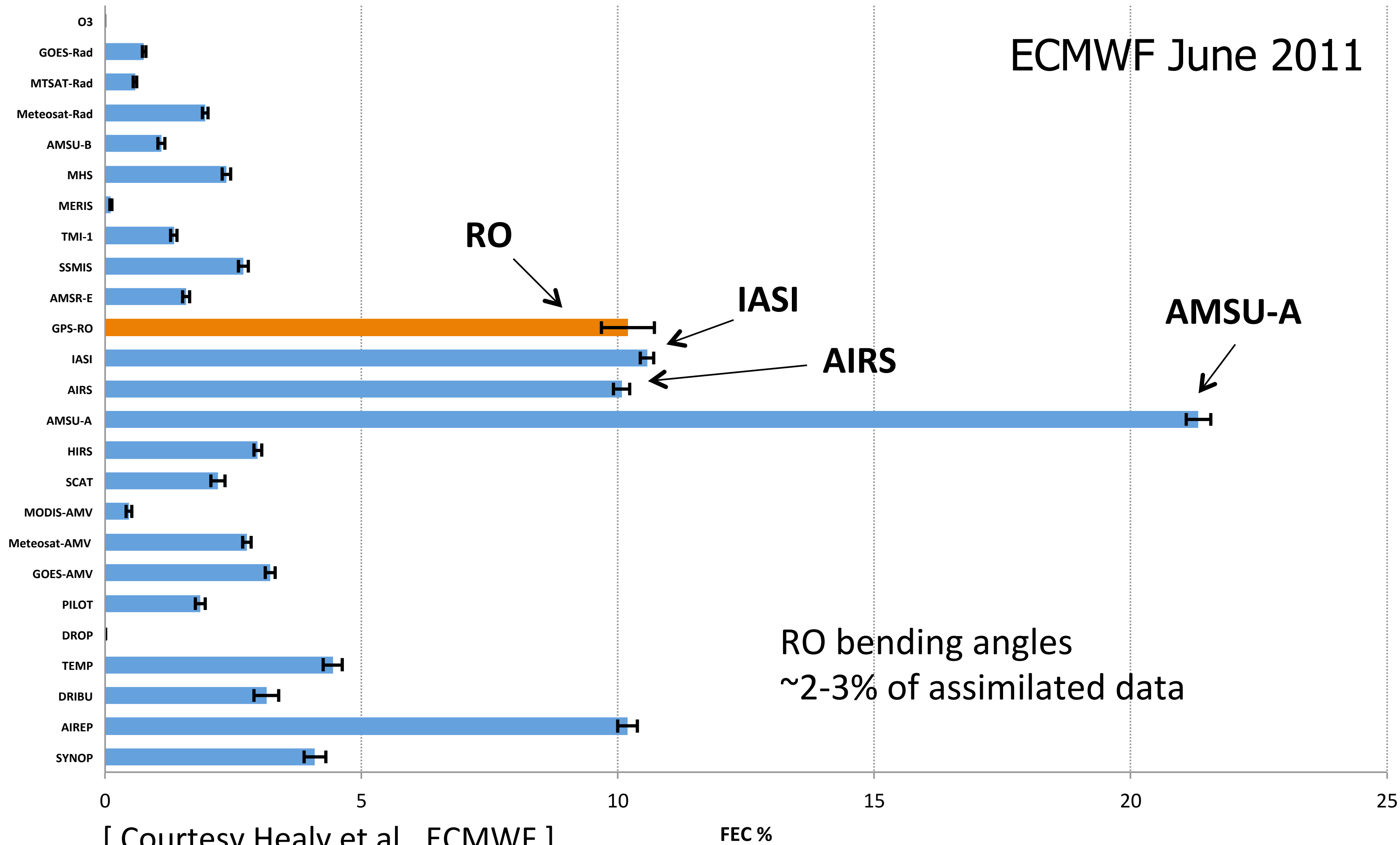
Mean departures of analysis (blue) and background (red) from southern hemisphere radiosonde temperatures (K) at 100hPa



- Clear improvement in time series for operational ECMWF model
- Initial operational implementation (Dec 6, 2006) represented a conservative use of data
  - No measurements assimilated below 4 km, no rising occultations
- Nov 6, 2007 operational assimilation of rising and setting occultations down to surface

Reduction in Forecast Error

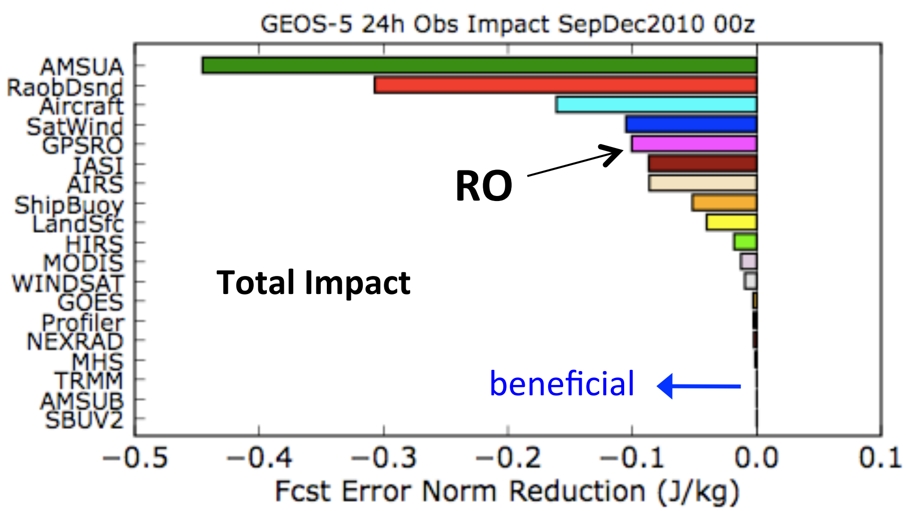


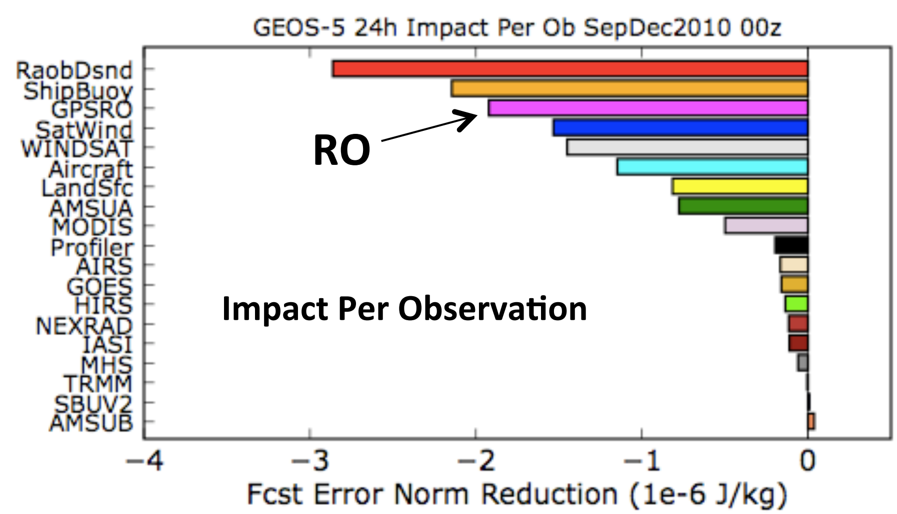
[Courtesy Healy et al., ECMWF]

- RO typically in top five contributing systems

RO Reduction in Forecast Error

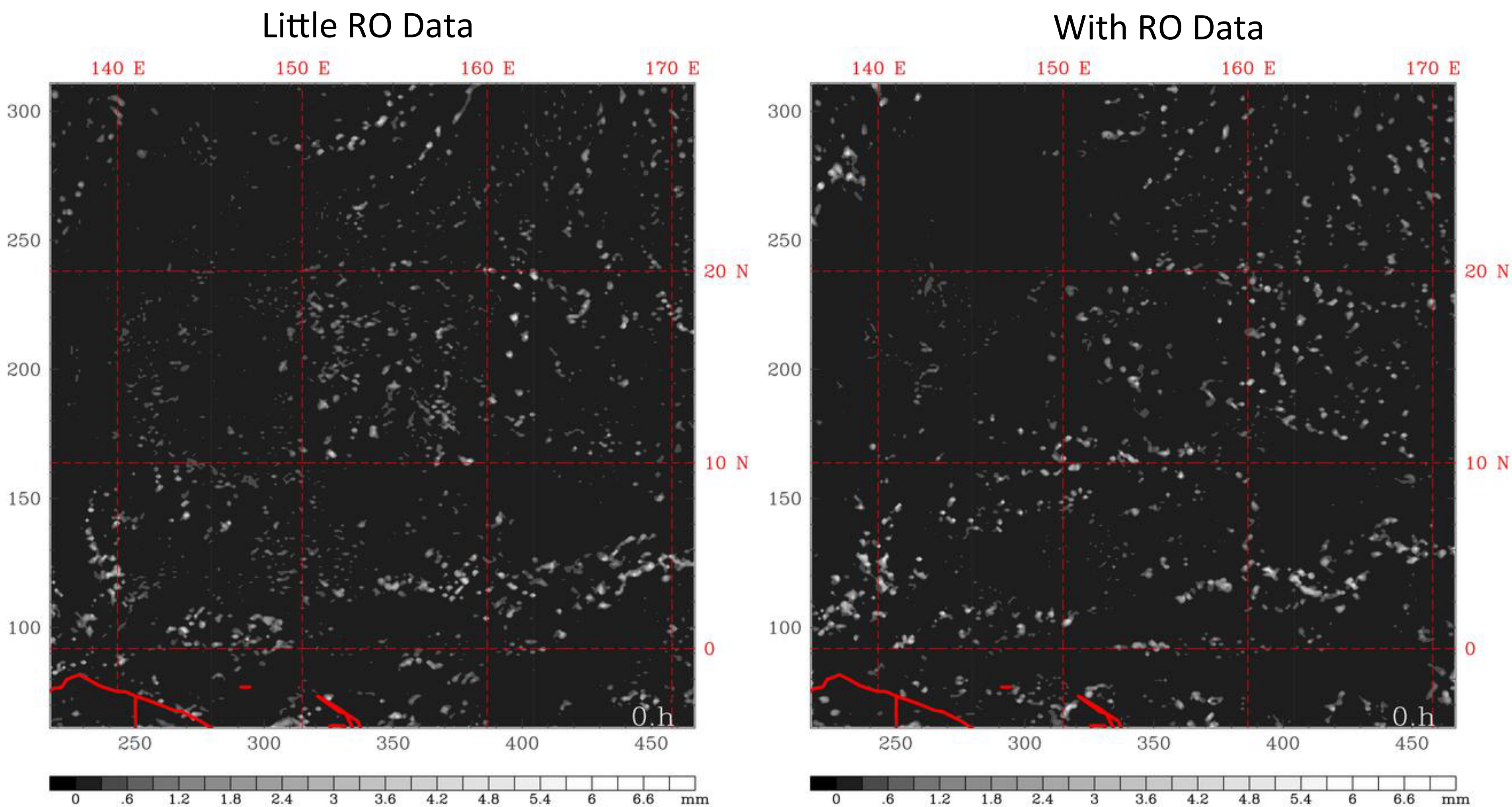
- NCEP study on impacts to Goddard Earth Observing System (GEOS) Model v5
  - Study period Sep-Dec 2010
  - GPS RO 5th most significant contributor, 3rd most impact per observation
  - Highlights observation gap as COSMIC-1 observations decline





Typhoon Nuri (2008)

- NCAR Weather Research and Forecast model after 3 days of data assimilation with and without GPS RO
  - Recent study by Kuo and Chen (UCAR)



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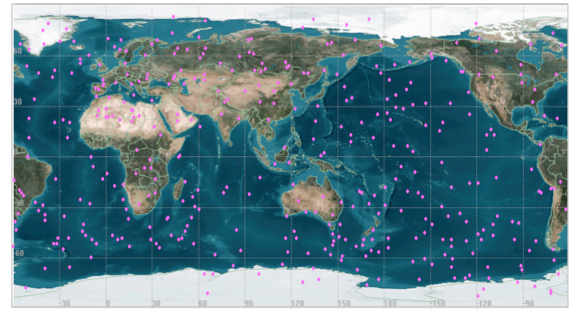
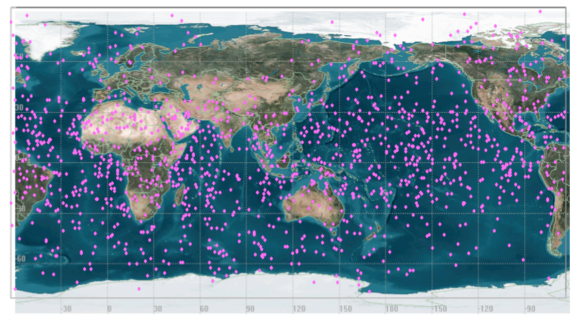
COSMIC-2 Overview

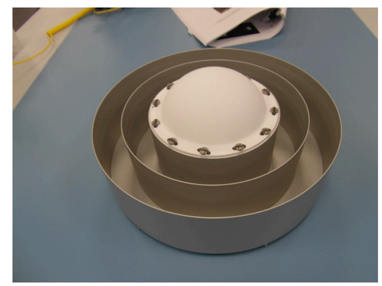
- US (NOAA, AF) and Taiwan (NSPO) partnership
- UCAR manages project on behalf of NOAA and provides operational data processing center
- Two sets of satellites
  - COSMIC-2 Equatorial
    - Launching Q1 2017
    - 6 satellites, low inclination (24 deg) at 520 km
  - COSMIC-2 Polar
    - Estimated launch ~2019 (not fully funded)
    - 6 satellites, high inclination (72 deg) at 800 km
  - Expect > 10000 RO soundings/day, 30 minute average latency
- GNSS payload
  - JPL/BRE TriG receiver, 2 POD choke-ring antennas, 2 phased array RO antennas, GPS +GLONASS
    - GPS L1C/A, L2P, L2C; GLONASS L1C/A, L2C/A
- Secondary payloads are ion velocity meter, tri band RF beacon, laser retro reflector

FORMOSAT-3 Occultations – 3 Hrs Coverage



FORMOSAT-7 Occultations – 3 Hrs Coverage





COSMIC-2 Overview

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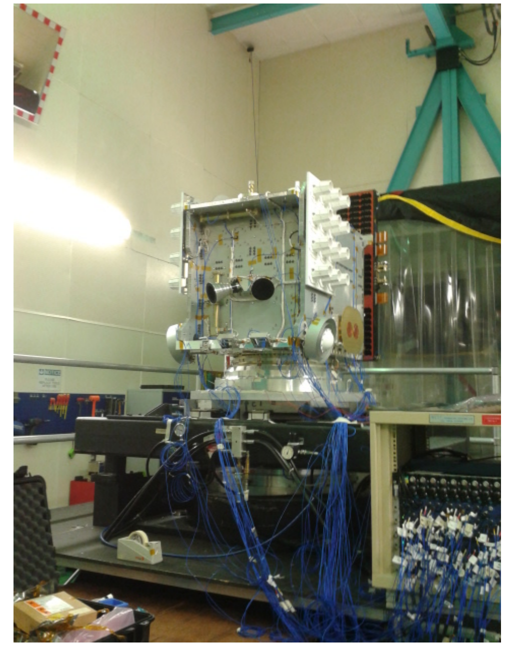
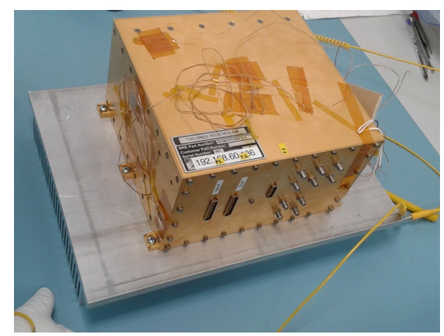
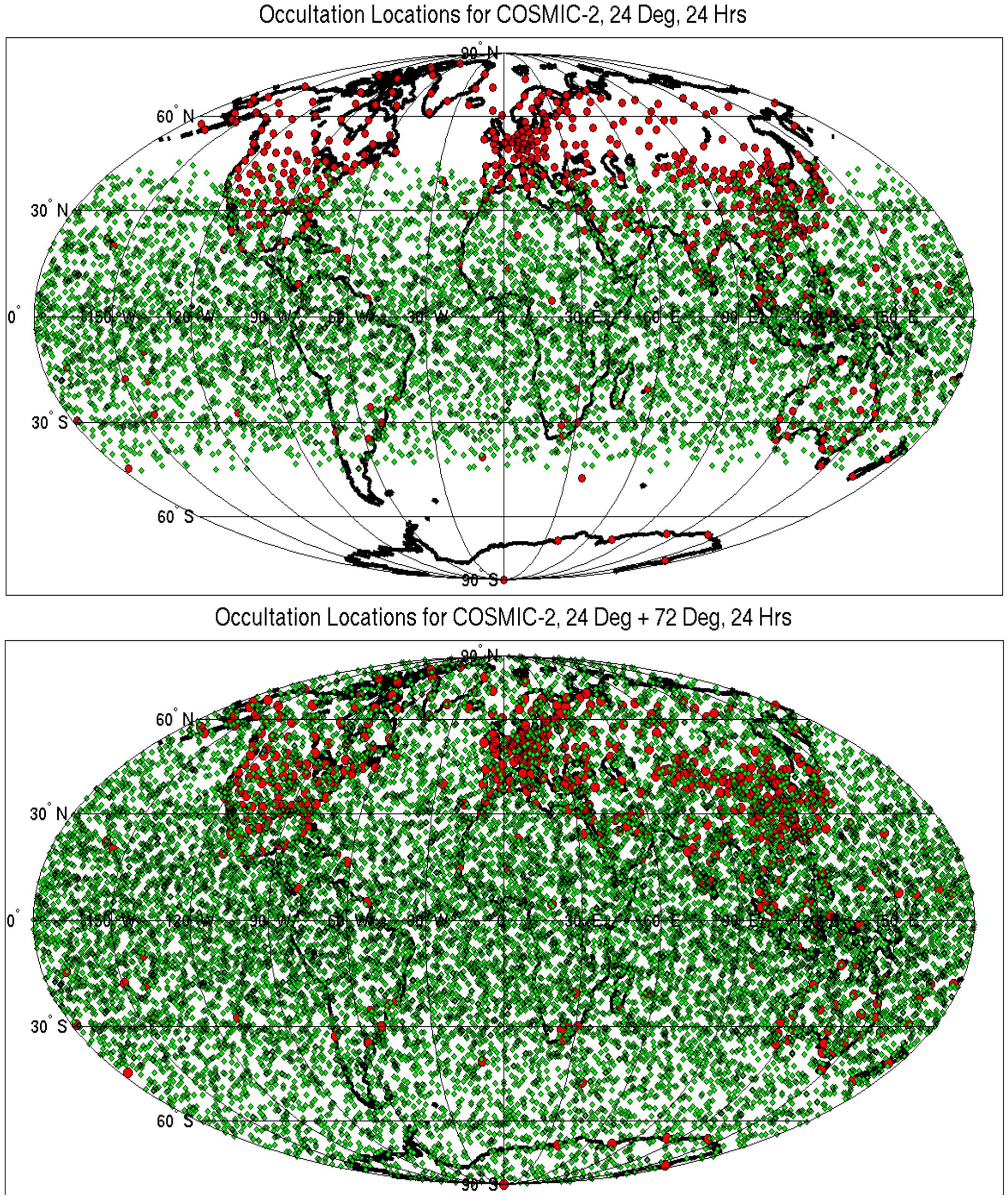
- Surrey Space Technology spacecraft bus
  - ~300 kg
  - 2x star camera, 2x sun sensor, 3 axis stabilized
  - Significant improvement over COSMIC-1
- First satellite assembled and tested in UK, remaining 5 in Taiwan
- Assembly/test of 5 satellites complete
- Launch on SpaceX Falcon Heavy from Kennedy Space Center
- NSPO will manage on-orbit satellite operations
- Post-launch orbit configuration
  - 800 km initial altitude, then reposition one at a time to 520 km
  - Transition takes 4-5 weeks
  - Transition at 12-16 week intervals over 18 months
  - Close proximity for first 1-2 months supports cal/val





COSMIC-2 Overview

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH



CDAAC Enhancements for COSMIC-2

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- Enhanced data management system
  - Coordinates downlink scheduling and telemetry data transfer
  - 9 downlink sites, 2 with uplink capability
- GNSS (GPS + GLONASS)
- Low latency processing to meet 30 minute neutral atmosphere retrieval requirement
  - Drives 30 sec GNSS clock estimation at 10 minute cadence
- IVM processing and product generation
- Redundant archive systems

CDAAC Enhancements for COSMIC-2

- Geographically separated processing centers
  - NCAR Mesa Lab
    - Backup datacenter with operational string, development and staging systems
  - NCAR Wyoming Supercomputing Center
    - Primary datacenter running two operational strings
    - Redundant power grid and Internet backbone connections, fiber optic network to ML

GNSS Ground Network

- Ground based GNSS observations for transmitter clock determination
  - GPS + GLONASS
  - 10 minute cadence
  - 30 sec estimation interval (nominal)
  - Ultra-rapid orbit predicts
  - Bernese GNSS Software
- Navigation data messages
  - Raw 50bps messages
  - Nav bits must be removed from open loop RO tracking

GNSS Ground Network

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- Utilizing real-time streams provided by several partner agencies
  - NTRIP and manufacturer specific formats
  - Casters and direct connections
- Installing sub-network of geodetic GNSS receivers in collaboration with partners
  - ~12 sites planned by end of this year
  - Replaces and enhances legacy "bit grabber" network
  - Will provide data to IGS community as NTRIP streams and RINEX files

Darwin Downlink Station

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- NOAA/UCAR/Bureau of Meteorology partnership
- Installed October 2015

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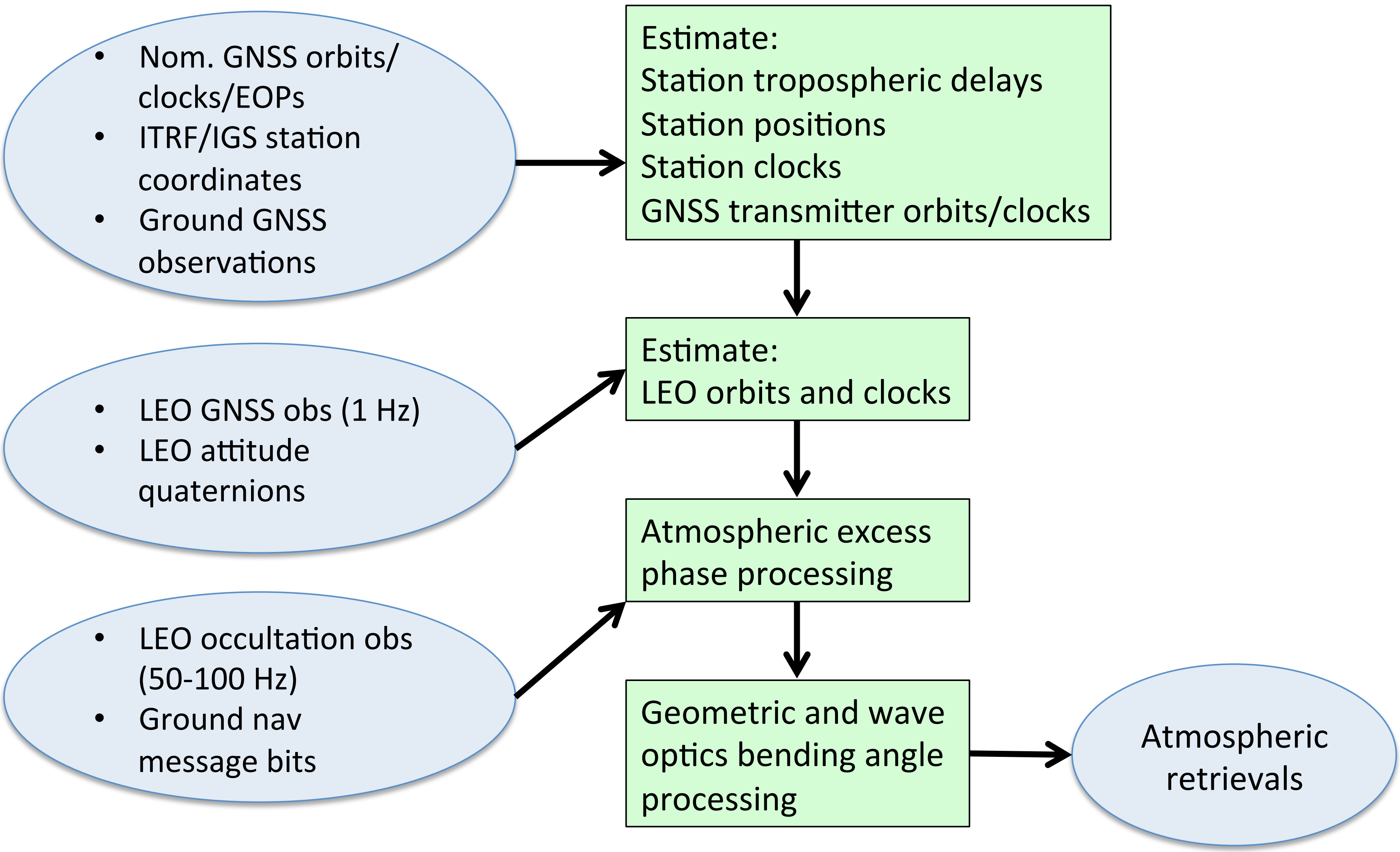
RO Processing Overview



IGS Interfaces

- Significant contributions by IGS and supporting agencies
  - Orbit/clock/EOP products
  - GNSS observations
    - Real-time streams contributed by many agencies
  - IGS realization of ITRF
  - Products/data used for validation, research
- COSMIC Program wishes to engage with IGS more in the future
  - Contributing GNSS observation data, navigation bits
  - Orbit/clock/troposphere products

Acknowledgements

UCAR
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NSPO

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

NASA

NSF

SURREY
SATELLITE TECHNOLOGY LTD

AIUB

RÉSEAU Banian
STATIONS GPS PERMANENTES
NOUVELLE-CALÉDONIE

DITTT
Direction des Infrastructures, de la Topographie et des Transports Terrestres

Bundesamt
für Kartographie
und Geodäsie

CISL
Computational & Information Systems Lab

EUMETSAT

GFZ
Helmholtz Centre
POTSDAM

Australian Government
Geoscience Australia

IGN

IGS
INTERNATIONAL
GNSS SERVICE

ILRS

ipma
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mar e da atmosfera

Land Information
New Zealand
Toitū te whenua

SURVEY OF ISRAEL

UPF
UNIVERSITÉ
DE LA POLYNÉSIE FRANÇAISE

NWSC NCAR-Wyoming
Supercomputing Center

UNAVCO