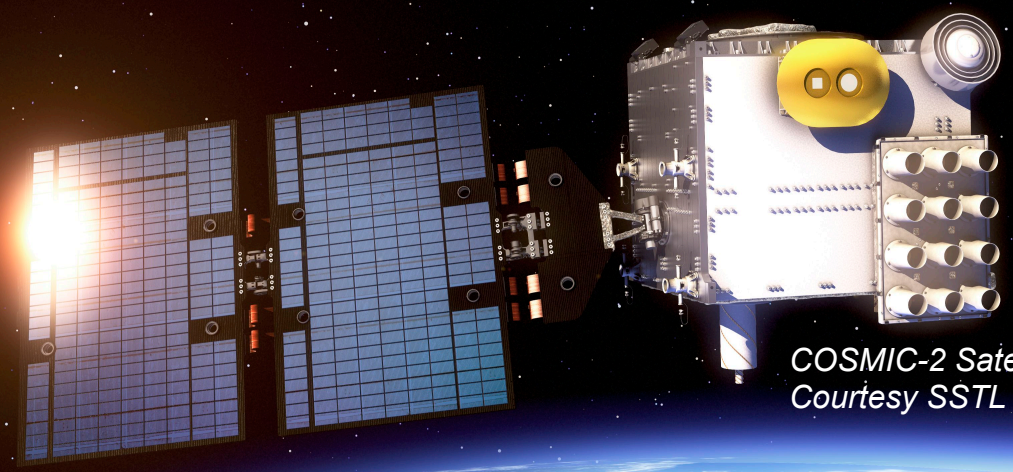
Overview of GPS Radio Occultation, COSMIC, and COSMIC-2

Bill Schreiner, schrein@ucar.edu
UCAR COSMIC Program
Mar 23, 2018



COSMIC-2 Satellite
Courtesy SSTL

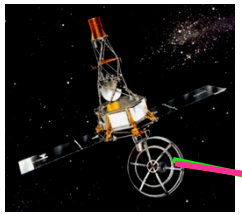
www.cosmic.ucar.edu

Outline

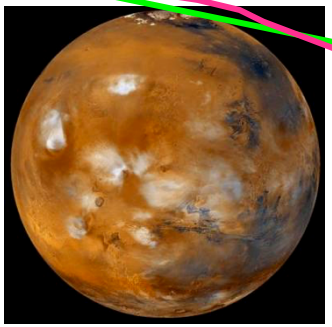
- Overview of the GNSS radio occultation technique
- COSMIC Overview
- Scientific application of COSMIC data for research and operations
- COSMIC-2 Overview
- Summary

History of Radio Occultation

Radio Occultation (RO) was pioneered by NASA/JPL and Stanford in the 1960's to study planetary atmospheres.
Launched a space probe from Earth to Mars and sent a known radio frequency back to Earth.



Mariner IV
July 1965



As the signal grazes the planet's Limb it's radio signal is occulted (thus radio occultation)

If the planet has no atmosphere the radio signal received on Earth will travel on a straight line

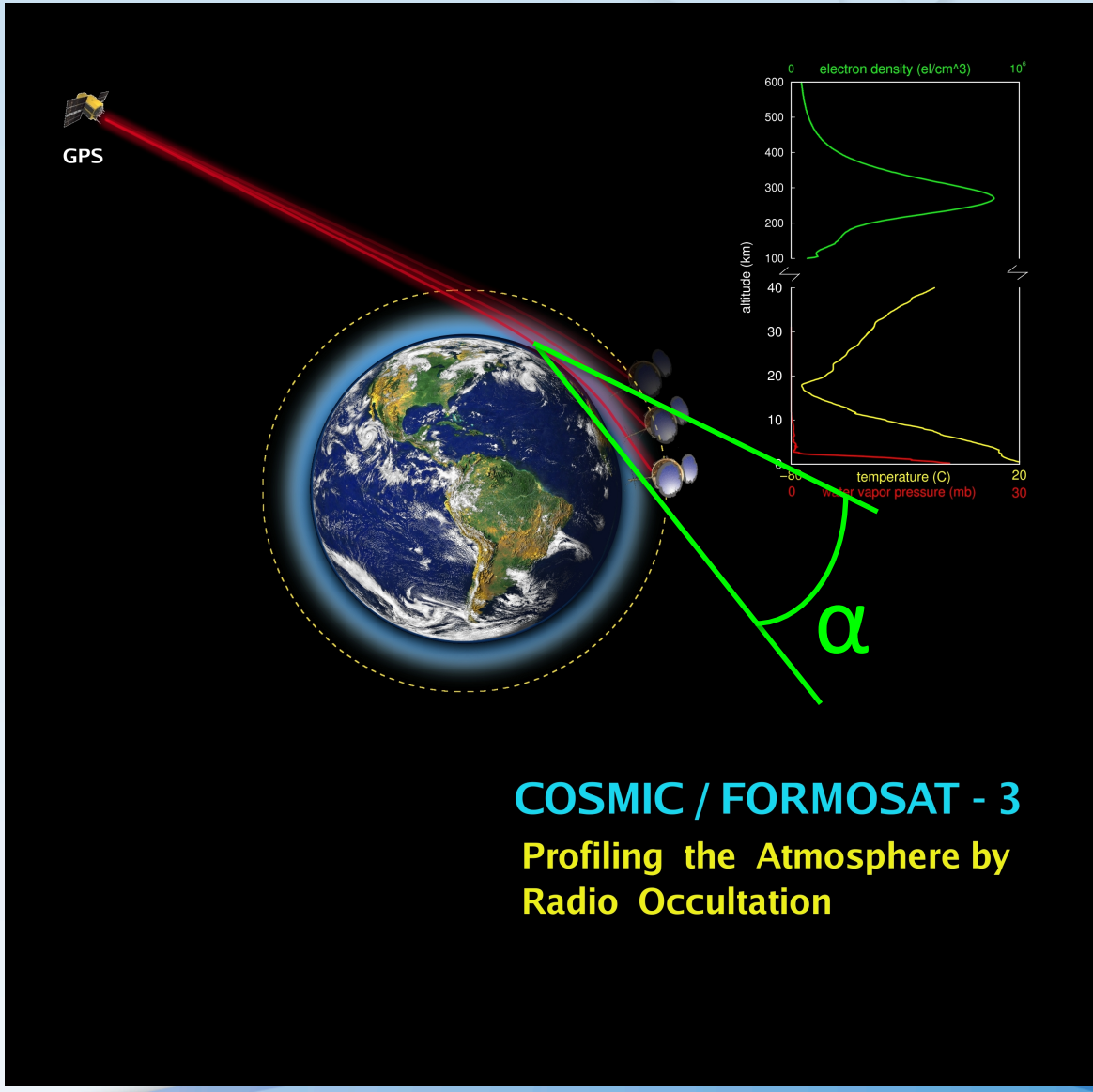
…. but if there is an atmosphere the ray will be bent and the Doppler shift will be noticeably different!

GPS Radio Occultation

GPS RO is a new method (first demonstrated in 1995 by UCAR) for performing atmospheric measurements on Earth.

As a satellite in low-Earth orbit carrying a radio receiver passes behind Earth, the radio waves for two L-band frequencies (L1 and L2) from a GPS satellite pass through the atmosphere and are slowed and bent along the way.

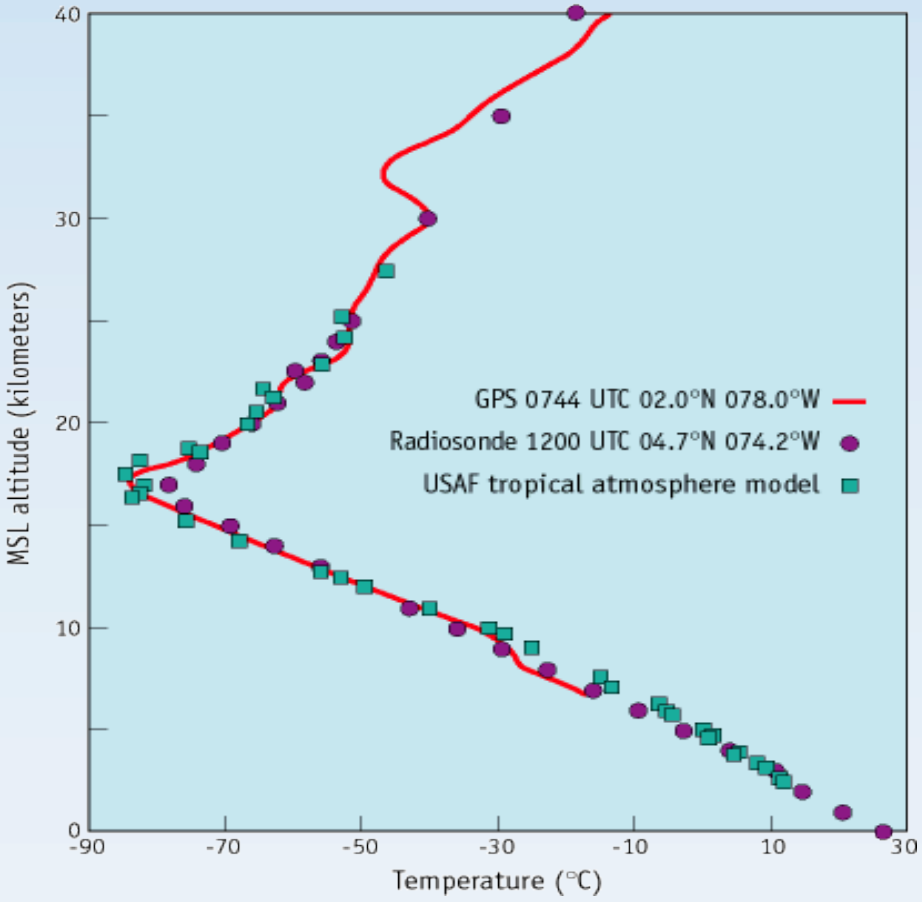
The amount of bending, depends on the temperature and water vapor in the lower atmosphere and the electron density in the ionosphere.



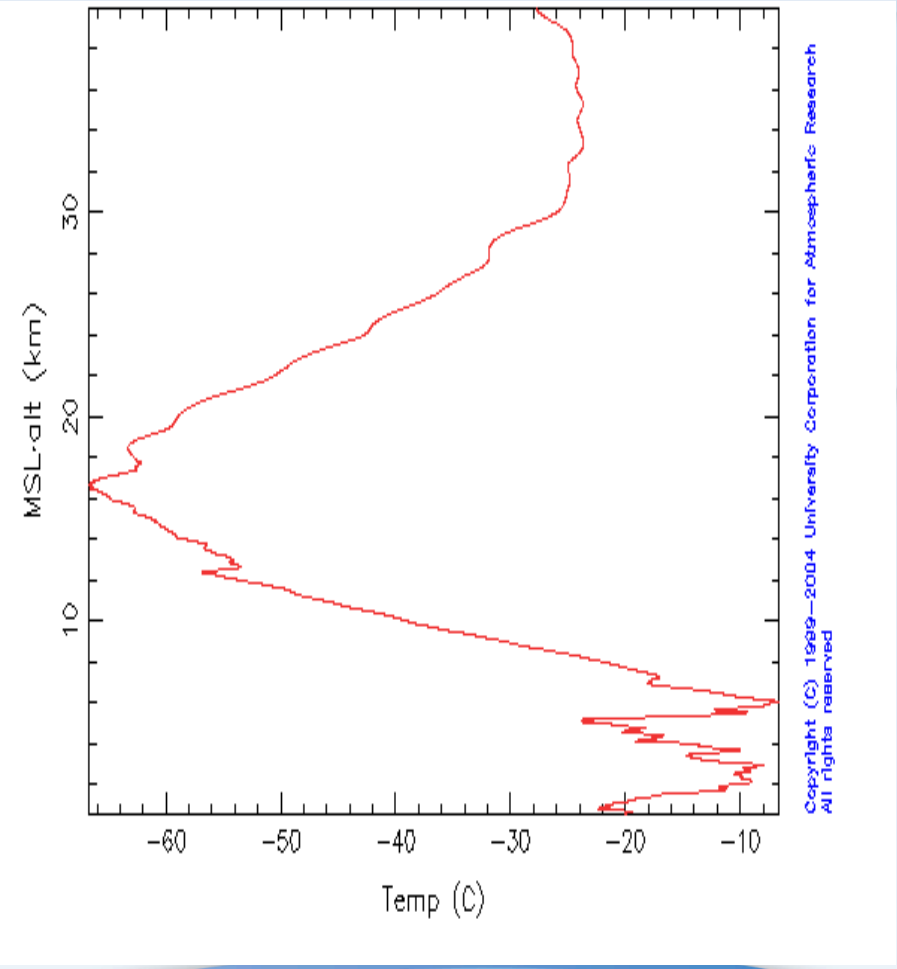
UCAR COMMUNITY PROGRAMS
www.ucp.ucar.edu

Initial GPS RO Soundings from GPS/MET and COSMIC

GPS/MET
The first GPS RO sounding of Earth,
UCAR, Apr 16, 1995



COSMIC
The first COSMIC Sounding,
UCAR, Apr 21, 2006



UCAR COMMUNITY PROGRAMS
www.ucp.ucar.edu

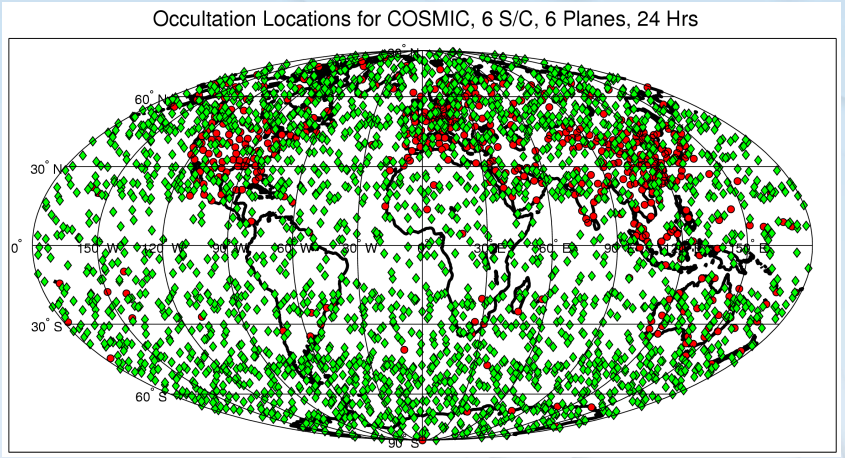
Characteristics of RO Data

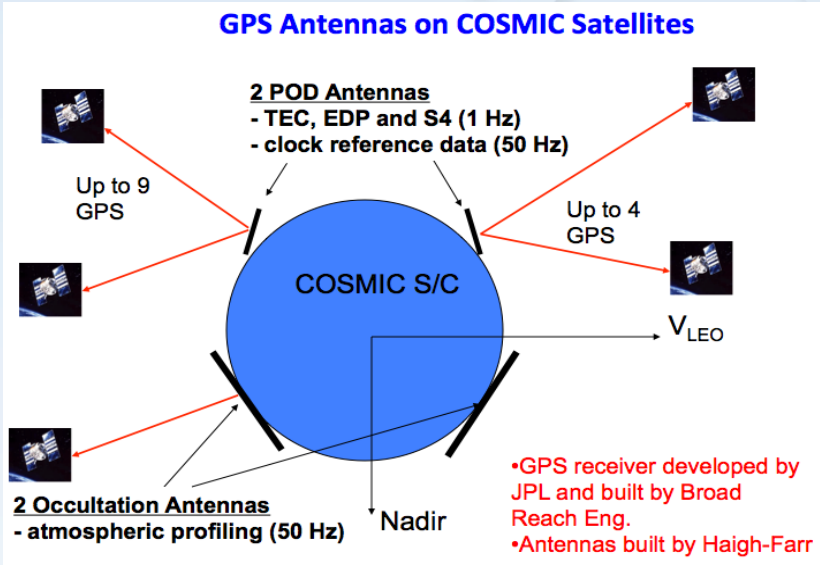
- Limb sounding geometry complementary to ground and space nadir viewing instruments
- Global coverage
- Profiles ionosphere, stratosphere and troposphere
- High accuracy (equivalent to <0.5 K; average accuracy <0.1 K)
- High precision (0.02-0.05 K)
- High vertical resolution (0.1 km near surface – 1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

All of these characteristics have been demonstrated in peer-reviewed literature.

COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate)

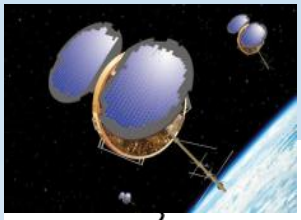
- US/Taiwan Collaboration
- 6 Satellites launched in April 2006
- Three instruments:
  - GPS receiver, TIP, Tri-band beacon
- Weather + Space Weather data
- Global observations of:
  - Bending angle, Refractivity
  - Pressure, Temperature, Humidity
  - Ionospheric Total Electron Content (TEC) and Electron Density
  - Ionospheric Scintillation
- Demonstrate quasi-operational GPS sounding with global coverage in near-real time





UCAR COMMUNITY PROGRAMS
www.ucp.ucar.edu

COSMIC Operations Diagram



E.g. C1 sites:
Alaska
Norway
McMurdo
Hanscom

Taiwan Analysis Center for COSMIC (TACC)

Research Community

CDAAC

NOAA NESDIS

Global Telecomm System

BoM (Australia)

Canada Met

DWD (Germany)

ECMWF

CWB (Taiwan)

NOAA JCSDA

NOAA NCEP

JMA (Japan)

Meteo France

UKMO (UK)

GNSS ground data (NTRIP real-time and files)
IGS orbit products
NOAA GFS Forecast

AF 557WW

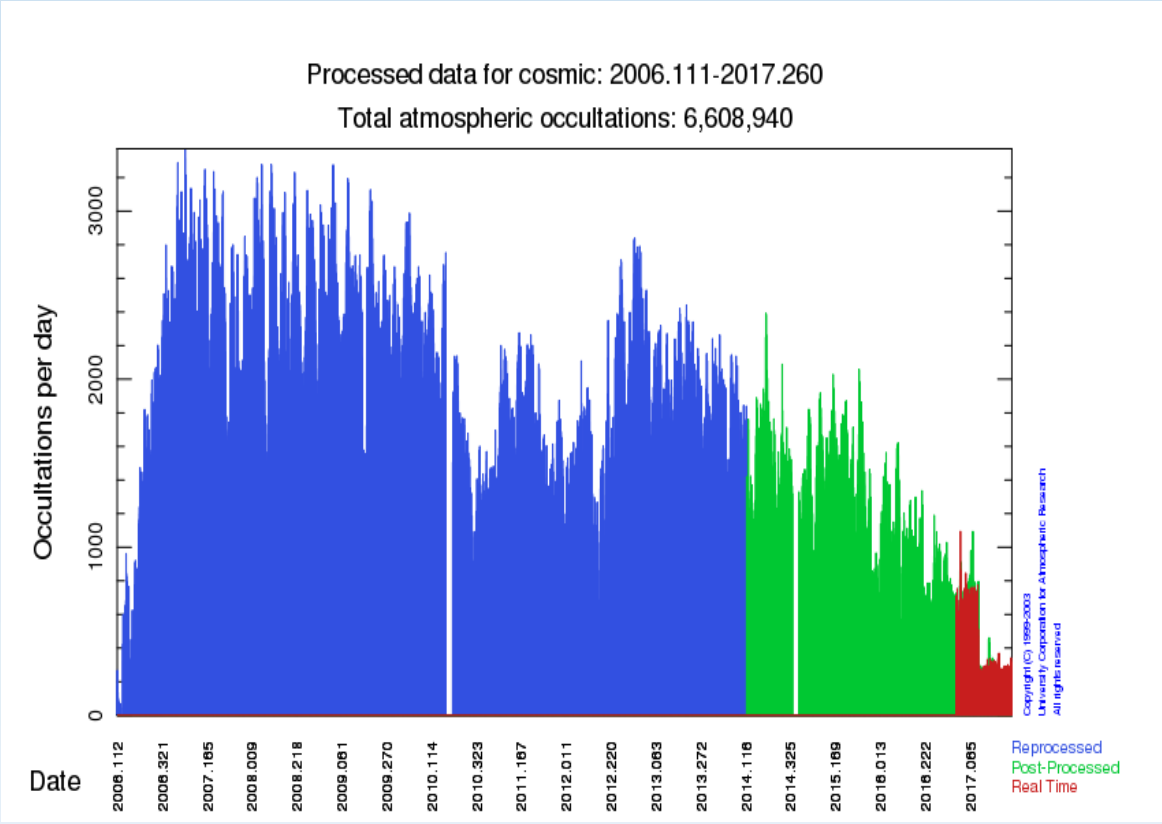
NCAR HPSS Archive

UCAR | CC PROGRAMS
www.ucp.ucar.edu

CDAAC (COSMIC Data Analysis and Archive Center), http://cdaac-www.cosmic.ucar.edu/cdaac/products.html

> 6.6 Million COSMIC Profiles

4/21/06 – 9/17/2017



Last Updated: Mon Sep 18 23:25:02 MDT 2017

MISSION	Total Atm Occs	Total Ion Occs
CHAMP	468029	306318
CNOFS	150772	0
COSMIC	6633961	4449234
GPSMET	5002	0
GPSMETAS	4666	0
GRACE	522698	242634
KOMPSAT5	201298	0
METOPA	2121734	0
METOPB	974528	0
SACC	353756	0
TSX	666333	0
Total	**12102777**	**4998186**

COSMIC: 1-2 spacecraft still operating 11+ years after launch (design life: 2-3 yr)

COSMIC continues to provide up to ~300 GPS soundings per day

CDAAC Capabilities

- High-Availability (> 99.7%) - Geographically separated processing centers
- Automated processing of Global Navigation Satellite System (GNSS) data.
- Radio occultation (RO) retrieval processing.
- Modular framework that enables a user to incorporate or “plug in” new sensors and processing algorithms.
- FISMA-Moderate implementation
- Can be licensed for research and commercial applications

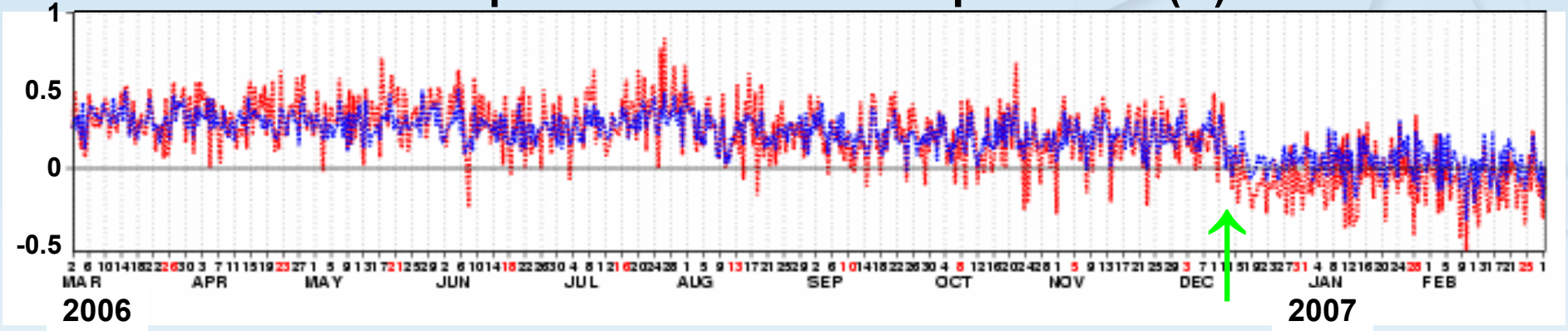
Geographically-separated data centers

Scientific Uses of Radio Occultation Data

- **Weather**
  - Improve global weather analyses, particularly over data void regions such as the oceans, tropics, and polar regions
  - Improve skill of numerical weather forecasts, including hurricanes
  - Improve understanding of tropical, mid-latitude and polar weather processes 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

ECMWF Operational implementation of GPSRO on Dec 12, 2006

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



Obvious improvement in time series for operational ECMWF model.

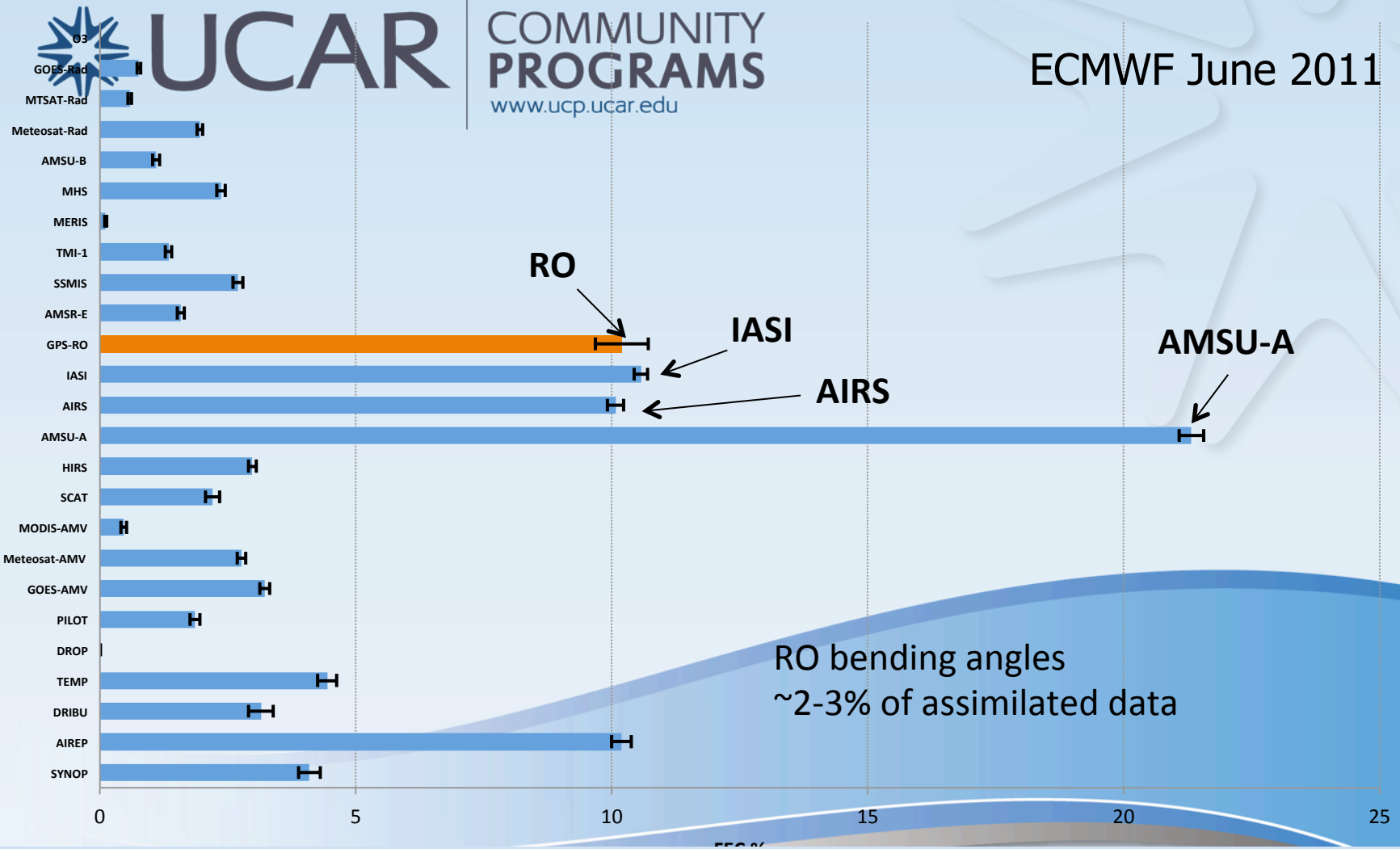
Dec 12, 2006 Operational implementation represented a quite conservative use of data. No measurements assimilated below 4 km, no rising occultations.

Nov 6, 2007 Operational assimilation of rising and setting occultations down to surface

Contributions to forecast accuracy by observing system

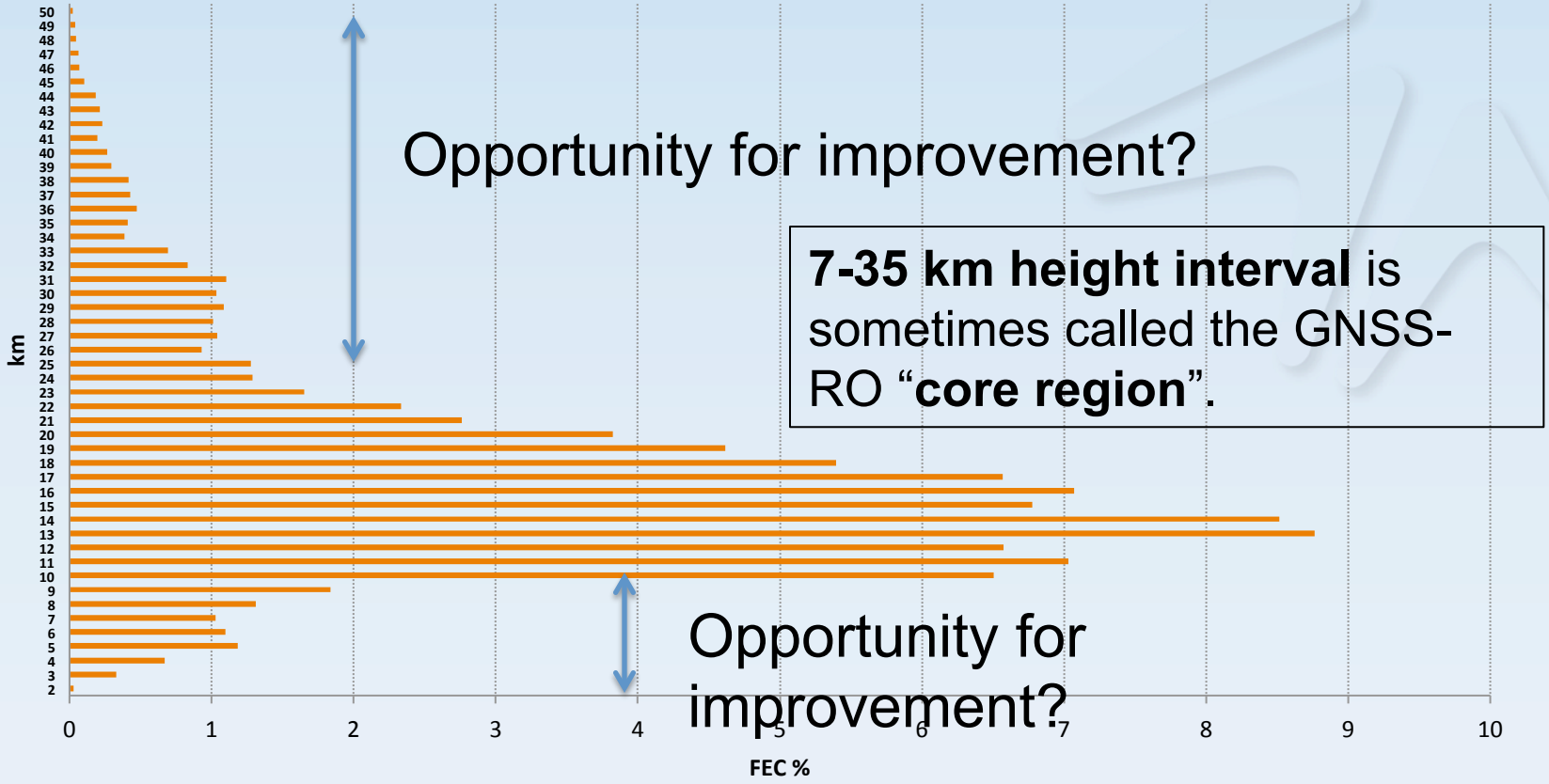
UCAR COMMUNITY PROGRAMS
www.ucp.ucar.edu

ECMWF June 2011



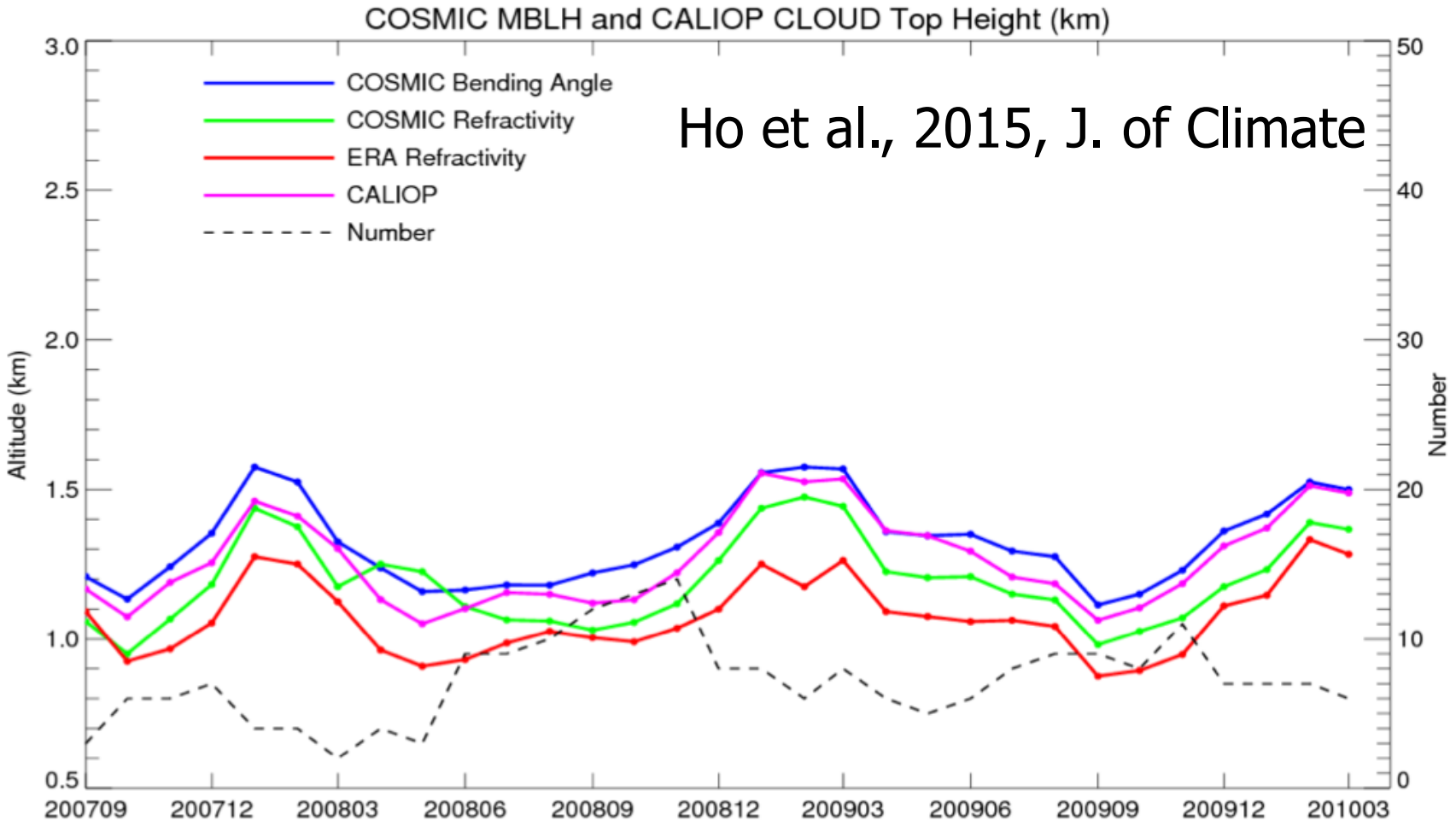
Four of the type five observational systems contributing the operational weather forecasting accuracy are sounding systems. RO is typically in the top five, even though the number of soundings is small compared to other sounding systems

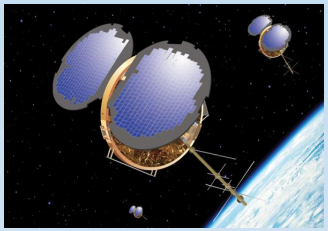
Heights where GNSS-RO is reducing the 24hr forecast errors



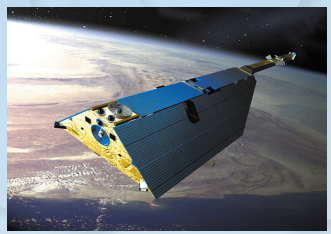
Florian Harnisch, Sean Healy, Peter Bauer, Steve English, Nick Yen, 2013

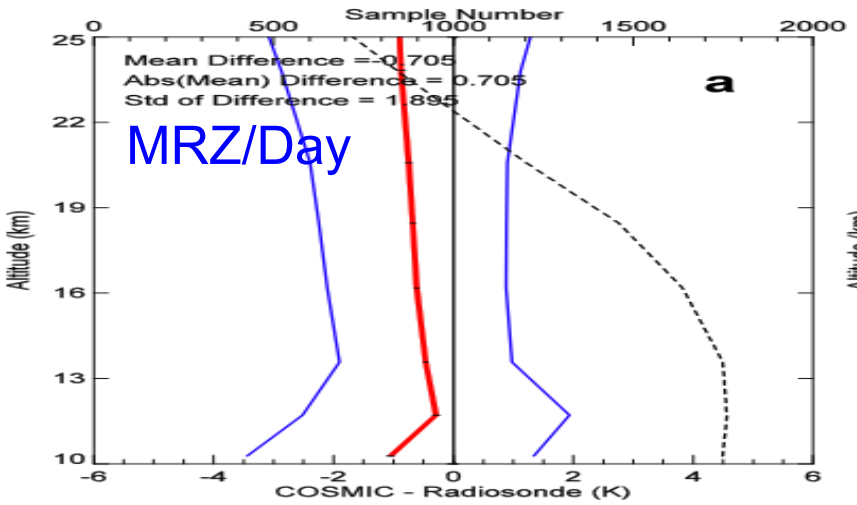
Comparison of CALIPSO Cloud Top Heights and COSMIC ABL Heights in the VOCALS region Sept 2009-Mar 2010

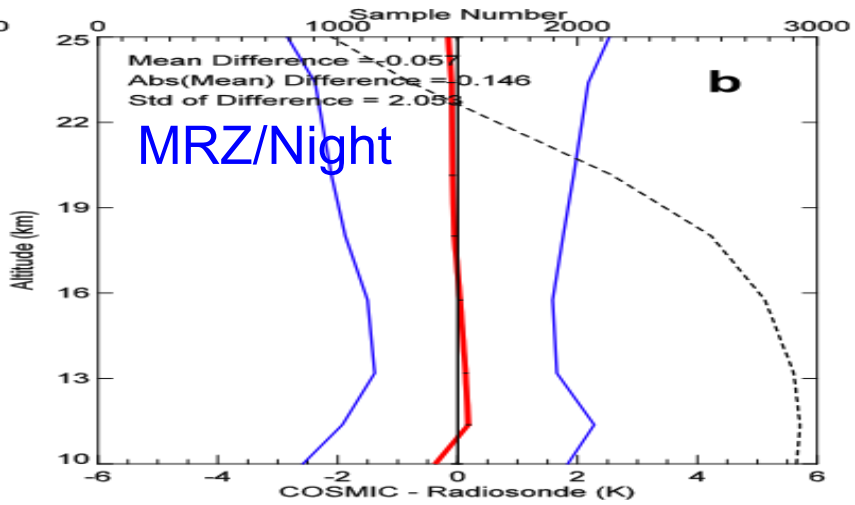


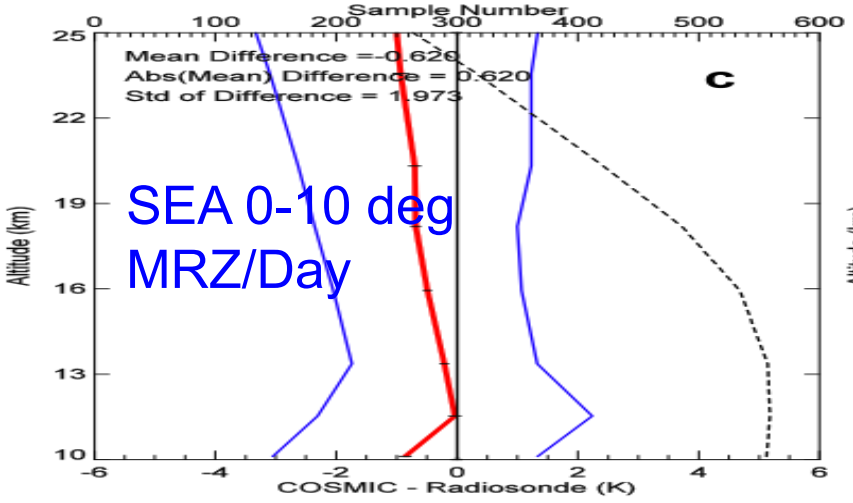


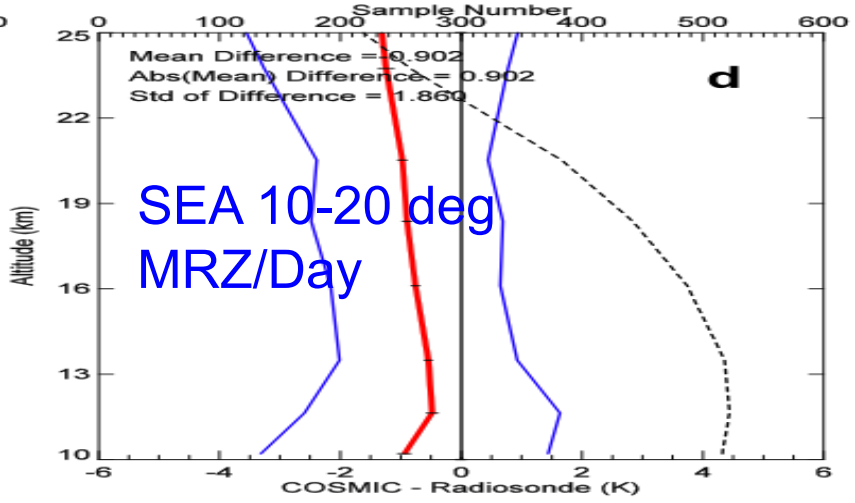
Identify systematic radiosonde temperature biases using RO data







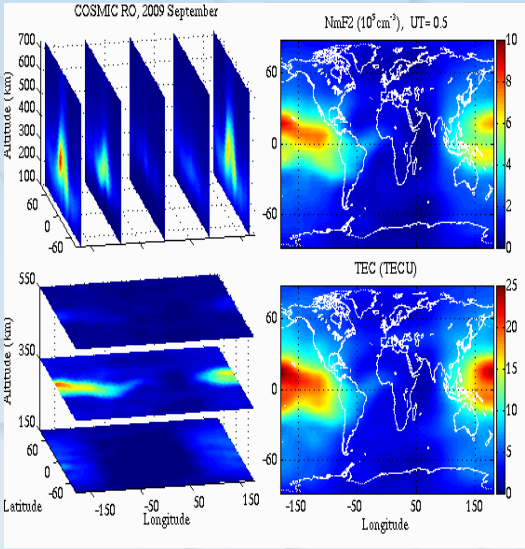


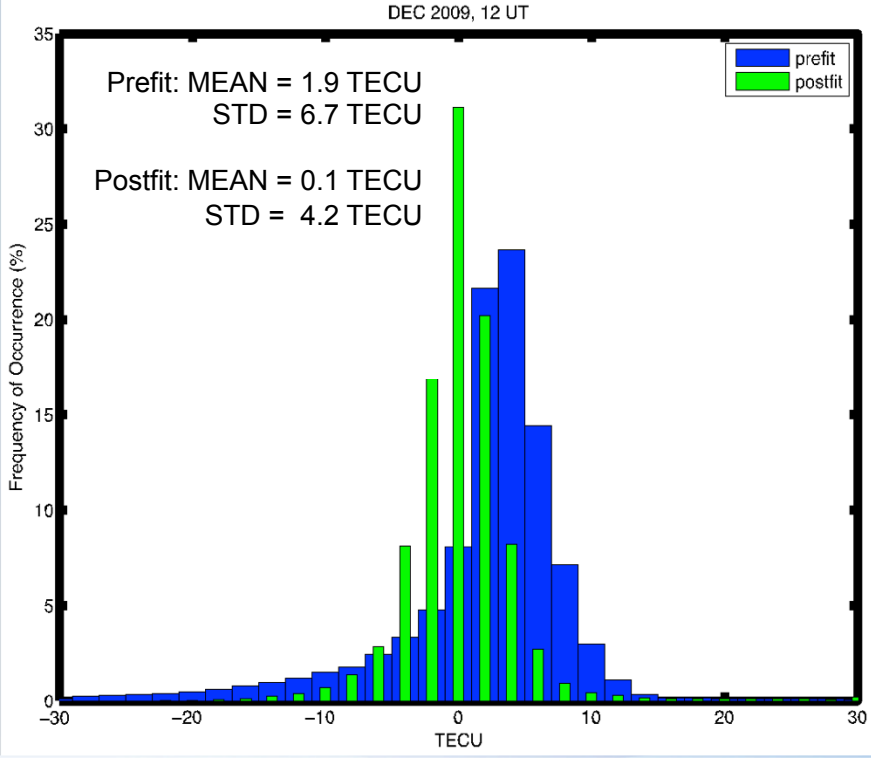


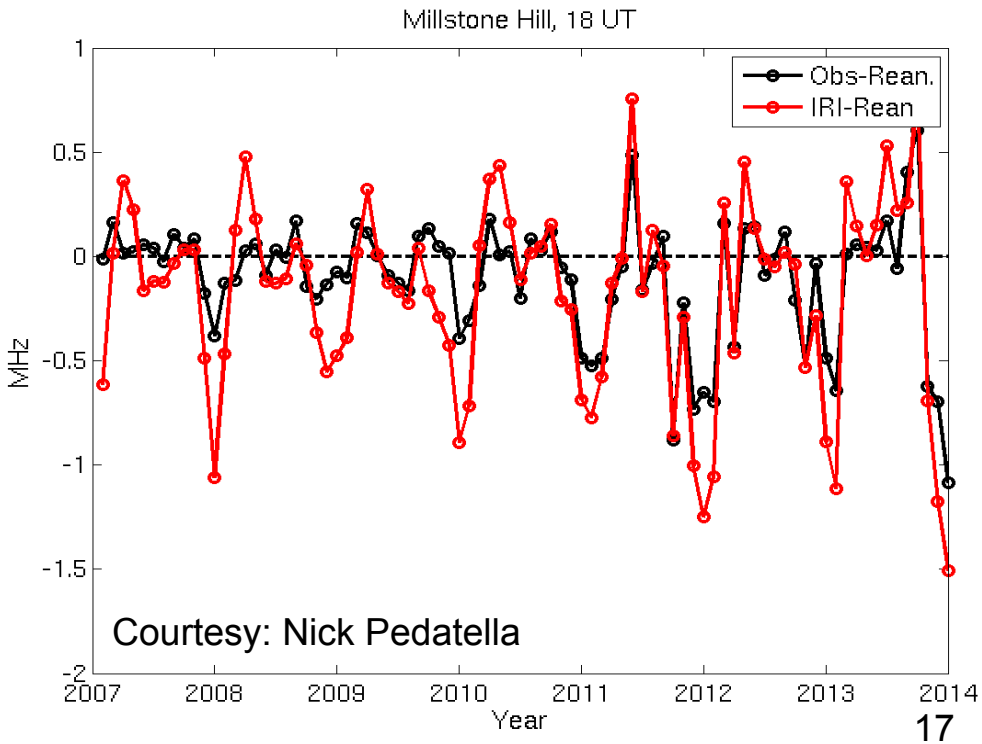
(He and Ho 2009 GRL)

Ionosphere Reanalysis with COSMIC

- Assimilation of COSMIC and ground based GPS total electron content observations into the International Reference Ionosphere (IRI) model (Yue et al., 2012)
- Provides monthly mean 4-dimensional (universal time, latitude, longitude, height) gridded electron density product
- Pre- and post-fit residuals (left) and comparison with independent ionosonde data of the F-region peak height (NmF2, right) illustrate that the assimilation results improve upon the empirical IRI model.





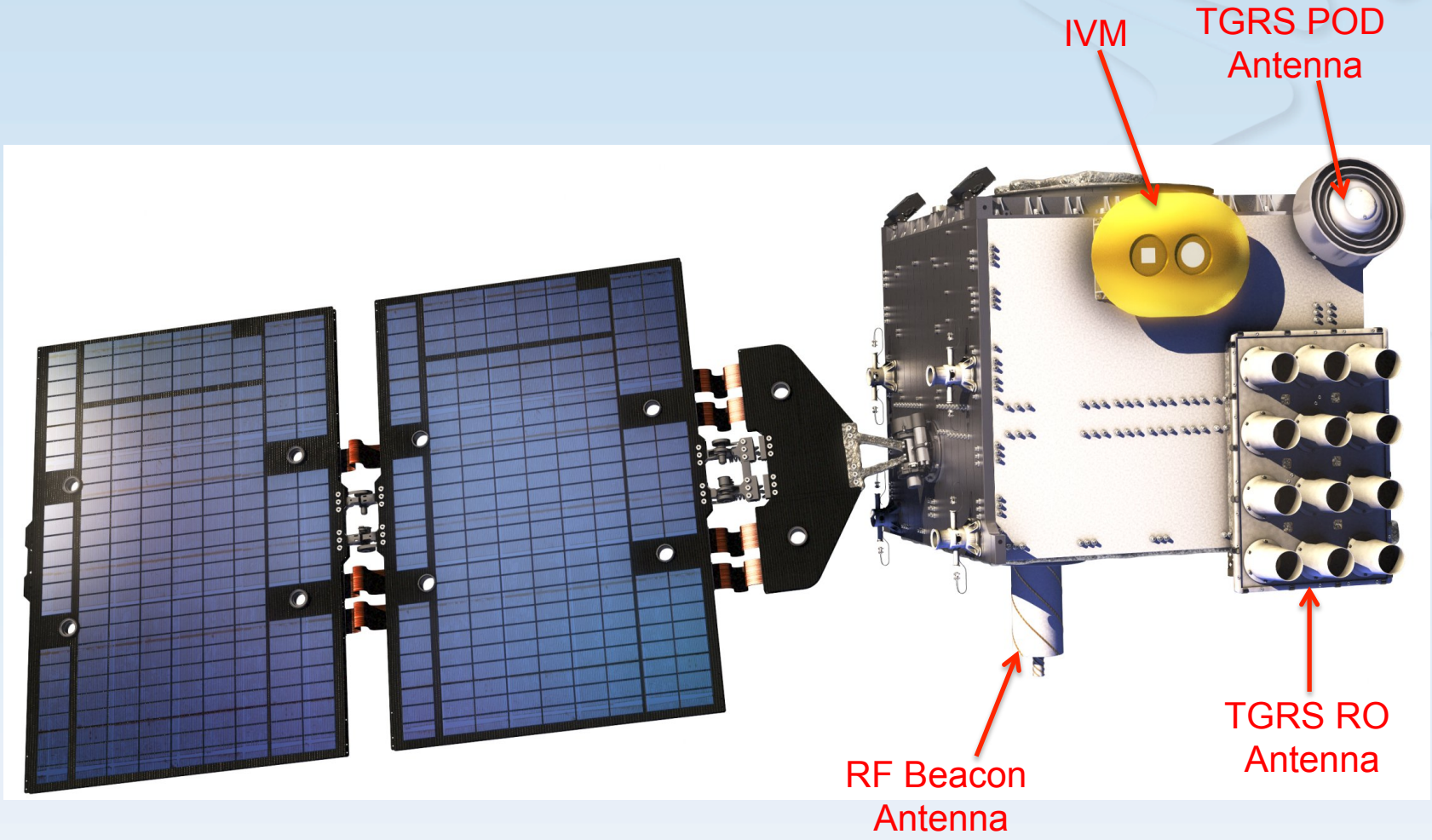


The COSMIC-2/FORMOSAT-7 Partnership

Organization	Responsibilities
Taiwan NSPO	• 12 Spacecraft (From SSTL) • Command & control (1 ground site) • Secondary sensors for polar SVs
NOAA	• Lead US agency • COSMIC-2 ground sites • TGRS ground processing • TGRS sensors for polar SVs
USAF	• All sensors for equatorial SVs • Launch • RF Beacon ground system • RF Beacon/IVM ground processing
NASA	• TGRS TriG Electronics Development at JPL

COSMIC-2/FORMOSAT-7 is jointly sponsored by NOAA and NSPO, as designated representatives of AIT and TECRO.

COSMIC-2 Spacecraft

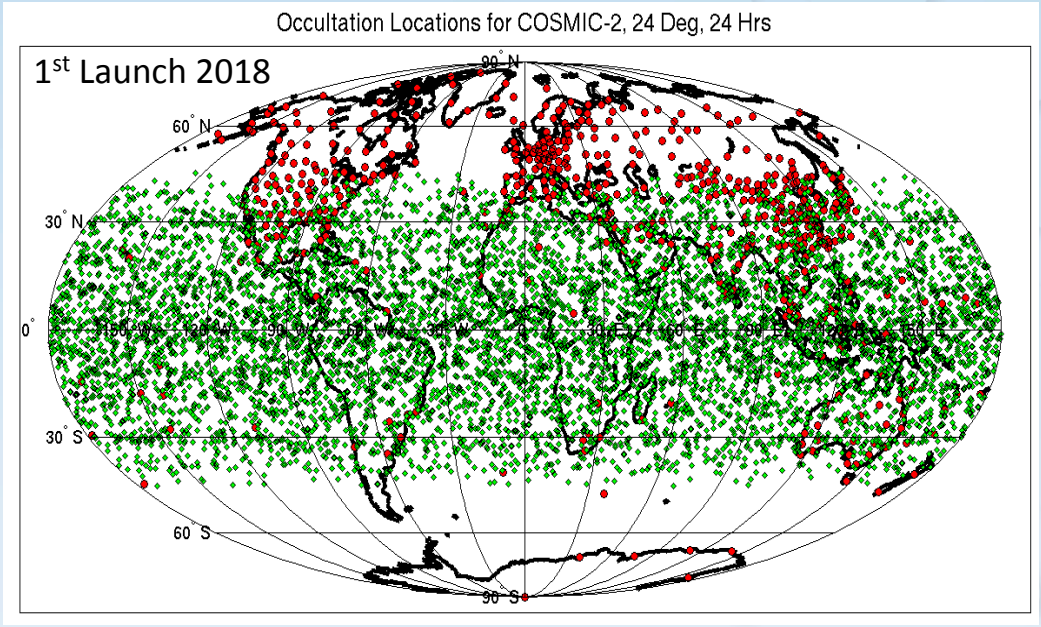


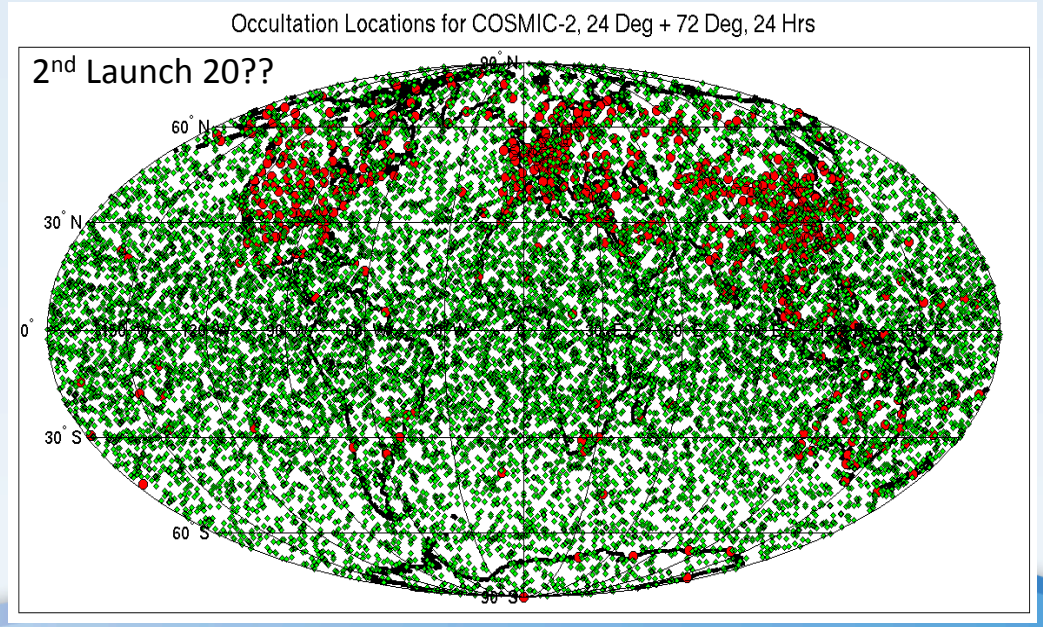
The COSMIC-2 spacecraft are being developed by Surrey Satellite Technologies Limited (SSTL) Under Contract to Taiwan's National Space Organization

Graphic courtesy SSTL

COSMIC-2 Summary

- Joint U.S./Taiwan Mission
- 12 satellites with JPL TriG receiver and high-gain antennas
  - 6 launched into Equatorial orbit Q3 2018
  - 6 launched into polar orbit (not yet fully funded)
- Ion Velocity Meter and RF Beacon payloads
- ~10,000 soundings/day with 30 min latency
- Total cost (10 years) ~$450M





UCAR COMMUNITY PROGRAMS
www.ucp.ucar.edu

COSMIC-2 EDR Products

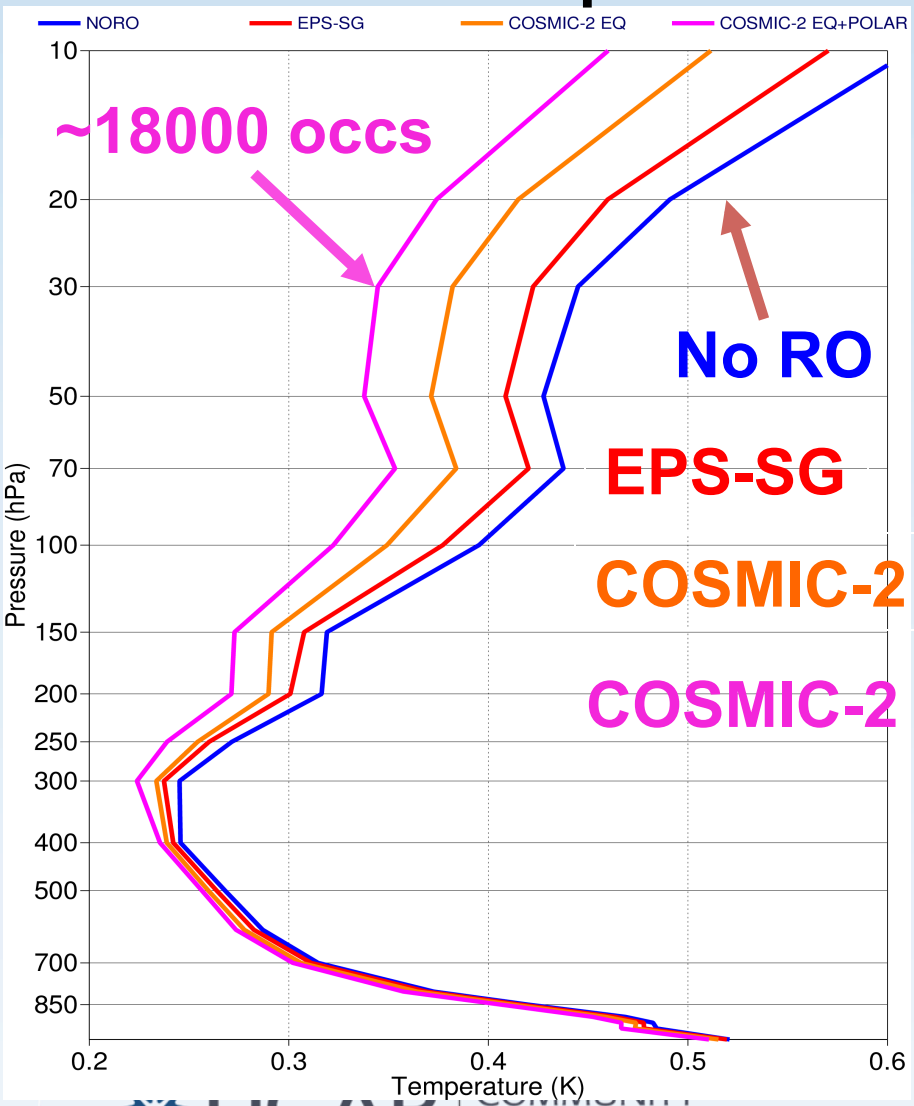
Product	Description	Requirement	UCAR/CDAAC* filename
TGRS neutral atmospheric profiles	# of profiles	>667/satellite	Level2/atmPrf (high-res dry profiles), Level2/bfrPrf (WMO BUFR profiles)
	Bending Angle (BA)	2 µrad for 30<alt<60km	
	Temperature (T)	1 K for 10<alt<30km	
TGRS TEC arcs	# of iono soundings/day	>1000/satellite	Level1b/podTc2
	Absolute TEC	3 TECU	
	Relative TEC	0.3 TECU	
TGRS Scintillation	S4/σ_ϕ measurement uncertainty	0.1/0.1 radians	Level1a/scn1c2, Level1b/ scnLv2, Level2/scnSpc
IVM	In-situ ion density accuracy	5%	Level2/ivmLv2
	In-track/Cross drift measurement accuracy	±10/5 m/s	
TGRS & IVM Latency	Median data latency	30 min	

UCAR COMMUNITY PROGRAMS www.ucp.ucar.edu

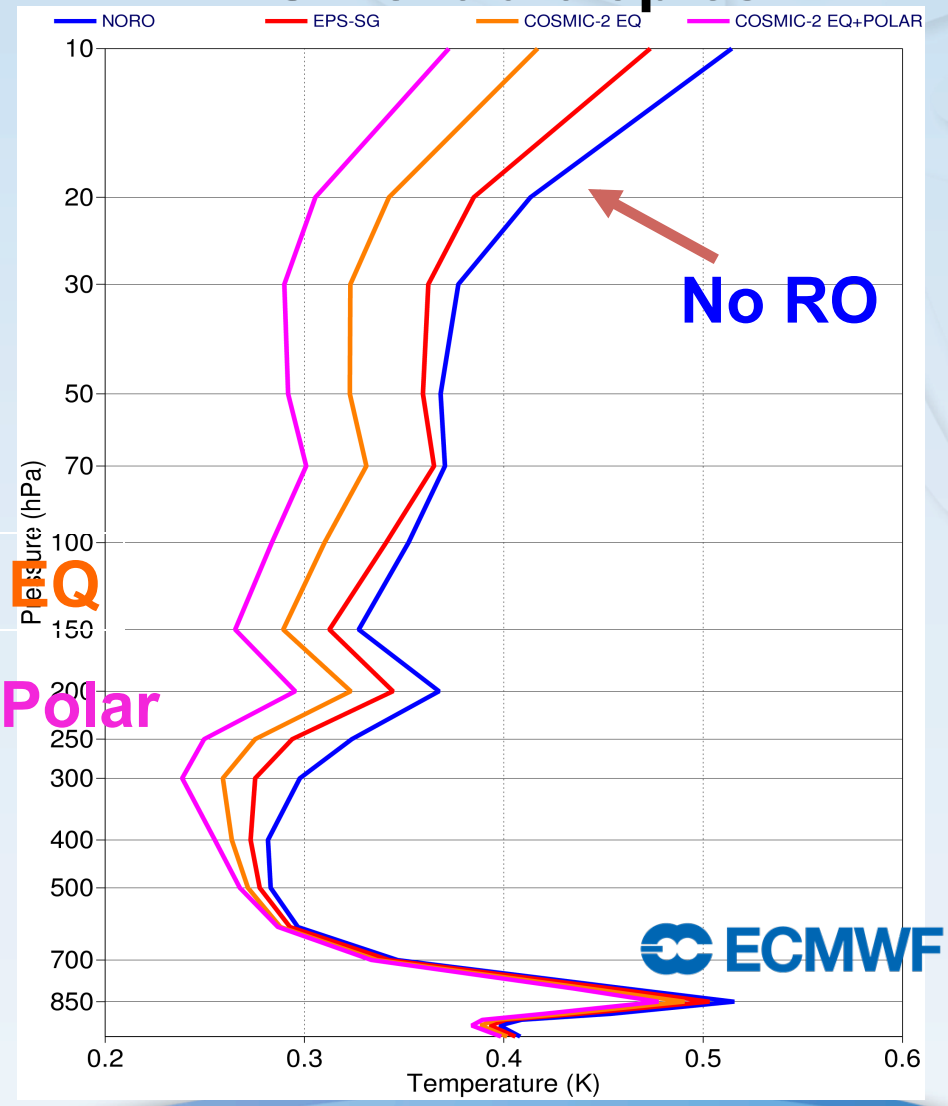
* COSMIC Data Analysis and Archive Center, http://cdaac-www.cosmic.ucar.edu/cdaac/products.html

The temperature impact of COSMIC-2 Polar: EPS-SG + COSMIC-2 EQ + COSMIC-2 Polar

NH extra-tropics



SH extra-tropics

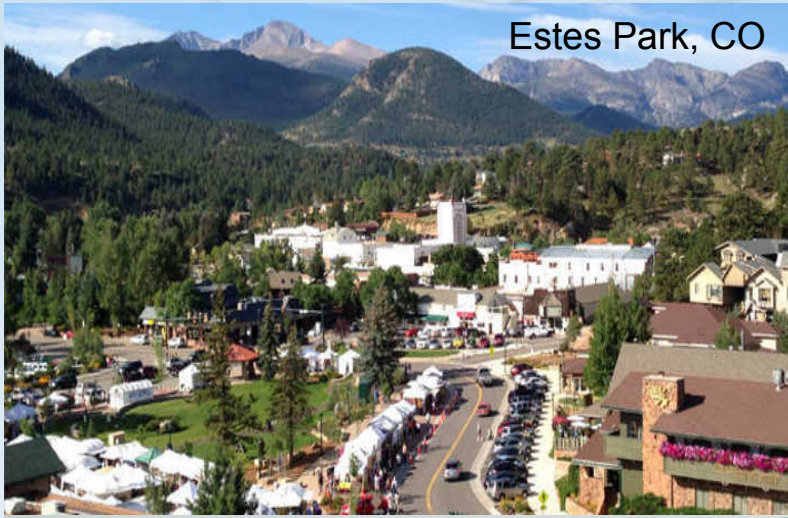


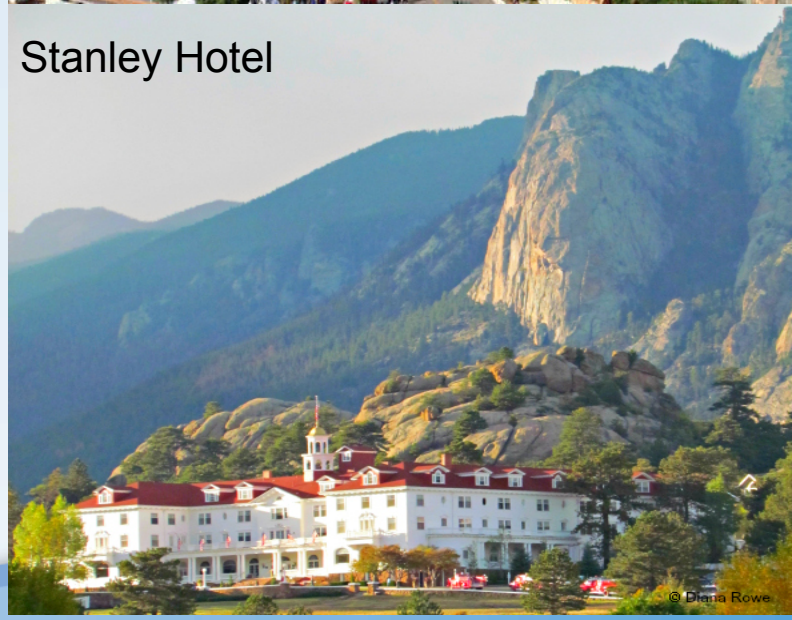
UCAR COMMUNITY PROGRAMS www.ucp.ucar.edu

Courtesy ECMWF and EUMETSAT

Joint COSMIC Data Users' Workshop and IROWG-6 Meeting

- COSMIC Data Users' Workshop
  - ~100 RO science presentations/posters
- International Radio Occultation Working Group (IROWG–6) Meeting
  - Permanent Working Group of CGMS
  - RO community develops recommendations for consideration at CGMS meetings
- Sept 21-27, 2017 (Thurs-Wed)
- Stanley Hotel
- Estes Park, CO





Courtesy: Google Images

Summary

- Radio Occultation is a proven high-impact and low-cost global observing system
- COSMIC data provide significant positive impact on weather forecasts
- COSMIC data are useful to specify ionospheric electron density and its irregularities for space weather applications
- COSMIC-2 high-gain antennas will reduce retrieval errors in lower troposphere (LT), and allow detection of tropospheric ducts
- With COSMIC-2 and upcoming commercial data, an even greater impact is expected on weather, space weather, and climate applications

Acknowledgements