



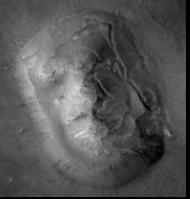
A Brisk Tour of GPS Radio Occultation

Past, Present and Future

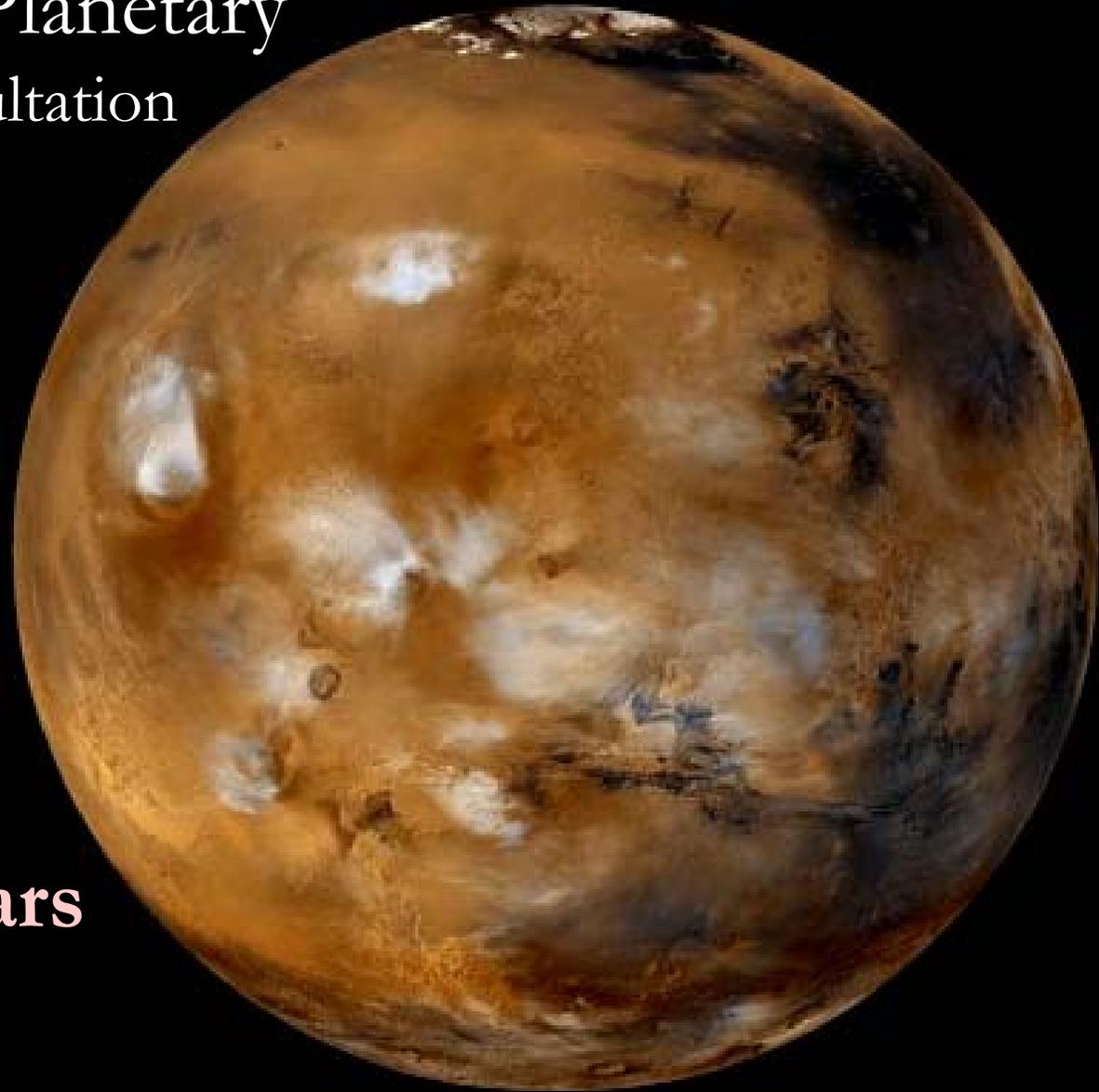
Thomas P. Yunck

Presentation to NOAA

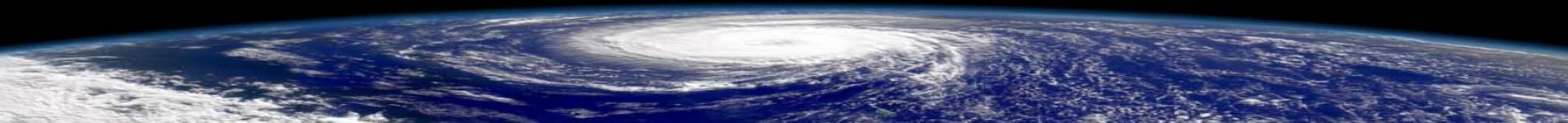
May 17, 2007

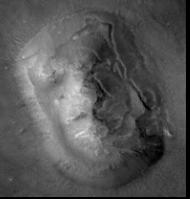


Origins-II: Planetary Radio Occultation



Mariner IV at **Mars**
July 1965



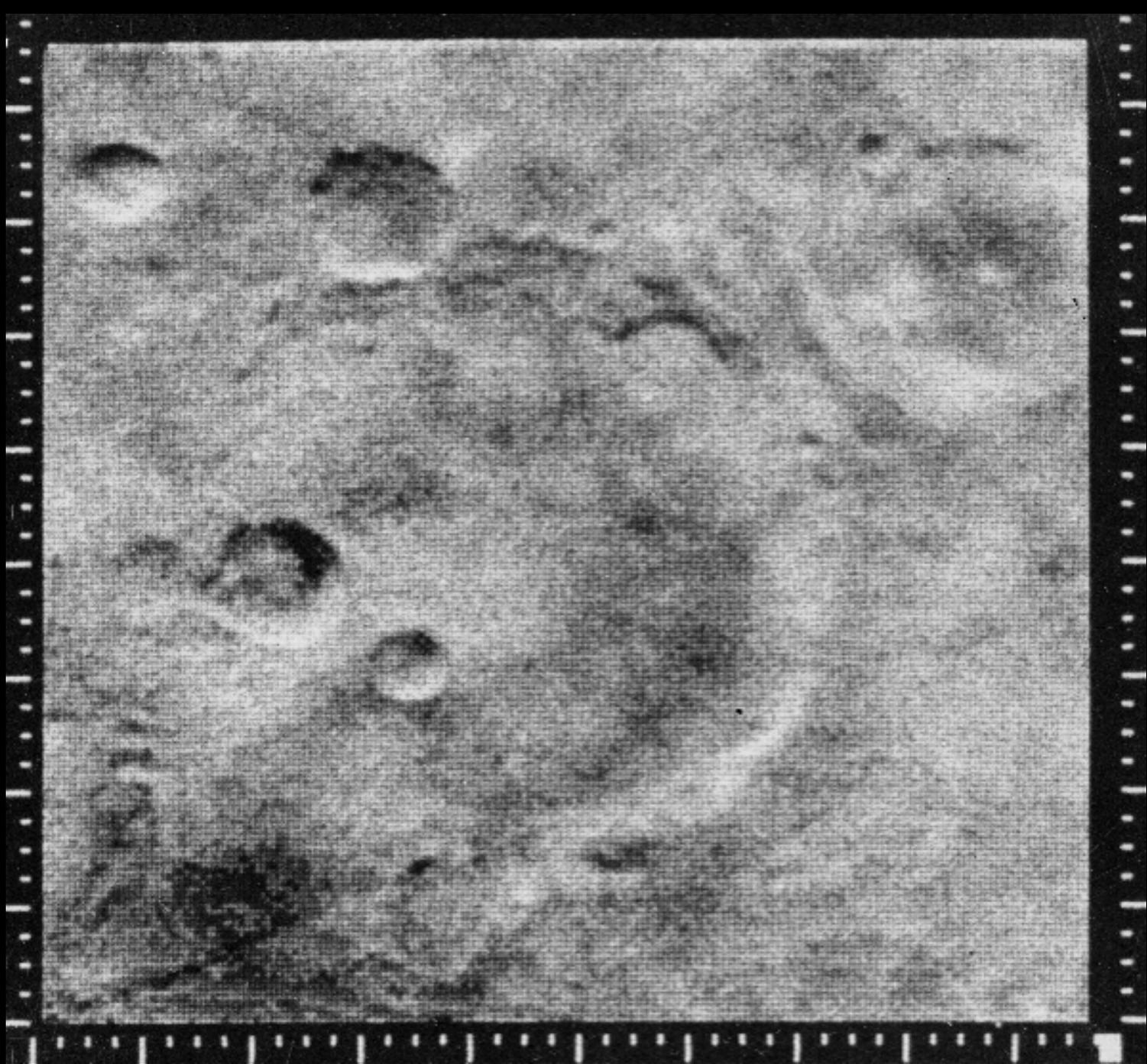


Mariner IV

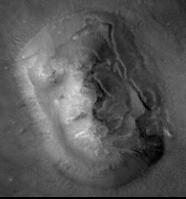
Mars

15 July 1965

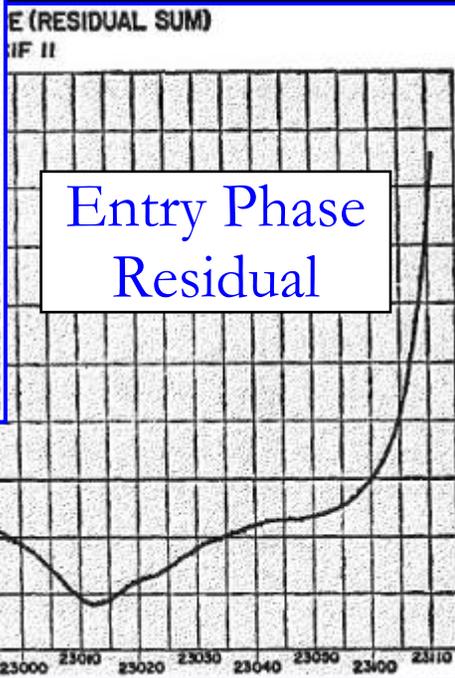
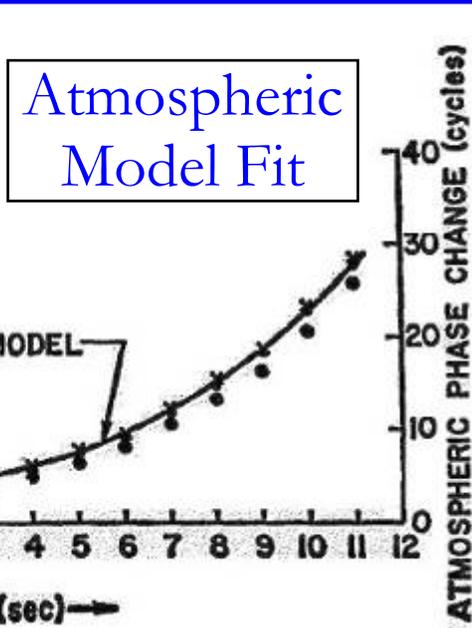
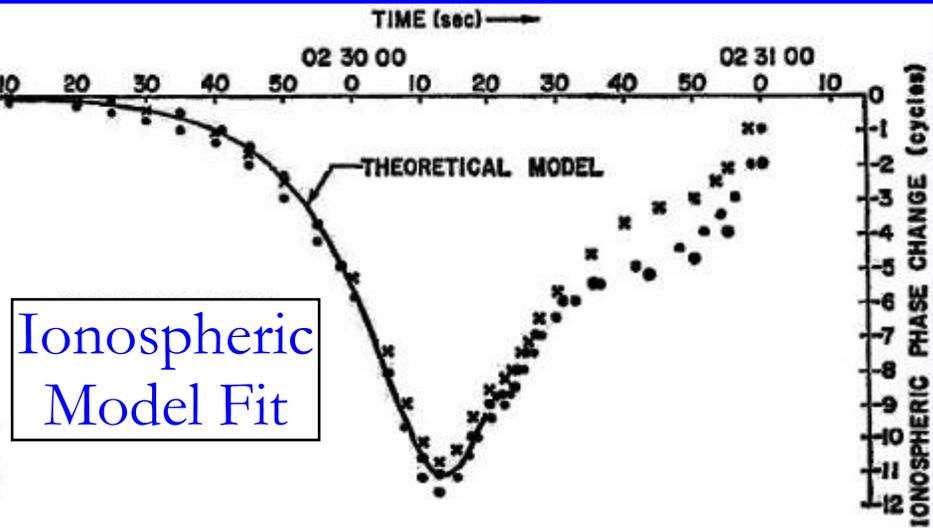
(JPL
wirephoto)



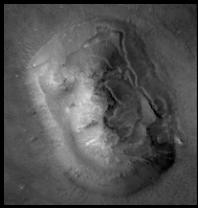
Mariner IV Occultation at Mars: Earliest Results



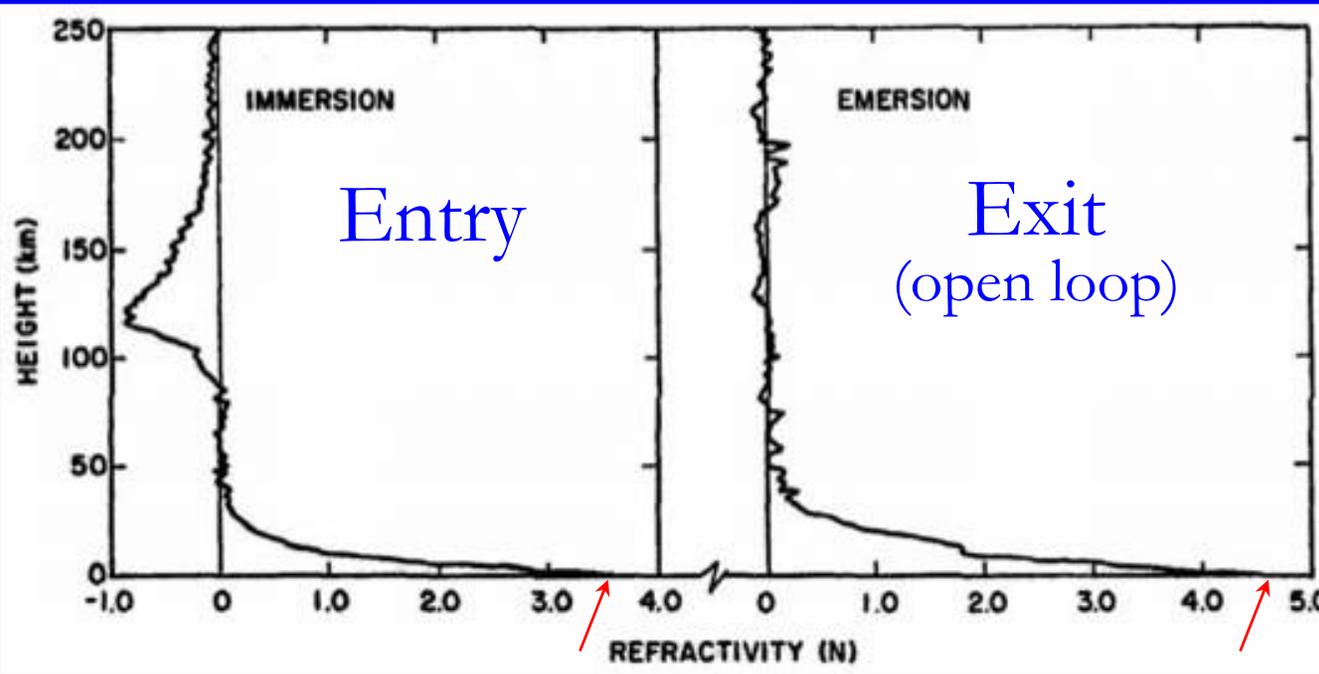
Science, 10 Sep 65



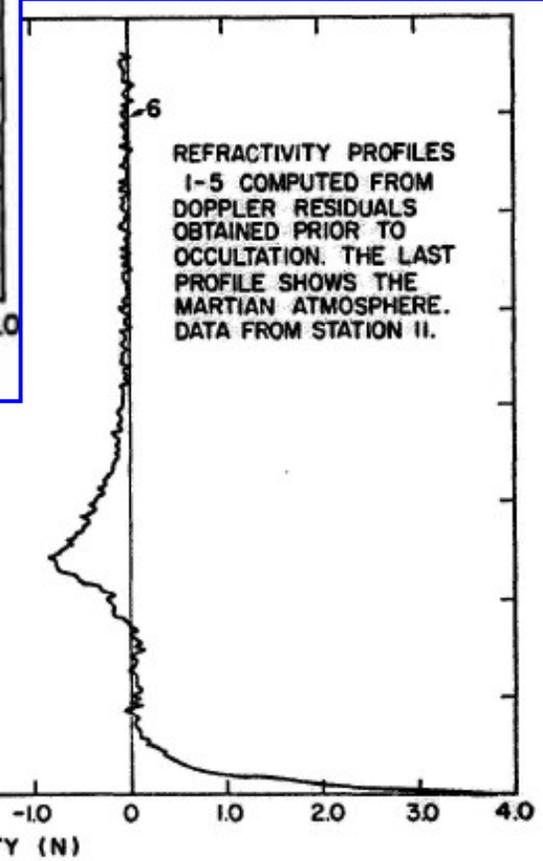
Kliore et al.,
1965



Mariner IV Occultation at Mars: Refined Results



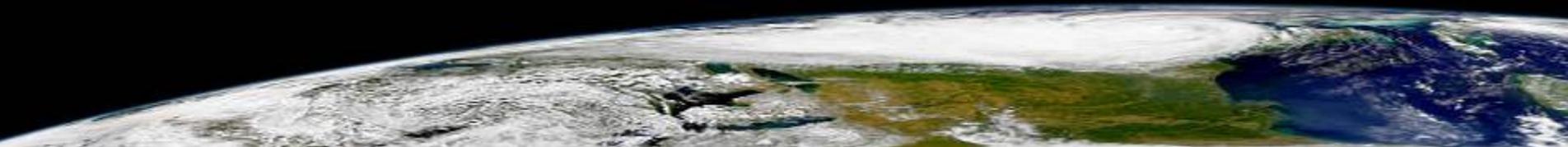
Fjeldbo et al.,
Planet. Space Sci.
1968





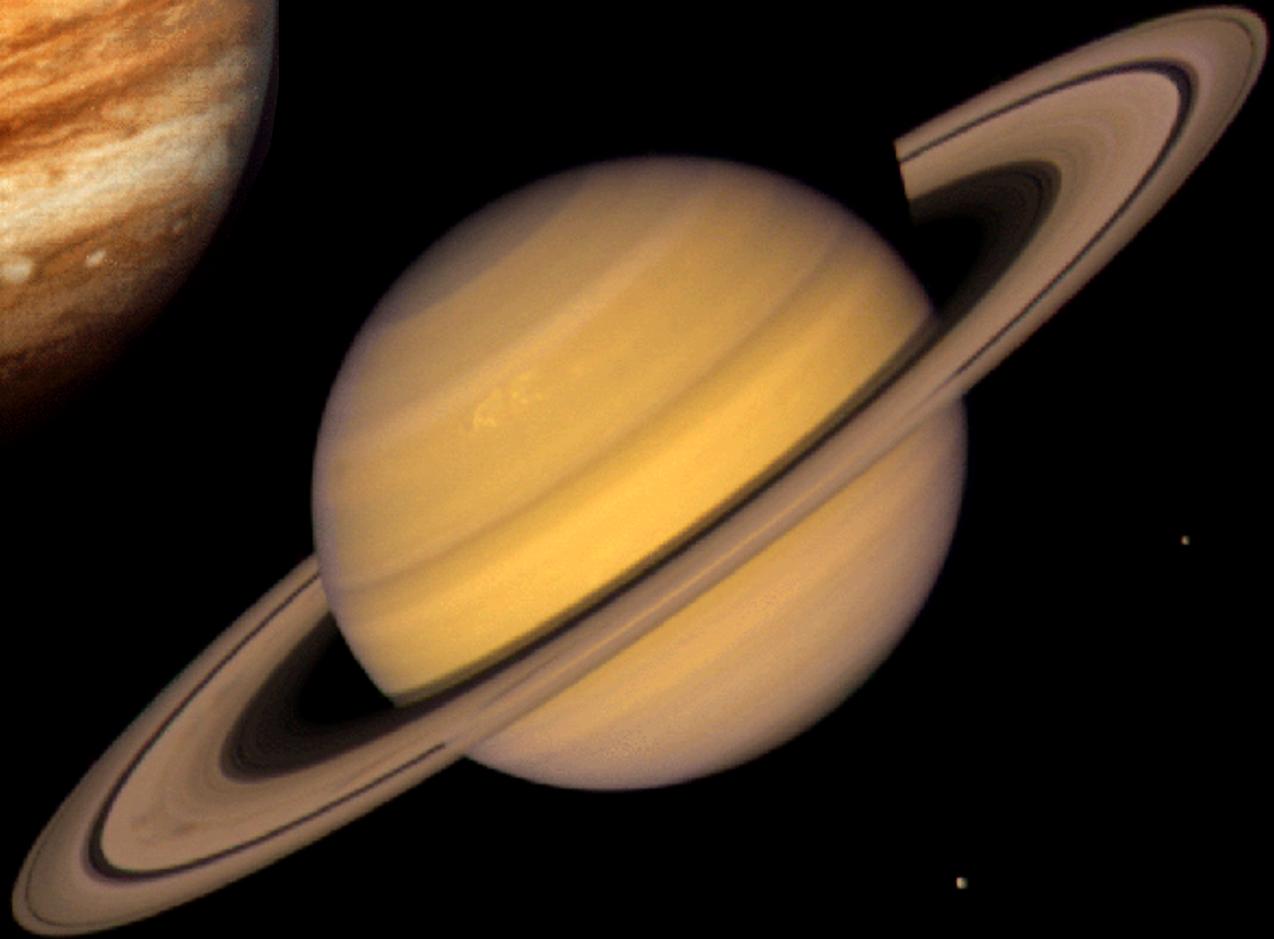
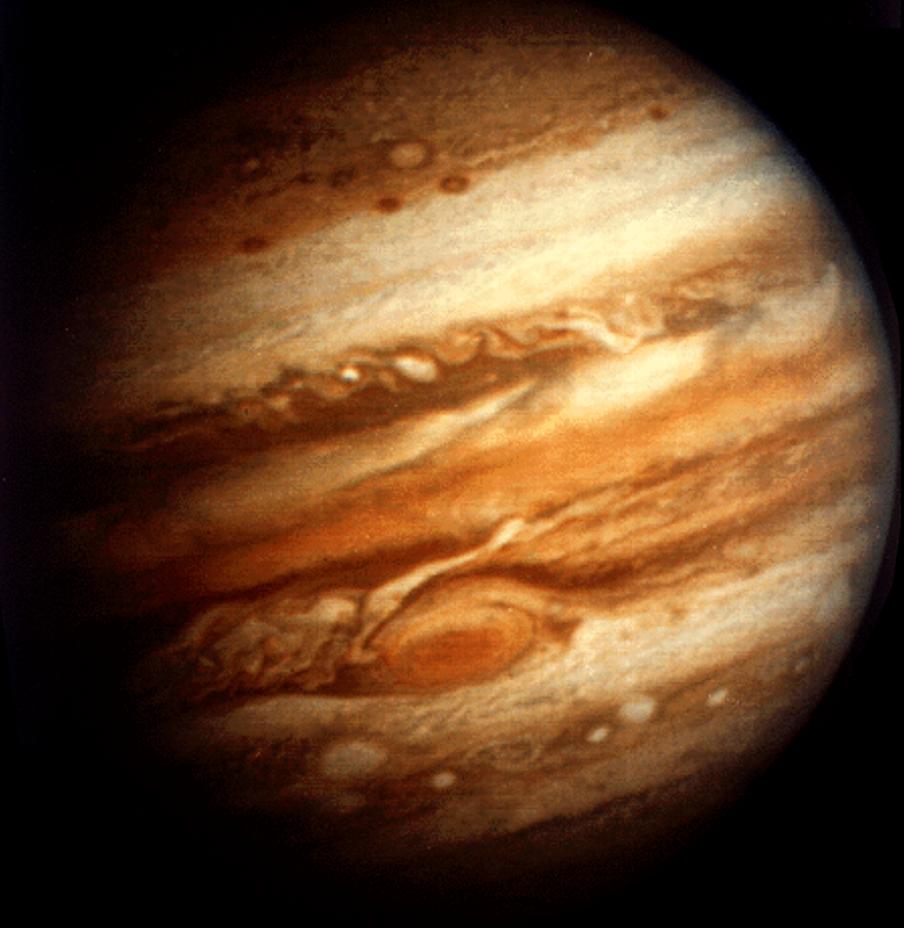
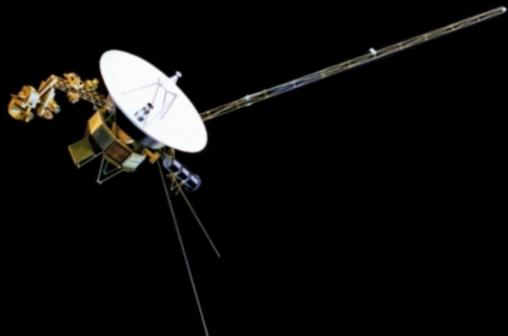
Mariner V at Venus

19 October 1967



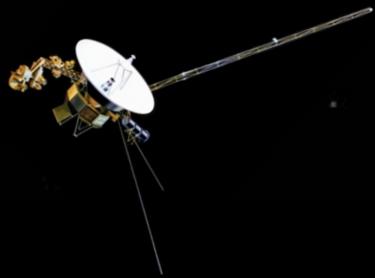
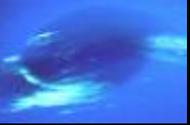
Outer Planets – I

Jupiter and Saturn



Outer Planets – II

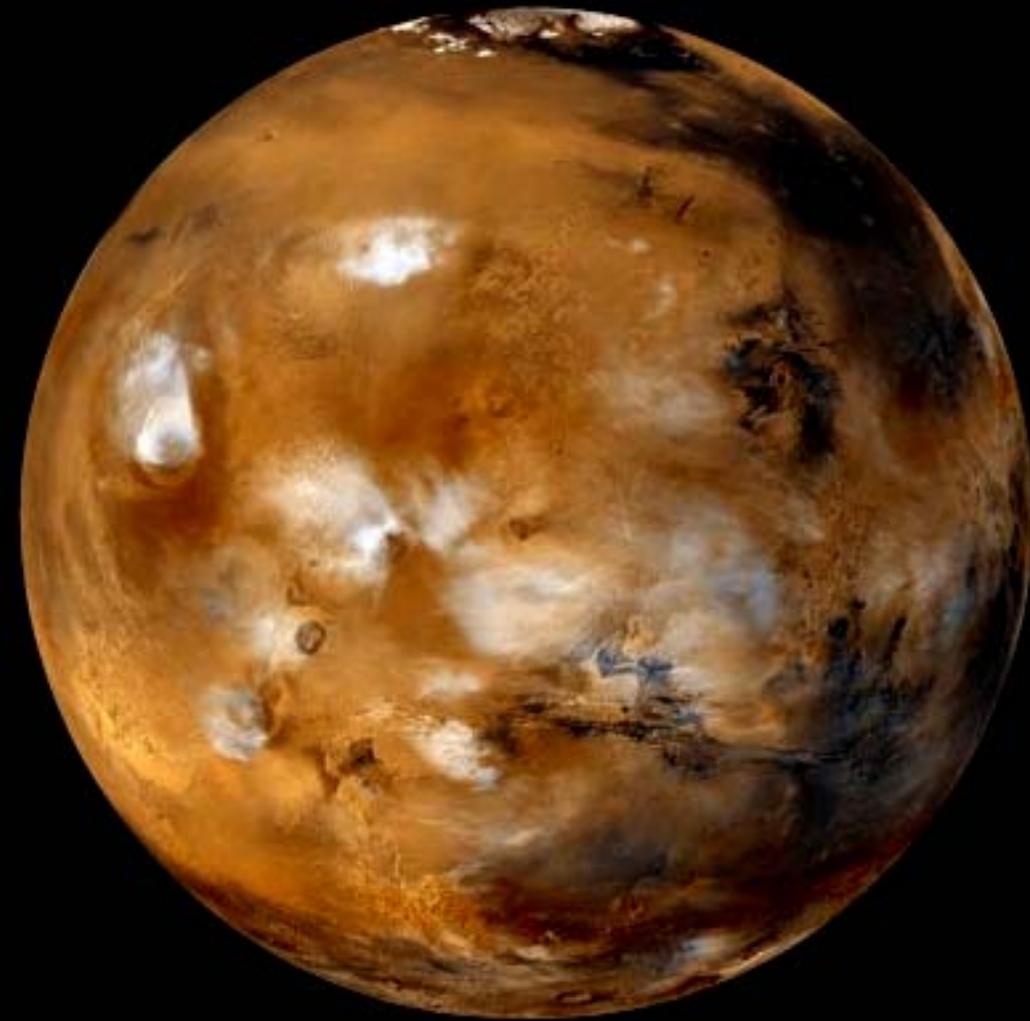
Uranus and Neptune



Occultation Subjects: A Group Portrait



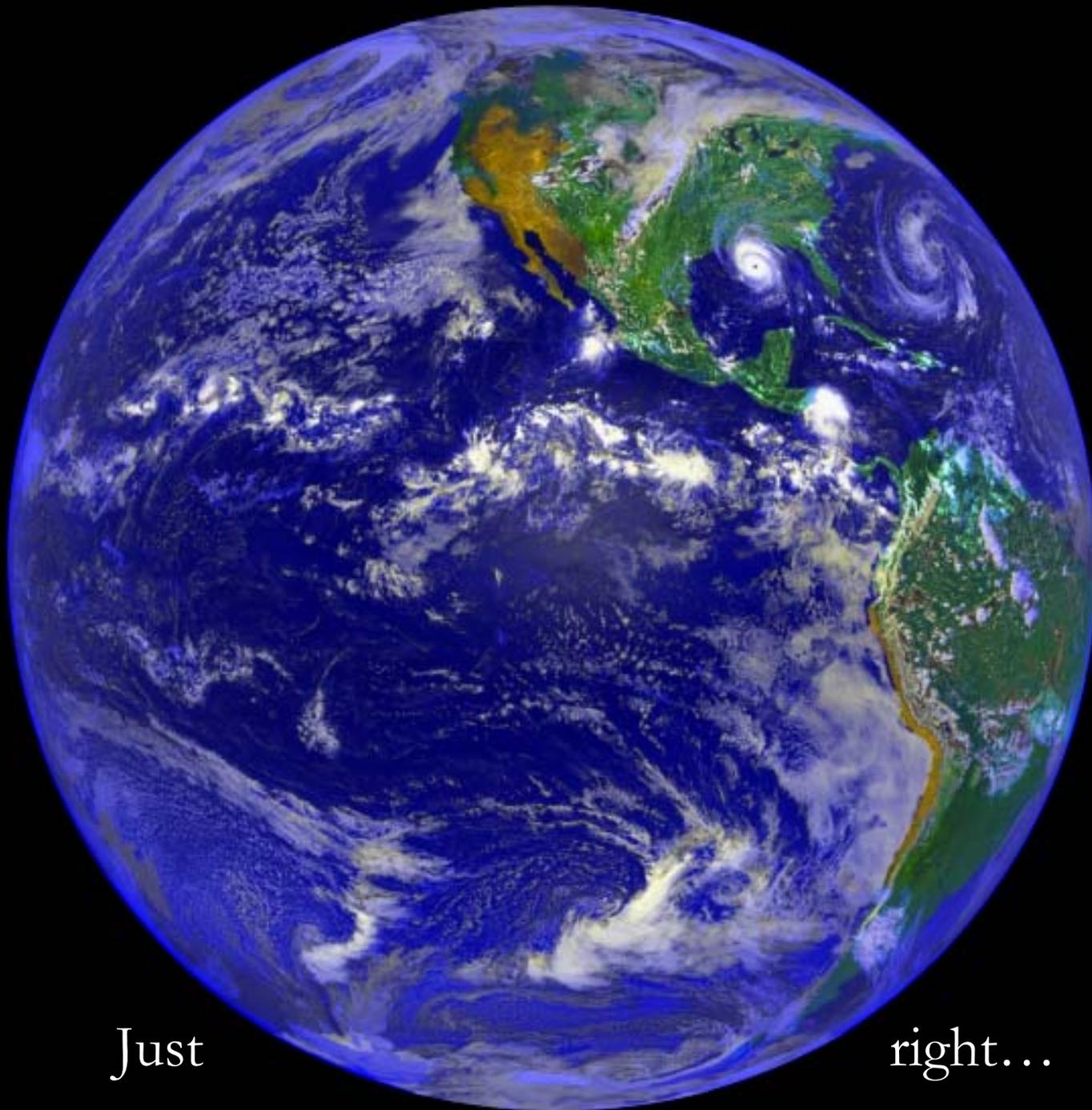
An Observation on the Terrestrial Planets



This atmosphere is too thin



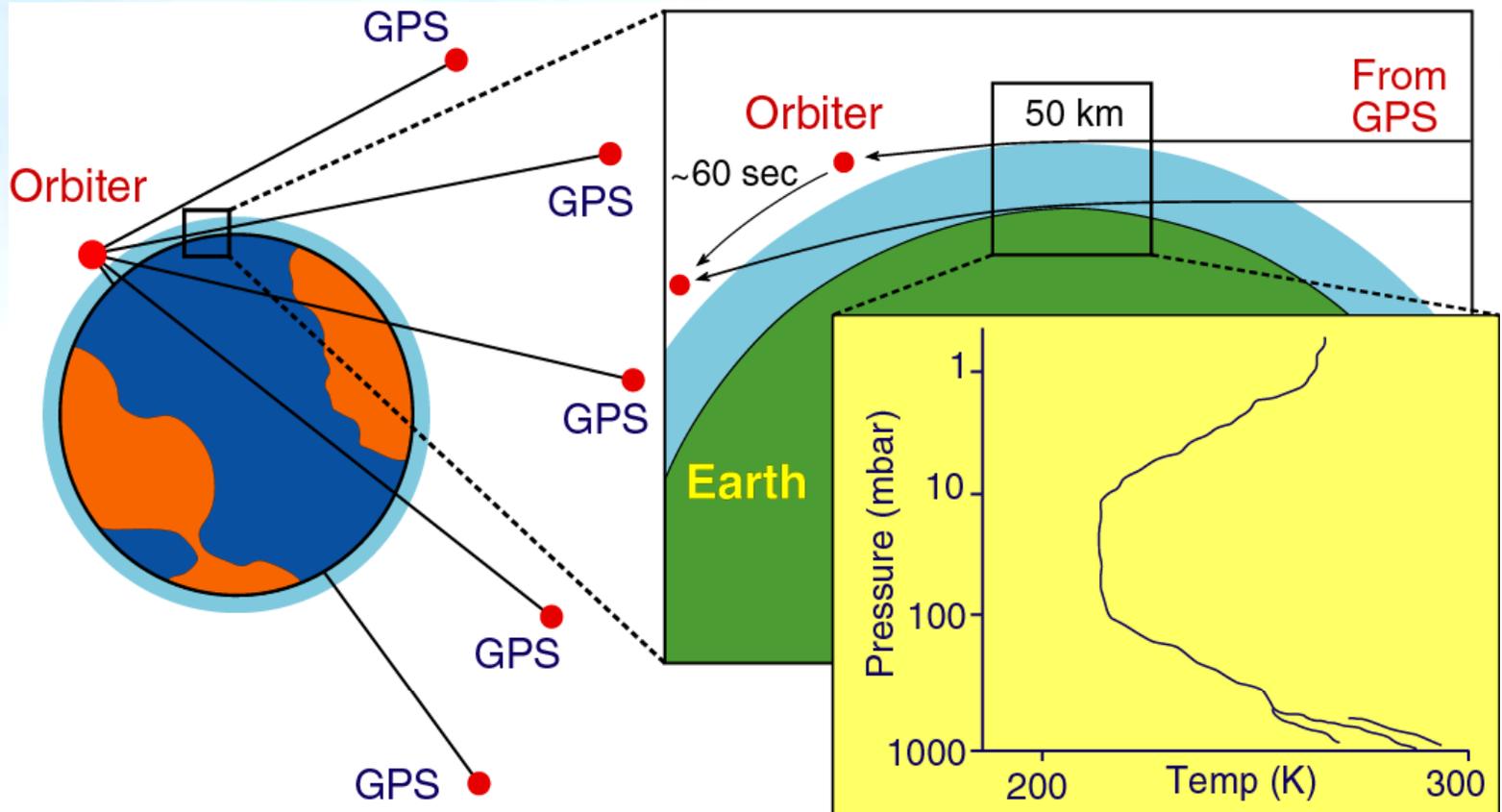
This atmosphere is too thick



Just

right...

Atmospheric Limb Sounding

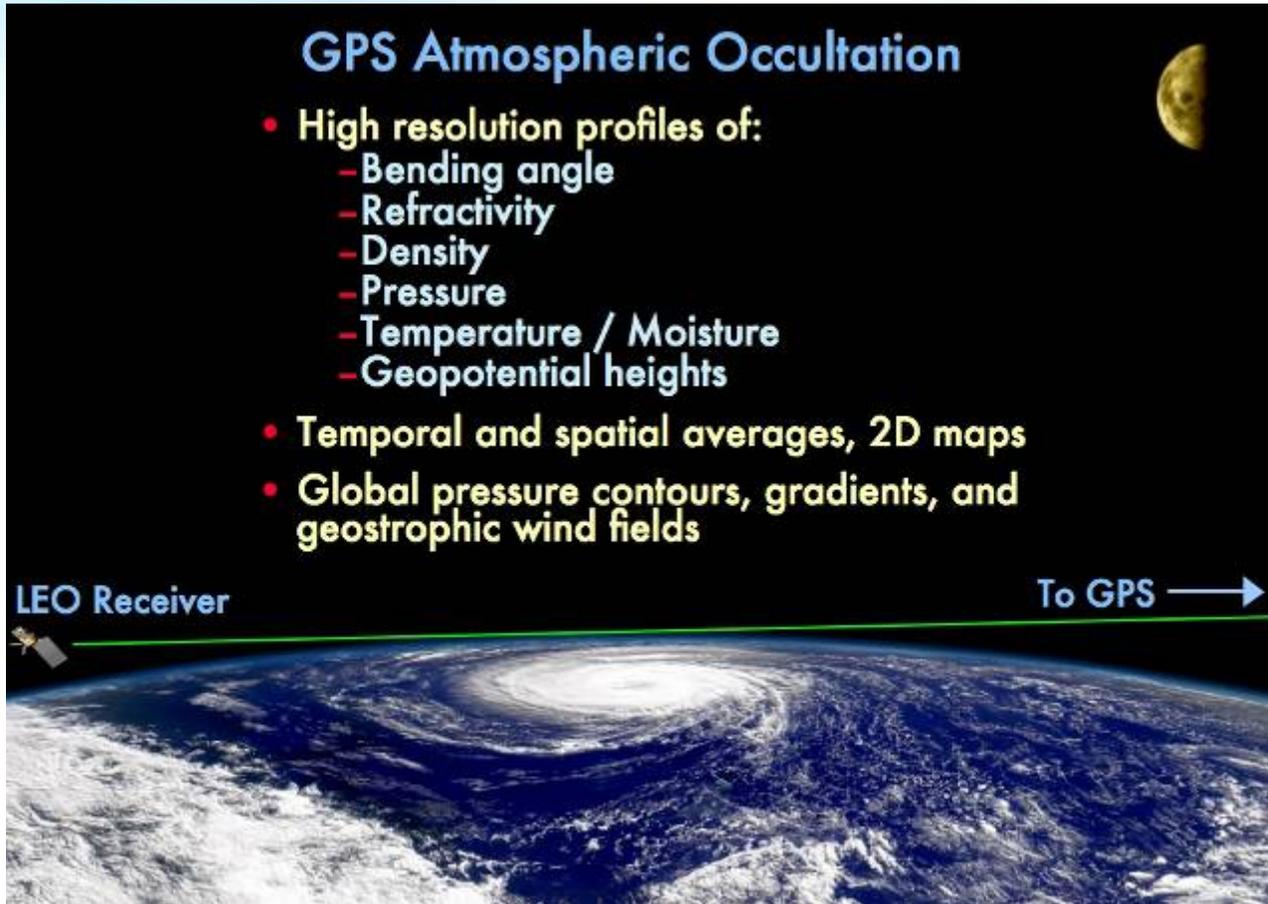




GPS RO is a breakthrough in high-accuracy, high-resolution sensing of the atmosphere

GPS Atmospheric Occultation

- **High resolution profiles of:**
 - Bending angle
 - Refractivity
 - Density
 - Pressure
 - Temperature / Moisture
 - Geopotential heights
- **Temporal and spatial averages, 2D maps**
- **Global pressure contours, gradients, and geostrophic wind fields**

A diagram illustrating the GPS Atmospheric Occultation process. It shows a satellite labeled "LEO Receiver" in orbit above the Earth's surface. A green line represents the signal path from the satellite to a "GPS" receiver on the ground, with an arrow pointing right. The background features a satellite view of the Earth with a prominent cyclone system. A crescent moon is visible in the upper right corner of the diagram.

LEO Receiver

To GPS →

- Entirely different physical principles from radiometry
- Results directly traceable to an absolute SI standard



Some Key Attractions of GPS RO

Seven Cardinal Virtues of GPS Radio Occultation

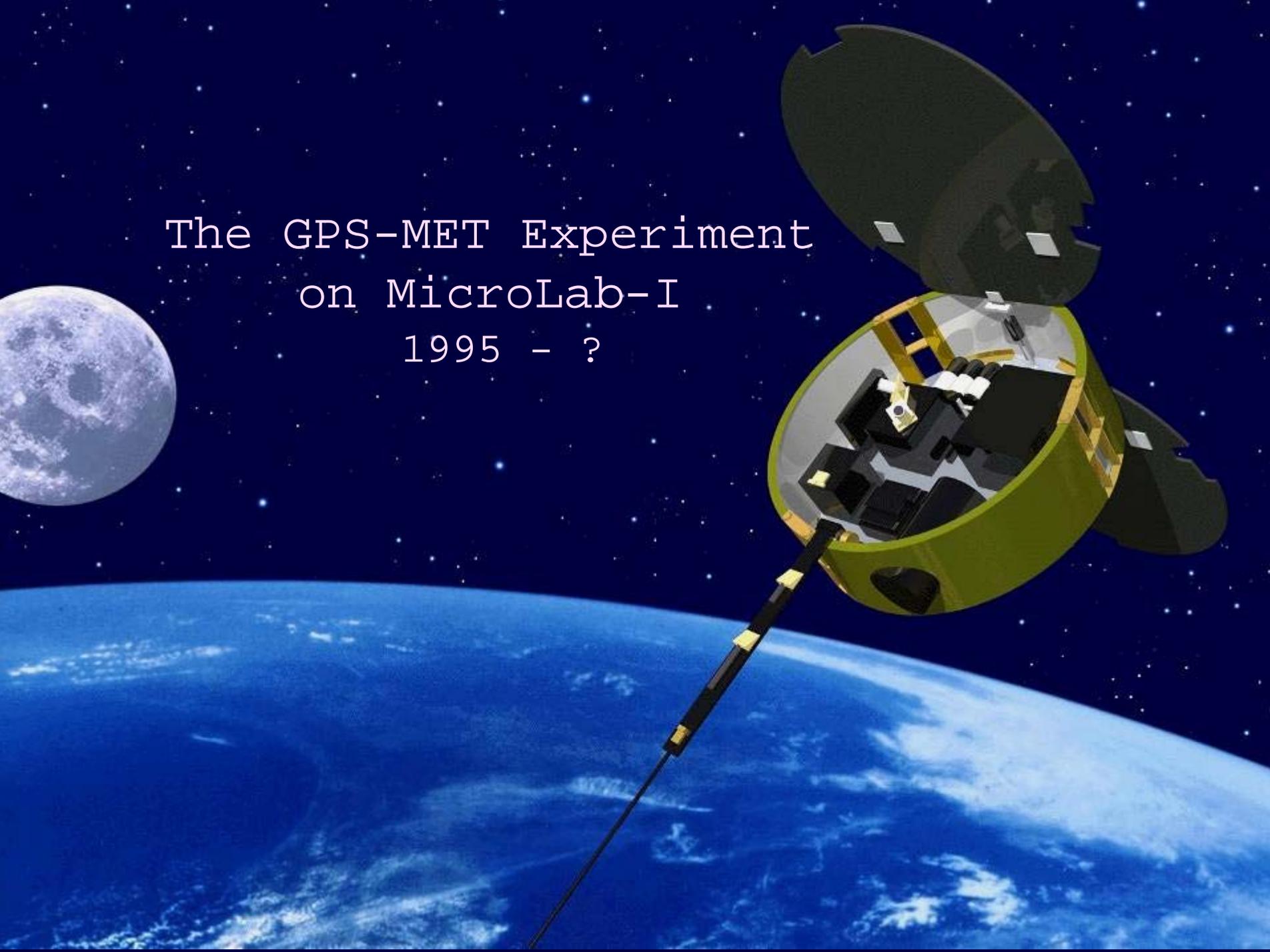
1. High accuracy: Averaged profiles to <0.05 K
2. Assured long-term stability
3. All-weather, day-night operation
4. Global 3D coverage: stratopause to surface
5. High vertical resolution: ~ 100 m in lower trop
6. Independent height & pressure/temp data
7. Compact, low-power, low-cost sensor



GeoOptics

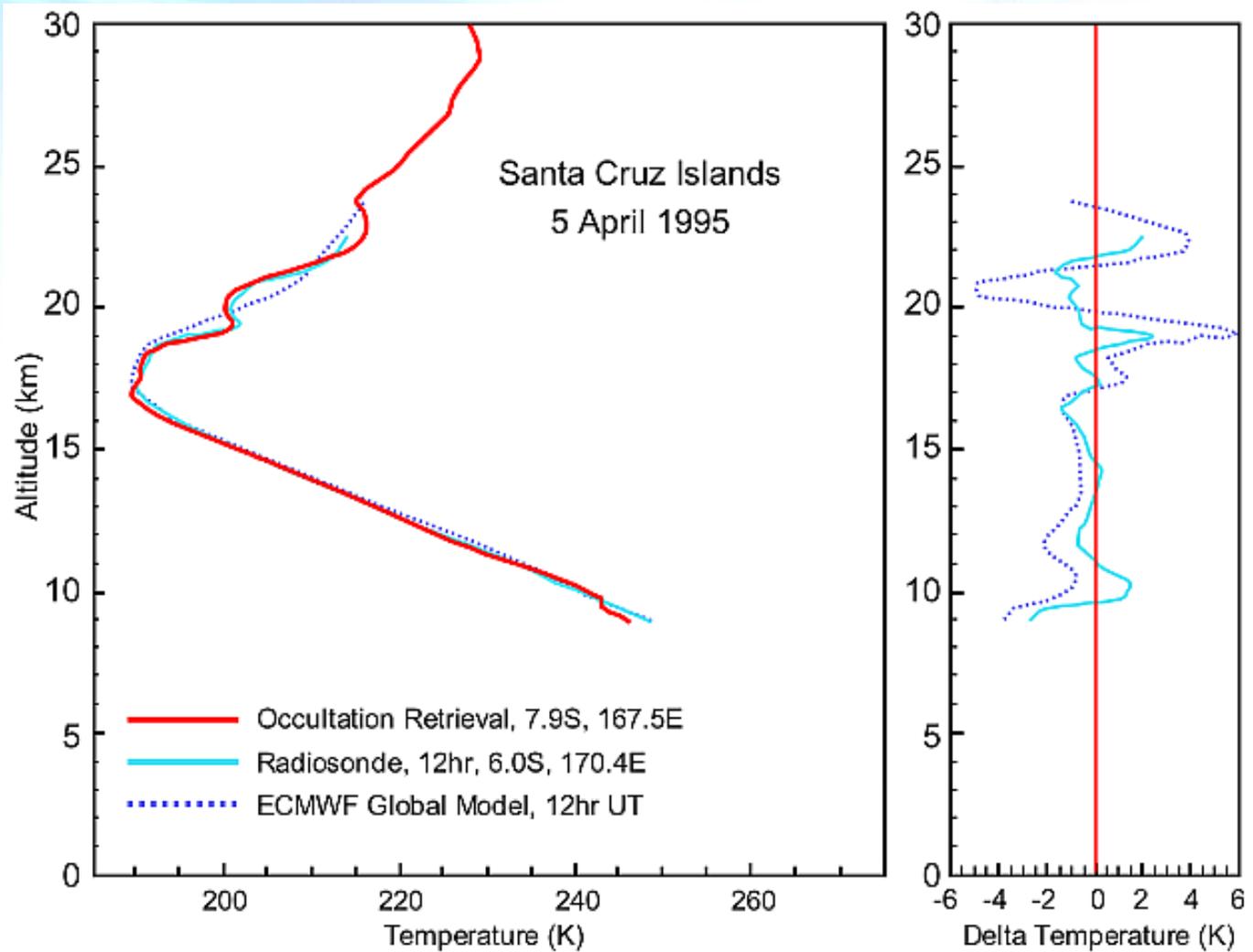
- Only technique that can monitor climate change throughout the atmosphere
 - Stunning new results from NCAR in hurricane forecasting

The GPS-MET Experiment
on MicroLab-I
1995 - ?



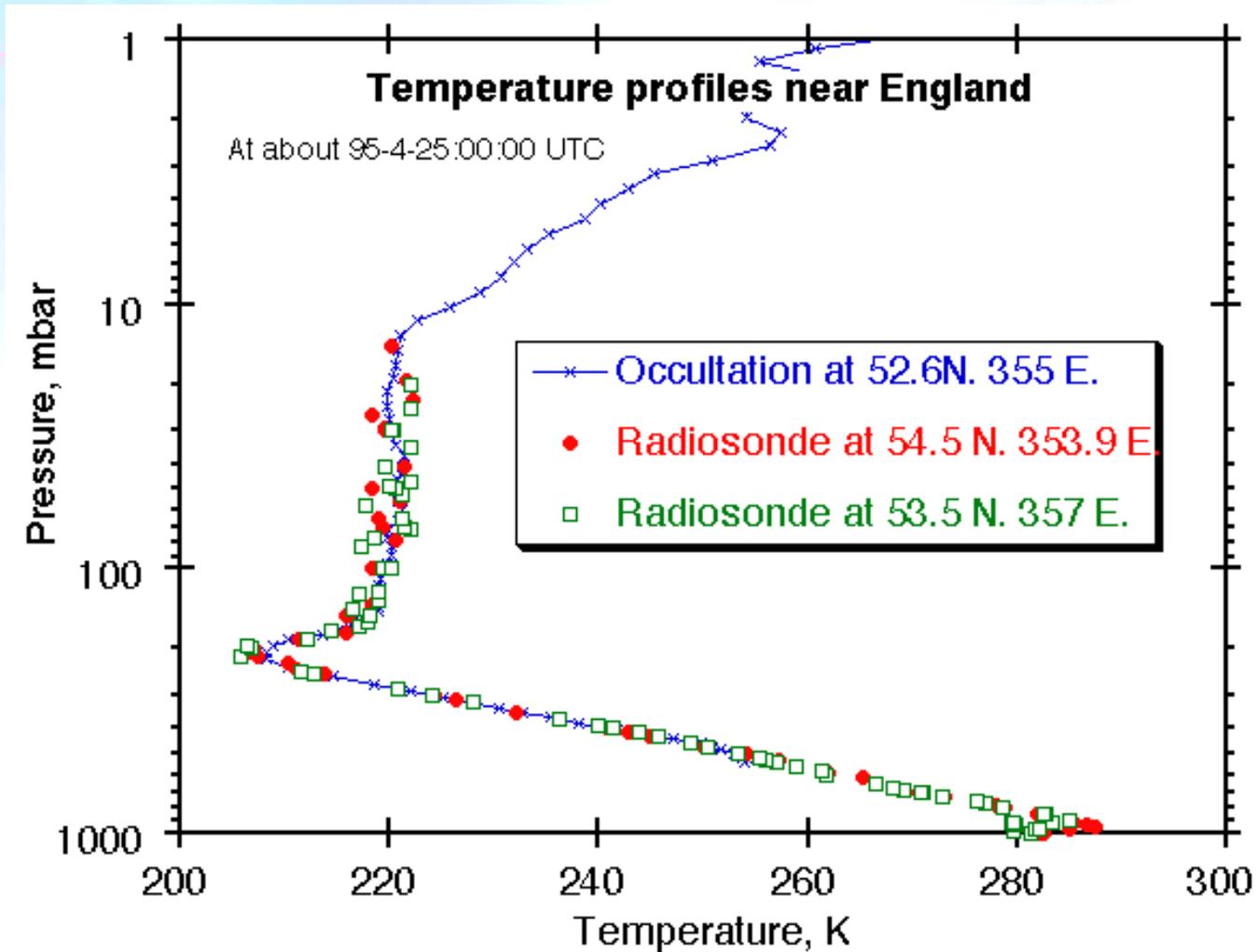


Early GPS-MET Profile (1995)



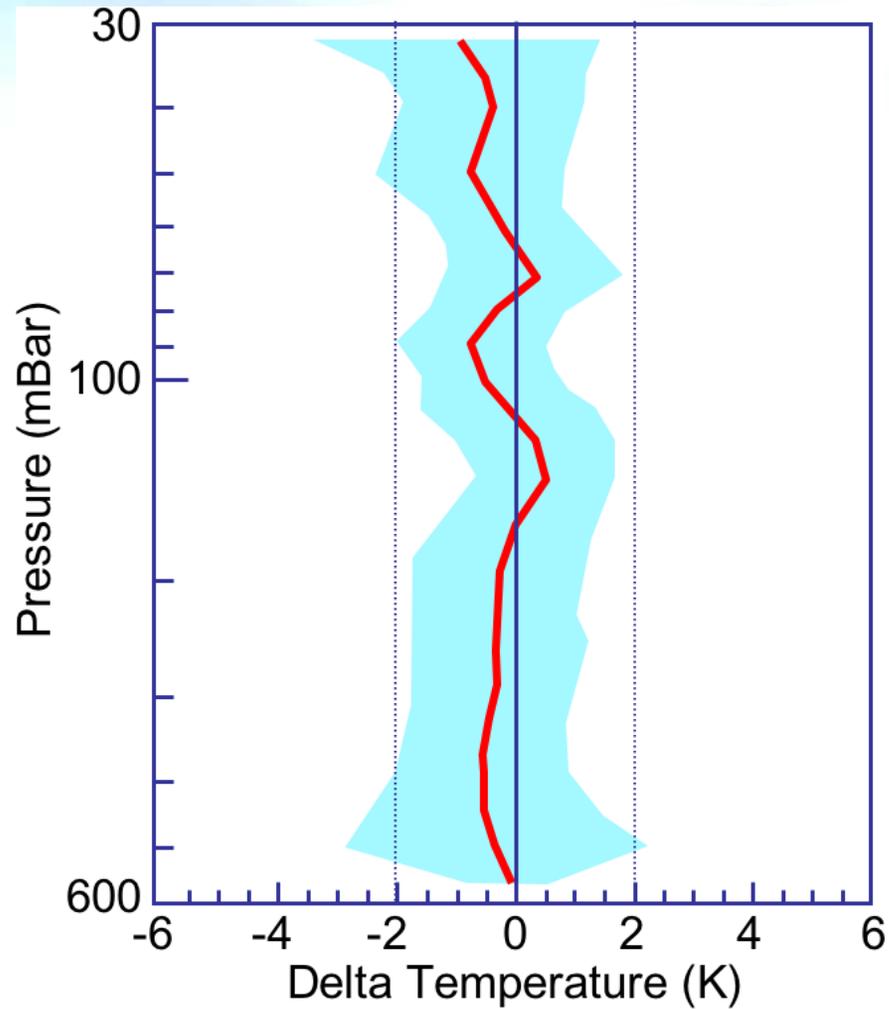


Early GPS-MET Profile (1995)

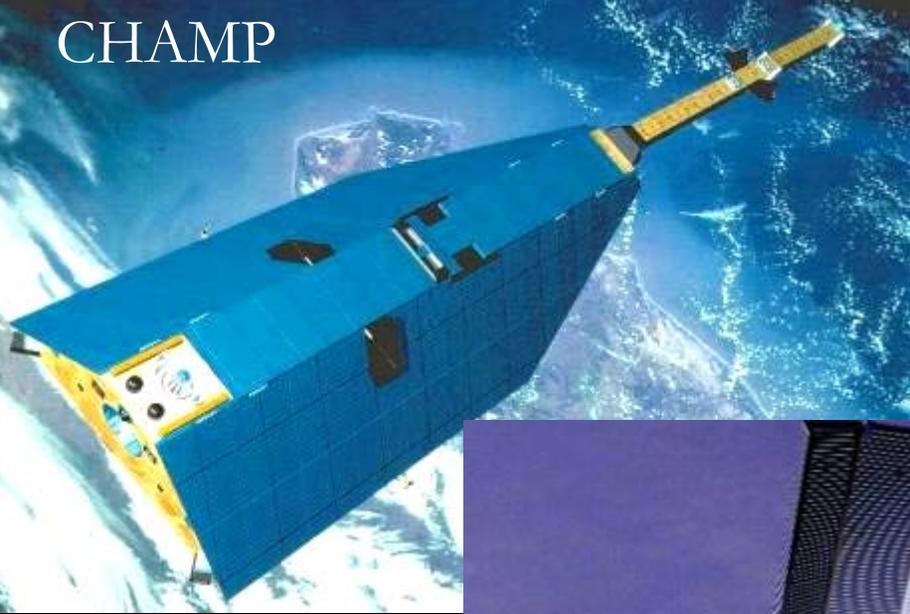




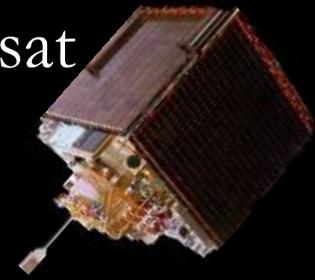
GPS-MET Agreement with Radiosondes (1995-96)



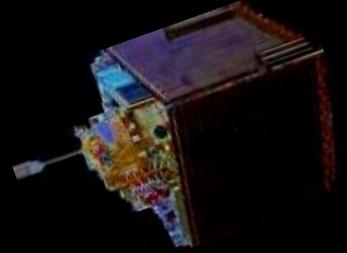
CHAMP



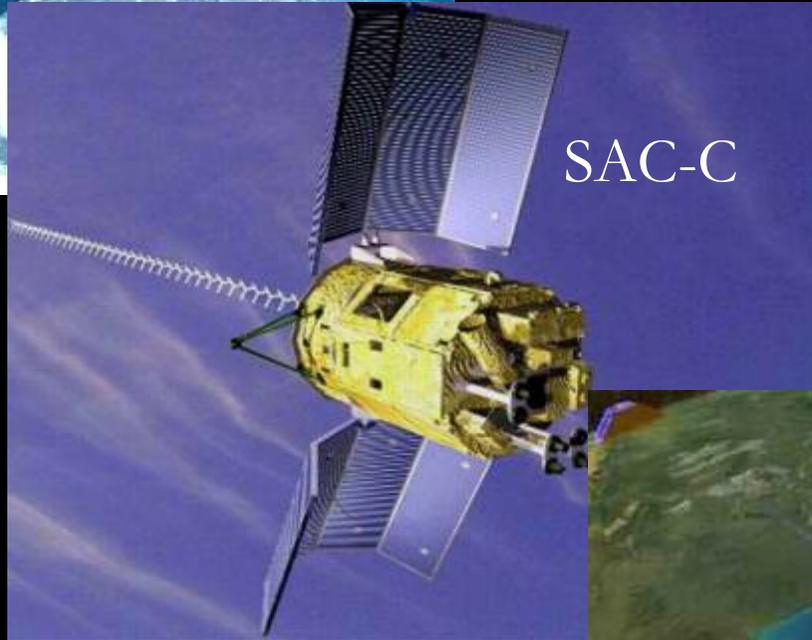
Sunsat



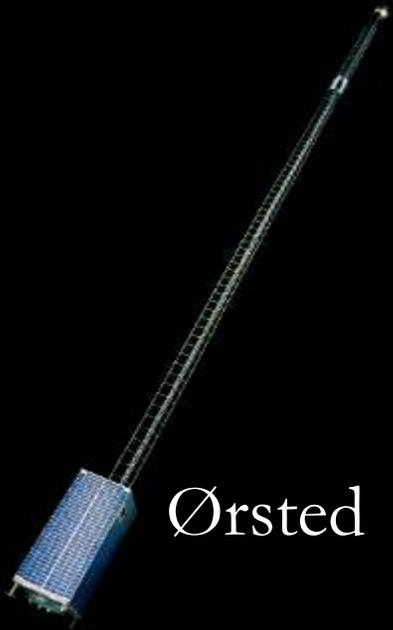
IOX



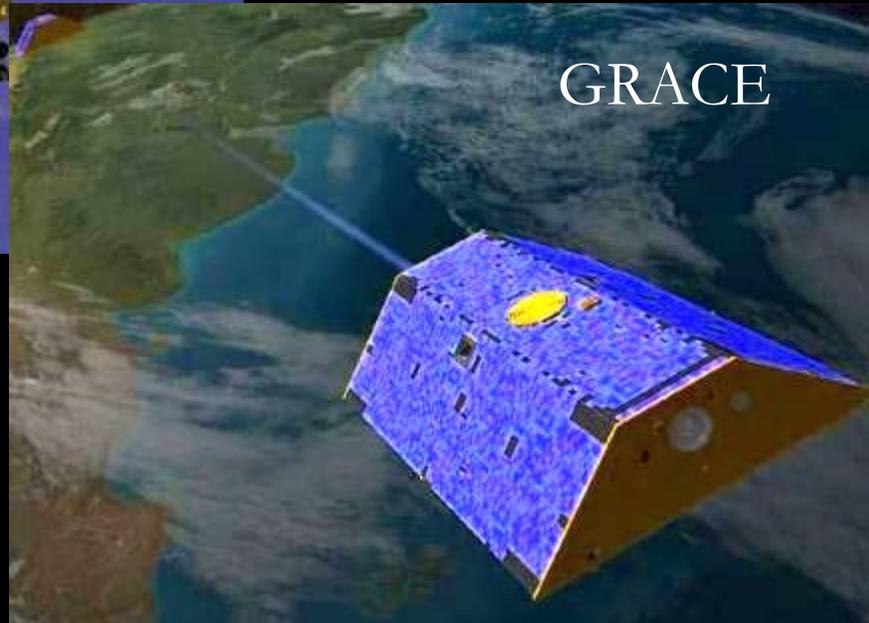
SAC-C



Ørsted

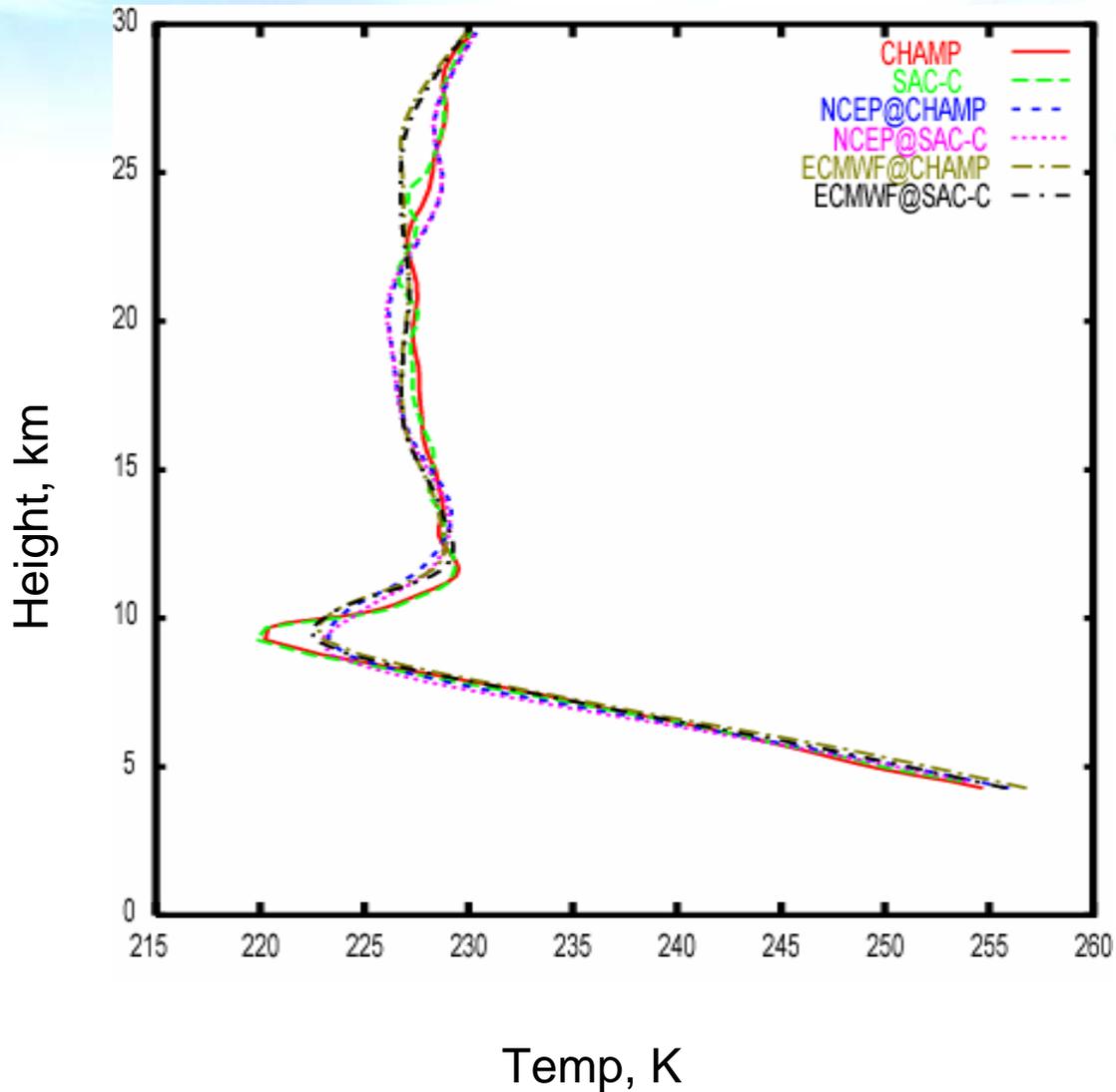


GRACE





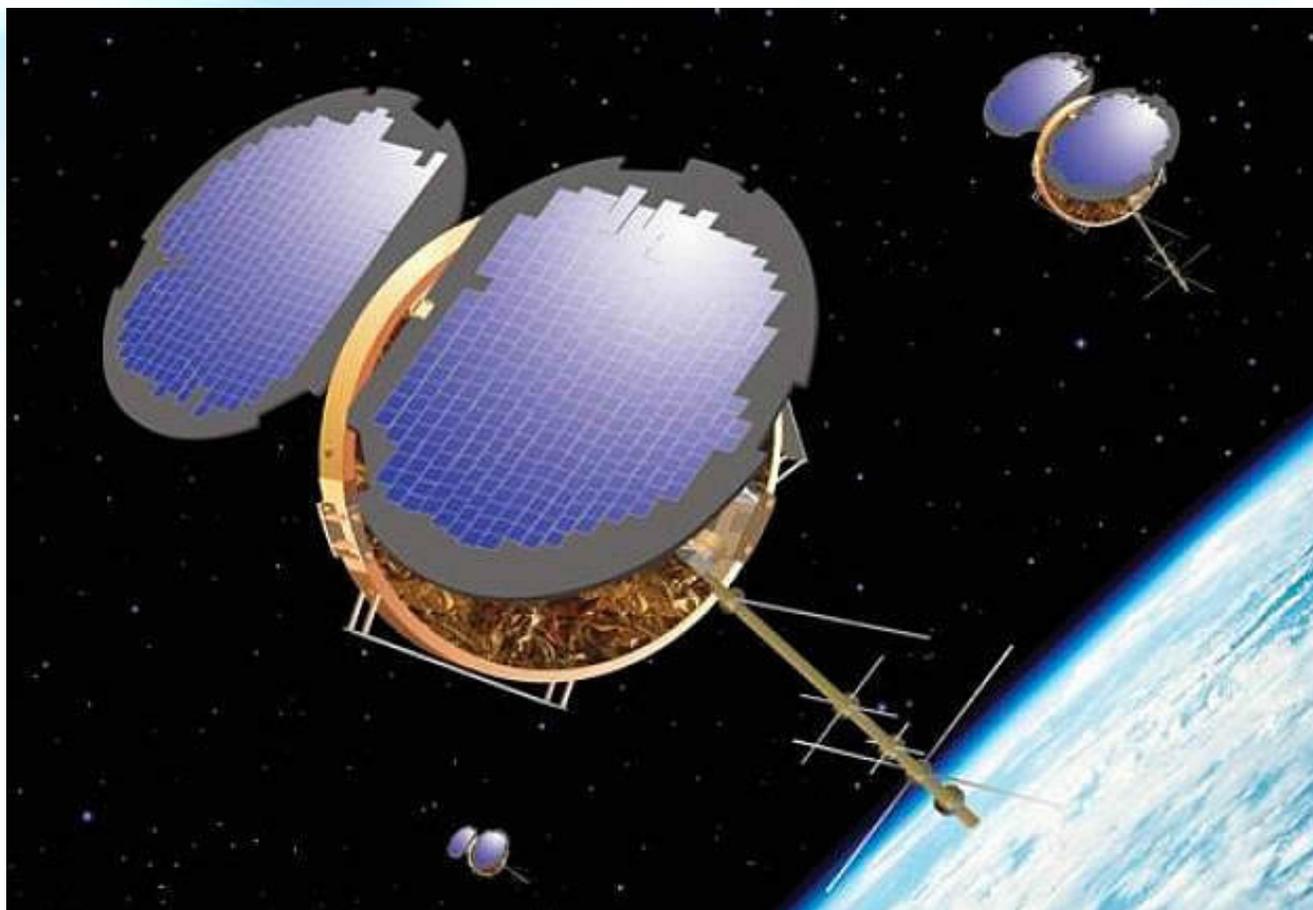
CHAMP-SACC Profile Comparison





Tour of GPS Radio Occultation

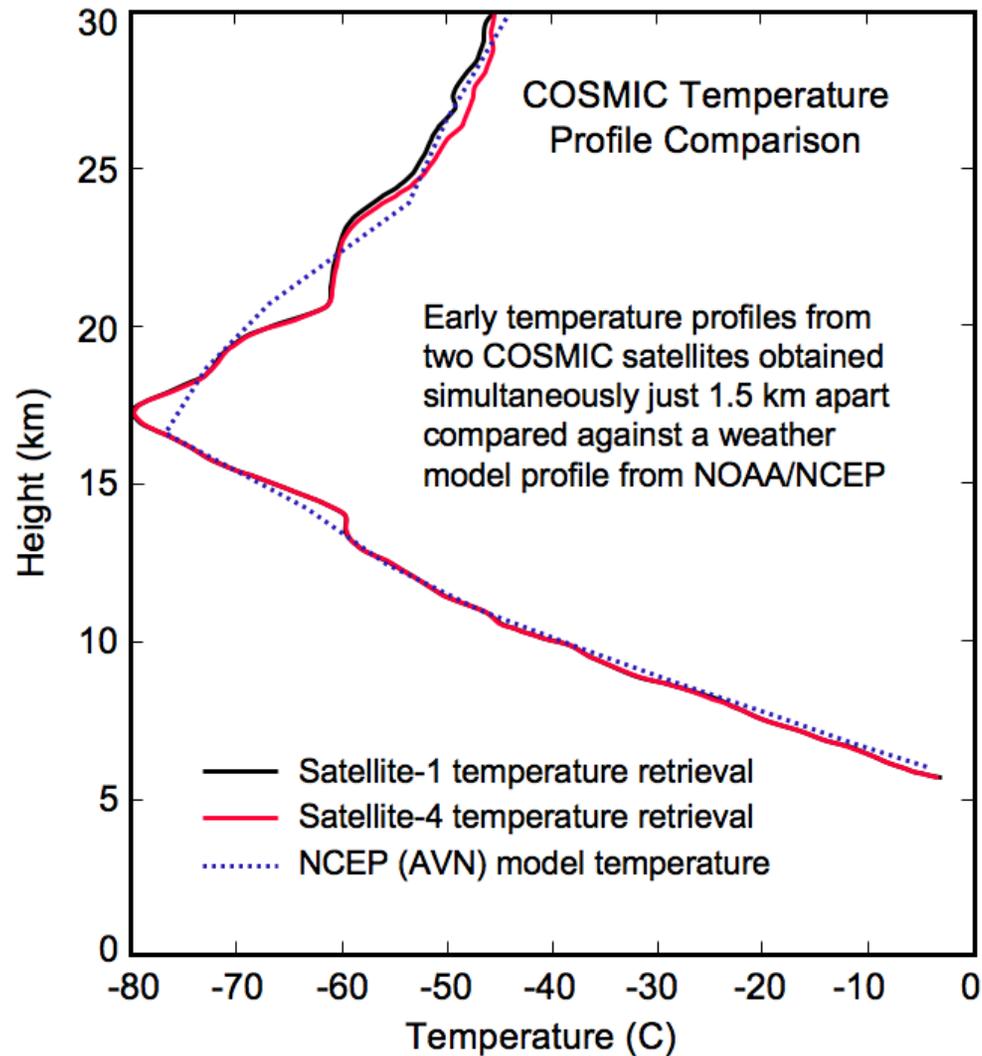
COSMIC: 2006 – ~2011



COSMIC is a 6-satellite mission funded by Taiwan and the US to demonstrate operational use of GPSRO. NCEP and other agencies around the world are now assimilating COSMIC data into their daily forecasts.

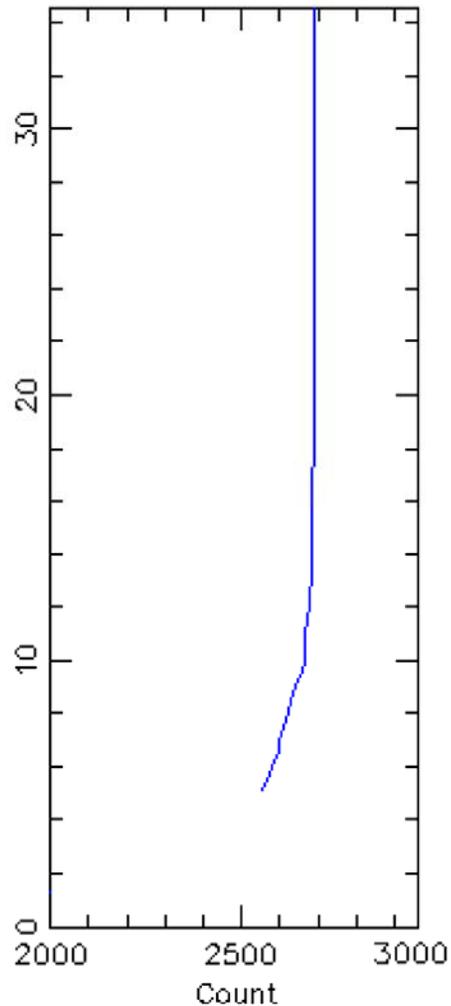
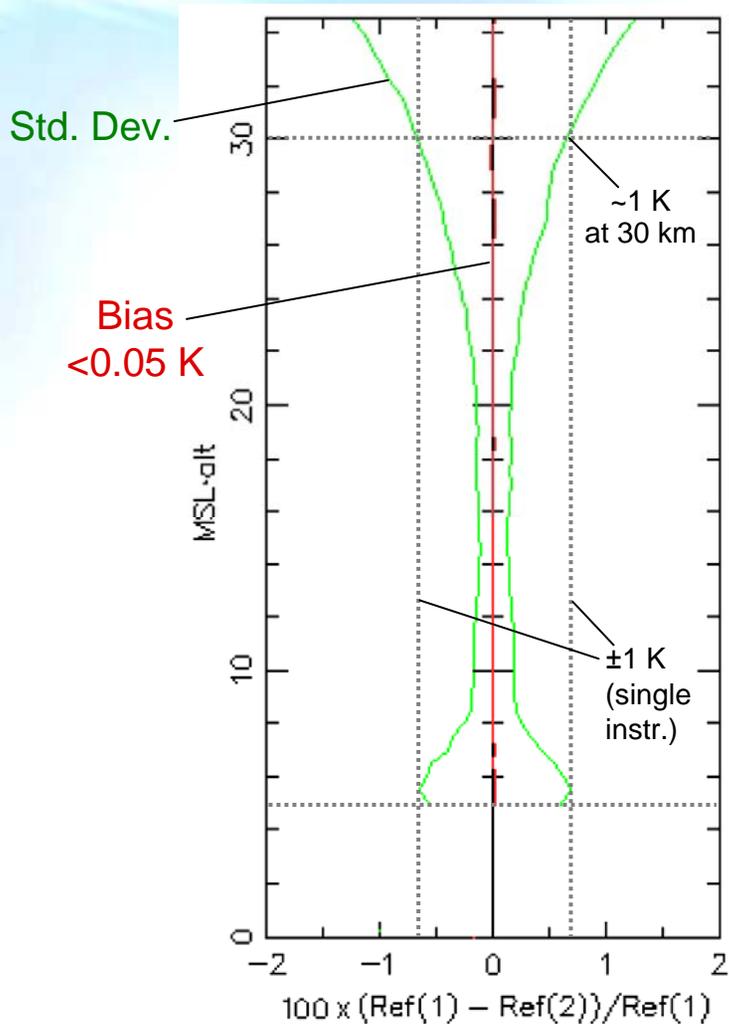


Early COSMIC Pair: <1.5 km separation





GPS-GPS Comparison Stats from COSMIC



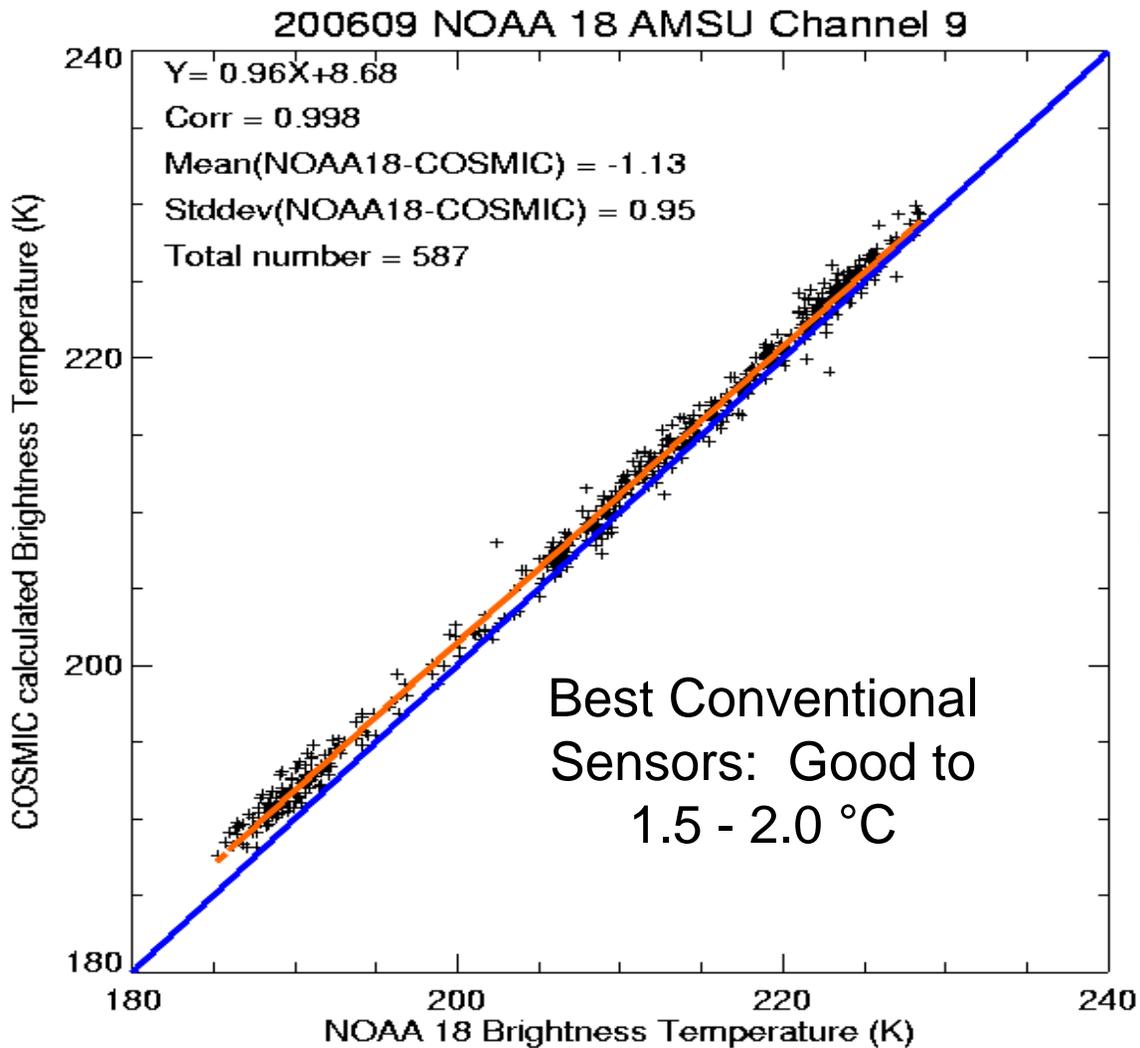
No cloud or weather sensitivity

No corrections or calibrations required

Performance traceable to an absolute SI standard



AMSU v. GPSRO



Inadequate
for climate
monitoring by
factor of 5-10

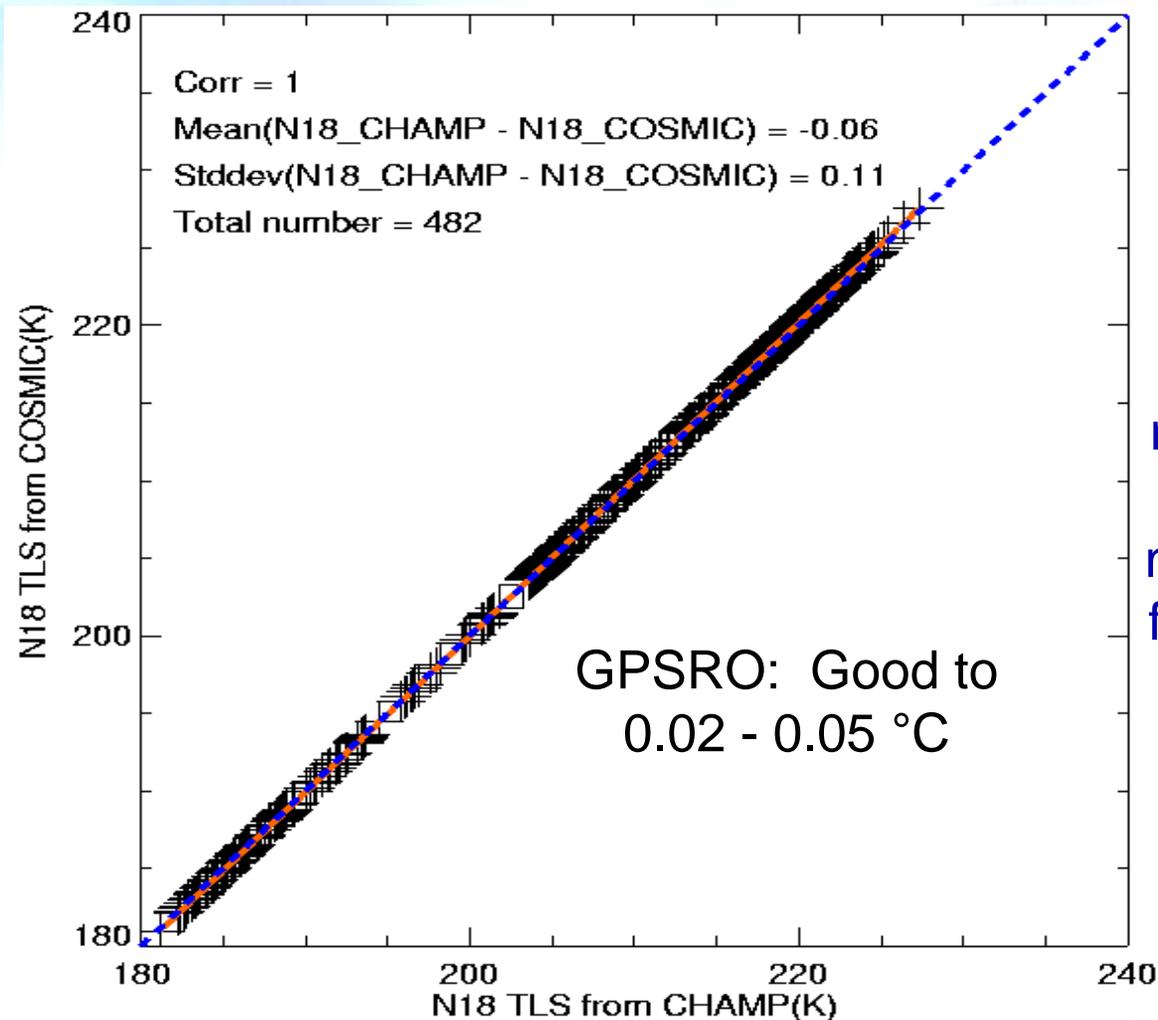
Best Conventional
Sensors: Good to
1.5 - 2.0 °C

Ben Ho (NCAR), Jan 07

AMSU v. COSMIC GPSRO



GPS v. GPS: Sensors Launched 6 yrs Apart



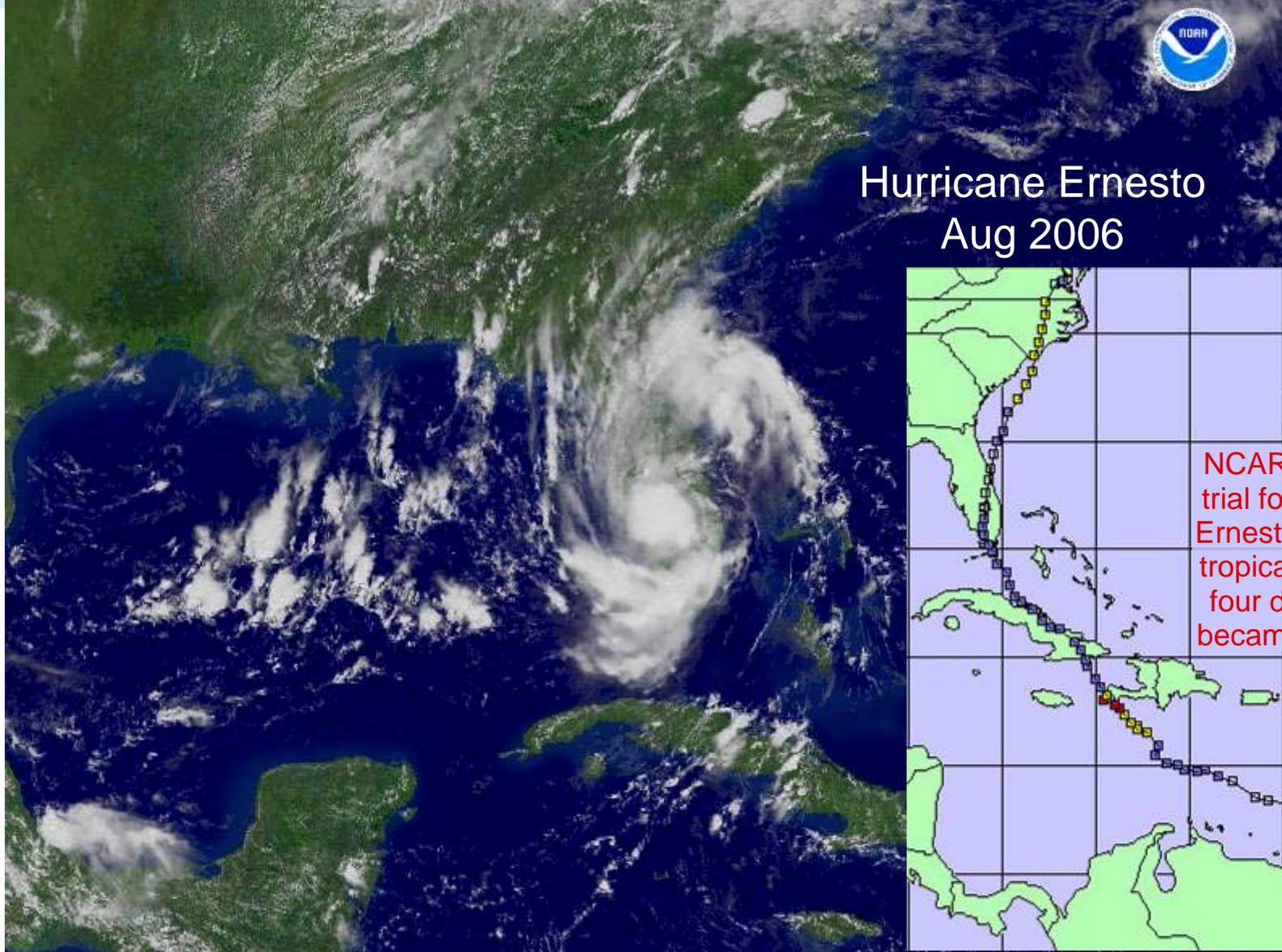
Surpasses
requirements
for climate
monitoring by
factor of 5-10

Ben Ho (NCAR), Jan 07

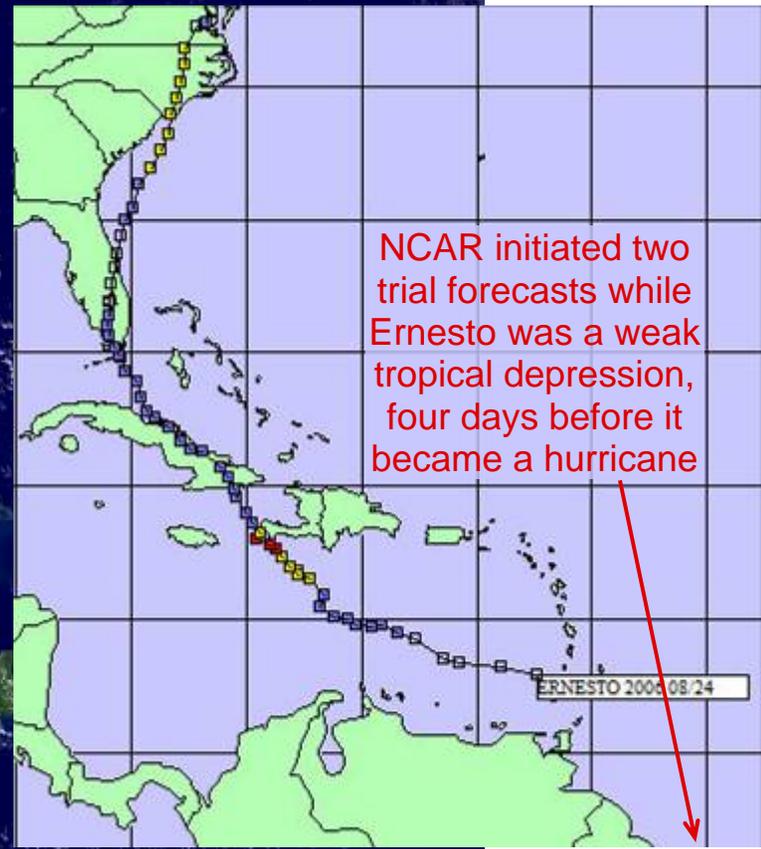
COSMIC GPS v. CHAMP GPS



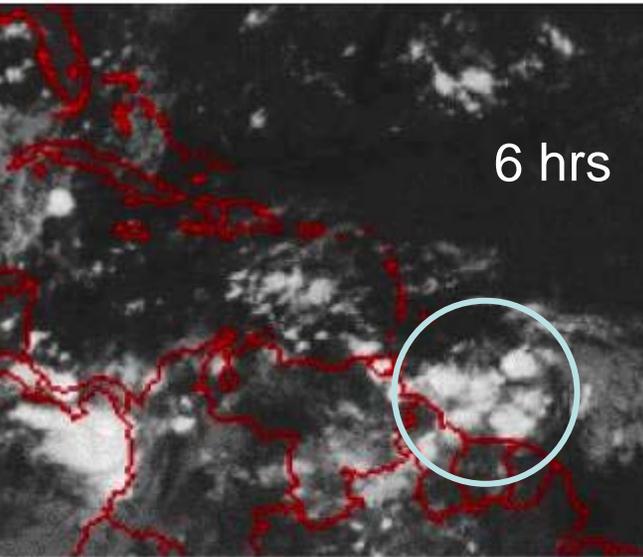
Severe Weather Forecasting



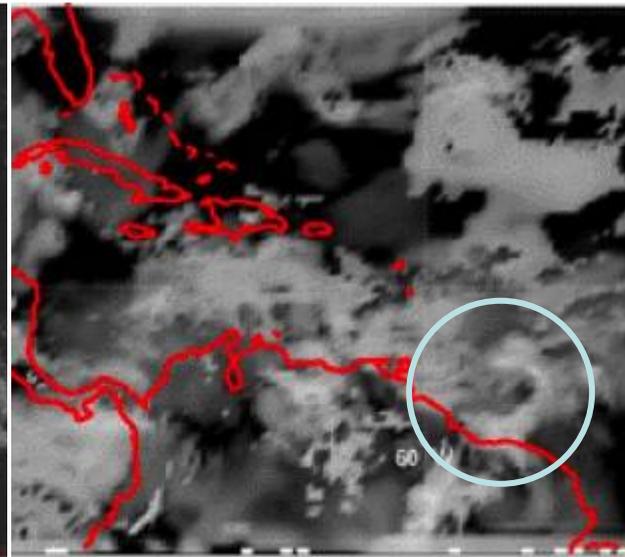
Hurricane Ernesto
Aug 2006



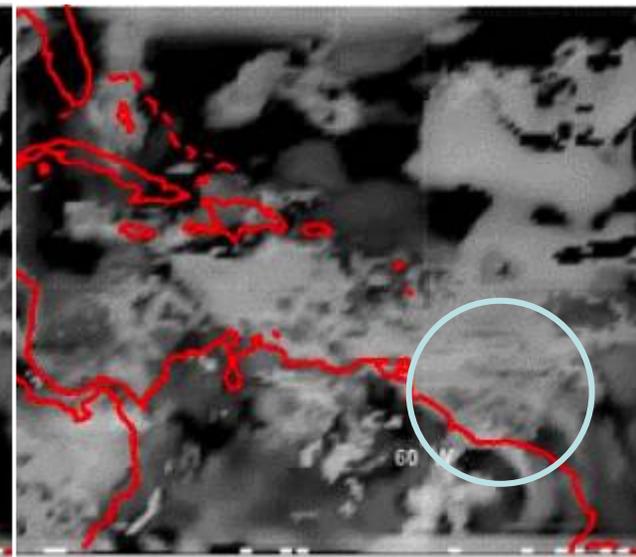
4-Day Ernesto Forecasts



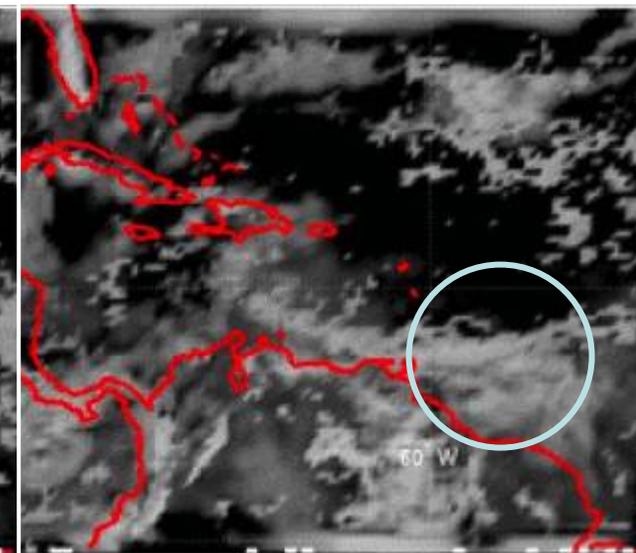
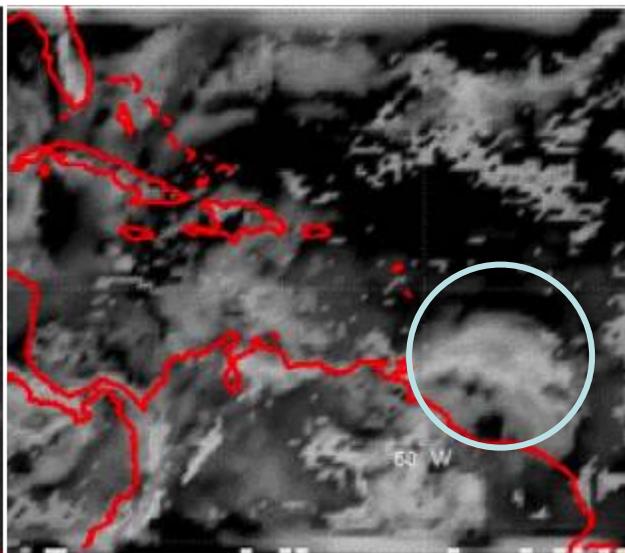
Satellite Photo



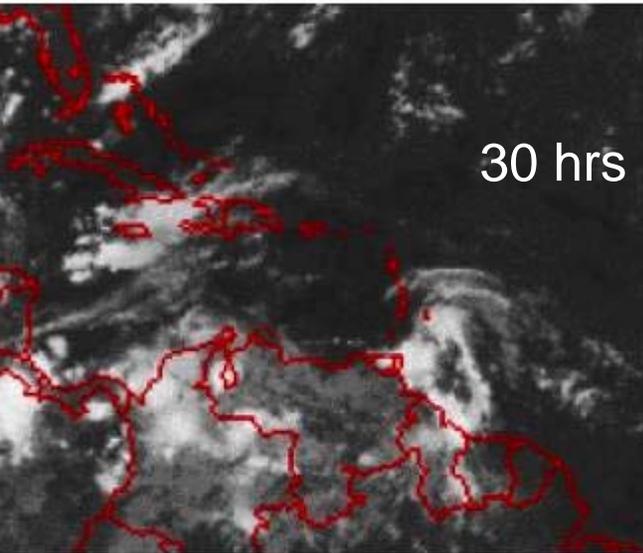
Forecast-1



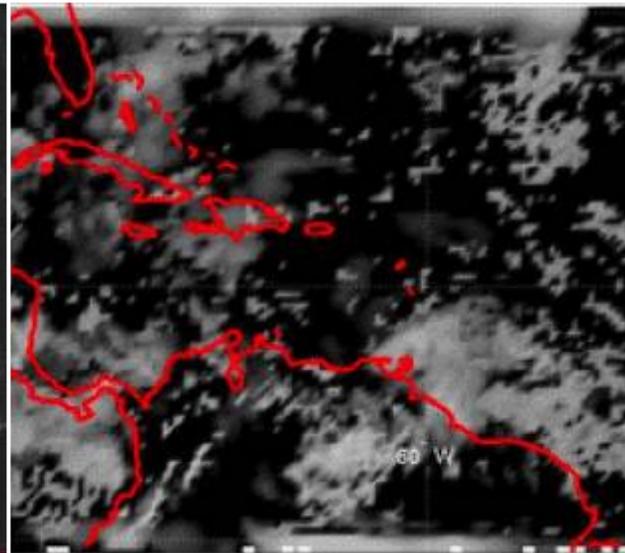
Forecast-2



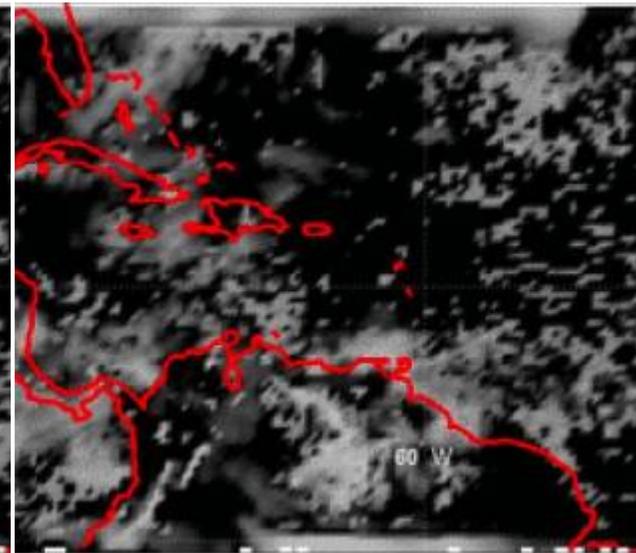
4-Day Ernesto Forecast



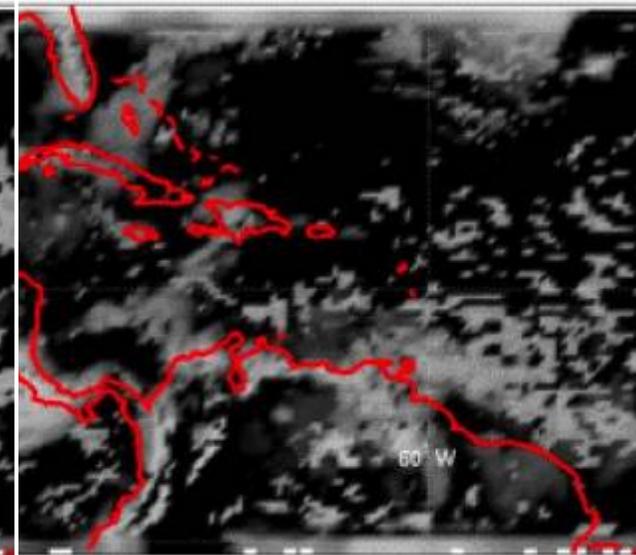
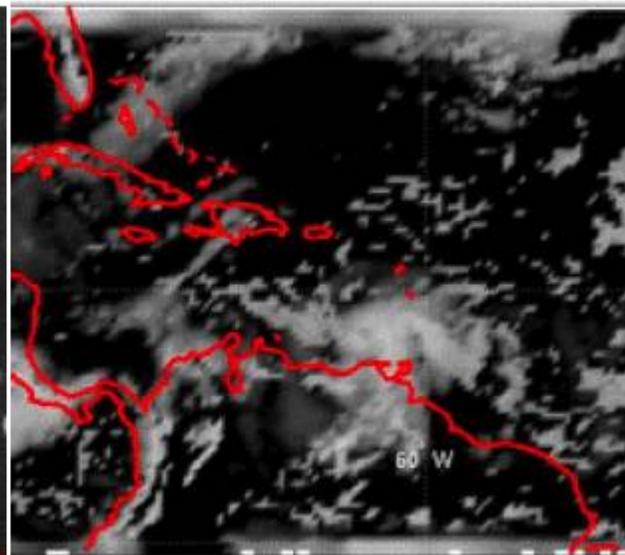
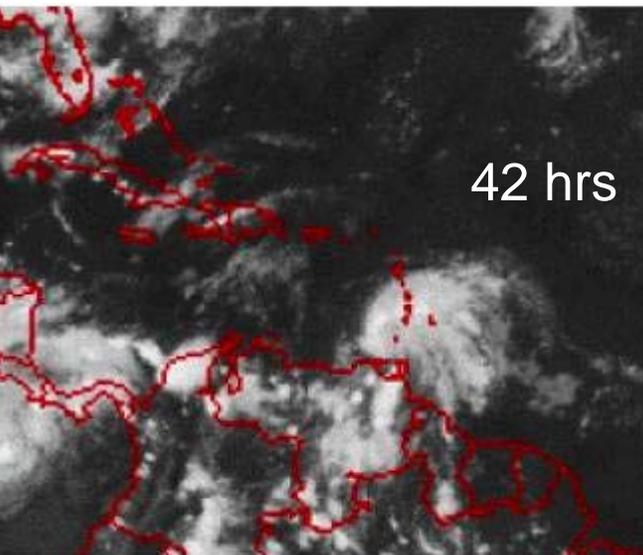
Satellite Photo



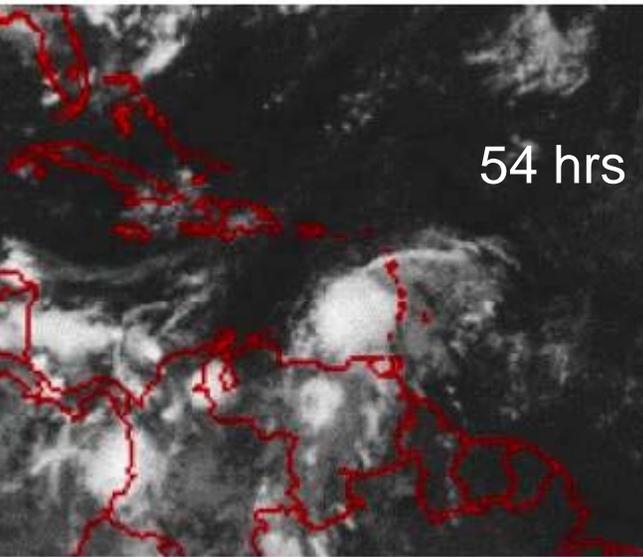
Forecast-1



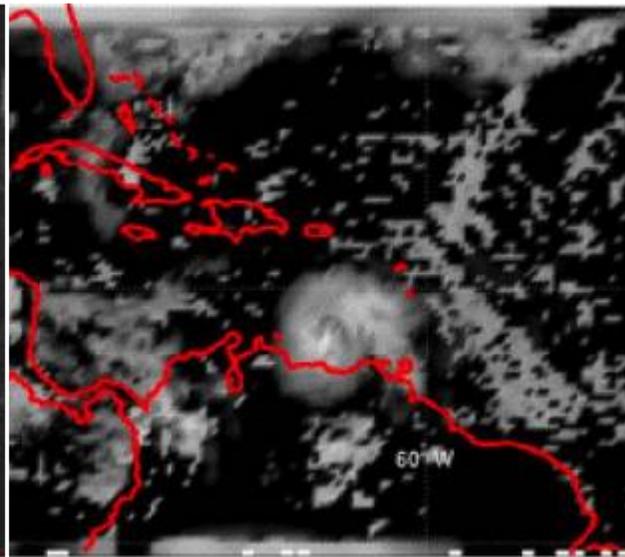
Forecast-2



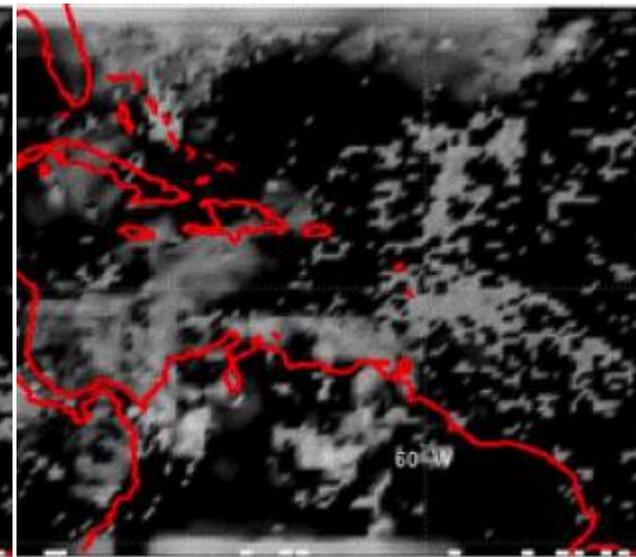
4-Day Ernesto Forecast



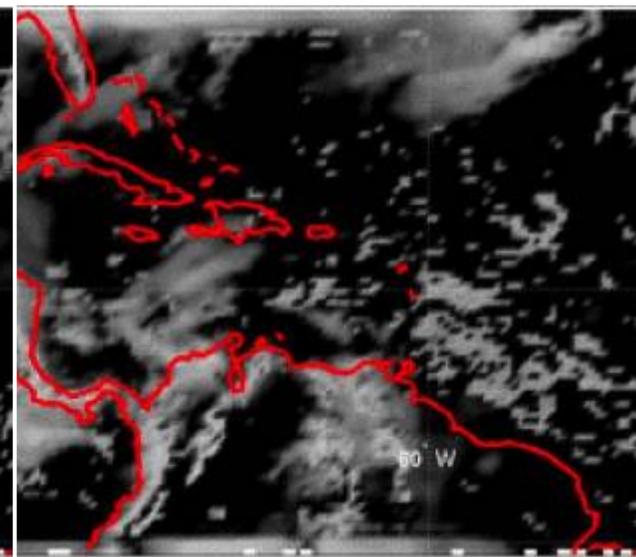
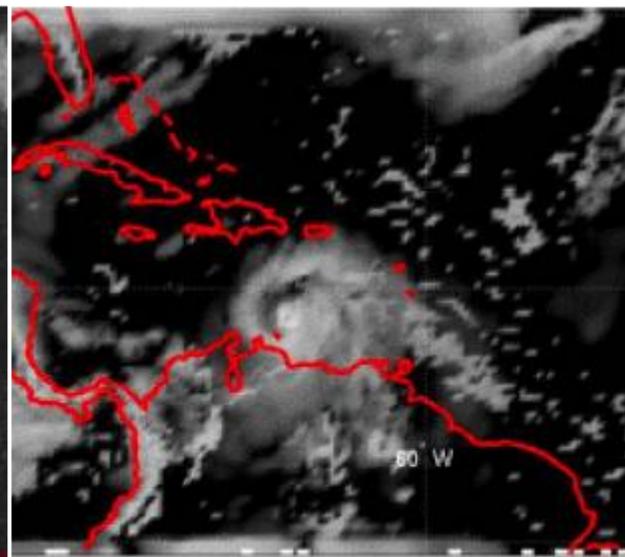
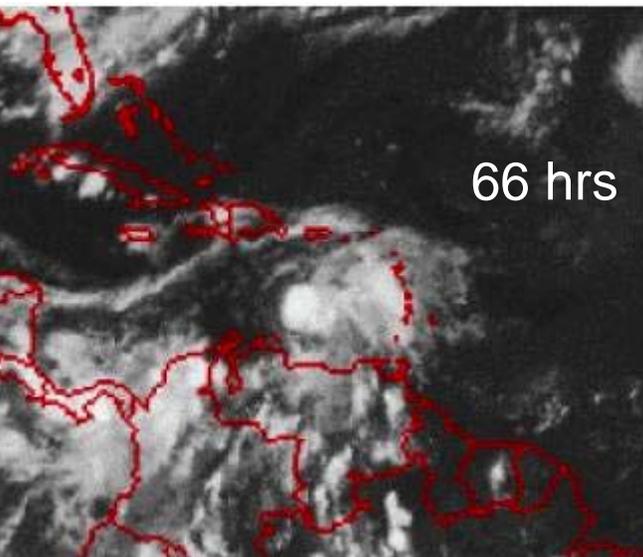
Satellite Photo



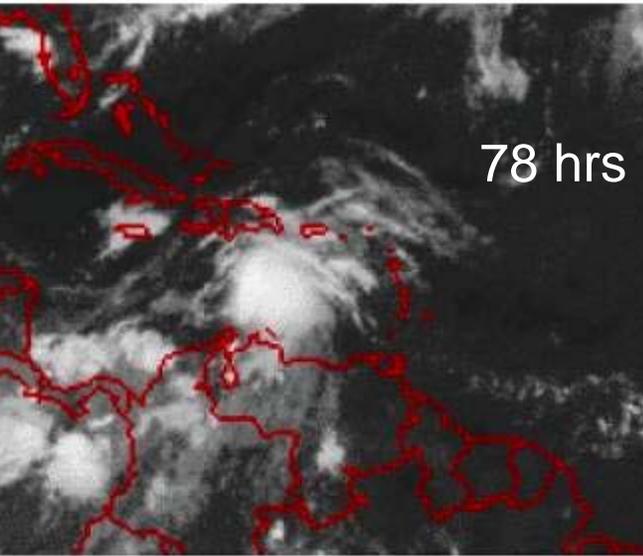
Forecast-1



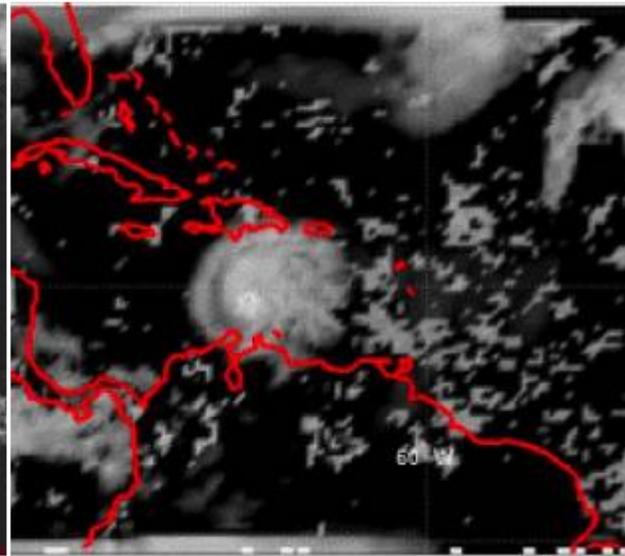
Forecast-2



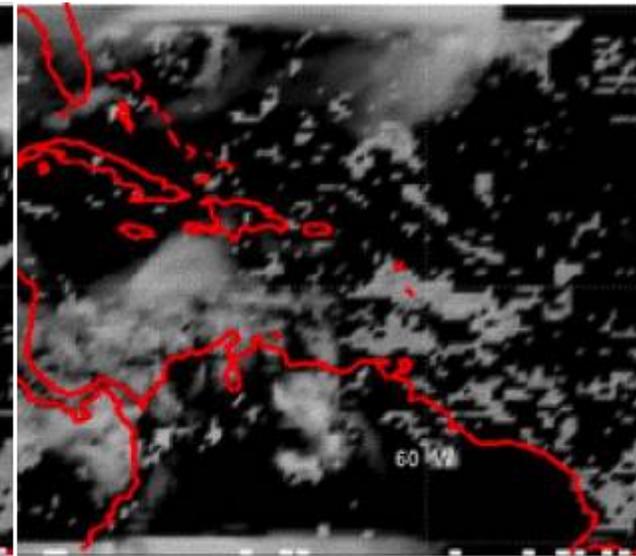
4-Day Ernesto Forecast



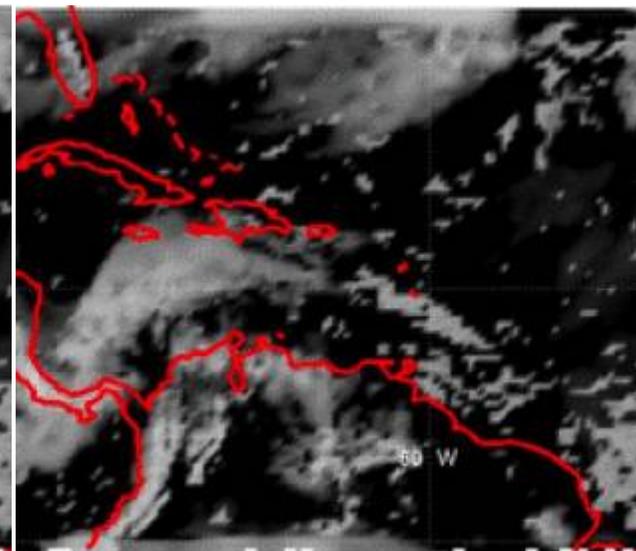
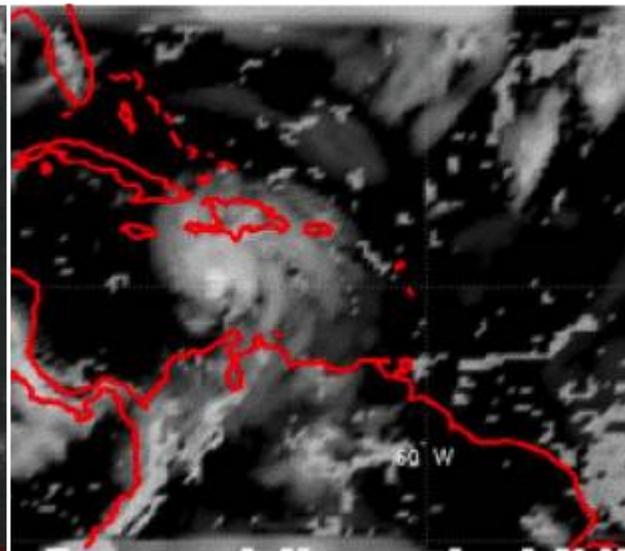
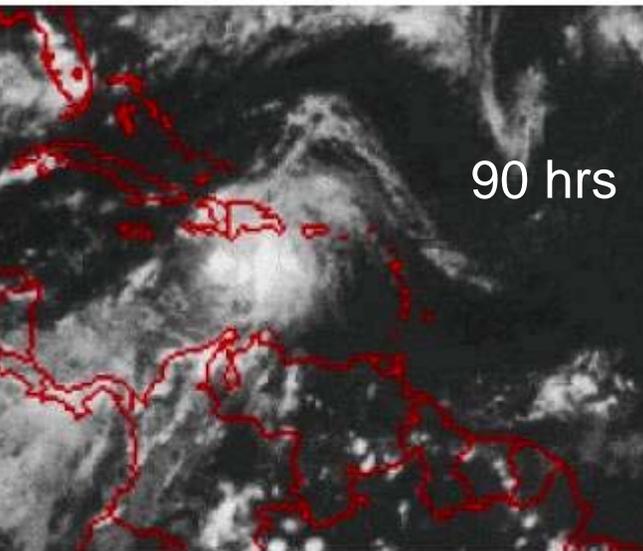
Satellite Photo



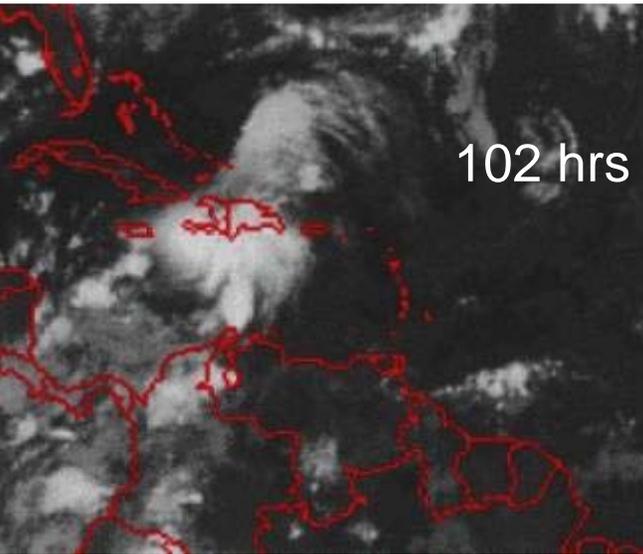
Forecast-1



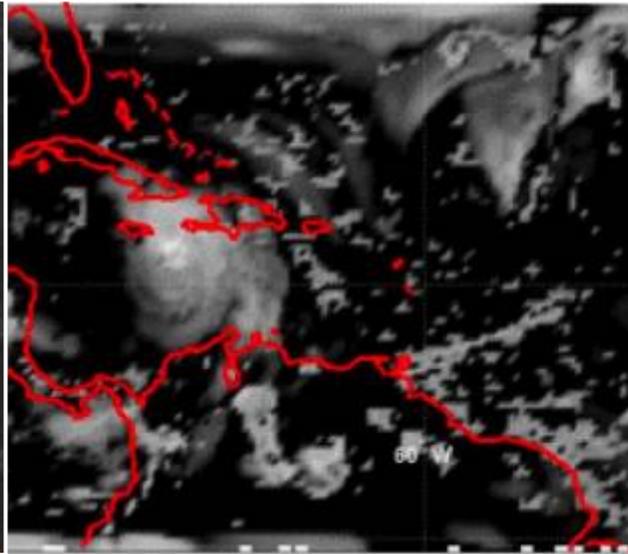
Forecast-2



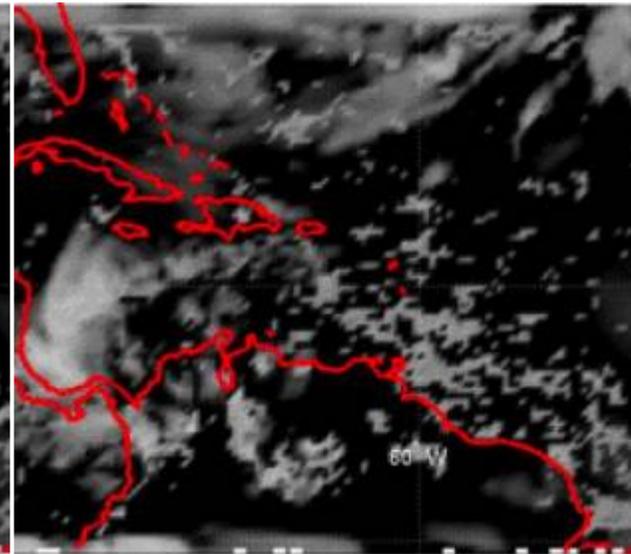
4-Day Ernesto Forecast



Satellite Photo



Forecast-1



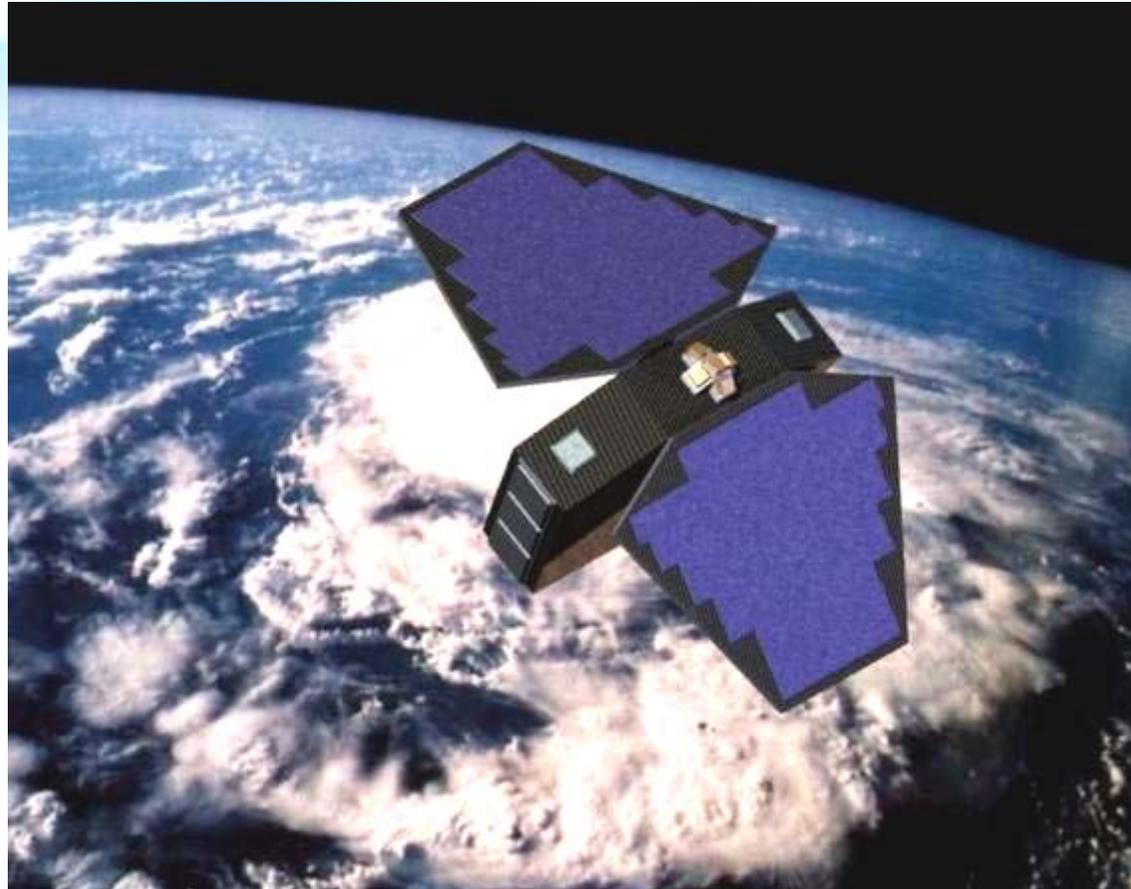
Forecast-2

Forecast-2: Best conventional forecast

Forecast-1: GPS added to Forecast-2



COSMIC-2: 201? – ??



Several COSMIC-2 proposals have been floated in recent years. These tend to be baselined at 6 satellites with optional expansion to 12. This image is from a 2005 UCAR proposal to NOAA. Estimated 10-year full life-cycle costs for an operational constellation typically run from 300M\$ for 6 satellites to 480M\$ for 12.



Tour of GPS Radio Occultation

Community Initiative for Continuing Earth Radio Occultation

The **CICERO** Project
Improving Earth Forecasts

GeoOptics

*"The world is so made that certain signs precede certain events."
-- Cicero, 44 B.C.
On Forecasting (i, 52)*

Forecasting...

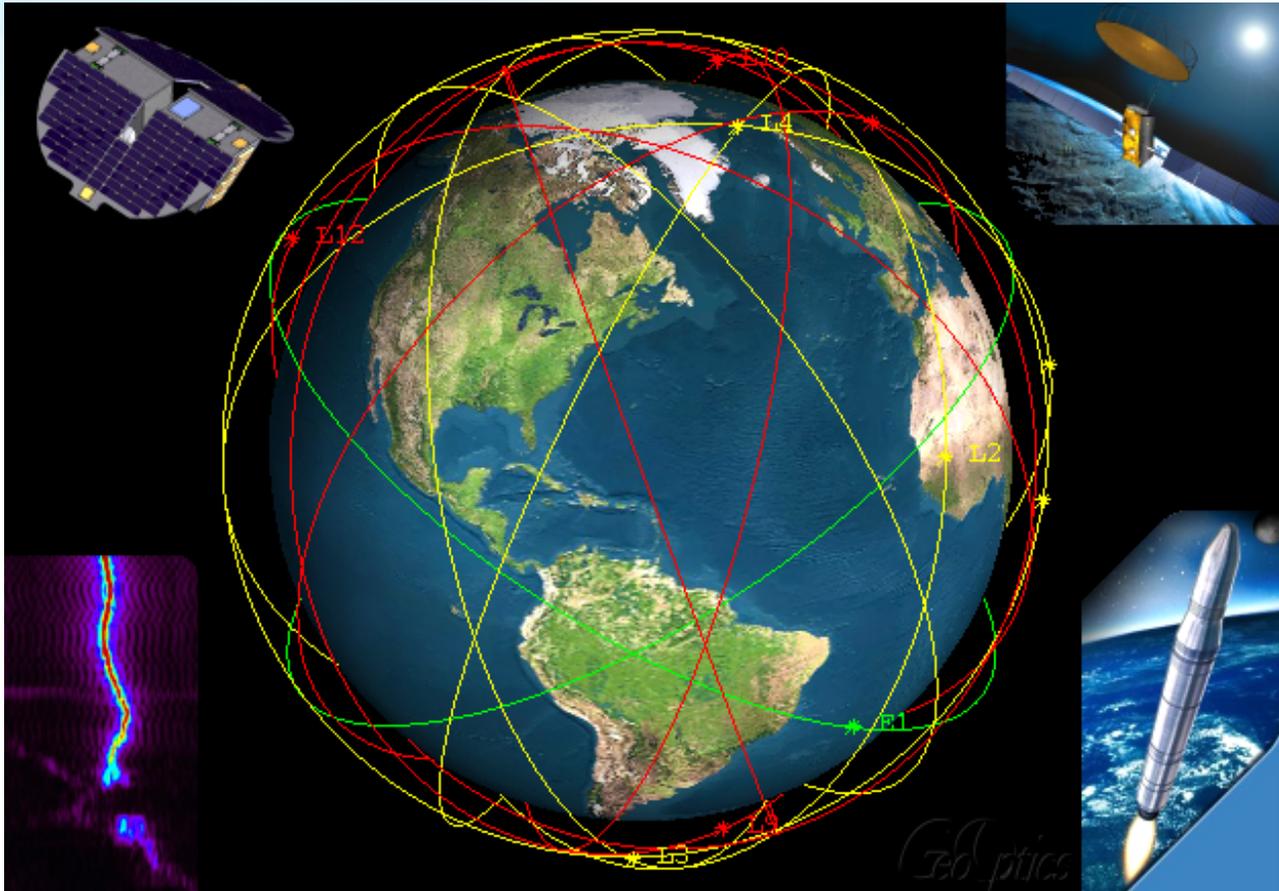
Climate **Weather**

Space Weather **Earth's Future**

Climate • Weather • Space Weather

Tour of GPS Radio Occultation

CICERO is a follow-on to COSMIC for performing operational GPS atmospheric radio occultation

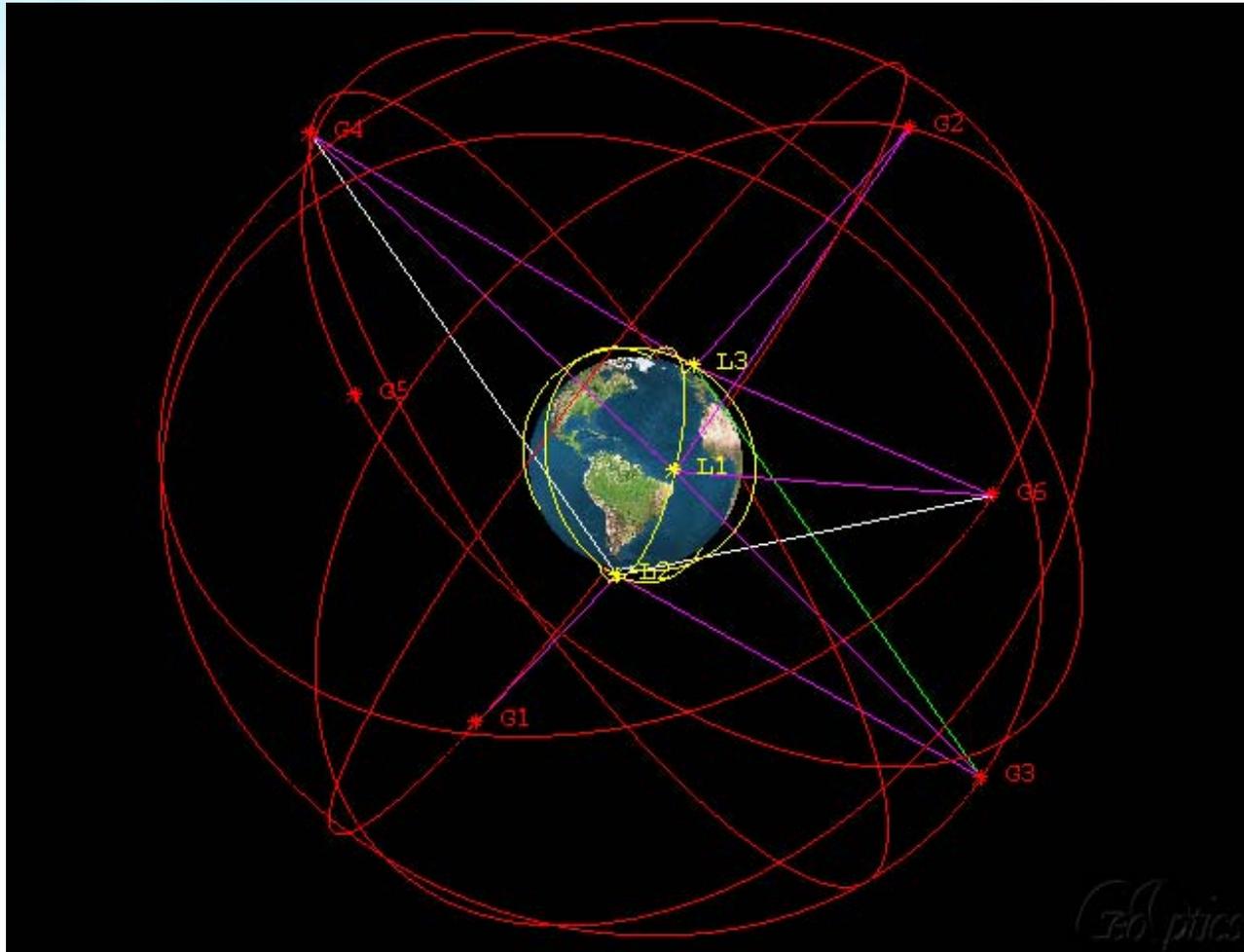


- 20 satellites by 2011
- 100 satellites by 2016



Tour of GPS Radio Occultation

CICERO will track signals from GPS and Galileo
(and later Glonass)

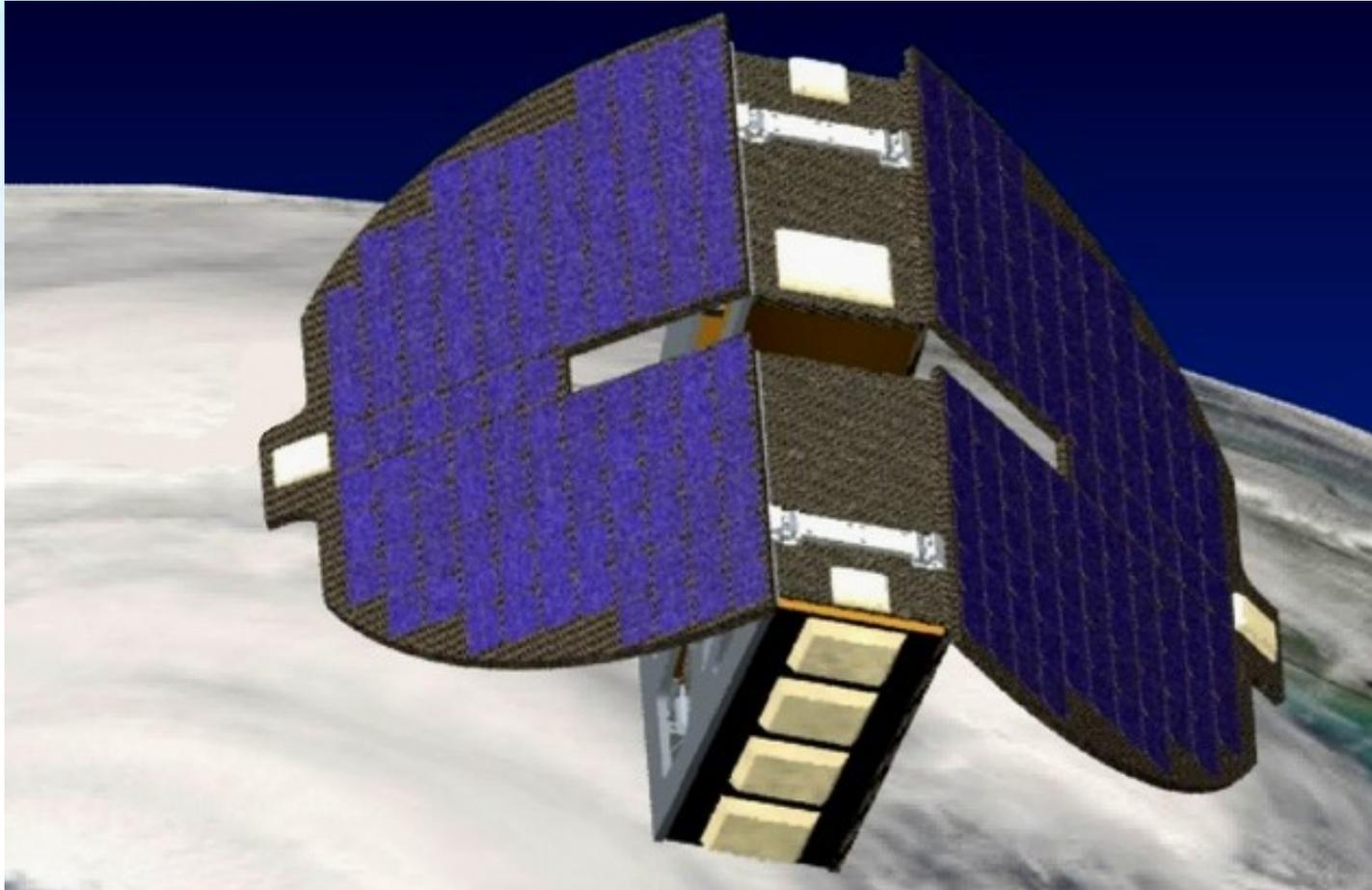


- 20,000 profiles/day by 2012
- 120,000 profiles/day by 2016



Tour of GPS Radio Occultation

The CICERO spacecraft weighs in at ~30 kg



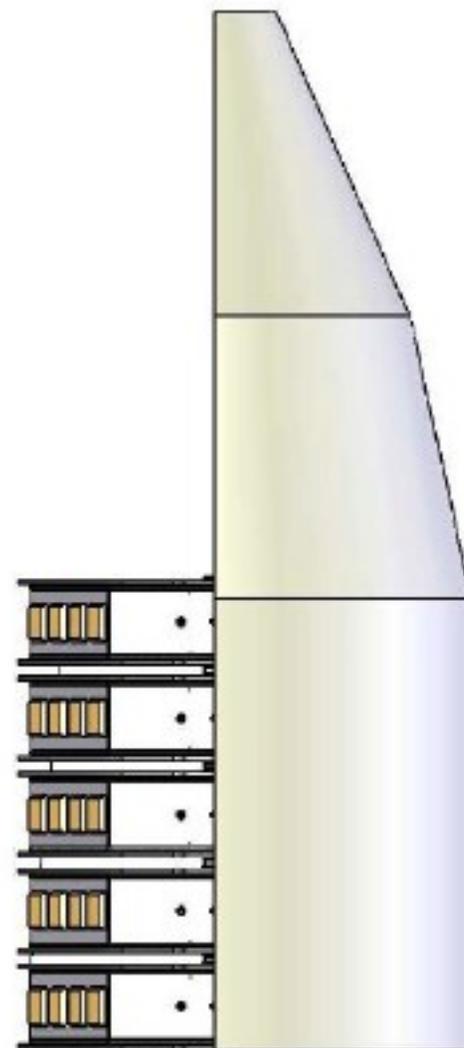
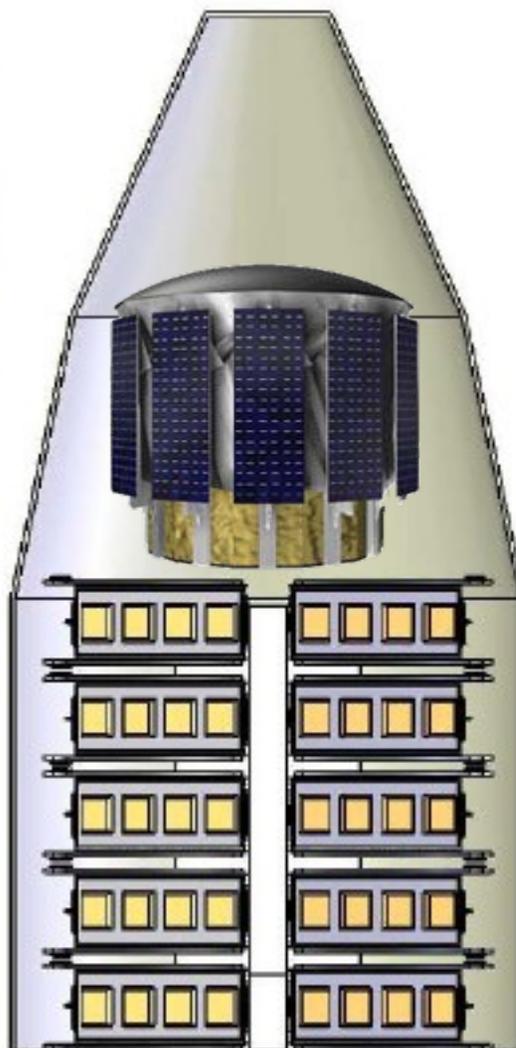
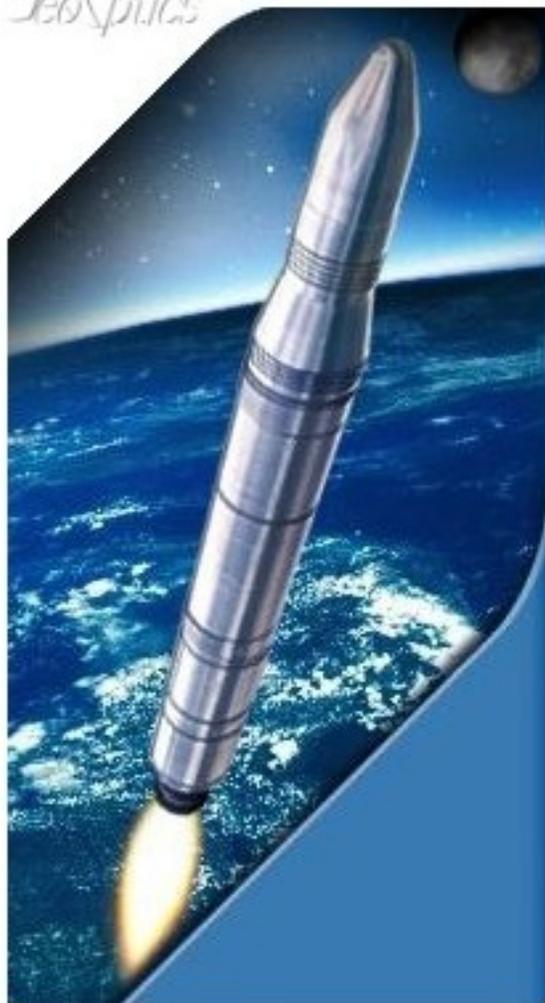
The instrument and spacecraft will be built by
Broad Reach Engineering of Golden, CO



Tour of GPS Radio Occultation

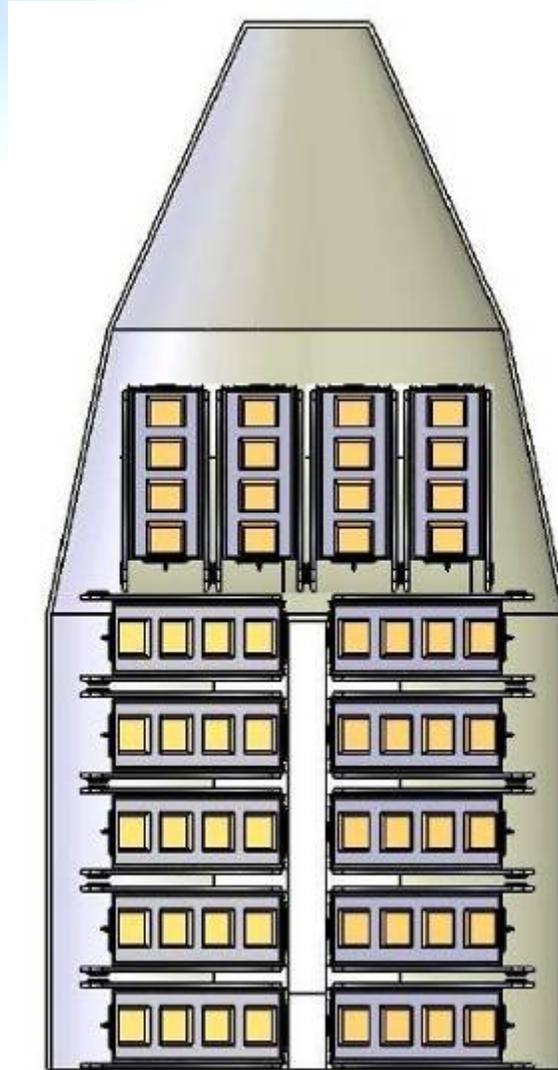
Up to 14 sats can be launched on a Falcon-1

GeoOptics





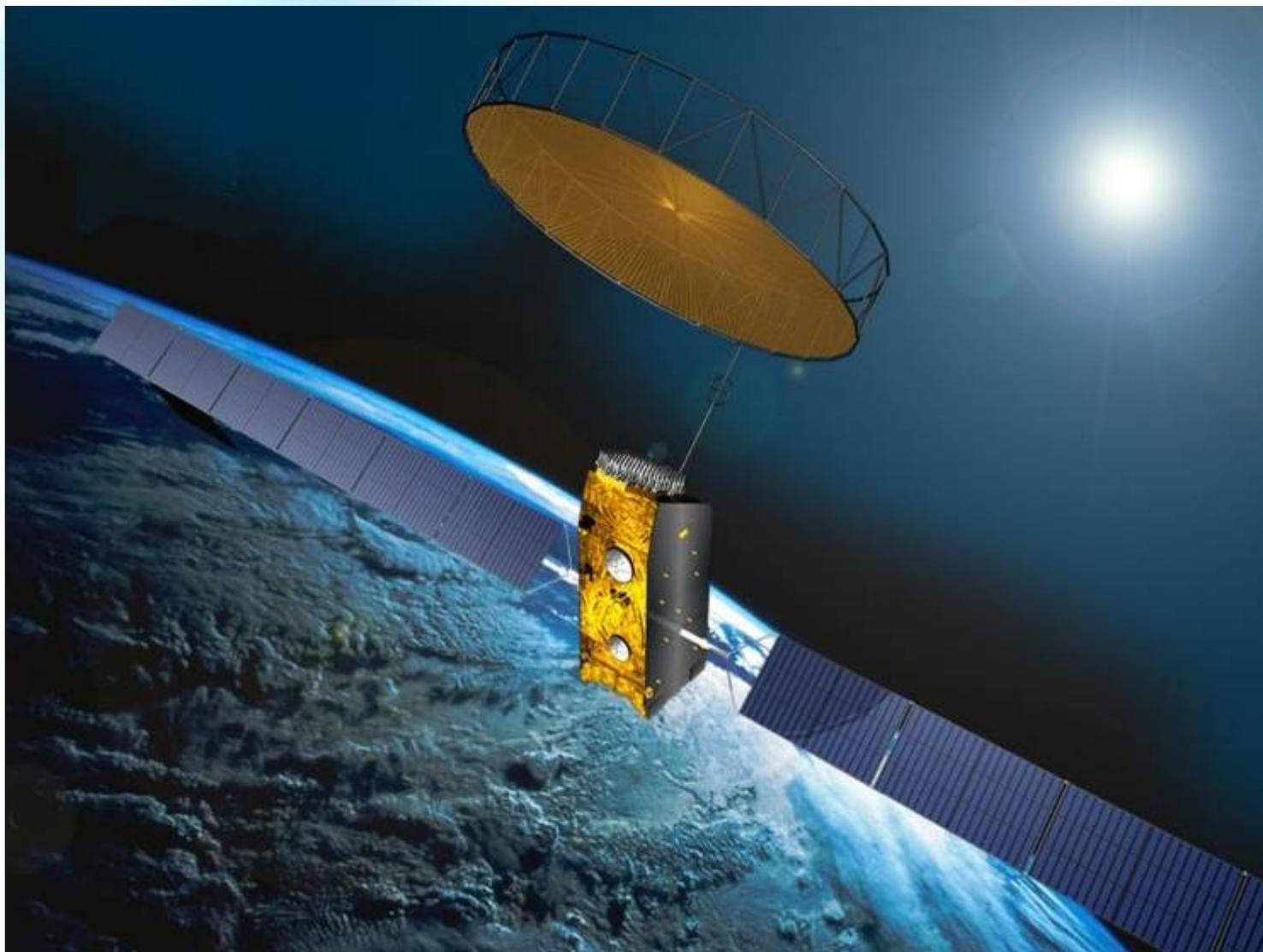
Tour of GPS Radio Occultation





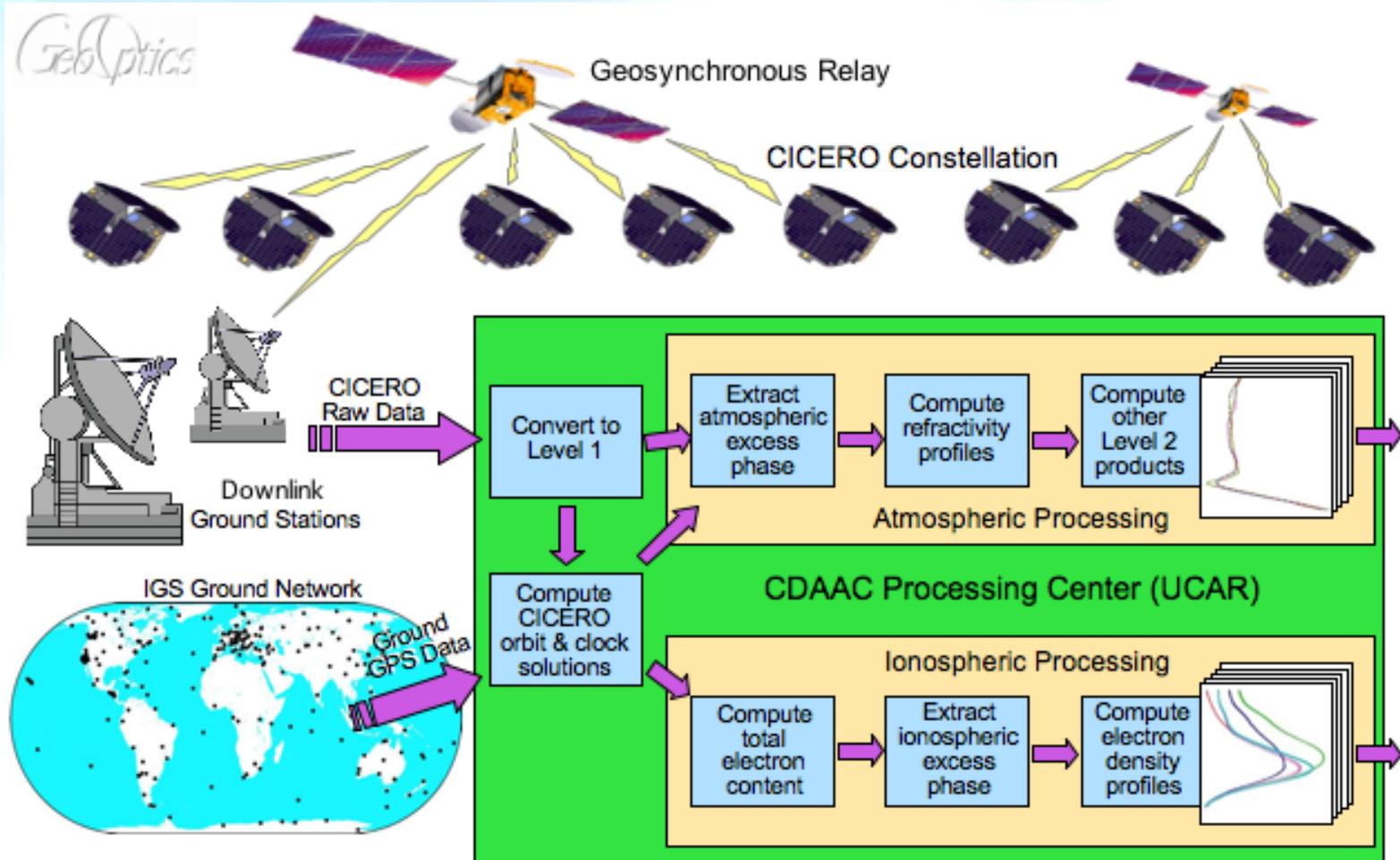
Tour of GPS Radio Occultation

Data Return by Geosynchronous Relay





End-to-End Data Path





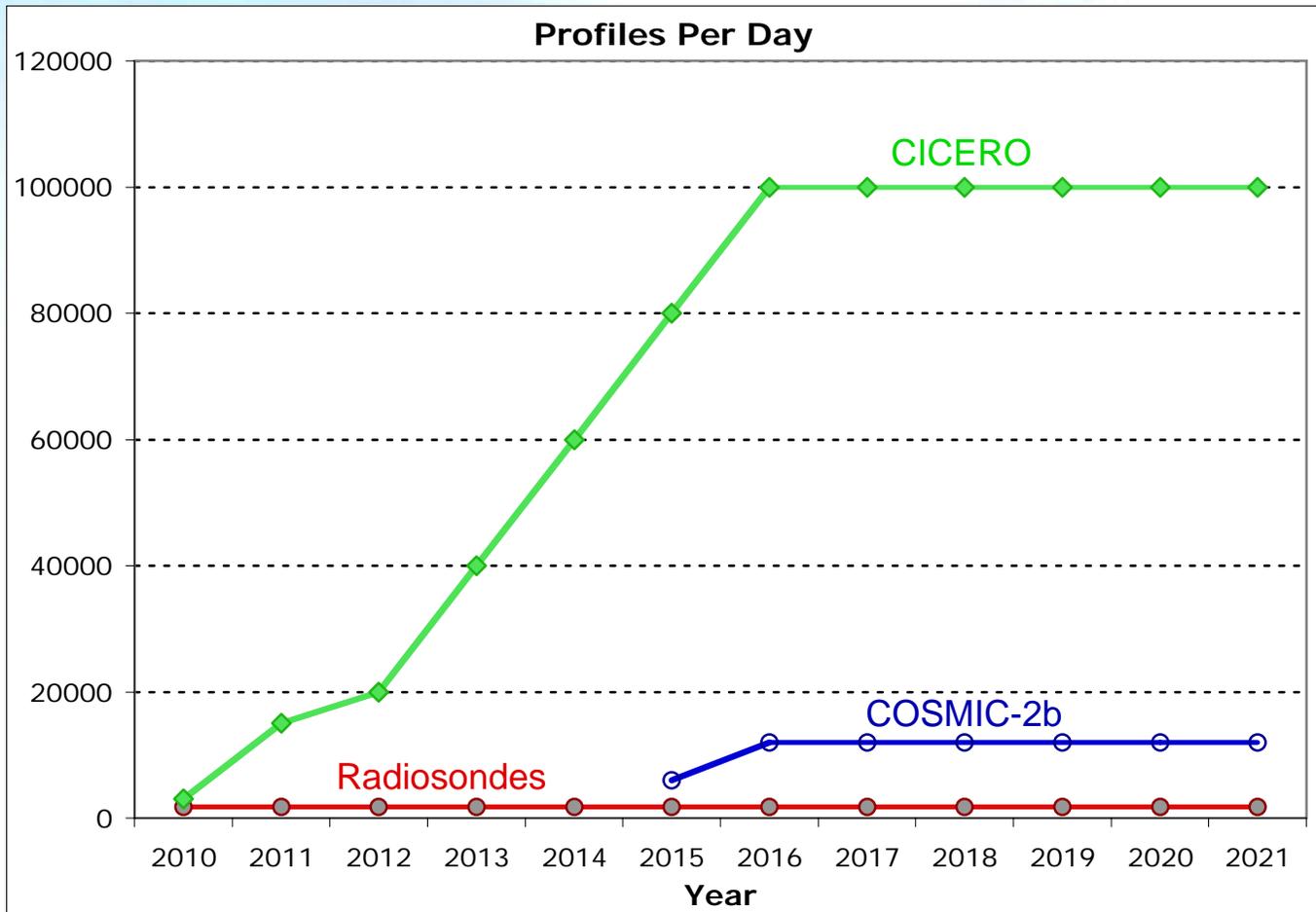
Comparison of Proposed Post-COSMIC Systems

	COSMIC-2a	COSMIC-2b	CICERO
Operational Date	2015	2015	2010-11
Satellites in 2016	6	12	100
Profiles per day	6,000	12,000	100,000*
Profiles/day in a hurricane region	2-3	4-6	40-60
Approx. 10-year cost to NOAA	300M\$	480M\$	135M\$
Approx. cost per profile to NOAA	\$20	\$16	\$0.60
Pre-data cost to NOAA	140M\$	200M\$	0
Risk to NOAA	100%	100%	0

*Assuming only GPS and Galileo.

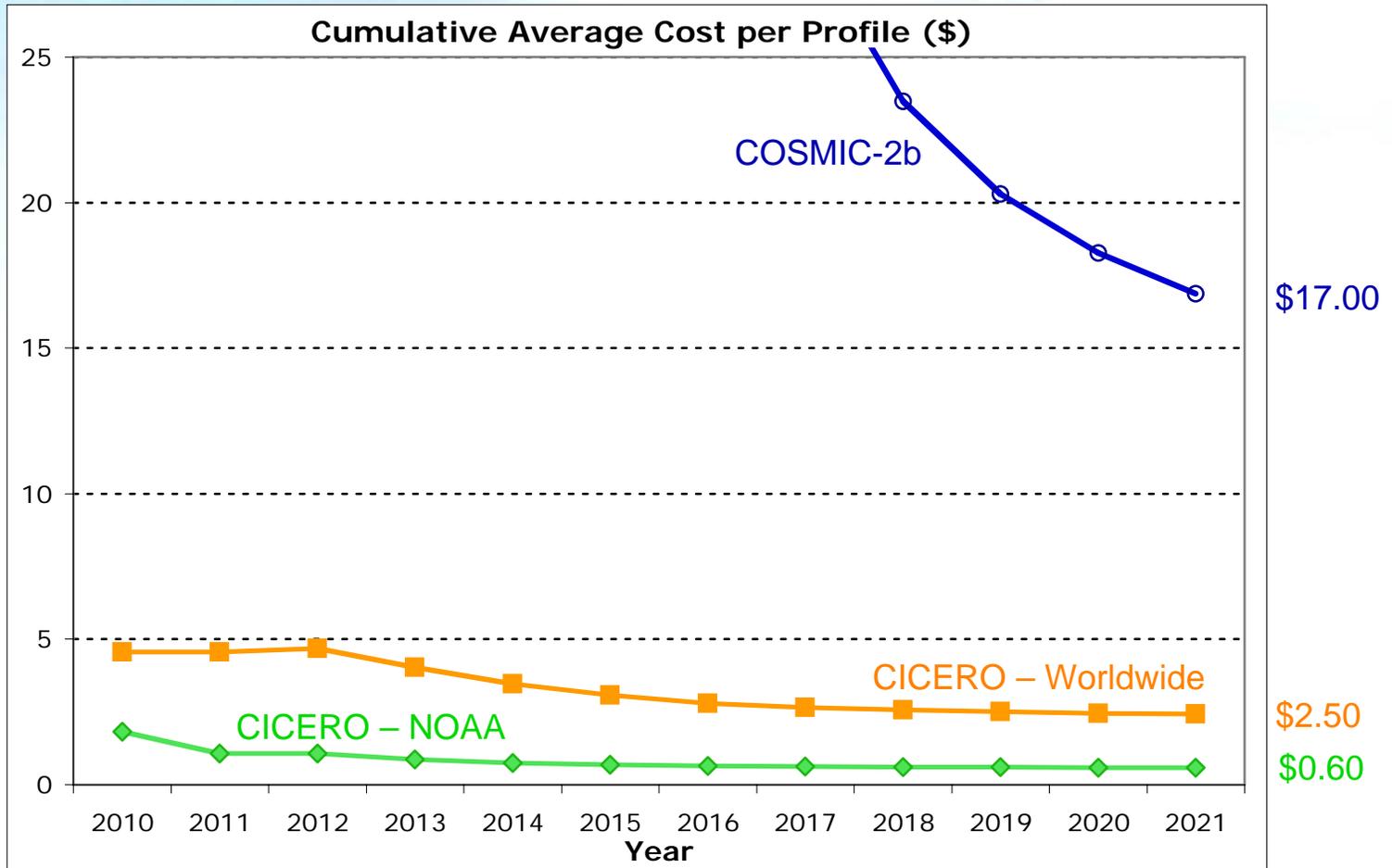


Radiosondes v. COSMIC-2b v. CICERO





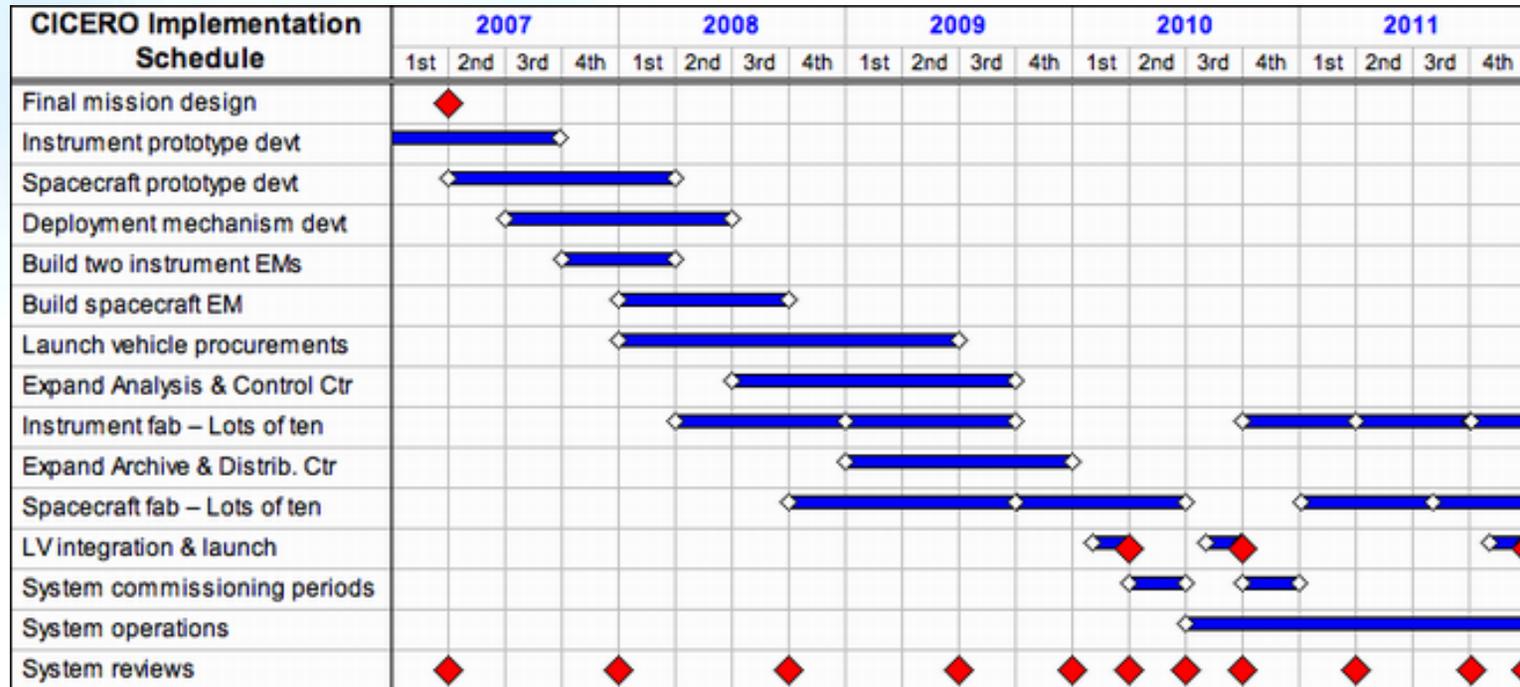
Radiosondes v. COSMIC-2b v. CICERO



Cumulative Avg. Cost/Profile = Total expended to date / Total profiles to date.



The CICERO Development & Deployment Schedule



- First launch of 10 satellites by mid-2010
- Succeeding launches every 4-6 months