2333-17

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

GNSS Remote Sensing: Troposphere Profiling through Radio Occultation

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Workshop on Science Applications of GNSS in Developing Countries
11-27 April, 2012

The Abdus Salam
International Centre for Theoretical Physics

GNSS REMOTE SENSING: TROPOSPHERE PROFILING THROUGH RADIO OCCULTATION

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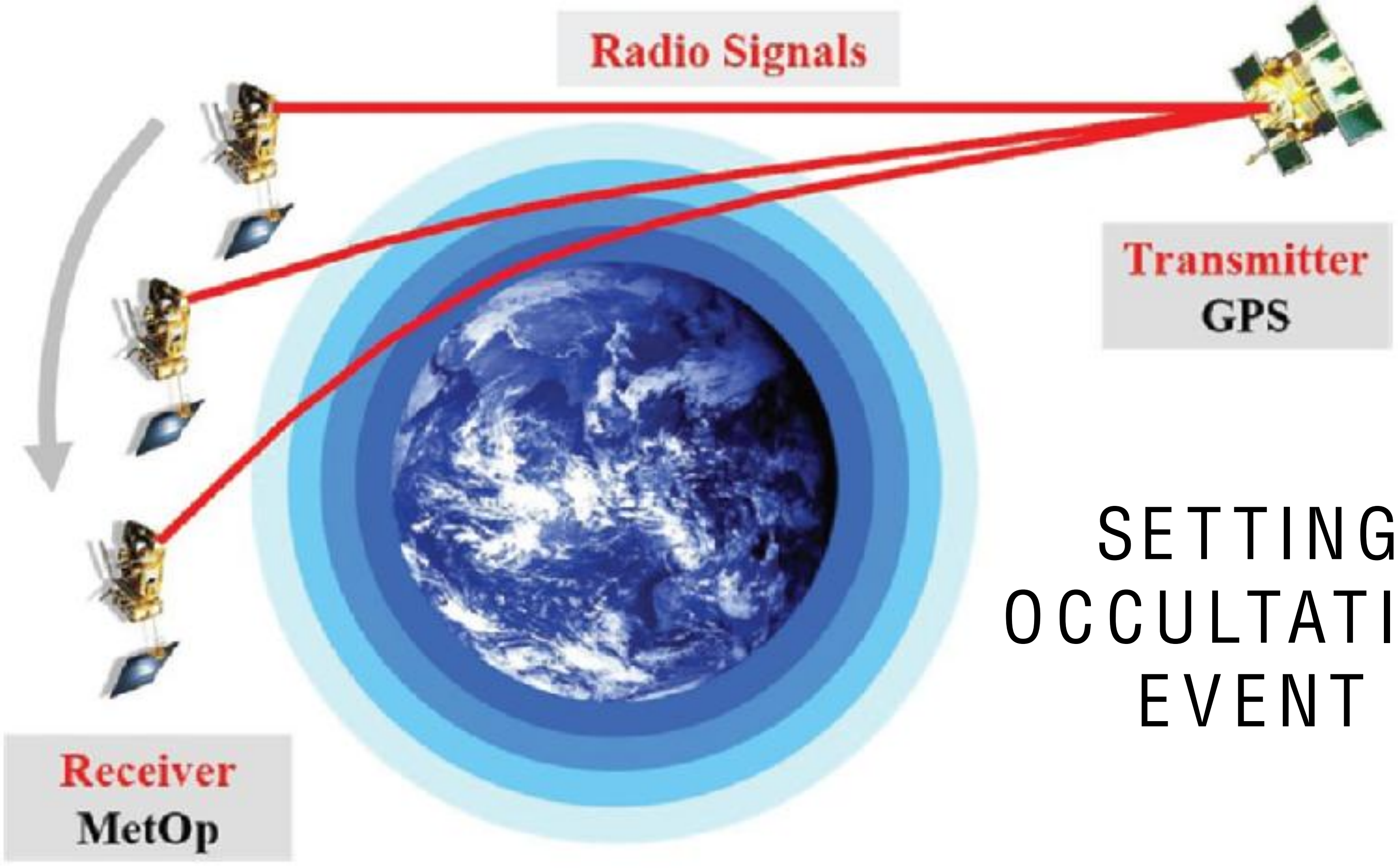
REMOTE SENSING GROUP
POLITECNICO DI TORINO

Sun and „satellite“ sets

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

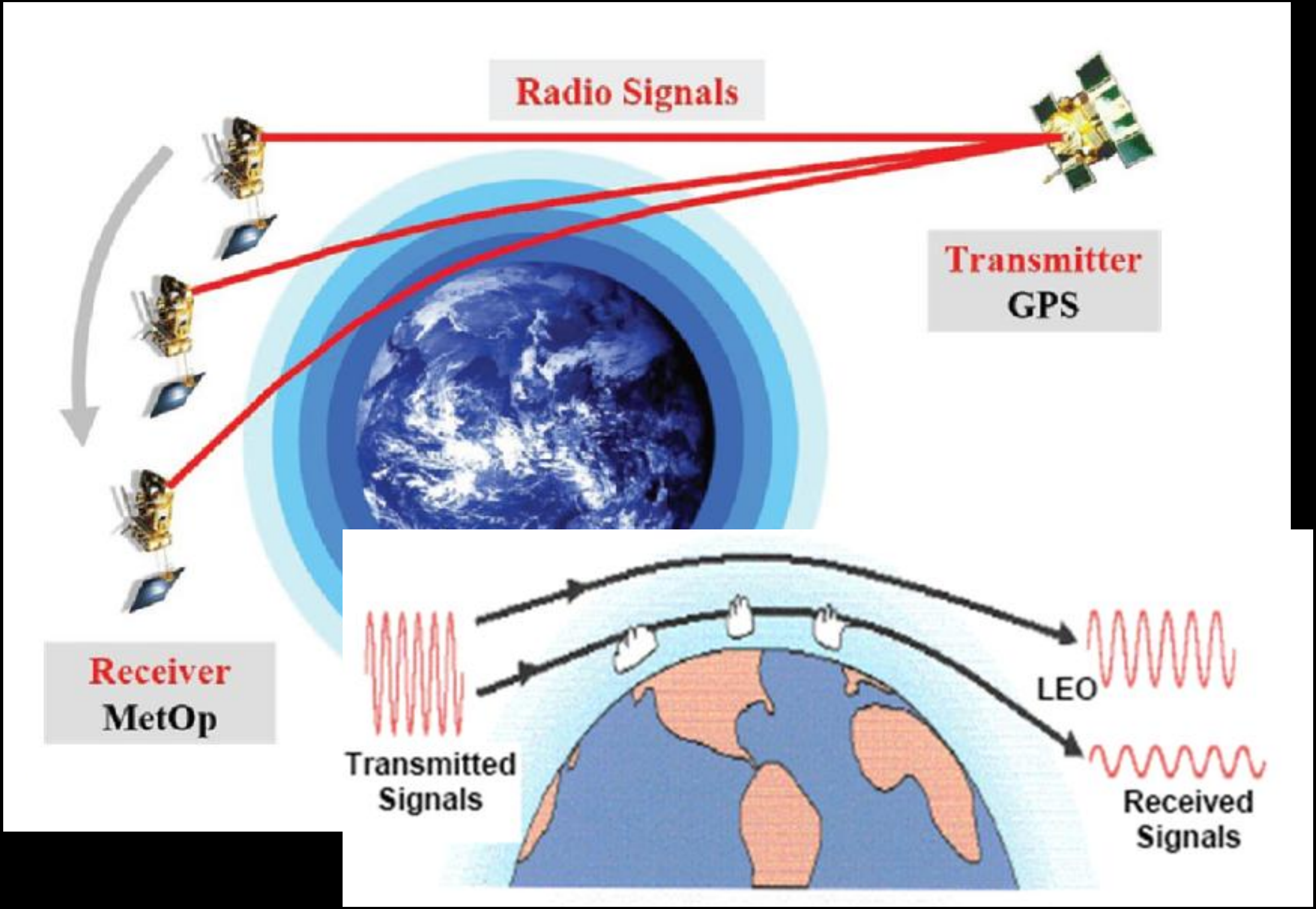
GNSS RADIO OCCULTATION PRINCIPLE



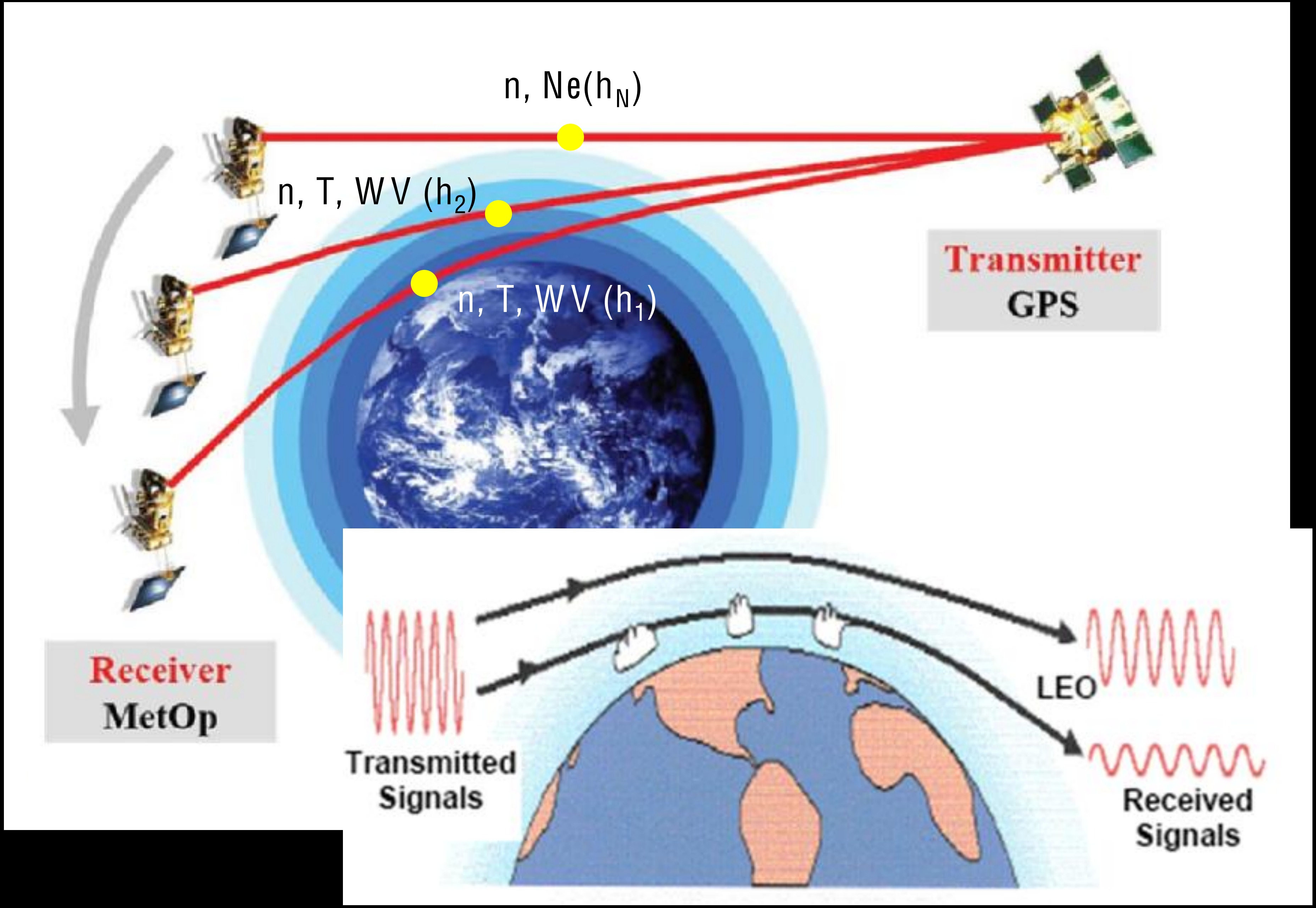
SETTING
OCCULTATION
EVENT

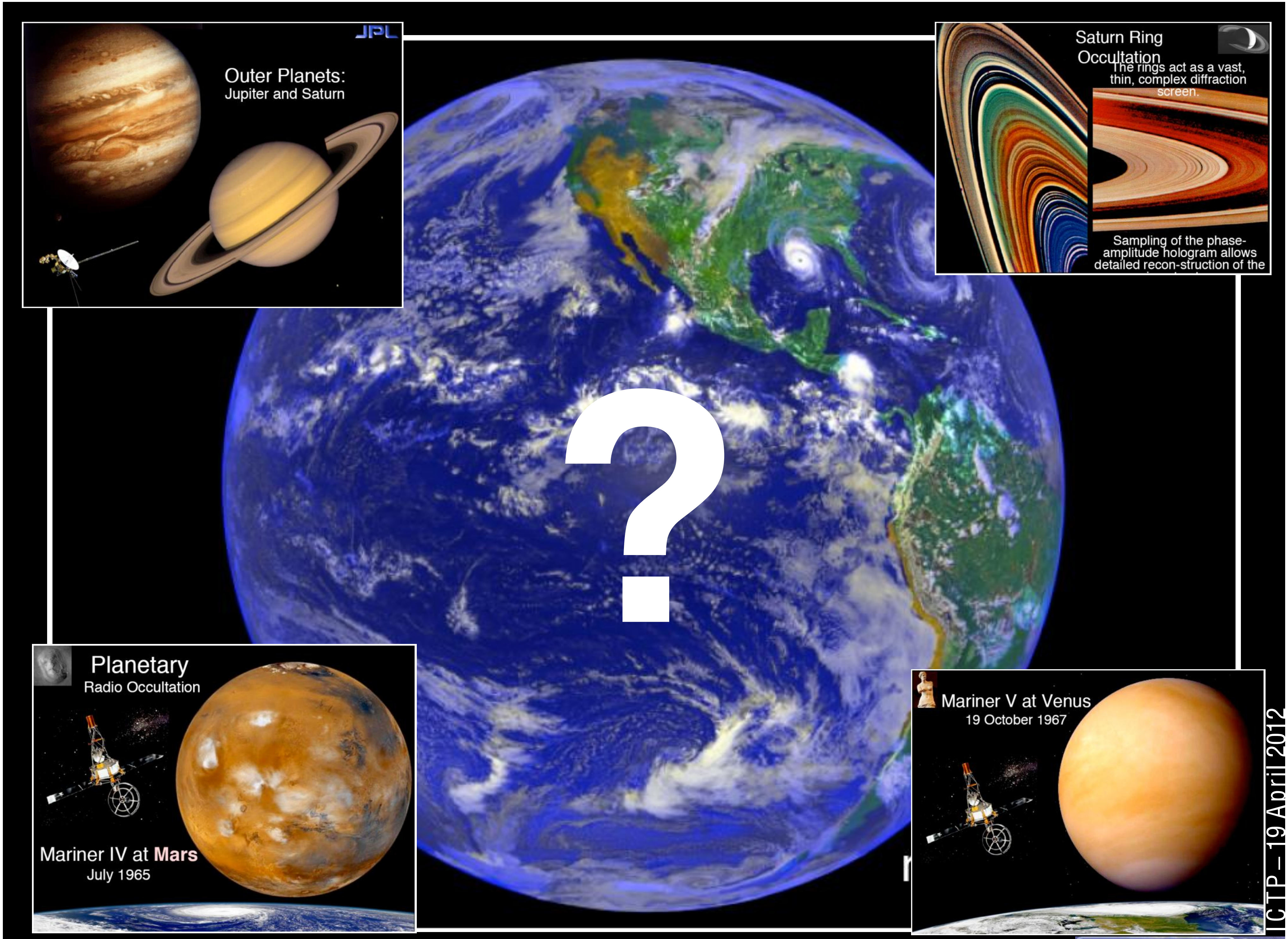
J.-P. Luntama et al., “Prospects of the EPS GRAS Mission for Operational Atmospheric Applications”, *BAMS*, Dec. 2008

GNSS RADIO OCCULTATION PRINCIPLE



GNSS RADIO OCCULTATION PRINCIPLE





Outer Planets:
Jupiter and Saturn

Saturn Ring
Occultation

The rings act as a vast, thin, complex diffraction screen.

Sampling of the phase-amplitude hologram allows detailed recon-struction of the

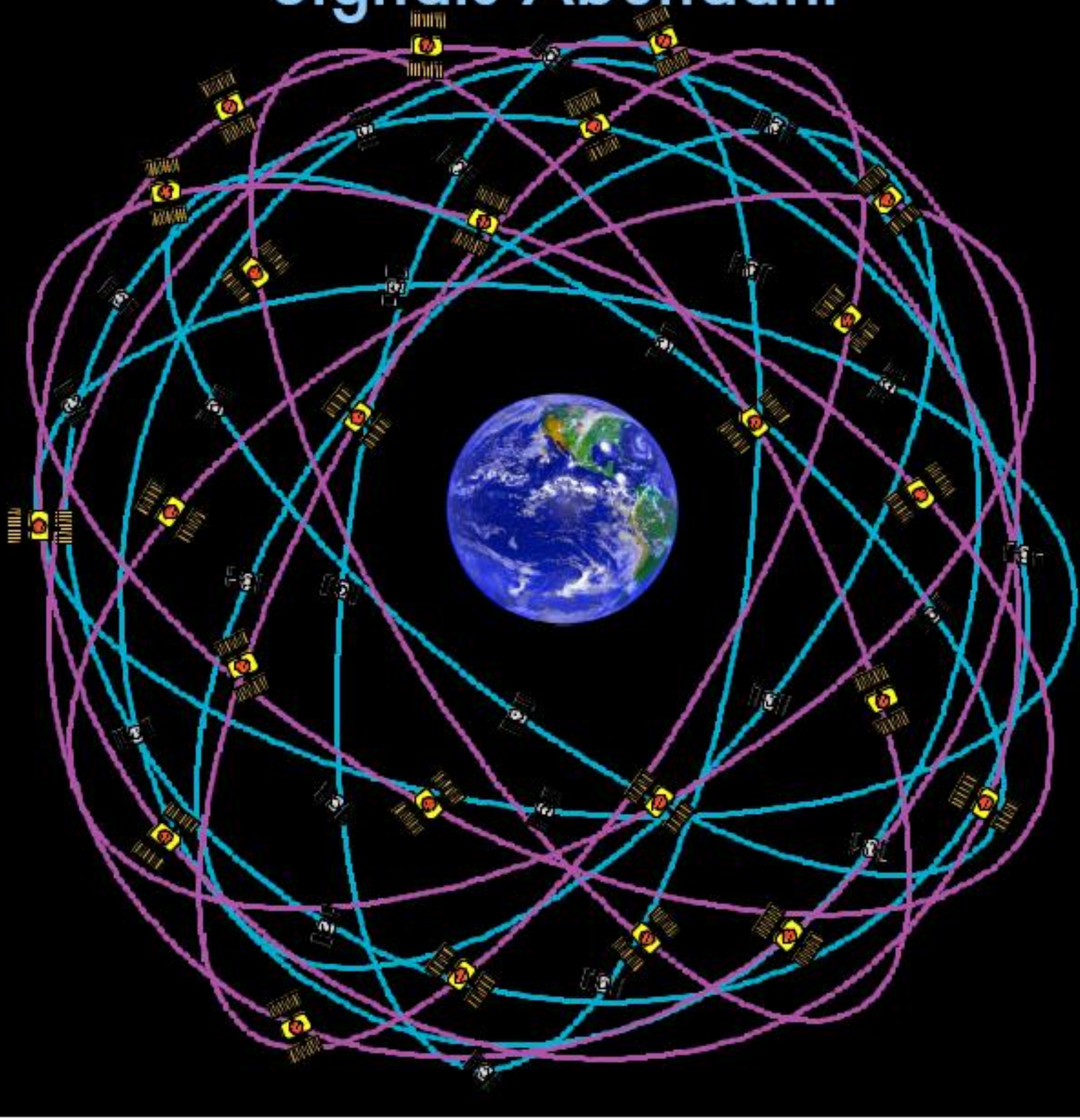
Planetary
Radio Occultation

Mariner IV at **Mars**
July 1965

Mariner V at Venus
19 October 1967

T. P. Yunck, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

Signals Abundant



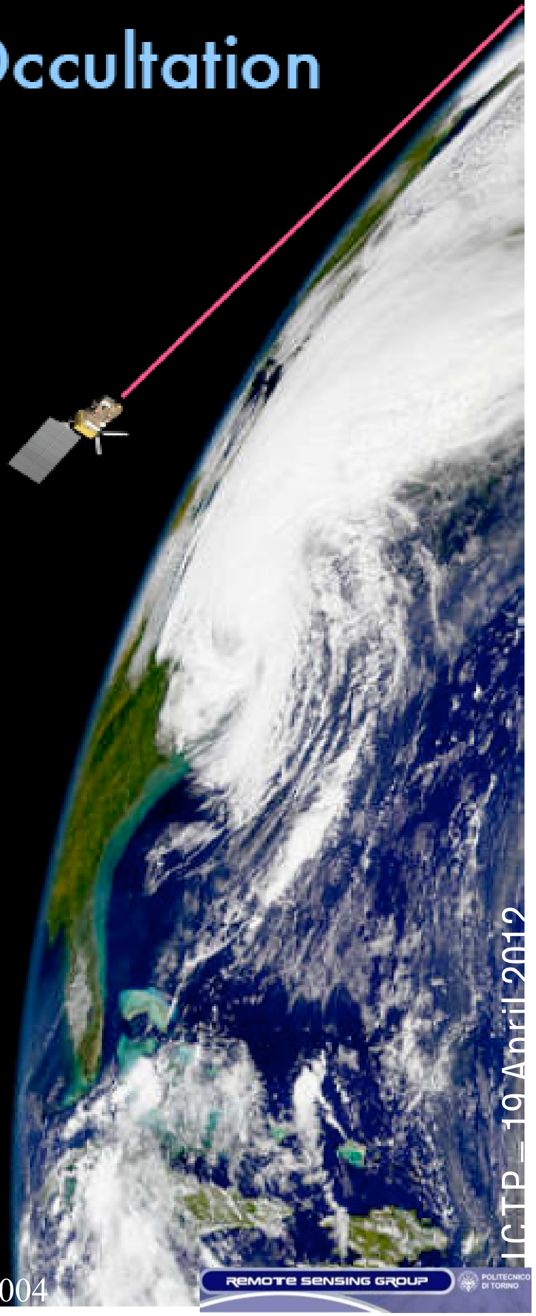
GPS
Glonass
Galileo

60–90
sources
in space

T. P. Yunck, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

Unique Attractions of GPS Radio Occultation

1. High accuracy: Averaged profiles to < 0.1 K
2. Assured long-term stability
3. All-weather operation
4. Global 3D coverage: stratopause to surface
5. Vertical resolution: ~100 m in lower trop
6. Independent height & pressure/temp data
7. Compact, low-power, low-cost sensor



T. P. Yunck, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

Unique Attractions of GPS Radio Occultation

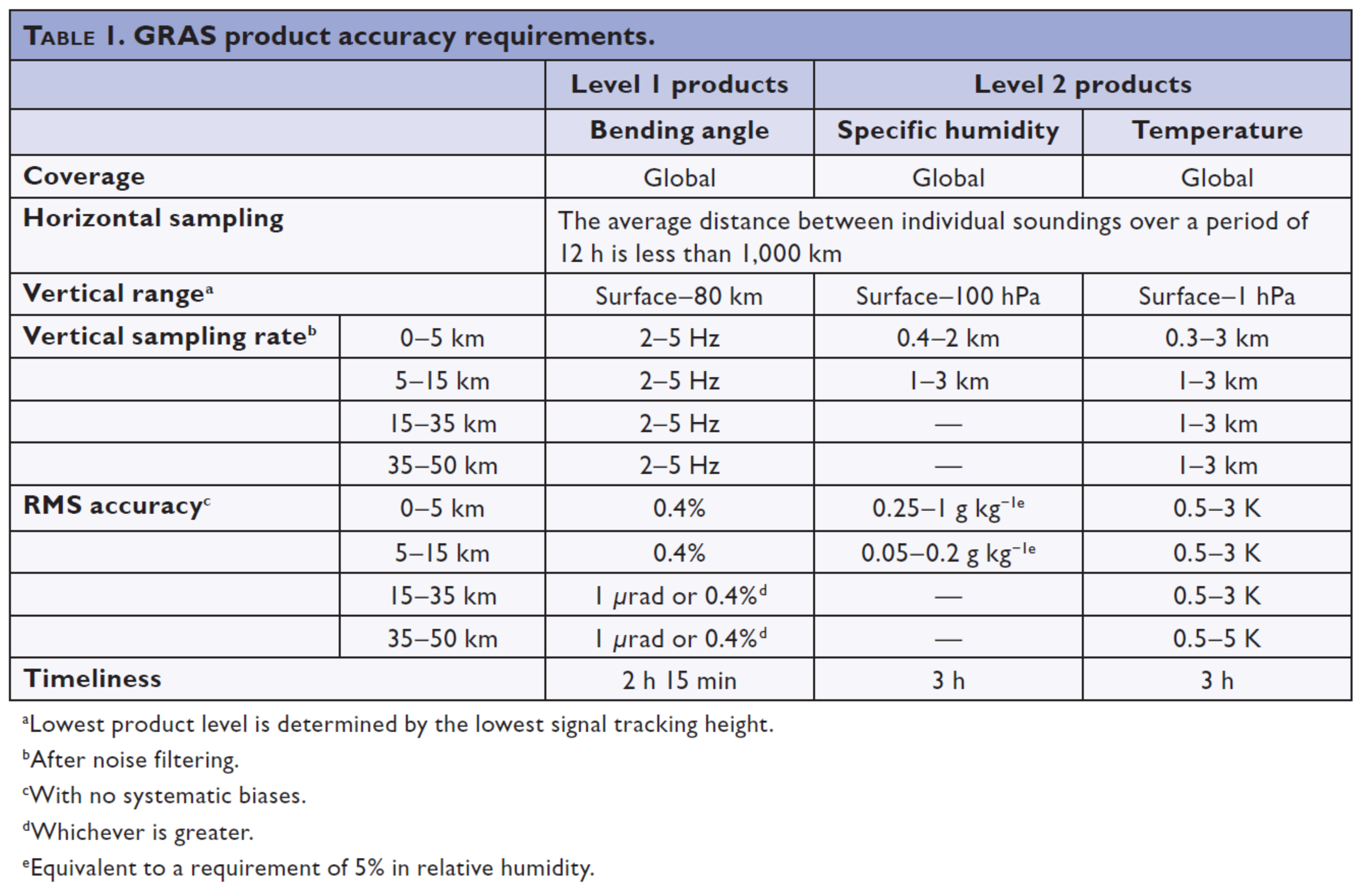


TABLE 1. GRAS product accuracy requirements.

		Level 1 products	Level 2 products	
		Bending angle	**Specific humidity**	**Temperature**
Coverage		Global	Global	Global
Horizontal sampling		The average distance between individual soundings over a period of 12 h is less than 1,000 km		
Vertical range[a]		Surface–80 km	Surface–100 hPa	Surface–1 hPa
Vertical sampling rate[b]	0–5 km	2–5 Hz	0.4–2 km	0.3–3 km
	5–15 km	2–5 Hz	1–3 km	1–3 km
	15–35 km	2–5 Hz	—	1–3 km
	35–50 km	2–5 Hz	—	1–3 km
RMS accuracy[c]	0–5 km	0.4%	0.25–1 $g\ kg^{-1e}$	0.5–3 K
	5–15 km	0.4%	0.05–0.2 $g\ kg^{-1e}$	0.5–3 K
	15–35 km	1 μrad or 0.4%[d]	—	0.5–3 K
	35–50 km	1 μrad or 0.4%[d]	—	0.5–5 K
Timeliness		2 h 15 min	3 h	3 h

[a] Lowest product level is determined by the lowest signal tracking height.

[b] After noise filtering.

[c] With no systematic biases.

[d] Whichever is greater.

[e] Equivalent to a requirement of 5% in relative humidity.

J.-P. Luntama et al., "Prospects of the EPS GRAS Mission for Operational Atmospheric Applications", *BAMS*, Dec. 2008

RO Measurement Resolution

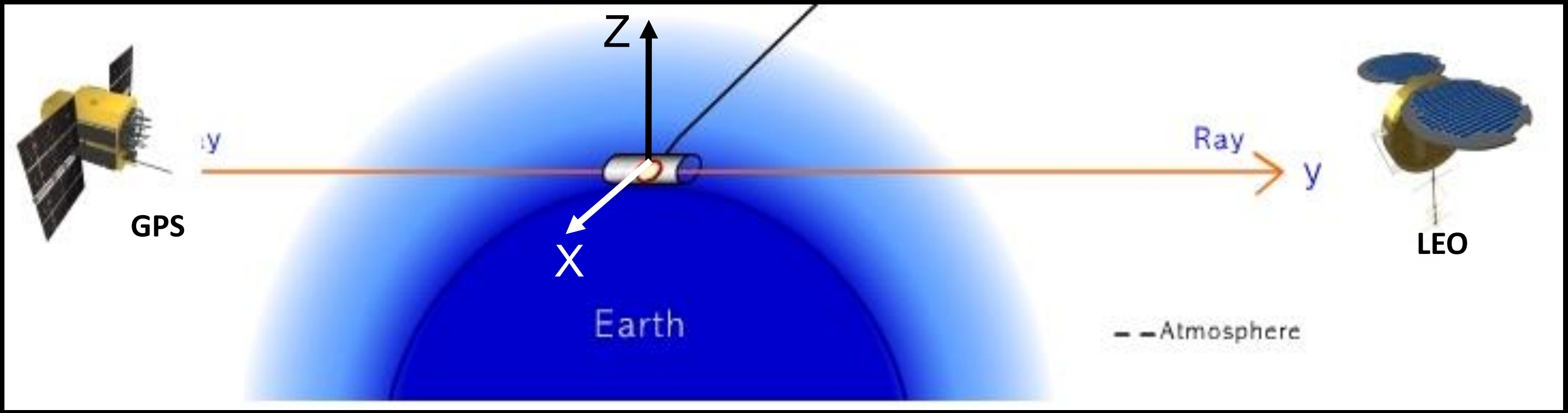
Cross-track Resolution (driven by First Fresnel Zone dimension)

- Δz ~ 2 km in stratosphere
  ~ 0.5 km in the lower troposphere (using GO algorithms) or ~ 100 m using Radio Holographic inversion methods

- Δx ~ 2 km

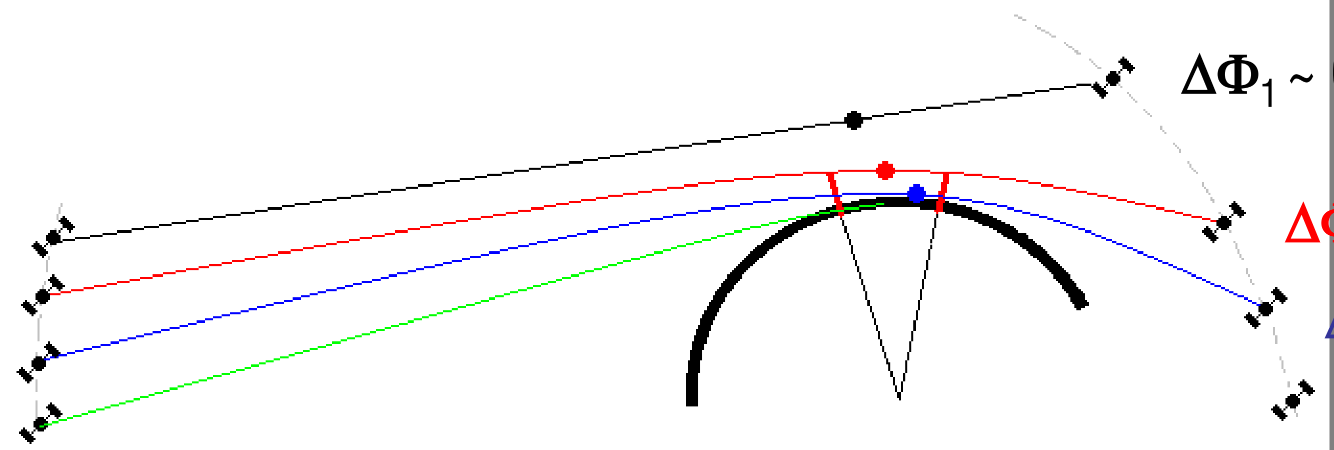
Along-track Resolution

- Δy ~ 600 km in stratosphere
  ~ 200 km in in the lower troposphere



GPS RADIO OCCULTATION TECHNIQUE

PHASE DELAY



$\Delta\Phi_1 \sim 0$

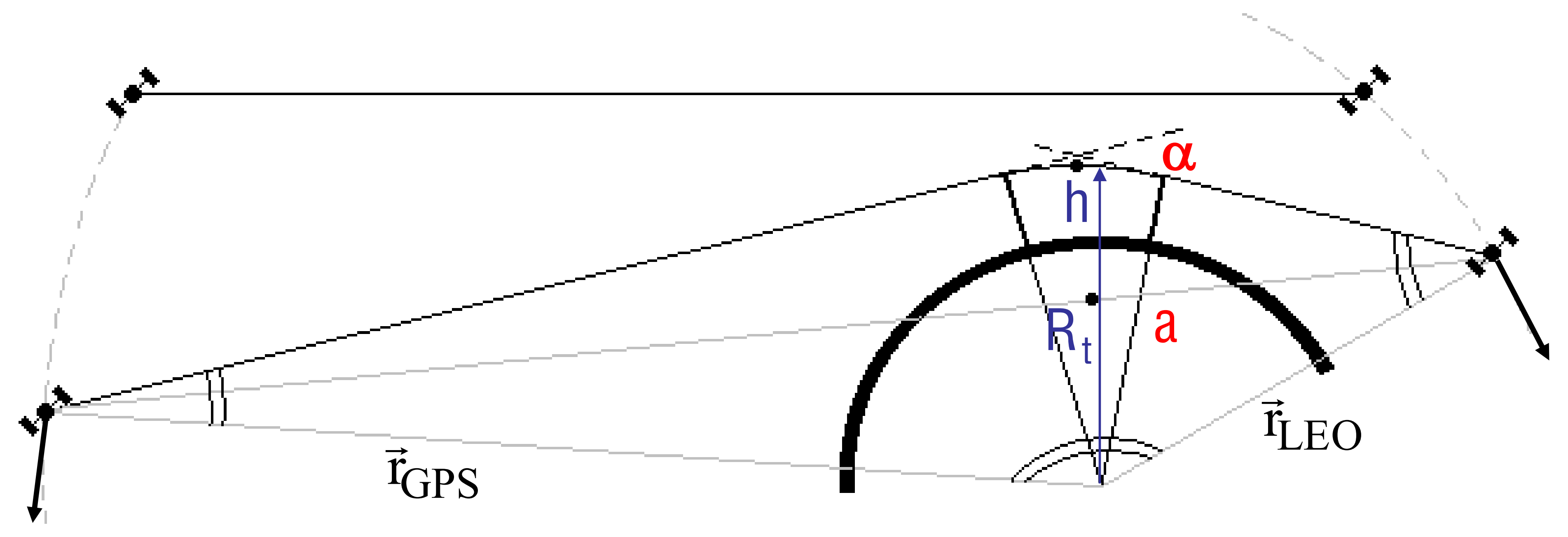
$\Delta\Phi_2$

$\Delta\Phi_3$

GPS OBSERVABLES

$\left|\vec{E}(t)\right|$ and $\Delta\Phi(t)$

GPS RADIO OCCULTATION TECHNIQUE



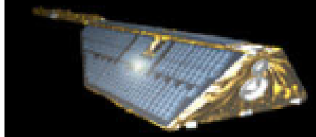
$$\vec{E}(t) \longrightarrow \alpha(a) = -2a\int_a^{\infty} \frac{1}{\sqrt{(R_t+h)^2 n^2(h) - a^2}} \frac{1}{n(h)} \frac{dn(h)}{dh} dr$$

- Geometric Optics
- Radio Holographic methods

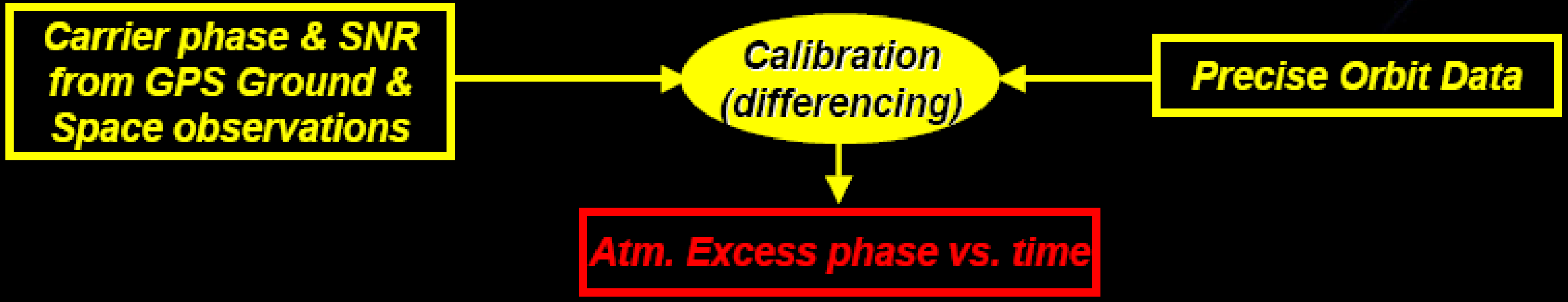
Spherical symmetry hypothesis

$\downarrow$ ABEL

$$[n_{retr}(h)-1]10^6 = 77.6\frac{p_d(h)}{T(h)} + 3.75\cdot 10^5 \frac{e(h)}{T^2(h)} \longleftarrow n_{retr}(h) \longleftarrow$$



Data analysis (Overview)



Carrier phase & SNR from GPS Ground & Space observations

Calibration (differencing)

Precise Orbit Data

Atm. Excess phase vs. time

Radio occultation measurement are based on phase measurements on L_1/L_2 GPS carrier frequencies onboard CHAMP. The carrier phase can be described by the expression :

$$\Phi = \rho + c(dt - dT) - d_I + d_A + d_{MP} + dq + dQ + \lambda N + \varepsilon \quad [m]$$

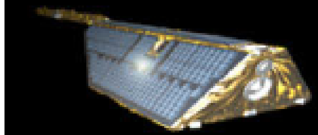
ρ	true range between GPS satellite and receiver along ray path s
c	velocity of light
dt	satellite clock error
dT	receiver clock error
d_I	Ionospheric phase delay along s
d_A	Atmospheric phase delay along s
d_{MP}	error due to multipath
dq	instrumental bias of the satellite
dQ	instrumental bias of the receiver
λ	wave length of the radiowave
N	phase ambigiuity number (integer)
ε	residual error on carrier phase

To calculate

Simplification mainly due to the fact, that bending angles will be derived from Doppler frequencies gives:

$$\Phi = \rho + c(dt - dT) - d_I + d_A + \varepsilon$$

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004



Differencing

Double differencing (GPS/MET):

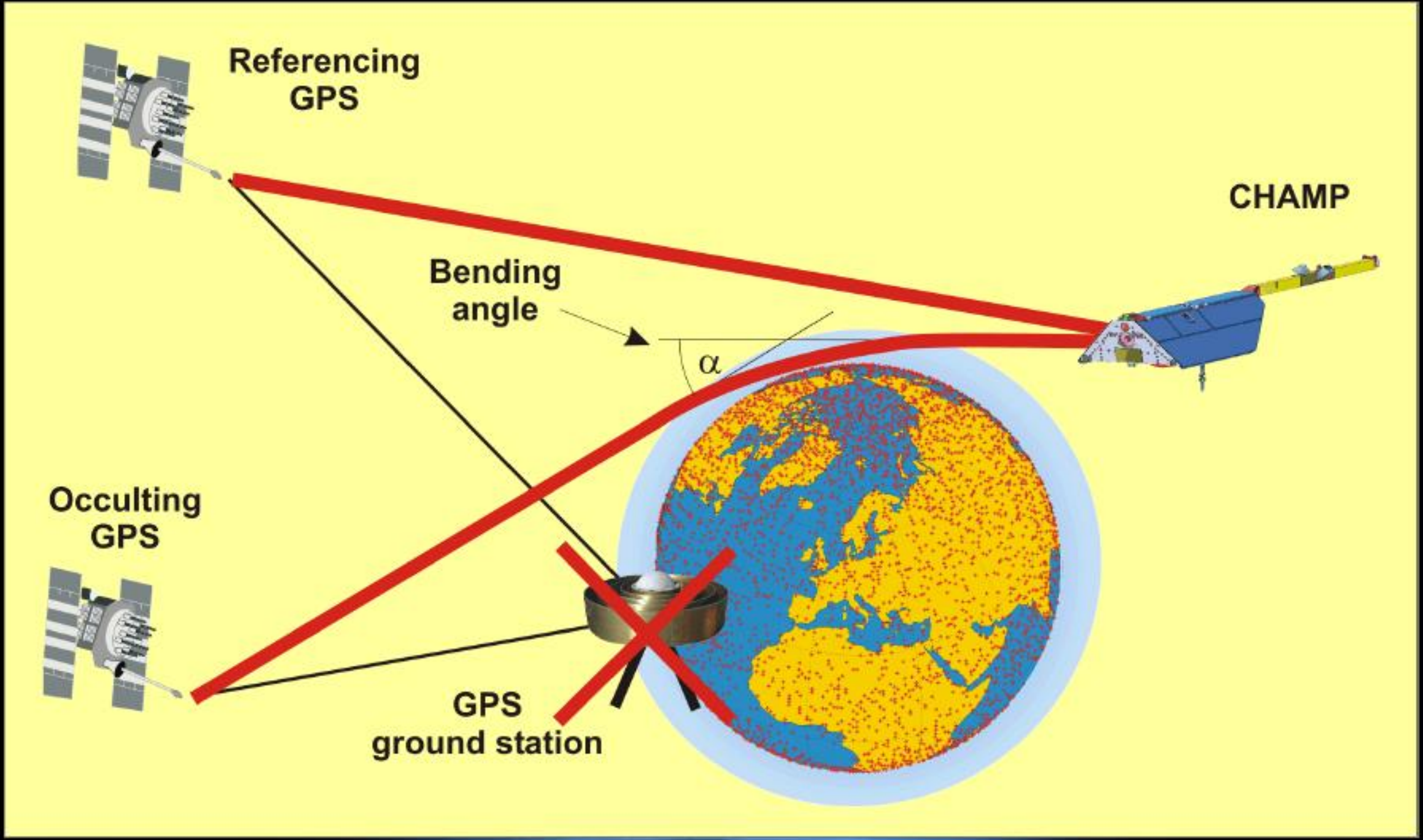
(„bad“ LEO oscillator, GPS oscillators with activated S/A)

Single differencing (CHAMP):

(„bad“ LEO oscillators, GPS with deactivated S/A)

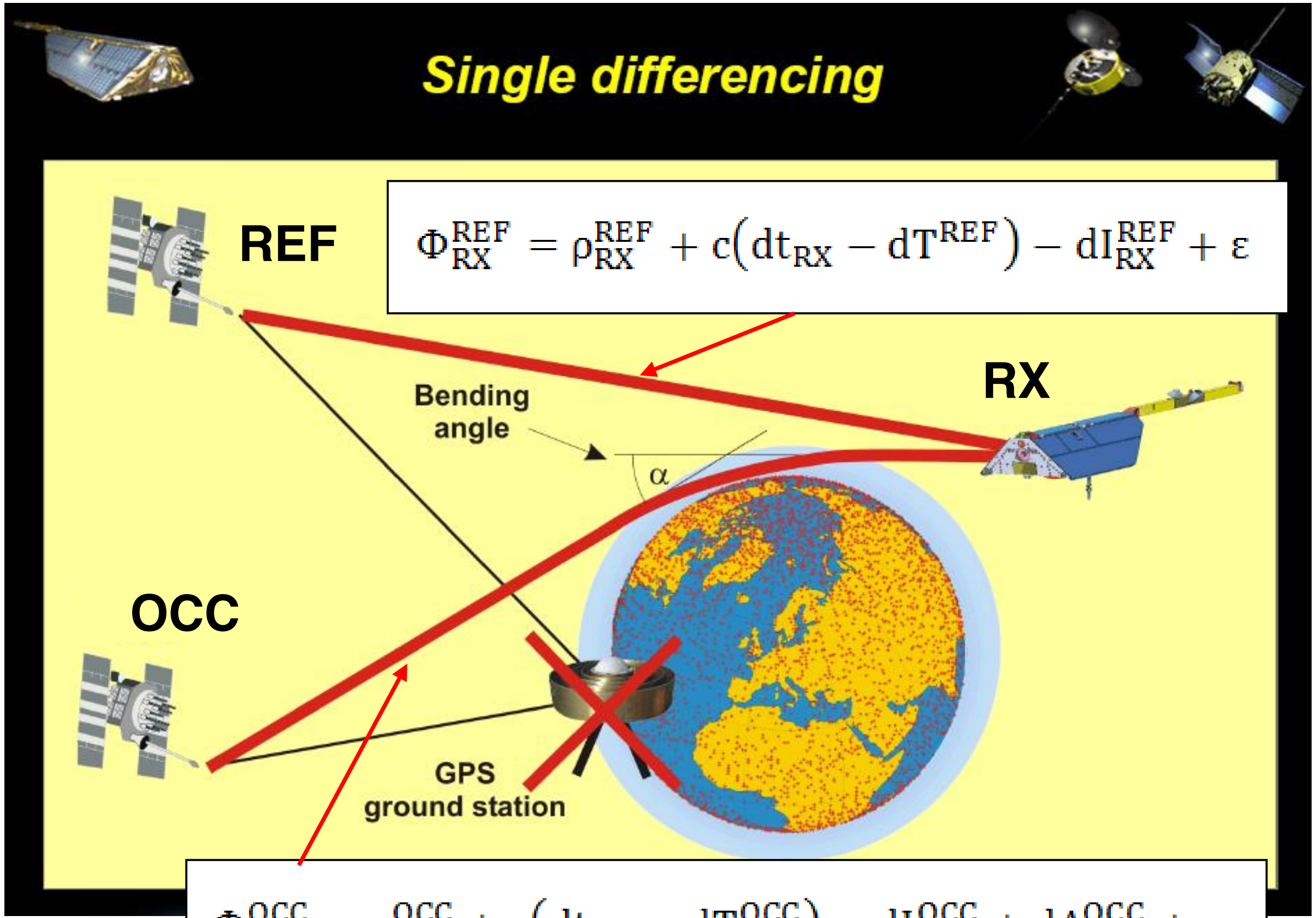
J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

Single differencing



J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

Single differencing



$$\Phi_{RX}^{REF} = \rho_{RX}^{REF} + c\left(dt_{RX} - dT^{REF}\right) - dI_{RX}^{REF} + \varepsilon$$

$$\Phi_{RX}^{OCC} = \rho_{RX}^{OCC} + c\left(dt_{RX} - dT^{OCC}\right) - dI_{RX}^{OCC} + dA_{RX}^{OCC} + \varepsilon$$

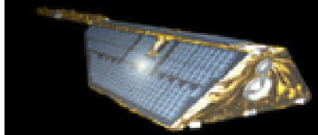
Single Differencing allows the removal of any receiver Clock “error” dt_{RX}

ρ_{RX}^{OCC} and ρ_{RX}^{REF} are estimated by Orbit Determination SW tools

dT^{OCC} and dT^{REF} are normally taken by IGS or are estimated in the framework of Orbit Determination SW

dI_{RX}^{REF} has to be compensated for

After Single Differencing, the so-called Excess Phase ($-dI_{RX}^{OCC} + dA_{RX}^{OCC} + \varepsilon$) still remain



Differencing

Double differencing (GPS/MET):

(„bad“ LEO oscillator, GPS oscillators with activated S/A)

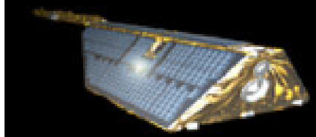
Single differencing (CHAMP):

(„bad“ LEO oscillators, GPS with deactivated S/A)

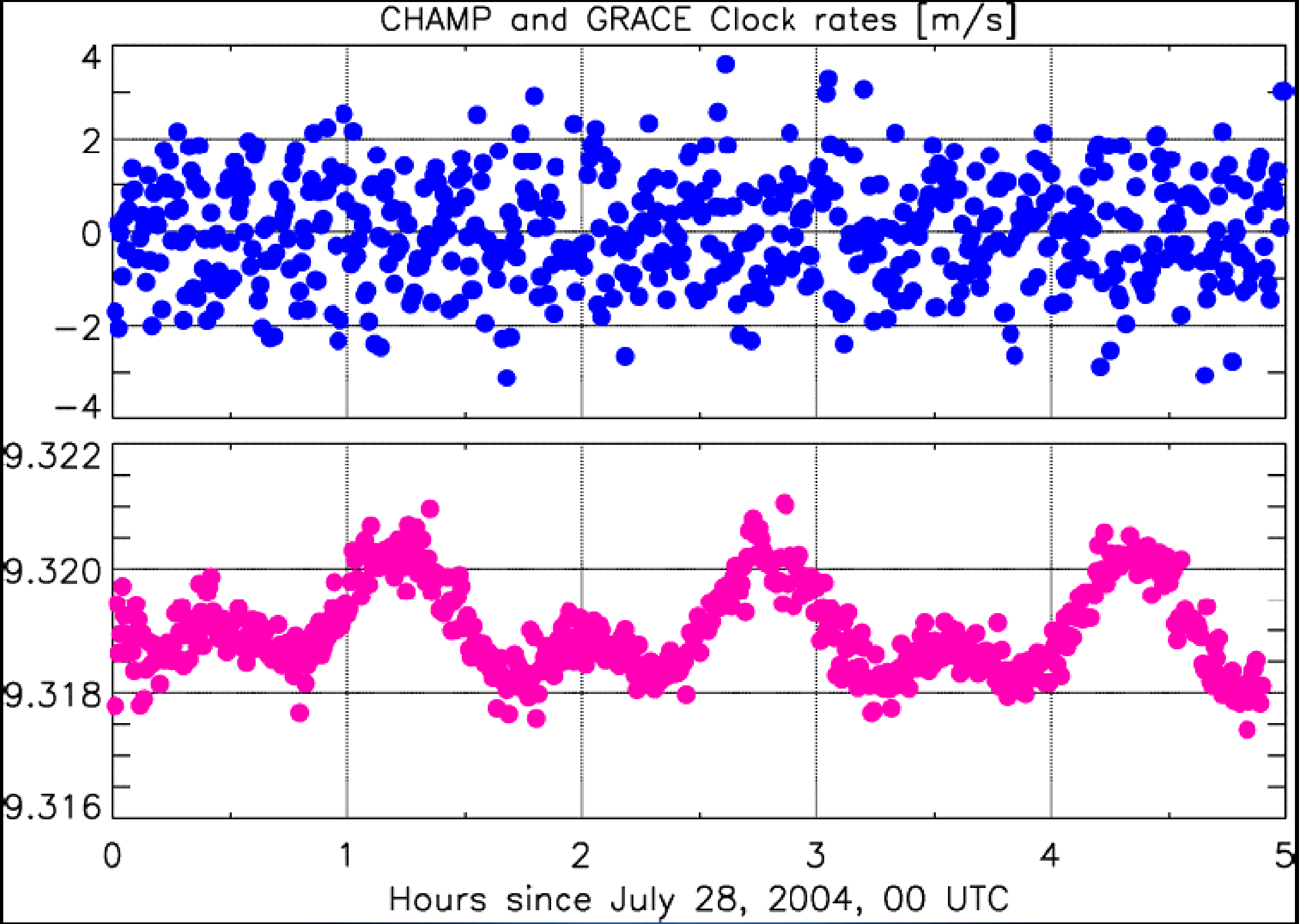
Zero differencing (GRACE):

(stable LEO oscillator, GPS with deactivated S/A)

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

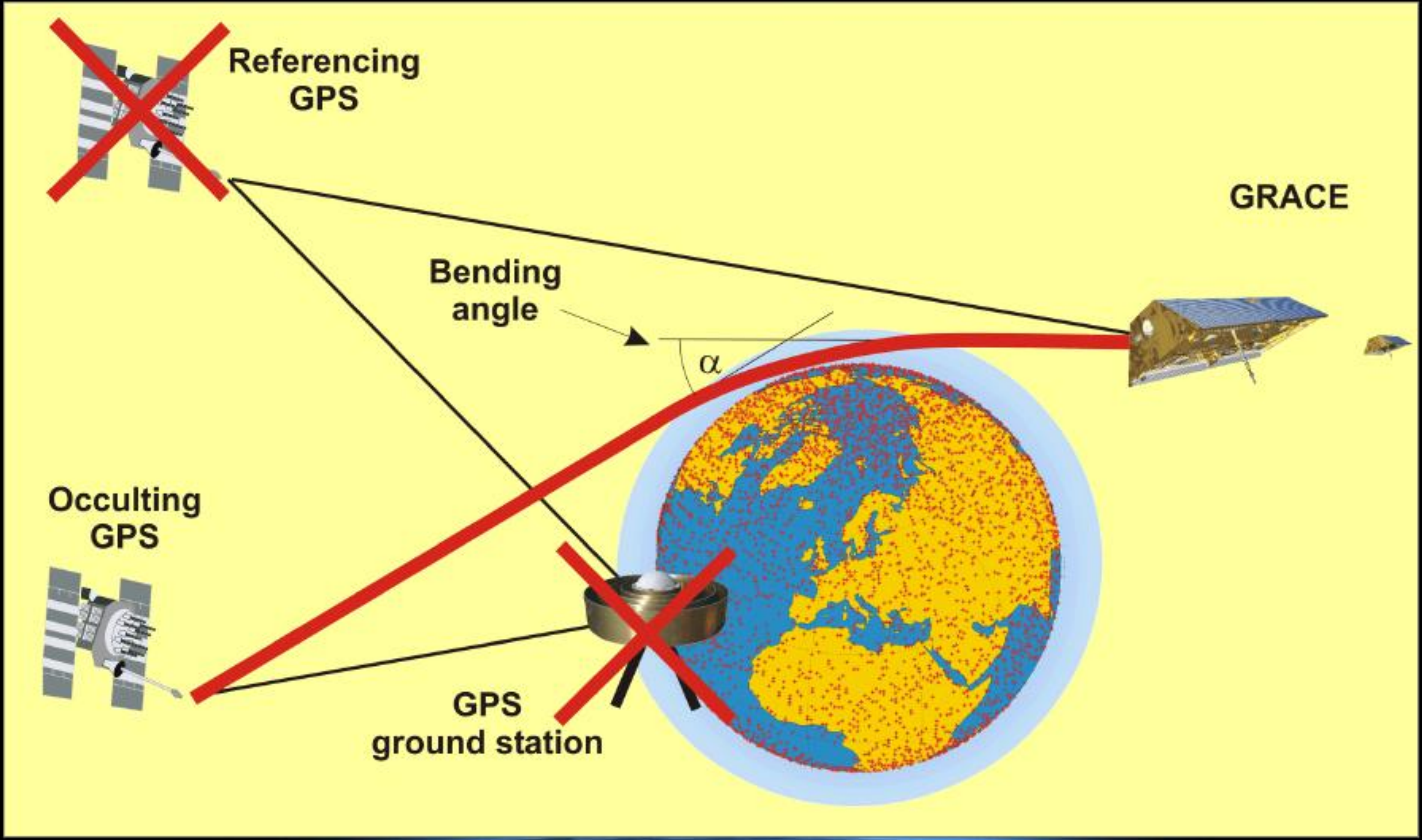


CHAMP and GRACE



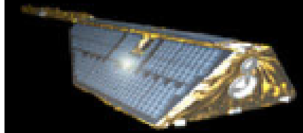
J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

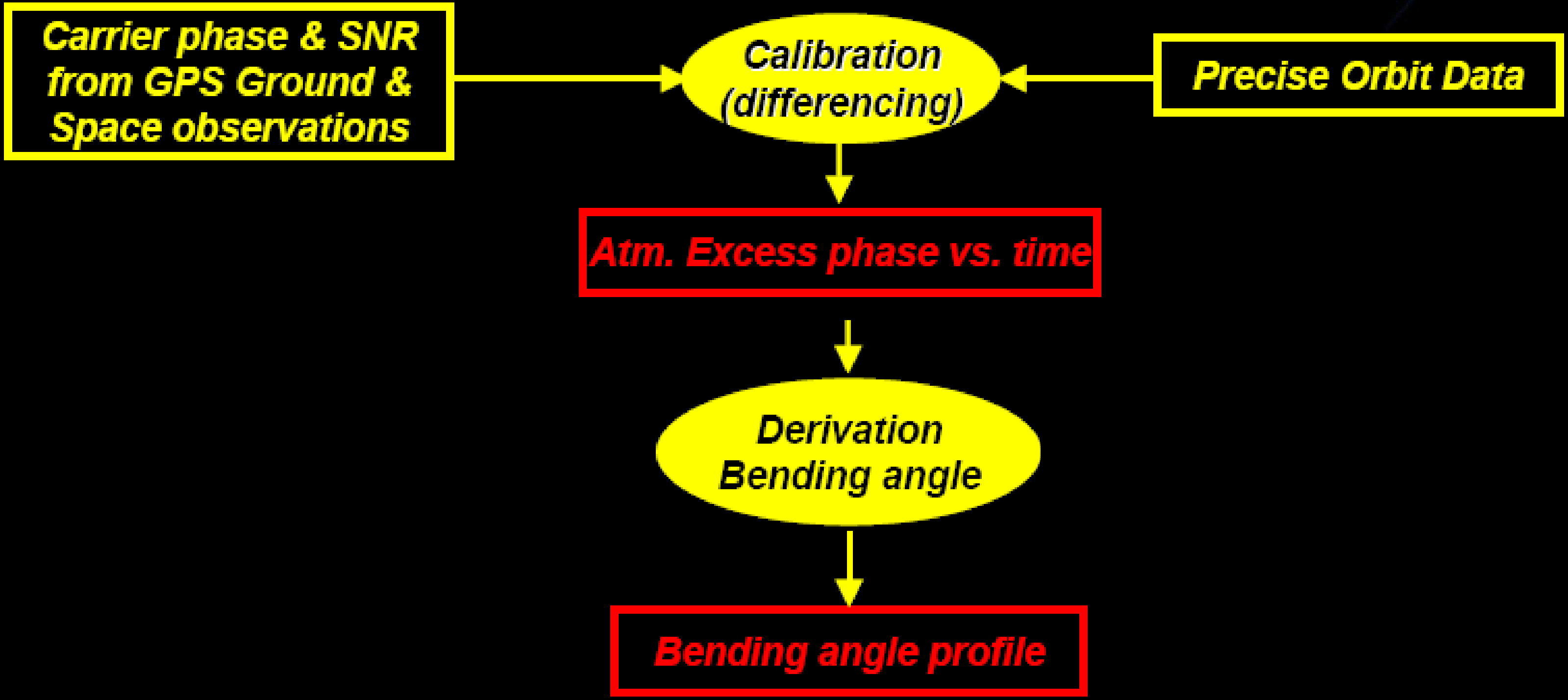
Zero differencing



J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

Data analysis (Overview)





Carrier phase & SNR from GPS Ground & Space observations

Calibration (differencing)

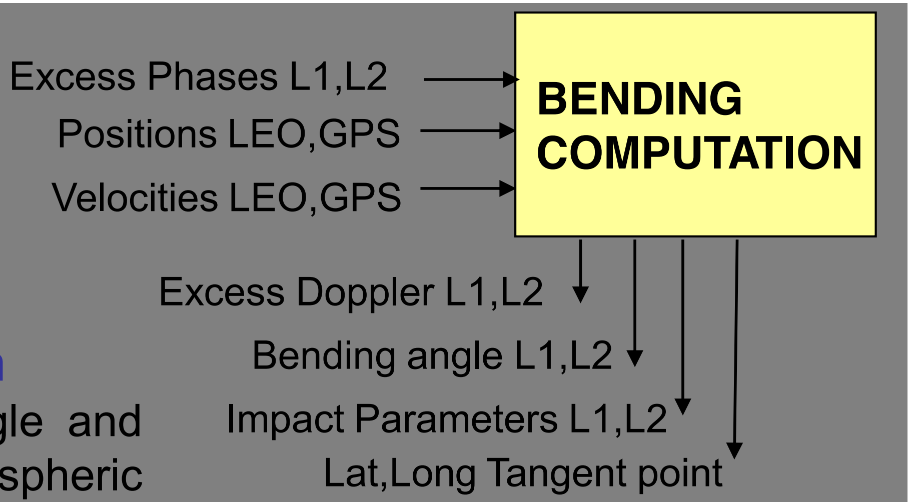
Precise Orbit Data

Atm. Excess phase vs. time

Derivation Bending angle

Bending angle profile

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004



Excess Phases L1,L2

Positions LEO,GPS

Velocities LEO,GPS

BENDING COMPUTATION

Excess Doppler L1,L2

Bending angle L1,L2

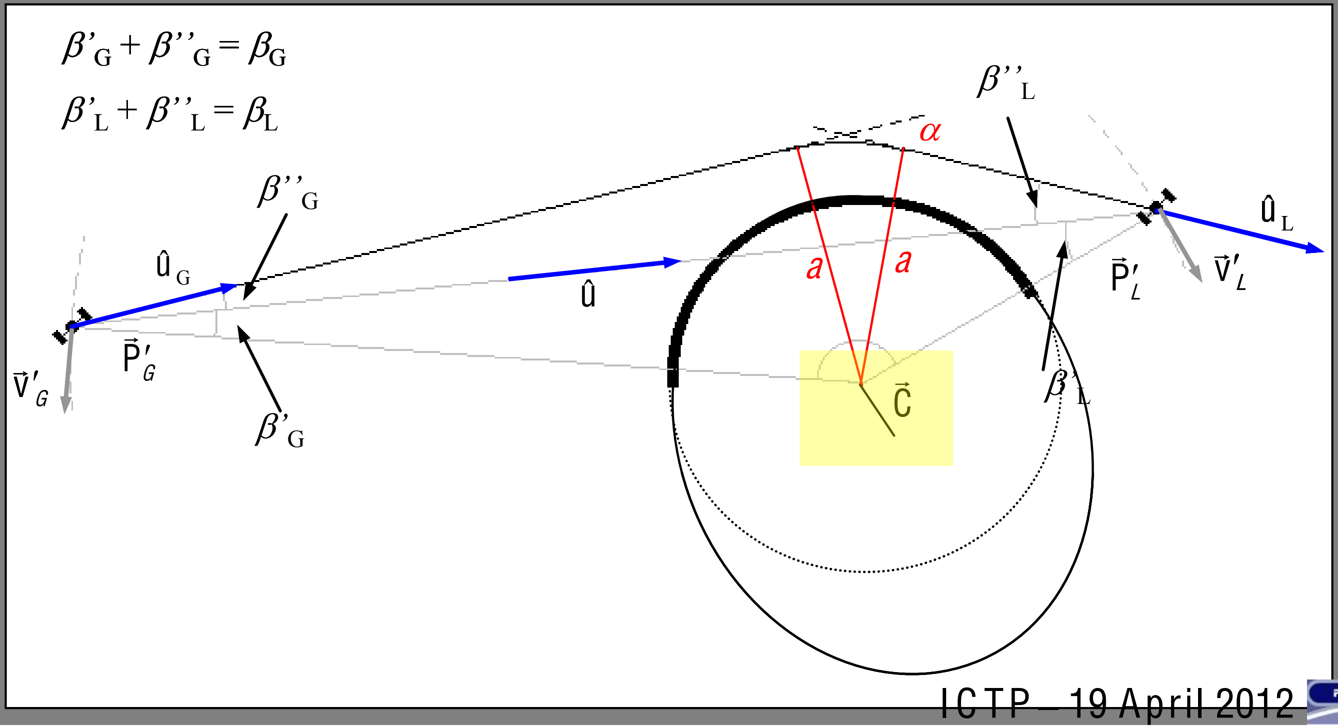
Impact Parameters L1,L2

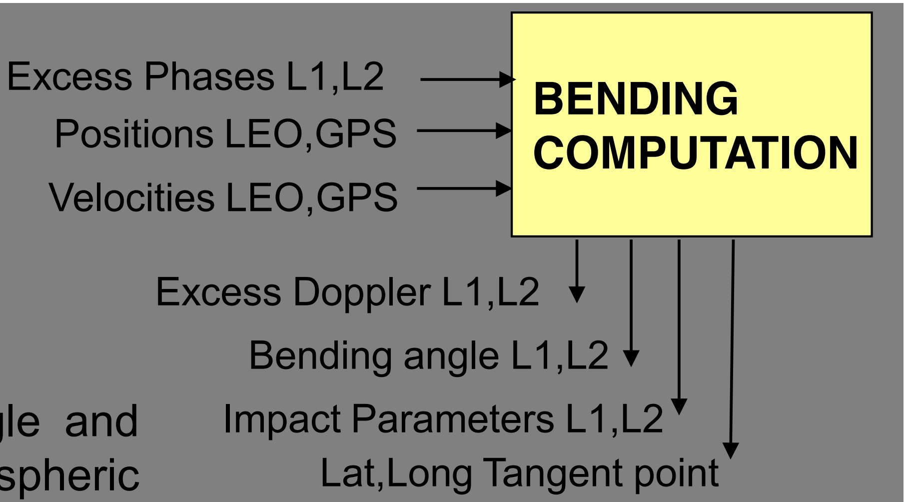
Lat,Long Tangent point

- Excess Phases data filtering

- Refraction (symmetry) Centre computation

Since the formal expression between bending angle and refractivity is based on the hypothesis of atmospheric simmetry the refractivity centre is defined as the centre of the sphere which locally approximates the WGS-84 ellipsoid.





Excess Phases L1,L2

Positions LEO,GPS

Velocities LEO,GPS

BENDING COMPUTATION

Excess Doppler L1,L2

Bending angle L1,L2

Impact Parameters L1,L2

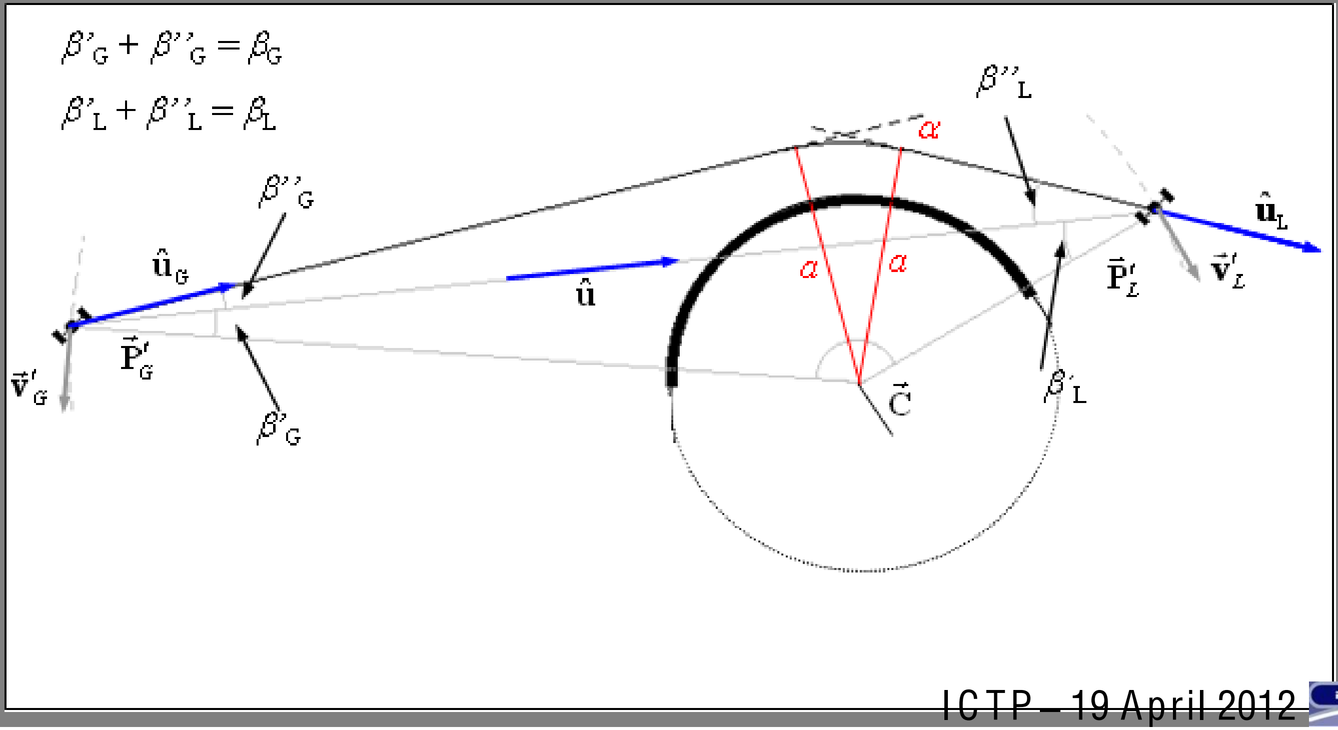
Lat,Long Tangent point

- Excess Phases data filtering

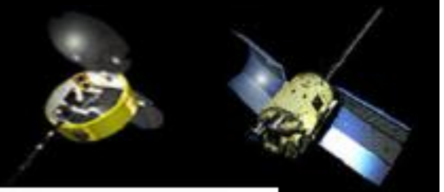
- Refraction (symmetry) Centre computation

Since the formal expression between bending angle and refractivity is based on the hypothesis of atmospheric simmetry the refractivity centre is defined as the centre of the sphere which locally approximates the WGS-84 ellipsoid.

- Bending angle vs impact parameter profile



Ionosphere correction



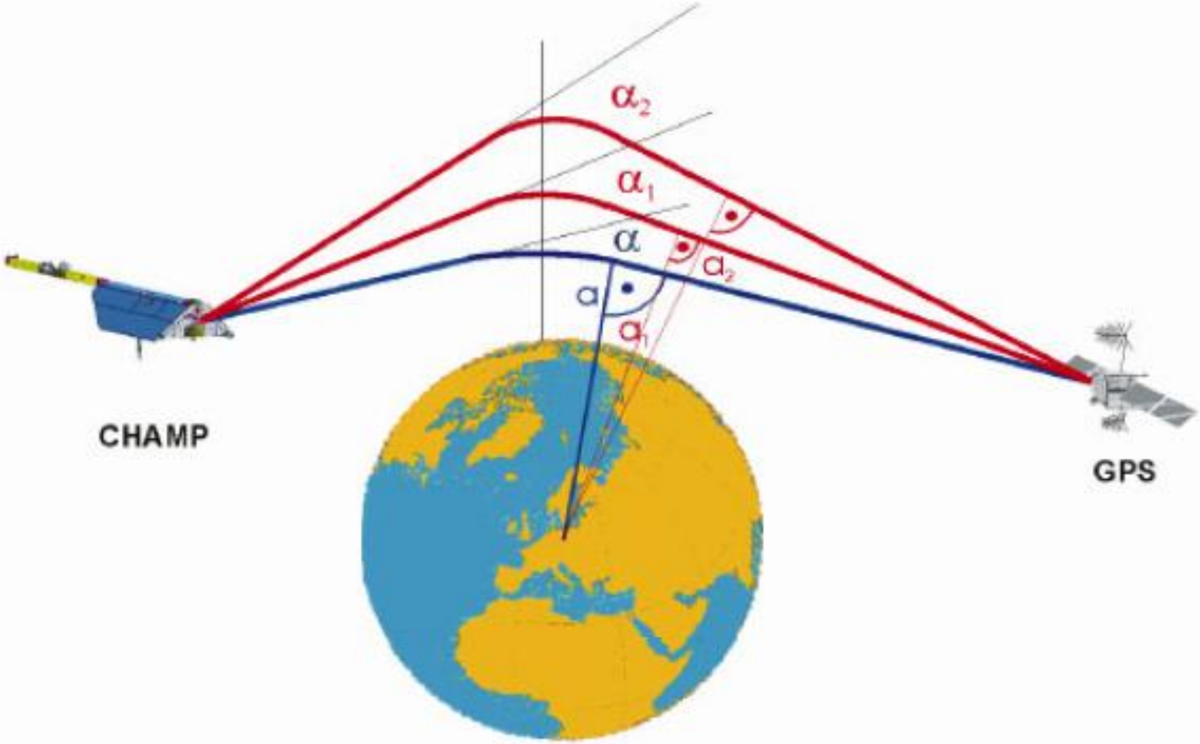
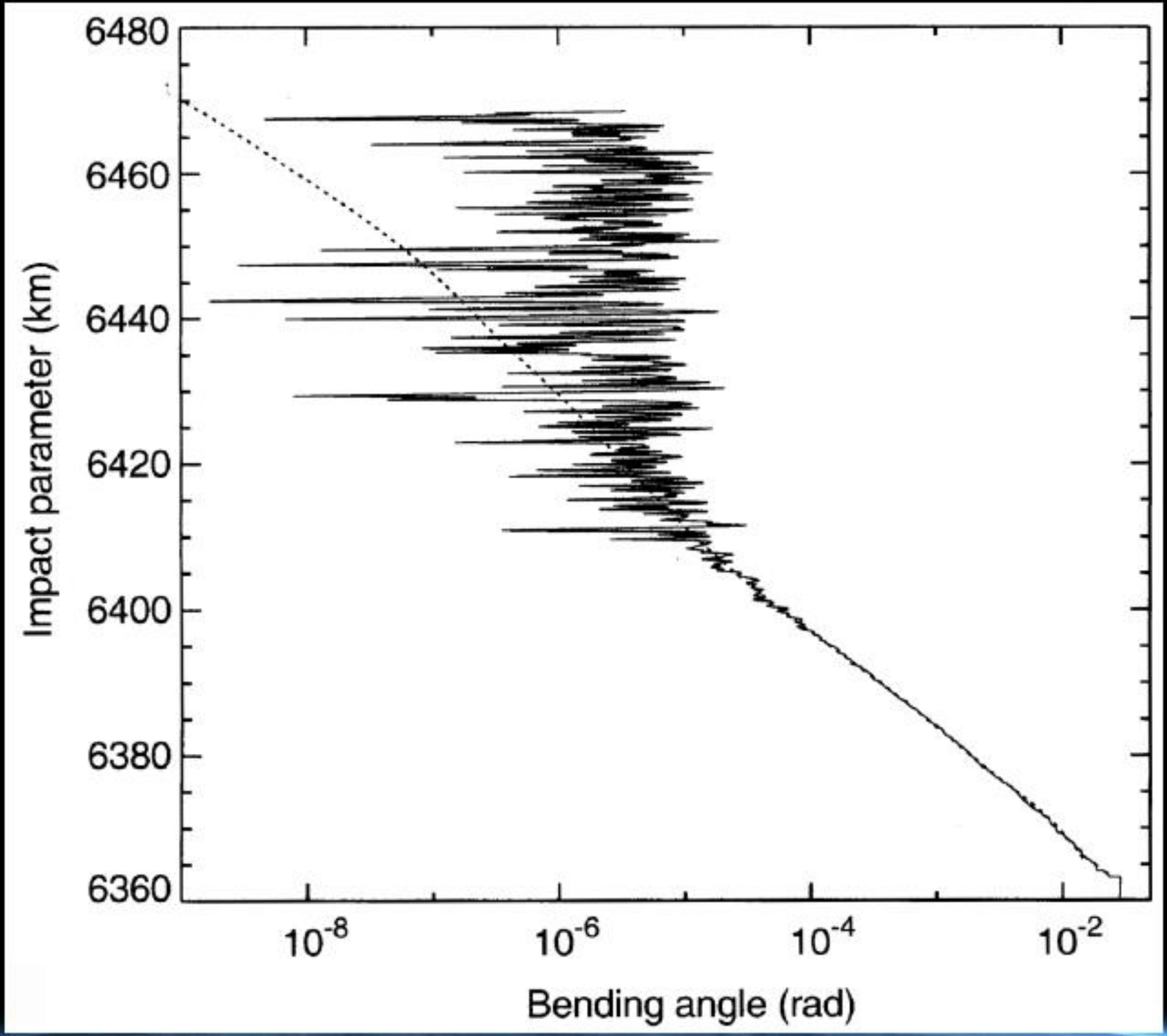


Abb. 3.15: *Separierung der Strahlenwege der L1- und L2-Signale (rot) durch die dispersive Ionosphäre. Mit blau ist der fiktive Strahlenweg ohne Ionosphäreneinfluss gekennzeichnet.*

$$\alpha(a) = \frac{f_1^2}{f_1^2 - f_2^2}\alpha_1(a) - \frac{f_2^2}{f_1^2 - f_2^2}\alpha_2(a). \tag{3.50}$$

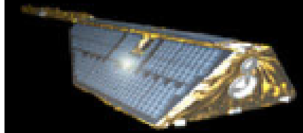
J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

„Optimization“ of the bending angle

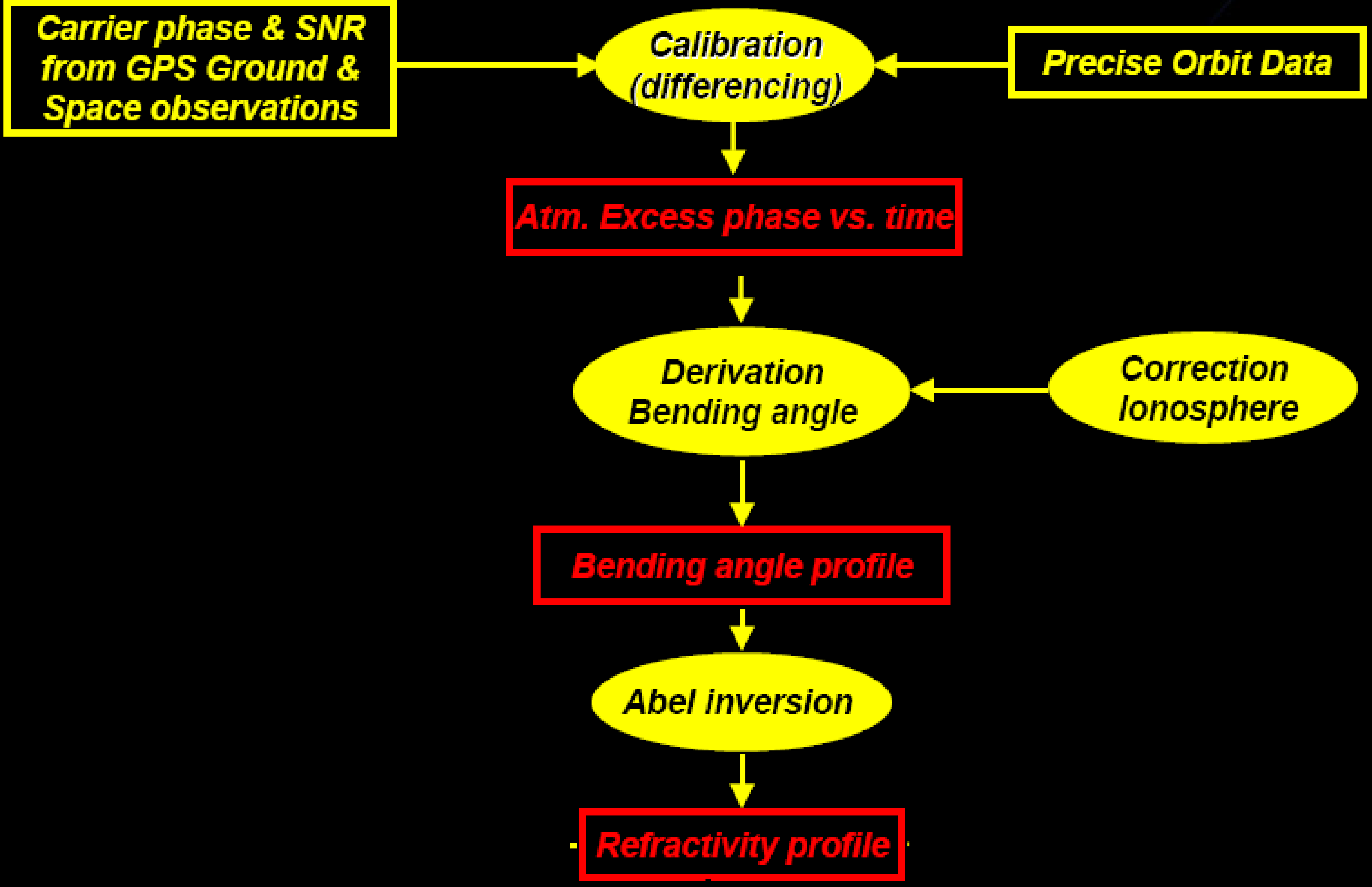


Hocke, 1997

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004



Data analysis (Overview)



Carrier phase & SNR from GPS Ground & Space observations

Calibration (differencing)

Precise Orbit Data

Atm. Excess phase vs. time

Derivation Bending angle

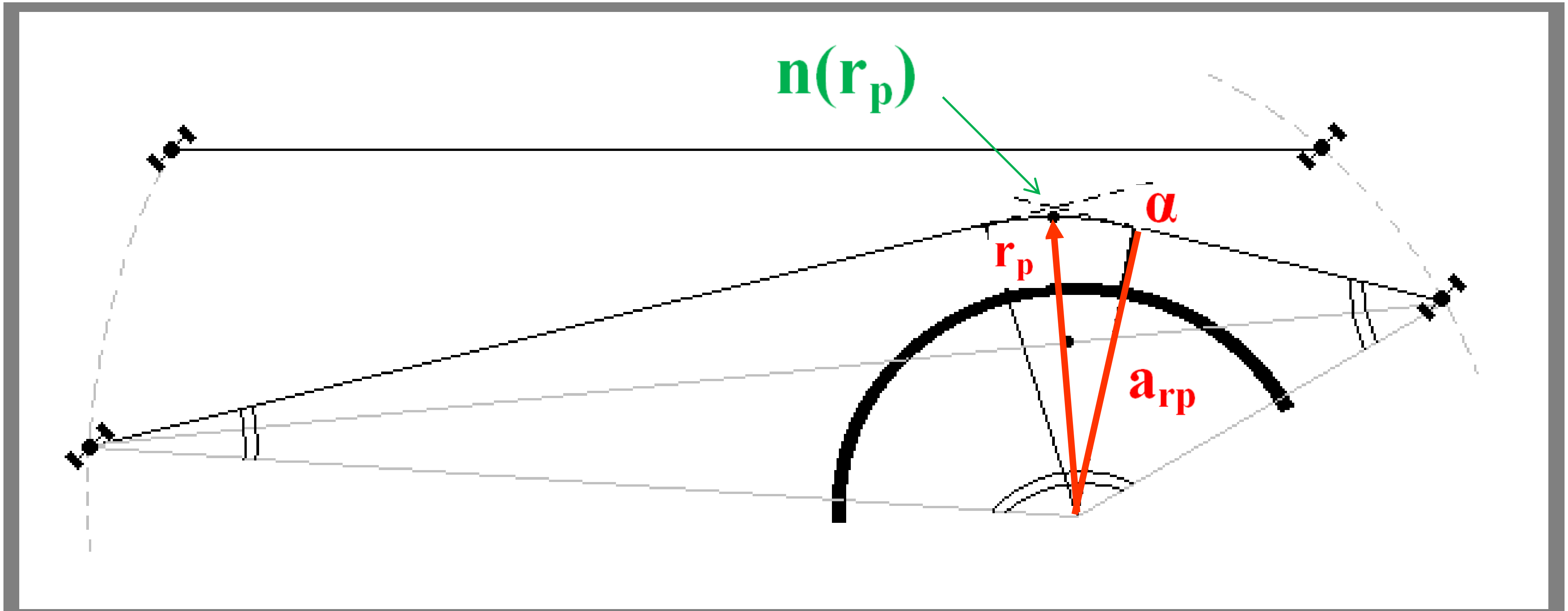
Correction Ionosphere

Bending angle profile

Abel inversion

Refractivity profile

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004



$$\alpha(a) = -2a\int_{a}^{\infty} \frac{1}{\sqrt{(R_t + h)^2 n^2(h) - a^2}} \frac{1}{n(h)} \frac{dn(h)}{dh} dr$$

For each Trajectory (i.e. Excess Doppler value)

REFRACTIVITY PROFILE

$$n(r_p)\begin{cases} n = e^{-\frac{1}{\pi}\int_{a_{r_p}}^{a_M} \ln\left[\frac{a}{a_{r_p}} + \sqrt{\frac{a^2}{a_{r_p}^2} - 1}\right]\frac{d\alpha}{da} da} \\ n(r) r \sin(\psi) = cost = n(r_p) r_p = a_{r_p} \end{cases} \Rightarrow r_p = \frac{a_{r_p}}{n(r_p)}$$

Statist. Optim. Bending angle →
Lat,Long Tangent point →
Impact parameter →

REFRACTIVITY PROFILE

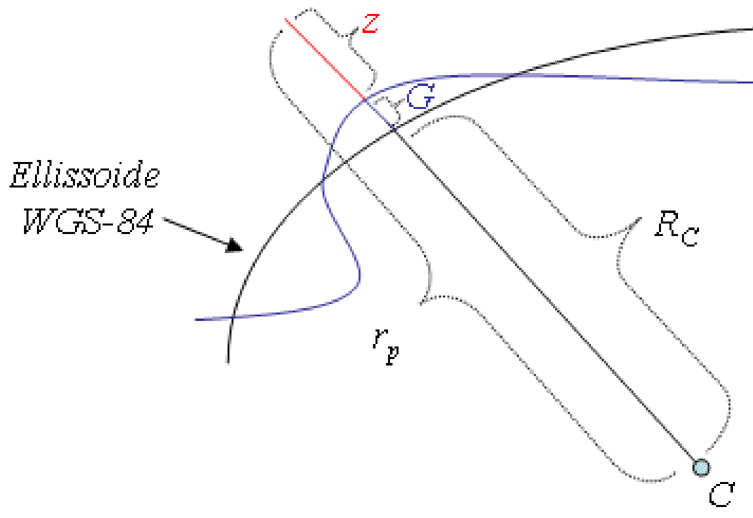
↓ Refractivity
↓ Dry Pressure
↓ Dry Temperature
↓ Tangent point Height

- Abel Inversion

- Heigths from surface

Considering the Geoid undulations (hundred of meters with respect the Ellipsoid), Refractivity profile can be given with respect to the true height (the height above sea level) :

$$z = r_p - R_S = r_p - Rc - G$$

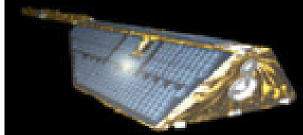


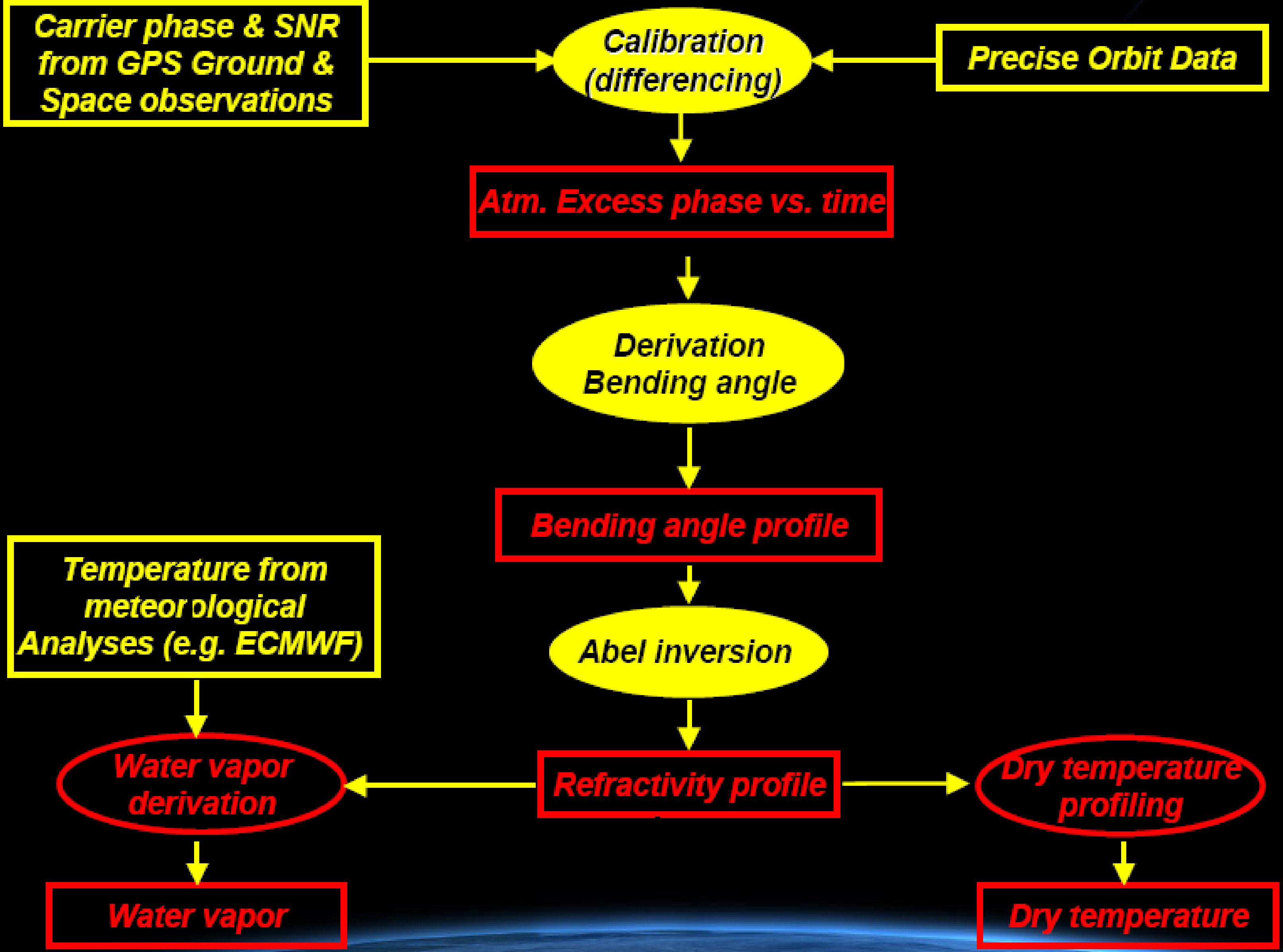
r_p Tangent point distance from the refraction centre

R_C Local Curvature Radius

G Geoid correction

Data analysis (Overview)





Carrier phase & SNR from GPS Ground & Space observations

Calibration (differencing)

Precise Orbit Data

Atm. Excess phase vs. time

Derivation Bending angle

Bending angle profile

Abel inversion

Temperature from meteorological Analyses (e.g. ECMWF)

Water vapor derivation

Refractivity profile

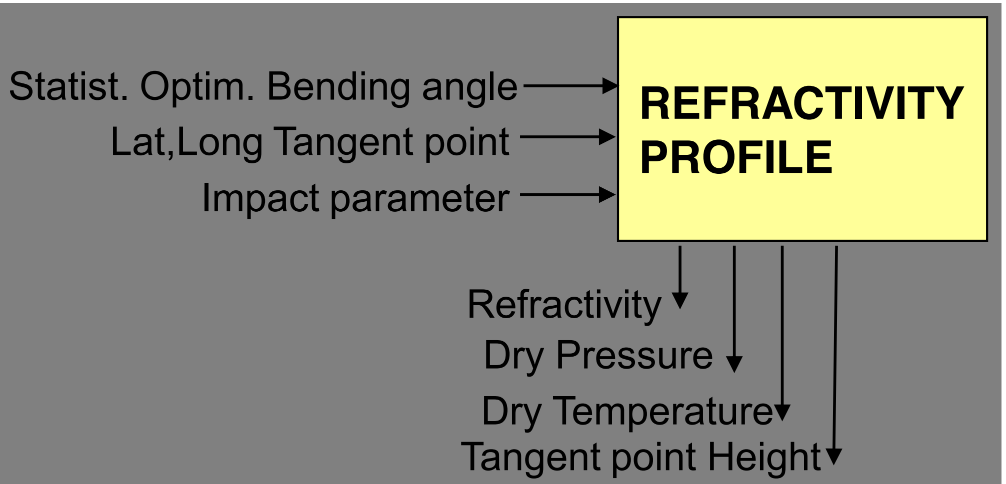
Dry temperature profiling

Water vapor

Dry temperature

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

- **Abel Inversion**
- **Heigths from surface**
- **Atmospheric profiles extraction**


Statist. Optim. Bending angle

Lat,Long Tangent point

Impact parameter

REFRACTIVITY PROFILE

Refractivity

Dry Pressure

Dry Temperature

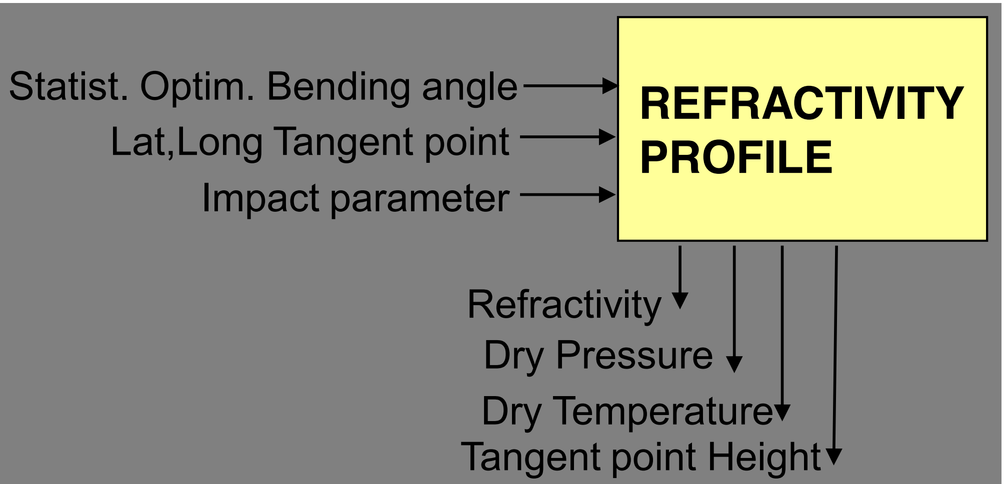
Tangent point Height

$$N = 77{,}6\frac{p_D}{T} + 3{,}75\cdot 10^5\frac{e}{T^2} + \xcancel{40{,}5\cdot 10^7\frac{n_e}{f^2}}$$

Water Vapour contribution

Exploiting the Ionospheric Compensation, this term vanishes

Dry contribution



Statist. Optim. Bending angle

Lat,Long Tangent point

Impact parameter

REFRACTIVITY PROFILE

Refractivity

Dry Pressure

Dry Temperature

Tangent point Height

- **Abel Inversion**
- **Heigths from surface**
- **Atmospheric profiles extraction**
- **Air Density profile evaluation**

Where water vapour can be neglected:

$$N = 77{,}6\frac{p_D}{T}$$

Considering the ideal gases state law:

AIR DENSITY

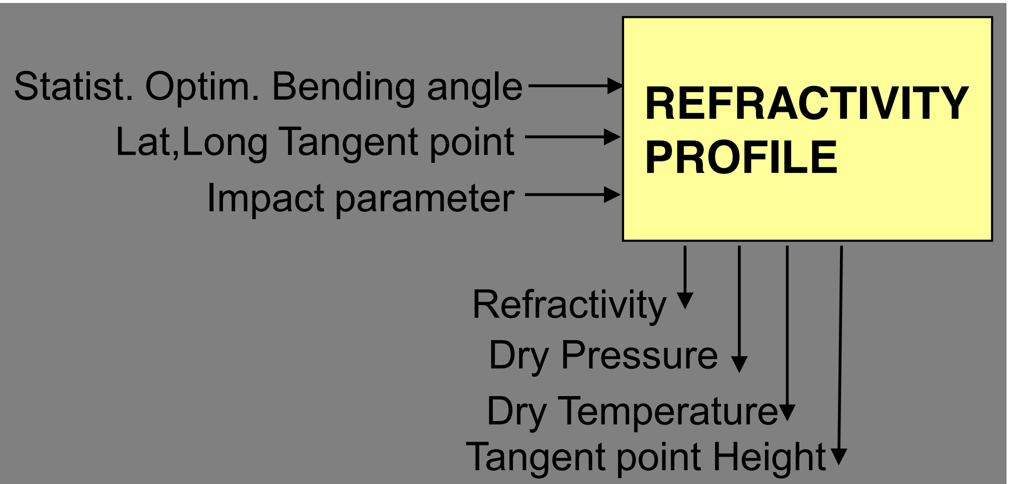
DRY AIR MOLECULAR WEIGTH

$$\rho = \frac{p_D}{T}\frac{\mathrm{M}_0}{\mathrm{R}_D}$$

DRY GASES UNIVERSAL CONSTANT

Thus:

$$\rho(z) = \frac{N(z)}{77{,}6}\frac{M_0}{R_D}$$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REFRACTIVITY PROFILE

Refractivity

Dry Pressure

Dry Temperature

Tangent point Height

- **Abel Inversion**

- **Heigths from surface**

- **Atmospheric profiles extraction**

- **Air Density profile evaluation**

Where water vapour can be neglected:

- Dry Pressure profile

It can be evaluated through integration of Hydrostatic equation

$$dp_D(z) = -g\rho(z)dz$$

Gravity acceleration

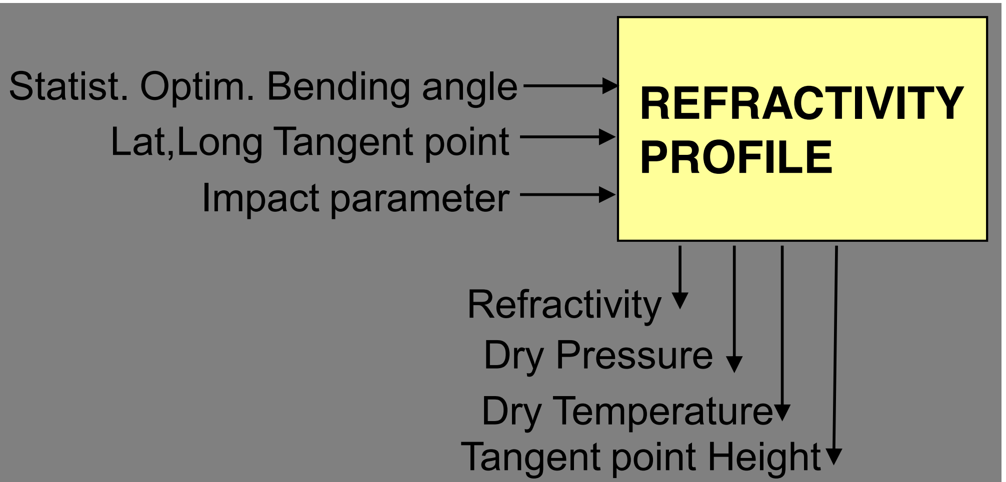
The result is the following

$$p_{D,}(z_{M\text{-}1}) = p_{D,}(z_M) + g\int_{z_{,M-1}}^{z_M}\rho(z)dz$$

$$p_D(z_{M\text{-}2}) = p_D(z_{M\text{-}1}) + g\int_{z_{M-2}}^{z_{M-1}}\rho(z)dz$$

$z_M, z_{M\text{-}1}, .., z_0$ are the heigths of each atmospheric layer

$p_D(z_0)$ (from Climatology)



- **Abel Inversion**

- **Heigths from surface**

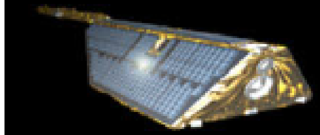
- **Atmospheric profiles extraction**

- **Air Density profile evaluation**
Where water vapour can be neglected:

- **Dry Pressure profile**
It can be evaluated through integration of Hydrostatic equation

- **Dry Temperature profile**

$$T(z) = 77{,}6\frac{p_D(z)}{N(z)}$$



Water vapor retrieval

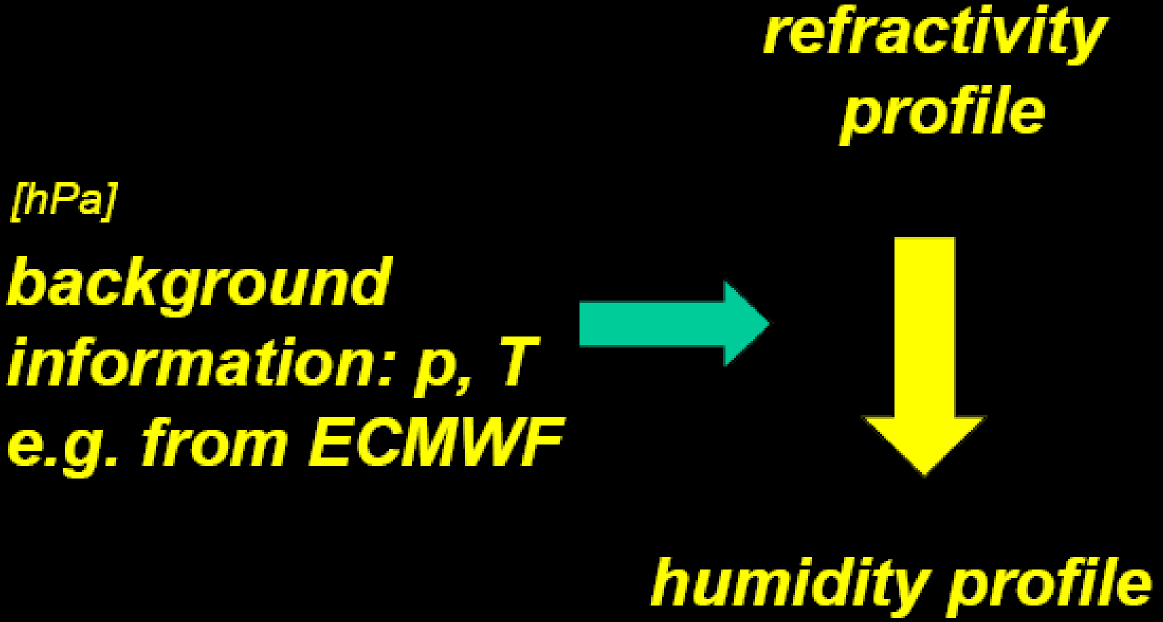
$$N = 77.6\frac{p}{T} + 3.73\times10^{5}\frac{p_w}{T^2}$$

N: atmospheric refractivity

T atmospheric temperature [K]

p : atmospheric pressure [hPa]

p_w : water vapor partial pressure [hPa]

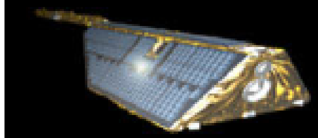


refractivity profile

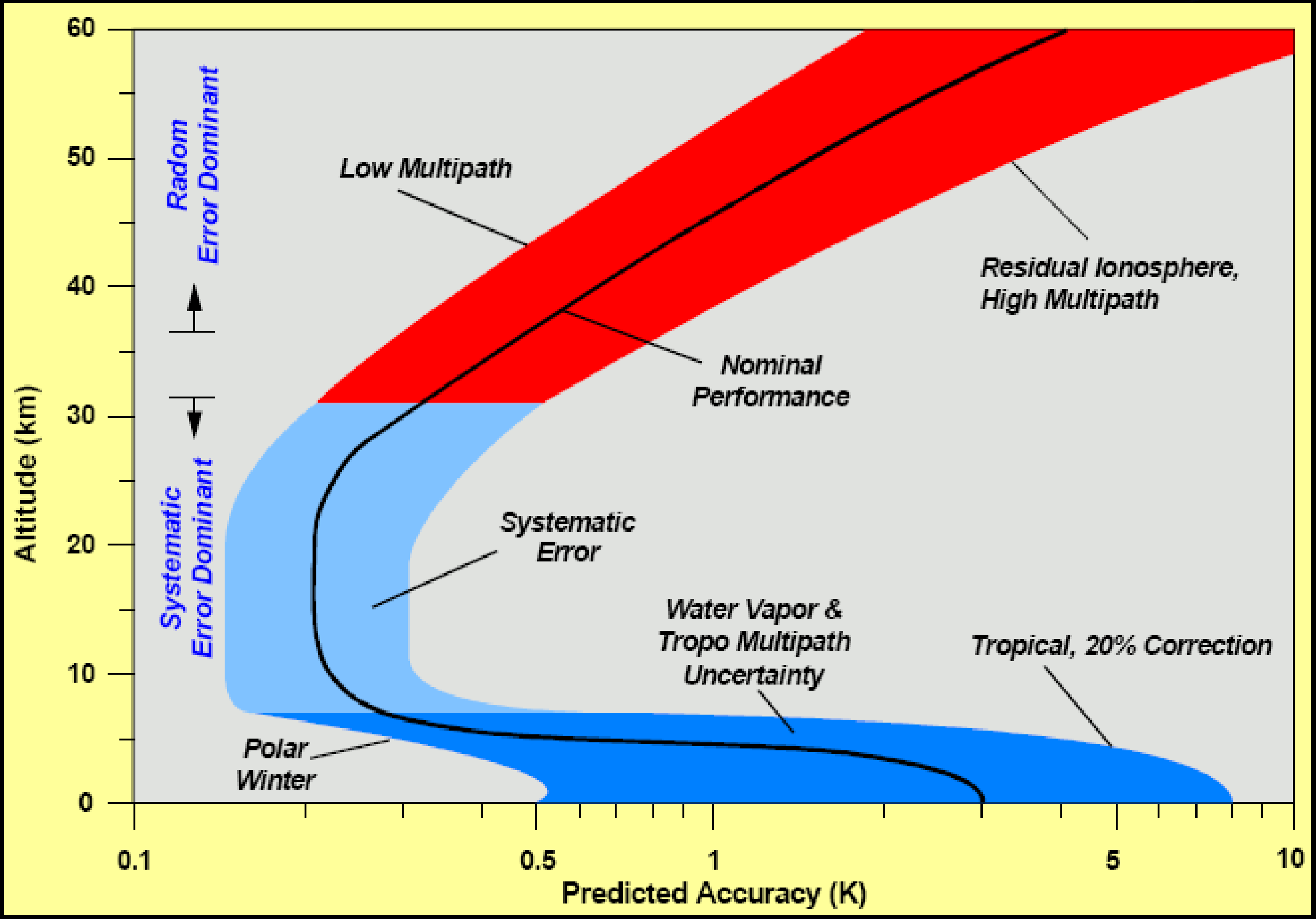
background information: p, T e.g. from ECMWF

humidity profile

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004



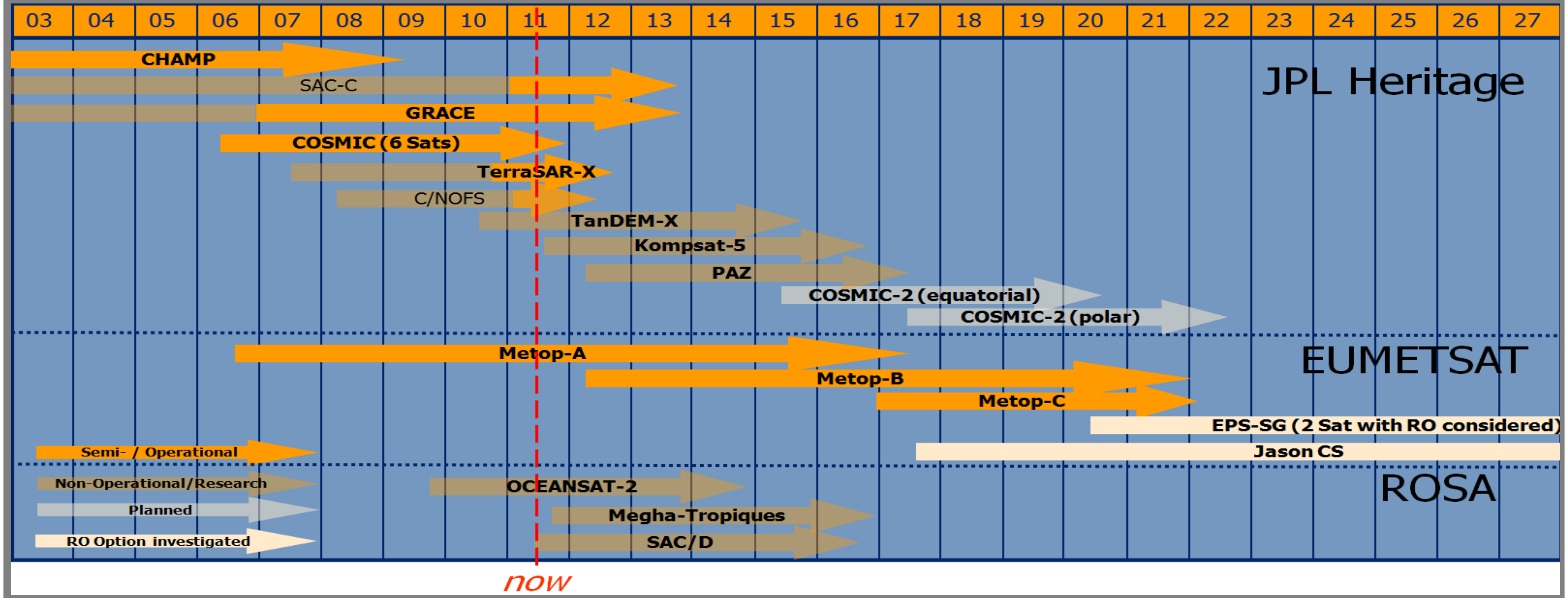
Error Estimation



Melbourne et al.,1994

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

Radio Occultation missions

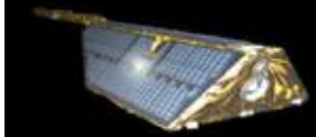


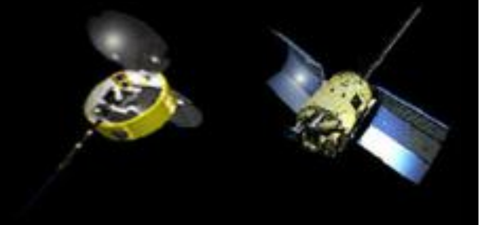
Recent EUMETSAT Activities

GRAS Team at EUMETSAT

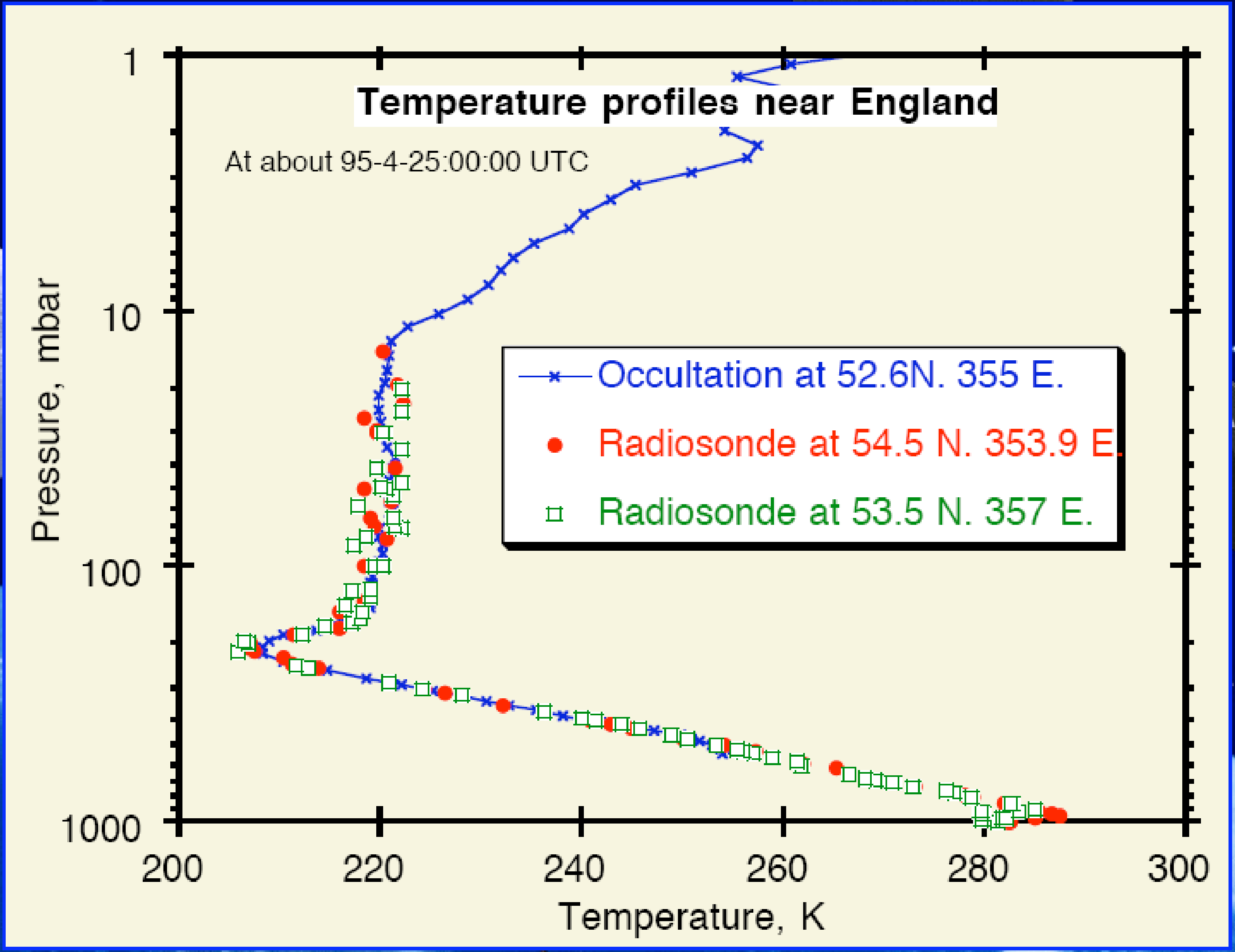
GRAS SAG 26, EUMETSAT
22nd, 23rd of June 2011

EUMETSAT





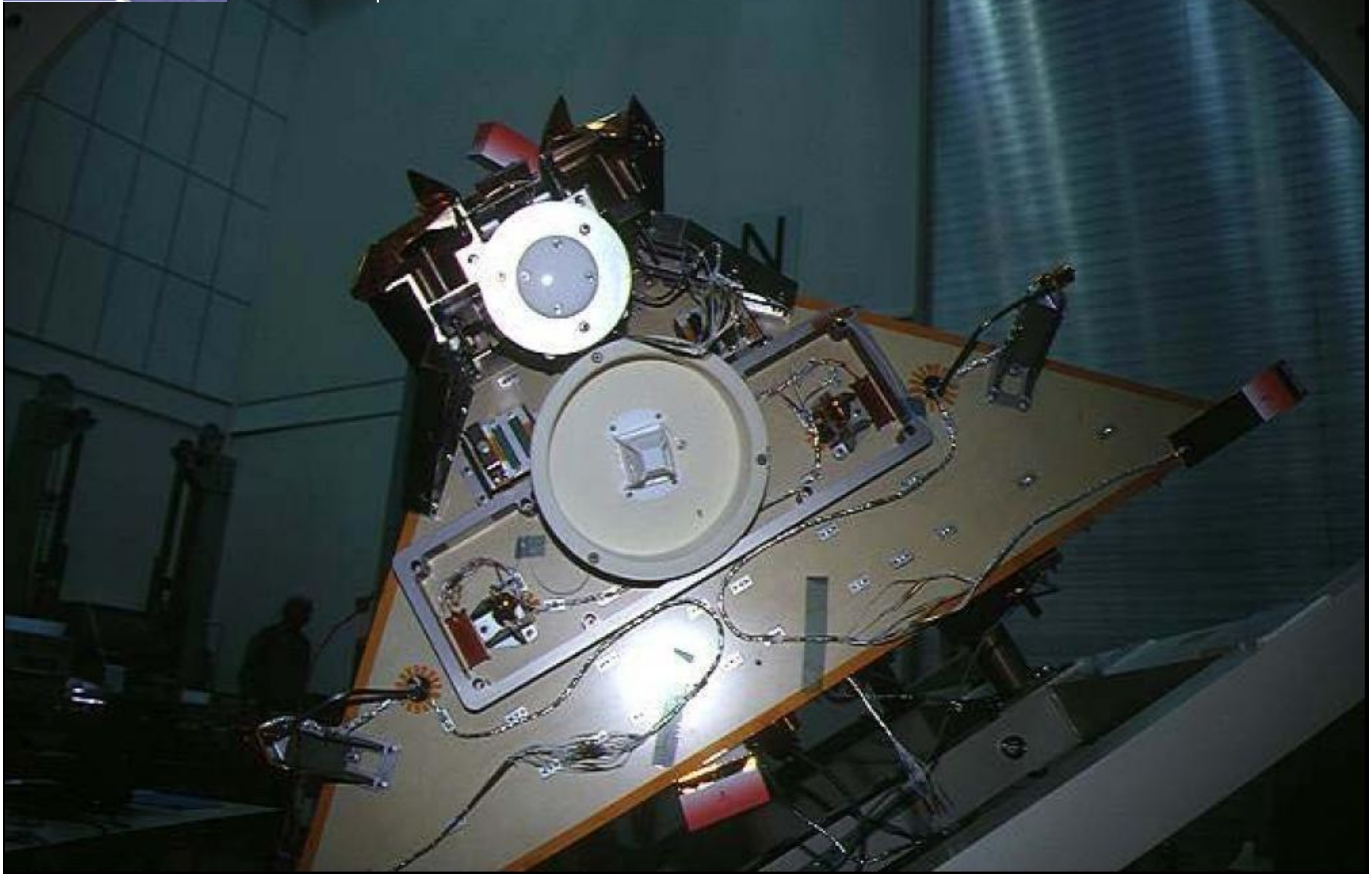
GPS/MET:
The pioneer



T. P. Yunck, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

CHAMP

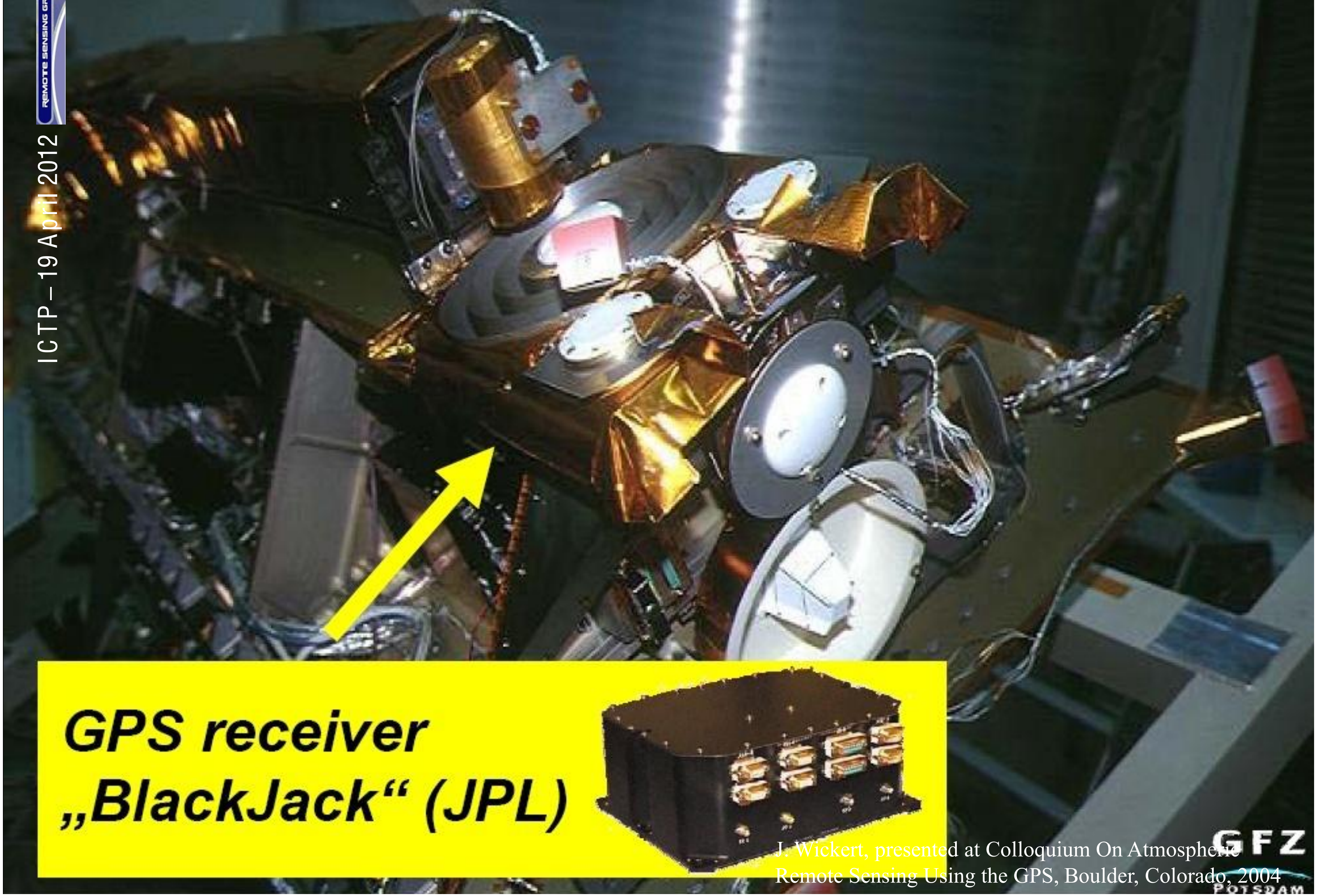
J. Wickert, presented at OPAC-2 Workshop, Graz, 2004



Occultation antenna

J. Wickert, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

„BlackJack“ and GPS antennas aboard CHAMP

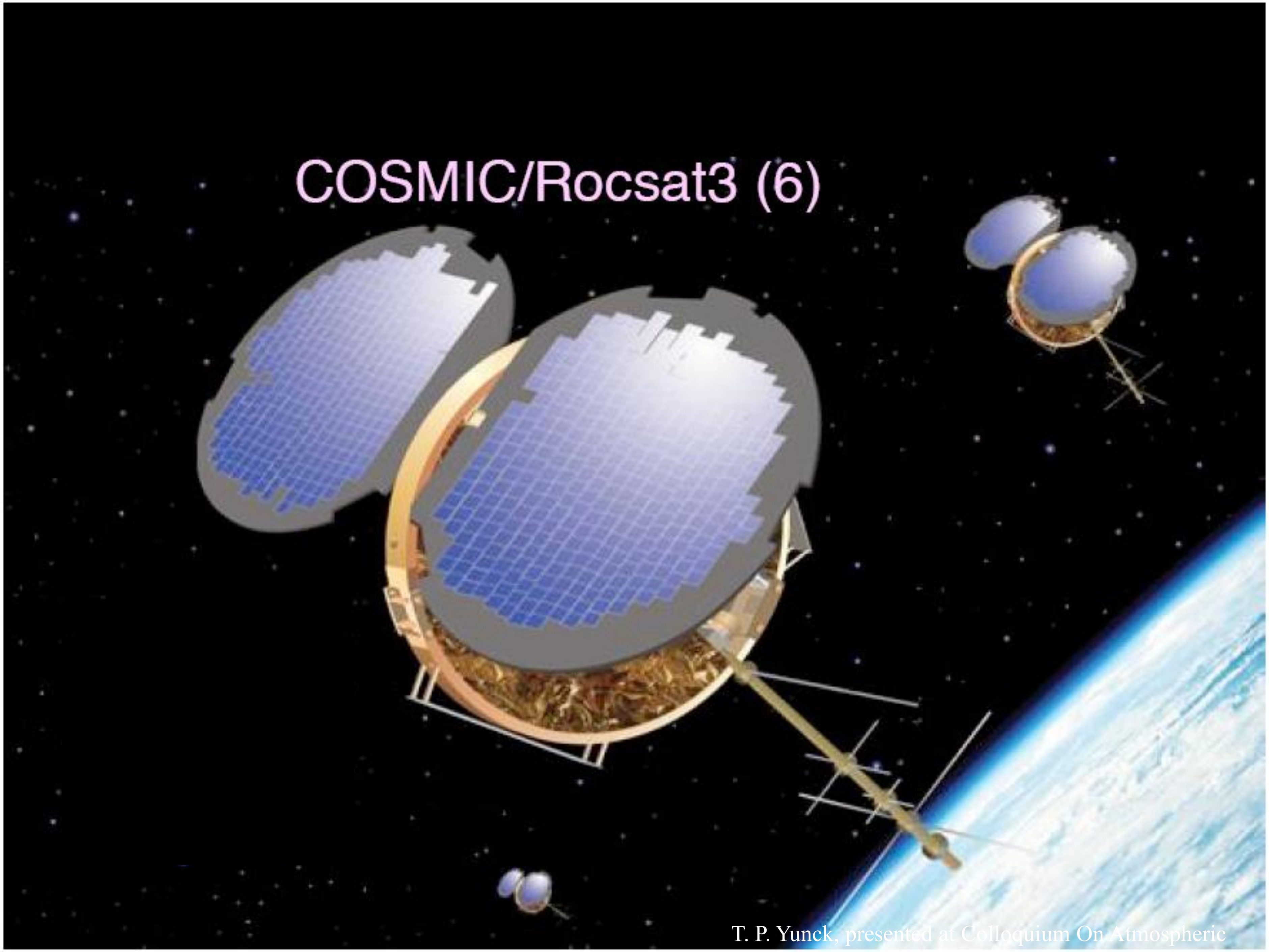


GPS receiver „BlackJack“ (JPL)

J. Wickert, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

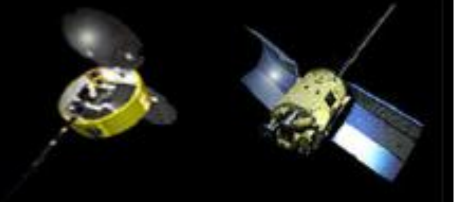
OTHER RO MISSIONS

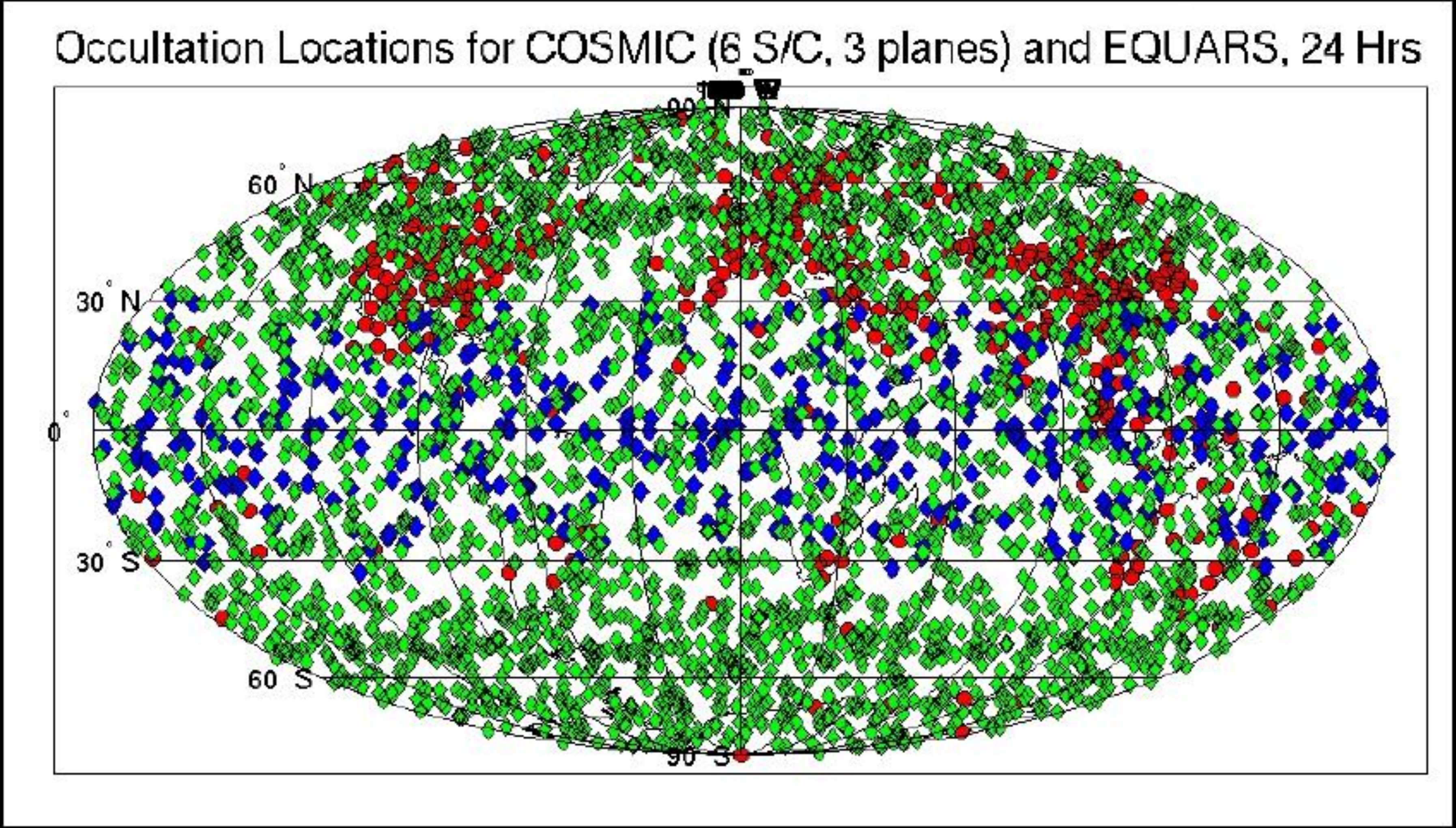
COSMIC/Rocsat3 (6)



T. P. Yunck, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

COSMIC&EQUARS

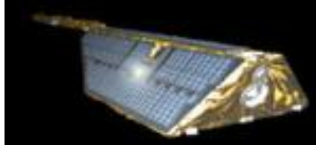




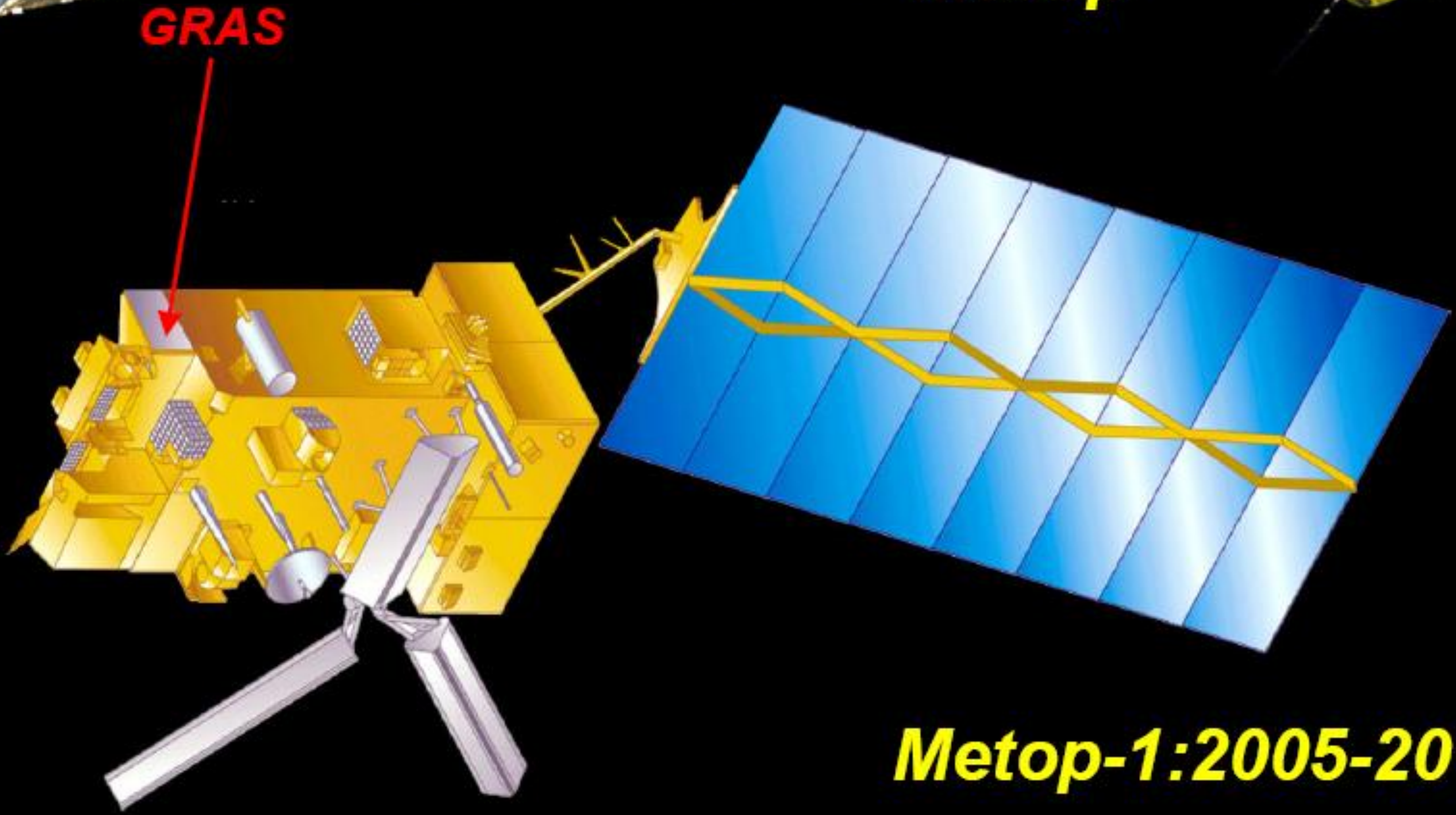
Simulation: COSMIC, EQUARS, Radiosondes

Danke: C. Rocken, H. Takahashi

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004



MetOp



Metop-1:2005-2010

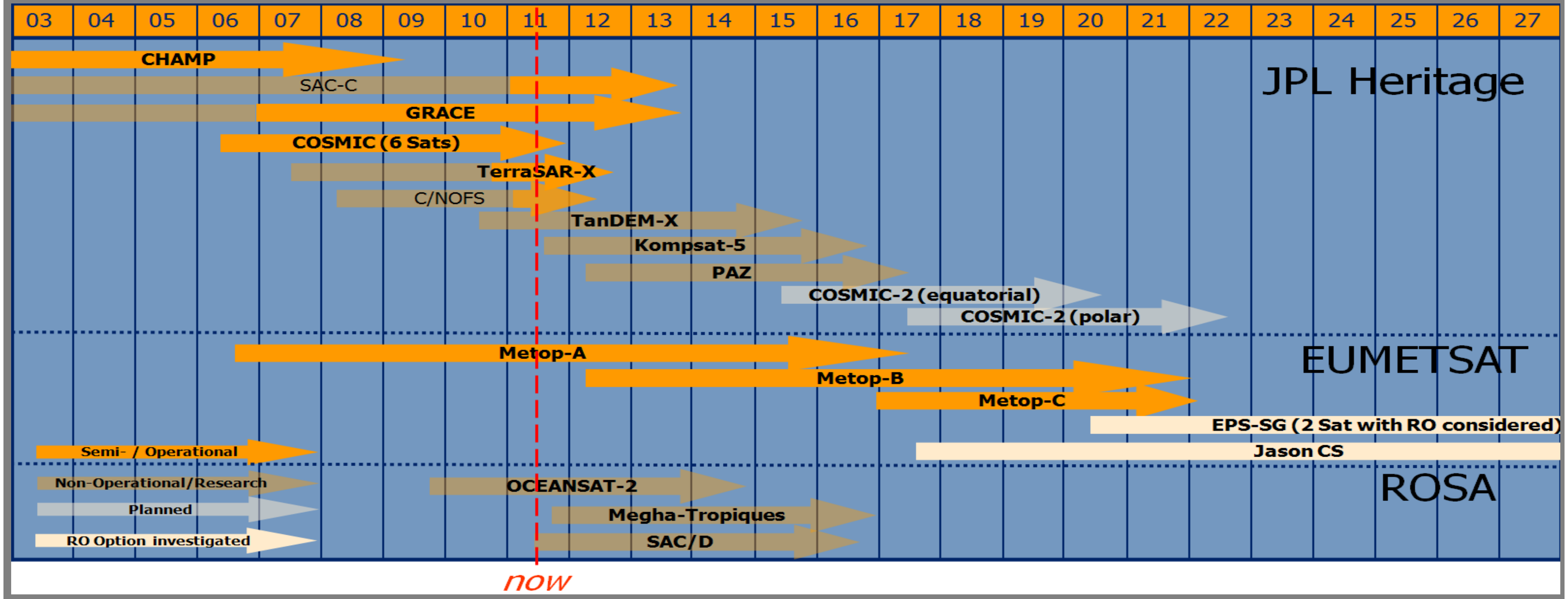
Metop-2:2010-2014

Metop-3:2014-2018

Danke: G. Larsen

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

Radio Occultation missions



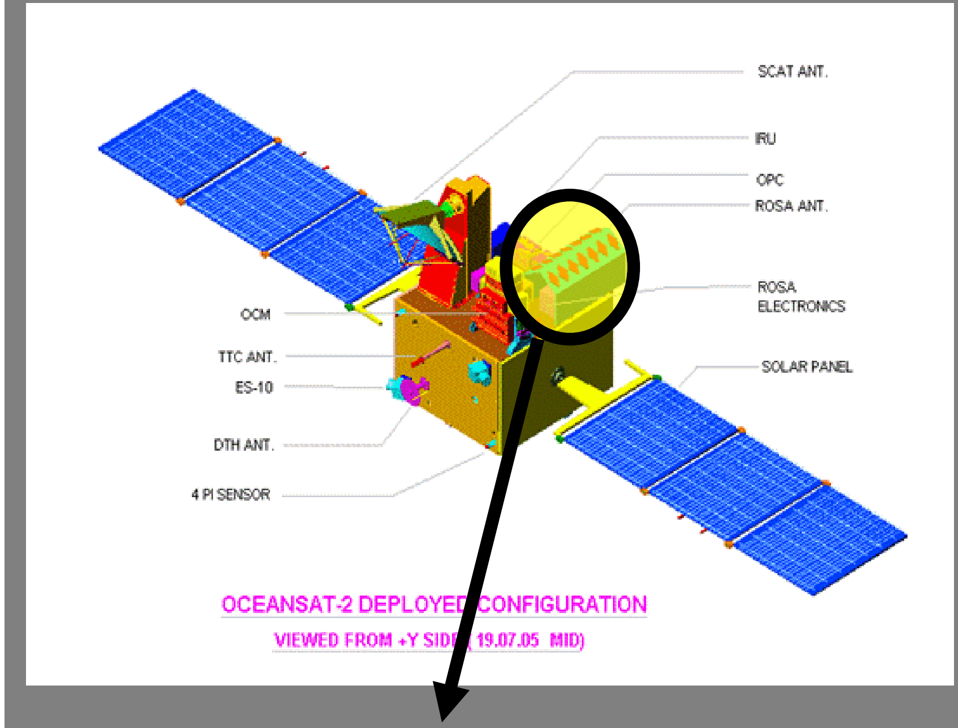
Recent EUMETSAT Activities

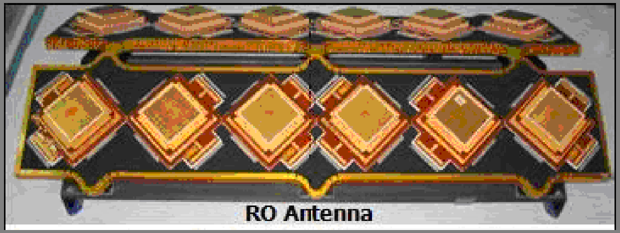
GRAS Team at EUMETSAT

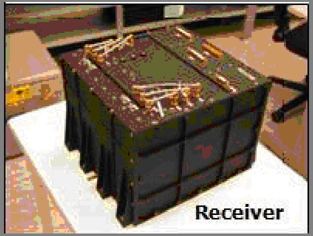
GRAS SAG 26, EUMETSAT
22nd, 23rd of June 2011

EUMETSAT

THE ITALIAN RO Receiver (ROSA)




RO Antenna


Receiver


POD Antenna

Radio Occultation Sounder for Atmosphere (ROSA)

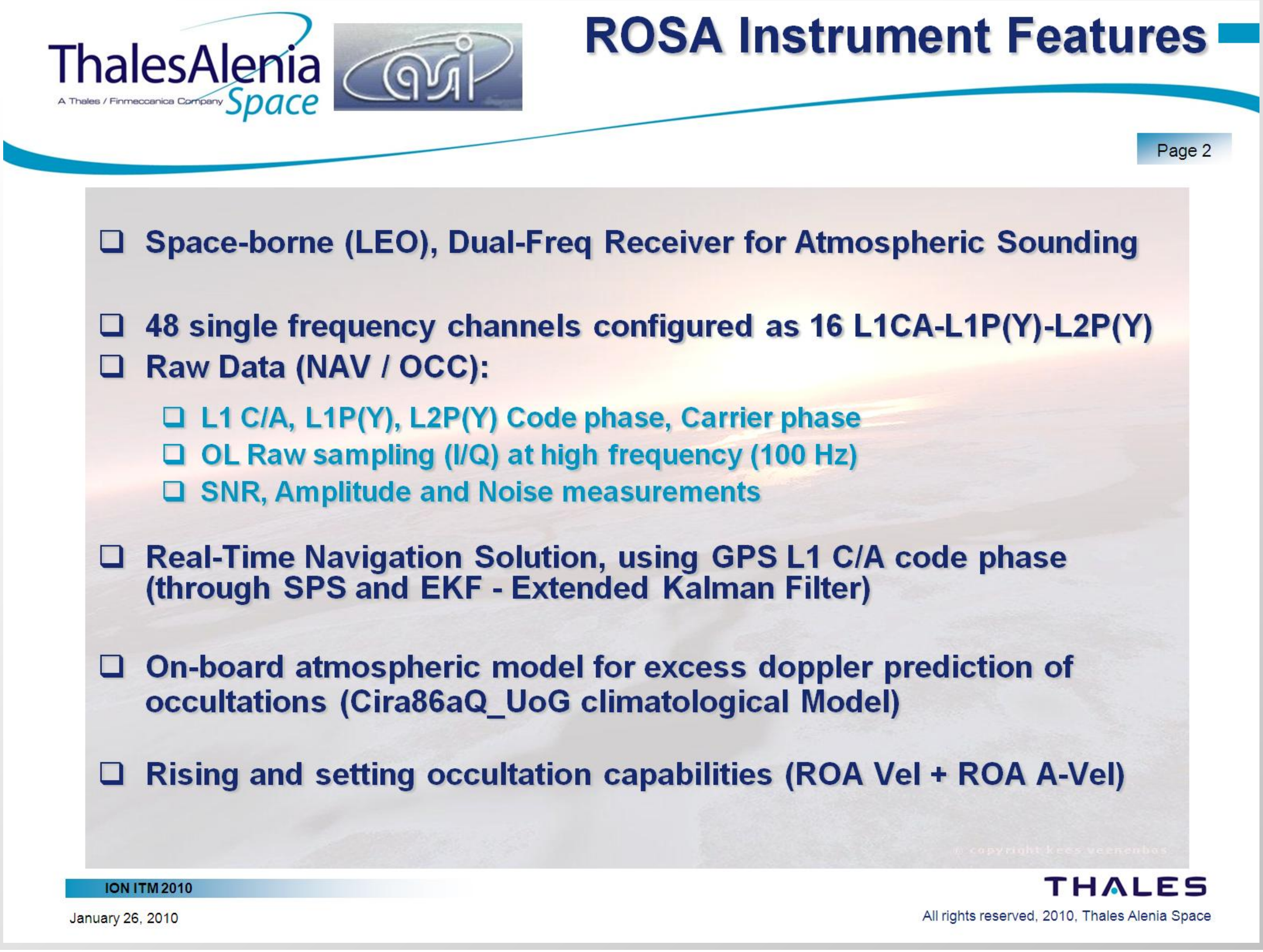
- Radio Occultation GPS receiver

- Developed for Italian Space Agency by Thales Alenia Space

- Open loop (raw sampling) tracking for low troposphere sounding, for **multi-tone low SNR signals and for a faster tracking in rising occultations**

- High Gain Radio Occultation antenna

ION 2010 International Technical Meeting Program
January 25-27, 2010 • Catamaran Resort Hotel • San Diego, CA



ThalesAlenia Space
A Thales / Finmeccanica Company

ROSA Instrument Features

- ❑ Space-borne (LEO), Dual-Freq Receiver for Atmospheric Sounding
- ❑ 48 single frequency channels configured as 16 L1CA-L1P(Y)-L2P(Y)
- ❑ Raw Data (NAV / OCC):
  - ❑ L1 C/A, L1P(Y), L2P(Y) Code phase, Carrier phase
  - ❑ OL Raw sampling (I/Q) at high frequency (100 Hz)
  - ❑ SNR, Amplitude and Noise measurements
- ❑ Real-Time Navigation Solution, using GPS L1 C/A code phase (through SPS and EKF - Extended Kalman Filter)
- ❑ On-board atmospheric model for excess doppler prediction of occultations (Cira86aQ_UoG climatological Model)
- ❑ Rising and setting occultation capabilities (ROA Vel + ROA A-Vel)

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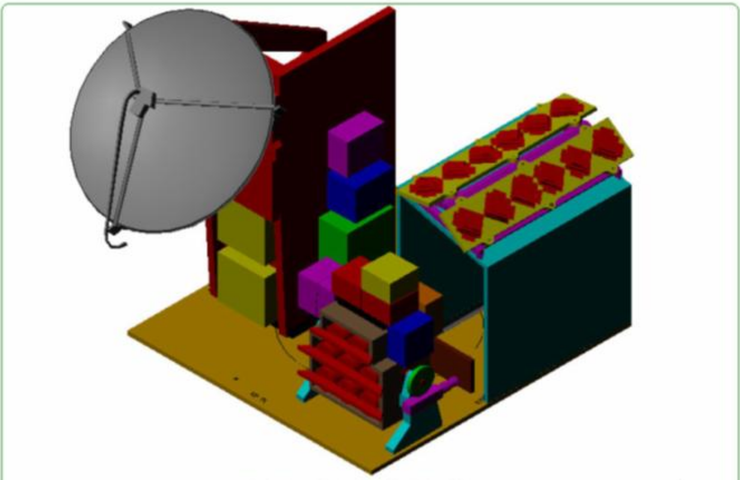
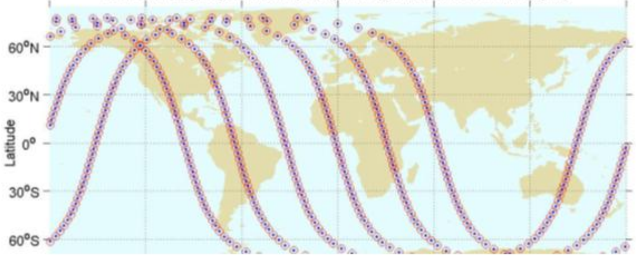
ROSA on OCEANSAT-2

- ISRO OCS-2 mission launched Sept 23, 2009
- Ocean studies, meteorology and prediction of Monsoon
- Opportunity Mission for in-flight Verification of ROSA
- ROSA configuration limited to one directive Velocity antenna (rising only)
- RO +/- 45° azimuth, 0 to -30° elevation
- 15°+20° tilt wrt velocity direction

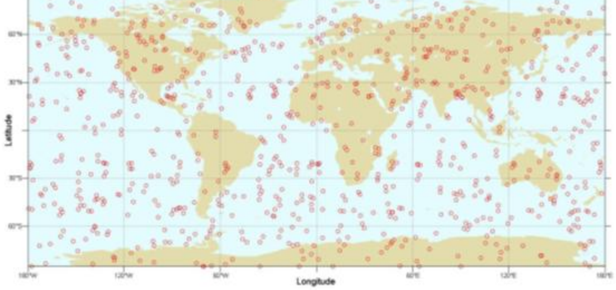


TOP DECK OF OCEANSAT-2 S/C

OCEANSAT2 set1669 Difference Orbit in ECEF
between TLE [blue](SPG4 orbit propagation algorithm) and SPS solution [red]



OCEANSAT2 Occultation Geolocation Distribution on 3 days of Flight data



THALES

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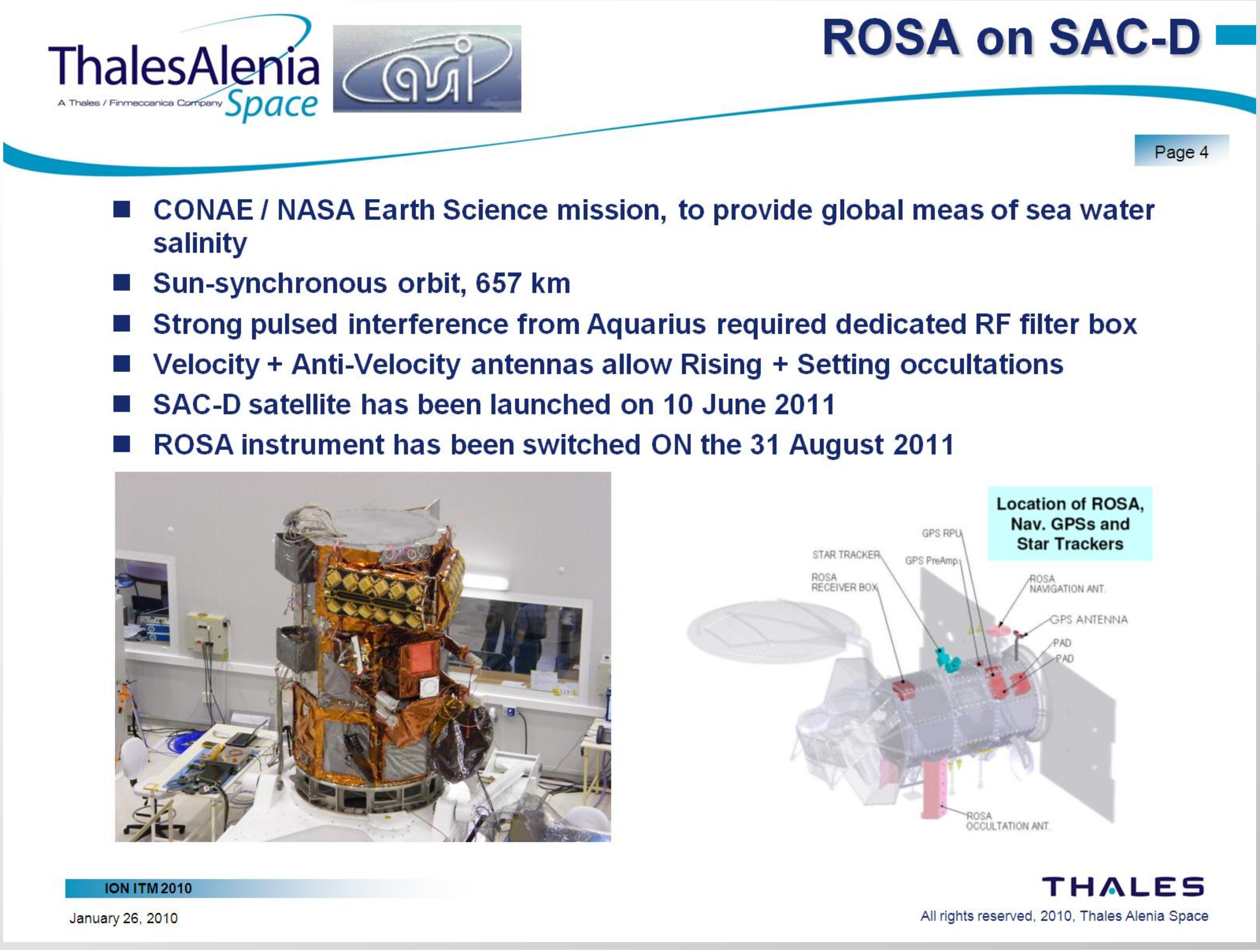

ThalesAlenia Space
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ROSA on SAC-D

- CONAE / NASA Earth Science mission, to provide global meas of sea water salinity
- Sun-synchronous orbit, 657 km
- Strong pulsed interference from Aquarius required dedicated RF filter box
- Velocity + Anti-Velocity antennas allow Rising + Setting occultations
- SAC-D satellite has been launched on 10 June 2011
- ROSA instrument has been switched ON the 31 August 2011

Location of ROSA, Nav. GPSs and Star Trackers

ION ITM 2010

January 26, 2010

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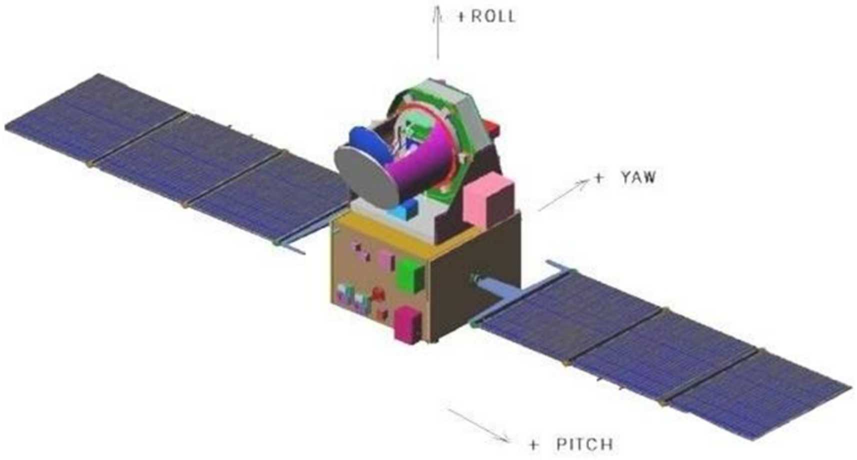
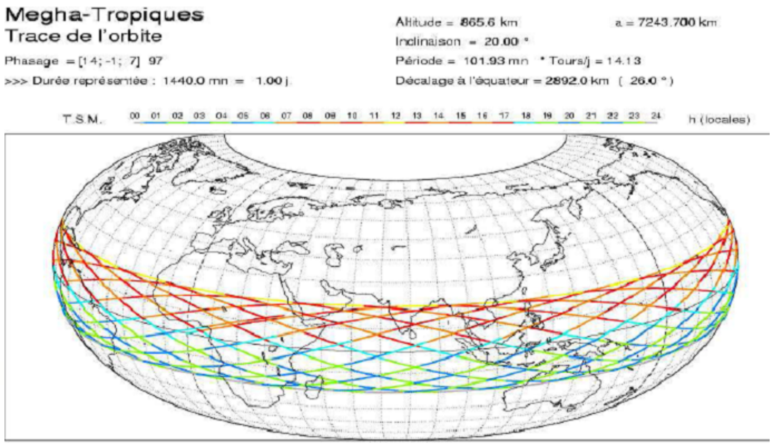
ROSA on MeghaTropiques

- ISRO mission dedicated to tropical atmosphere studies: 3 radiometric instruments to observe water vapour, condensed water and radiative fluxes
- Highly repetitive sampling of inter-tropical band: latitudes 10°-20°, 870Km
- MT periodically performs yaw axis rotation causing ROSA to exchange velocity ROA with anti-velocity ROA
- RO Antennas are one half 6-patch panel, azimuth FOV limited to ±35°
- MEGHA TROPIQUES satellite has been launched on 12 October 2011
- ROSA instrument has been switched ON 12 October 2011





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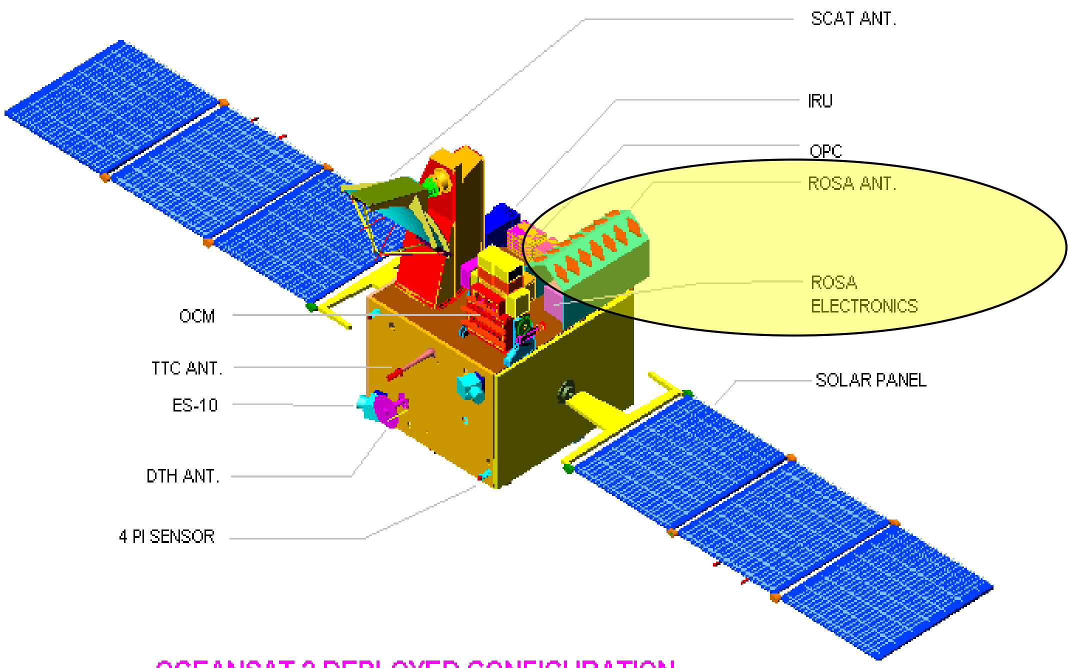
ROSA-ROSSA: Radio Occultation Software for ROSA on-board OCEANSAT-2 data processing

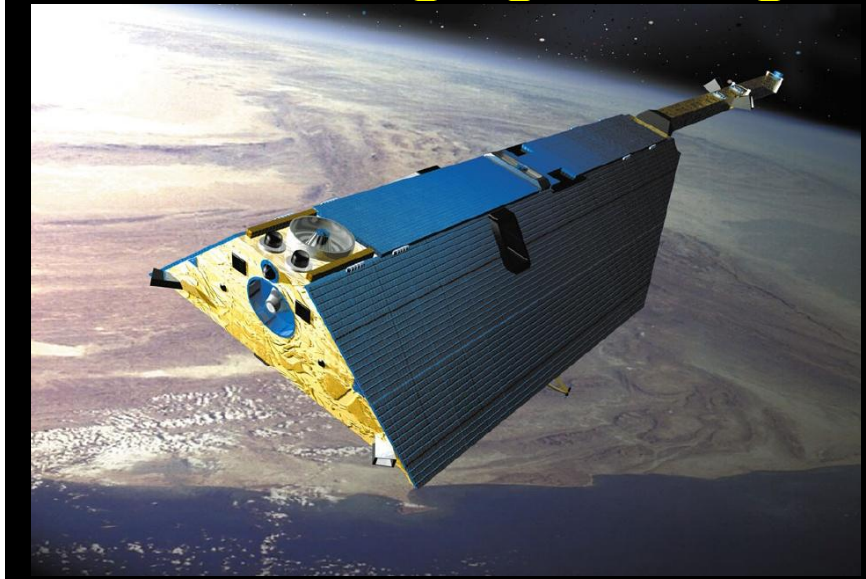


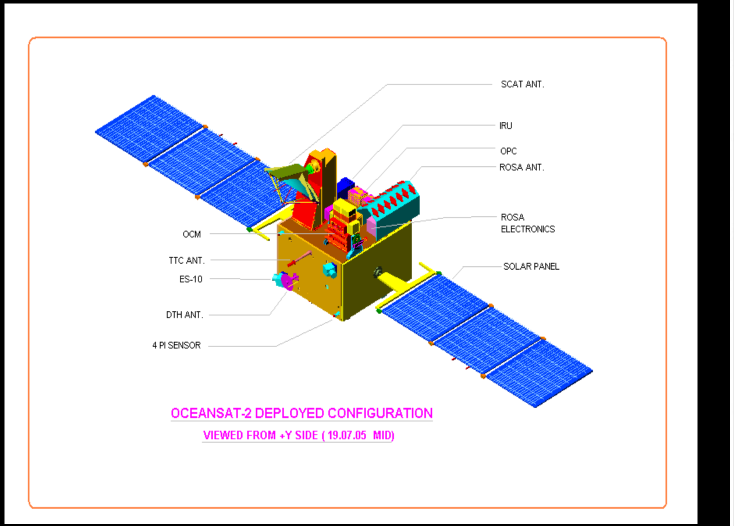
OCEANSAT-2 DEPLOYED CONFIGURATION

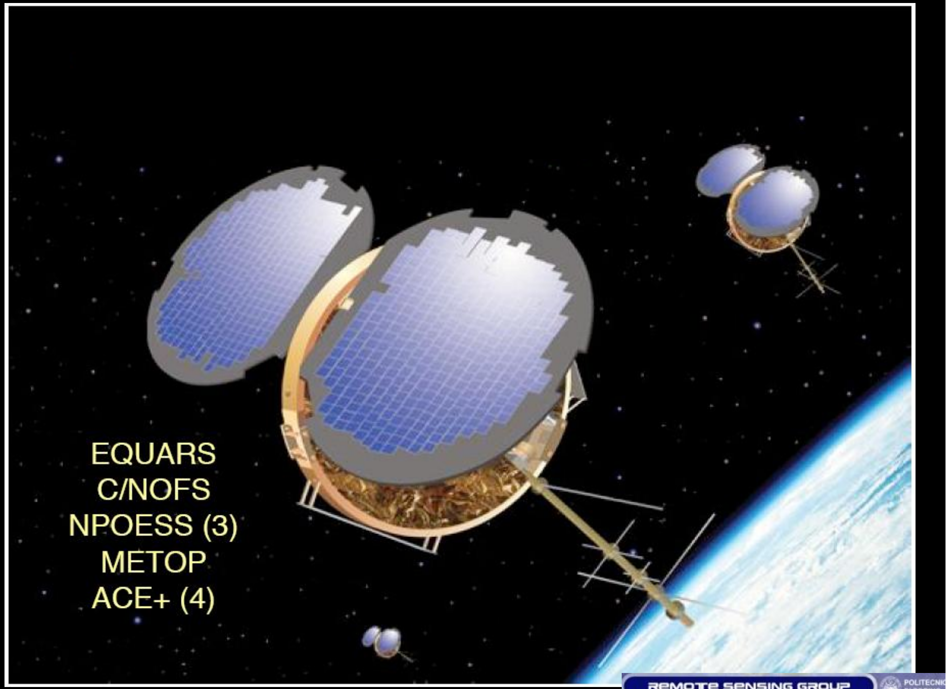
VIEWED FROM +Y SIDE (19.07.05 MID)

ICTP – 19 April 2012

… SOME SUMMARIZING RESULTS

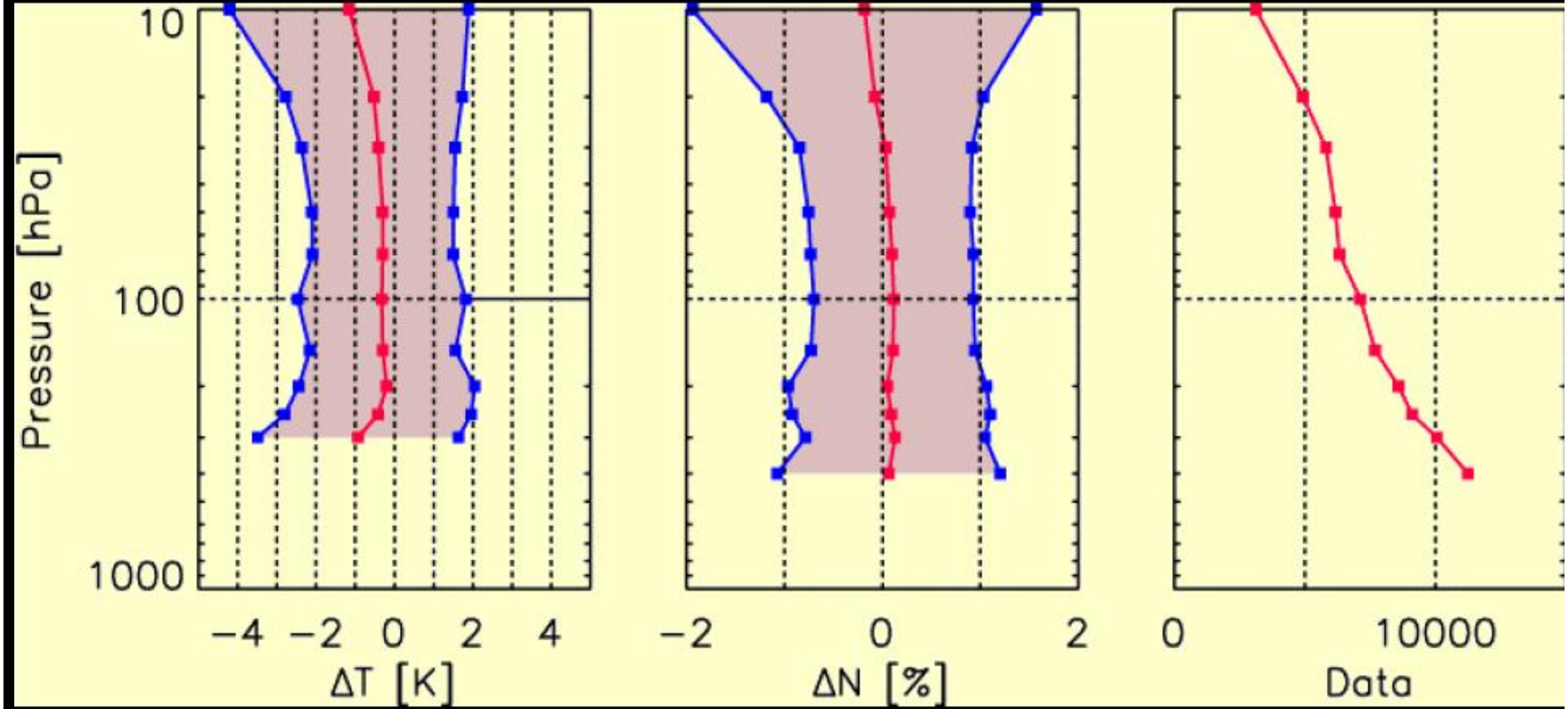






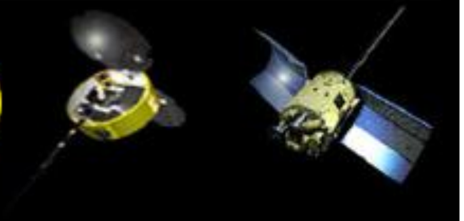
Comparison with RS

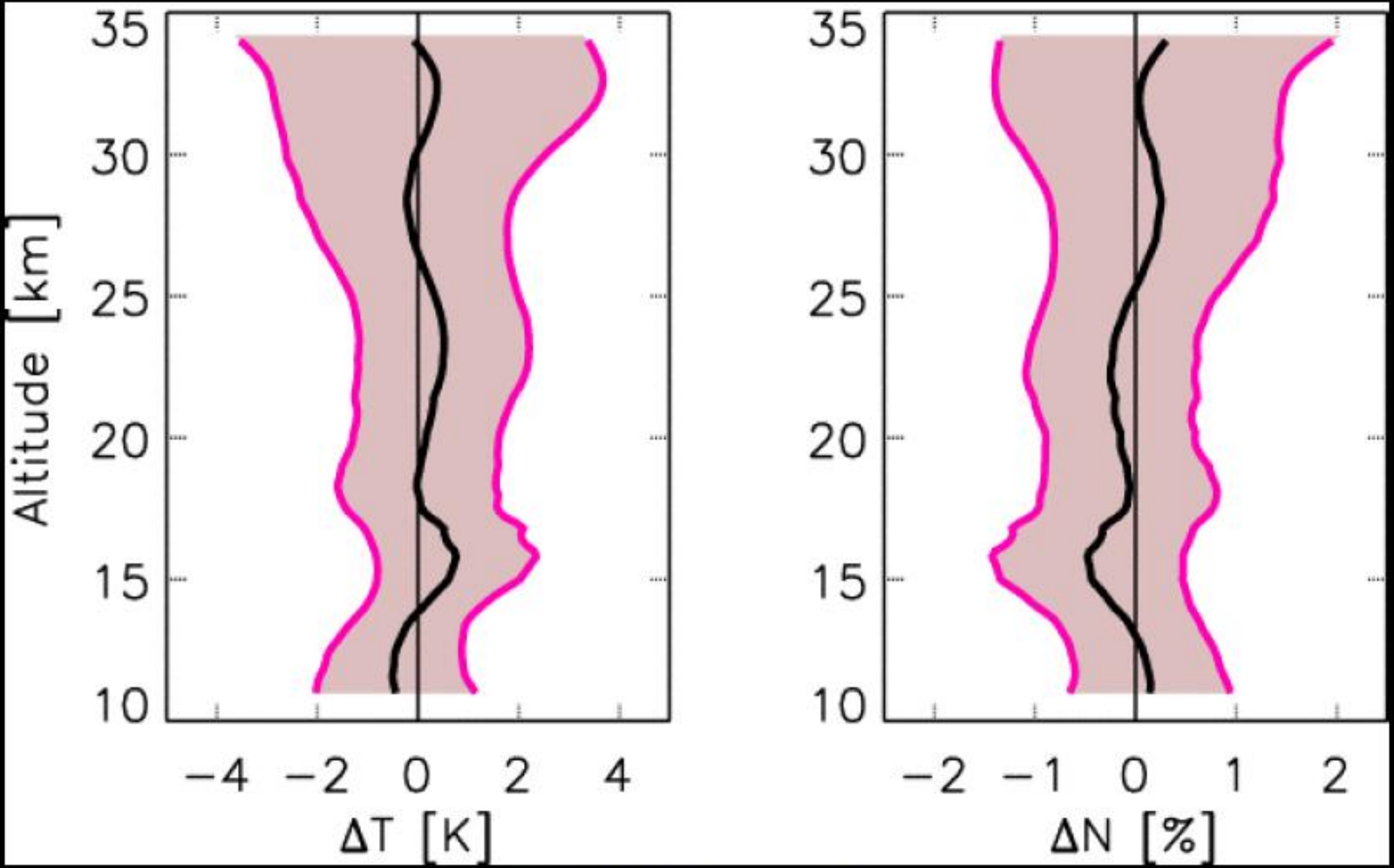
(2003)



J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

Comparsion with ECMWF (2003)

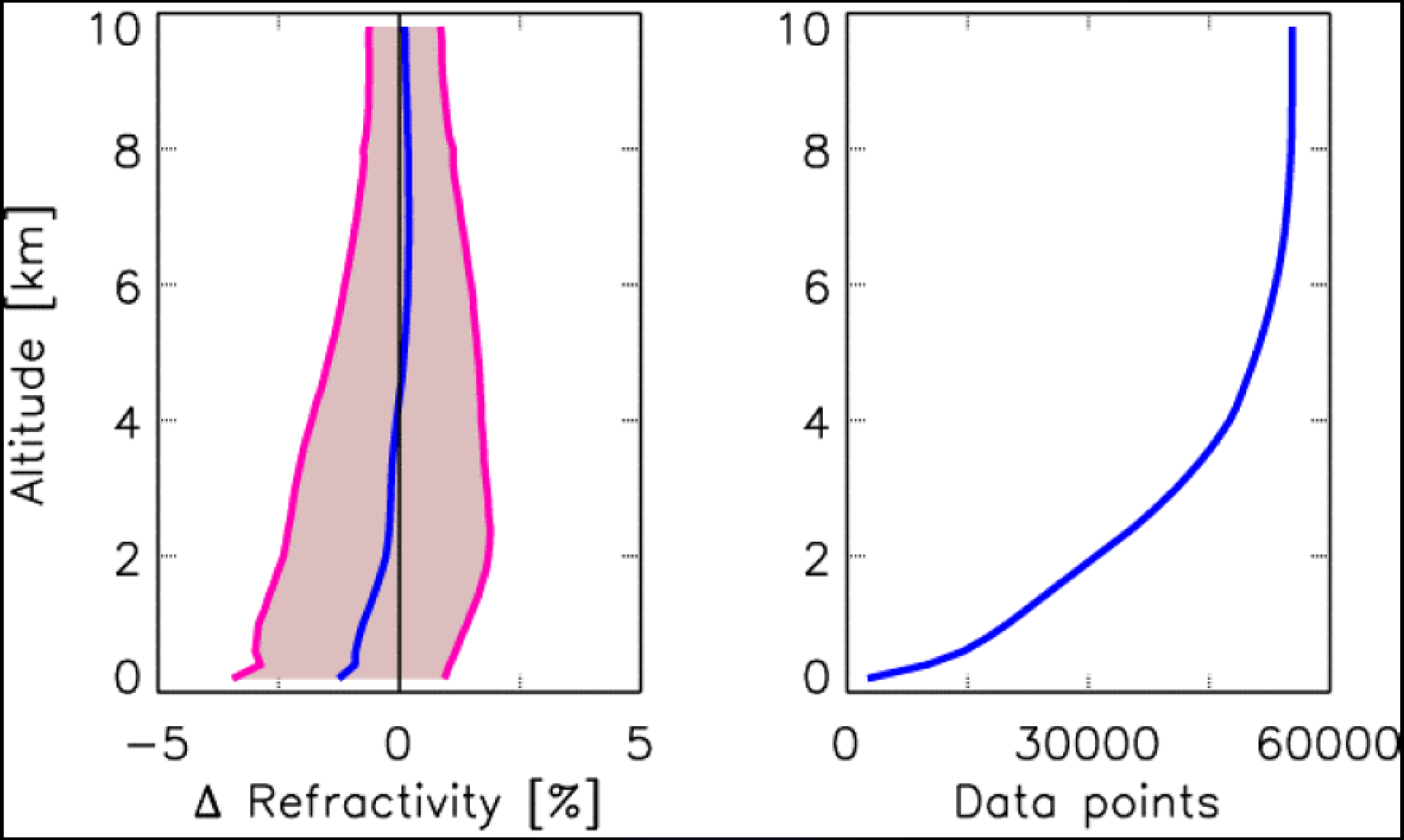




~60,000 profiles

J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

Comparsion with ECMWF



J. Wickert, presented at OPAC-2 Workshop, Graz, 2004

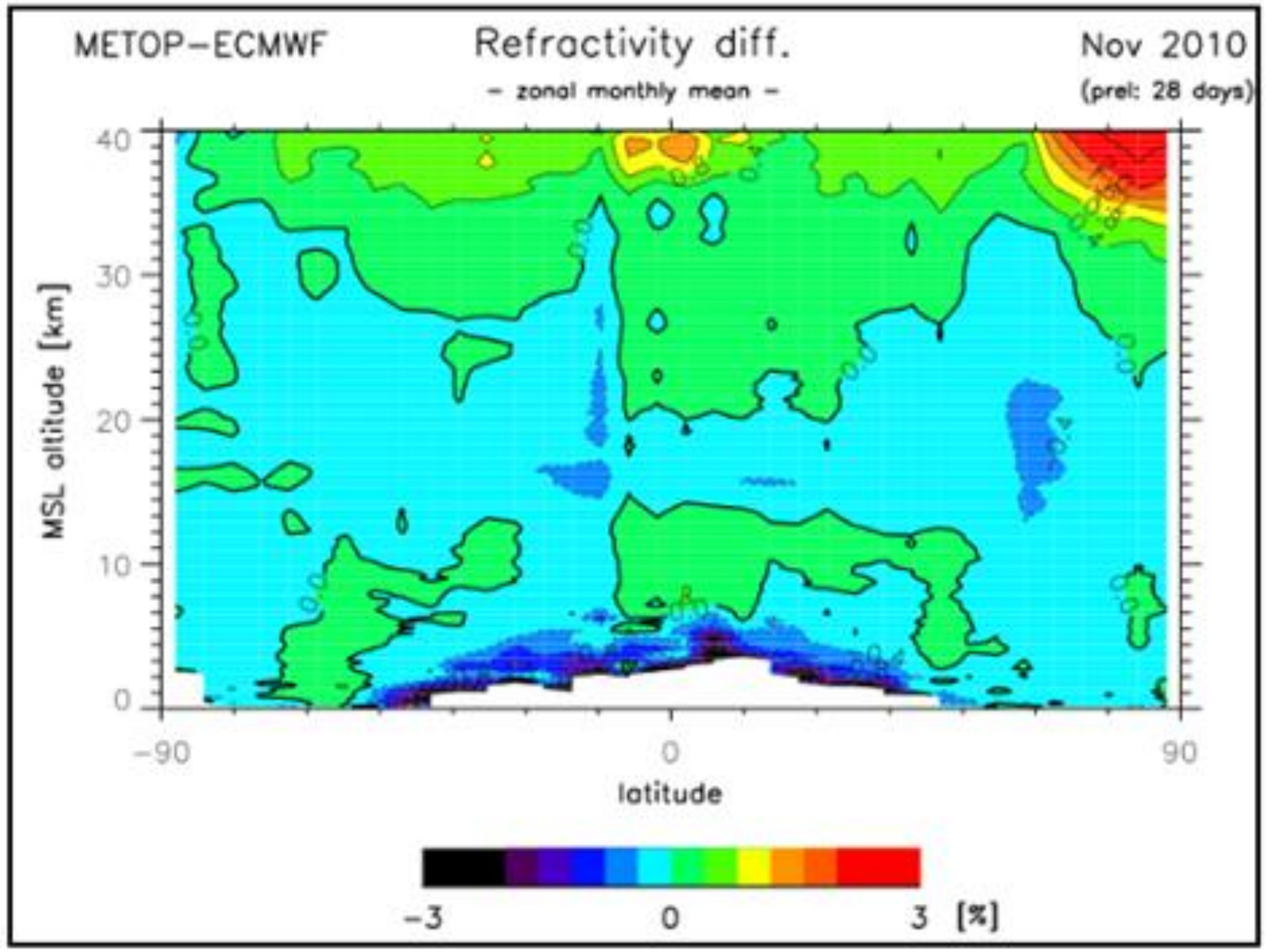
GRAS SAF Climate Products

SAG26, EUMETSAT, 22-23 June 2011

Hans Gleisner & Kent B. Lauritsen

Danish Meteorological Institute

Metop REF O-B/B



GRAS SAF Climate Products

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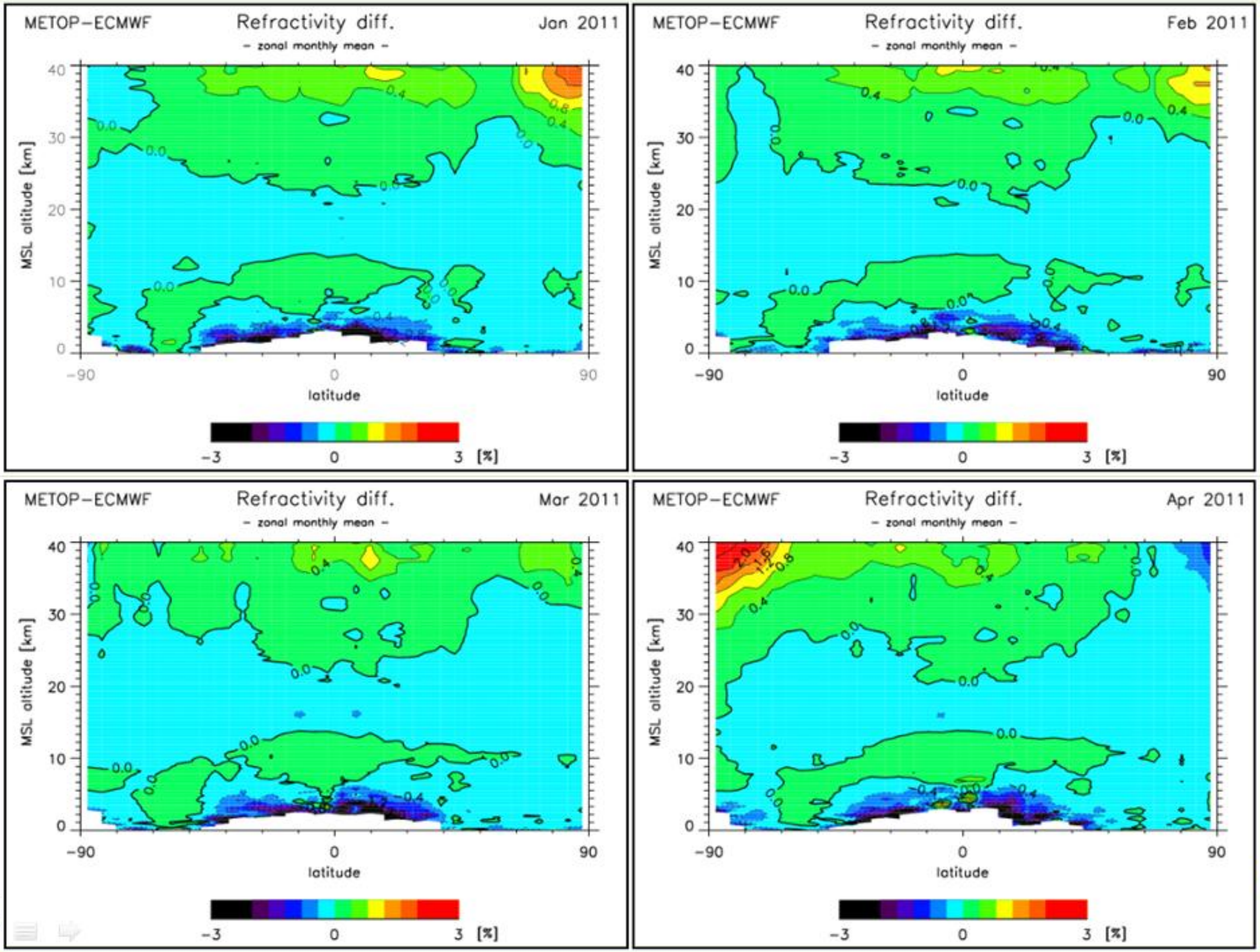


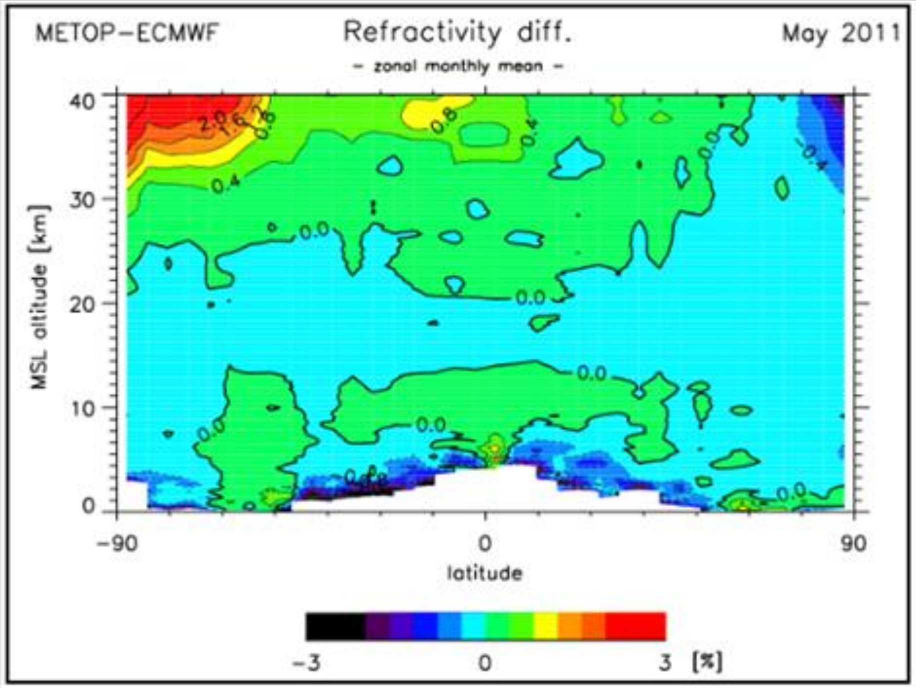
ICTP – 19 April 2012

SAG2

Hans Gleisner & Kent B. Lauritsen

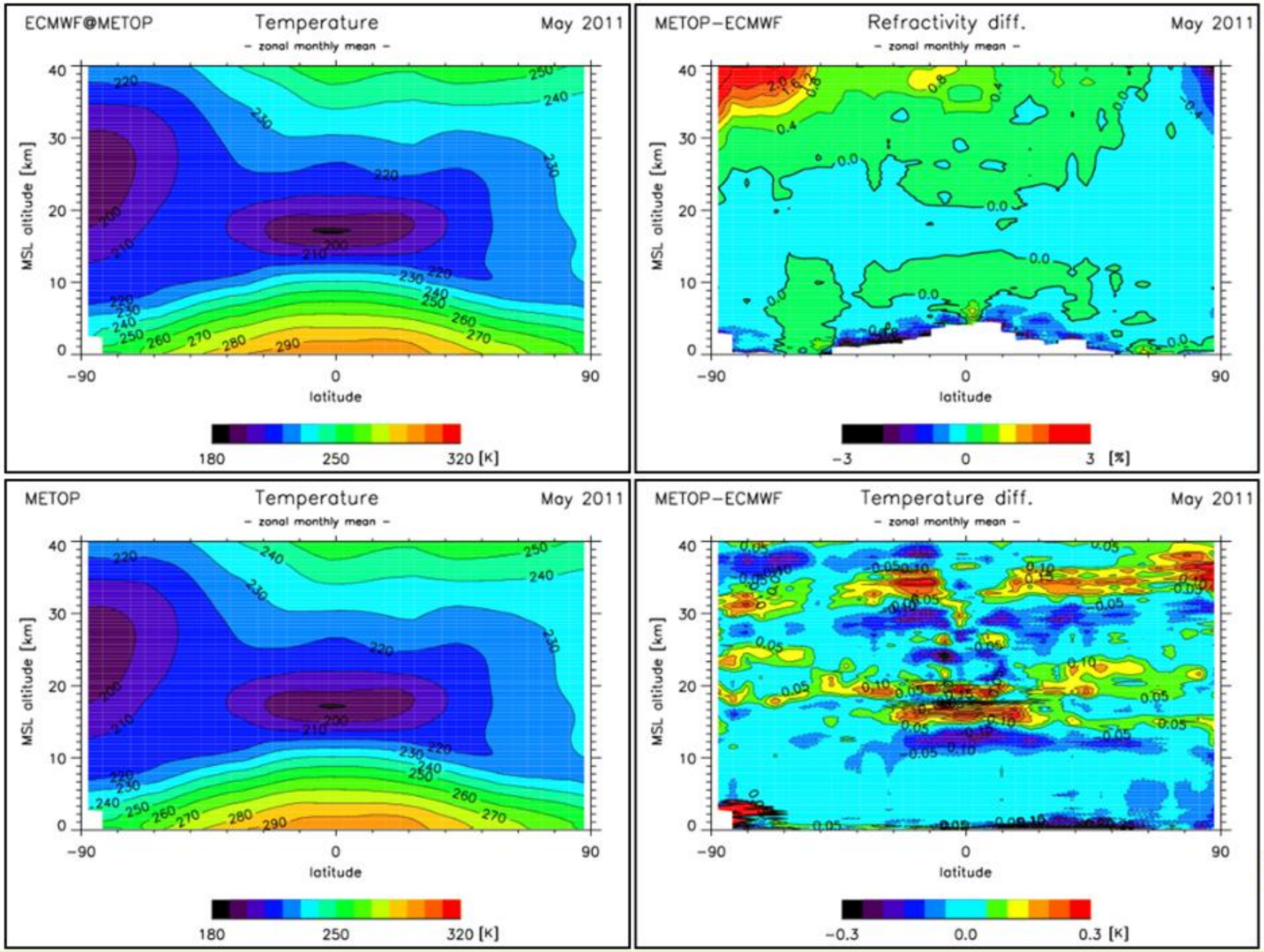
Danish Meteorological Institute

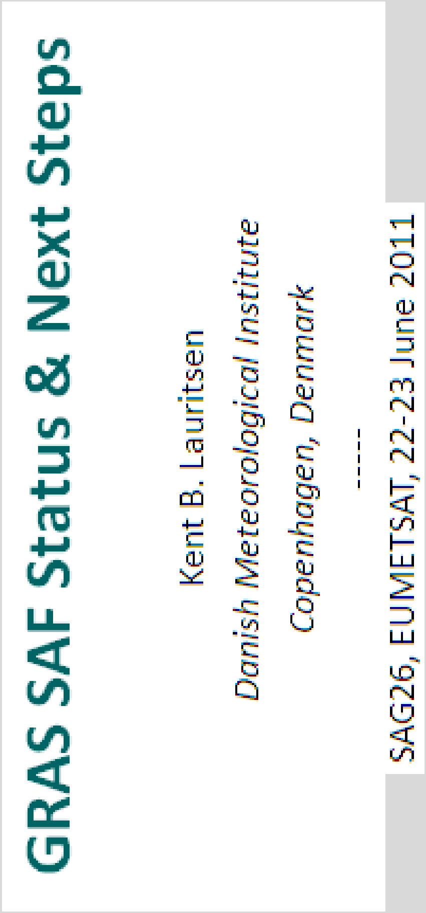
Metop REF 0-B/B



Hans Gleisner & Kent B. Lauritsen
Danish Meteorological Institute

Metop REF & T: Polar bias May 2011





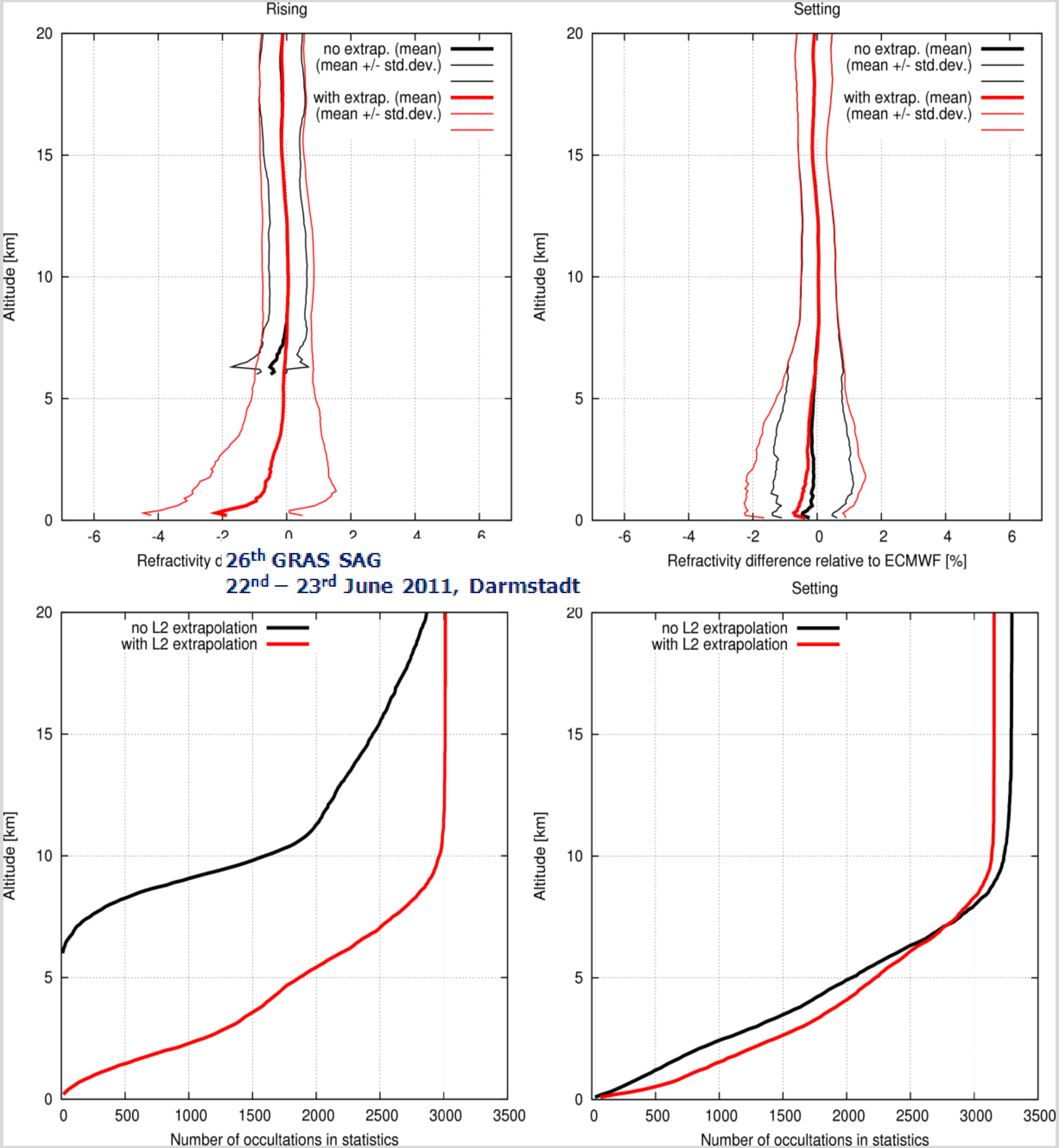
GRAS SAF Status & Next Steps

Kent B. Lauritsen

Danish Meteorological Institute

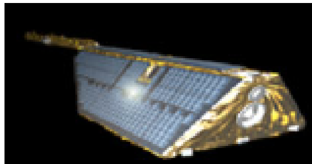
Copenhagen, Denmark

SAG26, EUMETSAT, 22-23 June 2011



26th GRAS SAG
22nd – 23rd June 2011, Darmstadt

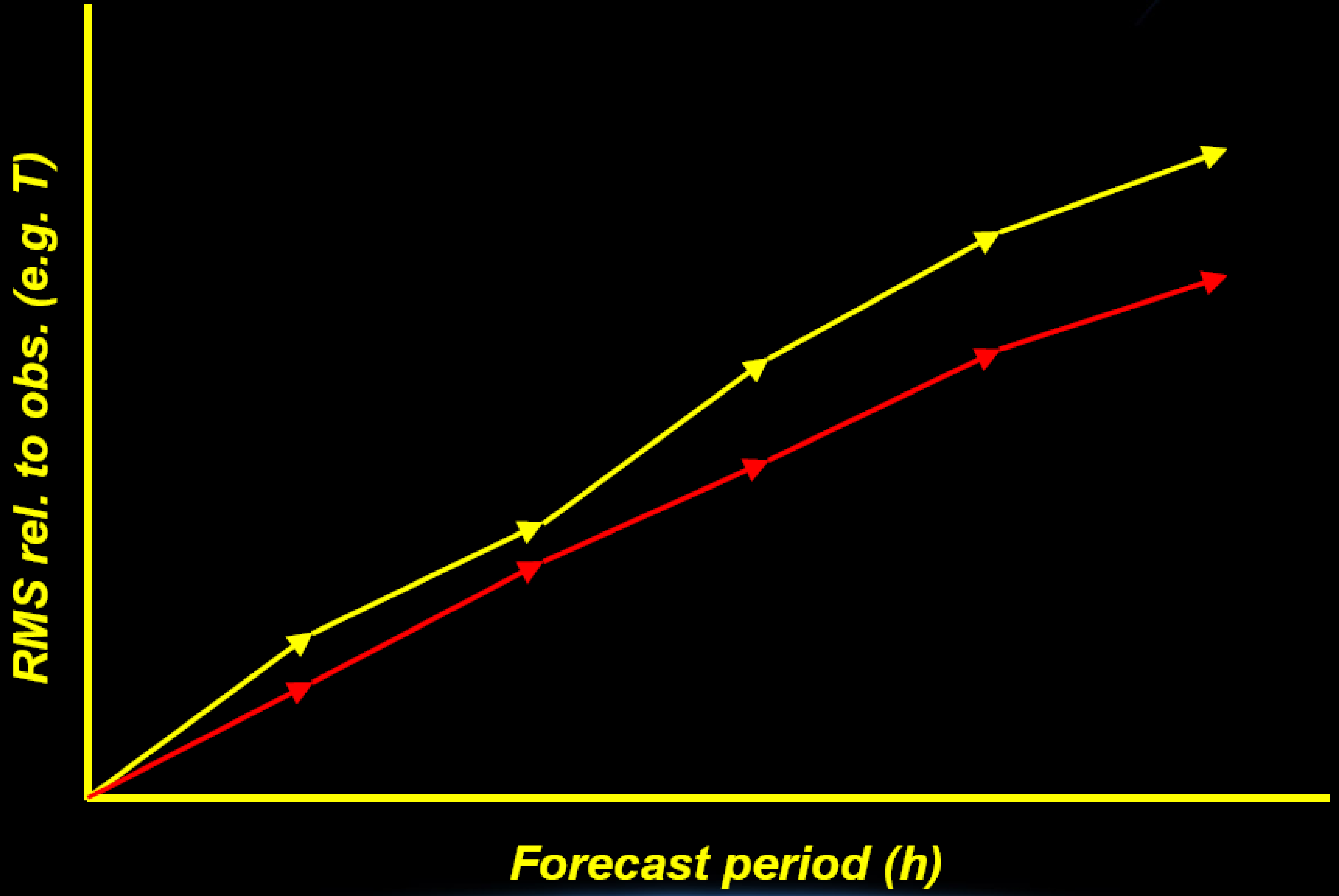
Data observed in Dec 2010



Application: Weather forecast

(study by S. Healy et al.)

How to evaluate the impact of GPS RO ?

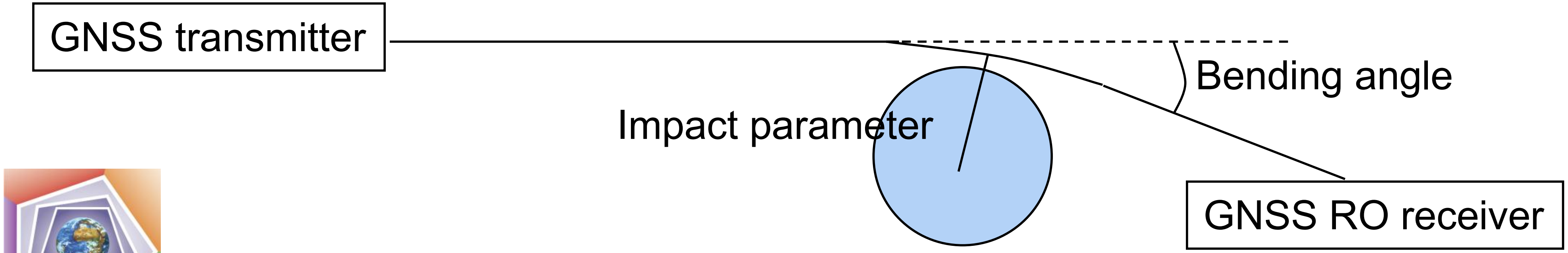


J. Wickert, presented at Colloquium On Atmospheric
Remote Sensing Using the GPS, Boulder, Colorado, 2004

GNSS Radio Occultation Assimilation Methodology

Methodology developed by Healy and Thépaut (2006) for NWP

- Assimilation of bending angles as a function of impact parameters
- No bias correction (data assumed unbiased)
- Between the near-surface and 40 km altitude
- Observation errors assumed uncorrelated in the vertical



Poli et al., "Climate Applications of GNSS Radio Occultation in European Global Reanalysis", *2nd Galileo Colloquium*, Padua, 2009

Observations available for ERA-Interim

“Conventional”

Radiosondes

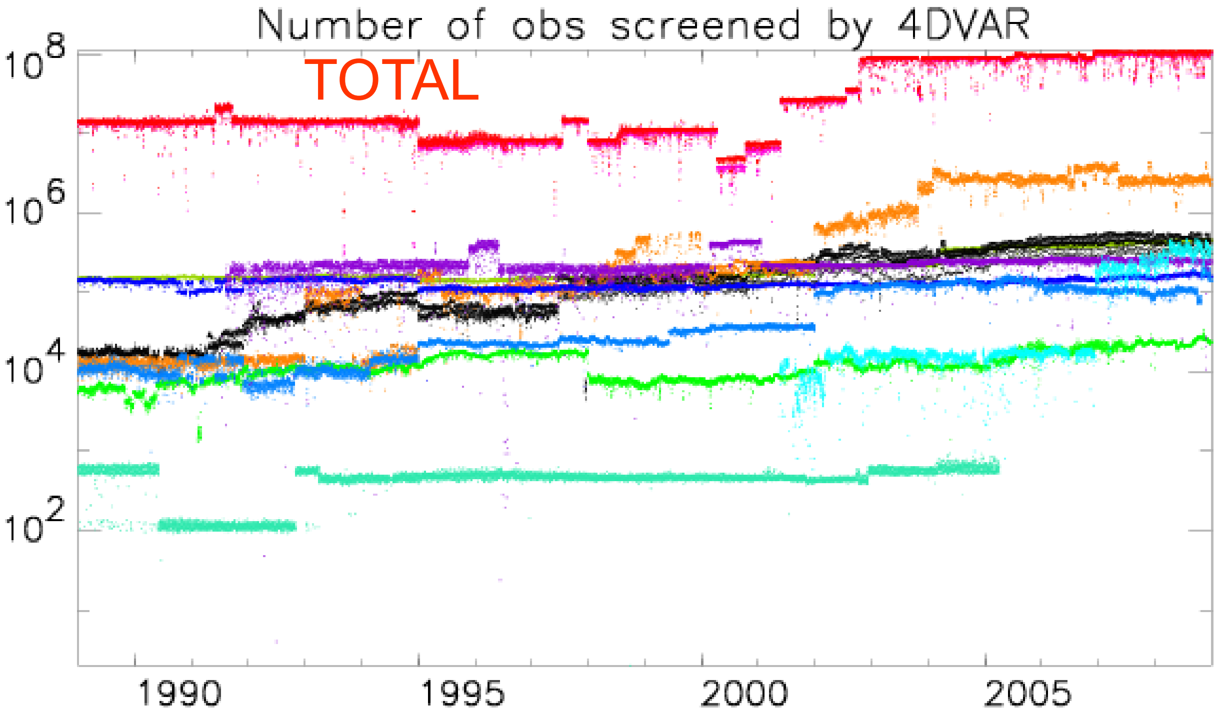
Surface

Aircraft

Radiosondes (wind only)

Drifting buoys

Surface pressure pseudo-observations from Australian Bureau of Meteorology (PAOB)



“Satellite”

Radiances

Atmospheric motion vectors

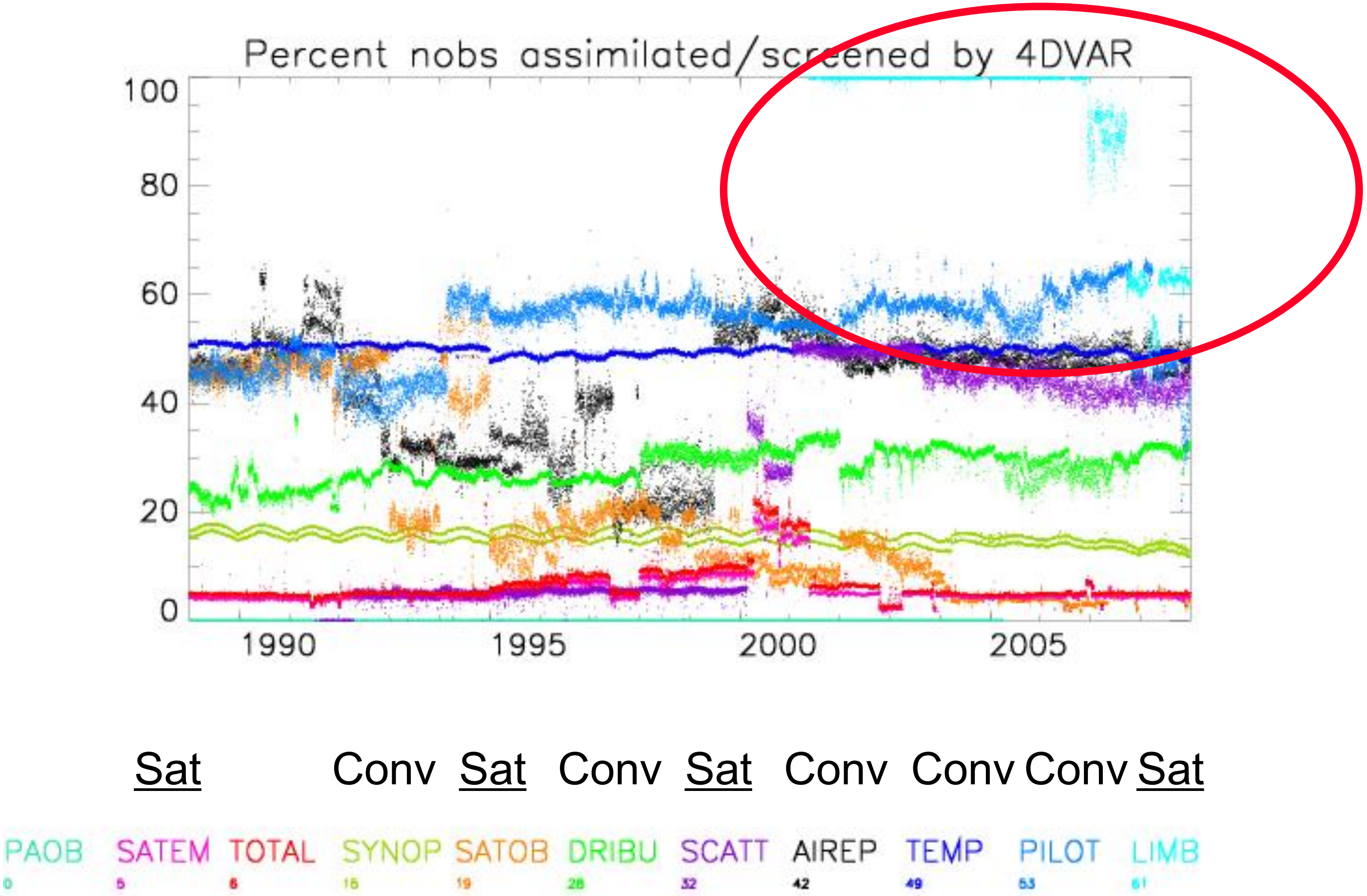
Scatterometers

GNSS Radio Occultation

Reanalysis involves many observations and types of observations

Poli et al., “Climate Applications of GNSS Radio Occultation in European Global Reanalysis”, *2nd Galileo Colloquium*, Padua, 2009

Average daily usage rate, by data-type

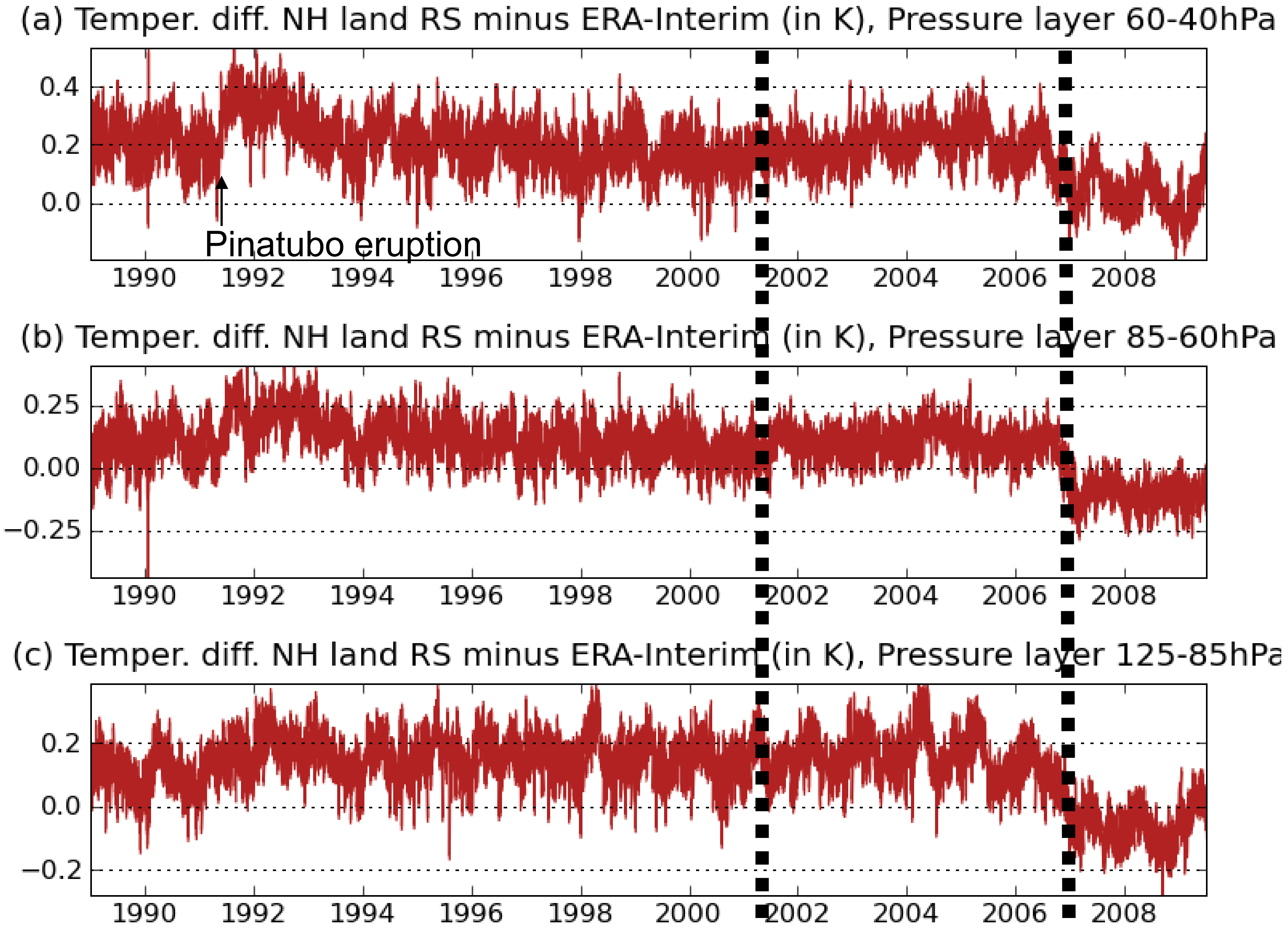


Sat Conv Sat Conv Sat Conv Conv Conv Sat

GNSS Radio Occultation are the most largely used (i.e., readily usable)

Poli et al., "Climate Applications of GNSS Radio Occultation in European Global Reanalysis", *2nd Galileo Colloquium*, Padua, 2009

Radiosonde temperature validation, North Hemisph.



(a) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 60-40hPa

(b) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 85-60hPa

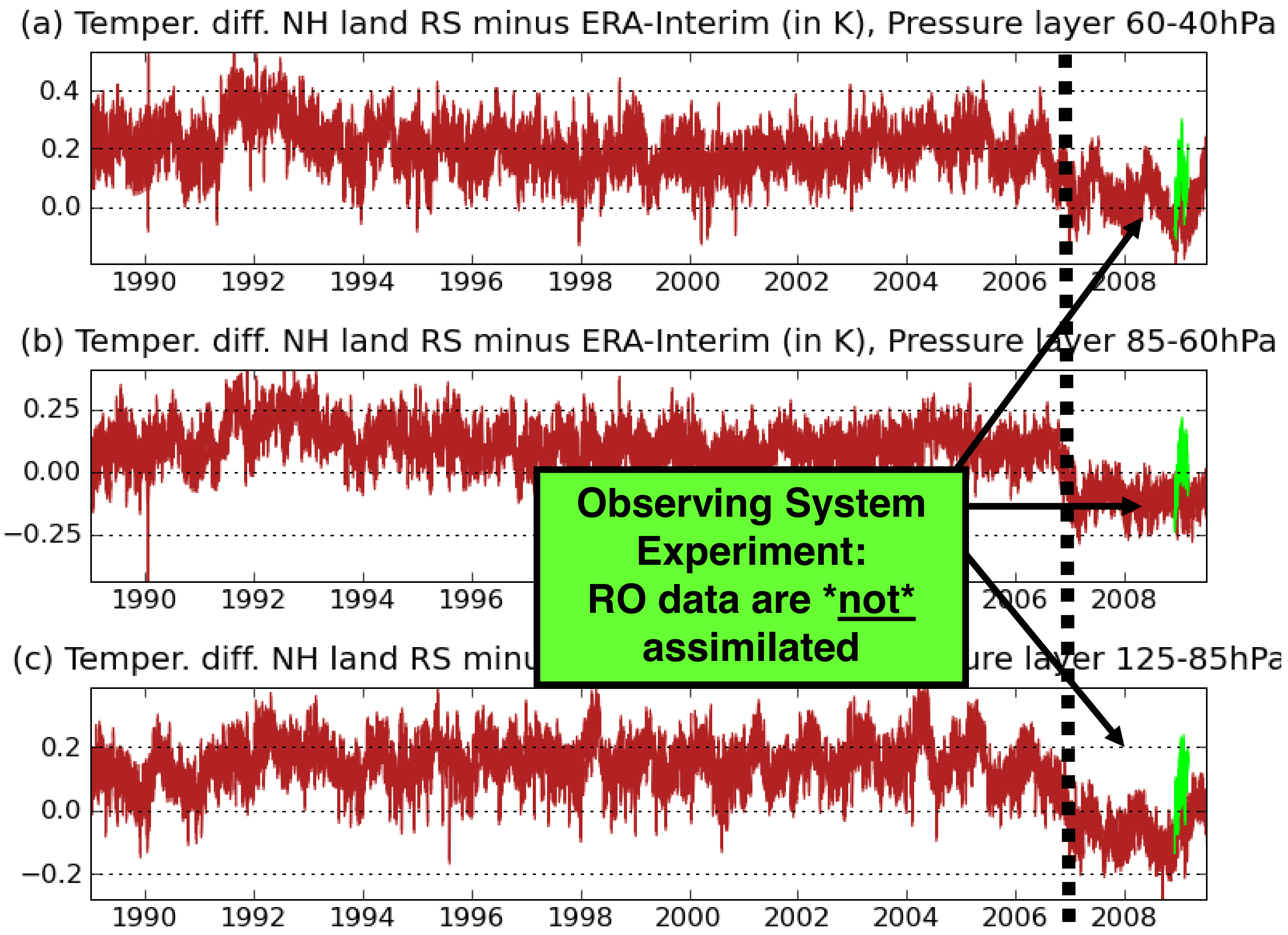
(c) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 125-85hPa

Introduction of CHAMP

Introduction of COSMIC

Poli et al., "Climate Applications of GNSS Radio Occultation in European Global Reanalysis", *2nd Galileo Colloquium*, Padua, 2009

Radiosonde temperature validation, North Hemisph.



Observing System Experiment:
RO data are *<u>not</u>* assimilated

Introduction of COSMIC

Poli et al., "Climate Applications of GNSS Radio Occultation in European Global Reanalysis", *2nd Galileo Colloquium*, Padua, 2009

Applications:

Climate, Tropopause, ABL detection, Impacts on Tropical Cyclones Forecast

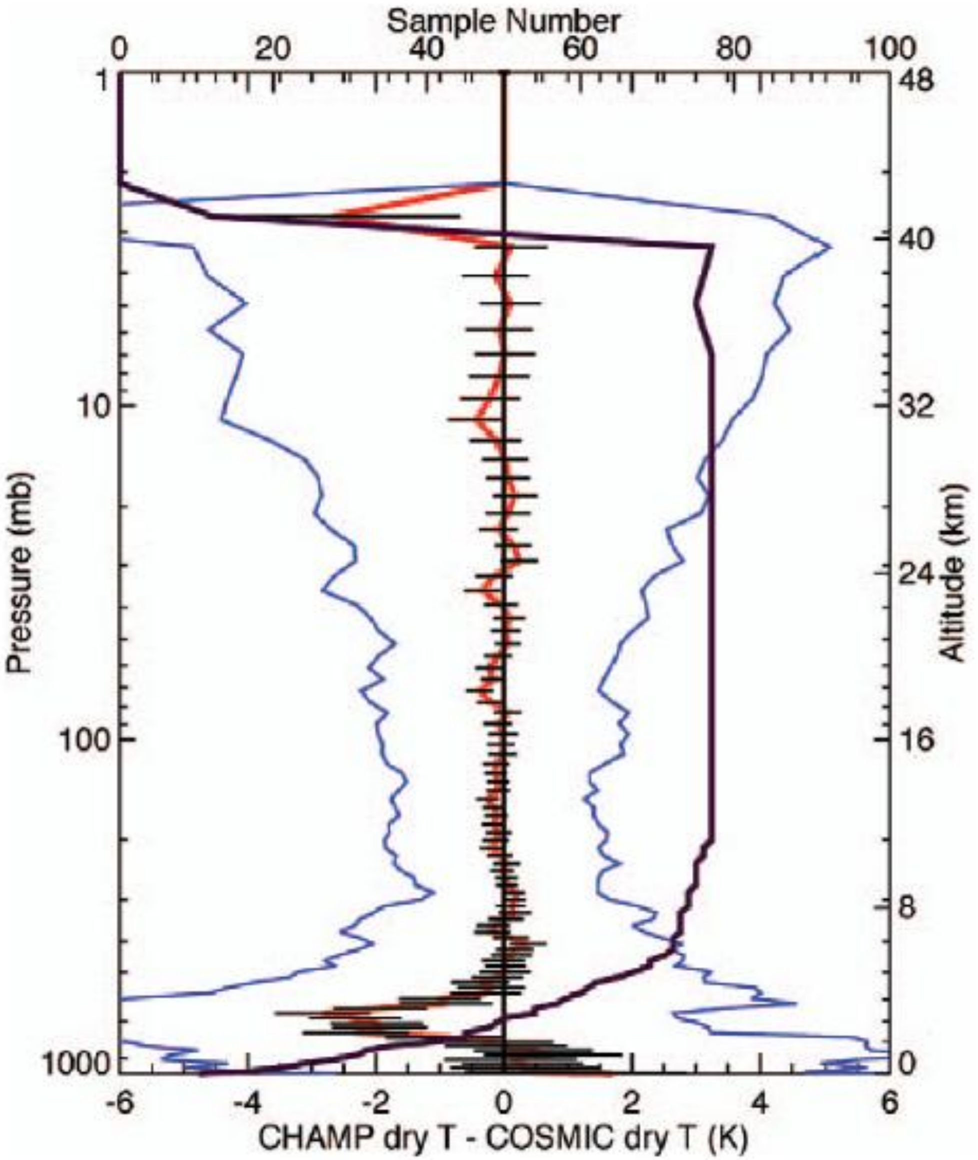
CLIMATE APPLICATIONS

- WMO climate monitoring requirements: 0.5K accuracy and 0.04 K/dec stability
- RO observations are thus well suited for establishing a stable, long-term record required for climate monitoring
- Remember that the fundamental observations is a measurement of time! Given the long-term stability assured by the GPS system, an accurate measurement of time of flight and time of flight variations with long-term stability can be achieved.
- Consequently, RO products are theoretically expected to have the accuracy and stability required for climate applications
- Finally RO products are also expected to be mission independent (results from actual RO missions can be directly compared [using the same processing software] directly to results from RO missions that will be launched many decades from now

As an example: …

CLIMATE APPLICATIONS

RO results are mission indipendent!



Comparison statistics (mean: red; standard error of the mean: horizontal black lines superimposed on the mean; std dev: blue; sample number of compared soundings: solid black line) of 80 CHAMP and COSMIC profiles that were collocated within 200 km and 90 min from 1 Sep to 31 Oct 2006, within 60°S–60°N.

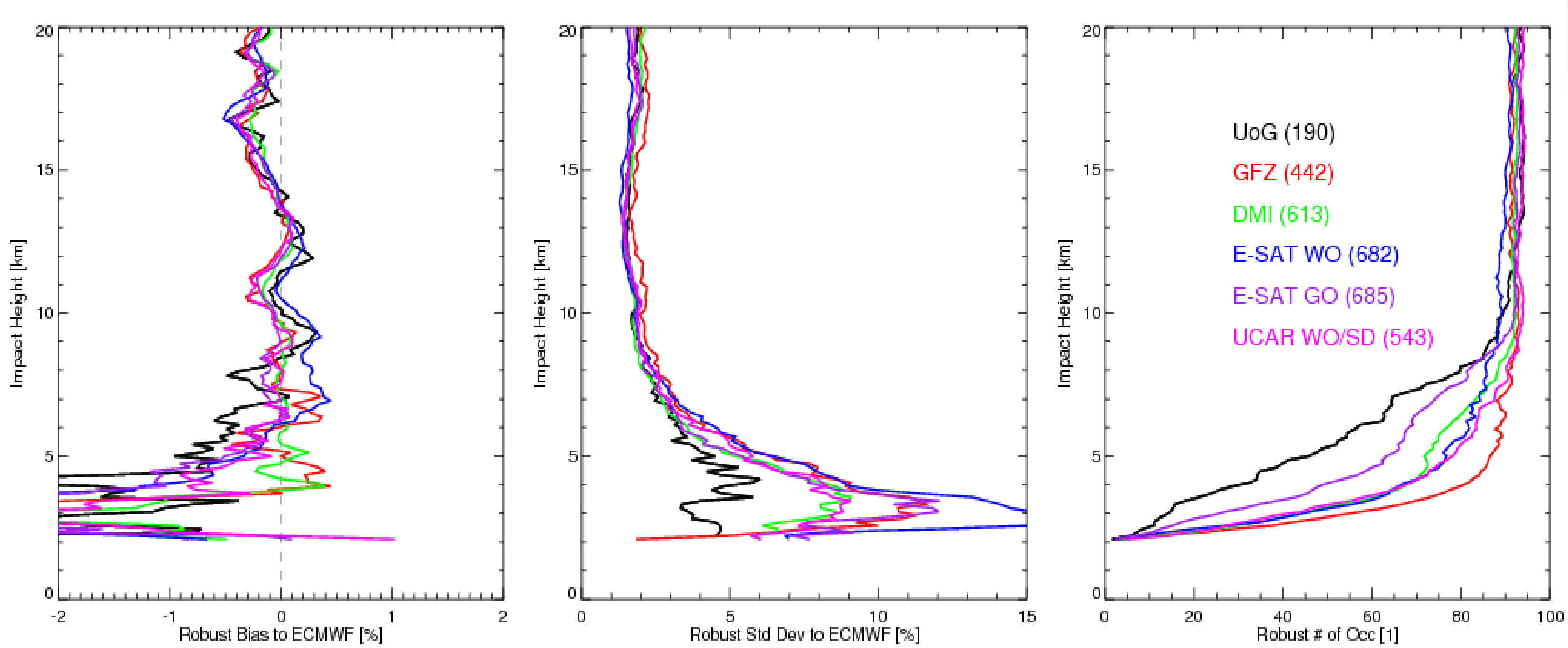
Ho et al., "A comparison of lower stratosphere temperature from microwave measurements with CHAMP GPS RO data", *Geophys. Res. Lett.*, 34, 2007.

Tropospheric Intercomparison

Studies on
GRAS Data Quality
C. Marquardt & Study team

26th GRAS SAG
22nd – 23rd June 2011, Darmstadt

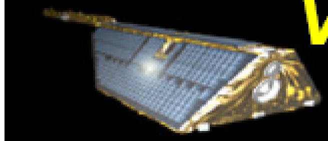
- GRAS raw sampling measurements extensively studied within ESA study
- First systematic cross-comparison of advanced tropospheric retrievals (ever!)
- Statistics includes UCAR retrievals of GRAS data from EUMETSAT's Structural Uncertainty study



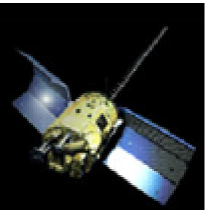
Bending angle bias (left), standard deviations (middle), and penetration depth (right) of GRAS raw sampling data processed by different centres. Statistics are against ECMWF forecasts. Number of occultations processed on sample day (30/09/2007) in brackets.

26th GRAS SAG
22nd – 23rd June 2011, Darmstadt

EUMETSAT



Vertical structure atmospheric structure e.g. Tropopause



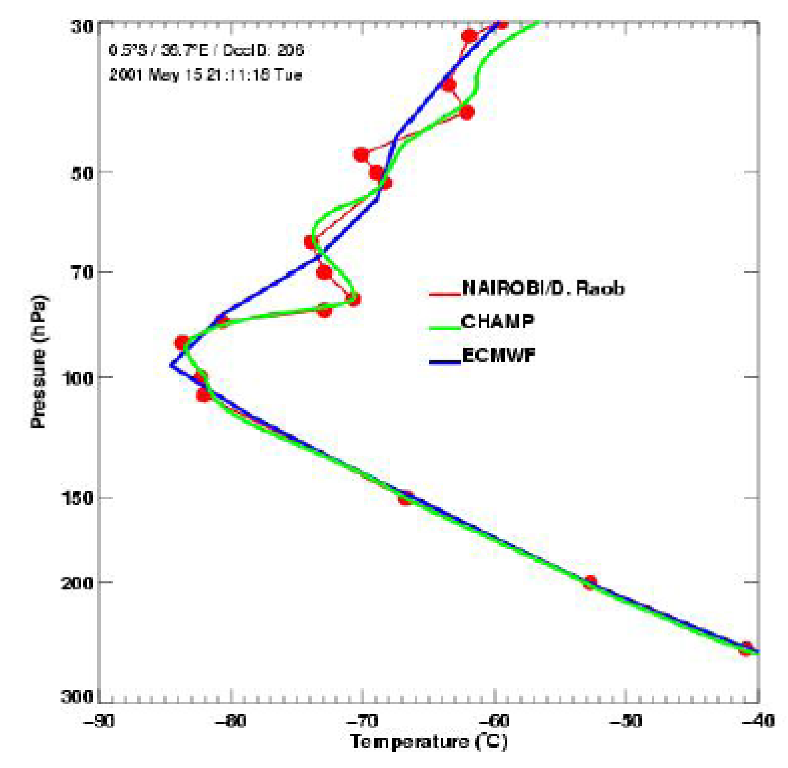
Perfect for climate monitoring, E.g. Tropopause:

←

Precise monitoring of vertical atmospheric structure with high vertical resolution on global scale

↓

Temperature and altitude is indicator for climate change (Warming of the troposphere, cooling in the stratosphäre)



J. Wickert, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004

DETECTING THE ATMOSPHERIC BOUNDARY LAYER

- ABL is the lowermost atmosph layer (affected by Earth's surface interaction)
- It is the boundary between turbulent mixed layer (below) and stably stratified layer (above)
- It is characterized by temperature inversion phenomena and decrease of humidity
- The Top of ABL is sharper (its detection is possible only with High Resol measurements)
- It's depth is an important parameter for Numerical Weather Prediction and Climate models

DETECTING THE ATMOSPHERIC BOUNDARY LAYER

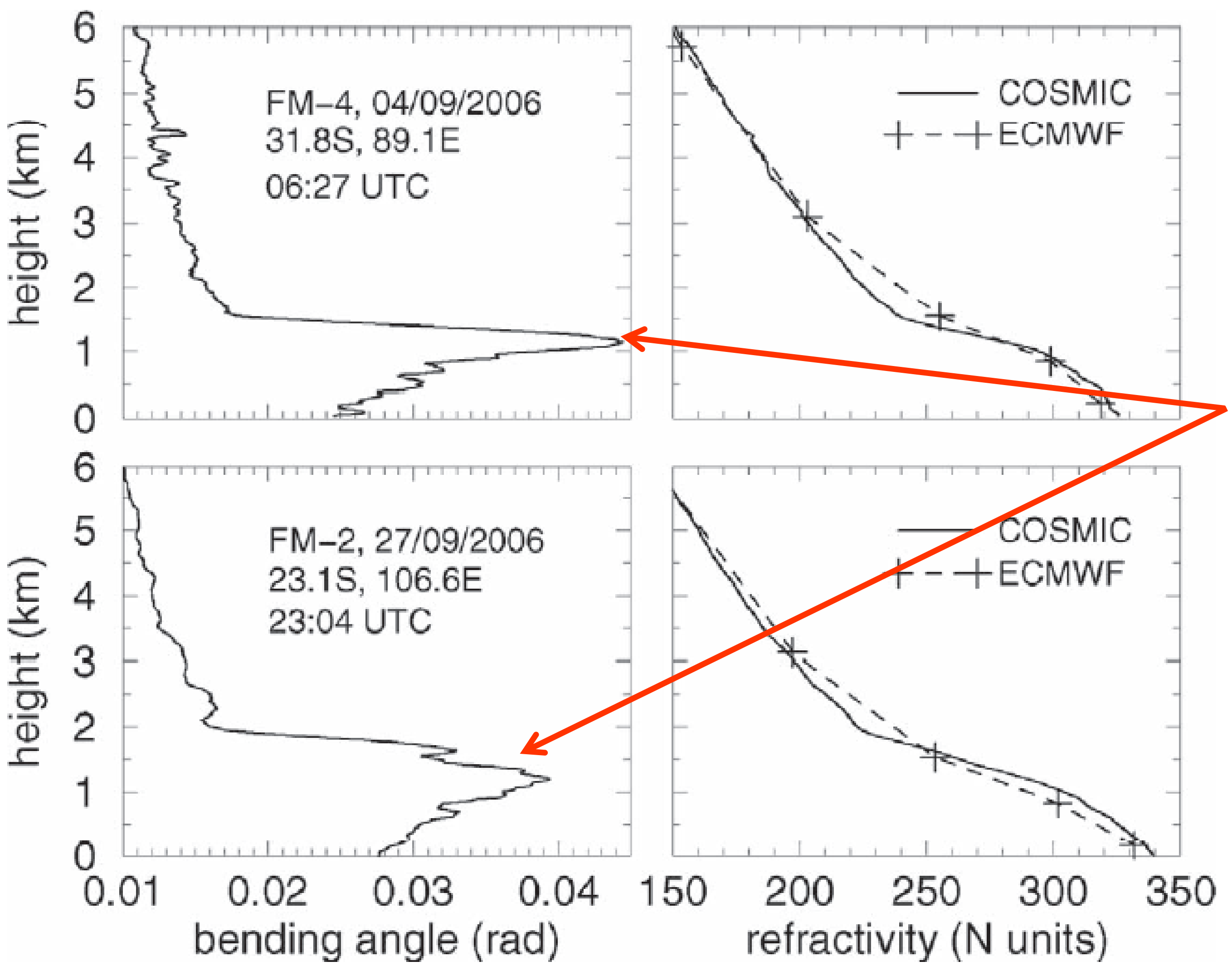


FIG. 5. Examples of COSMIC RO-retrieved bending angle and refractivity profiles in the subtropics, showing the sharp ABL top compared to ECMWF analyses.

Thanks to high resolution and Open Loop capabilities, ABL can be detected by RO observations and its parameters can be accurately measured

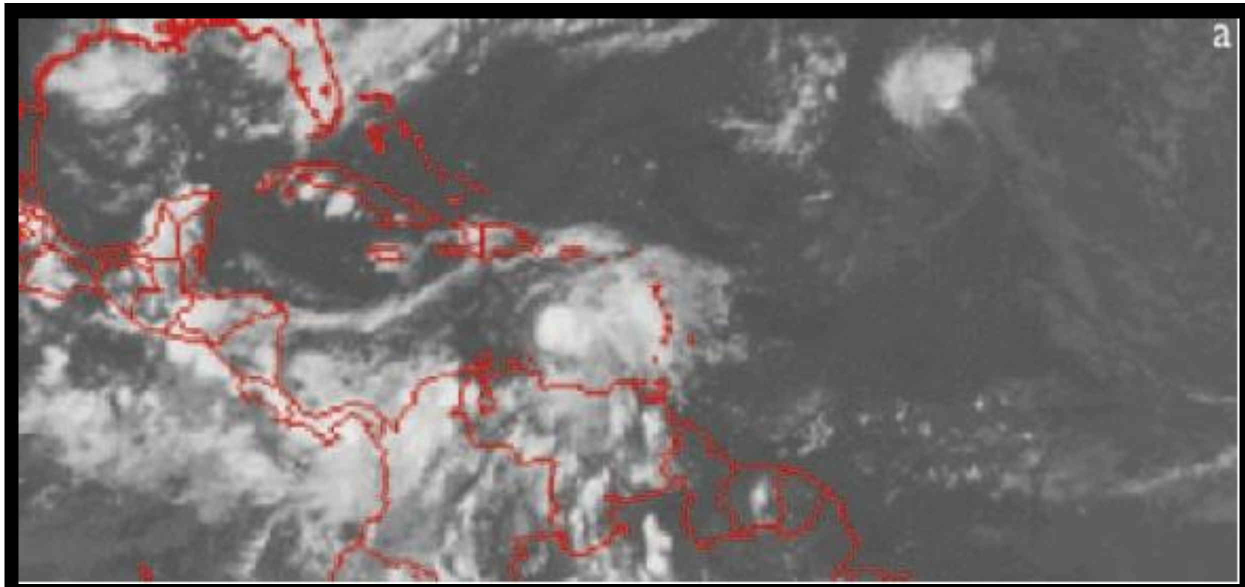
R.A.Anthes et al., “The COSMIC/FORMOSAT-3 Mission”,
BAMS, March 2008

IMPACT ON TROPICAL STORM FORECAST

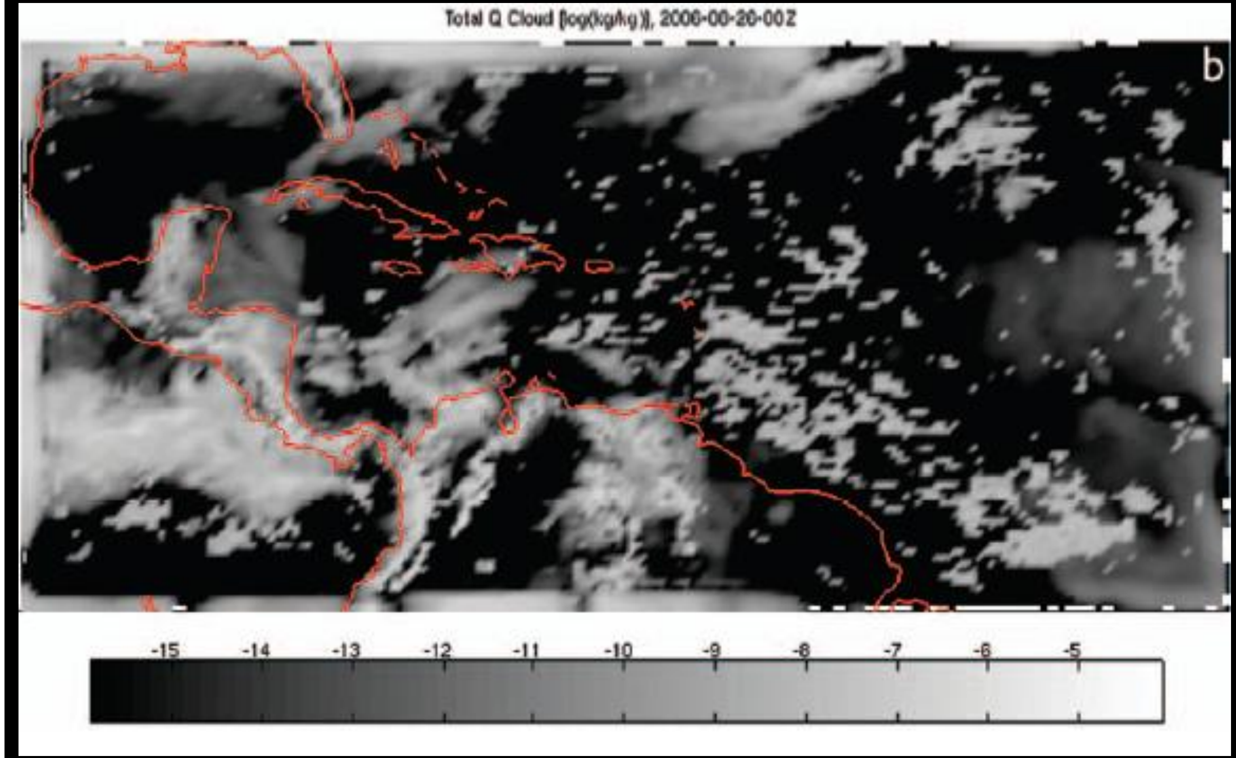
- Observations of moisture fields over oceans (where tropical storms/cyclones form and spend most of their life) is critical. Consequently, the numerical forecast of their development (cyclone genesis) often fails.

- RO observations provide accurate and valuable informations on tropospheric moisture and temperature. Thus they have great potential to improve tropical cyclone predictions.

- As an example, Tropical Storm Ernesto, originated from East Africa on 18 August 2006, crossed the Atlantic Ocean.

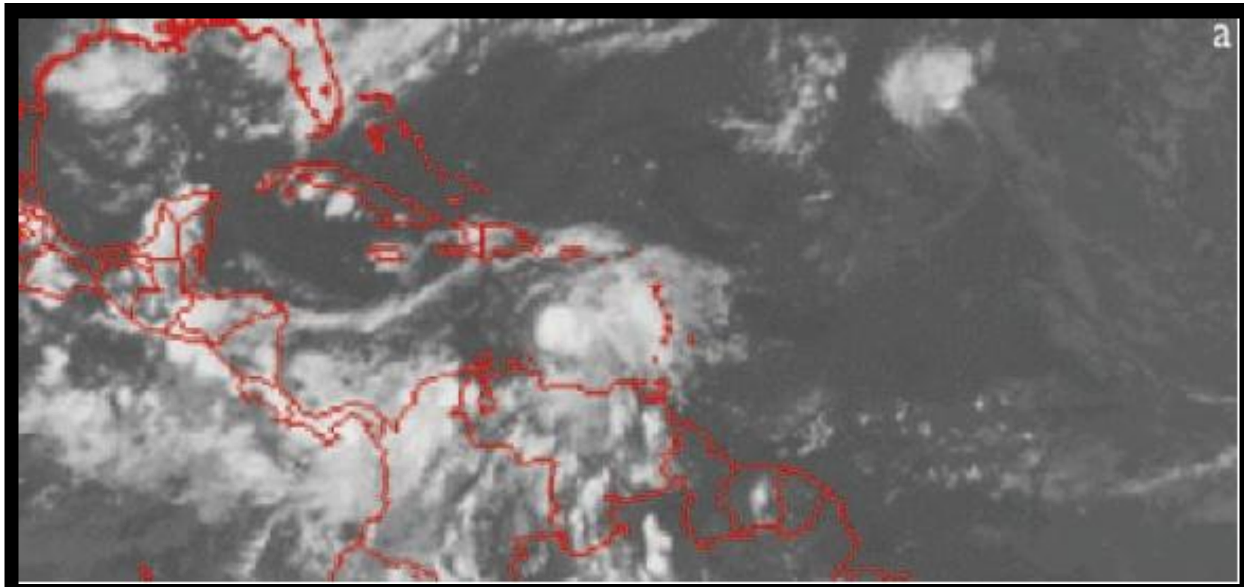


IR satellite photo of Tropical Storm Ernesto for 00:00 UTC, 26 Aug 2006

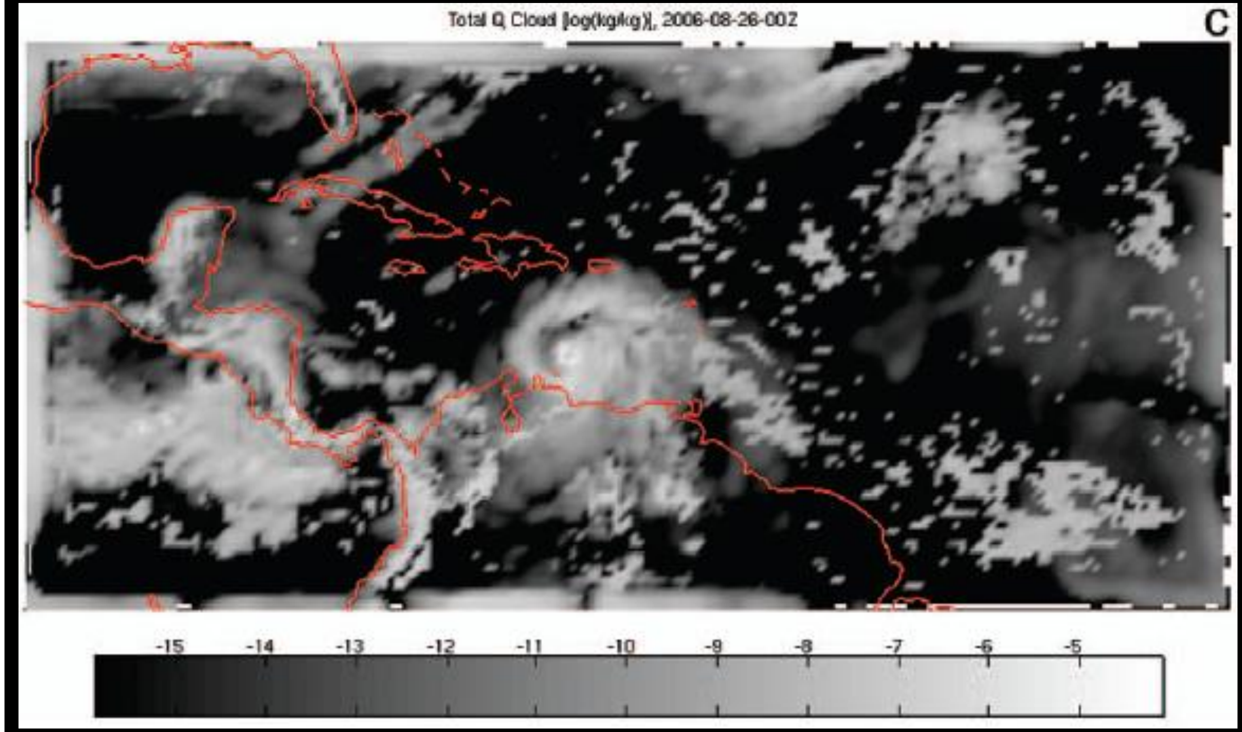


66 h forecast of vertically integrated cloud water mixing ratio generated by WRF NWP Mdl (initialized using NCEP analysis at 06:00 UTC, 23 Aug, 2006) without RO observations assimilation

R.A.Anthes et al., “The COSMIC/FORMOSAT-3 Mission”, *BAMS*, March 2008

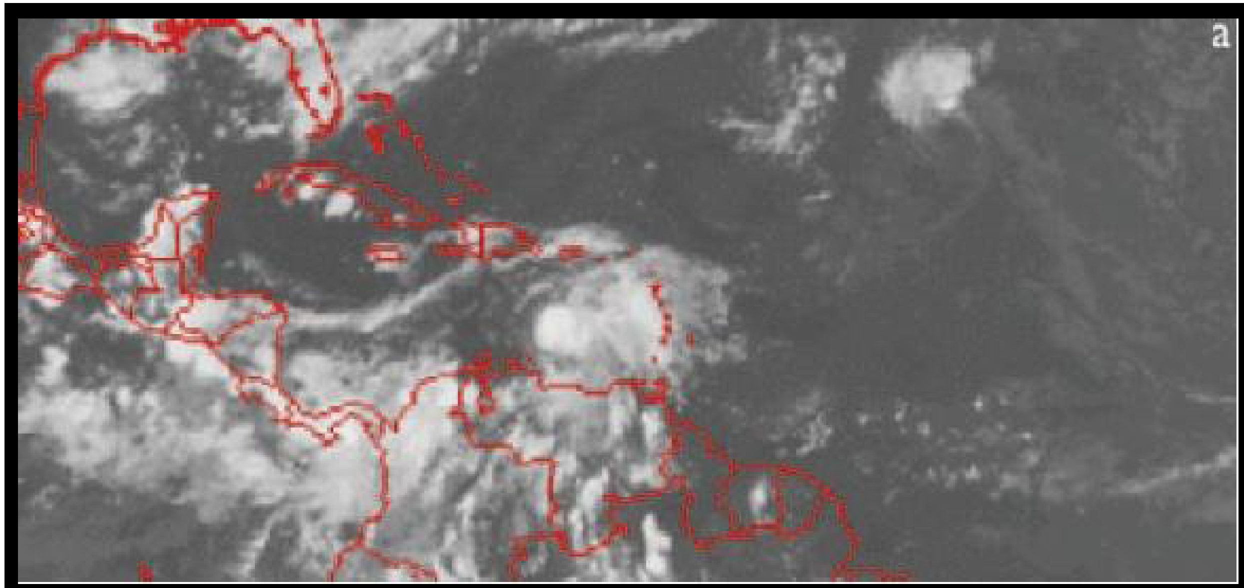


IR satellite photo of Tropical Storm Ernesto for 00:00 UTC, 26 Aug 2006

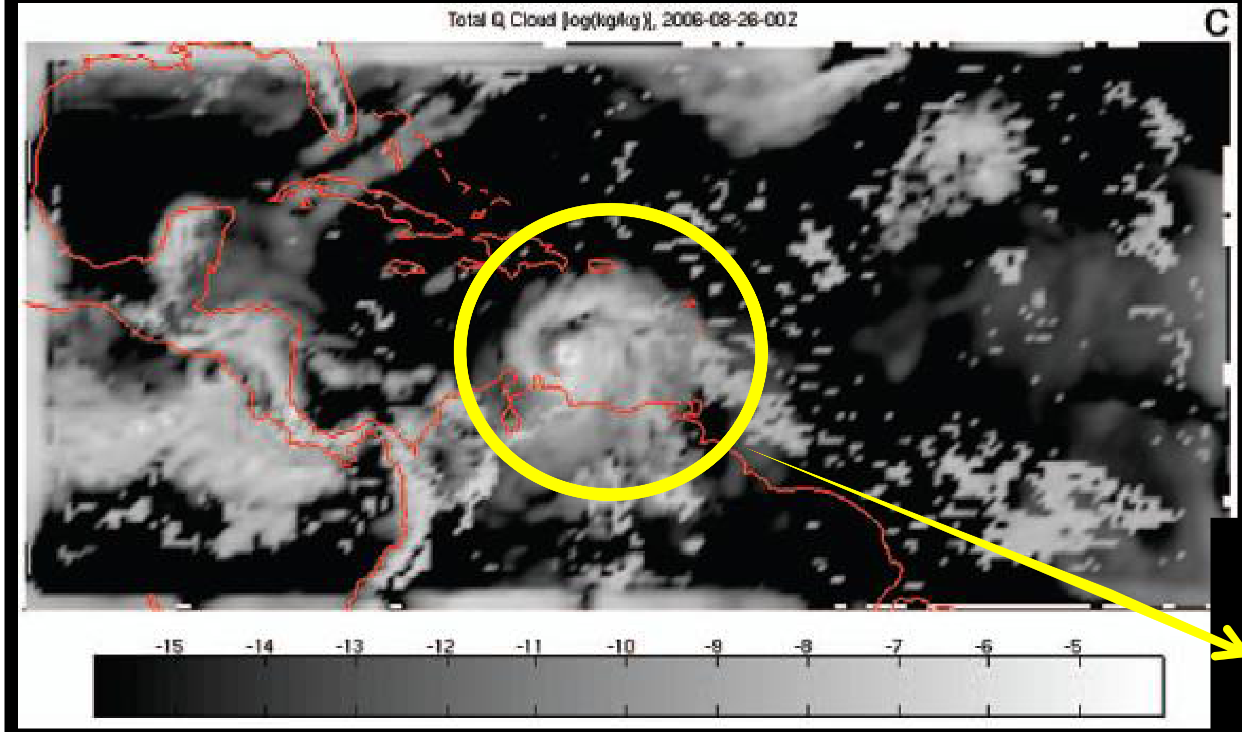


66 h forecast of vertically integrated cloud water mixing ratio generated by WRF NWP Mdl (initialized using NCEP analysis at 06:00 UTC, 23 Aug, 2006) with the assimilation of 15 COSMIC RO observations performed between 03:00 and 09:00 UTC, 23 Aug, 2006

R.A.Anthes et al., “The COSMIC/FORMOSAT-3 Mission”, *BAMS*, March 2008



IR satellite photo of Tropical Storm Ernesto for 00:00 UTC, 26 Aug 2006



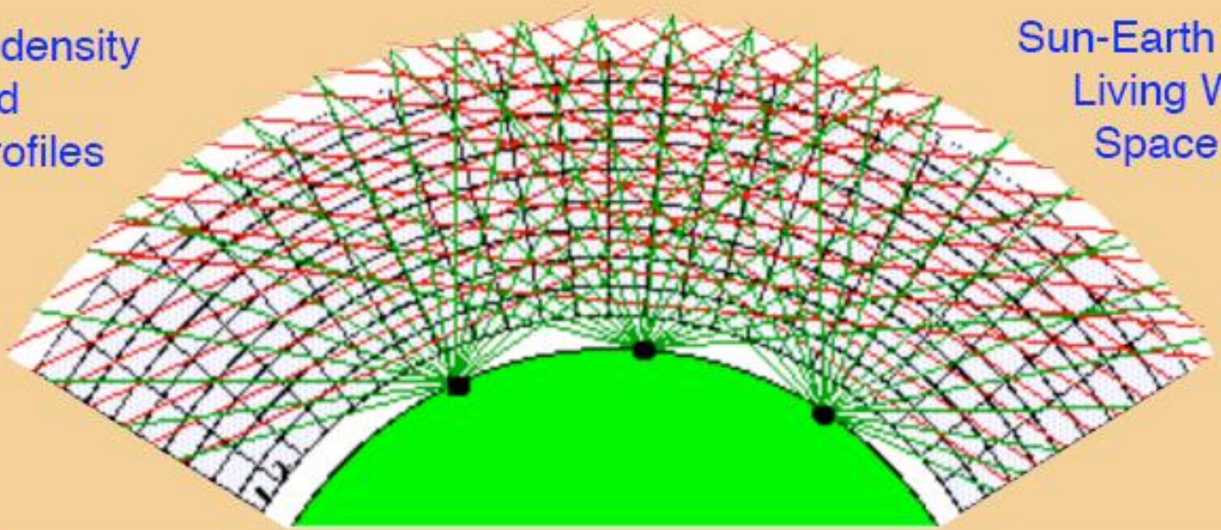
GPS RO data may be useful in improving numerical forecasts of tropycal cyclone genesis

R.A.Anthes et al., “The COSMIC/FORMOSAT-3 Mission”, *BAMS*, March 2008

Applications:

IONOSPHERE PROFILING IMAGING AND SPACE WEATHER

Snapshot 3D Ionospheric Imaging



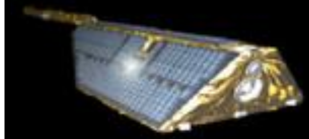
Electron density
and
TEC profiles

Sun-Earth Connections
Living With a Star
Space Weather

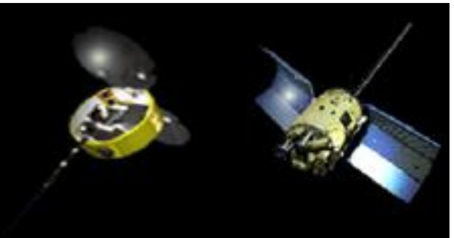
Applications

- Observe ionospheric dynamics and refine models
- Chart the course and evolution of space storms
- Provide near term prediction of space weather
- Study TIDs and global energy transport
- Probe iono-thermo-atmosphere interactions

T. P. Yunck, presented at Colloquium On Atmospheric Remote Sensing Using the GPS, Boulder, Colorado, 2004



Ionospheric profiling



… DETAILS ABOUT THIS VERY EFFECTIVE APPLICATION WILL BE GIVEN IN THE FRAMEWORK OF THE NEXT TALKS. In particular, for the RO point of view…

B. Nava: "GNSS Remote Sensing: Electron Density Profiling through Radio Occultation"

Workshop on Science Applications of GNSS in Developing Countries
11-27 April, 2012

The Abdus Salam
International Centre for Theoretical Physics

THANK YOU FOR YOUR ATTENTION!

ANY QUESTION ???

GNSS REMOTE SENSING: TROPOSPHERE PROFILING THROUGH RADIO OCCULTATION

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