United Nations/Austria/European Space Agency
Symposium on
"Space Tools and Solutions for Monitoring the Atmosphere
in Support of Sustainable Development"

Climate Change Monitoring and Atmospheric Change Analysis by Radio Occultation

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with contributions from

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thanks for funds to

Graz, Austria, 11–14 Sep, 2007

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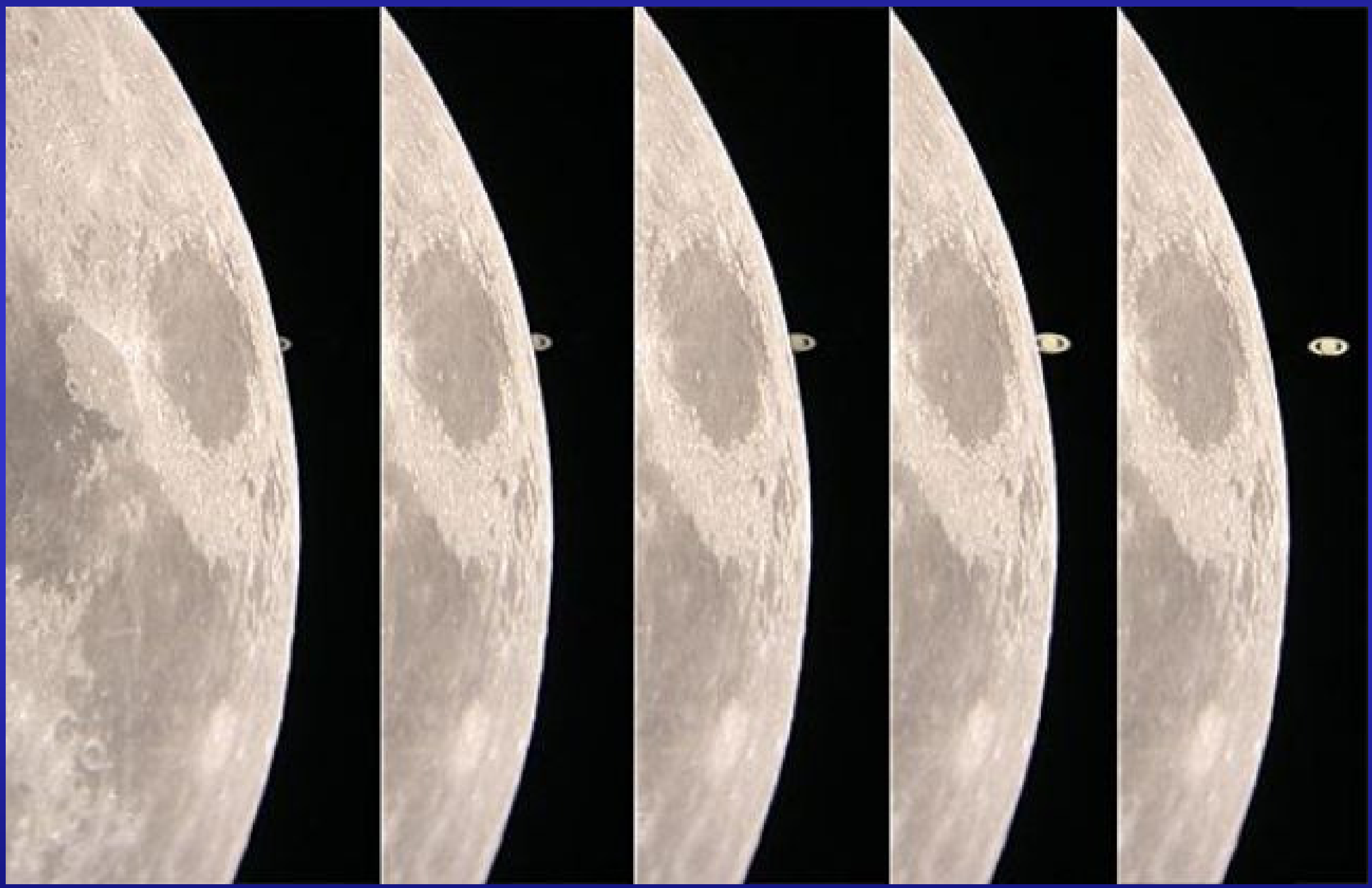
Outline

- Heritage of Radio Occultation (RO)
- RO missions
- RO measurement principle
- Retrieval of atmospheric variables
- RO based climatologies
- Analysis of RO climatologies
- Applications and climate utility

Occultation (1)

Stellar Occultation by the Venus (courtesy J. Wickert)

Occultation (2)



Saturn Occultation by the Moon (courtesy T. Martinez)

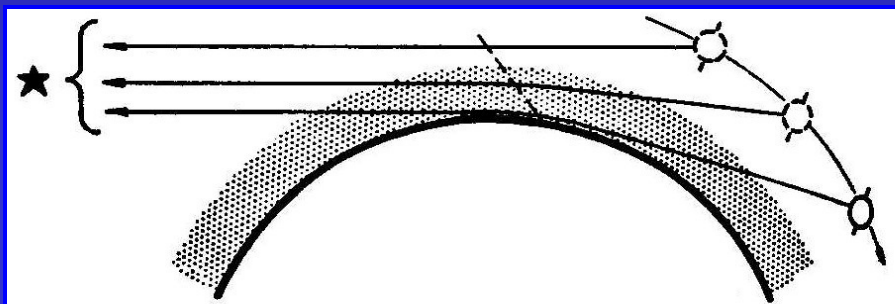
Occultation (3)

Solar Occultation by the Earth's Atmosphere (courtesy D. Pivato)

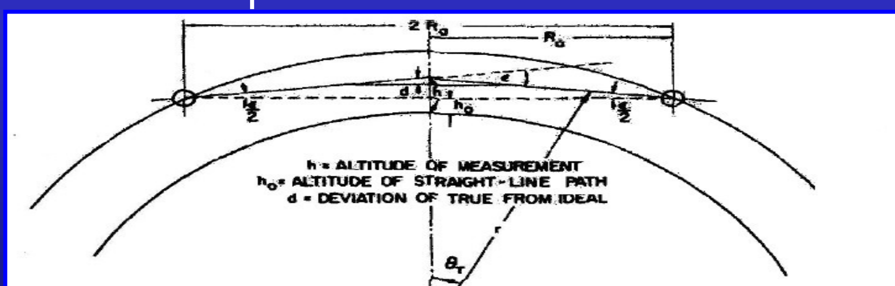
Earth Occultation

Initial Concepts

Fishbach, 1965: Stellar occultation from LEO



Lusignan et al., 1969: Radio sounding with tandem LEO's at a fixed separation

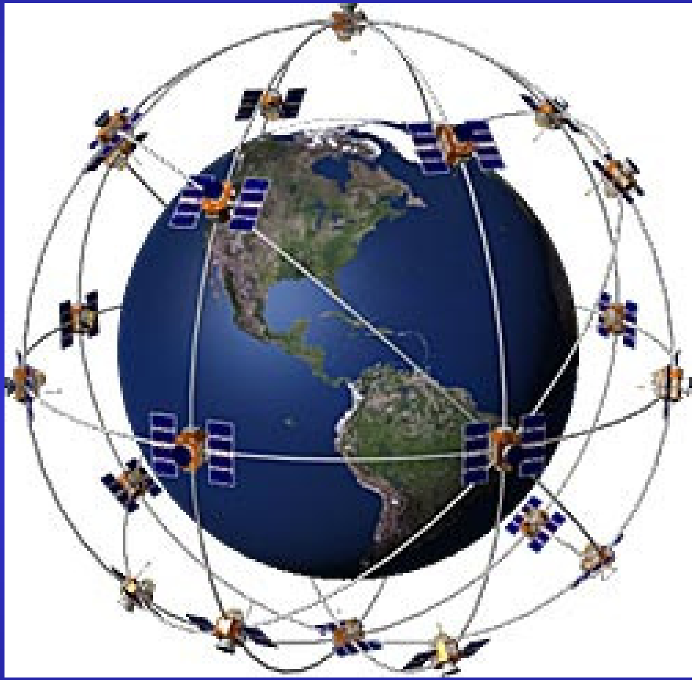


Gurvich and Krasil'nikova, 1987:
Navigation satellites for sensing Earth's atmosphere

GNSS Radio Occultation

Signal Source: GNSS Global Navigation Satellite System

- **GPS (Global Positioning System, U.S.)**
  since 1978, 1994 full constellation
  2 frequencies: 1575,42 MHz (0,19 m)
  1227,60 MHz (0,24 m)
  positioning with mm accuracy
  24 (29) satellites
  ~20.200 km height

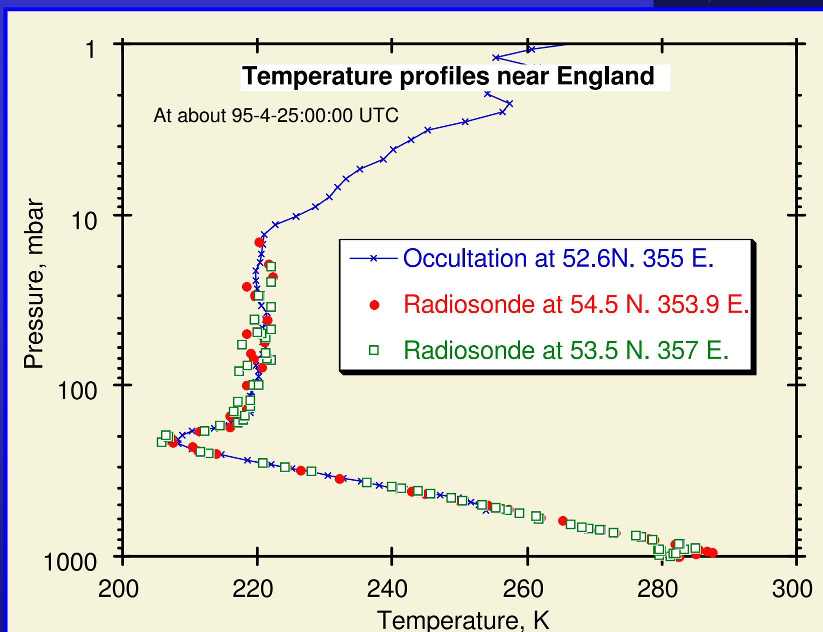


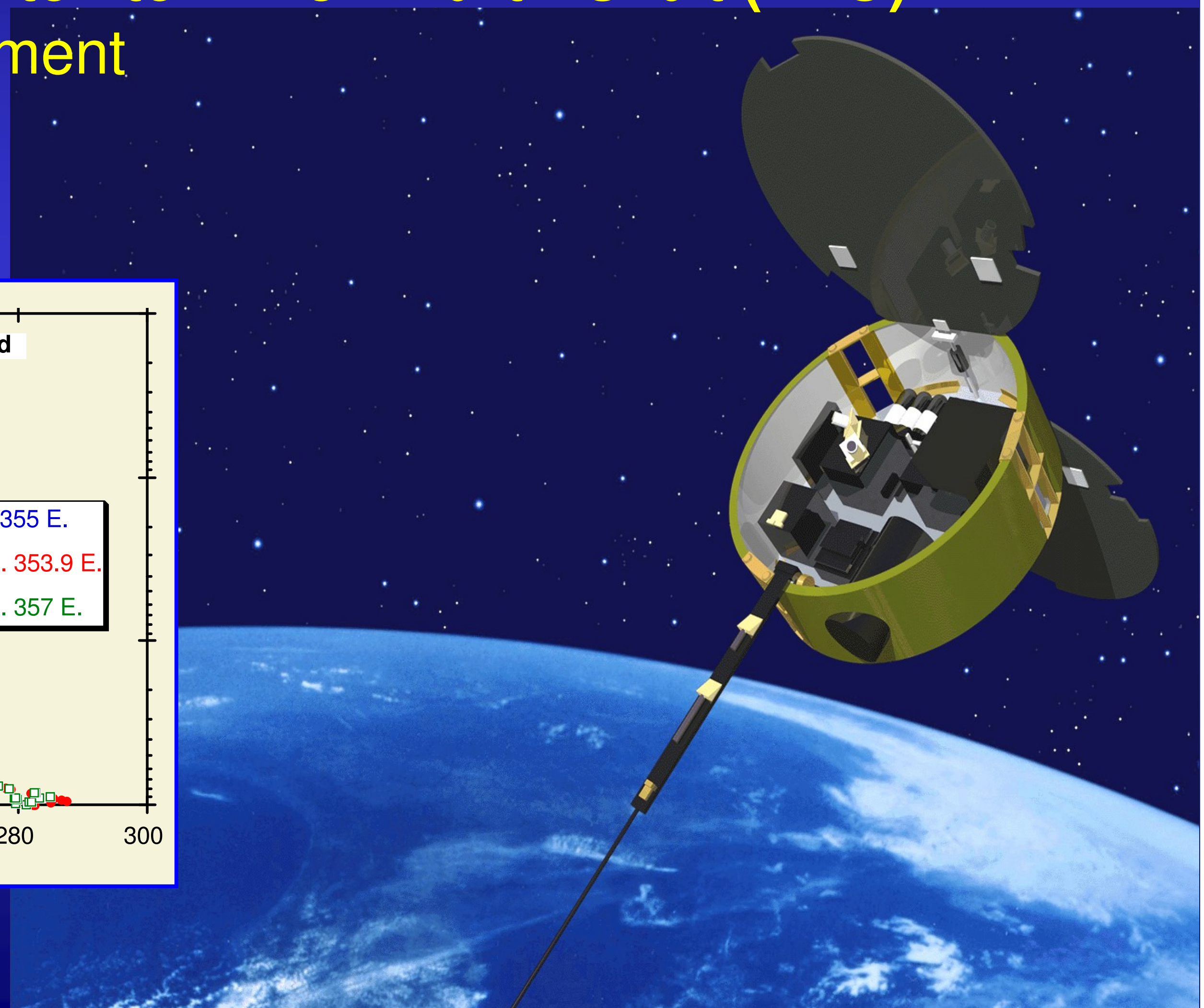
- **GLONASS (Russia)**
  since 1982; 1996 (21 Satelliten); 2001 (9)
  ~20.000 km Orbit
- **GALILEO (Europe)**
  ~2010 planned, 30 Satelliten (27+3 reserve)
  ~23.200 km

RO Missions (1)

GPS Receivers on Satellite in Low Earth Orbit (LEO)

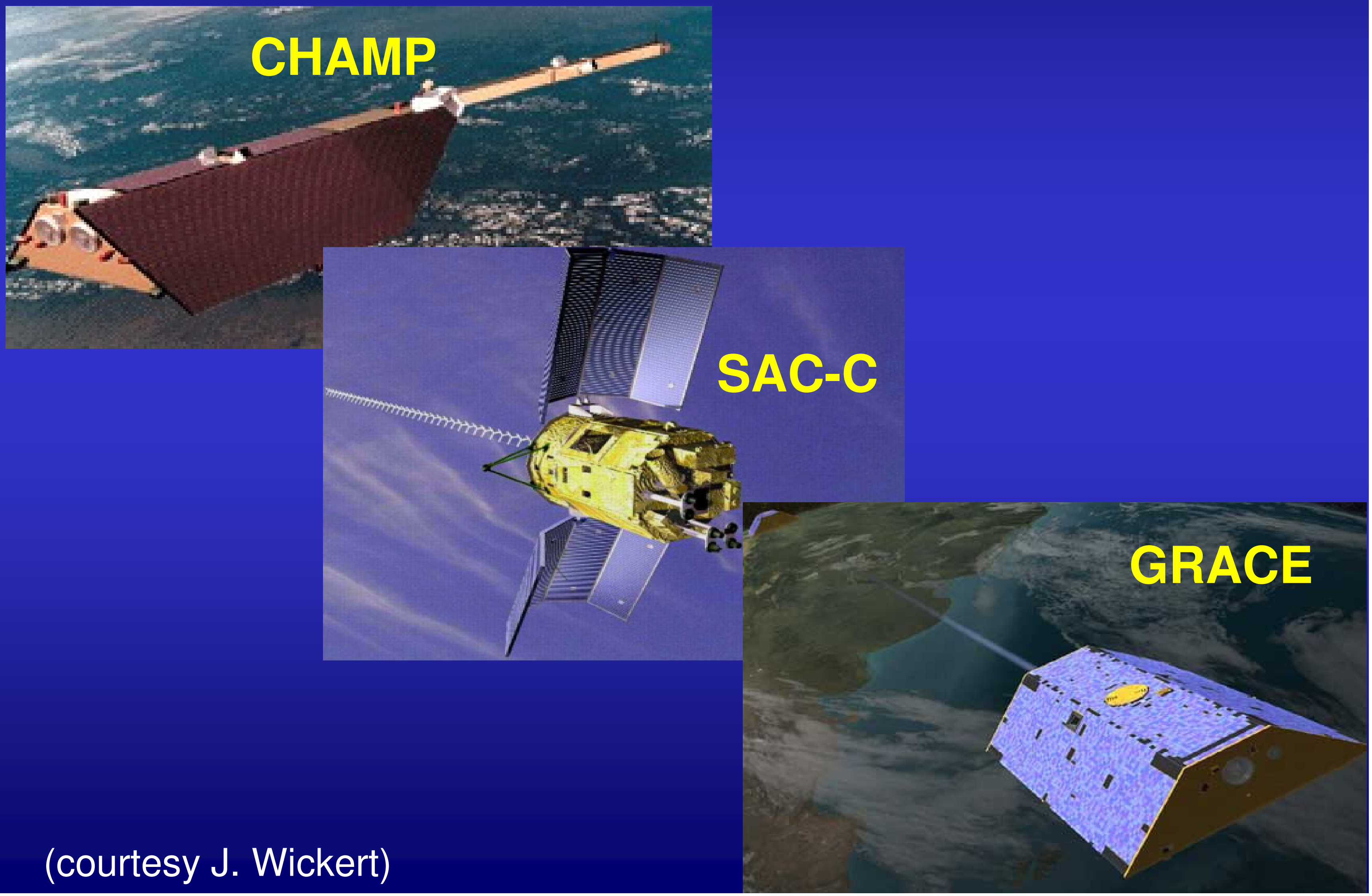
The GPS-MET Experiment
on MicroLab-I 1995
Proof of Concept





Courtesy: UCAR

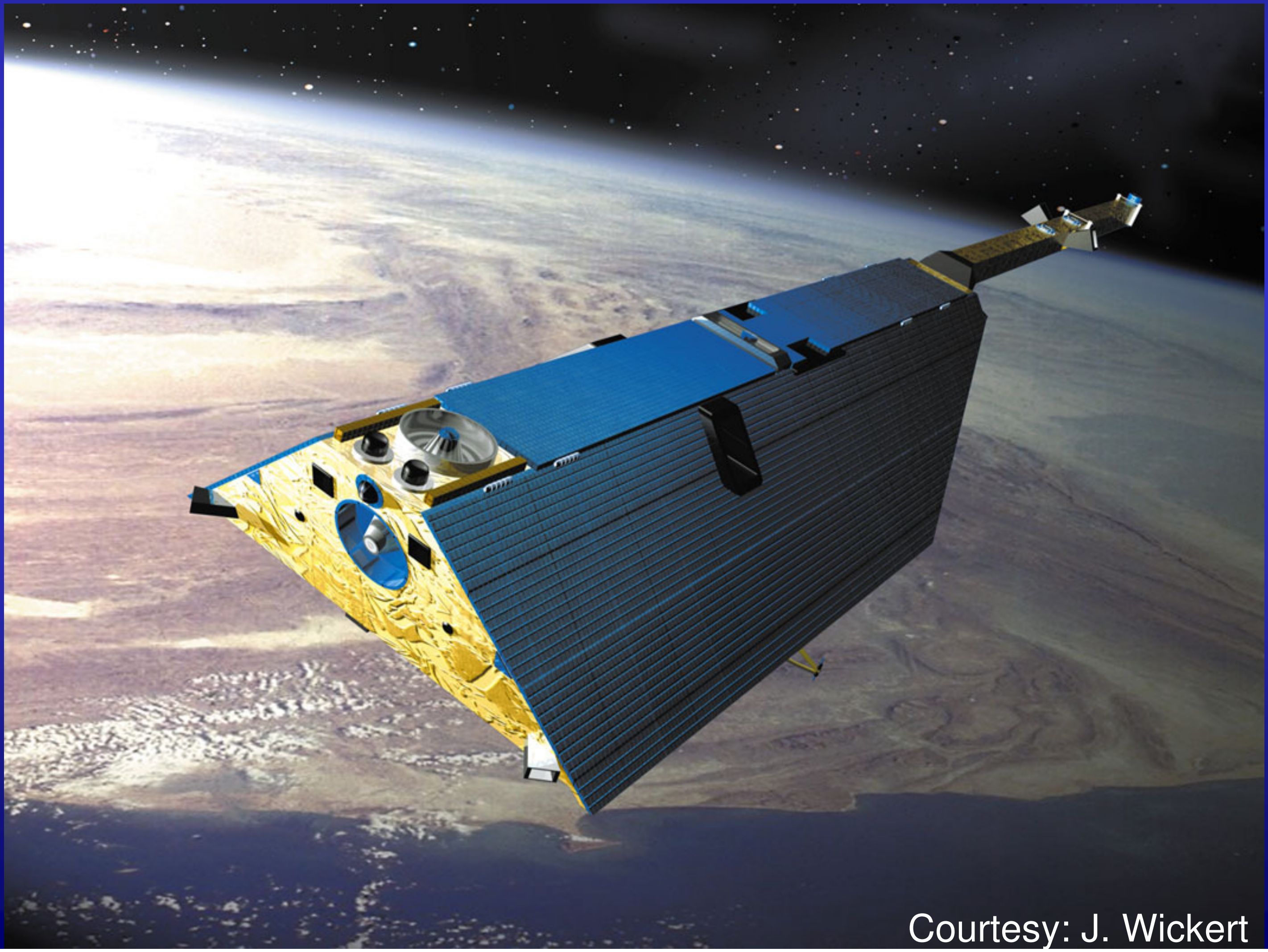
RO Missions (2)



(courtesy J. Wickert)

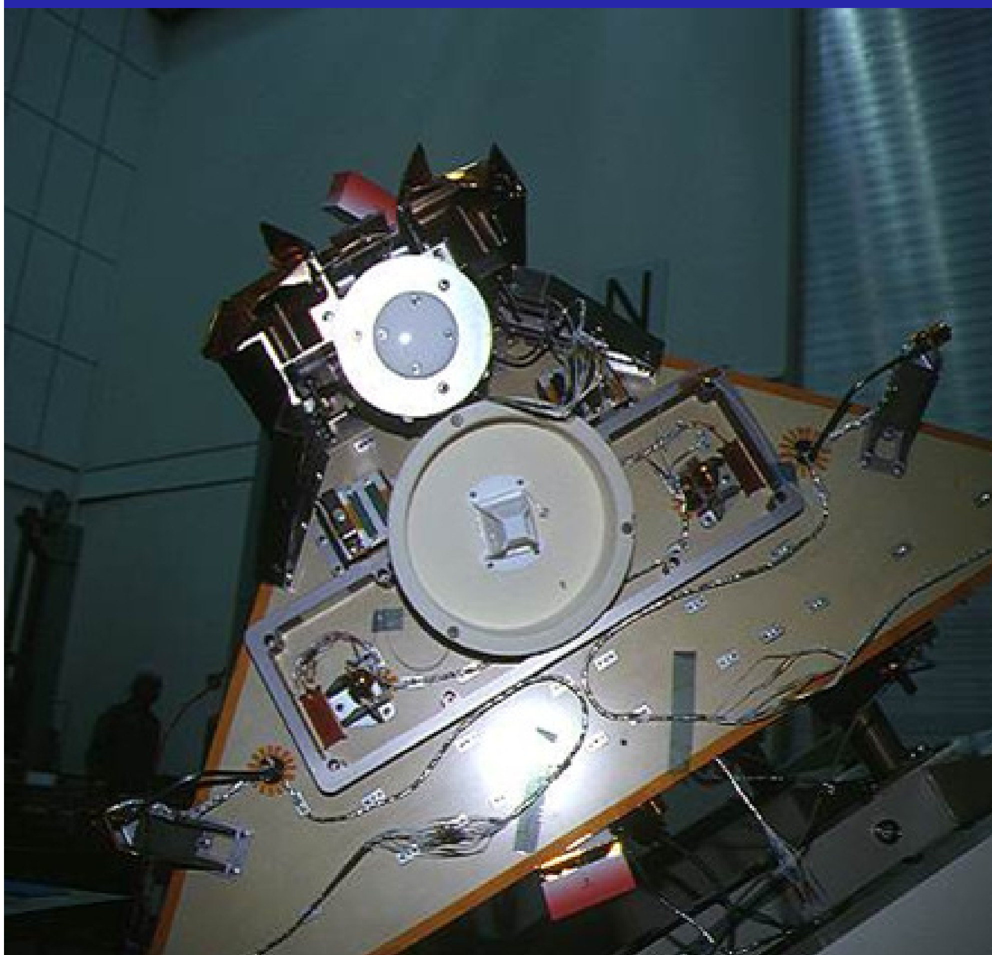
RO with CHAMP (1)

CHAMP in orbit since July 15, 2000



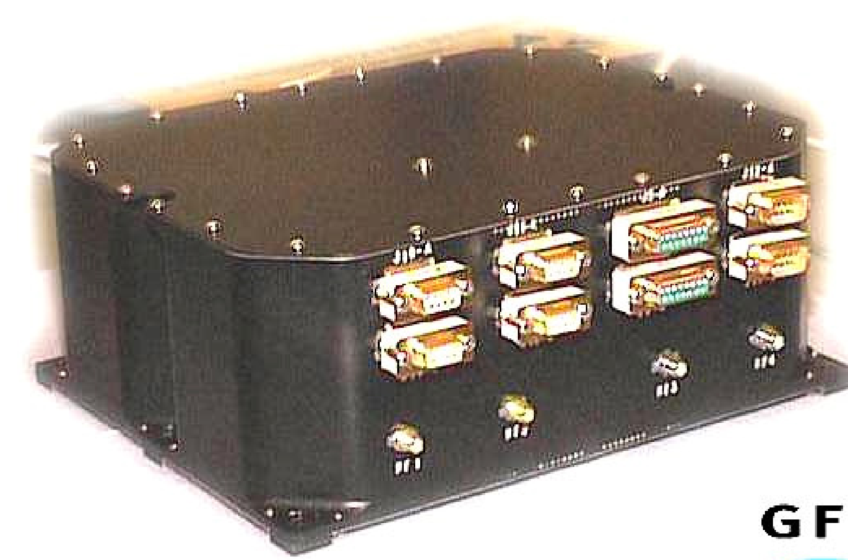
RO with CHAMP (2)

Occultation antenna



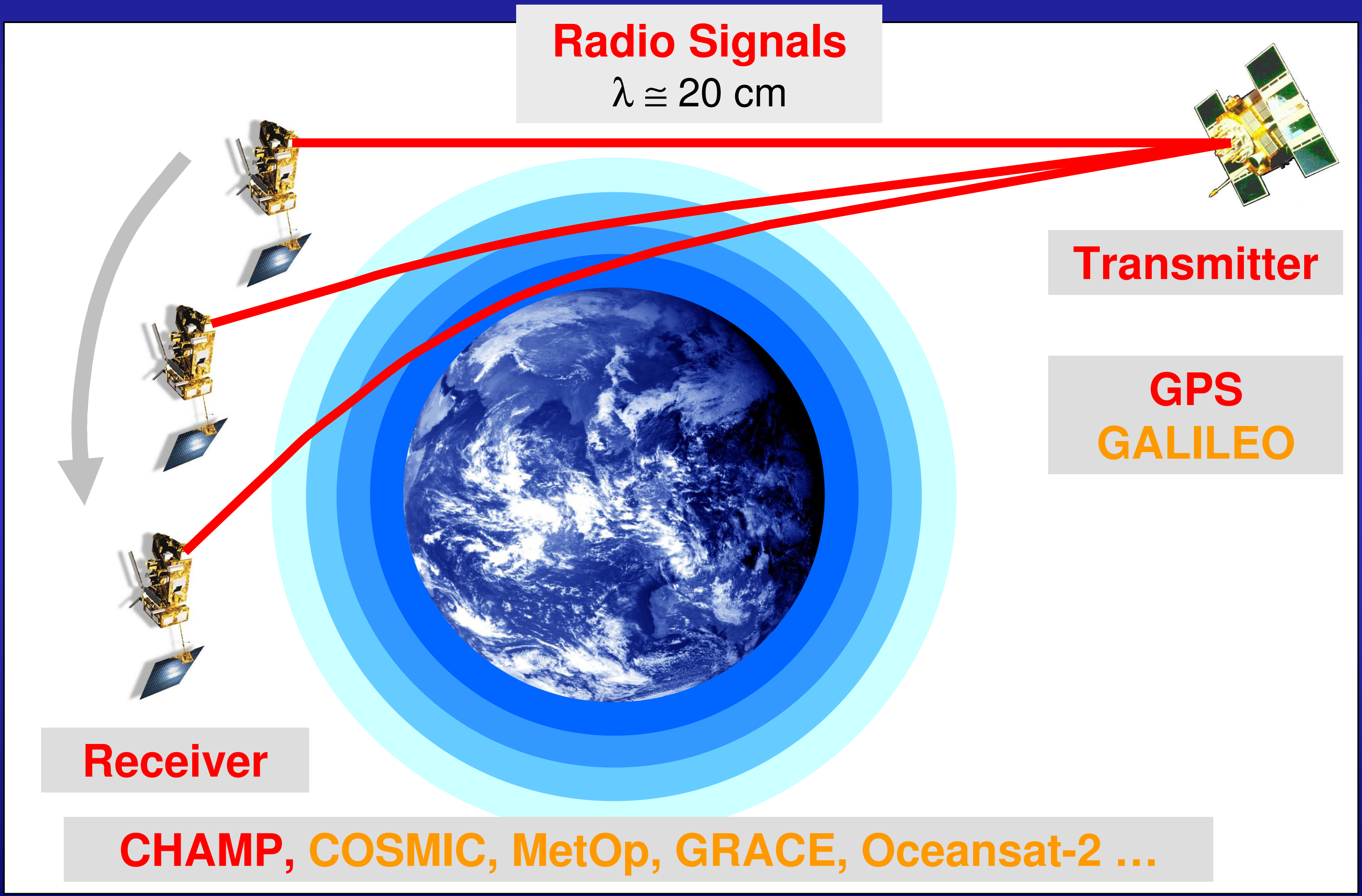
Courtesy: J. Wickert

GPS Receiver
onboard CHAMP



GFZ
POTSDAM

Radio Occultation Principle



Courtesy: U. Foelsche

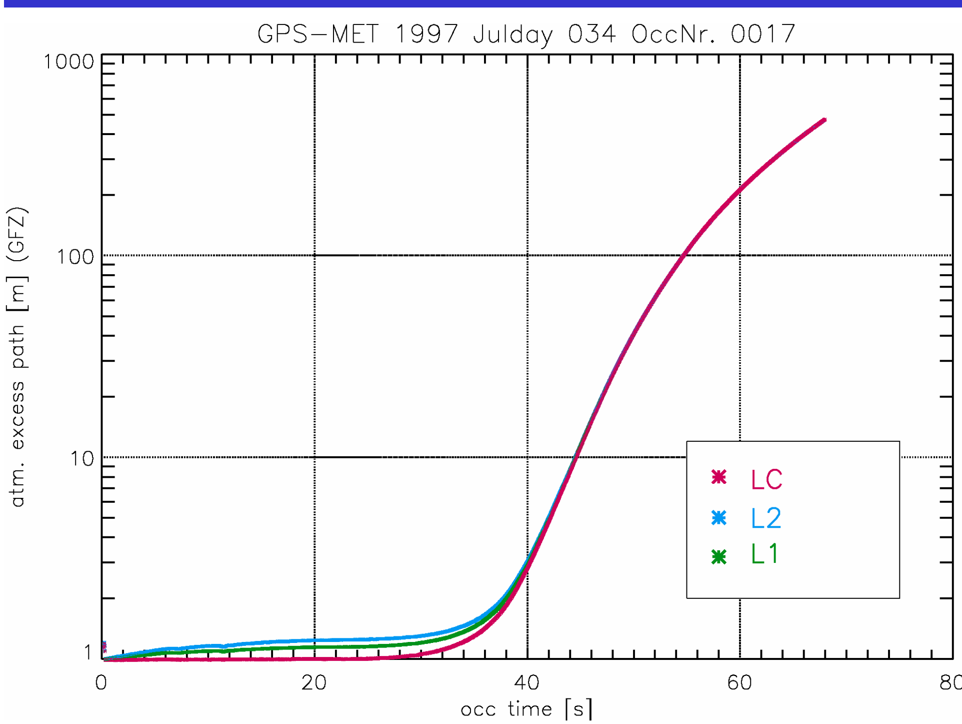
RO Measurements

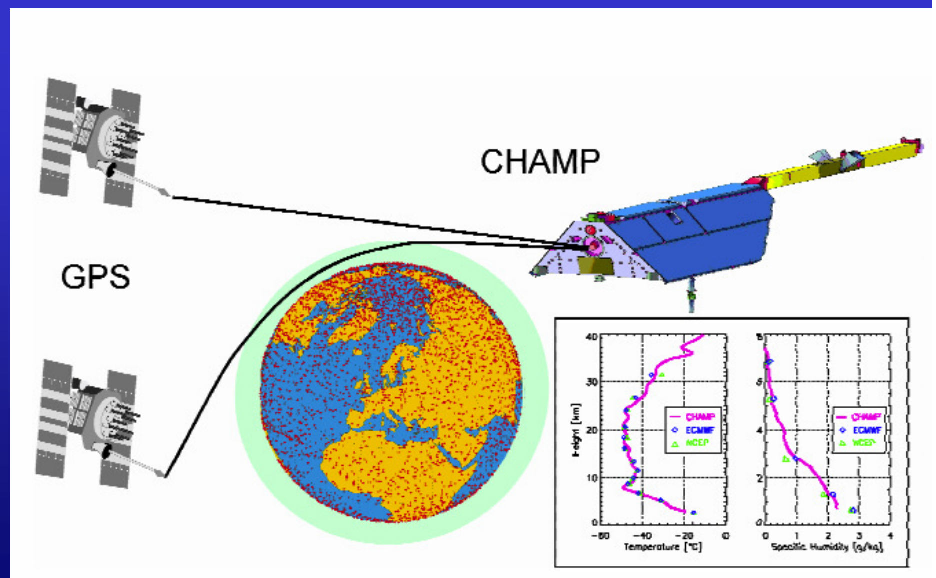
Phase path measurements:

- Removal of geometric path using orbit information of satellites
- Elimination of ionospheric influence through combination of L1 and L2 phases
- **Atmospheric phase path LC**

~ 1 mm	Mesopause	(~80 km)
~ 20 cm	Stratopause	(~50 km)
~ 20 m	Tropopause	(8–17 km)
~ 1–2 km	Surface	

Occultation Event Duration: 1–2 min





Retrieval of Atmospheric Variables

Phase Delay

↓ Orbit Information, Ionospheric Correction

Bending Angle

↓ Abel Transform

Refractivity

Clausius-Mossotti Relation

$$\rho(h) = \frac{M}{R} * \frac{p(h)}{T(h)} = \frac{M}{R \cdot 77{,}6} N(h)$$

Density

↓ Hydrostatic Integral

$$p(h) = \int_{h}^{\infty} g(h')\rho(h')dh'$$

Pressure

↓ Ideal Gas Law

$$T(h) = \frac{M}{R} \frac{p(h)}{\rho(h)}$$

(Dry) Temperature

Stratosphere
Upper
Troposphere

Refractivity → Temperature → **Water Vapor**

Refractivity → Water Vapor → **Temperature**

Lower/Middle
Troposphere

RO Data Characteristics

Properties

- Global coverage

  ~250 RO events/day →

  130 –180 atmospheric profiles/day

- All weather capability
- High accuracy and

  high vertical resolution

  in the Upper Troposphere and

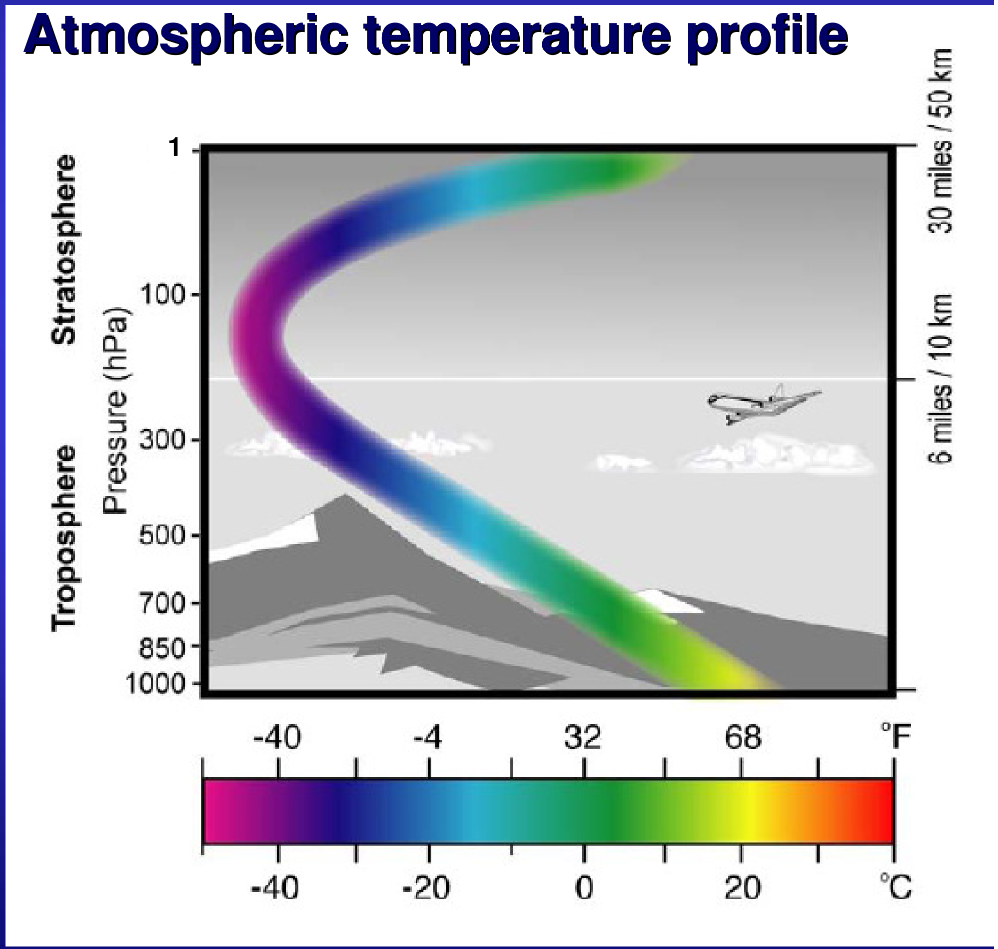
  Lower Stratosphere (UTLS)

  (~ 8–30 km)

- Long–term stability

  due to intrinsic self–calibration

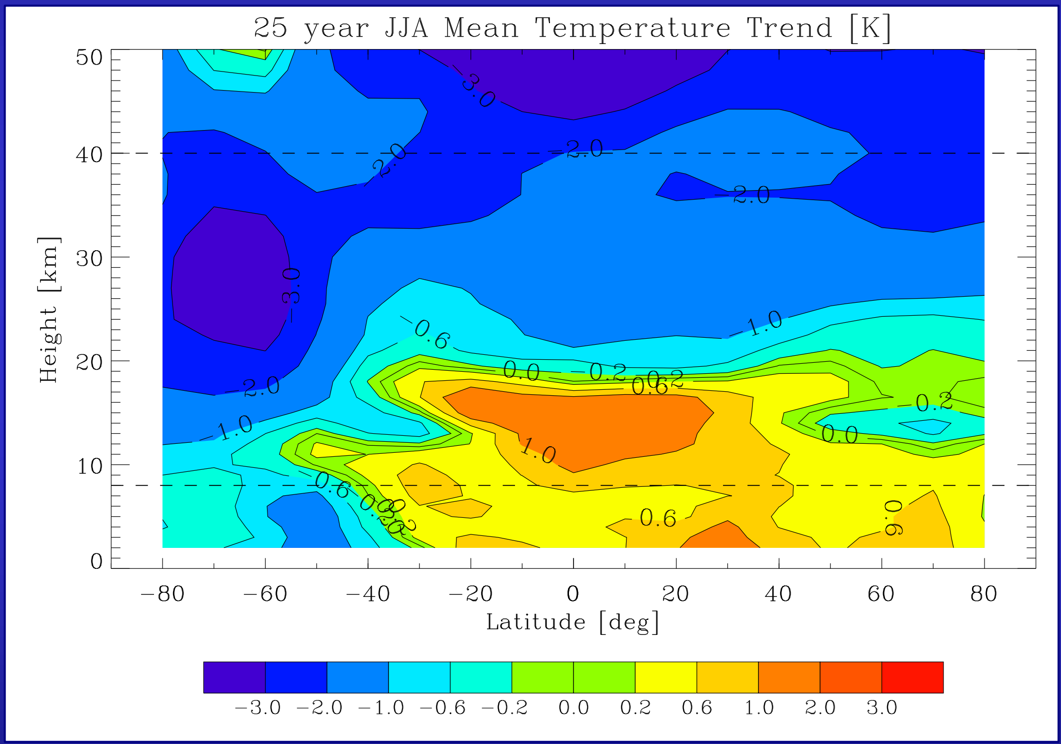
  precise timing with atomic clocks



Context – Climate Change

Signals of GHG increase >>> Thermodynamic state of UTLS

Model Simulation ECHAM5



Temperature trend:

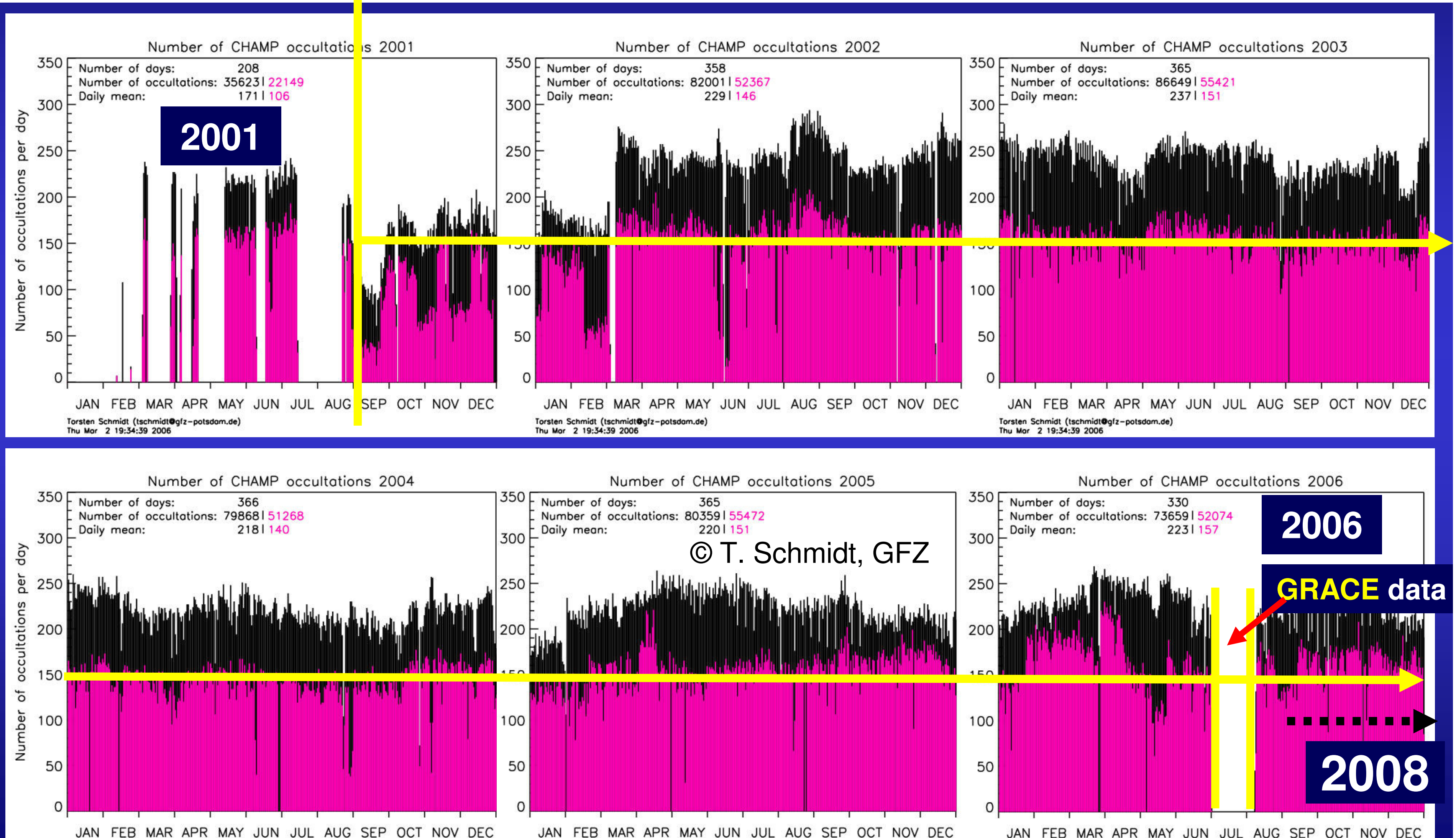
Lower stratosphere: cooling

Upper troposphere: warming

Long-term stability requirements for upper-air temperature observations for climate monitoring (GCOS 2006): troposphere 0.05 K/decade

stratosphere 0.1 K/decade

CHAMP RO data record

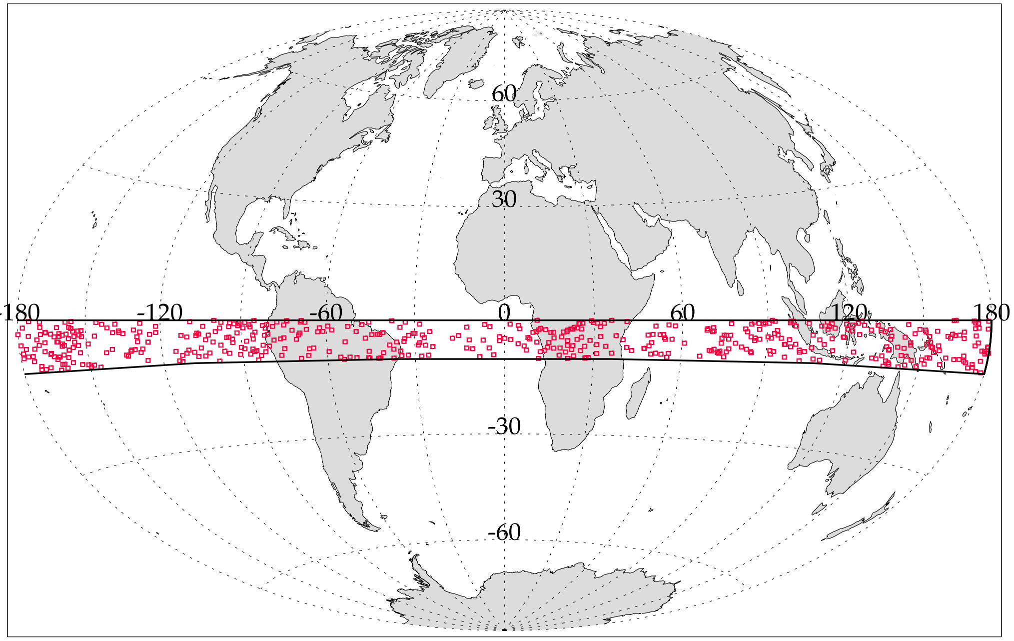


CHAMP: First Opportunity to create RO Climatologies

First RO based Climatologies

Example Season – Winter 2003/04

DJF 2003/04: CHAMP Event Distribution



- Since Sep 2001
- ~130 – 180 RO profiles/day
- Zonal mean fields
- Binning and Averaging
- 18 latitude bands
- 10° latitudinal width

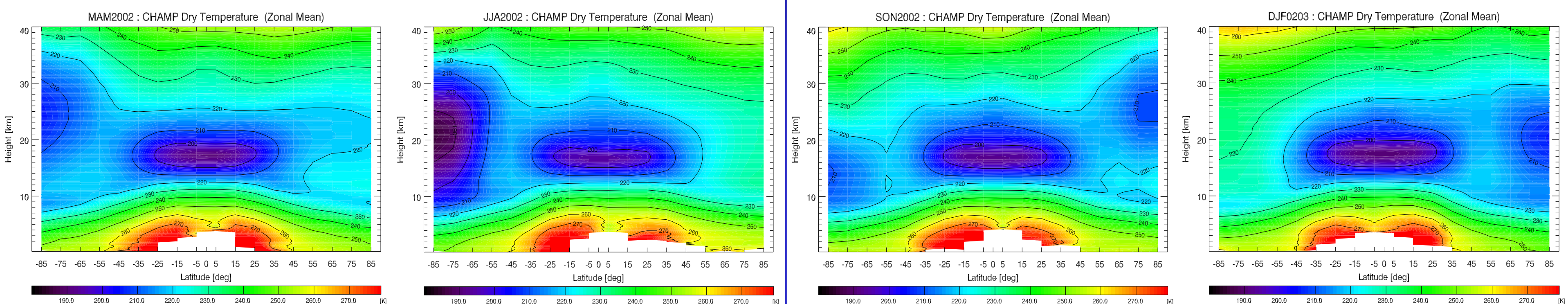
WegCenter Retrieval using phase and orbit data from GeoForschungsZentrum (GFZ) Potsdam

CHAMP RO Climatologies

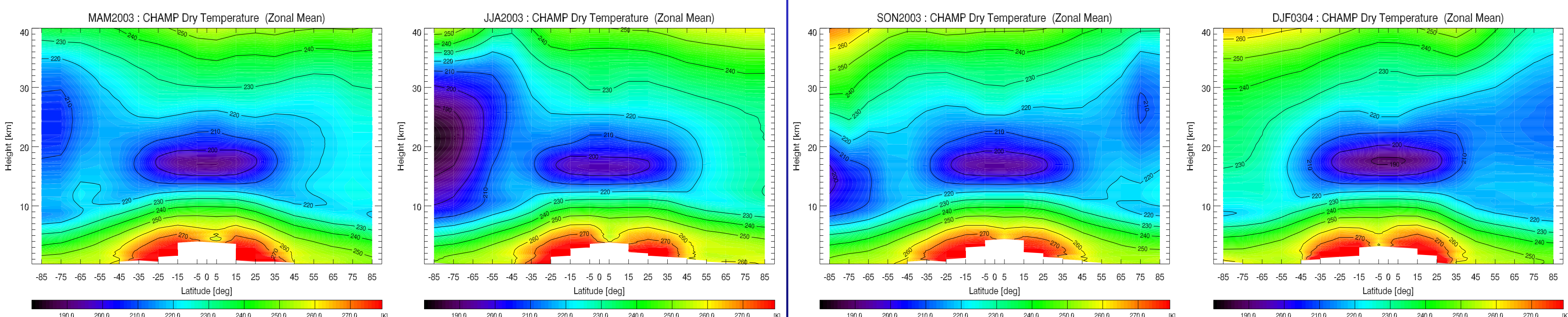
Wegener Center
www.wegcenter.at

CHAMPCLIM: seasonal, zonal mean climatologies of dry temperature

Mar 2002 - Feb 2003, MAM – JJA – SON – DJF seasons, zonal - mean T_{dry}



Mar 2003 - Feb 2004, MAM – JJA – SON – DJF seasons, zonal - mean T_{dry}



[Figures: Gobiet & Borsche, WegCenter/UniGraz]

Climate variability monitoring by GNSS occultation, real data

Error Characterization

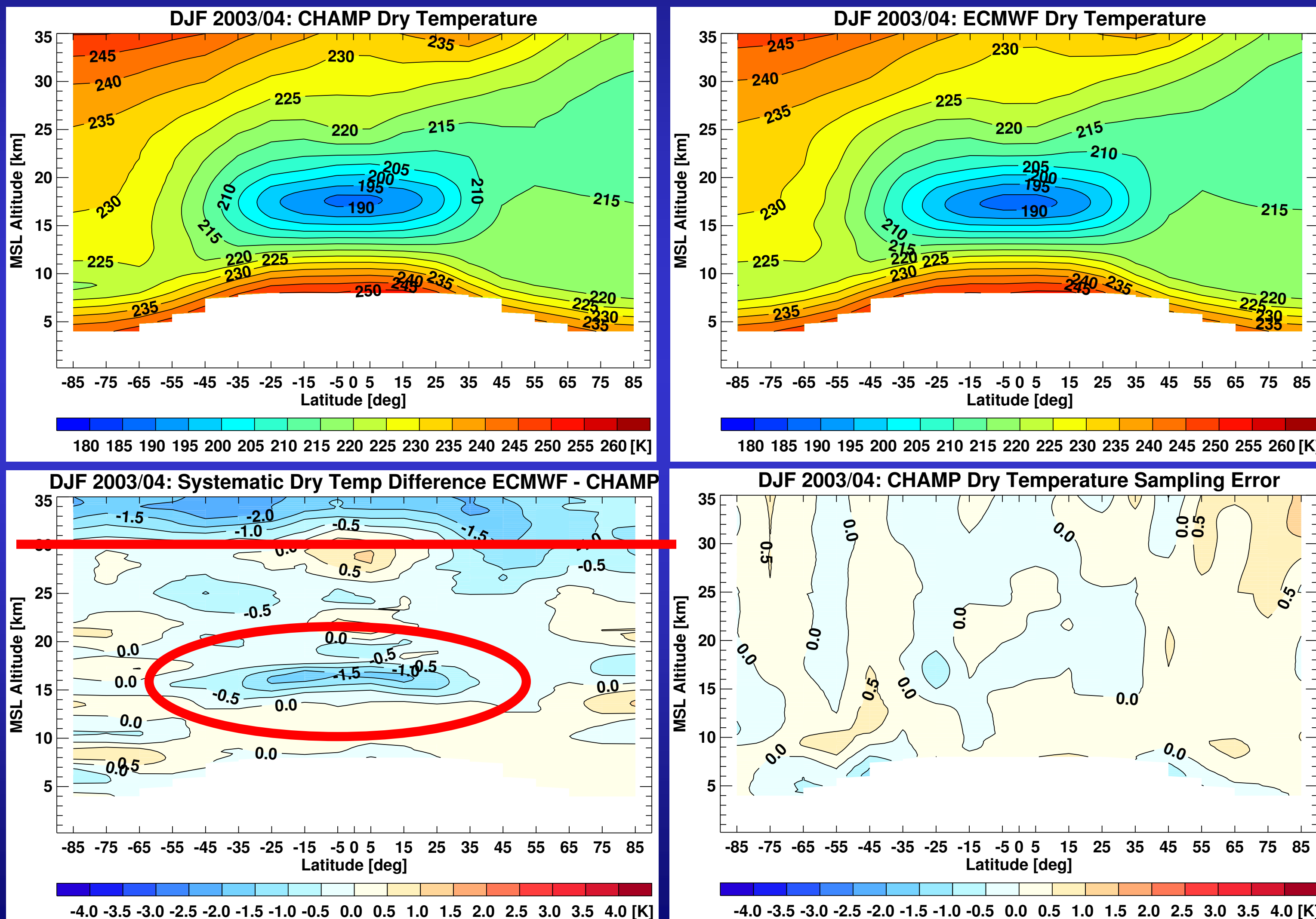
Comparison to ECMWF analyses fields

assumed to represent the "true" temporal and spatial evolution
enables estimation of sampling error

- **Sampling Error:** Undersampling of the true spatial and temporal temperature evolution. Estimation as "True" profiles at the RO locations minus "True" mean field
- **Systematic Difference:** CHAMP minus ECMWF collocated profiles
- **Statistical Error:** rms error of the mean
- **Observational Error:** Statistical error + systematic difference, the latter dominates
- **Climatological Error:** observational error + sampling error

(ECMWF: European Centre for Medium-Range Weather Forecasts)

Comparison–ECMWF Analyses



Foelsche et al., *Clim. Dyn.*, 2007, revised

Systematic Difference – Tropical Tropopause: Cold Bias in ECMWF

Analysis of RO Climatologies

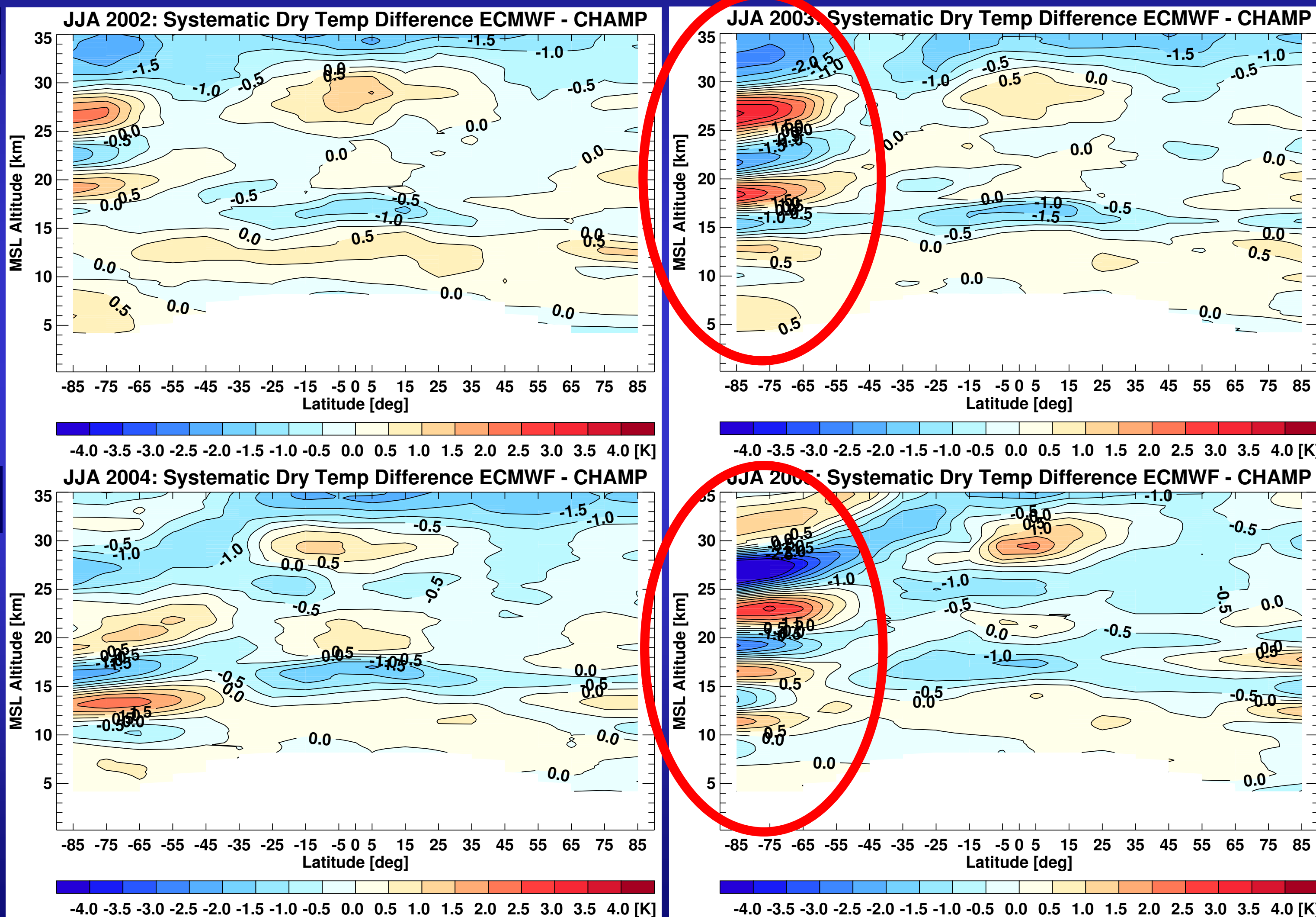
Wegener Center
www.wegcenter.at

UNI GRAZ

2002

Warmer, polar vortex split late Sep.

2003



2004

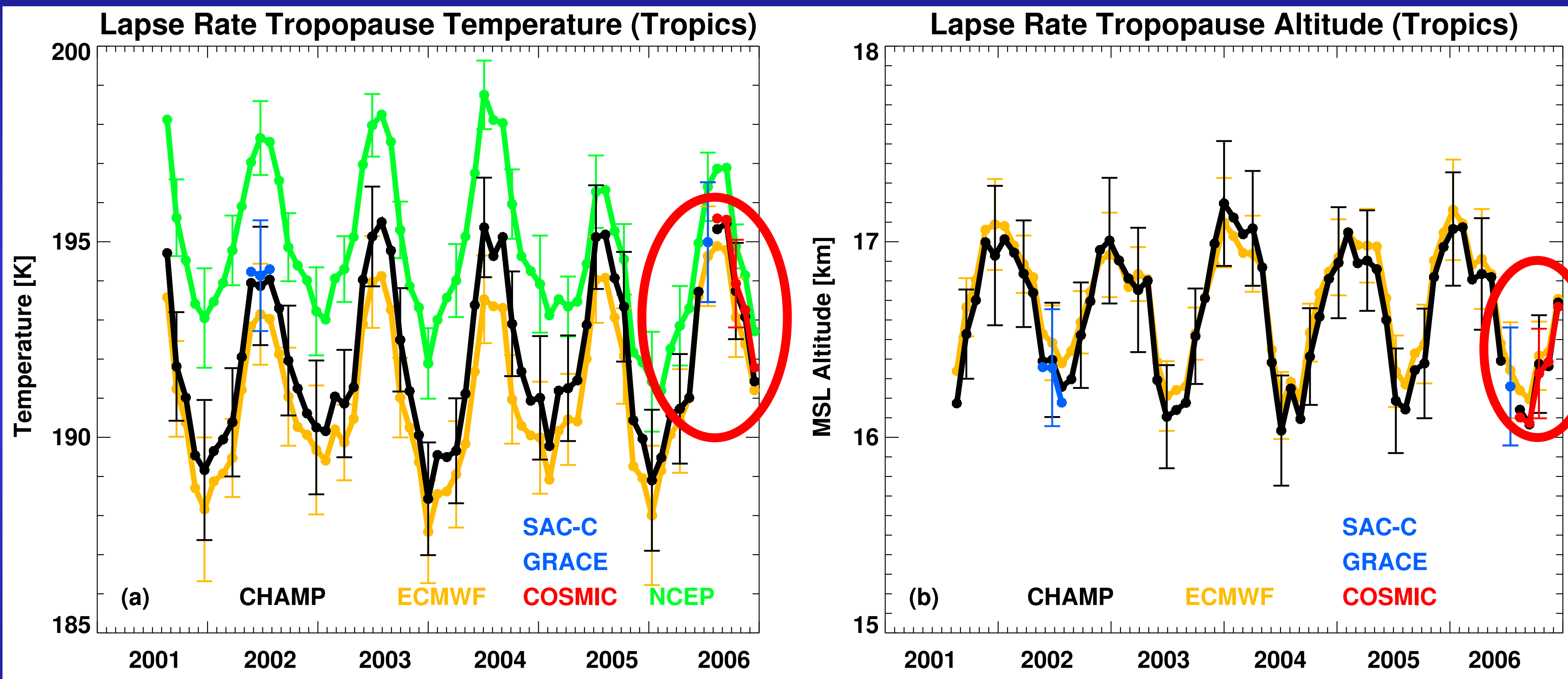
wave pattern: >20 km: red. magnitude, rev. sign
Below: shape more pronounced than 2002/03

2005

Gobiet et al. GRL, 2005

Wave–like bias structure: Deficiencies in representation of Antarctic polar vortex in ECMWF

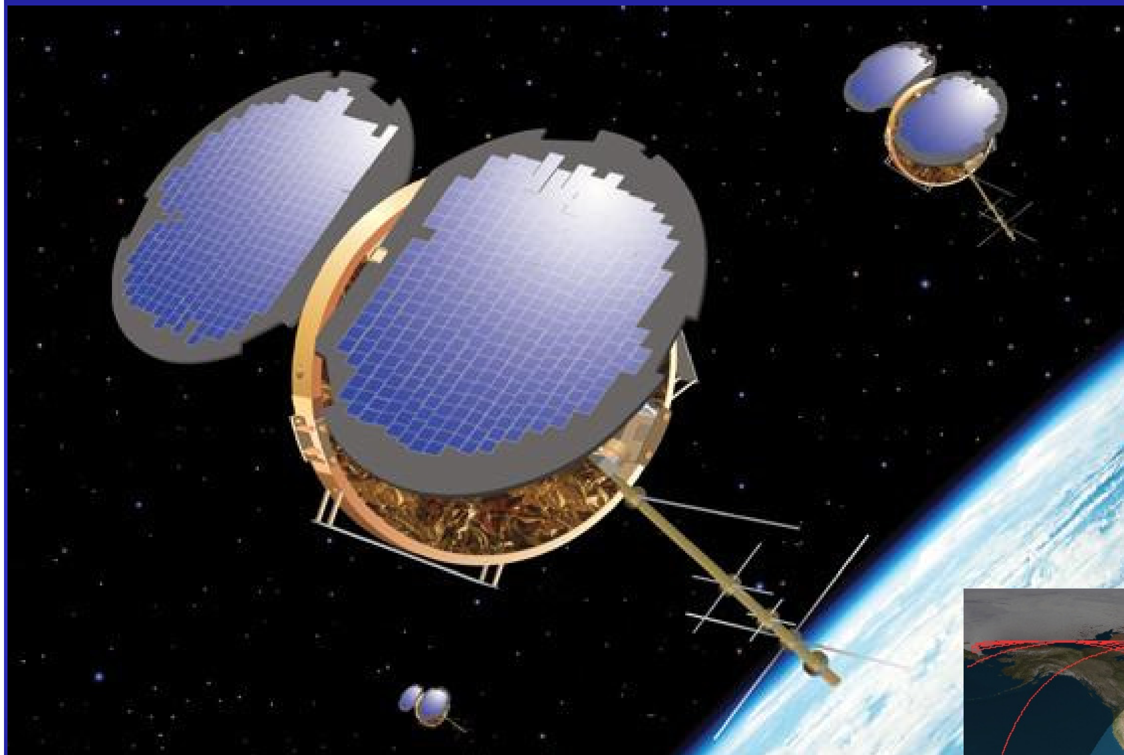
Analysis –Tropical Tropopause



Borsche et al., 2007, *Geophys. Res. Lett.*

- CHAMP **tropical tropopause** consistently **warmer** than ECMWF until February 2006, then ECMWF model resolution improvement, ECMWF follows CHAMP.
- **FORMOSAT-3/COSMIC and CHAMP results for Aug–Dec 2006 almost identical – consistency of RO data from different satellites**

FORMOSAT–3/COSMIC Mission



FORMOSAT–3/COSMIC

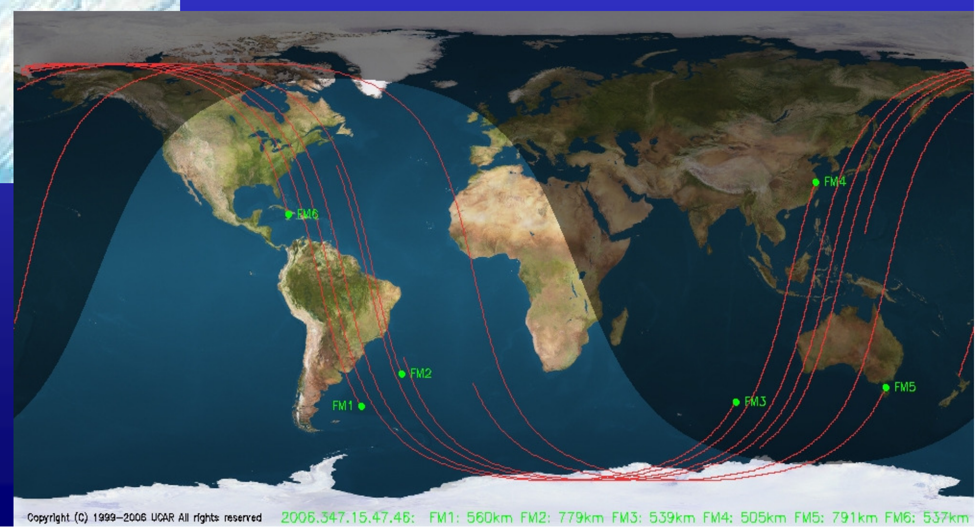
Taiwan/US mission

6 satellites

Launch April 14, 2006

~800 km final orbit

~2500 RO profiles per day

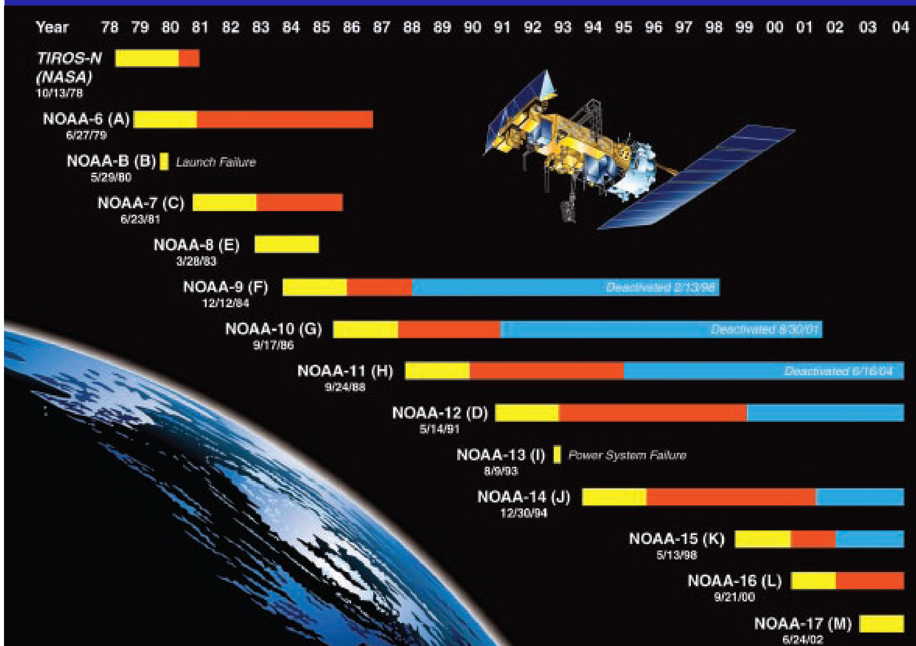


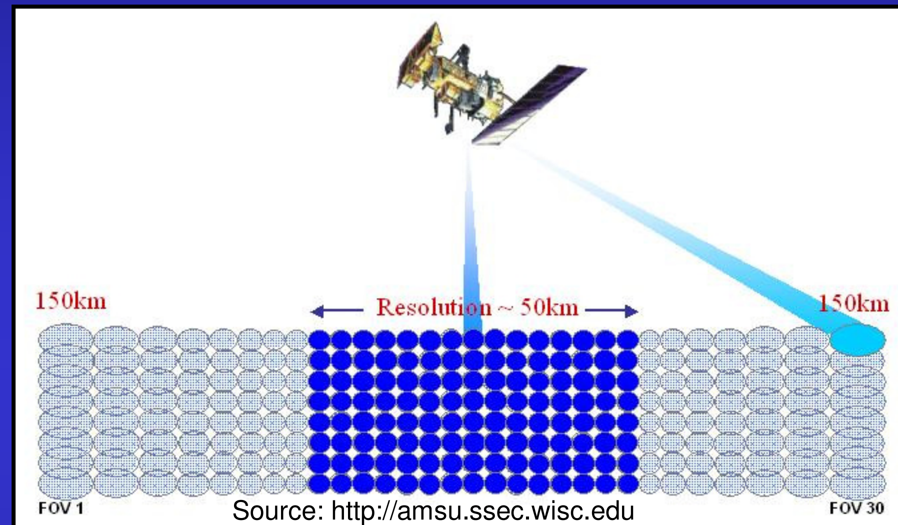
Courtesy: UCAR

Comparison to upper air temperature records

(Advanced) Microwave Sounding Unit

(Advanced) Microwave Sounding Unit (AMSU/MSU) on NOAA satellites



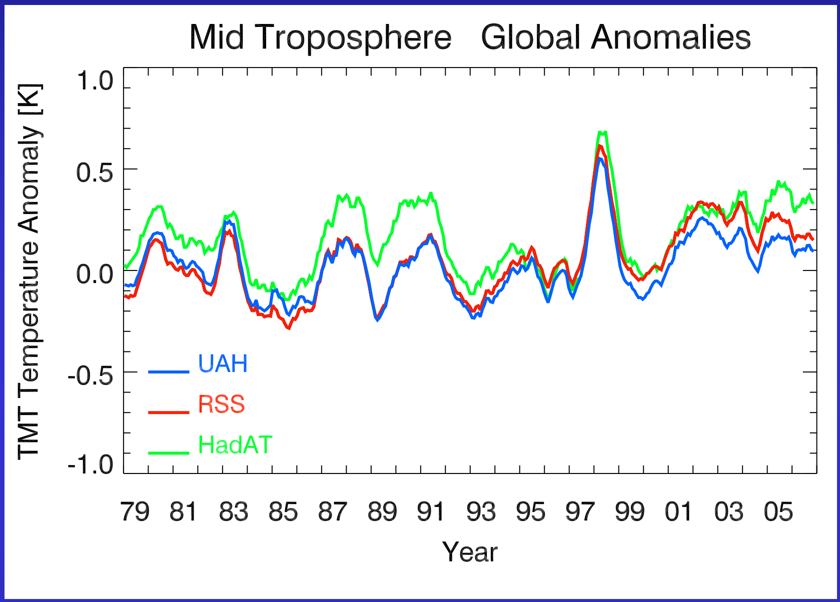


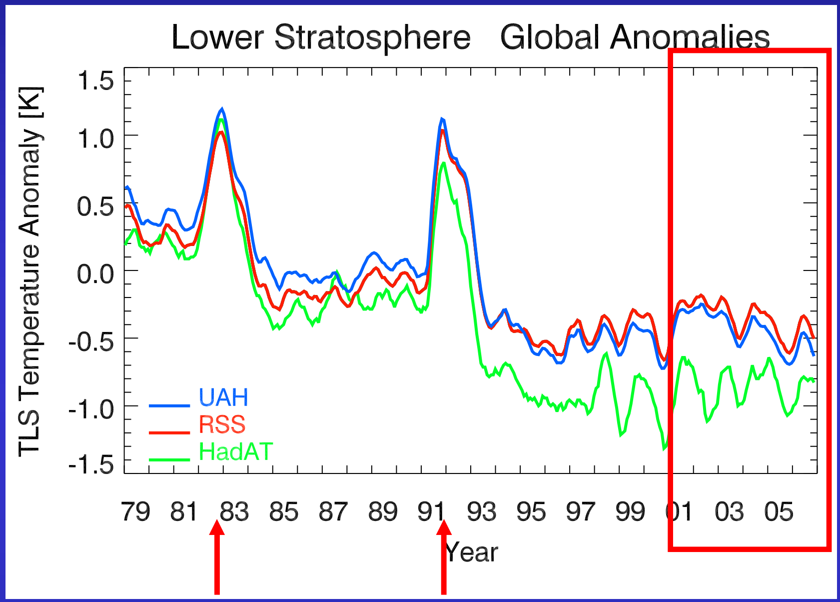
Source: http://amsu.ssec.wisc.edu

Passive microwave sensor

- measures Earth‘s microwave emissions using the 60 GHz oxygen absorption line.
- error sources: diurnal drift, orbital decay, intersatellite biases, calibration changes
- intercalibration and correction procedures
- provision of layer average temperatures
- discrepancies between different retrievals and wrt to Radiosonde measurements

MSU/AMSU Records





Tropospheric Warming
(MSU/AMSU TMT(T2) channel)

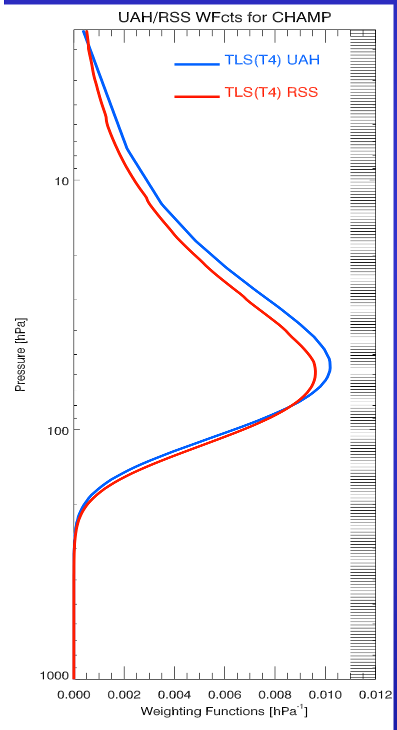
Stratospheric Cooling
(MSU/AMSU TLS(T4) channel)

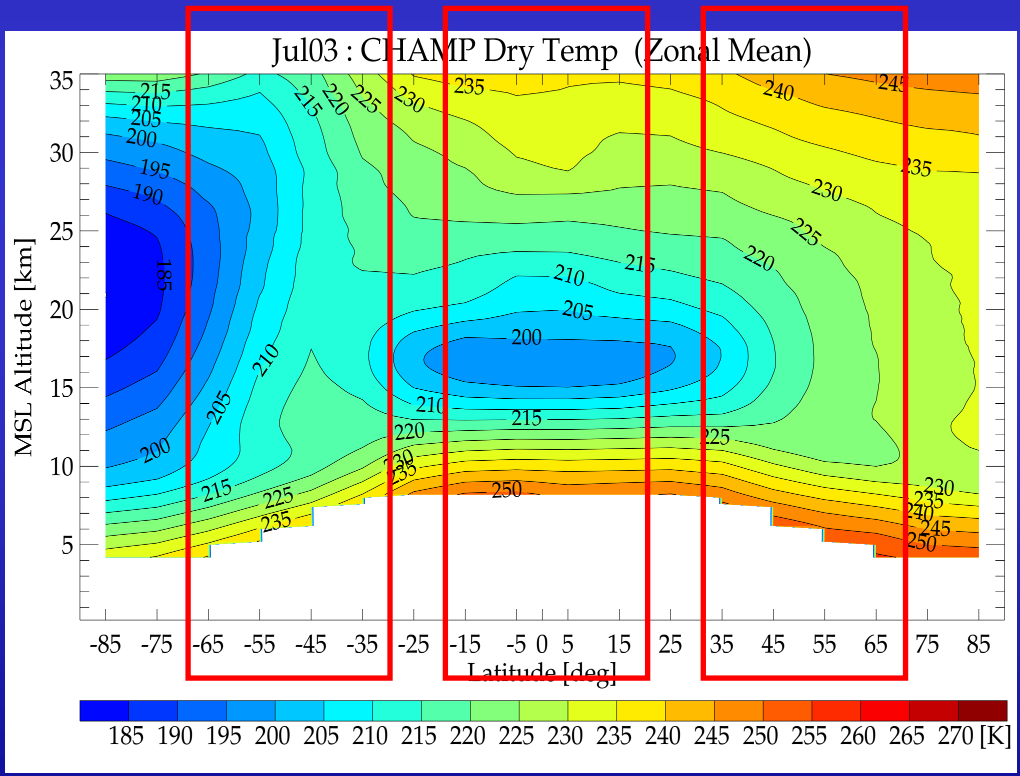
U.S. CCSP Report 2006: Temperature trends: Surface and Upper Air
State of the art data: Surface observations, Radiosonde–, Satellite data, Reanalyses
Discrepancies between data sets regarding trends

Reference: Karl, T. R., S. J. Hassol, C. D. Miller, and W. L. Murray (Eds.) (2006), Temperature trends in the lower atmosphere: Steps for understanding and reconciling differences, *A Report by the Climate Change Science Program and the Subcommittee on Global Change* Research, Washington, DC.

MSU TLS Temperature Calculation from RO

Calculation of synthetic MSU temperatures T_{MSU} using weighting functions

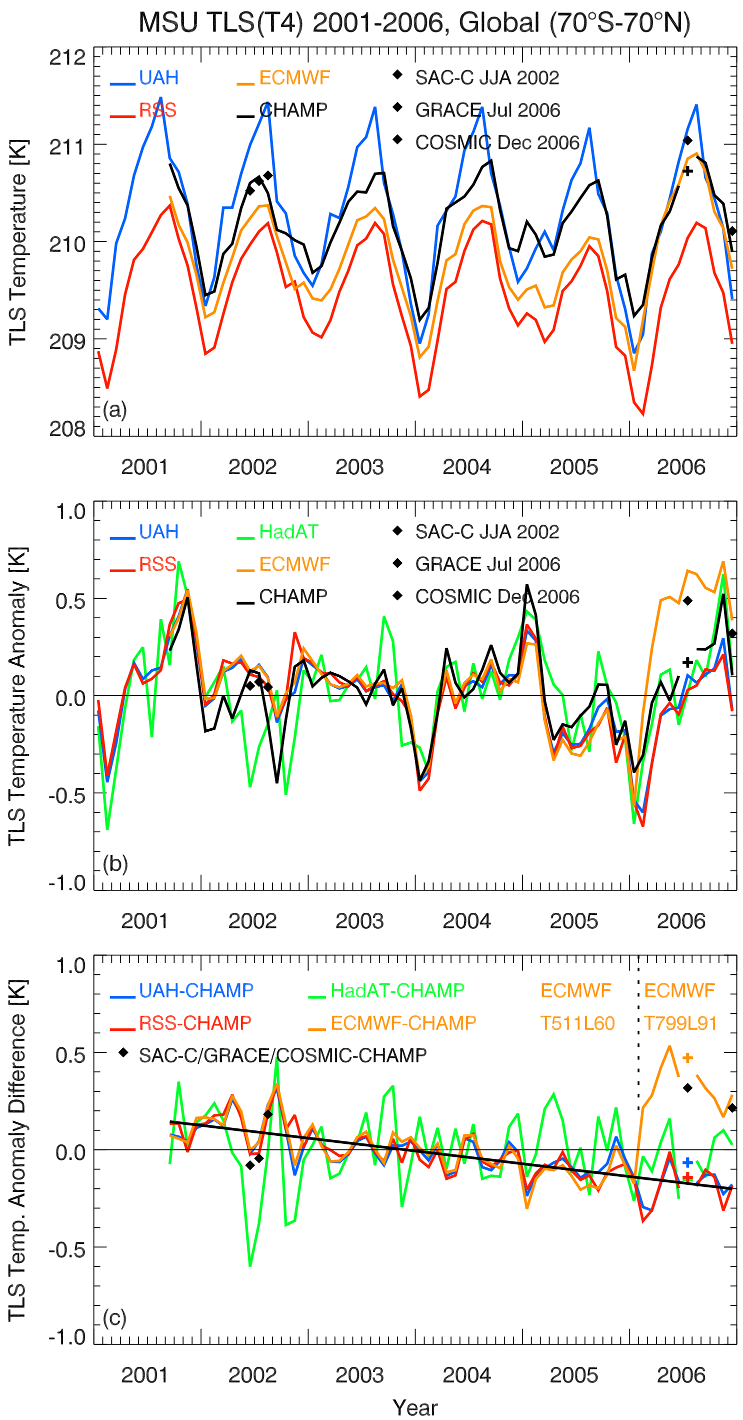




$$T_{MSU} = \frac{\sum_{i=1}^{N} T_i(p_i) * wf_i}{\sum_{i=1}^{N} wf_i}$$

Regions

Global (70°S–70°N)
Tropics (20°S–20°N)
Extratropics
NH (30°N–70°N)
SH (30°S–70°S)



MSU records from RO

- **TLS Absolute Temperature:** Global offsets
  UAH–CHAMP 0.11 K (±0.31 K)
  RSS–CHAMP -0.69 K (±0.16 K)
  ECMWF TLS agrees best with RSS until Jan07, then with CHAMP due to improvement in ECMWF resolution.

- **TLS Temperature Anomalies:** Overall very good agreement of CHAMP anomalies with UAH, RSS, ECMWF anomalies for intra–annual variability (RMS difference < 0.1 K globally, 0.1 K tropics, < 0.25 K extratropics). HadAT2 anomalies show larger intra-annual variability differences (factor 2).

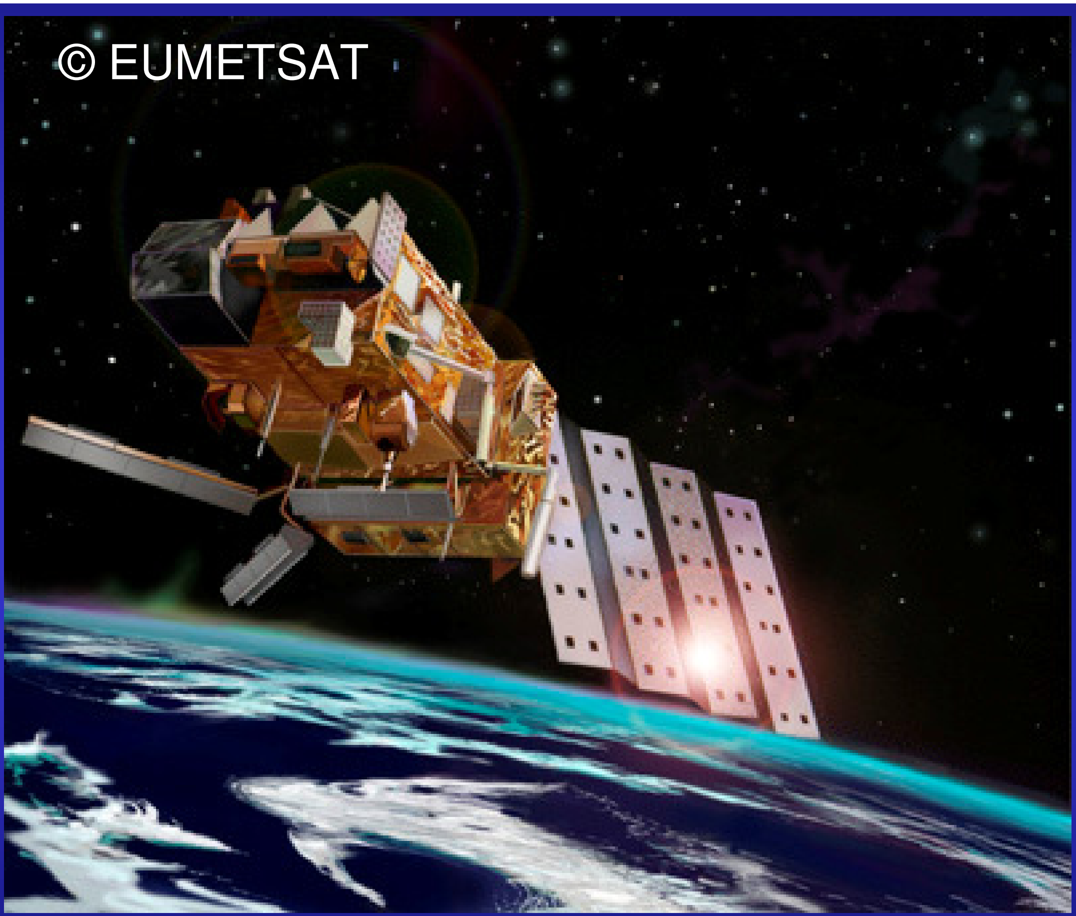
- **2001–2006 TLS Trends:** HadAT2 and CHAMP coincide well, UAH and RSS show a statistically significant cooling trend difference to CHAMP globally (–0.30 to –0.36 K/5yrs) and in the tropics (–0.40 to –0.42 K/5yrs).
  Contribution of known error sources regarding the RO data and related TLS computation is an order of magnitude smaller.

Conclusions

RO datasets show:

- **Utility as reference climatologies** obtainable from a single RO receiver
- **Improvement of modern operational climatologies and NWP**
- **Provision of upper air temperature records** (AMSU comparison)
- **Homogeneity and consistency** despite very different orbits, different instruments and raw processing chains
- Great potential for **monitoring the global climate**
- Great potential to qualify as a **benchmark for global UTLS climatologies of thermodynamic variables** and to enable overcoming the long–standing problem with weakly reliable trends from radiometric satellite data.

Outlook – MetOp/GRAS



MetOp A

Successfully launched

19 October, 2006

first GRAS data

RO data from completely different receiver GRAS

Availability of operational MetOp/GRAS data until 2020