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

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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)
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

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

Temperature profiles near England
At about 95-4-25:00:00 UTC

Pressure, mbar
Temperature, K

Occultation at 52.6 N. 355 E.
Radiosonde at 54.5 N. 353.9 E.
Radiosonde at 53.5 N. 357 E.

Courtesy: UCAR
RO Missions (2)

(courtesy J. Wickert)
CHAMP in orbit since July 15, 2000

Courtesy: J. Wickert
Occultation antenna

GPS Receiver onboard CHAMP

Courtesy: J. Wickert
Radio Occultation Principle

Radio Signals
\[ \lambda \approx 20 \text{ cm} \]

Transmitter
GPS GALILEO

Receiver
CHAMP, COSMIC, MetOp, GRACE, Oceansat-2 …

Courtesy: U. Foelsche
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
  - ~ 20 cm: 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

- **Density**
  - Hydrostatic Integral

- **Pressure**
  - Ideal Gas Law

- **(Dry) Temperature**
  - Stratosphere
  - Upper Troposphere

- **Temperature**
  - Water Vapor

- **Water Vapor**

Mathematical Expressions:

- \[ p(h) = \frac{M}{R} \frac{p(h)}{T(h)} = \frac{M}{R \cdot 77.6} N(h) \]

- \[ p(h) = \int_{h}^{\infty} g(h') p(h') dh' \]

- \[ T(h) = \frac{M}{R} \frac{p(h)}{\rho(h)} \]
**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**

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

CHAMPCLIM: seasonal, zonal mean climatologies of dry temperature

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


[Figures: Gobiet & Borsche, WegCenter/UniGraz]

Climate variability monitoring by GNSS occultation, real data
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

(EMWF: European Centre for Medium-Range Weather Forecasts)
Comparison–ECMWF Analyses

Systematic Difference – Tropical Tropopause: Cold Bias in ECMWF

DJF 2003/04: CHAMP Dry Temperature

DJF 2003/04: ECMWF Dry Temperature

DJF 2003/04: Systematic Dry Temp Difference ECMWF - CHAMP

DJF 2003/04: CHAMP Dry Temperature Sampling Error

Systematic Difference -- Tropical Tropopause: Cold Bias in ECMWF

Foelsche et al., Clim. Dyn., 2007, revised
**Wave-like bias structure**: Deficiencies in representation of Antarctic polar vortex in ECMWF.

- **2002**: Systematic Dry Temp Difference ECMWF - CHAMP
  - Warmer, polar vortex split late Sep.

- **2003**: Systematic Dry Temp Difference ECMWF - CHAMP
  - Gobiet et al., GRL, 2005

- **2004**: Systematic Dry Temp Difference ECMWF - CHAMP
  - Wave pattern: >20 km: red. magnitude, rev. sign
  - Below: shape more pronounced than 2002/03

- **2005**: Systematic Dry Temp Difference ECMWF - CHAMP

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Analysis of RO Climatologies
• **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 (AMSU/MSU) on NOAA satellites**

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**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

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

Resolution ~ 50 km
MSU/AMSU Records

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

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

State of the art data: Surface observations, Radiosonde−, Satellite data, Reanalyses
Discrepancies between data sets regarding trends

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

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

**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