Institute for Geophysics, Astrophysics, and Meteorology / University of Graz
Atmospheric Remote Sensing and Climate System Research Group
ARSCliSys — on the art of understanding the climate system

Climate Change Monitoring by Radio Occultation:

From Simulation Studies via CHAMP to COSMIC and ACE+ Constellations

Gottfried Kirchengast

ARSCliSys Research Group, IGAM, University of Graz, Austria
(*www.uni-graz.at/igam-arsclisys*)

Invited Talk; COSMIC RO Science Workshop/Session “Climate+Meteorology“; August 23, 2002; UCAR, Boulder, CO, U.S.A.


ARS CliSys Research Group
Atmospheric Remote Sensing and Climate System — ARS CliSys — on the art of understanding the climate system
(founded 1996, status August 2002)
IGAM
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Thanks to...
RO - Radio Occultation
RO
Andrea Steiner
Sabine Tschürtz
RO
Gottfried Kirchengast
Christoph Bichler
RO
Ulrich Foelsche
RO
Johannes Fritzer
Marc Schwärz
Members (at IGAM)
Head
2 Senior Scientists
2 Post-Doc Scientists
5 Ph.D. Students
1 M.Sc. Student
1 Admin. Assistant
Colleagues at IGAM
RO
Colleagues Worldwide
Christian Retscher
Christoph Rehrl
RO
Josef Ramsauer
RO
Armin Löscher
RO
Andreas Gobiet

Climate Change Monitoring by Radio Occultation
Outline

- **Radio Occultation (RO) – Climate Change Monitoring Promise**
  - on the principle of spaceborne occultation measurements
  - RO methods (GNSS-LEO, LEO-LEO) and close friends
  - relevance for climate monitoring and research

- **Simulation Studies – Climate Monitoring Simulation 2001-2025**
  - a climate GNSS RO observing system simulation experiment
  - results of performance analysis (JJA 1997 "testbed" analysis)
  - perspectives for the full experiment (time period 2001-2025)

- **CHAMP, COSMIC, ACE+,… – Current & Future RO Research**
  - RO-related research aims at IGAM/Univ. of Graz
  - on current research (START- and ENVI-ATCHANGE, ESA-R&D)
  - on initialized future research (ECCMAR/CHAMPCLIM, ACE+)

- **Concluding Remarks**

Climate Change Monitoring by Radio Occultation

RO – Climate Change Monitoring Promise

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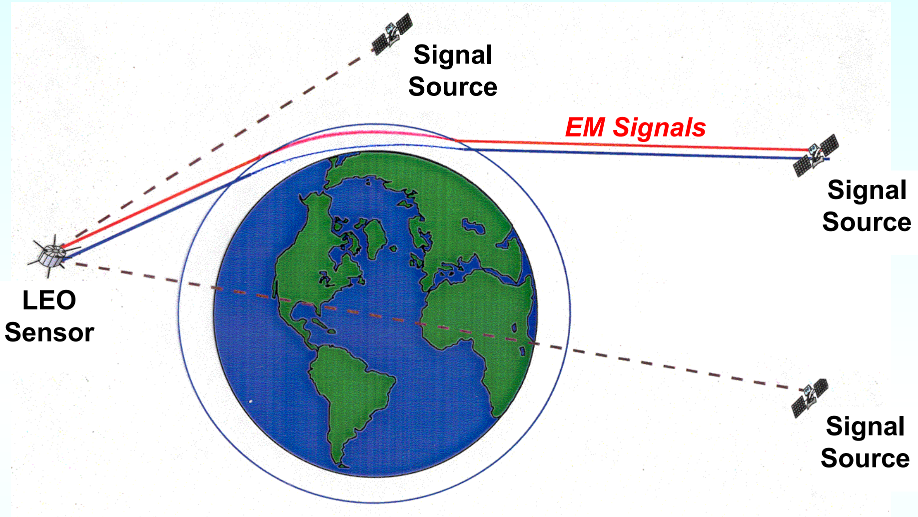
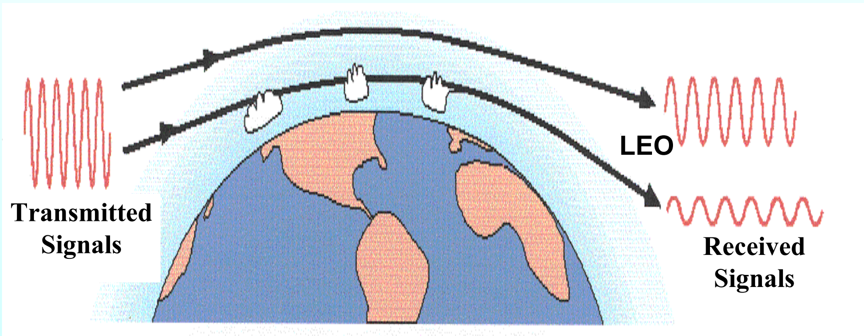
RO – Climate Change Monitoring Promise
principle of spaceborne occultation measurements



[basic figures from D. Feng, Univ. of Arizona, priv. communications, 2001 (modified)]



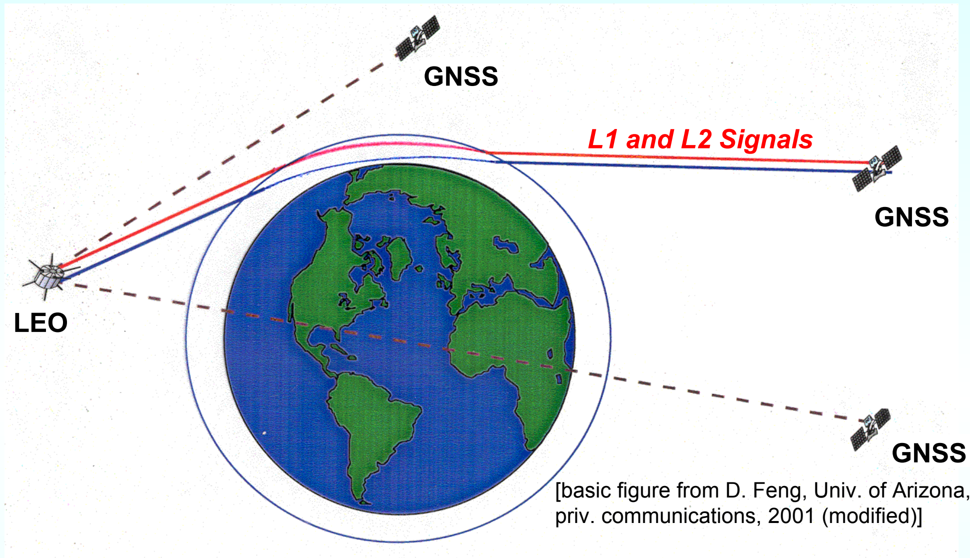
Occultation Methods

- exploit extinction and/or refraction of electromagnetic signals along limb paths
- providing measurements of transmission and/or Doppler shift profiles
- leading via absorption or column density, bending angle, and (complex) refractivity
- to key climate parameters such as temperature, humidity, ozone, and geopotential height.

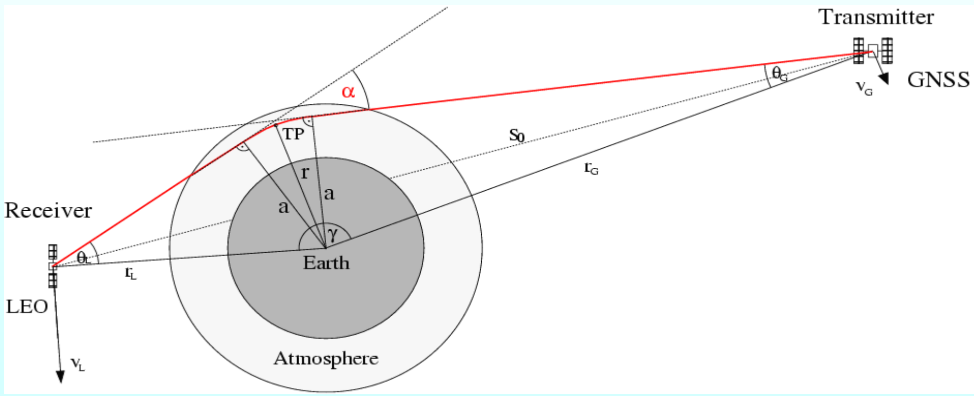
Inversion of Occultation Data

- is a virtually well-posed and close to linear problem solved by
- direct inversion/retrieval or
- data assimilation.

RO – Climate Change Monitoring Promise
GNSS-LEO radio occultation



[basic figure from D. Feng, Univ. of Arizona, priv. communications, 2001 (modified)]



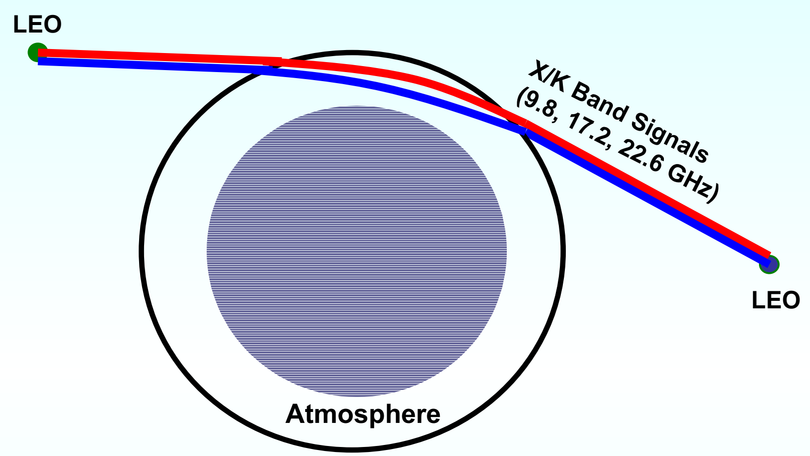
GNSS-LEO Radio Occultation

- exploits (mainly) refraction of L-band signals along limb paths
- providing **self-calibrated** measurements of Doppler shift
- leading via atmospheric bending angle and refractivity profiles
- to key atmosphere and climate parameters such as temperature, humidity, and geopotential height.

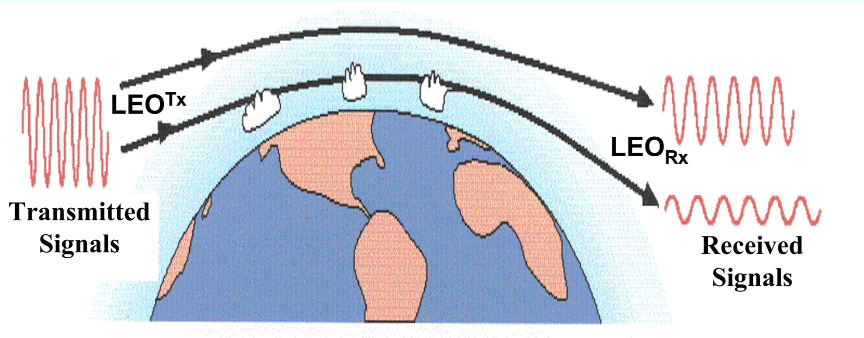
Inversion of GNSS Occultation Data

- is a virtually well-posed and close to linear problem solved by
- direct inversion/retrieval or
- data assimilation.

RO – Climate Change Monitoring Promise
LEO-LEO radio occultation



[basic figures from D. Feng, Univ. of Arizona, priv. communications, 2001 (modified)]



LEO-LEO Radio Occultation

- exploits absorption & refraction of X/K-band signals along limb paths
- providing **<u>self-calibrated</u>** measurements of attenuation and Doppler
- leading via absorption, bending angle, and (complex) refractivity
- to key atmosphere and climate parameters such as temperature *T*, humidity *q*, and geopotential height.

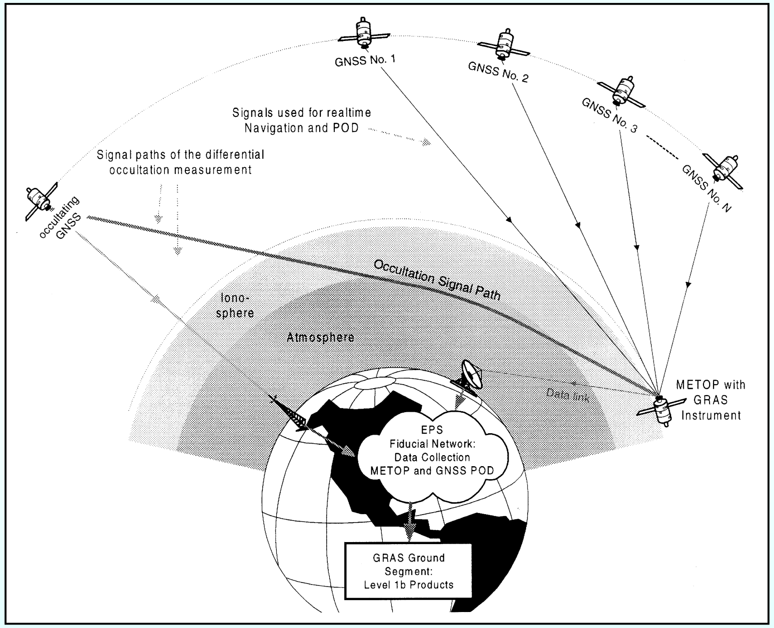
Inversion of LEO-LEO Occultation Data

- similar to GNSS-LEO but providing *T* and *q* independently; also solved by
- direct inversion/retrieval or
- data assimilation.

RO – Climate Change Monitoring Promise
close friends of radio occultation

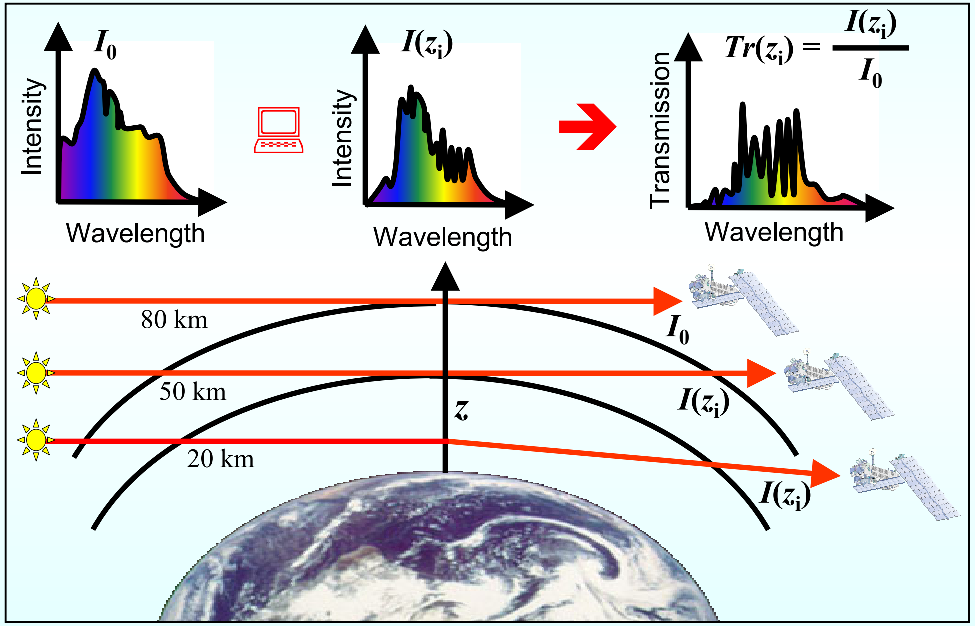
Close friends of GNSS- and LEO-LEO occultation are Stellar and Solar/Lunar Occultation

GNSS-LEO occultation exploits refraction of radio signals along limb paths



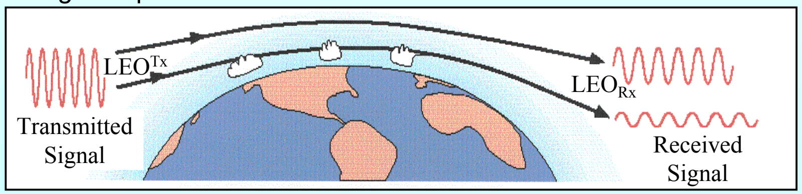
(Source: Dornier Satellite Systems, Friedrichshafen, Germany, 1998)

Stellar and Solar/Lunar occultation exploit extinction of optical signals along limb paths



(Source: C. Zehner, ESA/ESRIN, Frascati, Italy, 2001; adapted)

LEO-LEO occultation exploits extinction & refraction of MW signals along limb paths



(Source: D. Feng et al., Inst. of Physics/Univ. of Arizona, U.S.A., 2001; adapted)

- Each of these complementary methods exploits the unique properties of the occultation principle.
- Each of them addresses a different height range/ different parameters with optimal sensitivity.

RO – Climate Change Monitoring Promise

relevance for climate monitoring and research

...from the 9 ***"high priority areas for action"*** *noted in the recent* ***IPCC 2001 report***
(Summary for Policymakers, IPCC Working Group I, page 17):

"- ***sustain and expand the observational foundation for climate studies by providing accurate, long-term, consistent data*** *including implementation of a strategy for integrated global observations."*

Such **accurate, long-term, consistent data** on the thermal (*T*), moisture (*q*), and geopotential height (*Z*) structure of the troposphere and stratosphere **can be furnished by** a constellation of 4 – 24 micro-satellites carrying

- **GNSS- and LEO-LEO radio occultation sensors**
  (CHAMP, GRACE, COSMIC/BJ-GPS, METOP/GRAS, ACE+/AGRAS&CALLS,...)

These **occultation sensors deliver** an unique combination of

- global coverage (equal observation density above oceans as above land)
- all-weather capability (virtual insensitivity to clouds and aerosols; wavelengths > 1 cm)
- high accuracy and vertical resolution (e.g., T < 1 K, q < 5% at ~1 km resolution)
- **long-term stability due to intrinsic self-calibration** (drifts < 0.1 K, < 2%r.h. / decade)

Climate Change Monitoring by Radio Occultation

Climate Monitoring Simulation Study

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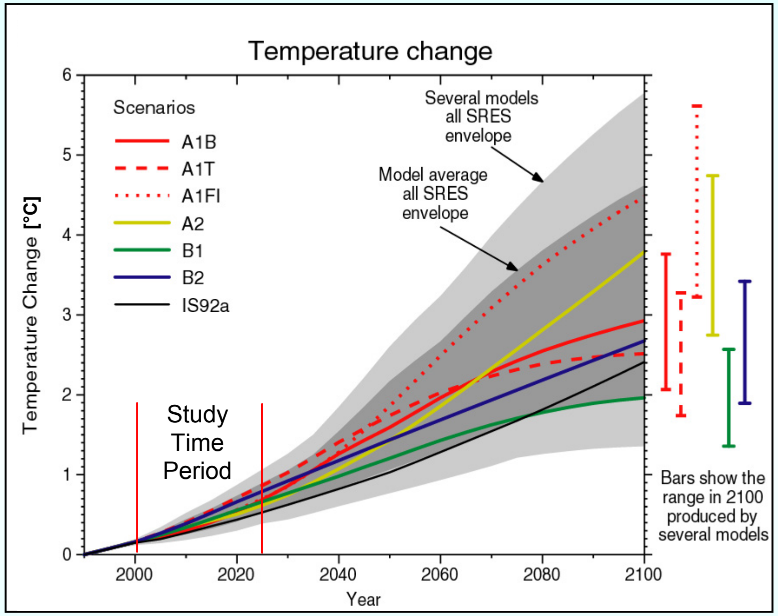
Climate Monitoring Simulation Study

a climate observing system simulation experiment

Surface temperature change according to IPCC 2001 scenarios



(Source: IPCC WG I Report, 2001; adapted)

In General: Perform a rigorous quantitative evaluation of the promise GNSS radio occultation is perceived to hold for climate change monitoring.

In Particular: Test the capability of a small GNSS occultation observing system for detecting anthropogenically influenced temperature trends within the coming two decades.

Methodology: Given the lack of adequate real data, perform a realistic end-to-end climate observing system simulation experiment over a sufficient period of time.

Spin-off: Set up all necessary elements of a climate monitoring system, which can later generate high-quality temperature and geopotential height climatologies also based on real data (foreseen to be started based on the CHAMP/GPS data flow).

Climate Monitoring Simulation Study
study design

For the summer seasons (JJA) during 2001 to 2025 perform

- Realistic modeling of the neutral atmosphere and ionosphere.
- Realistic simulations of observables for a small constellation of GNSS occultation sensors (6 satellites, 5x5yrs COSMIC|ACE+ type mission).
- State-of-the-art data processing for temperature profiles retrieval in the troposphere and stratosphere to establish a set of realistic simulated temperature measurements.
- An objective statistical analysis of temporal trends in the “measured” states from the simulated temperature measurements (and the “true” states from the modeling, for reference).
- An assessment of how well a GNSS occultation observing system is able to detect climatic trends in the atmosphere over the coming two decades.

Testbed for setup of tools and performance analysis: JJA 1997

Climate Monitoring Simulation Study

main simulation tool: EGOPS

The End-to-end GNSS Occultation Performance Simulator version 4 (EGOPS4)

Overview, Exemplary Applications, and Future Avenues

G. Kirchengast[1], W. Poetzi[1], J. Ramsauer[1], J. Fritzer[1], A.K. Steiner[1], P. Silvestrin[2], S. Syndergaard[3,5], M. Gorbunov[4], G.B. Larsen[5], K. Schultz[6], L. Kornblueh[7], H. Reichinger[8], S. Healy[9] (plus several others in the Institutions involved)

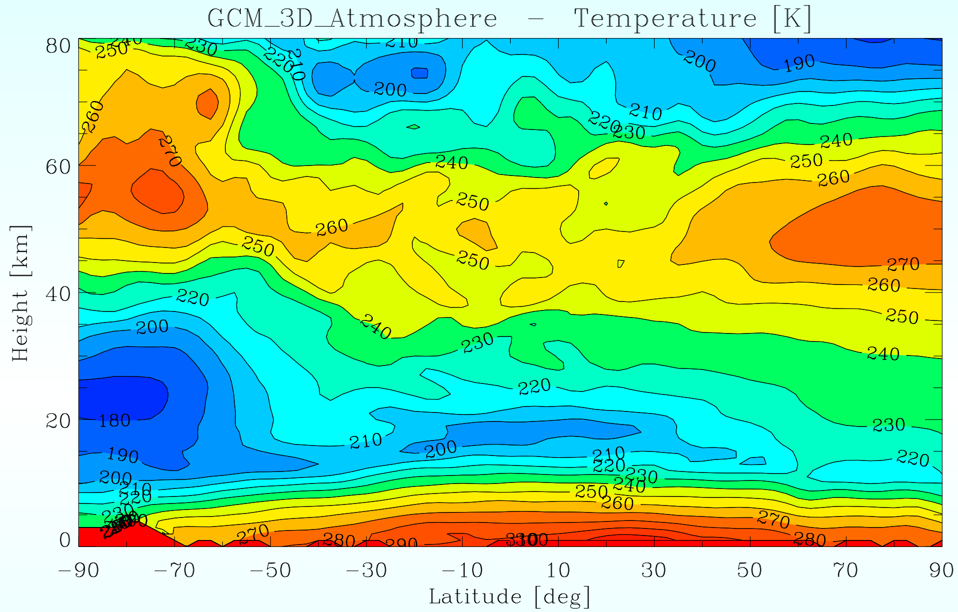
[1] ARSCliSys Research Group, IGAM/UG Graz, Austria
(Point of contact: gottfried.kirchengast@uni-graz.at)
[2] ESA/ESTEC (APP-FPP), Noordwijk, Netherlands
[3] Inst. of Atmospheric Physics, Tucson/AZ, U.S.A.
[4] Inst. of Atmospheric Physics, Moscow, Russia
[5] Danish Met. Institute, Copenhagen, Denmark
[6] TERMA Elektronik A/S, Birkerød, Denmark
[7] MPI for Meteorology, Hamburg, Germany
[8] Austrian Aerospace, Vienna, Austria
[9] The Met. Office, Bracknell, U.K.

Thanks to...

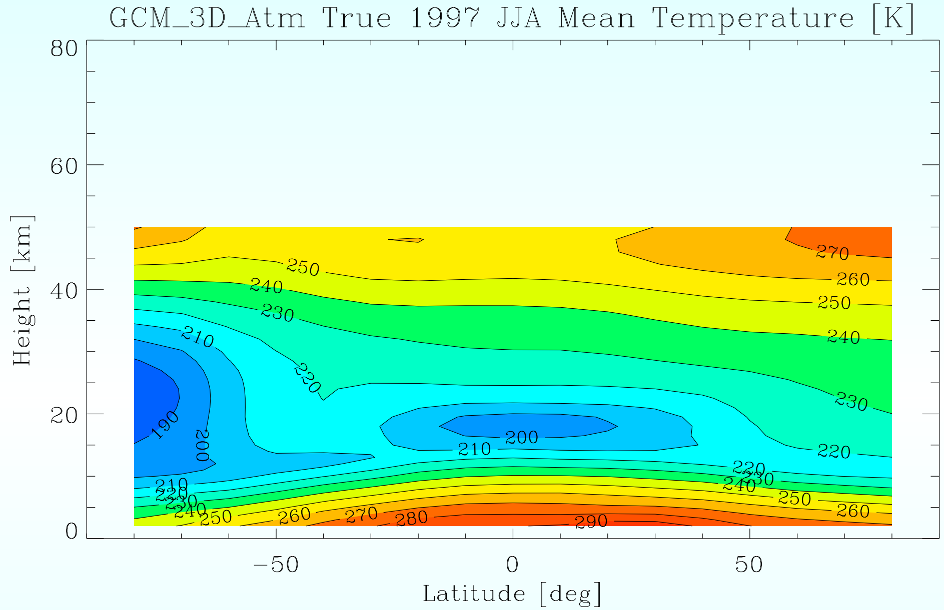
more infos on EGOPS:
www.uni-graz.at/igam-iemc

EGOPS was developed with financial support by the European Space Agency (ESA)

Climate Monitoring Simulation Study
atmosphere modeling



Date: July 15, 1997; UT: 1200 [hhmm]; SliceFixDim=Lon: 0.0 [deg]

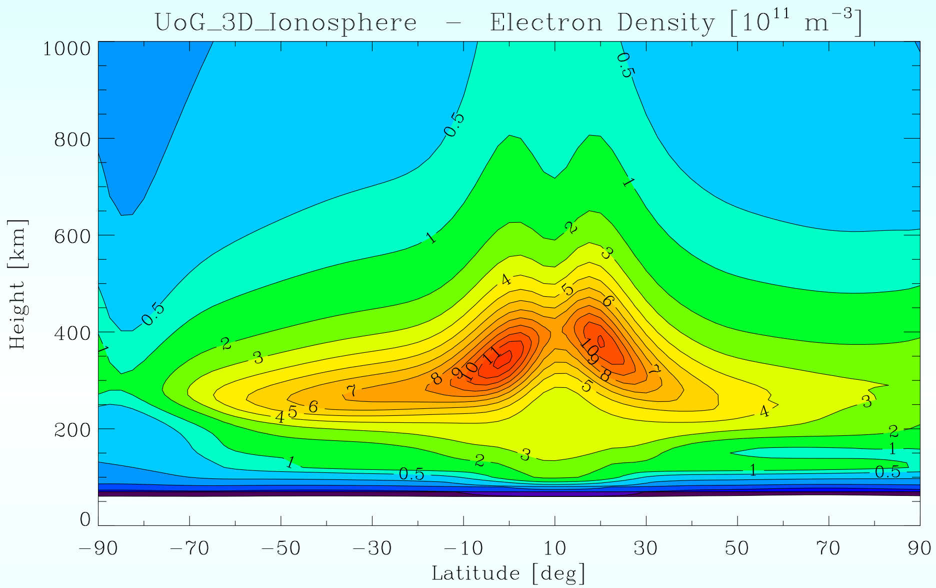


Mean *T* field in selected domain: “True” JJA 1997 average temperature

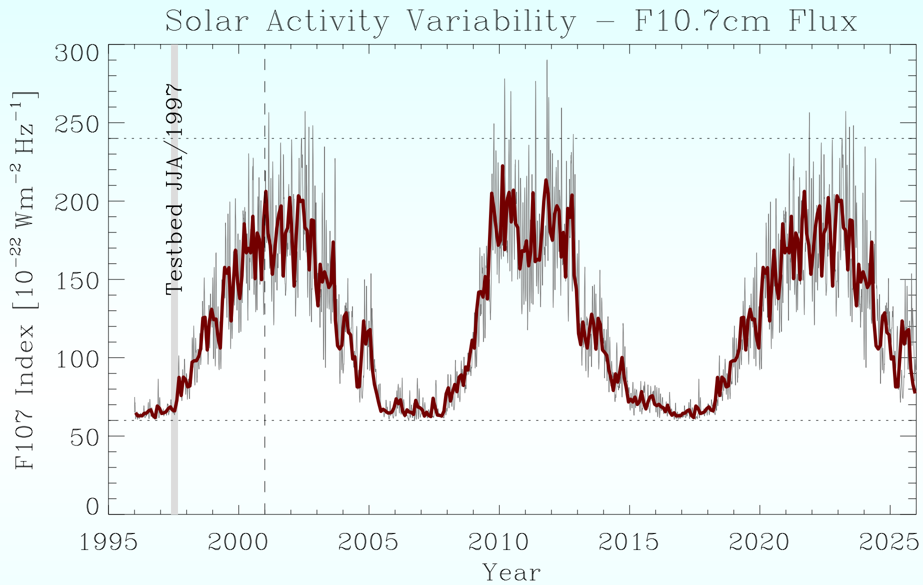
Atmosphere model: ECHAM5-MA (MPIM Hamburg)
Model resolution: T42L39 (up to 0.01hPa/~80km)
Model mode: Atmosphere-only (monthly mean SSTs)
Model runs: 1 run with transient GHGs+Aerosols+O_3
1 control run (natural forcing only)

Change monitoring: In JJA seasonal average *T* fields as they evolve from 2001 to 2025
Domain: 17 latitude bins of 10 deg width
34 height levels from 2 km to 50 km
vertical resolution 1 – 2 km
core region 8 km to 40 km

Climate Monitoring Simulation Study
ionosphere modeling



Month: July; UT: 1200 [hhmm]; SAc/F107: 120; SliceFixDim=Lon: 0.0 [deg]

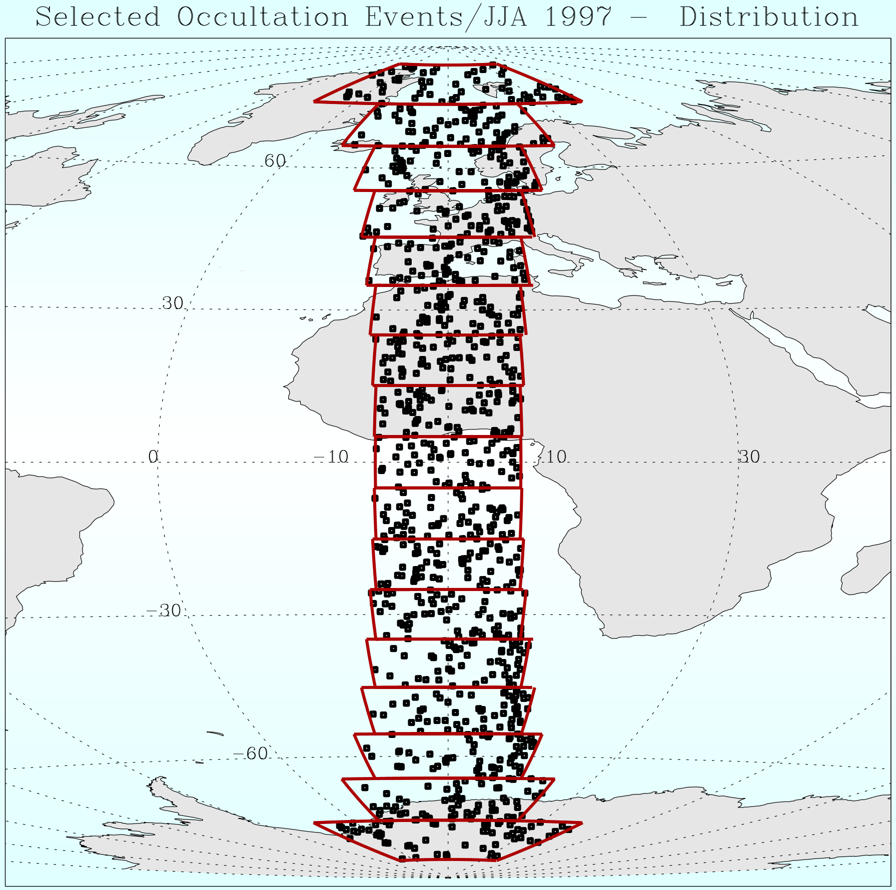


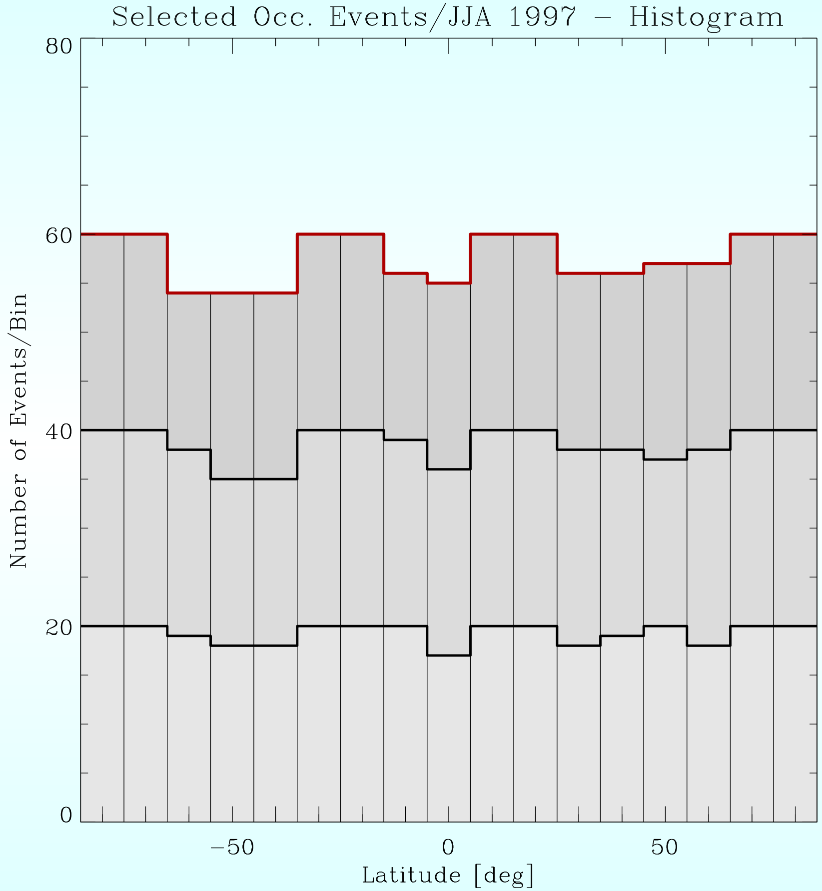
Solar activity 1996-2025: day-to-day F107 values and monthly mean values

Ionosphere model: NeUoG model (IGAM/UG)
Model type: Empirical 3D, time-dependent, sol.activity-dependent model
Mode: Driven by day-to-day sol.act. variability (incl. 11-yrs solar cycle, etc.)

Solar activity prescription: Representative day-to-day F107 values (weekly history averages)
Future F107 data (2001-2025): from past data of solar cycles 21, 22, and 23 (1979-1999)

Climate Monitoring Simulation Study
observation simulations – spatial sampling



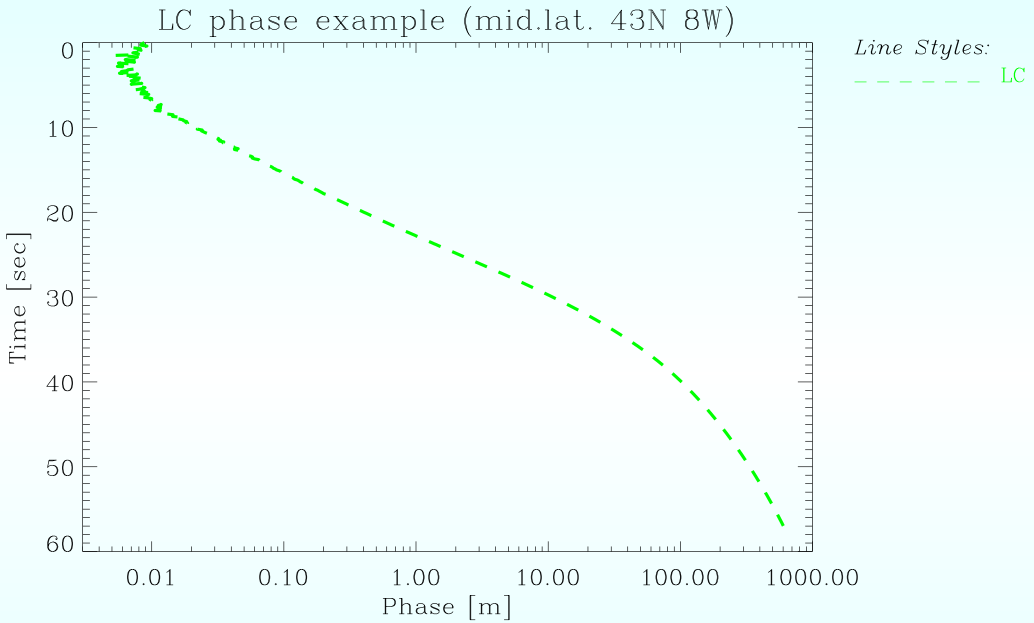


Sampling into 17 equal area latitude Bins
- 85°S to 85°N (10°lat x 15°lon at equator)
- No. of occultation events > 50 per Bin for each JJA season (max. 60/Bin)

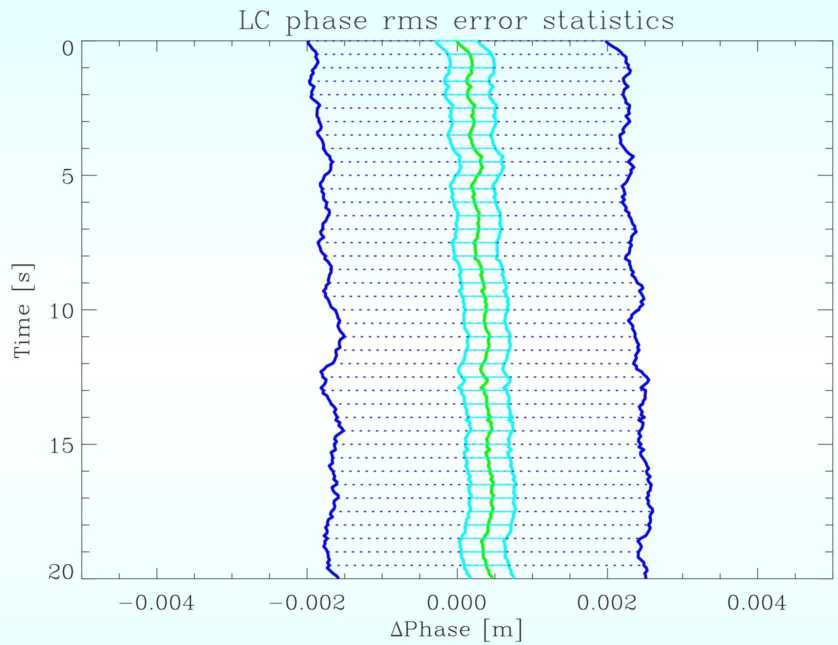
No. of occultation events per Bin and month
- light gray: June events only
- light&medium gray: June+July events
- light&medium&dark gray: June+July+August

Climate Monitoring Simulation Study

observation simulations – simulated observables



Occ–No Occ.Date&Time (UT) OccEType LEO–Id GNSS–Id
49 97 06 05/156 13:00 SETTING ACEsat hilc1/A1 GLO/1–03/FC21
Sampling Rates: 10.0 Hz/L1, 10.0 Hz/L2
File/Id: GCtst/FoMod/F199706_0100–1024_0049.ssd



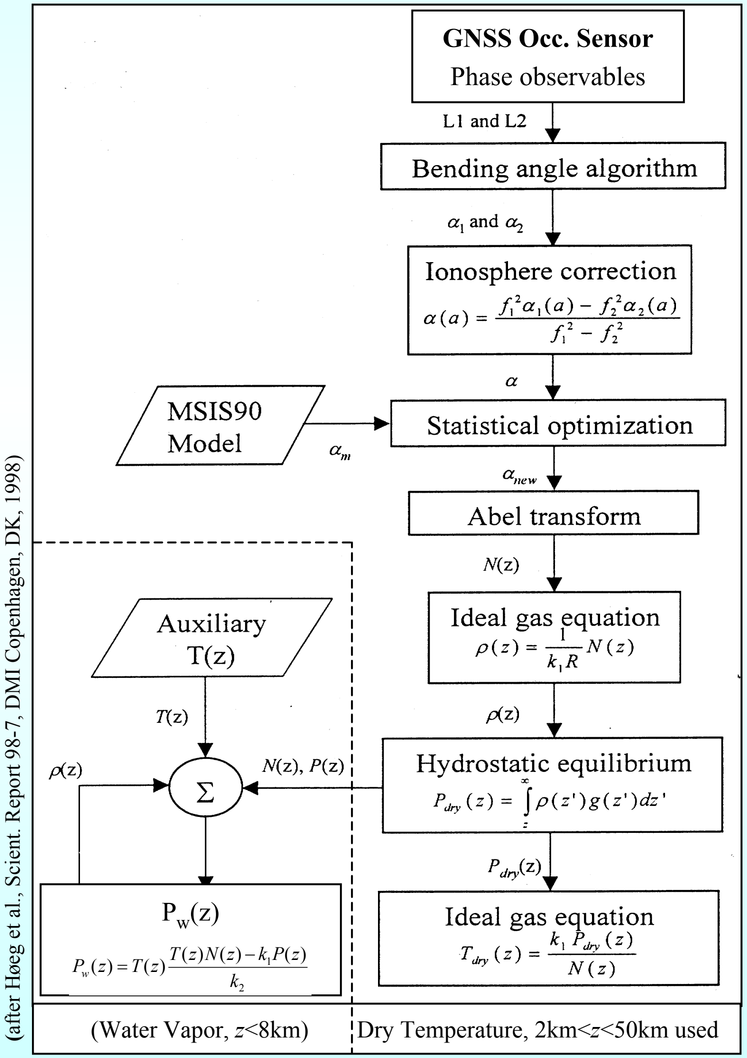
Occ.Date: 199706_0100–1024 OccNoRange: 1 to 99 step 2, 50 events.

Simulated observables are phase path delays/Doppler shifts and amplitudes

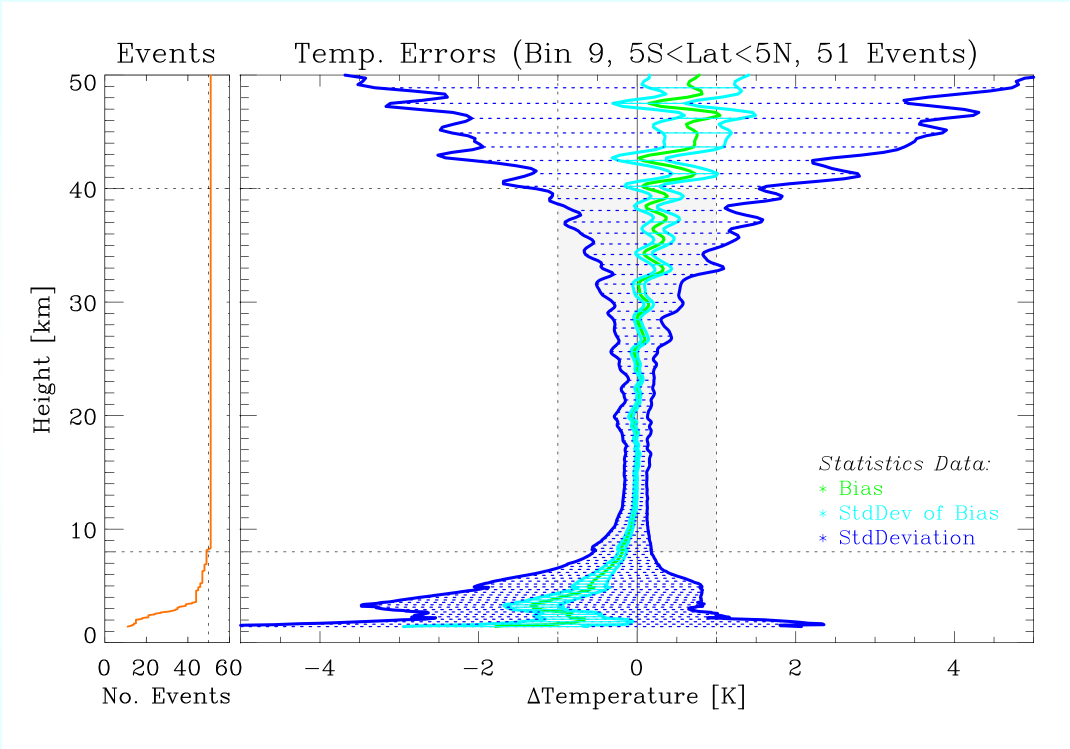
- Path delays for the GNSS carrier signals in L band: L1 (~1.6 GHz), L2 (~1.2 GHz)
- Atmospheric path delay (after correction for ionosphere): LC *(illustrated above)*
- LC phase rms error statistics realistically reflect GRAS-type performance

Climate Monitoring Simulation Study
data processing – temperature profiles retrieval

Retrieval scheme



Typical example of *T* profile errors (~50 events)



Retrieval of 50-60 $T_{dry\ air}$ profiles per latitude Bin

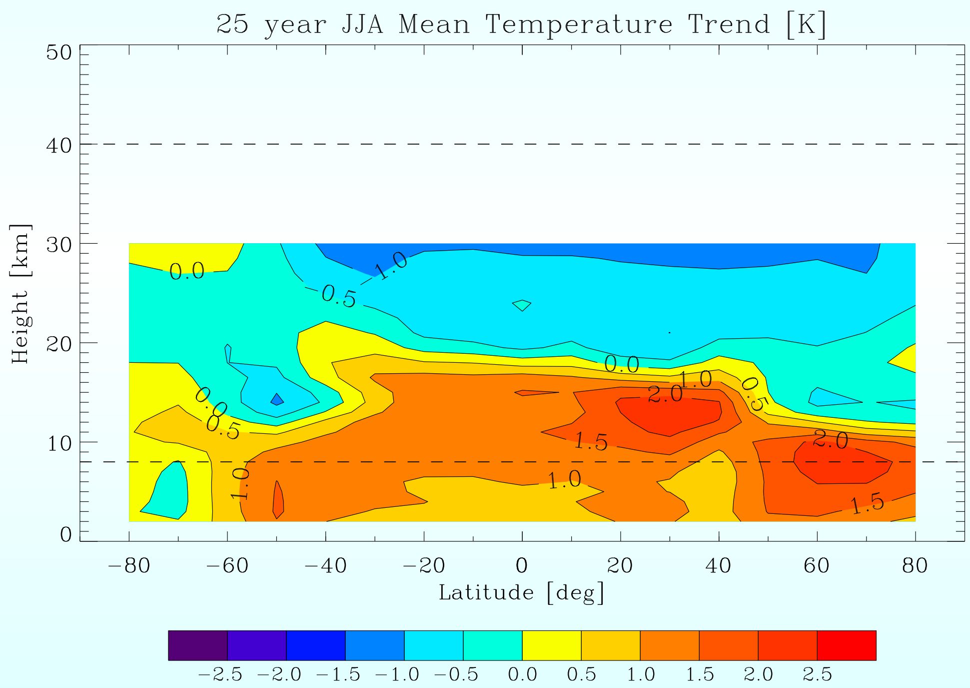
– Temperature errors < 0.5 K within upper troposphere and lower stratosphere for individual *T* profiles

– Errors in T_{Av} for ~50 events < 0.2 K (8 km < *z* < 30 km)

Climate Monitoring Simulation Study

analysis and detection of temperature trends

Exemplary simulated temperature trends over the time period used (2001–2025)



Computed for the selected Bins based on the *T* fields of the ECHAM4 T42L19 experiment *GSDIO* (Roeckner et al., J. Climate, 12, 3004-3032, 1999)

Objective statistical analysis scheme

– Temperature trends estimation (using $T_{JJA\ Av}$)

– Time period 2001 to 2025

– Latitude x height slices (17 x 34 matrix)

– Weighted least-squares analysis approach (time-evolution analysis):

Fit design model $T_t = A_{ti} x_i + e_t$

Best fit model $\mathbf{x}_{fit} = \mathbf{S}_{fit} \mathbf{A}^T \mathbf{S}_e^{-1} \mathbf{T}$

$$\mathbf{S}_{fit} = (\mathbf{A}^T \mathbf{S}_e^{-1} \mathbf{A})^{-1}$$

Detection tests on temperature trends

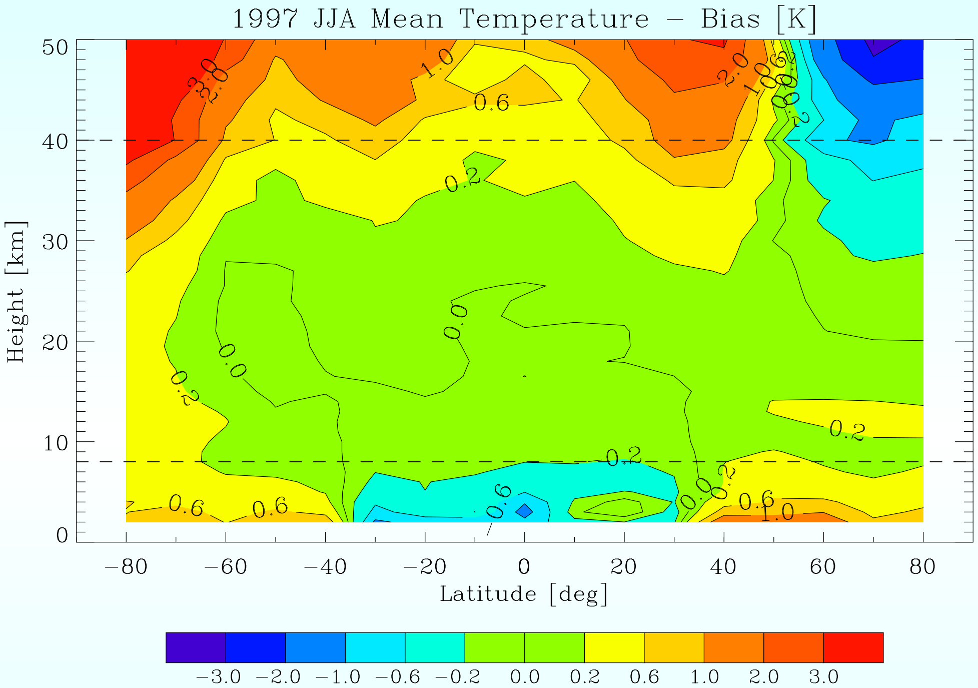
– in the model run with transient forcings

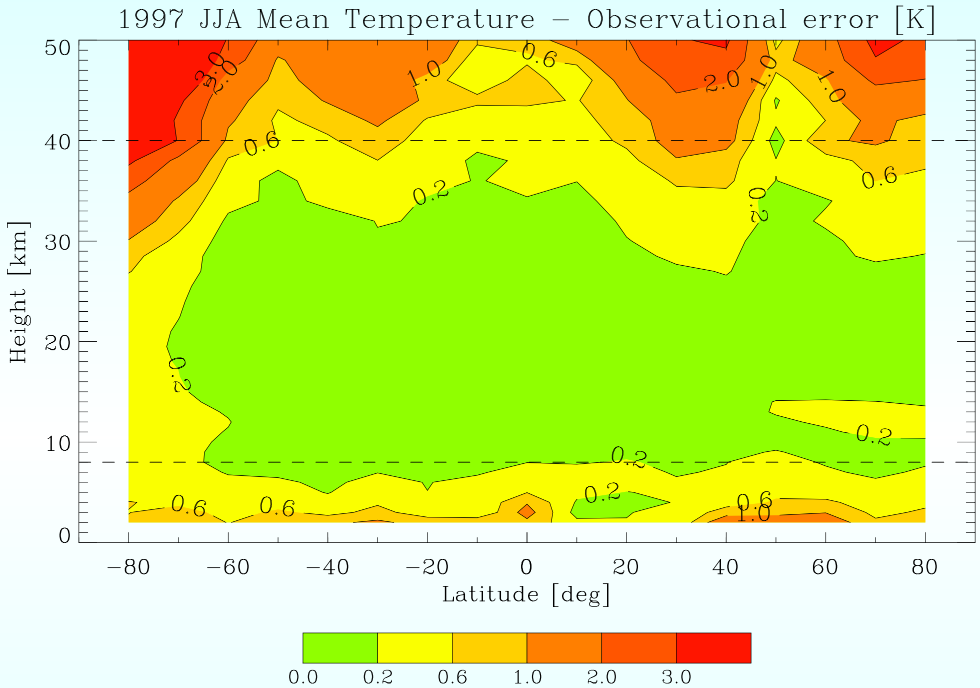
– in the control run for comparison

– relative to estimated natural variability

Climate Monitoring Simulation Study

results of performance analysis: observational error





Bias error in temperature climatology

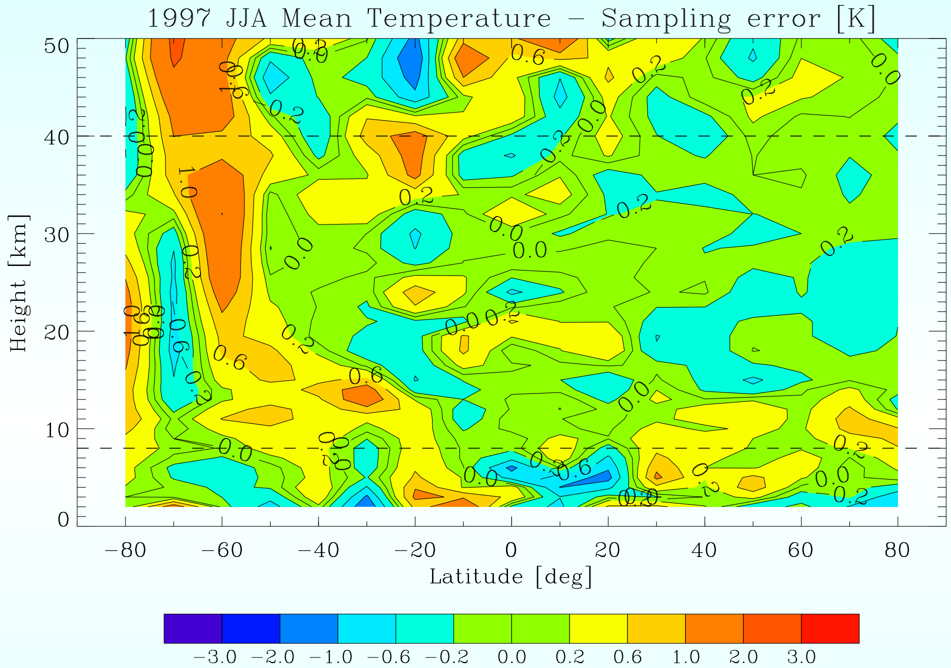
$$\Delta T_{ij}^{bias} = Interp_i\left[\frac{1}{N_i}\sum\left(\Delta T_j^{retr} - \Delta T_j^{true}\right)\right]$$

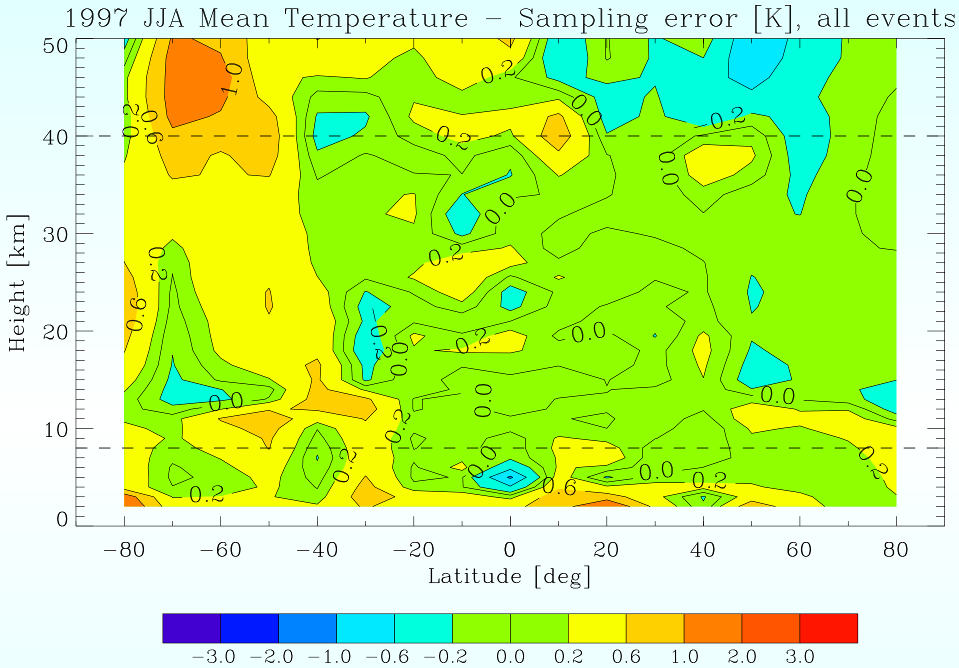
Total observational error (rms of bias error)

$$\Delta T_{ij}^{obs} = \left[\left(\Delta T_{ij}^{bias}\right)^2 + \left(\frac{\Delta T_{ij}^{stddev}}{\sqrt{N}}\right)^2\right]^{\frac{1}{2}}$$

Climate Monitoring Simulation Study

results of performance analysis: sampling error





Sampling error for the selected events

– Difference between the “sampled” JJA average *T* field (from the “true” *T* profiles at the event locations) and the “true” one

– ~55 selected events per Bin (total ~1000)

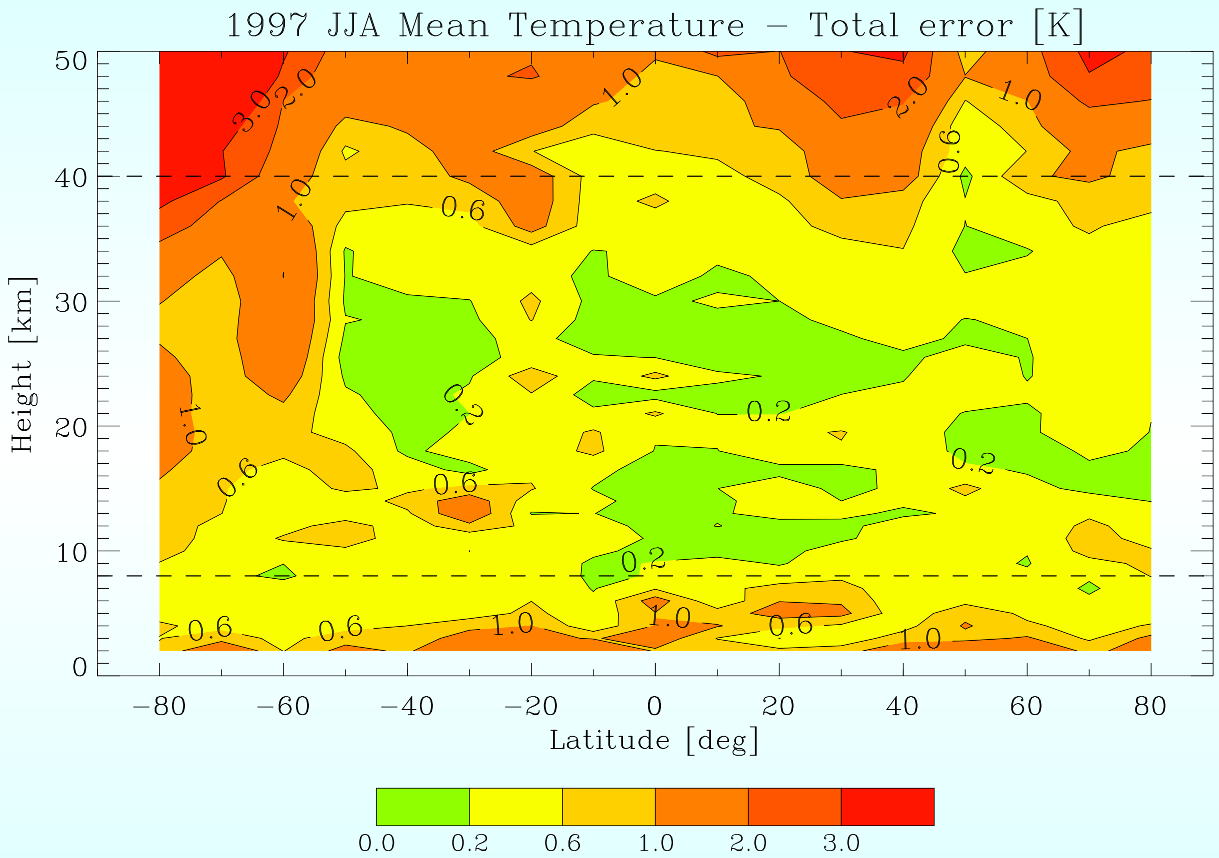
Sampling error if all events used

– Difference “sampled”-minus-“true” JJA average *T* field using all occultation events available in the Bins

– ~750 events per Bin (~13000 in total)

Climate Monitoring Simulation Study

results of performance analysis: total climatological error



Total climatological error (observational plus sampling error)

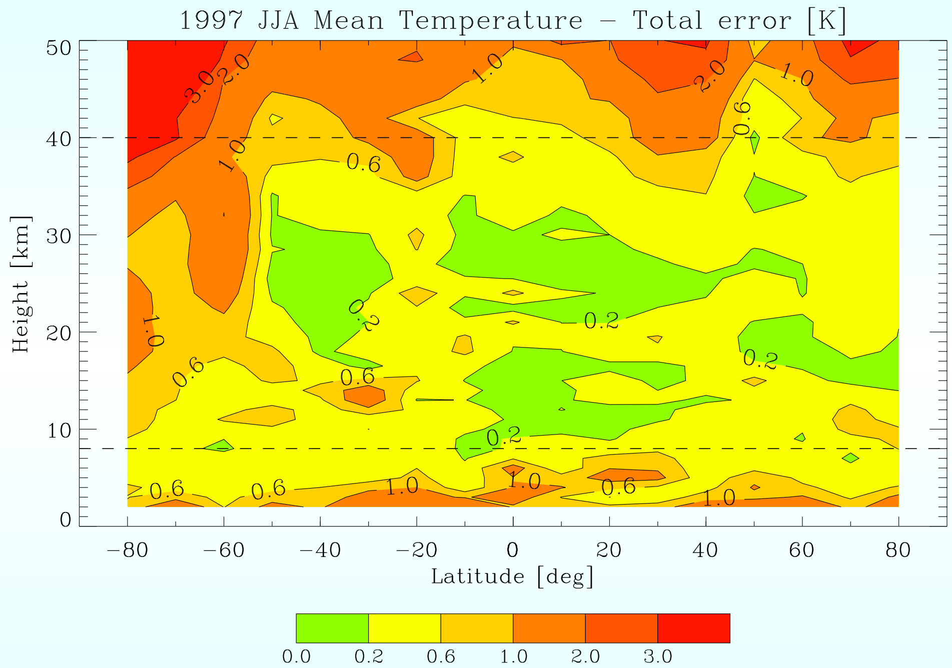
$$\Delta T_{ij}^{total} = \left[\left(\Delta T_{ij}^{obs} \right)^2 + \left(\Delta T_{ij}^{sam} \right)^2 \right]^{\frac{1}{2}}$$

Climate Monitoring Simulation Study

perspectives for the full experiment (2001-2025)

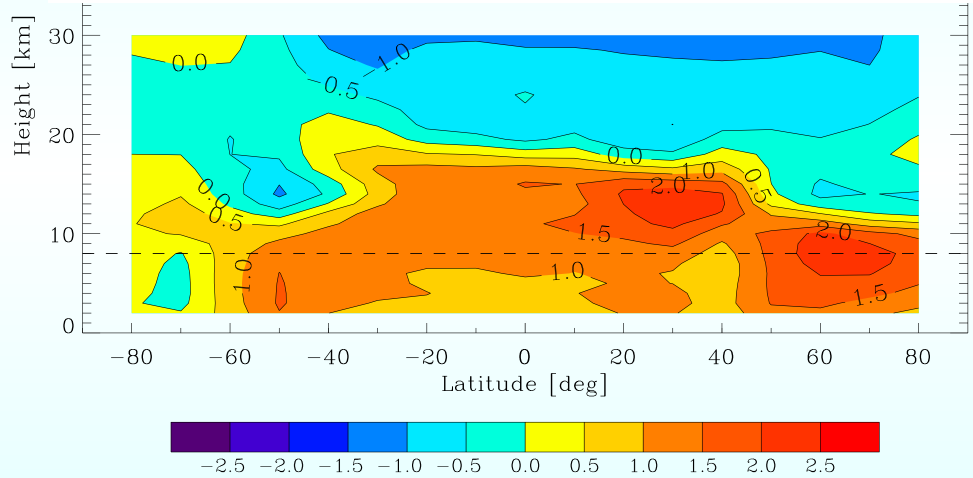
Arbitrary but reasonable GNSS occultation based temperature error field realization for a single JJA season

(atmospheric evolution based on ECHAM4-MA T42L39 Testbed experiment)



Arbitrary but reasonable JJA season temperature trend field realization for the period 2001–2025

(climate evolution based on long-term ECHAM4 T42L19 GSDIO experiment including transient anthropogenic forcings due to greenhouse gases, aerosols, and tropospheric ozone)



- GNSS occultation based JJA *T* errors are expected to be < 0.5 K in most of the core region (8–40 km) northward of 50°S.
- 2001–2025 JJA *T* trends are expected to be > 0.5 K per 25 yrs in most of the core region northward of 50°S.

↙ Significant trends (95% level) expected to be detectable within 20 yrs in most of the core region

↙ Aspects to be more clearly seen in the long-term: ionospheric residual errors, sampling errors, performance southward of 50°S (high-latitude winter region)

Climate Monitoring Simulation Study
intermediate summary, conclusions, and outlook

Summary

- We perform a first rigorous evaluation of how well a small GNSS occultation observing system can detect human induced *T* trends within the coming two decades.
- Study of high interest for planned research & demo missions (e.g., COSMIC, ACE+)

Conclusions

- Encouraging performance found within 8-40 km core region northward of 50°S
- *T* trends expected detectable within next two decades in most of the core region
- High latitude winter areas found most challenging

Outlook

- Full 25 year (2001–2025) experiment scheduled in 2002; climate runs are completed
- Application of the monitoring system to create CHAMP/GPS *T, Z* climatologies
- Closer look into climate change detection & attribution aided by occultation data

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CHAMP, COSMIC, ACE+,... – Current & Future Research

RO-related research aims at IGAM

- **Improved monitoring of climatic changes, both due to natural and anthropogenic influences, in the atmosphere's thermal, moisture, ozone, and geopotential height structure**
  - **Occultation sounding and advanced IR sounding for climate change monitoring (climatologies & analyses) in T, Z, q, O_3**
  - **Use of the sounding data for atmospheric trend and variability studies (seasonal to decadal scales)**
- **Exploitation of climatologies&analyses expected to be climate evolution monitors of unprecedented climatological utility**
  - **Assessment of potential improvements to climate model physics (e.g., in radiation, humidity, and cloud modeling) and forcings (e.g., on volcanic and solar forcing)**
  - **Preparation of climate change detection & attribution schemes using the novel datasets as rigorous observational constraints**

CHAMP, COSMIC, ACE+,... – Current & Future Research
on current RO research

- ***START-ATCHANGE* Programme:**
  - **Advanced Spaceborne Sounding and Climate Modeling for Atmospheric Change Analysis**
  - timeframe 1999–2004 (budget source FWF/BMBWK)
- ***ENVI-ATCHANGE* Programme:**
  - **Atmospheric Change Analysis based on Spaceborne *T*, *q*, O_3 Sounding Involving GOMOS, MIPAS and GNSS Limb Sensors**
  - timeframe 2000–2005 (budget source ASA/BMVIT)
- ***ESA-R&D* Programme:**
  - **End-to-end Occultation System Performance Simulation and Advancement of Data Processing Methodology & Algorithms**
  - timeframe ≥1996 (budget source ESTEC/ESA)

CHAMP, COSMIC, ACE+,... – Current & Future Research
on initialized future RO research

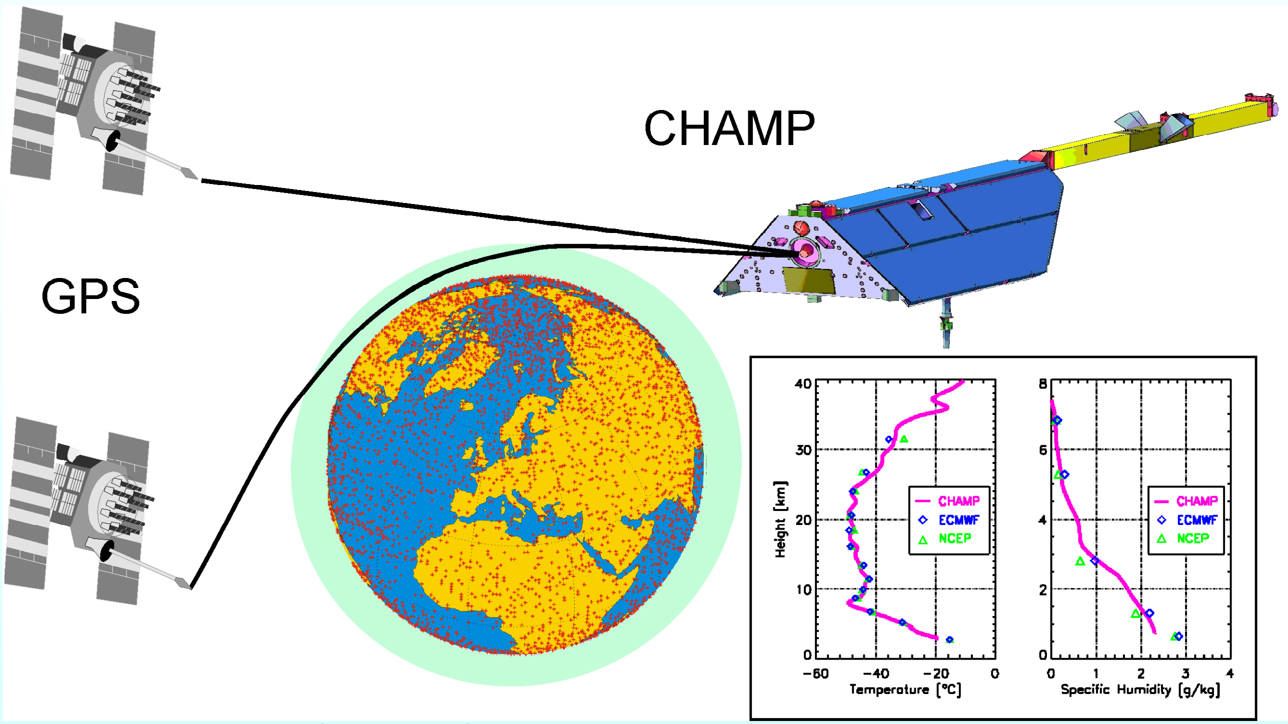
- ***ECCMAR Programme:***
  - **European Center for Climate Monitoring, Analysis, and Research – research and user services on key global climate datasets**
  - timeframe ≥2002 (IGAM budget ≥2004: EU&Nat.)
  - *Seed Project:* CHAMPCLIM – climate monitoring based on CHAMP/GPS
    - timeframe 2002–2004 (budget: ASA/BMVIT "seed money")

- ***ESA-ACE+ Programme:***
  - **ACE+ – Atmosphere and Climate Explorer**
    Based on GPS, GALILEO, and LEO-LEO Radio Occultation
    (ESA Earth Explorer Opportunity Mission)
  - timeframe 2002–2012 (launch: 2007/08), mission cost ~115 MEUR, (IGAM budget ≥2003: ESA&EU)
  - *Seed Project:* ACEPASS – ACE+ phase A science study (on LEO-LEO)
    - timeframe 2002–2003 (budget: ESA "seed money")

CHAMP, COSMIC, ACE+,... – Current & Future Research
ECCMAR seed project CHAMPCLIM (1)

CHAMPCLIM – Radio Occultation Data Analysis Advancement and Climate Change Monitoring Based on the CHAMP/GPS Experiment

Main partners: IGAM/University of Graz and Division 1/GFZ Potsdam; cooperation also with: MPIM Hamburg, IAP Moscow, IAP/U.o.Arizona Tucson, SA/CNRS Verrieres-le-Buisson

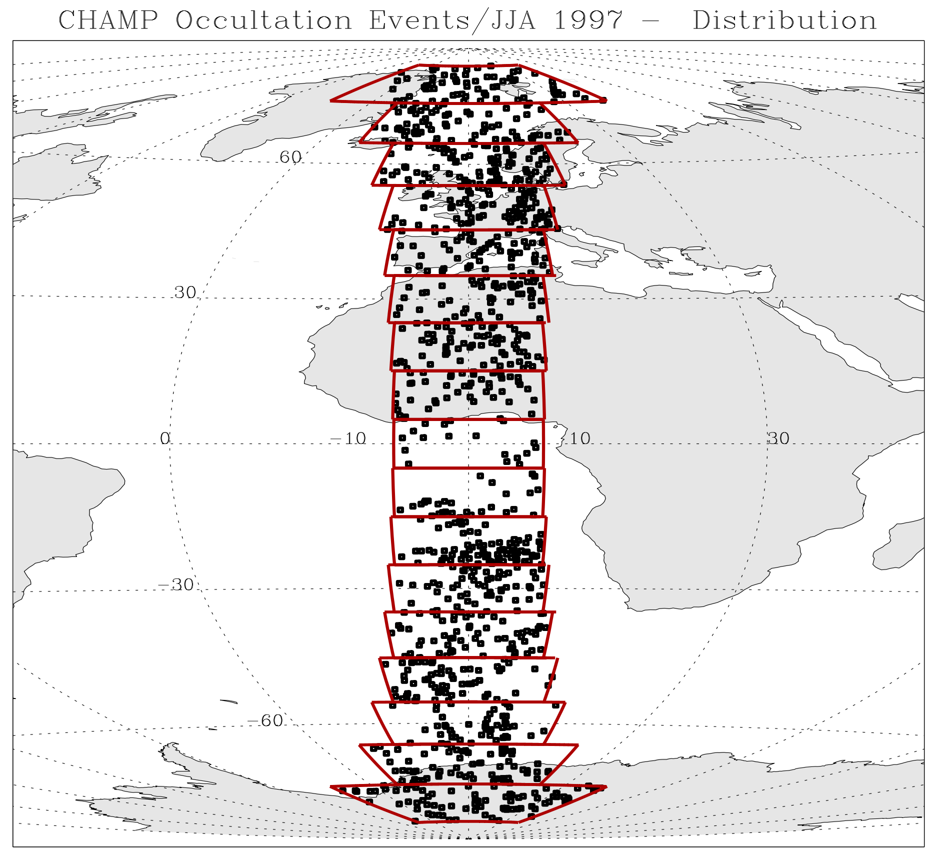


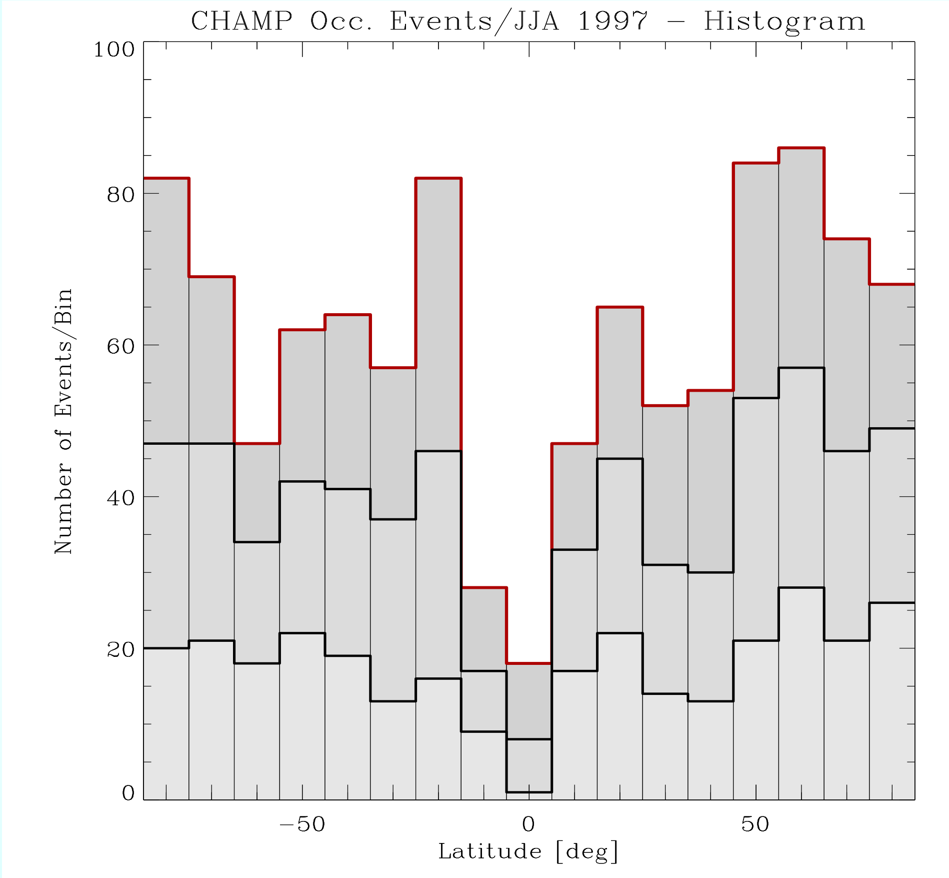
[Figure prepared by: J. Wickert, GFZ Potsdam, Germany, 2002]

Main Scientific Objectives:

- RO data and algorithms validation based on CHAMP/GPS data
- RO data processing advancements for optimizing the climate utility of the data
- Global RO based climatologies for monitoring climate variability and change

CHAMP, COSMIC, ACE+,... – Current & Future Research
ECCMAR seed project CHAMPCLIM (2)

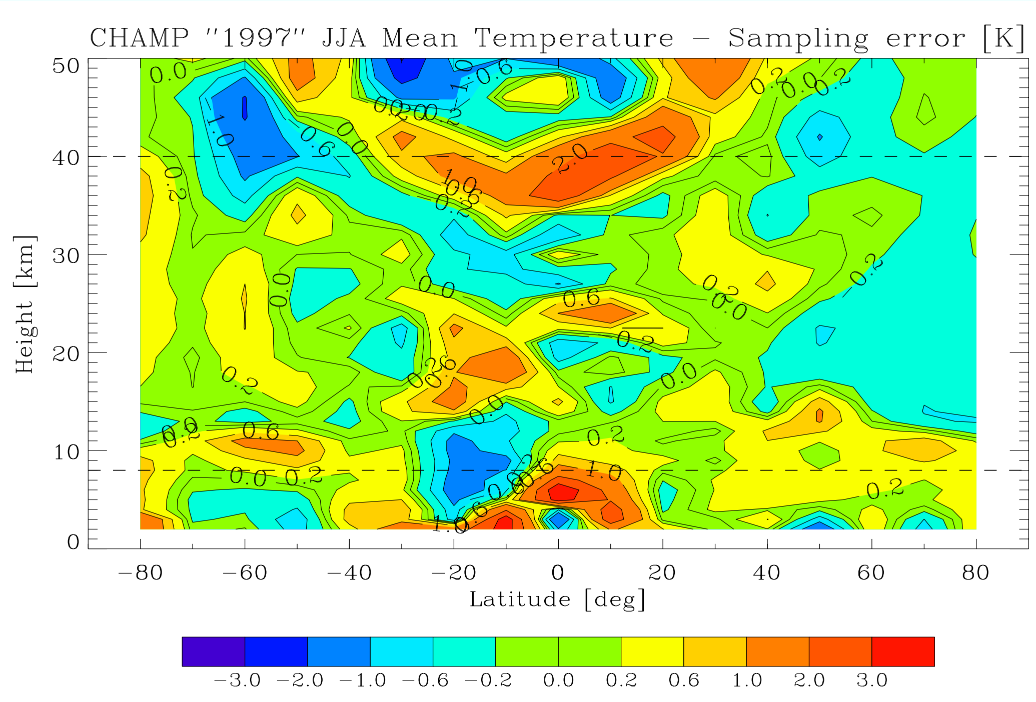


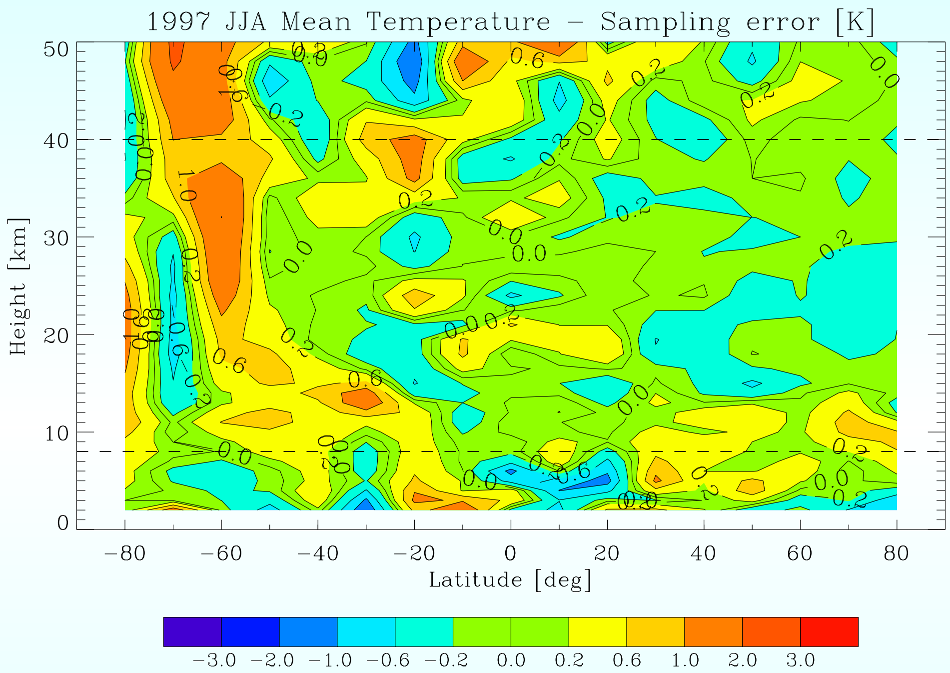


Sampling into 17 equal area latitude Bins
- About 61 per Bin on average, 1039 in total
- 18 events in equator Bin (only 1 in June), 86 events in the 60°N-Bin

No. of occultation events per Bin and month
- light gray: June events only
- light&medium gray: June+July events
- light&medium&dark gray: June+July+August

CHAMP, COSMIC, ACE+,... – Current & Future Research
ECCMAR seed project CHAMPCLIM (3)





Sampling error - all CHAMP/GPS events

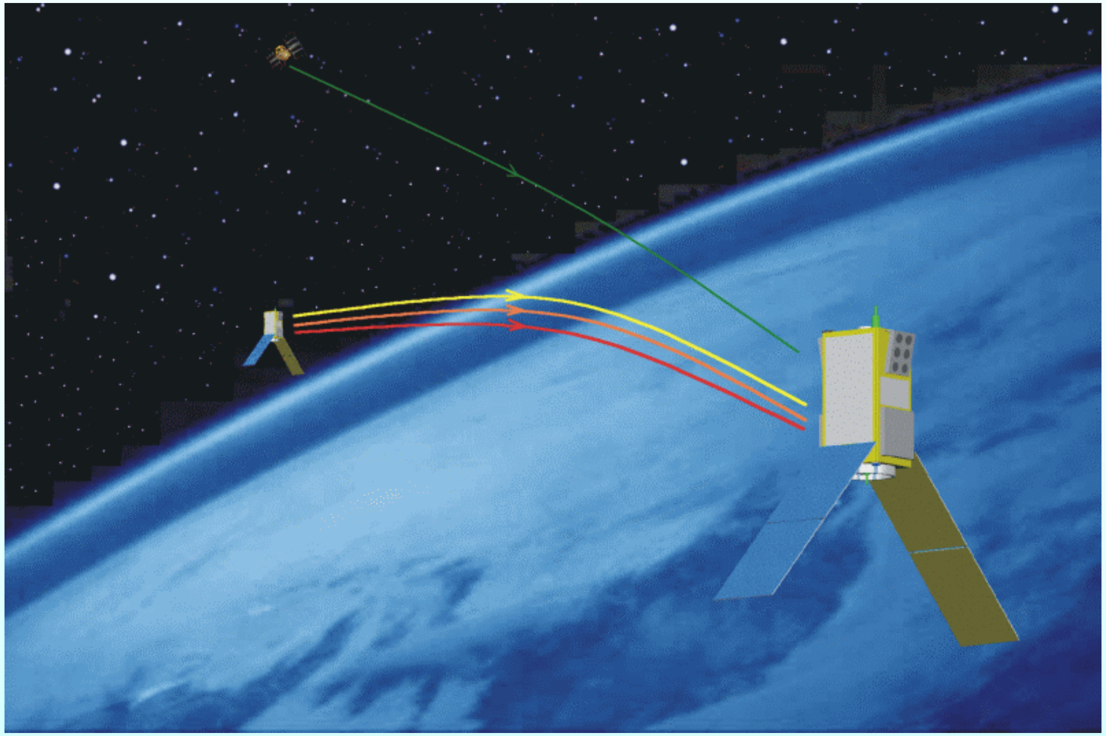
- Difference between the “true” JJA average *T* field and the “sampled”one using all CHAMP/GPS occultation events
- ~60 events per Bin on average (1039 in total)

Sampling error - simul.study selected events

- Difference between the “sampled” JJA average *T* field (from the “true” *T* profiles at the event locations) and the “true” one
- ~55 selected events per Bin (total ~1000)

CHAMP, COSMIC, ACE+,... – Current & Future Research
ACE+ atmosphere and climate mission

ACE+ – Atmosphere and Climate Explorer based on GPS, GALILEO, and LEO-LEO radio occultation
ESA Mission, Science: Lead Investigators P. Hoeg and G. Kirchengast, Mission Advisory Group (appointed by ESA), International Science Team (partners worldwide)



Basic Facts:

- selected by ESA in May 2002 as top priority future Earth Explorer Opportunity Mission
- 4 LEO satellites exploiting GPS, GALILEO, and LEO-crosslink signals
- ~5000 GNSS-LEO events/day, ~230 LEO-LEO events/day
- phase A 2003, after confirmation end 2003 phases B-D until 2007, operations 2007/08-2012

ACE+ mission: primary mission goals

ACE+ primary goals focus on climate and include:

- To monitor climatic variations and trends at different vertical levels and throughout all seasons. This to improve our understanding of the climate system as well as to detect the different fingerprints of global warming.
- To improve the understanding of climatic feedbacks defining the magnitude and characteristics of climate changes in response to given forcings.
- To validate the simulated mean climate and its variability in global climate models.
- To improve and tune – via data assimilation – the parameterization of unresolved processes in climate models and to detect variations in external forcing of climate.

CHAMP, COSMIC, ACE+,... – Current & Future Research

ACE+ mission: scientific objectives

Main Objectives:

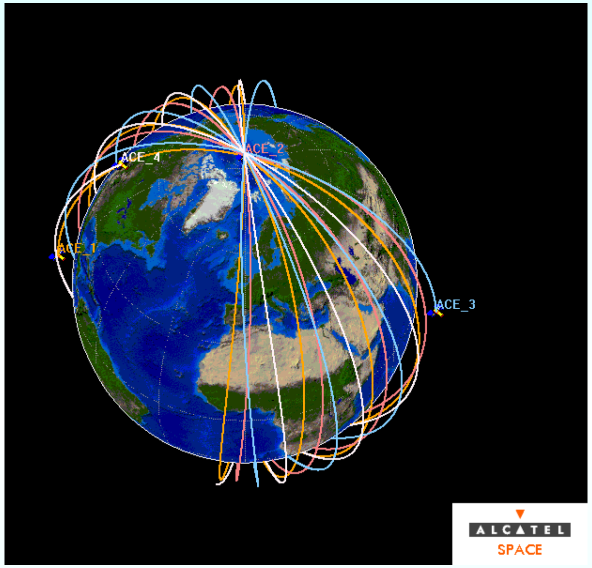
- To establish a highly accurate (< 0.003 g/kg or < 3 %, whatever is larger) and vertically resolved (0.5 km) climatology of humidity in the troposphere with global all-weather measurements of its concentration.
- To establish a highly accurate (< 0.2 K) and vertically resolved (0.5 to 1 km) climatology of temperature in the troposphere and the stratosphere with global all-weather measurements of its vertical structure.
- To support research on climate variability and climate change and on validation and improvement of atmospheric models.
- To support advancements of NWP (Numerical Weather Prediction).
- To support analysis and validation of data from other space missions.
- To demonstrate a novel active self-calibrating atmosphere sounding method.

Spin-Off Objectives:

- Ionospheric climate & weather and space weather investigations.
- Assessing and improving present water vapor attenuation models.

CHAMP, COSMIC, ACE+,... – Current & Future Research

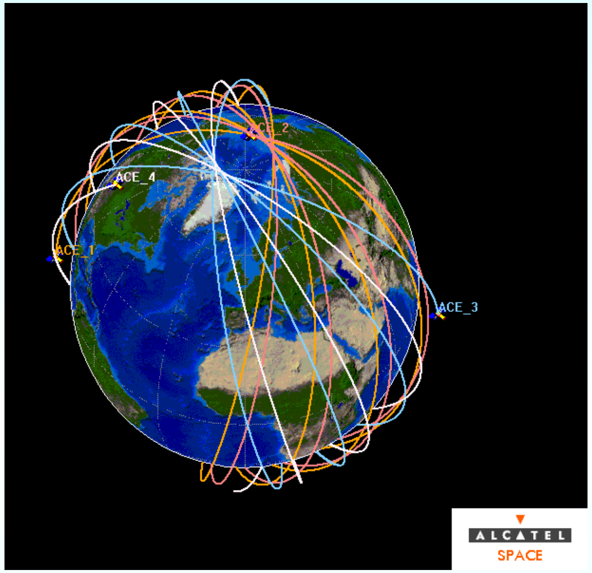
ACE+ mission: constellation concepts



Concept 1:

- 2 orbital planes, counter-rotating sats
- 2 micro-satellites/plane
- polar inclination (i = 90°)
- 2 altitudes (~650 & 850 km)
- antenna FOV: +/– 7° in azimuth

best LEO-LEO performance/link budget



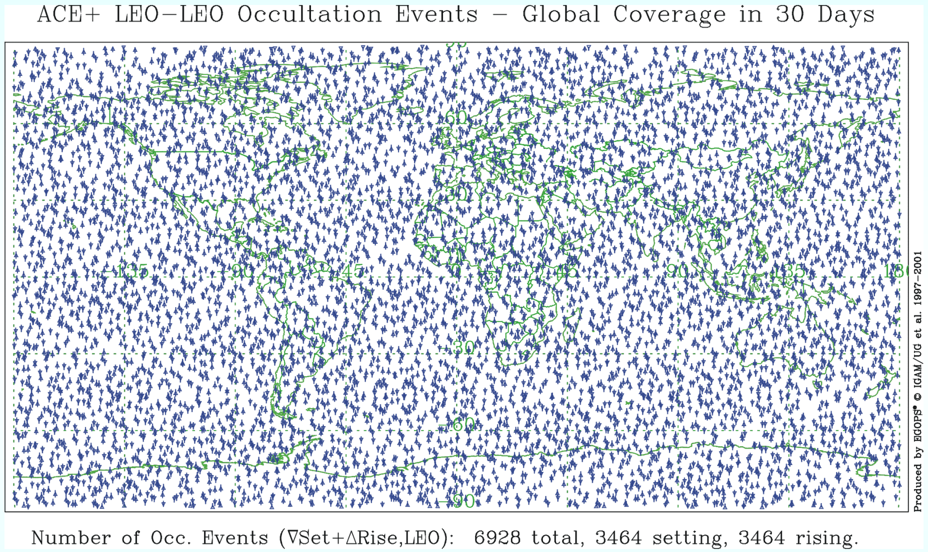
Concept 2:

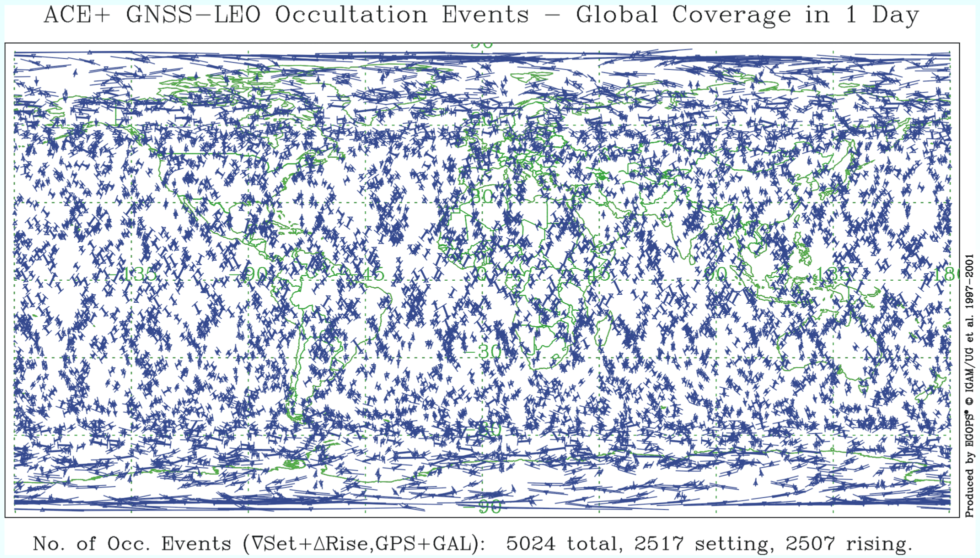
- also 2 orbital planes
- 2 satellites/plane, sun-synchronous (i ~ 98°)
- also opposite nodal crossing (counter-rotating)
- 2 altitudes (~650 & 850 km)
- antenna FOV: +/– 25° in azimuth

may be favorable in terms of cost (due to sun-sync)

CHAMP, COSMIC, ACE+,... – Current & Future Research

ACE+ mission: LEO-LEO and GNSS-LEO coverage





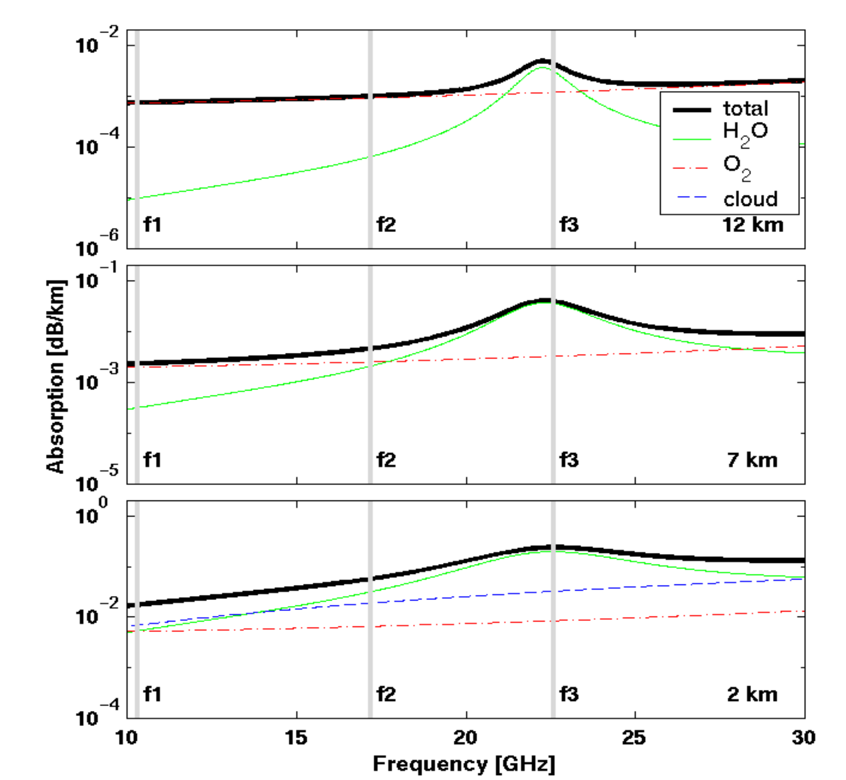
LEO-LEO occultation coverage amounts to ~7000 events/month

GNSS-LEO occultation coverage amounts to ~5000 events/day

(2Rx+2Tx ACE+ polar-orbiting LEO satellites, 54 GNSS satellites; 24 GPS and 30 GALILEO)

CHAMP, COSMIC, ACE+,... – Current & Future Research

ACE+ mission: LEO-LEO observation performance



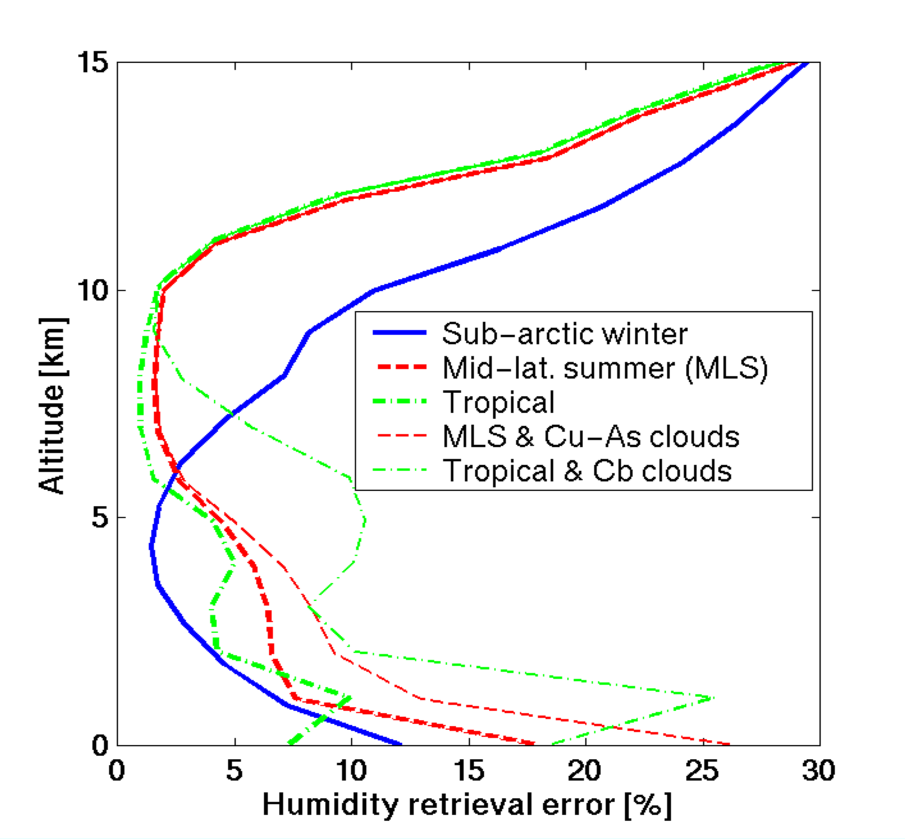


Illustration of absorption properties and humidity retrieval performance for LEO-LEO occultations (realistic sensor errors, moderate cloudiness, no horizontal variability)

- Radio Occultation (RO) – Climate Change Monitoring Promise
  - on the principle of spaceborne occultation measurements
  - RO methods (GNSS-LEO, LEO-LEO) and close friends
  - relevance for climate monitoring and research
- Simulation Studies – Climate Monitoring Simulation 2001-2025
  - a climate GNSS RO observing system simulation experiment
  - results of performance analysis (JJA 1997 “testbed” analysis)
  - perspectives for the full experiment (time period 2001-2025)
- CHAMP, COSMIC, ACE+,… – Current & Future RO Research
  - RO-related research aims at IGAM/Univ. of Graz
  - on current research (START- and ENVI-ATCHANGE, ESA-R&D)
  - on initialized future research (ECCMAR/CHAMPCLIM, ACE+)
- **Concluding Remarks**

Climate Change Monitoring by Radio Occultation
Concluding Remarks (1)

- ➔ A suite of GNSS- and LEO-LEO radio occultation sensors, complemented by stellar and solar occultation sensors, holds potential to become the leading backbone of the GCOS (Global Climate Observing System) for climate change monitoring in *T*, *q*, O_3, and *Z* throughout the entire atmosphere up to ~100 km.

- ➔ From the occultation methods, GNSS occultation is presently most advanced and LEO-LEO occultation most intriguing for its novelty and water vapor promise. Both together can serve as fundamental building block of a GCOS occultation backbone.

- ➔ Current multi-year single RO sensors such as on CHAMP, GRACE, METOP are important initial components for starting continuous RO based climate change monitoring. As a next step, constellations like COSMIC and ACE+ need be implemented with high priority and fully in line with current time schedules.

Concluding Remarks (2)

"The good method is like a sack (bag):
it retains everything.
The better method is like a sieve (filter):
it only retains what matters."

(after Hellmut Walters)

Deutsches Originalzitat (Hellmut Walters):
„Das gute Gedächtnis ist wie ein Sack:
es behält alles.
Das bessere Gedächtnis ist wie ein Sieb:
es behält nur, worauf es ankommt."

By the way…
OPAC-1 Workshop

1st International Workshop on Occultations for Probing Atmosphere and Climate (OPAC-1)

September 16-20, 2002 • Graz, Austria

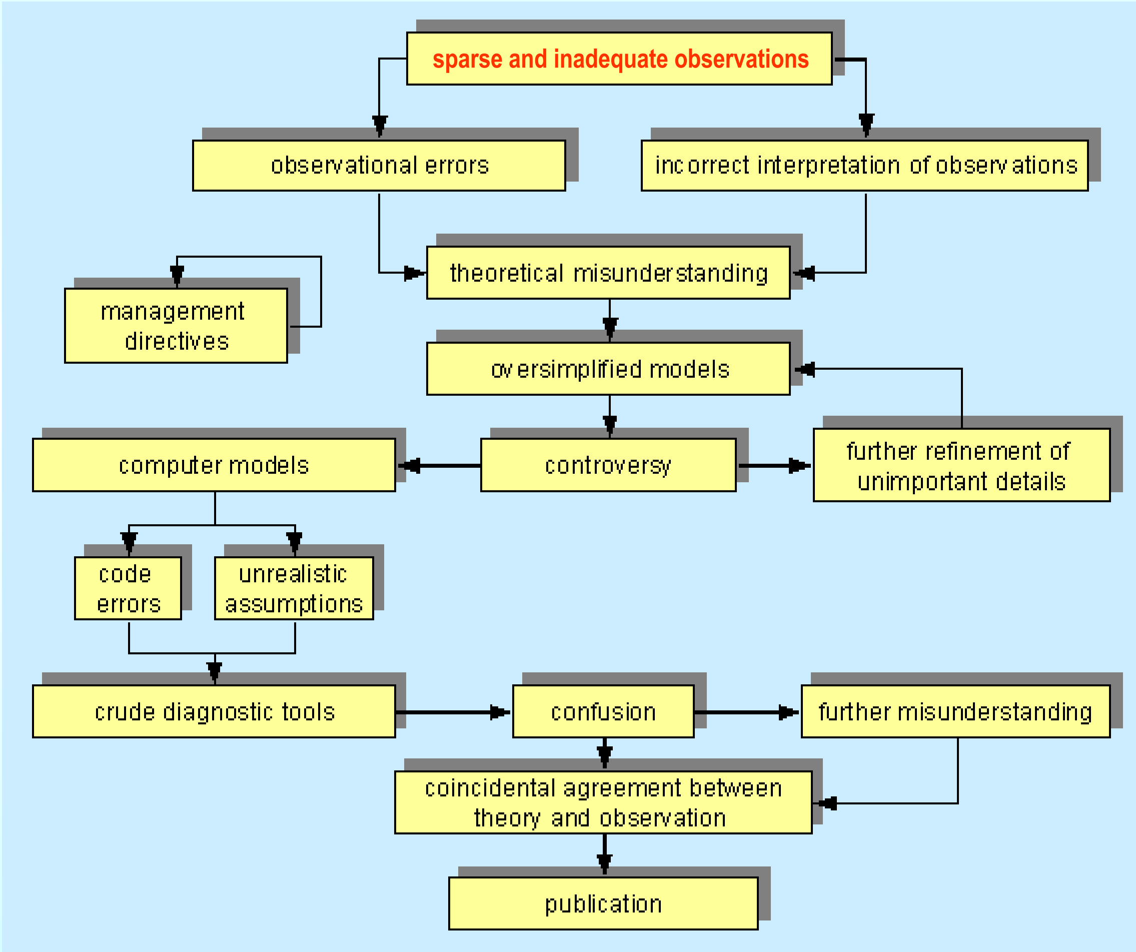
http://www.uni-graz.at/OPAC1Workshop-Sep2002

Welcome to OPAC-1 – Welcome to Graz!

Climate Change Monitoring by Radio Occultation (optional slide)

on the key role of adequate data

Fatal Workflow... (only too true sometimes?)



(Received from: J. Lerner, priv.communications, 2001; slightly adapted)

...occultations cure right at the start.