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

End-to-End Simulation of Atmospheric Sounding by Occultation Sensors — EGOPS4 and Beyond

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Talk at OPAC-1/Session "Occ. Methodology: Data Exploitation and Performance Simulations "; Sept. 17, 2002; Univ. of Graz, Graz, Austria.

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

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Thanks to...

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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)

Thanks also to...

Andrea Steiner

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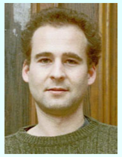

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2 Senior Scientists

2 Post-Doc Scientists

5 Ph.D. Students

1 M.Sc. Student

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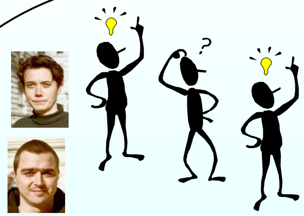
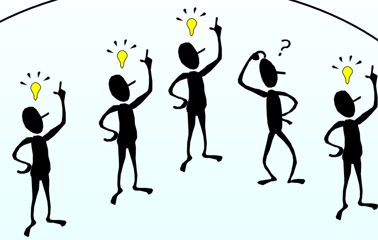


Colleagues at IGAM



Colleagues Worldwide

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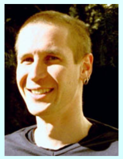

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Outline

- **EGOPS4 Rationale – Major Objectives**
- **EGOPS Overview**
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- **What is New in EGOPS4?**
  - Major new features summarized
- **EGOPS4 Application Examples**
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  - EGOPS*5.x* major objectives
  - On the birth of EGOPS*5x* (EGOPS*5-0.0*)
  - ACE+: main initial EGOPS*5x* driver
  - Stellar&solar occultation simulations involving EGOPS*5-0.0*
- **How to get EGOPS? – The Int'l EGOPS Maintenance Center (IEMC)**

"Never seen occultations so bright. – EGOPS."

EGOPS4 Rationale – Major Objectives

Basic Rationale: Given the promise of GNSS occultation science, a tool is highly desirable for *integrated simulation of the GNSS-based radio occultation technique in an end-to-end manner* — from the GNSS satellites transmitting the signals down to final data products like atmospheric profiles of temperature and water vapor.

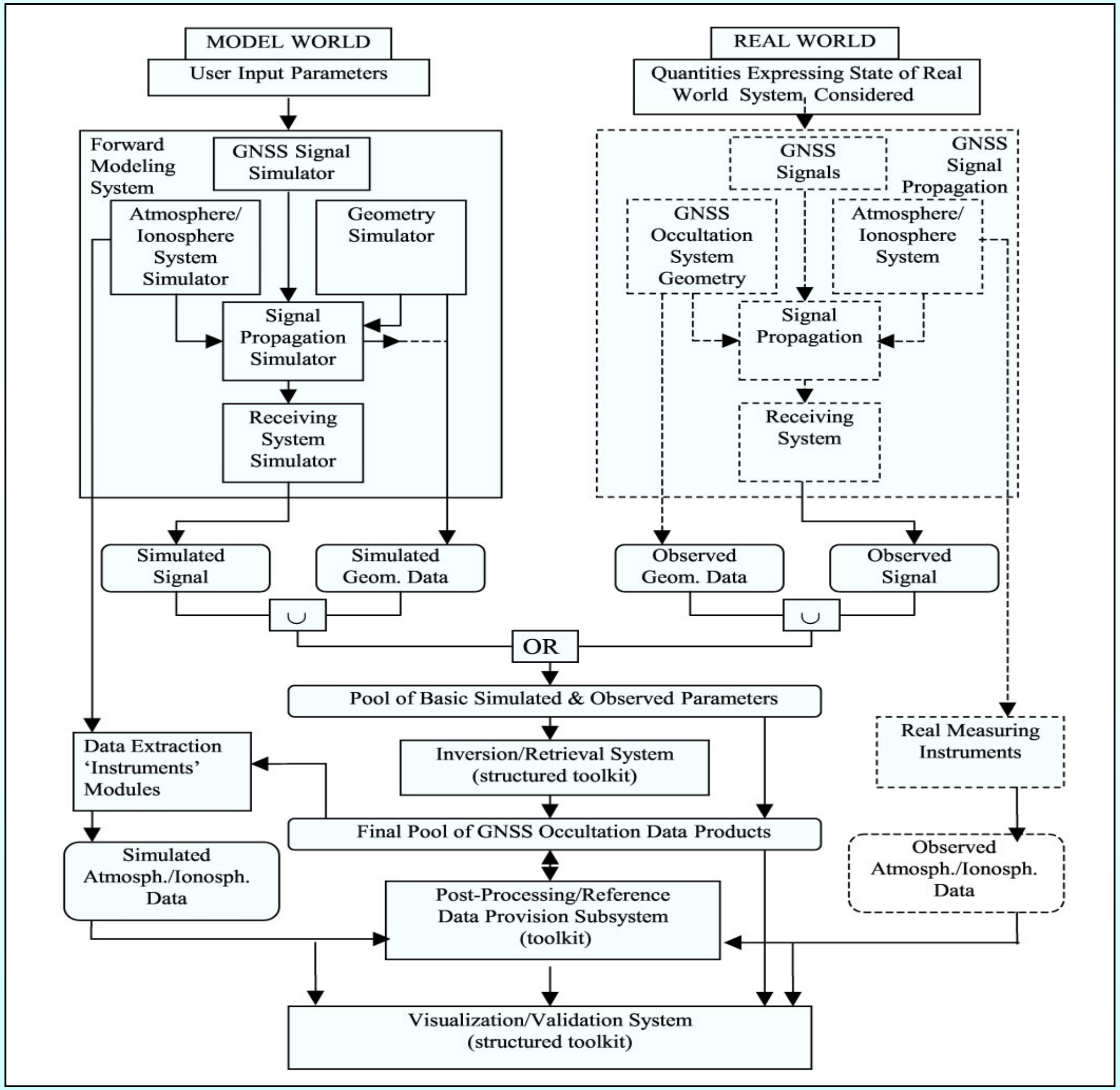
Major Objectives:

- **Mission Analysis and Planning** for generic satellites in Low Earth Orbits (LEOs) equipped with GNSS receivers (e.g., GRAS). *Complementary add-on:* Mission analysis and planning for GNSS scatterometry ("ocean-reflections").
  - Geometry of occultation (reflection) events, coverage by events, various statistics for given GNSS/LEO/ground-station constellations and antennae field-of-views.
- **Simulation of Occultation Observations** (forward and observation system modeling).
  - GNSS-to-LEO signal propagation through the atmosphere/ionosphere system plus effects of the observing system such as POD errors, antenna pattern, local multipath, receiver noise, and clock drifts.
- **Processing of simulated and observed occultation data** (inversion from phases and amplitudes to atmospheric or ionospheric profiles).
  - Data processing of the simulated observables as well as of real data, such as from GPS/MET [and CHAMP/GPS], by a variety of different processing chains.
- **Integrated visualization/analysis** of all simulator results.

Overall Objective: Effective treatment of all relevant aspects of GNSS occultation by an integrated, flexible, and user-friendly tool open for continuous improvements.

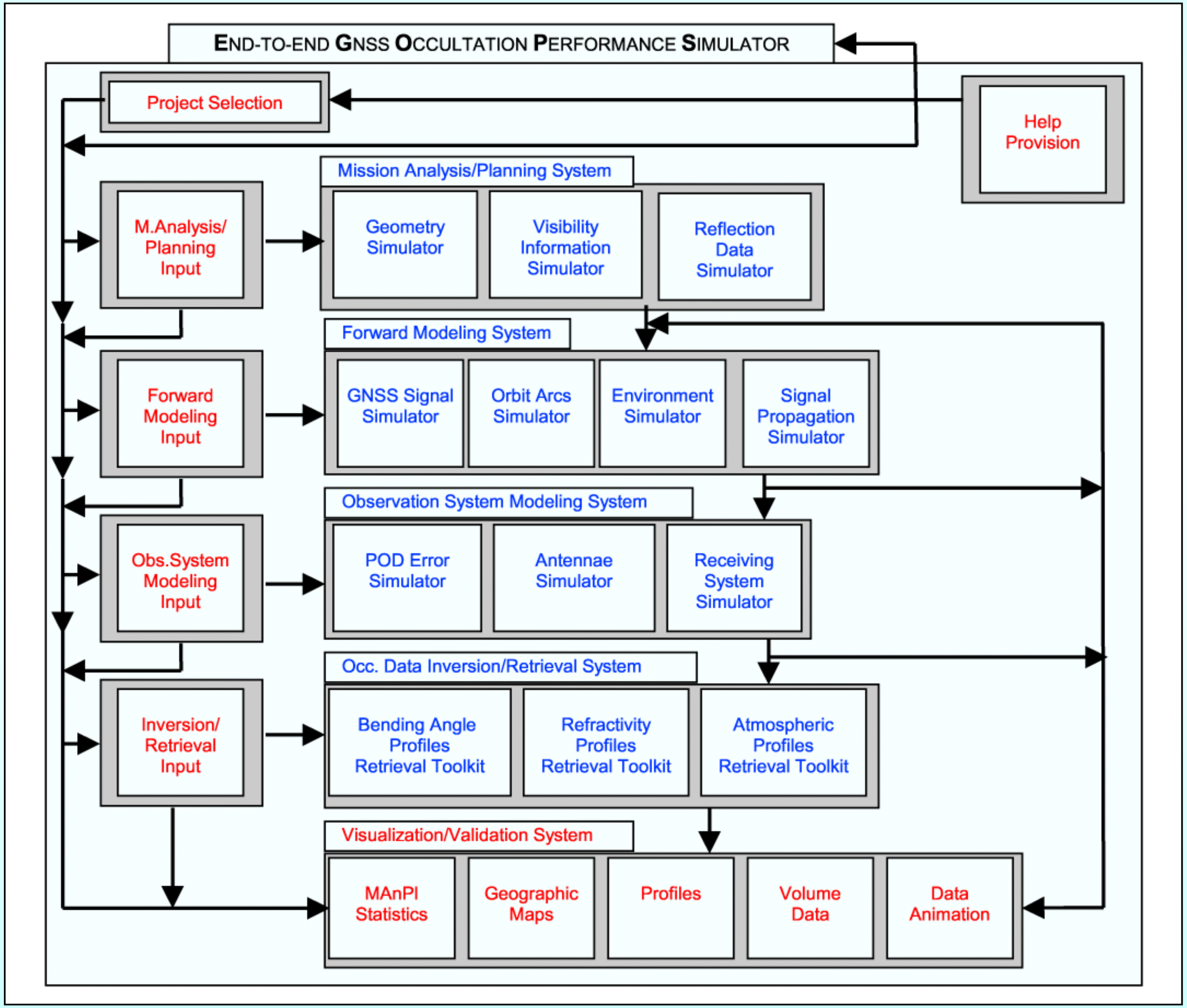
EGOPS Overview

Concept&Design - Conceptual View



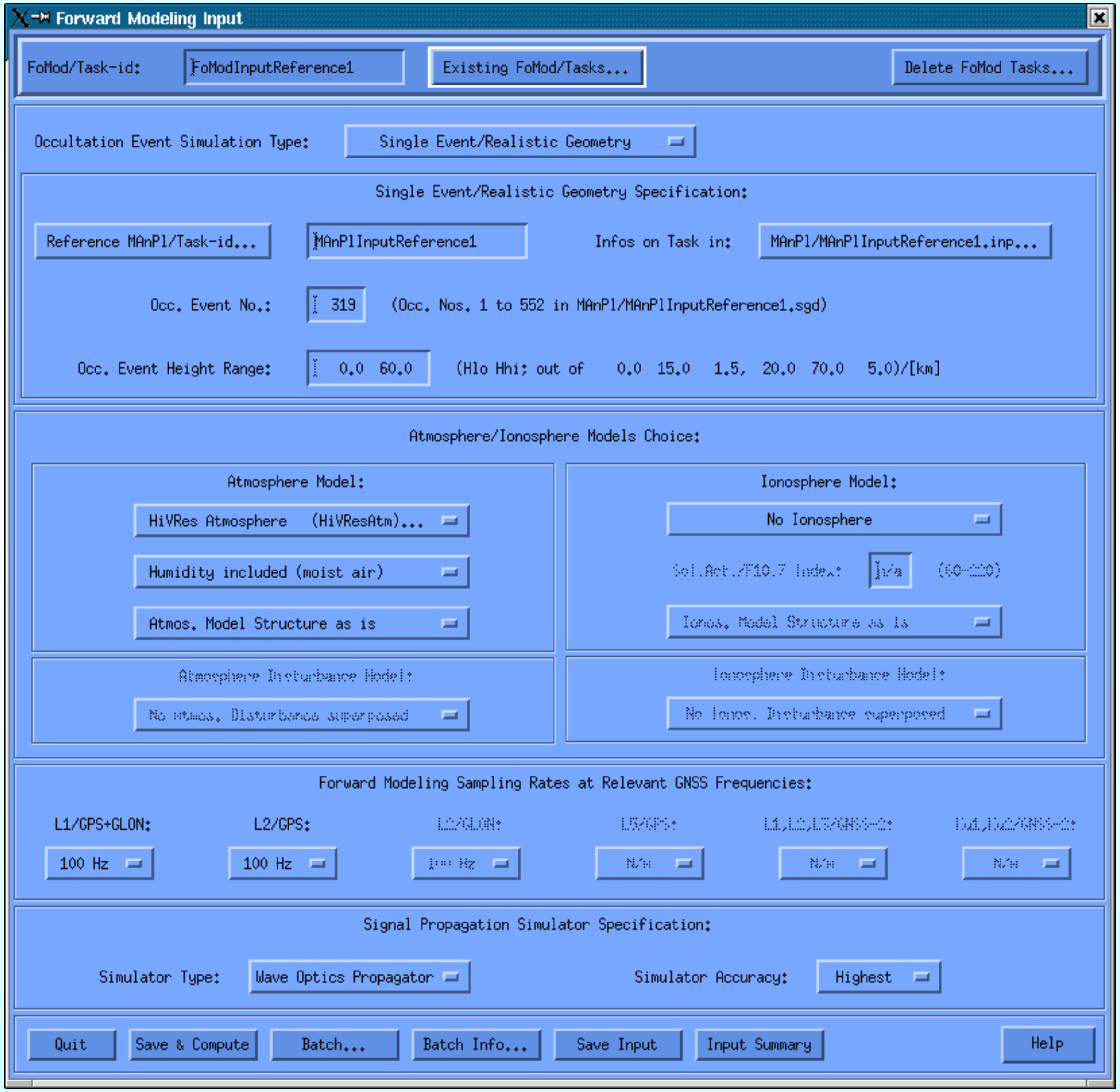
EGOPS Overview

Concept&Design - Modular View



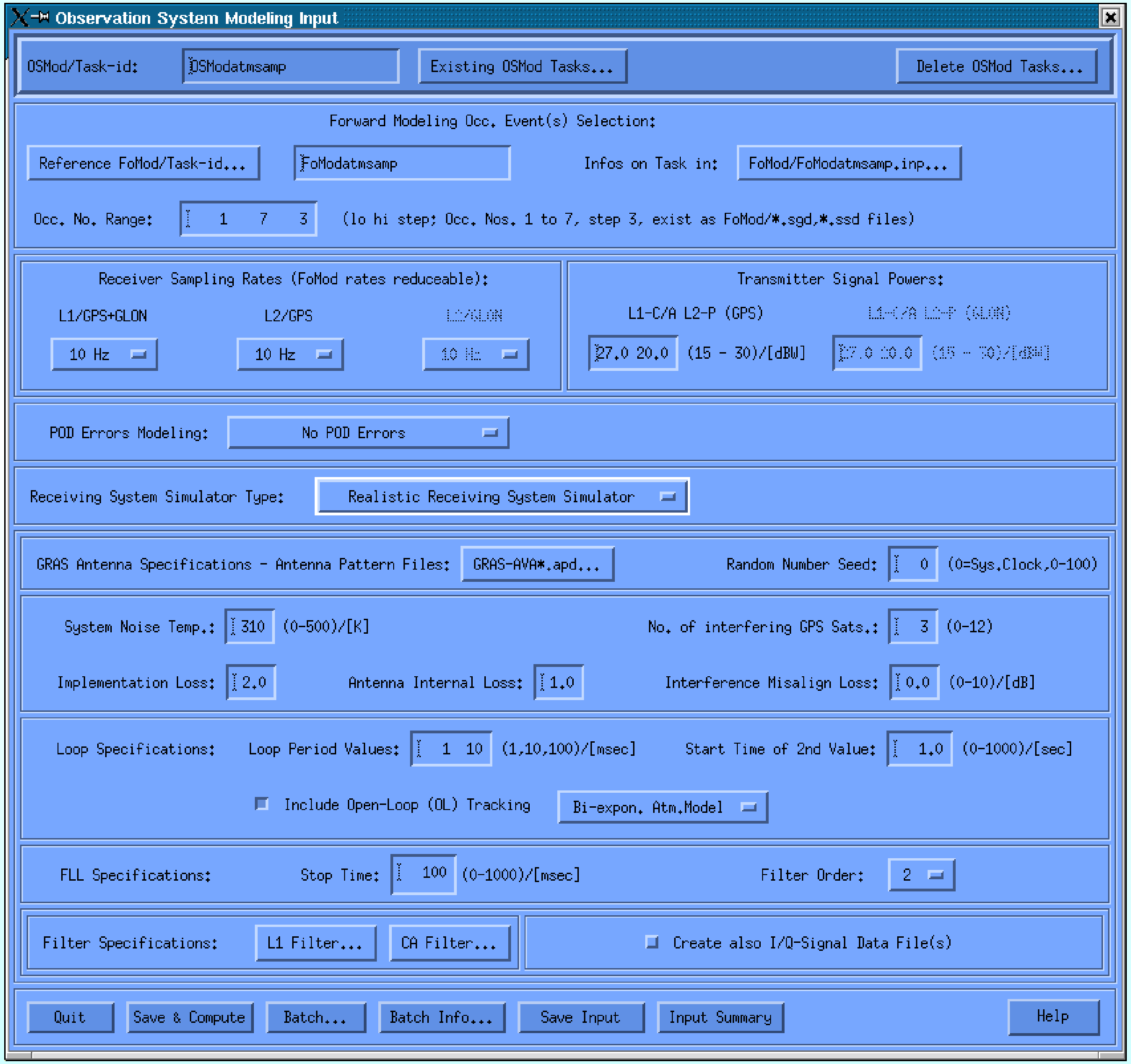
EGOPS Implementation: The User's View

FoMod User I/F Example Window



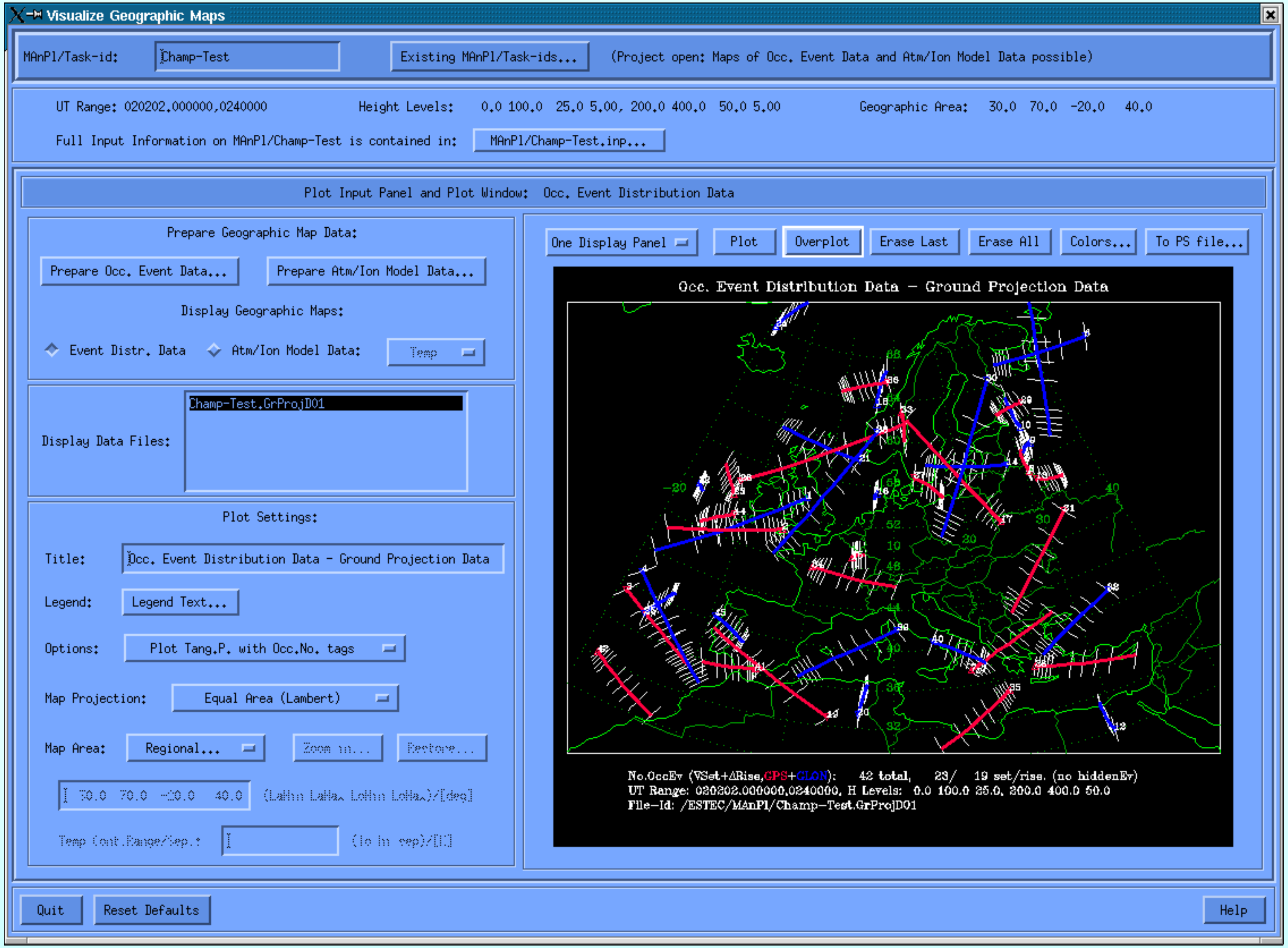
EGOPS Implementation: The User's View

OSMod User I/F Example Window



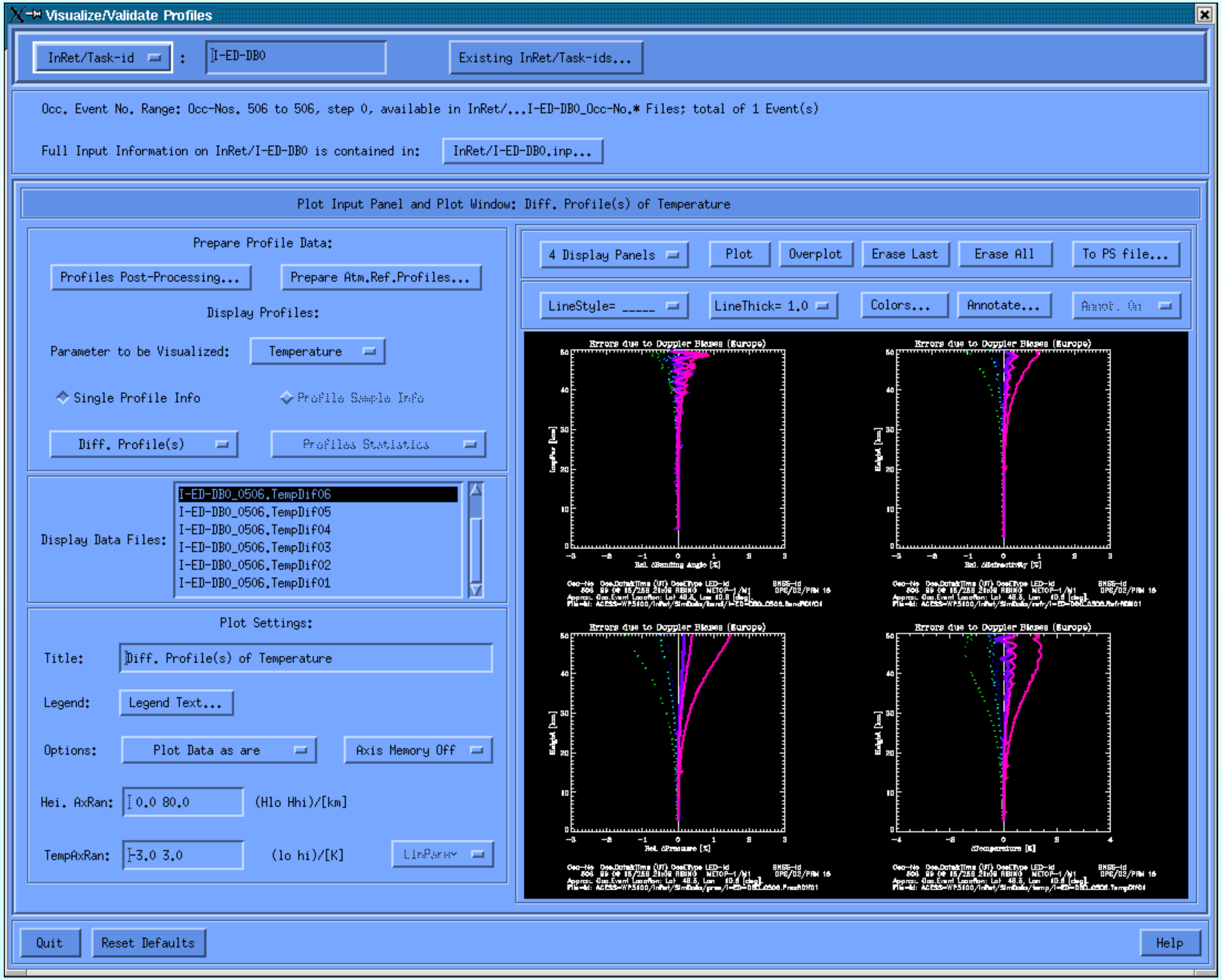
EGOPS Implementation: The User's View

Visualize Geographic Maps User I/F Example Window



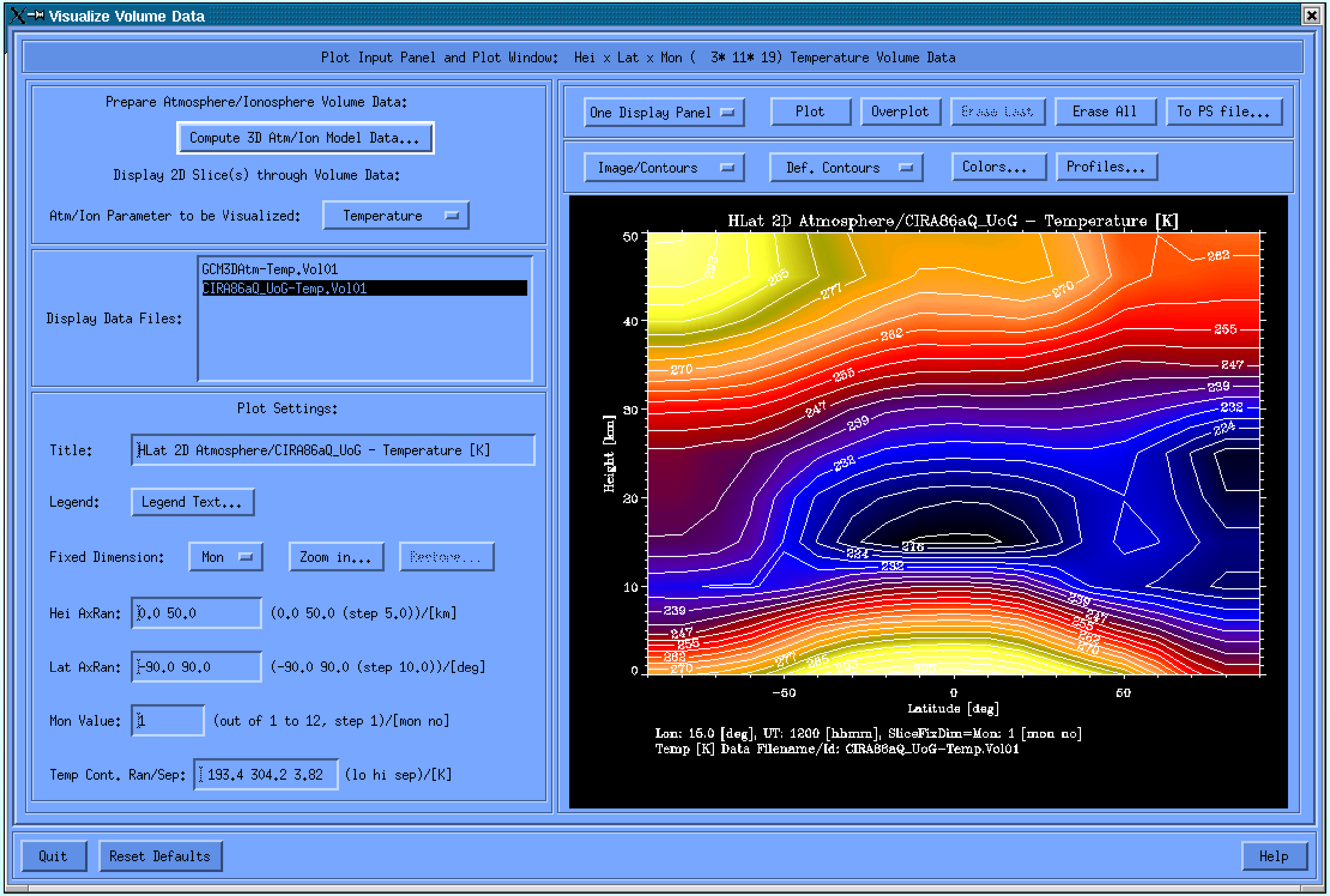
EGOPS Implementation: The User's View

Visualize/Validate Profiles User I/F Example Window



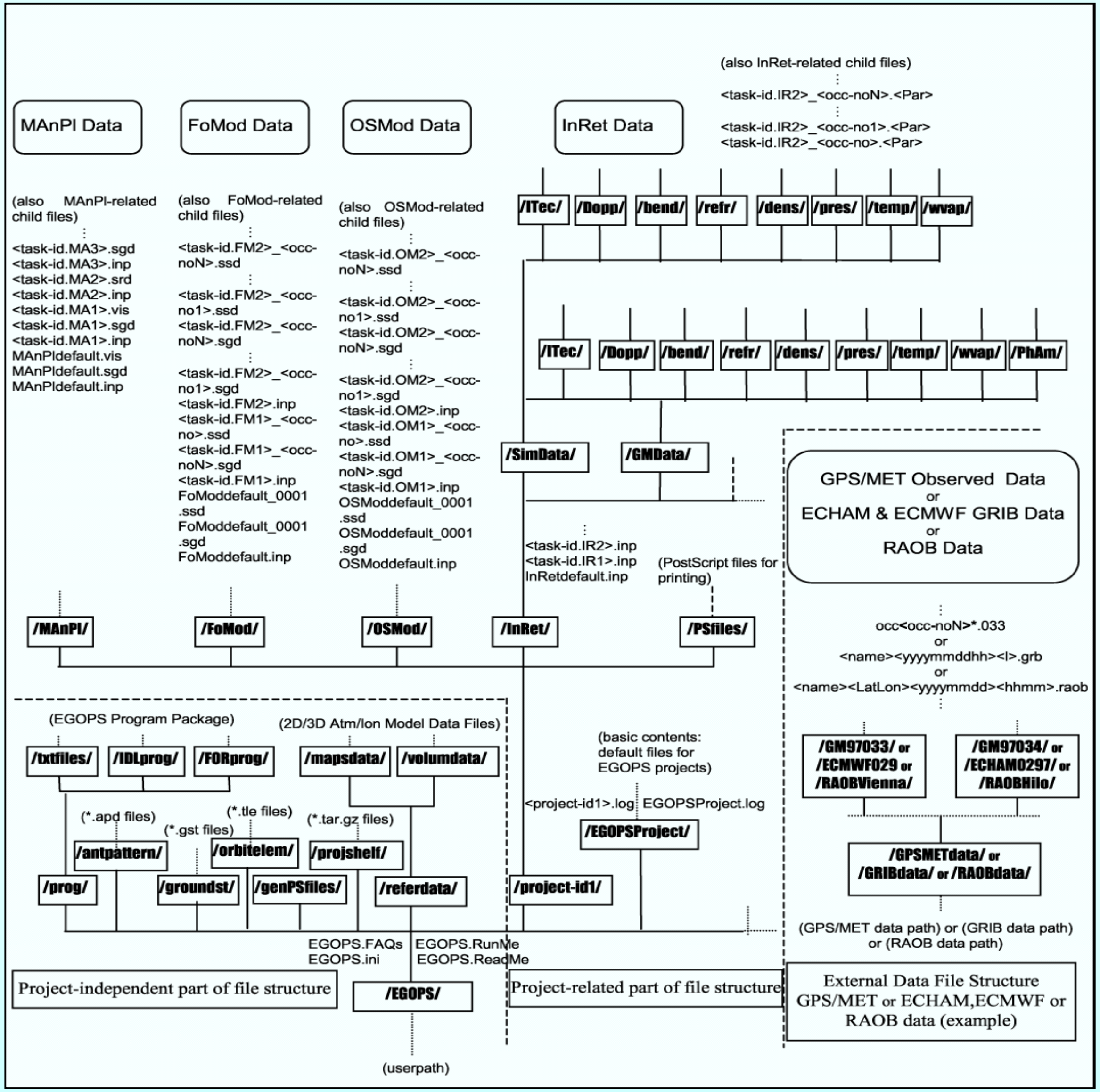
EGOPS Implementation: The User's View

Visualize Volume Data User I/F Example Window



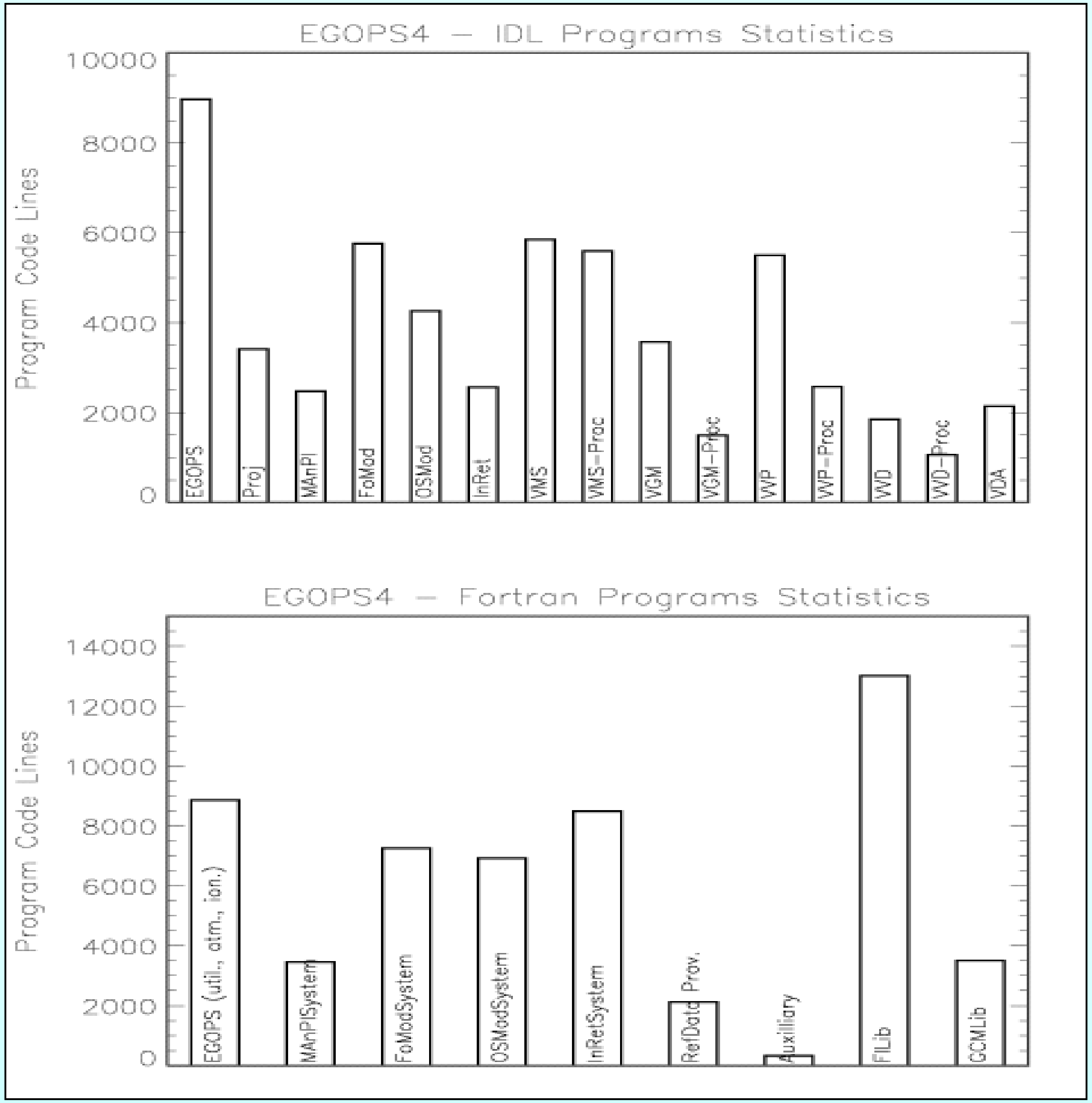
EGOPS Implementation: The Disk's View

File Structure of EGOPS



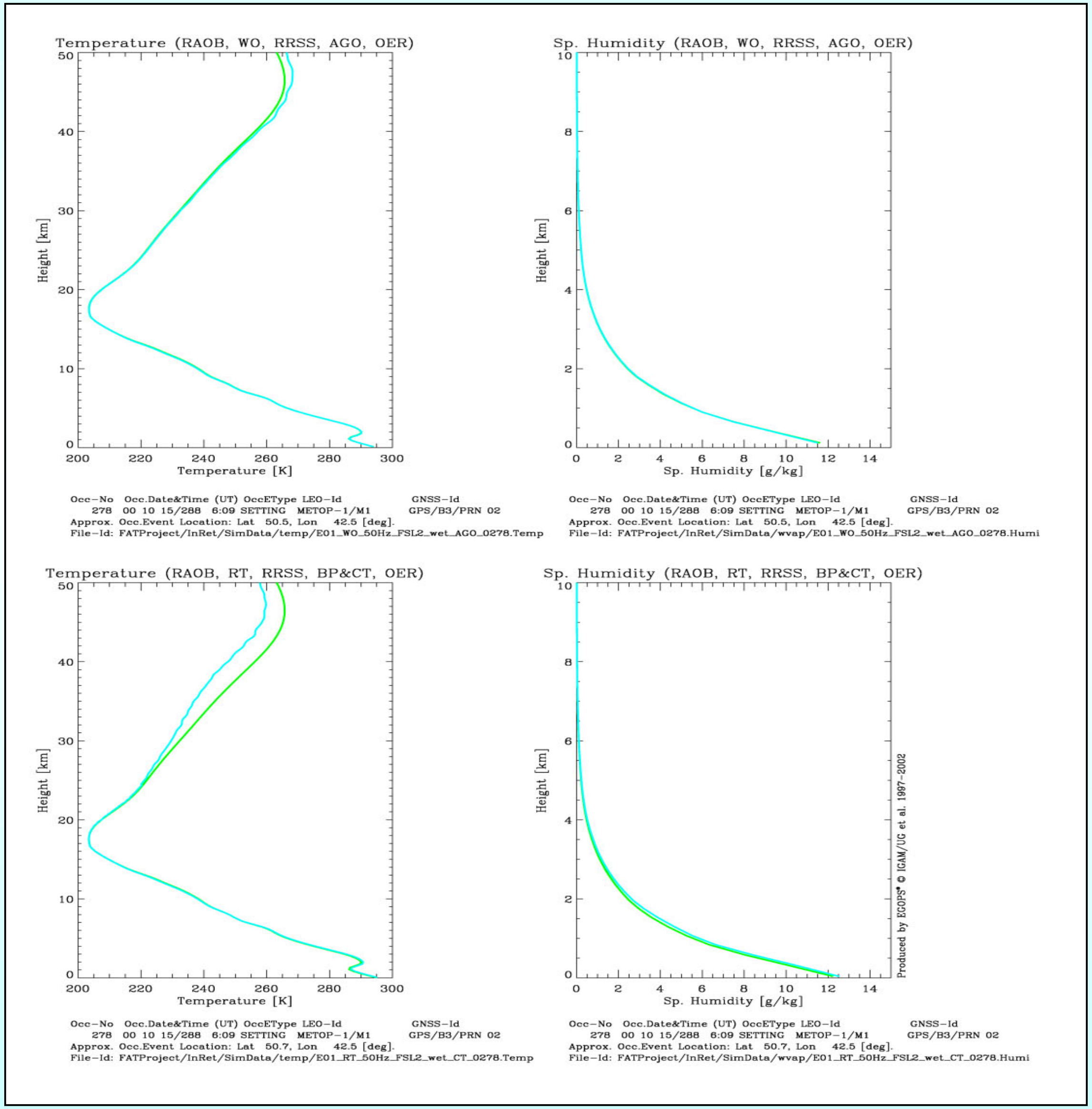
EGOPS Implementation: The Disk's View

EGOPS4 Source Code Statistics



EGOPS Test — Example#1

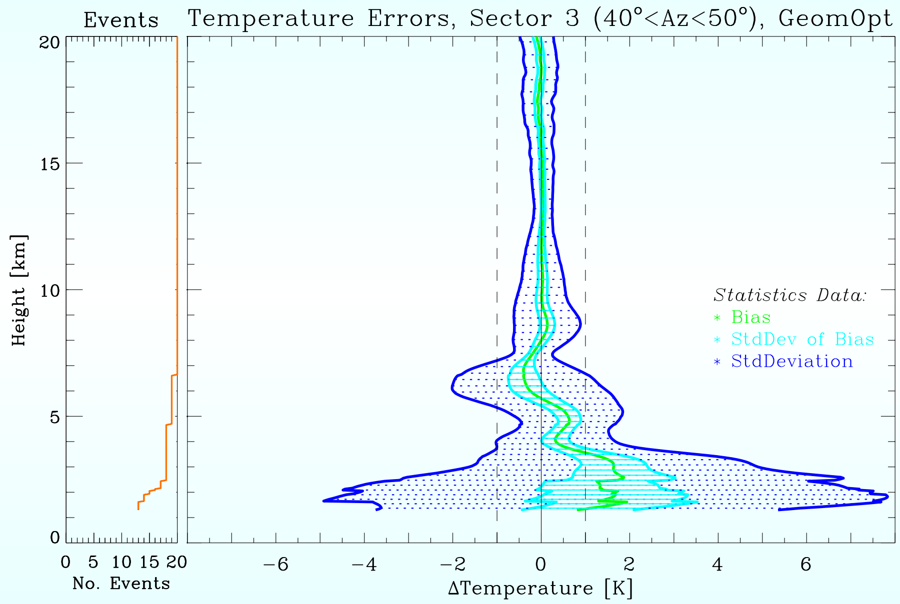
Forward-Inverse Consistency

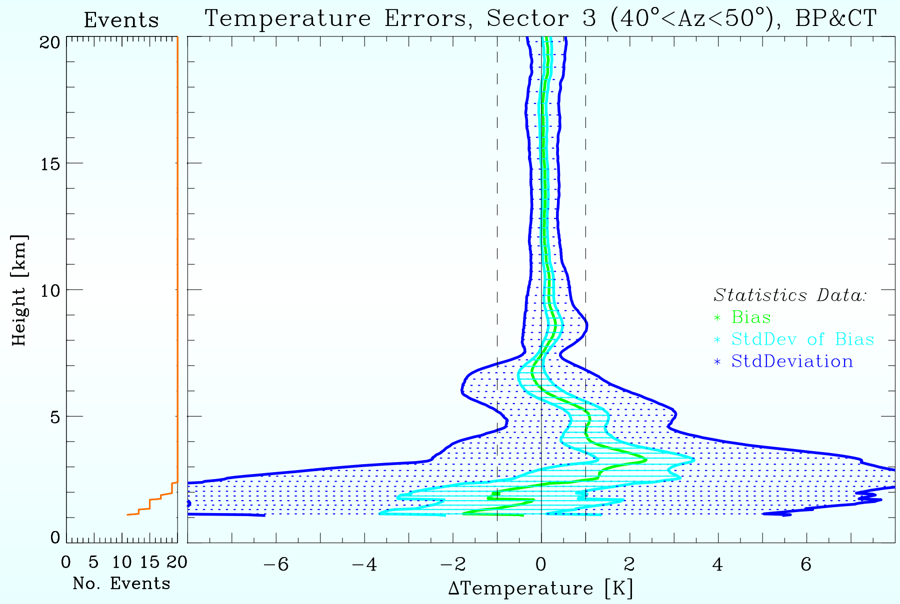


EGOPS Test — Example#2

Geometric Optics vs. Wave Optics

Statistics for 20 occultation events with 40–50 deg angle-of-incidence (off antenna boresight)





Result based on EGOPS4 Advanced Geometric Optics Retrieval Algorithm (incl. advanced statistical optimization)

Result based on EGOPS4 Advanced Wave Optics Retrieval Algorithm (incl. backpropagation&canonical transform)

What is New in EGOPS4?

Major New Features Summarized (1)

- **High-vertical-resolution (HiVRes) atmospheric model:** seamless access to (high-res) radiosonde data files of different formats (e.g., NOAA/FSL format)
- **Local spherical symmetry mode for all atmospheric & ionospheric models:** allows to rigorously analyze horizontal asymmetry and variability effects of all kinds
- **Up to 500 Hz sampling rate for advanced tropospheric observation simulations:** 100/250/500 Hz data, e.g., for high-res lower troposphere studies
- **Realistic Receiving System Simulator (RRSS) in observation system modeling:** realistically models GNSS (L1) signal tracking, loss of phase-lock detection, open-loop tracking, optional I/Q output
- **Mission analysis/planning and simulation of observations for airborne GNSS receivers:** for studying observations from airplanes in addition to LEO observations
- **Advanced wave optics occultation data processing:** optimized backpropagation (PB) algorithm and state-of-the-art PB&Canonical Transform algorithm, allowing tropospheric bending angle retrieval even in case of severe atmospheric multipath

What is New in EGOPS4?

Major New Features Summarized (2)

- **Advanced geometric optics bending angle retrieval:** state-of-the-art geometric optics bending angle retrieval algorithm with advanced statistical optimization
- **Advanced moist air profiles retrieval:** optimized classical moist retrieval (both based on iterative and integration techniques) and state-of-the art optimal estimation (1DVAR) temperature and humidity retrieval algorithm
- **Project archival capability:** convenient compression, shelve/restore, and exchange of entire EGOPS projects
- **Batch processing capability:** all FORTRAN system computations can be done also in batch mode (no longer blocking of the User I/F by CPU expensive tasks)
- **A myriad of user I/F, post-processing, visualization/validation enhancements:** vast speedup of some post-processing functions (e.g., profiles differencing), “true” reference profiles also along actual 3D tangent point trajectories, interactive profiles display based on volume data slices, MPEG storage of animations, advanced plot customization (e.g., linestyles, line thicknesses, text annotations), non-framed .eps files for immediate import into other applications, and many more...

EGOPS4 Application Examples

A few exemplary areas of use at IGAM:

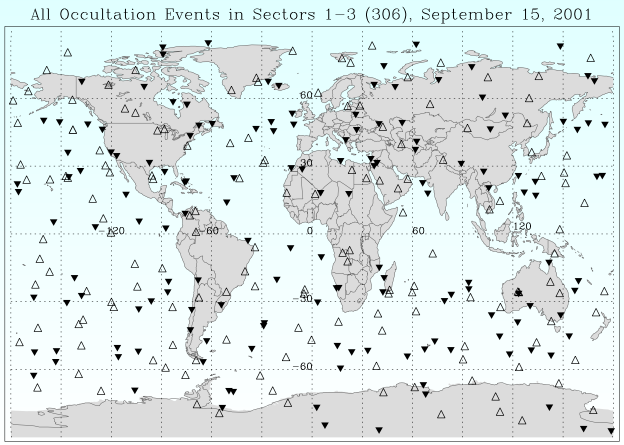
- **end-to-end simulations and error analyses**
- **climate change monitoring simulation study**
- **minimizing biases for optimal climate utility**

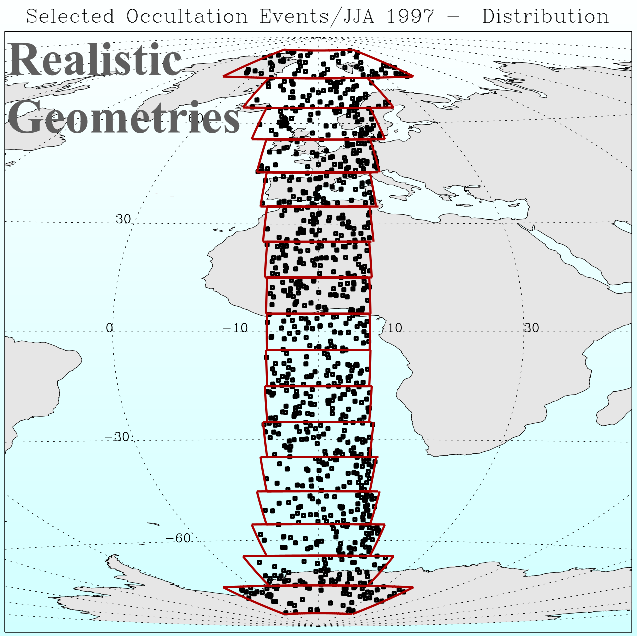
...there are many more areas of use, at IGAM and at ~2 dozen user institutions in research & industry worldwide

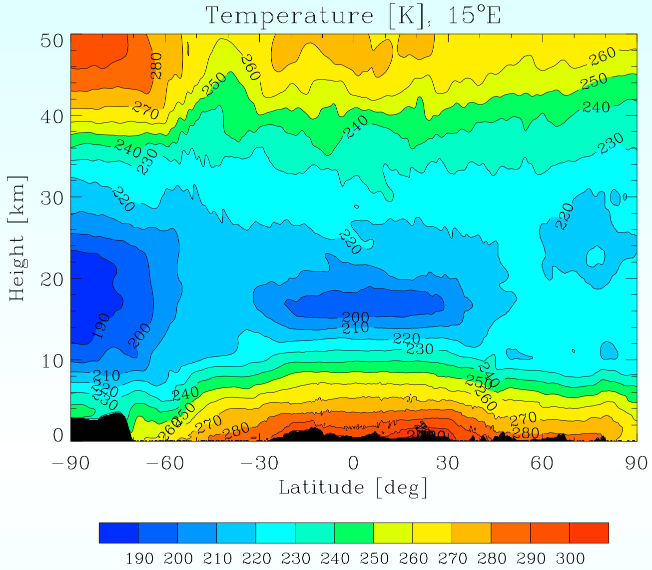
"Never seen occultations so bright. – EGOPS."

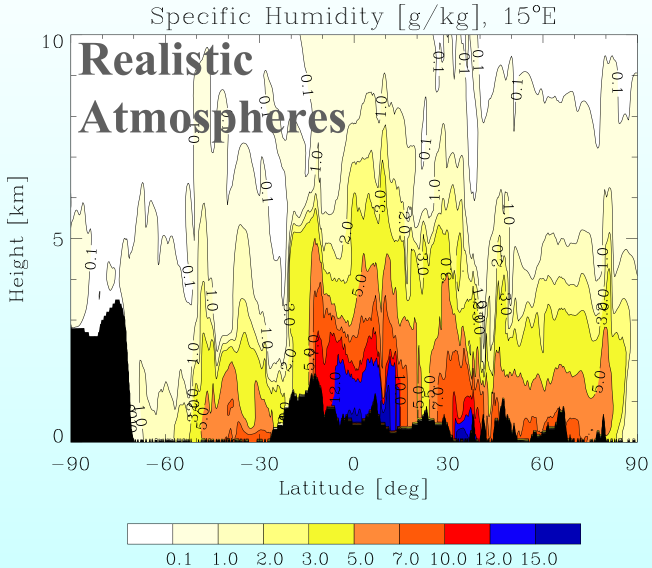
end-to-end simulations and error analyses

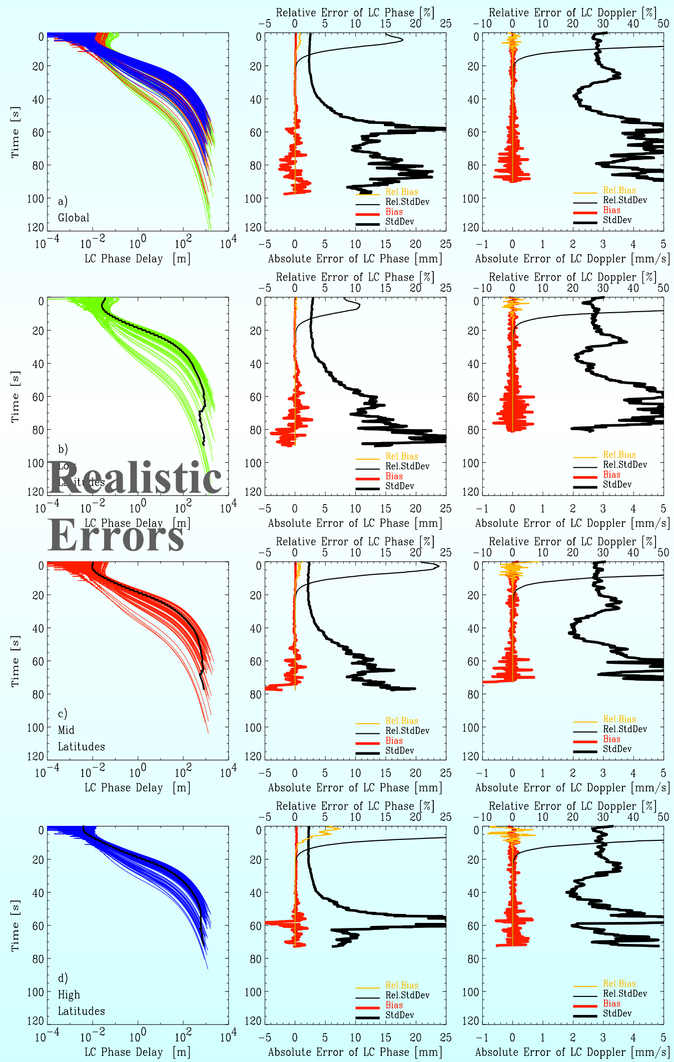
realistic end-to-end performance simulations







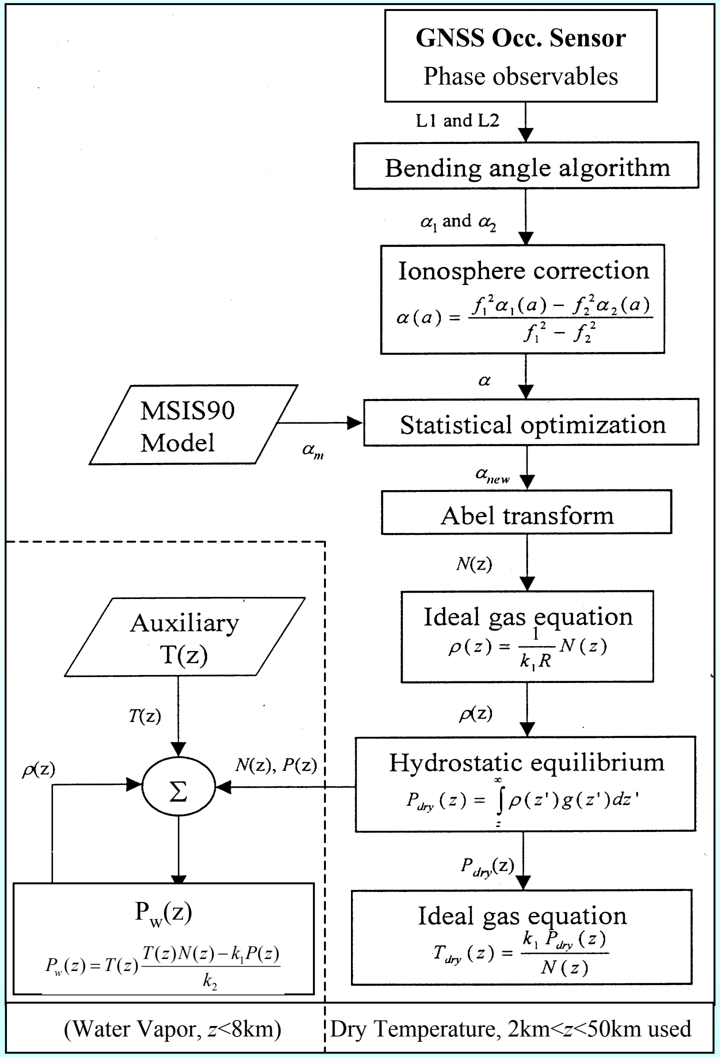




end-to-end simulations and error analyses

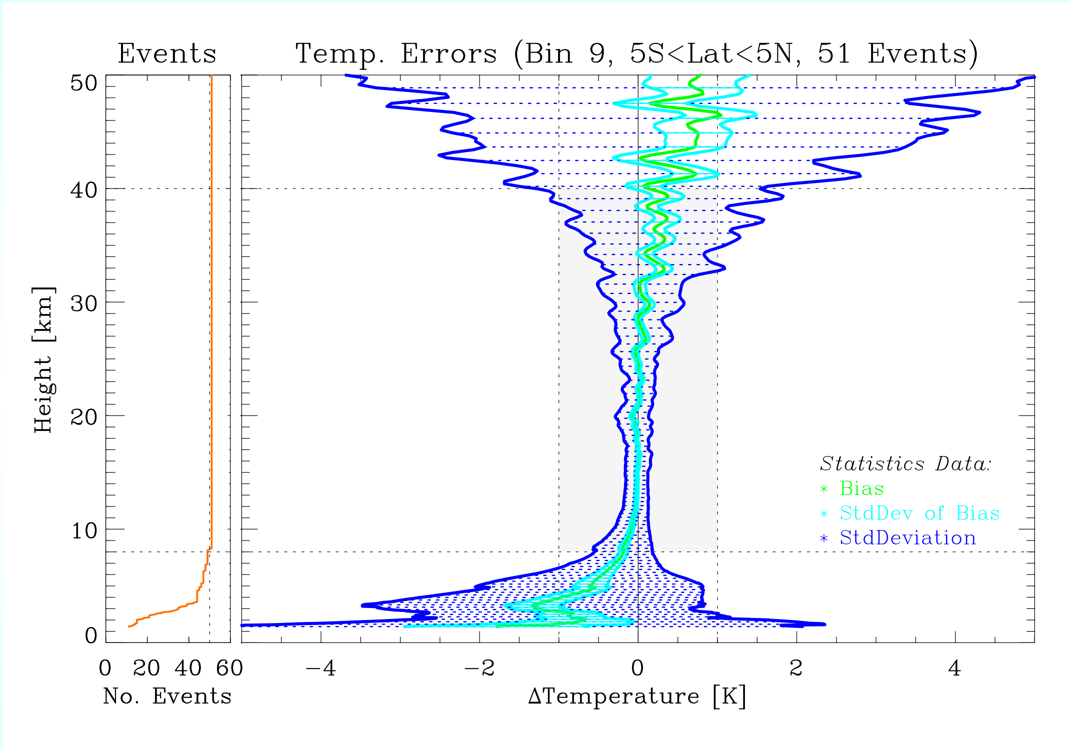
bias, standard deviation, and rms errors

Advanced Retrieval schemes



(after Høeg et al., Scient. Report 98-7, DMI Copenhagen, DK, 1998)

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



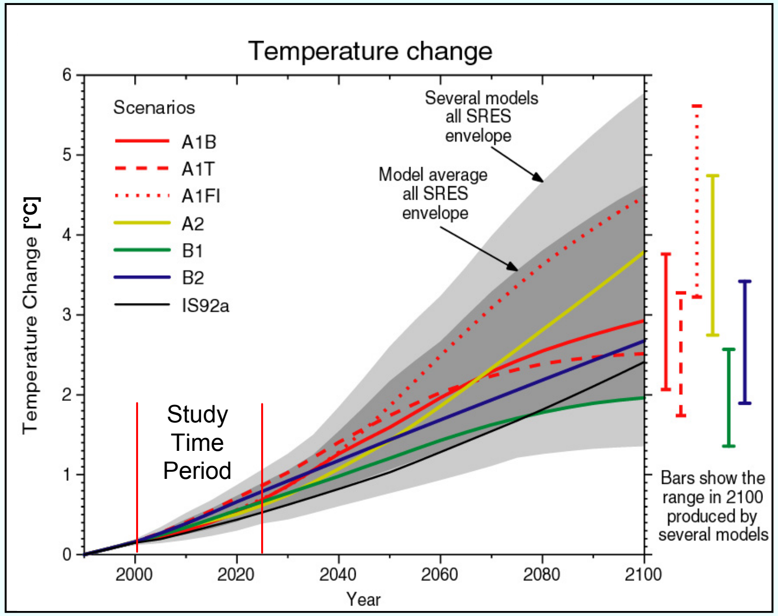
Retrieval of 50-60 $T_{dry\ air}$ profiles per latitude Bin

- 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 change monitoring simulation study
end-to-end climate monitoring experiment 2001–2025

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

Surface temperature change according to IPCC 2001 scenarios



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

***In Particular:* Test the capability of a small GNSS occultation observing system for detecting anthropogenically influenced temperature trends within the next 2 decades.**

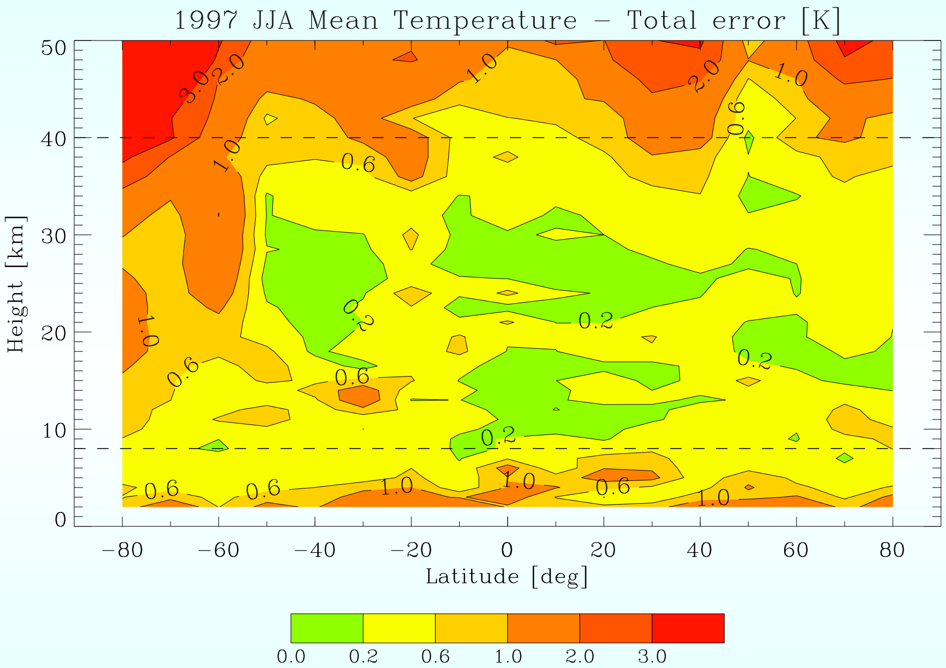
Methodology: Given the lack of adequate real data, perform a realistic end-to-end climate observing system simulation experiment over a sufficient period of time (using EGOPS).

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).

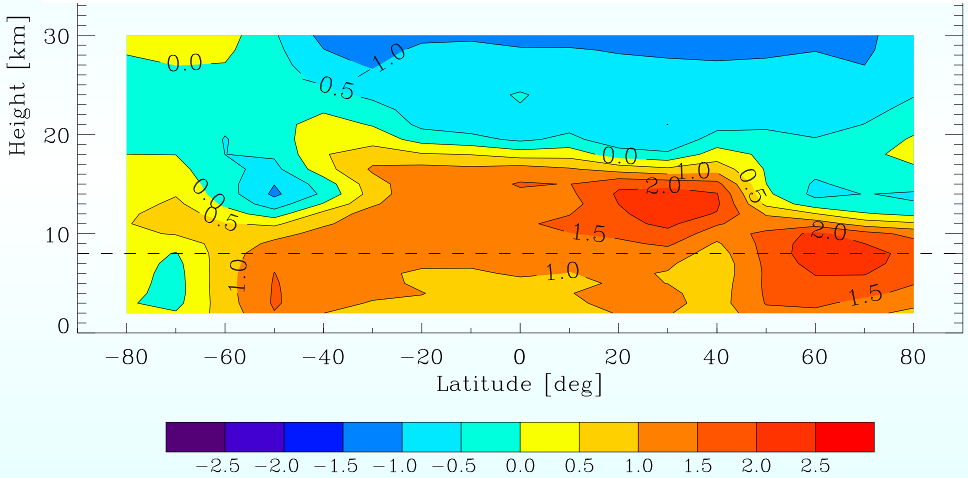
climate change monitoring simulation study

perspectives for climate trend analysis (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)

minimizing biases for optimal climate utility

iono.correction & stat.optimization biases (strato)

- statistical optimization (lead method)
  - inverse covariance weighting optimization (with a priori profile search in MSIS90):

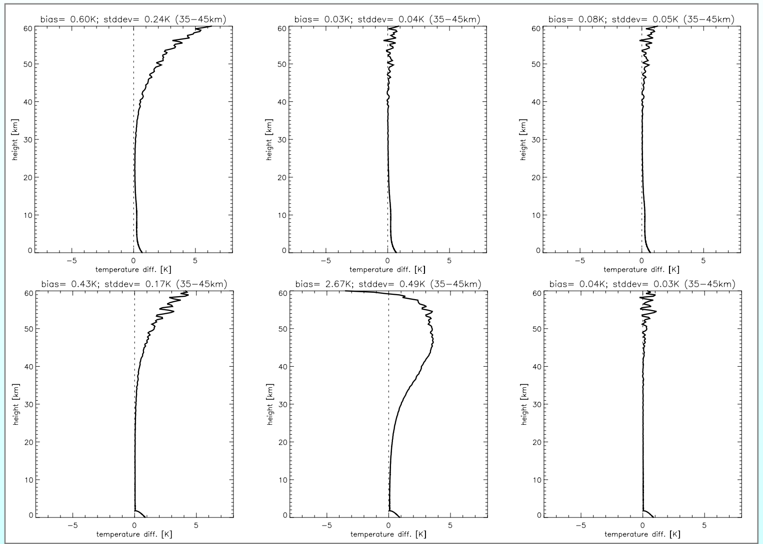
$$\alpha_{opt} = \alpha_b + (\mathbf{B}^{-1} + \mathbf{O}^{-1})^{-1}\mathbf{B}^{-1}(\alpha_o - \alpha_b)\,,\ \sigma_o(z): \text{estimated from } z > 70\text{km}$$

$$\mathbf{B}_{ij} = \sigma_i \sigma_j \exp\left(-\frac{(a_i - a_j)^2}{l^2}\right),\ \text{same form for } \mathbf{O}_{ij}$$

	no optim.	heuristic optim., no search	inv. cov. optim., search

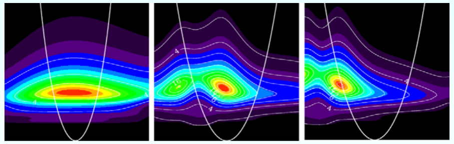
NICE, no ionosph., ideal receiver

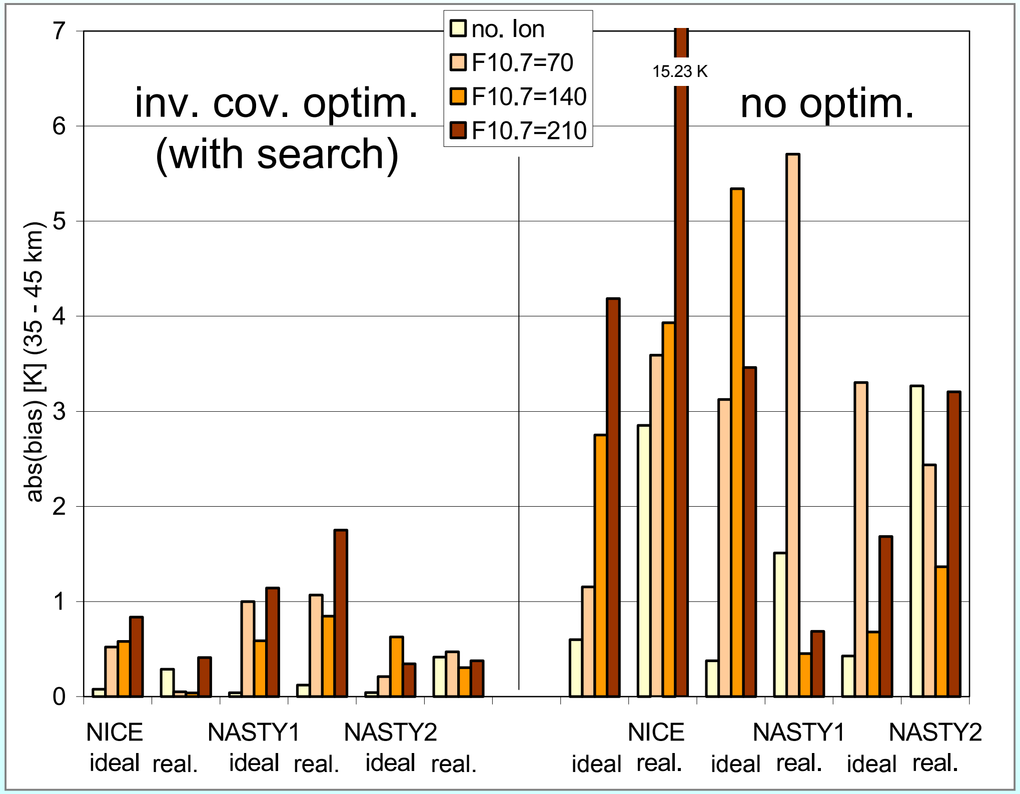
NASTY2, no ionosph., ideal receiver



- ionospheric correction (lead method)
  - linear combination of bending angles:

$$\alpha_{LC}(t) = \frac{f_1^2 \alpha_1(t) - f_2^2 \alpha_2(t)}{f_1^2 - f_2^2}$$



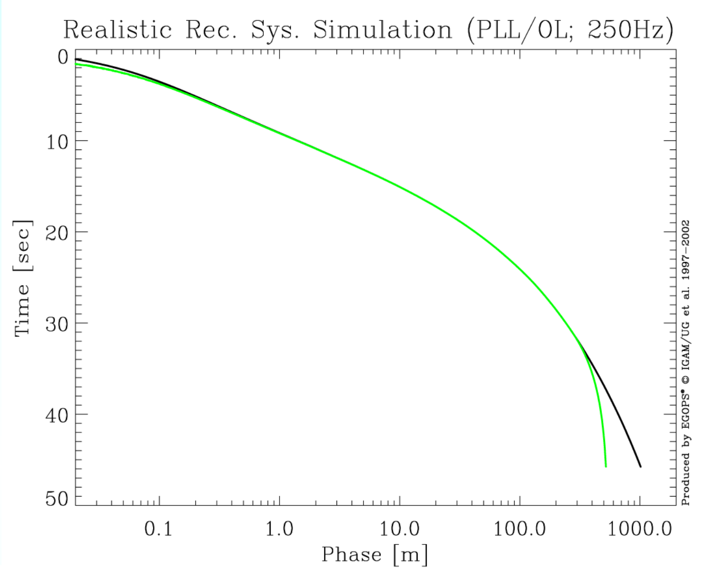


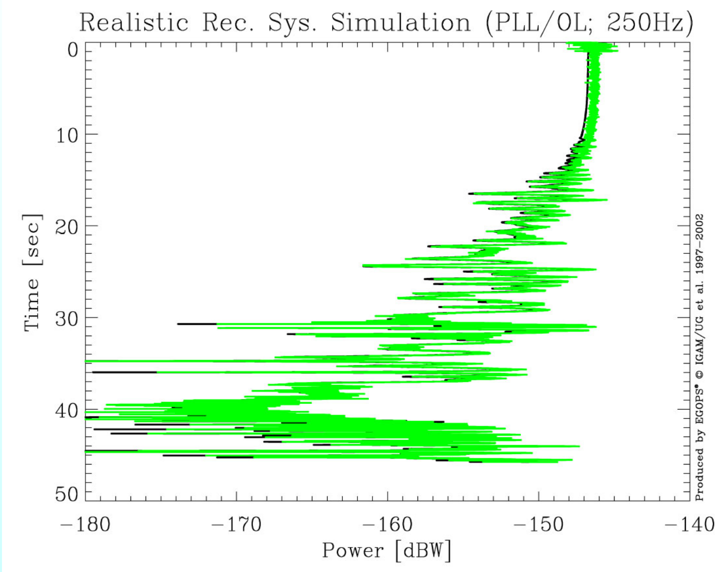
minimizing biases for optimal climate utility

biases due to tracking & algo weaknesses (tropo)

- **tropospheric tracking weaknesses**
  - "negative refractivity bias" if PLL (phase-locked loop) faces challenging tropospheric conditions (none if simulations with parameterized sensor)
  - PLL "flywheel" fallback - or loss-of-lock - under challenging conditions
  - OL (open loop/raw sampling) promising alternative, but only started to be proven

- **tropospheric algorithmic weaknesses**
  - mean tangent point assumption is inadequate
  - geometric optics algorithms fail under challenging tropospheric conditions
  - great advances in wave optics processing (e.g., canonical transform), but 2D plane assumption
  - not yet any bias-tested/bias-optimized wave optics algorithm
  - OL algorithms only started to be developed
  - proper statistics for *unbiased T,q* opt.estimation not well quantified in the troposphere





beyond EGOPS4.0

from EGOPS4.0 to EGOPS4.x

EGOPS4.x – plans for enhancements until end 2003...

- **Simulation of Geometry and Observations**
  - integration of GALILEO system functionality at equal level with GPS and GLONASS
  - simulation of “true” bending angles simultaneously with phase and amplitude observables
  - ray-tracers advanced to cope also with complex tropospheric refractivity structures
  - alternative advanced wave optics propagator based on Maslov-Fourier method
  - advanced GPS Realistic Receiving System Simulator (L1&L2 carrier and code tracking)
- **Processing of Occultation Data**
  - seamless processing of real CHAMP/GPS and GRACE/GPS data
  - climate-optimized retrieval algorithms
  - intrinsic 3D tangent point trajectory estimation in leading retrieval algorithms
  - open-loop data processing algorithm
  - retrieval processing for airborne occultations
- **General, User I/F, Visualization/Analysis**
  - extension to full vis/val capability also for bending angle and geopotential height
  - geoidal surface (MSL altitudes) and actual topography (orthometric heights) capability
  - “event geometry” 3D visualization capability

...and further ideas are in the pipe. *(realization depends on resources)*

Beyond EGOPS4 – EGOPS*5x*

EGOPS*5x* Major Objectives

EGOPS*5x* – End-to-end *Generic* Occultation Performance Simulator

EGOPS*5x* is a generalization of EGOPS4, strongly building on its heritage, for end-to-end simulation of LEO-LEO radio occultation, stellar occultation, and solar/lunar occultation in addition to GNSS radio occultation.

Major Objectives:

- **Mission Analysis and Planning** for Low Earth Orbits (LEOs) satellites equipped with GNSS, LEO-crosslink, stellar, or solar/lunar occultation sensors (geometry of events, coverage by events, various statistics for given GNSS/LEO/star/sun/moon/ground-station constellations).
- **Forward Modeling:** Simulation of transmisson/phase delay/bending angle profiles as seen by a sensor (signal propagation through atmosphere-ionosphere system from source to sensor, based on a hierarchy of atmosphere-ionosphere models and signal propagation tools).
- **Simulation of Occultation Observations:** observation system modeling using forward-modeled profiles as input and imposing realistic errors on them, such as modeling of signal detection/tracking and of relevant sensor system errors.
- **Processing of Simulated & Real Observations:** inversion of transmission/phase delay/bending angle observables to atmospheric/ionospheric profiles by a range of different processing chains.
- **Integrated visualization/analysis** of all simulator results.

Overall Objective: Effective treatment of all relevant aspects of occultation observing systems by an integrated, flexible, and user-friendly tool open for continuous improvements.

Beyond EGOPS4 – EGOPS*5x*
on the birth of EGOPS*5x*

EGOPS*5x* – Current Status and Next Steps:

- **Current status of EGOPS*5x* (EGOPS*5-0.0*)**
  - prototype mission analysis/planning tool for the additional occultation techniques
  - prototype combined raytrace&signal extinction integrator for rigorous geometric optics transmission simulation for 3D-varying refractive, absorptive, and scattering atmospheres
  - prototype wave optics propagator for rigorous LEO-LEO phase and attenuation simulations
  - simple instrumental error models for optical and radio sensors for the additional occ. techniques
  - prototype direct inversion and optimal estimation retrieval algorithms for columnar content and density profile retrievals from stellar and solar occultation transmission data
  - EGOPS*5-0.0* used so far for analyses on ACE+/CALLS, ENVISAT/GOMOS, and <x>/SMAS

- **Next steps on EGOPS*5x***
  - advance prototype algorithms, add further algorithms, and more user I/F advancement work
  - **primary focus is on development of LEO-LEO capabilities, driven by the ACE+ mission**

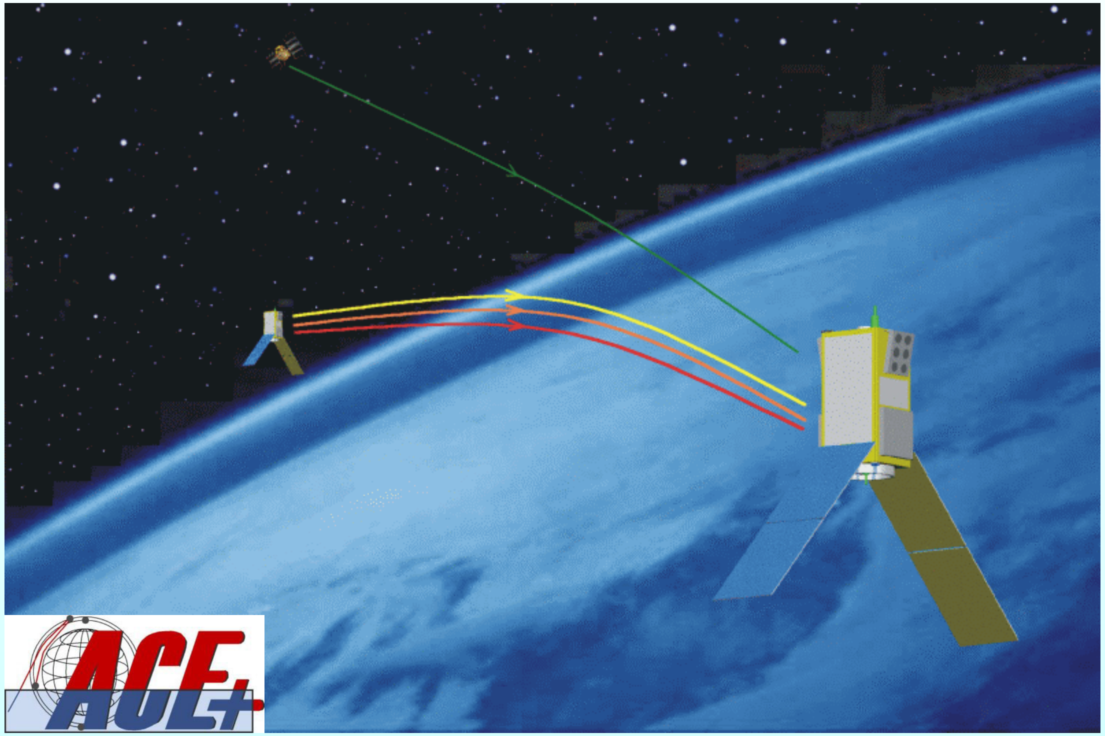
EGOPS*5x* should be available in a 1st version, EGOPS5.0, by end 2003.

Beyond EGOPS4 – EGOPS5x

ACE+: main initial EGOPS5x driver

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); Industry: European Consortium (decided on by end 2003 after competitive phase A)

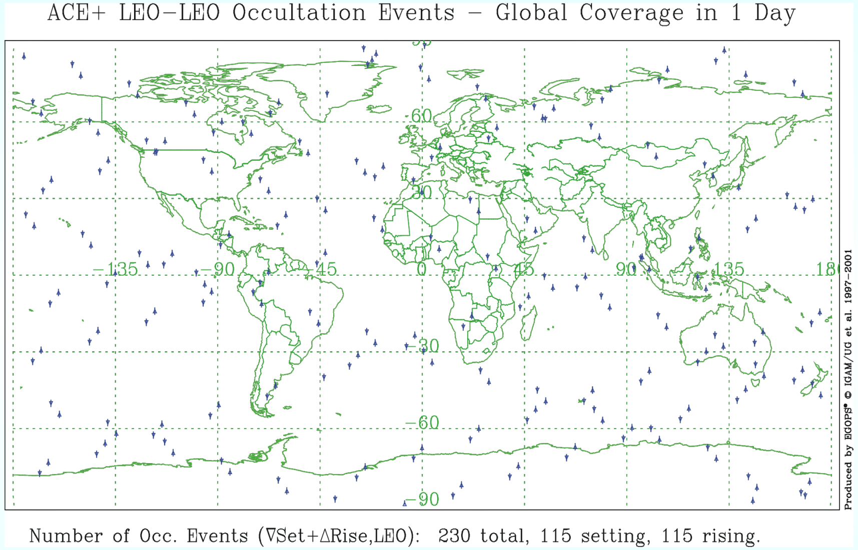


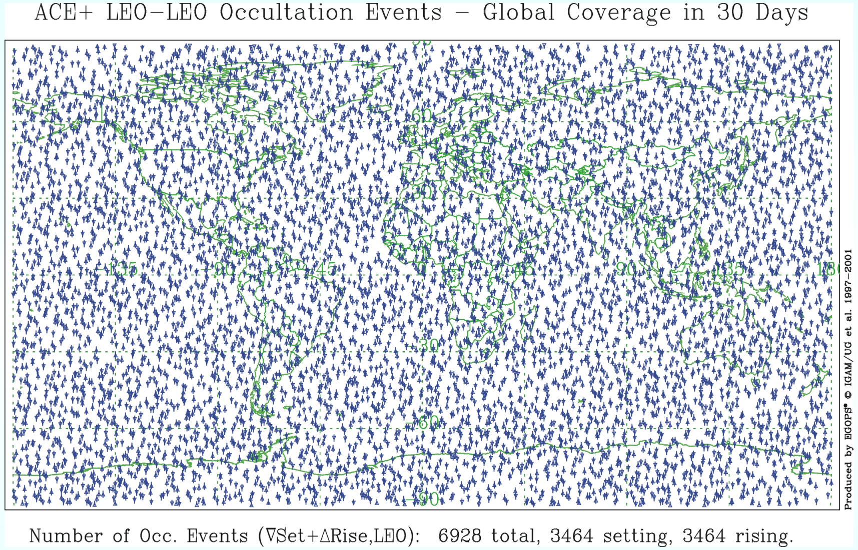
Basic Facts:

- selected by ESA in May 2002 as top priority future Earth Explorer Opportunity Mission
- 4 LEO satellites exploiting GPS, GALILEO, and LEO-crosslink signals
- primary science objectives on climate plus a series of others (NWP, atmos. physics, etc.)
- phase A 2003, after confirmation early 2004 phases B-D until 2007, operations 2007/08-2012

Beyond EGOPS4 – EGOPS5x
ACE+/CALLS Coverage Simulations (EGOPS5-0.0)

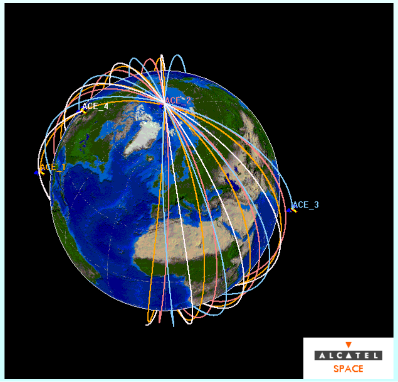
ACE+ LEO-LEO Coverage per Day & per Month





~230 LEO-LEO occultation events/day

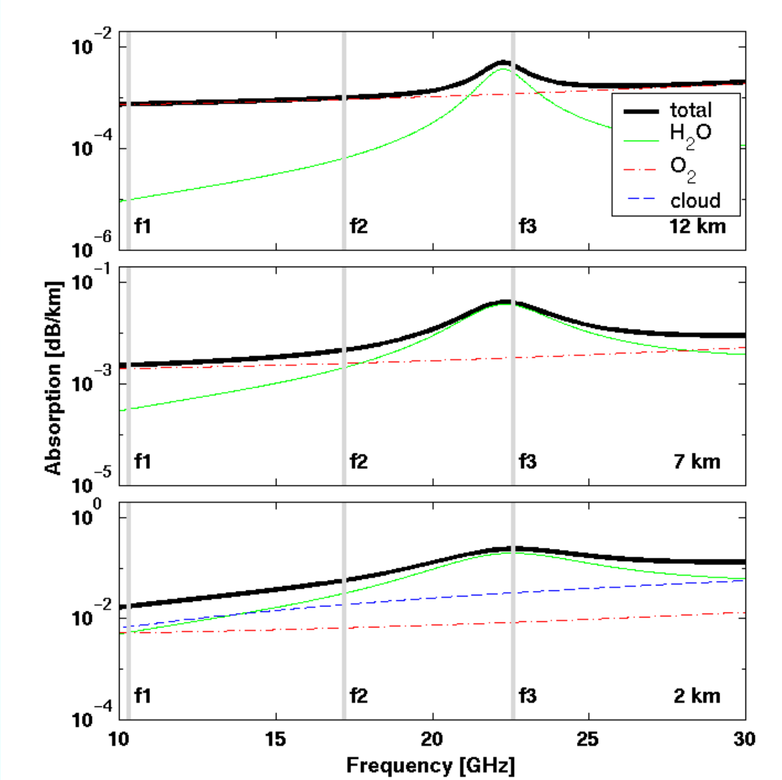
~7000 LEO-LEO occultation events/mon



(2Rx+2Tx ACE+ polar-orbiting LEO satellites;
2 planes, ~650 & 850 km, counter-rotating sats)

Beyond EGOPS4 – EGOPS5x
ACE+/CALLS Retrieval Simulations (Eriksson et al.)

ACE+ LEO-LEO Observation Performance



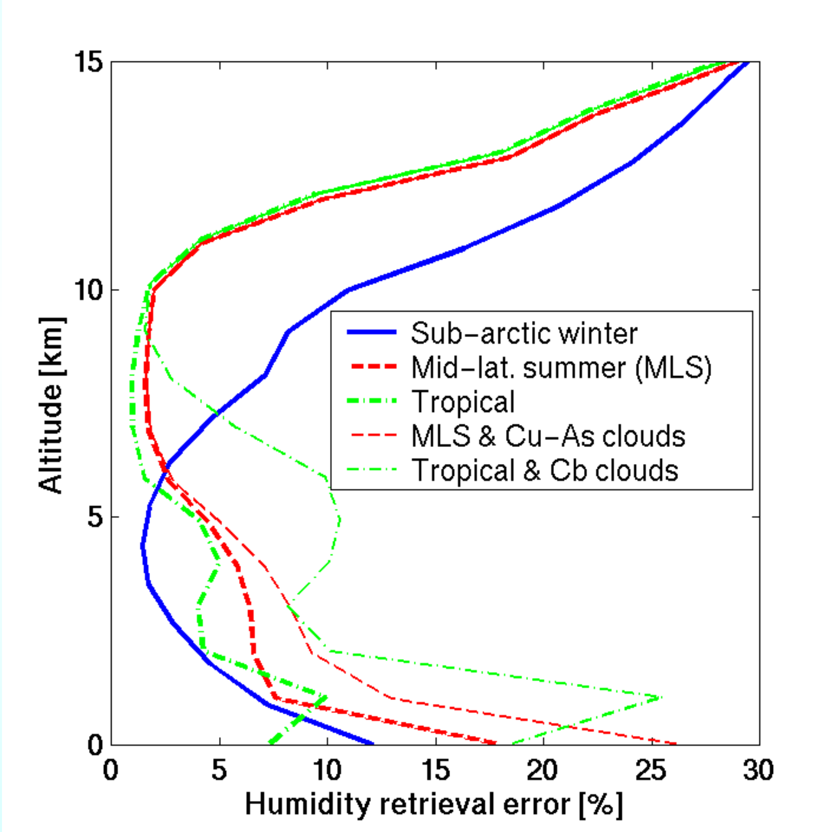
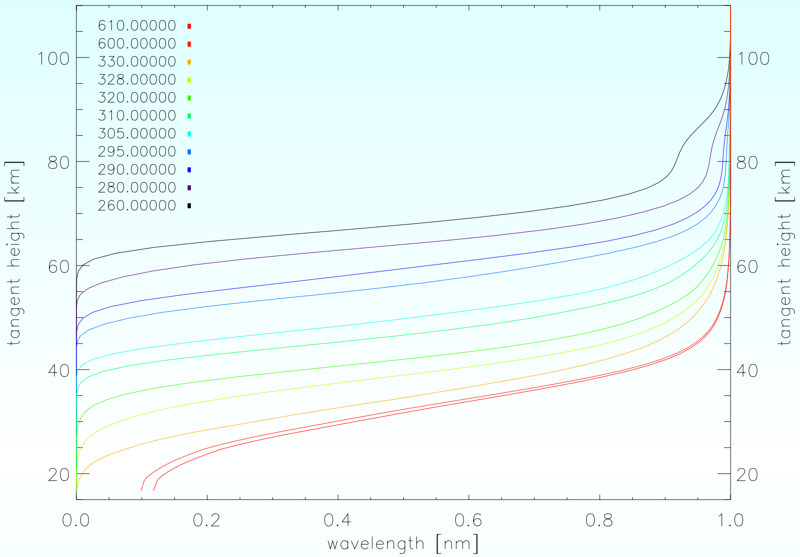
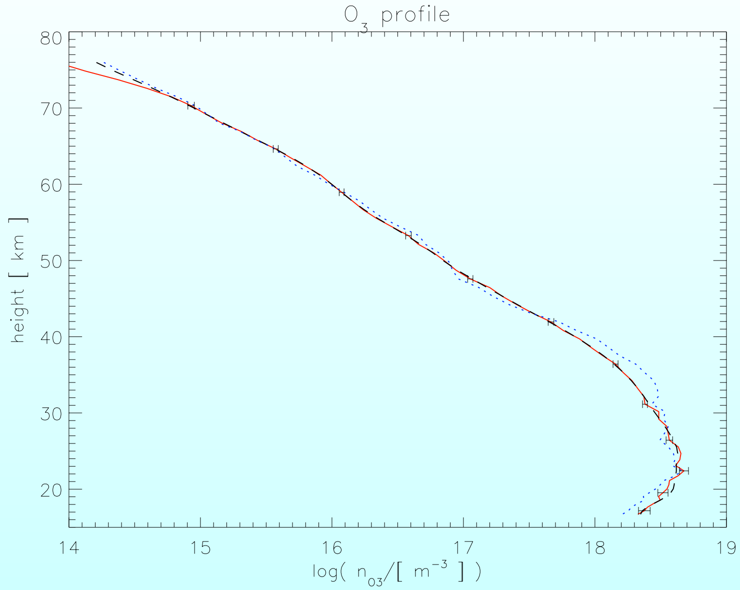


Illustration of absorption properties and humidity retrieval performance for LEO-LEO occultations (realistic sensor errors, moderate cloudiness, no horizontal variability)

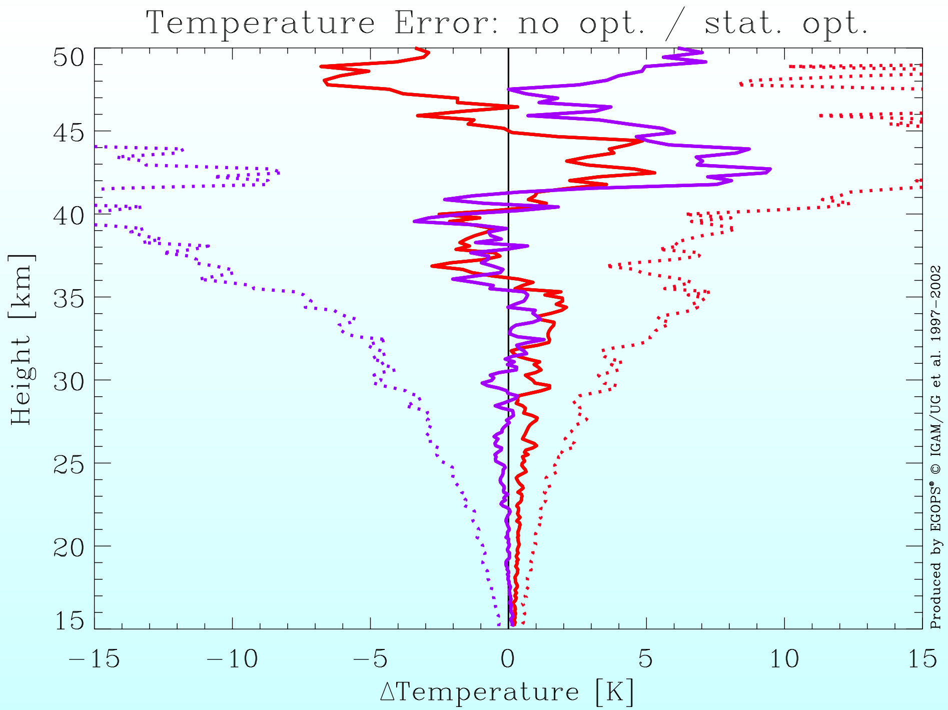
Beyond EGOPS4 – EGOPS5x
ENVISAT/GOMOS Simulations (EGOPS5-0.0)





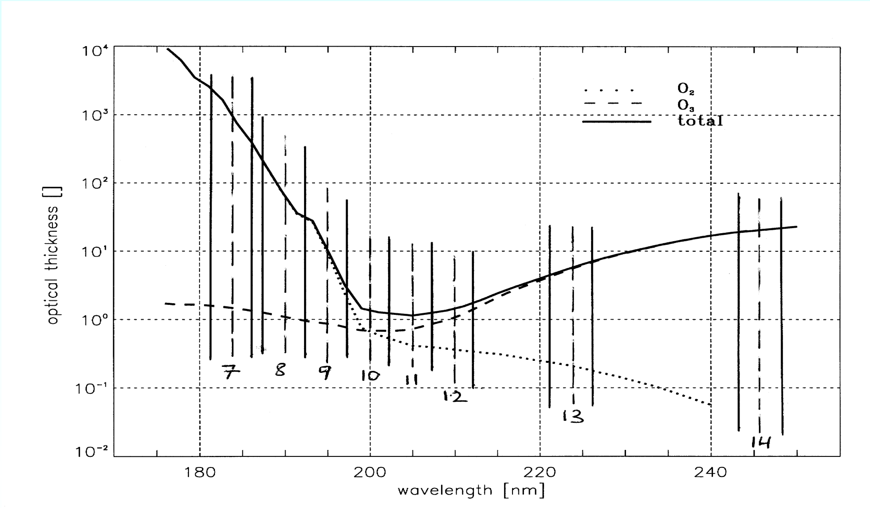
GOMOS - Global Ozone Monitoring by Occultation of Stars

(more info: talk by C. Retscher on Wed)



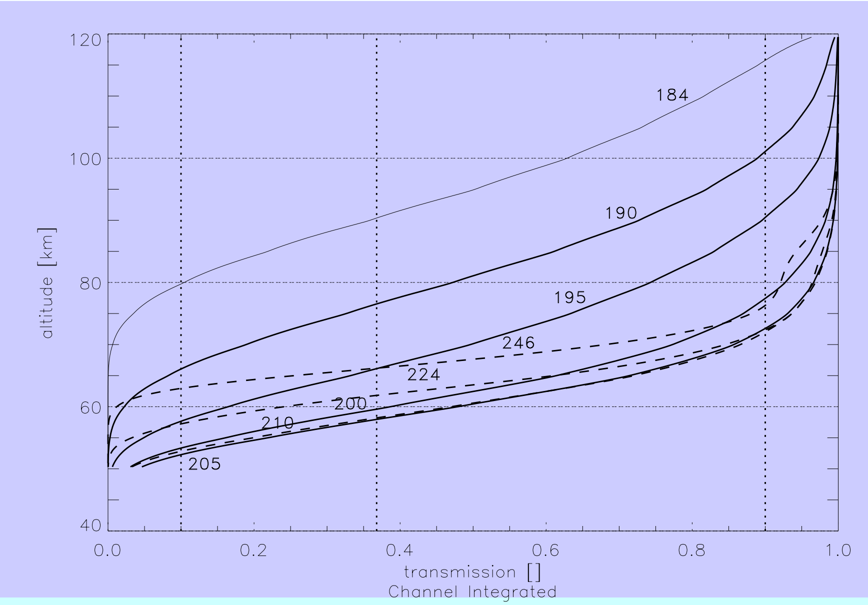
Beyond EGOPS4 – EGOPS5x

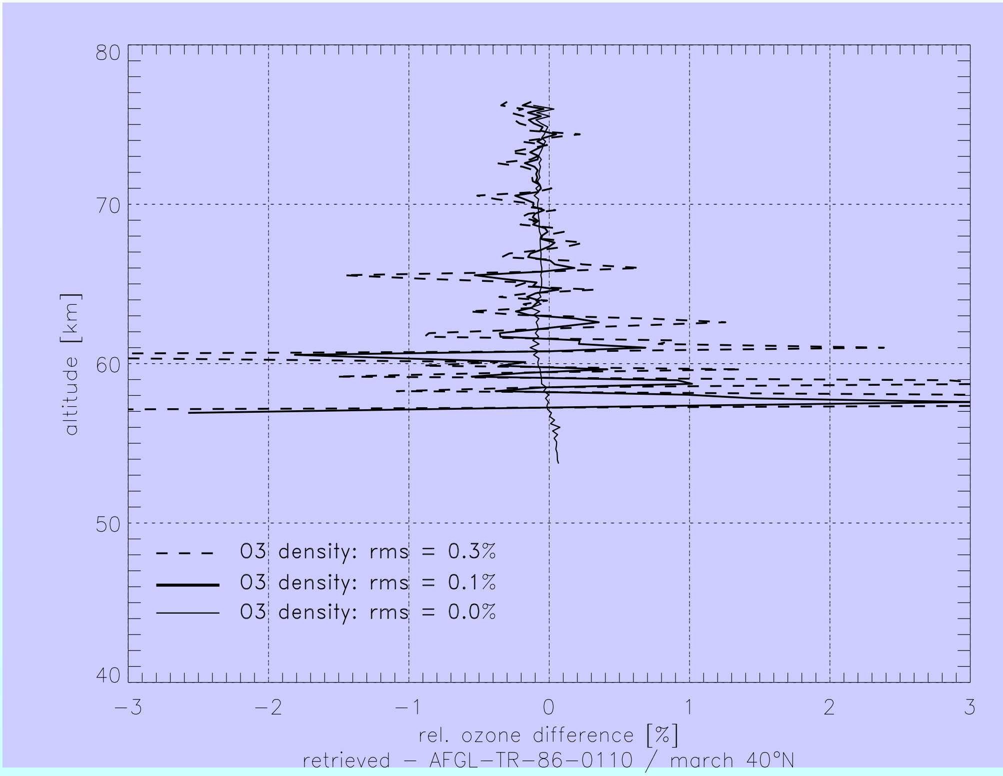
SMAS Performance Simulations (EGOPS5-0.0)



SMAS - Sun Monitor and Atmospheric Sounder

(more info: poster P5 by Rehrl and Kirchengast)





How to get EGOPS?
The Int'l EGOPS Maintenance Center (IEMC)

What is the International EGOPS Maintenance Center (IEMC)?
A service center hosted by IGAM/UG with the mission to provide, at best effort within available resources, a variety of EGOPS support services for the EGOPS user community.

IEMC Services.
Distribution and Licensing Services — 3 license options: Commercial-User License (COL), **Science-User License (SCL)**, ESA-User License (ESL; from ESTEC).
Support and Training Services — 3 support options: annually-renewable Support and Upgrade Agreement (SUA), Hours-based Support Agreement (HSA), Free-will Support (basic no-cost aid); — training: intensive two-day training courses at IGAM.
Study and Consulting Services — Cover the full field of occultation science and applications in meteorology, geophysics, and more. Modalities vary widely dependent on services provided.

IEMC Point of Contact and More Information.
Director: Gottfried Kirchengast, IGAM/UG Graz, Austria
E-Mail: *iemc.igam@uni-graz.at* or *gottfried.kirchengast@uni-graz.at*
Website: *http://www.uni-graz.at/igam-iemc*

"Never seen occultations so bright. – EGOPS."