wege entstehen, indem wir sie gehen
paths emerge in that we walk them

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The Reference Occultation Processing System approach to interpret GNSS Radio Occultation as SI-traceable Planetary System Refractometer

G. Kirchengast, M. Schwaerz, J. Schwarz, B. Scherllin-Pirscher, C. Pock, J. Innerkofler, V. Proschek, A.K. Steiner, J. Danzer, F. Ladstaedter, U. Foelsche

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Thanks to all further colleagues at WEGC (ARSCliSys Research Group) and all partners worldwide for valuable contributions and advice. See next slide for international advisers and cooperation partners…

Thanks for funds to esa, asap FFG, FWF

“Towards Reference Processing“ Session Presentation, OPAC-IROWG 2016, Seggau/Leibnitz, Austria, 12 September 2016

…international advisers and cooperation partners

- EUMETSAT: Christian Marquardt, Yago Andres, Axel von Engeln, Riccardo Notarpietro
- EUM/ROM SAF (DMI, ECMWF): Stig Syndergaard, Joe Nielsen, Kent Lauritsen, Sean Healy
- UCAR, JPL: Bill Schreiner, Doug Hunt, Tony Mannucci, Chi Ao
- IAP, TUG: Michael Gorbunov, Torsten Mayer-Gürr
- AIUB, DLR: Adrian Jäggi, Oliver Montenbruck
- NSSC/CAS, IGG/CAS, RMIT: Congliang Liu, Ying Li, Kefei Zhang

…and more may join as the work proceeds…thanks all!

Two main lines of cooperation:

- joint papers (on specific processing-related key issues to be solved)
- advice & expert meetings (~1-day review/advice meetings at WEGC)

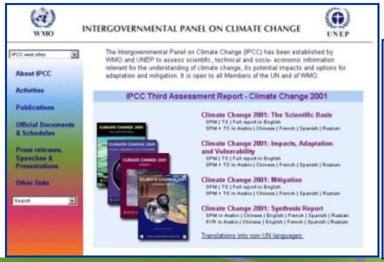
motivation 1: monitor the climate – three major reasons

We must solve the global climate monitoring problem with *benchmark data* techniques since…

…these unique data serve as fundamental backbone and “true” reference standard to atmosphere and climate science & services,

and more specifically, three major reasons:

- to rigorously observe and learn, independent of models, how weather and climate variability and change evolve, over weekly, monthly, seasonal, interannual, and decadal scales
- to test and guide the improvement of weather and climate models and thereby enhance their predictive skills for estimating future weather and climate
- to use the data as accurate observational constraints for natural and anthropogenic climate change detection and attribution



*...from the 9 **“high priority areas for action”** noted in the **IPCC 2001 report** (Summary for Policymakers, IPCC WG I, p. 17) - **still valid 15 years later in 2016:***

*“- **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.**”*

motivation 2: help solve with rOPS* – three views, one goal

* rOPS…Reference Occultation Processing System

Address the decades-long demand by IPCC, WCRP, WMO/GCOS,…:

- Accurate, long-term, consistent data, traceable to SI standards and providing a benchmark, are the backbone of contemporary climate science. => rOPS: provide it for atmospheric thermodynamic ECVs.

Address WEGC's overarching research question #1 (from its research strategy 2016-2020), for thermodynamic ECVs:

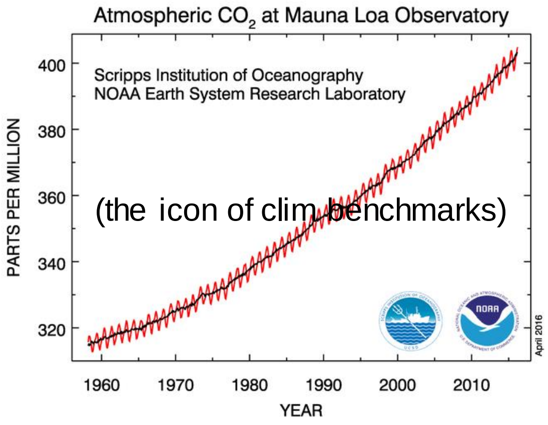
- How can we solve the global climate monitoring problem for the fundamental state of the atmosphere as imprinted in the most basic variables such as temperature and water vapor? => rOPS: solve it for (L, D, α, N,) $\boldsymbol{\rho}$, $\mathbf{p}$, (Z_p,) $\boldsymbol{T}$, *tropospheric* $\boldsymbol{q}$.

Address Rick Anthes' claim that he emphasized in opening talks at OPAC-IROWG 2013 and IROWG-4 2015, expanded to tropo.humidity:

- "GNSS radio occultation is the most accurate, precise, and stable thermometer & hygrometer from space." => rOPS: prove it for $\boldsymbol{T}$, *tropo.*$\boldsymbol{q}$

Which properties need such benchmark data to have and can GNSS RO provide these?

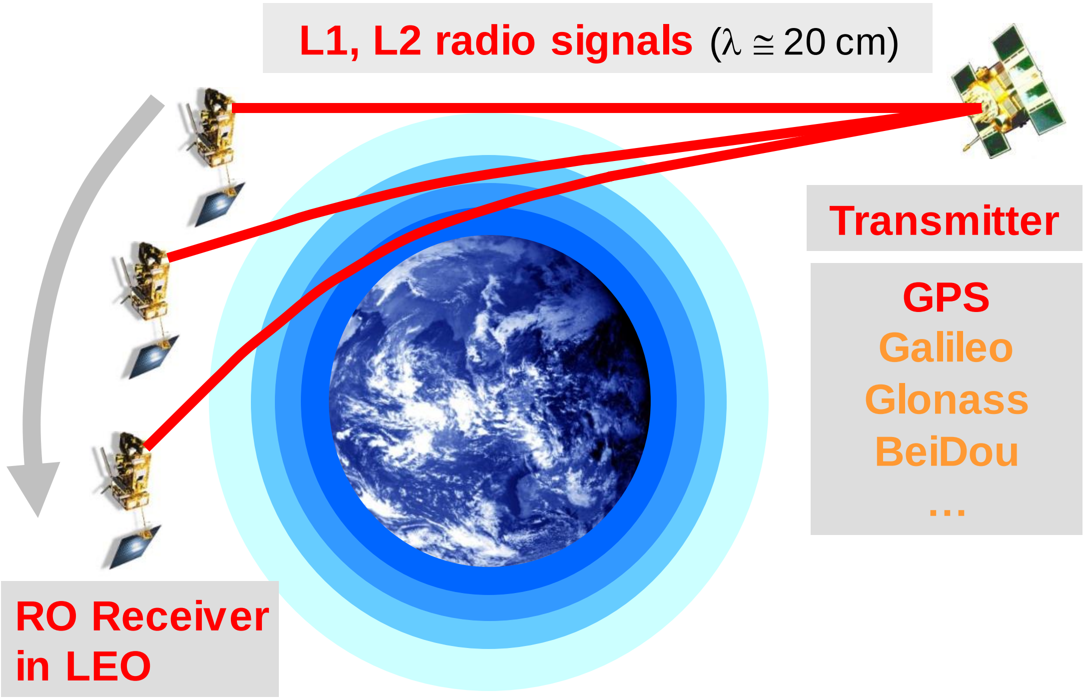
Key properties:



- long-term stable (over decades and longer)
- accurate (traceable to SI standards)
- globally available (all weather, same above land and oceans, etc.)
- measure sensitive indicators of atmosphere and climate change, in a physically consistent manner, in particular: => GCOS Essential Climate Variables (ECVs) (in the atmosphere: temperature, water vapor, wind, greenhouse gases, etc.) [e.g., GCOS Guideline, GCOS-143(WMO/TD No.1530), May 2010]

GNSS RO can provide such data for thermodynamic core ECVs over the (free) troposphere and stratosphere (i.e., TBL upwards).

GNSS RO – the principle and the promise



RO missions in Low Earth Orbit (LEO) so far:
GPS/Met (demo1995-97); CHAMP (2001-08), SAC-C, GRACE-A, F3/COSMIC, MetOp-A/-B, TerraSAR-X,…

- setting & rising RO events in an active limb sounding geometry (occultation geometry) exploit the
- atmospheric refraction of two GNSS L-band signals, providing
- self-calibrated measurements of excess phase path *L* / Doppler shift *D* traceable to universal time (SI second) for the retrieval of
- bending angle α and in turn key atm&clim variables (core ECVs) refractivity, air density N, ρ, pressure, geopot.height p, Z_p, temperature, tropo.humidity T, q.

The ***RO promise*** *for climate (and beyond) – unique combination of:*

\+ high accuracy & long-term stability (from SI traceability), at high vertical resolution; regular, all-weather global coverage;

=>bench-qual reference processing needed to really meet the promise=>rOPS.

GNSS & LEO systems – RO data coverage & availability...

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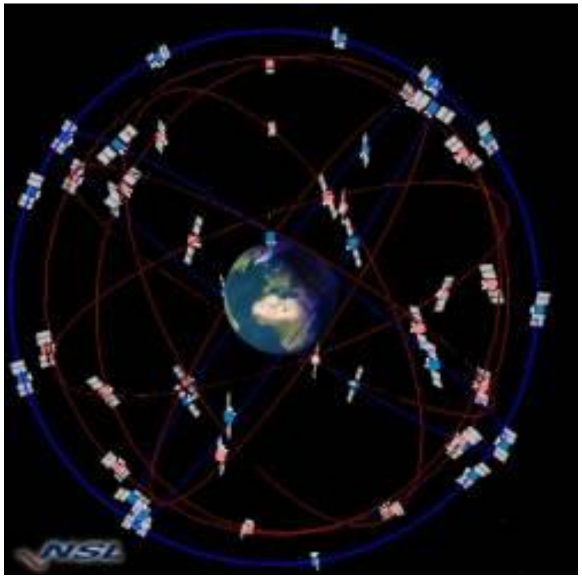
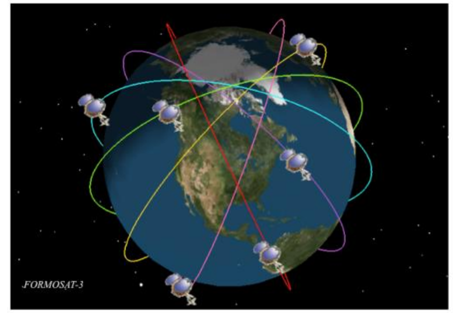
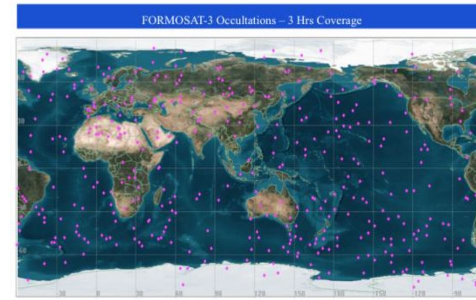
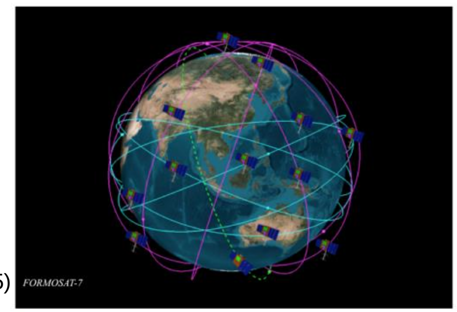
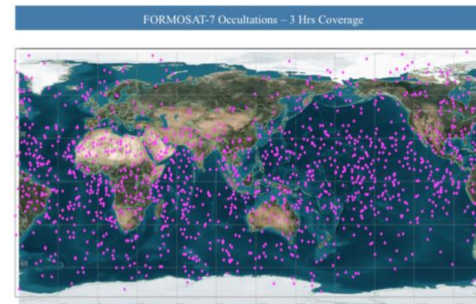


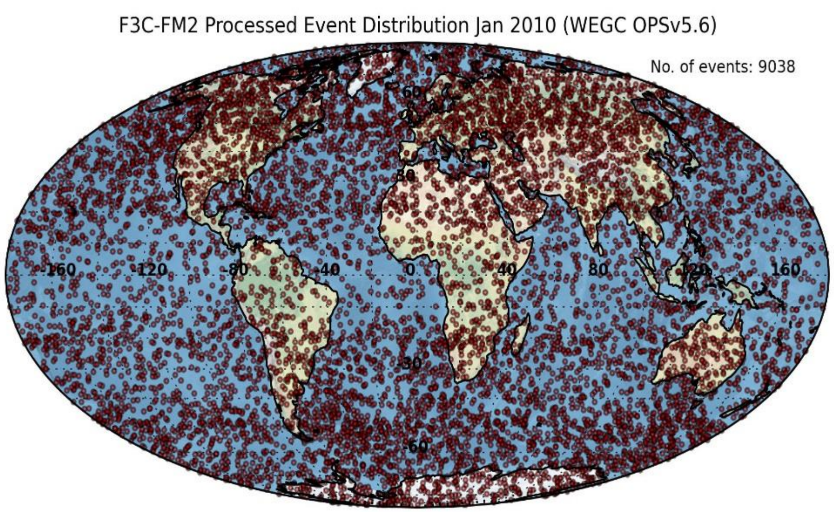




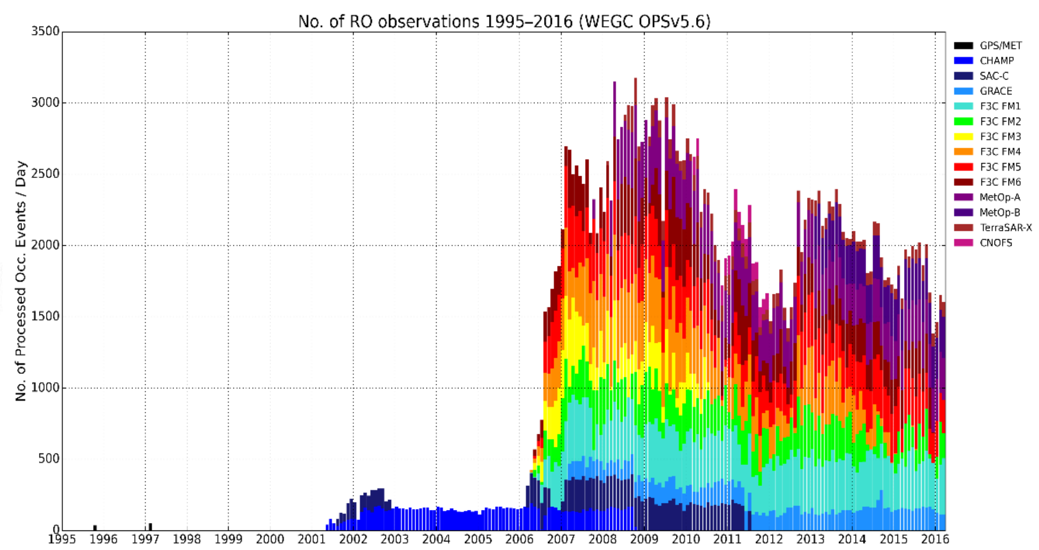




(Fig. courtesy: InsideGNSS (top), UCAR Boulder (right), 2015)



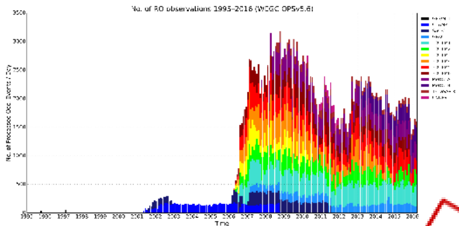
(Fig. courtesy: F. Ladstädter/WEGC, 2016)

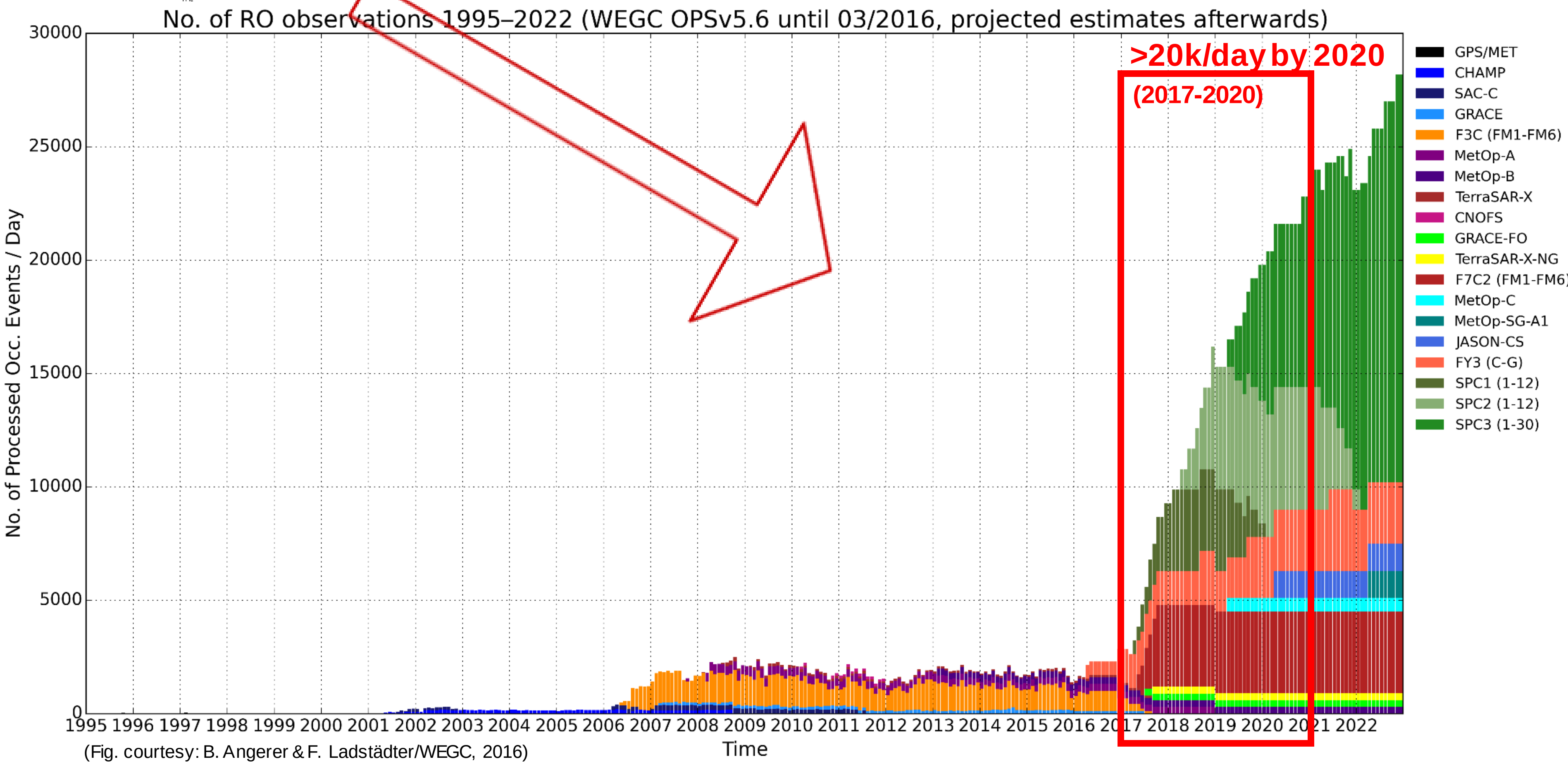


(Fig. courtesy: B. Angerer & F. Ladstädter/WEGC, 2016)

Projections show about-10-fold increase until 2020

- Ops RO (COSMIC's, MetOp's, FY3's,...) remain core basis
- New private/public Nanosat RO constellations heavily add





(Fig. courtesy: B. Angerer & F. Ladstädter/WEGC, 2016)

=>state-of-the-art multi-sat ref. data capability needed to cope with=>rOPS.

RO data quality – high consistency, accuracy, stability

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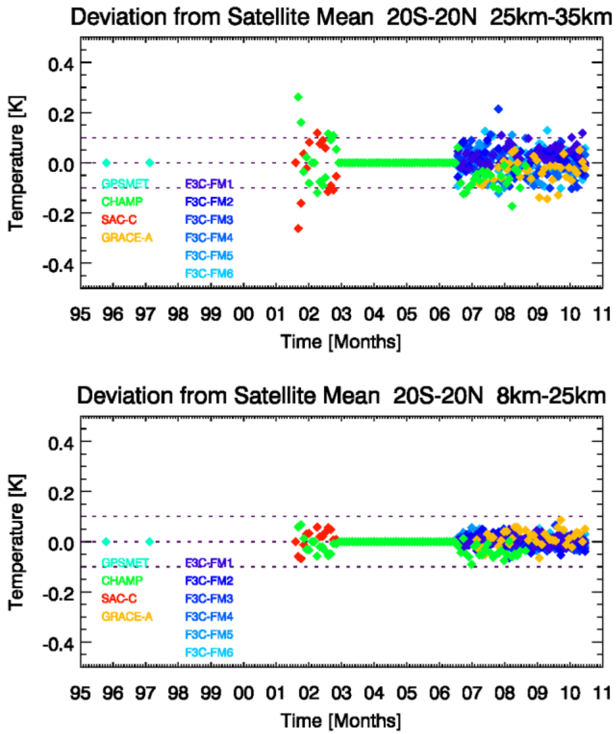
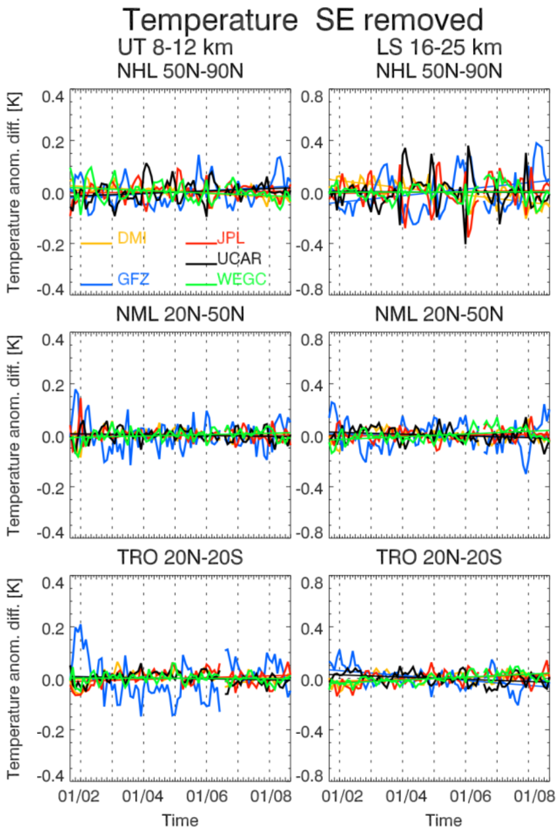
- **consistency of different satellites**
  One processing center WEGC



- **different processing centers**
  Structural uncertainty CHAMP



- **meeting WMO/GCOS climate monitoring targets** in upper troposphere/lower stratosphere (UTLS)
- **long-term stable within ~0.1 K/decade**

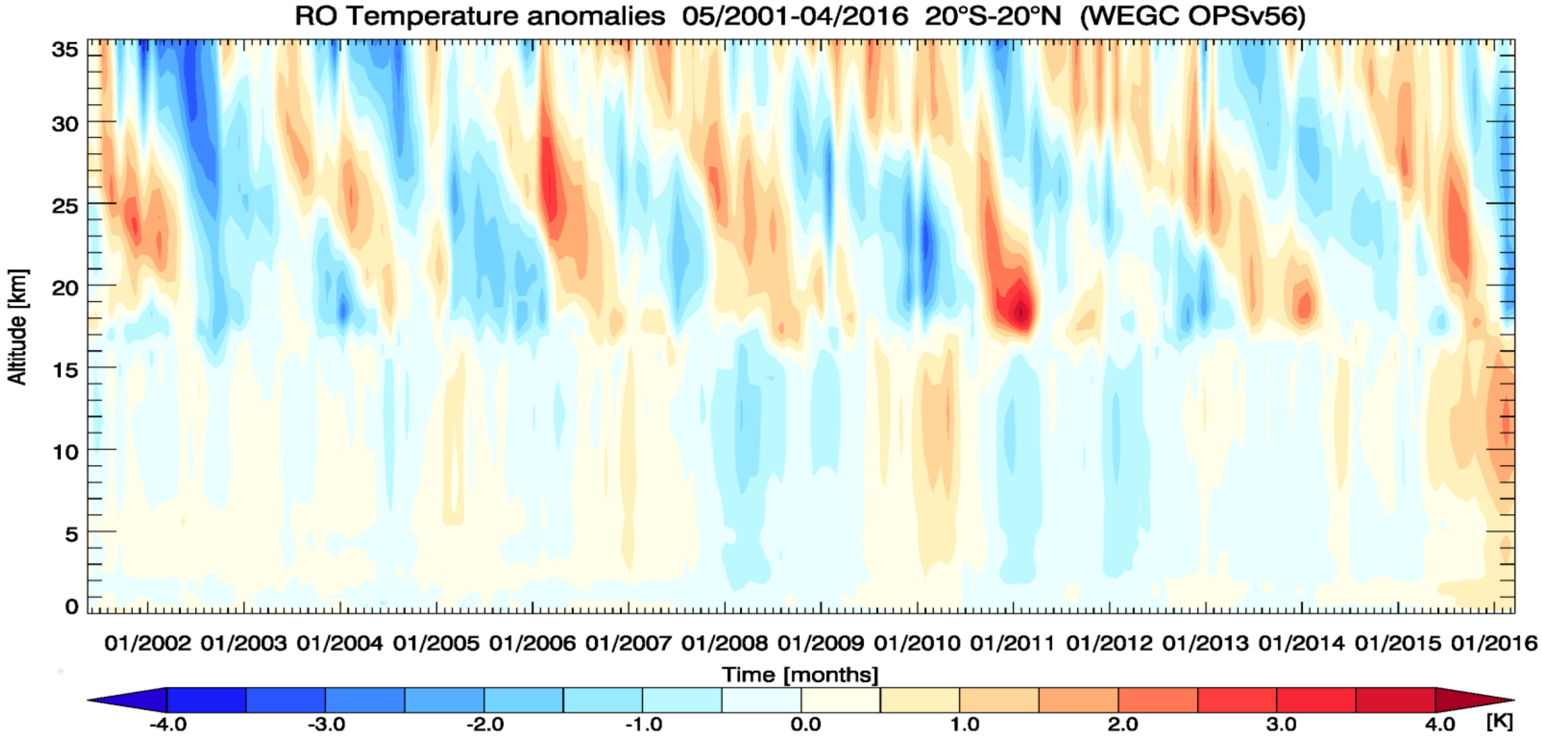
[Foelsche et al. *TAO* 2009, *AMT* 2011; Ho et al. *JGR* 2009, 2012; Steiner et al. *GRL* 2009, *ACP* 2013]

Quasi-Biennial Oscillation (QBO)

- Tropical lower **stratosphere**, core band ~10°S–10°N, ~28 months period
- Seasonal-interannual changes in radiative heating & wave momentum fluxes

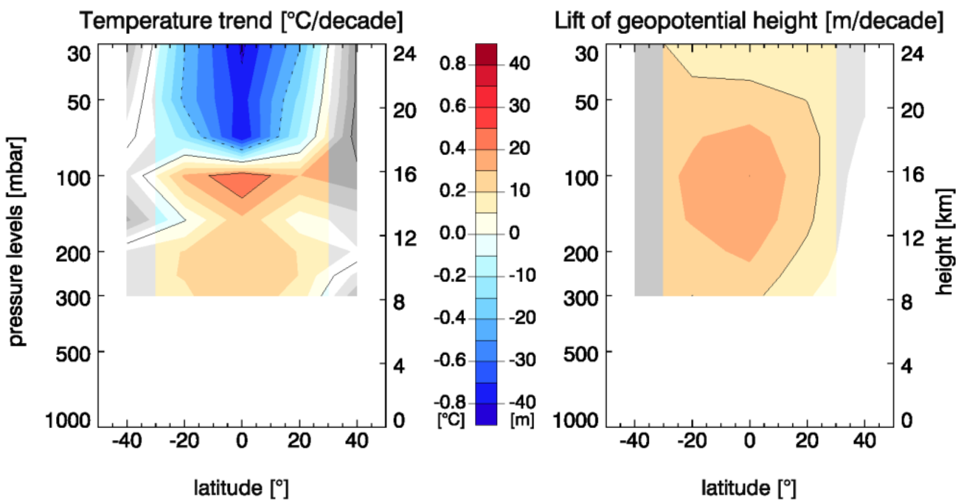
El Niño Southern Oscillation (ENSO)

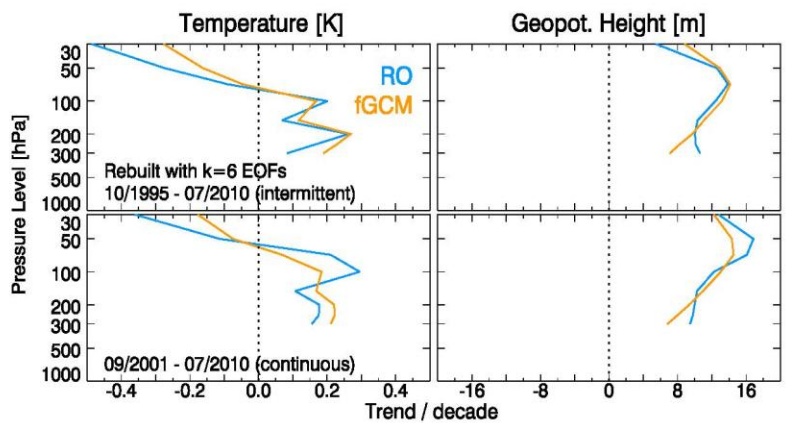
- Phenomenon with quasi-periodicity of about 3 to 7 years in **troposphere**
- Interannual changes in sea surface temperature of the tropical Pacific



[Scherllin-Pirscher et al. *GRL* 2012; fig. updated 2016]

Climate change signal detection





Mean Trend 50°S–50°N

- Emerging climate change signal in the RO record
- Warming of the troposphere, Cooling of the stratosphere
- Uplift of geopotential height levels in upper troposphere
- Temperature (90% conf. level), geopotential height (95% conf. level)
- Consistency with detection times of ~10–16 years, *Z(p)* first

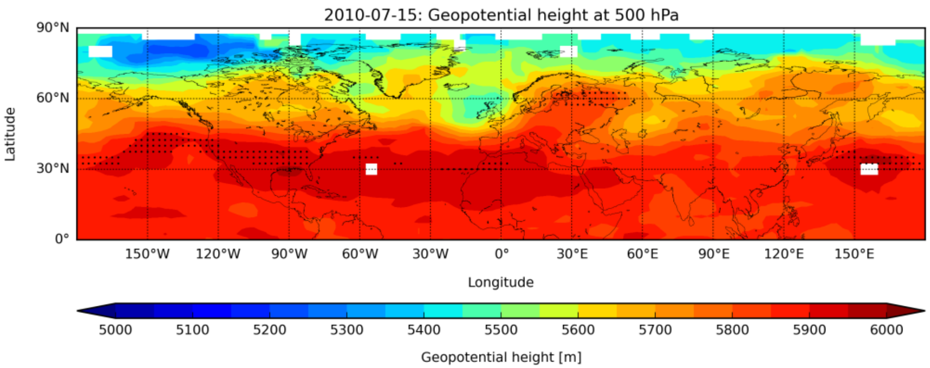
  [Leroy et al. *JGR* 2006, Foelsche et al. *JGR* 2008, Ringer and Healy *GRL* 2008].

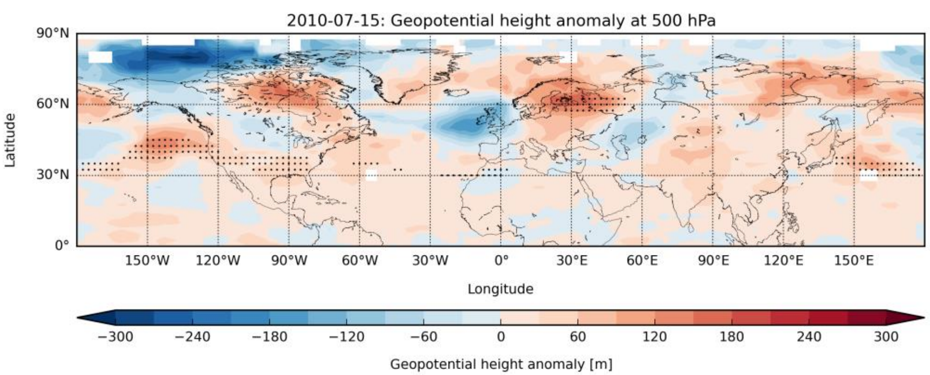
[Lackner et al. *JCLIM* 2011; Steiner et al. *Radio Sci.* 2011]

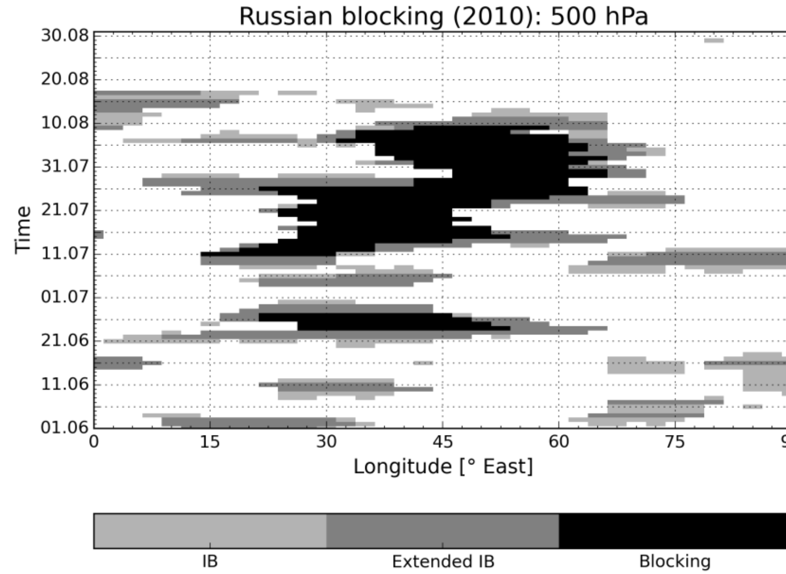
climate extremes from RO – example mid-lat blocking

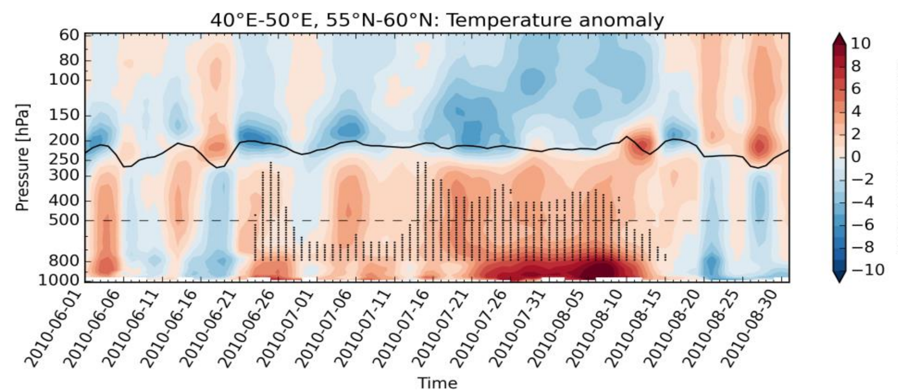
- Tracking Atmospheric blocking with RO
- Blocking pattern & identification at 500 hPa
- Vertical structure of blocking in geopotential height, and thermal structure anomalies

Example: **the famous "Russian Blocking" of Jul-Aug 2010 that led to an extreme heat wave**









[Brunner et al. *ACP* 2016]

existing RO quality – status good in 'core region' but… (1)

Atmos. Chem. Phys., 13, 1469–1484, 2013
www.atmos-chem-phys.net/13/1469/2013/
doi:10.5194/acp-13-1469-2013

Atmospheric Chemistry and Physics
Open Access

Quantification of structural uncertainty in climate data records from GPS radio occultation

A. K. Steiner[1,2], D. Hunt[3], S.-P. Ho[3], G. Kirchengast[1], A. J. Mannucci[4], B. Scherllin-Pirscher[1,3], H. Gleisner[5], A. von Engeln[6], T. Schmidt[7], C. Ao[4], S. S. Leroy[8], E. R. Kursinski[9], U. Foelsche[1], M. Gorbunov[10], S. Heise[7], Y.-H. Kuo[3], K. B. Lauritsen[5], C. Marquardt[6], C. Rocken[3], W. Schreiner[3], S. Sokolovskiy[3], S. Syndergaard[5], and J. Wickert[7]

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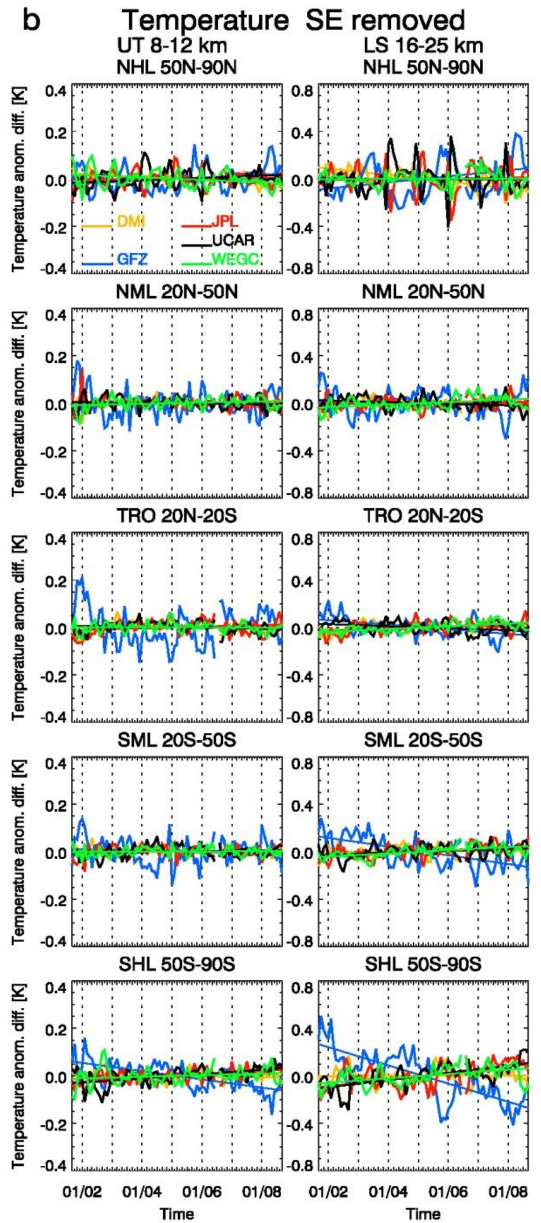
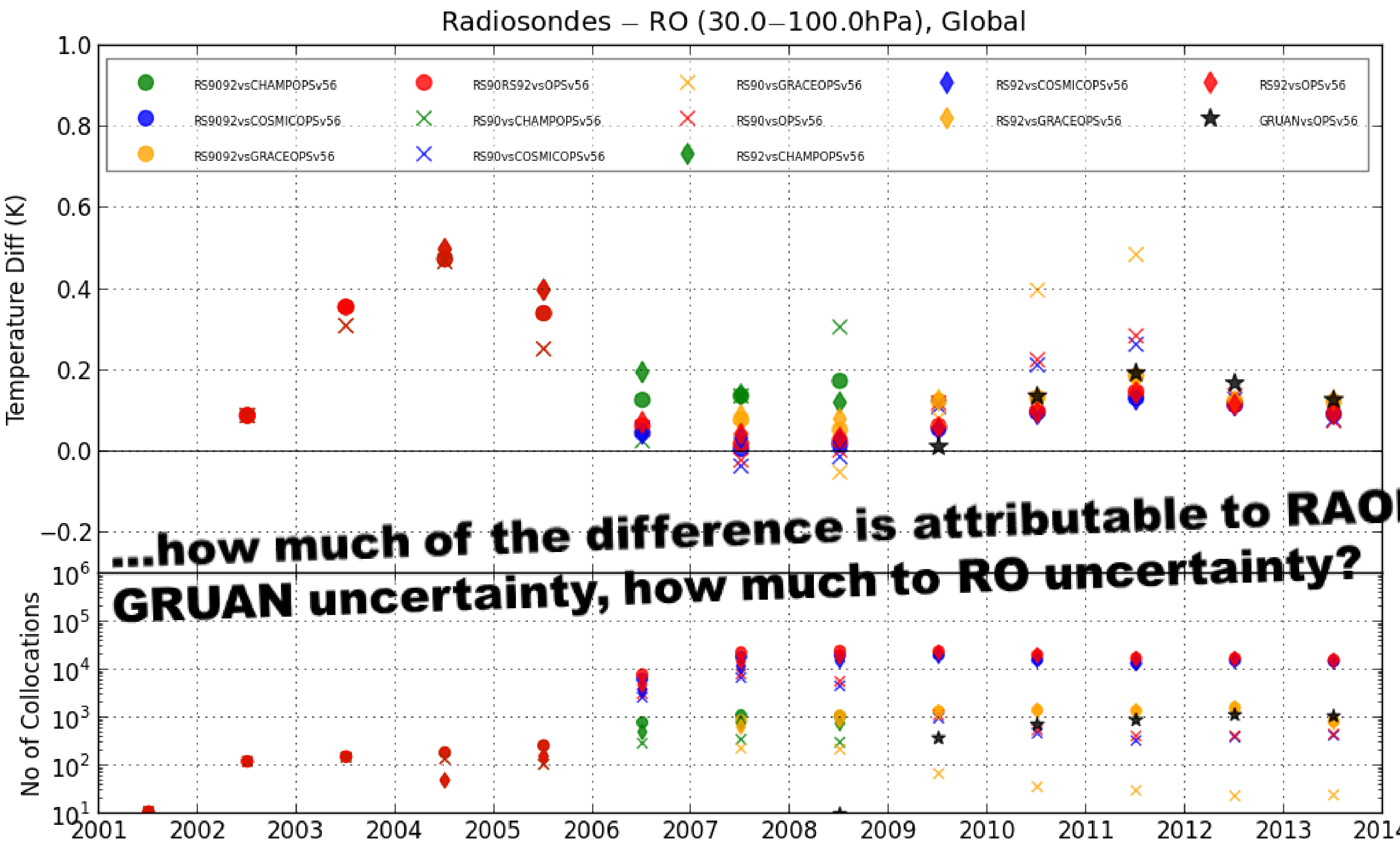


"…Larger structural uncertainty above about 25 km and at high latitudes is attributable to differences in the processing schemes…climate trend assessment is bound to 50°S to 50°N…" *=> We need more…*

[Steiner et al. *ACP* 2013]

RAOBs V90/92 and GRUAN vs RO-OPSv5.6 CHAMP, GRACE, COSMIC

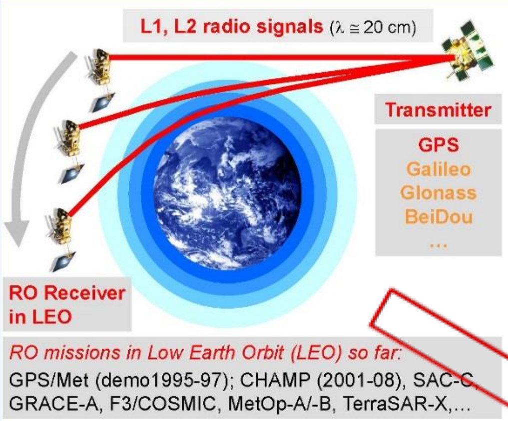
- Annual-mean temp differences (global, example altitude range 100hPa–30hPa)



…how much of the difference is attributable to RAOBs & GRUAN uncertainty, how much to RO uncertainty?

[Ladstaedter et al. *AMT* 2015]

so what? rOPS! – the view of planetary system analysis (1)



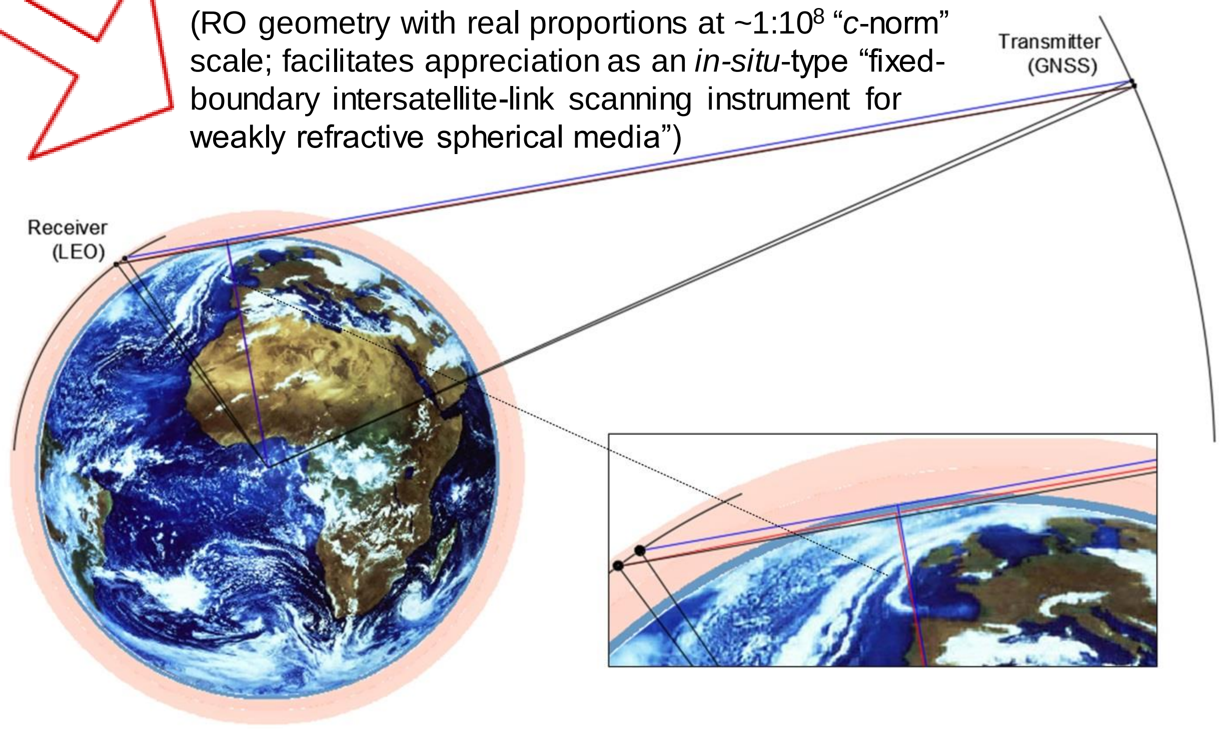
- setting & rising RO events in an active limb sounding geometry (occultation geometry) exploit the
- atmospheric refraction of two GNSS L-band signals, providing
- self-calibrated measurements of excess phase path L / Doppler shift D traceable to universal time (SI second) for the retrieval of
- bending angle α and in turn key atm&clim variables (core ECVs) refractivity, air density N, ρ, pressure, geopot.height p, Z_p, temperature, tropo.humidity T, q.

rOPS change of viewpoint is key: from a classical remote-sensing-type view of RO ("remote sensing data inversion chain approach") to viewing it as an *in-situ-type planetary system instrument* ("system modeling & data analysis approach")

Overall goal of the rOPS:

provide benchmark-quality reference RO data for calibration/validation and for climate monitoring, research, and services, complementary to NRT.

(RO geometry with real proportions at ~1:10^8 "c-norm" scale; facilitates appreciation as an *in-situ*-type "fixed-boundary intersatellite-link scanning instrument for weakly refractive spherical media")



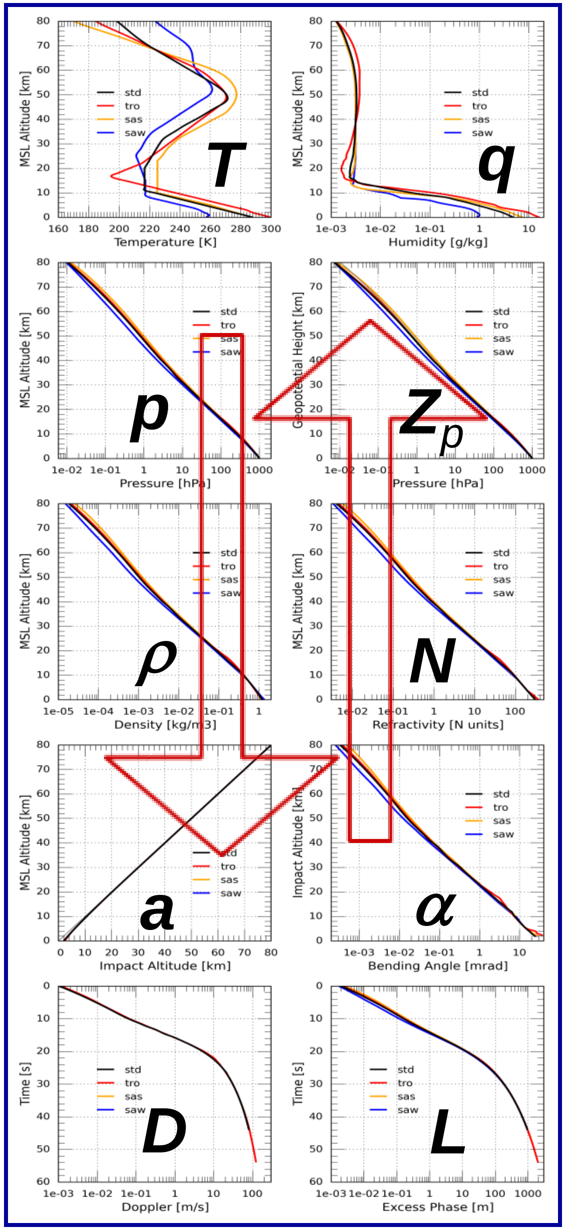
so what? rOPS! – the view of planetary system analysis (2)

The fresh rOPS approach allows highly reversible analysis up and down the chain of all RO variables, enables SI-traced profiling and uncertainty estimation.

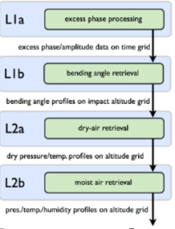
Logic of the rOPS system modeling and data analysis approach:

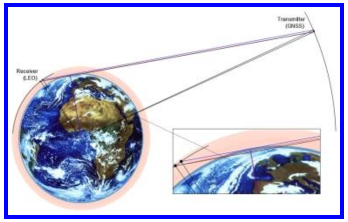
Category	System	Subsystem	Description
System modeling	Background and obs. system modeling (daily)	Atmosphere system and Atm.Uncertainty system	ECMWF (An, Fc): atmos. state, forward modeling; weather-filtered data for uncertainties&correlations
		Ionosphere system	CODE & IGS: GNSS vTECs incl. uncertainties
		Geometry system (GNSS and LEOs)	CODE & IGS: GNSS orbits incl. uncertainties; then from Bernese & Napeos: LEO orbits, uncertainties
	Occultation event system modeling (per event)	Event geometry model	WGS84/EGM2008/ECEF: RO event geometry
		L2 data model L1 data model Vertical grid model	ECMWF Fc, An at RO event loc. (T, q, p, ρ, p_d, T_d, N) ECMWF Fc forward modeled ($N \rightarrow \alpha \rightarrow D \rightarrow L$) altitude z / pressure $p \leftrightarrow$ imp.parameter $a \leftrightarrow$ time t
		Geometry operators	Link the chain $L \leftrightarrow D \leftrightarrow \alpha \leftrightarrow N \leftrightarrow p_d, T_d \leftrightarrow \rho, p, T, q$
		Residual bias modeling	Bias estimates for RO retrieval approximations (e.g., spherical symmetry, hydrostaticity, clear air)
Data analysis	RO data processing (per event)	L1a processor	Raw data ($L0_p$) to excess phase level data (L1a)
		L1b processor	Excess phase/SNR to atmos. bending angle (L1b) $t \rightarrow a$ space; obs. only, no bgr. info
		L2a processor	Bending angle to refrac. and dry-air variables (L2a) $a \rightarrow z$ space; bgr. from high-alt. initialization only
		L2b processor	Dry-air variables to moist-air variables (L2b) tropospheric retrieval in z space; bgr. info on T, q

Output: SI-traced atmospheric profiles and uncertainty estimates (estimated systematic and combined standard uncertainties, error correlation matrices, obs-to-bgr weighting ratios)



rOPS – data processing with 4 processors along 3 tracks





Four processors:

- Level 1a processor: Raw data ($L0_p$) to excess phase level data (L1a)
- Level 1b processor: Excess phase/SNR to atmos bending angle (L1b)
  ($t \rightarrow a$ space; obs only, no bgr info)
- Level 2a processor: Bending angle to refrac and dry-air variables (L2a)
  ($a \rightarrow z$ space; bgr info from high-altitude initialization only)
- Level 2b processor: Dry-air variables to moist-air variables (L2b)
  (tropo moist-air retrieval in z space; bgr info on T, q)

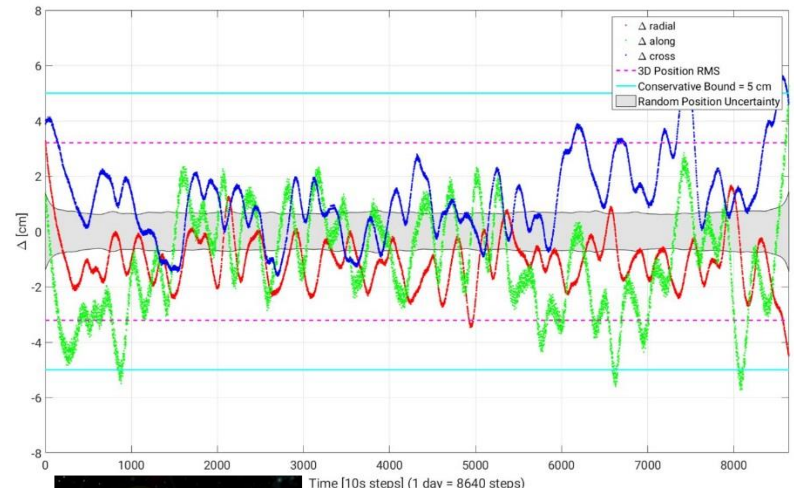
Three processing tracks:

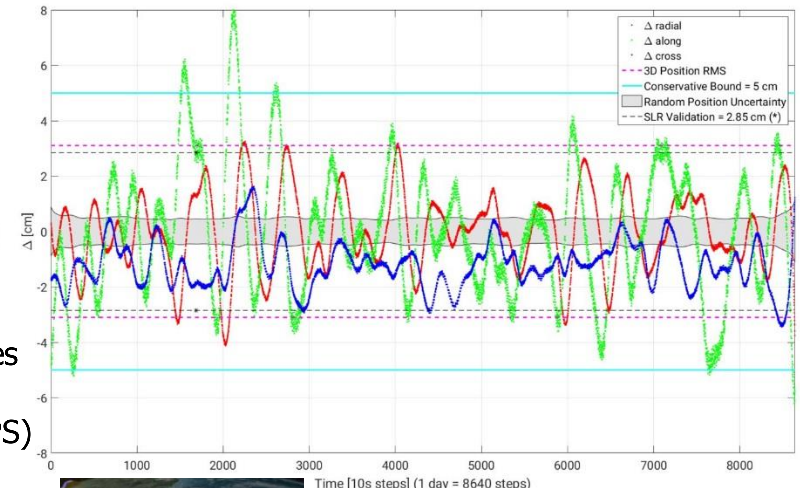
- Fast-track reference (FTR) data: daily on follow-on day of observations
- Postprocess-track reference (PTR) data: daily within one month latency
- Re-processing reference (RPR) data: occasionally (kicked of manually), as highest-fidelity climate records over entire multi-satellite periods

Asset ⇒ the prior systems modeling enables innovative processing design

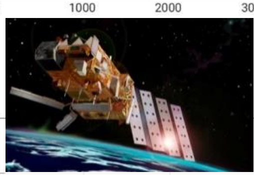
rOPSv1 LEO Rx system modeling – daily LEO orbit example results

- Bernese vs. Napeos and SLR validation consistent within < 5 cm, < 0.05 mm/s

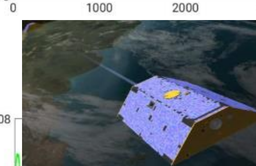




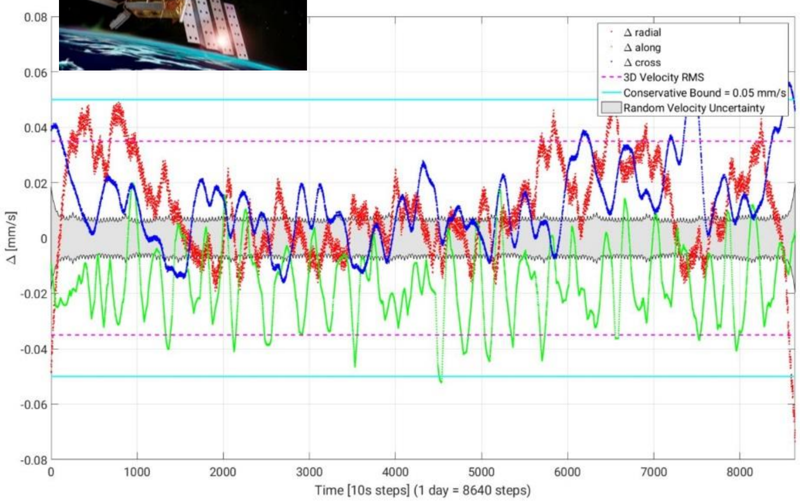
position (Bernese–Napeos differences X, Y, Z; CODE-GPS)

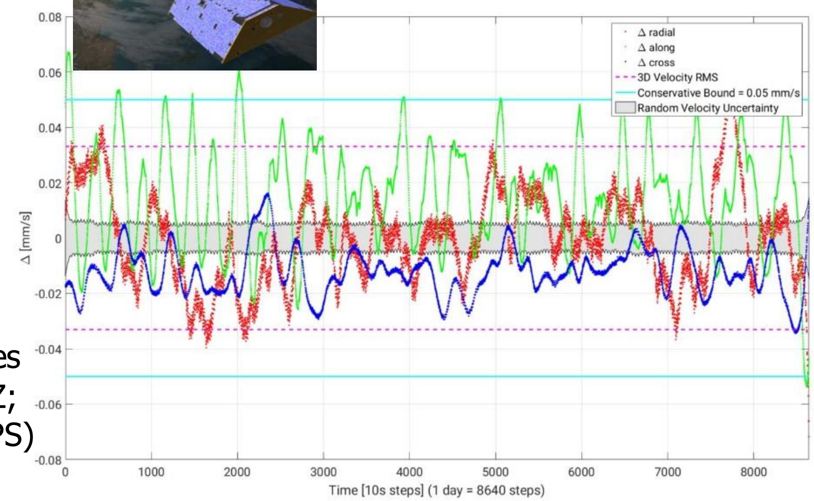


MetOp-A (test day 15 Jan 2011)



GRACE-A (test day 22 Apr 2012)





velocity (Bernese–Napeos differences vX, vY, vZ; CODE-GPS)

*More info DSM & L1a => **Innerkofler et al. next talk!***

rOPS – L1b-L2a uncert. propagation example ($\alpha \rightarrow p_d, T_d$)

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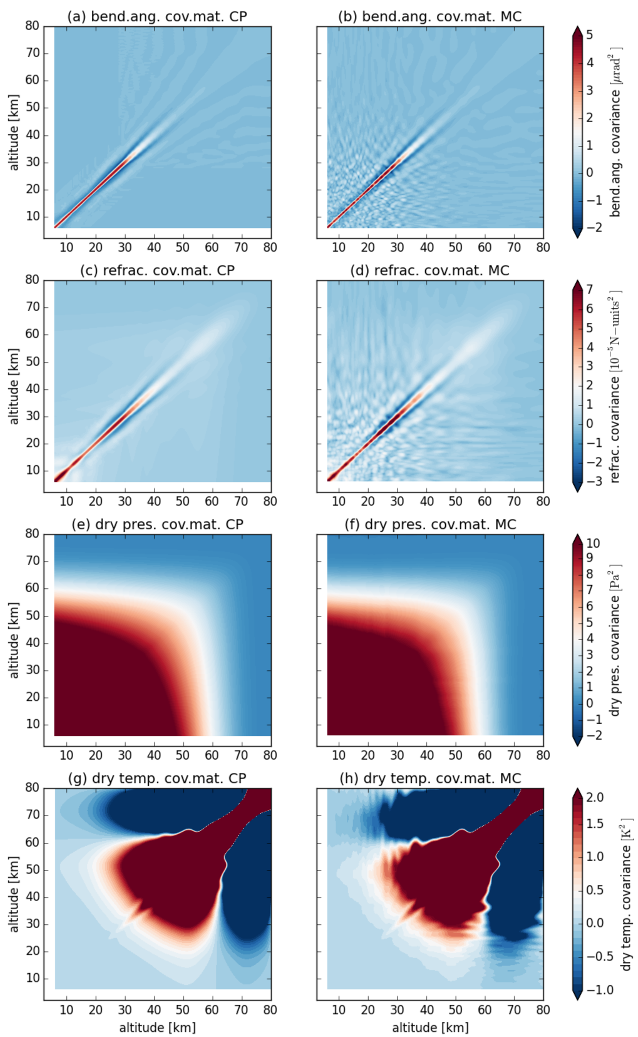
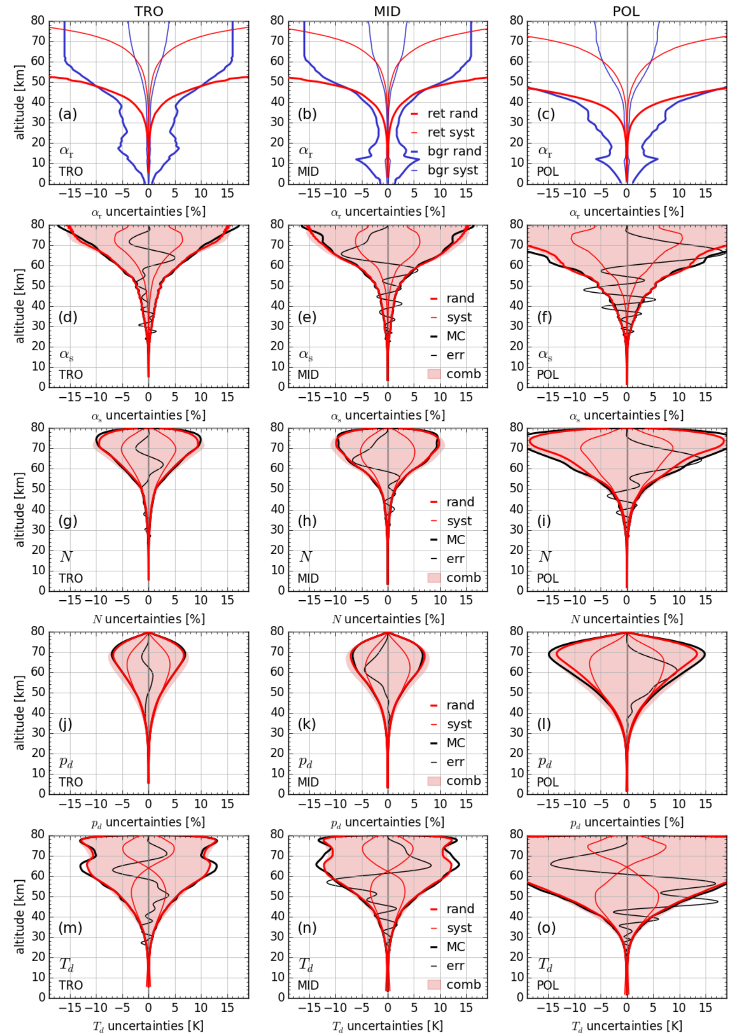
rOPSv1 L2a bend.angle to dry-air processing chain – example results

- Covariance propagation and flow of random & systematic uncertainty estimates

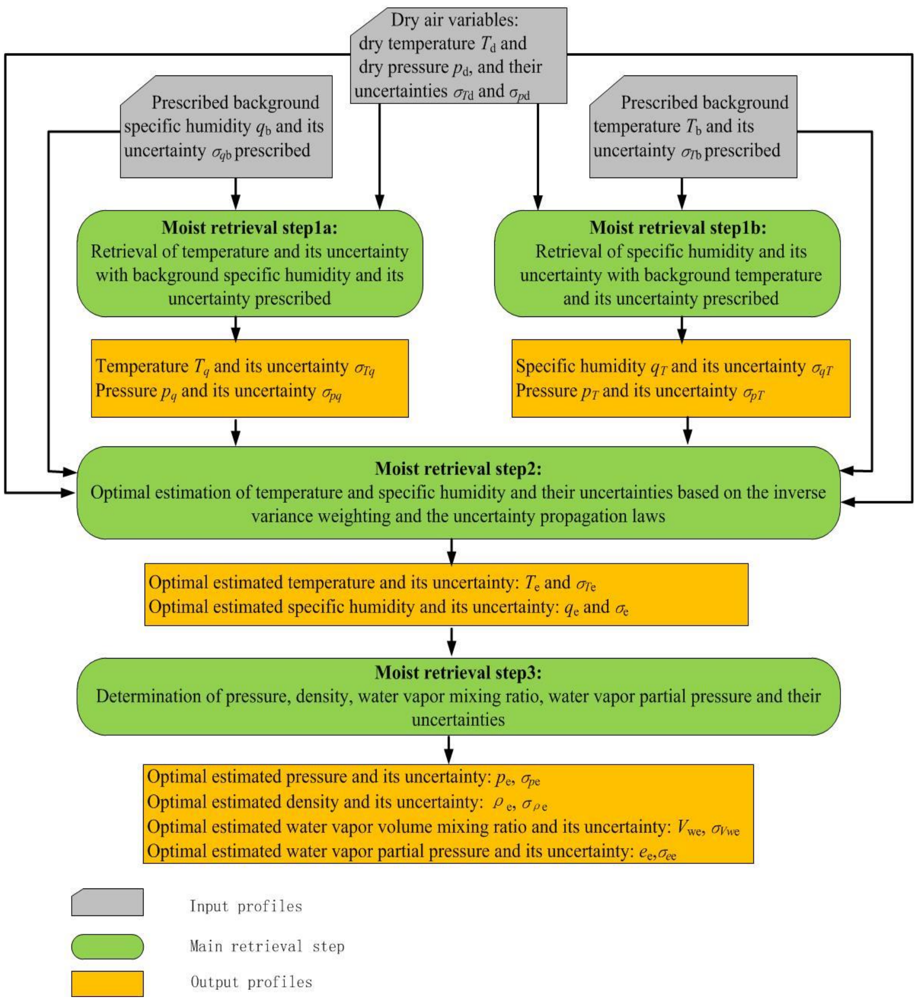


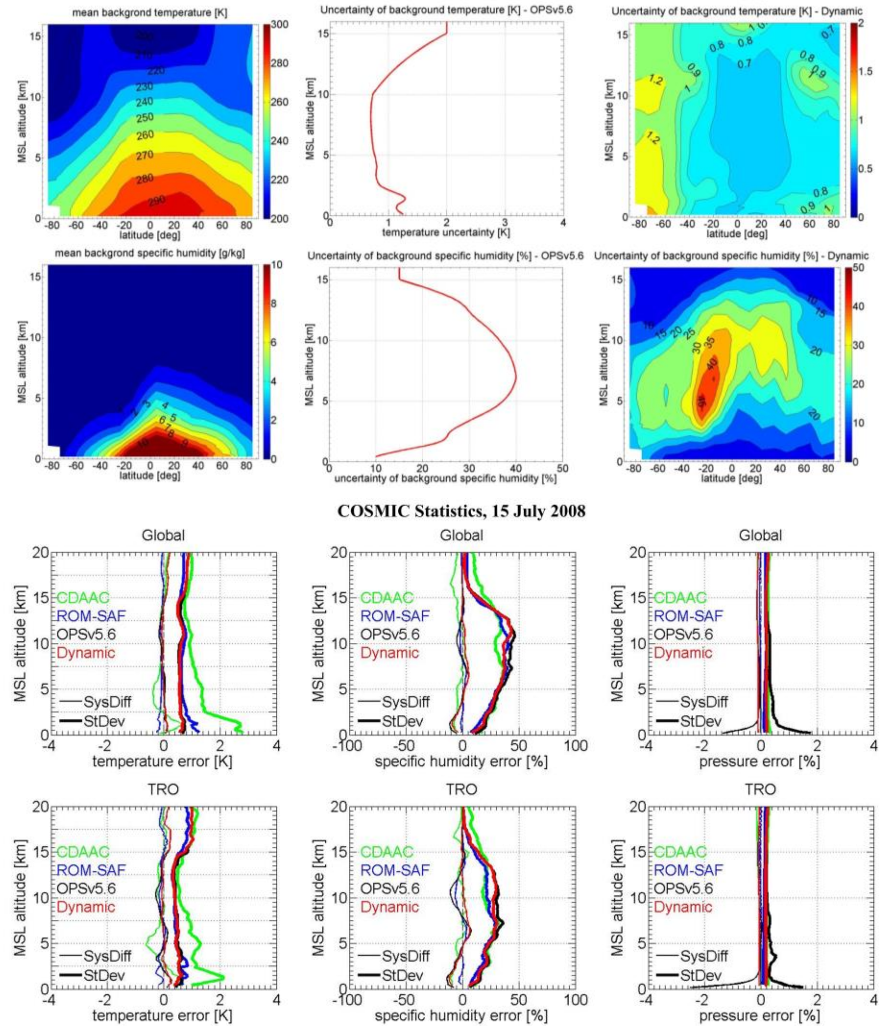


*More info L1b & L2a => **Schwarz et al. 2nd-next talk!***

rOPSv1 L2b moist-air processing chain evaluation – example results

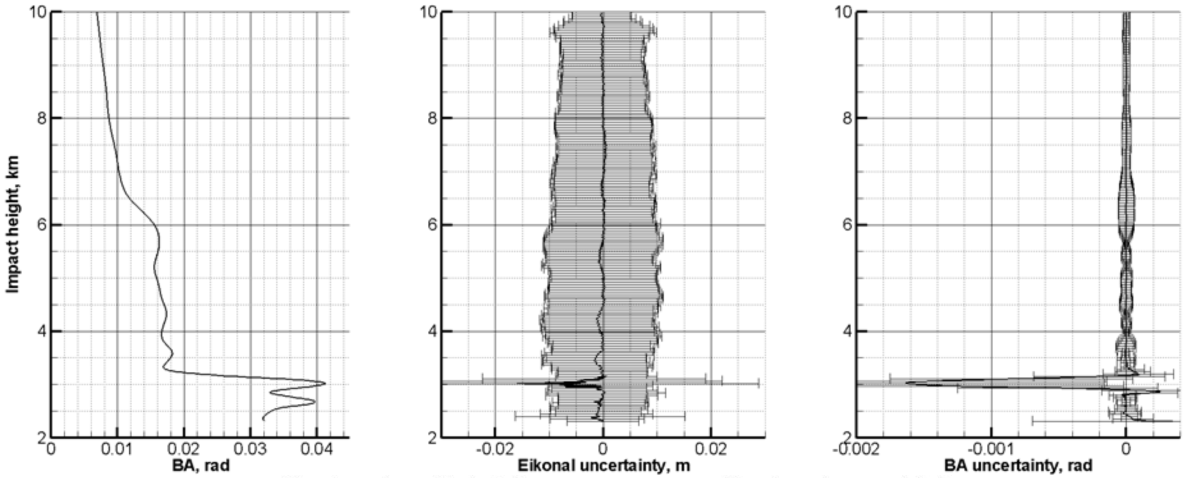
- New moist-air algorithm, dynamic bgr. uncertainties, results intercomparison…





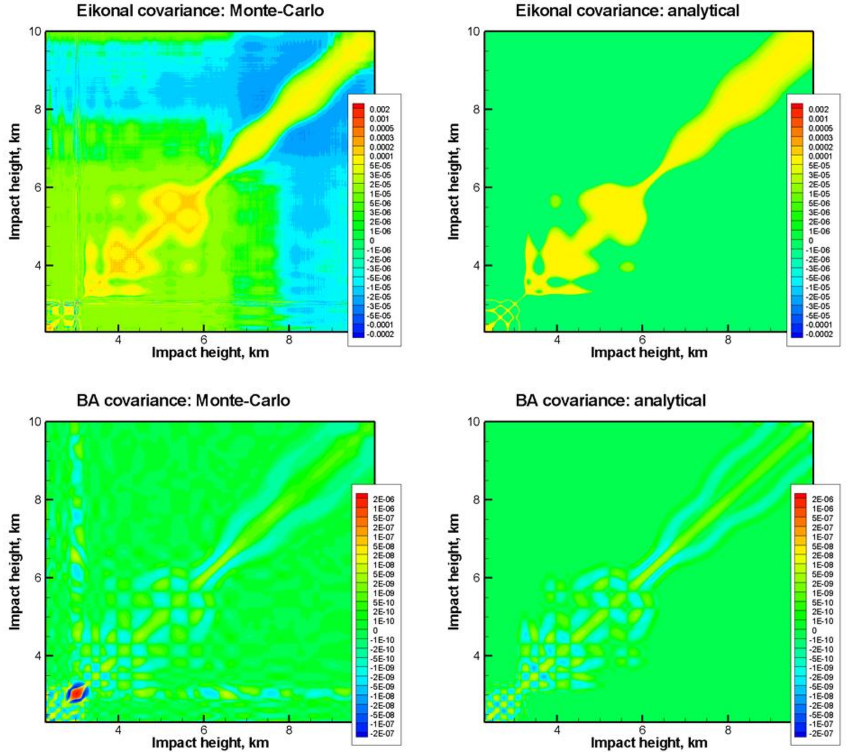
*More info L2b => **Li et al. 3rd-next talk!***

rOPS – WO-based uncert. propagation example ($L \rightarrow \alpha$)



Tropical example case for wave optics uncertainty propagation– excess phase to bending angle

(from Gorbunov and Kirchengast, *Radio Sci.*, 2015, Uncertainty propagation through wave-optics retrieval…)



$$u(t) = A(t)\exp\left(ik\Psi(t)\right) = \exp\left(ik\Sigma(t)\right),$$

$$\chi(t) = \ln A(t),$$

$$\Sigma(t) = S_0(t) + \Delta S(t) - i\frac{\chi(t)}{k} = \Psi(t) - i\frac{\chi(t)}{k},$$

$$\Sigma(t) = \Sigma_0(t) + \delta\Sigma(t) = \Sigma_0(t) + \Sigma_1(t) + \Sigma_2(t),$$

$$v(p) = \exp\left[ik\left(\Sigma_1(t_s(p)) + \Sigma_2(t_s(p))\right)\right]v_0(p),$$

$$v(p) = \left(\tilde{A} + \delta\tilde{A}\right)\exp\left(ik\left(\tilde{\Psi}(p) + \delta\tilde{\Psi}(p)\right)\right).$$

$$\left\langle \delta\tilde{\Psi}(p_1)\delta\tilde{\Psi}(p_2)\right\rangle = \left\langle \delta\Psi(t_s(p_1))\delta\Psi(t_s(p_2))\right\rangle.$$

$$\delta\varepsilon(p) = \delta\theta \approx \delta Y(p), \quad t_s(p) = t(Y_s(p))$$

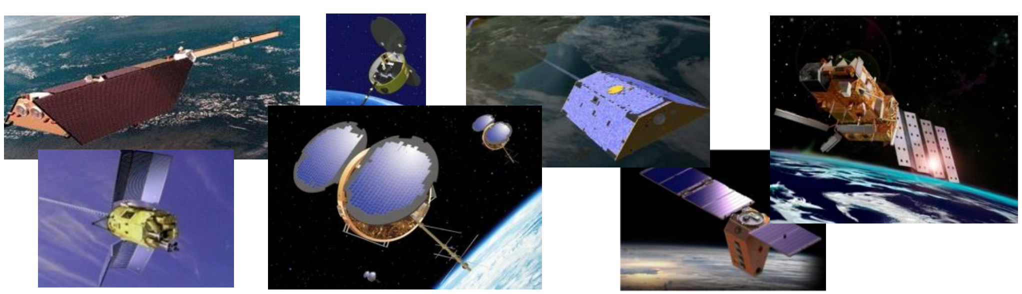
$$\left\langle \delta\varepsilon(p_1)\delta\varepsilon(p_2)\right\rangle = \frac{\partial^2}{\partial p_1 \partial p_2}\left\langle \delta\tilde{\Psi}(p_1)\delta\tilde{\Psi}(p_2)\right\rangle.$$

More info WO estim => ***Gorbunov-Kirc 4th-next talk!***

so rOPS looks useful – let's sum up and see what's next

Planetary System Refractometer by rOPS – Conclusions & Prospects:

- WEGC's rOPS is a fresh RO processing system aiming to help solve the global climate monitoring problem for the fundamental state of the atmosphere for thermodynamic ECVs, by providing SI-tied atmospheric profiling of these ECVs with integrated uncertainty estimation.
- In terms of research and applications, the key use is benchmark-quality reference RO data provision for calibration/validation and for climate monitoring, research, and services, complementary to NRT.
- rOPS, developed as v1 over 2013 to 2016, will replace WEGC's OPSv5 processing system operating over 2007-2016 (following EGOPSv2-v4/ CCR heritage of 1996-2006). OPSv5.6, which recently completed RO re-processing over 2001-2015+, is the final OPSv5 data version.
- rOPS is published in a set of papers over 2015-2017 – stay tuned!



Thank You! ☺