Multi-Mission Multi-Center Level 1 Data Inter-Validation towards Wegener Center Reference Occultation System Reprocessing

J. Innerkofler[1,2], G. Kirchengast[1,2], M. Schwärz[1], Y. Andres[3], C. Marquardt[3], A. Jäggi[4], D. Hunt[5]

(1) Wegener Center for Climate and Global Change (WEGC) and Institute for Geophysics, Astrophysics and Meteorology/Institute of Physics, University of Graz, Graz, Austria
(2) FWF-DK Climate Change, University of Graz, Graz, Austria
(3) EUMETSAT, Darmstadt, Germany
(4) Astronomical Institute, University of Bern, Bern, Switzerland
(4) COSMIC Program, UCAR, Boulder, CO, USA

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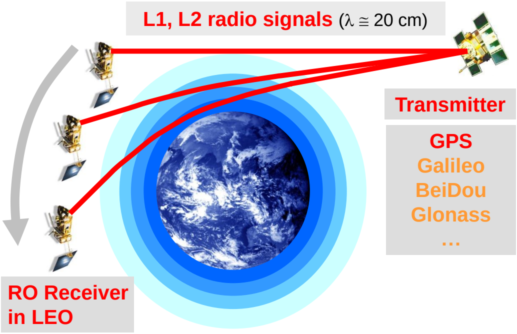
Outline

1. Introduction
   - Reference Occultation Processing System
2. Precise Orbit Determination
3. Excess phase processing
4. Summary & Outlook

The Radio Occultation method

Wegener Center · UNI GRAZ



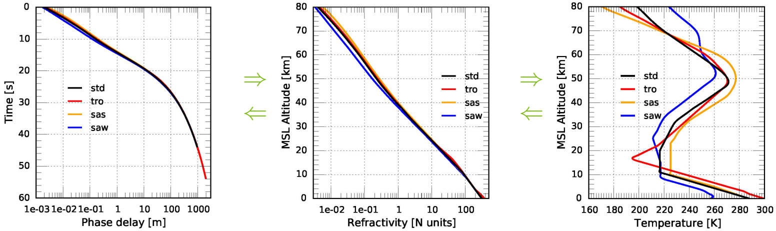
RO missions in Low Earth Orbit (LEO) so far:
GPS/Met (demo1995-97); CHAMP (2001-08), SAC-C, GRACE-A, F3/COSMIC, MetOp-A/-B, FY-3C/-3D, …

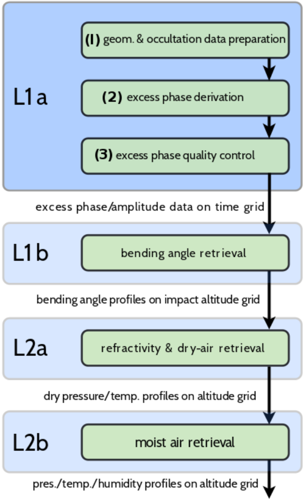
- setting & rising RO events in an active limb sounding geometry (occultation geometry) exploit the
- atmospheric refraction of two GNSS L-band signals, providing
- self-calibrated measurements of excess phase path L / Doppler shift D traceable to universal time (SI second) for the retrieval of
- bending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

Kirchengast [2018], IGL-1

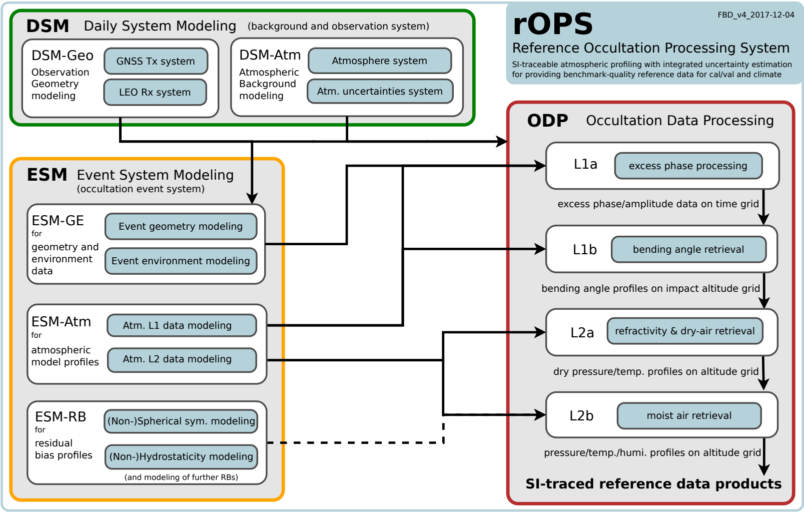
Reference Occultation Processing System

- **Reference Occultation Processing System (rOPS)**, providing reference RO data for calibration/validation and climate monitoring (Kirchengast et al. [2016], OPAC-IROWG)
- Aims to **process the full chain from the SI-tied raw data to the ECVs with integrated uncertainty propagation**: highly reversible analysis along the RO retrieval chain and its variables

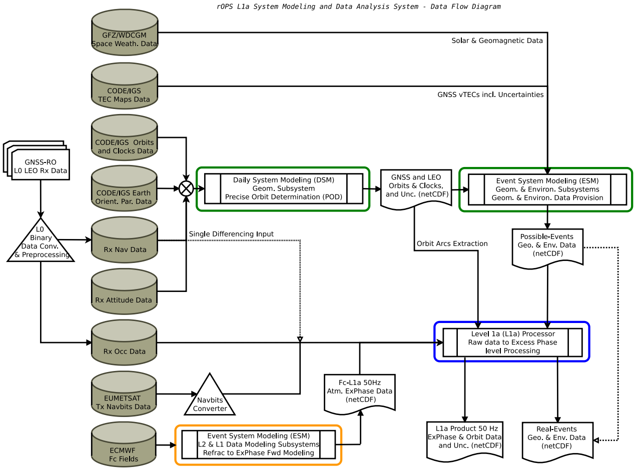




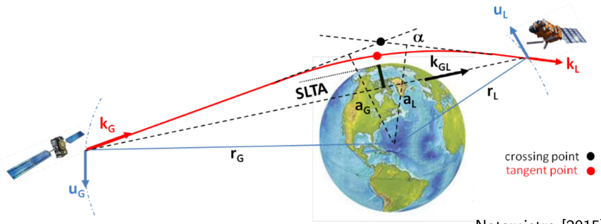
rOPS system overview



Level 1a processing scheme



Observation Geometry Modeling



Notarpietro [2015]

- **L1a Excess Phase Processing:** calculation of the difference between straight line propagation and real path
- **Observation Geometry Modeling:** accurate determination of position, velocity, and clocks of GNSS and LEO satellite

GNSS and LEO orbit input data so far ...

- was provided as part of the external excess phase (L1a) products
- from CDAAC[1] and EUMETSAT[2]

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[1] https://cdaac-www.cosmic.ucar.edu/

[2] https://eoportal.eumetsat.int/

Precise orbit determination for GNSS-RO

- ... so why bother with an independent POD processing?
  - external orbit processing represents a blackbox
  - various differences between different solutions:
    → different software packages, force models, parameterizations ...
  - strong dependency in occultation phase data calibration:
    → measurement time-stamp correction through clock bias estimates
    → orbit position inherent to range calculation for excess phase
- ... in order to tackle this challanges we:
  - employ two independet software packages,
  - use data from different GNSS orbit archives,
  - provide measures for the orbit quality,
  - and aim at orbit uncertainties to be within 5 cm (position) and 0.05 mm/s (velocity), for highest quality of derived RO profiles

GNSS and LEO orbit input data

- we use data from different GNSS Orbit archives:
  - CODE[3] - Center for Orbit Determination Europe
  - IGS[4] - International GNSS Services

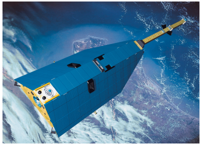
- LEO L0 and L1a input data from:
  - **EUMETSAT**, Darmstadt: MetOp-A/-B/-C
  - **UCAR**, Boulder: COSMIC, CHAMP, GRACE
  - **JPL**, Pasadena: CHAMP, GRACE, SAC-C
  - **GFZ**, Potsdam: CHAMP
  - **NSSC**, Beijing: FengYun-3C/-3D
  - **SPIRE**, Boulder: Lemur-2

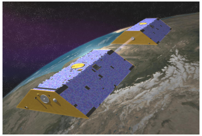
[3] http://www.aiub.unibe.ch/research/code___analysis_center/index_eng.html

[4] http://www.igs.org/

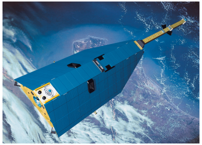
Core mission details (nominal parameter)

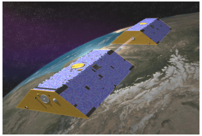
	CHAMP	GRACE-A	Metop-A	Metop-B
Altitude	450 km	500 km	817 km	817 km
Inclination	87.2 deg	89.0 deg	98.7 deg	98.7 deg
Period	93.6 min	94.5 min	101 min	101 min
Mass	522 kg	431 kg	4093 kg	4093 kg
POD-Antenna	1	1	1	1
RO-Antenna	1	1	2	2
GPS-Receiver	BlackJack	BlackJack	GRAS	GRAS
LRA	yes	yes	no	no
Launch	2000-07-15	2002-03-17	2006-10-19	2012-09-17
Status	ended 2008	ended 2017	operational	operational





POD software



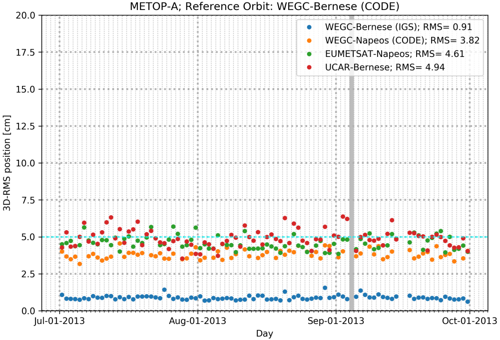


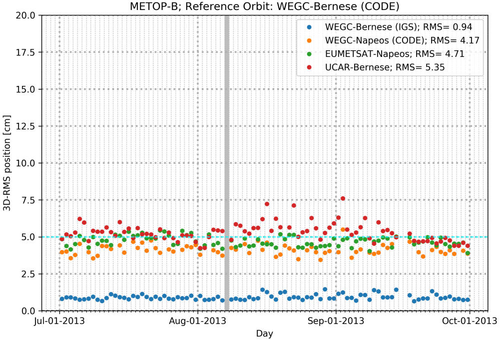
	Bernese	Napeos
Software	Bernese v5.2 (AIUB[1])	Napeos 3.3.1 (PosiTim[2])
Arc length	24 hours	24 hours
Sampling	30 sec	30 sec

[5] http://www.bernese.unibe.ch/

[6] http://www.positim.com/

Orbit comparison - Metop-A, Metop-B

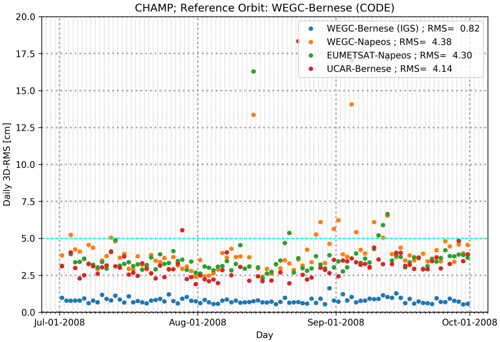


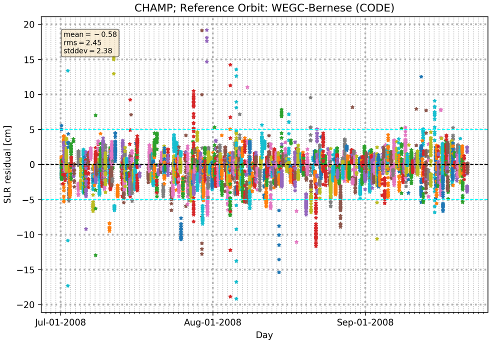


	IGS	NAP	EUM	UCAR
Radial	0.34	2.73	2.88	2.93
Along	0.68	2.16	2.61	2.93
Cross	0.49	1.57	2.49	2.69
3D	0.91	3.82	4.61	4.94

	IGS	NAP	EUM	UCAR
Radial	0.36	2.93	3.08	3.41
Along	0.71	2.57	3.00	3.46
Cross	0.51	1.49	1.95	2.24
3D	0.94	4.17	4.71	5.35

Orbit comparison - CHAMP



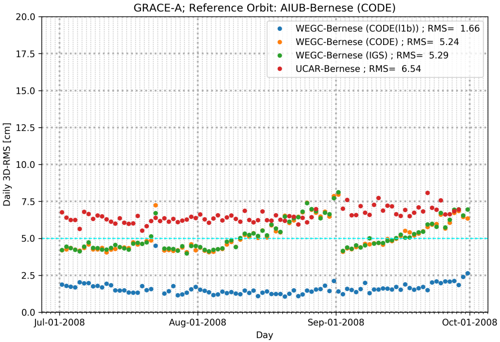


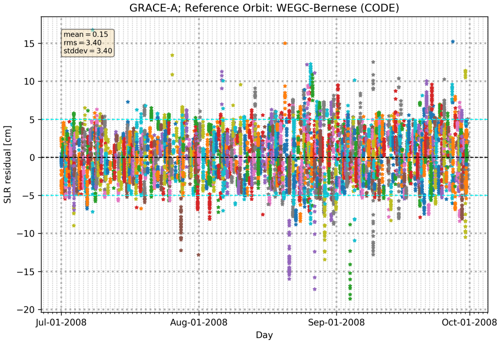
	IGS	NAP	EUM	UCAR
Radial	0.28	2.62	2.09	1.92
Along	0.58	2.51	3.23	3.43
Cross	0.46	3.34	1.58	1.40
3D	0.82	4.38	4.30	4.14

mean [cm]	stddev [cm]	RMS [cm]
-0.58	2.45	2.38

- no station selection
- elevation cut-off angle 10 degree

Orbit comparison - GRACE-A



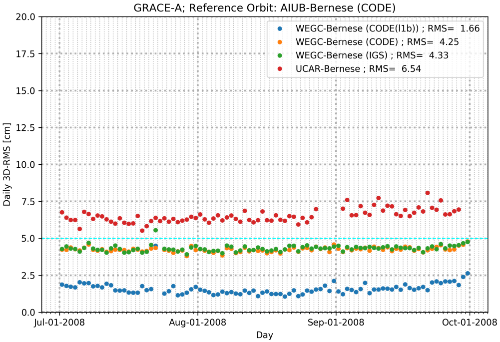


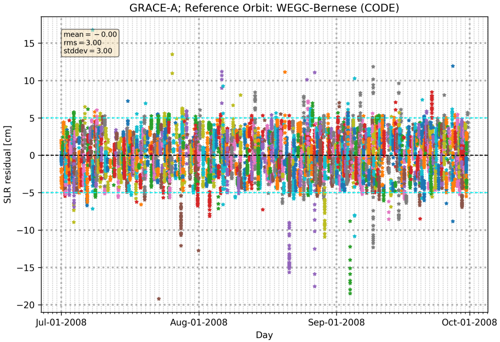
	COD(l1b)	CODE	IGS	UCAR
Radial	0.54	0.80	0.85	3.51
Along	1.47	5.27	5.16	4.56
Cross	1.15	1.22	1.44	3.12
3D	1.66	5.24	5.29	6.54

mean [cm]	stddev [cm]	RMS [cm]
0.15	3.40	3.40

- no station selection, outlier correction 20cm
- elevation cut-off angle 10 degree

Orbit comparison - GRACE-A ... improved





	COD(l1b)	CODE	IGS	UCAR
Radial	0.54	0.62	0.62	3.51
Along	1.47	4.42	4.36	4.56
Cross	1.15	1.18	1.39	3.12
3D	1.66	4.25	4.33	6.54

mean [cm]	stddev [cm]	RMS [cm]
0.00	3.00	3.00

- no station selection, outlier correction 20cm
- elevation cut-off angle 10 degree

Orbit uncertainty estimates

random uncertainty:

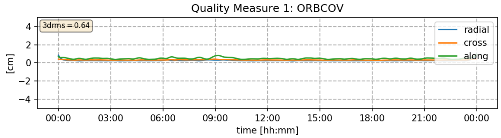
- error propagation in Bernese (ORBCOV) [Jäggi 2007]:
  → estimation essentially based on the satellite constellation only
  → optimistic estimates, hence empirical coverage factor 2 applied

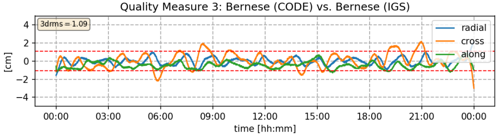
systematic uncertainty:

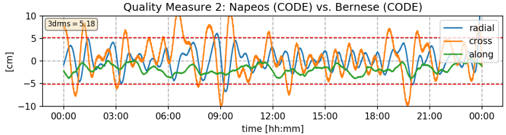
- estimates based on the combination of:
  → the differences b/t Bernese and Napeos orbit solution
  → the differences b/t Bernese solution based on CODE and IGS input
  → SLR residuals (if satellite equipped with a laser retroreflector)

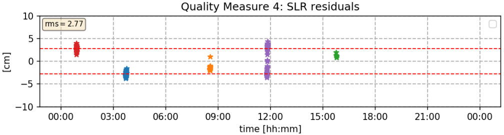
CHAMP orbit quality - "ordinary" day

day: 2008-07-16





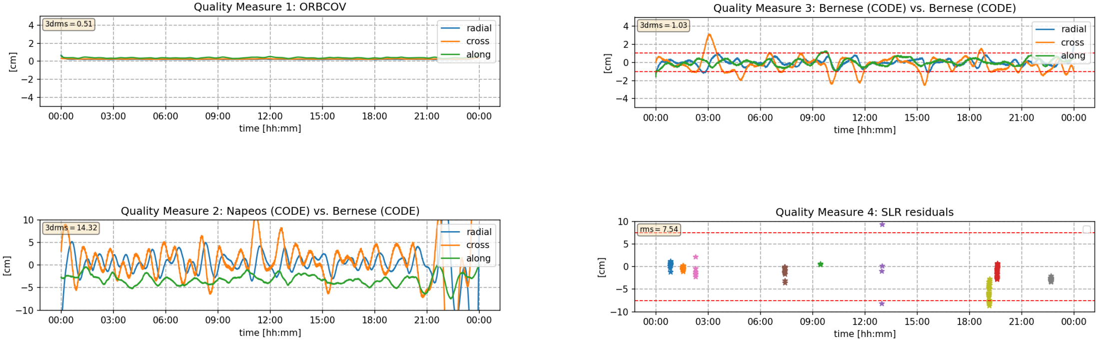




- all measures below 5 cm except quality measure 2 slightly exceeding the target specifications
- additional SLR measure

CHAMP orbit quality - “degraded” day

day: 2008-08-29



- both quality measure 2 and 4 indicate a degraded orbit solution

Daily Uncertainty Estimates - Metop-B, CHAMP

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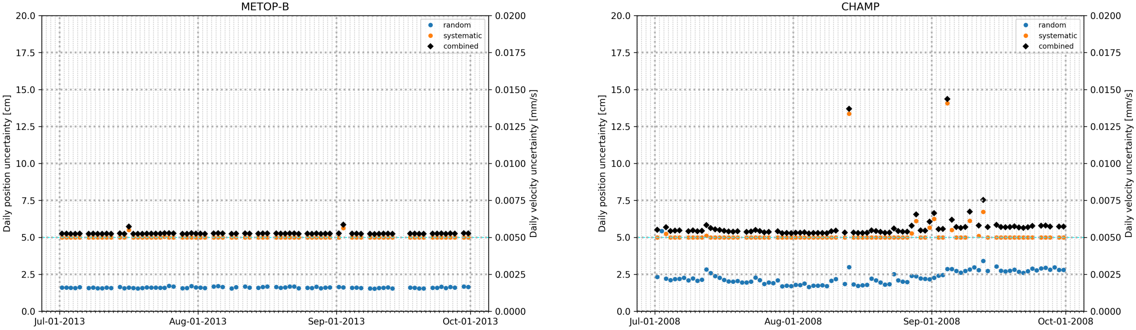


- robust uncertainty estimate time series
- single days exceeding 5 cm threshold

- periods of increased uncertainty estimates
- most of the days around 5 cm threshold

From raw phase to excess phase

raw phase — excess phase

$$\boxed{L_r^t} = \rho_r^t + c\delta_r - c\delta^t + \lambda N_r^t + \boxed{\delta\rho^t_{r,atm} - \delta\rho^t_{r,ion}} + \rho^t_{r,corr_L} + \epsilon_L$$

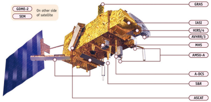
- $\rho_r^t \ldots$ geometric distance between receiver and transmitter[1]
- $c\delta_r, c\delta^t \ldots$ transmitter and receiver clock biases[2]
- $\delta\rho^t_{r,atm}, \delta\rho^t_{r,ion} \ldots$ neutral atmosphere and ionosphere excess phase
- $\rho^t_{r,corr} \ldots$ modeled effects: relativistic effects, antenna offset & phase center corrections
- $\epsilon \ldots$ unmodeled errors: thermal noise, local multipath, residual cycle slips, ...
- $\lambda N_r^t \ldots$ integer phase ambiguity

[1] Distance b/t receiver at receive time t and transmitter at transmission time $t-\tau$, where τ is the signal travel time.
[2] The receiver clock bias at time t and the transmitter clock bias at time $t-\tau$.

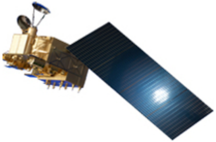
Excess phase comparison

- software:
  - WEGC rOPS L1a processor for internal processing and conversion of external data
- input:
  - WEGC orbits & clocks,
  - raw occultation measurements,
  - level 1a products from:

    → WEGC, EUMETSAT, UCAR, NSSC/NSMC, Spire
- things to consider:
  - antenna offsets applied correctly, relativistic correction applied in POD, closed loop to open loop measurement combination, reference frames, orbit and clock interpolation ...



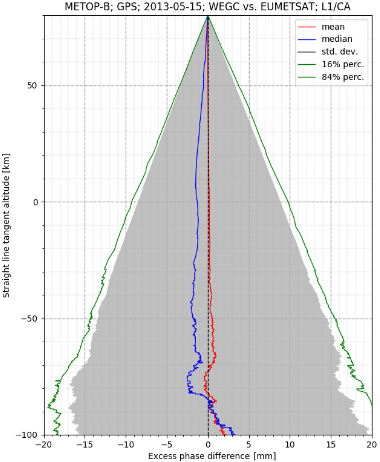
Courtesy: EUMETSAT



Courtesy: CMA-NSMC

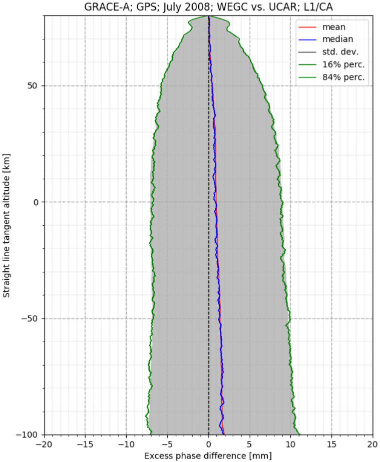
Courtesy: Spire

METOP-B; WEGC vs. EUMETSAT



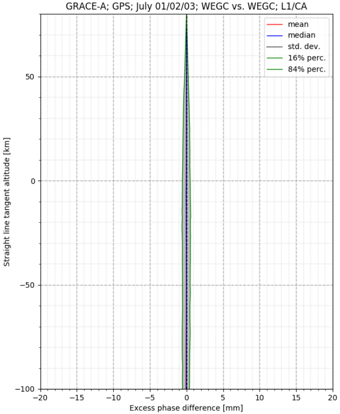
- MetOp-B on May 15, 2013
- WEGC-rOPS/WEGC-Bernese vs. EUM-Yaros/EUM-Napeos
- mean difference < 1 mm
- standard deviation < 15 mm

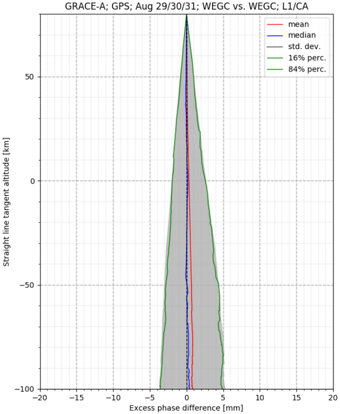
GRACE-A; WEGC vs. UCAR



- GRACE-A July 2008
- WEGC-rOPS/WEGC-Bernese vs. UCAR-atmPhs/UCAR-Bernese
- mean difference < 2 mm
- standard deviation < 10 mm

GRACE-A; orbit degradation





- GRACE-A Jul 01-03, 2008 (left); 'ordinary' POD
- GRACE-A Aug 29-31, 2008 (right); 'degraded' POD
- comparison using WEGC-rOPS, but different orbit and clock input
- increased mean and stddev for 'degraded' case

Summary and Outlook

- the **rOPS** with focus on the **DSM-Geo modeling** and **ODP-L1a processing**, comprising the **LEO POD** and **excess phase processing**, was introduced
- **orbit** and **excess phase intercomparison** acknowledge the **quality of WEGC POD LEO orbit** output
- the POD subsystem delivers **reliable orbit and clock products** including **uncertainty estimates**
- the **rOPS excess phases** show a high consistency compared to existing processing systems from EUMETSAT and UCAR.

next steps, ongoing ...

- analyze and characterize uncertainty of the **excess phase processing**
- processing of test month ensembles of **FY-3C** (JLOAC) and **Spire** (ESA study) data
- support the **reprocessing** of MetOp, CHAMP, GRACE, COSMIC data by **rOPS**

Thank you for your attention!

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