Assimilation of Radio Occultation Data at the German Weather Service

Detlef Pingel[*], Andreas Rhodin

German Weather Service (DWD)

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Outline

3-D Variational Data assimilation

- data assimilation: combination of observational and background (model) information prior to numerical forcast
- combination in a statistically optimal way
- minimize cost function

$$J(x) = J_b + J_o = (x - x_b)^T B^{-1}(x - x_b) + (y - H(x))^T R^{-1}(y - H(x)).$$

  with forward operator $H(x)$

- minimization in observation space
- benefits:
    - reduced size of the equations to be solved
    - allows assimilation of observations with highly nonlinear dependence on the background variables (e.g. satellite data)

GPS-RO forward models of the 3D-Var

- assimilation of GPS RO bending angles
- forward operator $H(x)$: mapping of background variables of model (t, q) into observations space (bending angle)
- Two forward operators are implemented in the 3D-Var (both by M. Gorbunov):
  - three-dimensional ray-tracing operator
  - one-dimensional operator

Three-dimensional ray-tracing GPS-RO forward operator

- based on geometrical optics
- horizontal gradients of t, q
- drift of the rays' tangential point
- higher accuracy expected
- also high demand of memory size/computing time (setup of background error covariance matrix)

# One-dimensional GPS-RO forward operator

- inverse Abel transform
- assuming spherically symmetric fields of t, q
- assuming constant impact parameter
- variations ("simulation" of drift of tangential points):
    - occultation point as given by the CT2 (1d)
    - occulation point is average of the rays' tangential points over the lowest 20 km of the occultation profile (1dmn)
    - the inverse Abel transform is applied to each ray separately, occulation point is tangential point of ray (2d)

GPS-RO forward operators of the 3D-Var: Evaluation

- test data set for evaluation: CHAMP phase delay data (ROPIC, january/july 2005)
- bending angles obtained by canonical transform method CT2 (developed by M. Gorbunov)

GPS-RO forward operators of the 3D-Var: Evaluation

- Innovation statistics of forward operators: 3d (left), standard deviation of 1d, 1dmn, 2d relativ to standard deviation of 3d (right)
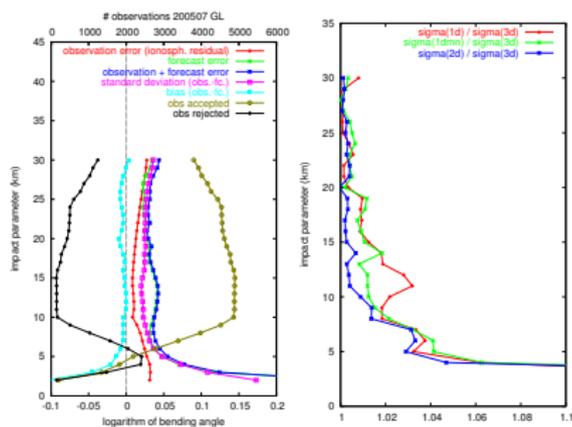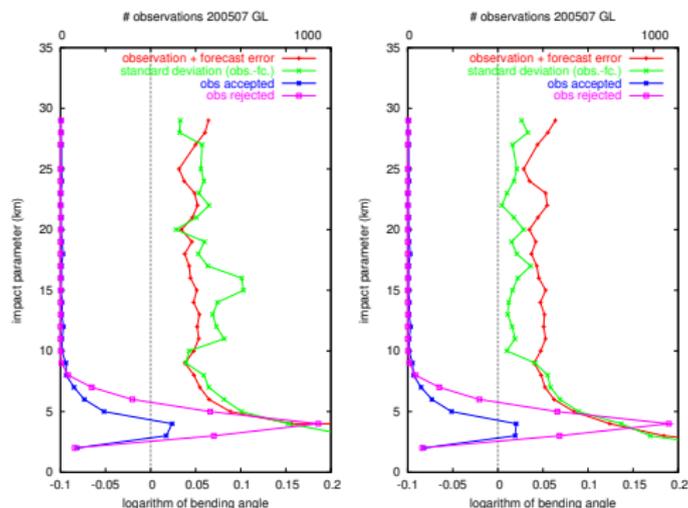

- decrease of standard deviation: 1d → 1dmn → 2d → 3d
- > 10 km: 2d close to 3d, < 10 km: horizontal gradients (q)

GPS-RO forward operators of the 3D-Var: Evaluation

- As the different forward operators "say the same" for most
  observations:
  Consider the innovation statistics for those observations where
  they differ.

- selection criterion: $|fg_{1d,1dmn,2d} - fg_{3d}| > \epsilon \cdot fg_{1d,1dmn,2d,3d}$
  with $\epsilon = 1\%, 2\%, 3\%...$

GPS-RO forward operator of the 3D-Var: Evaluation

- standard deviation of 1dmn (left) vs. 3d (right) forward model, $\epsilon = 5\%$

- increase of closeness of forward model first guess to observation: 1d $\rightarrow$ 1dmn $\rightarrow$ 2d $\rightarrow$ 3d

GPS-RO forward operators of the 3D-Var: Evaluation

- Simulation of tangential point drift has largest effect on reduction of standard deviation (up to 4%)

- 1d forward operator seems to be sufficiently accurate

- higher resolution of background model necessary to get full benefit of ray tracer?

GPS-RO forward operators of the 3D-Var: Evaluation

- P. Poli and J. Joiner: 2d ray tracing model on CHAMP + SAC-C data (Q. J. R. Meteorol. Soc., 130, p. 2807-2825, 2006)
  - considering tangential point drift caused larger reduction of innovation standard deviation than including horizontal gradients
  - globally, reduction is relatively small

- S. Healy et al.: Comparison of 1d and 2d (account for along-ray horizontal gradients) forward operators (CHAMP) (Q. J. R. Meteorol. Soc., 133, p. 1213-1227, 2007)
  - maximal decrease of standard deviation $\approx 5\%$ in extra tropics lower troposphere, elsewhere less
  - no significant 1d-2d differences in verification against radiosondes and forecast scores

Monitoring of radio occultations

- forward operator 1dmn
- Data sets:
    - Dataset 1: CHAMP/GRACE-A (NRT)
    - Dataset 2: CHAMP/GRACE-A (CT2)
    - Dataset 2: COSMIC

Dataset 1: CHAMP/GRACE-A (NRT)

- bending angles of CHAMP + GRACE-A
- near real time (NRT) product (GFZ)
- observation error:
  - no estimate of observation error derived in processing
  - functional model of observation error instead (S. Healy):
    - 0km $\rightarrow$ 10km impact height: 10% $\rightarrow$ 1% linearly
    - above 10km impact height: 1%, minimal 6×10^{-6}rad
    - constant in time and latitude

Dataset 2: CHAMP/GRACE-A (CT2)

- bending angles of CHAMP + GRACE-A
- phase delay data by GFZ
- bending angles by CT2 (DWD)
- observation error:
- CT2 also provides estimates of observation errors:
  - stratosphere: ionospheric residuum is estimated from the L_1 and L_2 signal fluctuations
  - lower troposphere: observation errors is derived from width of the transformed spacial spectrum
- observation error varies in time and latitude

Dataset 3: COSMIC

- bending angles of COSMIC 01 - 06
- observation error estimates from
    - stratosphere: bending angle differences to climatology, SNR, Doppler errors (p)
    - troposphere: amplitude fluctuation of signal
- observation error varies in time and latitude

Number of profiles

- Monthly means of zonal averages of march 2007, bins 1km $\times$ 10°
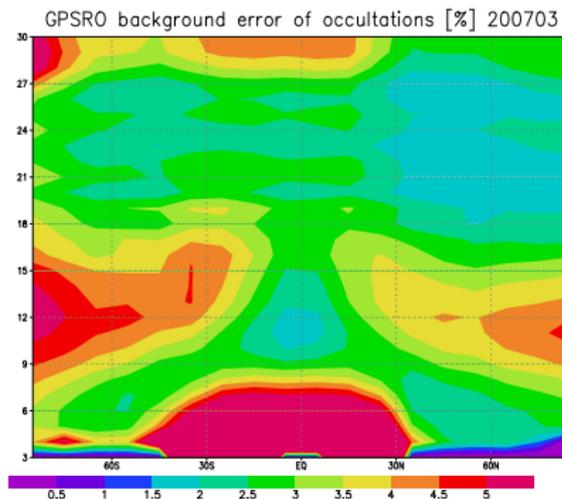- GPS RO data from CHAMP/GRACE-A (NRT), CHAMP/GRACE-A (CT2), COSMIC
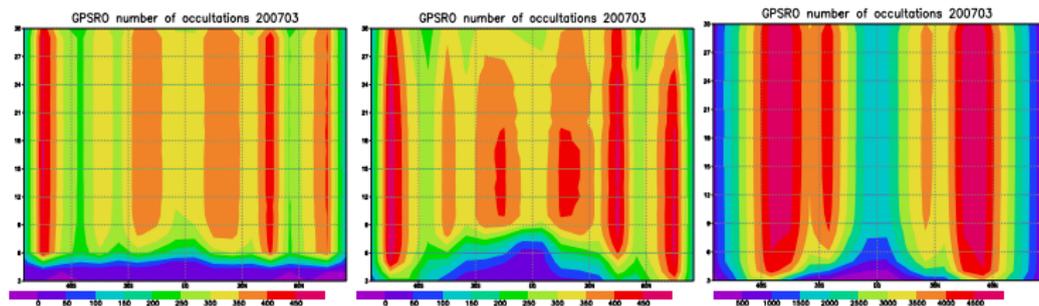
Observation errors

- Relative observation errors (% of first guess)
- GPS RO data from CHAMP/GRACE-A (NRT),
  CHAMP/GRACE-A (CT2), COSMIC
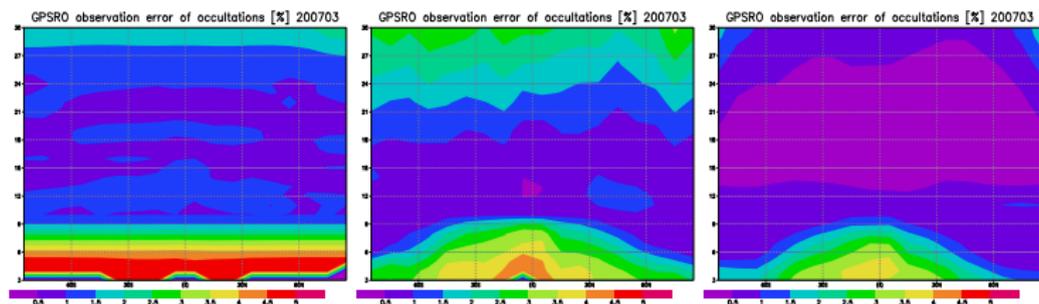
- zonal variation: for fixed impact height, minima of observation errors at high latitudes, maximum in tropics ($\rightarrow$ humidity)

Background error

- Relative background error GME (CHAMP/GRACE-A (NRT), % of first guess)

GPSRO background error of occultations [%] 200703

- background error generally large compared to observation error
- this implies large statistical weights of observations in data assimilation

Consistency of errors

- Standard deviation (% of first guess, top) of innovations vs. sum of errors $\sqrt{e_{obs}^2 + e_{bg}^2}$ (bottom)
- GPS RO data from march 2007, CHAMP/GRACE-A (NRT), CHAMP/GRACE-A (CT2), COSMIC
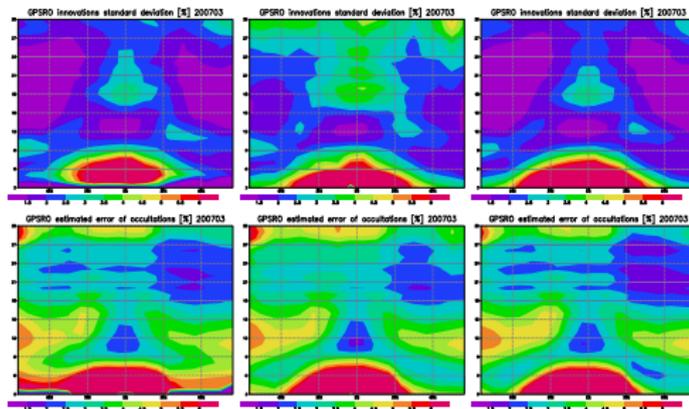
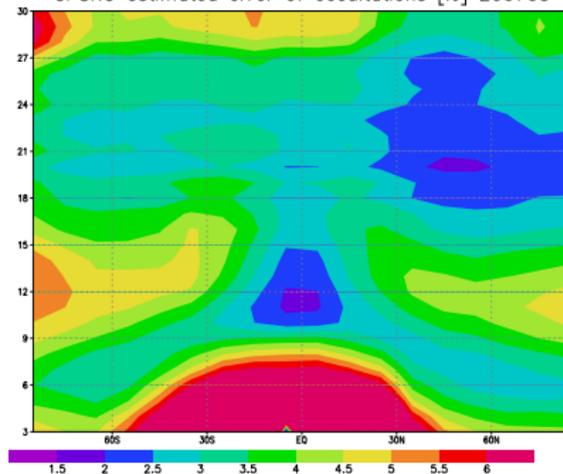# Consistency of errors: Data set 1

- Standard deviation (% of first guess, left) of innovations vs. sum of errors $\sqrt{e_{obs}^2 + e_{bg}^2}$ (right)
- GPS RO data from march 2007, CHAMP/GRACE-A (NRT)
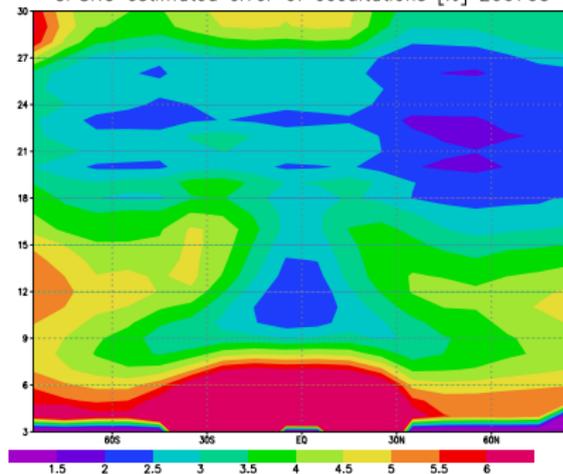
Consistency of errors: Data set 2

- Standard deviation (% of first guess, left) of innovations vs. sum of errors $\sqrt{e_{obs}^2 + e_{bg}^2}$ (right)

- GPS RO data from march 2007, CHAMP/GRACE-A (CT2)
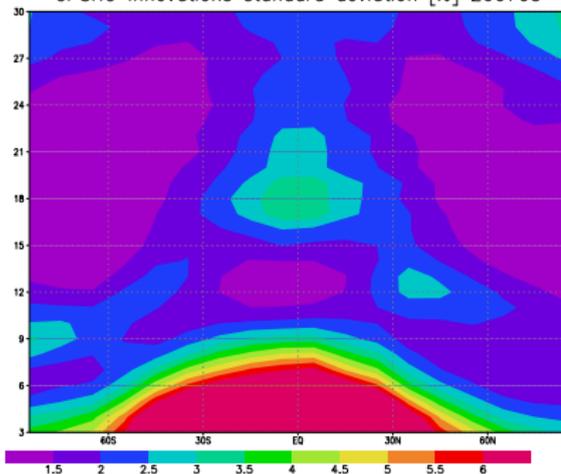

GPSRO innovations standard deviation [%] 200703
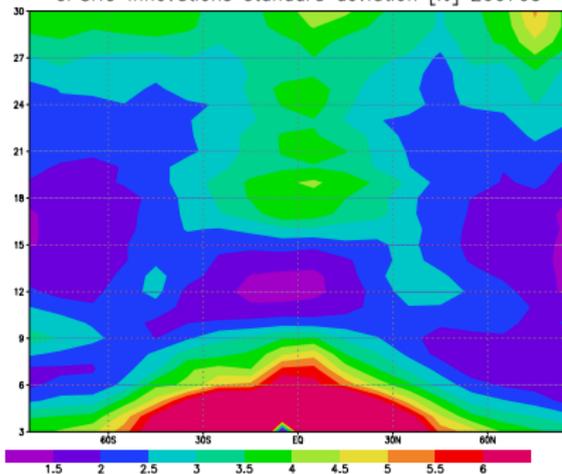
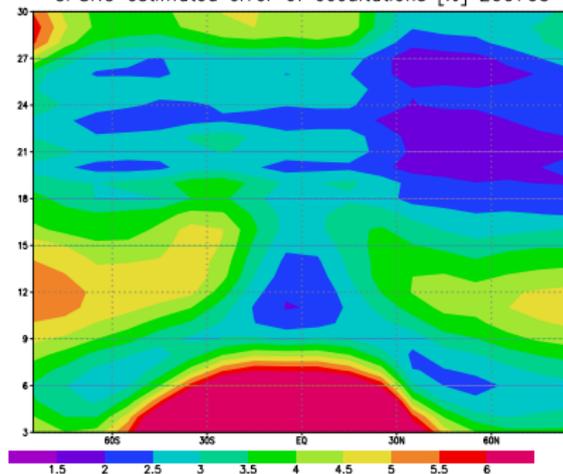GPSRO estimated error of occultations [%] 200703

Consistency of errors: Data set 3

- Standard deviation (% of first guess, left) of innovations vs. sum of errors $\sqrt{e_{\text{obs}}^2 + e_{\text{bg}}^2}$ (right)

- GPS RO data from march 2007, COSMIC

GPSRO innovations standard deviation [%] 200703   GPSRO estimated error of occultations [%] 200703

Monitoring of radio occultations: Consistency of errors

- $\sqrt{e_{\text{obs}}^2 + e_{\text{bg}}^2}$ dominated by background error e_{bg}
- qualitatively corresponding pattern of (specified) observation errors, background error and spread of innovation statistics
- consistency of values in tropics
- outside the tropics $\sigma_{\text{Inn.}} < \sqrt{e_{\text{obs}}^2 + e_{\text{bg}}^2}$, scaling factor $\approx 0.5 - 0.7$ (over-estimation of background error)

Monitoring of radio occultations: Bias

- Bias (% of first guess) of innovations
- GPS RO data from march 2007, CHMP+GRAA (GFZ), CHMP+GRAA (DWD CT2), COSMIC
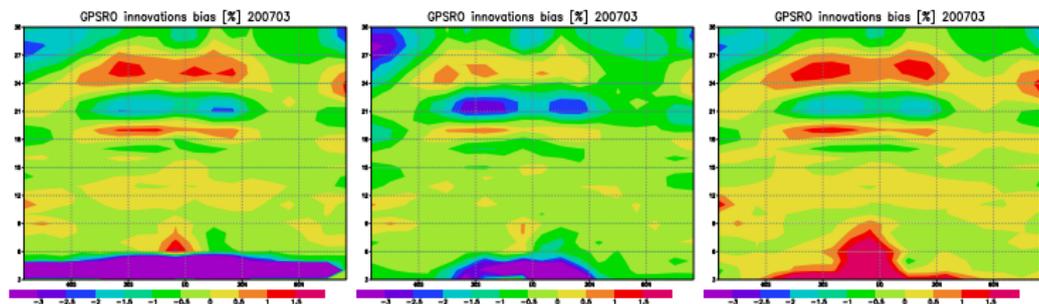
- oscillating vertical variation of bias, maximal at $\pm 20°$ latitude
- bias of CT2 processed (DWD) data slightly smaller

Setup of assimilation experiments:

- Experiment 1: convential observation data only:
    - SYNOP
    - TEMP
    - PILOT
    - AIREP
    - DRIBU
    - SATOB
- Experiment 2: above + GPS-RO (COSMIC, 1dmn forward operator)
- start 2007051000
- 3h assimilation time window

Deviation of 500 hPa geopotential to IFS analysis: RMS
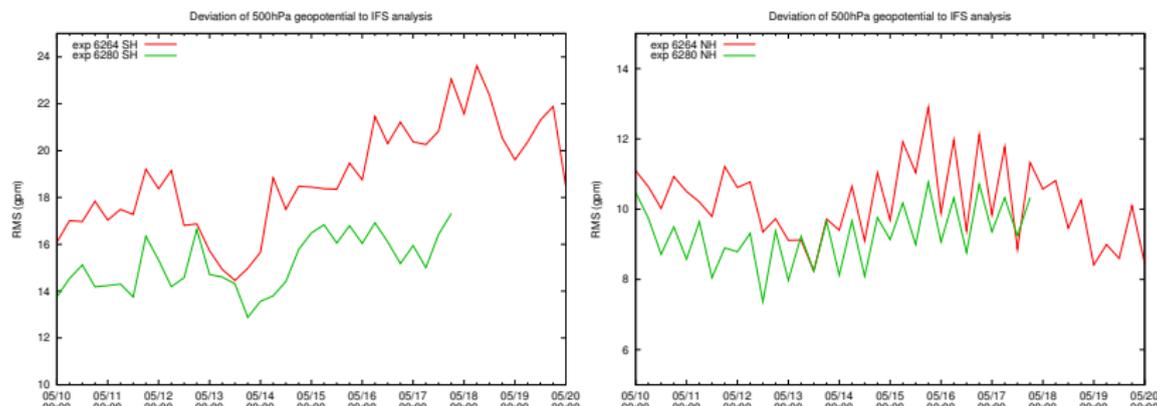
- SH (left), NH (right), green (GPSRO), red (control)
- assimilation of GPS RO seem to reduce analysis differences to IFS significantly
- impact on forcast scores still to be assessed

Conclusions:

- RO data provide a valuable source of meteorological information
- Innovation statistics show only minor differences beween the different forward operators tested
  $\longrightarrow$ choice of the numerically cheapest operator
- Monitoring indicate a qualitatively consistent pattern of specified errors and innovation statistics.
  However, in etxra tropics, the spread of the innovations correspond to background errors smaller than specified.
- In assimilation experiment, RO (in addition to conventional observations) seem to reduce the the analysis differences to IFS for geopotential/temperature (longer experiment with forcast runs still necessary to assess the impact)

Acknowledgements: