Assimilation of GPS Radio-Occultations at DWD

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NWP Models at DWD

**GME**
Global model, hydrostatic
Triangular grid, mesh size: 20 km
60 levels (top: 5 hPa)
(1474562×60 grid points)
Forecast times:
174h from 00Z, 12Z;
48h from 06Z, 18Z

**COSMO-EU**
Non-hydrostatic
Mesh size: 7 km
40 levels
Forecast times:
78h from 00Z, 12Z;
48h from 06Z, 18Z

**COSMO-DE**
Non-hydrostatic, “convection allowing”
Mesh size: 2.8 km
50 levels
Forecast times:
21h from 00Z, 03Z, . . . , 21Z

**COSMO-DE-EPS**
(Pre-operational)
Ensemble prediction system
20 ensemble members
(operationally: 40 members)
Forecast times:
21h from 00Z, 03Z, . . . , 21Z
Global Data Assimilation System at DWD

- **3D-Var-PSAS**, 3-hourly update cycle
- **Available Forward models for GPSRO**
  - 1d bending angle operator (Implementation by Michael Gorbunov); fixed/effective tangent point for profile or individual tangent point
  - 3d ray tracer (Michael Gorbunov)
- Implementations tested and evaluated in collaboration with GFZ using data from CHAMP and GRACE (Pingel and Rhodin, 2009)
  - Ray tracer: best in terms of std.dev. of OBS-FG, numerically expensive! Ray tracer also needs additional data not provided in BUFR messages (satellite positions and velocities)
  - 1d-operator (Abel integral) with effective location of occultation probably good enough for initial operational implementation (still needed major optimization efforts for the NEC SX-9)
- **Refractivity**
  3-term expression as recommended by GRAS-SAF
- **“Initialization”**
  MSIS-90 climatology matched at model top (∼ 36 km)
Assimilation of GPS Radio-Occultations

- **Observation errors** (S. Healy):
  - Linear decrease from 10% to 1% for impact height from 0 to 10 km
  - 1% from 10 km to 30 km

- **Quality control** of observations:
  - Consistency checks of profiles
  - Observation-minus-first guess check: $4\sigma$ (should be made stricter)
  - B.a. < 0.02 rad to avoid ducting (replace by condition on refractivity)
  - Clip lowest section of GPS-RO profiles when non-monotonous

- **Vertical thinning** to model resolution, exponential smoothing

- Use **impact heights** 3 km–30 km

- Exclude occultations starting above 20 km

- **GPS Radio-Occultations operationally used since 2010-08-03**
  - COSMIC/FORMOSAT-3 FM 1-2, 4-6 (FM-3 dead since 2010-08-01)
  - GRACE-A
  - GRAS on METOP-A
  - TerraSAR-X (since 2010-12-09)
  - C/NOFS, SAC-C (since 2012-02-29)
Impact of the Assimilation of GPSRO

- Better fit to radiosondes in upper troposphere/lower stratosphere, esp. southern hemisphere (but mixed results in Antarctic)
- Significant forecast improvements with assimilation of GPSRO

Anomaly Correlation of Geopotential 500 hPa, Southern Hemisphere for July 2010 ⇒ gain of several hours vs. operational system

H. Anlauf et al., Atmos. Meas. Tech., 4, 1105–1113
Comparison to Radiosondes

- Mean departures of temperature and rel. humidity observations from radiosondes to 3-h forecasts, Southern Hemisphere

(blue: ctrl (operational), red: GPSRO experiment)
Problems with the Assimilation of GPSRO over Antarctic

Statistics for Temperature from RS

Statistics for Temperature from RS

EXP=rou

EXP=roup

OBS minus FG/AN for: Surface=all Flag=used SatId= 5

OBS minus FG/AN for: Surface=all Flag=used SatId= 5

Time period = 20100615 00UTC - 20100704 21UTC, STEP=3h

Time period = 20100615 00UTC - 20100704 21UTC, STEP=3h

- Large temperature bias, got even worse with assimilation of GPSRO!
- Partially understood: poor representation of vertical correlations in operational assimilation system, revised in December 2010
- Some issues with the forecast model, but investigations ongoing
Issues with Assimilation of GPSRO Data (I)

- Bias, RMS differences for different satellites (processing, model, . . .)
- Lower troposphere: largest bias in the tropics, smaller in extratropics

Statistics for Bending Angles from METOP / GPS RO
EXP=rou
Statistics for Bending Angles from COSMIC / GPS RO
EXP=rou
OBS minus FG/AN for: Surface=all Flag=used SatId= 4
OBS minus FG/AN for: Surface=all Flag=used SatId= 740
Time period = 20110101 00UTC - 20110831 21UTC, STEP=3h
Time period = 20110101 00UTC - 20110831 21UTC, STEP=3h

Tropics
Issues with Assimilation of GPSRO Data (I)

- Bias, RMS differences for different satellites (processing, model, . . .)
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Statistics for Bending Angles from METOP / GPS RO EXP=rou
Statistics for Bending Angles from COSMIC / GPS RO EXP=rou
OBS minus FG/AN for: Surface=all Flag=used SatId= 4
OBS minus FG/AN for: Surface=all Flag=used SatId= 740
Time period = 20110101 00UTC - 20110831 21UTC, STEP=3h
Time period = 20110101 00UTC - 20110831 21UTC, STEP=3h

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Issues with Assimilation of GPSRO Data (II)

- Apparent positive bias for non-GRAS data due to bugs in *first-guess check implementation* (non-symmetric w.r.t. OBS and FG!)
- Current GRAS data are (known to be) biased below $\sim 8$ km
  - Rising occultations (globally)
  - Setting occultations (notably tropics, lower troposphere)
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GRAS, $30^\circ S$–$30^\circ N$, 3-4 km
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**3dvar monitoring**

**Bending Angle [radian]**

Level Max/Min: 6938.00 / 6090.30

Date: 2011070100 - 2011073121

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GRAS, 30°S–30°N, 6-7 km
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Bias might be tolerable for small bending angles ($\lesssim 15$ mrad)
Issues with Assimilation of GPSRO Data (III)

- Occasionally poor convergence of the 3D-Var
  - Forward operator was evaluated outside domain of validity, e.g.
    - $\frac{d(r \cdot n(r))}{dr} < 0$ for some $r$, or
    - rays were extrapolated below model orography (mostly Antarctic) in line-search during minimization
  - Extend forward operator and first-guess checks (not yet operational)
    - minimum geometric height of rays above orography (1 km)
    - require $\frac{d(r \cdot n(r))}{dr} > 0.5$
  - Enhance optimization algorithm to enable detection and removal of bad rays during minimization
  - Variational Quality Control (VQC) scheme initially used for surface pressure observations (Gaussian+Flat) while using an approximate (modified) Huber-function for the other observations didn’t work well
Variational Quality Control

- In variational assimilation schemes, VQC enables dealing with bad observations during minimization
  - Observational cost function for Gaussian error distribution ($p$)
    \[ J_o(y - \mathcal{H}(x)) = -\log(p(y - \mathcal{H}(x))) = \frac{1}{2}(y - \mathcal{H}(x))^T R^{-1}(y - \mathcal{H}(x)) \]
    \[ \Rightarrow \text{Pull of outliers same as for good observations} \]
  - Gaussian+Flat: large outliers have zero impact, but strong non-linearities, possible multiple minima, slow convergence
  - ‘Huber norm’ (ECMWF): quadratic/linear for small/large departures; outliers have small impact, but better convergence, no multiple minima
  - **Approximate (modified) Huber-function**
    \[ J_{qc} \sim \alpha \cdot \left( \sqrt{\frac{x^2}{\beta}} + 1 - 1 \right), \quad \text{with parameters} \quad \alpha, \beta = \beta(R, \ldots) \]
    \[ \Rightarrow \text{Similar to Huber norm, but smooth gradient, 2nd derivative} \]

We now use the approximate (modified) Huber-function approach for all observations.
Results from revised first-guess checks and QC

- Bias for lower troposphere reduced, more rays used (except GRAS)
- Example: TerraSAR-X (blue: control, red: experiment)

Statistics for Bending Angles from TerraSar / GPS RO  EXP=8565
Statistics for Bending Angles from TerraSar / GPS RO  EXP=8670
OBS minus FG/AN for:  Surface=all  Flag=used  SatId= 42
OBS minus FG/AN for:  Surface=all  Flag=used  SatId= 42
Time period = 20110701 00UTC - 20110731 21UTC,  STEP=3h
Time period = 20110701 00UTC - 20110731 21UTC,  STEP=3h

(blue: ctrl, red: experiment)
Results from revised first-guess checks and QC

- Bias for lower troposphere reduced, more rays used (except GRAS)
- Example: GRAS (blue: control, red: experiment)

Statistics for Bending Angles from METOP / GPS RO EXP=8565
Statistics for Bending Angles from METOP / GPS RO EXP=8670
  OBS minus FG/AN for: Surface=all Flag=used SatId= 4
  OBS minus FG/AN for: Surface=all Flag=used SatId= 4
  Time period = 20110701 00UTC - 20110731 21UTC, STEP=3h
  Time period = 20110701 00UTC - 20110731 21UTC, STEP=3h

(blue: ctrl, red: experiment)
Comparison to Radiosondes

- Mean departures of T, rH obs. to 3-h forecasts, Southern Hemisphere

(Images of graphs showing bias and RMS error of temperature and relative humidity at different pressure levels)
Summary and Outlook

GPS Radio-Occultations are a useful component of the global observing system for Numerical Weather Prediction at DWD

- Improved analyses and forecasts in particular in data-sparse regions
- Improved stability of (static) bias correction for satellite radiances
- Exhibit deficiencies in the data assimilation (e.g. background error model)
- Help locating forecast model deficiencies
- Strong non-linearity of forward operator poses challenges for quality control in data assimilation

Future developments

- Optimize and test impact of forward operator with tangent point drift
- Implement ROPP 2d forward operator
- Evaluate options to re-activate 3d ray tracer (needs satellite positions and velocities missing in BUFR!)
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A big Thank You to all involved in making data available in Near Real-Time!