GPS RO support to the JCSDA: status report

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Outline

- Recent accomplishments
- Status of current and future GNSS RO sensors
- Work under development
- Outlook

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Recent accomplishments

1. Operational implementation of the assimilation of bending angles instead of refractivities in the NCEP's GDAS (22 May 2012).
   – The top of the profiles has been raised from 30 to 50 km.
   – Algorithms to include the compressibility factors in the computation of the model geopotential heights have been implemented.
2. Operational assimilation of GPS RO refractivities in NAM (18 October 2011). However, the use of GPS RO observations in the global model already provided feedback to the regional – through boundary and initial conditions.
3. Evaluation of the complementarity of the operational assimilation of GPS RO (bending angles & refractivities) and radiances, and the impact of the assimilation of GPS RO on the temporal evolution of the bias correction of the MW and IR satellite radiances.

(1) Forward Model for refractivity observations

$$N = 77.60\frac{P_d}{T} + 70.4\frac{P_w}{T} + 3.739\times 10^{-5}\frac{P_w}{T^2}$$

- *Relatively* easy to implement: interpolation of modeled pressure, water vapor and temperature values from the model grid points to the location of the observation. [Dependence of the geometric height of model levels on the model variables needs to be taken into account as well.]
- However, the resulting modeled refractivity would only match the *observation* (assuming perfect model and retrieval algorithms) if the atmosphere were strictly spherically symmetric.
- Ignores the existence of horizontal gradients of refractivity in the atmosphere (global spherical symmetry approximation).
- <u>Refractivity observations</u>
  - require the use of some climatology or auxiliary information, which affects the profiles above ~ 30 km.
  - are negatively biased below the PBL height under very large gradients of atmospheric refractivity (super-refraction conditions).

(1) Bending angle observations

- Retrieval of bending angles makes use of approximation of bilateral symmetry around the ray path tangent height (not global).
- Not weighted with climatology information.
- Do not suffer from the negative bias in the lower troposphere caused by super-refraction conditions.
- Errors are vertically less correlated than in refractivity profiles because there is no use of an Abel transform.
- Retrieved earlier than refractivity in the processing of the GPS RO observations, which makes it more attractive from a data assimilation point of view.
- However, their use in data assimilation algorithms is more challenging due to the large variability of the vertical gradients of refractivity (water vapor).

(1) Forward Model for bending angle

$$\alpha(a) = -2a\int_a^\infty \frac{d\ln n / dx}{(x^2 - a^2)^{1/2}}\,dx$$

$$(x = nr)$$

In collaboration with Jim Purser (NCEP/EMC)

- The bending angle forward operator is singular at the lower limit of the integral and under super-refraction conditions.
- NCEP's Bending Angle Method (NBAM) avoids the numerical singularity by evaluating the integral in a new grid.
- The integral is then evaluated in an equally spaced grid, so the trapezoidal rule can be easily and accurately applied.
- NBAM does not require the refractivity to decay exponentially with height (only above the model top).
- NBAM makes use of a quadratic interpolator that preserves continuity of the refractivity values and their derivatives in both the model model vertical grid and the new integration grid.
- QC and observation errors have been tuned similarly to refractivity.
- As all the implemented FO at NCEP, the drift of the tangent point is taken into account

(1) NBAM characteristics

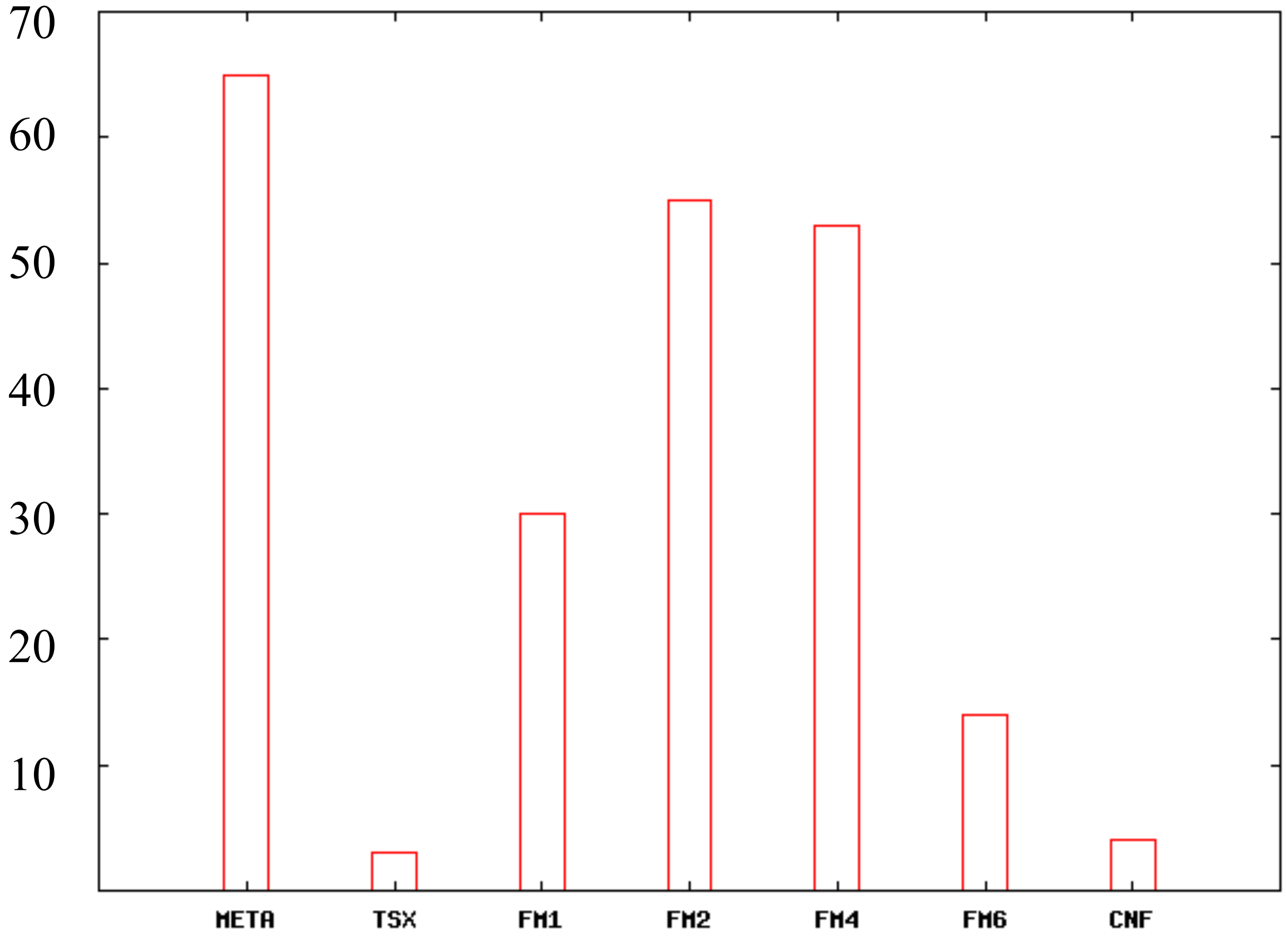
- Enables the assimilation of GPS RO observations up to 50 km – QC procedures and observation error structures have been tuned up to this height.
- Algorithms to include the compressibility factors in the computation of the geopotential heights have been implemented to compute a more accurate forward operator for GPS RO.
- Both refractivity and bending angle codes have the option to use the compressibility factors.
- When the compressibility factors are used, the GPS RO forward operators use a more accurate set of refractive indices (Rüeger coefficients).
- The use of compressibility factors will affect the assimilation of GPS RO observations as well as all the observations that use geopotential heights. In fact, any subroutine within the assimilation code that makes use of the geopotential heights will be affected by the changes.
- The implementation of NBAM resulted in an overall slight improvement in weather forecast skill wrt the assimilation of refractivities. Details on the design and implementation of NBAM can be found in *Cucurull, Derber, and Purser (2012), in review, JGR.*
- Since NBAM reverses the procedure of assimilating refractivities, it still suffers from errors induced by deviations from spherical symmetry.

(2) GPS RO in NAM

- Near-real time monitoring of the system can be found under

http://www.emc.ncep.noaa.gov/gmb/wx20cl/STATS_GPSRO/NAM/

Daily number of profiles per satellite mission



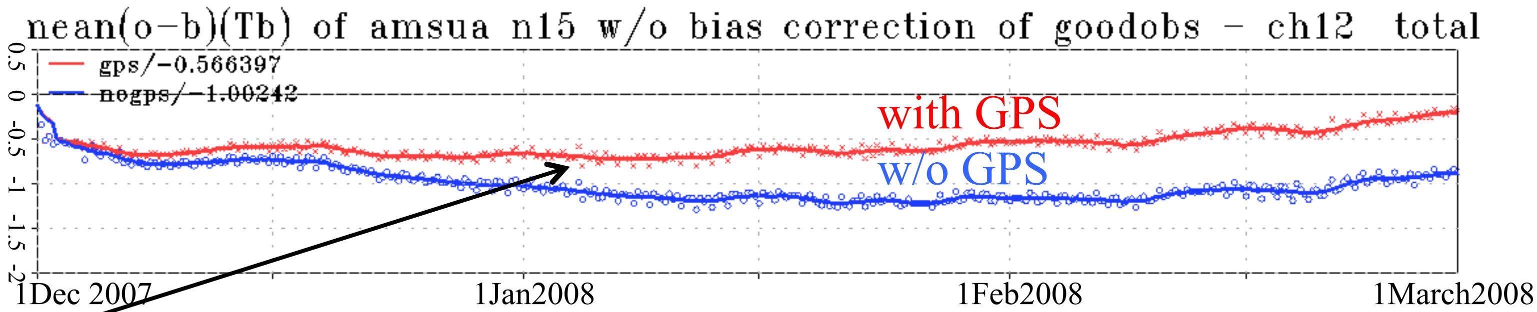
(3) Satellite radiance assimilation

In collaboration with
Ling-Ling Tsao (CWB)

- Radiance observations contain systematic errors (i.e. biases), either in the retrievals, instruments and/or forward models.
- These biases can be larger than the signal, so the use of radiances in DA require the utilization of significant bias corrections.
- Typically, these biases corrections do not account for biases that might exist in the model, which requires some measurements to be assimilated without bias correction to 'anchor' the model, avoiding a drift of the bias correction algorithms.
- GPS RO is an <u>anchor measurement</u>: unbiased observations – or at least their bias is small enough so they do not need to be bias corrected.

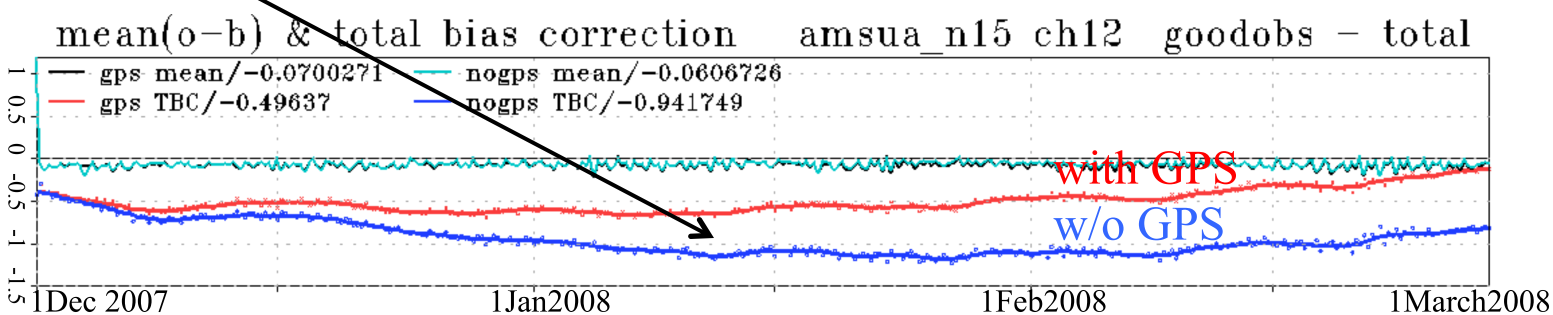
(3) AMSU-A NOAA-15, Channel 12
Weighting function peak: 10 hPa

Temporal evolution of (o-b) without bias correction



Difference of ~ 0.5 K

Temporal evolution of the total bias correction



(3) Satellite radiances and GPS RO

- The experiment with GPS RO produced better forecast skill for all fields and pressure levels:
  - Direct impact of the GPS RO data
  - Indirect impact on the assimilation of satellite radiances:
    - Given good quality satellite radiances and a less biased forecast model – due to the assimilation of unbiased GPS RO observations, the amount of bias correction applied to radiance observations over time was found to be significantly lower.
    - More information was extracted from the satellite radiances
    - Improvement in weather prediction skill.
- The use of bending angles resulted in a further lower bias correction of the satellite radiances than the use of refractivities.
- A more detailed evaluation can be found in *Cucurull and Tsao (2012), submitted, JAOT.*

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GPS RO: current sensors

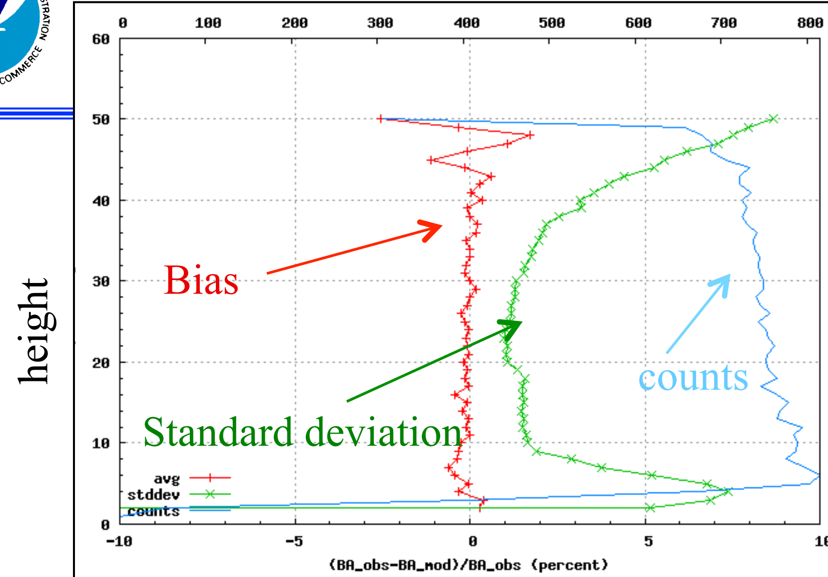
- NCEP Global Data Assimilation System (GDAS) assimilates operationally the following RO instruments for total daily soundings of ~ 2,100:

  - **COSMIC 1-6** (US and Taiwan) – since May 2007
  - **Metop/GRAS** (Eumetsat) - since February 2010
  - **GRACE-A** (Germany) - since February 2010
  - **SAC-C** (Argentina) – since May 2011 (not in NAM)
  - **C/NOFS** (US Air Force) – since May 2011(not in NAM)
  - **TerraSAR-X** (Germany) - since May 2011(not in NAM, only setting occs.)

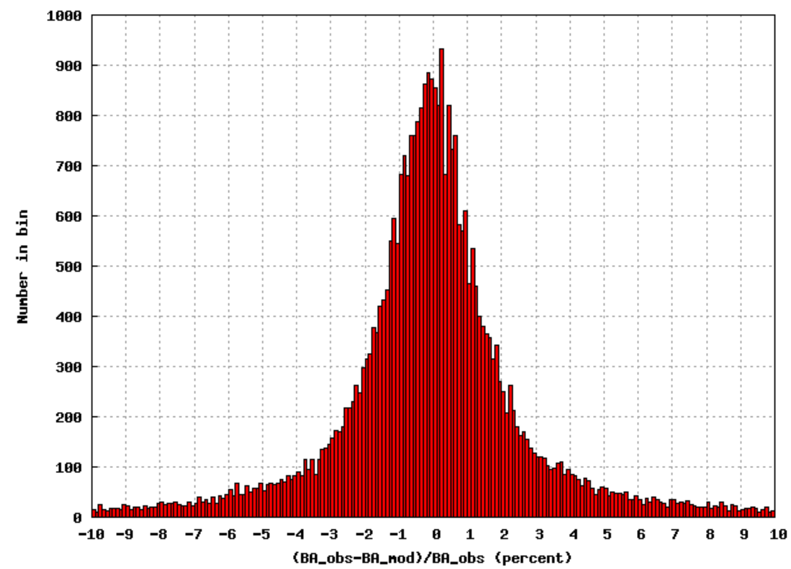
- Near-operational monitoring of the systems above can be found in:

http://www.emc.ncep.noaa.gov/gmb/gdas/ under "GPSRO Monitoring"

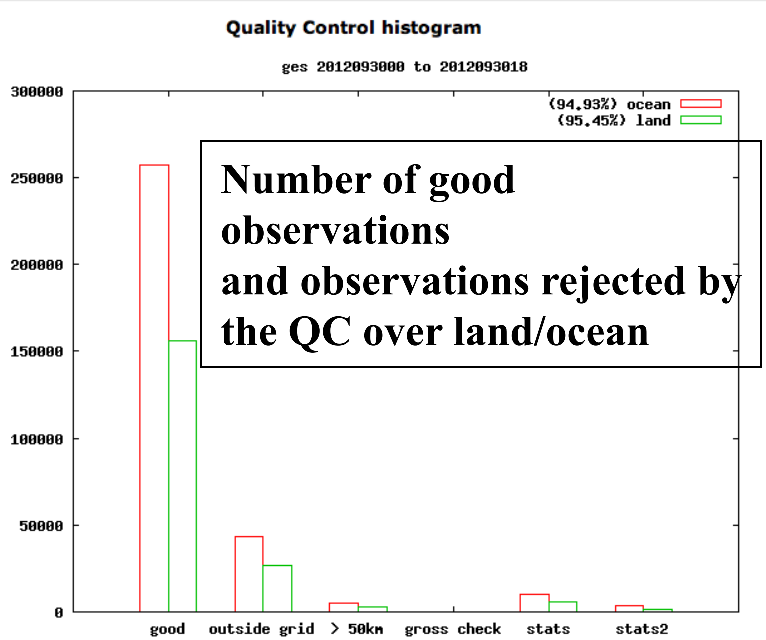
Differences in BA (%)

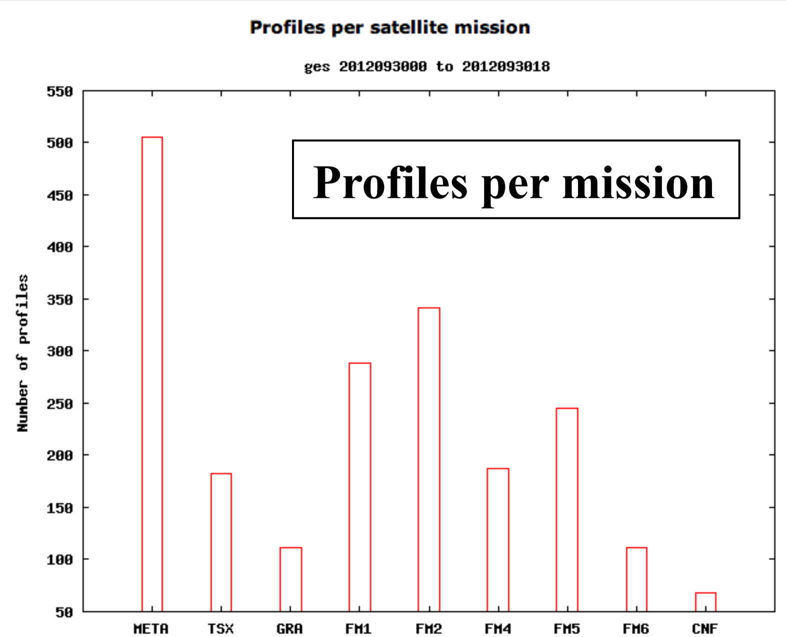


Histogram of differences (%)



COSMIC FM2 | Northern Hemisphere | Only good observations | Incremental bending angle | submit | Histogram | Time Series Plot





Some considerations…

- **SAC-C** has not been available for ~ 1 year – satellite issues.

- **COSMIC** is degrading - one of the satellites is dead and others are having battery issues.

- **As a consequence, the impact of GPS RO in NWP is decreasing – this is already seen in the "impact plots" (eg. adjoint technique) at the difference NWP centers.**

RO instruments already flying but not yet available to NWP

- **Oceansat-2** (Sept. 2009), **Megha-Tropiques** (Oct. 2011), and **SAC-D/Aquarius** (June 2011):
  - EUMETSAT is working on the acquisition and evaluation of the data
  - Few data available for testing
  - Issues with L2 signal
  - Data not available in RT yet
  - Process moving very slowly…
  - New type of RO receiver - <u>evaluation of the data and new quality controls and error characterization algorithms will need to be developed and implemented at JCSDA prior to testing for operational assimilation</u>
- **Tandem-X** (June 2010)
  - In tandem with TSX (separation of ~ 200 m)
  - Only rising occs will be available to NWP
  - RT data should be available soon
- **MetOp-B** (Sept. 2012)
  - In commissioning phase (until Jan/Feb 2013)
  - Software improvements to be uploaded in the instrument ~ Nov-Dec 2012 - also to be implemented in MetOp-A at a later time
  - <u>JCSDA will need to prepare for these changes accordingly: existing quality controls and error characterization algorithms will need to be modified in the DA algorithms</u>
  - RO data expected to be available in RT ~ Jan-Feb 2013

Near future RO instruments

- **KOMPSAT-5** (Korea) – to be launched in ????.

- **PAZ** (Spain) – to be launched late 2013.

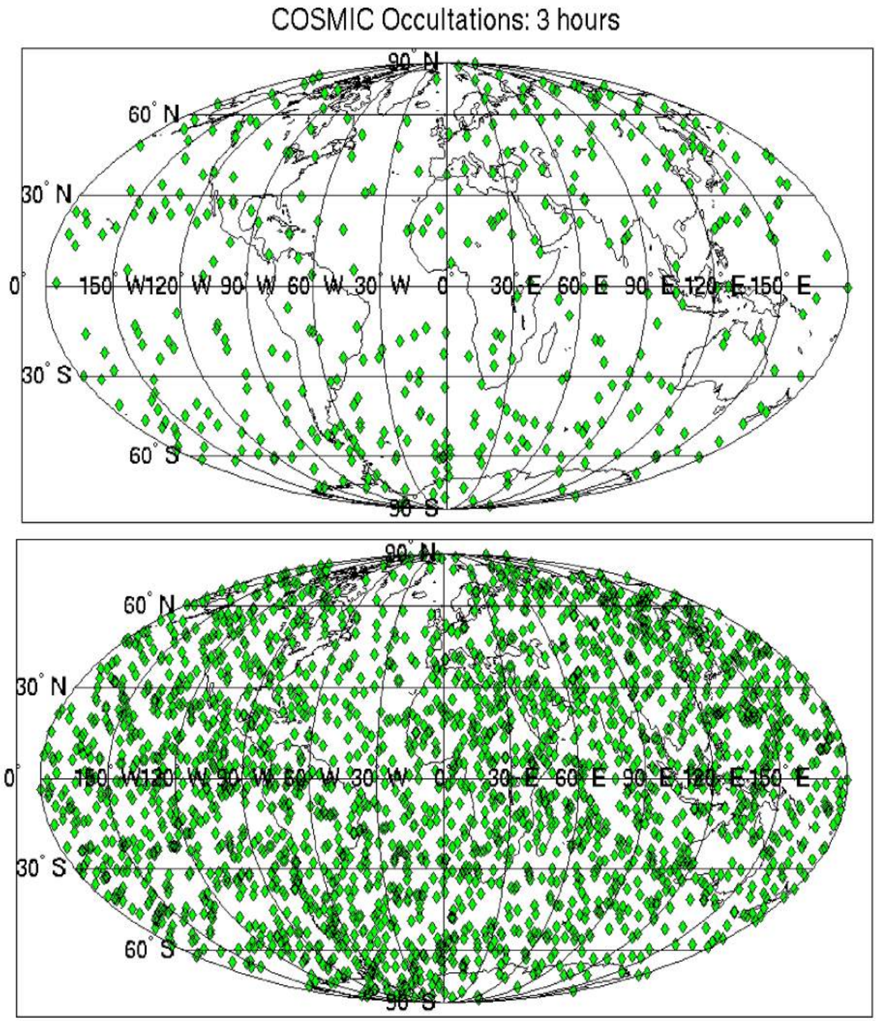
- **COSMIC-2** – first launch planned for early 2016.
  - Taiwan - US (Air Force, UCAR, JPL, and NOAA).
  - Will fly more capable receivers than COSMIC-1, producing at least double the soundings per payload.
  - At this point, only the first launch with 6 satellites in equatorial orbits has been funded.
  - US is studying possibilities to fund the second 6 satellites, to be deployed in polar orbits in 2018.

COSMIC soundings within 3 hours

courtesy of UCAR

COSMIC

COSMIC-2



Up to 12,000 profiles/day with full constellation

GPS RO

- Complimentary to other existing observing systems (e.g. satellite radiances).
- Has shown to provide significant positive impact in forecast weather skill.
- There are several scientific open questions in both the retrieval and assimilation aspects of the GPS RO observations.
- The larger amount of observations from future GPS RO missions (e. g. COSMIC-2) that will be available to NWP requires addressing all these scientific questions to extract more benefits from the assimilation of these observations.

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Current work

In collaboration with
Sergey Sokolovskiy (UCAR)

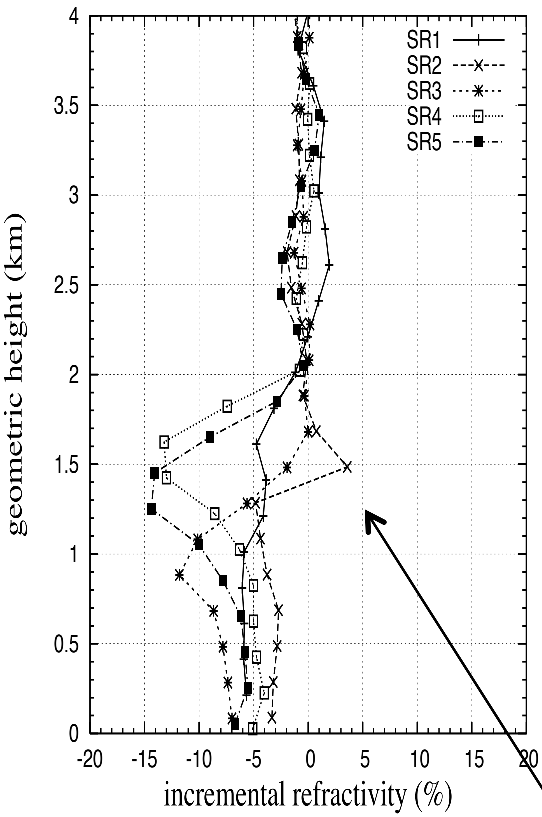
- Improve the assimilation of the lower observations, in particular under super-refraction (SR) conditions (top of the PBL).
- SR occurs when the gradient of atmospheric refractivity is so large (~ -157 N-units/km) that the ray doesn't leave the atmosphere.
- Rays that have tangent points inside an elevated atmospheric SR layer are internal (ie. are trapped within the layer).
- Regions of high occurrence frequency of SR are the west coast of major continents in the subtropical oceans and trade wind regions.
- Under SR, the assimilation of GPS RO below the height of the SR layer is an ill-conditioned problem: there is an infinite number of atmospheric states that would reproduce the same exact GPS RO profile.

Current work (cont'd)

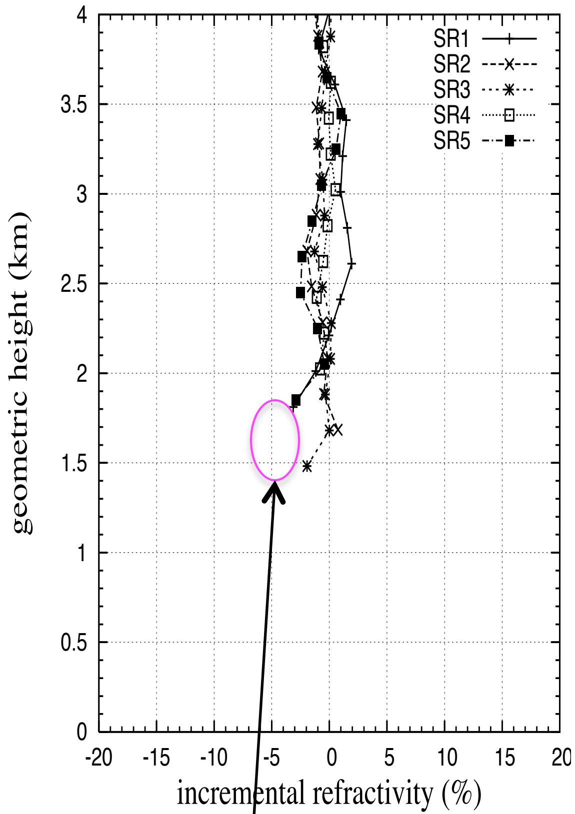
- When profiles of bending angles are inverted into refractivities at the processing centers, one of the possible solutions is retrieved: the one that has the lowest refractivity value.
- Therefore, refractivity observations are negatively biased under SR conditions at and below the height of the SR layer. In this case, observations need to be rejected in data assimilation.
- On the other hand, observations of bending angle still contain the indetermination - observations might be rejected in a data assimilation system.
- From an observational point of view, we cannot know for sure whether SR occurred (S. Sokolovskiy is working on this).
- We must address this issue in the GSI in preparation for the large amount of observations that COSMIC-2 and other GPS RO missions will bring.

Refractivity profiles under SR

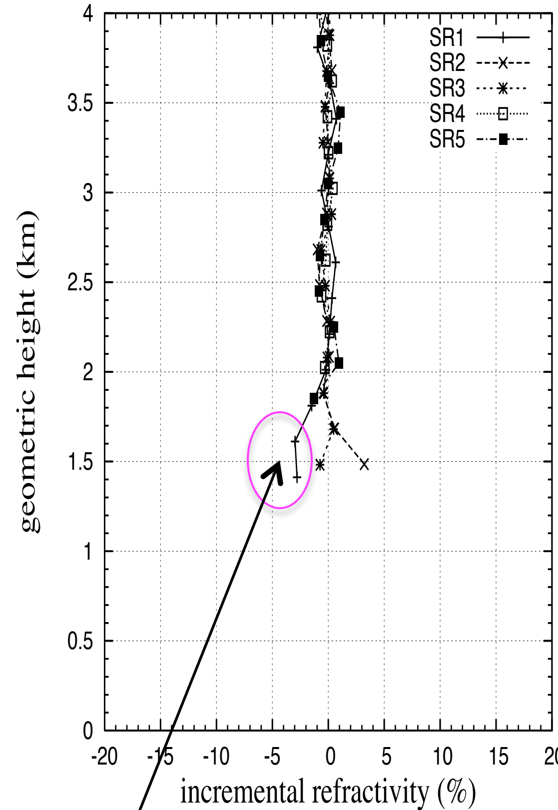
guess



guess after standard QC



miter=2 after standard QC

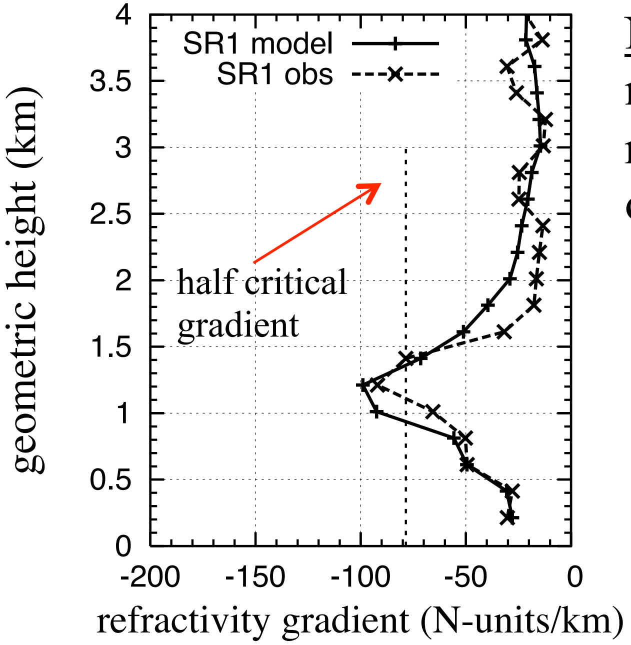


Large negative bias

Obs rejected in first outer loop

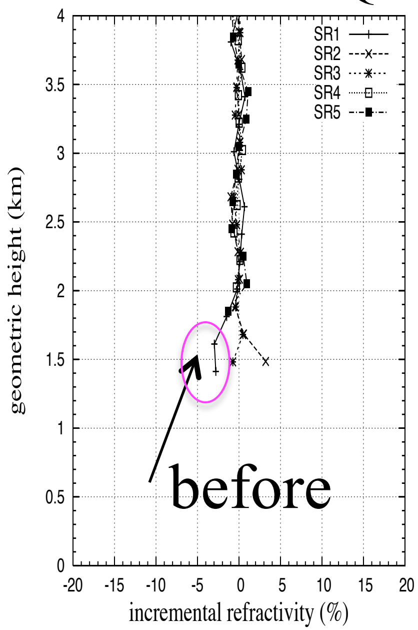
Some residual obs from profile SR1 passed the standard QC in second outer loop

Refractivity profiles: additional SR QC

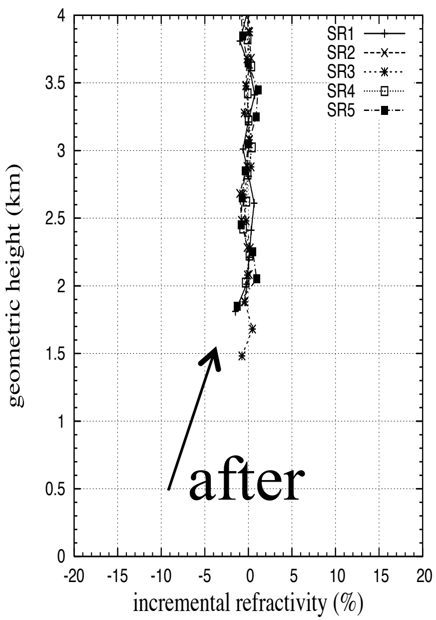


New SR QC (below 3 km): obs is rejected if either the model or the observational gradient of refractivity reaches half the critical gradient. If this happens, the rest of the profile below that observation is rejected as well.

miter=2 after std QC

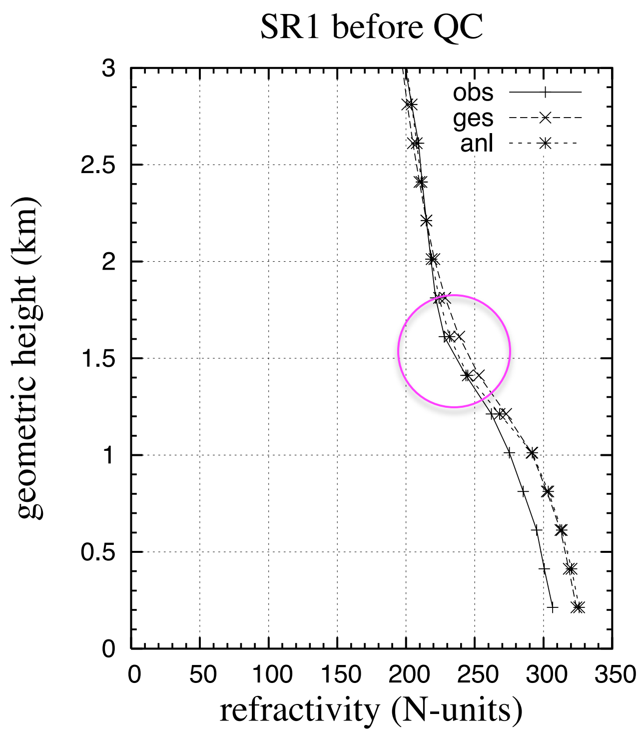


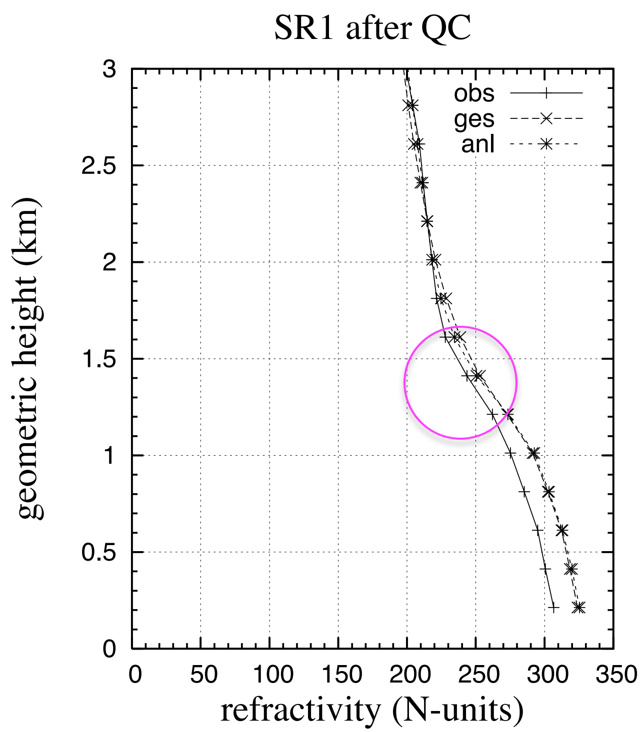
miter=2 after std & SR QC



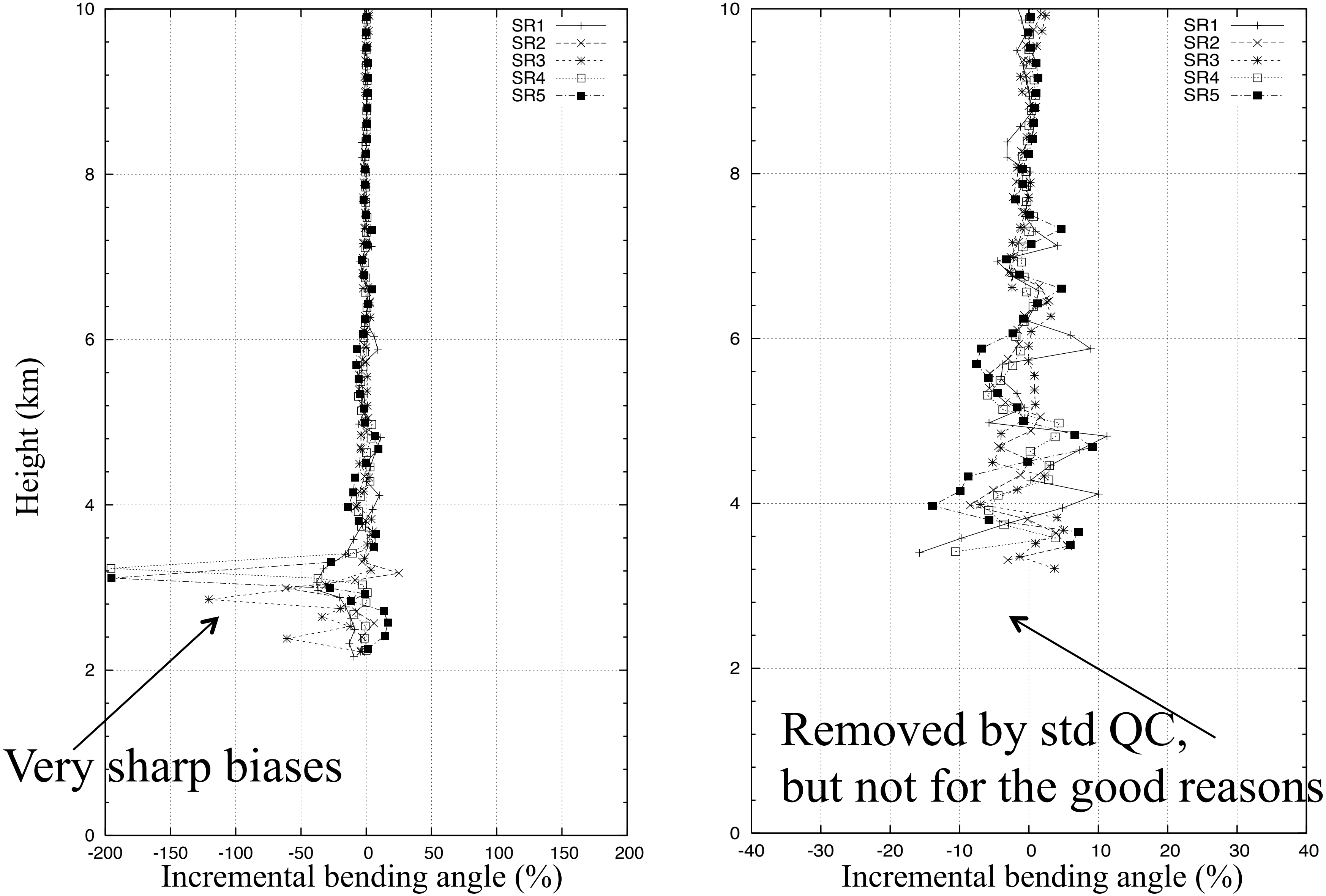
Refractivity profiles: better analysis

After SR QC, the analysis tends to the background field at the heights of the negative-biased observations

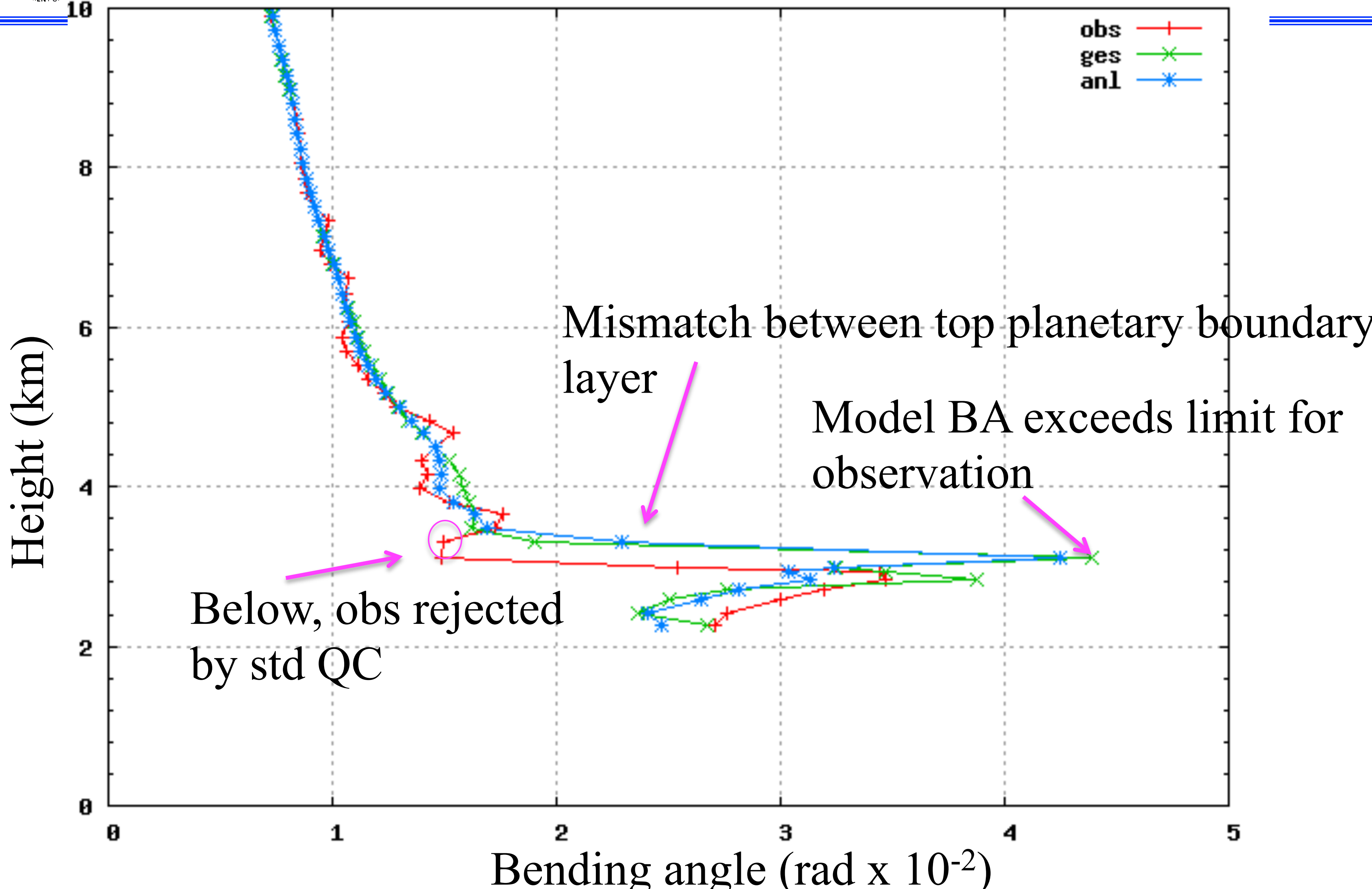




Bending angle profiles under SR



A better QC for bending angles is necessary



Outlook

- Monitor current GPS RO observations (maintain operational effectiveness).
- Evaluate current/future RO sensors (as early as possible) to enable operational assimilation of the new data as soon as possible.
- Operational transition from refractivities to bending angles in NAM.
- R2O work
  - Finalize QC work on super-refraction for the assimilation of bending angles – will require retuning of the error characterization
  - evaluate standard & improved variational quality control techniques (in collaboration with J. Purser)
  - quantify sensitivity of the forward operators to extra-components
  - more realistic ionospheric correction (in collaboration with NCEP/SWPC)
  - develop, test, and implement a forward operator that takes into account the horizontal gradients of refractivity in the atmosphere
  - assimilation of ground-based GPS satellite data (PW and ZTD forward operators)
  - applications of PBL heights derived from GPS RO
  - Etc…..