Estimates of forward model and instrument error statistics in the troposphere

S. Healy[1], A. Carlström[2], J. Rasch[2], and J. Christiansen[2]

1 ECMWF 2 RUAG

Together ahead. RUAG

Background

The successful exploitation GNSS radio occultation (GNSS-RO) in numerical weather prediction (NWP) requires a good understanding of ***total*** measurement uncertainty, so that the data can be weighted appropriately during the assimilation process. The ***total*** measurement uncertainty is related to both the instrument performance and representation/forward modelling errors.

ESA study (Contract 4000120495) aimed to assess the relative importance of instrument error and representation/forward modelling errors in the troposphere.

- Does instrument error or representation/forward model error limit GNSS-RO performance in the troposphere? Importance of improved forward models?
- What are the benefits of a high-quality receiver (**HQ**, e.g., the Metop Second-Generation GNSS-RO receiver) versus a miniaturised, medium-quality (**MQ**) receiver?

Method: Perform wave optics simulations (**Figure 1**) with a 55 1D profile and 2D slice dataset designed to provide challenging measurement conditions. **Two independent wave optics codes used**.

- **The RUAG wave optics simulation code** has a GNSS receiver model, including the actual onboard tracking algorithms. This is used to investigate the HQ and MQ differences (**Figure 2**) in the troposphere using **1D refractivity profiles**. The phase matching approach is used to produce bending angles, and these are compared with a 1D geometric optics (**GO**) calculation.
- **The ROM SAF wave optics code** is used to simulate measurements for both 1D profiles and **2D slices (2D will be in ROPP 10)**. **This code does not include a receiver model**. The phases and amplitudes at the LEO are inverted with FSI, and these bending angles are compared with 1D and 2D GO simulations.

Figure 1. Wave optics forward modelling with a Multiple-Phase-Screen (MPS) approach, then invert with phase matching or FSI.

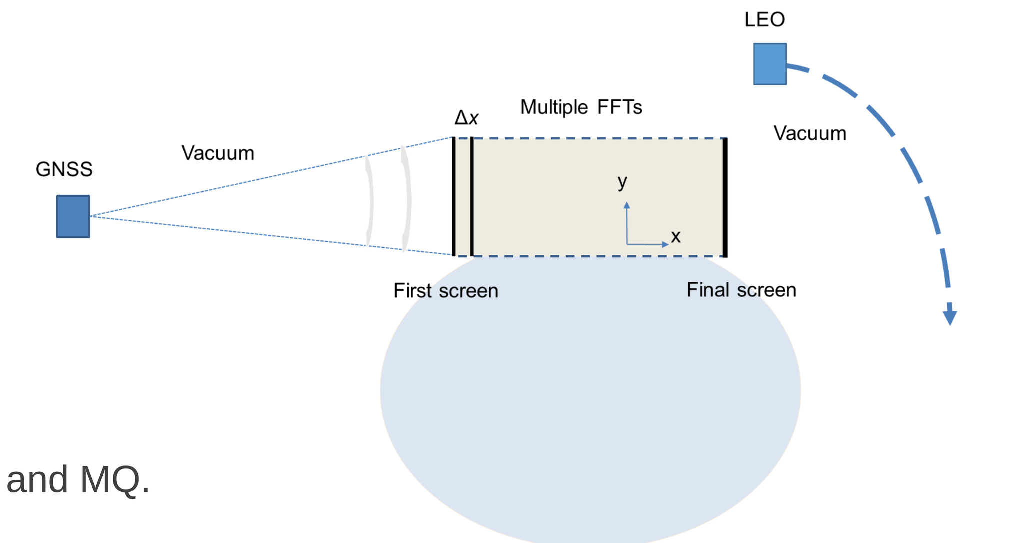

Figure 2. HQ and MQ.

High Quality: HQ

- Metop-SG GNSS-RO instrument
- Bending angle noise is less than 0.5 urad (1σ) at 35 km
- Advanced Open Loop tracking (output from 10 correlators)

Medium Quality: MQ

- Miniaturized GNSS-RO instrument
- Bending angle noise is 2-3 urad (1σ) at 35 km (***mainly caused by instrument clock noise***)
- Advanced Open Loop tracking, and standard tracking (1 correlator output).

Some key results

The 55 profiles are split into four categories based on the peak refractivity gradient at the centre of the 2D slice.

Two "***challenging***" examples from the 55 profile dataset, one with a maximum gradients close to ducting conditions (CASE 12) and the other strong horizontal gradients (CASE 16).

The 1D simulations use the refractivity profile at the centre of the 2D slice, illustrated by the dashed white line in **Figure 3**. **Figure 4** shows the bending angle differences for the RUAG HQ simulation and the 1D ECMWF perfect receiver simulation. "**Truth**" is a numerical solution of the standard 1D GO bending angle integral (ROM SAF):

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

Figure 5 is a challenging 2D case with large gradients. Figure 6 includes these horizontal gradients in the ECMWF wave optics/FSI simulation, and compares this output with three forward models:

- **A 1D solution of the bending angle integral (above), but including tangent point drift (tpd).**
- **A 2D GO estimate of bending angle solving the ray-path equations, including tpd, and using the impact parameter defined in the FSI to determine the tangent point height**.
- **A 2D GO estimate of bending angle, including tpd, but assuming the impact parameter defined in the FSI is the value at the LEO (LEO-imp). *This is valid because we assume a stationary GNSS satellite in the ECMWF simulations.***

Figure 6. shows "*impact multipath*" in lowest few km. By definition the FSI cannot produce multiple bending angles for a given impact parameter (Sokolovskiy, pers. comm.), but the 2D GO calculations suggest it should in this case. This is a representation (or forward model) issue, not an instrument error. How do we use this measurement in NWP? QC out (e.g., Zou et al, 2019 QJRMS, https://doi.org/10.1002/qj.3520)?

Figure 7. Compares the RUAG HQ simulations with ECMWF 1D WO calculations for the 55 cases. In the lowest km, the independent WO calculations agree with each other better than with the 1D GO calculation.

Figure 8. Compares instrument error statistics with 1D and 2D forward model (FM) error statistics for rising L1 measurements for impact heights 3-10 km (forward model errors do not depend on rising/setting).

HQ,MQ with "advanced tracking" have error statistics well below the 1D FM values. However, MQ using single correlator output has comparable error statistics to the 2D operator. Not generally correct to assume forward model error >> instrument error in the troposphere when considering 2D operators.

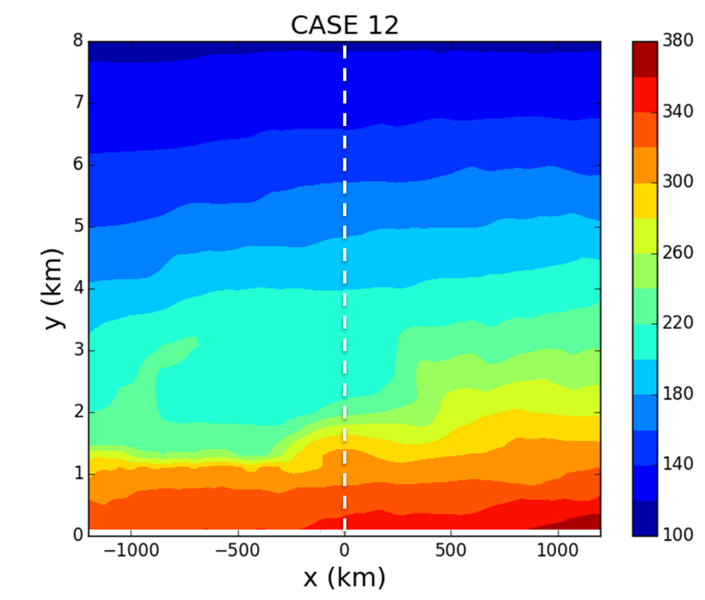

Figure 3. The refractivity 2D slice used in CASE 12. The 1D calculations use the central profile at the dashed white line.

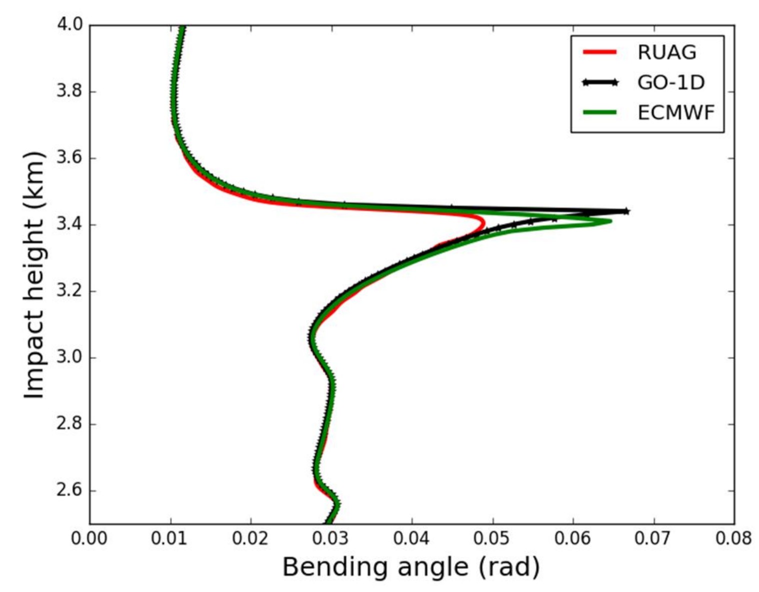

Figure 4. The 1D geometrical optics (GO) and the RUAG and ECMWF perfect wave optics results for CASE12.

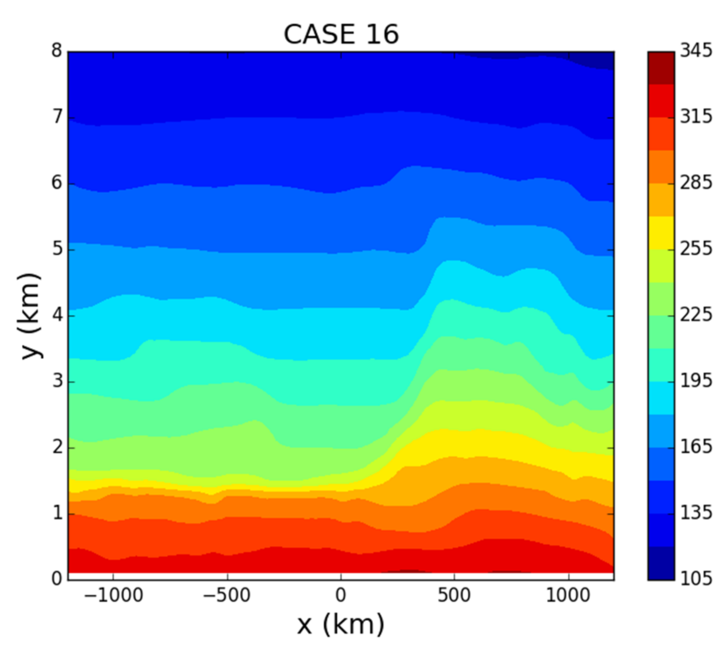

Figure 5. CASE 16 with strong horizontal gradients.

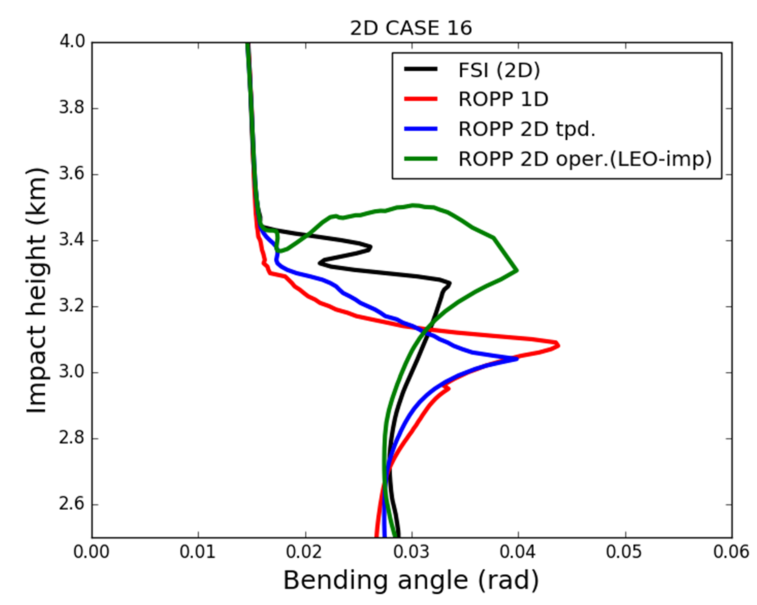

Figure 6. The bending angle profiles in the lower-troposphere for CASE 16.

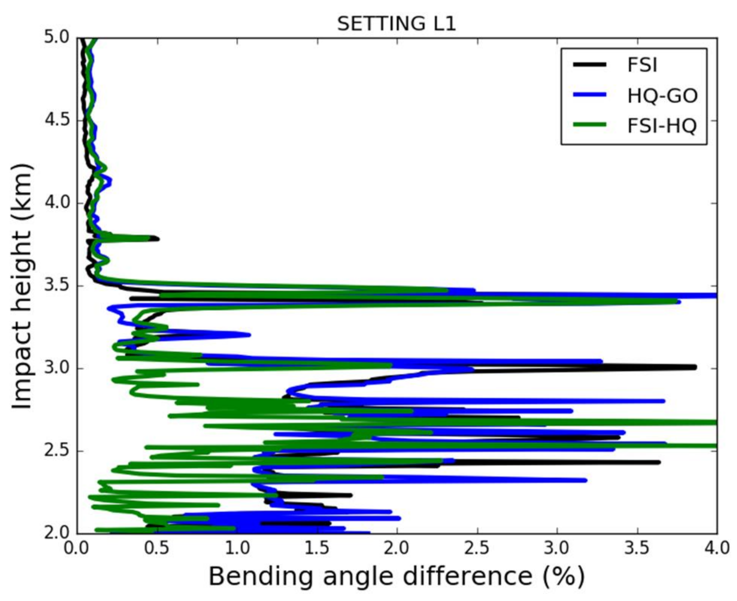

Figure 7. The 1D difference statistics comparing both FSI and HQ vs GO, and FSI vs HQ wave optics.

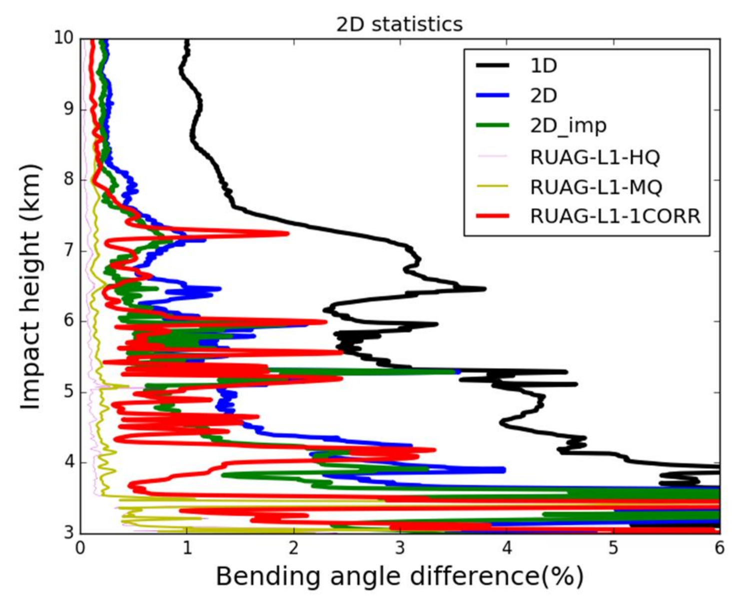

Figure 8. The bending angle error statistics for L1 rising measurements for the 55 cases.

Concluding Remarks

This work attempts to estimate the relative importance of forward model and instrument uncertainty in the troposphere. The sample is quite small, but it includes challenging cases. This work is relevant to assumptions made in OSSEs. Decisions based on comparing instrument performance with current forward model error statistics have to be considered carefully. Forward models will improve. Further, the GNSS-RO data will be used in future climate reanalyses in 20??.