

Processing GRAS Instrument Real Data with Ground Processor Prototype

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INTRODUCTION

GRAS GPP is the Ground Processor Prototype for GPS Receiver for Atmospheric Sounding. The Ground Processor Prototype (GPP, [1]), developed by GMV under an ESTEC/ESA contract, is a software tool for isolating the atmospheric contribution in GPS Radio Occultation sounding measurements. Its output will be used to provide atmospheric profiles of temperature, pressure, and water vapour as well as total electron content. The purpose of the GPP is the development and validation of the algorithms to convert the GPS observables into atmospheric properties, and to verify the end-to-end performances of the system. The GPP tool is the prototype of the operational processor and it is part of the GRAS contract, led by SES.

In the frame of the GPP validation, GRAS data delivered by the Instrument Flight Model has been tested with the GPP. GRAS is an atmospheric-sounding instrument that forms part of the payload of the Metop series of meteorological satellites. SES is developing and manufacturing the GRAS instruments, [2].

In this case, the GRAS output data comes from an experiment where the GRAS instrument was directly connected to a GPS Signal Simulator. Atmospheric effects (both atmosphere and ionosphere) were considered in the simulation environment as a part of the GPS sounding measurements. The GPP has processed this GRAS Real Data and it has retrieved the atmospheric profiles at bending angle levels. GPP processing involves a complex set of algorithms; the reconstruction of the GPS measurements, the correction for instrument effects, the compensation for the different components in the GPS measurement (range, clocks, cycle slips and receiver noise) and finally the computation of atmospheric properties (bending angle). The retrieved atmospheric profiles have been compared versus the experienced atmospheric conditions and great agreement has been assessed.

This paper describes the simulation environment of the GPP when using GRAS real data and will analyze the most important findings when validating the retrieved atmospheric properties. Results of the validation of GPP with GRAS real data, and GRAS-GPP end-to-end performances are addressed.

SIMULATION ENVIRONMENT

Fig. 1 provides a scheme for the data flow in the system test with real data. A brief explanation of this simulation environment is:

- The GPS Signal Simulator is physically connected to the GRAS instrument. The reference scenario in the GPS signal simulator is defined for a given METOP and GPS constellation ephemeris. Atmospheric effects are considered.
- GRAS Flight Model Instrument provides the level 0 products, which are converted into standard GPS measurements by the GPP 1a process.
- The GPP Level 1a corrects the GPS measurements for instrument delays. For this purpose, an instrument characterisation database is used.
- The GPP Level 1b process retrieves the atmospheric effects in GPS measurements up to bending angle level. For this purpose, several algorithms are needed:

- Geometric range correction. To compute the geometrical components, the simulated METOP and GPS orbits are propagated using an orbit propagator similar to the one used inside the GPS signal simulator. The instrument characterization database is also needed.
- Clock correction. Among the different clock correction approaches implemented in the GPP, the more adequate for this simulation scenario is the Frequency Bias Estimation (FBE):
 - The differential modes are not applicable because ground station measurements are not available in this scenario. Single differences with respect to the zenith antenna, SD1, would not improve the performances because the effect of the GPS clock will remain in the observable.
 - Clock correction based on estimated clocks (PBCC), is not feasible because we have not available information about the simulated clocks (GRAS nor GPS).
 - FBE is based on using a reference atmospheric profile to compute and compensate for a bias in the Doppler measurement at high altitude. The reference atmospheric profile is available because it is an input of the GPS signal simulator.
- Cycle slip correction. The measurement provided by GRAS is corrected from cycle slips.
- Retrieval algorithms. The GPP includes two possible retrieval methods: one method is based on geometrical optics theory (GO, [3]) and the other is the back-propagation (BP, [4]) method. These two methods are used for the performance assessment.
- Neutral bending angle estimation. The GPP computes the neutral bending angle from the total dual frequency bending angle profiles.

In addition to these correction algorithms, the GPP mitigates the receiver thermal noise by means of filters. The filters in the occultation flow are located at different steps:

- Height-adaptive filter in the Doppler. This filter conforms the diameter of the first Fresnel zone to provide smoother profile with a good resolution.

There are several algorithms that are not applied in the GPP:

- Relativistic corrections are not considered, because neither GRAS nor GPS emitters are physically in orbit. Therefore, relativistic effects do not appear.
- Instrument correction due to GRAS receiving antennas are not considered, because in the simulation environment, the GPS signal simulator is physically connected to the GRAS Instrument without using antennas.

The parameter on which the performances are evaluated is the neutral bending angle. For this purpose, the refractivity profile used in the simulation definition is converted to neutral bending angle with the inverse of the Abel Transform.

The comparison in terms of atmospheric residual carrier phase is also feasible because the GPS signal simulator provides this parameter as output.

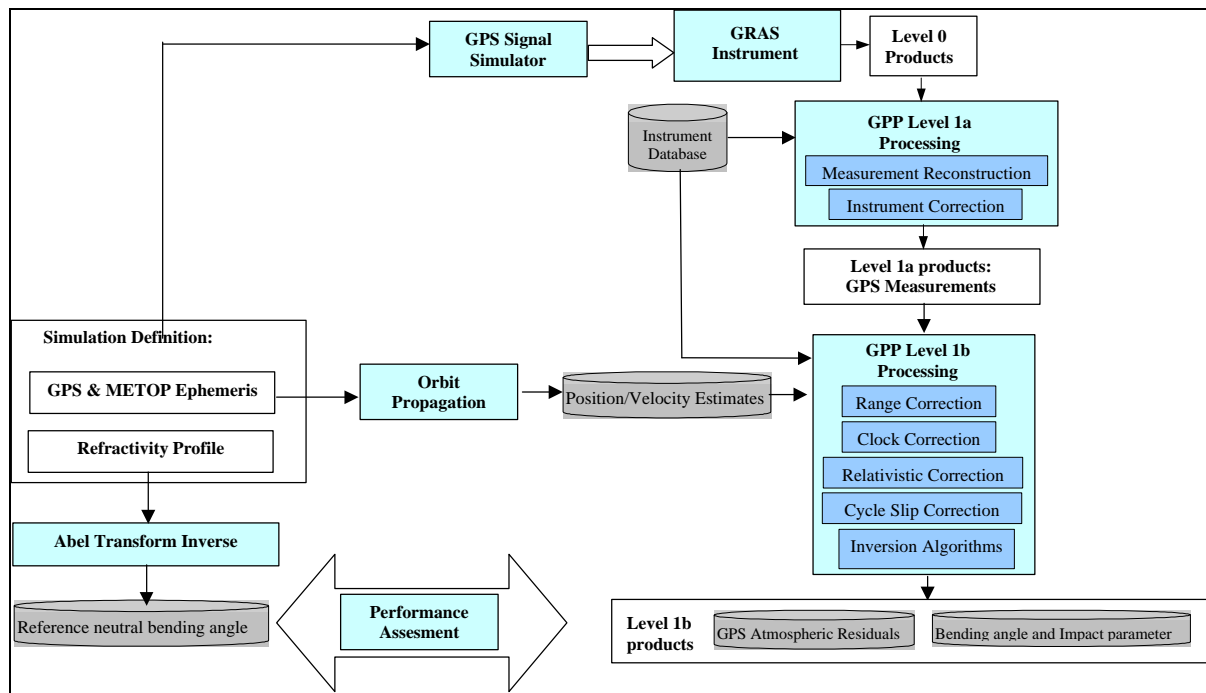


Fig. 1. Scheme for the Data Flow in the Test with “real” Data

ATMOSPHERIC AND IONOSPHERIC SIMULATED TRUTH

From the definition of the simulation, the truth is known. To cover different cases, the scenario used lasts for 40 minutes and includes 18 occultations of GPS satellites, either rising or setting.

Neutral Atmospheric Refractivity Model

The neutral atmosphere is described by refractivity, $N = (n - 1) \cdot 10^6$, where “n” is the refractive index. “N” is a bi-exponential function of height, “h” in km, and determined by the parameters N_{0h} , H_h , N_{0w} , and H_w as:

$$N = N_{0h}e^{-h/H_h} + N_{0w}e^{-h/H_w} \quad (1)$$

where: H_h : scale height for the dry component of the atmosphere

H_w : scale height for the wet component of the atmosphere

The neutral atmosphere for occultations with SVIDs 26, 23, 8, 15, 31, 28, 11, 1, 25, 20, 7, 4 and 30 is modelled with $N_{0h}=300$ N-units, $H_h=7.9$ km, $N_{0w}=100$ N-units and $H_w=2.5$ km (i.e a dense-wet atmosphere representative of tropical environment).

The neutral atmosphere for occultations with SVIDs 10, 17, 3, 27 and 22 is modelled as: $N_{0h}=200$ N-units, $H_h=7.5$ km, and $N_{0w}=0$ (i.e a thin-dry atmosphere representative of a dry polar environment).

Ionospheric Model

The ionosphere is described by electron density, N_x . N_x is a double Chapman profile with height, “h”, and determined by the parameters N_E , Z_E , H_E , N_F , Z_F , and H_F as:

$$N_x = N_E \cdot e^{\frac{1}{2}(1 - Z_E - e^{-Z_E})} + N_F \cdot e^{\frac{1}{2}(1 - Z_F - e^{-Z_F})} \quad (2)$$

where $Z_E = \frac{h - Z_E}{H_E}$ and $Z_F = \frac{h - Z_F}{H_F}$. The model parameter values are:

Table 1. Considered parameters in the ionospheric model

N_E	$2e^{11}$ [el/m ³]
H_E	10 [km]
Z_E	105 [km]
N_F	$3e^{12}$ [el/m ³]
H_F	50 [km]
Z_F	300 [km]

Both ionosphere and atmosphere as defined above are included for all occultations.

Simulation limits

As mentioned previously, while the GRAS Flight Model Instrument is used, a GPS simulator has to be used to generate L-band signals including effects of atmosphere, ionosphere and satellites velocity. In order to have access to these features, the most powerful simulator has been used. However, it has some limitations, as Radio Occultation sensing is more demanding than just the need to know one position in 4D. Indeed, we are looking at the error on the position measured due to the atmosphere while the Transmitter and Receiver are moving at 3.7 and 7.5 km/s.

ANALYSIS OF RESULTS

GPP has been run successfully over the 18 occultations present in the scenario. As an example for occultation number#1, a rising occultation with the PRN10 that considers a thin-dry neutral atmosphere, the following performances have been assessed:

Detailed Results for First Occultation

Fig. 2 plots in the same scale the neutral bending angles as a function of impact parameter. The retrieved values from GPP geometrical optics are compared versus the bending angle computed with inverse of the Abel Transform (providing the scenario truth). At this scale, appreciable differences are not seen between the profiles.

In order to evaluate the error in the retrieved neutral bending angle, Fig. 3 shows the difference between the neutral bending angle from GO processing and the reference neutral bending angle computed by the inverse of the Abel Inverse. In this figure, the threshold limits provided by the criteria of the maximum of 1 mrad or the 0.4% of the neutral bending angle are also depicted. This threshold limit is very interesting because it guarantees errors lower than $1\text{ }^\circ\text{K}$ in the obtained temperature profiles at level 2 processing. Fig. 4 is a zoom in Fig 3. The error is presented as function of $h = a - R_c$, where a is the impact parameter and R_c is the local radius of curvature of the occultation. In Fig. 4, some few Bending Angle errors are out of limit. The highest errors appear at a time where a ringing effect is observed between 10 and 40km height. However, this ringing error in neutral bending angle is due to the interpolation error performed inside the GPS Signal Simulator in the atmospheric phase. It seems that the simulator needs to perform a cubic interpolation and this leads to errors. This interpolation error is not possible to be simulated in the reference Abel Inverse (AI) neutral BA because the time reference is lost in this AI process. Then results will be fully within specification with margin if one could remove errors introduced by the simulator's limitations.

Fig. 5 shows the neutral bending angle error in the first occultation using BP processing. Fig. 6 is a zoom in Fig. 5. The same threshold limit of the neutral bending angle profiles (relative error less than 0.4% or an absolute error less than 1 mrad) is also included. For height, $h = a - R_c$, below 4-km, no results are plotted because BP results are not feasible at very low altitudes (i.e there is not enough LEO data to back-propagate).

We can conclude that the performances reached are very good.

Height and Altitude

Height in GPP results is plotted in order to have a physical reference value. The plotted height is assumed to be $h = a - R_c$ since the real height is unknown for GPP Level 1b. The true value for height is $h = r - R_c$, where $a = n \cdot r$. As $n > 1$ the represented height is higher than the real height.

For a dense-wet atmosphere, $N(h = 0) = 400$ N-units, and the plotted height, $h = a - R_c$, is about 2.55 km higher than the real height at low altitudes.

For a thin-dry atmosphere, $N(h = 0) = 200$ N-units, and the plotted height $h = a - R_c$ is about 1.28 km higher than the real height. As occultation number #1 considers a thin-dry atmosphere, Fig. 7 shows the low part of the occultation considering as x-axis the real height computed as $h = n(h) \cdot r - R_{loc}$. For occ#1, for close loop data processed by GO, the minimum height is $h = a - R_c = 3.39$ km, corresponding to the minimum real altitude of $h = n(h) \cdot r - R_c = 2.48$ km (in close loop data processed by GO).

It should be noted that this atmosphere is the most difficult to track a signal as this occultation is rising. Indeed the bending angle is smaller at low altitude for a thin atmosphere than for a dense one. This means that the altitude of the GPS signal over the Earth will increase very quickly, letting less time for the receiver to succeed in acquiring and tracking the GPS signal.

However, GRAS Instrument has an Open Loop mode, which provides carrier phase measurements/spectrum which could be used to retrieve Bending Angle measurements below this altitude of 2.48km in close loop.

Results for Other Occultations

These results are completely applicable to the rest of occultations processed by GPP when using as input real data from GRAS.

In addition, it has been seen a great dependence of the performances at low altitudes with respect to the considered local radius of curvature in the inverse of the Abel Transform. As an example, Fig. 8 shows the error in neutral bending angle for occultation number#2. The shape of the error in neutral bending angle has a tendency for $h < 30$ km, the lower altitude the higher error. After investigating the error in neutral bending angle we have concluded that this error is due to a difference in the assumed local radius of curvature for the occultation in the different modules (GPP Level 1b, Abel Transform Inverse, Forward Modeling and GPS Signal Simulator).

To analyse the effect of the radius of curvature, we have run the Abel Inverse again (for occ#02) but with a slightly modified radius of curvature. The computed radius of curvature by GPP level 1b is 6355.391 km and when using in the

Inverse of the Abel Transform a radius of curvature 40 metres higher ($R_c=6355.43$ km), the assessed neutral bending angle errors are shown in Fig 9 for the GO case. The error has disappeared with this 40 metres difference in radius of curvature. Note that in the processing scheme, a unique radius of curvature is assumed in the algorithms. However, when the occultation takes place, the tangent point of each ray is located in a slightly different point of the Earth surface and the radius of curvature is not constant during the occultation.

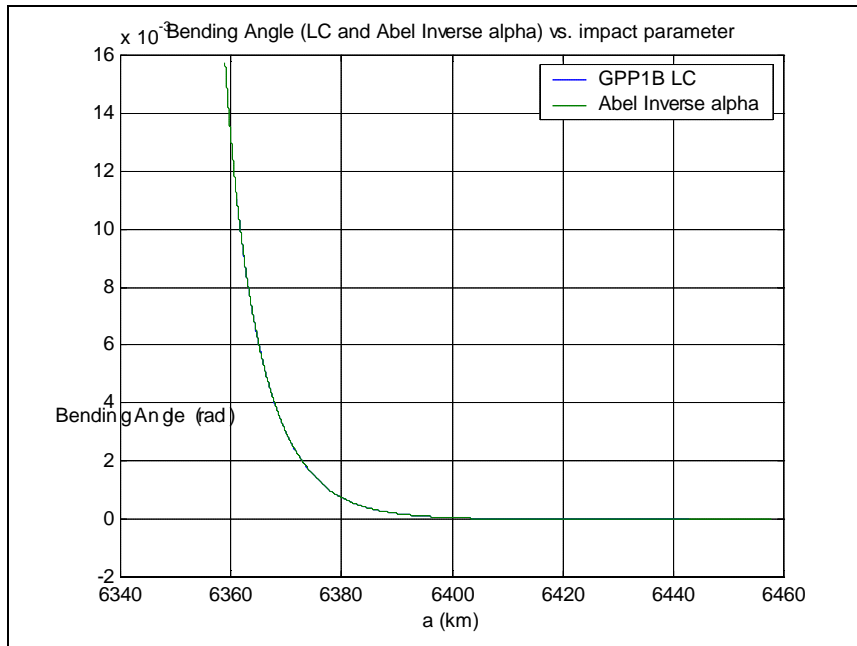


Fig. 2: Neutral bending angle profiles as a function of impact parameter

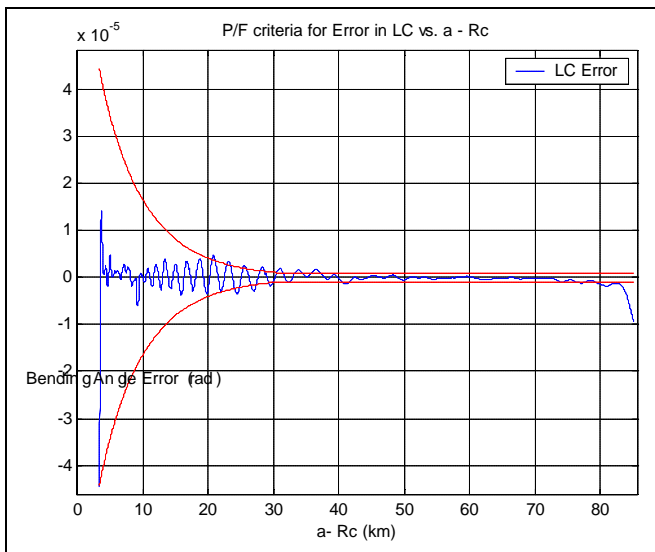


Fig. 3: Error in GO Neutral Bending Angle as a function of $h = a - R_c$

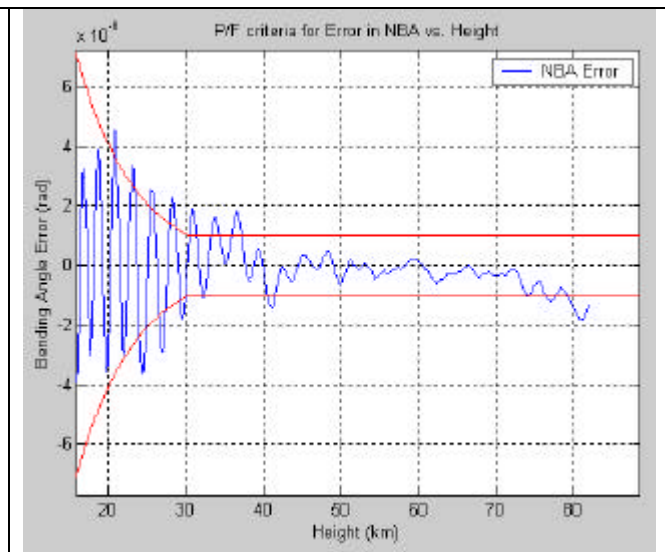


Fig. 4: Zoom in Fig. 3. Error in GO Neutral Bending Angle as a function of $h = a - R_c$

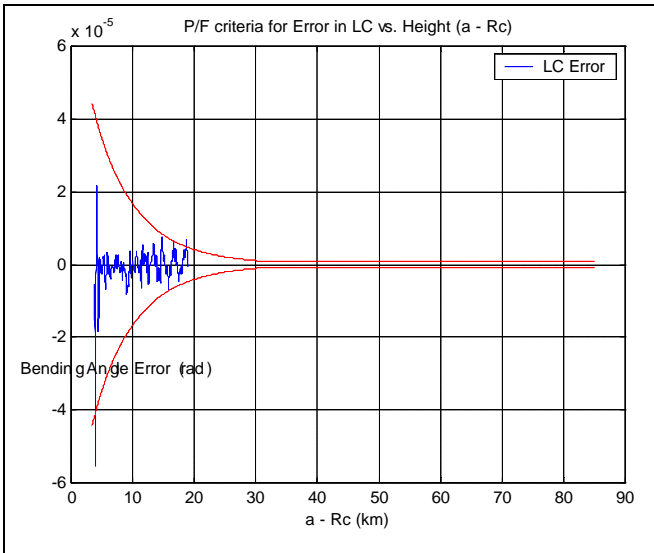


Fig 5: Neutral Bending Angle Error (rad) between GPP Level 1B (BP) and Abel Inverse algorithm.

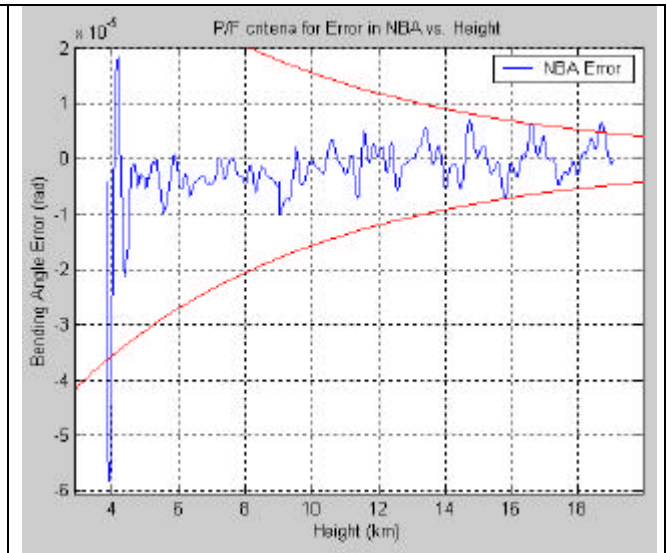


Fig. 6: Zoom in Fig. 5. Error in BP Neutral Bending Angle as a function of $h = a - R_c$

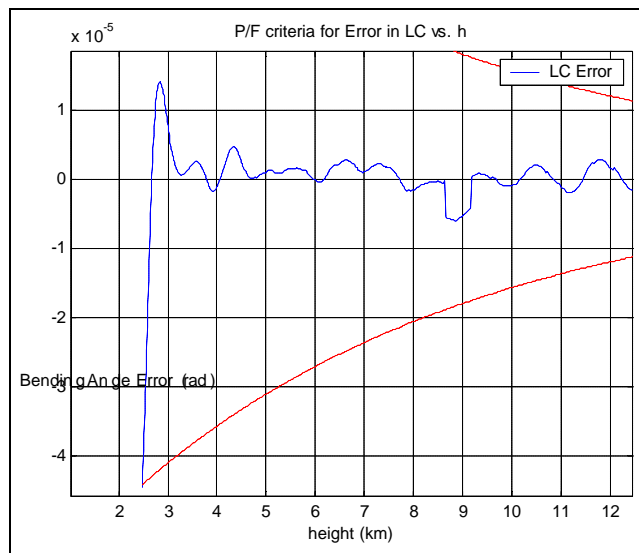


Fig. 7: Neutral Bending Angle Error between GPP Level 1B (GO processing) and Abel Inverse algorithm

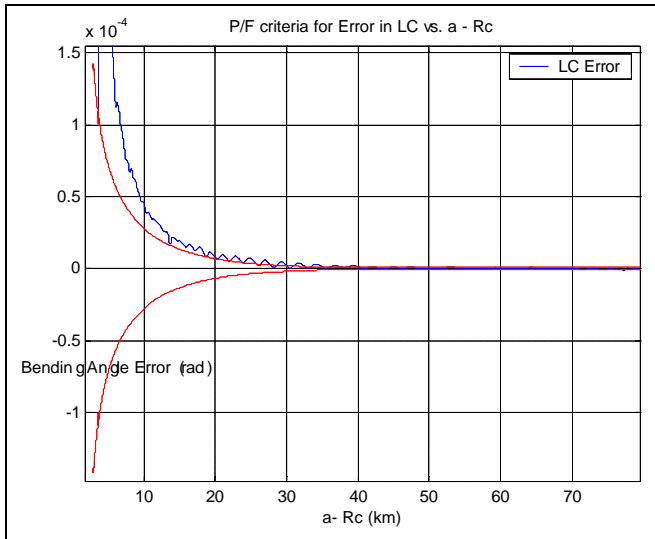


Fig. 8: GO performances with the original radius of curvature (the same than computed by GPP level 1b)

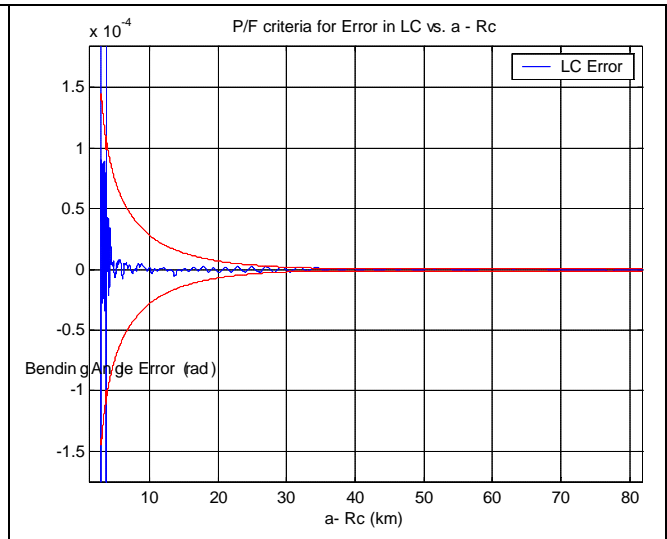


Fig. 9: GO performances with a slightly modified radius of curvature (40 m.) in the Abel Transform Inverse.

CONCLUSIONS

The results of this work show that the GPP is able to process GRAS real data. It is also demonstrated that the defined algorithms to convert the GPS observables into atmospheric properties provide good performances well within specifications. The error in neutral bending angle is lower than 0.4% of the total bending or an absolute error less than 1 *μrad*, whatever is larger. The good results in this work are also relies on the high GRAS instrument performances. Besides this test with data processed through the real GRAS Flight Model Instrument demonstrates that the Ground Processor Prototype is fully compatible with the real instrument outputs. Interface verification is at the same time performed.

Therefore, the end-to-end performances of the technique are verified with real data.

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