OVERVIEW OF ROSA RADIO OCCULTATION PROFILING CAPABILITIES ON-BOARD OCEANSAT-2

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ABSTRACT

This contribution focuses on results obtained by processing, for the first time, ROSA Radio Occultation observations performed on-board the Indian mission OCEANSAT-2. It summarizes an in-depth quality check of ROSA data, performed during a Visiting Scientist activity funded by the ROM-SAF (Radio Occultation Meteorology – Satellite Application Facility) and in close cooperation with EUMETSAT and the Italian Space Agency. The focus here is on the potential use for operational weather forecasting.

A set of ROSA raw data was processed using the EUMETSAT YAROS processor, a prototype created to develop new algorithms and to test them before introducing them into the operational chain. YAROS outputs are phases-amplitudes (at level 1a) and bending angles over impact parameter (at level 1b). Robust bias and standard deviation of bending angles against forward propagated ECMWF atmospheric data are used to evaluate the quality of the ROSA observations.

Moreover, the ROM-SAF ROPP (Radio Occultation Processing Package) processor was also used for ROSA data processing. This second part focuses in addition on bending angles, refractivity and higher level products obtained from the YAROS level 1a input data. The validation was again based on ECMWF and also on co-located occultation profiles.

The main issue affecting the ROSA data quality is tracking of the second GPS frequency L2. L2 data is often only acquired at altitudes above 20km, which makes the extrapolation of this data problematic. This currently severely limits the usefulness of the ROSA data (at least on OCEANSAT-2) and requires the development of more robust ionospheric correction algorithms and an investigation and possible mitigation of the problems onboard the satellite.

1. ROSA RECEIVER

ROSA is a dual-frequency GPS receiver developed for space applications and tailored for GPS radio occultation studies. It is developed and manufactured by Thales Alenia Space Italia under a contract with the Italian Space Agency (ASI) and is designed to establish accurate global profiles of temperature and water vapor in the lower atmosphere. Moreover, the extended coverage of the ROSA antenna allows the retrieval of total electron Content (TEC) profiles in the ionosphere for space weather applications.

The ROSA instrument is flying on three satellites: the first one (OCEANSAT-2 – Indian) launched in September 2009, the second one (SAC-D – Argentinean) launched in June 2011 and the third (MEGHATROPIQUES – Indian) launched in October 2011. Availability of Rosa data is seen as an opportunity by the scientific community, to partly cover the 2013-2016 gap that will be left by the Taiwan/US COSMIC-FORMOSAT3 constellation, which is already beyond its intended life time. Like all the other Radio Occultation receivers, the ROSA receiver is able to track both "rising" and "setting" occultation events, since it has the possibility to collect data from two occultation antennas (looking in the "forward" and "aft" direction). An exception was made on-board OCEANSAT-2, since only the "velocity" antenna could be accommodated. Moreover, whenever it is possible, the signal is tracked in closed-loop following the same technique used for all the traditional GPS RO receivers. From a defined height, the receiver automatically activates (or stops) the open-loop tracking, i.e., the receiver quickly searches and follows the received frequency aided by an ad hoc atmospheric-based model of the incoming frequency, implemented in the on-board software. Consequently, the signal can be analyzed for a longer time duration, allowing a better characterization of the lower atmospheric layers.

2. DATA DESCRIPTION

The Visiting Scientist activity was performed at EUMETSAT and DMI (November 2011 to February 2012) with the aim of processing, for the first time, ROSA data acquired on-board OCEANSAT-2. For this, the Italian Space Agency and Thales Alenia Space -

Italy provided one month of ROSA native binary data (Level 0) observed from 15 August 2010 to 14 September 2010, together with corresponding Oceansat-2 attitude data (orbits and quaternion data).
After an ad-hoc preprocessing of the downloaded telemetry, ROSA raw data are available through 5 different data files:
- Navigation solution file (Tabular ASCII format) containing a first estimate of satellite orbit computed on-board;
- Navigation file (Rinex 2.10 format) for Precise Orbit Determination;
- Observation Low Rate file (Rinex 2.10 format), containing data taken both by the POD antenna and the RO antenna at 1Hz sample rate;
- Observation High Rate file (Rinex 2.10 format), containing observations performed by the RO antenna at different sampling rates (50 Hz from surface to stratosphere);
- Observation Open loop file (Rinex 2.10 format).
In the actual study, the EUMETSAT Radio Occultation software prototype (YAROS) was updated for the processing of the Navigation Data and the Observation High Rate data files only. Although data was available for an entire month, analysis and results has been performed on a shorter time interval. Specifically, thirty hours from 13:30 UTC of 24 August, 2010 to 17:40 UTC of 25 August 2010 were deeply analyzed during the Visiting Scientist activity and results are shown here.

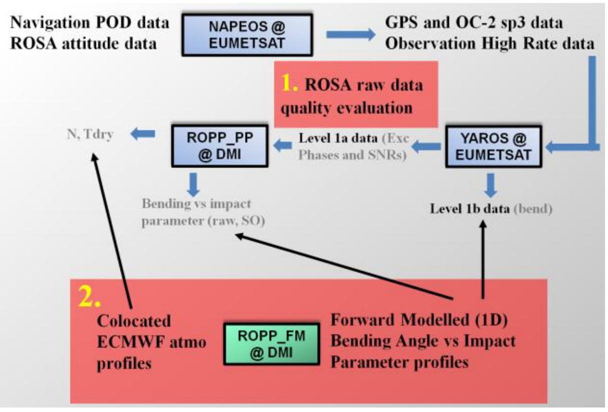

Figure 1. Data Validation

3. ROSA DATA VALIDATION STRATEGY

Fig. 1 summarizes the data processing and validation strategies. Navigation data and OCEANSAT-2 Attitude data were first processed by the EUMETSAT implementation of the Precise Orbit Determination processor (NAPEOS) which provided instantaneous positions and velocities of the GPS and OCEANSAT-2 satellite. Such information, together with Observation High Rate ROSA data, were the formal input to the YAROS software which generated NetCDF files (Level 1a data) containing Excess-phases and Signal-to-Noise ratio profiles for each observed occultation event. This first YAROS module was updated in order to be interfaced with the ROSA data format and data characteristics. YAROS Level 1a data was provided, as input, both to the second YAROS module for the generation of Level 1b files (containing Bending Angle and impact parameter profiles – BA in what follows) and, after a reformat procedure, to the ROPP_PP (which is the Radio Occultation Processing Package developed by the ROM SAF consortium). Output of ROPP_PP used here were both BA profiles and Dry Atmospheric profiles (Refractivity, Dry Temperature). From the other side, the Forward Modelling ROPP module (ROPP_FM) was used to generate BA profiles from co-located ECMWF (Numerical Weather Predictions from the European Centre for Medium-Range Weather Forecast) atmospheric data. Such modeled BA profiles were used as ground truth for YAROS Level 1b data and ROPP_PP BA statistical validation. We also note that refractivity and dry temperature profiles derived from the ROPP_PP processing chain were then individually compared with collocated ECMWF data (refractivity and temperature) and with collocated occultation products (bending angles, refractivity, temperature) derived by other RO missions (COSMIC, METOP-A and TERRA SAR-X) and by other processing software (CDAAC).
Before describing the results obtained from the above mentioned validation, the next section summarizes some aspect related to the ROSA raw data quality check.

4. ROSA RAW DATA QUALITY CHECK

Geometrical parameters related to the continuous L1 and L2 Excess-phase segments are extracted from the YAROS Level 1a output file. Such parameters (mainly SLTAs - Straight Line Tangent Altitude and time tags) were statistically analyzed in order to check the quality of the raw ROSA occultation observables. In particular, the analysis was performed considering the minimum SLTA from which L1 and L2 Excess-phases are available, and on the time interval length for which continuous segments were available.
280 continuous L1 segments were observed and, without considering a very small number of outliers, L1 CA code tracking started below -100 km SLTA and it continued without interruptions up to the orbit height of ~800 km. Quite different results were obtained when analyzing L2 continuous segments. Firstly, 477 continuous segments were recognized. 240 of those (~50%) started from a certain height and are continuously available at least up to 100 km SLTA. Their cumulative distribution in function of the start SLTA for which they are tracked is shown in Fig. 2.
As a general comment on the ROSA data quality, it has to be noted that, even though L1 data are in line with that observed by other Radio Occultation instruments, L2 data showed some problems. There are several

problems which are mainly related to OCEANSAT-2 issues. As already said, ROSA on-board OCEANSAT-2 was equipped only with the Velocity Radio Occultation antenna, therefore, only rising events can be recorded. Moreover local multipath on-board OCEANSAT-2 is very strong because of solar panels and because of the scatterometer antenna which both are moving. In particular this local multipath was not modelled or measured on ground, since an in-orbit platform manoeuvre was made necessary and created a permanent and unexpected yaw bias of the platform. All these problems might mainly impact L2 tracking which basically starts too high in the atmosphere and which is affected by long data gaps. Some procedures of L2 interpolation/extrapolation were already implemented in the YAROS software, but these procedures should be carefully adjusted to ROSA data.

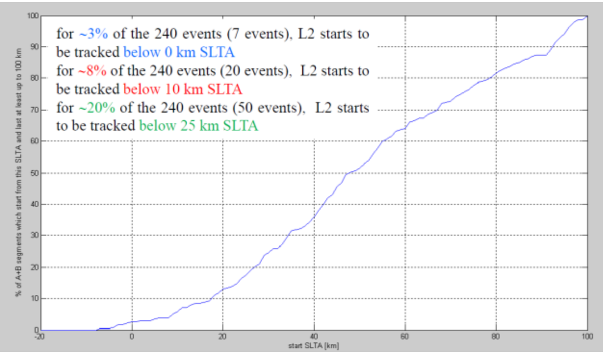

Figure 2. Cumulative distribution of ROSA occultation events in function of minimum SLTA

5. ROSA ATMOSPHERIC PROFILES

In this section a quantitative analysis describing the results obtained when processing the Level1a YAROS data with the ROPP_PP software is provided (see Sect. 3 and Fig. 1 for details). The analysis was performed considering each single ROSA profile against the corresponding collocated ECMWF profile and the corresponding collocated (+/- 10° lat and long, +/- 1.5 hours) profile observed by one of the other Radio Occultation missions (COSMIC, METOP-A and TERRA SAR-X). For each identified and processed ROSA occultation, several comparisons are evaluated. For example Fig. 3 shows the comparison between Tdry and Refractivity profiles against corresponding ECMWF collocated profiles. For this example, three COSMIC colocated profiles were found. Fig. 4 shows the traces of occultation ray perigees for these COSMIC events (green, red and black lines), for the ROSA one (blue line), together with the results of dry Temperature absolute comparison. The comparison of BA and Refractivity profiles is shown in Fig. 5.

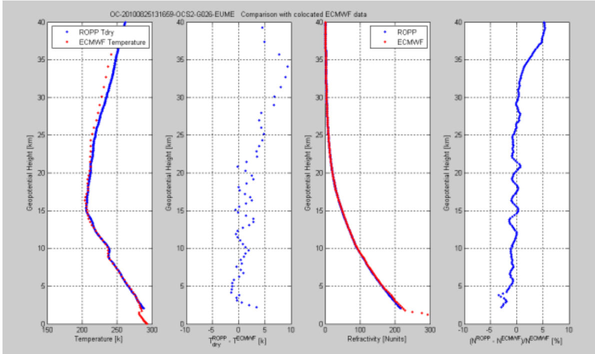
Figure 3. Comparison between ROSA and ECMWF Temperature and Refractivity profiles

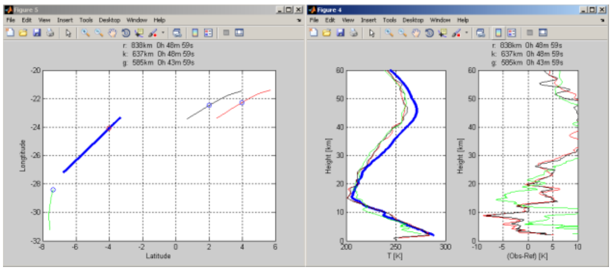
Figure 4. ROSA vs COSMIC co-located profiles: Tdry profile comparisons

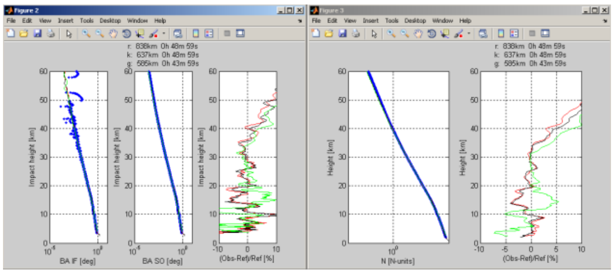
Figure 5. ROSA vs COSMIC co-located profiles: BA and Refractivity profile comparisons

This is only one example. Several other comparisons can be produced, in particular for those ROSA observations for which L2 was available from lower heights. It has also to be pointed out that such profiles were extracted using the ROPP Radio Occultation software which is not optimized for ROSA data processing. Therefore, some final statistical results cannot actually be provided.

6. BA PROFILES STATISTICS

Finally, a global analysis based on statistical comparisons between the bending angle profiles obtained from ROPP_PP and YAROS, and profiles obtained from forward modeling ECMWF co-located data. The analysis is based on all available profiles with L2 $\leq$ 10 km SLTA (Fig. 6). Error profiles are shown as fractional errors of (Observed-Background)/Background Mean and Standard Deviation. It is evident that, for these occultation events, bending angles generated by ROPP_PP and by YAROS are very similar, even if the statistics are based on a small number (~ 20).

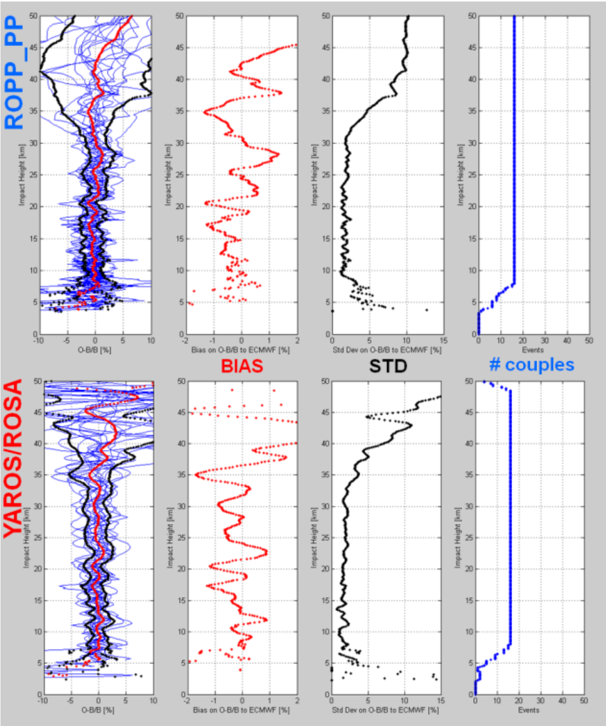

Figure 6. ROPP_PP and YAROS BA comparisons against ECMWF Forward Modelled BA

A second analysis was performed using all profiles for which L2 is available below 40 km SLTA. Here, results obtained from YAROS and ROPP_PP start to be different. A summary in terms of fractional error profile, its mean and its standard deviation is given in Fig. 7.

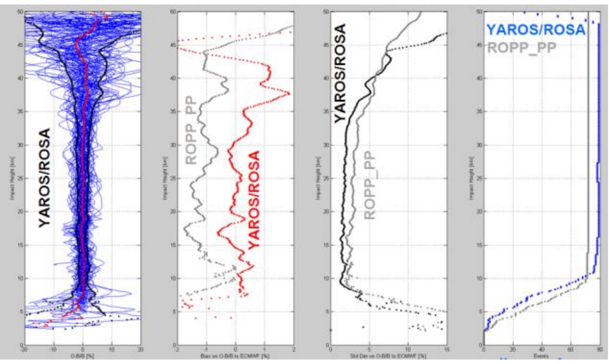

Figure 7. Same as Fig. 6, but with a different dataset

The negative bias of 1% observed from the ROPP_PP results is probably due to the impact of L2 downward extrapolation, necessary when L2 is not available, which is surely not optimized for ROSA data. From the other point of view, YAROS does not seem to be impacted too much by the L2 downward extrapolation problems.

7. CONCLUSION AND FUTURE REMARKS

Thanks to this ROM-SAF Visiting Scientist activity, ROSA Radio Occultation data handling has been implemented and tested using the EUMETSAT and ROM SAF processing tools. About thirty hours of a one month data set were analyzed. ROSA L1 data quality seems to be similar to other known Radio Occultation instruments. Platform issues on OCEANSAT-2 might severely impact L2 data quality and the L2 signal starts to be properly tracked too high in the atmosphere. Several data gaps worsen L2 data quality.

A data quality analysis has been performed on Level1a output files of the YAROS prototype. This data was then further processed to Level 1b (BA profiles) using YAROS and also the ROPP_PP (BA, refractivity and dry temperature profiles) tools. Comparisons with collocated ECMWF data and with collocated Radio Occultation profiles were performed. The bending angle analysis based on YAROS Level 1b data reveals a better agreement with ECMWF forward modeled data than the one obtained from ROPP_PP (Note that the L2 tracking problem requires extra processing steps which are under development and have not yet been implemented in ROPP). Above 100 km and up to the OCEANSAT-2 orbit height, vertical profiles of quiet horizontal TEC measurements always show the F2 peak. Just above 100 km (near to a systematic dip on both L1 and L2 Signal-to-Noise ratios) there is often a structure on “uncalibrated” TEC which may be caused by sporadic E-layer. This is a potential ionospheric study application.

Three main issues can be considered for future work:

- an in-depth analysis on the L2 tracking problem on the receiver side is required, this might potentially correlate with the OCEANSAT-2 platform issues (multi-path);
- further development of processing capabilities to allow mitigation of the L2 tracking issue;
- an analysis of the signal from 90 km to 110 km SLTA in order to understand if SNR strong fadings (and corresponding L2 data gaps) are due to ionospheric perturbations or to receiver/platform problems.

It is also strongly recommended to extend this investigation on the data obtained from the other two flying ROSA receivers.

8. ACKNOWLEDGEMENT

This research was made possible thanks to the ROM SAF Visiting Scientist program and ASI agreement. Thanks to Thales Alenia Space (A. Zin, S. Landenna) for their support and documentation provision.