IN ORBIT VERIFICATION RESULTS FROM GRAS RECEIVER
ON METOP-A SATELLITE

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Abstract
This paper summaries the results from the successful In Orbit Verification phase of the GRAS GNSS Receiver instrument on-board MetOp-A satellite. The In-Orbit Verification phase consists in demonstrating that the instrument is functioning and performing as specified. The algorithms to process the instrument raw data up to level1B products are also verified. The key result is that it is the first time that a GPS receiver is able to measure rising occultations on an operational basis. More than 650 occultations are recorded daily equally repartitioned between rising and setting ones, which is beyond the expectation number of 500. The performances of the instrument as a standard GPS receiver for navigation as well as a radio-occultation instrument are opening new areas for scientific research and modelling.

INTRODUCTION
MetOp-A satellite has been launched successfully on 19 October 2006. On-board this satellite several meteorological instruments are accommodated, one of them being the GRAS instrument. GRAS is a GNSS Receiver performing Atmospheric Sounding through Radio Occultation principle. After a presentation of the instrument, this paper will pursue with the characterisation of its capabilities. The atmospheric sounding performance will be described, and outlook for future research will be presented.

GRAS TEAM
MetOp Mission is a serie of 3 sun-synchronous polar orbit satellites of which the first one, MetOp-A, is flying since 19 October 2006. The satellites have been developed and manufactured by EADS Astrium in Toulouse and Friedrichshafen. GRAS instrument to be flown on the 3 MetOp satellites has been developed by Saab Ericsson Space in Sweden, supported by Austrian Aerospace (Austria) for software development and ground testing equipments. SENER in Spain provided the antenna deployment mechanism, and GMV (Spain) developed the ground processor prototype. Beyond this industrial consortium, scientific support was provided by the GRAS Scientific Advisory Group (SAG) in conjunction with the GRAS Satellite Application Facility (SAF) providing the level 2 processing facility and products. Eumetsat (Germany) is the overall Mission responsible, also processing the instrument raw data into level1b products within the Operational Processor. ESA (The Netherlands) is responsible for the development of the satellites and the verification of the satellite and instruments such as GRAS in orbit.
GRAS INSTRUMENT

The demonstration of the GPS Radio Occultation Principle was initially made in 1995 and since then many satellites (GPS/MET, Oersted, CHAMP, SAC-C, GRACE, COSMIC) carry a GPS atmosphere sounder. GRAS incorporates many improvements with respect to previous sounders, including wide beamwidth high gain dual-frequency rising and setting antennas (>10dB), a specially designed AGGA-2a ASIC with advanced semi codeless tracking, an oven-controlled Ultra Stable Oscillator, a rising occultation antenna and an Open Loop mode.

The GRAS Instrument (Fig. 1) is composed of three antennas, two occultation antennas to track rising and setting GPS satellites crossing the Earth limb and one zenith antenna to obtain coarse real-time measurements of the satellite position as well as precise code and carrier phase measurements for Precise Orbit Determination (POD). One Radio Frequency conditioning unit is placed next to each antenna to minimize the noise on the GPS signal. A single GRAS Electronics Unit (GEU) processes all GPS dual-frequency signals. The setting occultation antenna is mounted on a deployment mechanism in order to minimize signal reflections from the spacecraft.

More detailed information on the satellite, ground segment as well as the instrument can be found within references 2 to 6.

Figure 1: GRAS is composed of 3 antennas, 3 Radio Frequency conditioning units, 1 electronic box and a deployment mechanism

GRAS STATUS

During the Launch and Early Orbit Phase the GRAS setting occultation antenna has been successfully deployed. On 26 October 2006 the GRAS instrument was switched on. Within 23 seconds the instrument tracked a first GPS satellite, and 64 seconds after the first navigation solution was achieved. On 27 October the instrument was switched to occultation mode and the first occulting GPS satellites were measured.

GRAS encountered a single anomaly. On 8th January 2007 had recorded four occultations in raw sampling mode within less than one minute. In this mode the data rate is 1kHz instead of nominally 50Hz, causing the measurement buffer to be full. This condition may occur for the largest GPS
constellation now flying with 30 operating GPS satellites. The issue was understood within two days and the instrument resumed. Until the conference in September 2007 this event had not re-occurred. However the on-board software will still be modified.

RESULTS AS GPS RECEIVER

The GRAS zenith antenna (GZA) allows tracking of dual frequency signals from the GPS constellation. The electronics box includes 2 AGGA-2a chips which track up to 8 satellites, and a 10 degrees elevation masking angle has been set.
In more than 50% of the time, all the 8 channels are occupied. At least 6 GPS are tracked with more than 98% of the time. The minimum number of satellites tracked is 4 and rarely observed, in less than 1% of the time.
In average the number of satellites tracked is 7.5.

The real time on-board navigation solution has an accuracy varying between 12 and 22 metres (3D, 1 sigma). This is well within the specifications of 100 metres.

The temperatures are very stable along the orbit, changing by less than 1.5 degrees for GRAS units mounted within the MetOp spacecraft. For externally mounted units (the three antennas), the temperature variation is below 30 degrees.
All temperatures are within expected ranges.

ATMOSPHERIC SOUNDING RESULTS

The two larger antennas (with 18 elements) visible in Fig. 1 are the occultation antennas which allow to track GPS satellites that set or rise at the Earth’s limb. These occultations last between 40 seconds and 120 seconds depending on the azimuth angle under which the GPS is seen by the GRAS occultation antenna, as well as the type of atmosphere traversed by the GPS signals.

The geographical coverage of the measured occultations within 1st November 2006 is presented in Fig. 2. On that day 660 occultations were recorded, 338 setting ones and 322 rising ones. The coverage is globally homogenous, which demonstrate that GRAS will provide precious profiles over sparsely covered regions such as oceans and polar regions.
The required number of occultation per day is 500, which is met with substantial margins.

**Figure 2**: Geographical coverage of the occultations within a day period
The main level 1b products from the GRAS instrument is the bending angle of the GPS signal. The bending angle corresponds to the angle due to the refraction of the GPS signals in the earth atmosphere. At 30km altitude and above, the atmosphere is quite thin and does not influence or bend the GPS signal path substantially. Below 30km altitude the atmosphere contribution is increasing and will bend the GPS signal with angles up to two degrees. The bending angle is retrieved with high accuracy thanks to a very high short term stability of the Ultra Stable Oscillator clock on board the instrument.

The tracking states of the GPS signals tell when both GPS L1 and L2 signals are tracked by the receiver, when the L2 signal is lost due to low signal to noise ratio, and when the raw sampling mode is set to capture the L1 signal based on the on-board open loop model.

Figure 3 shows the tracking states of the GPS signals versus Straight Line Tangent Altitude (SLTA). SLTA is the altitude from Earth surface to the straight line between the GPS and the receiver (i.e. ignoring the atmospheric diffraction effect). As such this value can go down to 140km below the earth surface. SLTA beyond +35km are equivalent to GPS signal path altitudes as atmosphere above 35km is rather weak.

At high altitude GRAS tracks both L1 and L2 GPS signals, Dual Frequency (DF) being represented in blue.

For setting occultations (left part of Figure 3) the loss of the L2 signal happens below a Straight Line Tangent Altitude (SLTA) of -20km, leading to a parallel switch-on of the instrument in Single Frequency (SF) and Raw Sampling (RS). The RS is visible by the red squares hiding the green crosses (representing SF).

On the right part of Figure 3, one can see that GRAS tries to acquire rising occultations as soon as SLTA reaches -140km. Raw sampling is continuous when red colour is continuous. SF tracking starts before SLTA = -35km, and DF is achieved between SLTA = -25/+15km.

This confirms the efficiency of tracking rising occultations which are more demanding than the setting ones.
In figure 4 the SLTA has been converted to tracking altitudes above the Earth’s surface. Note that RS without parallel SF have been removed for better visibility in these plots. This means that when RS red squares are visible also SF tracking is present.

On the left part of Figure 4, the setting occultations are tracked in DF down to an altitude varying between 1 and 7km, and SF is maintained down to 2km, in average.

Rising occultations (right part of Figure 4) leave RS to SF alone in average around 4km, while DF is locked around 10km. Note that RS alone is available in average from 2km (not represented on this figure).

OUTLOOK

Raw Sampling data on GRAS instrument is a novel feature for radio occultation atmospheric sounding. It provides information when tracking GPS signals is not possible with closed loop carrier tracking. Raw Sampling data can be used to investigate the GPS signal behaviour propagating through the atmosphere as well as at Earth boundary. Figure 5 is an example where Raw Sampling data is available between SLTA of -70km and -110km.
In SF mode (for SLTA above -70km), the GPS signal is tracked with a main Doppler content around -10 to -2Hz. Twenty seconds of RS data at 1kHz have been processed to remove the GPS navigation message bit flip at 50Hz, and are presented for SLTA going from -110km to -70km.

The RS signal retrieved is coherent with SF data. At lowest altitude (-110km SLTA) the signal content is null, corresponding to the GPS signal being totally blocked behind the Earth.

At low altitude and in tough atmospheric conditions, the GPS signal cannot be further considered as propagating as a single optical ray. The signal has to be regarded as a wave to properly take into account the atmosphere media.

Wave transform algorithms can retrieve the bending angle in these atmospheric multipath conditions. An example based on Back Propagation retrieval is presented in Figure 6.

![Back-Propagation close loop - Bending Angles. Occ. No. 10](image)

**Figure 6:** Example of processing using Back Propagation wave transform

**PROCESSING BEYOND LEVEL1B PRODUCTS**

Bending angle profiles will be further processed within the GRAS-SAF facility to be converted in refractivity profile, further converted to pressure, temperature and humidity profiles over the Earth surface.

These level 2 products are expected to have a temperature accuracy better than 1 degree Kelvin for an altitude range from 5 to 30 kilometres.

The GRAS level1b as well as level2 products will be ingested into meteorological assimilation processes to assess improvement of weather forecasts. The second main objective of GRAS products will be their use in Climate monitoring, thanks to their high vertical resolution and very good temperature accuracy.
CONCLUSIONS

Thanks to an extensive ground testing and a very good behaviour of the GRAS instrument, the In Orbit Verification activities have been very simple and successful.

All performances for GRAS as a simple GNSS receiver and as an atmospheric sounder are well within specifications. This is the first radio-occultation instrument able to track as many rising occultations as setting ones and designed to measure as many occultations as possible, i.e. reaching 660 occultations per day. These outstanding performances indicate that level2 temperature vertical profile will be accurate to better than 1 Kelvin from ground to 35km altitudes.

These outstanding performances and the innovative capabilities are expected to pave the way for improvements in forecast models and climate monitoring.

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REFERENCES