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GPS radio occultation on-board the OCEANSAT-2 mission: An Indian (ISRO) – Italian (ASI) collaboration

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In the first quarter of 2008, the Indian satellite OCEANSAT-2 will be launched. The Italian Space Agency (ASI) signed a Memorandum of Understandings with the Indian Space Research Organization (ISRO) in which it is agreed to put on-board the OCEANSAT-2 satellite the Italian GNSS receiver devoted to Radio Occultation (ROSA–Radio Occultation Sounder of the Atmosphere). The ROSA receiver has been developed with a new-concept hardware configuration with respect to that normally characterizing a GNSS receiver: it will track the GPS "occulted" signal both just before its setting and just after its rising from the local horizon using an open loop technique, and it will automatically switch from (or to) the standard closed loop approach when the signal crosses higher atmospheric regions. Observations from ROSA will be downloaded both to the Indian and the Italian receiving stations where they will be processed by the ROSA Ground Segment, developed by Italian universities and research centres. In particular, the first version of the processing software will be integrated in a ground segment installed in Matera (Italy) and mirrored at Hyderabad (India). Its second version will be installed in a distributed ground segment implemented by connecting, on a web-based GRID, hardware and software infrastructures installed at the research centres and universities involved in its development.

Keywords: Global positioning system (GPS), Radio occultation, Oceansat-2, Radio occultation sounder of the atmosphere (ROSA)

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1 Introduction

One of the most recent and promising atmospheric remote sensing technique is the radio occultation applied to GPS measurements (hereafter GPS RO). Its importance has been increasing during the last decade, since the first related mission (the GPS/MET proof of concept mission[1,2]) highlighted its possibilities.

The GPS RO technique is based on the inversion of excess-phase measurements related to the signal transmitted by a GPS setting or rising satellite and detected by a GPS receiver placed on a low earth orbit (LEO). A conceptual drawing of the GPS RO principle is shown in Fig. 1 where the atmospheric refraction effects (in terms of trajectory bending and the consequent defocusing and phase delay) are put in evidence. The result of the inversion is a very-accurate and high-resolution[3,4] atmospheric refractivity profile, from which the corresponding temperature and humidity profiles can be extracted. In principle, using only signals transmitted by GPS satellites, one single LEO GPS receiver could observe up to 500 globally distributed occultation events per day (both risings and settings), consequently profiling the atmosphere almost from the surface up to the receiver orbit height. Long-term stability, all weather capabilities and low cost of GPS receivers are significant characteristics making the GPS RO technique attractive and easily implementable in Earth's observing satellite missions. Many papers related to this technique have been written[5-7].

Due to the presence of water vapour in the troposphere, defocusing, multipath and other anomalous propagation phenomena are quite common. For phase locked loop (PLL) tracking devices (closed

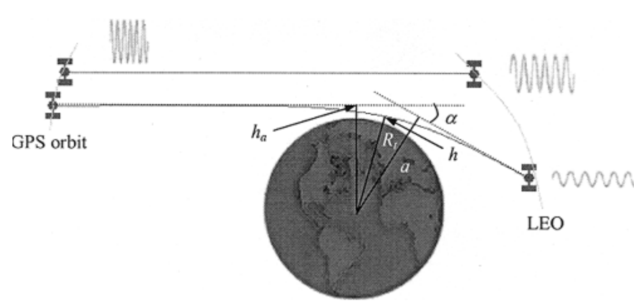

Fig. 1–GPS radio occultation principle, radio occultation geometry and parameters used in Eq. (1)

loop tracking), main effects in reception can be the early loss of the phase lock and the following tracking failure. Consequently, the corresponding atmospheric profiles lack data in the lower atmospheric layers. Moreover a negative bias in the retrieved refractivity values is often observed, especially in tropical low tropospheres[8-10].

The correct tracking of the signal up and down to the terrestrial surface (for rising and setting events, respectively) and the compensation of the negative refractivity bias are the most important challenges for the new occultation missions already operative: the German GRACE twin satellites (first results in summer 2004[11]), the US/Taiwan COSMIC constellation satellites mission (operative from July 2007) and the European GRAS mission (operative from November 2006).

In Italy, starting from 1998, the Italian Space Agency (hereafter ASI) supported a research group (ASTRO, i.e. Atmospheric Sounding Through Radio Occultation) in order to verify if occultation data would be able to improve the understanding of climate processes in the Mediterranean area. At the end of its work, a satellite constellation carrying on board a new generation of more sophisticated GPS receivers (i.e.: the ROSA receiver) has been suggested[12] in order to satisfy the challenges of the climate processes in the Mediterranean area (horizontal resolutions, dynamics of the climate variations, high vertical resolution starting from ground level).

The ROSA receiver is able to manage 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). Moreover, whenever it is possible, the signal will be tracked in closed-loop following the same technique used for all the traditional GPS RO receivers. However from a chosen height down, the receiver will automatically activate the open-loop tracking: in this case, the tracking loops will quickly search and follow the received frequency aided by an atmospheric-based model of the incoming frequency, implemented in the on-board software[13-16]. Consequently the signal could be analyzed for a longer time and a better characterization of the lower atmospheric layers will become possible.

During the first quarter of 2008 the Indian satellite OCEANSAT-2 will be launched and it will carry on-board the ROSA payload, in agreement with the Memorandum of Understandings signed by ASI and ISRO. Observations from ROSA will be downloaded both to the Indian (Hyderabad-National Remote Sensing Agency/NRSA) and the Italian (Matera–Space Geodesy Centre/CGS-ASI) receiving stations, where the data will be processed by the ROSA ground segment, developed by Italian universities and research centres. The operative version of the processing software will be integrated in a ground segment installed in Matera and mirrored at Hyderabad. Meanwhile, a pre-operative and more sophisticated version will be developed, and it will be installed in a distributed ground segment implemented by connecting, on a web-based GRID, hardware and software infrastructures installed at the research centres and universities involved in its development.

2 RO technique

As it has been introduced in the previous section, the GPS RO technique is based, on its simplest form, on the inversion of the excess-phase evolution (which varies from 0 km up to 1 km at the end of a setting occultation event) measured on the GPS signal received on-board a LEO satellite, when it is occulted with respect to the transmitter. When the signals cross the atmosphere, they are delayed and their path is bent. Therefore, the overall effect is the signal reception, also below the terrestrial limb (when the satellites are not yet in view). This is the radio occultation (RO) concept. The time derivative of the phase delay measurable under such conditions is defined as the excess-Doppler. Computing both the excess-Doppler and the amplitude of the received signal, and applying geometric optics (GO) algorithms based on spherical symmetry[17] or wave optics algorithm and Fourier operators[18,19], it is possible to derive the time evolutions of two important parameters identifying each trajectory followed by the signal: the total bending (α) and the impact parameter (a), i.e. the distance from the Earth's mass centre of the trajectories asymptotes (Fig. 1).

From the other side, assuming that the terrestrial atmosphere is locally spherically distributed (i.e., all its parameters depend only on the radius from the local centre of refractivity), bending angles and impact parameters are related to the atmospheric refraction index $n(h)$ through the following integral formulation[2,17]:

$$\alpha(a) = -2a \int_a^{\infty} \frac{1}{\sqrt{(R_t + h)^2 n^2(h) - a^2}} \frac{1}{n(h)} \frac{\mathrm{d}n(h)}{\mathrm{d}r} \mathrm{d}r \quad \ldots (1)$$

where $a = h_a + R_t$ and $r = h + R_t$ (R_t is the Earth's radius and h_a is the so-called impact height). This formulation identifies an Abel integral that can be inverted in a closed form, given thus the possibility to retrieve the refractive index profile $n(h)$ from the knowledge of the $\alpha(a)$ profile observed during the entire occultation event. Informations about the temperature $T(h)$, pressure $P(h)$ and humidity $q(h)$ profiles can be extracted from this refractive index profile using the Smith and Weintraub formula[20], the hydrostatic approximation and independent observations (for the water vapour or temperature) collected by other instruments[1].

Radio occultation applied to the inversion of stellar and man-made signals was one of the techniques adopted to study the atmospheres of the main solar system planets in the framework of the first NASA missions during 1965-1970 (for example the Mariner IV mission for the study of Mars atmosphere, Mariner V at Venus, Voyager at Jupiter, Saturn and Titan). For what concerns its applicability to the Earth's atmosphere remote sensing, only an observing system (built by space transmitters and receivers) allowing global coverage in time and space could have added some value to the already advanced knowledge of that time. This possibility was realised thanks to the implementation of the space segment of the GPS. In fact, the GPS/MET mission, launched in 1995 after collaboration between NASA, Jet Propulsion Laboratory, National Science Foundations and University Corporation for Atmospheric Research, was thought as a proof-of-concept mission in order to demonstrate the possibility to use GPS signals to characterize the Earth's atmosphere and ionosphere using the radio occultation technique.

On the basis of the good results obtained by GPS/MET[2], several other satellites carrying on-board a GPS receiver for the radio occultation sounding of the atmosphere were planned and launched (for example the Oersted satellite developed by the Denmark Meteorological Institute and the South African SUNSAT, developed by the University of Stellenbosch). Before 2006, at least two missions operatively provided to the scientific community atmospheric profiles retrieved with such a technique: the German CHAMP mission, and the Argentinian SAC-C. Between July and November, 2006, two further missions with an operative RO payload were launched: the U.S./Taiwan COSMIC constellation satellites mission (six satellites) and the European GRAS mission. In the future, several other Earth's observing satellite missions carrying on board a GPS receiver for occultation purposes are planned and will be launched. The Indian OCEANSAT-2 is one of such missions.

The GPS/MET proof-of-concept mission confirmed the effectiveness of the occultation principle applied to the GPS signal. The CHAMP mission has carried, up to now, the most useful operative instrument (the BlackJack GPS receiver, developed by Jet Propulsion Laboratory) for RO purposes. Since its first measurement (made on 11 Feb. 2001)[21] around 300,000 occultations have been correctly processed after 5 years of operations. This means that, up to now, CHAMP has been able to distribute to the community about 150 atmospheric profiles of pressure, temperature and humidity per day, nearly uniformly distributed around the globe (more informations can be found at the website: http://www.gfz-potsdam.de/pb1/op/champ). The BlackJack receiver carried on-board CHAMP is able to process setting occultations only, since it acquires the occulted GPS signal from an antenna that is placed on the aft direction of the satellite. Moreover only closed loop signal tracking is possible. Consequently, when signals emerge from the troposphere, the effects of water vapour, defocusing, multipath, etc., may easily cause the loss of the phase lock. However the BlackJack receiver is able to quickly search the GPS signal and to establish a new link, thanks to the extrapolation of the last phase samples correctly processed (this modality is called fly-wheeling[22]).

Anyhow, as already stated in the introduction, a negative bias in the retrieved refractivity values is often observed, specially in tropical low tropospheres: considering the comparisons between CHAMP refractivity profiles obtained from 2001 to 2004 (~ 160000 profiles) and the correspondent profiles deduced by the European Center for Medium Weather Forecast (ECMWF). Figure 2 gives a quantitative overview[23] of the distribution of this negative bias with the latitude and the height. Proper tracking of signals coming from the low tropospheres from one side and the new inversion algorithms proposed in literature (Canonical Transform[18] or Full Spectrum Inversion[19]) from the other, allow to infer important informations about these perturbed atmospheric layers. In fact, it has been demonstred that the application of the full spectrum inversion to CHAMP

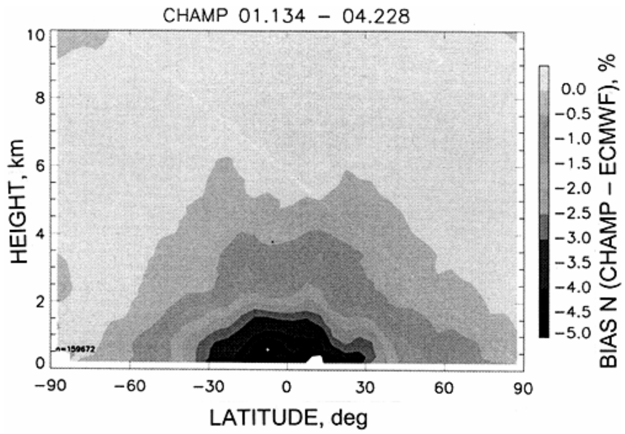

Fig. 2–Refractivity negative bias evaluated comparing ~3 years of CHAMP RO refractivity profiles with the correspondent profiles deduced by ECMWF[23]

data significantly reduces the negative bias on the refractivity, with respect to those observed, adopting the classic geometrical optics retrieval scheme[23].

3 Indian OCEANSAT-2 mission and the ROSA payload

During the first quarter of 2008 the Indian satellite OCEANSAT-2 will be launched and it will carry on-board the ROSA payload. The OCEANSAT-2 will follow IRS-P4 (OCEANSAT-1), the first dedicated Indian satellite for ocean observations, which was launched in May 1999. It carried two payloads – the Ocean Colour Monitor (OCM) and a Multi-frequency Scanning Microwave Radiometer (MSMR), which provided valuable data usable for various applications, related to the identification of potential fishery zones and prediction of monsoon's arrival. A three-axis stabilized spacecraft, OCEANSAT-2 will be placed in a circular near-polar (98.3° inclination) sun-synchronous orbit at an altitude of 720 km (period of 99.31 min and 2 days repetitive cycle) and it will provide continuity of IRS-P4 operational services. In particular data observed by OCEANSAT-2 will provide data for new applications in the areas of ocean studies, including prediction of cyclones trajectories, fishering, coastal zone mapping and atmospheric studies. A new OCM, a Ku-band scatterometer and the ROSA payloads will provide to the community several geophysical parameters on an operational basis, like chlorophyll content, suspended sediments, yellow substances and phytoplankton content, sea surface temperatures (SST), wind fields over ocean surface, sea state including significant wave height (SWH) and atmospheric profiles deduced from GPS RO measurements.

Actually, no polar receiving station for the download of OCEANSAT-2 in-orbit observations has been foreseen. In particular, measurements collected by the ROSA instruments will be downloaded through the telemetry channel both at the National Remote Sensing Agency (NRSA), Shadnagar /Hyderabad, India and at the Space Geodesy Centre of the Italian Space Agency (CGS/ASI, Matera, Italy) acquisition systems. Simulations carried on using an orbit management software tool (the Satellite Tool Kit – STK®) showed that during a complete OCEANSAT-2 orbit cycle, the satellite will be in view four times and seven times respectively, from Hyderabad and Matera (see Fig. 3 and Table 1). Simulations are referred to an hypothetical configuration, without restriction in the field of view of the transmitting and receiving antennas and considering the OCEANSAT-2 possible orbital positions occurred during the period 1-2 July, 2006. Although ROSA raw data will be mirrored between the two acquiring stations, the satellite will be in view six times per day on an average. This will limit the quasi real time availability of radio occultation processed products. Consequently, many ROSA observations carried on-board OCEANSAT-2 cannot be included as input to the Numerical Meteorological Prediction Models. Anyhow, such observations can be surely used for climatological purposes.

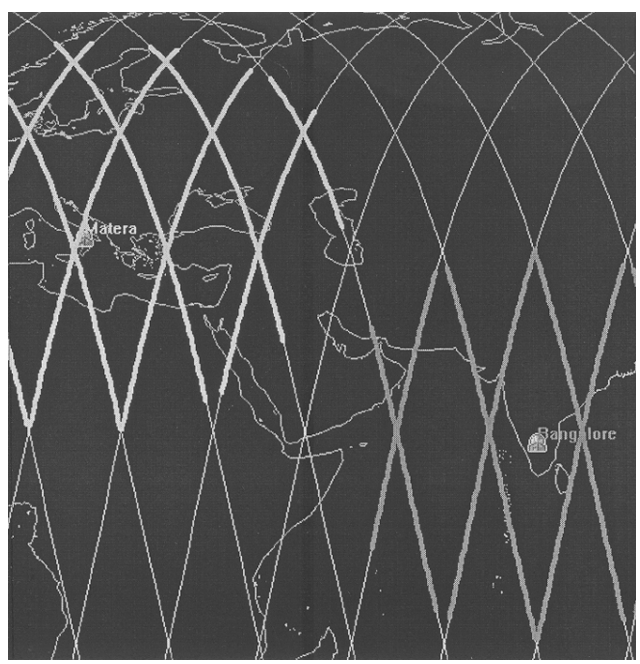

Fig. 3–Simulation related to one-cycle OCEANSAT-2 (2 days: 1 and 2 June, 2006), carried on using Satellite Tool Kit to establish the ground visibility from the two Matera and Hyderabad acquisition centres

Table 1–Details related to one-cycle OCEANSAT-2 ground visibility (2 days) from the two acquisition centres of Matera and Hyderabad

Start visibility	End visibility	Duration, s	GS
1 June 2006 12:03:47.97	1 June 2006 12:17:03.15	795.176	Matera
1 June 2006 13:45:33.87	1 June 2006 13:48:27.17	173.299	Matera
1 June 2006 18:07:06.70	1 June 2006 18:20:57.02	830.321	Hyderabad
1 June 2006 19:46:46.26	1 June 2006 19:57:22.52	636.256	Hyderabad
1 June 2006 20:01:04.11	1 June 2006 20:06:46.06	341.950	Matera
1 June 2006 21:33:52.52	1 June 2006 21:47:29.03	816.508	Matera
1 June 2006 23:12:17.80	1 June 2006 23:25:27.82	790.017	Matera
2 June 2006 06:24:44.03	2 June 2006 06:38:42.48	838.453	Hyderabad
2 June 2006 08:04:17.37	2 June 2006 08:14:36.08	618.711	Hyderabad
2 June 2006 09:37:30.71	2 June 2006 09:48:07.01	636.300	Matera
2 June 2006 11:14:24.61	2 June 2006 11:28:40.54	855.923	Matera

Another important aspect to be taken into account is that, in the framework of this mission, the antenna devoted to the reception of the occulted GPS signal will be oriented along the satellite velocity. Thus, ROSA receiver will be able to observe only rising occultation events, more critical respect to the setting ones. It will acquire and track signals detected by the occultation antenna (which is characterized by a higher gain with respect the RO CHAMP's antenna) using an open loop scheme, and it automatically switch to the standard close loop tracking as soon as possible. While in the last case, raw outputs of the receiver are directly the carrier phases related to both the L_1 and L_2 GPS frequencies received, in the first case (open loop tracking), only the L_1 carrier in-phase (I) and quadra-phase (Q) components (100 Hz sampled as suggested by Sokolovskiy[13,14]) will be available. The real excess-phase will then be reconstructed (in post-processing) from these components. Although these aspects appear critical, the validation of the open loop performances of a bread board (i.e. an engineering model) of the ROSA instrument carried on in the Thales Alenia Space, Italy (the ROSA's manufacturer) laboratories gave good results. Moreover, as demonstrated by the COSMIC and the METOP missions, the open loop tracking of a signal "observed" by a high-gain occultation antenna is the correct approach for a longer detection (and consequently for a better characterization of the low tropospheres) of the occulted signal, and it will increase our confidence in the success of the ROSA payload on-board OCEANSAT-2.

4 ROSA ground segments for OCEANSAT-2 mission

The ROSA raw data, downloaded both at the NRSA and at the CGS/ASI acquisition centres, will be processed by the ROSA ground segment developed by Italian universities and research centres. Initially, the operative version of the data processing software will be integrated in the so-called Data Processing Centre, which is the ground segment installed in Matera and mirrored at Hyderabad. This version will implement the classical processing scheme (which is based on the geometric optics approach) and it will be delivered before the commissioning phase of the ROSA payload, in order to be able to process ROSA data as soon as possible after the launch of OCEANSAT-2. Figure 4 summarizes the data flow. The level 1a data (ROSA occultation and navigation data, data observed by the International GNSS Service (IGS) or by the Italian Space Agency Ground Fiducial Network) will be collected and processed in order to obtain the precise GPS and OCEANSAT-2 orbits (Level 1b data). Excess-phases and occultation tables will be generated (Level 2 data) adopting the single differences scheme[24]. The double differences scheme, which is necessary to remove both the transmitter and receiver clock errors will also be implemented, while the option of the zero differences processing[25] scheme, could surely be taken into account, given the high accuracy of the ROSA on-board clock. Figure 5 shows a conceptual draw of the various types of differencing schemes. Bendings and impact parameters will then be computed on both the received GPS frequencies following the classical geometrical optics approach (Level 3a data), and a linear combination will be applied in order to compensate for the ionospheric effects (Level 3b data relate to iono-free bendings and impact parameters profile). An optimized version of bendings and impact parameters profile based on a climatological stratospheric initialization will be computed (Level 3c data) and the corresponding refractivity profile, dry air temperature and pressure profiles will be evaluated through Abel inversion and hydrostatic equation

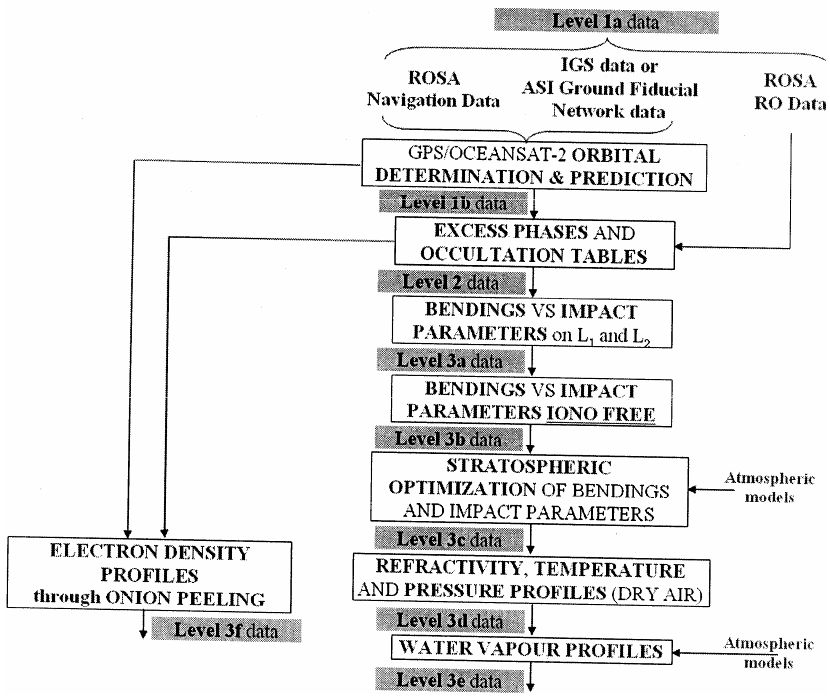

Fig. 4–ROSA RO observation processing data flow

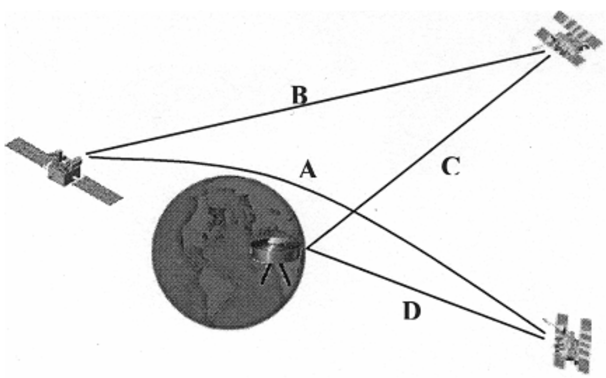

Fig. 5–Differencing schemes [Double Differences [(A – B) – (C – D)] will remove both GPS and ROSA on-board clock errors; Single Differences [(A – B)] can be applied if GPS on-board clock errors are well known (in particular when Selective Availability is OFF); Zero Differences: if also the ROSA on-board clock is sufficiently accurate, excess-phases can be computed considering only the link A]

(Level 3d data). Water vapour profiles will then be extracted using meteorological data (Level 3e data), while electron density profiles will be computed following the onion-peeling inversion scheme (Level 3f data).

In the second version of the ROSA processing software, more advanced orbit determination algorithms, physical optics algorithms necessary for a better characterization of the low tropical and wet tropospheres and a tomographic approach to the reconstruction of the three-dimensional electron density in ionosphere will be incorporated in the ground segment. This improved version of the data processing will be implemented through a Web-based GRID of hardware and software infrastructures installed at the research centres and universities involved in its development. This will represent a pre-operative ground segment for the ROSA data, and it will demonstrate the possibility to process ROSA observations in a quasi real-time basis on a distributed infrastructure. The GRID infrastructure was chosen both for its well known high performing computing (HPC) capabilities (necessary, in particular to drastically decrease the processing time for the orbit reconstruction) and also as a collaborative engineering instrument. With the adoption of GRID infrastructure and the modular architecture of the RO processing software, each institution will develop and validate its own software module before its integration in the overall ground segment (for further information on GRID computing see Ref. 26). Then a GRID scheduler based on the Globus Toolkit environment will manage both the overall processing steps (from Level 1b to Level 3 ROSA data products) and the data exchange between the various software modules and the ROSA database, which will be a node of the same GRID. Figure 6 summarizes both the ROSA ground segments–the operative ROSA ground segment for the OCEANSAT-2 mission and

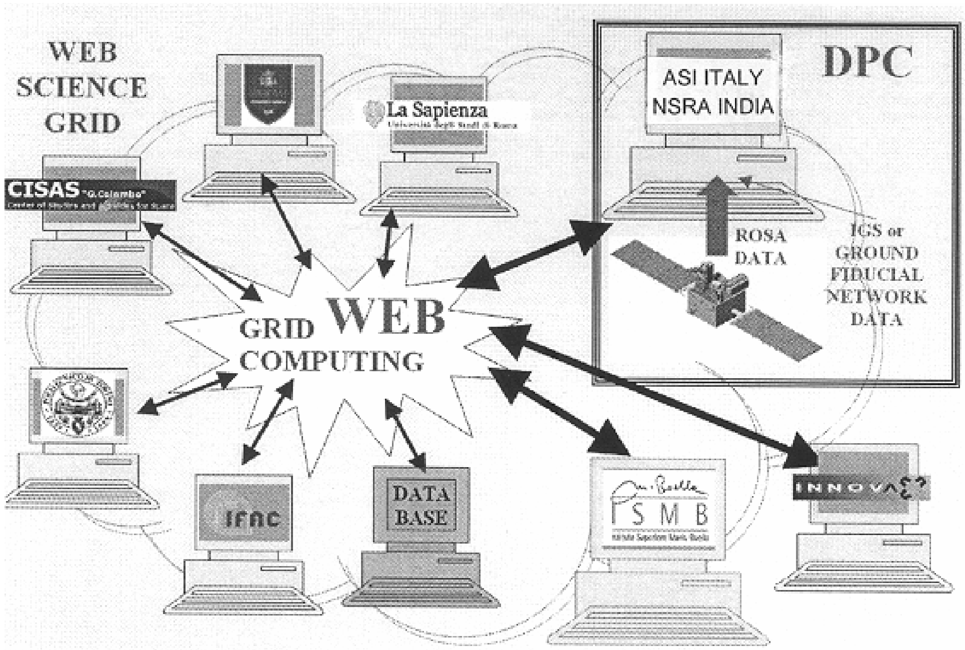

Fig. 6–ROSA ground segments [The DPC (Data Processing Centre) will be the operative ground segment for ROSA on-board OCEANSAT-2 (available for the commissioning phase of the ROSA payload). The Web Science Grid will be the pre-operative distributed ground segment (it will be also used for the development phase of the ROSA radio occultation software)]

the pre-operative, distributed ground segment, which is called Web Science Grid.

5 Scientific activities

As stated in the introduction, together with the development of the ROSA ground segments, a number of scientific activities will be undertaken to make use of the ROSA radio occultation data as follows:

(i) The Physics Department of Università "La Sapienza" di ROMA will develop climatic studies, mainly focused on tropopause temperature and height determination, on large scale water vapour analysis, on the geopotential field retrieval for dynamic indexes, on evaluation and comparison of RO data with LIDAR profiles in stratosphere.

(ii) The Physics Department of Università di CAMERINO will carry on activities related to the assimilation of radio occultation data into numerical weather prediction models, both for real time prediction and for climatological studies. Main themes will be a sensitivity study on different vertical and horizontal resolutions, an evaluation of possible modification of forecasts by numerical weather prediction models, a comparison between different vertical resolutions for assimilating RO data and studies of observed and modelled gravity waves.

(iii) The Istituto dei Sistemi Complessi di Firenze (ISC) will devote themselves to the use of radio occultation data for ionospheric studies and space weather applications. Three aspects will be focused. The first one consists of monitoring the plasmaspheric total electron content as a space weather tool. The second deals with a statistical study of ionospheric scintillations introduced in the LEO-GPS links, in order to detect and model the influences of some solar/geophysical parameter on radio communications and space weather monitoring. Finally a systematic comparison of electronic density profiles obtained through different techniques will be carried on.

(iv) The Politecnico di Torino will carry on systematic comparisons of RO data from nearly-contemporary events observed by different RO payloads, identification and study of reflection induced patterns on the received signal, development and validation of an inversion scheme for ground based GPS occultation measurements.

(v) The INNOVA consortium will develop ionospheric tomography and space geodesy-related studies.

6 Conclusion

The ROSA payload on-board the Indian OCEANSAT-2 satellite will be one of the now operative RO missions. This payload shows some interesting advanced technological implementations. A noteworthy effort is done to allow the exploitation of ROSA data from the scientific community and to develop, in parallel, a few specific topics related to atmospheric, ionospheric and plasmaspheric physics.

Acknowledgement

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