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Radio occultation experiments with INAF-IRA radiotelescopes

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Abstract. The Radio Occultation research program performed at the Medicina and Noto Radioastronomical Stations of the Istituto Nazionale di Astrofisica (INAF) - Istituto di Radioastronomia (IRA) includes observations of spacecraft by satellite and satellite by satellite events. The Lunar Radio Occultation (LRO) part of the program consists in collecting data of the lunar Total Electron Content (TEC), at different limb longitudes and at different time, in order to study long term variation of the Moon's ionosphere. The LRO program started at Medicina in September 2006 with the observation of the European probe SMART-1 during its impact on the lunar soil. It proceeded in 2007 with the observation of the lunar occultations of Saturn and Venus, and with the observation of Mars in 2008. On this occasion the probes Cassini, Venus Express, Mars Express, Mars Reconaissance Orbiter and Mars Odissey were respectively occulted by the moon. On Dec 1st 2008 a Venus lunar occultation occurred. On that occasion we performed the first Italian-VLBI (I-VLBI) tracking experiment by detecting the carrier signals coming from the Venus Express (VEX) spacecraft with both the IRA radiotelescopes together with the Matera antenna of the Italian Space Agency. The second part of the radio occultation program includes the observation of satellite by satellite occultation events, as well as mutual occultations of Jupiter satellites. These events are referred to as mutual phenomena (PHEMU). These observations are aimed to measure the radio flux variation during the occultation and to derive surface spatial characteristics such as Ios hot spots. In this work preliminary results of the Radio Occultation program will be presented.

Key words. Occultations – Planets and satellites: atmospheres – Planets and satellites: individual: inospheres

1. Introduction

The Radio Occultation research program performed with INAF-IRA radiotelescopes is composed of two parts: Lunar Radio Occultation (LRO) and Satellite by Satellite Occultation (SSO) program.

2. LRO program

From the middle of 1960s onwards, radio occultation techniques have been used with

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Table 1. LRO experiments performed at today with INAF-IRA radiotelescopes.

Sep 2006	SMART-1 (13 measurements. S-band, MC, NT)
Jun 2007	VEX (2 measurements. X-band, MC)
May 2008	MEX, MRO, MO (6 measurements. X-band, MC, NT)
Dec 2008	VEX (6 measurements. S/X-band, I-VLBI tracking, MC, NT, MT)

great success by planetary missions to measure vertical profiles of temperature, air and electron density of the planets atmosphere (Reasoner et al. 1972). To further understand the morphology of the lunar ionosphere we performed radio occultation experiments by using the radio sounding technique. This method mainly consists in the analisys of the effects produced on the radio wave transmitted from the spacecraft to the Earth when it crosses the atmosphere. The wave amplitude and phase undergo modifications that are correlated to the physical parameters - i.e. electron density - of the crossed medium. The first lunar occultation of the probe Pioneer-7 in 1966 allowed astronomers to prove the existence of a thin ionosphere around the Moon. The electron density determined at that time was 4×107 el/m^3. Further readings of the electron number density acquired by in situ measuments were provided by the Charged Particle Lunar Environment Experiment (CPLEE) onboard the US Apollo 14 mission. The measured concentration was $\sim$ 104 el/cm^3 with a particle distribution covering several hundred meters of altitude during lunar day time (corresponding to a cutoff frequency larger than 1 MHz). Few years later, measurements performed in dual frequency with the soviet spacecrafts Luna-19 and Luna-22 revealed the presence of a 10 Km plasma layer characterized by an electron number density of approximately $0.5 \div 1 \times 103$ el/cm^3 corresponding to a cutoff frequency of $\sim$ 0.3 MHz (Vyshlov 1976) . Since few years, the interest in the study of the lunar ionosphere has risen also due to the worldwide space agencies installation program of lunar radioastronomical stations. Moon based radiotelescopes could in fact avoid the problem of terrestrial interferences and/or atmospheric/ionospheric terrestrial effects. New measurements are of extreme importance in order to build a long term map of the electron distribution of the lunar ionosphere. Particular interest should be dedicated to the determination of day-night variations of the ionospheric density since the cutoff frequency is strictly correlated to this parameter. A further step consists in finding possible correlations between the plasma produced by regolite sputtering and the solar activity or cosmic radiation (Manka et al. 1994; Stubbs et al. 2005). LRO program is aimed to collect data of the lunar Total Electron Content (TEC), at different limb longitudes, in different time periods. It studies long term variations of the Moon's ionosphere. The first experiment was performed during the lunar occultation of the European probe SMART-1 on September 2006 (Fig.1). Further observations were performed on May and June 2007 on the occasion of the lunar occultations of Saturn and Venus by the Cassini and the Venus Express spacecrafts respectively (Fig.2, 3) (Pluchino et al. 2008). Table 1 shows a summary of the LRO experiments performed at today with INAF-IRA radiotelescopes.

Radio occultation measurements were performed in S- and X-band by using the Medicina and Noto 32-m fully steerable dishes of the Istituto di Radioastronomia. The signal was received by radioastronomical frontends cryogenically cooled. The Medicina parabolic dish is a Cassegrain radiotelescope that works either for interferometric observations, together with other antennas in the framework of the EVN consortium (European Very Long Baseline Interferometry Network), or as a single dish instrument. The telescope can receive signals ranging from 1.4 GHz up to 26 GHz. It is characterized by a $0.10 \div 0.16$ K/Jy

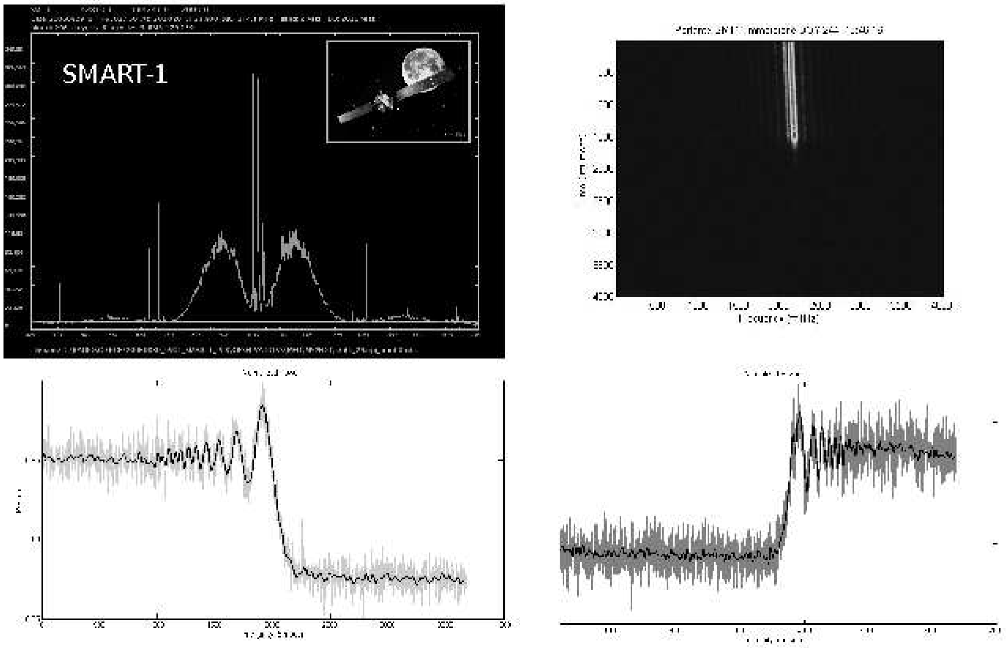

Fig. 1. The SMART-1 radio signal received on earth few orbits before the impact on the lunar soil. Clockwise from the top: The signal carrier coming from the probe. Spectrogram of the SMART-1 S-band carrier signal during an occultation ingress. Radio signal recorded at Noto radiotelescope, Sep 1st, 2006, S-C egress. Illuminated limb. Elev: 14° above the horizon. Radio signal recorded at Noto radiotelescope, Sep 1st, 2006, S-C ingress. Dark limb. Elev: 7° above the horizon.

maximum gain, and a maximum resolution of 38.7 arcmin/f (GHz). The Noto Radiotelescope works either in primary focus or in Cassegrain configuration. Although the mechanical structure is very similar to the Medicina dish, it can perform observations at much higher frequencies (from 1.4 up to 43 and even 86 GHz). This requires an active surfacesystem for compensate gravitational deformation effects. The Noto Radiotelescope besides working as a single dish antenna it also joins the EVN network for VLBI astrophysics and geodetics programs.

On May 10th, 2008 a Mars lunar occultation occurred. On that occasion we performed the first triple radio occultation experiment by detecting simultaneously in X band the carrier signals coming from the Mars Express (MEX), Mars Odyssey (MO) and Mars Reconaissance Orbiter (MRO) spacecrafts with both the 32 meters INAF-IRA radiotelescopes (Fig.4). Only the egress occurred from the illuminated lunar limb. The time of disappeareance/reappearance of each spacecraft was little different because the Marscentric position of each of them. Many differences in the occultation pattern of the carrier signals between dark and illuminated lunar limb were identified and they will be included in our LRO model of lunar ionosphere.

On December 1st, 2008 a Venus lunar occultation occurred. On that occasion we performed the first Italian-VLBI (I-VLBI) tracking experiment by detecting the carrier signals coming from the Venus Express (VEX) spacecraft with both the IRA radiotelescopes together with the Matera antenna of the Italian Space Agency. For geographical reasons the typical diffraction pattern was visible by Medicina meanwhile Noto was still receiving the direct signal. Occultations observed by

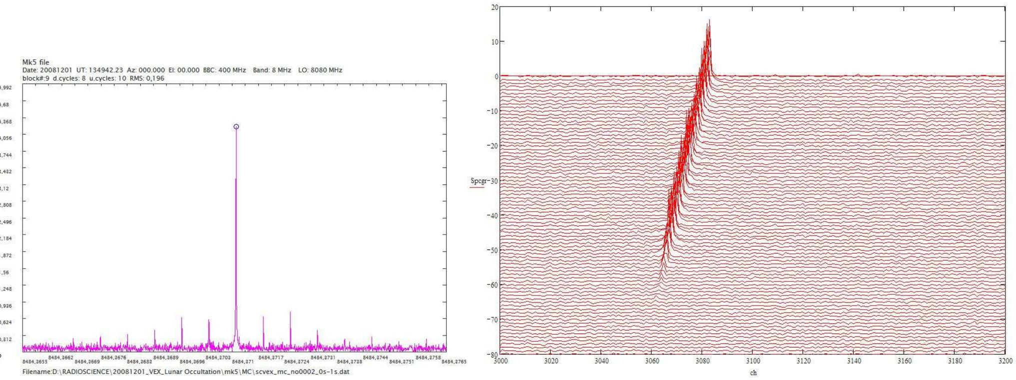

Fig. 2. On the left: Power spectrum of ESA Venus Express signal at X-Band during lunar radio occultation occurred on June 18th, 2007. MC dish, FFT 1Mch, 8 Hz/ch, ASTRA Spectrometer. On the right: Doppler of carrier, residuals of TEC after subctraction of doppler, diffraction pattern of the emersion.

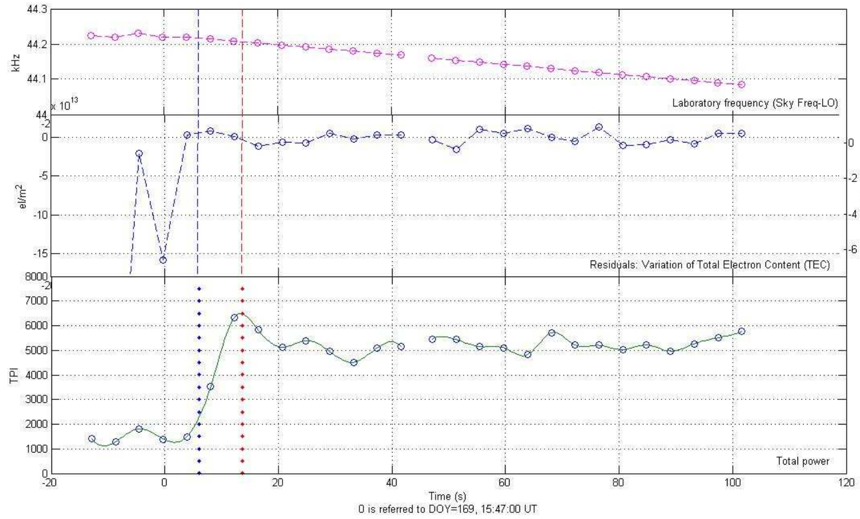

Fig. 3. Observation at 8.419 GHz of the day side limb egress. On X axes: observation time (t=0 is referred to DOY=169, 15.47.00 UT). On Y axes from the top: lab. frequency, TEC residuals variation, Total Power Intensity. FFT = 524288 ch, BW = 125 kHz, Res = 0.2384 Hz/ch.

different stations take place with offsets of several km with respect to the Moons limb and therefore are shifted in time by several seconds (see Fig.5). In this case at Noto a grazing occultation occurred with a grazing line passing at about 6 km (at azimuth 139 deg.) from the antenna. Noto radiotelescope location falls within the occultation footprint area.

The preliminary results showed a strong SNR of X-band carrier signal in each radiotelescope 8 MHz bandwidth (see Fig.7 left). Further narrow band analisys on time-frequency domain showed the immersion and emersion occultation patterns in good agreements with the simulations (see Fig.7 right). A first correlation of the fring test and S/C data

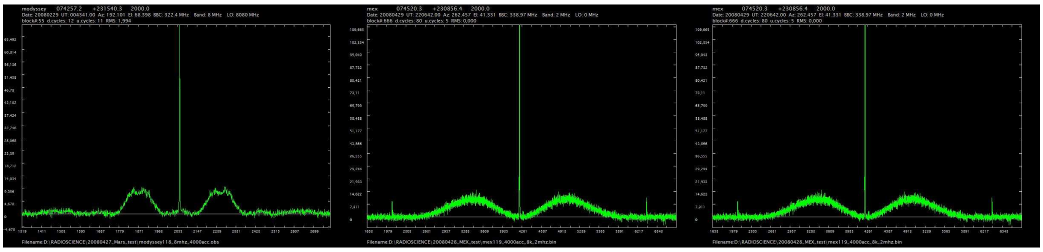

Fig. 4. From the left: averaged power spectra of Mars Odyssey, Mars Express and Mars Reconaissance Orbiter. The spectra were acquired with an FFT high resolution spectrometer.

Table 2. On the left, the lengths of the interferometric baselines (in km) used in the I-VLBI VEX tracking experiment. On the right a brief summary of the recording system used in each radiotelescope station. We used MKIV formatter for Medicina and Matera, and VLBA4 for Noto.

BASELINE LENGTHS (km)				RECORDING SYSTEM		
	Mc	Ma	Nt	Station	Drive type	DAR
Mc	0	597	893	MEDICINA	MARK5A	MKIV
Ma	597	0	444	MATERA	MARK5A	MKIV
Nt	893	444	0	NOTO	MARK5A	VLBA4

has been performed with DiFX software correlator (Deller et al. 2007). DiFX is a suite of programs which allow the correlation of interferometric baseband radio data. It is designed to run on in a cluster computing environment, and uses MPI to enable parallel processing. Usually DiFX performs correlations of extragalatic sources and in the case of spacecraft targets, because of the near field corrections, its necessary to use an appropriate model. The main program is called mpifxcorr (the actual software correlator) but there are a bunch of associated programs handling geometric model generation, FITS file building etc. Further correlation tasks are planned in agreement with IRA DifX group to better investigate the use of the correlator and calibration with phase reference source.

3. Satellite by Satellite Occultation (SSO) program

It includes the observation of SSO events, as well as mutual occultations phenomena of Jupiter satellites (PHEMU) (Arlot et al. 2006). These phenomena occur only when the Sun is in the orbital plane of the satellite for the eclipses and when the Earth is in this plane for the occultations and during a period when the Sun and the Earth are close to this plane because the planet is not a point and the shadow or the disc is sufficiently large to allow the phenomena to occur not only one time. The common orbital plane of the main satellites of Jupiter is the equatorial plane of the planet. So, the Sun is in this plane when its planetocentric declination becomes zero, i.e. when it is the equinox on the planet. The periodicity of the equinox is the half-duration of one orbital revolution around the Sun, as it is on Earth.

These observations are aimed to measure the radio flux variation during the occultation and to derive surface spatial characteristics such as Ios hot spots (Howell 1998; Spencer et al. 1994). The advantage in the observation of mutual occultations is that the satellites have no atmosphere so that the shadow cones are very sharp and easy to

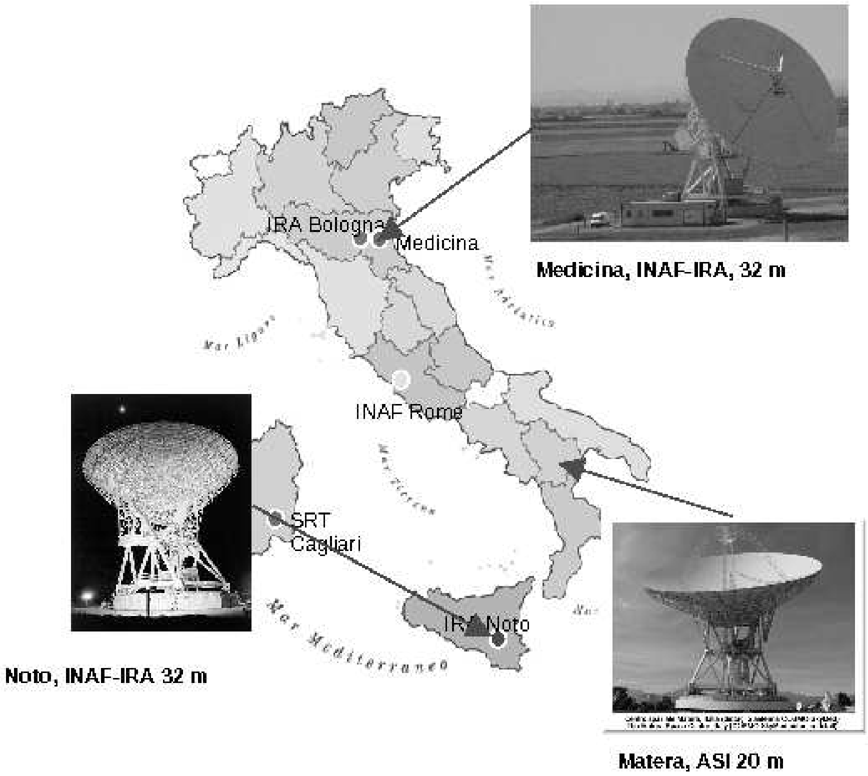

Fig. 5. The INAF-IRA antennas involved in the first I-VLBI doppler tracking experiment together with the Matera antenna of the Italian Space Agency (ASI).

model. During a mutual eclipse or occultation, the optical light received from the satellites decreases and increases for a few minutes.

During an occultation, the disc of a satellite passes in front or behind the disc of another satellite. The radio flux received from both satellite decreases compared to the flux of the satellites taken separately, have a minimum and come back to the value of the flux of the two satellites taken separately. A phenomenon occurs when the apparent distance between two satellites is smaller than the sum of the apparent radii (as seen from the Earth for the occultations and from the Sun for the eclipses). The phenomena may be partial, total or annular (as for the Moon). So far mutual phenomena, and in particular mutual satellites occultations, have been rarely studied at radio wavelengths. The major problem in observing the Galilean satellites with single dish radiotelescopes is in fact the strong jovian radioemission that may fall within the primary beam pattern of the antenna. The Jupiter flux density observed with VLA is about 10 Jy at 6 cm and 35 Jy at 2 cm (de Pater et al. 1984). Observations of occultations by Jupiter do not provide the high angular resolution possible in mutual events whereas they can be obtained when Io is in eclipse and therefore radio flux density measurements are more sensitive to

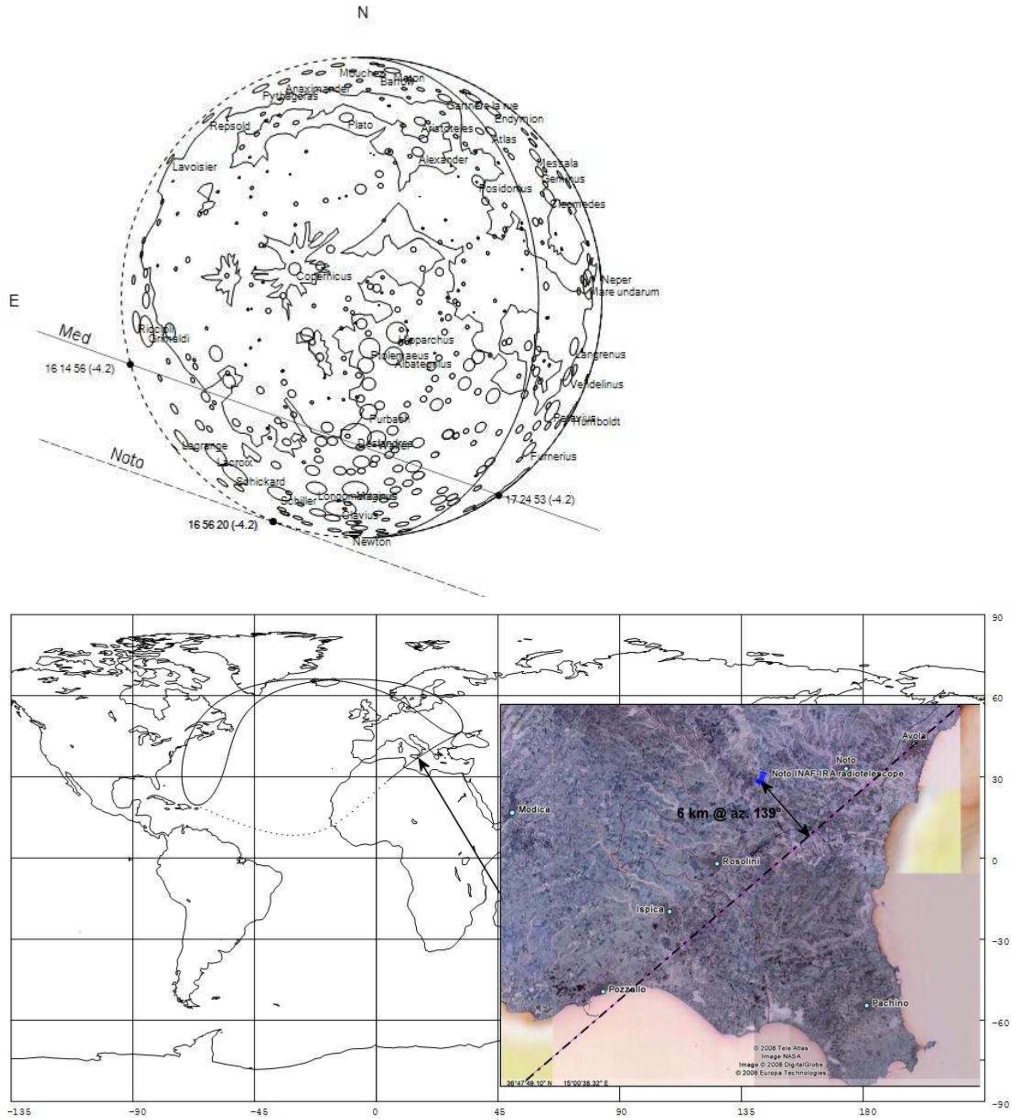

Fig. 6. At the top: occultations observed by different stations take place with offsets of several km with respect to the Moons limb and therefore are shifted in time by several seconds. At the bottom: a detailed map of the Noto location where the grazing line is passing at about 6 km from the antenna.

faint hot spots. Since no thick atmosphere surrounds the Galilean satellites, the observations of these phenomena are extremely accurate for astrometric purposes. In the case of Io, flux density variability depends on the wavelength, on time and on the location on the surface of the satellite hot spots. Ground-based observations at radio wavelengths are therefore extremely important in order to collect further information on the characterization, localization and time evolution of the Io's volcanoes. A numerical model of the each occultation curve was computed and displayed by a customized software developed by our team.

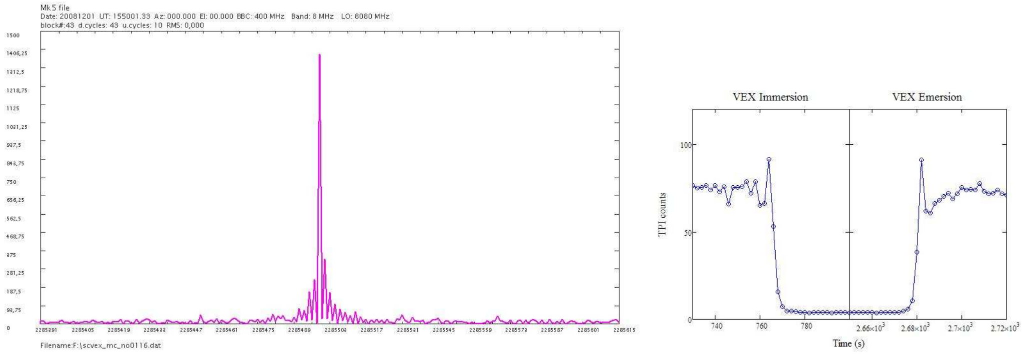

Fig. 7. On the left: Total Power high resolution spectrum (4M channels, spectral resolution of 2 Hz/ch) of the X-band carrier. Mk5 acquisistion system at MC, post processing with ASTRA software. On the right: Diffraction patterns of immersion and emersion of the X-band carrier. iBob-BEE2 acquisition system. Post processing: FFT at 320000 ch (full spectrum), Averaging: 1s, Res [Hz/ch]: 25, Res [el/cm^2]: 1.6 × 1014 el/cm^2.

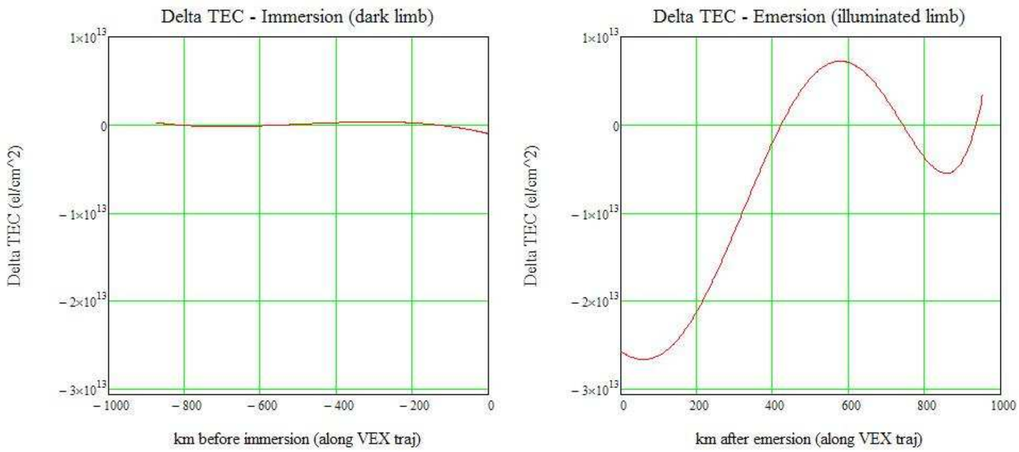

Fig. 8. Total Electron Content (TEC) variation during immersion (on the left) and the emersion (on the right) of VEX behind the Moon limb on Dec 1, 2008 with Medicina radiotelescope using the iBob-BEE2 acquisition system. Delta TEC reaches ~ 10^{13} el/cm^2, i.e. ~ 30 TECU (1 TECU=1016 el/m^2).

The software is able to simulate the flux density variation of any mutual event, by setting key parameters such as satellites radii, mean flux densities, impact parameter and time duration. In this case the analysis of the residual difference between the total power data and the model showed interesting slight effects probably caused by thermal features on the Io surface. We have studied PHEMU of the Galilean satellites at radio wavelengths by using the radio occultation technique. This method requires to point the occulted satellite (Io in this case) and to track it while it is occulted by the other one (Europa or Ganymede). Observations were performed with the Noto and Medicina 32-m antennas of the Italian Istituto di Radioastronomia and with the 100-m radiotelescope of the Max-Planck-Institute for Radioastronomy, Bonn. Observational frequencies were 43 GHz (Nt), 22 GHz (Mc) as well as 10 and 32 GHz (Eb). At Medicina and Noto data were recorded with the Mark

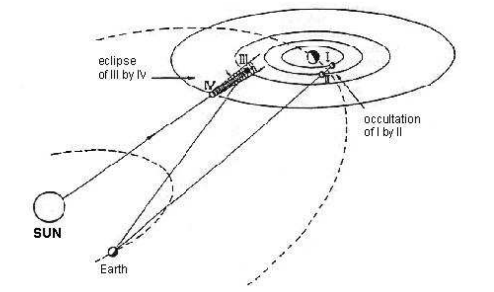

Fig. 9. Mutual events (occultations and eclipses) between Jupiter satellites.

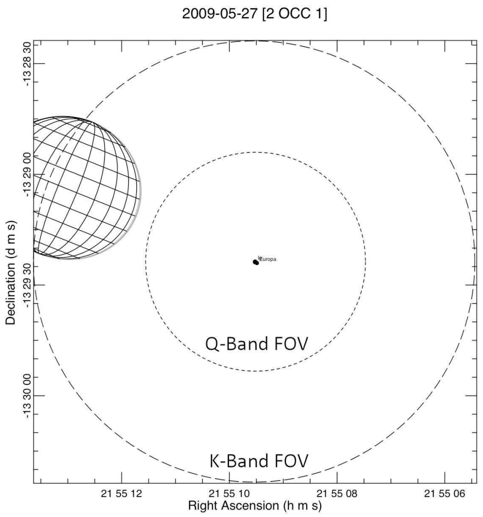

Fig. 10. Field of View (FOV) of 2OCC1 event on 27th May, 2009 (occultation of Io by Europa) performed by online software simulator of Rings Node of NASA's Planetary Data System.

IV backend for VLBI. On this occasion the newly installed Medicina K-band receiver was tested coupled with the new Enhanced Single-dish Control System (ESCS). At Effelsberg data were taken with the Digital Backend used for continuum observations. Data acquired by the Italian antennas were post processed with the Advanced Software Tools for Radio Astronomy (ASTRA) developed by our group. Data collected at Effelsberg were analized with the CONT2 subpackage of the Toolbox package for the analysis of single-dish radio obser-

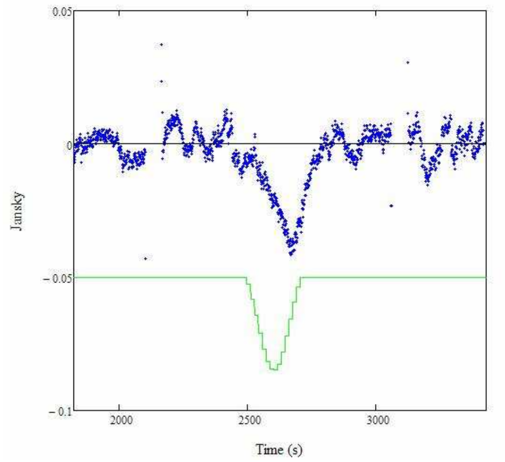

Fig. 11. Flux density variation measured during 2OCC1 P occultation on 18th Dec, 2009. The signal is total power, already on-off corrected and calibrated. Blue curve indicate the flux density measured at 22 GHz by the Medicina antenna. Signal integration was performed over the entire available bandwidth. Green curves indicate the expected flux density variation according to the numerical model.

vations. The Total Power Integration (TPI) was performed over the entire available bandwidth. Experimental results are in good agreement with the expected values obtained according to the numerical model (see Fig.11). The observational campaign is still ongoing, however results from annular occultation measurements clearly show the necessity of further studies. Further measurements are already planned to confirm previous results and explain observed phenomena. Simultaneous measurements performed at optical and/or IR wavelengths could help to explain observed phenomena.

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