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Radio occultation measurements of the lunar ionosphere

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Abstract. Radio occultation measurements by using interplanetary probes is a well known technique to obtain information on planetary atmospheres. 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 data set was obtained during the lunar occultations of the European probe SMART-1 shortly before impacting the lunar soil on September 3^{rd}, 2006. During this experiment several radio occultation measurements of the signal transmitted by the spacecraft were performed in S and X band by using the 32 meters radiotelescopes (at Medicina and Noto) of the Istituto di Radioastronomia - Istituto Nazionale di Astrofisica. Further experiments were performed during lunar occultations of Saturn and Venus. On May 22^{nd} and June 18^{th} 2007 the Cassini spacecraft, orbiting Saturn, and the Venus Express spacecraft, orbiting Venus, respectively were occulted by the Moon. The variation of the Total Electron Content (TEC) measured by our instruments ($\sim 10^{13}$ el/m^2) on this occasion is in agreement with values of the electron number density acquired by in situ measuments of the US Apollo missions and the USSR Luna 19 and 22 probes.

Key words. Radio occultations – Moon – Electron density – Artificial satellites, space probes

1. Introduction

From the middle of 1960s onwards, radio occultation techniques have been used with great success by planetary missions to measure vertical profiles of temperature, air and electron density of the planets atmosphere. The first lunar occultation of the probe Pioneer-7 in 1966 allowed astronomers to prove the exis-

Send offprint requests to: S. Pluchino tence of a thin ionosphere around the Moon. The electron density determined at that time was 4×10^7 el/m^3. Further readings of the electron number density acquired by in situ measurements were provided by the Charged Particle Lunar Environment Experiment (CPLEE) onboard the US Apollo 14 mission. The measured concentration was 10^4 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) (Reasoner & Burke 1972). 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 $0.5 \div 1 \times 10^3$ el/cm^3 corresponding to a cutoff frequency of 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 also 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). In this paper we present the results of the measurements performed with the two Italian Radiotelescopes of the Istituto di Radioastronomia - INAF, during the recent lunar occultation of the spacecrafts SMART-1, Cassini and Venus Express.

2. The experiment

From September 2006 a lunar occultation measurements program started at the Istituto di Radioastronomia - Istituto Nazionale di Astrofisica (INAF - IRA) with the aim of collecting data of the Moon ionospheric Total Electron Content (TEC) at different longitudes and at different time in order to build a more accurate model of the lunar ionosphere. The first experiment was performed during the lunar occultation of the European probe SMART-1 on September 2006. 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.

2.1. The radio occultation technique

With this technique ((Hazard)) radio waves that are transmitted from the spacecrafts to the Earth, passing through the atmosphere (either during a rise event or a set event as seen from the receiver), are refracted at an angle that is determined by the refractivity gradients along the path. The refractivity variation, in turn, depends on the gradients of air density (and hence temperature), water vapour and electron density. A measurement of the refracted angle therefore contains information on these atmospheric variables. At radio frequencies it is not possible to measure the refraction angle directly. However, the refraction introduces an additional Doppler shift into the received signal. This Doppler shift (or the related phase shift) can be measured very accurately by the receiver and is directly related to the refraction angle. The refraction effects on the signals in the ionosphere must be corrected using signals at two frequencies at which these effects are substantially different. In addition, the presence of such effects provides information on the ionosphere's electron density field.

2.2. The experimental setup

Radio occultation measurements were performed in S and X band by using the Medicina and Noto VLBI 32 m fully steerable dishes of the Istituto di Radioastronomia (Fig. 1). 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 23 GHz. It is carachterized by a 0.10 ÷ 0.16 K/Jy 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 surface system 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.

Data were contemporary acquired and analyzed in both frequency and time domain with two backends. The signal was digitized and stored in time domain by the VLBI standard formatter MK-V, whereas the programmable spectrometer MSpec0 performed a real-time analysis of the signal in the frequency domain. (Fig. 2). Both the telescopes use a VLBI back end system: a Mark IV for Medicina and a VLBA IV for Noto. This type of back end consists of a series of 14 base band tunable filters (0.025:16 MHz) that slice the Intermediate Frequency (100-500 Mhz) coming down from the downconverted sky frequency measured by the front-end receivers. Signals are succesively A/D converted with a variable data sampling rate (16 Mbit/sec), and two bits of quantization; information is then formatted in a stream of data recorded by the Mark V recorder at a high bit data rate. Recorded data are stored in the Mark V disk bank and then post-processed by SPARKLE (SPectrum Analyzer using maRK 5 for Line Emission), a software devloped by our group and dedicated to the analysis of spectral data coming from the VLBI back end. This software extracts data from Mk4 word and performs an FFT analysis of phase and amplitude of the signals, also calculating istantaneous power of a selected portion of the received band. Contemporary to the time domain acquisition data are also analyzed in piggyback mode

Fig. 1. From the top: Noto and Medicina VLBI 32 m parabolic antennas

Table 1. Experimetal setup for Medicina and Noto lunar occultation measurements

S/C	Date	DOY	BAND	Medicina backend	Noto backend	Type
SMART-1	2006/08/30	242	S	MSPEC0	-	IMM
SMART-1	2006/08/30	242	S,X	MKV, MSPEC0	-	EGR
SMART-1	2006/08/31	243	X,Ka	-	MKV	EGR
SMART-1	2006/08/31	243	S	MKV, MSPEC0	-	IMM
SMART-1	2006/08/31	243	S	MKV, MSPEC0	-	EGR
SMART-1	2006/09/01	244	S	-	MKV	IMM
SMART-1	2006/09/01	244	S	-	MKV	EGR
SMART-1	2006/09/01	244	S	MKV, MSPEC0	MKV	IMM
SMART-1	2006/09/01	244	S	MKV, MSPEC0	MKV	EGR
CASSINI	2007/05/22	142	X	MKV, MSPEC0	-	IMM
CASSINI	2007/05/22	142	X	MKV, MSPEC0	-	EGR
VEX	2007/06/18	169	X	MKV, MSPEC0	-	IMM
VEX	2007/06/18	169	X	MKV, MSPEC0	-	EGR

by the MSPEC0 system, an FFT-based digital spectrometer (Montebugnoli et al. 1996) designed for radioastronomy applications. The system was originally build to implement a top performance spectrum analyser for line observations in the microwave range. The system has been constantly upgraded and the current version of the MSPEC0 is powered by two ultra-fast commercial DSP boards in a VME environment. The DSP computing core is completely programmable in terms of input bandwidth, number of channels, and number of spectra to be averaged before the storage phase on a capable hard disk. The system constantly computes the FFT of an input data streams from an A/D converter giving as output the signal spectra. Spectra can be averaged over a programmable number of repetitions. During the observations the spectrometer and converter rack were configured to 2048 frequency channels in a 2 MHz bandwidth centred at 2.235 GHz.

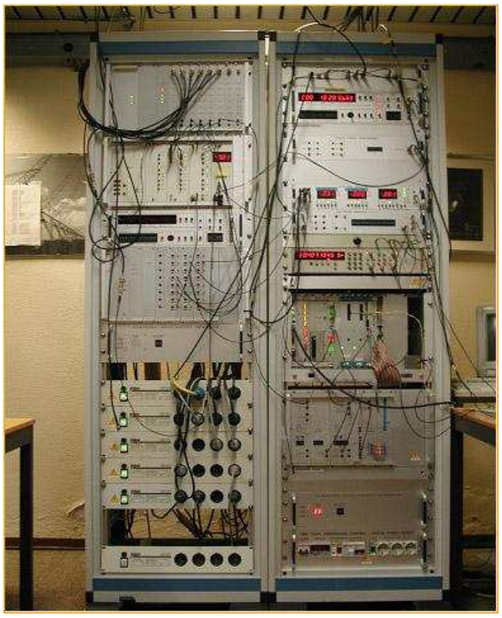

Fig. 2. The programmable spectrometer MSPEC0 for radioastronomical spectral data acquisition in frequency domain

Table 1 gives a summary of the experimetal setup features used during the lunar occultation measurements. The observations were performed with a bandwidth of 125 KHz, a frequency resolution of 0.2384 Hz/ch obtained with an FFT processor operating at 524288 channels.These parameters were chosen in order to allow an optimized doppler tracking of the spacecraft carriers.

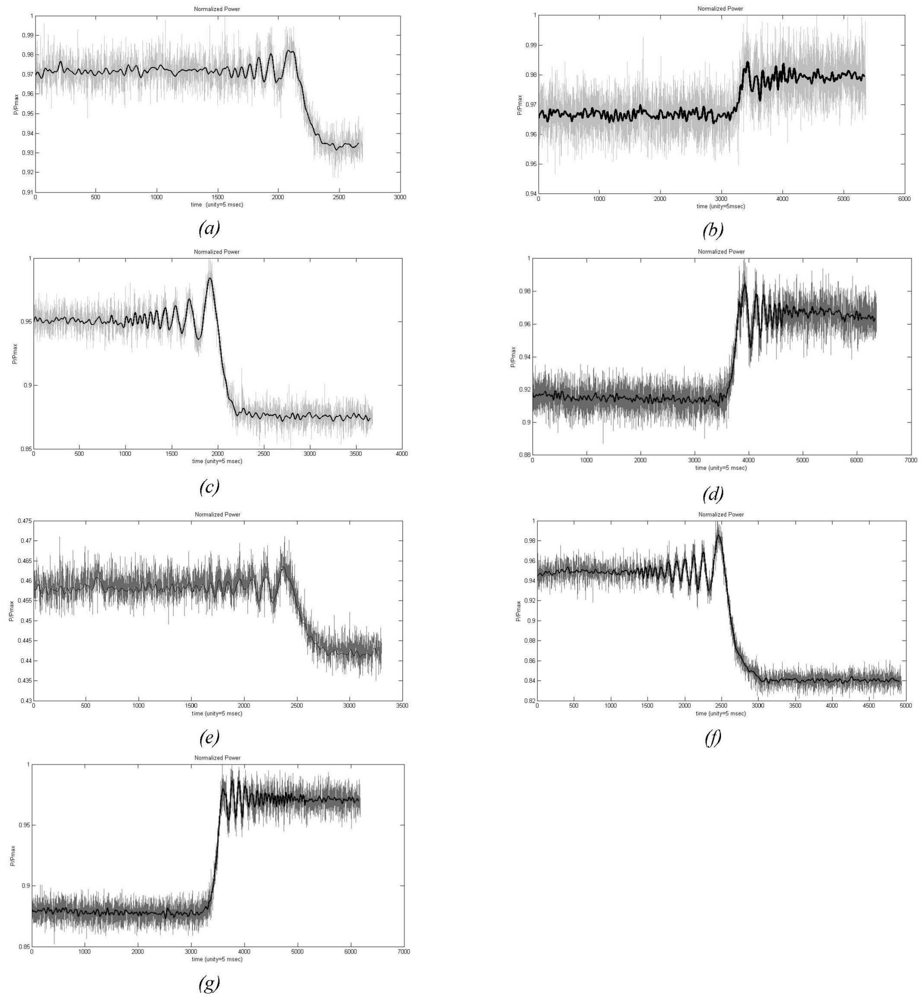

Fig. 3. SMART-1 radio occultation patterns. From the top, from left to right: a) Medicina, 31 August, immersion to brightened limb, Moon at 18 deg of elevation above the horizon; b) Medicina, 31 August, emersion from dark limb, Moon at 15 deg of elevation above the horizon; c) Noto, September 1, immersion to dark limb, Moon at 7 deg of elevation above the horizon; d) Noto, September 1 , emersion from brightened limb, Moon at 14 deg of elevation above the horizon; e) Medicina, September 1, immersion to dark limb. Moon at 15 deg of elevation above the horizon. f) Noto September 1, immersion to dark limb. Moon at 21 deg of elevation above the horizon; g) Noto September 1, emersion from brightened limb, 17 deg of elevation above the horizon

3. Results

Fig. 3 shows the radio occultatio patterns of the SMART-1 probe as seen from the two antennas. The measurements performed in S and X band by using both the Medicina and Noto radiotelescopes gave as result a TEC value of the order of 10^{13} el/m^2 (see Fig. 4 and Fig. 5).

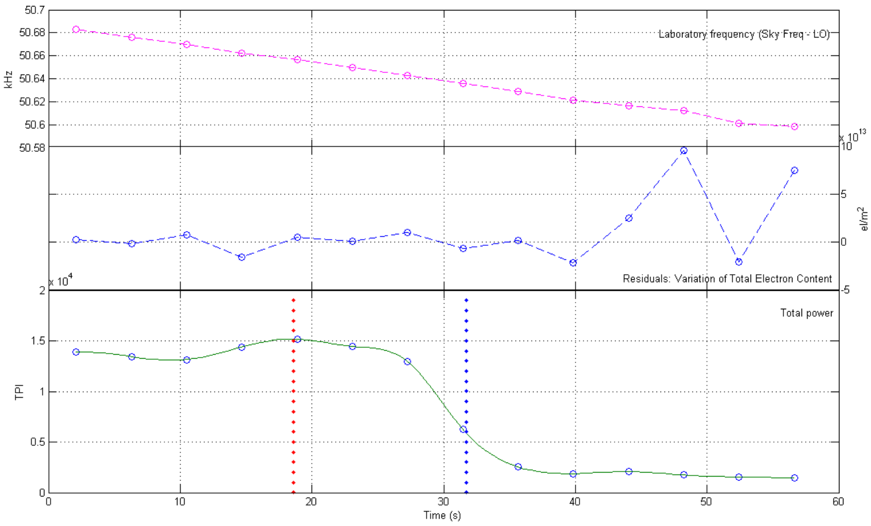

Fig. 4. VEX - Observation at 8.419 GHz of the night side limb ingress. On X axes: observation time (t=0 is referred to DOY=169, 14.36.00 UT). On Y axes from the top: lab. frequency, TEC residuals variation, Total Power Intensity

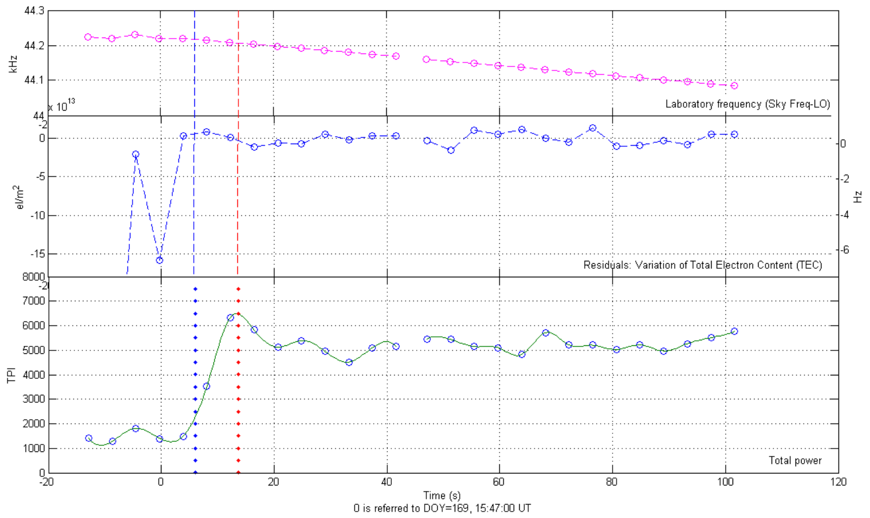

Fig. 5. VEX - Observation at 8.419 GHz of the day side limb egress. On X axes: observation time (t=0 is referred to DOY=169, 15.47.00 UT). On Y axes from the top: lab. frequency, TEC residuals variation, Total Power Intensity

4. Conclusions

Radio sounding experimets were performed during some lunar occultations of the probes SMART-1, Cassini and Venus Express by using the 32 m radiastronomical antennas of the Italian Istituto di Radioastronomia. On this occasion few hundreds of Gigabytes of data were produces. The variation of the Total Electron

Content (TEC) measured by our instruments ($\sim 10^{13}$ el/m^2) is in agreement with values of the electron number density acquired by in situ measuments of the US Apollo missions and the USSR Luna 19 and 22 probes. However new radio occultation measurements are of extreme importance in order to build a more accurate model of the lunar ionosphere. In particular our group is now working on a physical model that is able to simulate all diffractive and refractive effects encountered in each occultation.

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