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Studying the Lunar Ionosphere by Virtue of the SMART-1 Signals

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Abstract. The European probe SMART-1, in orbit around the Moon until it crashed on it on September 3rd, 2006, provided a new, good opportunity to investigate the radial density and refractive index of the tiny ionosphere surrounding the Moon. In fact, the carriers emitted by the probe in S, X and Ka bands were picked up by radiotelescopes on Earth and analyzed by virtue of the traditional occultation techniques. In Italy, the Team led by Salvatore Pluchino as the P.I., with Claudio Maccone, Luca Derosa and Christian M. Firrone as co-investigators, was able to gather a host of data by virtue of the two 32-meter radiotelescopes available at Medicina (near Bologna) and Noto (near Siracusa, in Sicily). Strong support also came from the Medicina Radiotelescope Team led by Stelio Montebugnoli. Furthermore, a joint cooperation with the Team of the Hat Creek Observatoryin northern California, led by Jill Tarter, provided a sound opportunity for cross-checking the data in S and X bands. In conclusion, it is hoped that these experimental investigations will finally produce an improved mathematical model of the tiny Lunar ionosphere that would be pivotal to construct a future radiotelescope on the Farside of the Moon (2000, 1986), as suggested by Maccone at the conclusion of his IAA Cosmic Study about the "Lunar Farside Radio Lab" (2005) (Maccone 2003, 2005) .

Key words. Moon: ionosphere – Occultations – Radio continuum: solar system

1. Introduction: the SMART-1 2006 opportunity

The existence of a tiny lunar ionosphere was suggested since the 1950's/60's during the first radio observations of some lunar occultations (Vasil'ev et al. 1974; Zhang et al. 1990; Kliore et al. 1969). In 2006, the SMART-1 European spacecraft (s/c), launched by ESA in 2003, provided a wonderful opportunity to investigate again the tiny lunar ionosphere directly as well as the attenuation of radio waves beside (and behind) the Moon. In fact, the radio waves emitted by SMART-1 were crossing the lunar ionosphere completely whenever the probe hided behind the Moon and whenever it re-emerged on the other side (Pluchino et al. 2007, 2004). We just took this opportunity of SMART-1 spiralling along decreasing

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orbits around the Moon (until it finally crashed on the lunar surface on September 3rd, 2006) to gather a HOST OF DATA about the intensity, phase and polarization of the incoming waves that crossed the lunar ionosphere. Later data reductions are expected to provide us with the refraction index and the radial electron density of the tiny lunar ionosphere that may also change according to the position of the Moon with respect to the Sun and the magnetic tail of the Earth. A good theory of the lunar ionosphere and lunar signal attenuation would then hopefully emerge.

Fig. 1. The Medicina VLBI dish and, in the forefront, part of the Northern Cross Array (North/South arm).

Fig. 2. The Noto 32 meter VLBI dish, equipped with an active mirror (F_{max}= 43 GHz)

Fig. 3. The large Northern Cross Array, 560 meters (East-West arm) x 640 meters (North-South arm).

The Istituto di Radioastronomia (IRA) of the Istituto Nazionale di Astrofisica (INAF) (formerly Italian National Research Council - CNR) runs 3 radiotelescopes :

1. The Medicina (near Bologna) 32 meter VLBI dish shown in Fig. 1. Operating frequency: 1.4 23.5 GHz (Montebugnoli et al. 1996).
2. The Noto (near Siracusa) 32 meter VLBI dish, shown in Fig. 2, equipped with active mirror. Operating frequency: 1.4 43 GHz.
3. The 30.000 m^2 collecting area Northern Cross Array, a large cylindrical reflector T-shaped array. Operating frequency: 408 MHz ± 2.5 MHz (Fig. 3).

The Northern Cross Array (5632 dipoles) is one of the largest transit telescopes in the northern hemisphere. Its collecting area is equivalent to three football stadiums and, because of this, is one of the most suitable instruments to be transformed into a test bed for the very large SKA (Square Kilometre Array). Finally, a 64 meter parabolic antenna is cur-

Table 1. SMART-1 Lunar occultation ephemeris from August 29 to September 2, 2006 as seen by the Medicina and Noto IRA-INAF radiotelescopes. The grey rows indicate the scheduled occultation events because of its favourable altitude. The last column gives the band at which the occultation event was actually observed.

	PRI	GS	OCCULTAT.	START TIME	OCCULTAT.	END TIME	EL1	EL2	DUR	BAND
01	MOO	83	2006/08/29	04:50:23.1	2006/08/29	04:51:26.5	-53.	-52.	1.1	
01	MOO	84	2006/08/29	04:50:20.8	2006/08/29	04:51:55.8	-54.	-54.	1.6	
02	MOO	83	2006/08/29	09:40: 7.3	2006/08/29	10:14:27.2	-6.	0.	34.3	
02	MOO	84	2006/08/29	09:40:12.8	2006/08/29	10:14:39.4	-1.	6.	34.4	
03	MOO	83	2006/08/29	14:40:41.8	2006/08/29	15:24:16.9	26.	26.	43.6	S,X
03	MOO	84	2006/08/29	14:40:50.6	2006/08/29	15:24:10.5	34.	34.	43.3	
04	MOO	83	2006/08/29	19:43: 4.8	2006/08/29	20:33: 6.8	1.	-7.	50.0	
04	MOO	84	2006/08/29	19:43:16.5	2006/08/29	20:32:59.3	2.	-6.	49.7	
05	MOO	83	2006/08/30	00:46: 1.6	2006/08/30	01:43: 4.3	-50.	-58.	57.0	
05	MOO	84	2006/08/30	00:46:12.4	2006/08/30	01:43:12.1	-55.	-65.	57.0	
06	MOO	83	2006/08/30	05:49: 8.3	2006/08/30	06:52: 8.4	-54.	-44.	63.0	
06	MOO	84	2006/08/30	05:49:16.0	2006/08/30	06:52:23.1	-55.	-43.	63.1	
07	MOO	83	2006/08/30	10:52:25.2	2006/08/30	11:58:46.2	-5.	5.	66.3	
07	MOO	84	2006/08/30	10:52:29.8	2006/08/30	11:58:53.9	1.	12.	66.4	
08	MOO	83	2006/08/30	15:56: 6.2	2006/08/30	17:04:10.0	22.	20.	68.1	S,X
08	MOO	84	2006/08/30	15:56: 9.8	2006/08/30	17:04:11.4	29.	27.	68.0	X,Ka
09	MOO	83	2006/08/30	21:00:25.0	2006/08/30	22:10: 4.7	-7.	-18.	69.7	
09	MOO	84	2006/08/30	21:00:30.9	2006/08/30	22:10:10.4	-6.	-18.	69.7	
10	MOO	83	2006/08/31	02:05: 7.5	2006/08/31	03:16:13.6	-58.	-67.	71.1	
10	MOO	84	2006/08/31	02:05:15.6	2006/08/31	03:16:25.8	-63.	-74.	71.2	
11	MOO	83	2006/08/31	07:09:46.1	2006/08/31	08:21: 4.5	-52.	-40.	71.3	
11	MOO	84	2006/08/31	07:09:53.4	2006/08/31	08:21:14.3	-51.	-37.	71.3	
12	MOO	83	2006/08/31	12:14: 9.5	2006/08/31	13:24:38.3	-3.	7.	70.5	
12	MOO	84	2006/08/31	12:14:13.7	2006/08/31	13:24:43.0	4.	14.	70.5	X,Ka
13	MOO	83	2006/08/31	17:18:40.1	2006/08/31	18:28:16.9	18.	15.	69.6	S
13	MOO	84	2006/08/31	17:18:42.5	2006/08/31	18:28:23.7	25.	21.	69.7	S
14	MOO	83	2006/08/31	22:23:49.3	2006/08/31	23:32:13.3	-14.	-25.	68.4	
14	MOO	84	2006/08/31	22:23:54.2	2006/08/31	23:32:25.9	-13.	-26.	68.5	
15	MOO	83	2006/09/01	03:29:32.8	2006/09/01	04:35: 2.0	-65.	-72.	65.5	
15	MOO	84	2006/09/01	03:29:41.5	2006/09/01	04:35:12.7	-70.	-79.	65.5	
16	MOO	83	2006/09/01	08:35:18.3	2006/09/01	09:35:59.0	-48.	-38.	60.7	
16	MOO	84	2006/09/01	08:35:27.6	2006/09/01	09:36: 0.7	-46.	-34.	60.6	
17	MOO	83	2006/09/01	13:40:42.9	2006/09/01	14:36:34.5	0.	7.	55.9	
17	MOO	84	2006/09/01	13:40:48.0	2006/09/01	14:36:36.0	7.	14.	55.8	S
18	MOO	83	2006/09/01	18:46:14.8	2006/09/01	19:37:59.8	15.	12.	51.8	S
18	MOO	84	2006/09/01	18:46:16.3	2006/09/01	19:38:12.7	21.	17.	51.9	S
19	MOO	83	2006/09/01	23:53: 3.6	2006/09/02	00:38:23.6	-21.	-28.	45.3	
19	MOO	84	2006/09/01	23:53: 8.9	2006/09/02	00:38:40.3	-20.	-28.	45.5	
20	MOO	83	2006/09/02	05:02:14.9	2006/09/02	05:34:28.5	-70.	-73.	32.2	
20	MOO	84	2006/09/02	05:02:32.7	2006/09/02	05:34:26.0	-77.	-81.	31.9	

rently under construction at San Basilio, close to Cagliari (Sardinia island).

2. Planning the radio science experiments involving SMART-1

To investigate the radial density and refractive index of the tiny ionosphere surrounding the Moon, we performed a campaign of measurements of radio occultation events that involved the SMART-1 probe. Using the two VLBI (32-meters in diameter) antennas of IRA-INAF we obtained both high resolution spectra and total power data. To plan our experiments firstly we had to solve the following problems:

1. Finding out which lunar occultation of the SMART-1 probe would occur inside our target visibility windows and match with our observing time slots.
2. Getting the confirmation by the ESA SMART-1 Team that the probe was to transmit during the occultation.
3. Which type of transmitters would the s/c have used (S, X or Ka? see below).
4. How much proper motion the s/c would have had during each observation session.
5. How much Doppler effect we would have had to face from our two radiotelescopes.

Let us consider more in detail each of these problems. For the Smart-1 spacecraft there were two “occultation seasons” every month, each one lasting several days. During each “season” a lunar occultation took place once every orbital revolution, i.e. about every

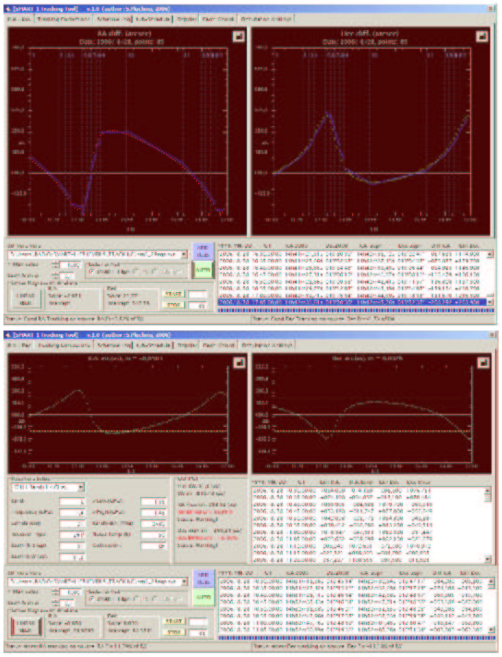

Fig. 4. Two screenshots of the software tool developed by S. Pluchino (Experiment Manager) to analyze the proper motion of the SMART-1 probe and to compute its Right Ascension and Declination tracking rates.

Table 2. The MGA (Medium Gain Antenna) passages used to plan the X and Ka band observations.

Date	UT Start	UT Stop
Aug 28	14:45:00	16:57:30
Aug 29	16:10:00	18:20:50
Aug 30	15:34:35	19:44:15
Aug 31	11:52:55	16:03:05

Table 3. Characteristics of the receivers used for the SMART-1 radio occultation experiments at IRA-INAF radiotelescopes.

Band	GHz	BW (ap)	Noise Temp (K)
S	2.3	18	40
X	8.3	5	25
Ka	32	0.88	-

5 hours. In particular, during August 2006, the first season ended on August 21 and the next one started on August 29. Because of this, and taking into account the observing time allocated to our Team at Medicina and Noto, we scheduled no more than six occultation events, some of them being visible by both our radiotelescopes at the same time. The SMART-1 probe in orbit around the Moon emitted electromagnetic waves on three different frequencies:

1. S-band, centered at 2.2351 GHz; with an output power of +37 dBm, used only for telemetry purposes. It was the most observed carrier because of its good visibility conditions at any time when the s/c was above the horizon.
2. X-band, centered at 8453.024225 MHz; with an output power of about +10 dBm was used during the KaTE experiment (Ka Band Transponder Experiment). For the first time on an ESA science mission, KaTE was an experiment to demonstrate the performance of the next generation of radio links between Earth and a distant spacecraft orbiting the Moon.
3. Ka band, centered at 32121.49350 MHz; with an output power of about +20 dBm was primarly used during the KaTE experiments as the X-band transmitter.

SMART-1 transmitted in S-band all the time because of its telemetry purposes, but this was not true for X and Ka transmissions. So, we had to ask STOC (the ESA Science Technology Operations Coordination) the schedule of the all useful passages of the MGA (Medium Gain Antenna) that matched with our observing slots, as showed in table 2. We scheduled 4 observations at X and Ka bands (please see on table 1 the events 03 (Medicina), 08 (Medicina and Noto) and 12 (Noto)). One more problem that had to be solved was the tracking of SMART-1 in RA and Dec, since the probe moved across the sky with at an unusually fast proper motion. It was necessary to develop a customized software tool (see Fig.4) to analyze the ephemeris

Table 4. The table shows the slots of observing time allocated at the Medicina and Noto radiotelescopes and each observation of the SMART-1 lunar radio occultations performed in between August 30th and September 1st, 2006.

DATE	OCC. PH	MEDICINA				NOTO			
		UT Start	UT Stop	Band	NOTE	UT Start	UT Stop	Band	NOTE
2006/08/30	imm	15:50:00	16:00:00	S	MSpec	NOT OBSERVED			
2006/08/30	eme	16:55:00	17:15:00	S, X	MSpec + CW				
2006/08/31	imm	NOT OBSERVED				NOT OBSERVED			
2006/08/31	eme					13:15:03	13:35:00	X,Ka	CW
2006/08/31	imm	17:10:00	17:30:00	S	MSpec + CW	NOT OBSERVED			
2006/08/31	eme	18:20:00	18:40:00	S	MSpec + CW				
2006/09/01	imm	NOT OBSERVED				13:30:02	13:45:00	S	CW
2006/09/01	eme					14:25:02	14:40:00	S	CW
2006/09/01	imm	18:35:00	18:50:00	S	CW	18:35:03	18:50:00	S	CW
2006/09/01	eme	19:25:00	19:45:00	S	MSpec + CW	19:25:02	19:45:00	S	CW

of SMART-1 and compute the Right Ascension and Declination tracking rate for each single session. To accomplish this goal, the software firstly analyzes the ephemeris of the probe (kindly provided to us by the ESA SMART-1 Team), then it computes the best partitioning of the schedule to obtain a good tracking with an accuracy better than 0.1 of the antenna beamwidth (please see Tab. 3 for other details).

3. Conclusions

At the end of the experiments, we produced a few hundreds of Gigabytes of data, whose reduction will require some months of work. We are now working on a physical model enabling us to simulate all diffractive and refractive effects we have encountered in each occultation. We will perform a careful analysis on all spectral and total power data to detect the tiny lunar ionosphere.

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