Radio observation of SMART-1 in its last perilune orbit

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Draft 03.09.2006 / Updated 09.09.2006

Abstract. The opportunity to measure SMART-1 telemetry beacon before 3rd of September 2006 was a really rare occasion. I wanted to take it, before SMART-1 impacts the surface of the moon. The ESO spacecraft SMART-1 in its last perilune orbit is in addition an ideal transmitter (telemetry beacon) to check the functionality and sensitivity of our small radio telescope which, considered by itself, is dedicated to solar radio astronomy. All measurements were successfully completed with audible sound and an acceptable SNR of up to 30dB.

Key words. S-band, beacon, doppler, noise.

1. Introduction

Observing space crafts with small radio telescopes is rather challenging since many system parameters have to be optimized in parallel. In some cases it's very difficult to get these data ready at the right time. One has to know the exact position at a certain time in space as well the transmission frequency, the transmission power, the antenna gain, the doppler shift and at least an assumption about the bandwidth of the received signal. On September 2th 2006 our 5m telescope was equipped with a logarithmic periodic antenna 1GHz...12GHz dedicated to solar radio observations in L-band and S-band. The calibration unit exceptionally was bypassed to guarantee minimal noise figure of the focal plane unit. A critical issue was the fact that the moon was rather low in elevation. There was a real risk that during the moon observation the antenna may point to the strong sources of electromagnetic interference (nearby man made noise). Luckily, this was not the case, the noise floor away from the measured beacon signal was real noisy and not disturbed by any man made noise. Different acronyms used in labels and text are described in table 5.

2. Sensitivity estimation

As a first test, I measured the quiet sun, also at very low elevation of 5 degree (behind brushes and trees), to get an idea about pointing accuracy and system temperature T_{sys} of the telescope. The result was not very promising since the signal to noise ratio or, in this case the so called Y-factor was in the order of only 2.2dB.

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Fig. 1. 5m parabola with logarithmic periodic feed, focal plane unit containing a high gain low noise preamplifier. In this picture the dish is just pointing to the moon on 2006-09-02 at about 18:52UT

$$Y = \frac{V_{hot} - V_{cold}}{g} = 2.24dB \pm 0.5dB \quad (1)$$

Where $V_{hot} = 664mV$ was the measured voltage while pointing to the sun, $V_{cold} = 608mV$ the voltage while pointing to cold sky. Variable g was the detector gradient of nominally $g = 25mV/dB$. Remark: a couple of days earlier with the sun high above horizon, I got 11dB for Y-factor. Taking into account the interpolated quiet solar flux of about $S = 60sfu$ (NOAA) on September 2th at

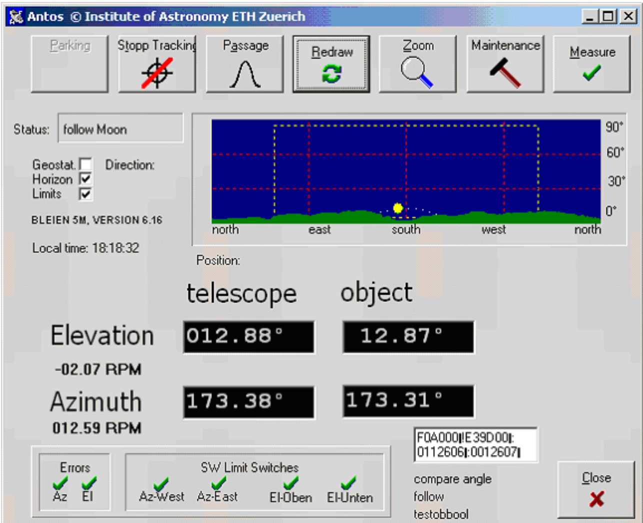

Fig. 2. Screenshot of antenna control application which permanently tracks the center of the moon. Maximum elevation during the observation was always below 13°.

2235.1MHz we can estimate the system temperature T_{sys} to

$$T_{sys} = \frac{SA_{eff}}{2k\ (Y-1)} = 3'230Kelvin \tag{2}$$

Where A_{eff} is the effective receiving area of the parabola antenna of

$$A_{eff} = \pi\ r^2\ \eta = 9.8m^2 \tag{3}$$

where $r = D/2 = 2.5m$ and $\eta = 0.5$ the efficiency factor (Kraus, 1965) as a first order assumption. The system temperature of September 2th was extremely high compared to 183Kelvin when the source (sun) a few days earlier was high above the horizon.

3. Station description

A 5m radio telescope, see figure 1, was pointed to the moon in two different tracking modes [a) continuous tracking and b) on-/off source]. The incoming signals were amplified by a high gain low noise preamplifier of MITEQ company and fed via a low ohmic loss coaxial cable to our communication receiver AR5000, see figure 3. The receiver AR5000 was nominally set to 2235.100000MHz with a small offset to compensate for fast changing doppler shift of -23KHz...+12KHz. For a more detailed setup configuration, see table 3. The CW signal could be heard very clearly in the attached loudspeaker. The audio output was fed to a sound card of a standard PC and analyzed on line with the free software spectrum analyzer SpectrumLab, for details, see table 4. The weather conditions were not ideal but sufficient for radio observations, for detail, see environmental parameter table 1.

Environmental parameter	Readings
Sky	cloudy
Wind	2,3 m/sec, 231°
Outside temperature	$17,3°C$
Outside humidity	$85,8\%rh$
Receiver temperature	$23°C$
Receiver humidity	$32\%rh$

Table 1. Weather conditions during observation of SMART-1 beacon spectrum at the observation place in Bleien 50km south of Zurich.

Telescope-Parameter	Value
Telescope type	azimuthal
Angular resolution	0.08°
F/D ratio	0.507
Minimum elevation	5°
Dish diameter	5 m
Beam angle	$60°\frac{\lambda}{D} = 1,6°$
Polarization	linear 45° versus horizon
Longitude	08° 06′ 44”
Latitude	47° 20′ 26”
Height above sea level	469 m

Table 2. Relevant observatory and observation parameters.

Receiver-Parameter	Settings
Frequency min	2235.077000 MHz
Frequency max	2235.112000 MHz
Resolution	500 Hz
Detector low pass filter	12 KHz
Automatic gain control	OFF
Receiver bandwidth	30 KHz
Receiving mode	CW
Antenna attenuation	-6 dB

Table 3. Important setup parameter for communication receiver AR5000.

FFT-Parameter	Settings
FFT size	16’384 samples
Audio sampling	11’025 s/sec
Spectral resolution	672,913 mHz
FFT average	first 10x, later on 32x
Windowing	Hanning
Anti alias filter	ON
Display range	-50 dB ... -10 dB
Spectrum Lab	Version V2.7 b4

Table 4. Actual setup parameter for SpectrumLab software during observation of SMART-1 beacon spectrum.

4. SNR estimation

I wanted to have a rough value of the expected SNR. Given the transmission power P_T of 5W on an isotropic helical antenna with a gain of $G > -3dBi$, $G_{typ} = 0dBi$ at a distance between moon and earth of about $r = 384'000km$,

Fig. 3. Commercial communication receiver AR5000 set to beacon frequency 2235.100000MHz plus audio offset of 12KHz.

Abbreviation	description
AR5000	Commercial receiver 10KHz ... 2.6GHz
Argos	FFT-spectrometer 2Gs/sec
Bleien	Observatory of ETH Zurich
CFHT	Canada-France-Hawaii Telescope
CW	Continuous Wave
dB	Deci Bel
ESA	European Space Agency
ETH	Eidgenössisch Technische Hochschule
FFT	Fast Fourier Transformation
FITS	Flexible Image Transport System
FPU	Focal plane unit
GPS	Global positioning system
L-band	1GHz ... 2GHz
LHCP	Left hand circular polarization
MITEQ	Commercial manufacturer
NOAA	National Oceanic and Atmospheric Administration (USA)
RHCP	Right hand circular polarization
S-band	2GHz ... 4GHz
septum	staircase-like metal sheet
SMART-1	Small Missions for Advanced Research and Technology
SNR	Signal to noise ratio
SpectrumLab	Software FFT-analyzer on PC
WAV	Audio file format of SpectrumLab
X-band	8GHz ... 12GHz

Table 5. Acronyms mentioned in labels and comments.

we can calculate the power flux density P_{FD} at Bleien observatory to

$$P_{FD} = \frac{P_T\ (G...G_{typ})}{4\pi r^2} = (1.3...2.7)\ 10^{-16}\ W/m^2 \tag{4}$$

And from that one may evaluate receiving antenna power P_{SMART} of space craft SMART-1 at the antenna terminals to

$$P_{SMART} = P_{FD}\ A_{eff}\ p\ \eta = 6.4\ 10^{-16}...1.3\ 10^{-15}\ W \tag{5}$$

where $p = 0.5$ denotes to polarization loss due to linear reception of a circularly polarized wave. To get the internal system power P_{sys} we need to know the signal bandwidth

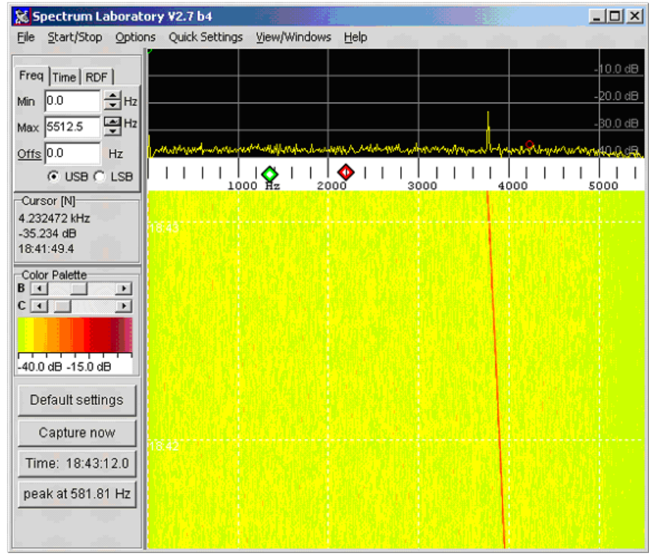

Fig. 4. Screen shot of continuous observation of SMART-1 beacon spectrum at 2235.112000MHz using SpectrumLab at 18:43:12UT. The actual SNR is about 15dB.

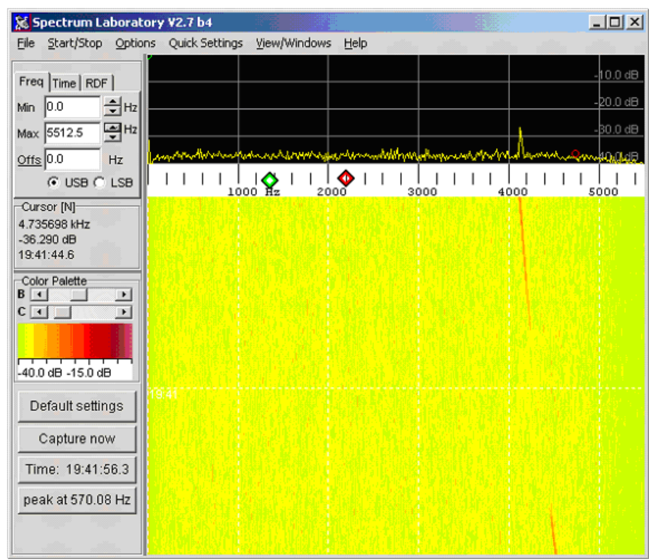

Fig. 5. Screen shot of intermittent observation of SMART-1 beacon spectrum at 2235.077000MHz using SpectrumLab at 19:41:56UT. Telescope was moved about 5 degrees away from the moon center for approximately 1 minute to prove that the source of the received signal really was originating near the actual position of the moon.

$\Delta\nu$ which was measured using SpectrumLab to 12Hz ... 15Hz according to figures 4 and 5.

$$P_{sys} = k\ T_{sys}\ \Delta\nu = (5.3...6.7)\ 10^{-19}\ W \tag{6}$$

Now we are in a position to evaluate the expected SNR for SMART-1 beacon frequency from equations 5 and 6.

$$SNR = \frac{P_{SMART}}{P_{sys}} = 30dB...34dB \tag{7}$$

This level was occasionally measured but the average value was much lower, in the order of $20 \pm 10dB$. Sometimes the

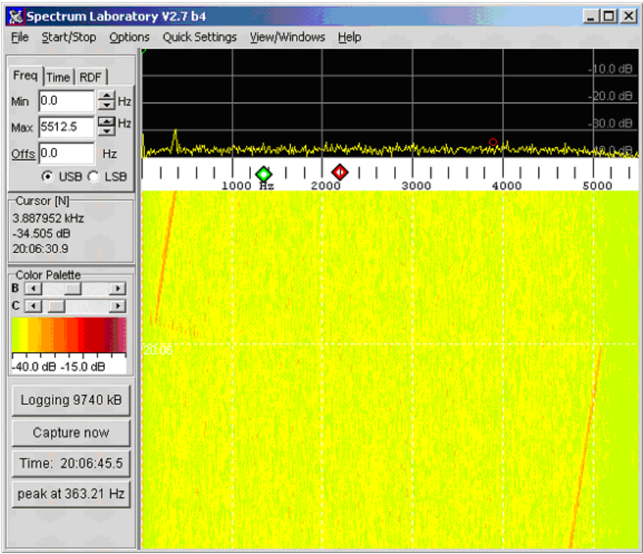

Fig. 6. Screen shot of SMART-1 beacon spectrum using SpectrumLab. Due to high doppler shift the receiver frequency had to be adjusted from 2235.082000MHz up to 2235.087000MHz. Observation time of this plot was 20:06:45UT.

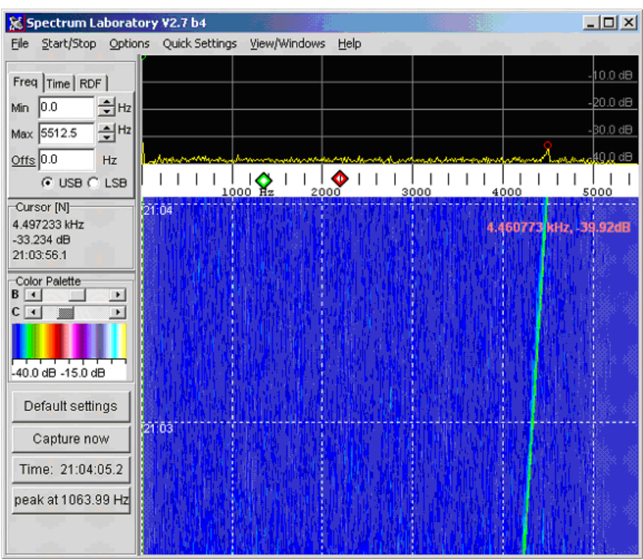

Fig. 7. Screen shot of SMART-1 beacon spectrum at 2235.097000MHz using SpectrumLab at 21:04:05UT. Since the SNR went quite low to the end of the observation, the number of integrations of the FFT algorithm had to be increased from 10 to 32 samples.

signal even disappeared completely. I assume the reason is in the low elevation of the telescope with high level of electromagnetic interference. Or, it might be destructive addition (interference) of a direct received signal and a signal which was reflected at the moon surface (?).

5. Results

The received signals could be heard despite of high system temperature and polarization loss due to linear reception of circular waves. I got similar results expressed in SNR

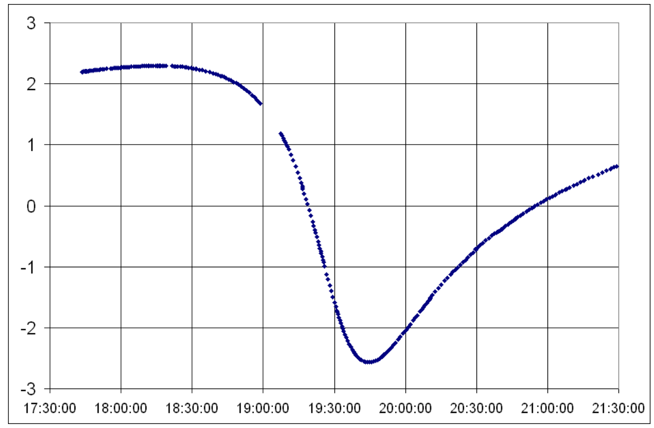

Fig. 8. Plot of the calculated (from spectra) radial velocity of SMART-1 radio spectrum on its last orbit around the moon. X-axis in universal time synchronized by GPS, Y-axis in kilometers per second.

with our 7m dish were I could select both polarizations LHCP or RHCP separately. The 7m dish has a somewhat higher system temperature due to internal calibration hardware components in the FPU. Unfortunately, it was not possible to observe SMART-1 beacon with our new spectrometer ARGOS because the reception bandwidth (12.2KHz ... 60KHz) is too large compared to the signal bandwidth of just a few hertz. Using the analysis function of SpectrumLab under best conditions I got a measured signal to noise ratio of $SNR_{measured} \approx 30dB$ which perfectly fits with the theoretical estimation $SNR_{eval} = 32.0 \pm 2dB$. All wav files were converted into fits files offline to be analyzed easier using a standard Java viewer dedicated to fits files. The doppler shifted beacon signal was then transferred into a simple EXCEL sheet and plotted as radial velocity versus time, see figure 8. Since the transfer was done manually, there is some 'noise' in the pixels of the velocity plot. The radial velocity was calculated by

$$v = \frac{\nu - \nu_0}{\nu_0}\, c \qquad (8)$$

where $c = 3 * 10^8 m/sec$ denotes to the speed of light in vacuum. ν is the measured frequency using sound card and SpectrumLab, while $\nu_0 = 2235.100000MHz$ denotes to the given telemetry transmission frequency of SMART-1 space probe. The calculated velocity was a bit higher than the officially reported value of $2km/sec$ in daily press.

6. Conclusions

With our present hardware configuration it is quite easy to observe spacecrafts as long as all observation parameters are known. Gain, system temperature and pointing accuracy (although not perfect) are sufficient to observe satellites in L- and S-band. The present setup is ideal for further observations for students exercises because a success can almost be guaranteed. Thus, observations of Mars-Express at 8.419926GHz, Mars Global Surveyor at

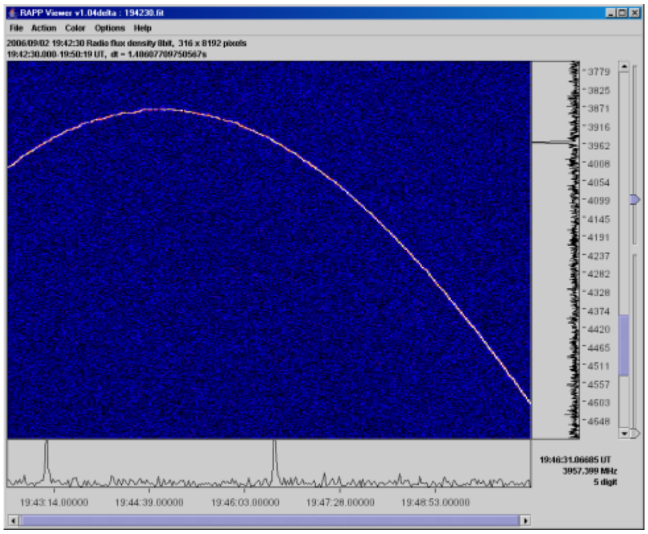

Fig. 9. Screen shot of a wav file which was converted into a fits file and afterwards viewed with a Java fits-viewer. Remarkable the 'beautiful' noise floor beside the beacon plot. Luckily, no electromagnetic interference can be reported in that frequency range. X-axis in UT from left to right and Y-axis in reverse frequency order expressed in hertz.

8.422744GHz, NASA's Spitzer at 8.4136188GHz and other planetary probes in X-band shall be part of another test together with people of University Zurich using a dual polarization septum feed horn on our 5m telescope.

7. Relevant internet adresses

7.1. ESA

`http://sci.esa.int/science-e/www/area/index.cfm?fareaid=1`

7.2. CFHT

`http://www.cfht.hawaii.edu/News/Smart1/`

7.3. ETH 7m Bleien

`http://www.astro.phys.ethz.ch/rapp/status/status_nf.html`

7.4. ETH 5m Bleien

`http://www.astro.phys.ethz.ch/rag/status/status5m.html`

7.5. ETH 5m Zurich

`http://www.astro.phys.ethz.ch/rapp/praktikum/praktika_nf.html`

Acknowledgements. I thank Pascale Ehrenfreund of Leiden University/ESOC and Dr. H. Paul Shuch (Executive Director Emeritus, SETI-league) for additional information about SMART-1 transmitter data and transmission schedule. I also Thank L. Gurvits for additional comments during the observations at Bleien observatory.

References

John. D. Kraus, *Radio Astronomy*, Quasar Books Company, New York, 1965.