S-band ground station prototype for low-earth orbit nanosatellite missions

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Rezumat. *Acest articol prezintă un prototip de stație terestră în banda S, destinată experimentelor de comunicații cu rată mare de transfer de date cu nanosateliți aflați pe orbită terestră joasă. In măsura în care funcționarea ei va fi demonstrată în timpul misiunii GOLIAT sau a altora similare, acest sistem de comunicații va permite recepția unei cantități mari de date, făcând fezabilă transmisia de imagini de pe nanosateliți. O altă caracteristică importantă a acestei stații este costul său redus comparativ cu stațiile comeciale existente pentru comunicații în banda S cu sateliți aflați pe orbită terestră joasă, făcând-o astfel accesibilă echipelor care dezvoltă un proiect spațial cu buget mic.*

Cuvinte cheie: *nanosatelit, orbită terestră joasă, banda S, stație la sol, misiunea Goliat.*

Abstract. *This paper presents an S-band earth station prototype for high data-rate communication experiments with low earth-orbit nanosatellites. As far as it will be demonstrated during the GOLIAT mission or other similar ones, this communication system will allow the downlink of large quantities of data, making nanosat imaging feasible. Another important feature of this station is its low cost compared to existing commercially available S-band LEO ground stations, in order to make it accessible to teams developing a small budget space project.*

Keywords: *nanosatellite, low-earth orbit, S-band, ground station, Goliat mission.*

1. Introduction

Recent efforts to provide low cost access to space for education, science and space-based component testing has led to the development of nanosatellites (the term "nanosatellite" is usually applied to the name of an artificial satellite with a mass between 1 and 10 kg).

Tiny satellites lack the power supply and the necessary room for a large conventional radio transponders on board. It is why various miniaturized or innovative communication systems have been proposed over years. However, few of these have been demonstrated in practice.

With very few exceptions, space-ground communications are actually made in VHF/UHF bands where the hardware requirements (such as antenna pointing accuracy) are not as critical as for higher frequencies. In VHF/UHF bands, a reliable and cheap ground station can be integrated using commercial off-the-shelf amateur radio hardware and software. Compared to typical existing amateur radio VHF/ UHF systems on nanosatellites, S-band communication offers data throughput improvements by taking advantage of broader available bandwidth and higher frequency.

The purpose of this project was to build a low cost S-band earth station prototype which is able to provide reliable communications between a Low-Earth Orbit nanosatellite and the ground.

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2. Space communication system architecture

The simplified space communication system architecture, presented in Fig. 2.1, is splited into two physically separated units: the nanosatellite transceiver and the ground station. The nanosatellite and the ground station can communicate via a circular polarized (LHCP/RHCP) link operating in some S-band portion allocated to Earth-space communications or to amateur radio service. The ground station has a modular architecture in order to meet different communication requirements which are application dependent. The station main sub-systems are:

- the elevation-azimuth motorized antenna;
- a radio unit (satellite or application dependent);
- the satellite tracking module;
- a GPS module for time synchronization;
- the TLE data update module.

3. Ground station prototype implementation

Most of the components which are integrated in sub-systems are commercial off-the-shelf radio hardware and software. The components were selected to meet the requirements imposed by the uplink and downlink budgets for the first Romanian nanosatellite.

3.1. Elevation & Azimuth motorized antenna sub-system

The ground antenna consists of a radio amateur highly directional 3M (F/D= 0.4 ratio) parabolic mesh dish antenna. The operating range of the antenna is from 1 to 6 GHz and has 65% efficiency. The gain at 2400 MHz is more than 35 dBd and the -3dB beam width is approximately 2.9°. The mesh minimizes problems with wind loading on the mounting hardware caused by periodic local windstorms. For dish specifications – see Table 3.1.

Table 3.1

The 3 meter mesh dish specifications (Efficiency 65%)

Frequency	Gain [dBd]	-3dB angle (degrees)
1296 MHz	30.3	5.7
2320 MHz	35.4	3.2
3456 MHz	38.8	2.1
5760 MHz	43.3	1.3
Weight	40 kg	

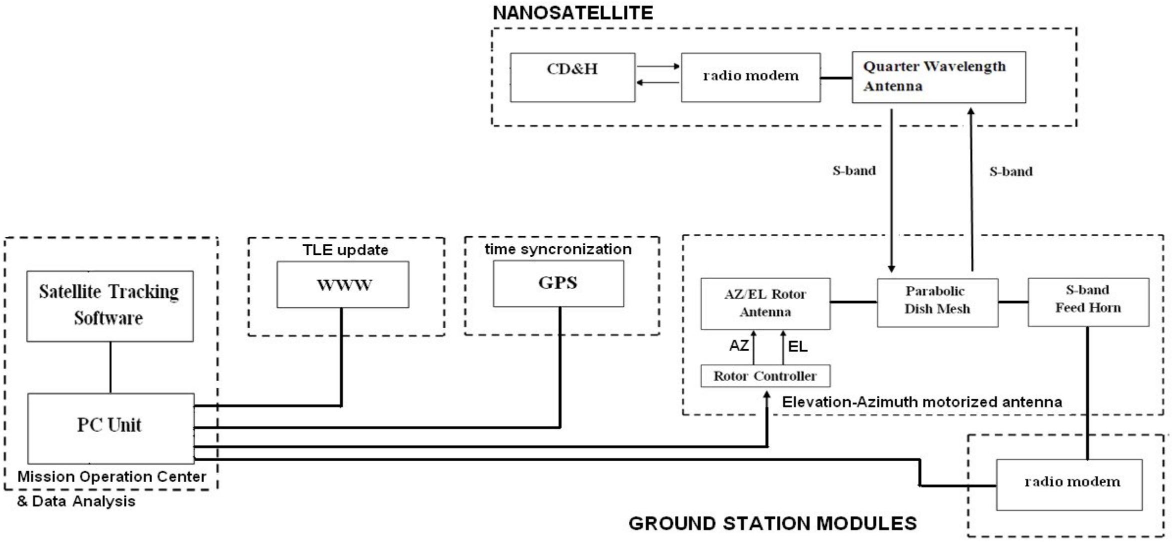

Fig. 2.1. Basic Architecture of the S-Band Space Communication System.

For antenna pointing, an AlphaSpid BIG RAS AZ/EL rotator [1] was selected due to its high performance (0.5° accuracy and high torque at low voltage) – see Table 3.2 The remote control of the AlphaSpid rotor is done by the digital interface Rot2Prog [2] through 8 wires (4 wires for each azimuth and elevation). This interface is equipped with a serial RS-232 interface and allows steering the antenna beam toward the satellite, using orbital TLE data.

Table 3.2

Rotator technical data

Azimuth angle of turn	360° ; +/- 180°
Elevation angle of turn	180° ; +/-20°
Azimuth rotation speed	120 sec. (12V), 60 sec. (24V)
Elevation rotation speed	80 sec. (12V), 40 sec. (24V)
Motor voltage	24 DC/1.5A (12 DC/2.5A)
Weight	22 kg

A feed horn for the 2400 MHz communication channel was mounted on the antenna tripod at the focal point. It was especially designed to work in the frequency domain of 2100-2700 MHz and it is suitable for parabolic antennas with F/D radio 0.4-0.5. The feed horn is excited by two probes at 90 degrees from each other through a 3dB hybrid coupler to provide the appropriate right hand circular polarization (RHCP). The feed horn provides an 6dB gain, more than enough to cover a -3dB linear to circular polarization mismatch. An optional low-noise amplifier mounted behind the feed can further increases the antenna gain and correct for line losses.

A short notice on choosing a circular polarization (CP) for the feed horn: the nanosatellite antenna is usually a quarter-wave monopole which is linear polarized (LP). Using a linear polarized ground antenna feedhorn, in an ideal case where the two antennas' polarizations are perfectly aligned (co-polarized), then there will be no polarization loss between them. However, a nanosatellite has attitude control limitations and it is spinning with an unknown frequency. As the angle between the two antennas increases to 60 degrees, the loss increases to 3dB, the same loss as between CP and LP antennas. As the angle approaches cross-polarization at 90 degrees, polarization loss can exceed 20dB, which would prevent a successful communication link. Another problem which can arise from this LP – LP configuration is that of Faraday rotation as the signal passes through the atmosphere. Near 2400 MHz, we can expect typical polarization rotation of approximately 20 degrees, which is added to the antennas' polarization angles mismatch.

3.2. The radio modem

The chosen radio modem for this station prototype is MHX-2400 since it was already tested for space missions [3], [4], [5]. MHX-2400 is a frequency hopping spread spectrum radio modem that works in ISM band (2400-24835 MHz), and was developed by Microhard Systems [6]. The unit can transmit up to 1 Watt (30 dBm, or 0 dB) of RF power, and has a receive sensitivity of -108 dBm (-138 dB) with a bit error rate (BER) of 1 in 10^{-6}.

Other advantages of MHX-2400 are a relatively slow frequency hop time interval, a compact size, and an operational flexibility. The equipment includes built-in features like addressing, retransmission protocols, encryption and FEC. The module provides a theoretical maximum throughput of 83kbps and the over-the-air data rate is fixed at 172 kbps. The modulation used is Gaussian Frequency Shift Keying (GFSK). It has 20 pseudo-random user selectable frequency hopping patterns and it is a full radio-modem that performs packetization, modulation and demodulation.

The MHX-2400 module is designed to connect to external logic circuitry through unshifted (0-5V TTL)

RS-232, and to an antenna through a 50-Ohm MCX connector – see Fig 3.1. The electrical interface of MHX-2400 is simple and promotes rapid integration. It accepts regulated 5V from the electrical power subsystem and communicates with the Command Data and Handling (CD&H) processor through a serial port with selectable data rates of up to 115200 baud. Hardware flow control is used to manage data flow.

Fig. 3.1. The MHX-2400 modem and the modem board with RS 323 port.

In addition, this modem can be integrated in the ground station without any separate radio or transceiver equipment, because the modem transparently supports Doppler shift correction up to 60 KHz, automatic channel selection, and frequency detection. The MHX-2400 transmitted signal is approximately 200 kHz wide. The receiver bandwidth is about 400 kHz. While this can be considered an inefficient feature of the receiver, due to the unnecessary increase in noise entering the unit, it allows for Doppler signal shifts to fall within the receiver bandwidth – see Table 3.3.

The table below [7] shows how Doppler shift increases with frequency. The other issue with Doppler shift is how it varies during the satellite pass itself. This is highly dependent on the pass itself. Low elevation passes have a fairly linear variation of Doppler shift, spread out over the pass. On the other hand, a pass directly over local Zenith has most of the Doppler shift variation concentrated around the middle of the pass.

3.3. The satellite tracking module

The chosen satellite tracking program is Orbitron [8]. This application computes the position of satellites at any given moment (in real or simulated time) using as input Two Lines Elements (TLE) data and sends azimuth and elevation angle data to the antenna rotor digital interface. Satellite position predictions are based on the NORAD SGP4/SDP4 model and the theoretical accuracy is close to 100 ms or 1 meter at the Equator. Satellite TLE data are provided on-line by USSPACECOM (United States Space Command) for approved users. For low orbiting objects (400-1000 km), TLE data must be updated every few days. Because the ground station is located in a remote rural area, the only option for TLE data update was to use a VSAT terminal.

The accurate geographical position and time reference for the tracking module is provided by a Hopf 6039 GPS [9]. The Hopf 6039 GPS equipment is composed of a PCI board which is connected through a coaxial cable to an external Hopf FG449010 antenna mounted on the roof of the station, in order to have a visibility of 360°. Using NTP (Network Time Protocol) it is possible to achieve PC synchronization of other units' clocks.

Table 3.3

Maximum Doppler shift vs frequency for an LEO satellite at 800 km altitude

Band	Frequency [MHz]	Max Doppler	Band	Frequency [MHz]	Max Doppler
15 m	21.280	+/- 477 Hz	23 cm	1269.000	+/- 28.5 kHz
10 m	29.400	+/- 659 Hz	13 cm	2401.000	+/- 53.8 kHz
2 m	145.900	+/- 3.27 kHz	3 cm	10250.000	+/- 230 kHz
70 cm	435.070	+/- 9.76 kHz			

3.4. The link budget for the GOLIAT nanosatellite

GOLIAT is the first Romanian nanosatellite, scheduled for launch in 2010. The main purpose of this satellite is to detect micrometeorites and cosmic rays and to take photos of the Earth with a 3Mpx digital camera [10]. The satellite is equipped with a MHX-2400 Slave modem and an 2400 MHz quarter wavelength monopole antenna which will be used to transmit payload data to the ground station.

The space-earth link budget for Goliat was evaluated using the AMSAT / IARU Annotated Link Model System [11].

For the alleged Kepler elements – see Table 3.4 and Fig. 3.

The orbital parameters can suffer minor changes and the exact values are known after a successful launch of the nanosatellite.

Table 3.4

GOLIAT nanosatellite orbital parameters

Parameter	Value	Unit	Parameter	Value:	Unit:
Earth Radius	6.378,14	km	Period	102,989	minutes
Height of Apogee (ha)	1.450,0	km	dw/dt	-1,4917	deg./day
Height of Perigee (hp)	350,0	km	dW/dt	-2,0664	deg./day
Semi-Major Axis (a)	7.278,1	km	Mean Orbit Altitude	900,00	km
Eccentricity (e)	0,075569		Mean Orbit Radius	7.278,14	km
Inclination (I)	71,00	degrees	Sun Synchronous Inclination	98,93	degrees
Argument of Perigee (w)	180,0	degrees	Elevation Angle (δ)	**45,0**	degrees
R.A.A.N. (W)	7,13482	degrees	Slant Range (**S**)	**1.202,33**	km.
Mean Anomaly (M)	0,00	degrees			

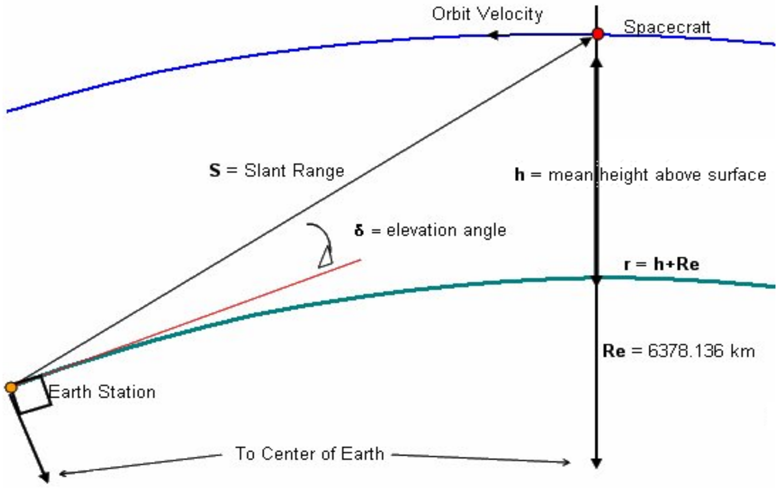

Fig. 3.2. Slant Range to Spacecraft vs. Elevation Angle according with the variables in Table 3.4.

Table 3.5

GOLIAT nanosatellite downlink budget

Downlink Data Budget					
Spacecraft	**GOLIAT** (Elliptical; 71 deg. inclination; 357 x 1447 km Altitude)				
Parameter	**Units**	**Value**			
Elevation angle	degree	**15**	**25**	**45**	**65**
Spacecraft Transmitter Power Output	watts	1.0	1.0	1.0	1.0
	dBW	0.0	0.0	0.0	0.0
	dBm	30.0	30.0	30.0	30.0
Spacecraft Total Transmission Line Losses	dB	1.0	1.0	1.0	1.0
Spacecraft Antenna Gain	dBi	2.2	2.2	2.2	2.2
Spacecraft EIRP	dBW	**1.2**	**1.2**	**1.2**	**1.2**
Downlink Path					
Propagation and Polarization Loss	dB	3.0	3.0	3.0	3.0
Propagation Path Length	km	2224.2	1726.8	1202.3	980.0
Path Loss	dB	167.0	164.8	161.7	159.9
Isotropic Signal Level at Ground Station	dBW	**-168.9**	**-166.7**	**-163.5**	**-161.7**
Ground Station (EbNo Method)					
Ground Station Antenna Pointing Loss	dB	0.5	0.5	0.5	0.5
Ground Station Antenna Gain	dBi	35.4	35.4	35.4	35.4
Ground Station Total Line Losses	dB	0.5	0.5	0.5	0.5
G.S Effective Noise Temperature	K	585	585	585	585
Ground Station Figure of Merrit (G/T)	dB/K	7.2	7.2	7.2	7.2
G.S. Signal-to-Noise Density (S/No)	dBHz	66.5	68.7	71.8	73.6
System Desired Data Rate	bps	**9600**	**9600**	**9600**	**9600**
	dBHz	39.8	39.8	39.8	39.8
Data System Eb/No for the Downlink	dB	26.7	28.9	32.0	33.8
Demodulation Method Seleted		**GFSK**	**GFSK**	**GFSK**	**GFSK**
System Allowed or Specified BER Rate		1.0E-05	1.0E-05	1.0E-05	1.0E-05
Demodulator Implementation Loss	dB	1	1	1	1
Telemetry System Required Eb/No	dB	13.5	13.5	13.5	13.5
Eb/No Threshold	dB	14.5	14.5	14.5	14.5
System Link Margin	dB	**12.2**	**14.4**	**17.5**	**19.3**

Our simulations has shown that a reliable communication between Goliat and our ground station prototype is feasible even in worst condition scenario. The link budget may suffer further improvements.

3.5. Ground station installation and first tests

Interference is an important problem, since the amateur radio service uses the relatively unregulated ISM band. The widespread of devices which take advantage of the ISM service has resulted in a high level of noise through Cluj-Napoca region. Even though, the ground antenna has a very tight 2.9º main beam width, it will still receive these signals through its side and back lobes. Signals received in those lobes, will be more powerful than the heavily attenuated signals from a nanosatellite more than 1000 km away, and therefore be sufficient to interfere with effective modem operation.

Fig. 3.3. Ground station antenna.

Fig. 3.4. Ground station command and control equipment.

In order to improve its overall performances, the ground station has been installed in a test bed at 1200 m altitude, in a quiet electromagnetic rural area, which is 55 km far from Cluj-Napoca, in the Apuseni Mountains. The exact coordinates of the antenna ground station are 46°40’34” N latitude and 23°07’45”E longitude. The ground station is located in a small valley. It is why West and South-West facing elevations from the ground antenna are blocked below approximately 15º by foothills.

Until today, two types of tests have been completed with good results. The first one was to estimate the antenna automatic pointing error, using several known geostationary C band transponders.

The second one was to track and receive data from the 2400 MHz AO-51 nanosatellite FM transponder [12] in order to measure the signal strength (for this experiment the MHX-2400 modem has been replaced with an UEK-3000 down-converter [13] and an Icom IC-910H radio [14]).

The main results are that the antenna pointing error is within $\pm 0.5^0$ and that a LEO 2W FM transponder can be received from more than 2000 km distance.

Direct earth to space communication tests using the MHX-2400 modem could not be performed until today, since actually there is no operational satellite on orbit equipped with this modem. It is why several long range terrestrial communication tests have been planned for the next few months.

4. Conclusions

As far as it will be demonstrated in a real space mission, this low-cost S-band ground station will provide higher speed communications with nanosatellites than those obtained using UHF communications. Consequently, a larger range of science objectives can be achieved using a nanosatellite platform.

Another important feature of this ground station is that can support any nano/micro LEO satellite mission with minor upgrades (such as the antenna feed horn and preamplifier or the radio unit which has to match that one of the satellite).

This S-band ground station prototype is an important step towards a new class of low-cost high frequency ground stations planned at BITNET CCSS in support of future Romanian nanosatellite missions in low-earth orbit.

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