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SWARM TO EARTH COMMUNICATION IN OLFAR

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Abstract - New science drivers have recently emerged in radio astronomy for observation of low-frequency radio waves, below 30 MHz. Exploring this frequency requires a space-based radio telescope with a very large aperture that is impossible to realize in a monolithic fashion. A distributed system consisting of a swarm of 50 or more nano-satellites is used to realize such an instrument. Equipped with low-frequency antennas, the very small spacecraft provide the needed aperture to capture and sample ultra-long electromagnetic waves. The distributed low-frequency telescope has to fulfill multiple tasks in which drawbacks such as the size and the limited power available are overcome by the large number of satellites. Sending the processed data to a base station is one of these aforementioned tasks that is critical for the functionality of the system. In our paper we analyze the challenges of downlinking data from a swarm of nano-satellites to Earth and propose a diversity scheme that helps the system to achieve its mission.

I. INTRODUCTION

In the past decades radio astronomy attracted a lot of interest from the science community as it had the potential to extend our understanding of the Universe. By analyzing the cosmic background radiation, radio astronomers were able to provide additional information over the already known celestial objects, and also reveal phenomena and bodies invisible to the optical telescopes. Radio astronomy experienced a rapid growth, and many radio telescopes, both Earth- and space-based, were developed. Observatories such as Herschel Space Observatory and Planck were launched into space to take snapshots of the cosmos in far infrared and submillimeter wavebands, and, respectively, at infrared and microwave frequencies. On Earth very large dish telescopes (e.g. The Arecibo Observatory) and arrays (LOFAR [1], Square Kilometre Array [2]) were built or are currently under construction in order to observe the lower frequency bands (down to 30 MHz).

One of the last unexplored frequency bands is 0–30 MHz, and observing cosmic radiation in this band is very interesting. It will provide better understanding of the already known phenomena, and reveal details about the birth of the Universe, about the so-called astronomical dark ages. However, it is very difficult to explore this frequency band with either Earth- or space-based instruments. Ionospheric scintillation and opaqueness (for frequencies below 15 MHz), added to the man-made radio interference [3], make it impossible to distinguish the ultra-long EM waves of cosmic origin at ground level. Radio telescopes such as the Ukrainian T-shaped Radio telescope, second modification (UTR-2) [4] were built to operate at frequencies as low as 8 MHz. Yet their performances strongly depend on the meteorological conditions and atmospheric composition. Furthermore, building a similar aperture in space would be very costly, and even impossible if we would consider a single spacecraft mission.

The evolution and miniaturization of technology led to the emergence of a new space hardware segment focused on very small and simple spacecraft (nano-satellites), and after multiple successful launches and missions (Delfi-C3 [5]) a new range of applications became feasible. In [6] it has been shown that that technology reached a maturity level that allows us to build a low-frequency radio telescope in space.

The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) project aims to develop the large aperture required for very low frequency (below 30 MHz) observations by employing a swarm of 50 or more nano-satellites that will sample the cosmic noise, process the samples in a distributed manner, and send the results to a base station on Earth for further analysis. The project exhibits many challenges in terms of system engineering, mechanical and RF design, as well as data processing. In previous work several aspects of the OLFAR swarm of satellites were analyzed. The radio telescope functionality and reliability of the distributed approach were discussed in [7] and [8], respectively. Solutions for synchronization and localization were proposed in [9], while data distribution within the swarm of satellites was analyzed in [10] and [11]. Furthermore, antenna systems for radio observation and inter-satellite links (ISLs) were proposed in [12] and [13], respectively.

In this paper we continue the work on the communication layer of the project, and the design of the swarm-to-Earth

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communication link is presented. In the following section the requirements for OLFAR's downlink are stated and the corresponding challenges are analyzed. The rest of the paper is organized as follows. In Section III an analysis of the link parameters is conducted and the link budget for a single satellite communication is realized. In Section IV the effect of the swarm (of the antenna diversity) on the communication link is described. Concluding remarks are made in Section V.

II. DOWNLINK REQUIREMENTS

As stated in the previous section, realizing an aperture sensitive to ultra-long EM waves in space is only possible in a distributed manner. 50 or more nano-satellites, each containing radio observation antennas (ten meter long dipoles), are spread in a satellite cloud with a diameter of 100 km and sample the cosmic noise. Precise time stamping and localization of the antennas enable interferometric imaging algorithms to transform the samples into images of the sky in the low-frequency domain. In order to make high-resolution images and to fulfill the radio telescope functionality, each satellite will collect a large amount of data (in excess of 6 Mbit/s/satellite). The information will be processed at the swarm level by means of distributed correlators, and the end result will have to be downlinked to a base station on Earth. The required data rate for the swarm-to-Earth communication will be 900 kbps [14].

Such data rates are not unusual for satellite downlinks. However, the peculiar implementation details of the OLFAR swarm make it difficult to comply with the requirement.

One of the major obstacles to overcome is the link distance. In Section I it was mentioned that man-made radio interference (RFI) makes it difficult to identify the cosmic noise. As a result, the OLFAR system should be placed in orbit so that it is protected from the sources of RFI. One solution would be a dynamic solar orbit, Earth-trailing or -leading. Being far away from the Earth will drastically decrease the level of RFI, but will also increase the path loss. The more attractive solution in this case is a lunar orbit. Being sensibly closer to Earth than the dynamic orbit, placing the swarm in a lunar orbit has its advantages in terms of launching costs and communications. The Radio Astronomy Explorer B [15] revealed that the Moon acts as a shield against RFI, and, therefore, the radio-silent region behind the Moon is an appropriate position for a radio telescope. International regulations forbid any wireless transmissions in the radio-silent zone, meaning that only an observation task can be conducted by the swarm while shielded by the moon. In Figure 1 we propose a lunar orbit for OLFAR and divide the functioning into three (possibly four) major tasks. Each of the tasks depends on the orbit position.

1. Observation task: in the radio-silent region, satellites will only sample the cosmic background radiation.
2. Data distribution and processing: once sampled, the data is shared among all the members of the swarm, and processed by means of distributed correlation.
3. Downlink: while facing Earth, satellites will send the processed data to a base station on Earth.
4. The fourth stage is optional. If it is necessary this stage can be used to finalize the distribution and processing task or it can be an idling stage when the only task is the solar power conversion.

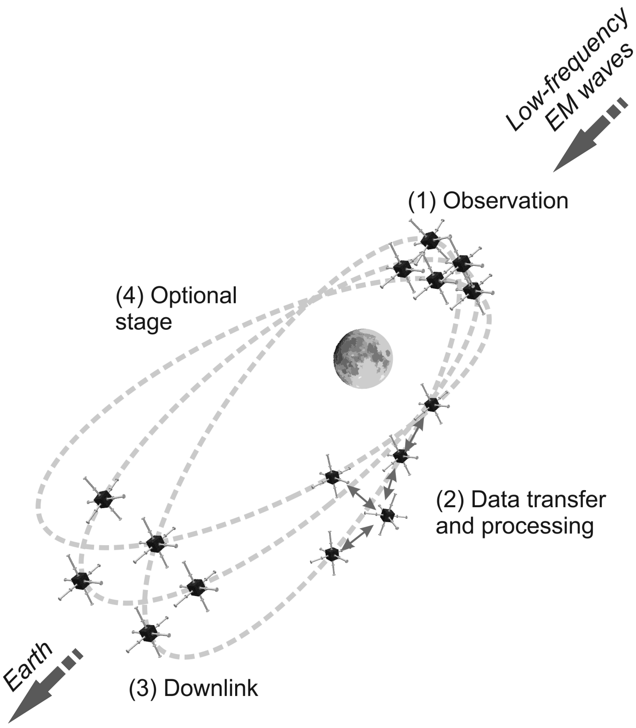

Figure 1: OLFAR swarm on a lunar orbit.

A lunar orbit offers protection from the man-made RFI while placing the swarm relatively close to Earth. Even so, in a worst-case scenario (lunar apogee), the distance to Earth will be around 405,000 km.

Another important aspect to consider is the limited available power in a nano-satellite. OLFAR plans to use a three-unit cubesat platform for the nano-satellites, similar to Delfi-C^3 [5]. Cubesats have a small available area for solar panels and limited space for batteries. Deployable solar panels will be able to provide around 30 watts of power [16], that will have to be shared by all the subsystems (processing unit, propulsion, attitude control, and communication block). By making the same considerations as in [17], it is expected that only several watts of power will be available for the data downlink.

The outer surface of a cubesat will not only serve for the solar cells, but will also have to accommodate downlink antennas, ISL antennas and sun sensors [11]. The high data rate ISL will require that an antenna is placed on each facet of the cubesat, thus limiting the area for the downlink antennas even more. For cubesat scenarios the patches are a potential solution for the radiation elements. They provide a reasonable gain (up to 9 dBi), while being lightweight, conformal and efficient. Moreover, they have wide receiving/transmitting angles, and do not require any deployment mechanism. In literature inflatable parabolic reflector antennas have also been proposed for cubesats platforms in order to achieve better directivity [18]. The increased complexity and reduced viability of such a system make it unattractive for a satellite swarm.

When designing the downlink antenna system, the stability of the cubesat will play an important role. The maximum antenna gain will be achieved when the transmitting antenna (cubesat) and the receiving antenna (base station on Earth) are aligned and facing each other. A change in the orientation of the satellite will have an impact on the total gain of the system, and on the communication link. Let us consider a scenario with a cubesat that uses only one planar antenna for the downlink, placed on one of the facets. The antenna is assumed to have a $\cos^2$ radiation pattern, resulting in a 90° half power beamwidth. The cross section of the radiation pattern is shown in Figure 2. The cubesat has no internal stabilization, and rotates freely around the three axes (roll, yaw and pitch), as shown in Figure 3.

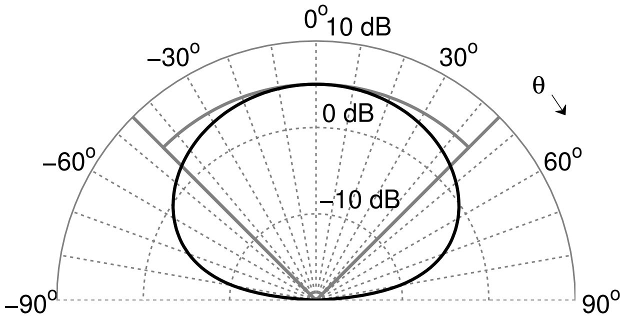

Figure 2: Downlink antenna 2D pattern. Antenna gain as a function of the polar angle θ.

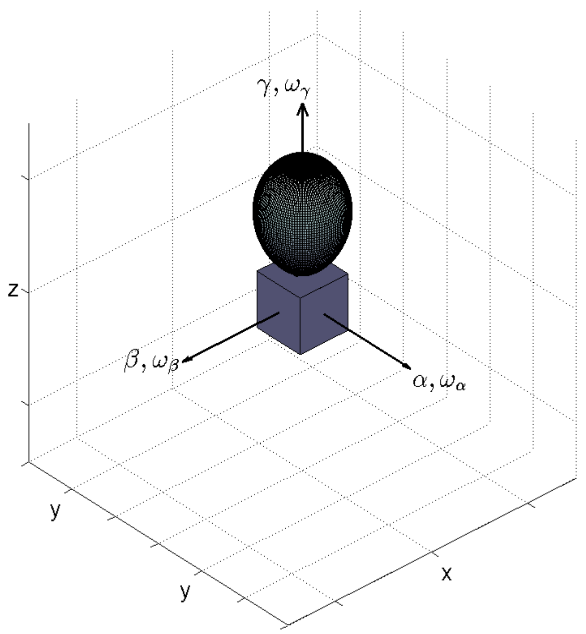

Figure 3: Cubesat with patch antenna on the top facet and 3D radiation pattern attached. Rotation axes. α corresponds to roll, β to pitch, and γ to yaw.

In Figure 4 the variation in time of the transmission gain is illustrated. The results were attained after simulating the following scenario. A cubesat with a single patch antenna placed on the top facet was considered. The satellite has no internal stabilization and rotates freely along the three rotation axes (as shown in Figure 3). An initial rotation of the cubesat framework of ($\alpha = 0.312$ rad, $\beta = 2.379$ rad, $\gamma = 3.436$ rad) and angular speeds of ($\omega_\alpha = 0.0057$ rad/timestep, $\omega_\beta = 0.0063$ rad/timestep, $\omega_\gamma = -0.0127$ rad/timestep). The values for the rotation angles and angular speeds were randomly generated. They do not match the real case. However, this does not have any impact as the purpose of the simulation was to point out that the transmission gain depends strongly on the orientation of the spacecraft. The stability of the satellite is very important for the quality of the communication link. In a single satellite scenario it is important to stabilize the spacecraft so that it will exhibit a high transmission gain through its whole lifecycle. In the case of a swarm of cubesats the gain variations can be compensated by the large number of transmitting antennas.

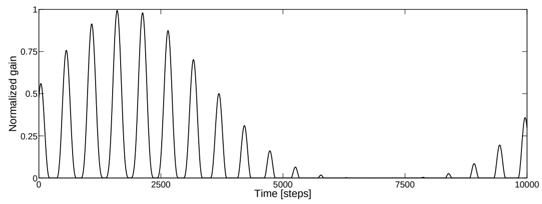

Figure 4: Normalized linear transmission gain as a function of time.

Having stated the requirements and challenges we proceed to analyzing the link budget of a single satellite scenario.

III. LINK BUDGET

Establishing communication links between the satellites in the swarm and the base station is important for the entire downlink process. Thus, by assessing the quality of these links, a downlink strategy can be applied to the swarm in order to maintain reliable communication. The quality of each link (in terms of signal-to-noise ratio, SNR) is calculated as shown in Figure 5.

In Table 1 the parameters of a typical cubesat-to-base station link are summarized.

Parameter	Symbol	Value [Unit]
Carrier frequency	f_c	2.35 GHz
Transmission power	P_{TX}	4 W
Transmitter/receiver losses	L_{TX}, L_{RX}	2 dB
Path loss	PL	211.8 dB
Link margin	LM	5 dB
Noise temperature	T_{sys}	140 K
Data rate	D_{req}	900 kbit/s
Bandwidth	BW	500 kHz
Receiving antenna gain	G_{RX}	70 dBi
Transmitting antenna gain	G_{TX}	5 dBi
Signal-to-noise ratio	SNR	0.1 dB

Table 1: Link budget analysis for the worst-case scenario of swarm-to-Earth communication.

The following assumptions have been made:

1. The carrier frequency f_c has been chosen to be 2.35 GHz. The 13 cm band is a license-free band that can

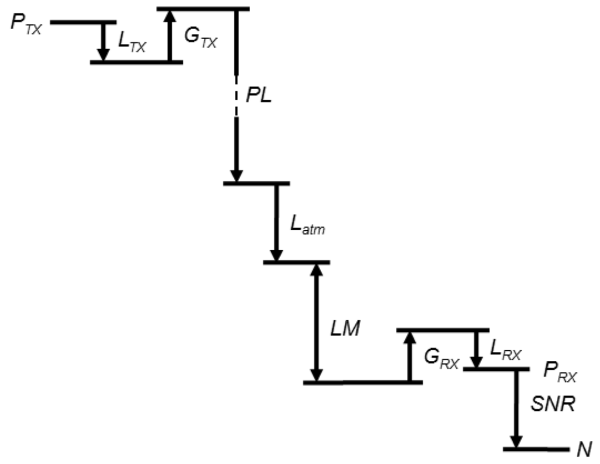

Figure 5: Link budget analysis.

be used for satellite communications [19]. The dimensions of the radiating patch element for this frequency band match the requirements imposed by the cubesat standard [20]. Furthermore, $\lambda/4$-spaced arrays of such elements can be placed on the cubesats facets or deployable solar panels to improve the link quality.

2. The transmission power P_{TX} is set to 4 watts. The same amount of power that is used for ISLs in [17] is used for the downlink communication. In this manner, by switching from one communication task to the other, the load remains constant.
3. The atmospheric losses are neglected due to the fact that the atmosphere has little influence on EM waves with frequencies higher than 1 GHz.
4. PL is the free-space path loss calculated for the worst case scenario (maximum distance between the swarm and base station—lunar apogee).
5. The link margin LM covers for other unaccounted losses (polarization, impedance mismatches).
6. The bandwidth BW has to fit the required data rate D_{req} while using an appropriate modulation technique (for example FQPSK [21]), and guard intervals.
7. G_{TX} is the gain of the antenna of the satellite. 5 dBi is a typical achievable gain for a planar (patch) antenna.
8. G_{RX} represents the gain of the antenna of the base station. Since both available gain and power at the satellite level are very limited, it is mandatory to compensate for these values with a high receiving gain. A very large dish antenna or a radio telescope such as LOFAR [1] can be used to achieve this.

The link budget calculation results in a very low value for the SNR. This leads to the conclusion that a reliable link between a nano-satellite orbiting the moon and a base station on Earth is difficult to establish. A strong channel coding might relax the requirements for the SNR, while increasing the required data rate. However, even so, an SNR of 0 dB will not be sufficient. Therefore, a cooperative communication strategy that uses multiple satellites can be employed to improve the quality of the swarm-to-Earth communication.

IV. ANTENNA DIVERSITY OF THE SWARM

As previously stated, the OLFAR swarm consists of 50 or more nano-satellites. Thus, it consists of 50 or more downlink antennas grouped together in a 100 km diameter cloud. This can be exploited to improve the quality of the link to the base station by employing an adequate communication strategy. Two scenarios can be thought of: antenna array strategy or spatial diversity strategy.

In the first scenario all the satellites transmit the same signal towards the receiving antenna. By means of phase shifters the different propagation delays are corrected and the signals add up in phase at the reception point. This results in an increased received power. This was concluded after performing the following simulation: 50 cubesats were randomly spread in a sphere of 50 km radius using a uniform distribution. The sphere was placed at a distance equal to the lunar apogee from the receiving point. Each satellite has only one patch antenna placed on one of its facets. Every satellite starts in a randomly oriented position relative to the base station. This orientation is given by the azimuthal and the polar angles that are uniformly distributed between 0 and 2π, and, respectively, $-\pi/2$ and $\pi/2$. Each satellite exhibits rotations over all three axis (pitch, yaw and roll), and all the rotations speeds are uniformly distributed in the interval $[-0.01\pi/\mathrm{timestep}; 0.01\pi/\mathrm{timestep}]$. The improvement of the link quality is displayed in Figure 6.

In the second scenario every satellite sends its data using a separate transmission channel. At the reception the spatial diversity of the transmitting antennas is exploited. The very low bandwidth requirement makes it possible to use frequency-separated independent channels. Therefore, we use a maximum-ratio combining diversity (MRC) scheme which is optimum for the independent channels with additive white Gaussian noise (AWGN). In Figure 7 it can be seen that the MRC scheme provide around 10 dB of gain over a selection scheme (selection of the best link). The results were attained after simulating the previously described scenario.

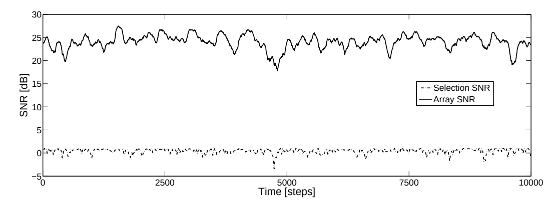

Figure 6: Simulated SNR: SNR of the selection scheme and SNR of the array strategy as a function of time.

V. CONCLUSION

The link budget analysis conducted in Section III proved that it is difficult to establish a reliable link between a nano-satellite (cubesat) that orbits the Moon and a base station placed on the ground. Nonetheless, the further from Earth these miniaturized spacecraft will have to go, the lower the probability of a successful communication, and, hence, of

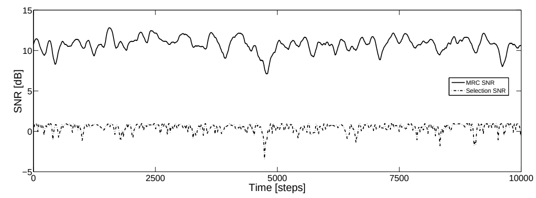

Figure 7: Simulated SNR: SNR for a selection diversity scheme and a MRC diversity scheme as a function of time.

a successful mission will be. Such remote missions will have to exploit the advantage of the large number of nanosatellites to fulfill all the tasks (sensing but also communicating).

In case of the OLFAR swarm sending the processed data to Earth will have to be the result of a collective effort. An MRC diversity scheme will improve the global SNR and make it possible to establish a reliable link between the swarm and the base station. It has the advantage that it requires no extra hardware (phase shifters) at the swarm level, but will shift the complexity to the receivers at ground level.

Further work needs to be done on improving some of the link's parameters. An antenna system that uses the large area of the backside of the solar panels and their steering properties has to be designed, and wave polarization has to be taken into consideration in all calculations.

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