Orbiting Low Frequency Array for Radio Astronomy

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Abstract—Recently new and interesting science drivers have emerged for very low frequency radio astronomy from 0.3 MHz to 30 MHz. However Earth bound radio observations at these wavelengths are severely hampered by ionospheric distortions, man made interference, solar flares and even complete reflection below 10 MHz. OLFAR is Orbiting Low Frequency ARray, a project whose aim is to develop a detailed system concept for space based very low frequency large aperture radio interferometric array observing at these very long wavelengths. The OLFAR cluster could either orbit the moon, whilst sampling during the Earth-radio eclipse phase, or orbit the Earth-moon L2 point, sampling almost continuously or Earth-trailing and leading orbit. The aim of this paper is to present the technical requirements for OLFAR and first order estimates of data rates for space based radio astronomy based on the proposed scalable distributed correlator model. The OLFAR cluster will comprise of autonomous flight units, each of which is individually capable of inter satellite communication and down-link. The down-link data rate is heavily dependent on distance of the cluster from Earth and thus the deployment location of OLFAR, which are discussed.

1. INTRODUCTION

The spectacular success of radio astronomy relies largely on the Earth's broad transparent ionosphere window spanning from 30 MHz to 30 GHz. Recently new and interesting science drivers have emerged in the lower end of this spectrum of 0.3-30 MHZ. This band is well suited for studying the early cosmos at high hydrogen red shifts, the so-called dark ages, extragalactic surveys, (extra) solar planetary bursts and high energy particle physics [1] [2]. However ground based astronomical observations at these long wavelengths are severely limited by Earth's ionospheric distortions below 50 MHz and complete reflection of radio waves below 10 MHz [3]. Advanced calibration techniques [4] which are currently employed in LOw Frequency Array (LOFAR) [5] telescope array, can be used to remove these distortions, provided the time scales of disturbances is much longer than the time needed for calibration process. However during turbulent conditions, especially during the solar maximum period, scintillation may occur and the celestial signals will suffer from de-correlation among the elements of a telescope array. In addition to ionospheric distortion, man made strong transmitter signals below 30 MHz also impede observations.

Because of the above mentioned reasons, the very low frequency range of 0.3 MHz- 30 MHz, remains one of the unexplored frequency ranges in astronomy. An unequivocal solution is to have a distributed array of radio telescopes in space, far from Earth's ionosphere and terrestrial interference. Until now, such a system in space was financially and technically constrained. However, more recent studies such as DARIS [6] and FIRST [7] have shown that with extrapolation of current signal processing and satellite technologies, a low frequency radio telescope in space could be feasible in the coming years. DARIS has already shown that a 9 satellite cluster , with a centralized system can be implemented in moon orbit with today's technology.

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Number of satellites (or antennas)	$\geq$ 10, scalable
Number of polarizations	2 or 3
Observation frequency range	0.3 - 30 MHz
Instantaneous bandwidth	$\geq$ 1MHz
Spectral resolution	1 kHz
Snapshot integration time	1 to 1000 s, dependent on deployment location
Maximum baseline between satellites	100 km
Deployment location	Earth orbit, moon orbit, moon far side, L2 point

Table 1. OLFAR system requirements

2. OLFAR MISSION

OLFAR project aims to develop a detailed system concept and to design and build scalable autonomous satellite flight units to be used as an astronomical instrument for low frequencies. Table 1 lists the preliminary system requirements of OLFAR. To achieve sufficient spatial resolution, the minimum distances between the satellites must be more than 10 km and due to inter stellar scattering this maximum baseline is limited to 100 km, giving a resolution of 1 arc minute at 10 MHz. The OLFAR 3-dimensional cluster will a comprise of more than 10 satellites, each containing a dipole (or tripole) antenna, observing the sky from 0.3-30MHz. Extrapolation to higher frequencies will increase data bandwidth and processing overload, which nevertheless will be met by Earth based telescopes such as LOFAR [5] and SKA [8]. On the other hand, the number of satellites could vary from 10 to larger than 10000 and still meet various science requirements [2]. The satellites will employ passive formation flying and yet maintain sufficient position stability for a given integration time. In the presence of a stable orbit and thus stable baseline, position estimates can be more precisely known and thus the integration time can be extended upto 1000 seconds and thereby reducing the down-link data rate as will be shown in section 3. For astronomical observations, mechanical dishes will be very expensive in terms of mass, power and operation. Instead OLFAR satellites will use a relatively simple antenna such a dipole, which is an efficient receptor at these long wavelengths.

3. DISTRIBUTED SIGNAL PROCESSING

In radio astronomy, sky maps are made by calculating the fourier transform of the measured coherence function [9]. The coherence function is the cross correlation product between two antenna signals $x_i(t)$ and $x_j(t)$ is given by $E(x_i(t)x_j^*(t-\tau_{ij}))$ where (*) denotes conjugation and τ_{ij} is the geometrical delay between observation of the same plane wave at the two spatial positions labeled i and j. $E(.)$ is the expectation operator applied over the cross-correlation matrix over a period of the integration time T_{int}. One way to implement such a system is using the traditional XF correlator [10] $i.e.,$ cross correlation first and fourier transform later and the more recent FX correlator which measures directly the cross-power spectrum between the two antenna signals. Although the XF architecture is beneficial because bandwidth can be traded for spectral resolution, FX architecture reduces processing requirement and offers scalability when the number of antennas is large [11] [12]. Since OLFAR proposes a scalable system, we choose to use the FX architecture.

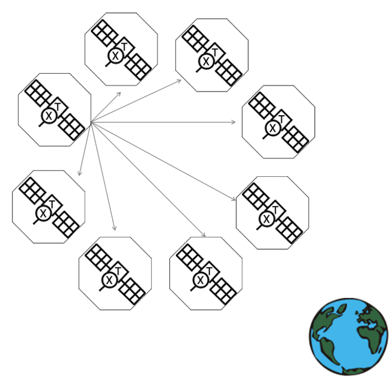

Figure 1. Distributed Correlator , Distributed downlink

Frequency distributed FX correlator

All terrestrial correlators for radio astronomy use a centralized architecture, wherein post-processed signals from antennae are sent to a central processing unit for making the cross correlation matrix. Centralized correlation depends heavily on the healthy operation of a single correlation station, which introduces a single point of failure for large array of satellites in space. To counteract this, we propose a frequency distributed hybrid FX correlator. In this case, each individual satellite is preassigned to correlate a specific sub-band Δf_{sb} of the observed instantaneous bandwidth Δf_i. Thus all satellites transmit their narrow bands of observed data to respective satellites. Such a distributed processing architecture also ensures scalability of the system. In addition we also propose that after the processing each station down-links the data independently to Earth based station. Hence every station does both correlation 'X' and downlink 'T' as denoted by 'XT' in the figure 1).

Node level signal processing

Since the total observational bandwidth of 30 MHz is low, Direct Digital Conversion (DDC) will be employed. Astronomical signals received by each antenna will be be signal conditioned and nyquist sampled at 60 MHz with a 16-bit Analog to Digital Converter as shown in figure 2. After successful RFI mitigation, only N_{bits}=1-2 bits will be used in further processing stages. A coarse Poly-phase Filter Bank (PFB) [13] is used to selectively choose the desired instantaneous bandwidth of Δf_i= 1MHz. The total data generated for N_{pol} signal paths for each satellite is given as

$$D_{obs} = 2\Delta f_i N_{pol} N_{bits} \quad \text{(bits/sec/station)} \quad (1)$$

Intra - satellite communication

A second fine PFB is used to further split Δf_i into N_{sb} sub bands, each of bandwidth $\Delta f_{sb} = \Delta f_i / N_{sb}$. For even distribution of data, we enforce the number of sub-bands equal to the number of stations $i.e.,\ N_{sb} = N_{sat}$. The intra-satellite communication layer then transmits $N_{sb} - 1$ sub-bands to corresponding satellites.

Each station receives $(N_{sb} - 1)N_{pol}$ signal paths each of bandwidth Δf_{sb} from all the other $N_{stat} - 1$ stations in the cluster, with a single sub-band of bandwidth Δf_{sb}. The total intra satellite reception rate for each station is then

$$D_{in} = 2\Delta f_{sb}(N_{sb} - 1)N_{pol}N_{bits} \quad \text{(bits/sec/station)} \quad (2)$$

Correlation and downlink to Earth

As mentioned earlier, every satellite is pre-assigned to cross-correlate a specific bandwidth of Δf_{sb} Hz. The data received by each satellite is delay corrected and further divided into 1 kHz spectral resolution using a third and final Poly-Phase Filter Bank (PFB), to meet the narrow band criterion [14]. The output of the PFB contains $N_{bins} = \Delta f_{sb}/1$ KHz separate channels. Cross correlation products are made for each of the N_{bins} channels for all antennae over an integration time of T_{int}. The data rate of the final correlated output is

$$D_{down} = \left(\frac{2N_{sat}^2 N_{pol}^2 N_{bins} N_{bits}}{T_{int}} \right) \quad \text{(bits/sec/station)} \quad (3)$$

Table 2 presents first order data rates for a cluster of 10 satellites. The observed data rate (D_{obs}) per satellite is 6 Mbit/sec under the modest assumption of 1 MHz instantaneous bandwidth and 1-bit processing, post RFI mitigation. It is worth noting that this data rate does not depend on the number of satellites in the cluster but scales linearly with the instantaneous bandwidth Δf_i and the number of bits N_{bits}. The intra satellite transmission/reception D_{in} is lower than the observed data rate D_{obs} since $N_{sb} = N_{sat}$ and only $N_{sb} - 1$ bands are transmitted. Although this has huge savings for $\leq$ 10 satellites, it makes little difference with the increase in the number of satellites. The down-link data rate increases quadratically with the number of satellites in the cluster. It can however be reduced by increased integration times under stable orbital conditions.

4. OLFAR CLUSTER

The OLFAR space segment will consist of a swarm of nano-satellites which will form a sparse distributed array with baselines up to 100 km. Satellite swarms are scalable clouds of functionally identical agents, cooperating to achieve a common goal [15]. A swarm is mostly self-managed which relieves the ground-station operators from having to control all elements individually and allows them to instruct the swarm as a whole to assume a certain configuration or perform a given function both in space and time. Moreover, due to the large number of nodes, nano-satellites limit the launch costs and allow for insertion of large numbers per single launch. Within the OLFAR cluster we can distinguish two communication elements, the intra-satellite wireless data transport, the inter-satellite data transport.

Intra-Satellite transport

The intra-satellite links transport the signals from the various sensors (e.g. antennas, position, time) to the back-end of the satellite. Most of this communication will be wired, however, part of it might be done by wireless communication. An example of such an autonomous wireless sensor system is the sun sensor used in the Delfi-C3 cubesat mission [16]. The communication link between the OLFAR array and Earth is realized using diversity techniques. As the satellites ultimately will be at large distances to the Earth and may have large inter-satellite distances, the communication schemes should also allow

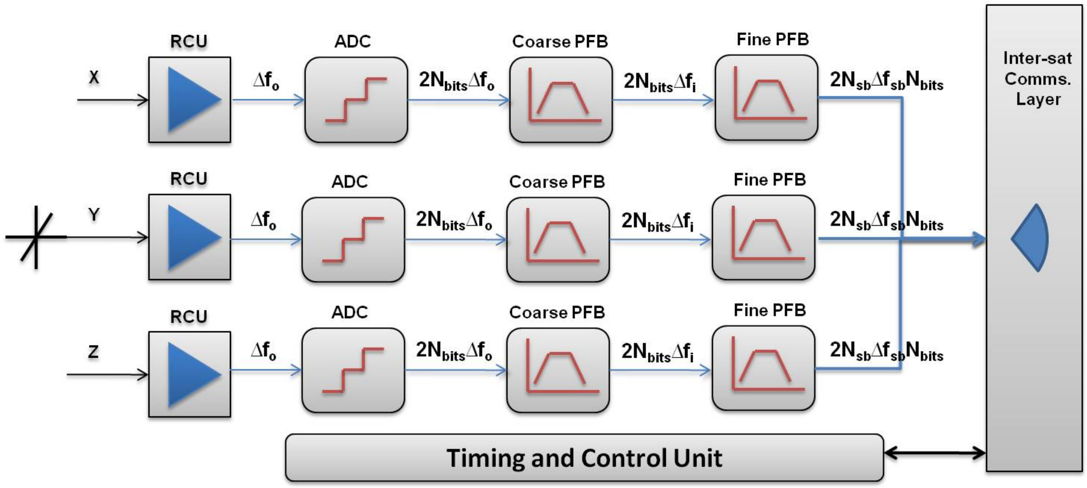

Figure 2. Node level signal processing

Derived inputs from OLFAR specifications		
Number of satellites (or antennas)	N_{sat}	10, scalable
Number of polarizations	N_{pol}	3
Number of bits	N_{bits}	1
Observation frequency range	Δf_o	0.3 - 30 MHz
Instantaneous bandwidth	Δf_i	1 MHz
Number of sub-bands	$N_{sb} = N_{sat}$	10
Sub-band bandwidth	$\Delta f_{sb} = \Delta f_i / N_{sat}$	100 kHz
Spectral resolution	Δf_{res}	1 kHz
Number of bins	ΔN_{bins}	100
Snapshot integration time	T_{int}	1 second
Data rates		
Observed data rate	D_{obs}	6 Mbit/second/satellite
Inter-satellite reception	D_{in}	5.4 Mbit/second/satellite
Earth down link data rate	D_{down}	180 kbit/second/satellite

Table 2. First order data rates estimated for a cluster of 10 satellites based on frequency distributed FX correlator

for communication diversity (clustered transmit and receive schemes).

Inter-Satellite link (ISL)

The most challenging data transport is the inter-satellite communication. The satellites need to transmit their captured astronomical data, position, time and other meta information to all the satellites in the array , needed for distributed correlation. The data processing is done on all the raw data obtained from all the satellites. The resulting, correlated and integrated, data stream will have a much lower data rate than the raw data.

The ISL is a two way communication link. The captured astronomical data of each of the satellites must be transported to the other nodes for correlation, as been discussed in section 3. The correlated data must be gathered and prepared for the data downlink to Earth. Besides these two data streams, a third data stream for housekeeping, control, timing and synchronization is implemented. The total data stream for each satellite in OLFAR determines of various design parameters listed in Table 2

The ISL channel is in principle is constrained by just free space loss. Multi-paths or even Doppler effects can be neglected. Interference from other satellites in the configuration and also other spectrum users in space can be of impact of the channel. However, for now, we assume just the free space loss of the channel. Both the transmitter and receiving gains are dimensionless quantities. This leads to the Friis free space path loss P_L:

$$P_L(db) = 10log\left(\frac{\lambda}{4\pi r}\right)^2 \quad (4)$$

For example, if we assume an ISL average frequency of 2.4 GHz, the free space path loss with 100 kilometer node-to-node distance is 140 dB. Even though the wavelength appears in the path loss equation, it does not follow that the received power would increase proportionally to the square of the wavelength, because the wavelength also affects the gain of the receiving antenna.

For link budget calculation several approaches can be made. One can define a required Eb/N0 and calculate the necessary transmit power to achieve this. One of the parameters in the link budget is the gain of the antennas. Because the satellites can be in any position with respect to each other, the overall antenna pattern for each satellite must be almost isotropic. The implementation can be done more efficiently, as we know the direction of the ISL.

On each of the six faces of the satellite a patch antenna is mounted for the ISL. Knowing the direction for the ISL, one can select the optimal patch for the link. On the receive side, each patch antenna has a separate LNA. After the amplification of the signals, the signals are first detected and the on-board computer will combine the signals of each of the six signal paths. Several techniques can be used to assure that the data can be selected by the individual receivers. The possible dimensions for multiple access are time, frequency, code and space. One of most straightforward implementations is frequency division multiplexing (FDM). Each node will transmit its data using PSK-modulation in a narrow band-width channel. The channels are separated by large guard bands to prevent interference between the channels. For housekeeping and control, a separate band in the spectrum is allocated. If all channels is transmitted simultaneously, the overall data rate will be the sum of the data rates of all channels.

For the Inter-Satellite Link (ISL), an omni-directional antenna pattern is highly desirable with full-duplex communication. The minimal inter-node distance is about 10 km, whilst the longest node-to-node link equals approximately 100 km. This would allow for a data-relay when each node includes a router functionality, in the event the link budget proves insufficient for copying the data-set to all nodes. A peer-to-peer file-distribution strategy, in which elements start sharing the data blocks they have already received with other peers in the vicinity will probably be assumed, as it is the most optimal data-distribution method in this case [17].

For the ISL, a QPSK modulation scheme is chosen, together with a 3/4 LDPC Forward Error Correction scheme, since it is one of the more advanced methods available with today's technology [18]. The reason for choosing this scheme, rather than 1/2 LDPC is that for the inter-satellite link, more link margin is expected to be available, allowing for a higher spectral efficiency scheme to be used for E_b/N_0 value of a 2.7 dB [18]. The data rates are determined by calculating the available link margin, and the resulting bandwidth. The bit-error rate (BER) is taken to be 10^{-6}, as this scenario is the most common, and it allowed for a quick comparison between different modulation techniques.

When performing the link budget calculations for the inter-node links, many scenarios are envisaged, based on different frequencies. As the elements are nano-satellites, COTS transceivers will likely be used, as they are the most highly integrated and optimized solutions available, at the lowest cost. This limits the frequencies used however, mostly to the ISM band frequencies of 433, 915, 2400, 5800 MHz and 24.125 GHz.

Table 3 lists the different ISM bands and the available link capacity with an omni-directional link for both short-range, $i.e.,$ 20 km and long-range, $i.e.,$ 100 km are tabulated. As can be seen, much of the higher frequency interlinks are limited by the larger free space loss, but mostly by the available output power, as the links cannot achieve their allowed bandwidths of 20/40 MHz for the 2.4 GHz and 5.8 GHz bands for example. The situation at 24.125 GHz rules out this option due to limited availability of high-efficiency power amplifiers.

If the available inter satellite bandwidth is limited, either due to a large number of satellite nodes, and thus large data rates, or simply by regulations, then a more bandwidth efficient modulation is required. One of the promising techniques to achieve this is OFDM (Orthogonal Frequency Division Multiplexing) [19] [20] [21]. OFDM has been adopted as standard for DVB, DAB and WLAN. The main advantages of OFDM it that, it iss very well suited to frequency selective channels and it potentially offers a good spectral efficiency. With OFDM, the separation between each channel is equal to the bandwidth of each channel, which is the minimum distance

ISM Frequency	433 MHz	915 MHz	2.4 GHz	5.8 GHz	24.125 GHz
Output power	400 mW	4.5 W	4 W	3.5 W	2 W
Free space loss (20 km separation)	111.2 dB	117.7 dB	126 dB	133.7 dB	160
Free space loss (100 km separation)	125.2 dB	131.7 dB	140 dB	147.7 dB	160 dB
Available bandwidth (20 km)	1.46 Mbit/s	39 Mbit/s	126 Mbit/s	19 Mbit/s	630 Kbit/s
Available bandwidth (100 km)	1.55 Mbit/s	39 Mbit/s	5 Mbit/s	760 Kbit/s	30 Kbit/s
Limits	above permissable 1.3 kHz	Maximal allowed bandwidth	Output power limited	Output power limited	Output power limited

Table 3. The inter-satellite link budget analysis and theoretically achievable bandwidths for an omnidirectional link

by which the channels can be separated. The individual channels (in this case the signal of a single node) will be modulated using a form of Phased Shift Keying-PSK, Amplitude Shift Keying-ASK, or a combination QAM (Quadrature Amplitude Modulation).

5. Down-link to Earth

Deployment locations

The deployment location of OLFAR must avoid RFI from Earth, maximize down-link data rate and ensure orbital stability to keep the cluster within a sphere of 100Km. To avoid interference either the cluster must be located far from Earth or must be shielded by the far side of the moon. The Radio Astronomy Explorer RAE 2 satellite [22] showed that interference at very low frequencies is significantly reduced behind the moon, making it ideal for radio astronomy observations. However, during the eclipse behind the moon the swarm has no communication with Earth [23]. Alternatively, Earth leading/ trailing is an optimal solution for all time communication, however the cluster will be affected by RFI and data rates are lower. Earth-moon L2 point has a stability to ensure that the cluster remains intact, however transmission and reception rates are too low. The configuration of the swarm changes with an altered location however, as well as the constraints set on the communication links. In this section we focus on the first order constraints set on communication links for various deployment locations.

Down-link

The satellites are assumed to feature phased array antenna panels, which for the analysis are assumed to be pointed towards Earth. The envisaged panel configurations are either a double 3 x 1, 90 x 90 mm panel, rendering a total surface area of 486 cm^2, or a double 3 x 3 panel configuration, rendering a total surface area of up to 1458 cm^2. These panels sizes were used as a reference, as they are relatively easily deployable from a triple cubesat-sized spacecraft, and as this mission is an astronomical mission, the ground station quality is assumed to be significant, allowing for a decent (equivalent) antenna surface area.

Common link parameters for long-range communication analysis are listed in Table 4. In order to calculate the beam angle, resulting from the use of a phased array antenna, the relation $\theta = 0.886\lambda/L_{x/y}$ [24], in which $L_{x/y}$ represents the length of the antenna in either x- or y-direction. This is the ideal focussing angle of a phased array, and no pointing errors were included in the analysis, in order to give all scenarios a fair assessment. Please note that in reality, the pointing accuracy of the satellites will at least have to be sufficient to allow pointing of the arrays at the beam angle or less towards Earth, and that at the distances involved, the Earth disc angle can be very small, resulting in quite stringent pointing requirements. The Effective Isotropic radiated power (EIRP) of the panels was determined using $EIRP = N^2 P_{MOD}(D_{cell})(1 - |\Gamma|^2)$ [24]. In this case, the reflectivity (Γ) is assumed to be 50%, the directivity D_{cell} is assumed to be 1, and the total output power (P_{MOD}) was divided by the number of elements. Finally, the number of elements N was simply estimated by counting the number of 1 λ-sized square elements available in the surface area of the antenna.

Lunar orbit

A swarm in lunar orbit allows for large link budgets, as will be discussed in more detail in this section. When the swarm orbits the moon, it enters a "cone-of-silence" once every orbit, in which no radio-contact with Earth is possible since the moon blocks Earth from view. This cone extends beyond the second libration point at 61347 km [23], hence quite adequate time can be spent in it for

Transmitter output power(unless noted otherwise)	3.5 W
Ground station receiver temperature	150 K
Ground station equivalent antenna diameter	10 m
BER	10^{-6}
Eb/N0	1.70 dB
Modulation scheme	QPSK + $\frac{1}{2}$ Low Density Parity-check (LDPC) Codes
Antenna beam angle, 6 panels (5.8 GHz)	9.72°× 29.15°
Antenna beam angle, 6 panels (24.125 GHz)	2.33°× 7.01°
Antenna beam angle, 18 panels (5.8 GHz)	9.72°× 9.72°(5.8GHz)
Antenna beam angle, 18 panels (24.125 GHz)	2.33°× 2.33°(24.125GHz)
Effective Isotropic Radiated Power (EIRP), 6 panels (5.8GHz)	47.25W
Effective Isotropic Radiated Power (EIRP), 6 panels (24.125 GHz)	826.87W
Effective Isotropic Radiated Power (EIRP), 18 panels (5.8 GHz)	144.37 W
Effective Isotropic Radiated Power (EIRP), 18 panels (24.125 GHz)	2478 W

Table 4. Common link parameters and theoretical values for long-range communication analysis

scientific observations. The time spent varies with the orbital height, as displayed in table 5, and it shows that the time increases with orbital altitude. This has quite a few advantages, as lunar orbits at higher altitudes are generally more stable, whilst the time to transmit and process the data extends as well, at the expense of the system's duty cycle. Fortunately, the swarm can be instructed to split up into a long observation-time section, and a high duty cycle section, although this will require much more elements in orbit.

Due to the significant distance between Earth and the moon (≈400,000 Km), the link budget will be restricted, especially given the small size and modest power budgets which are expected for the swarm elements. Note that it is not allowed for the satellites to communicate whilst at the backside of the moon, in order to maintain a radio-silent zone, which will require the satellites to perform a significant part of the pre-processing in the phase between exiting the science phase, and exiting the radio-silent zone.

Earth-moon L2—Another scenario consists of the satellites staying in the Earth-moon L2 point. This point is quite stable, and located 61347 km away from the moon. This point is still in the radio-silent zone, and it allows for continuous observations, provided the processing and transmitting can be done in real-time. A significant disadvantage exists in that the OLFAR swarm itself becomes the sole transmitter in this region, which is dedicated as a radio-quiet zone. Interference with the scientific observations of the OLFAR swarm itself won't occur, but future potential missions could be placed at a disadvantage.

The link budget suffers from this configuration, as the satellites will have to transmit their data through relay-elements in lunar orbit. Assuming the relay elements consist of elements in transit to the swarm, they will consist of identical satellites, with identical phased array transceivers. Therefore, the Moon-Earth bandwidths remain the same, but the inter-swarm bandwidth becomes limited, as is shown in Table. 6

Earth-leading/trailing— For OLFAR, Earth leading or Earth trailing orbits are positioned anywhere between 2 to 4 million kilometers from Earth. They allow for continuous observations, but the distance severely limits the available down-link bandwidth, even for an 18 panel configuration, as is shown in Table 6. As the Earth disc is limited to 0.36° from a distance of 2 million kilometer, pointing accuracy is much desired, even thought he beam angle of an 18-panel phased array is only 2.33° and at 4 million kilometers, the angle is even smaller, at 0.18°. Hence, bandwidth-wise, these orbital locations are quite poor, yet the control delta-V requirements could still prove beneficial.

In the case of the OLFAR swarm, the used ISM frequencies can be optimized per orbital, as was shown in the previous sections. In all cases, the inter-satellite link would benefit from omni-directionality, in which case, longer wavelengths are more useful, as the efficiency of those components is much higher. Moreover, the free-space loss is still significant, causing the lower frequencies to suffer less from the distance. As a higher band-

Altitude (km)	Orbital period(h)	Eclipse time(%)
500	2.64	24.6
1000	3.58	20.1
2000	5.70	14.6
3000	8.13	11.4
4000	10.84	9.4
5000	13.79	7.9
6000	16.97	6.9
7000	20.37	6
8000	23.96	5.4
9000	27.74	4.8
10000	31.71	4.4

Table 5. Altitude Vs Orbital period for a lunar orbiting satellite

	5.8 GHz	24.125 GHz
Lunar Orbit		
Distance to Earth	$\approx 384,000$ km	$\approx 384,000$ km
Free space loss	219 dB	231 dB
Available capacity for 6 panels	$\approx$ few tens of kbit/s	$\approx$ few hundreds of kbit/s
Available capacity for 18 panels	$\approx$ few hundreds of kbit/s	$\approx$ few Mbit/s
Earth-moon L2		
Distance to Earth	$\approx 378,000$km	$\approx 378,000$km
Free space loss	219 dB	231 dB
Available capacity for 6 panels	$\approx$ few kbit/s	$\approx$ few tens of kbit/s
Available capacity for 18 panels	$\approx$ few tens of kbit/s	$\approx$ few hundreds of bit/s
Earth leading/trailing		
Distance to Earth	$\approx 2 \times 10^6$ km- 4×10^6km	$\approx 2 \times 10^6$km- 4×10^6 km
Free space loss	233 dB-239 dB	246 dB- 252 dB
Available capacity for 6 panels	$\approx$ few kbit/s	$\approx$ few tens of kbit/s
Available capacity for 18 panels	$\approx$ few tens of kbit/s	$\approx$ few hundreds of kbit/s

Table 6. Table lists theoretical down-link estimates and power requirements at 5.8GHz and 24.125GHz ISM bands for Lunar Orbit, Earth-moon L2 and Earth leading/trailing.

width eventually allows for a reduced energy consumption, due to the higher transfer speed, the most optimal frequency band is the 915 MHz band, even if only a link speed of 5 Mbit/s per satellite is required.

When analyzing the down-link for the various orbital positional scenarios, the Earth-leading and Earth trailing options is singled out, as its a tough challenge to maintain a data rate above the required 900 Kbit/s. In which case, a 24 GHz link will be required, as it provides much more link capacity, at the expense of a much higher complexity. For the Earth-moon link a 5.8 GHz link is sufficient, greatly simplifying the system's complexity and at 24 GHz, a smaller antenna size is acceptable. The Earth-moon L2 case is a special one, as separate "relay" elements are required to transfer data from the back-side of the moon towards Earth. This inter-satellite link forms a significant bottleneck for this scenario, even though scientifically, it is at least as interesting as the Earth leading or trailing case, since it allows for uninterrupted observations.

6. Conclusion

The OLFAR specifications along with preliminary requirements on data rates for a cluster of 10 satellites have been presented. The estimated signal processing data rates are based on a frequency distributed hybrid FX correlator. Such an architecture saves inter-satellite communication bandwidth and avoids single point of failure. For inter-satellite communications ISM band frequencies are used for analysis since they have several advantages for a nano-satellite due to the ready availability of highly efficient components. Theoretically achievable data rates are presented for both short range (20Km) and long range (100Km) inter-satellite communication. Multi-hop based communication would avoid long range communication and save precious power consumption. The down-link data rate is one of the key factors governing the choice of deployment location for OLFAR cluster. For the down-link, a phased array approach is presented along with first order theoretical values are given to have a comparative study of potential deployment locations. Although the lunar orbit appears an optimistic choice, the cluster communication with Earth and within the cluster is disconnected during the eclipse. Alternatively Earth-moon L2 and Earth leading/trailing offer all time communication but with limited data rates. As is in case of OLFAR, for a cluster of many satellites, an in-depth system feasibility study is needed along with detailed orbital stability models to further investigate these deployment locations.

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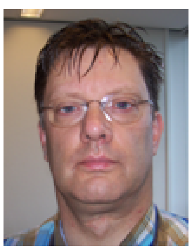

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