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High Data-Rate Inter-Satellite Link (ISL) For Space-Based Interferometry

Visweswaran Karunanithi [a,b] *, Raj Thilak Rajan[a], Prem Sundaramoorthy[a,d], Maneesh Kumar Verma[a], Chris Verhoeven[a], Mark Bentum[c,d], Earl W. McCune[a]

[a] *Department of Microelectronics, Delft University of Technology (TU Delft), Mekelweg 5, 2628 CD Delft, The Netherlands, V.Karunanithi-1@tudelft.nl ;R.T.Rajan@tudelft.nl ; M.K.Verma@student.tudelft.nl; P.P.Sundaramoorthy@tudelft.nl; C.J.M.Verhoeven@tudelft.nl; E.W.McCuneJR@tudelft.nl.*
[b] *Innovative Solutions in Space. BV, Motorenweg 23, 2623 CR Delft, Netherlands, vs.karunanithi@isispace.nl*
[c] *Netherlands centre for Radio Astronomy (ASTRON), Dwingeloo, The Netherlands, bentum@astron.nl*
[d] *Department of Electrical engineering, Technical university of Eindhoven, The Netherlands, m.j.bentum@tue.nl*
* Corresponding Author

Abstract

The inter-satellite link (ISL) in swarm and constellation missions is a key enabler in the autonomy of the mission. OLFAR (Orbiting Low Frequency Array for Radio astronomy) is one such mission where 10 to 50+ nanosatellites are placed in the Lunar orbit and perform astronomical observations from the far-side of the moon. Each of the nanosatellite in the swarm would carry a receiver that performs observations between 0.3 - 30 MHz, which are the least explored frequency bands in radio astronomy, thus attracting a large scientific interest.

Observations in this frequency bands from Earth are highly challenging as the ionosphere is opaque to these frequency bands. Furthermore, RFI (Radio Frequency Interferences) generated on Earth makes it highly challenging to perform astronomical observations below 30MHz band. The impediments faced by Earth-based or near-Earth-based radio astronomy for these frequency bands is the motivation to perform measurements from the far-side of the moon.

The purpose of using a swarm of nanosatellites to perform low frequency observations is to enable the realization of long observation baselines and additionally, the effective aperture of observation increases with the number of satellites. For the swarm of nanosatellites to operate as a single aperture, it is very important to cross-correlate the information collected by each satellite and this is where the ISL becomes very crucial. Apart from exchanging data collected by the payload, other information such as attitude and timing information needs to be exchanged.

This work derived mission level requirements which would be used to define a suitable communication architecture for space-based radio astronomy missions such as OLFAR. The approach chosen for communication system for such a swarm mission will comprise of two types of ISL: High data-rate directional link that will be used to exchange payload date and low data-rate omni-directional link that will be used to exchange attitude, timing information and be used for localization, positioning and ranging of the nanosatellites in the swarm. This work will present link budgets to show the feasibility of the proposed communication architecture and derive the specs to further design the transceivers.

Keywords: *Space-based radio astronomy, nano-satellite, inter-satellite link, high data-rate communication.*

Acronyms/Abbreviations

RFI	Radio Frequency Interference
OLFAR	Orbiting Low Frequency Array for Radio astronomy
LOFAR	Low Frequency Array
LF	Low Frequency
VLF	Very Low Frequency
ISL	Inter-Satellite Links
NCLE	Netherlands China Low Frequency Explorer
CME	Corona Mass Ejection
EML-1	Earth Moon Lagrangian - 1
RAE-2	Radio Astronomy Explorer-2
ITU	International Telecommunication Union

1. Introduction

Low frequency radio astronomy has gained interest in the past decades, and existing antenna array on the earth such as LOFAR show that there is very interesting science in the low frequency regime yet to be explored. Due to the opaqueness of earth's ionosphere at LF and VLF, it is not possible to perform radio astronomy from earth below 30 MHz [1] [2]. One other drawback of performing low frequency astronomical observations from the earth or earth orbits is the RFI generated on earth and this results in very low signal to noise in the receiver. Such drawback has resulted in investigating the possibility of performing observations from the far-side of the moon.

Early missions such as RAE-2 which was launched in 1971 into the lunar orbit showed enough evidence that Moon can act as a shield from the RFI generated from the Earth [3]. This has motivated multiple studies to look into the feasibility of deploying a swarm of nanosatellites to perform LF observations from the far-side of the moon. Some of the studies carried out in the past are listed in [3], namely: DARIS, FIRST, SURO, DSL, NOIRE, RELIC, NCLE and OLFAR. Among these studies NCLE was launched in early 2019 and at the time of writing this paper, results from this mission are still expected. NCLE payload comprised of 3 monopoles 5-meters each, which was deployed at EML-2 on the far side of the moon. Apart from NCLE, all the other studies baselined on a swarm of satellites meant to observe as a distributed antenna array in VLF and LF frequency bands. Among all the studies since OLFAR was baselined on using nanosatellite swarms, rest of this paper discusses communication architectures directed towards OLFAR, but can also be extended to similar space-based interferometry missions.

This paper reiterates some of the already proposed solutions for ISL and compares it with an alternate solution using a fractionated swarm concept and analyse the most suited communication architecture for OLFAR. A fractionated swarm concept makes use of dedicated swarms to perform astronomical observations around the moon and a dedicated swarm used to relay the scientific data back to the earth. Section 2 provides some of the science cases that OLFAR can address and derive system level requirements for one of the science cases that is relevant to the proposed communication architectures. Section 3 provides mission overview for the two discussed communication architectures. This section translates some of the science case requirements derived in Section 2 into subsystem level requirements that are relevant to the communication system. Section 4 elaborates on the two communication architectures, with communication subsystem level details and Section 5 validates the communication architectures using link budget tools.

2. Science cases for radio astronomy

The OLFAR satellite array should be capable of observations between 0.3 to 30 MHz, and at these frequencies the sky brightness temperatures can be as high as 10^7 K. This presents a significant challenge, since the astronomical signals are orders of magnitude lower than the sky noise. Some of the science cases that are interesting in this frequency band are; Cosmology, Planetary radio emissions, Galactic and stellar astrophysics, Space weather and detecting ultra-high energy particles [3]. One of the major technology bottlenecks in realizing such a missions using nanosatellites is high data rate inter-satellite communications; as large amounts of data is generated by each nanosatellite that need to be exchanged with the other nanosatellites in the swarm, which is possible only with high data rate inter-satellite communication.

The science cases of interest for OLFAR are listed in Table.1 [3].

Table 1. Possible science cases between 0.3 to 30 MHz.

Science case	Observation
Cosmology	Mapping and tomography of the H1 distribution.
Planetary radio emission	Radio emissions from magnetized planets.
Galactic and stellar astrophysics	Mapping and monitoring of Galactic and extra-galactic sky.
Space weather	Tracking initial launch of CME and tracking solar winds.

Apart from the science cases listed, one other popular science case is detection of dark-ages signals and to realize this science case, studies show that over 10^4 antennas are required to perform studies on emission from Extrasolar bodies [1]. Galactic and stellar astrophysics is another popular science case and from literature [3], it is possible to perform scientific measurements with fewer number of satellites (in the

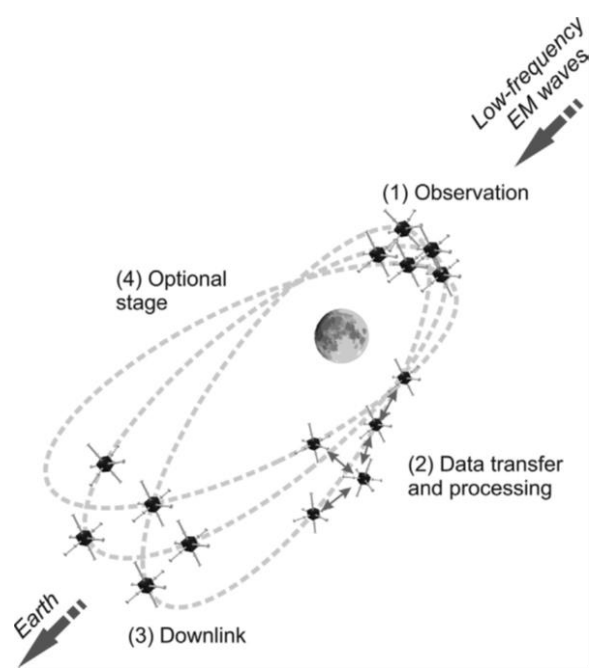

Figure 1. OLFAR Mission concept [5]

order of 10+ satellites). In order to perform extra galactic survey, the instrument shall be sensitive enough to measure signal strength in the order of 65 mJy with a spatial resolution of ~1`. In [4] an analysis is performed on the number of satellites needed to achieve the required sensitivity of 65 mJy and it can be seen that with varying the integration time, it is possible to optimize the number of satellites needed to achieve the desired requirement. The important requirements that would have an impact on the communication architecture is the integration time, number of satellites, observation bandwidth (corresponds to the total data generated by the payload) and the baseline between the satellites.

3. Mission Overview

The Figure 1 [5] shows the various functions performed by the swarm of nanosatellites in OLFAR mission. The observation phase is carried out on the far-side of the moon, this can range from 1000 to 2500 seconds based on the orbital altitude chosen for the swarm, after the observation phase the satellites move into data transfer and processing phase, the ISL plays a very important role in exchanging the observed data between the nanosatellites for the purpose of cross correlation. Since large amounts of data are generated during the observation phase, high data rate ISLs in the order of tens to hundreds of Mbps are needed to exchange the payload data between the nanosatellites in the swarm. As the swarm moves close to the near-earth side, the processed data is downlinked to the earth. During the data transfer and processing phase, since the raw data is processed before downlink, the data rate needed to downlink to the earth is reduced [4]. In the optional stage, the nanosatellites communicate meta-data such as attitude, timing and synchronization information which are key for cross correlation. This phase is also used for localization and positioning. Since the data exchanged during this phase is not much, low data rate ISLs are sufficient.

Based on the science case requirements discussed in the previous section, the mission overview is presented. The previous designs mainly looked into the possibility of placing the complete swarm in a circular orbit around the moon between 200 to 3000 km [6] and as shown in Figure 2, the satellites use the eclipse period to perform astronomical observations and as the satellites come out of the eclipse, they start to exchange the observation data, perform downlink to the Earth and perform relative localization and synchronization before the next observation.

The main drawback of the previously proposed architecture is that it requires every satellite in the swarm to have an ISL to exchange the data between the satellites, which then must be processed and transferred via a downlink to an earth ground station. The complexity of such an architecture does not scale favourably with data size and becomes cumbersome and challenging when the amount of data becomes large, so in this paper an alternate architecture is proposed where some of the satellites in the swarm would be deployed around the EML-1 (Earth-Moon Lagrangian) point and these satellites would be dedicatedly used to relay the payload data from the observation nanosatellites swarm orbiting the moon to the Earth. This architecture is considered to be a fractionated swarm since the functionality of the swarm is distributed in nature, but data-processing perspective, this architecture is considered centralized since the observation satellites transfer the data to a centralized swarm for processing and downlinking the data back to the earth.

One of the main advantages of this architecture is that the design of relay swarm can be optimized only for communication purpose, for example with high gain antennas and higher processing capability, whereas the observation swarm can be optimized better to accommodate the payload and perform observations. The payload antennas are known to occupy the most volume as each dipole antenna can be as long as 10 meters tip-to-tip and each satellite can host up to 3 such antennas, thus by following such a fractionated approach, larger communication antennas can be accommodated in the communication relay swarm and improve the quality of link between the Earth and EML-1 point. Use of relay satellites in EML-1/L2 points is not a new concept and has already been proven in the Chang E 4 mission with a single relay satellite at EML-2 point. Figure below shows the distances between Earth, Moon and the Lagrangian points [7]. A simple Halo orbit is considered for the relay swarms in EML-1, some of the possible orbits at EML-1/2 are discussed in [8], Halo orbit was chosen for the fractionated swarm architecture.

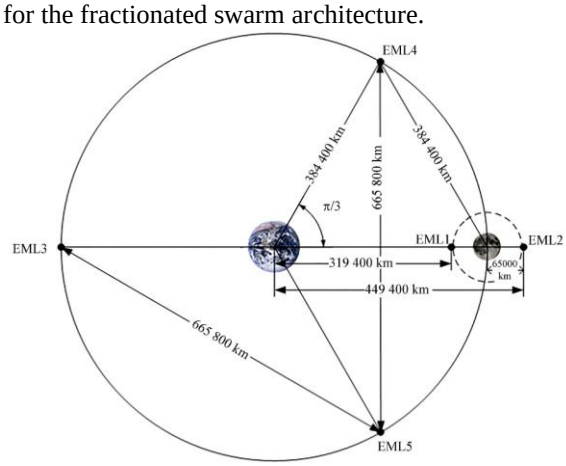

Figure 2. Earth-Moon Lagrangian geometry

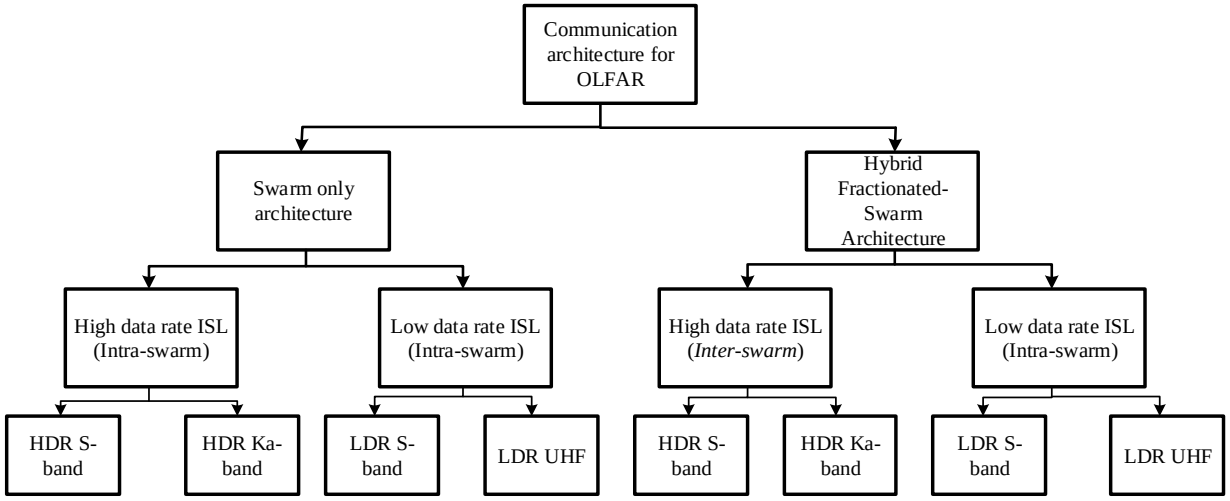

Figure 3. OLFAR Design options for communication systems

Since the fractionated swarm architecture was not considered in the past studies, this paper mainly focuses on comparing the fractionated swarm architecture against the swarm only architecture and derive a ballpark estimation of the subsystem level specifications such as antenna gain, transmitter power and achievable data rates for a given ISL distance. The data rate requirements based on the data processing architectures are discussed in [9]. In either case, the data generated by each satellite is ~6Mbps for a 1-bit correlator and this is a basic minimum.

4. Communication Architecture for Inter-satellite link

One of the main technology challenges in implementing a space-based interferometry using distributed swarm of nanosatellites is to establish Inter-satellite links between the observation satellites [3]. Generally, the payload data is large and a function of observation time (> 6 Mbps/satellite), whereas the other meta-data are in the order of kilobits/orbit/satellite. As the first step to designing the communication scheme for OLFAR, it is important to know the ITU frequency allocation and corresponding bandwidths that are available for inter-satellite links. Table 2 shows the allocations available for inter satellite links. In the UHF band, the allocation from 410 to 420 MHz is available for SR (Space Research) and suites well for low bandwidth communications well suited to exchange meta-data. The most popularly used frequency bands for ISL is in S-band and larger bandwidths are available compared to UHF. The 2025 – 2110 MHz allocation is shared between SR and EESS (Earth Exploration Satellite Services), using this band in moon orbits for SR will not conflict with EESS allocations. The other allocation in S-band is from 2200 to 2290 MHz, this band is sheared between Space-to-Earth services which is very popularly used and Space-to-Space services. Getting an allocation in this band can be a bit challenging and needs to be consulted with the regulatory body before selecting this band. Unfortunately, the next allocation for ISL services is in Ka band between 22.55 GHz to 33 GHz

Table 2. ITU allocations for Inter-Satellite Links [10]

Band	Frequency [MHz]	Bandwidth [MHz]	Region 1/2/3
UHF	410 – 420	10	**SR** [Space-to-Space]
S-band	2025 – 2110	85	**SR** [Space-to-Space], **EESS** [Space-to-Space]
	2200 – 2290	90	**SR** [space-to-Earth] [space-to-space]
Ka-band	22550 – 23150	600	**ISL**, **SR** [Space-to-Space]
	23150 – 23550	400	**ISL** [Space-to-Space]

24450 – 24650	200	**ISL** [Space-to-Space]
25250 – 27500	2250	**EESS**, **ISL** [Space-to-Space]
32300 – 33000	700	**ISL** [Space-to-Space]

(The specific bands are listed in Table 2). The advantage of using Ka-band for ISL is the availability of larger bandwidths but closing the links could be challenging for nanosatellites at this band. Further in this paper link budget calculations are performed using different frequency bands to show the requirements on the ISL communication system.

Based on the available frequency bands allocations and possible architectures, the design options are presented in Figure 3. For both the proposed architectures, two separate ISLs are required; High data rate (HDR-ISL) to exchange the payload data and a Low data-rate ISLs for meta-data, localization and synchronization.

Swarm only/Distributed processing architecture

The communication architectures for OLFAR have been presented and discussed in earlier literature [11] [5], these were mainly based on a distributed architecture; were all the nanosatellites in the swarm are identical, with the same hardware and functionality. The functional diagram of the previously proposed architecture is shown in the Figure 4. Some of the advantages of this architecture are:

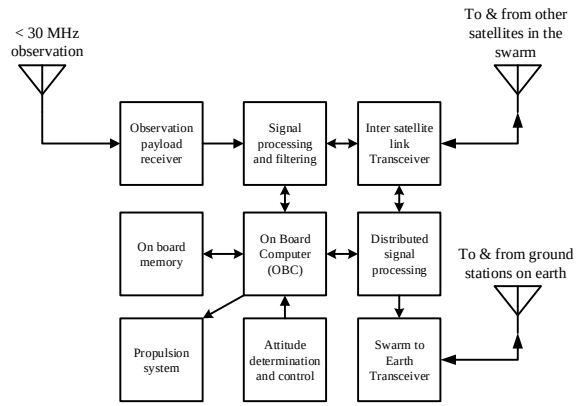

Figure 4. Functional block-diagram of distributed swarm architecture/swarm only architecture.

- The system is scalable; the number of satellites in the swarm can be scaled-up in multiple phases.
- Reduced risk of Single Point of Failure (SPoF): Failure of a few satellites in the swarm will not drastically affect the overall mission performance. Failure of a few satellites could be compensated by increasing the observation time to attain a given performance.

Although the advantages show that a swarm only architecture is robust and suits well for a mission such as OLFAR, some of the drawbacks of the distributed architecture for OLFAR are listed below:

- Increased mass and power budget: Since all the satellites in the swarm must be capable of performing payload observations, distributed processing, inter-satellite communication and swarm-to-earth communication, the overall mass and power budget increases.

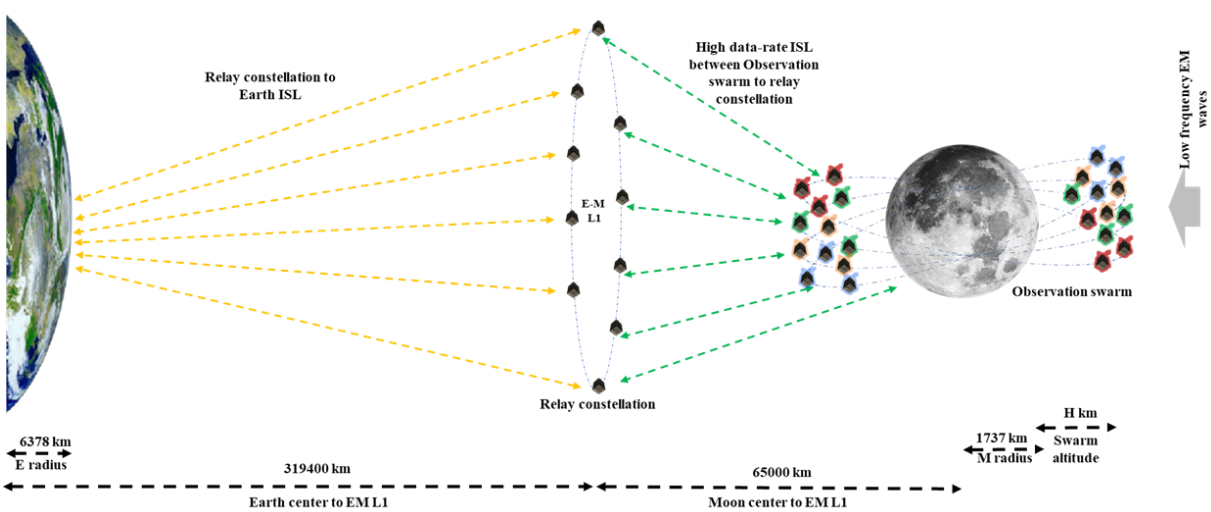

Figure 5. Hybrid fractionated swarm architecture.

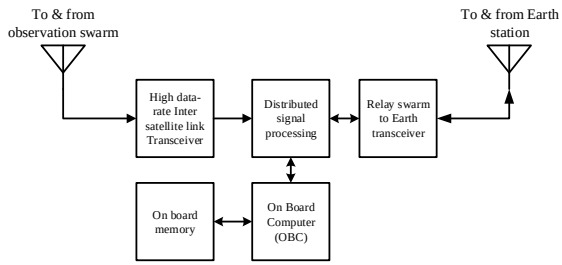

Figure 6. Functional block diagram of communication relay swarm.

- Limited communication window for swarm-to-earth link: Since the swarm can communicate to the earth only when they come to the near-earth side, the duration of communication is small and due to the large distance between earth and moon, this communication link can only be possible with low data rate links.

Hybrid fractionated swarm /Centralized processing architecture

An alternative to distributed architecture is centralized architecture; where a centralized node/satellite acts as mother-ship that primarily performs the task of collecting the raw observation data from the daughter-ships and process it before downlinking it to the Earth-station. Some of the main reasons for not choosing a purely centralized architecture for OLFAR in the previous studies are:

- SPoF: With a centralized node acting as the mother-ship, there is a great chance the complete mission might fail if the central node fails or cause an ambiguity in deciding a subsequent mother-ship if a mother-ship fails.
- Larger ISL data rate: In a frequency distributed architecture the required ISL data rate decreases by a factor of N (number of satellites in the swarm) as compared to centralized architecture.

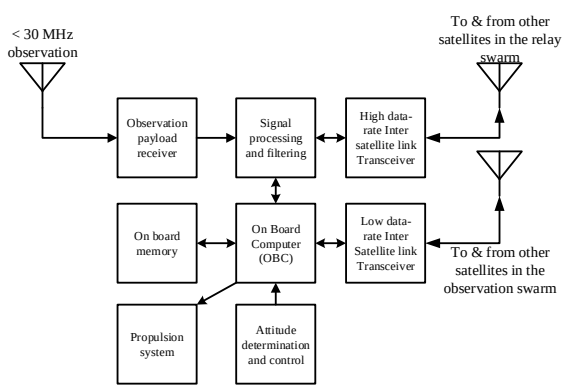

Figure 7. Functional block-diagram of observation swarm.

An alternative approach to negate SPoF is a centralized architecture using fractionated swarm; use a dedicated swarm to orbit the moon and perform observations and another dedicated swarm orbiting in the EML-1 to process the observation data and relay it to the earth station. An illustration of this concept is shown in the Figure 5. In such an architecture, the observation swarm are placed in multiple orbital planes around the moon which will perform low-frequency observations on the far-side of the moon and when they come close to the near-side of the earth, relay the payload data to the a dedicated communication relay swarm placed at EML-1.

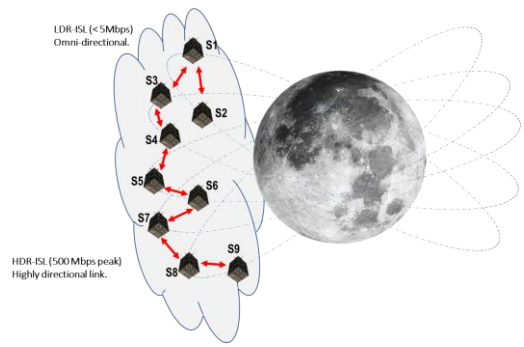

Figure 8. LDR ISL and HDR ISL for intra-swarm communication.

With a fractionated approach, functionalities of the two swarms are more streamlined and helps in better design optimization based on their functionality. The functional diagram of the observation swarm and the communication relay swarm is shown in Figure 6 and Figure 7 respectively.

As can be noticed in the functional block diagrams, the communication relay swarm takes over the task of signal correlation and downlinking the data to earth station. The main advantage of such an architecture is that the design of relay swarm can be optimized better for communication using high-gain antennas for both Inter-satellite links with the observation swarm and link to earth-station. This would be a challenge with the fully distributed

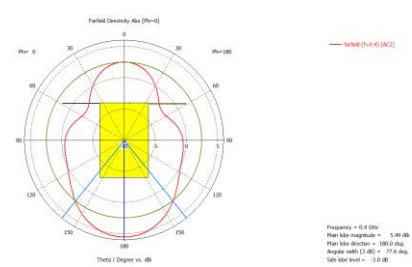

Figure 9. Radiation pattern of UHF turnstile on a 12U structure.

architecture as the payload antennas was large and accommodating all of them in a nanosatellite can be a challenge. Compared to the previous studies, since the centralized node in this case is a swarm and not a single satellite, there is no risk of SPoF.

One of the biggest challenges in this approach is closing the communication link between the observation swarm and relay swarm since the distance between the EML-1 and Moon is ~64000 km. The next section addresses the link budget aspects for the two architectures and provide a list of communication specs to close the link.

In addition to the high data rate directional ISLs, this paper also addresses the possibility of using a low data-rate omnidirectional link which is essential for synchronization, localization and positioning using algorithms discussed in [4]. The low data rate omni-directional link can be realized using simple UHF turnstile antennas on all the satellites in the observation swarm. As shown in Figure 9 the radiation pattern of a UHF turnstile antenna is near omni-directional providing reasonable gain in all the directions which is very essential for each satellite in the swarm to communicate with the rest in the swarm. This concept is illustrated in [12].

When ISLs in Ka-bands are used, the low data rate ISLs are very essential for the satellites to know their relative positions in the swarm which is useful in pointing the high gain Ka-band antennas in the correct direction. Section 5 discusses the link budget aspects of this low data rate ISL in UHF band.

Following a qualitative discussion on the advantages and disadvantages of the two architectures, a quantitative link budget analysis for the different cases needs to be performed to derive the specifications of the communication system that can be accommodated in a nanosatellite. The next section discusses the link budget calculations for the various scenarios discussed so far.

5. Link Budget Analysis

Link budget analysis is very critical in determining if the proposed communication architecture is feasible and helps derive the specs for the communication system that is needed to close the link. For the various design options shown in Figure 3, this section shows the link budget calculations. The link budget calculations for various design options show the maximum ISL distance up to which a certain symbol rate can be achieved. The link calculations use the DVB.S2 modulation and coding schemes since this is a well-known standard used in the space industry and commercially off the shelf transceivers are available to incorporate the baseband section of the transceiver.

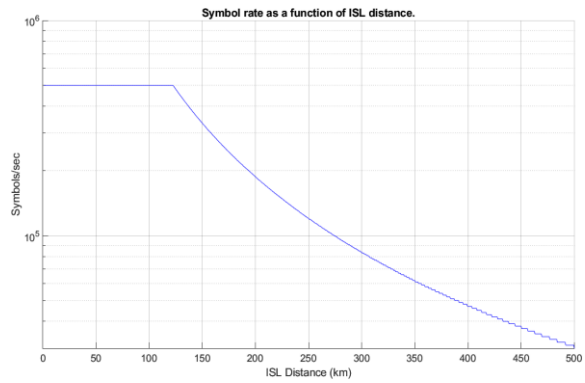

Figure 10. Symbol rate vs ISL distance using S-band for LDR-ISL.

The modcode-6 combination is used for all the design options which corresponds to QPSK modulation and code rate of 2/3. In the case of HDR ISLs, the two design options considered is for Inter-swarm communication which is applicable for centralized fractionated architecture and Intra-swarm communication for distributed architecture.

LDR ISL for Intra-swarm communication

The first design option that will be discussed is the low data-rate UHF link. This link is critical for the swarm to exchange telemetry, localization and synchronization information. This link is common to both centralized and distributed architecture. Since the amount of data that need to be exchanged is not much (generated in the order of kbits per orbit), the data rate needed to close the link is assumed to be < 1 Mbps. Figure 11 shows the symbol rate as a function of ISL distance.

A maximum possible data rate of 5.33 Mbps can be achieved up to a distance of 200 km, which is larger than the baseline distance. The antenna gains considered in this case was for a worst case of -3 dB

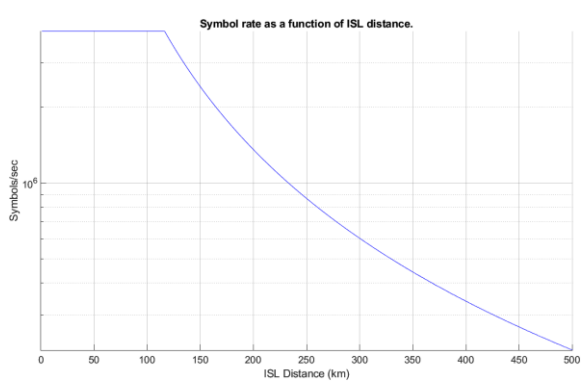

Figure 11. Symbol rate vs ISL distance using UHF link.

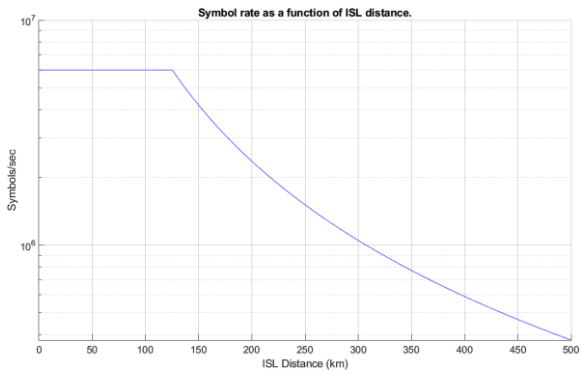

Figure 12. Symbol rate vs ISL distance using S-band for HDR-ISL

on both the transmitter and the receiver, the transmit power of 1 watt.

An alternate approach is to realize an omni-directional S-band link to achieve LDR ISL, which can be realized using at least two microstrip patch antennas on the opposite sides of a nano-satellites. In such a configuration the worst-case antenna gains that needs to be considered for link calculation is ~ 0 dBi. A graph of the achievable symbol rate vs ISL distance is shown in the Figure 10, Both the S-band and UHF LDR ISL are intended for Intra-swarm communication and applicable for both distributed and centralized fractionated architectures.

HDR ISL for Intra swarm communication.

The first design option that will be discussed in HDR ISL for intra-swarm (within a swarm) communication is using S-band links, the graph below shows the achievable symbol rate vs the ISL distance in S-band.

A data-rate of 8 Mbps can be achieved using a S-band link. The specification needed to achieve this link is summarized in the Table 3. When Ka-band is used for HDR ISL between the nanosatellites in the swarm, the achievable data-rate for a baseline distance of 100 km is ~466 Mbps, a graph of the symbol rate vs ISL distance is shown in Figure 13:

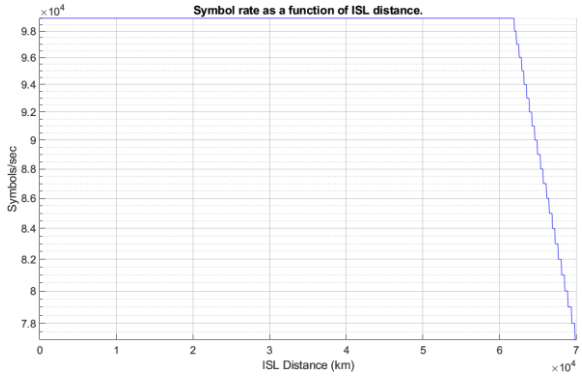

Figure 14. Symbol rate vs ISL distance using S-band for HDR-ISL (Inter-swarm)

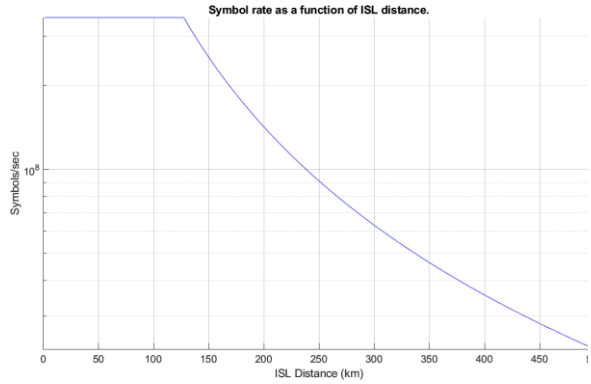

Figure 13. Symbol rate vs ISL distance using Ka-band for HDR-ISL (Intra-swarm)

HDR ISL for Inter swarm communication

The two possible design options available for inter swarm communication is using S-band or Ka-band and it is assumed that the nanosatellites in the observation swarm carry a 0.5-meter dish and the ones in relay swarm carry a 1-meter deployable dish. In the case of Inter-swarm communication, the nano-satellites in the observation swarm communicate with the communication swarm located at the EML-1 which is 61000 km away from the moon orbit, which is challenging compared to the 100 km baseline distance discussed in Intra-swarm communication link. The Figure 14 shows the achievable symbol rate vs distance for S-band:

The data rate that can be achieved in S-band for inter swarm communication is ~133 kbps. In the case of Ka-band, since the gain of the antenna is higher compared to S-band, higher data-rates can be achieved. The

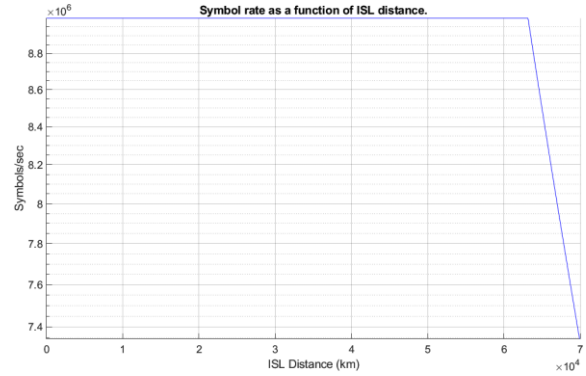

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Figure 15. Symbol rate vs ISL distance using Ka-band for HDR-ISL (Inter-swarm)

symbol rate vs ISL distance for Ka-band inter-swarm communication is shown in the Figure 15:

With a 0.5-meter dish on the observation swarm and 1-meter dish on the communication relay swarm, it is possible to achieve ~12 Mbps in Ka-band. The results of all the design options is summarized in Table 3 below:

Table 3. Summary of the specs for the discussed design options.

	LDR UHF link	**LDR S-band Link**	**HDR Ka-band (Intra-swarm)**	**HDR S-band (Intra-swarm)**	**HDR Ka-band (Inter- swarm)**	**HDR S-band (Inter-swarm)**
Frequency (MHz)	415	2200	22500	2200	22500	2200
Max data rate (Mbps)	5.33	0.66	466	8	12	0.133
Max distance (km)	100	100	100	100	61000	61000
Tx Antenna gain (dBi)	-3	0	23	4	39	19
Rx Antenna gain (dBi)	-3	0	23	4	45	25
Tx Power (dBm)	30	30	33	33	33	33
Modulation scheme	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK
Code rate	2/3	2/3	2/3	2/3	2/3	2/3
Filter roll-off	0.2	0.2	0.2	0.2	0.2	0.2
Occupied BW (MHz)	5.3	0.6	420	7.2	10.8	0.12

The antenna gains and transmit powers play an import role in closing the HDR ISL links, the link budget analysis shows that 0.5-meters dish for the observation swarm and 1-meter dish for the communication relay swarm are needed to close the link. Also, for the centralized fractionated architecture, Ka-band communication provides better data-rates. The 1-meter dish is feasible on the communication relay swarm based on the deployable dish design presented in [13].

6. Conclusions

Realization of space-based radio interferometer for missions such as OLFAR using nanosatellite swarms pose some major technology bottlenecks, and one of them is implementing high data rate inter satellite link between the observation swarms or between the observation swarm and communication relay swarms. This paper discusses the possible design option based the available frequency allocations and communication architectures, namely: distribute centralized architecture and distributed architecture. The past studies showed that centralized architecture posed was not suitable due to a high chance of SPoF and need for higher downlink data rate, but an alternate approach is discussed in this paper where the centralized node is replaced by a dedicated swarm meant to process and relay the data back to the ground. This paper also validates the design options using budget analysis and derives the specs needed to close the link for various approaches discussed. The analysis shows that with the existing technology in S-band, it is possible to achieve a bare minimum with 1-bit correlator, and if higher data rates are needed, Ka-band and a fractionated swarm architecture has an advantage over the swarm only concept. In order to achieve this, some of the technologies that pose a challenge are in designing efficient, high gain antennas and higher efficiency transmitter front-ends architectures that can operate for longer duty cycles and not generate a lot of heat and add additional constraints to the power system and thermal management.

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7. References

[1] S. Engelen, C. Verhoeven and M. Bentum, “OLFAR, A RADIO TELESCOPE BASED ON NANO-SATELLITES IN MOON ORBIT,” *Small Satellite Conference,* no. SSC10-III-6, 2010.

[2] Mark. Bentum., Chris. Verhoeven. and Albert-Jan. Boonstra., OLFAR - Orbiting Low Frequency Antennas for Radio Astronomy, ProRISC.

[3] M. Bentum, M. Verma, R. Rajan, A. Boonstra, C. Verhoeven, E. Gill, A. van der Veen, H. Falcke, M. Klein Wolt, B. Monna, S. Engelen, J. Rotteveel and L. Gurvits, “A Roadmap towards

a Space-based Radio Telescope for Ultra-Low Frequency," *Advances in Space Research,* 2019.

[4] R. T. Rajan, A. Jan, M. Bentum, M. K. Wolt, F. Belien, A. M and N. Saks, "Space-based Aperture Array For Ultra-Long Wavelength Radio Astronomy," *Springer Netherlands, Exp Astron,* no. 41: 271, 2016.

[5] A. Budianu and A. B. M. Meijerink, "Swarm-to-Earth communication in OLFAR," *Acta Astronautica,* no. 107 (2015) 14-19, 2014.

[6] E. Dekens, S. Engelen and R. Noomen, "A satellite swarm for radio astronomy," *Acta Astronautica,* no. 102 (2014) 321-331, 2014.

[7] Weiren. WU, Yuhua. TANG, Z. Lihua and Dong. QIAO2, "Design of communication relay mission for supporting lunar-farside soft landing," *Science China; Information Sciences,* vol. 61 040305:1–040305:14, 2018.

[8] C. F. David, A. P. Thomas, F. H. Amanda and C. H. Kathleen, "Preliminary Design Considerations For Access And Operations In Earth-Moon L1/L2 Orbits," *AAS 13-339.*

[9] R. T. Rajan, M. Bentum, A. Gunst and A. Boonstra, "Distributed correlators for interferometry in space," *IEEE Aerospace Conference,* 2013.

[10] k. S. Dong, "Frequency and Channel Assignments," *Deep Space Network,* 2014.

[11] B. Alexandru, J. W. C. Teodoro, M. Arjan and J. B. Mark, "Inter-satellite links for cubesats," *IEEE Aerospace,* p. #2276, 2013.

[12] K. Visweswaran, C. Verhoeven and E. McCune, "Solution to Data Congestion in Space; mmWave Communication for Nano-satellites," *IEEE Aerospace,* 2019.

[13] Nacer. Chahat, Jonathan. Sauder, Matthew. Mitchell, N. Beidleman. and G. Freebury., "One-Meter Deployable Mesh Reflector for Deep Space Network Telecommunications at X- and Ka-band," *13th EuCAP,* 2019.

[14] B. Alexandru, J. W. C. Teodoro, M. Arjan and J. B. Mark, "Antenna Architecture of a Nanosatellite for Radio Astronomy," *IEEE Aerospace* , p. #2120, 2014.

[15] B. Kul and H. Jeffrey, "Developing Architectures and Technologies for an Evolvable NASA space communication Infrastructure," *NASA/TM—2004-213108; AIAA–2004–3253,* p. 3253, 2004.