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**DARIS, A LOW-FREQUENCY DISTRIBUTED APERTURE ARRAY
FOR RADIO ASTRONOMY IN SPACE**

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DARIS (Distributed Aperture Array for Radio Astronomy in Space) is a radio astronomy space mission concept aimed at observing the low-frequency radio sky in the range 1-10 MHz. Because of the Earth's ionospheric disturbances and opaqueness, this frequency range can only be observed from space. The astronomical science cases include sensitive extragalactic surveys, radio transients such as Jupiter-like burst and Crab-like pulses, and coronal mass ejection tracking. The focus of the DARIS concept study is on feasibility aspects of a distributed aperture synthesis array in space, consisting of small satellite nodes and a mother-ship. The study selected suitable science cases, antenna concepts, communications, signal processing, orbital design, and mission analysis. With current-day technologies a satellite cluster can be built consisting of at least eight satellite nodes and a mother-ship, which could be launched with a Soyuz rocket from Kourou. Such a satellite cluster would open up the last unexplored frequency range for astronomy.

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I. INTRODUCTION

The frequency band below 30 MHz is one of the last unexplored bands in radio astronomy. This band is well suited for studying the early cosmos at high hydrogen redshifts, the so-called dark ages, extragalactic surveys, (extra) solar planetary bursts, transient radio sources and high energy particle physics. In addition, space research such as space weather tomography, are also areas of scientific interest. Due to ionospheric scintillation (below 30MHz) and its opaqueness (below 15MHz, depending on the ionospheric conditions), earth-bound radio astronomy observations in these bands are either severely limited in sensitivity and spatial resolution or

	f (MHz)	$\delta\Omega$	N_{ant}	τ (5σ)
Cosmology				
- global signal	30-150	2π Sr	≥ 1	2h-
- EoR	30-150	1'-	$\geq 10^3$	30yr
tomography,		20°		~yr
spatial				
mapping				
Extragalactic	10	1'	300	2 yr
surveys				
Galactic surveys				
- Solar system	0.1-10	deg.	10-100	~yr
neighbourhood				
- Cosmic rays	0.1-30	1''	10^5	100d
Transients				
- Solar, planetary	0.1-30	deg.	1-100	min-h
- Extra-solar	0.5-30	$\leq 1'$	$\geq 10^4$	

Table 1: Overview of low frequency science cases and main requirements from the DARIS project and from [7].

entirely impossible. A radio telescope in space obviously would not be hampered by the Earth's ionosphere.

In 2009 an ESA project, Distributed Aperture Array for Radio Astronomy in Space (DARIS), set out to investigate the space-based radio telescope concept. The focus of this feasibility study is on a moderate size three-dimensional satellite constellation operating as a coherent large aperture synthesis array. This aperture synthesis array would consist of 5 to 50 antennas (satellites) having a maximum separation of 100 km. Several antenna concepts were considered and simulated. An active antenna dipole array concept would be well suited, with moderate length (5 m tip-tip) dipoles at element level, would lead to a sky noise limited system. Multiple digital signal processing scenarios were considered as well. Ultimately, although a distributed signal processing approach would be favourable in terms of reliability and scalability, for complexity reasons the project has chosen to have several identical receiving nodes, and

one centralized processing node. Analysis has shown that with current technologies, one MHz bandwidth can be processed with full duty cycle. The main limiting factor is the inter-satellite link bandwidth. Several deployment locations, such as Moon orbit, Earth-Moon L2, and dynamic solar orbits were investigated. Each of those locations has its pro's and con's such as interference levels from the Earth, relative speed-vectors of the satellite nodes, and achievable down-link bandwidth to Earth. Two preferred deployment location were selected: Moon orbit and dynamic Solar orbit. The DARIS concept can be realized with only minor technological development with eight satellite antenna nodes and a mother-ship, launched by a Soyuz from Kourou.

II. SCIENCE CASE

The frequency band below 30 MHz is one of the last frequency bands which can only be observed from space [1-6,9-11], and which are not yet (significantly) explored by astronomers. But also science in the frequency bands above 30 MHz [7] would benefit from a space-based radio telescope as in those bands the ionosphere, man-made radio interference, and (changing) environmental effects also affect system performance.

In the DARIS project and in a study by Jester and Falcke [7], inventories were made of low-frequency sciences cases below ~100 MHz. These studies also related the science cases to required spatial resolution, number of antennas, bandwidth, and required integration time. Table 1 lists low-frequency science cases and main observational requirements.

The first column lists groups of science cases for the low-frequency regime: cosmological studies, galactic and extragalactic surveys, transients, and ultra-high energy particle physics. The other four columns specify the frequency range of interest, the spatial resolution required, the number of antennas required (in this frequency range phased-array antennas are more efficient than telescope dishes), and the integration time required to achieve a 5 sigma detection.

Cosmological studies predict spectral features related to changes in the early universe (Epoch of Reionization - EoR, dark ages) which in principle can be detected with a single antenna. Spatial mapping and tomography of cosmological signals require baselines of up to 20 km. As the expected signal for spatial searches is very weak, a very large number of antennas is needed to achieve sufficient sensitivity.

A second science case is extragalactic surveys. These surveys are limited in spatial resolution due to the interstellar medium (plasma), which distorts the

radio wave fronts. This limits the maximum achievable spatial resolution, which is frequency dependent, to roughly 1' in the DARIS frequency range. For 10 MHz this corresponds to a satellite baseline length of 100 km. At low frequencies (the DARIS frequency range), the observations are expected to be confusion limited; at higher frequencies this is no longer the case.

A third science case is galactic surveys. These surveys include investigating the origin of cosmic rays. Cosmic ray detection in our galaxy can be based on observing synchrotron radiation from relativistic electrons in the line of sight towards optically thick HII regions [6]. As this science case would require arcsecond resolution and very high sensitivity, it probably would be more efficient to study these phenomena at higher frequencies using ground-based telescopes.

The Solar system neighbourhood, the “local bubble”, is another galactic survey science case. The clumpiness and the three-dimensional structure of the inter-stellar medium (ISM) close to our Solar system can be measured by observing and modelling observed emissivity.

Solar and planetary bursts originate from the interaction of charged particles with the magnetic fields of Sun or planets. The emissions from magnetized planets, such as Jupiter, can be as intense as emissions from the Sun, and could easily be detected by a single antenna. Obtaining spatial information of the burst regions on Jupiter however would require impractically long baselines.

Planetary and extra-solar planetary bursts usually are polarized, whereas Solar bursts usually are not. This offers a way to separate the two types of sources. The pulse broadening of the ISM is not a limiting factor. As the transient signals from extra-solar planets are relatively weak (order mJy), of the order of 250 antennas are required to detect them.

Given the required number of antennas, spatial resolution, and integration time as specified in Table 1, it is clear that already with a 5 to 10 satellite system interesting science cases can be covered. Such an array would focus on extragalactic surveys and transients. In addition, also the Solar system neighbourhood can be mapped (“local bubble”), and such a cluster could also be used for space weather sensing.

III. SYSTEM CONCEPT

In the previous section possible science cases were described; the main design considerations for a low-frequency array in space relate to these science cases. The configuration of the satellite constellation and the achievable communication and processing bandwidths in relation to the imaging capabilities are crucial design considerations.

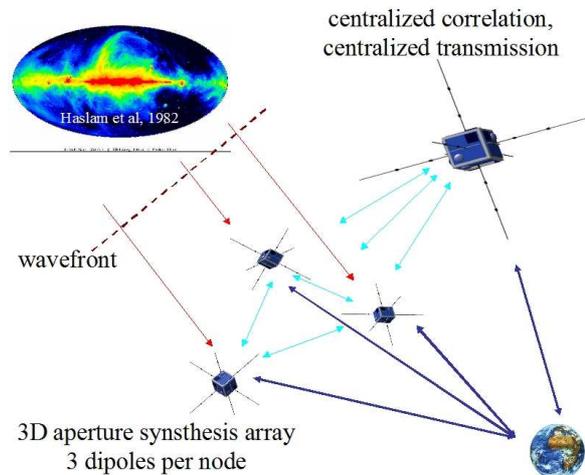


Figure 1: Schematic diagram of a low-frequency aperture synthesis array with a central spacecraft.

For a space-based low frequency array the band of interest is between 0.03 and about 30 MHz. Signals below ~0.03 MHz will be scattered/absorbed by the interstellar medium and therefore not observable for the array. Above ~30 MHz, Earth-bounded telescopes can take over. DARIS will operate in the 1-10 MHz band, with an option to extend it to the 0.03-30 MHz range.

The scientific requirements mentioned in the previous section imply that a very large distributed aperture array is needed in order to meet the specified spatial resolution and sensitivity. The DARIS project focuses on a satellite based concept, although a telescope on the far-side of the Moon obviously would be scientifically very interesting as well. A Moon-based concept potentially would allow a larger bandwidth and more receiving nodes than a satellite based concept, but it also would be more expensive.

The imaging principle of the distributed satellite antenna cluster is aperture synthesis. Eight satellites receive radio waves from the sky which are digitized and sent to a central satellite, the mother-ship, which correlates the signals, called spatial coherencies or correlation products. These correlated and time-integrated signals are sent to Earth where they are converted to sky images. Figure 1 shows a schematic diagram of the concept. In the figure only three of the eight satellites nodes are shown.

III.I Space-based aperture synthesis array

As explained in the science section, extragalactic surveys at the frequencies around 10 MHz are limited to about 1 arcminute spatial resolution. This corresponds to a maximum baseline length (separation between satellite pairs, interferometers) of 100 km. For

nearby galactic research, much larger baselines would be useful, but this was not pursued further as this would require much more power and satellite mass.

A channel frequency resolution of 1 kHz was chosen so that the band, for baselines up to 100 km, can be considered narrow-band. This means that time delays can be represented by phase rotations. Because the narrow-band assumption is valid, all-sky images can be made using obtained correlation matrices. Time delays applied prior to correlation would limit the field of view, so that many parallel signal processing paths would be needed to cover the entire sky, or many observations would be needed for different directions on the sky.

The integration time chosen is one second. This is a compromise between required bandwidth for the data downlink to Earth and maximizing the number of independent observed coherencies (correlations). By making use of bandwidth synthesis, i.e. observing coherencies at different frequencies yielding different wavelength-normalized baselines, about half a million independent (“u,v,w”) sample points can be obtained in a year. This would mean that about half a million point sources could be detected in the extragalactic survey. At this stage further integration does not make sense as the system will be confusion limited: the spatial resolution will not allow detection of additional sources.

It is required that the relative drift of the satellites will remain within a fraction of a wavelength within the integration time. Increasing the integration times, if possible (depending on the deployment location), will reduce the data downlink bandwidth to Earth considerably.

The satellite constellation may be deployed in Moon orbit or in a dynamic solar orbit as will be explained later in this paper. An overview of the main technical specifications for DARIS is listed in table 2.

Property	Value
Frequency range	1-10 MHz (0.03->30 MHz)
Spectral resolution	1 kHz
Instantaneous bandwidth	1-10 MHz
No. of satellites	≥ 9
Antennas	Three perpendicular dipoles
Antenna configuration	3D random cloud
Max. baseline length	100 km
Snapshot integration time	1 s
Sensitivity (surveys)	Confusion limited
Deployment location	Moon orbit or Dynamic Solar orbit

Table 2: Overview of DARIS specifications.

III.II System description

DARIS will consist of 8 satellite nodes along with a mother ship, totalling to 9 observational satellite nodes. The 8 satellite nodes will observe the sky in frequency range of 1-10MHz and will communicate the chosen instantaneous bandwidth of 1 MHz to the mother ship. In the mother ship the correlation and integration will be performed. The cross correlated data will be sent to Earth for further processing.

Each satellite node will consist of deployable antennas. The sky signals will be amplified using an integrated ultra-low power direct sampling receiver and digitizer. Using digital filtering, any sub-band within the LNA pass-band can be selected. The data will be distributed to the central mother-ship in space. On-board signal processing will filter the data, invoke RFI mitigation algorithms (if necessary), and finally, correlate the data in a phased array mode. The final correlated or beam-formed data will be sent to Earth as part of the telemetry data using a radio link.

There are many challenges in the DARIS project. One of the challenges will be discussed in more detail in the next section, the communication and especially the Inter Satellite Communication.

III.III Communications

The communications scenario for the DARIS mission is shown in Figure 2. The mission consists of a ground segment, which includes the ground station for transmission and reception of signals to and from the space segment. In DARIS, the mother ship is responsible for all communications between the space segment constellation and the Earth, and for relaying those to and from the node satellites. The highest quantity of data is the science data from the nodes to the mother ship, where correlation is then performed, and a lower data volume is forwarded to Earth, called the Inter Satellite Link (ISL). Telemetry (TM) and telecommands (TC), as well as timing and ranging, are also passed between the nodes and mother ship, and mother ship and ground station on Earth.

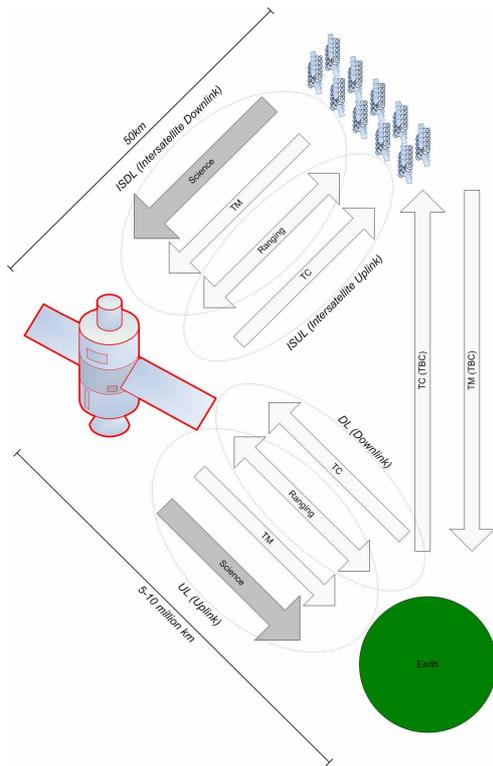


Figure 2. DARIS communications.

In theory also direct communication from Earth to the nodes is possible, but this requires large antennas at each node.

The ISL is a two way communication link, existing of a downlink of the (astronomical) data towards the central correlator in the mother ship and an uplink for housekeeping, control, timing and synchronization. Note that the total array consists of the number of nodes and the mother-ship itself. The data rate of the uplink is rather small. We assume a data rate of 100 kb/s for the housekeeping, control, timing and synchronization. The data rate of the downlink is much higher. In total three antenna systems will be used for every node, each sampling twice the required bandwidth of 1 MHz. With a bandwidth of 1 MHz, this leads to a data rate of 6 Mega samples per second. To calculate the data rate in bps, the number of bits for each sample needs to be chosen. This highly depends on the location of the DARIS array in space. In case of an RFI free environment, one bit is enough. In case of more RFI, more bits are needed for necessary dynamic range. In this study we assume a free RFI environment (after spectral filtering and band selection), which gives us a requirement of 1 bit for each sample, resulting in a downlink data rate of 6 Mbps from each node to the mother ship.

Although implementation of this ISL by means of optical devices is theoretically possible, an RF link is the most practical approach for the ISL. The ISL

channel is in principle 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 on the channel. However, for now, we assume just the free space loss of the channel. An ISL average frequency of 2.4 GHz results in a free space path loss with 50 kilometre node-to-mother-ship distance of 134 dB. Setting up the link budget results in a 5W transmitter to send the 6 Mbps from the node to the mother-ship.

FDMA is chosen for the multiple access scheme. Each node will send its data on a separate channel to the mother-ship. An additional channel is used for the uplink data from the mother-ship to the nodes. In case substantially more nodes will be used in the DARIS array, the required bandwidth might be larger than the available bandwidth. Currently special OFDM techniques are researched to be used in this case. The available bandwidth is divided in channels with orthogonal carriers. The individual channels hold the data of one of the nodes. Although OFDM is a more bandwidth efficient technique, its implementation is more complex as is its demands on timing synchronization is much higher.

At the mother-ship the data from the nodes is correlated and the reduced data stream is sent to Earth for post processing. A Medium Gain Antenna (MGA) is sufficient to transmit the data to the Earth. A 60W X-band transmitter on the mother ship can establish the data downlink to Earth (with a 30m dish on Earth).

III.IV Deployment locations

Two important aspects will determine the deployment location of DARIS: the choice of passive formation flying and the attenuation of the RFI from Earth.

Keeping nine spacecrafts (eight nodes and a mother-ship) within a 100 km range with active controls is extremely complex. To reduce heavy engines or orbital maintenance equipment, passive formation flying is chosen. Making this choice requires a relative stable deployment location. All spacecraft should stay in the 100 km cloud in space. That does not mean that the spacecrafts should stay at a relative stable position with respect to each other. On the contrary, the more they move with respect to each other, the better it is. That will create changing baselines between any two nodes in the correlator and therefore improves the imaging quality.

The RFI from the Earth must be avoided as much as possible. This can be done by either increasing the distance to the Earth or by shielding from the Earth. The closest possibility for shielding is using the Moon as protection against the noise, by an orbit in the Earth-

Moon L2-point or an equatorial orbit around the Moon. In both cases the shielding of the Moon is not 100% of the time. By increasing the distance to the Earth, the communication with the Earth becomes more of a challenge.

In the DARIS study we looked in detail at solar orbits close to Earth, and Moon orbit. It has been shown that in both cases it is possible to have a formation with none or minimal orbital maintenance and to keep this formation in a 100 km cloud for several years of operation. The trade-off between relative velocity and eclipse time is a disadvantage of the lunar orbit. The solar orbit has the problem of the high sensitivity. The solar orbit is the preferred orbit due to the low relative velocity, but still needs more detailed research. The lunar orbit remains a good alternative [10]

IV. CONCLUSIONS

The proposed distributed low-frequency radio astronomy array with nine satellite antenna systems supports a variety of science cases, ranging from sensitive high spatial resolution extragalactic surveys to transient effects of near-by sources. As the targeted frequency range has not been explored before, at least not with the spatial resolution and sensitivity that DARIS would provide, is very likely that new astronomical phenomena will be observed as well.

Scaling-up the array to a larger number of satellite nodes, and to an extended frequency range and instantaneous bandwidth is in principle possible, but with current-day technologies this would increase mass and costs. An interesting concept in which much wider bandwidths and more nodes are foreseen is a low-frequency radio telescope on the far-side of the Moon, as described for example in [7].

The satellite cluster senses the electric field and provides integrated spatial coherencies which can be converted to all-sky maps. Flexible digital signal processing functions would allow reconfiguration, which would make the concept also suitable for other applications. These potentially could include tasks for radio tracking of ships, space-weather sensing, subsurface sounding, or interplanetary sensing. As the radio frequency for some of these applications would be an order of magnitude higher than for the DARIS concept, the required accuracies for range, range-rate and for clocks are, obviously, higher.

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