OLFAR - Orbiting Low Frequency Antenna for Radio Astronomy

Mark Bentum and Albert Jan Boonstra

***Abstract*—New interesting astronomical science drivers for very low frequency radio astronomy have emerged, ranging from studies of the astronomical dark ages, the epoch of reionization, exoplanets, to ultra-high energy cosmic rays. However, astronomical observations with Earth-bound radio telescopes at very low frequencies are hampered by the ionospheric plasma, which scatters impinging celestial radio waves. This effect is larger at lower frequencies. Below about 5 MHz at night or about 10 MHz during daytime, the ionosphere is even opaque for radio waves. That means that Earth-bound radio astronomy observations in those bands would be severely limited in sensitivity and spatial resolution, or would be entirely impossible. A radio telescope in space would not be hampered by the Earths ionosphere, but up to now such a telescope was technologically and financially not feasible. However, extrapolation of current technological advancements in signal processing and small satellite systems imply that distributed low frequency radio telescopes in space could be feasible. We propose an autonomous distributed sensor system in space to explore this new low-frequency band for radio astronomy. The array will have identical elements (satellites), and ideally no central processing system. An advantage of such a system is that it is highly scalable and, due to the distributed nature, virtually insensitive to failure or non-availability of a fraction of its components. In this paper we present this novel concept of OLFAR, the orbiting low frequency antennas for radio astronomy in space.**

***Index Terms*—low-frequency astronomy, interferometry, space exploration**

I. Introduction

ONE of the last unexplored frequency ranges in radio astronomy is the frequency band below 30 MHz. This band is scientifically interesting for exploring the early cosmos at high hydrogen redshifts, the so-called dark-ages. This frequency range is also well-suited for discovery of planetary and solar bursts in other solar systems, for obtaining a tomographic view of space weather, and for many other astronomical areas of interest [7].

Research at low frequencies is one of the major topics at this moment in radio astronomy and several Earth-based radio telescopes are constructed at this moment (eg. the LOFAR project in the Netherlands [3], [4]. Because of the ionospheric scintillation below 30 MHz and the opaqueness of the ionosphere below 15 MHz, Earth-bound radio astronomy observations in those bands would be severely limited in sensitivity and spatial resolution, or would be entirely impossible. A radio telescope in space would not be hampered by the Earths ionosphere, but up to now such a telescope was technologically and financially not feasible. With todays technological advancements in signal processing and small satellite systems we can design a distributed low frequency radio telescopes in space which could be launched within 10 years time [2], [5].

In order to achieve sufficient spatial resolution, a low frequency telescope in space needs to have an aperture diameter of over 10-100 km. Clearly, only a distributed aperture synthesis telescope-array would be a practical solution. In addition, there are great reliability and scalability advantages by distributing the control and signal processing over the entire telescope array.

In OLFAR (Orbiting Low Frequency Antenna for Radio Astronomy), we make use of distributed sensor systems in space to explore the new frequency band for radio astronomy. Such an array would have identical elements, and ideally no central processing system. Advantages of such an array would be that it would be highly scalable and, due to the distributed nature, such a system would be virtually insensitive to failure of a fraction of its components. Initially, such a system could be tested in Earth orbits. In later stages, swarms of satellite arrays could be sent to outer space.

Individual satellites consist of a deployable antenna for the frequency band between 1 and 30 MHz. The sky signals will be amplified using an integrated ultra-low power direct sampling receiver and digitizer. The signal bandwidth available for distributed processing is relatively low: only a fraction of the bandwidth. Using digital filtering, any subband within the LNA passband can be selected. The data will be distributed over the available nodes in space. On-board signal processing will filter the data, invoke (if necessary) RFI mitigation algorithms and finally, correlate the data in a phased array mode [1], [8]. If more satellites are available, they will automatically join the array. The final correlated or beam formed data will be sent to Earth using a VHF link. The reception of this data can be done using the LOFAR radio telescope [4] (by use of the Transient Buffer Board capacity) or using a dedicated system. In the next section the specifications of OLFAR will be given and the research and design challenges are addressed. A breakdown of the system is presented in sections III and IV. This paper will end with conclusions and further research.

II. Specifications

The main design considerations for an astronomical low-frequency array in space relate to the physical characteristics of the interplanetary and interstellar medium as described for example in [6]. The configuration of the satellite constellation and the achievable communication and processing bandwidths

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in relation to the imaging capabilities are also crucial design considerations. This leads to the main initial specifications of an OLFAR array as listed in Table I.

Frequency range	1-30 MHz
Antennas	dipole or tripole
Number of antennas / satellites	50
Maximum baseline	between 60 and 100 km
Configuration	formation flying
Spectral resolution	1 kHz
Processing bandwidth	t.b.d. 100 kHz
Spatial resolution at 1 MHz	0.35 degrees
Snapshot integration time	1s
Sensitivity	confusion limited
Instantaneous bandwidth	to be determined
Deployment location	Moon orbit, L2 point

TABLE I
OLFAR PRELIMINARY SPECIFICATIONS

To realize such an astronomical instrument in space, several major technical challenges have to be met in the course to final operation of this instrument. The following research and design challenges are addressed.

- Mechanics and systems engineering. This includes the mechanical design and implementation of the complete satellite, integration, testing and preparation of launch ready flight units.
- Absolute and relative navigation and attitude. Design of the algorithms and software for determining the relative position and velocity and attitude and attitude rate of the satellites within the cluster and the absolute position and velocity and attitude and attitude rate of the cluster.
- Inter-satellite link. The satellites need to transfer data, spread processor load, exchange house-keeping data and determine their relative distance. For synchronized transmission and reception, and for correlation, the satellites need to synchronize clocks and reference oscillators.
- Active antenna system for low frequency radio astronomy. Design (mechanics and electronics) of the active antenna, including the LNA.
- Sensors for relative attitude determination. Development of MEMS sensors to determine the relative attitude and attitude rate of the satellite.
- Star trackers for absolute attitude determination. Miniaturizing star trackers with minimal impact on the mass, volume and power budget will be considered.
- Constellation maintenance. For the array of satellites it is important to measure, predict and correct for gradually drift of relative positions of satellites. A minimal thrust scenario ensuring a long life-time of the micro-propulsion system will be developed.
- Correlation software and hardware. Development of algorithms, software and hardware for both the receiving beam for radio astronomy and the transmitted beam for the downlink.
- Protocols. The OLFAR systems will be open standard and it will be possible for satellites designed by other teams to join the radio telescope network (a real autonomous sensor system).

III. System concept

Several mission concepts are considered, as formation flying in-orbit around the Earth, in-orbit around the moon, L2 and also Earth leading and tailing constellations. One of the reasons to explore space implementations of astronomical instruments is the Earth-bound RFI, especially at long-wave frequencies. A moon-orbit distributed array would be preferable, in which the moon screened elements of the array observe the universe and therefore will not be hampered by Earth-bound RFI. The rest of the array could be used for both data processing and for the data link to Earth. In later stages, swarms of satellite arrays could be sent to outer space, using the same techniques and concepts developed in this project. The level of the Earth-bound RFI will determine the number of bits in the Analog-to-Digital convertors in the satellites. The number of bits will be of large impact in the data transfer between the satellites. In case of (almost) no RFI, only one bit sampling is enough for the astronomical signals. Therefore far locations, like L4 and L5 but also other Earth leading or tailing locations will be considered. The drawback of far locations is the limitation on the downlink.

IV. System level

OLFAR is an autonomous distributed sensor system in space. Such an array would have identical elements, and ideally no central processing system. Advantages of such an array would be that it would be highly scalable and, due to the distributed nature, such a system would be virtually insensitive to failure of a fraction of its components.

Individual satellite positions (especially the relative position between the satellites), attitude, time, and status are important information and special positioning and synchronization techniques are implemented. The satellites are all identical: no central processing or processing units are available. The need of a mother spacecraft will however be considered in the project. A central satellite might be needed if the communication and processing at the individual satellites can not be fit into small satellites. In that case it is possible to send the raw data to a central mother spacecraft in which the correlation is performed and the downlink to Earth is made.

The individual array elements (satellites) are broken down in five major subsystems: the spacecraft, the antenna design, the frontend, backend and data transport. The data transport includes both intra-satellite and inter-satellite transport; it also includes the data transport to Earth.

A. Spacecraft

Each element of the system will be an individual satellite. This requires a lot of spacecrafts to fill the large aperture; we consider 50 elements as an absolute minimum. Small satellites are considered as carrier of the individual elements of the instrument.

The spacecraft will house the astronomical instrument. The nature of the mission sets some special requirements to the spacecraft:

- The absolute position in space is needed to a high accuracy.

- The relative position to other satellites is very important. Centimeter accuracies are needed, even for the longer baselines in space.
- During the observations the attitude of the antennas must be stable.
- Exact timing and synchronization is required to be able to use the system as an interferometer.
- As small satellite systems are considered for the telescope array, and giving the amount of processing that is required, low power systems are clearly needed.

B. Antenna concept

The proposed frequency band of the antenna array is 1 to 30 MHz. The design of the antennas is both simple and economical. The power transmitted to the receiver will depend of the antenna length. In the design a deployable wire antenna will be considered. The efficiency drops as the antenna wire is shortened.

The advantage of using tripoles for 3-D imaging is that it does not suffer from gain loss in off-axis antenna directions. Its disadvantage is that tripoles consume three backend input channels per antenna unit. As a result an array of dipoles will have more antenna units and therefore offer better aperture (u,v) coverage than an array of tripoles for the same dimensions of the backend.

C. Frontend

The low noise amplifier is situated directly behind the antenna to limit signal loss and ensure a low contribution of the analogue electronics to the overall system noise power. Since the sky noise temperature is orders of magnitudes larger than the receiver noise, no classical power matching is needed and we can tolerate a serious impedance mismatch and still have the sky noise contribution to the overall system temperature dominate over the receiver noise contribution. Before the received and amplified signal can be sent to the backend, the signal needs to be converted to an appropriate frequency and digitized. The aim is to develop ultra-low power receiver electronics for amplification of the sky signals and for digitization. The goal is to develop an LNA chip for the frequency range from 1 to 30 MHz. This chip includes an integrated ADC and signal processing hardware. The signal bandwidth available for distributed processing is relatively low: only a fraction of the bandwidth. By digital filtering, any subband within the LNA passband can be selected. Given the fact that the observational frequency is low, direct sampling is applied so there is no need for analog mixing schemes.

D. Backend

The data of the individual satellites will be distributed over the available satellites (nodes) in the array. The distributed data processing consists of subband filtering, beamforming, RFI mitigation techniques and correlation. After the processing the correlated data will be transferred to Earth. Various signal processing techniques are used, depending also on the mission concept. In case of a moon-orbit mission, part of the array will be screened by the Moon and therefore not hampered by the Earth-bound RFI. That part of the array will be used for reception of the astronomical signals. The rest of the array is used for data processing and the data transport to Earth. Since array nodes will dynamically join and leave the receiving and transmitting subarrays, special configuration and calibration techniques must be considered and studied.

E. Data transport

The data transport consists of three elements:

- Intra satellite wireless data transport (e.g. sensors, positioning data). The function of the intra satellite data transport subsystem is to transport the signals from the various sensors (e.g. antennas, position, time) to the backend of the satellite. Part of the communication will be done wireless.
- Inter satellite data transport (control, subband data, correlated data). The satellites need to transmit their captured data, position, time, and some other meta information needed for the distributed signal processing (beamforming and correlation) to all the satellites in the array. The data processing is done on all the raw data of all the satellites. The resulting data stream will be a much lower data rate than the raw data. In astronomy this is often called 'reduction of the data'.
- Data communication between the array and Earth (diversity techniques for large array-Earth distances). 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 for communication diversity (clustered transmit and receive schemes).

In addition, there are great reliability and scalability advantages by distributing the control and signal processing over the entire telescope array.

V. Conclusions and Further Research

In this paper we presented a novel concept for a radio astronomy for very low frequencies. Due to the limitations of building an instrument on Earth, we presented OLFAR, the orbiting low frequency antennas for radio astronomy in space. To realize a large aperture, multiple satellites are used. Each satellite receives the astronomical signals and transports the data between the other satellites. Data processing is done in space and the processed data will be send to Earth for further off-line processing. The key communication challenge is the inter satellite communication.

This concept will be researched in more detail. This includes simulations of the satellite constellations in various locations in space, virtual distributed system and sattelite architecture design, design of radio architectures for the communication in distributed arrays and distributed autonomous signal processing.

In OLFAR we implement an autonomous sensor systems in space to explore this new frequency band for radio astronomy. We expect this route will lead to new science both in astronomy and engineering.

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