A novel astronomical application for formation flying small satellites

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OLFAR, Orbiting Low Frequency Antennas for Radio Astronomy, will be a space mission to observe the universe frequencies below 30 MHz, as it was never done before with an orbiting telescope. Because of the ionospheric scintillations below 30 MHz and the opaqueness of the ionosphere below 15 MHz, a space mission is the only opportunity for this as yet unexplored frequency range in radio astronomy. The frequency band is scientifically very interesting for exploring the early cosmos at high hydrogen redshifts, the so-called dark-ages and the epoch of reionization, the discovery of planetary and solar bursts in other solar systems, for obtaining a tomographic view of space weather, ultra-high energy cosmic rays and for many other astronomical areas of interest. Because of the low observing frequency the aperture size of the instrument must be in the order of 100 km. This requires a distributed space mission which is proposed to be implemented using formation flying of small satellites. The individual satellites are broken down in five major subsystems: the spacecraft bus, the antenna design, the frontend, backend and data transport. One of the largest challenges is the inter-satellite communication. In this paper the concept and design considerations of OLFAR are presented.

1. Introduction

In 1932 at Bell Telephone Laboratories Karl Jansky built an antenna, designed to receive terrestrial radio waves at a frequency of 20.5 MHz. After recording signals from all directions, Jansky categorized them into three types of static: nearby thunderstorms, distant thunderstorms, and a faint steady hiss of unknown origin. This was the discovery of extra-terrestrial radio signals and in fact the start of radio astronomy science. It took some time before these results were taken serious and radio astronomy started to build new instruments. After World-War-2 new instruments were built, but at higher frequencies. So, although radio astronomy started at low frequencies, the focus was on higher frequencies.

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 (e.g. the LOFAR project in the Netherlands [3,4], covering the 30- 240 MHz range). It is considered as one of the last unexplored frequency ranges [11]. Low-frequency radio astronomy has focused his operation mainly on the frequency regime above ~50 MHz. Below this frequency, Earth-based observations are limited due to:

- Severe ionospheric distortions
- Complete reflection of radio waves below 10-30 MHz
- Solar eruptions
- Radio frequency interference (RFI) of man-made signals.

There are however, a number of interesting scientific processes that naturally take place at these low frequencies, but which are hampered by the limitations mentioned above.

The band is scientifically interesting for exploring the early cosmos at high hydrogen redshifts, the so-called dark-ages and the epoch of reionization. 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, ultra-high energy cosmic rays and for many other astronomical areas of interest [7].

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 Earth's ionosphere, but up to now such a telescope was technologically and financially not feasible. With today's 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 may be demonstrated and tested in Earth orbits. In later stages, swarms of satellite arrays could be sent to outer destinations in space.

Individual satellites consist of a spacecraft bus and the radio astronomy payload. The payload comprises 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, cross-correlate or beam-form ,data from all satellite nodes [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. 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.

Having described the basic ideas of OLFAR, we will focus on the various aspects in the remainder of this paper. In section 2 the limitations of Earth-based observations will be discussed which motivates a space mission for low-frequency radio astronomy. In section 3 a brief overview of the science will be given. This results in a list of specifications and research and design challenges for OLFAR, presented in section 4. A breakdown of the proposed system is presented in sections 5 and 6. Finally, conclusions are drawn and an outlook to further research is given.

2. Why a space mission?

To study the physical processes in the Universe, observations are done at various wavelengths, from Gamma rays to optical and radio frequencies. Only certain parts are not blocked by the atmosphere of the Earth and can be observed by Earth-based observatories. Blocked frequency bands must be observed using space-based instruments. Low-frequency radio astronomy below 30 MHz is recently taken into consideration. Because of the long wavelengths very large scale instruments are required to obtain sufficient angular resolution. Recent technological developments for transporting the huge amount of information makes it possible nowadays to build such instruments [3, 4].

New Earth-based low-frequency instruments are focusing their operation mainly on the frequency regime above ~50 MHz. Below this frequency several problems will occur.

The first problem for radio waves below 50 MHz is the Earth's ionosphere. The ionosphere plasma will scatter the radio waves and below the so-called plasma frequency, propagation of the radio waves is not possible at all. This happens between 5 and 10 MHz (depending on day and night, and on solar activity). Below these frequencies no observations are possible with Earth-based observatories.

But even for higher frequencies the ionosphere causes significant angular displacements, broadening and intensity fluctuations. This can be compared with viewing the sun from the bottom of a swimming pool. The sun can be seen, but the image is blurred by the surface variations of the water.

These distortions are also a challenge for the new low-frequency Earth-based observatories and ionospheric calibration of the instruments is one of the main topics.

Another reason for a space mission is man-made and naturally occuring Radio Frequency Interference (RFI) There are several potential threats concerning the RFI environment of the Earth [9]:

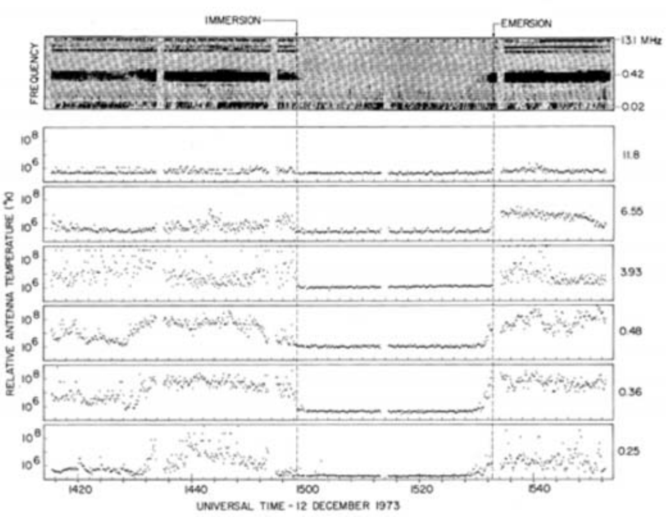
- Earth-bound transmitters, mainly commercial HF transmitters
- Auroral kilometric radiation (AKR), mainly in the 0.15-0.3 MHz band
- Spherics from lightning, burst-like

Depending on the RFI levels, more bits must be used in the A/D converters. This will be a major burden on the computational power needed for the instrument. Similarly, RFI levels will also influence the required data transport bandwidth between the antennas.

A space mission will lower the RFI levels and will allow less bits in the A/D convertors. Clearly, in Moon-orbit (at the backside of the Moon), at the Earth-Moon L2 point, or at the Sun-Earth L4/5 points, these effects will not be present, or will be reduced substantially. Calculations on the RFI levels can be done easily using Free Space Path Loss equations.

Two space missions whose primary purpose was low-frequency radio astronomy have been launched so far: the Radio Astronomy Explorers (RAE) 1 and 2 (1968, 1973)[10]. RAE-1 orbited the Earth and it detected strong man-made RFI and interference from AKR and from solar winds interacting with the Earth's magnetic field. RAE-2 was therefore sent into a Moon orbit. As can be seen in Figure 1, there is still a lot of RFI present in the data if the Moon is not shielding the RFI from Earth. On the backside of the Moon the RFI levels are very low. A Moon orbit for OLFAR is therefore considered.

Figure 1: Observations of the RAE-2 satellite orbiting the Moon. The shielding of the Earth-based RFI by the Moon can be seen clearly.



We can conclude that low-frequency observations below 30-50 MHz must be done using space-based instruments. In the next section a short overview of interesting low-frequency radio science will be given.

3. Low-frequency science

With OLFAR a new unexplored frequency band will be observed, most likely leading to new discoveries. In [6], Jenster and Falcke made an extensive science case for a low-frequency observatory to be built at the back side of the Moon. This location is almost perfect for a low-frequency observatory: (almost) no man-made RFI, very accurate knowledge of the position of the antennas, and no problems with the Earth's ionosphere. However, Moon-based missions are very expensive. Also making a 100 kilometer distributed array will be a major challenge on the surface of the Moon.

This science case is the same as for OLFAR. The main science drivers are [6]:

- *Cosmology*. What happened in the early universe between the moment of the Cosmic Microwave Background Radiation (CMB) at around 380.000 years after the Big Bang and the Epoch of Reionization (about 400 million years after the Big Bang), the so-called Dark Ages.
- *Extra galactic Surveys and Galactic Surveys.*
- *Transients*, like solar/planetary bursts, X-ray binaries, pulsars, exoplanets.
- *Ultrahigh energy particles.*
- *Tomographic views of space weather.*

And of course "*serendipity*" since a complete new frequency window will be opened for the first time.

4. Specifications

The main design considerations for an astronomical low-frequency array in space relate to the physical characteristics of the interplanetary and interstellar medium. The configuration of the satellite constellation and the achievable communication and processing bandwidths 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 1.

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 also 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 needs to be developed.
- *Correlation software and hardware*. Development of algorithms, software and hardware for both the receiving beam for radio astronomy and the transmit 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).

Table 1. OLFAR preliminary specifications

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	100 kHz
Spatial resolution at 1 MHz	0.35 degrees
Snapshot integration time	1 s
Sensitivity	Confusion limited
Instantaneous bandwidth	To be determined
Deployment location	Moon orbit, Earth-Moon L2 or Sun-Earth L4 / 5

5. Destination

Based on the specifications, the science objectives, as well as the constraints imposed by the engineering feasibility of various solutions, there are several options for locating the array:

- formation flying in-orbit around the Earth
- in-orbit around the moon,
- Earth-Moon L2
- Sun-Earth L4 and L5, and Earth leading and tailing constellations.

One of parameters for determining the possible destinations 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 as can be seen in Figure 1. The rest of the array could be used for both data processing and for the data link to Earth.

The level of the Earth-bound RFI will determine the number of bits in the Analog-to-Digital converters 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 of course the bandwidth limitation of the downlink.

Another parameter is the stability of the orbit of the destination. One of the requirements is the maximum constellation diameter. This is set to 100 kilometer. That means that all the satellites must be within this range. If a destination is unstable, this condition can not be guaranteed without the need for (expensive) thrusters.

6. System level

OLFAR is aimed to be an autonomous distributed sensor system in space. Such an array would ideally be constituted by identical elements without a central processing system. Such an array would be highly scalable and, due to its distributed nature, it would be virtually insensitive to failure of a fraction of its elements.

Individual absolute satellite positions as well as relative positions between the satellites, attitude, time, and status information, are important information and special positioning and synchronization techniques are required. The satellites are considered to be all identical: no central processing or processing units are available. The need of a mother spacecraft will however be considered in the project. Preliminary design studies suggest that the required functionalities may well be implemented into small satellites. A central satellite might be needed, however, if the communication and processing at the individual satellites can not be fit into the small satellites which constitute the elements of the array. In that case it is possible to send the raw data to a central mother spacecraft for correlation and data downlink.

The individual array elements (i.e. satellites) may be broken down in two parts: the spacecraft bus and the payload. The payload comprises the antenna design, the frontend, backend and data transport. The data transport includes both intrasatellite and inter-satellite transport; it also includes the data transport to Earth.

6.1 Spacecraft Bus

Each element of the system will be an individual satellite. This requires a lot of spacecraft to fill the large aperture. We consider 50 elements as a target scenario. Small satellites are considered as carrier of the individual elements of the instrument.

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

- The absolute spacecraft position is needed to a high accuracy.
- The relative position between satellites is very important. Decimeter 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.

6.2 Antenna concept

The proposed frequency band of the antenna array is 1 to 30 MHz. The power transmitted to the receiver will depend on 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 coverage than an array of tripoles for the same dimensions of the backend.

6.3 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 a 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.

6.4 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 for calibration and imaging. 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. The shielded 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.

6.5 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 wirelessly.
- 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, correlated and integrated, data stream will have a much lower data rate than the raw 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 considerable reliability and scalability advantages by distributing the control and signal processing over the entire telescope array.

One of the main challenges of the OLFAR system design is the inter-satellite link. In the next section a closer look into the inter-satellite link is given.

7. Inter-satellite link

The number of satellites is an important parameter for the design of the inter-satellite communication hardware. Because of the distributed data processing, all the data of all satellites must be send to all other satellites in a decentralized architecture. Each satellite will choose the relevant channel and will correlate the data.

A baseline is defined as the relative position vector between any two antennas in the array. It is expected that the maximum baseline length for OLFAR will be 100 km. This is either the diameter of a circular or spherical arrangement, or the maximum separation in another shape of a surface-based array. For the inter-satellite communication this maximum number of 100 kilometer will be taken as requirement.

With:
- N_{sat} = number of satellites
- B = observing bandwidth
- f_s = sampling frequency
- N_{bits} = used number of bits
- N_{pol} = number of polarizations

the data rates between the satellites can be calculated as follows:

$$R_{sat} = 2BN_{bits}N_{pol} = f_s N_{bits} N_{pol} \qquad (1)$$
$$R_{tot} = N_{sat}R_{sat}$$

For the current design of OLFAR the values are $N_{sat} = 50$, $B = 1$ MHz, $f_s = 2$ MHz, $N_{bits} = 1$, $N_{pol} = 2$.

This results in a data rate of 4 Mbps for each satellite, adding up to a total data rate of 200 Mbps of the total array. Note that these are the numbers for 1 bit sampling! In case of 8 bit sampling, the numbers will be 32 Mbps for each satellite and 1.6 Gbps for the array.

Each satellite will send its data to all the other satellites. Several techniques can be used to assure that the appropriate data can be selected by the individual nodes. The possible dimensions for multiple access are time, frequency, code and space. One of most straightforward implementations is frequency division multiplexing (FDM). Each satellite will transmit its data using (eg) PSK-modulation in a narrow bandwidth channel. The channels are separated by large guard bands to prevent interference between the channels. If each channel is transmitted simultanuously, the overall data rate will be the sum of all the channels.

A more efficient modulation is required for high data transmission. One of the promising techniques is OFDM (Orthogonal Frequency Division Multiplexing). OFDM had been adopted as standard for DVB, DAB and WLAN. With OFDM, the separation between each channel is equal to the bandwidth of each channel, which is the minimum distance by which the channels can be seperated.

8. Conclusions and outlook

In this paper we propose a novel and innovative concept for a radio astronomy at very low frequencies. As the Earth's atmosphere excludes observations at these frequencies, we present OLFAR, the orbiting low frequency antennas for radio astronomy in space. To realize a large aperture, a decentralized space architecture is to be developed, which consists of multiple satellites flying in formation. Each satellite receives the astronomical signals and shares these data with all the other satellites. Data processing is done in space and the processed data will be sent to Earth for further off-line processing. The key communication challenge is the inter-satellite communication.

This concept holds a variety of opportunities and challenges which require more detailed research. This includes simulations of the satellite array at various locations in space, virtual distributed system and satellite architecture design, design of radio architectures for the communication in distributed arrays and distributed autonomous signal processing.

With OLFAR we propose an autonomous sensor system in space to explore this new frequency band for radio astronomy. We expect this route will lead to new science both in astronomy, space science and engineering.

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