

OLFAR - Orbiting Low Frequency Antennas for Radio astronomy

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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. Huge efforts are currently made to establish low frequency Earth-bound instruments, since today’s technology is able to support this. 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 Earth’s 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.

I. INTRODUCTION

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 [5], [6]). The frequency band below 30 MHz is one of the last unexplored frequency ranges in radio astronomy. Since the spatial resolution of an instrument scales with the wavelength, very huge telescopes are needed for detailed observing at low frequencies. Previous research was therefore focused on higher frequencies. This band, however, is scientifically very interesting, for instance for exploring the early cosmos at high hydrogen redshifts, the so-called dark-ages. This low-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 [8]. And, since it is not explored before, unknown discoveries might happen.

The science drivers are the reason low frequency radio telescopes are developed and realized at this moment. These Earth-based low-frequency instruments are focusing their operation mainly on the frequency regime above approximately 50 MHz. Below this frequency several problems will occur. In [1] we presented these problems: man-made RFI, ionospheric scintillation and even opaqueness of the ionosphere below 15 MHz, ionospheric patch problem, and limiting the size of the interferometric array (and so limiting the resolution).

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. However, extrapolation of current techno-

logical advancements in signal processing and nano and femto satellite systems imply that distributed low frequency radio telescopes in space could be feasible in 10 years time [4], [7].

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..

Low frequency arrays on the back-side of the moon have been considered e.g. in [11], as well as arrays in free space, e.g. in [12]. In OLFAR (Orbiting Low Frequency Antenna for Radio Astronomy), we consider a distributed sensor systems in space to explore the new frequency band for radio astronomy. Such an array would have identical elements (small satellites), 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.

In short the concept of OLFAR consists of individual satellites with 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 antenna 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 [3], [9]. 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 radio link. The reception of this data could be done using the LOFAR radio telescope (by use of the Transient Buffer Board capacity) or using a

dedicated system. As the satellites will ultimately be sent to larger distances from Earth, communication to and from Earth requires diversity communication schemes using all of the individual satellites.

In this paper we present this research project on autonomous sensor systems in space to explore this new frequency band for radio astronomy. We expect this route will lead to new science by breakthroughs in experimental astronomy and engineering sciences. In the next section a specification of OLFAR will be presented. In section III a system overview of OLFAR is presented. We will discuss the technical aspects in more detail in section IV. We will end with describing the current status of the project and conclusions.

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 [10]. 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 I.

Frequency range	1-30 MHz (0.3-30MHz preferably)
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.
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.

III. SYSTEM OVERVIEW

Several mission concepts are considered, as formation flying in-orbit around the Earth, in-orbit around the moon, L2 and also Earth leading and trailing constellations. One of the reasons to explore space implementations of astronomical instruments is the Earth-bound RFI, especially at long-wave frequencies [1]. 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 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 trailing locations will be considered. The drawback of far locations is the limitation on the downlink.

IV. TECHNICAL CHALLENGES

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 four major subsystems:

- the spacecraft bus (powersystem, attitude determination and control, housekeeping etc.)
- the antenna system
- the radio system (intra and inter satellite communication and link to the groundstation)
- the signal processing system

A. *The antenna system*

Considering the wavelength of the astronomical signals of interest it is unlikely that the satellites can carry antennas of sufficient length to actually receive power in these frequencies. They will be too short. For transmission this would be a problem, but for reception it is not at all. A short antenna has a capacitive impedance. At the output a voltage related to the field can be observed, but due capacitive nature it is not possible to obtain power from the antenna. Especially at the low frequencies considered it is easy to design an amplifier that is able to measure the antenna voltage without loading it which would destroy the signal. There are already many examples of so-called active antennas that work satisfactory with a short antenna for frequencies from down to 10kHz to 100MHz using just one amplifier. [13], [14]

Noise levels of these antennas are already proven to be good enough for use in the OLFAR system. The challenge is in making a space qualified version of the system. Presently and integrated version of this amplifier is being designed for testing in the Delfi-n3Xt satellite [15]. In that case the VHF antennas used by the satellites for communication to the ground station will be also used for the LF astronomy amplifier verification. A phasing network makes it possible to use the antennas for both radio transmission and LF sampling at the same time. The experiment will also give clues about the effect of EMI caused by the satellite itself on the quality of the radio astronomy signal reception.

It is very likely that also the OLFAR satellites will share the antennas between the long distance

communication system and the LF signal sampling circuit. But since transmission and sampling tend to occur at different sides of the Moon the problem of interference might even be less complex than in the delfi-n3Xt (of course only if a Moon orbit is chosen for the satellite constellation). The antenna hardware configuration is dominated by the design for the reception of the radio astronomy signals. A tripole configuration is considered. Proper phasing networks at the various frequencies will make it possible to optimize the antenna system for both transmission to the ground station and reception of the radio astronomy signals. The signal frequency bands are conveniently far apart.

B. The radio system

The radiosystem has three different functions:

- Intra satellite wireless data transport (e.g. wireless sun sensors, wireless temperature sensors etc.). The function of the intra satellite data transport subsystem is to transport the signals from the various sensors to the bus system of the satellite. The benefit of wireless sensors is that no cables or connectors are necessary to integrate the sensors in the satellite. This saves weight and volume which is very important considering the small size of the satellites. It greatly enhances the system flexibility. There is much more freedom to relocate a sensor or even replace a sensor, since it has no impact on the cable harness of the satellite. This saves both money and time and eases co-design of the sensors and the satellite bus.
- Inter satellite data transport (control, sub-band data, correlated data). The satellites need to share their captured data, position, time, and some other meta information needed for the distributed signal processing (beamforming and correlation) with other satellites in the array. The data processing is done on all the raw data of all the satellites. The resulting data containing just the features of interest will be much less than the raw data. This 'digestion' of the raw data, called data reduction in astronomy, is a delicate combination of data exchange between the satellites and data

processing in each node without one of the satellites being 'in command'. The individual satellites are not 'aware' of the size of the array. They may just keep sampling data until their buffer is full and then join the reduction effort. Without control the array can switch between capture mode and reduction mode automatically and easily incorporate more satellites without limit.

- Data communication between the array and Earth (diversity techniques for large array-Earth distances). As the satellites are not aware of their presence in the array, they can only decide to transmit to the ground station when their observation the amount of data is not reducing anymore. Then they switch to the transmit mode. Probably the transmission of one satellite is not sufficient to transmit the data to the groundstation. As long as there is no success the satellite will keep transmitting. Over time more satellites will enter the transmission mode. Via the inter satellite link the transmitting satellites share a synchronization signal. This results in synchronized transmission of the satellites. Increasing power of the shared synchronization signal (more satellites join) may stimulate other satellites to join the transmission effort. At some point transmission to the groundstation is successful. Then the groundstation can send a signal to the array to acknowledge the satellite to knowledge good reception, thereby stimulating satellites to go back to the sampling mode after they have uploaded their data and preventing other satellites to join the transmission. They can skip the transmission and go back to sampling immediately. Also this scenario allows for an unlimited increase of the number of satellites, so also the transmission power can be increased without limit just by adding more satellites.

The typical uncoordinated swarm-like operation of the process of capturing, processing and transmitting data makes the most important parameters in the link budget a function of the number of satellites and not solely on the performance of an individual satellite. This number is in principle unlimited.

Faulty, 'misbehaving' satellites will not be able to hang up the system, but will be just overruled by the majority. A very important research topic is to find the minimal number of satellites that results in proper operation. Performance increases when the number of satellites is increased.

C. The signal processing system

The data of the individual satellites is shared with the available satellites (nodes) in the array. The distributed data processing that should take place consists of subband filtering, beamforming, RFI mitigation techniques and correlation. The satellites can not have very powerful processors. Limited power and cooling facilities make it impossible to use top-end processors in each satellite. On the other hand also in this case the total amount of available small processors is not limited. It is likely that the more processors are available, the shorter the array 'stalls' in the data reduction phase. An increase in the processing power of an individual satellite reduces the number of satellites needed to obtain a certain time-to-result. An interesting aspect of this mechanism is that there is basically not a lower limit to the number of satellites to process the data, but below a certain number the 'digestion phase' will take an uncomfortably long time. Still even an array with this little mishap, will produce images never seen before. When these results are promising, the uptime of the array can be easily increased by adding more satellites. Part of the array will be screened by the Moon and therefore not hampered by the Earth-bound RFI. When only that part of the array samples data of the astronomical signals signal processing demands are reduced. The rest of the array works data processing or data transport to Earth. Satellites can now individually if they are on the right side of the moon for sampling and can individually decide to join the sampling effort or not. Since they will dynamically join and leave the sampling effort, special configuration and calibration techniques must be considered and studied. Also in this case a faulty satellite will hardly be able to mess up the sampled signals with RFI from the earth, since it will be overruled by the majority.

D. The spacecraft bus

Actually the spacecraft bus is very similar to the Delfi-C3 and Delfi-n3Xt buses. The scientific instruments of the two satellites will not be used, but some other systems are added. Verification and launch will be arranged in a way similar to Delfi-C3 and Delfi-n3Xt. The added systems are more sensors for attitude determination and an electric micro-propulsion system [16], [17] combined with basic attitude control for the Earth-Moon transit.

It is not very clear yet how to decide how many satellites are needed to obtain the desired self organization. To fill the large aperture, we consider 50 elements as an absolute minimum for the science experiment. The high number enforces the use of very small satellites as the individual elements of the array.

The nature of the mission sets some special requirements to the spacecraft:

- The absolute position in space is needed.
- The relative position to other satellites must be known. Centimeter accuracies are needed, even for the longer baselines in space.
- During the observations the attitude of the antennas must be stable enough.
- Good 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.

V. CONCLUSION

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 sent 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 satellite architecture design, design of radio architectures for the communication in distributed arrays and distributed autonomous signal processing.

In OLFAR we study 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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REFERENCES

- [1] M.J. Bentum, C.J.M. Verhoeven, A.J. Boonstra, A.J. van der Veen and E.K.A. Gill, *A Novel Astronomical Application for Formation Flying Small Satellites*, 60th International Astronautical Congress, Daejeon, Republic of Korea, 12-16 October, 2009.
- [2] C.J. Verhoeven, M.J. Bentum, J. Rotteveel and B. Monna, *On the Origin of satellite Swarms*, 60th International Astronautical Congress, Daejeon, Republic of Korea, 12-16 October, 2009.
- [3] A.J. Boonstra and A.J. van der Veen, *Gain calibration methods for radio telescope arrays*, IEEE Transactions on Signal Processing, 51(1):2538, January 2003.
- [4] E.K.A. Gill, G.L.E. Monna, J.M.A. Scherpen, and C.J.M. Verhoeven, *Misat: Designing a series of powerful small satellites based upon micro systems technology*, In 58th International Astronautical Congress, September 2007. IAC-07-B4.6.05.
- [5] A.W. Gunst and M.J. Bentum, *Signal processing aspects of the low frequency array*, In IEEE Conference on Signal Processing and Communications, November 2007.
- [6] A.W. Gunst and M.J. Bentum, *The Current Design of the LOFAR Instrument*, URSI-2008, Commission J8: Radio Astronomy, URSI General Assembly, Chicago, August 2008.
- [7] R.J. Hamann, C.J.M. Verhoeven, A.A. Vaartjes, and A.R. Bonnema, *Nanosatellites for microtechnology pre-qualification: The Delft program of Delft University of Technology*, In 6th Symposium on Small Satellites for Earth Observation, April 2007.
- [8] R. Manning, *Instrumentation for space-based low frequency radio astronomy*, In R.G. Stone et al., editor, *Radio Astronomy at Long Wavelengths*. American Geophysical Union, 2000. ISBN 0-87590-977-9.
- [9] J. Raza, A.J. Boonstra, and A.J. van der Veen, *Spatial filtering of RF interference in radio astronomy*, IEEE Signal Processing Letters, 9(2):6467, February 2002.
- [10] S. Jester and H. Falcke, *Science with a lunar low-frequency array: From the dark ages of the universe to nearby exoplanets*, *New Astronomy Reviews*, -, 2009.
- [11] ESA Very Low Frequency Astronomy Study Team, *Very Low Frequency Array on the Lunar Far Side*, Report, ESA, 1997.
- [12] B. Dennison et al, *The Low Frequency Space Array*, Naval Research Laboratory, Report 5905, December 26, 1986.
- [13] E. Nordholt and D. van Willigen, *A new approach to active antenna design*, IEEE Transactions on Antennas and Propagation, Vol. 28, No. 6, pp 904-910, November 1980.
- [14] E. Nordholt and D. van Willigen, *Active Aerial*, US Patent 4414690, 8 November 1983.
- [15] C.J.M. Verhoeven and W.J. Ubbels, *Delfi-C3, past, present and future*, in proceedings of ProRISC 2008, Veldhoven, The Netherlands, November 2008.
- [16] H.M. Sanders, J.M. Boscher, A.T. Hogedoorn, J.L.P.A. Moerel, B.T.C. Zandbergen and M.C. Louwerse, *System Analysis and Development of a Cool Gas Generator Based Micropropulsion System*, in proceedings of the ESA/ESTEC Workshop, Noorwijk, 2007.
- [17] E. van Breukelen, H.M. Sanders and C. Schuurbijs, *Cool Gas Micropropulsion System for Cubesats*, 60th International Astronautical Congress, Daejeon, Republic of Korea, 12-16 October, 2009.