Space-based Ultra-long Wavelength Radio Astronomy – an overview of today's initiatives

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Abstract

Space based ultra-long wavelength radio astronomy has recently gained interest. The need for large effective apertures spread over long ranges implies that advanced technologies are required, which is in reach at this moment. This together with the unexplored frequency band below 30 MHz makes these initiatives very interesting. Due to a combination of ionospheric scintillation below ~30MHz, its opaqueness below ~10MHz, and man-made radio frequency interference (RFI), earth-bound radio astronomy observations are either severely limited in sensitivity and spatial resolution or entirely impossible. In this paper we will present current initiatives to reach this new and unexplored low frequency band below 30 MHz.

1. Introduction

Low-frequency radio astronomy to date has focused its operation mainly on the frequency regime above ~30 MHz, for example LOFAR, the low frequency array [1]. Below 30 MHz, earth-based observations are limited due to a combination of severe ionospheric distortions, the complete reflection of radio waves below 10-30 MHz, solar eruptions and the radio frequency interference (RFI) of man-made signals [2]. There are however, a number of interesting scientific processes that naturally take place at these low frequencies. A space or Lunar based low-frequency radio array would suffer significantly less from these limitations and hence would open up the last, virtually unexplored frequency domain in the electromagnetic spectrum. This is a region of the electromagnetic spectrum which is essentially unexplored by astronomy. The only space-based observations done at low frequency are done by the Radio-Astronomy-Explorer 2 satellite in the seventies [3], but are very limited in resolution and sensitivity since it was a single antenna instrument. Opening this last region of the electromagnetic spectrum of at least three orders of magnitude, the likelihood of discovering new processes and objects is great.

In the past several concept studies and workshops have been started and organized [4..12], however, until today no real instrument is in operation yet. Recently new initiatives have been started. In this paper we will present these initiatives.

2. Science case

In a study by Jester and Falcke [13], inventories were made of low-frequency sciences cases below ~100 MHz. The first science case is cosmological studies. These studies predict spectral features related to changes in the early universe (Epoch of Reionization, dark ages) which in principle, assuming perfect calibration, 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' for frequencies of about 10 MHz. This corresponds to a satellite baseline length of 100 km.

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. The Solar system neighborhood, the "local bubble", is another galactic survey

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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 modeling observed emissivity.

3. Today's Initiatives

In this section we will summarize the current initiatives for space-based low frequency radio astronomy instruments.

3.1. DARIS

DARIS (Distributed Aperture Array for Radio Astronomy In Space) [14,15] is an ESA mission study aimed at conduction conduct radio astronomy in the low frequency region from 1-10MHz. DARIS focuses on extragalactic surveys of the low frequency sky, and can also detect some transient radio events such as solar or planetary bursts. To achieve these scientific objectives, DARIS comprises a space-based array, forming a very large effective aperture, as required for such a long wavelength survey. Each station in the array (each required to be a small satellite to ensure several nodes can be flown) carries three orthogonal dipole antennas, each 5m in length. The more station nodes in the array, the more sensitive the antenna. The entire fleet remains within a 100km diameter cloud.

A very large data volume is generated by each node, as the antennas have to capture all radio signals below 10 MHz, after which the data can be correlated to find the astronomical signal in the noise. As the astronomical signals also have a noise-like nature, no compression is possible on the data captured by the nodes. The data volume is too high to transfer directly to Earth, and will need to be correlated in space. Distributed correlation between the nodes is technically challenging, and therefore a mothership acts as the central correlator and then downlinks the correlated data (lower volume) to Earth.

A Soyuz launcher will allow several small satellites to be carried, with the mothership also carrying a set of the astronomical antennae. The current mass budget allows for 6 to 8 small satellites. The mothership will also act as the carrier craft to transport all the spacecraft to their final orbit. The nodes are small satellites (less than 100kg), and cannot carry much propellant. However, the nodes must remain in formation, requiring formation flying (defined as maintaining position to within a particular fraction of the wavelength being observed, which in this case is long). Therefore, significant effort was invested to find orbits where the satellites remain formation flying with little or no orbital maintenance. The position must not change by more than 3m within an integration period, which determines the maximum relative range rates.

3.2. FIRST

The FIRST Explorer [16] constellation study includes six daughter spacecraft with radio astronomy antennas, and a mother spacecraft for science and metrology data processing and communications. The location of the constellation at the second Lagrange point (L2) allows for a stable, low-drift orbit that is sufficiently far away from Earth to avoid severe radio frequency interference (RFI), while at the same being close enough to maintain operations using standard telemetry systems. A novel use of credit card sized mini solar sails on the spacecraft enables the constellation to stay within an overall mission envelope. The main science objective of this pathfinder mission is to provide an all-sky survey at very low radio frequencies, which cannot be observed from the ground; because the ionosphere effectively acts like a shield for frequencies below ~10 MHz.

3.3. SURO

SURO is a Space-based Ultra-long wavelength Radio Observatory [17] proposal, consisting of a low cost and low maintenance formation of nine slowly moving spacecraft, each with tripole antennas, forming the distributed aperture elements of the radio telescope - eight spherically distributed Daughters and one central Mothership - locked in a low relative-drift stable orbit. This facility, long wished for by astronomers, can now be achieved at low cost using current established and small spacecraft engineering solutions. SURO will operate in the virtually un-explored frequency domain, which is inaccessible from Earth, by avoiding ionospheric blocking and man-made radio frequency interference. The SURO telescope will provide the first extra-galactic low-frequency survey with high sensitivity (down to 55 mJy over 1 year) and high resolution (1.1 arcmin @ 30 km) to give it the potential to detect up to 2 million new sources, and provide a new tool to research questions in a diverse range of scientific areas.

SURO has three main observing modes: a) All-Sky Imaging with omnidirectional spatial resolution of the sky, time resolution of 1-10 seconds and a frequency range from 0.1 MHz up to 30 MHz, b) Rapid Burst Monitoring using all sky imaging and 100 ms integrations for responding to rapid solar and galactic events, and c) Targeted Burst Monitoring, a beamforming mode to phase the array for observation of transient radio sources and variable planetary emissions.

3.4. OLFAR

In the previous three projects the focus was on technology available at this moment, with an outlook and technological development plan/roadmap to be exploited for the future. Using current-day technologies, a space-based low-frequency array would be bulky and, thus, costly. A logical next step would be to investigate possibilities to miniaturize the electronics and use very small satellites, perhaps even nano satellites with masses between 1-10 kg to build the radio telescope. The approach is to use a swarm of satellites to establish a virtual telescope to perform the astronomical task. This is investigated in the OLFAR (Orbiting Low Frequency Array) project [2,18..20]. The OLFAR radio telescope will be composed of an antenna array based on satellites deployed at a location where the Earth's interference is limited, and where the satellites can be maintained in a three-dimensional configuration with a maximum diameter of 100 km. A Moon orbit could be suitable option.

Each individual satellite 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 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 RFI mitigation algorithms (if necessary), and finally, correlate the data in a phased array mode. If more satellites are available, they will automatically join the array. The final correlated or beam-formed data will be sent to Earth as part of the telemetry data using a radio link. As the satellites will be far away from Earth, communication to and from Earth will require diversity communication schemes, using all the individual satellites together.

5. Discussion

The results of the DARIS and FIRST studies are very promising. Building a very large effective receiving antenna aperture in space was concluded to be feasible. This is especially the case for ultra long wavelengths as the localization accuracies are not extremely stringent. The focus of the DARIS concept study was 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. The focus of the FIRST study was to use a free flying drifting constellation. The study selected the L2 Lagrange point and concluded that it is feasible to build a radio telescope based on a free-flying drifting constellation.

The FIRST and DARIS study teams worked together on the SURO proposal. With today’s technology a radio telescope in space, consisting of 8 small satellites and a mothership, is feasible.

A satellite cluster of nine nodes is scientifically very interesting. To enlarge the science case even more, we should scale up the array to a larger number of satellite nodes, and to an extended frequency range and instantaneous bandwidth. This is in principle possible, but with current-day technologies this would increase mass and costs significantly. More research is needed in significantly reducing the mass and costs of each satellite node. This is the main driver of the OLFAR project. In the OLFAR project the following aspects will be researched:

- The design an implementation of a highly potential micro-propulsion system that enables the orbit change , orbit control, and further maneuverability, which includes reliable end-of-life solutions to mitigate potential increase of orbital debris.
- The design and implementation of the hardware and software needed for control.
- The design and implementation of a (deep)space navigation system. Using highly miniaturized star trackers, or novel new technologies.
- The formulation of a systems engineering theory that is tailor made for efficient and reliable design of small-satellites and small-satellite constellations.
- The development of high speed and robust RF Inter-satellite communications techniques.

- Cooperative satellite-swarm to Earth communications.
- Antenna design for low frequency reception.
- Development of efficient imaging techniques.

The first results in the OLFAR project are already obtained and will be published soon. One of the results is the development of a novel localization algorithm to determine the position (and baseline) of each of the satellites.

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