A FEASIBILITY STUDY FOR A VERY LOW FREQUENCY SATELLITE BASED RADIO INTERFEROMETER

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Abstract

Due to the non transparency of the Earth's ionosphere, the parts of the electromagnetic spectrum lower than few tens of MHz can be explored only using an interferometer placed above it. With the rapid advances in the technology in the past few years, a satellite based low frequency interferometer of significant scientific merit no longer seems a distant dream. We have started a feasibility study for such a space mission. The main goal is to estimate the parameters of an interferometer which can be realised in near future. The straw-man design emerging from this on-going study is presented.

Introduction

Although radio astronomy was born at the low frequency of $20.5\ MHz$ in the 1930s, it moved rapidly towards higher frequencies in a quest for higher resolution, better sensitivity and lesser problems due to the ionosphere. The interest in the low frequency radio band is now reawakening as it remains the last window of the electromagnetic spectrum, accessible from the Earth, yet to be explored systematically. Radical and ambitious ground based low frequency radio interferometer projects like LOFAR and SKA are in advanced stages of consideration.

Below about $30\ MHz$, ionospheric absorption and refraction make imaging of cosmic sources from ground based telescopes extremely difficult. By about $10\ MHz$, the ionosphere is opaque almost all the time practically all over the Earth. It is beyond doubt that for sensitive observations at these frequencies there will be no alternative but to go above the ionosphere. A space based radio interferometer providing radio imaging of the sky with a respectable angular resolution, at frequencies below the ionospheric cutoff, will throw open this last unexplored part of the electromagnetic spectrum. This idea has been explored earlier as well, for instance in [1, 2, 3, 4]. With the rapid advances in the space qualified technology, formation flying capabilities and computational resources it is now prudent to reassess the feasibility of such a mission. We are in the process of conducting such a study, which aims at laying down the design and performance parameters for a scientifically desirable satellite based radio interferometer expected to become feasible in near future.

This study, named *COnstellation Dedicated to Radio-Interferometry in Space* (CODRIS), is a collaborative effort between three French institutes: the Laboratoire de Physique et Chimie de l'Environnement (LPCE), the Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA) from the Paris-Meudon Observatory and the Nançay radio astronomy station.

Scientific Objectives

The 0.3–$3\ MHz$ frequency band is about as different from the well explored 0.3–$3\ GHz$ radio astronomy band, as the infra red band is from the ultra violet. There is ample scientific justification for investigating this part of the electromagnetic spectrum. The subject has been discussed at length in a few dedicated publications and we refer the reader to them for details [5, 6, 7]. We merely note that the areas to which such a mission can contribute range widely, from the studies of the Sun and the Planets, Galactic and Extra-galactic objects to Earth's own magnetosphere and the Auroral Kilometric Radiation.

One can justifiably expect to find some previously unknown and radically different phenomena, new sources of coherent radio emission and very steep spectrum sources unseen at higher frequencies. This mission will, hence, have a considerable discovery potential, as is expected from a first exploration of a new part of the spectrum.

It is important to realise that there have been no interferometric measurements in this part of the spectrum. The few observations in this spectral region have been from individual spacecraft and hence at too coarse a resolution to yield any detailed information. The multi frequency all sky images produced by this mission will be an improvement by more than two orders of magnitude in resolution and a similar amount in sensitivity.

Straw-man Configuration

We envisage the space based interferometer to comprise of a fleet of about 16 free floating satellites. The performance parameters of astronomical interest and some technical details are given along with brief justifications of the choices made and the anticipated challenges to be met.

Frequency Range – The lower limit of the frequency range for the space interferometer has been chosen to be about $0.1\ MHz$, to remain comfortably above the plasma frequency of the Interplanetary Medium (IPM), known to be about a few tens of kHz at $1\ AU$. The higher frequency limit comes from the fact that it will be much more economical and scientifically rewarding to use the more powerful and versatile ground based low frequency instruments like LOFAR by about $30\ MHz$. None the less, we advocate an overlap in the frequency ranges covered by the space array and the ground based instruments and suggest $50\ MHz$ as the upper frequency limit for the space array. This will allow the space array to benefit from the information of the sky obtained by the ground based array. A reliable and detailed model for the low frequency sky will provide a very good anchor point from where to boot strap to proceed to even lower frequencies.

Field of View – In order to keep the project economically feasible, we envisage the space array to be a cluster of *micro-satellites*. This inevitably imposes strict constraints on the weight and power budget available. The very large wavelengths corresponding to the frequency range under consideration and the necessity of deploying the cluster in space restrict the choice of the interferometer element to a *short dipole antenna*. Each of the micro-satellites will be equipped with three, mutually orthogonal, short dipoles, in order to capture all the information in the electromagnetic field impinging on the satellite. A short dipole is usually not a preferred choice for an interferometer element at higher frequencies because of it's fractionally large contribution to the system temperature, T_{sys}, but in this frequency range, the Galactic background emission is so strong that it dominates the T_{sys} by far [8]. The choice of the interferometer elements specifies the field of view, or the primary beam size, for the array and for a short dipole it is $8\pi/3\ sr$, about $27 \times 10^{3} deg^2$.

Baseline range – The resolution of the interferometer is usually determined by its longest baseline. However, at these frequencies for baselines longer than about a hundred km, the angular resolution achieved, in most directions, is limited not by the baseline length but by the angular broadening due to the plasma of the Interstellar Medium (ISM) and the IPM [9]. We envisage maximum baselines of the order of several tens of km. A convenient number to note is that a baseline of $20\ km$ provides a resolution of 1° at $1\ MHz$. In addition, to be sensitive to the expected strong large scale emission and for Solar studies, baselines as short as about half a km are essential.

Data Analysis Strategy – No existing radio interferometer has ever needed to map a field of view which covers practically the entire sky. Rather than trying to limit the field of view, we prefer the approach of mapping the whole of it simultaneously. This choice is a major driver for the interferometer design. It necessarily requires that the visibilities receive correlated contribution from all parts of the field of view. However, due to the finite bandwidth of observation, the signal from regions away from the phase center tends to get decorrelated. This effect, described by the *Fringe washing function*, can be reduced satisfactorily by correlating signal over sufficiently narrow bandwidths, $\sim kHz$ for the present case.

The visibilities, gridded over the three dimensional *u-v-w* space, can be related to a three dimensional *Image volume* by a three dimensional *Fourier transform* [10]. The intersection of the image volume with a unit sphere represents the celestial sphere, the object of our interest. This allows the possibility of imaging the entire $4\pi\ sr$ by performing a three dimensional fourier transform of visibility cube. The dimensions of the visibility cube can be arrived using the criteria that the resulting image volume should have enough resolution to Nyquist sample the entire sky with the resolution of the cluster. Though this approach provides a satisfactory and elegant solution to the problem of whole sky mapping, it has not been considered feasible in the past because it required performing fourier transforms of dimensions beyond the capabilities of the computing power available then. With the continuing rapid and enormous increase in the computing power available, this will now be the preferred approach for data analysis. An alternative strategy, based on the approach proposed for LOFAR [11] can also be considered. This approach, often referred to as *Patch processing*, relies on dividing the field of view into smaller patches and imaging each of them individually. A *Global Sky Model*, a large database of suitably

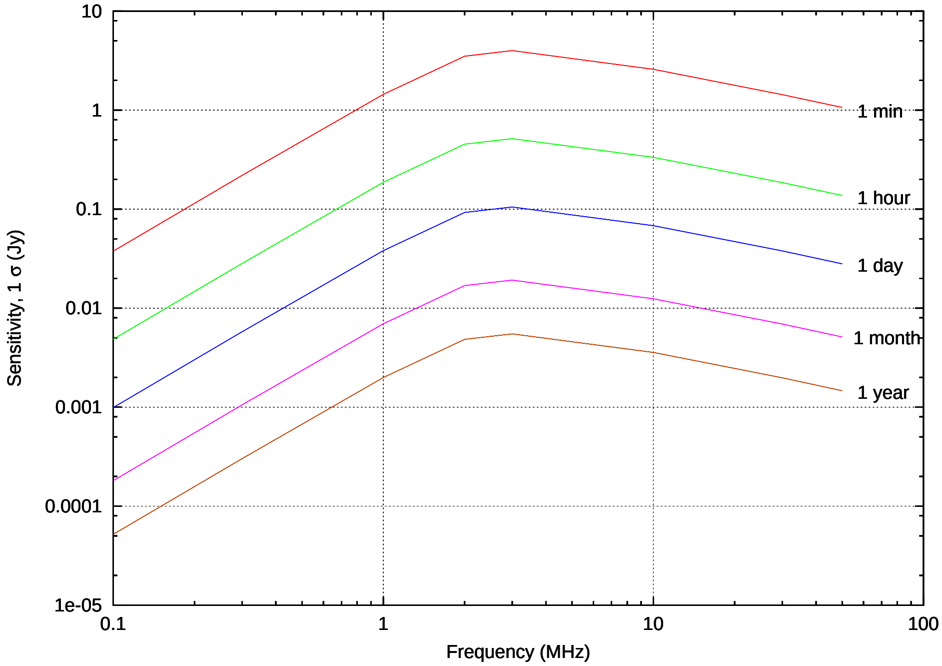

Figure 1: **Point source sensitivity in the frequency range of interest as a function of integration time** – These curves show 1σ levels and correspond to a cluster of 16 satellites, each equipped with 3 dipoles. A 2 MHz radio frequency bandwidth has been assumed for each of the dipoles.

parameterised information about the sources in the low frequency sky, is used to predict and subtract the contributions of sources outside the patch from the visibilities before mapping.

Bandwidth of Observations – As mentioned earlier, it is necessary to construct visibilities using narrow spectral channels, no more than a few kHz wide. The advances in the *Digital Signal Processing* (DSP) hardware provide a very powerful and flexible way of achieving this in near future. Using suitable DSP schemes, it is possible to achieve the required spectral bandwidth of about a kHz over the entire bandwidth from $\sim 0-50$ MHz simultaneously. The actual bandwidth of observations would be a few MHz and it will be possible to select an arbitrary sub set of frequency channels. A very useful feature of the DSP schemes is that they allow one to maximise the advantage of *Multi-frequency synthesis* which helps offset the disadvantage of having a small number of instantaneous baselines (16 satellites yield 120 instantaneous baselines). By spreading the individual frequency channels judiciously over the digitised radio frequency band one can cover the *u-v-w* volume much more efficiently. A more uniform and complete sampling of the *u-v-w* volume leads to a synthesised beam with lower side lobe levels which is very desirable.

Sensitivity – The sensitivity of an interferometer is the RMS fluctuations on the thermal noise which it achieves. It is proportional to T_{sys} and inversely proportional to the root of the product of bandwidth and the duration of observation, the effective collecting area of the interferometer elements and the number of baselines used. The point source sensitivity achieved by the proposed design for the space array, using the Galactic Background emission as given in [8] is shown in Figure 1. The described configuration yields a sensitivity of about 1 Jy at 1 MHz for 1 min of integration time.

Cluster Configuration – The unique demand of simultaneous omni-directional imaging poses an unprecedented requirement for the cluster configuration. In order to meet such a demand the spatial distribution of satellites must yield a good *u-v-w* coverage for all directions at all times. This implies that the space distribution of the satellites should not have a preferred direction and a spherical distribution suggests itself as a natural candidate. A quasi uniform distribution of satellites on a spherical surface, first proposed by Steve Unwin, has come to be known as *Unwin sphere* in the literature [1]. However such a distribution does not ensure that the small baseline constraint is respected. Modified cluster configuration based on the Unwin sphere concept are under study. The final compromise configuration will be arrived at by simulations.

Choice of Orbit – In order to keep it feasible to maintain the distribution of satellites roughly on the surface of a sphere for the entire duration of the mission, it is necessary to restrict the choice of orbits to those where the differential gravity over the length scales of the cluster size is very low. Therefore, only distant Earth orbits are of interest for this mission. We consider the Distant Retrograde Orbit and a halo orbit around the L1 Lagrange point suitable candidates for this mission.

Telemetry requirements – It is a major challenge to achieve the telemetry bandwidth required to bring home the data from space array within the constraints of a *micro-satellite* based approach. A telemetry bandwidth of $8\ Mbps$ (Mega bits per sec) is regarded as within reach. Using this bandwidth to transmit Nyquist sampled time series from each of the 3 dipoles leads to bandwidths of observations of about $85\ kHz$. Constructing the visibilities on-board and averaging over them for only $1\ sec$ reduces the data rate by 25 (using $1.5\ kHz$ wide spectral channels and a 16 bit representation for complex visibilities). Thus, respecting the same telemetry constraints, it provides us with more than $2\ MHz$ bandwidth of observation. Longer time integration will lead to a linear gain in bandwidth of observation.

Conclusion

Even with versatile and powerful instruments like LOFAR, envisaged to commence full scale operation in this decade, pushing low frequency radio astronomy to its furthest limits achievable from the ground, there will remain a significant and scientifically interesting part of the electromagnetic spectrum accessible only from above the ionosphere. A space based array will benefit considerably from the knowledge of the low frequency sky gained from such ground based arrays and will in turn provide information complementary to that obtained from ground. With the steady increase in performance of space qualified hardware and formation flying and computing capabilities, the demands of a satellite based interferometer seem within reach in near future. It is, hence, timely to lay down the specifications for a space low frequency interferometer, based on realistic expectations for technology available in near future and access its scientific desirability.

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