ALL-SKY RADIO SETI.

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Over the last decade, Aperture Arrays (AA) have successfully replaced parabolic dishes as the technology of choice at low radio frequencies. AA based telescopes present several advantages, including sensitivity to the sky over a very wide field-of-view. As digital and data processing systems continue to advance, an all-sky capability is set to emerge, even at GHz frequencies. We argue that if SETI events are both very rare and transitory in nature, an instrument with a large field-of-view, operating around the so-called "water-hole" (~ 1-2 GHz), might offer several advantages over contemporary radio searches. Prototype instruments are currently being developed under the auspices of the Square Kilometre Array (SKA) project. Their potential to transform the field of traditional radio-based SETI research programmes is only matched by the enormous data flows generated – the latter can only be fully exploited via the use of advanced AI (artificial intelligence) systems.

1. SETI and Aperture Arrays

The Search for Extraterrestrial Intelligence (SETI) is a scientific pursuit that has been undergoing a significant revival for several years now, accelerated by initiatives such as the recent establishment of the Breakthrough Listen (BL) project [1]. BL is expected to invest ~ 100M$ in the field over the next 10 years, and has recently embarked on ambitious surveys of the sky using the Greenbank and Parkes radio telescopes. In addition, the rapid development of radio astronomy capabilities in general, in key areas such as sensitivity, wavelength coverage, and spatial/spectral/temporal resolution is also very encouraging. It seems humankind is now better placed than ever before, to make a SETI detection using these new instruments.

The BL project currently focuses on surveys using large parabolic telescopes. While this maximises sensitivity in a particular direction, the field-of-view is set by the diameter of the dish – so bigger, more sensitive telescopes, produce narrower beams. The use of aperture array technology promises to create telescopes with both good sensitivity and a wide field-of-view. Aperture arrays are formed from a network of many thousands of individual antennas (e.g. simple dipoles) that are combined together electronically, with appropriate delays applied to each antenna, maximising sensitivity in a particular direction on the sky. Since each individual antenna is sensitive to the whole sky (or something close to that), additional electronics can form multiple-beams, resulting in sensitivity (gain) to many different directions simultaneously. In principle, an aperture array can provide all-sky coverage, given the right architecture and sufficient electronic processing power (data sampling, digitisation and beam forming). The concept of forming a parabolic dish electronically permits us to consider an aperture of gigantic proportions, pointing in many directions simultaneously. Such a huge and highly sensitive aperture also has no moving parts and can point to any area of sky almost instantaneously.

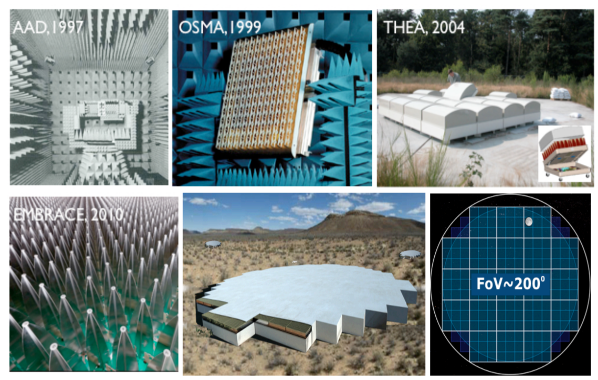

Fig.1 Some of the engineering test systems that have advanced the development of Aperture Array technology for radio astronomy under the leadership of ASTRON [9]. Far right: The SKA MFFA pathfinder MANTIS.

Impressive progress has already been made in realising such systems at lower frequencies (typically < 300 MHz) e.g. LOFAR [2] and its "all-sky" derivative AARTFAAC [3], the MWA (Tingay [4]) and LWA [5]. At GHz frequencies various small-scale engineering systems have shown good results e.g. Argus [6], and most recently the EMBRACE system has demonstrated that a large-scale aperture array system capable of making competitive astronomical measurements is now within reach [7-9]. What is absolutely clear is that so long as data sampling and processing costs continues to fall, the construction of a scientifically productive large aperture array operating at GHz frequencies becomes more a question of when and not if. Fig. 1 presents the advance of aperture array technology operating at cm wavelengths through the last few decades.

2. SETI event rates and the need for field-of-view

Searches for SETI signals have been on-going for many decades [10]. So far these searches have proven unsuccessful e.g. [11], despite the fact that the figure of merit of the associated instrumentation has increased by at least 6 orders of magnitude. In particular, major advances have been made in terms of raw sensitivity, instantaneous bandwidth and spatial, spectral & temporal resolution. These advances, coupled with much greater back-end processing power have permitted radio astronomers to detect a range of periodic or transitory phenomena to be discovered such as pulsars, singular giant pulses, rotating radio transients, and most recently, Fast Radio Bursts (FRBs) [12].

The lack of progress in detecting a SETI signal suggests that emissions from advanced extraterrestrial technologies are extremely rare. Such a conclusion is reinforced by the pristine nature of our own solar system and the lack of evidence for the signatures of Kardashev Type II and Type III civilisations [13] in astronomical data [14] – [18]. All the evidence suggests that advanced civilisations (even Type I civilisations) located in the Milky Way Galaxy might be very rare indeed. If the SETI source counts are similar to cosmic source populations (e.g. AGN), we might expect to find a few very rare events that occasionally lie well above our sensitivity threshold but many more events that lie below it. If this scenario is correct, and if SETI signals are also transitory in nature, any reasonable SETI Figure of Merit must strive to maximize both the telescope's sensitivity but also its field-of-view.

A good example of the importance of field-of-view is the study of FRBs. FRBs are relatively bright flashes of radio emission that last for a few milliseconds, and although the phenomena that gives rise to these events is as yet unknown, the timescales involved suggest that they are related to the coalescence of massive compact objects. Despite the fact that we have only detected a handful of FRBs to date (around 31 at the time of writing), it is estimated that the total event rate (across the sky) is ~ 5000 events per day (~ 1 ever 20 seconds) [19]. The reason that we only detect a tiny fraction of these events is directly related to the limited field of view of traditional, parabolic telescopes. Compared to other metrics (e.g. instantaneous bandwidth and spectral resolution), field-of-view is one area in which progress in radio astronomy has been rather modest.

The history of the detection of FRBs is also a timely reminder that although our capacity to detect transient objects is now greatly improved over the last decade, there is still a long way to go. We also still have a lot to learn about the nature of the transient radio sky – in hindsight, it is perhaps not so very surprising that we have yet to detect a SETI signal.

3. First steps towards an 'all-sky" radio SETI capability

Mid-Frequency Aperture Arrays (MFAA) are expected to form a major component of the next generation technology required to realise the SKA-2. MANTIS (Mid-Frequency Aperture Array Transient and Intensity-Mapping System) [20] is a proposed SKA-2 precursor that could represent the first step towards an all-sky radio SETI capability at GHz frequencies. The MANTIS telescope would be located in South Africa, alongside the SKA-1 and the SKA1 precursor, MeerKAT.

The current ambition is to realise a collecting area of around 1500-2000 square metres using of order 250000 antennas. The preliminary specifications of the MANTIS telescope are presented below:

- System Equivalent Flux Density (SEFD): 74 - 44 Jy.
- Frequency range: 0.45-1.45 GHz.
- Bandwidth: 500 MHz.
- Optical Field-of-View: 200 sq. degrees at 1 GHz.

The proposed location of MANTIS is at the SKA site in South Africa, specifically the area known as "K4". This has the advantage that the telescope can also act as an "early-warning" transient detector for both MeerKAT and SKA1-mid. SETI research is a stated goal of the SKA [21] and the MANTIS precursor with such a the large field-of-view can be seen as a first step towards an all-sky radio SETI capability at these frequencies. For the most part, SETI observations could run commensally with other astronomical observations.

4. Summary

The emergence of highly capable and flexible Mid-Frequency Aperture Arrays (MFAA) with a large field-of-view can be very important for all manner of astronomical research, but in particular SETI. The recent detection of FRBs is a useful example with which to explore the range of parameter space that traditional SETI research programmes need to probe. The proposed MANTIS MFAA precursor represents a step towards realising an all-sky radio SETI capability. This is not the first time such an instrument has been proposed, the great scientific visionary, Sir Arthur C. Clarke, proposed something very similar (though at much lower frequencies) in his book Imperial Minds [22]. Large-scale conventional SETI radio searches e.g. [1] are only now beginning to make a small dent in the vast parameter space that such searches represent. So far, we have barely scraped the tip of the proverbial iceberg. If SETI events are both rare and transient in nature, an all-sky instrument could represent the type of technology breakthrough that transforms the field.

5. Additional Information

This paper suggests that an all-sky SETI serarch capability might be important in realizing a conventional detection of artificial ETI radio signals that may be rare in our own Galaxy and other extragalactic systems. There are several aspects of this work that are relevant to the *Alien Mindscape* article [23]:

- The proposed methodology makes no assumption about the location of the signal – all sky coverage does not require potentially biased target selection procedures to be made.
- All-sky coverage attempts to mitigate against the non-astronomical factors in the Drake equation being small, including the communicating lifetime of a civilization, *L*.
- The approach is unconventional because it prioritises field-of-view over other areas of parameter space that are historically more favoured (e.g. frequency coverage & sensitivity) – in other words it assumes that while SETI events could be very rare, they are not (necessarily) faint.
- While the "all-sky" approach continues the traditional search for "life as we know it", it seems reasonable that any form of communicating intelligence will be restricted to the same laws of physics and technologies as we are, especially so if *L* is small. Searching for artificial radio signals that are readily detectable on galactic (and perhaps even intergalactic) scales, remains a powerful tool for SETI research.
- Finally, we note that an all-sky SETI radio instrument would generate enormous data flows in excess of 1 exabyte/day. Advanced forms of AI and Machine Learning will be required in order to fully exploit the data unbiasedly.

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