

Site Testing Issues for the Frequency Agile Solar Radiotelescope

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ABSTRACT

The Frequency Agile Solar Radiotelescope (FASR) will be a broadband synthesis imaging array with 3 km or larger baselines, operating over a broad frequency range of 0.1-30 GHz. The instrument demands a site with low levels of Radio Frequency Interference (RFI) over this entire band. The site also must be large enough to accommodate the expected size of the array configuration and ideally would provide room to grow with future upgrades. The site must have a benign environment in which at least 100 separate elements will operate with little degradation and weather-related downtime. Several sites in the U.S. are being considered. We discuss what criteria are being used to assess the sites, and give some initial results of testing some of the sites.

Keywords: Sun, radio instrumentation

1. INTRODUCTION

A number of new concepts for radio arrays operating in the microwave and lower frequency range are currently being pursued, and because of their similar mode of operation they share many common site requirements. The new concepts include

1. the Allan Telescope Array¹ (ATA), being built by the SETI Institute;
2. the Low Frequency Array² (LOFAR), being studied by an international consortium including the Naval Research Lab and Massachusetts Institute of Technology in the United States, and ASTRON in the Netherlands;
3. the Square Kilometer Array³ (SKA), being studied by groups in the U.S., Canada, The Netherlands, China, and Australia;
4. the Frequency Agile Solar Radiotelescope^{4,5,6} (FASR), the subject of this paper.

To this list might be added the Extended VLA project⁷, which will greatly increase the bandwidth of the currently operating Very Large Array. Common characteristics of these instruments that are relevant to site selection are: (i) large numbers of antennas; (ii) very broad bandwidths; and (iii) continuous frequency coverage.

The first common characteristic—large numbers of antennas—drives the need for the site to have a benign weather environment with low moisture. This is because the impact of failures due to rust, corrosion, leakage of moisture into cables and the like, are magnified due to the large number of systems in the field. With of order 100 elements, the FASR design must minimize the burden of regular maintenance tasks, and this cannot be accomplished in a hostile environment.

The second common characteristic—very broad bandwidths—drives the need for the site to be in a radio-quiet area that minimizes band occupancy of Radio Frequency Interference (RFI). The requirement for FASR is somewhat less extreme than for some of the other instruments, because the FASR system temperature for normal operation is set by the high flux density of the Sun. However, narrowband communication signals can be so strong that they still dominate the band power, and FASR also needs to observe calibration sources at lower system temperature, so a clean RFI environment is highly desired.

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What this means in practical terms is that the site must be far from population centers, ideally with nearby mountains that block direct line-of-sight signals from more distant population centers. Paradoxically, however, using very broad bandwidths (of order several GHz) can actually reduce the gain compression effects of strong, isolated narrowband interference by making such interference a smaller part of the integrated band power.

The third common characteristic—continuous frequency coverage—plays a similar role as the broad bandwidth characteristic discussed above in defining the site characteristics. But this also means that the instrument is going to be operating well away from the protected astronomy bands. Therefore, siting the array within a designated radio-quiet-zone would be advantageous. No matter where the instrument is sited, however, RFI from communications satellites cannot be avoided. This means that, beyond a certain level, algorithms for excising RFI in real time or in post processing will be required anyway, and so a certain level of ground-based interference may not add significantly to the overall problem.

In addition to these site characteristics driven by the new designs being studied, there are other site characteristics that are needed for logistical reasons. These are: land availability (parcel size, usage restrictions) and suitability (latitude, topography, natural or man-made obstacles); existing infrastructure (buildings, roads, power and data links); and accessibility (travel time from major airports, heavy equipment access).

This paper describes some of these issues in more detail, for the specific case of FASR. In section 2 we describe the FASR instrument concept in more detail. In section 3 we discuss progress to date in testing various sites, and some of the reasons for selecting them for testing. In section 4 we look in more depth at RFI studies and their impact on site selection. We conclude in section 5 with a discussion of future site testing plans.

2. THE FREQUENCY AGILE SOLAR RADIOTELESCOPE

Before giving details of site selection and testing, it is necessary to give a short overview of the planned instrument. As mentioned in the introduction, FASR is a multi-frequency (~0.1-30 GHz) imaging array composed of many (~100) antennas. It is designed specifically for observing the Sun. It will produce high-quality images of the Sun with high spatial resolution (1" at 20 GHz), high spectral resolution ($dv/v \sim 0.01-0.03$), and high time resolution (<1 s), across more than two decades in frequency. In so doing, it will produce a continuous, three-dimensional record of the solar atmosphere from the chromosphere up into the mid-corona.

These qualities represent a quantum leap beyond existing solar radio instruments, yet are well within reach of emerging technologies. The range of science that can be addressed by such an instrument is as broad as solar physics itself. Virtually every solar feature from within a few hundred km of the visible surface of the Sun to high up in the solar corona can be studied in detail with the unique diagnostics available in the radio regime. Particular diagnostics include measuring coronal magnetic field strengths in active regions and elsewhere (coronal magnetography), measuring the properties of both thermal and nonthermal electrons accelerated in solar flares from the largest events to the tiniest microflares/nanoflares, and mapping kinetic electron temperatures/energies throughout the chromosphere and corona. Details of the instrument and the science to be addressed can be found in the paper by Bastian⁶ in these proceedings.

The specific design of the FASR instrument is still being worked out, but the current thinking is that at least two separate designs for the individual antenna elements will be required to cover the full frequency range. For example, an array of "fat dipoles"⁷ may be used at low frequencies (~0.1-0.5 GHz), while an array of ~100 dish reflectors of order 5 meters in diameter may be used from 0.5-30 GHz. A compact central array of smaller dishes may be needed at 1-30 GHz to fill in the large spatial scales. Of most relevance to site selection, the maximum baseline will be of order 5 km, and the necessity for good snapshot imaging requires an array configuration that does a good job of filling the aperture. Thus, the site must provide a roughly circular land area of diameter about 5 km.

Because the instrument is optimized to observe the Sun, it must have a nearly circular synthesized beam for declinations from +23.5 to -23.5 degrees. This suggests a low-latitude site. Combined with the requirements mentioned in the introduction that the site have a dry, benign environment, far from population centers, and yet be easily accessible to users, this strongly suggests the choice of a site in the southwestern United States. The beam can be made more circular by elongating the N-S extent of the array.

3. SITES AND SITE TESTING FOR FASR

FASR is currently in a “Phase A” study meant to refine the basic design and overall cost to a precision that will allow a follow-on proposal for detailed design and construction. The selection and evaluation of potential sites is at an early stage, and considerable additional work is required to fully characterize each site. However, some rough characterization has been done for some sites, and further selection and testing is underway. We present a progress report in this section, in order of depth of study of the sites.

3.1 Owens Valley Radio Observatory, Big Pine, CA

One of the instruments that provides the inspiration for FASR is the Owens Valley Solar Array (OVSA) instrument at the Owens Valley Radio Observatory (OVRO). The OVRO site is an excellent one for cm- λ radio astronomy for several reasons: (i) it is a flat valley floor between two 4300 m mountain ranges, and is well isolated from population centers; (ii) the local climate is dry, with little precipitation; (iii) the local population density is low *and static* due to the fact that the water in the valley is owned by the Los Angeles Department of Water and Power (DWP), limiting the number of people who can be supported by the valley; (iv) it is already the site of considerable radio astronomy infrastructure; and (v) it is currently the site of the Caltech mm array, which within the next few years will combine with the Berkeley-Illinois-Maryland Array (BIMA) to become the Combined Array for Research in Millimeter-wave Astronomy (CARMA). By then, the existing dishes will have been vacated from the site, leaving it fully available for development of a new instrument. Under this scenario the current OVSA instrument could be used as a prototyping and testing instrument for the development of FASR, and would eventually be replaced by FASR.

It is natural, therefore, that the OVRO site would be the first one to be investigated in detail. The main problem is that the existing site is too small to fully enclose the entire instrument. Additional land would have to be added. The land is currently leased from DWP for scientific use, and all of the adjoining land is also owned by DWP, so a dialog was initiated with the local DWP office in 2002 March to investigate whether it is possible to enlarge the lease. The result of these discussions was that additional land might be available, but that the array should not cross the Owens River, which borders the western side of the existing lease. A topological map with a circular area of 3 km is shown in Figure 1, relative to the existing OVRO site lease boundaries. The figure shows that the restriction of not crossing the river means that a 5 km array will not be possible, and even a 3 km array gets uncomfortably close to the mountains on the east side of the valley. An antenna near the eastern edge of a 3 km array would have a maximum horizon of about 22°, and sunrise would occur at considerably different times for different parts of the array. At present, it appears that the OVRO site is a viable site only if the array can cross the Owens River. Further discussion is planned with DWP to see if there are some conditions under which some antennas could be allowed on the west side of the river. There will likely be increased costs associated with locating some antennas across the river, but these may be more than offset by cost savings in infrastructure, so it is worth investigating further.

One can get a better feeling for what FASR might look like on the OVRO site from the artist’s conception in Figure 2. This 3D view uses a correct digital elevation map (DEM) to represent the mountains to the east, and shows one possible array configuration—a three-armed log-periodic spiral. In this artist’s conception, the small white dishes are 3 m in size, and the large wire-mesh antennas are 6 m in size. This is an earlier design that differs from the design suggested in § 2, where fat dipoles are called for instead of the wire-mesh antennas.

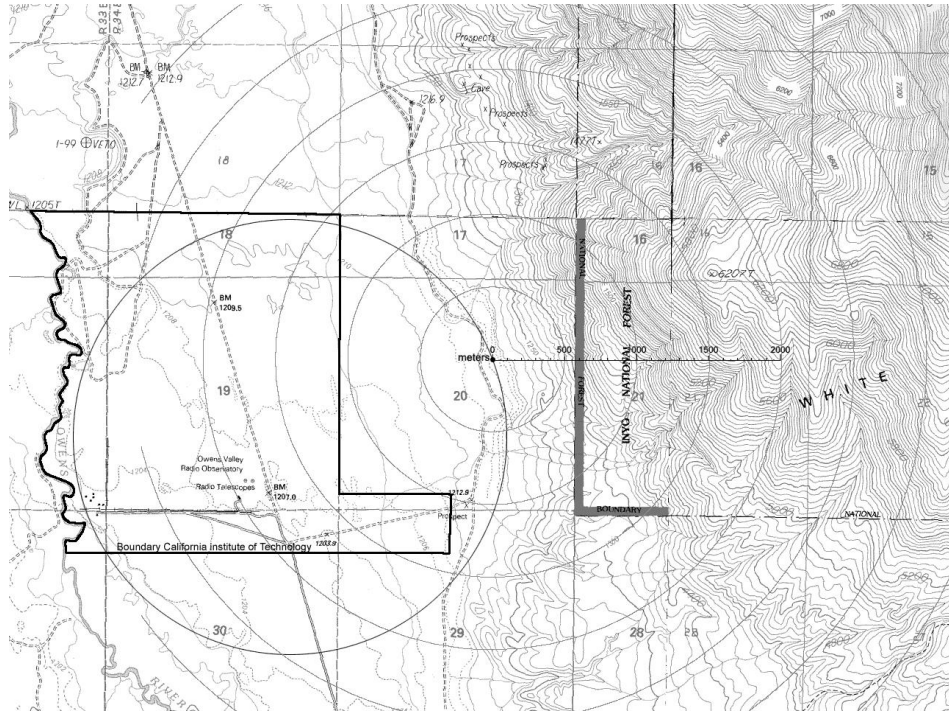


Figure 1. Topographical map of the area near and to the east of the current OVRO site lease boundaries (outlined in the heavy black line). The circle shown by the thick solid curve is 3 km in diameter and shows how a roughly circular 3 km area might fit on the site. FASR could be situated within this circle and remain on relatively level ground without crossing the Owens River. The thin, concentric circles are drawn every 500 m, centered on a point on the eastern rim of the 3 km circle, in order to show the horizon due to the nearby mountains. An antenna at this point in the eastern edge of the array would have a maximum eastern horizon of about 22° , and sunrise would occur at considerably different times for different parts of the array. A 5 km circle cannot be accommodated at OVRO without crossing the river.

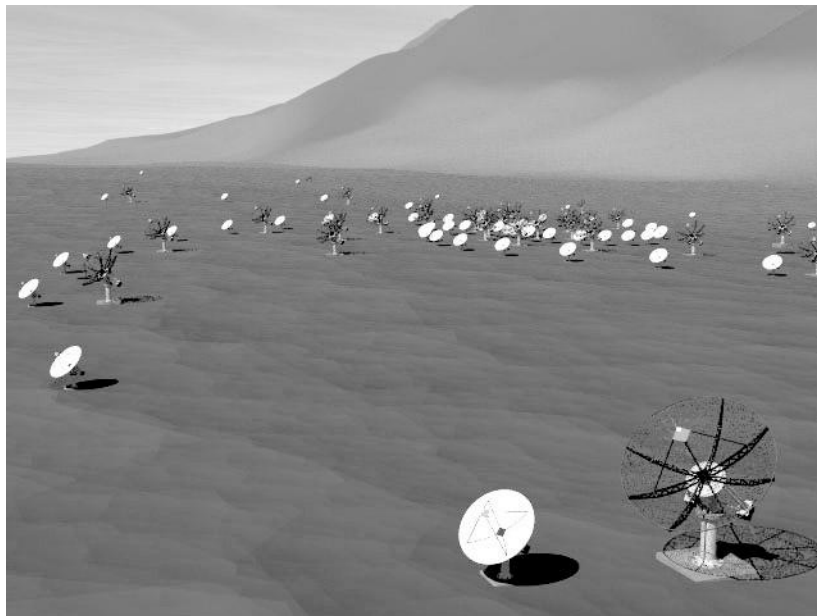


Figure 2. Artist's conception of what one version of FASR might look like on the OVRO site. This is a view looking northeast, and the array configuration is a three-armed log spiral.

Because of the long experience with the frequency-agile OVSA instrument at the OVRO site, we have a good idea of the interference environment in the OVSA operating frequency range from 1-18 GHz. Figure 3 shows the receiver plus sky amplitude (in arbitrary units), including several intervals of strong interference (saturated at 2047 units). New RFI has appeared in the past year near 2.0 GHz, probably due to a transponder at the small airport in Bishop, about 20 km away. These signals are measured with a 2m diameter antenna pointing near the zenith. Additional interference can be expected from satellites, especially geosynchronous communication satellites (which are found near -5.8° declination at the OVRO site).

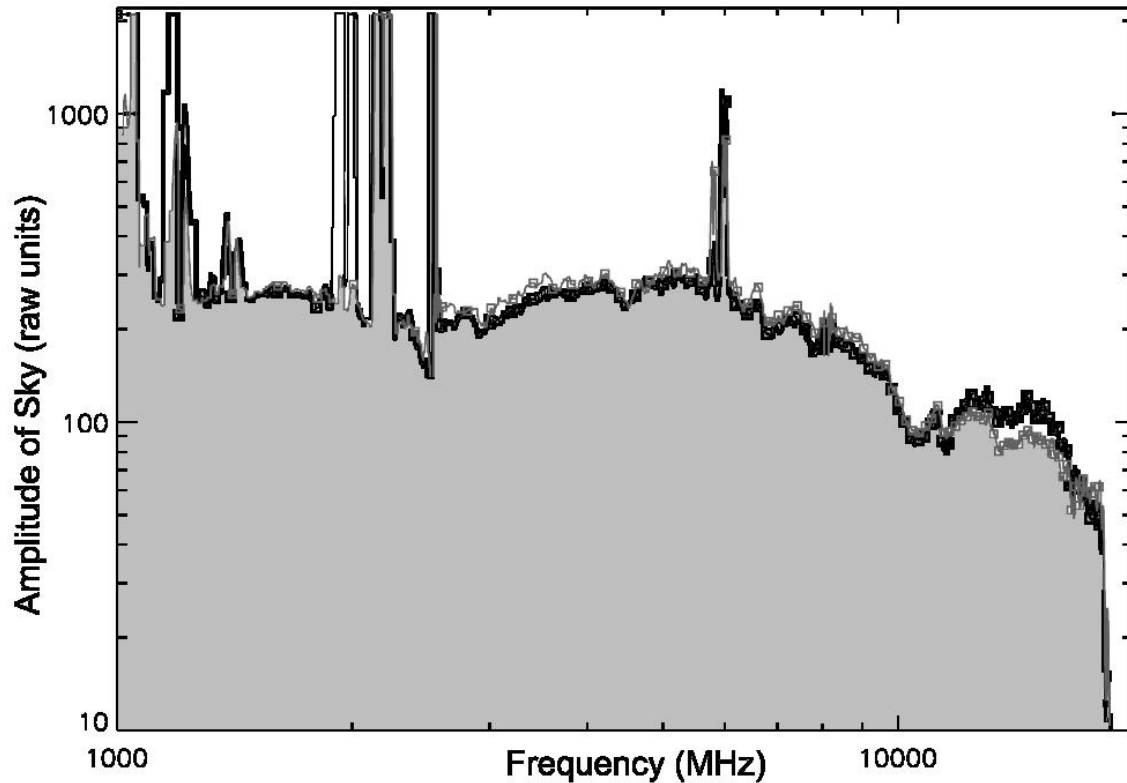


Figure 3. Receiver plus sky amplitude spectrum showing RFI at the OVSA site in the range 1-18 GHz. The RFI spikes appear much broader than they actually are, and double-peaked, because they are convolved with the dual sideband OVSA bandpass of 60 MHz. Two spectra are shown taken one year apart, in February 2001 (gray) and February 2002 (black). New interference spikes near 1.2 and 2.0 GHz are present in 2002 that were not present earlier.

A more thorough testing of RFI is planned at the OVRO site and all other sites to be considered for FASR. This includes expanding the coverage to include the important range 0.1-1 GHz, a far narrower-band sweep, a higher time cadence to determine channel occupancy, and a more omni-directional reception pattern. See §4 for more details on RFI testing.

3.2 LOFAR Sites in the U.S. Southwest

A number of sites are being considered for the LOFAR instrument by the “southwest” consortium, comprising individuals from University of New Mexico, Los Alamos National Labs, New Mexico State University, New Mexico Institute of Mining and Technology, and University of Texas. The FASR site survey team is coordinating with the SW consortium to consider some of these sites as possible FASR sites. There are several advantages to such coordination since, as mentioned in the Introduction, LOFAR and FASR share many of the same requirements for a site. There is also sufficient overlap in science (since LOFAR can dedicate one of its multiple beams to the Sun), technology (at least the low-frequency part of FASR could use the fat dipole technology envisioned for LOFAR, and the two share similar problems with

the ionosphere and RFI excision), and logistical requirements (site maintenance and personnel) that co-locating FASR and LOFAR could be advantageous.

The LOFAR instrument comprises approximately 100 “stations,” with each station being a phased array of about 100 individual elements. The entire LOFAR array would be about 400 km across. The plan is that FASR could share a site with one of the stations, perhaps the highly condensed central station. Even if the LOFAR instrument should ultimately be constructed at one of the other sites (Europe and western Australia are also being contemplated), it now appears likely that the SW consortium will be involved with prototyping activities that could lead to developing a joint site with FASR.

The sites being considered by the SW consortium are parcels of land owned in New Mexico or West Texas by one of the institutions involved in the consortium. The VLA site is also being considered. Each site is relatively isolated, radio quiet, and enjoys a dry climate with mild winters. The sites are currently being surveyed for RFI characteristics from 30 MHz to 2 GHz by the SW consortium. We plan to extend the RFI studies to 18 GHz in order to cover most of the FASR frequency range.

3.3 Other Sites

Other sites may also be considered for FASR. For example, the Green Bank site is in a radio quiet zone, and has more than the requisite infrastructure. However, preliminary investigation of the area available for an instrument suggests that a roughly circular area with 5 km maximum baseline is not possible. Additional sites in the southwestern United States, and possibly in other areas, will be considered as they are identified. One possibility is to locate FASR in an area close to the location of the new optical solar telescope, the Advanced Technology Solar Telescope (ATST), or at least close to the operating center at National Solar Observatory (currently in New Mexico), to allow joint and coordinated operations.

4. NON-LOCAL RADIO FREQUENCY INTERFERENCE

As mentioned in the Introduction, even sites with minimal local interference will still be subjected to ubiquitous interference from communications satellites in low-Earth and geosynchronous orbits. Given the need to deal with these sources of interference, a certain level of ground-based interference may not add significantly to the overall problem. It is necessary to consider such ubiquitous RFI in the design of the instrument, and in subsequent post-processing of the data. This is now a widely recognized problem in radio astronomy⁸, and a number of algorithms are being developed to deal with the problem.

The first place that RFI can cause problems for radio arrays is at the front end, where the integrated band power must not cause saturation or gain compression of the first or second stage amplifiers. For broadband amplifiers, isolated strong but narrow lines may not cause a sizable integrated power increase, and hence can be tolerated. When the interference channels become too many or too strong, however, it may be necessary to devise notch filters to exclude the problem frequencies. For FASR, which will have amplifier set points appropriate to the solar power, a reasonably quiet local environment should be all that is necessary to avoid amplifier gain compression.

Even when the front-end amplifiers remain in their linear response regime, strong interference can cause severe gain compression in the backend sampler and digital electronics. Since FASR is designed for the strong solar signal, in the absence of RFI it is possible to use one-bit correlation and live with the 63% correlation efficiency that entails. However, in the presence of strong RFI, the digital sampling will have to be done at many bits to give the amplitude precision required to faithfully reproduce both strong and weak signals. One approach is to implement an FX correlator, with the “F” part performed at many bits. Then channels with strong interference would be detected in real time and discarded, so that only clean channels are selected for further correlation (the “X” part) at one bit. However, the detailed FASR architecture has yet to be decided.

Even when the above steps are implemented, weak and intermittent RFI can still find its way into the data and reduce the dynamic range of the final maps. Because FASR is to automatically make images in a pipelined post-processing mode, it will be extremely important to implement robust methods for identifying and removing weak interference in real time. One technique that is being considered for the ATA,

LOFAR, and SKA is the ability to “steer” a null in the synthesized beam (so-called spatial filtering⁸) in the direction of an expected (or detected) interfering source. This might be adapted for fast moving sources such as Iridium or GPS satellites, for example, but it requires certain capabilities to be built into the correlator or post-processing algorithms. It has not yet been decided whether this is a viable technique for FASR, since FASR will not normally be operating in a “beam forming” mode like the above-mentioned instruments. Other RFI mitigation techniques mentioned by Fridman and Baan⁸ include thresholding (removing strong interference due to its power being outside some limits), temporal and spectral filtering, and using an external RFI monitoring antenna for adaptive interference cancellation. Each of these techniques may be somewhat problematic for the Sun, since the real solar signal can include narrowband, very spiky variations and even semi-regular pulsations.

5. CONCLUSIONS

The Frequency Agile Solar Radiotelescope is an instrument that has certain characteristics in common with other newly proposed instruments, which are all multi-element arrays operating at a wide range of frequencies with large instantaneous bandwidth. We have listed the issues for selecting a site that such arrays face in general. Although the task of selecting and evaluating sites for FASR is in its early stages, we have made some early progress. In particular, we have found the following:

1. The Owens Valley Radio Observatory is in many respects an ideal location, with a fortuitous opportunity of using the site for a new instrument brought about by the CARMA project. However, in order to make the site large enough for FASR, we will have to negotiate use of land on the west side of the Owens River, across the river from the current site.
2. Several sites in New Mexico and the southwestern U. S. are being evaluated for possible LOFAR station sites, and it may be possible to use one of these sites for FASR.
3. Even in the case where LOFAR and FASR do not share a site, the experience in evaluating RFI will be useful to the FASR site selection, so the FASR site survey team is collaborating with the LOFAR SW consortium and will expand the frequency range of the survey to higher frequencies of interest to FASR.
4. The RFI surveys are at some level a moot point, since even locally radio-quiet sites will still be exposed to ubiquitous RFI from overflying communications satellites. Therefore, RFI mitigation strategies are necessary, and allowance for certain strategies need to be made at the early design stage.

Because FASR is not the sole instrument with these problems to overcome, we expect to collaborate with other groups who are also seeking to solve them. The recent and future advances in computing and high-speed electronics is opening a new era in signal processing, and should make the problem of RFI excision addressable in real time. By careful selection of a radio quiet site, careful design of the instrument with RFI excision in mind, and fast post-processing of the data, we can be confident that FASR will meet its design goals of high dynamic range spectroscopic imaging in near real time.

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