Progress on the Frequency Agile Solar Radiotelescope

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ABSTRACT

The Frequency Agile Solar Radiotelescope (FASR) is a solar-dedicated, ground based, interferometric array optimized to perform broadband imaging spectroscopy from $\sim 0.1 - 30+$ GHz. It will do so with the angular, spectral, and temporal resolution required to exploit radio emission from the Sun as a diagnostic of the wide variety of astrophysical processes that occur there. FASR represents a major advance over existing radioheliographs, and is expected to remain the world's premier solar radio instrument for two decades or more after completion. FASR will be a versatile and powerful instrument, providing unique data to a broad users community. Solar, solar-terrestrial, and space physicists will exploit FASR to attack a broad science program, including problems of fundamental interest: coronal magnetography, solar flares and particle acceleration, drivers of space weather, and the thermal structure and dynamics of the solar atmosphere. A design study and implementation planning are underway. Recent progress is reviewed here.

Keywords: radio interferometry, spectroscopy, broadband data transmission, optical fibers, digital signal processing

1. INTRODUCTION

The *Frequency Agile Solar Radiotelescope* (FASR) is a solar-dedicated radio interferometric array which combines superior imaging capabilities with broad frequency coverage and high time resolution. The major observational advance offered by the FASR, therefore, is that it will provide the brightness temperature spectrum and its polarization at every point within the field of view of the instrument, and its evolution in time. Solar-optimized imaging spectroscopy will revolutionize our view of the solar chromosphere and corona and the astrophysical processes which occur there. This is because FASR will use a variety of radio diagnostic tools to perform coronal magnetography, study magnetic energy release, particle acceleration and transport, study coronal mass ejections and associated phenomena such as MHD shocks and filament eruptions, and map the thermal structure and dynamics of the solar chromosphere. In addition to its priority mission as a basic research instrument, FASR will provide important, unique, and timely data products for use in forecasting solar activity.

A design study of the instrument and implementation planning for construction of the instrument are underway. These activities are described in §2. A summary of the main science drivers of the instrument design is given in §3. The resulting instrument requirements and goals are established in §4. Strawman concepts for the instrument are reviewed in §5 and concluding remarks are presented in §6.

2. FASR DESIGN STUDY AND IMPLEMENTATION PLAN

In preparation for a proposal for the construction of FASR, a NSF-funded, two-year study of the instrument design and implementation planning commenced in 2002. The design study will produce a detailed strawman system design, sufficient to evaluate instrument subsystems, to weigh available or anticipated technologies and their associated risks against the science requirements and costs, and to identify preferred and "fallback" options for each critical subsystem of the instrument. These include a detailed assessment of array antennas and their mounts and drives, broadband feeds and front ends, IF/LO and data transmission, and digital signal processing.

A number of additional studies are also being carried out. These include: 1) A site survey, in which potential sites for the instrument are identified and characterized[1]; 2) Configuration studies, to identify the optimum size(s) and configuration(s) of antennas that meet the science requirements; 3) Calibration strategies,

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to identify one or more schemes to calibrate antenna pointing, baselines, complex gain, polarization, bandpass, etc.; 4) Data management, including pipelined calibration, reduction, and archiving; 5) Science simulations and data visualization, to develop new inversion and analysis tools to exploit the fundamentally new type of data that FASR will produce.[2]

To guide these activities, the FASR Project has sought the active participation of the wider solar physics community. A *Science Definition Workshop* was held at the NRAO in Green Bank, WV, in May 2002. The first *FASR Technical Meeting* was held at the NRAO in Charlottesville, VA, in August 2002. The first *Data Management Meeting* will take place in spring, 2003.

3. FASR SCIENCE DRIVERS

The Sun confronts us with number of outstanding problems. Of fundamental importance is understanding the origin of solar activity - flares, coronal mass ejections, and related phenomena. These, in turn, yield a fascinating array of phenomena such as plasma heating, particle acceleration, collisional/collisionless shocks, wave-particle interactions, coherent MHD oscillations, and more, all of broad astrophysical interest. Solar activity is also of practical interest because it drives space weather, manifestations of which have a direct impact on the near-Earth environment.

Most, if not all, solar activity is believed to be magnetic in origin. Hence, an understanding of solar activity requires an understanding of the creation, emergence, and evolution of magnetic fields in the Sun and in the solar atmosphere, and of the closely related problems of magnetic energy storage and release. Frustrating attempts to achieve the requisite understanding of solar magnetic fields has been the fact that observations of solar magnetic fields have been largely limited to observations of the Zeeman effect in photospheric and chromospheric lines. Information on magnetic fields above and below these layers is by indirect means of limited reliability. It is of critical interest to develop and exploit new observational and analysis techniques to measure magnetic fields well above and below the photosphere. FASR offers the means to measure magnetic fields above the photosphere.

The key science priority of FASR, therefore, is to 1) measure coronal magnetic fields. A variety of techniques are available for this purpose, briefly summarized below. From this top priority follow the next two priority science drivers: 2) solar activity and drivers of space weather. This includes fundamental processes in solar flares – energy release, plasma heating, particle acceleration and transport – and 3) coronal mass ejections, filament eruptions, MHD shocks, and associated phenomena. A final key science driver is 4) understanding the thermal structure and dynamics of the "quiet" solar atmosphere – how the chromosphere and corona are heated and the origin of the solar wind. We briefly discuss each of these drivers.

3.1. Coronal magnetography

Radio observations offer a number of tools for measuring or constraining the coronal magnetic field. The most straightforward of these is to perform imaging spectroscopy of gyroresonance absorption. This measurement utilizes the fact that gyroresonance emission renders the corona optically thick in regions of strong magnetic field ($\gtrsim$150 G). At a given frequency the radio emission originates from a very thin layer of constant magnetic field strength in the corona. The magnitude of the magnetic field can be obtained at the base of the corona along a given line of sight by measuring the break frequency in the spectrum of thermal gyroresonance emission where the electron temperature drops to sub-coronal values. In this way a two-dimensional map of the magnetic field strength at the base of the corona can be constructed in any region where $B \gtrsim 150$ G. The lower limit is determined by the fact that at low frequencies, free-free absorption eventually dominates along the line of sight.

FASR observations will, in addition, impose constraints on the vector magnetic field and its evolution in active regions. The particular isogauss level at which the corona is rendered optically thick to gyroresonance absorption depends on the magnetoionic mode of the radiation (ordinary or extraordinary) and the orientation of the field. The dense spectral coverage provided by FASR provides complete sampling of the coronal volume over active regions. Inversion of the gyroresonance spectrum or forward modeling of the same is an active research area.

Another observational diagnostic of magnetic fields in the corona is optically thin free-free radiation. The degree of circular polarization is linearly proportional to the longitudinal component of the magnetic field.

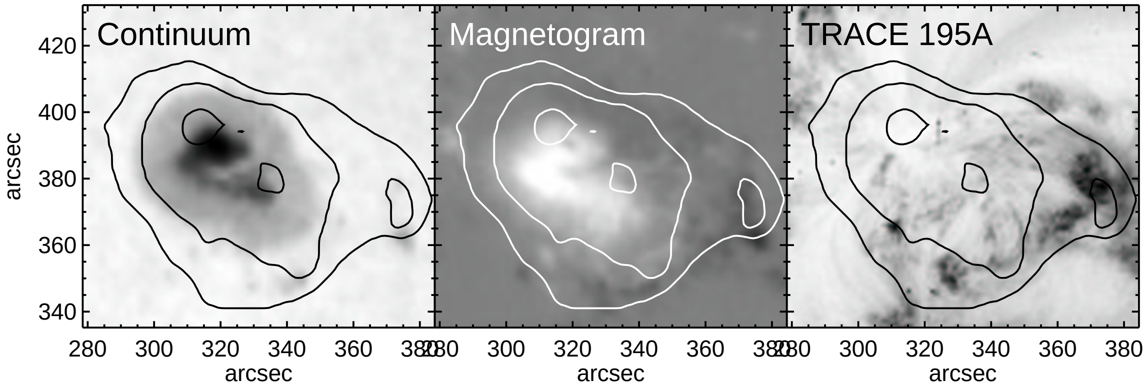

Figure 1. An example of a crude coronal magnetogram. In each panel the contours show the magnetic field strength at the base of the corona at field strengths of 600, 1000 and 1800 G. The contours are overlaid on (left) an optical continuum image, (middle) a longitudinal magnetogram (both from SOHO/MDI), and (right) a TRACE 195 Å Fe XII image. The contours are derived from VLA images of the active region at 5, 8 and 15 GHz and represent the boundaries where the gyroresonance surfaces at those field strengths drop below the corona. This is the best coronal magnetogram that can be obtained with the Very Large Array due to its sparse frequency coverage. FASR's broad frequency coverage and 1% frequency resolution will yield a vast improvement.

This diagnostic is less direct than gyroresonance absorption because it involves a line-of-sight integral over the electron number density and the longitudinal magnetic field. Nevertheless, it can provide an important constraint to the magnetic field in some circumstances.

FASR observations can also exploit mode coupling properties of radio radiation. When radio waves traverses a magnetic field wherein the longitudinal field component changes sign, the polarization of the radiation may reverse, depending on whether the coupling between the ordinary and extraordinary modes is strong or weak. As seen in projection against the Sun by a distant observer, the line which demarcates the reversal in the sense of circular polarization is called the "depolarization strip".[3] Using the frequency agility of the FASR, a "depolarization sheet" can be deduced above active regions over the frequency range where circularly polarized emission is present, thereby providing additional constraints on the nature of magnetic fields in the solar corona.

Magnetic field measurements will also play a critical role in understanding flares and CMEs. We address this issue below.

3.2. Solar flares

Flares involve the catastrophic release of energy in the low corona. Plasma is heated and particles are accelerated to relativistic energies on short time scales. A large flare may require the acceleration of $\approx 10^{37}$ electrons s^{-1} to energies > 20 keV for periods of tens of seconds. The study of flares offers one of the best available means of observing energy storage, energy release, particle acceleration, wave–particle interaction and particle transport in an astrophysical plasma in detail and under a variety of conditions.

FASR will, for the first time, allow full exploitation of microwave/decimetric emission for flare studies. Moreover, it will provide an *integrated* view of the role of coherent burst emissions at decimeter wavelengths and the incoherent gyrosynchotron and thermal free-free emission at centimeter wavelengths. The possibilities are numerous and exciting.

3.2.1. Location and properties of the energy release site

Work over the past decade, in large part at radio wavelengths, has demonstrated that energy release in solar flares is fundamentally a *fragmentary* process. Multitudes of type III and reverse drift type III bursts— resulting from bidirectional electron beams—accompany the impulsive phase of energy release in many flares.[4] The decimetric type III bursts are believed to be intimately related to the primary energy release, with each beam

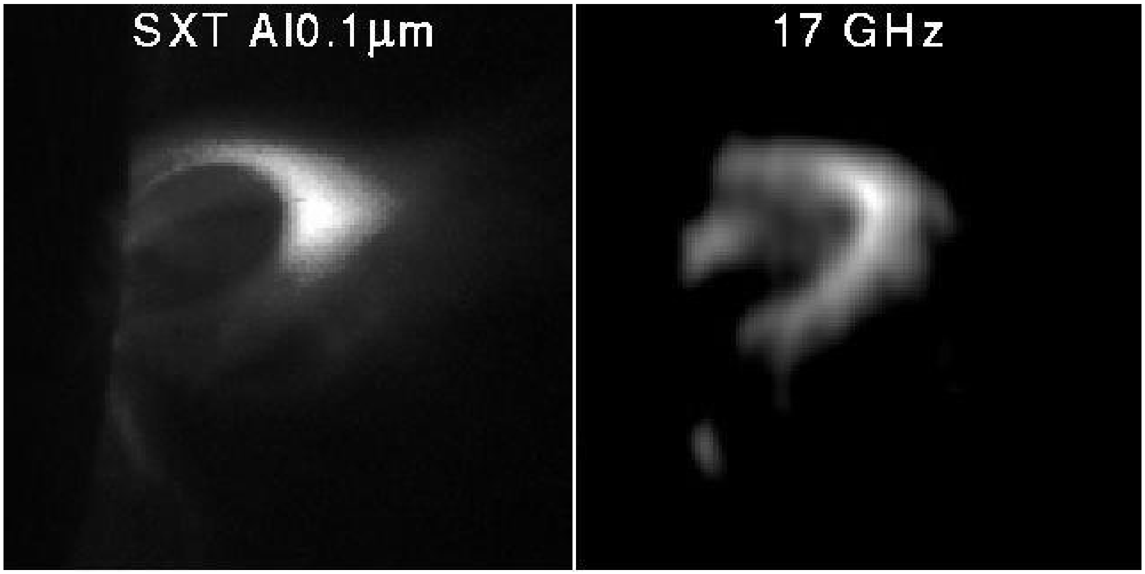

Figure 2. Example of a long duration flare observed on the west limb on 16 March 1993. *Yohkoh* soft-x-ray observations are show in the left-hand panel and 17 GHz observations made by the Nobeyama radiohelograph are shown in the right-hand panel (from Hanaoka 1994).

perhaps corresponding to an elementary energy release event. While spectroscopic observations of classical and reverse-drift type IIIs during flares have been performed, they have rarely been imaged directly at decimeter wavelengths, and then only at fixed frequencies. The most interesting information is the energy release site, the location where the type III and reverse-drift type III is initiated. Since this could be at any frequency over the decimetric range (but most typically in the 500–1000 MHz range), this can only be done with a broadband telescope such as FASR. Furthermore, broadband imaging spectroscopy will allow the trajectories of both upward and downward electron beams to be traced out in the flaring volume. The trajectory mapping will provide the means of identifying the location of the energy release, the electron number density in the energy release site, and will trace out the density along the electron beam trajectory. These measurements will place important, new, and unique constraints on the location and physical properties of the energy release site, on the relevant magnetic topology, and on the nature of the energy release process itself.

3.2.2. Magnetic field in the flaring volume

Microwave emission in flares is due to incoherent gyrosynchrotron emission from electrons with energies of several 10s of keV to several Mev that have been injected into coronal magnetic loops. The peak spectral frequency ν_{pk} at a given location depends sensitively on the local magnetic field strength and the angle between the line of sight and the local magnetic field vector. It typically occurs between 5-15 GHz. Joint observations of ν_{pk} and the source polarization will allow the magnetic field strength and orientation to be inferred for the flaring source as a function of time. Additional and independent constraints are available on the magnetic field. An example is the use of timing comparisons between HXR and microwave emissions which "calibrate" the harmonic of the emitting electrons as a function of location in the source and hence, the magnetic field.[5] No other techniques are available for this purpose.

3.2.3. Electron acceleration and transport

The microwave spectrum is a powerful diagnostic of the details of the emitting distribution of energetic electrons. The optically thin part of the spectrum is sensitive to the details of the electron distribution function, including high energy cutoffs and anisotropies. It is also worth pointing out that, due to the dispersive properties of coronal magnetic loops,[6] the relative timing of temporal features at different frequencies offers an additional diagnostic of acceleration and transport. In particular, joint microwave/HXR observations can be used to determine the roles of Coulomb collisions and wave-particle interactions (e.g., whistler waves) to pitch-angle scattering and electron acceleration in flares. Although space based HXR imagers provide images of the nonthermal HXR emission from $\lesssim 10$ keV to MeV energies (e.g., RHESSI), these emissions originate from precipitation points, where fast electrons impact the dense atmosphere at the foot points of flaring magnetic loops. In contrast, FASR will image emission whenever and wherever energetic electrons are present in the flaring volume.

3.2.4. Chromospheric ablation

Electrons accelerated to high energies can stream along the coronal magnetic field to the chromosphere if their pitch angle is sufficiently small. There, they collide with the relatively dense, cold, plasma and produce HXR emission via nonthermal bremsstrahlung. The electrons are thermalized and heat the chromospheric plasma which is ablated into the corona where it emits copious SXRs. In addition to diagnosing the magnetic field and the details of the energetic electron population, spatially and spectrally resolved radio observations over a broad frequency range offer a means of probing the changing density of the ambient plasma due to chromospheric ablation. Razin suppression depends on the density of the ambient plasma and the local magnetic field strength. Since the magnetic field will be constrained by other means, the ambient density may be inferred as a function of position and time during the course of a flare. An alternate and independent means of probing chromospheric ablation is to exploit the interaction of reverse-slope type IIIdm bursts with the ablated material.[7]

3.3. Drivers of space weather

The influence of solar activity on the Earth and near-Earth environment through particles, fast solar wind streams, shock waves, and coronal mass ejections (CMEs) is called space weather. The study of space weather is coordinated by the multi-agency National Space Weather Program. The ability to detect and study CMEs and associated shocks (via type II Radio bursts) at their time of initiation at the Sun is a key science goal for FASR. At frequencies below about 3 GHz, FASR will be a powerful tool for studying coronal mass ejections both on and off the disk of the Sun. CMEs should be detectable both for their thermal emission and through their nonthermal emission.[8] The power of observing nonthermal emission from CMEs has been demonstrated recently with the imaging nonthermal emission from a fast coronal mass ejection by the Nançay Radioheliograph in France[9] at frequencies between 164-432 MHz. The nonthermal gyrosynchrotron emission observed from this CME, resulting from electrons with energies of several MeV, traced the radio counterpart to the white light CME. The origin of the fast electrons is currently unknown. They may have been shock accelerated or accelerated in the associated flare. An exciting diagnostic provided by observations of this kind is the use of the Razin spectral cutoff to measure the CME magnetic field strength and the CME plasma density high in the corona.

Perhaps the most exciting possibility with FASR observations is that high-dynamic range spectroscopic imaging over a broad band will provide an integrated picture of the CME and associated phenomena, including the erupting filament (in microaves), the associated flare (microwaves and decimeter wavelengths), and shock waves - either blast-driven or piston driven. With regard to the latter, shocks are diagnosed by the plasma radiation the associated type II radio burst emits. The plasma frequency is proportional to the square root of the electron number density. The entire shock structure and its relation to the CME will be revealed by FASR broadband imaging observations. Longstanding and controversial problems regarding the initiation of CMEs, shock formation, and shock acceleration of particles will be addressed by such observations.

3.4. Thermal structure and dynamics of the solar atmosphere

One of the fundamental questions in solar physics is how the solar corona maintains its high temperature of several million Kelvin above a surface with a temperature of 6000 K. The power needed to maintain the corona above an active region against radiation and conduction losses is $> 10^{28}$ erg s^{-1}. The leading theoretical ideas for how the corona is heated is either some form of resonant wave heating[10] or "nanoflares",[11] although many other models exist. FASR will provide observational inputs with which to test these, and other types of model.

Wave heating models make specific predictions of where and on what time scales energy deposition occurs in coronal magnetic loops. The FASR will provide a detailed history of the temperature, density, and magnetic field in coronal loops in active regions, from which the rate of energy deposition can be calculated as a function of position and time.

The role of "nanoflares" – tiny, flare-like releases of energy from small magnetic reconnection events – depends critically on the rate at which such events occur. Numerous studies have shown that X-ray events ranging over as much as five orders of magnitude in energy, from 10^{27} to 10^{32} erg, form a single power law with slope 1.5-1.6. Smaller events cannot be energetically significant relative to the larger events unless the rate distribution at lower energies becomes significantly steeper. It is therefore of critical importance to characterize the distribution and energy content of the smallest energy release events on the Sun.

Recent observational work in this area at radio wavelengths has been promising. Numerous observations of microflares in active regions have been carried out in active regions at SXR and radio wavelengths.[12–14] VLA, SOHO EIT, and SOHO MDI data have been used to show that even tiny transient events in the quiet chromospheric network are, in fact, flare-like.[15] To date, however, the observations have been insufficient to determine the contribution of these tiny flare-like events to the coronal heating energy budget. The counting statistics and frequency coverage have been inadequate. The FASR will greatly improve on previous work by providing vastly better frequency coverage, counting statistics, and a sensitivity comparable to the VLA.

The chromosphere will be a particularly interesting target for the FASR. In recent years it has become evident that the prevailing semi-empirical chromospheric models, largely based on non-LTE UV/EUV line and IR/submm/mm continuum observations and computed under the assumption of hydrostatic equilibrium, are in stark disagreement with observations in bands of carbon monoxide (CO) and with microwave observations. In particular, observations of the CO molecule near 4.7μm show that the low-chromosphere contains a substantial amount of cool (3800 K) material leading to the view that the chromosphere is fundamentally bifurcated between cool and hot material.[16] Accurate broadband microwave (1–18 GHz) spectroscopy of the quiet Sun[17] convincingly demonstrates that the prevailing semi-empirical models include an over-abundance of warm chromospheric material.[18]

These developments have caused the solar community to re-think the solar chromosphere. Schematic multi-component models have been proposed which emphasize the pervasive cool component in the solar atmosphere.[16] Another approach has recognized that chromospheric dynamics play a critical role in understanding the structure of the chromosphere.[19] Testing of modern chromospheric models require spatially and temporally resolved observations of the thermal state of the chromosphere on the relevant spatial and temporal scales.

FASR will observe the thermal structure of the chromosphere down to the height where $T_e \sim 8000$ K. FASR will provide high quality maps of the mean thermal state of the chromosphere over its entire frequency range. FASR observations will therefore provide a comprehensive specification of the thermal structure of the chromosphere—in coronal holes, quiet regions, enhanced network, plages—as an input for modern models of the inhomogeneous and dynamic chromosphere.

3.5. Science requirements

FASR will be a high-resolution, fixed-configuration, Fourier synthesis array. Solar radio emission varies on short time scales and excellent snapshot imaging is therefore required. Many Fourier components of the radio brightness distribution must therefore be measured instantaneously, implying the need for a large number of interferometers and, hence, antennas. The key science summarized above imposes several requirements on the instrument. These are given here without detailed justification:

1. **Field of view**: A FOV of at least 3 degrees at 1 GHz is required, implying an antenna size of < 7 m.
2. **Angular resolution**: An angular resolution of $20"/\nu_9$ is required, implying a projected antenna baseline length of 3 km.
3. **Maximum angular scale**: Angular scales up to $40'$, corresponding to baselines of 86λ, must be measured (or accurately inferred).
4. **Frequency range**: 0.5-18 GHz.

5. **Spectral resolution**: A spectral resolution of 0.1% is required for frequencies < 3 GHz; this can be relaxed to 1% for frequencies > 3 GHz.
6. **Time resolution**: A time resolution of 10 ms is required for frequencies < 3 GHz. A time resolution of 100 ms is required for frequencies > 3 GHz.
7. **Polarization**: The Stokes I and V parameters are the required observables. An instrumental polarization < 5% is required from 2–18 GHz, reduced to less than 1% after calibration.
8. **Calibration**: Flux calibration with an accuracy of 5% is required between 2–18 GHz. A relative calibration (frequency to frequency) of 1% is required.
9. **Imaging**: A dynamic range $> 10^4 : 1$ is required during flares. A dynamic range of $1000 : 1$ is required for quiet Sun imaging in the presence of coronal brightness temperatures.

The brightness distribution and range of brightness temperatures varies dramatically with frequency on the quiet Sun. The requirement on image dynamic range given can perhaps be better stated as: we require an rms brightness temperature variation of no more than 1000 K in snapshot images. In the presence of flares, we regard the specification of $> 10^4 : 1$ as something that must be achieved routinely. We expect many cases where we will be able to do considerably better than the requirement.

4. INSTRUMENT REQUIREMENTS AND GOALS

Table 1. FASR instrument requirements and goals

	Requirement	Goal
Number antennas	$\sim$100	
Size antennas	< 7 m	
Angular resolution	$20''/\nu_9$	$20''/\nu_9$ (> 3 GHz)
Angular resolution		$2'/\nu_6$ (< 3 GHz)
Maximum angular scale	$40'$	
Frequency range	0.5–18 GHz	0.1-30+ GHz
Frequency resolution	0.1% (< 3 GHz) 1% (> 3 GHz)	
Time resolution	10 ms (< 3 GHz) 100 ms (> 3 GHz)	1 ms (< 3 GHz)
Polarization	**I, V**	**I, Q, U, V**
Signal dynamic range	20-40 dB	
Calibration	Flux: 5%	Flux: 5% (2-18 GHz)
	Phase: 5°	Phase: 5% (2-18 GHz)
	Pol'n: 5% inst.	Pol'n: 5% (2-18 GHz)
	1% calib.	Phase: 1% (2-18 GHz)

It is useful to distinguish between *instrument requirements* and *instrument goals*. An *instrument requirement* is an attribute that, if not met, will compromise key elements of the science program. An *instrument goal* is an attribute that leads to enhancements in the science yield of the instrument. Instrument goals should be met if at all possible given the technical and cost constraints encountered.

An important goal that will greatly enhance the scientific return of the instrument is to support an expanded frequency range of 0.1-30+ GHz. Additional goals include the support of full Stokes polarimetry, of integration times as short as 1 ms (this mode would be used on an occasional basis over a restricted bandwidth), and somewhat better angular resolution for frequencies < 3 GHz compared with that implied by a 3 km projected baseline. Baseline instrument requirements and goals are summarized in Table 1.

The main consequence of expanding the frequency range supported by the instrument is that no single antenna and feed design are likely to accommodate the entire range instantaneously at reasonable cost. Two or more antenna systems are likely needed.

5. STRAWMAN CONCEPTS

Here, we sketch some possibilities for the number, size, and configuration of the array. We go on to suggest possible options for the signal path and signal processing. We suggest strawman designs that can meet the requirements of the core frequency range and make suggestions for meeting the expanded range.

5.1. Array size and configuration

The reference angular resolution of 1" at a frequency of 20 GHz implies maximum projected antennas baseline lengths of 3 km. The Sun's apparent motion carries it to declinations of $\pm 23°$. FASR will probably have a northern latitude and its NS extent will be therefore be stretched by 3 km/cos(lat), which would bring the NS dimension to 3.8 km for a latitude of 35o. In order to achieve a nearly constant resolution over a range of hour angles $\pm 3 - 4$h, the array must also be extended in the EW dimension by a factor of $\sqrt{2}$–2, to 4.25-6 km. The optimum value will be determined by simulations and by the constraints imposed by the site. We note that for a fixed array, the angular resolution varies linearly with frequency. The requirements on angular resolution were selected to be a good match to the radio "seeing" imposed by inhomogeneities and turbulence in the solar corona.

We take it as a given, then, that FASR will be a large-N array confined to a footprint of 4 km × 4-6 km. While a single antenna design could support the core frequency range of $0.5 - 18$ GHz, it is unrealistic to suppose that a single antenna design can accommodate the design goal of $\sim 0.1 - 30$ GHz and adequately address the science requirements at reasonable cost. Recognizing that the scientific and technical imperatives differ for the low and high frequency ranges, we assume at the outset that two sets of antennas will be used to support the proposed frequency range.

Division of the frequency range into two or more segments still yields bandwidths of order 10:1. The demands of imaging over such large bandwidths suggest that self-similar array configurations are appropriate, as has been discussed elsewhere.[20, 21] In self-similar configurations, antenna spacings increase exponentially with distance from the array center. The antenna distribution and hence, the uv ddistribution, is highly centrally condensed.

For the purpose of discussion, let us divide FASR into two parts: a low frequency array (LFA) and a high frequency array (HFA). The optimum location of the frequency break between the two arrays depends on the antenna/feed sizes employed in each array. We briefly describe two possible configurations.

5.2. Antenna sizes

The LFA will employ an array of cheap, wire-mesh paraboloids and/or broadband feeds. The HFA will employ an array of smaller, higher performance antennas. Since the HFA addresses the core frequency range, we focus primarily on the HFA here.

The need for a large field of view, suggests the use of small antennas is needed in the HFA. The need to adequately sample short spatial frequencies in the Fourier domain - down to 86λ - also suggests that small antennas are needed, at least in the high frequency range. On the other hand, efficient calibration of a non-redundant array against sidereal standards suggests the use of a homogeneous array of larger antennas, or an array of small antennas calibrated against one or more large antennas. In addition, there are good reasons for employing larger, more sensitive antennas for certain science programs (see §3.4). Recognizing that there are trade-offs and compromises in any given approach to FASR, we propose two variations on the FASR strawman.

One is based on exploiting the 6.1-m offset Gregorian antenna design developed for use by the *Allen Telescope Array* (ATA). The other uses smaller, 2-m antennas.

The Allen Telescope Array (ATA) project has invested considerable effort in developing a 6.1-m offset Gregorian antenna,[22, 23] a broadband feed operating between 0.5-11 GHz,[24] and a cooled broadband receiver package that exploits microwave monolithic integrated circuit (MMIC) devices. The ATA has pioneered the production of such antennas at relatively low cost. Careful consideration will be given to the question of whether the ATA design, suitably modified, can be carried over to FASR without significantly compromising the science program. If ATA-style antennas were used, the frequency division would be 100-500 MHz (LFA) and 0.5-30+ GHz (HFA). The HFA would require modifications to the ATA antenna/feed/receiver performance.

The FOV of a 6 m antenna is $210'/\nu_9$ (or $7\lambda_{cm}$). The Sun is therefore resolved by an ATA antenna at a frequency of 6 GHz ($\lambda \sim 5$) cm). The advantages and disadvantages to this state of affairs are debatable on scientific grounds. The restricted FOV at high frequencies reduces the observing efficiency of energetic, transient phenomena. On the other hand, a positive consequence of resolving the Sun with the individual antennas is improved sensitivity to structure on the quiet Sun. A practical disadvantage is that in order to image the full disk of the Sun at higher frequencies mosaicing techniques must be used. Moreover, since antennas can be no closer than ≈ 1.25 diameters, visibilities with spatial frequencies corresponding to baselines $< 750/\lambda_{cm}$ wavelengths could not be measured. With accurate total power measurements, short-baseline informaton can be recovered to some extent via mosaicing and nonlinear deconvolution techniques.[25] But the question of measuring/recovering information on short spatial frequencies needs careful study.

The second possibility is to use an array of small (~ 2 m) antennas as the HFA. While it is possible to get performance down to 0.5 GHz with 2 m antennas, as is currently done with the USAF Solar Radio Burst Locator antennas, it is not clear whether the performance will be adequate for FASR science. The beam characteristics are poor, complicating RFI mitigation (see §5.6) and calibration. If an array of 2-m antennas is used for the HFA, it may be necessary to place the LFA/HFA frequency break at ~ 1 GHz. While this may eliminate some difficulties for the HFA, it places additional requirements on the LFA.

There are a number of advantages to using small antennas. First, the sensitivity of a radioheliograph is independent of antenna size for sources that dominate the system temperature and are unresolved by the individual antennas. An array of 2-m antennas is as sensitive to flare emissions as an array of 6-m antennas. Second, the FOV of a 2 m antenna is $21'\lambda_{cm}$. The entire Sun is visible over most of the frequency range, obviating the need for mosaicing except, perhaps, at the highest frequencies. Third, the antennas could be packed to separations of 2.5 m so that baselines $> 250/\lambda_{cm}$ wavelengths are measured. Fourth, 2-m antennas may well be cheaper than ATA-style antennas, even discounting the ATA antennas for the development costs that have already been absorbed. For if FASR were to use ATA antennas, a more robust and expensive mount, along with drives, actuators, etc, would need to be developed.

There are, of course, a number of disadvantages to using small antennas. While the size of the antennas is irrelevant for observing transient energetic phenomena on the Sun, it is relevant to observing the quiet Sun: larger antennas that resolve the quiet Sun are more sensitive than small antennas which don't. A practical disadvantage to a homogeneous array of 2 m antennas is that it is significantly less sensitive to sidereal sources, restricting calibration options. Calibration against sidereal standards is nevertheless possible. Moreover, signals from geostationary satellites could also be used to calibrate the array.

5.3. Feeds and receivers

The only practical feed options for FASR are frequency-independent feeds, which can provide the 10:1 bandwidths needed. The LFA will employ active dipoles, fat dipoles, or slot Vivalidi type antennas. For the HFA, the ATA development effort has produced a dual-linear, log-periodic feed that operates between $0.5 - 11$ GHz that may or may not be suitable for use with FASR. The ATA feed has been optimized for minimum noise temperature. The needs of the FASR core frequency range and the wish to extend to even higher frequencies justifies a careful look at modifying the ATA design or redesigning the feed entirely. We note that modifications to the ATA feed have been proposed[26] that extend its upper frequency limit to 22 GHz, which satisfies the upper limit of the FASR core frequency range.

The use of multiple feed systems on a single antenna is not an option unless they can be nested. Otherwise, the use of multiple feeds would involve timesharing through mechanical switching, placing feeds at the prime and Cassegrain foci of a given antenna for simultaneous use, or a complicated optical system that can illuminate multiple feeds. The feed must also be fixed during observations, in contrast to the ATA design, which refocuses the antenna as it changes frequency. The efficiency of the ATA design is not greatly reduced in the absence of focusing, however.

Good performance includes good polarization purity over the core frequency band. The science requirements call for support of Stokes I and V, most easily implemented in terms of RR and LL correlations. The specification is for better than 5% instrumental polarization across the band, reduced to <1% after calibration.

The ATA project has also made great progress in developing extremely compact, cooled, broadband HEMT receivers operating between 1-60 GHz. At the heart of these packages are MMIC devices. It is likely that FASR front ends will exploit similar devices. Switched attenuators will be employed in the front end to ensure that it operates within an optimum power range.

5.4. Data transmission

All data transferred between the antennas and a central processing point will be by means of optical fibers. The fact that maximum baselines will $< 4-6$ km implies that optical fiber runs will be less. Signal processing can be distributed between the antenna and a central processing point. Several options are therefore available for signal transmission. For example:

1. Use a conventional conversion to one or more IF pairs in the front end and transmit them to a central processing point for sampling, delay, filtering, and correlation. This approach would increase the complexity and cost of the front-end electronics in each antenna and make future upgrades to signal processing more difficult to implement. The bandwidth of the link would be perhaps 2-4 GHz.
2. Adopt the ATA approach of transmitting the entire RF block to a central processing point. This approach is attractive because it keeps the front end simple and also allows future upgrades to signal processing to be carried out more simply. The bandwidth of the link would be of order 10s of GHz.
3. Digitize the signal at the antenna. Depending on cost, anything from 0.1 to >1 GHz segments of the spectrum could be digitized and transmitted. The advantage to this scheme is that full control over the signal is obtained early in its path. We would want to transmit a minimum of two polarizations per array. Multiple band pairs are, of course, preferred (see below). The bandwidth of the link would be of order 2-4 GHz.

5.5. Digital signal processing

A variety of options are again available for signal processing, which can be distributed between the antenna and a central processing location. On the one hand, we want to maximize the reliability of the antennas in the field and therefore minimize their mechanical and electronic complexity. On the other hand, there are significant advantages in gaining control over the signal as early as possible in the signal processing chain.

Three data transmission options were mentioned above. Options (2) and (3) are the most attractive. They differ primarily as to where the signal is digitized, at the antenna or after transmission to a central processing location. The signal is transmitted to a central point where it is digitized and passed through a digital filter bank that can be (adaptively) programmed to remove channels corrupted by radio frequency interference (RFI). The many outputs from the filter bank would then be averaged as appropriate and correlated. In such a scheme the correlator could be relatively small since, if the RFI is removed, one-bit correlations may suffice. One-bit, two level sampling is attractive because the correlator is then insensitive to input power. Measurements of the system temperature are required to recover the correlation coefficient, however.

Whatever the solution, it is desirable to process as much of the bandwidth as possible in parallel, implying the use of multiple IF pairs. This is also attractive because one then has the option of observing in several different modes simultaneously. Depending on how data transmission is implemented, each IF or IF pair may need a dedicated link, which may be a cost driver.

The maximum spectral resolution required by the science is 0.1%, similar to the minimum needed to isolate RFI for excision. Another factor that determines the spectral resolution with which FASR must image is bandwidth smearing. Adopting the criterion that the amplitude loss at the solar limb or the half-power point of the primary beam (whichever is smaller) can be no more than 2%, a spectral resolution as high as a few times 0.1% is needed if an ATA-style antenna is used; or as high as few times 0.01% if a 2-m antenna is used.

For concreteness in considering signal processing, let us consider the following model: $\sim$64 antennas operating from $\sim 100 - 500$ MHz MHz (LFA), $\sim$100 2-m antennas operating from $0.5 - 30+$ GHz (HFA). Suppose the LFA frequency range is sampled by 2 IF pairs of 100 MHz bandwidth, and the HFA by 4 IF pairs of 250 MHz bandwidth (covering 0.5-3 GHz) and 4 IF pairs of 1 GHz bandwidth (covering 3–30+ GHz). The goals for the signal processing might then be summarized as follows:

Table 2. Signal processing

	100-500 MHz(LFA)	0.5-3 GHz (HFA)	3-30+ GHz (HFA)
Number antennas	$\sim$60	100	100
IF bandwidth	100 MHz	250 MHz	1 GHz
Number bits	8	8	3
Number channels/IF	256-1024	128-256	32-128
Integration time	4 ms	4	10
Duty cycle	10 ms	10	100
Correlations (1 bit)	RR, LL	RR, LL	RR, LL

There need not be any substantial difference between the HFA IF pairs. The bandwidth and number channels of each could be tailored to their particular task. Note the degree of frequency agility implied by the integration times and duty cycles for each IF. The above is meant to be illustrative. Much work remains to be done to identify an optimum scheme.

5.6. RFI mitigation

We conclude with some remarks on radio frequency interference (RFI). As is the case for the coming generations of all radio telescopes operating at m- to cm-λ (ATA, LOFAR, EVLA, SKA), FASR will be a broadband instrument operating well outside the protected bands. All such instruments will therefore be susceptible to RFI and steps must be taken to mitigate its harmful effects. FASR has an advantage over other instruments to the extent that the Sun dominates the system noise. The fractional contribution of RFI within a given band is therefore substantially less than it would otherwise be for a non-solar instrument.

Nevertheless, RFI will still be a significant problem. In addition to selecting a "clean" site and ensuring that RFI generated by the instrument itself is kept to a minimum, the system must be kept linear in the presence of RFI so that subsequent signal processing can be used to eliminate RFI in the signal, or greatly reduce its effect, prior to correlation (see below).

Preliminary consideration of RFI in a solar context suggests that signals of order 40 dB above the quiet Sun levels can be expected for frequencies below a few GHz. The problem is less severe for higher frequencies, although signals 20 dB above quiet Sun levels are certainly possible. The RFI environment will likely degrade over the lifetime of the telescope.

The simplest, yet most robust, RFI mitigation strategy or strategies remain to be seen. As mentioned above, the requirement that the signal remain linear means that it may need to be sampled with 6-8 bits at frequencies below a few GHz, and with 3-4 bits for higher frequencies. The details will depend on frequency, IF bandwidth, etc.

A possible approach to RFI mitigation is the following. Assume an FX correlator architecture is employed, as suggested above. Using a template - derived from routine surveys of the local RFI environment and prior knowledge of transient (satellite, radar) sources of RFI - the RFI could be excised from the data following the F stage. The X stage would then follow with only one bit and one lag. Dynamic identification and excision of RFI is perhaps more difficult to implement because the Sun itself produces highly variable and narrowband emissions. However, it might be possible to exploit the polarization properties of the Sun's transient emissions to guard against accidental excision.

6. SUMMARY

FASR is a solar-dedicated radio array designed to perform broadband imaging spectroscopy. It will do so on frequency, time, and angular scales commensurate with solar phenomenology. FASR will thereby bring a host of radio diagnostic tools to bear on a large number of outstanding questions in solar physics. A key driver of the FASR design is to support coronal magnetography. Additional drivers include support of flare physics, drivers of space weather, and the structure and dynamics of the solar atmosphere.

Conceptually, the FASR instrument definition and design is evolving rapidly. Rapid progress is being made in satisfying the science drivers with a detailed strawman. Similarly, good progress is being made in identifying approaches to such technical challenges as broadband signal reception and transmission, RFI mitigaton, and signal correlation. There is every reason to be optimistic that FASR can be built before the next solar maximum in 2010.

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