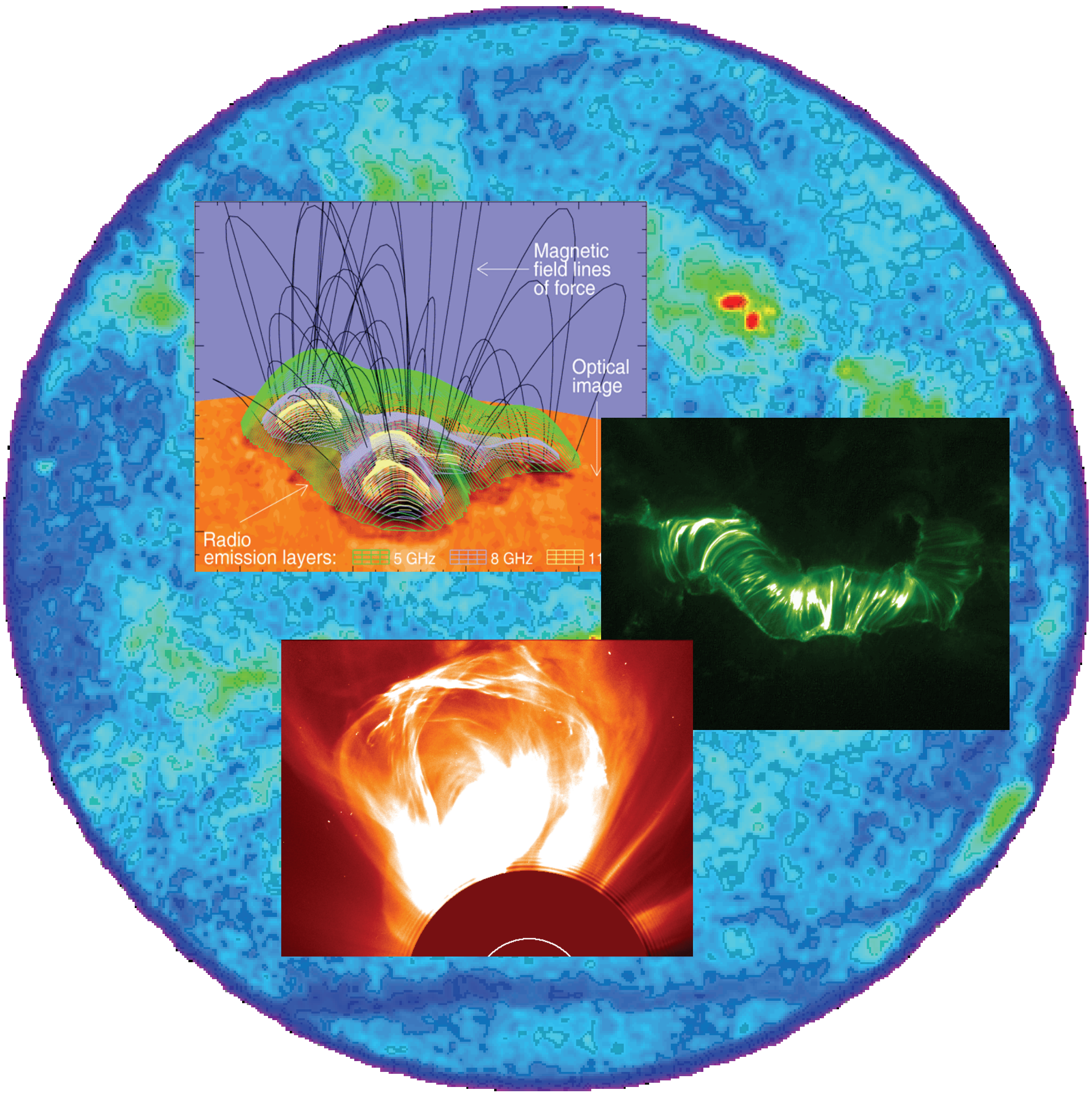
The Frequency Agile Solar Radiotelescope

A White Paper for

A Decadal Strategy in Solar and Space Physics



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1 Summary & Background

Solar activity represents a uniquely accessible example of the ubiquitous processes of energy release and particle acceleration that occur in a wide range of contexts, from the magnetosphere to the galaxy. Radio observations provide both a unifying perspective on solar activity and a unique sensitivity to solar magnetic fields, the energy source for solar activity. In addition, radio emission is unsurpassed in its sensitivity to accelerated particles. As a result, radio emission provides a powerful source of diagnostic information with the potential for transformational insights into solar activity and its terrestrial impacts.

The *Frequency Agile Solar Radiotelescope* (FASR) is a solar-dedicated radio telescope that provides a unique combination of superior imaging capability and broad instantaneous frequency coverage to address a wide range of science goals. The potential value of such a facility has been recognized by high-priority recommendations for FASR from three previous surveys of future science in the US conducted by the National Research Council. The previous decadal survey of astronomy and astrophysics, recommended FASR a moderate-sized initiative. The *Solar and Space Physics Survey Committee (2003)* made FASR its highest-priority "small project", in recognition of the unique and transformative role it will play in addressing basic research questions, as well as its complementary role to other important instruments being developed and deployed to address the Sun-Earth system. The recently concluded *New Worlds, New Horizons in Astronomy and Astrophysics (2010;* Astro2010) amplified its previous recommendation to endorse FASR as its number-two rated project in all of radio, millimeter, and submillimeter (RMS) astronomy, citing the project as "compelling" and in a high state of readiness.

FASR will be designed and constructed by a university consortium organized under Associated Universities, Inc. (AUI), the not-for-profit science management corporation that manages the National Radio Astronomy Observatory (NRAO). The project was presented in detail to Astro2010. More than 70 pages of documentation were provided to the survey via two "requests for information" (RFI-1 and RFI-2). As part of RFI-2, the project was independently assessed by the *Cost Risk and Technical Evaluation* (CATE) process (Aerospace Corp.). Based on this assessment the Astro2010 RMS panel report concluded "FASR is a mature effort that has been recommended in two previous NRC decadal surveys. Extensive development and design review have been funded and achieved, including the testing of prototype instrumentation and the detailed planning of FASR operations, maintenance, and management. Independent analysis of FASR characterized it as 'doable today'." A project based on FASR science and technology, roughly 10% of FASR in size and cost, is the Owens Valley Solar Array Expansion, funded by a $5.2 M grant from NSF to New Jersey Institute of Technology. This project, to be completed in 2013, will further mature FASR's technology, software and data handling.

The FASR project cost in FY09 dollars, provided to Astro2010, was $68.5M, including contingency and management fees. The CATE analysis estimated the cost to be $109M. Although the team is not privy to the details of the analysis, the RMS report states that the difference is "based primarily on higher estimates for project management, antennas, and reserves." The project team estimated annual operations costs of FASR to be $3M whereas the CATE analysis put the cost at $4M. Astro2010 assumed that FASR construction would be funded equally by the AST and AGS divisions at the NSF.

2 FASR Science

FASR is an interferometric array designed to perform Fourier synthesis imaging at radio wavelengths. Moreover, as a radioheliograph, FASR is designed and optimized to observe the Sun. The major advances offered by FASR over previous generations of solar radio instrumentation are its unique combination of ultra-wide frequency coverage, high spectral resolution, and outstanding image quality. FASR measures the polarized brightness temperature spectrum (from 50 MHz to 21 GHz) along every line of sight to the

Sun as a function of time. Radiation in this wavelength range probes the solar atmosphere from the middle chromosphere to well up into the corona. In essence, FASR images the entire solar atmosphere once every second from the chromosphere through the corona, while retaining the capability to image a restricted frequency range with as little as 20 ms time resolution. In so doing, FASR enables fundamentally new and unique observables. Moreover, FASR's panoramic view allows the solar atmosphere and the physical phenomena therein to be studied as a *coupled system*.

Here we summarize the main science goals of the proposed instrument while at the same time emphasizing the new observables enabled by FASR. The potential of FASR for breakthroughs in a wide range of science topics, resulting from extensive discussions among members of the solar and space physics community, is presented in detail in the book *Solar and Space Weather Radiophysics*[24]. Elements of FASR science are also discussed in various science white papers. With its unique and innovative capabilities FASR also has tremendous potential for new discoveries beyond those presently anticipated.

2.1 The Nature and Evolution of Coronal Magnetic Fields

Quantitative knowledge of coronal magnetic fields is fundamental to understanding essentially all solar phenomena above the photosphere, including the structure and evolution of active regions, prompt energy release, charged particle acceleration, flares, coronal mass ejections (CMEs), filaments, coronal heating, and acceleration of the solar wind (see the white paper entitled *Coronal Magnetic Fields* by White et al.). Useful quantitative measurements of the coronal magnetic field have been largely unavailable to date. Thus, considerable resources are devoted to *indirect* means of constraining the coronal magnetic field. For example, the field topology can be traced by hot, optically thin, thermal plasma emitting at EUV/SXR wavelengths. Measurements of the (vector) magnetic field distribution can be measured at photospheric and numerically extrapolated into the upper chromosphere and corona. Such extrapolations depend sensitively on measurement errors and rely on assumptions whose validity is questionable – that the magnetic field is potential or force free[35]. Hence, new observational techniques for directly measuring the coronal magnetic fields are being vigorously pursued. At optical/IR wavelengths, the Hanle and Zeeman effects are being measured for this purpose, but such measurements are only possible at the solar limb where photospheric fields are not well measured and results values are integrated along the line-of-sight[40].

Radio observations provide the most direct means of measuring coronal magnetic fields. The key radio technique for doing so is the well-established gyroresonance method[30,44,45]. Such radio measurements, effective from ≈120-2000 gauss, allow coronal magnetic fields in active regions to be measured both on the disk and above the solar limb. Gyroresonance emission is optically thick; by imaging at multiple frequencies, the thin resonance location varies in a systematic way, allowing a CAT-scan-like view of nested isogauss layers. The most straightforward application is to exploit the break in the brightness temperature spectrum along each line of sight to infer the (force free) magnetic field at the base of the corona, thereby producing a 2D **coronal magnetogram**. Several additional radio techniques[24] are available for measuring coronal magnetic fields in a wide variety of physical environments, including polarization measurements of free-free emission to measure the longitudinal magnetic field in the quiet corona[25,27] and dense structures such as filaments and prominences[2]; radio bursts at meter and decimeter wavelengths can be used to measure fields in the middle corona[17]; gyrosynchrotron emission can be used to deduce the magnetic field in flaring magnetic loops and in CMEs[10,33,] (see also §2.2-3); mode coupling phenomena can place additional, independent topological constraints on the coronal magnetic field[41].

FASR will be unique in its ability to deliver these transformative means of measuring the coronal magnetic field both on the solar disk and above the limb.

2.2 The Physics of Flares

Outstanding problems in the physics of flares include those of magnetic energy release, particle acceleration, and particle injection and transport. There has been significant theoretical and observational progress in recent years on three-dimensional magnetic reconnection[7,18,22,39,]. FASR brings new tools to bear on the problem of 3D magnetic reconnection. At centimeter wavelengths, gyrosynchrotron emission – radiation from nonthermal electrons with energies of 10s of keV to several MeV gyrating in a magnetic field – illuminates any magnetic coronal loop to which energetic electrons have access, showing when and where accelerated electrons are present. Such loops provide a valuable topological tool, linking the site of particle acceleration to more distant sites to which accelerated particles are transported during all phases of the flare. Moreover, FASR will provide quantitative measurements of magnetic fields in the flaring source through forward fitting of the spectrum, coronal loop oscillations[6,43,21], and timing comparisons between microwave and HXR fine structures[1,9].

At longer wavelengths, decimetric spike bursts and type-III-like bursts accompany impulsive energy release in flares[3]. They may be intimately related to the magnetic energy release process[8,12] associated with reconnection in both the impulsive phase of flares, and in post-flare loops[13]. FASR's dynamic imaging spectroscopy is urgently needed to identify the location of these emissions. The combination of spatial, spectral and temporal resolution gives the fascinating opportunity to directly image the diffusion region where the primary acceleration of the particles takes place.

In addition to probing the site, topology, and evolution of magnetic fields involved in 3D magnetic reconnection, *FASR will be a superb probe of the (anisotropic) distribution function of accelerated electrons and its spatiotemporal evolution*. Nearly every flare accelerates electrons whose gyrosynchrotron spectrum in microwaves can be forward fit and the relevant physical parameters thereby inferred[8,11,33]. The key to further exploitation of this approach is to add high-spatial-resolution imaging, allowing temperature, density, magnetic field strength[23], non-thermal electron energy and angular distribution[1,19,20,32] (see also the white paper entitled *Uncovering Mechanisms of Coronal Magnetism via Advanced 3D Modeling of Flares and Active Regions* by Fleishman et al. and references therein), and even the level of turbulence to be extracted for every resolution element and time. These diagnostics provide powerful means of testing theories of electron acceleration[36] and transport[4,5,34] (see also the white paper entitled *Particle Acceleration and Transport on the Sun* by Gary *et al.*). These observations will be an invaluable complement to hard X-ray emission, which typically originates from the conjugate magnetic foot points of coronal magnetic loops into which energetic electrons are injected, as well as to EUV/SXR emission.

FASR will provide new insights into magnetic energy release and quantitative measurements of the magnetic field and the evolving energetic electron distribution. It will provide access to the flare phenomenon as a coupled physical system.

2.3 The Drivers of Space Weather

The term "space weather" refers to phenomena that disturb the interplanetary medium and/or affect the Earth and near-Earth environment[29]. This includes recurrent structures in the solar wind (fast solar wind streams, co-rotating interaction regions), the ionizing radiation and hard particle radiations from flares, coronal mass ejections, and shock-accelerated particles. These drivers result in interfering radio noise, geomagnetic storms, changes in the ionosphere, and atmospheric heating which can, in turn, result in a large variety of effects that are of practical concern to our technological society: ground-level currents in pipelines and electrical power grids, disruption of civilian and military communication, spacecraft charging, enhanced atmospheric drag on spacecraft, etc. They can also disrupt the work, and endanger the lives, of humans living and working in space. The drivers of space weather are all solar in origin.

FASR will be sensitive to a large number of space weather phenomena, and particularly to coronal mass ejections (CMEs), filament/prominence eruptions, and type II radio bursts. Interest in CMEs is particularly strong because they are associated with the largest geo-effective events and the largest solar energetic particle (SEP) events. With the detection of synchrotron radiation from CMEs in cm to m wavelengths[10,33] *a new tool has become available to detect, image, and diagnose the properties of CMEs.* FASR will exploit this tool extensively. FASR will also make important contributions to the study of shocks and waves in the corona. Fast ejecta and/or a blast wave are sometimes produced by flares; a CME produces a piston-driven shock wave. The relationship between these shocks, their radio-spectroscopic signature, and other phenomena of interest such as Moreton waves and "EIT waves" – many of which FASR will also image[46] – remains a matter of considerable interest and controversy[14,26]. With its unique ability to perform imaging spectroscopy, FASR will be able to simultaneously image the basic shock driver (flare or CME signature), the response of the atmosphere to the driver (chromospheric/coronal waves and coronal dimmings), and the shocks themselves that may form due to the associated flare or the CME. Similarly, FASR will yield important new insights into the relationship between flares, CMEs, and solar energetic particles (SEPs) as it will image the CME precursor environment.

FASR's ability to provide a comprehensive and integrated picture of the flare phenomena applies equally to space weather drivers. It will enable consideration of the entire coupled physical system from the chromosphere out into the corona.

2.4 The Physics of the Quiet Sun

Radio emission from the quiet Sun is dominated by free-free opacity, which is proportional to the square of the electron density, and whose polarization is proportional to the longitudinal *B* field. At the highest FASR frequency, 21 GHz, FASR will sample the middle chromosphere while, by systematically tuning to lower frequencies, the sampled height of the (optically thick) emission moves through the top of the chromosphere and into the corona. The multifrequency imaging capability of FASR again provides a heretofore unexploited CAT-scan-like probe into the temperature, density, and *B* field structure of this important region of the Sun. The importance of this region for determining the global properties of the corona and solar wind is hinted at by the polar cap brightenings seen with Nobeyama[42]. FASR's multifrequency imaging will clarify the connection between the chromospheric structure and the origin of the solar wind.

FASR will also address the dynamics of this region of the solar atmosphere. First, resonance wave heating[16,37] represents one of many models for coronal heating and makes specific predictions of the location and time scales of energy deposition in coronal loops. Using free-free diagnostics, FASR observations of the resulting temperature changes in this region encompassing both the chromosphere and the adjacent corona can address the validity of such predictions. A second area is the role of "nanoflares"[38], and a host of perhaps related microflare phenomena that, collectively, may dominate the structure of the lower solar atmosphere. The energetics of such small events depends critically on their thermal properties and the role, if present, of accelerated electrons[15,28]. Again, the combination of FASR's frequency coverage and imaging can apply diagnostics to quantitatively address both thermal and nonthermal signatures of such events. See also the white paper entitled *The Solar Chromosphere* by McIntosh et al.

A third example, already mentioned in §2.1, is the strength, distribution and evolution of magnetic fields in prominences and filaments, as deduced from the polarization of free-free emission[25,27]. FASR can use imaging spectroscopy to directly measure the longitudinal magnetic field in filaments and prominences. Such measurements are critically important to understanding the formation, structure, and destabilization of such structures and their role in CMEs and interplanetary flux ropes.

The exploitation of free-free emission to determine the spatially-resolved temperature, density and magnetic fields in the quiet chromosphere, corona, and prominences is possible only as a result of FASR's unique attributes.

3 Overview of the Instrument

FASR's design is driven by a number of factors. First, the instrument meets the science specifications derived from the key science objectives outlined §2. Second, it meets the needs of the large and diverse scientific community that will exploit FASR data. Since most users will not be radio interferometrists, they should not bear the burden of data calibration and reduction. As a result, these functions will be performed by pipeline data processing that delivers high-level, fully calibrated data products to a broad user community. Third, it is imperative to control the long-term operating and maintenance costs. Finally, it is important to design an expandable/upgradable system in order to respond flexibly to opportunities presented by new resources, new technologies, and/or new science objectives in the future. *These broad drivers have resulted in a design that emphasizes simplicity, utility, reliability, maintainability, and expandability.*

The science objectives outlined in §2 flow down to the high-level science and technical specifications summarized in the Table. FASR is designed to perform Fourier synthesis imaging using well-established interferometric techniques. For an array of N antennas there are ~$N^2/2$ independent antenna pairs, each of which measures a single Fourier component, or complex *visibility,* of the Sun's radio brightness distribution at a given frequency, time, and spatial frequency. The ensemble of antenna pairs, or *antenna baselines*, therefore measures many Fourier components. Fourier inversion of the visibility measurements yields an image of the Sun's radio brightness at a given frequency, time, and polarization. Deconvolution techniques are then used to remove the effects of the *point spread function*, the response of the instrument to a point source.

Angular resolution	$20/\nu_{GHz}$ arcsec
Frequency range	50 MHz – 21 GHz
Number data channels	2 (dual polarization)
Frequency bandwidth	500 MHz per channel
Frequency resolution	Instrumental: 4000 channels Scientific: min(1%, 5 MHz)
Time resolution	~1 s (full spectrum sweep) 20 ms (dwell)
Polarization	Full Stokes (IQUV)
Number antennas deployed	**A** (2-21 GHz): ~100 **B** (0.3-2.5 GHz): ~70 **C** (50-350 MHz): ~50
Size antennas	**A** (2-21 GHz): 2 m **B** (0.3-2.5 GHz): 6 m **C** (50-350 MHz): LPDA
Array size	4.25 km EW x 3.75 km NS
Astrometry	1 arcsec
Flux calibration	<10% absolute 1% relative

FASR observations will cover the frequency range of 50 MHz to 21 GHz using three separate arrays of antennas, denoted FASR-A, -B and -C. Each array provides frequency coverage over roughly a decade of bandwidth: 2-21 GHz (FASR-A); 0.3-2.5 GHz (FASR-B), and 50-350 MHz (FASR-C). The number, type, and configuration of the antennas in each array are chosen to address the key science objectives summarized in §2. The antennas will be distributed over an area of approximately 4.25 x 3.75 km, providing an angular resolution of 1" at 20 GHz over an hour angle range of at least ±3 hr. The angular resolution scales linearly with wavelength from this fiducial value and is sufficient to resolve solar radio sources observed as well as being well matched to the capabilities of missions such as TRACE, SOHO, RHESSI, Hinode, and SDO. The instrument will be calibrated against sidereal sources to enable precision astrometry and an absolute flux calibration of better than 10%. The relative calibration across the more than two decades of bandwidth will be better than 1%.

4 FASR Construction, Operation, and Costs

The FASR construction project will be of five years duration. It will be implemented by a consortium of university partners and a national facility (NRAO) under AUI management. FASR has undergone several costing exercises. The most comprehensive costing exercises were the result of the FASR team's response to the NSF ATM Mid-Sized Infrastructure (MSI) Opportunity in 2008 and the Astro2010 RFI responses in 2009. The cost of FASR construction is estimated by the FASR team to be $68.5M in FY09 dollars. The amount includes contingency and management fees. The Astro2010 *Cost Risk and Technical Evaluation* (CATE), an independent assessment overseen by Aerospace Corp. on behalf of the Astro2010 survey, put the cost at $109M. While the FASR team is not privy to the CATE analysis, the Astro2010 RMS panel states that the higher cost estimated by CATE is "based primarily on higher estimates for project management, antennas, and reserves." The RMS panel adopted $100M as FASR construction cost and commented that FASR is a "mature" effort and characterized the project as "doable today".

As part of the FASR design and development effort, a detailed Operations and Maintenance (O&M) plan was prepared to assess the long-term costs of operating the instrument at the request of NSF. Details are available upon request. The FASR O&M Plan estimated the core long-term annual O&M cost to be approximately $3M in FY09 dollars whereas the Astro2010 CATE analysis estimated O&M costs to be $4M annually. Both estimates are significantly lower than the 10% of capital costs often used as a "rule of thumb" for estimating operating costs. The low operating cost estimate reflects the fact that FASR does not employ high maintenance technologies. Rather, FASR employs simple, non-cryogenic front ends; small, mechanically simple antennas; analog data transmission; signal processing confined to a shielded and environmentally controlled central hub, etc.). Since FASR is a solar dedicated instrument, pipeline data processing is both feasible and necessary to meet the needs of the user community. The software and data management plan describes the data pipeline – including data calibration, RFI excision, and data selection – the interim data archive, the applications data base, the user interface, and data acquisition and analysis tools in some detail. Instrument monitor and control functions are also considered. The user support model includes both quick-look data for operational needs, and a permanent archive of applications databases that can be accessed and mined via a web interface. The volume of data that will be permanently archived is estimated to be ~200 GBytes a day.

The O&M cost estimate does not include support of special observing modes, data products, or mission support, which, if added, would be supported with funds from other agencies (e.g., NASA, USAF, etc). Nor does the estimate include possible contributions, financial or in kind, from university and/or foreign partners.

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