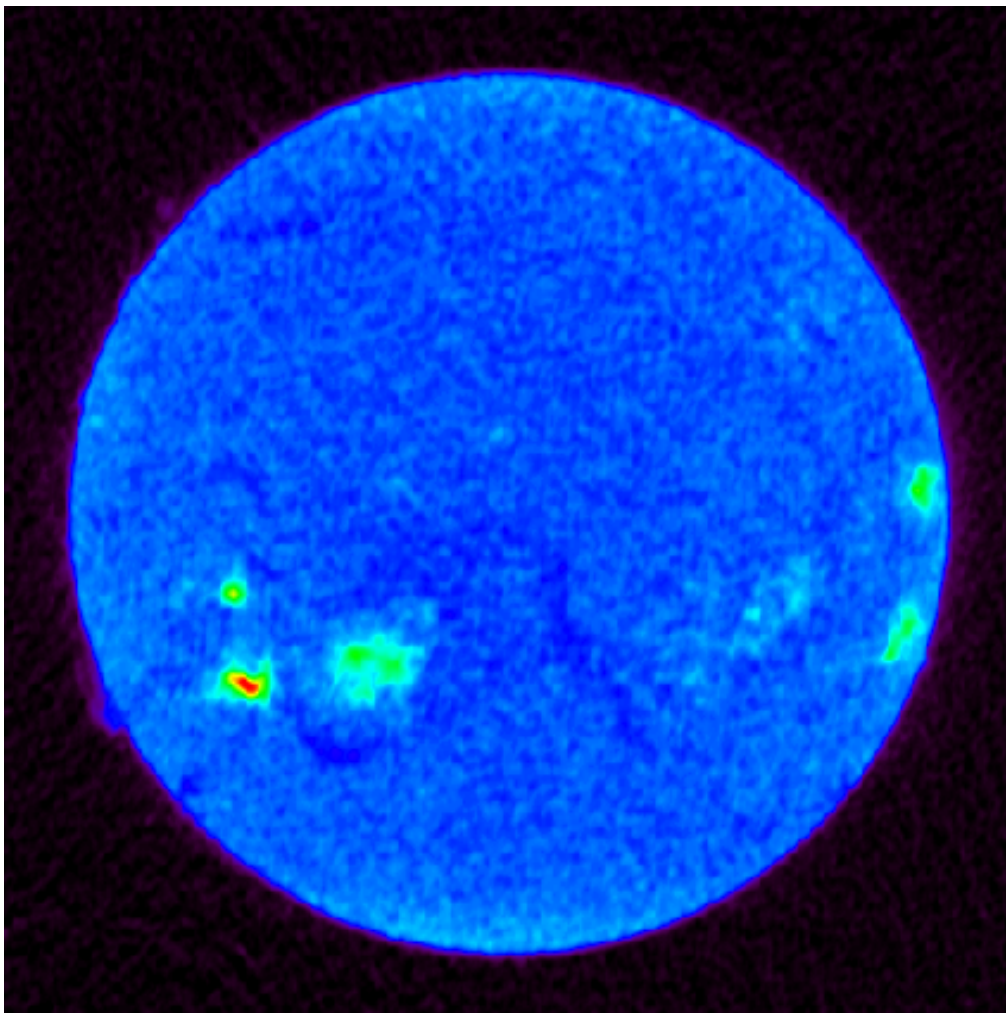


New Frontiers in Solar Physics:

Broadband Imaging Spectroscopy with the Frequency Agile Solar Radiotelescope

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1 Introduction

The Sun is an ordinary star rendered extraordinary by its close proximity. Despite its stature as an ordinary star it confronts us with a large number of problems that demand a fundamental understanding. These problems are of an importance that extends well beyond the Sun itself, for it is often against our understanding of the Sun that we measure our understanding of stars and other astrophysical objects and processes. Outstanding problems in solar physics include the magnetic dynamo and the solar cycle, the solar atmosphere and solar wind, and transient energetic phenomena such as flares, coronal mass ejections, shocks, and particle acceleration. Related problems include those associated with the impact of the Sun on the Earth and near-Earth environment – space weather – problems that have practical consequences for life and technology on Earth and in space. Radio observations have played an important role in increasing our understanding of all of these problems for many years. With the successful construction and commissioning of the radio telescope concept described here – the Frequency Agile Solar Radiotelescope (FASR) – radio observations will assume an even more central role. This is because FASR will produce data that will bring wholly unique and powerful observational diagnostics to bear on these problems. For this reason, it is expected that FASR will be the premier solar radio telescope for at least two decades or more.

Historically, exploration of radio emission from the Sun has proceeded along two, largely orthogonal lines: imaging observations and spectroscopy. Imaging observations have been performed at discrete frequencies with interferometric arrays for many years. Spatially unresolved broadband spectroscopy has been pursued using fixed-frequency polarimeters, while high-resolution spectroscopy has exploited swept-frequency or broadband digital spectrographs. The types and frequency coverage of instruments that are currently used for solar observations are summarized in Appendix A. In order to exploit fully the diagnostic potential of radio emission from the Sun, both imaging and spectroscopy must be obtained simultaneously over a large bandwidth with an angular resolution, time resolution, and spectral resolution commensurate with the properties intrinsic to solar radio emissions. A consensus exists in the solar and space physics community that it is technically feasible, scientifically desirable, and timely to construct such an instrument: an advanced, solar-dedicated radio telescope designed to perform dynamic broadband, imaging-spectroscopy.

The FASR project was endorsed by the National Academy of Science National Research Council *Astronomy and Astrophysics Survey Committee* decadal survey in 2001. Specifically, the solar panel of the AASC recommended an integrated suite of instrumentation designed to meet the challenges in solar physics during the coming decade and beyond. These are the *Advanced Technology Solar Telescope* (ATST), a ground based 4 m telescope optimized for performance at optical and infrared wavelengths; the *Solar Dynamics Observatory* (SDO), a space based observatory designed to be the successor to the Solar and Heliospheric Observatory (SOHO); and the *Frequency Agile Solar Radiotelescope* (FASR). More recently, in late-2002, the

NAS/NRC *Committee on Solar and Space Physics* decadal survey ranked the FASR project first among small projects (defined to be <\$250M), the top-ranked medium and large projects being the *Magnetospheric Multi-scale Mission* and the *Solar Probe*, respectively.

This document serves as a brief introduction to the FASR project and the science that it will address. In Section 2, the basic instrument concept and specifications are summarized. Radio emission mechanisms are described in Section 3. The FASR science program is discussed in Section 4. The strawman instrument is discussed in somewhat greater detail in Section 5. Preliminary ideas concerning FASR operations and data management are discussed in Section 6.

2 Overview of the Instrument

The Sun produces radiation at radio wavelengths through a variety of mechanisms and in a wide variety of physical contexts. The emissions vary greatly in morphology, intensity, spectral properties, polarization properties, and their degree of variability. Particularly interesting is the centimeter through meter wavelength range, a range which probes the middle chromosphere up to the middle corona and offers a rich variety of radio diagnostic tools that can be used to address a broad program of solar physics. FASR is designed to exploit these diagnostic tools.

FASR will be unlike any radio telescope yet built. While it will be similar to existing radio arrays to the extent that it will produce high-resolution, high-fidelity images, it will be wholly unique in that it will produce such images at a large number of frequencies over a frequency range of 30 MHz to 30 GHz on time scales as short as a fraction of a second. In other words, it will be designed to perform dynamic broadband imaging spectroscopy.

As an imaging instrument, FASR will exploit Fourier synthesis imaging techniques. It will comprise three separate arrays of antennas. The extent and possible configuration of these arrays are discussed elsewhere.

The data produced by FASR will be inherently three-dimensional in nature: data cubes composed of many image planes distributed along the frequency axis. The basic observable, then, will be the (polarized) brightness temperature spectrum along every line of sight to the source. Moreover, a new data cube will be produced for each integration time. The evolution of the brightness temperature spectrum will therefore be available along every line of sight to the source.

The data produced by FASR will provide unique and powerful new tools. These will be brought to bear on a wide range of problems. Perhaps the most important new observable will be direct and indirect measurements of coronal magnetic fields. Also included are new insights into the physics of flares, drivers of space weather, and the quiet Sun. Each of these is discussed in greater detail in Section 4.

An important goal of the FASR project is to mainstream the use of FASR data, much as the *Yohkoh* SXT and HXT mainstreamed the use of solar soft-X-ray (SXR) and hard-X-ray (HXR) observations, and SOHO/EIT and TRACE have mainstreamed the use of EUV data. This goal has important implications for operations and data management, which are discussed further in Section 5.

3 Solar Radio Emission Mechanisms

Before discussing the FASR science program, it is worth a brief digression to remind readers of the dominant emission mechanisms that occur on the Sun. For most astrophysical objects, continuum emission in the centimeter to meter wavelength range is due to incoherent synchrotron and/or free-free radiation. Emission and absorption in spectral lines is also available for study, notably HI, radio recombination lines, and molecular lines (e.g., OH, H₂O, SiO). The temperatures, densities, and magnetic field strengths encountered on the Sun are such that spectral lines play no role at centimeter, decimeter, and meter wavelengths. Furthermore, polarimetric techniques are limited. Strong differential Faraday rotation washes out any linearly polarized component in most cases (see Sections 4.1.2 and 4.3.1, however). Hence, most investigations are limited to studies of the Stokes I and V parameters.

Nevertheless, the radio spectrum at centimeter, decimeter, and meter wavelengths is rich in diagnostic potential because two of the natural frequencies of the solar atmosphere – the electron plasma frequency ν_{pe} and the electron cyclotron frequency Ω_{Be} – are often of the same order as the observed radio frequency. Three distinct radio emission mechanisms are widespread in the solar atmosphere and are commonly available for diagnosing physical conditions in the source:

Plasma radiation is a coherent emission mechanism that involves the nonlinear excitation of plasma waves by a non-equilibrium electron distribution – e.g., energetic electron beams (type III radio bursts) or MHD shocks (type II radio bursts) – and their subsequent conversion to electromagnetic waves near the electron plasma frequency $\nu_{pe} = 9n_e^{1/2}$ kHz and/or its harmonic $2\nu_{pe}$; n_e is the electron number density (cm⁻³). Plasma radiation processes typically produce radiation at decimeter and longer wavelengths.

Gyromagnetic radiation results from the acceleration experienced by electrons in a magnetic field due to the Lorentz force. It is convenient to refer to *thermal gyroresonance emission* and *thermal or nonthermal gyrosynchrotron emission*, the nonrelativistic and weakly-relativistic counterparts to synchrotron radiation. Thermal gyroresonance emission results from hot ($T_e \sim 2 \times 10^6$ K) thermal plasma interacting with strong magnetic fields ($B > 100$ G). It produces radio emission at low harmonics $s=1,2,3,4$ of the electron cyclotron frequency $\nu_{Be} = 2.8B$ MHz, where B is in units of Gauss. Gyrosynchrotron emission is produced by thermal or nonthermal populations of energetic electrons (10s of keV to

several MeV) at harmonics $s \sim 10 - 100$ of Ω_{Be} .

Bremsstrahlung radiation results from collisions between electrons and ions and is therefore ubiquitous. Thermal bremsstrahlung radiation is emitted by a thermal plasma, and provides diagnostics of temperature and density. The slight mode-dependence of this mechanism allows it to be used in some circumstances as a diagnostic of the longitudinal component of the magnetic field as well.

Several other emission mechanisms may play an important role on the Sun and offer additional diagnostics. These include the cyclotron maser (Melrose & Dulk 1982), radiation from electrons accelerated in strong DC electric fields (Tajima et al. 1990), and transition radiation resulting from the interaction of electrons with small scale turbulence (Fleishman & Kahler 1992). One, two, or even more of the possible emission mechanisms may occur simultaneously on the Sun.

The major advance offered by the FASR is time-resolved, broadband, imaging-spectroscopy. FASR will produce high-spatial-resolution images with excellent dynamic range and fidelity, and with sufficient spectral and temporal resolution to enable observers to measure the radiation spectrum and its evolution in time at each point in the field of view. In so doing it will enable full exploitation of the many radiative diagnostics available. We now turn to the major science themes that the FASR is designed to address.

4 FASR Science

Based on extensive discussions among members of the solar physics community, most recently the FASR Science Definition Workshop, hosted by the NRAO in Green Bank, WV, in May, 2002, several key areas have been identified in which FASR is expected to make significant new contributions. These are:

- The nature and evolution of coronal magnetic fields
- Physics of flares
- Drivers of space weather
- The quiet Sun

In the remainder of this section, we discuss each of these in greater detail, recognizing that with its unique and comprehensive capabilities, FASR has tremendous potential for new discoveries and unanticipated uses of the data it produces. Interested readers should also see Gary & Keller (2004).

4.1 *The Nature and Evolution of Coronal Magnetic Fields*

A key strength of FASR is that it provides unique observables of direct relevance to a number of outstanding problems in solar physics. One such problem is coronal magnetic fields, which have heretofore been inaccessible to quantitative study. Quantitative knowledge of coronal magnetic fields is crucial to virtually all solar physics above the

photosphere, including the structure and evolution of active regions, flares, filaments, and coronal mass ejections. The measurement of vector magnetic fields in the photosphere using optical and infrared lines is a well-developed technique, and in the absence of routine measurements of coronal magnetic fields, considerable resources are devoted to extrapolating the observed surface magnetic field distribution into the upper chromosphere and corona under the assumption that it is potential or force-free (see Fig. 2). These extrapolations are difficult, depend sensitively on measurements at the photospheric level, and rely on assumptions that need to be more thoroughly tested.

Radio observations provide the means of both directly and indirectly measuring magnetic fields in the corona. However, such measurements require a broadband imaging capability. The FASR provides that capability. We describe below several means of measuring or constraining the magnetic field in active regions and in quiet regions. We defer a discussion of magnetic field measurements in flares to Section 4.2.2.

4.1.1 Coronal magnetography using gyroresonance absorption

Active regions are those regions on the Sun where strong magnetic fields have buoyantly emerged through the photospheric surface into the corona. Their photospheric signature is manifest in sunspots, but their true nature is revealed by observations in EUV (Fig. 1), SXR, and radio emission: active regions are complex and evolving magnetic structures composed of magnetic loops containing hot plasma. As their name implies, flares and other forms of solar activity originate in active regions.

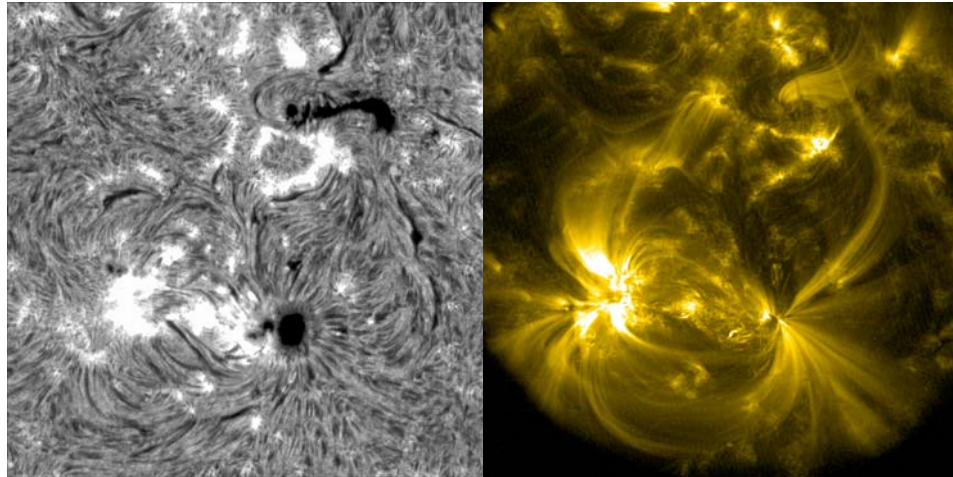


Figure 1: Example of an active region complex (AR9462/9463) observed by the Big Bear Solar Observatory in $H\alpha$ (left) and by the Transition Region and Chromosphere Explorer (TRACE; right) on 24 May 2001.

Radio observations provide the only means to measure coronal magnetic field strengths ≥ 100 G above the chromosphere. Strong magnetic fields render the corona optically thick to gyroresonance absorption at centimeter wavelengths (see White & Kundu 1997 for a detailed discussion). Emission observed at a given frequency originates from a narrow resonance layer where the frequency matches a low harmonic (typically, the

second or third harmonic) of the electron gyrofrequency Ω_{Be} , which is linearly proportional to the magnetic field strength. As the observing frequency is varied, the resonance layer – or isogauss surface – from which the emission originates also varies (Figs. 2, 3). The observed brightness temperature corresponds to the electron temperature in the resonance layer. At the base of the corona, the electron temperature drops precipitously from coronal to chromospheric values. Radio emission from the resonant layers passing through the base of the corona manifests itself as a break in the radio spectrum. By measuring the radio frequency at which the spectral break occurs along a given line of sight, the magnetic field at the base of the corona is determined. FASR will provide a brightness temperature spectrum along each line of sight through the source, thereby enabling a map of the magnetic field at the base of the corona to be assembled.

FASR will, in addition, constrain the vector magnetic field and its evolution in active regions. Fig. 2 shows how gyroresonance emission at different frequencies arises on nested surfaces of constant magnetic field. 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 strength and orientation of the field. The dense spectral coverage provided by FASR provides complete sampling of the coronal volume over active regions. Dense spectral coverage translates into continuous magnetic field strength coverage. When coupled with extrapolation techniques FASR observations provide the means of performing three-dimensional coronal magnetography where the magnetic field strength exceeds ~ 100 G.

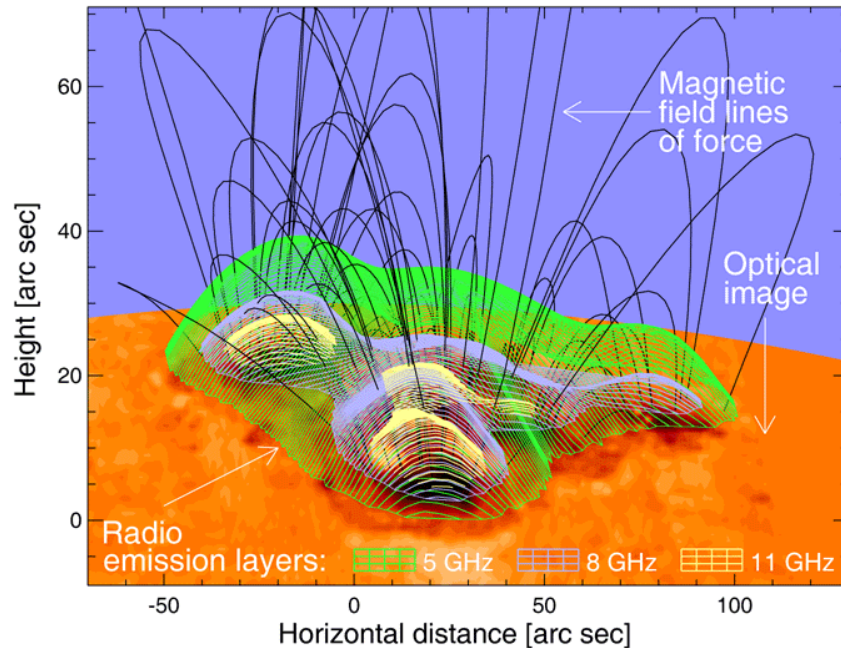


Figure 2: A perspective view of AR6615 (7 May 1991) is shown in white light continuum with extrapolated field lines from a nonlinear force-free calculation by Z. Mikic. The three surfaces are the gyroresonant surfaces in the corona that will dominate the radio opacity at each of three radio frequencies: 5 GHz ($B = 600$ G), 8 GHz ($B = 950$ G) and 11 GHz ($B = 1300$ G), assuming $s=3$. (from J. Lee/NJIT).

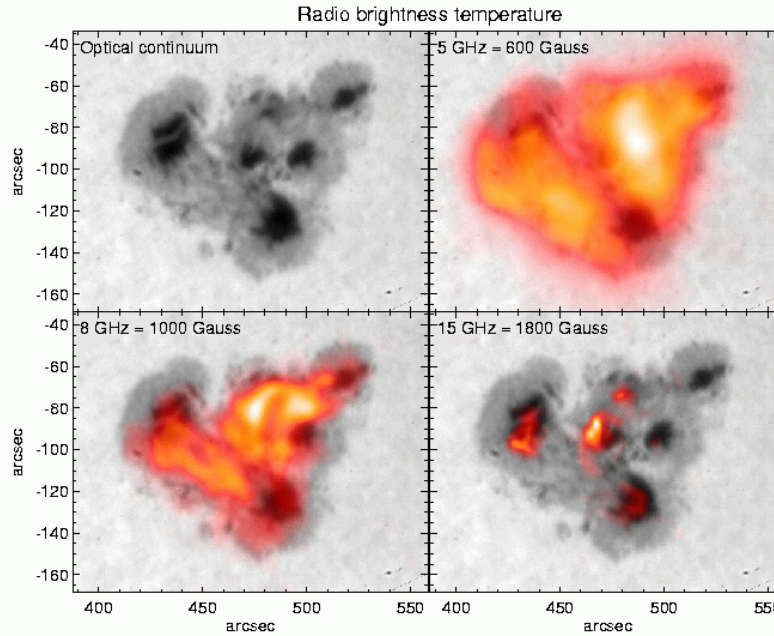


Figure 3: VLA observations of AR6615 at 5, 8.4, and 15 GHz. The radio brightness distribution has been superposed on the white light continuum image. The radio emission originates from an isogauss surface in each case. (after Lee et al. 1998).

4.1.2 Magnetic constraints from radio propagation

Another unique capability provided by the FASR is the means of constraining the magnetic field topology above active regions using the mode coupling properties of the radio radiation (Ryabov 2003). When radio radiation 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 that demarcates the reversal in the sense of circular polarization (Stokes $V=0$) is called the “depolarization strip” (e.g., Bandiera 1982). Using the frequency agility of the FASR, a “depolarization sheet” can be deduced above active regions, thereby providing a three-dimensional topological constraint on the magnetic field: i.e., the locations where it is perpendicular to the line of sight.

High in the corona, differential Faraday rotation is greatly reduced at centimeter wavelengths. If observed with a sufficiently narrow band with high resolution (10s of kHz), the Faraday oscillations of the linearly polarized emission associated with quasitransverse propagation can be observed (Alissandrakis & Chiuderi-Drago 1994, 1995). It is not yet clear, however, whether the FASR design will allow a mode with sufficient spectral resolution for this specialized purpose.

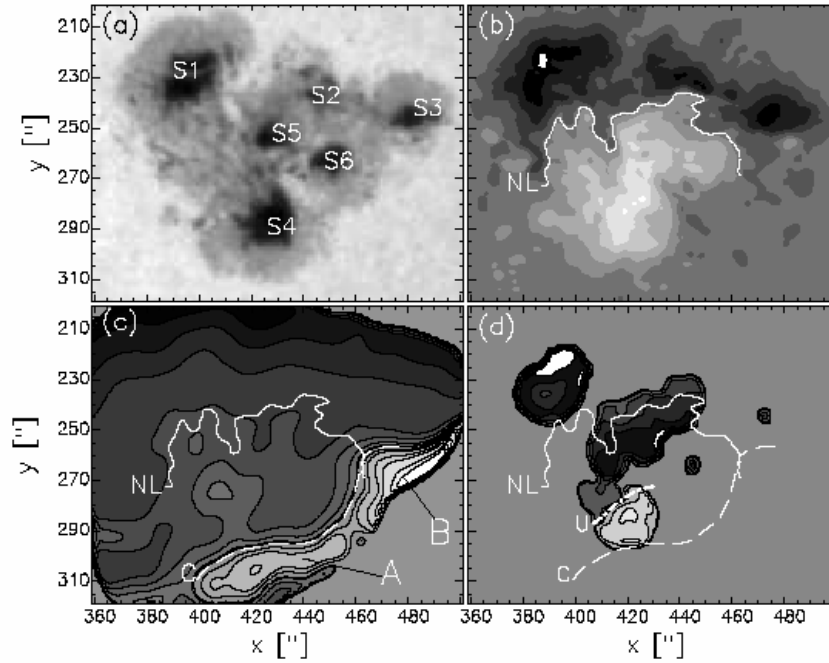


Figure 4: (a) white light continuum image of AR6615; (b) photospheric magnetogram of AR6615 – white indicates that the longitudinal component of the magnetic field is directed toward the observer; (c) a Stokes V map of the 4.9 GHz emission; (d) the same for the 15 GHz emission. Note that the magnetic neutral line, or depolarization strip, in the 4.9 and 15 GHz V maps (dashed lines labeled C and U, respectively) are significantly displaced from the magnetic neutral line in the photosphere (labeled NL; from Ryabov 2003).

4.1.3 Measuring weak magnetic fields using free-free emission

A magnetized plasma is “birefringent” to free-free radiation because the ordinary and extraordinary modes have different absorption coefficients. For a uniform thermal plasma, the degree of circular polarization of the optically thin emission is $\rho_c = V/I = 2\nu_{Be} \cos\theta / \nu$, where θ is the angle between the magnetic field vector and the line of sight, so that $B \cos\theta$ is the longitudinal component of the magnetic field. In reality, the density and magnetic field (and to some extent, the temperature) vary along the line of sight and ρ_c is represented by a density-weighted integral along the line of sight. Moreover, the emission at a given frequency is not always optically thin along a given line of sight. A more general treatment of the problem in the weak field limit (Gelfreikh 2003) shows that useful constraints on the coronal magnetic field may nevertheless be deduced from spectrally resolved observations of free-free emission. An example of an observation of a small active region by the Nobeyama Radioheliograph (NoRH) is shown in Fig. 5. FASR will have tremendous sensitivity as well as a large amount of frequency redundancy, thereby allowing it to constrain the longitudinal magnetic field in the corona to low limits (~ 10 G).

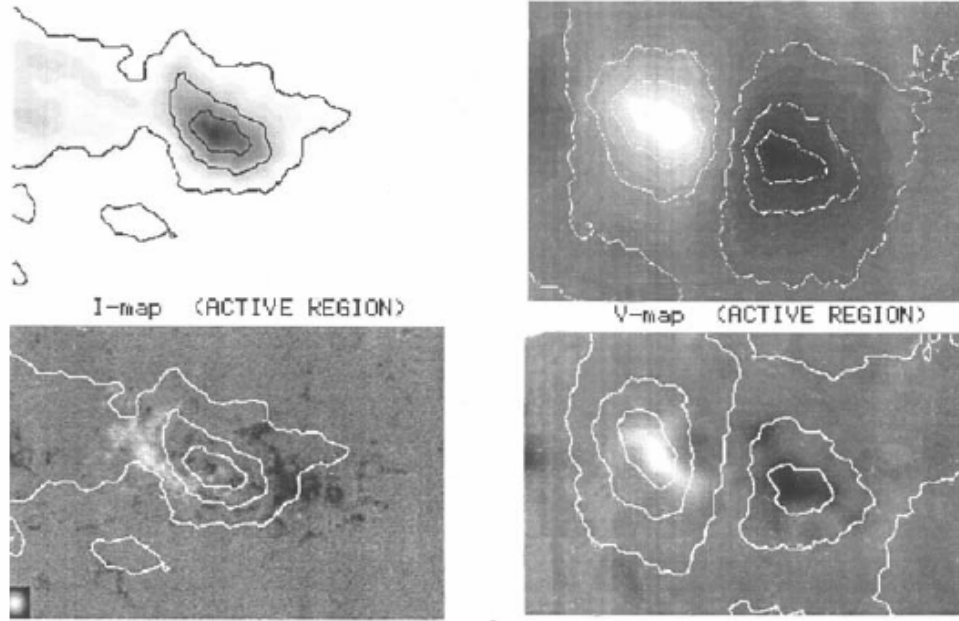


Figure 5: Thermal free-free emission from a active region, observed by the NoRH at 17 GHz. The upper left panel shows contours of total intensity superposed on a grayscale representation. The peak brightness temperature is $T_B = 27 \times 10^3$ K. The lower left panel shows the same contours superposed on a photospheric magnetogram. The upper-right panel shows contours of Stokes V superposed on the magnetogram degraded to the resolution of the NoRH, while the lower right shows contours of $\rho_c = V/I$, the peak of which is 2.8%.

Measurements of the magnetic field in and above active regions and elsewhere in the corona will provide critical new insights into the temporal evolution of coronal magnetic fields, the role of currents in the corona, and the storage and release of magnetic energy. In addition to providing critical inputs to the important problem of the nature and evolution of coronal magnetic fields, coronal magnetic field measurements may have practical utility as well. We return to this point in Section 4.5.

4.2 The Physics of 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 10^{37} electrons s^{-1} to energies >20 keV for periods of tens of seconds (Miller et al. 1998). Flares are often accompanied by the ejection of mass by an associated filament eruption and/or a coronal mass ejection (see Section 4.3).

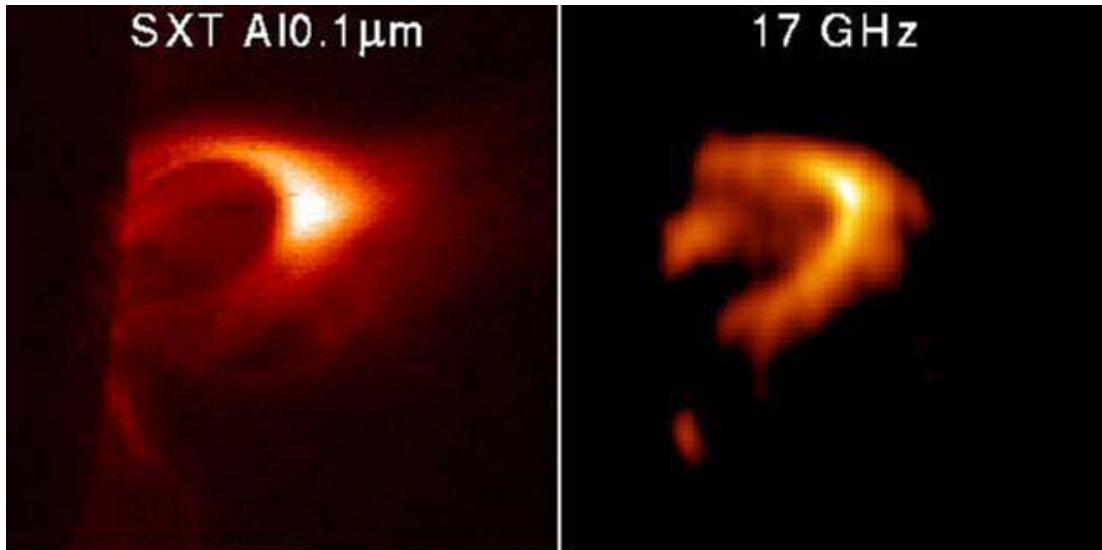


Figure 6: The flare of 16 March 1993 observed in soft X-rays by the Yohkoh SXT (left) and at 17 GHz by the NoRH (right). From Hanaoka (1994).

A schematic view of flares is given in Fig. 7. Briefly, magnetic energy release occurs in the low corona through fast magnetic reconnection. It is believed to be a highly fragmented process, with many discrete energy release events taking place (see below). The multitudes of type III-like bursts that occur during the impulsive phase of flares may be intimately connected to energy release. Electrons with access to open magnetic field lines produce classical type III radio bursts; some extend into interplanetary space. A blast wave and/or fast ejecta produced by the flare may produce MHD shocks in the corona and an associated coronal type II radio burst. Electrons and ions are promptly accelerated to high energies by quasi-static electric fields, shocks, and/or stochastic processes (Miller et al. 1998). Based on detailed studies of hard X-ray timing (Aschwanden 1998; Aschwanden et al. 1998; Aschwanden et al. 1999), as well as joint HXR/microwave studies (e.g., Lee et al. 2002) it appears that electron transport in many flares is well-described by the “direct precipitation and trap plus precipitation” (DPTPP) model. Energetic electrons with small pitch angles are guided by the magnetic field directly to the chromosphere, where they are stopped by relatively cool, dense material. Most of their energy goes into heating the ambient chromospheric plasma but a fraction is emitted radiatively via nonthermal bremsstrahlung as HXRs. Electrons with larger pitch angles are trapped by coronal magnetic fields and emit nonthermal gyrosynchrotron radiation. Eventually they are scattered into the loss cone via Coulomb collisions or wave-particle interactions and precipitate out of the magnetic trap, producing additional HXRs. Energy deposition in the chromosphere heats it to $>10^7$ K, causing it to expand dynamically into the corona (chromospheric evaporation), filling coronal magnetic loops at the flare site with dense, soft-X-ray-emitting plasma. In the aftermath of a flare, these hot, post-flare loops continue to emit SXR.

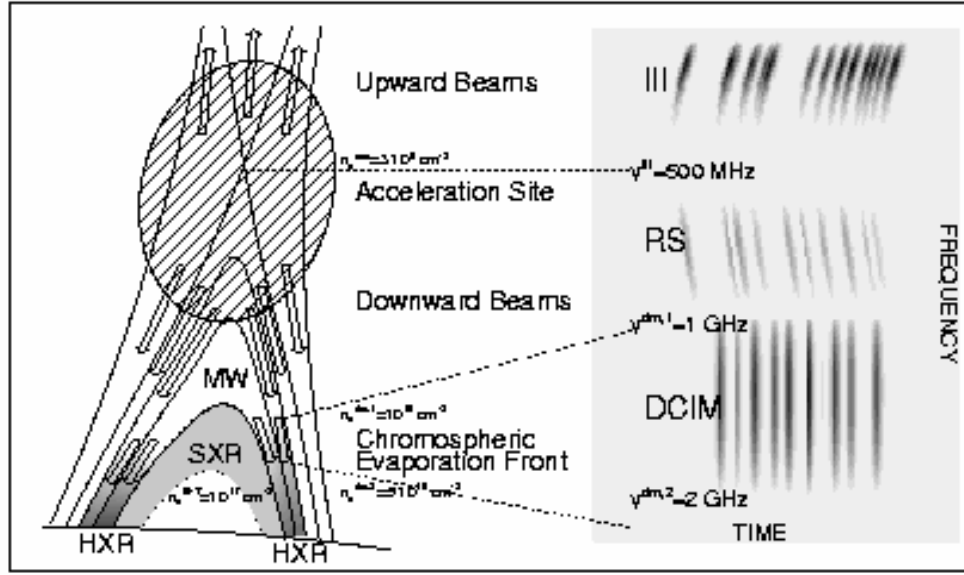


Figure 7: Cartoon of a flare model suggesting a global view of acceleration and ablation processes in the context of density measurements by coherent radio bursts and SXR emission. The panel on the right illustrates a radio spectrogram (dynamic spectrum) with bursts indicated schematically. The acceleration site is located in a low-density cusp from where electron beams are accelerated in upward (m - λ type III) and downward (reverse-slope bursts) directions. (from Aschwanden & Benz 1997).

The study of flares offers one of the best available means of studying magnetic energy storage, magnetic energy release, charged particle acceleration, wave-particle interactions, and charged 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 through meter- λ emissions for flare studies. Moreover, it will provide an *integrated* view of these emissions in time: the role of coherent burst emissions due to electron beams at decimeter wavelengths, of the incoherent gyrosynchrotron emission due to trapped and precipitating electrons at centimeter wavelengths, and associated phenomena (shocks, CMEs, escaping electrons) at meter wavelengths (see below). In other words, it will provide a three-dimensional view of important physical processes that occur during flares and will provide insight into the coupling between different parts of the flaring volume. We touch on a few of these possibilities here.

4.2.1 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. Progress has been made in recent years on identifying tracers of energy release in the solar corona (see Bastian, Benz, & Gary 1998 for a review). Decimetric type III bursts (type III_{dm}) occur most commonly in the 400-800 MHz range but have been known to occur at both lower and much higher frequencies. This frequency range corresponds to densities of $2\text{--}8 \times 10^9 \text{ cm}^{-3}$, i.e., the densities where energy release in flares is thought to take place. Multitudes of bursts are released during the course of the impulsive phase of a flare (Fig. 8). Type

III_{dm} bursts are more numerous than metric type IIIs and show positive or negative frequency drifts, indicating upward or downward motion in the corona. Some events show positive *and* negative drifts, indicating the presence of bi-directional electron beams. Outward propagating electron beams sometimes show a reversal in frequency drift (type U bursts), indicating that the beam is propagating along a closed magnetic loop. Type III_{dm} bursts are believed to be intimately related to energy release via magnetic reconnection.

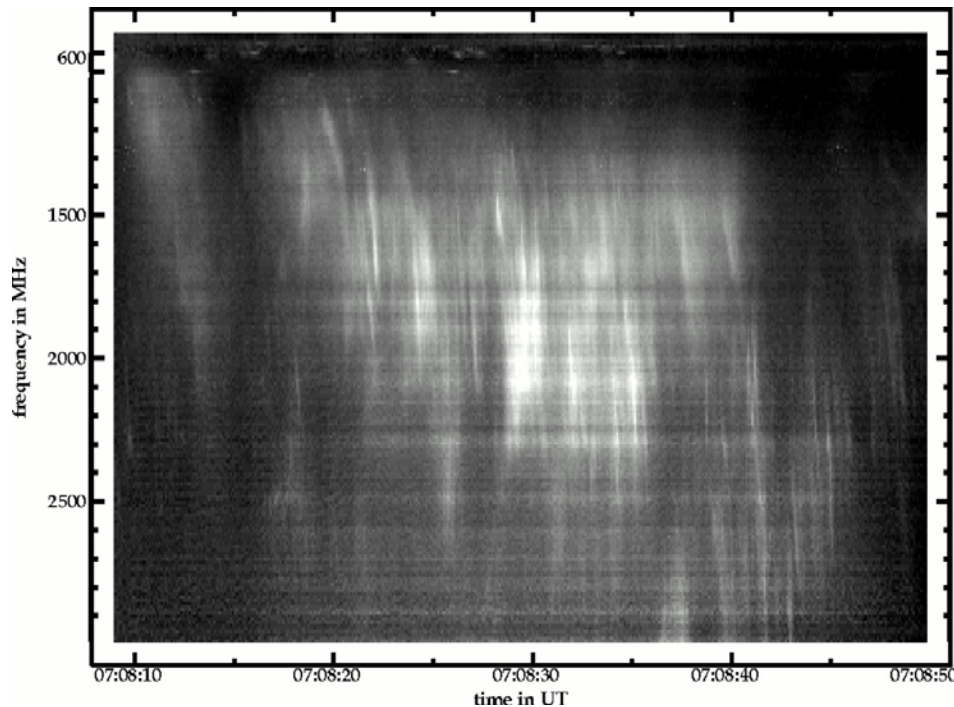


Figure 8: An example of a dynamic spectrum showing multitudes of reverse-slope type III_{dm} radio bursts during the impulsive phase of a flare. The fact that the burst frequencies drift in time from low to high frequencies indicates that the electron beam excitors are propagating downward from the corona to a denser environment. From Isliker and Benz (1994).

While spectroscopic observations of classical and reverse-drift type IIIs during flares have been performed for many years, they have been imaged directly at decimeter wavelengths rarely, and then only at a fixed frequency (e.g., Aschwanden et al. 1994). FASR will provide an unprecedented opportunity to image the energy release site in three dimensions. By imaging the trajectories of upward- and downward-directed electron beams, the location of energy release can be precisely determined. Furthermore, by measuring the trajectories of nonthermal electron beams, the local magnetic topology in the energy release site will be illuminated. Finally, the density in the energy release site will be determined directly from the frequency of emission. 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.

4.2.2 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 microwave spectrum and polarization, which depend sensitively on the electron distribution function and the local magnetic field, will be available at every location in the source. The spectral maximum typically occurs between 5-15 GHz. Hence both the optically thick and optically thin parts of the spectrum are useful for fitting the magnetic field strength and orientation in a flaring source as a function of position and time. Modeling efforts along these lines have been presented recently by Nindos et al. (2002).

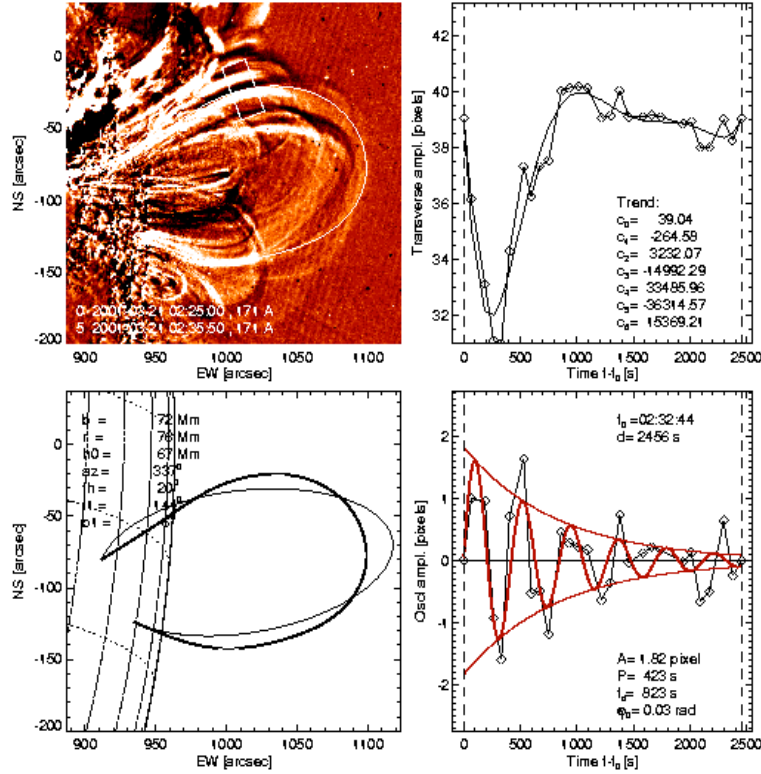


Figure 9: Example of damped loop oscillations observed by TRACE. From Aschwanden et al. (2002)

Additional and independent constraints are available on the magnetic field in a flaring source. Coronal loop oscillations have long been recorded at radio wavelengths (e.g., Trottet et al. 1981). With the discovery of loop oscillations at EUV wavelengths by TRACE (Shrijver et al. 2002; Aschwanden et al. 2002) there is renewed interest in “coronal seismology”, wherein loop oscillations excited by flares can be used as a probe of local plasma conditions, including the magnetic field. Another 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, thereby allowing the magnetic field strength to be inferred (Bastian 1999). Radio techniques are unique in their ability to provide quantitative measurements of coronal magnetic fields in flaring sources.

4.2.3 Electron acceleration and transport

The fundamental mechanism(s) of particle acceleration in flares remain(s) largely unknown. Broadband imaging spectroscopy will image the flaring source from chromospheric to coronal heights, yielding an integrated view of energy release, electron acceleration, and electron transport. The microwave spectrum is a particularly powerful diagnostic of the details of the emitting distribution of energetic electrons including high-energy cutoffs and anisotropies (Fleishman & Melnikov 2003ab). FASR will perform time-resolved imaging spectroscopy. The time evolution of the radiation spectrum and, hence, the electron distribution function, will be tracked at each positioning the flaring source.

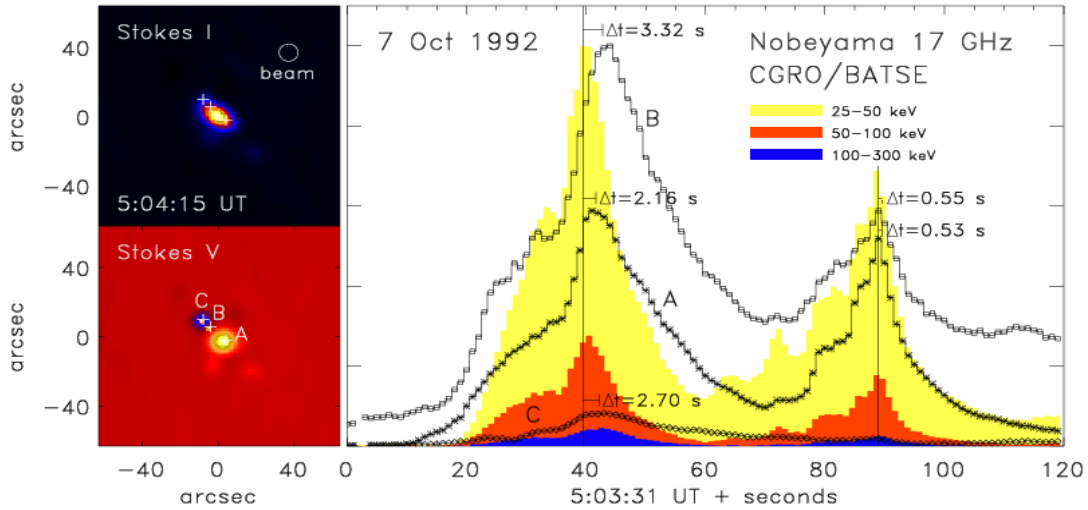


Figure 10: An example of the time variation of the NoRH 17 GHz brightness compared to the HXR count rate as measured by BATSE/CGRO for a simple flaring magnetic loop. The panels to the left show a 17 GHz map at the time of the flare maximum. Light curve B shows Stokes I near the loop top. Light curve A shows Stokes V at the right-circularly polarized footpoint; Light curve C shows the absolute value of Stokes V for the left-circularly polarized footpoint. B is delayed relative to A and C and all radio emission is delayed relative to the HXR emission. From Bastian, Benz, & Gary (1998)

It is also worth pointing out that, due to the fact that magnetic loops behave like dispersive elements, with more energetic particles emitting in weak-field regions and less energetic particles emitting in strong-field regions (Bastian, Benz, & Gary 1998), the relative timing of temporal features at different frequencies and different locations in the source offers an additional diagnostic of acceleration and transport. In particular, joint microwave/HXR observations can be used to constrain 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 such as RHESSI provide images of the nonthermal HXR emission from ~ 10 keV to MeV energies, 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 with the requisite sub-second time resolution.

4.2.4 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 SXR. 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 and, therefore, a means of tracking energy deposition.

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 III dm bursts with the ablated material (Aschwanden & Benz 1995).

4.3 Drivers of Space Weather

The term “space weather” refers to a vast array of phenomena that can disturb the interplanetary medium and/or affect the Earth and near-Earth environment. This includes recurrent structures in the solar wind (fast solar wind streams, co-rotating interaction regions), the ionising radiation and hard particle radiations from flares, radio noise from the Sun, coronal mass ejections, and shock-accelerated particles. These drivers result in 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.

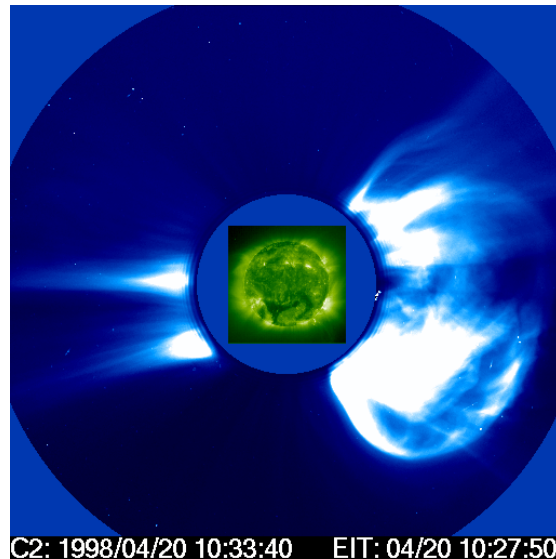
The drivers of space weather – fast and slow solar wind streams, flares, and coronal mass ejections – are all solar in origin. An understanding of space weather phenomena lies, in part, in gaining a fundamental understanding of these drivers. At a more practical level, space weather forecasting and “nowcasting” are of interest as a means of avoiding disruptions, protecting technological assets, and safeguarding the health of humans in space. Forecasting requires the identification and timely dissemination of information relevant to space weather drivers. In this section we briefly note several ways in which FASR will contribute to both a fundamental understanding of drivers of space weather. In

a separate section we discuss contributions FASR could play to forecasting/nowcasting activities.

4.3.1 Detection and characterization of coronal mass ejections

Coronal mass ejections (CMEs) involve the destabilization and ejection of a significant portion of the corona. CME masses range from $\sim 10^{14}$ - 10^{16} g and possess speeds of ~ 200 - 2000 km s^{-1} . The kinetic energy of a CME is therefore comparable to large solar flares.

Figure 11: SOHO/LASCO observation of a fast CME on 20 April 1998. A SOHO/EIT image of the Sun is shown for comparison.



Interest in coronal mass ejections (CMEs) has been 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 (Bastian et al. 2001) a new tool has become available to detect, image, and diagnose the properties of CMEs. An example is shown in Fig. 12, where radio emission is shown from relativistic electrons entrained in the expanding CME loops. Fits of a simple synchrotron model to two- and three-point spectra at various locations in the source illustrate the potential for imaging spectroscopy with FASR. The low frequency cutoff is due to Razin suppression. The fits yield not only the magnetic field of the CME, but the ambient density of the thermal plasma as well. Radio CMEs may be significantly linearly polarized by the time they propagate to several solar radii from the Sun. Detection of linearly polarized radiation from radio CMEs would provide additional leverage on the magnetic field in CMEs.

CMEs can be detected by other means. Using the Clark Lake Radio Observatory, Gopalswamy & Kundu (1993) report observations of thermal radiation signatures of a CME near the plasma level at 38.5, 50, and 73.8 MHz. More recently, thermal emission from CMEs (Kathiravan et al. 2002), and coronal dimmings resulting from the launch of a CME (Ramesh and Sastry 2000) have been reported in observations made by the Gauribidanur Radioheliograph between 50-65 MHz although Bastian & Gary (1997)

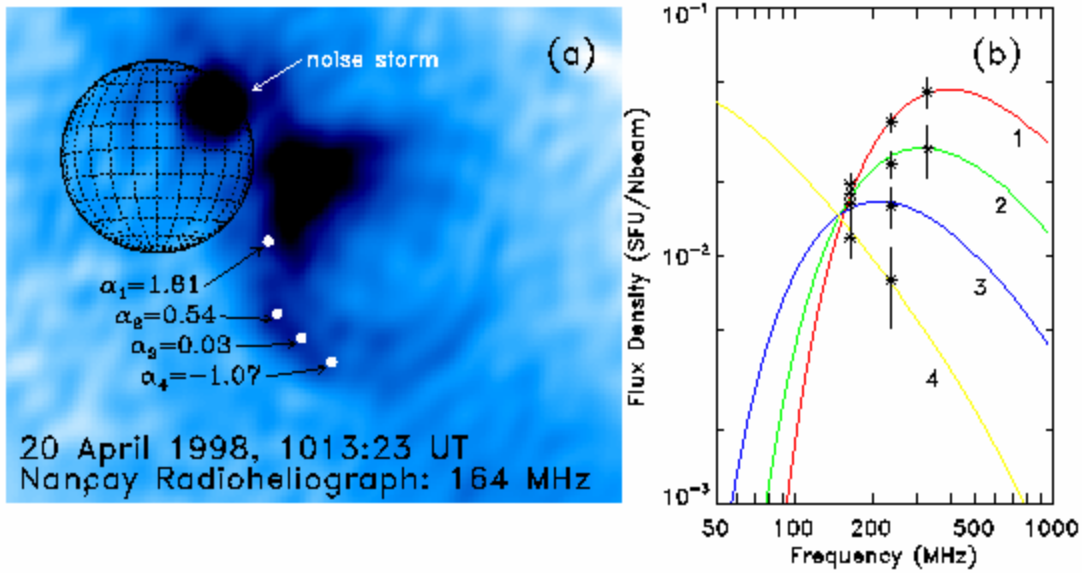


Figure 12: Example of a radio CME, the radio counterpart to that shown in Fig. 10, imaged by the Nancay Radioheliograph at a frequency of 164 MHz. The panel to the left shows the expanding CME loops (emission from the background Sun has been subtracted). The panel to the right shows model fits to multi-point spectra and the lines of sight indicated to the left.

show that similar phenomena should be detectable at decimetre/meter wavelengths as well.

The advantages of CME detection and characterization at radio wavelengths with FASR are: i) there is no occulting disk, so earth-directed CMEs may be detected; ii) CMEs will be detected in their nascent stages of development and can be directly associated with structures such as filament channel arcades; iii) unlike SXR and white-light observations, observations at radio wavelengths are sensitive to both thermal free-free emission from CMEs and nonthermal constituents. Owing to its frequency agility the FASR will provide a comprehensive observational picture of CMEs and associated phenomena over a wide frequency range.

4.3.2 Detection and characterization of “EIT waves” and dimmings

Coronal waves, possible analogs to chromospheric Moreton waves, were discovered by the SOHO/EIT instrument (Thompson et al. 1999, 2000; Biesecker et al 2002) although examples have since been discovered in SXR (Khan & Aurass 2002). They represent the dynamical response of the corona to a flare and/or an associated CME. An associated phenomenon is a coronal dimming, observed in SXR (e.g., Sterling & Hudson 1997) and EUV (Harra & Sterling 2001), believed to result from the removal of coronal material due to the lift-off of a CME.

A radio counterpart to an “EIT wave” was recently detected by the NoRH at 17 GHz (White & Thompson 2003) in association with a flare and CME on 24 Sep 1997. This,

coupled with observations of coronal dimmings mentioned in Section 4.3.1, suggests that FASR will excel in detecting and characterizing the response of the solar atmosphere to flares and coronal mass ejections. Since FASR will be sensitive to emissions from chromospheric to coronal heights, it will provide a complete view of chromospheric and coronal waves, dimmings, and the interaction of waves with surrounding structures such as active regions (e.g., Ofman and Thompson 2002).

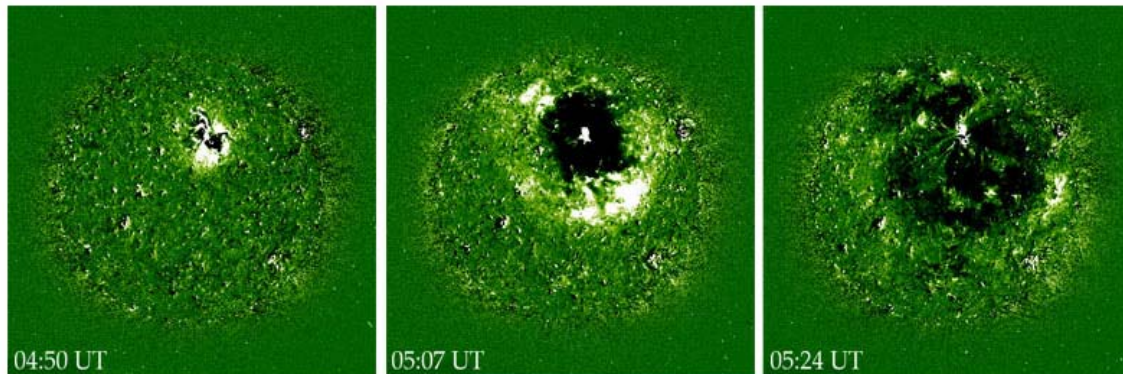


Figure 13: A sequence of SOHO/EIT difference images in Fe XII 195 Å (1.5 MK) showing an “EIT wave” observed on 12 May 1997. The coronal wave accompanied a “halo” (Earth-directed) CME.

4.3.3 Detection and characterization of MHD shocks

It is generally accepted that type II radio bursts are a tracer of fast MHD shocks. The shocks that produce coronal type II radio bursts may be driven by fast ejecta (Gopalswamy et al. 1997), by a blast wave (Uchida 1974, Cane & Reames 1988), or by a CME (Cliver et al 1999; Klassen & Aurass 2002). Fast ejecta and/or a blast wave are produced by a flare; 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” remains a matter of considerable controversy, as discussed by Cliver et al. (1999), Gopalswamy (2000), Gopalswamy et al. (2001) and Klassen et al. (2000).

With its unique ability to perform imaging spectroscopy, FASR will be able to simultaneously image the basic shock driver (flare or CME), the response of the atmosphere to the driver (chromospheric and coronal waves and coronal dimmings), and shocks which may form due to the flare or the CME. The emphasis placed on FASR’s ability to provide an integrated picture of the flare phenomena applies equally to CMEs and associated phenomena (type II radio bursts, EIT and Moreton waves, filament eruptions).

4.3.4 Origin of solar energetic particle events

Particle acceleration in flares and shocks has been of fundamental interest for many years. Of particular relevance to space weather studies are solar energetic particle (SEP)

events. During the past ~15 years, SEP events have been classified as impulsive or gradual events (e.g., Reames 1999) based on the properties of the associated soft X-ray flare, correlations with radio bursts of type III (impulsive) or types II/IV (gradual), abundances and charge states of the energetic particles, and the presence or absence of a CME. Impulsive SEP events were believed to originate in solar flares while the energetic particles in gradual SEP events were thought to be accelerated in CME-driven coronal and/or interplanetary shocks. Since the largest SEP events are gradual events in this scheme, interest in particle acceleration by CME-driven shocks has remained high.

Several analyses of radio spectroscopic and energetic particle data have called this simple picture into question (Klein et al. 1999; Laitinen et al. 2000; Klein & Trottet 2001), arguing that sustained particle acceleration can occur in the mid-corona. Based on an observed correlation between certain type III radio bursts and SEP events, Cane, Erickson, & Prestage (2003) have recently argued that flare particles have access to the interplanetary medium via open magnetic field lines. Detailed observations of abundances and charge states by the Advanced Composition Explorer (ACE) suggest that at the very least, the impulsive/gradual paradigm requires modification in recognition of complicating realities.

As an instrument that images coronal energy release and particle acceleration in the middle corona, tracers of coronal shocks, and the onset and ejection of certain coronal mass ejections, simultaneously, FASR will provide key observations that will help resolve the important and controversial problem of the origin of SEPs.

4.4 The Solar Atmosphere

Our understanding of the solar atmosphere has undergone significant changes of perspective over the years. All have been driven by observational advances. With the discovery of a high temperature corona in 1930s, and later the solar wind in the 1960s, a great deal of work has been devoted to understanding the nature of the nonradiative mechanism(s) required to sustain both phenomena. Early theories of the solar atmosphere were spherically or azimuthally symmetric. One of the most important lessons of the *Skylab* mission in the early-1970's was that the corona is far from symmetric -- it is highly structured by the magnetic field, as well as by density and temperature gradients, on a wide variety of scales. More recently, the SXT on board the *Yohkoh* satellite has revealed that, in addition, the solar corona is highly dynamic. It is constantly changing on time scales of seconds to minutes, hours, days, and years. Coupled with progress at radio, UV, and optical wavelengths, it is now appreciated that the entire solar atmosphere -- from the photosphere to the corona, and out into the solar wind -- is a highly structured and restless entity.

4.4.1 Coronal heating

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 $>10^{28} \text{ erg s}^{-1}$ (Shimizu 1995). The leading theoretical ideas for how the corona is heated include either some form of resonant wave heating (e.g., Ofman, Klimchuk, & Davila 1998) or “nanoflares” (Parker 1988), although there exist many other models. 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. 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. Recent observational work at EUV wavelengths suggests that it may not be (Benz & Krucker 1999; Aschwanden & Parnell 2002).

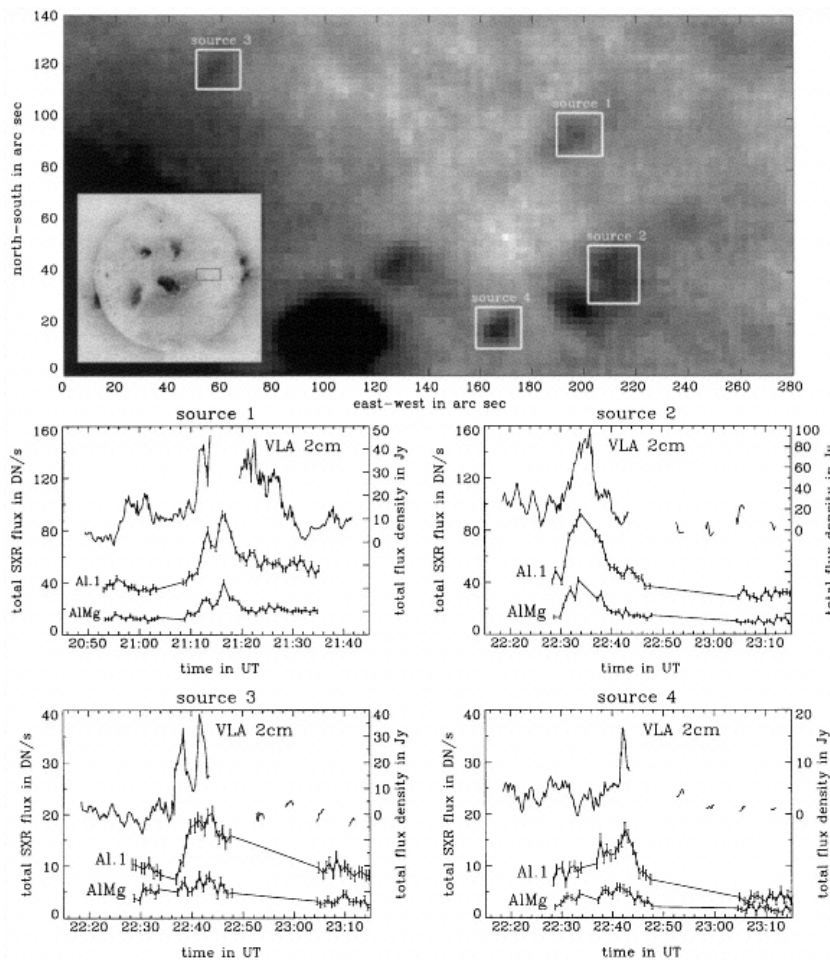


Figure 14: Temporal evolution of network flares observed in SXR and radio emission on 20 Feb 1995 by the VLA and *Yohkoh*. The image at the top shows the region observed in SXRs; the inset shows its location on the solar disk. Enhanced emission is dark. The locations of network flares are indicated by boxes. The plots below show the temporal variations of the SXR flux in the Al.1 and AlMg filters, and the 2 cm radio emission for the different network flares. (from Krucker et al. 1997)

At radio wavelengths Gary, Hartl & Shimizu (1997) established that the 10^{27} erg SXR events in active regions studied by Shimizu (1995) are accompanied by nonthermal electrons; i.e., they are flare-like. Even events that are near the limit of visibility for the *Yohkoh* SXT typically have radio counterparts that are easily detectable in total power by small non-imaging radio telescopes. High-quality imaging will lower the flux limit one achieves in microwaves by orders of magnitude. Krucker et al. (1997) and Benz & Krucker (1999), using multiband VLA and SOHO EIT and MDI data, have shown that even tiny transient events in the quiet chromospheric network are, in fact, flare-like.

FASR will greatly improve on previous work by providing vastly better frequency coverage and a sensitivity comparable to the VLA under some circumstances. The instrument's full-Sun capability should allow FASR to obtain accurate counting statistics on the occurrence rate of these events, and to determine whether that rate increases greatly enough at low energies to heat the corona.

4.4.2 Structure and dynamics of the chromosphere

In weak-magnetic-field regions, thermal gyroresonance emission is negligible and the radio emission is largely due to thermal free-free emission.¹ Microwave radiation is formed under conditions of LTE and the source function is therefore Planckian. For microwave observations the Rayleigh-Jeans approximation is valid and the observed intensity is linearly proportional to the kinetic temperature of the emitting material for optically thick sources (in contrast with lines in the visible and UV). By varying the frequency, one samples the thermal state of optically thick plasma at heights ranging from the mid-chromosphere to the low-corona. The broadband imaging capability of the FASR will be exploited to probe the thermal structure of the solar atmosphere in active regions, the quiet Sun, and coronal holes, as well as in filaments and prominences.

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 $4.7\mu\text{m}$ 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 (e.g., Ayres & Rabin 1996). Accurate broadband microwave (1 – 18 GHz) spectroscopy of the quiet Sun (Zirin, Baumert, & Hurford 1991) convincingly demonstrates that the prevailing semi-empirical models include an over-abundance of warm chromospheric material (Bastian, Dulk, & Leblanc 1996).

¹ As noted in the previous section, however, there is evidence that tiny, transient radio events in the chromospheric network may be flare-like and magnetic in origin (see Figure 14; Krucker et al. 1997; Benz & Krucker 1999). Small magnetic elements may therefore contribute a transient nonthermal component to the thermal background emission..

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 (e.g., Ayres & Rabin 1996). Another approach has recognized that chromospheric dynamics play a critical role in understanding the structure of the chromosphere (Stein & Carlsson 1997). Testing of modern chromospheric models requires spatially and temporally resolved observations of the thermal state of the chromosphere on the relevant spatial and temporal scales.

The FASR design will allow us to sample the thermal structure of the chromosphere down to the height where $T_e \approx 8000$ K. The sensitivity of the FASR, as presently conceived, will allow us to study the time variability of the thermal structure of the solar chromosphere in a single frequency band on a time scale ~ 1 min ($\Delta T_B \approx 100$ K). Over a period of several hours, the 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, plage – as an input for modern models of the inhomogeneous and dynamic chromosphere.

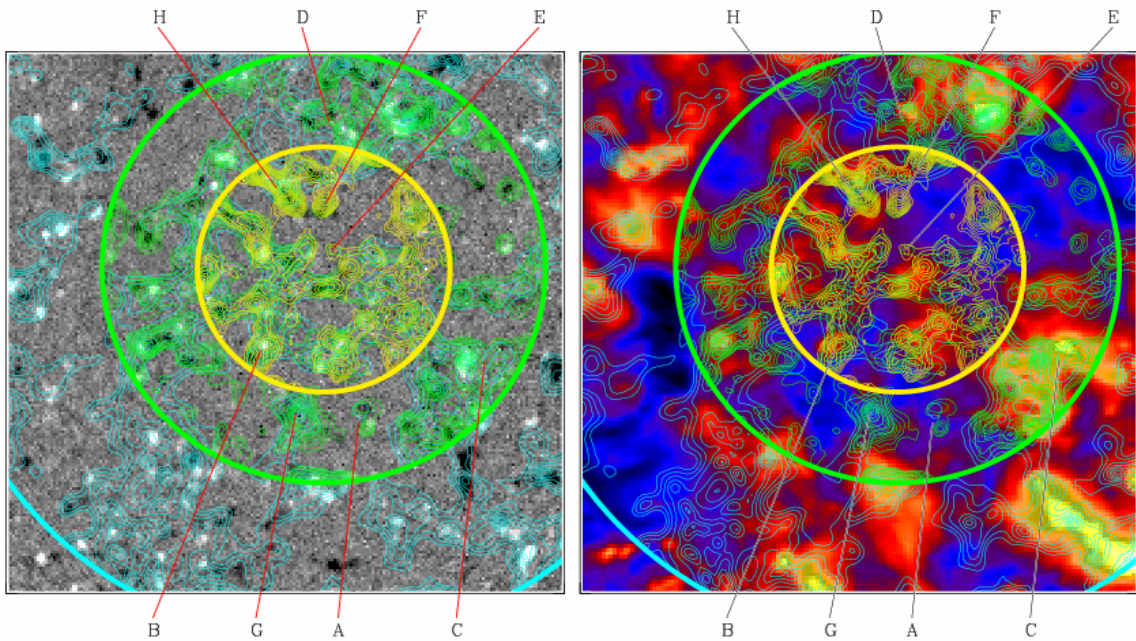


Figure 15: View of a quiet region near the center of the solar disk on 12 July 1996. The left panel shows the longitudinal component of the photospheric magnetic field as observed by SoHO/MDI. The contours represent radio intensities emitted by the chromosphere and transition region as observed by the VLA (yellow = 2 cm, green = 3.6 cm, blue = 6 cm). The right panel shows the coronal emission measure in the $1.1\text{--}1.9 \times 10^6$ K temperature range as derived from SoHO/EIT Fe IX/X and Fe XII lines. The contours are as before. (from Benz & Krucker 1999).

4.5 Synoptic Measurements and Solar Forecasting

The Sun occupies a unique position in astronomy and astrophysics because it has a direct impact on life on Earth and in space. Aside from the obvious fact that the Sun makes life on Earth possible, it is the vagaries of the Sun's activity cycle that may cause climatic change (e.g., the Maunder minimum in the late-17th C.). Moreover, as we have come to rely on both ground and space based technologies – for distribution of electrical power, gas and oil pipelines, fixed and mobile communications, navigation, weather and geological information – we have become more vulnerable to disruptions by transient phenomena on the Sun (flares, CMEs). Long-term studies of solar activity and both short- and long-term forecasting of solar activity are therefore of pressing interest.

FASR is designed to be flexible enough to carry out a wide variety of research programs requiring specialized data, but in addition it will carry out a strong synoptic role and produce certain data products that will be available in real-time, near real-time, or archivally. The forecasting community, ionospheric physicists, aeronomists and other interested parties will be free to download these products as they become available. As an example, the solar 10.7 cm flux has been used for many years as a proxy indicator of solar activity due to its close correlation with other diagnostics such as sunspot number and area, the emission in Ly β , Mg II, and EUV fluxes, and the total solar irradiance. The 10.7 cm flux remains the solar measurement in highest demand from NOAA/SEC. Schmahl & Kundu (1997) have shown that multi-radio-frequency measurements can be combined to yield superior proxies for both sunspots and irradiance. FASR will provide well-calibrated multifrequency observations suitable for exploiting such proxies. Additional examples of such data products include:

- Synoptic maps of the solar atmosphere at various frequencies (Fig. 16); synoptic maps of derived physical quantities: temperature, density, magnetic field.
- Maps of the magnetic field strength at the base of the corona in active regions.
- Measures of coronal magnetic activity. Strong gradients and/or high values and/or rapid evolution may be used as indicators of probable activity.
- Maps of brightness variance at selected frequencies. A high variance is indicative of evolving and/or emerging magnetic flux, and is an indicator of probable activity.
- Lists of flare events, erupting prominences, and CMEs; their location, size, and spectral properties as they occur.

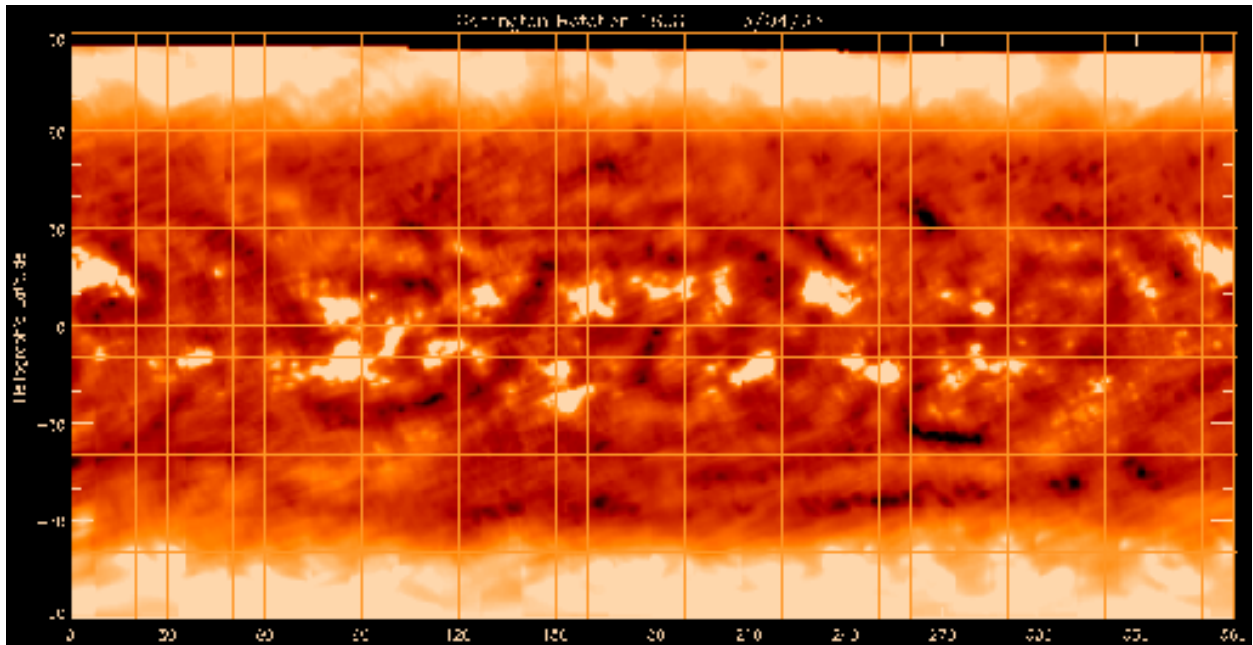


Figure 16: Example of a synoptic map constructed from observations by the NoRH at 17 GHz (from Shibasaki 1998).

5 The Frequency Agile Solar Radiotelescope

The science program outlined in the previous section imposes a number of specific science requirements on the instrument. In this section we summarize these requirements and then discuss a strawman concept for meeting these requirements.

5.1 Science requirements and instrument specifications

FASR will be designed to fully exploit solar radio emission from centimeter to meter wavelengths as a diagnostic of physical processes on the Sun. To this end, a number of science requirements have been identified:

Imaging: Radio emission on the Sun must be imaged with high dynamic range, fidelity, and angular resolution, with good sensitivity to both compact and extended sources of emission, instantaneously.

Field of view: A full disk imaging capability is desired to a frequency of 18 GHz. The upper frequency limit is determined by the typical upper frequency limit to which gyroresonance emission is expected to be relevant. A field of view to at least 10 solar radii is desired <500 MHz, determined by the requirement that radio CMEs can be

imaged.

Angular resolution: An angular resolution of 1" at a frequency of 20 GHz is required, and must be available whenever the Sun exceeds 30° elevation. This implies a maximum projected baseline of at least 3 km, or a physical baseline of 6 km. For a fixed array, the angular resolution scales linearly with frequency, yielding 10" at 2 GHz, and so on.

Instrumental bandwidth: Spectral coverage over a frequency range of 30 MHz to 30 GHz is desirable. Coronal magnetography requires frequency coverage from 1-18 GHz; the physics of flares requires coverage from 0.3-30 GHz; the study of drivers of space weather requires frequency coverage from the ionospheric cutoff (10-15 MHz) to 500 MHz (see Section 7).

Instantaneous bandwidth: An instantaneous bandwidth of 2 GHz should be supported. The cost of correlating three decades of bandwidth instantaneously is prohibitive and is not necessary. FASR will meet its scientific objectives through frequency agility.

Data channels: At least 2 independent data channels, one for each orthogonal sense of polarization, are required. For operational flexibility, 2-4 pairs of data channels are needed. The net bandwidth of the data channels will be of order 2 GHz.

Time resolution: Spectra must be acquired at a rate sufficient to resolve the time scale on which phenomena of interest evolve: 10 ms at decimeter wavelengths, 100 ms at centimeter wavelengths.

Spectral resolution: A spectral resolution of 0.1% is required at decimeter wavelengths and 1% at centimeter and meter wavelengths.

Polarimetry: Observations in the Stokes parameters I, Q, U, and V must be supported. The instrument must be optimized for observations of Stokes I and V. In some instances, it will be of interest to measure Q and U. It is not necessary to observe all four Stokes polarization parameters simultaneously.

The instrument specifications, based on the above science requirements, are distilled into a table below. Quantitative cross-comparisons of FASR observations with those in other wavelength regimes will require absolute source positions to 1". Absolute flux calibration to 5% is required at centimeter wavelengths. This can be relaxed to 10% at decimeter and meter wavelengths. As an operational requirement the instrument should not place the burden of data reduction on the user. Data calibration and reduction should be performed on-site and a wide variety of data products should be made available for the immediate and open use of the community at large.

Table I. FASR Instrument Specifications

Angular resolution	$20/v_{\text{GHz}}$ arcsec
Frequency range	30 MHz – 30 GHz
Number channel pairs	2-4
Total instantaneous BW	2 GHz
Frequency resolution	0.3-3 GHz: 0.1% <0.3,>3 GHz: 1%
Time resolution	0.3-3 GHz: 10 ms <0.3,>3 GHz: 100 ms
Polarization	IQ/UV
Number antennas	3-30 GHz: 100 0.3-3 GHz: 80 <0.3 GHz: 60
Size antennas	3-30 GHz: 2 m 0.3-3 GHz: 6 m <0.3 GHz: LPDA
Maximum antenna spacing	6 km
Absolute positions	1 arcsec
Absolute flux calibration	<5%
ΔT_B (snapshot)	1000 K

5.2 Strawman instrument

The science requirements resulting from the *Green Bank Science Definition Workshop* on May, 2002, were considered at the first *FASR Technical Meeting* in August, 2002, at the NRAO in Charlottesville, VA. The basic outline of FASR was refined and expanded, on the basis of discussions that occurred there.

5.2.1 Preliminary considerations and system overview

FASR will be a Fourier synthesis telescope. To image the Sun's radio brightness distribution with good dynamic range and fidelity requires many visibility measurements. Moreover, since the Sun's brightness varies continuously in time—sometimes dramatically so—Earth rotation aperture synthesis is not generally possible. Hence, the *instantaneous uv coverage* must be extremely good, and optimized to the solar imaging problem. This implies that a large number of antennas is required – of order 100.

FASR antennas will be designed to track the Sun every day during daylight hours. From an operational standpoint, it is highly undesirable to remove antennas from the array for maintenance or repair during daylight hours. Given the large number of antennas to

maintain, FASR antennas must be highly reliable in the field. This implies that the antenna and front end should be of a simple and robust design.

Turning to the source itself, the Sun differs from weak sidereal sources in important respects. First, it is an extremely powerful radio source, so much so that it completely dominates the system temperature. This has two consequences: 1) the front-end electronics need not be cooled; 2) large antennas are not needed for sensitivity. Second, the Sun's radio emission is highly variable. Depending on the frequency, the Sun's total radio flux may vary by as much as 40 dB. The variability can be on short time scales, as implied in Table I, and display narrowband structure. FASR must be designed to process such highly variable emission and at the same time employ countermeasures against radio frequency interference.

One of the most challenging aspects of the FASR project is the very large instrument bandwidth that must be sampled and processed on short time scales. It appears unlikely that a single antenna and feed can support the proposed instrument bandwidth. FASR will therefore be composed of three subarrays of antennas, each designed to support a subrange of frequencies. Even so, the range of frequencies to be covered in each subrange is technically challenging. It is important to point out that the low frequency limit of FASR is, as yet, undetermined. On scientific grounds, it should extend down to at least 30 MHz.

In keeping with the desire to keep the equipment associated with the antennas simple and robust, the bulk of the signal processing will be carried out at a central location. This has the added advantage that future upgrades to signal processing capabilities can be accomplished more conveniently.

5.2.2 Antennas

Multiple arrays are needed to meet the joint requirements of supporting a large instrument bandwidth, excellent imaging, and a large field of view. FASR will therefore employ *three* arrays of antennas using three separate antenna designs. Each will cover roughly a decade in frequency – corresponding roughly to meter, decimeter, and centimeter wavelengths – with an appropriate degree of overlap between each for cross-calibration. For the purposes of discussion, the three arrays are the low-frequency array (LFA), the intermediate-frequency array (IFA), and the high-frequency array (HFA).

LFA	30-300 MHz	Fixed log-periodic or active dipoles, or Vivaldi-type feeds
IFA	0.3-3 GHz	steerable 6 m paraboloids
HFA	2-24 GHz	steerable 2 m paraboloids

The LFA will likely employ fixed log-periodic crossed dipoles. We select symmetric 6 m paraboloids for the IFA and 2 m paraboloids for the HFA. These have fields of view of $\sim 1^\circ$ - 14° and $\sim 0.4^\circ$ - 5° , respectively, over the nominal frequency ranges. The cost of 2 and

6 m antennas will be modest. Future studies will address the optimum choices for the antenna mounts and drives (IFA and HFA).

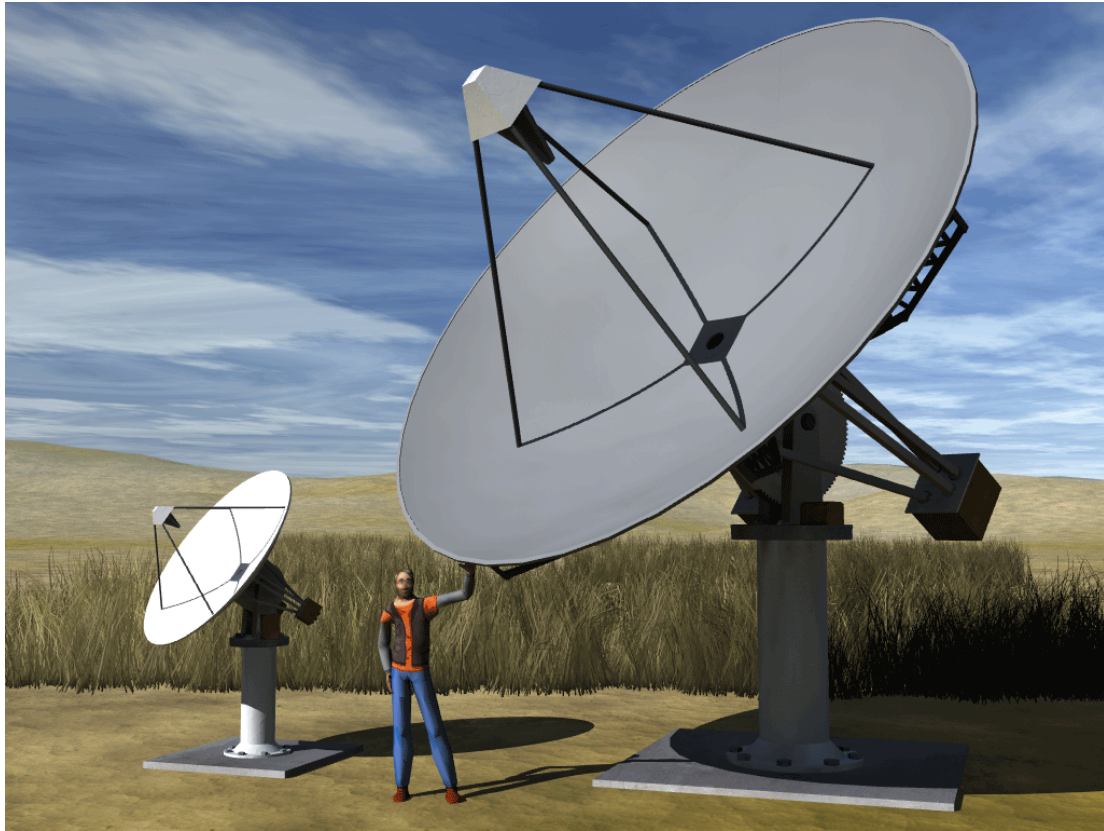


Figure 17: Artist's rendering of the 2 m and 6 m antenna elements proposed for use in the HFA and IFA arrays.

5.2.3 Array configuration

A Fourier synthesis telescope measures the Fourier transform of the radio brightness distribution, the so-called visibility function. The sampling of the visibility function is determined by the cross-correlation function of the antenna locations in the array. The point spread function (PSF) of the array is the inverse Fourier transform of the sampling function. The criteria by which antenna configurations are assessed depend on the imaging problem at hand. For a two-dimensional array of finite extent, uniform sampling in the Fourier, or uv , plane yields both the highest angular resolution and the best signal to noise ratio (Keto 1997). Alternatively, sidelobe minimization has been used to optimize array configurations (Kogan 1997). Additional criteria often come into play. In the case of the VLA (Napier, Thompson, & Ekers 1983), reconfigurability, scalability, and a practical means of accomplishing both led designers to choose a "Y" configuration, the antennas distributed along each arm according to a power law relation.

FASR is a special-purpose instrument best served by other considerations. Each of the three subarrays described in Section 5.2.2 must image the Sun with high degrees of dynamic range and fidelity over roughly a decade of bandwidth with a fixed configuration. For the HFA, the science requirements call for an angular resolution of $1''$ at a reference frequency of 20 GHz, or a projected baseline of 3 km. To meet this requirement over a significant range of hour angle (source elevation $>30^\circ$) suggests that a maximum baseline of 6 km is required. Since the angular resolution of a fixed array configuration varies linearly with wavelength, the angular resolution requirement varies between $0.8''$ - $10''$ in the HFA and, if the configuration footprints are similar for the IFA and LFA, the angular resolutions will be $7''$ - $80''$ and $1'$ - $3.5'$, respectively. Is this sufficient?

In fact, the angular resolution with which one can image the Sun is limited by scattering on inhomogeneities in the overlying corona – “coronal seeing” (e.g., Bastian 1994). Seeing limitations are frequency dependent and also depend sensitively on the details of the coronal medium (e.g., an active region source, a quiet region, whether the source is on the limb, whether the Sun is near maximum or minimum levels of activity, etc). Both observations (e.g., Leblanc et al. 2000) and theory (e.g., Bastian 1994) suggest that the proposed extent of the array is a good match to the expected variation in coronal seeing with frequency.

While the spatial extent of FASR is relatively modest, it must adequately sample the wide range of spatial scales present in solar radio emission – more than three orders of magnitude at high frequencies, although this may be relaxed for intermediate and low frequencies. By comparison, the ratio of the maximum to minimum spatial frequencies sampled by a given configuration of the VLA is 40. Many phenomena of interest occur on very short time scales. The snapshot imaging capabilities of the array, and hence the instantaneous uv coverage, must therefore be excellent. The FASR array configuration is therefore a challenging optimization problem, one that is presently under study.

Work to date, however, has shown that a promising approach is the use of “self-similar” array configurations (Bastian et al. 1998; Conway 1998, 2000) composed of a relatively large number of antennas (~ 100). The scale-free nature of self-similar configurations is ideal for imaging over wide bands. An example of a self-similar configuration is one composed of logarithmic spirals (Conway 1998). An example illustrating the imaging capabilities of a 108-element array composed of three log spirals is shown in Fig. 18. We note that self-similar configurations are also under study for LOFAR and SKA.

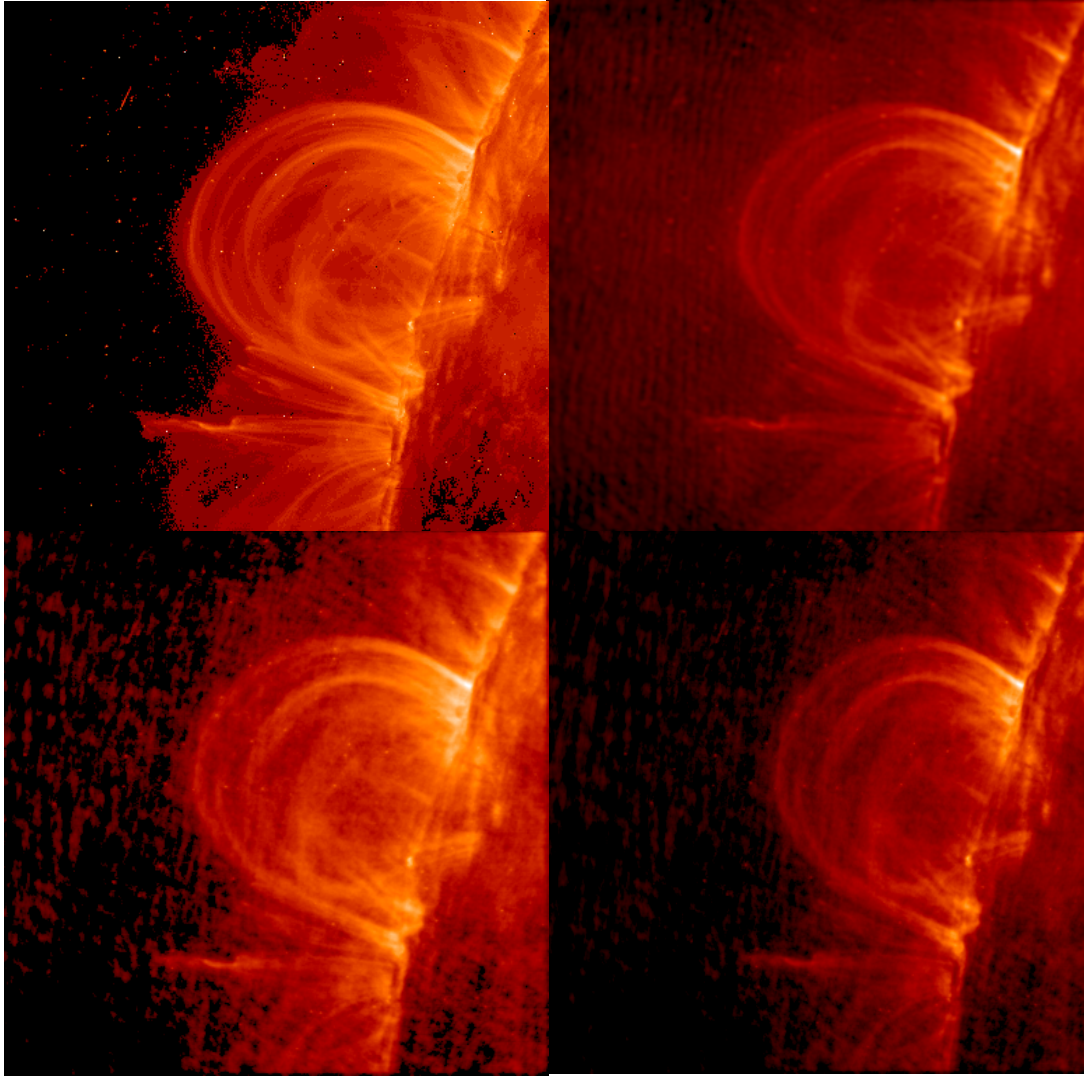


Figure 18: Imaging with a 108-antenna array composed of three log spirals. *Upper left:* TRACE EUV image from 6 Nov 1997, used as a model; *upper right:* snapshot image of the same at 5 GHz; *lower left:* snapshot image of the same at 22 GHz; *lower right:* 10 min Earth rotation aperture synthesis at 22 GHz.

5.2.4 Feeds and front ends

Both the IFA and HFA will employ broadband, dual-linear feeds. The precise nature of the feeds – log-periodic dipoles, log-periodic zig-zags (e.g., Engargiola 2002), sinuous feeds, or variants thereof – requires an R&D and evaluation effort. Unlike the ATA, the feeds will not be mechanically moved during observations to improve focus, but will be optimized for focus near the high-frequency end. The ~5-10% loss of efficiency at low frequencies may be acceptable if other losses are well controlled. A con-focal feed like the TRW feed now under evaluation for the ATA may be preferable if its efficiency and bandwidth are sufficient.

In similar fashion to the ATA, FASR will employ tightly integrated broadband RF packages. Because the Sun is a highly variable source (Fig. 17) the signal must be attenuated by variable amounts. A switched attenuator would be placed after the first LNA. The attenuator step size depends on how constant the input into the optical link and digitizers needs to be. One suggestion is to employ two stages of attenuation: one would be used to ensure that the second stage amplifier remained linear; the second attenuator would ensure constant power into the digitizers. A calibration signal may be needed – e.g., a switchable noise diode – but this remains uncertain until calibration of the instrument is better understood. While the front end need not be cooled to cryogenic temperatures, it does need to be thermally stabilized. This will likely be accomplished using inexpensive Peltier coolers.

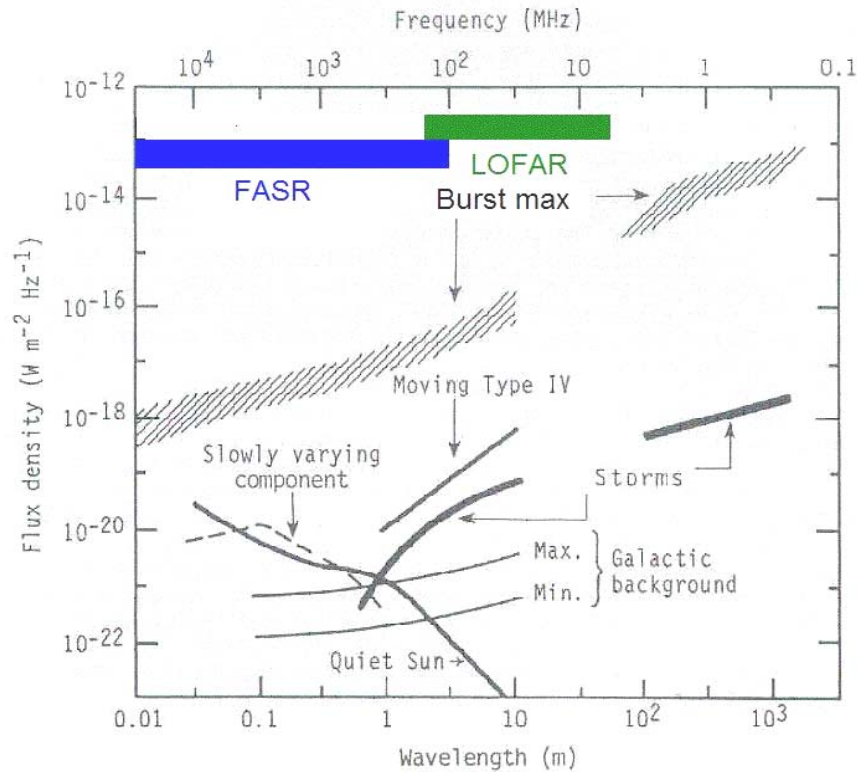


Figure 19: Schematic illustration of the variability of the Sun's emissions. The FASR and LOFAR frequency ranges are indicated along the top axis.

5.2.4 Signal Transmission

Signal transmission will be via bundles of single mode optical fibers over runs of several km. The fiber bundles will be buried to sufficient depth to eliminate diurnal temperature variations and hence, minimize daily variations in length. In the interest of designing as simple, inexpensive, and stable an instrument as possible, it is worth avoiding implementation of a round-trip phase measurement scheme, if possible. To this end, it may be sufficient to simply equalize fiber lengths.

The signals will be transmitted in analog form. The complexity and expense of digitizing the signals at the antenna, not to mention the need to carefully shield the requisite electronics at each antenna, outweighs the advantages of gaining full control over the signal at the antenna. The bandwidths of the LFA and the IFA are such that relatively inexpensive optical modems can be used to transmit the entire band. No frequency conversions are required at the antenna.

In the case of the HFA, the bandwidth is too large for optical modems currently available. The maximum bandwidth for low-cost units for the foreseeable future is ~12 GHz. Assuming that 12 GHz is the maximum transmittable band, sub-bands must be transmitted. One approach is to perform a single frequency conversion and, in effect, transmit two halves of the total HFA bandwidth. This could be accomplished by means of a direct photonic LO at a frequency in the DBS band near 12 GHz. A switch and single optical modem could be used to handle both sub-bands, or a pair of modems could be used to transmit both simultaneously. Support of frequencies >24 GHz would require a second LO.

5.2.5 Signal Processing

FASR lends itself to an FX-like approach to signal processing although the XF approach must be evaluated, too. Cost and future upgradability will be important factors in selecting either approach. The many details that must be addressed – such as phase switching and its interaction with fringe rotation and delay – await a decision on the basic approach that FASR will adopt for analog and digital signal processing.

Since, like all modern instruments, FASR will sample a large bandwidth, radio frequency interference (RFI) is a concern. It is likely that low frequencies will need to be sampled by as many as 8 bits, while high frequencies may require at least 3 bits. While the station-based nature of the F part of an FX approach is attractive, the use of a Fourier transform is unattractive in the presence of RFI because the frequency response is too broad. Isolation and excision of undesirable narrowband signals would be problematic. An alternative is to build a digital filter bank using polyphase filters (Bunton 2003). The use of polyphase filtering techniques is attractive because they can be implemented efficiently and yield sharply defined spectral channels. It should be relatively cheap to implement because the frequency resolution requirements of FASR are relatively modest. Another attraction of the digital filter bank approach is that it could adapt to the changing RFI environment dynamically. The output would be clean, narrowband channels. The delay correction and correlation requirements would be therefore be small.

5.2.6 RFI Issues

Preliminary consideration of radio frequency interference (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 (De Boer 2002; Fisher 2002). 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 most effective RFI mitigation strategy remains to be seen, but the first lines of defense are site selection and designing a clean instrument. Regardless of the strategy eventually adopted, it is important to quantize the signal with a sufficient number of bits. FASR will differ from other types of radio telescopes in that it will not observe spectral lines and its spectral resolution requirements are relatively modest on scientific grounds. RFI mitigation will likely dictate the spectral resolution designed into the system. Fisher (2002) has estimated that a spectral resolution of at least 0.1% is required to isolate frequencies corrupted by RFI.

A possible strategy is similar to that currently employed by the Solar Radio Burst Locator (SRBL) at OVRO. At the beginning of each observing day, it performs an RFI survey, identifying those frequencies to avoid for the day. If FASR employs an FX-like architecture, a similar survey could be used to identify all channels to blank in the digital filter bank. Use of prior information on when satellite and other sources of intermittent interferences are likely could also be factored into such a scheme. The polarization properties of the Sun could also be exploited to discriminate against sources of RFI. The Sun is not linearly polarized in general, so any linearly polarized signal would automatically be suspect. Weak and intermittent sources of RFI could be identified and excised during post-processing.

5.2.7 Calibration Issues

Calibration has many implications for the system design in each of the frequency regimes. Detailed calibration strategies must therefore be developed for each. A consideration that must drive the design of the instrument as a whole is that it must be designed to be as stable as possible in order to minimize instrumental drifts in the calibration parameters.

Ideally, the instrument would be so stable that the observing day would not need to be interrupted to determine the instrumental calibration. Instrumental calibration would be performed against sidereal standards during the night. Nevertheless, ionospheric variations and the changing galactic background would need to be calibrated during the observing day at low frequencies (LFA, IFA), and tropospheric variations would need to be calibrated at high frequencies. (HFA).

A number of calibration strategies are under discussion. In the case of ionospheric disturbances, the spatial extent of the array will be small compared to the scale of the disturbance. It will therefore behave like refracting wedge. The wedge introduces a simple phase gradient over the array, which manifests itself as a tip-and-tilt correction in the image domain. The approximate linearity of the phase gradient, its wavelength dependence, and prior knowledge of the source may be used to deduce the correction.

The troposphere is problematic, particularly at high frequencies. Periodic calibration of small groups of antennas against sidereal standards or satellite beacons is one possibility. Self-calibration is another. Bastian has recently suggested using absorption in the water vapor line against the Sun as another possibility (FASR Memo. #5). Each of these must be studied in detail.

6 Operations and Data Management

6.1 User Communities

An important goal of the FASR project is to mainstream the use of solar radio data – specifically broadband radio spectroscopic imaging data and associated data products – much as the use of X-ray observations were mainstreamed by *Yohkoh*, and EUV observations were mainstreamed by SOHO/EIT and TRACE. To do so requires shifting the burden of data acquisition, calibration, and image deconvolution from the user to the facility. FASR operations and data management therefore require careful planning and implementation as discussed further below.

A major emphasis will be placed on making FASR data as widely and as easily accessible as possible. The user-base for FASR will comprise the entire solar, solar-terrestrial, and forecasting communities. For example, it will be possible for someone working with hard X-ray observations to request FASR images for a given event from the standard database, and receive fully calibrated and optimally reconstructed images at each frequency for direct comparison with HXR images using an automated web-based server.

As we discuss further below, FASR will have two types of constituency: researchers and forecasters. A standard set of data products will be available to each type of user. Data will be archived in a variety of formats. Most users will use the archive of standard data products. Sophisticated users may wish to access the complex visibility data, calibration data, and/or monitor and control data.

We anticipate that the FASR will have a completely open data use policy. Current developments in mass-storage devices should make it feasible for us to keep the FASR data archive on-line for automated access by the processing software. Similar to the TRACE or RHESSI missions, the entire data archive will be available to users at any time.

6.2 Data management

Although a workshop was held at the University of Maryland on 28-29 May 2003 to address this issue, it is premature to discuss an operations and data management plan in detail. For now, a possible model is outlined:

- For maximum observing efficiency, FASR observations should be uninterrupted by calibration during daylight hours. Instrumental calibration will be carried out before and after the observing day.
- A standard, programmable, observing sequence will be used each day. This sequence will be designed to meet the key science objectives of the instrument. For example, it may involve continuous observing across the entire frequency range with a time resolution of 100 ms and a spectral resolution of 1%.
- Support of science objectives that require the highest data rates (e.g., imaging spectroscopy at decimeter wavelengths with 0.1% spectral resolution and 10 ms time resolution) may only be used on an occasional basis or deferred until they can be supported as part of the standard observing sequence.
- The high time/spectral resolution data will populate an interim database which expires in 24 hrs. It is expected that the size of the interim database will amount to ~10 Tbytes.
- RFI excision and time-independent calibration is applied in real time to the data as it is entered into the interim database.
- The interim database forms the input for several types of much smaller archival databases. “Observing modes” are implemented by flexible, parallel selection and averaging (time and frequency) of the interim database. An archival database would be the starting point for most data analysis. The size of the archival databases would be ~100 Gbyte.
- Archival data would be available to users with a latency of minutes to hours.
- Standard data products derived from the archival data would be generated automatically and made available to users on similar time scale.

As mentioned in Section 6.1, it is anticipated that users with different needs will use FASR data in different ways. The data analysis will proceed under the advisement of various constituencies in order to provide the desired data in a timely fashion. For

example, forecasters may wish to see quicklook data that alerts them to flares and their radio properties (location, intensity, spectral hardness, etc), to radio CMEs and their properties, and to type II/IV radio bursts and their properties. Forecasters may also make use of coronal magnetograms, made available every 30 min during the course of the day. Researchers will have different requirements. They will also require quicklook data products to provide them with an overview of available data and to provide them with an efficient means of selecting data. Users can then select standard data products for further analysis. For example, if a researcher is interested in a particular flare, a data hypercube of deconvolved images in Stokes I and V can be provided over a specified frequency range, with a specified frequency resolution and time resolution. Visualization and analysis tools will be provided to the user to explore, analyze, and compare the data with that from other instruments.

7 Synergy with planned and existing efforts

After a fallow period during the 1980s and 1990s, the U.S. radio astronomical community has embarked upon ambitious plans to build or upgrade innovative new ground based instruments. These include Atacama Large Millimeter Array (ALMA), the VLA expansion project (EVLA), the Long Wavelength Array (LWA), the Allen Telescope Array (ATA), the Combined Array for Millimeter Radio Astronomy (CARMA), and FASR. Each of these efforts confronts the community with unique technical challenges. Yet other technical challenges are shared by two or more projects. For example, essentially all instruments will be broadband to the extent that they will tune continuously over a broad frequency range, process large instantaneous bandwidths, and/or stray well outside the protected radio astronomy bands. As a result, all instruments must confront the problem of RFI mitigation. The similarity of certain instruments goes further: in the case of the ATA and FASR, both instruments will employ large numbers of antennas, both will observe over very large bandwidths, and both will employ broadband analog data transmission. The ATA technical effort is well underway and is serving a path-finding role for FASR and other instruments (notably, the U.S. SKA concept). The FASR/LFA and LWA must confront similar problems regarding RFI mitigation. Contacts have been (or soon will be) established with most of these projects in order to identify areas where FASR could benefit from existing or planned design and prototyping efforts.

8 Summary

The FASR is the first instrument of its kind, designed to take advantage of the unique observational opportunities presented by radio emission on the Sun. The FASR is designed to exploit these opportunities to attack a broad science program: understanding the nature and evolution of coronal magnetic fields through direct and indirect measurements; understanding the physics of flares, including energy release, particle acceleration, particle transport, and shocks; understanding drivers of space weather, including radio CMEs, filament eruptions, MHD shocks, and solar energetic particles; and understanding the nature of the chromosphere and corona in three dimensions,

coronal heating, the origins of the solar wind, and the structure and evolution of filaments. The FASR will provide unique and important insights into these fundamental problems, and make numerous unforeseen discoveries.

The FASR user base will be broad, including researchers in solar physics and space weather, as well as users with an interest in forecasting or “nowcasting” solar activity. The user base will also be deep, including both domestic and foreign constituencies. As a special-purpose instrument, FASR operations and data management will be largely automated, allowing open and rapid access to its data by the wider community. FASR is therefore expected to be the premier instrument for solar radiophysics for the foreseeable future.

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Appendix A: Existing solar radio facilities

We summarize in a table the capabilities of radio instruments around the world that spend all, or most, of their available observing time observing the Sun. It should be noted, however, that several general purpose, non-solar instruments have been extremely important to the solar physics community, too.

Observatory	Country	Angular resolution	Frequencies	Type
Guribidanur	India	5'	40-150 MHz	2D mapping
Nancay	France	1.5-5'	150-450 MHz	2D mapping
RATAN 600	Russia	15''-240''	1-20 GHz	Fan beam
OVRO	USA	5''-90''	1-18 GHz	2D mapping
SSRT	Russia	20''	6 GHz	2D mapping
Nobeyama	Japan	15''/7.5''	17/34 GHz	2D mapping
Itapetinga	Brazil	2'	48 GHz	Multi-beam
SST	Argentina	4'/2'	212/405 GHz	Multi-/single beam
Metsahovi	Finland		22/37/90 GHz	Single dish
BIRS	Tasmania		3-50 MHz	Spectrograph
Izmiran	Russia		25-260 MHz	Spectrographs
Ondrejov	Czech Rep.		0.8-4.5 GHz	Spectrographs
Tremsdorf	Germany		40-800 MHz	Spectrographs
Zurich	Switzerland		0.1-4 GHz	Spectrograph
Espinuncia	Portugal		150-650 MHz	Spectrographs
Nancay	France		10-40 MHz	Spectrograph
Culgoora	Australia		18-1800 MHz	Spectrographs
Hiraiso	Japan		25-2500 MHz	Spectrographs
ARTEMIS	Greece		100-469 MHz	Spectrograph
Beijing	China		0.7-7.3 GHz	Spectrometers
DRAO	Canada		2.8 GHz	Fixed freq.
Cracow	Poland		0.4-1.415 GHz	6 fixed freq.
SRBL	USA		0.4-15 GHz	Fixed freqs.
Nobeyama	Japan			7 fixed freqs.
Hiraiso	Japan		0.2, 0.5, 2.8 GHz	3 fixed freqs.

The VLA has been the workhorse instrument for solar radiophysics in the U.S. It supports observations in the 74 and 327 MHz bands, as well as the 1.4, 4.9, 8.4, 15, 22.5, and 43 GHz bands. The array of 27 antennas can be placed in four standard configurations with maximum baselines of 35, 11, 3, and 1 km – the A, B, C, and D configurations, respectively. The C and D arrays have been most useful for solar work. The best time

resolution available is 200 msec (continuum). In Russia, the RATAN 600 has been used to map the Sun in one dimension at transit at frequencies between 1-20 GHz. More recently a modest two-dimensional mapping capability has been developed. The Giant Meter-wave Radio Telescope (GMRT) has been used in recent years to observe the Sun at discrete frequencies in the 1.4 GHz band and lower.

At millimeter wavelengths, interferometric observations of flares have been made by the Berkeley, Illinois, Maryland Array (BIMA) at Hatcreek, California, at a wavelength of 3~mm since in 1989 (White & Kundu 1992). With an upgrade of BIMA to a nine-element, 2D array, mm - λ imaging has been performed (e.g., Silva et al 1996). The BIMA array was combined with the Caltech Millimeter Array into a new instrument, CARMA, in 2004.

Several other instruments have been used on an occasional basis for solar work. These include the WSRT, CSO, OVRO, Arecibo, and Haystack.