Chapter 3

THE FREQUENCY AGILE SOLAR RADIOTELESCOPE

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Abstract The Frequency Agile Solar Radiotelescope (FASR) will be a ground based solar-dedicated radio telescope designed and optimized to produce high resolution, high-fidelity, and high-dynamic-range images over a broad range of radio frequencies ($\sim$0.05–24 GHz). That is, FASR will perform broadband imaging spectroscopy, producing unique data and enabling a wide variety of radio-diagnostic tools to be exploited to study the Sun from the mid-chromosphere to coronal heights. FASR will address an extremely broad science program, including the nature and evolution of coronal magnetic fields, the physics of flares, drivers of space weather, the quiet Sun, and synoptic studies. FASR may also play an important role in forecasting solar activity and space weather. An important goal is to mainstream solar radio observations by providing a number of standard data products for use by the wider solar physics and space weather communities.

1. Introduction and Background

Radio observations have played an important role in solar physics for many decades. Beginning in the late 1940s, radio observations were first used to directly measure the kinetic temperature of the solar corona (Pawsey 1946), which is optically thick at meter wavelengths. Early radio interferometric techniques were first devised and applied to studies of compact, nonthermal radiation associated with sunspot groups (McCready, Pawsey & Payne-Scott 1947). These techniques were further refined, forming the underpinnings of modern Fourier synthesis imaging techniques (§4). In the intervening years, solar observations at radio wavelengths has proceeded along two lines:

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Spectroscopic observations of the Sun have been pursued primarily at decimeter, meter, and decameter wavelengths. These have been used to discover a rich taxonomy of radio burst activity that has been used to probe a wide variety of physical processes in the solar corona, including energy release, electron beams, shocks, and coronal magnetic fields. More recently, spectroscopic observations at centimeter wavelengths have matured, yielding insights on electron acceleration and transport in flares and the structure of active regions (e.g., Gary & Hurford 1994; Lee, Chapter 9). With the advent of space-borne instrumentation, spectroscopic observations were extended to hectometer and kilometer wavelengths, wavelengths that are inaccessible to study from the ground owing to the ionospheric frequency cutoff near 10 MHz. Space-based observations have allowed interplanetary electron beams and shocks to be studied as they propagate from the outer solar corona to 1 AU and beyond.

Imaging observations of the Sun and solar phenomena at discrete radio frequencies have been performed for decades from the ground, but are not yet available from space. The prevailing imaging technique is Fourier synthesis imaging (§4) although other techniques have been used in past years (e.g., "J_0 synthesis" was employed by the Culgoora Radioheliograph, as described in McLean & Labrum 1985). The Sun is routinely imaged with arcsecond resolution using Fourier synthesis imaging techniques at centimeter wavelengths with instruments like the Very Large Array (VLA; Thompson *et al.* 1983) or the Nobeyama Radioheliograph (NoRH; Nakajima *et al.* 1992), or with arcminute resolution at decimeter and meter wavelengths by the Nançay Radioheliograph (NRH; Delouise & Kerdraon 1997).

However, in order to exploit the information embodied in radio emission from the Sun requires fully wedding spectroscopic and imaging capabilities in a single instrument. Moreover, these capabilities must be available on time scales commensurate with those relevant to physical processes on the Sun. This is the motivating factor behind the Frequency Agile Solar Radiotelescope: an instrument that performs broadband imaging spectroscopy.

The Frequency Agile Solar Radiotelescope (FASR) had its genesis in an international workshop organized in 1995 at San Juan Capistrano in California. There, the solar physics and solar radiophysics communities first outlined the science requirements for the instrument. Since then, the instrument has gained support throughout the solar and space weather communities, culminating in the recent recommendations of decadal reviews by the Astronomy and Astrophysics Survey Committee (2001) and the Solar and Space Physics Survey Committee (2003), both sanctioned by the National Research Council. The latter survey ranked FASR as the number one small project ($<$ \$250M). On this basis, plans are underway to design and build the instrument.

This chapter serves as an introduction to FASR. In the next section, some preliminary concepts relevant to radio observations are outlined. Key drivers of the FASR science program are summarized in §3. More detailed discussions of radio diagnostic techniques and radio science that will be addressed with FASR are presented elsewhere in this volume. A summary of FASR's operational basis is given in §4. The instrumental requirements and a strawman design are summarized in §5. Some operational issues are discussed in §6 and concluding remarks are presented in §7.

2. Preliminaries

In order to understand the rationale for wedding imaging with spectroscopy in a single instrument, it is useful to revisit briefly elementary concepts of radiative transfer at radio wavelengths and to review relevant radio emission mechanisms.

2.1 Radiative transfer

At radio frequencies $h\nu \ll k_B T$ (in the Rayleigh-Jeans regime), where h is Planck's constant, ν is the (cyclic) radio frequency, k_B is Boltzmann's constant, and T_e is the effective temperature of the emitting material. In this regime, the specific intensity $\mathcal{I}_\nu$ and the source function $\mathcal{S}_\nu$ can be expressed in terms of the brightness temperature T_b and the effective temperature T_e through $\mathcal{I}_\nu = k_B T_b \nu^2/c^2$ and $\mathcal{S}_\nu = (\eta_\nu/\kappa_\nu) k_B T_e \nu^2/c^2$, respectively. The quantities η_ν and κ_ν are the radio emissivity and absorption coefficient, respectively; these embody the microphysics of radio emission and absorption for any given mechanism.

The radiative transfer equation for continuum radio emission is conveniently expressed along a given line of sight as

$$T_b = \int_0^{\tau_\nu} T_e(\tau'_\nu) e^{-\tau'_\nu} d\tau'_\nu + T_{b\circ} e^{-\tau_\nu} \tag{3.1}$$

where $\tau_\nu = \int \kappa_\nu dl$ is the optical depth. In the simple case of an isolated source where T_e is constant, Eq. 3.1 becomes $T_b = T_e(1 - e^{-\tau_\nu})$. When $\tau_\nu \gg 1$ the source is optically thick and $T_b = T_e$. When $\tau_\nu \ll 1$ the source is optically thin and $T_b \approx \tau_\nu T_e$.

For spatially unresolved radio observations the flux density, S_ν, is expressed in units of Jansky. In the case of solar observations, a more convenient unit is the *solar flux unit*, with 1 sfu = 10^4 Jy = 10^{-22} W m^{-2} Hz^{-1}. The total flux density S_ν of a radio source is related to T_b through

$$\mathrm{S}_\nu = \frac{2k_B\nu^2}{c^2} \int T_b d\Omega \tag{3.2}$$

where $d\Omega$ is the differential solid angle. In the case of an imaging instrument, observations are limited in angular resolution to a solid angle Ω_{bm}, referred to as the "beam" in radio astronomy, the value of which is intrinsic to the instrument. The measured quantity is then the flux density per beam: $\langle \mathrm{S}_\nu \rangle_{bm} = 2k_B \langle T_b \rangle \nu^2 \Omega_{bm}/c^2$ where $\langle T_b \rangle_{bm}$ is the mean source brightness over Ω_{bm}. The total flux density per beam is therefore an estimate of the specific intensity.

Spectroscopy is, of course, a powerful tool in all wavelength regimes. In the case of solar radio emission, bound-bound and bound-free atomic and molecular transitions play no role. Instead, free-free, wave-particle, and wave-wave interactions are responsible for the emission and absorption of radio waves. Even so, spectroscopy is a critical tool for identifying emission mechanisms and for diagnosing physical conditions in the source. In most cases, broadband, low-dispersion radio spectroscopy is the desired tool.

For an unresolved source the total, or integrated, spectrum can be measured as S_ν. As noted in §1, such measurements have been employed for many years using swept-frequency spectrometers or, more recently, broadband digital spectrometers. Typically, time-resolved spectra are used to construct a *dynamic spectrum* over some frequency range. Dynamic spectroscopy has been employed to characterize and study a variety of radio bursts from decimeter to decameter wavelengths on the ground (e.g., the classical radio bursts of types I–V) and from decameter to kilometer wavelengths in space (e.g., interplanetary radio bursts of type II and type III). Broadband dynamic spectroscopy has also been employed to study microwave bursts: e.g., the Owens Valley Solar Array.

While high resolution images of the Sun have also been available for many years from instruments like the VLA and the NoRH, these instruments can only produce images at a small number of widely spaced frequencies, which is insufficient for spectroscopy. What is needed is the ability to combine imaging with broadband spectroscopy in order to acquire time-resolved *brightness temperature spectra* everywhere in the source. The most effective way to satisfy this need is to design and build a solar-dedicated instrument which performs broadband imaging spectroscopy. This is the fundamental innovation of FASR.

2.2 Radio emission mechanisms

Radio emission mechanisms are discussed elsewhere in this volume by Gary & Hurford (Chapter 4) and will therefore be only touched on here. The radio spectrum from centimeter to meter wavelengths is rich in diagnostic possibilities because (1) a variety of coherent and incoherent emission processes occur; (2) both the optically thin and optically thick portions of emission spectra are accessible to study. Hence, tremendous observational leverage is available to measure or otherwise constrain the plasma temperature and density, the magnetic field, the electron distribution function, and importantly, the spatio-temporal evolution of these observational parameters.

There are two classes of incoherent emission mechanism that are important on the Sun: bremsstrahlung (or free-free) radiation and gyromagnetic (or magneto-bremsstrahlung) radiation.

- *Thermal free-free emission*, due to collisions between thermal electrons and ions, is ubiquitous on the Sun. Thermal free-free radiation can be used to diagnose physical conditions in the quiet Sun, active regions, and the decay phase of certain flares.

- *Thermal gyroresonance emission* is due to the gyromotion of thermal electrons in the presence of a magnetic field. In active regions, the magnetic field can be strong enough to render the corona optically thick to gyroresonance absorption at frequencies in the range 1–18 GHz. It is therefore a powerful tool for measuring magnetic fields in solar active regions.

- *Thermal and nonthermal gyrosynchrotron emission* play a dominant role in energetic phenomena such as flares. Extremely hot electrons or a nonthermal distribution of electrons emit a broadband continuum that strongly dominates the radio emission at frequencies $\nu >$ 1–2 GHz. Gyrosynchrotron radiation provides powerful diagnostics of physical conditions in flaring sources.

In addition to incoherent radiation from thermal and nonthermal distributions of electrons by the above mechanisms, coherent radiation due to wave-particle and wave-wave interactions plays a prominent role on the Sun at frequencies $\nu <$ 1–2 GHz:

- *Plasma radiation* is the result of a two-stage process wherein the electron distribution function becomes unstable to the production of plasma waves—due, for example, to the two-stream instability resulting from the passage of an electron beam, to the passage of a coronal shock, or to a loss-cone instability. The plasma waves are then converted to electromagnetic waves at the electron plasma frequency $\nu_{pe} = \sqrt{n_e e^2/\pi m_e} \approx 9\sqrt{n_e}$ kHz or its harmonic $2\nu_{pe}$. Examples of radio bursts that emit plasma radiation include those of type II and type III.

- *Other coherent mechanisms* include the electron cyclotron maser (Melrose & Dulk 1982; Melnikov & Fleishman and references therein) and possibly transition radiation (Fleishman & Kahler 1992). Additional, as yet unidentified coherent emission mechanisms, may prove to play a role in the Sun's radio repertoire.

3. Overview of FASR Science

In this section, key FASR science goals are summarized. The science background, motivations, and relevant radio diagnostics and techniques are discussed in greater detail elsewhere in this volume. The relevant chapters will be indicated where appropriate. The identification of FASR key science goals has been motivated by (i) the recognition of outstanding problems in solar physics by the wider scientific community, and (ii) the unique and innovative observational role that FASR can play in attacking these problems. FASR is therefore expected to play a central role in the following key science areas:

- The measurement of coronal magnetic fields
- The physics of flares
- The drivers of space weather
- The quiet Sun

In addition to these four key science areas, FASR could play an important role in synoptic studies (§3.5) . An independent, but nevertheless very important, role that FASR data products could play is in forecasting or "nowcasting" solar activity, and in providing new observational tools for assessing its potential impact on the near-Earth environment (§3.6).

3.1 Coronal magnetic fields

It is widely recognized that an understanding of the nature and evolution of coronal magnetic fields is of fundamental importance to acquiring a deeper understanding of a wide variety of outstanding problems, including coronal heating and the origin of the solar wind, solar flares, coronal mass ejections, and particle acceleration and transport. Yet quantitative measurements of the coronal magnetic field have remained elusive. A key capability of FASR will be to exploit a number of diagnostics to measure, or otherwise constrain, coronal magnetic fields. Because of the paucity of such measurements to date, and because of the difficulty of measuring coronal fields at other wavelengths, the impact of FASR may be greatest in its ability to measure fields through a variety of techniques.

Magnetic fields in active regions of strengths $>$ 150 G can be measured using *gyroresonance absorption* (see White, Chapter 5). A measurement of the magnetic field at the base of the corona is straightforward. Extraction of the three-dimensional magnetic field remains a research problem that will be solved through inversion techniques, forward modeling, or other means.

The longitudinal component of weak magnetic fields can be measured using the difference between the free-free absorption coefficient for the ordinary (o) and extraordinary (x) magneto-ionic modes. This difference manifests itself as circularly polarized emission, the magnitude of which depends on the longitudinal component of the coronal magnetic field. Gelfreikh (Chapter 6) discusses the technique in some detail, which can be exploited to constrain magnetic fields in both active and quiet regions on the Sun.

Propagation effects can also be exploited to measure or constrain the coronal magnetic field. Ryabov (Chapter 7) discusses the propagation of the the x- and o-modes through the solar corona and the consequences of strong and weak coupling between the two modes for the observed spatial distribution of circularly polarized radiation as a function of frequency. These effects can be used to constrain the strength and topology of the coronal magnetic field above and near solar active regions.

Solar activity also yields a number of diagnostic tools for measuring coronal magnetic fields. These include the use of gyrosynchrotron radiation to measure magnetic fields in flaring loops (Bastian 1999; Gary & Hurford, Chapter 4) and in the expanding loops of certain coronal mass ejections (Bastian *et al.* 2001). Statistical studies of the polarization properties of solar radio bursts at meter wavelengths have been used to constrain the macroscopic coronal magnetic field (e.g., Dulk 1976). With the availability of imaging spectroscopy, polarization measurements of specific radio bursts and their trajectories will yield magnetic field measurements in specific regions of the solar corona.

Clearly, FASR magnetic field measurements will often benefit from the use of complementary data. Soft X-ray (SXR) and extreme-ultraviolet (EUV) observations, provide powerful plasma density diagnostics and provide excellent constraints on the magnetic field topology, if not quantitative measurements. Brosius (Chapter 13) reviews the use of multiwavelength observations to measure coronal magnetic fields.

3.2 The physics of flares

FASR will be a superb instrument for investigating the physics of flares. FASR will be sensitive to both thermal and nonthermal emissions, will sample both coherent and incoherent emissions, and span both the optically thick and optically thin spectral regimes. Hence, a large number of radio diagnostics will be brought to bear on solar flares which are expected to yield significant new insights to energy release in flares, the acceleration and transport of electrons, magnetic fields in flares, and the origin of energetic particles in the interplanetary medium.

At frequencies $\nu < 1$–2 GHz, plasma radiation plays an extremely important role. At frequencies less than 200–300 MHz (meter wavelengths) the classical radio bursts will be imaged over a broad frequency range. Burst locations and, importantly, trajectories will be identified and their association with, and relation to, solar flares will be clarified. Pioneering work in this regard has been made by the NRH at discrete frequencies in the range of 150–450 MHz (see Chapter 2 and references therein, for example). Particularly important are radio bursts of type II (due to a coronal piston-driven or blast-wave shock), type III (due to suprathermal electron beams), and type IV (due to trapped populations of energetic electrons). At frequencies $0.3 < \nu < 1$–2 GHz (decimeter wavelengths), coherent plasma radiation from type III-like bursts and type IV bursts plays an important role. These are believed to be associated with energy release, but their source regions have not been adequately imaged before, let alone imaged over a frequency range sufficient to exploit the spectral diagnostic power they offer. Also intriguing are the meter-wavelength and decimeter-wavelength narrow-band spikes. Meter-wavelength spikes are associated with metric type IIIs and may be a signature of energy release. Benz reviews decimeter wavelength radio emissions in Chapter 10.

At frequencies $\nu > 1$–2 GHz (decimeter/centimeter wavelengths) incoherent gyrosynchrotron radiation from electrons with energies of 10s of keV to several MeV is the dominant mechanism. This is the same electron population responsible for hard X-ray (HXR) and γ-ray (continuum) radiation, although the emission mechanisms for hard X-ray, γ-ray, and radio radiation are quite different. HXR and continuum γ-ray radiation over this energy range are due to nonthermal electron bremsstrahlung resulting from collisions of energetic electrons with dense (mostly chromospheric) plasma, while the radio emission results from the gyromotion of these electrons in the magnetic field of the flaring source. Radio and HXR observations of flares are therefore highly complementary. Radio emission is sensitive to emission by nonthermal electrons everywhere in the source. With imaging spectroscopy, it is a powerful diagnostic of the electron distribution function, of the ambient plasma, and of the coronal magnetic field in the source. Gary & Hurford (Chapter 4) outline how some of these measurements are made. Time-resolved imaging spectroscopy will allow the spatio-temporal evolution of the electron distribution function and other physical parameters of the source to be observed. Lee (Chapter 9) demonstrates how time-resolved microwave spectroscopy provides key insights into the problem of electron acceleration and transport.

An extremely important aspect of FASR's capabilities will be the fact that it will provide a *comprehensive* and *integrated* ensemble of data over a wide wavelength range. FASR will provide simultaneous observations of tracers of energy release in the corona at decimeter wavelengths, of energetic, nonthermal electrons at centimeter wavelengths, of associated type II and/or type III radio bursts at meter wavelengths, and of the thermal response of the solar atmosphere at decimeter and centimeter wavelengths (see below). Hence, new insights into the way in which each of these phenomena are coupled to the others will likely emerge.

3.3 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 ionizing 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. A historical perspective of solar and solar radio effects on technologies is presented by Lanzerotti in Chapter 1. The drivers of space weather—fast and slow solar wind streams, flares, and coronal mass ejections—are solar in origin. An understanding of space weather phenomena lies, in part, in gaining a fundamental understanding the origin of these drivers.

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. Fits of a simple synchrotron model to two- and three-point spectra at various locations in the source yield not only the magnetic field in 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 (Bastian & Gary 1997). 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. Vourlidas provides a more comprehensive overview of radio signatures of CMEs in Chapter 11.

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 liftoff of a CME. A radio counterpart to an "EIT wave" was recently detected by the NoRH at 17 GHz (White & Thompson 2004). Observations of radio counterparts to EIT waves and of coronal dimmings mentioned above, suggests that FASR will provide a rather 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) and filaments.

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; Classen & 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 such as Moreton waves and "EIT waves" remain matters of considerable interest and controversy. Gopalswamy reviews interplanetary type II radio bursts and their relation to interplanetary shocks and CMEs in Chapter 15. With its unique ability to perform imaging spectroscopy, FASR will in some cases 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 and/or the CME. The emphasis placed on FASR's ability to provide an integrated picture of flare phenomena in §3.2 applies equally to CMEs and associated phenomena (type II radio bursts, EIT and Moreton waves, filament eruptions). 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 also provide key observations that will help resolve the important and controversial problem of the origin of solar energetic particles in the interplanetary medium.

3.4 The quiet Sun

Radio emission from the quiet Sun is reviewed by Keller & Krucker (Chapter 12). One of the fundamental questions in solar physics is how the solar corona maintains its high temperature of several $\times 10^6$ K. The leading theoretical ideas for how the corona is heated involve either some form of resonant wave heating (e.g., Ofman, Klimchuk, & Davila 1998) or "nanoflares" (Parker 1988), although there exist other models. 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. 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. FASR will greatly improve on previous work by providing vastly better frequency coverage and a sensitivity comparable to the VLA under some circumstances (e.g., Krucker *et al.* 1997). 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 enough at low energies to contribute significantly to the corona's energy budget.

The structure and heating of the solar chromosphere is also an outstanding problem in solar physics. To date, most chromospheric models have been static. The semi-empirical models of, e.g., Vernazza *et al.* (1981), Fontenla *et al.* (1993) were calculated under the assumption of hydrostatic equilibrium and employ observations of non-LTE UV/EUV lines and disk-averaged IR/submm/mm continuum observations. Separate models are calculated for active region, network, and cell interior contexts. However, observations of CO near 4.7 μm show that the low-chromosphere contains a substantial amount of cool material while broadband microwave (1–18 GHz) spectroscopy of the quiet Sun (Zirin *et al.* 1991) convincingly demonstrate that the semi-empirical models include an overabundance of warm chromospheric material (Bastian *et al.* 1996). Moreover, observations have emphatically shown that the chromosphere is a dynamic entity. Carlsson & Stein (2002, and references therein) have explored dynamic models of the solar chromosphere, wherein acoustic waves are driven through the atmosphere using a sub-photospheric piston. The acoustic waves increase in amplitude as they propagate upward and steepen into shocks at a height of $\sim$ 1000 km where they produce temperature differences as great as 10^4 K. The dynamic model therefore yields material at temperatures considerably higher than that found in the static model chromospheres. However, high temperature material exists only relatively briefly, so that the mean atmosphere in these models is a relatively constant throughout most of the chromosphere.

The FASR design will allow the thermal structure of the chromosphere to be probed down to the height where $\mathrm{T_e} \approx 8000$ K. The sensitivity of the FASR, as presently conceived, will allow the time variability of the thermal structure of the solar chromosphere to be studied in a single frequency band on a time scale < 1 min ($\Delta T_b \sim 100$ 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, plages—as an input for modern models of the inhomogeneous and dynamic chromosphere.

3.5 Synoptic measurements and 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 (see Lanzerotti, Chapter 1). 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 Lyα, 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.

It is possible that FASR will play a prominent role in forecasting or "now-casting" solar activity and space weather. FASR could produce a number of quicklook data products in near-realtime for this purpose. What is difficult to predict at present, given the unique character of the data that FASR will produce, is which radio diagnostics will prove to be the most useful and robust for forecasting. It is likely that a number data products and/or indices based on the data will prove to be useful. While their utility as forecasting tools remains speculative at this point, examples of such data products include:

- Synoptic maps of the solar atmosphere at various frequencies; 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 of the coronal magnetic field 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, local heating, and may be an indicator of probable activity.

- Lists of flare events, erupting prominences, and CMEs; their location, size, and spectral properties as they occur.

4. Description of the Instrument

We now turn to the nature of the instrument itself. It is useful to digress briefly in order to sketch the operational basis of imaging instruments at radio wavelengths in general before discussing FASR specifically.

4.1 Operational basis

High-angular resolution images of celestial sources are formed at radio wavelengths using interferometric techniques. This is because of the fundamental limitation imposed by Rayleigh resolution: the angular resolution of an aperture of diameter D is $\theta \sim \lambda/D$, where λ is the wavelength of the radiation. For example, if an angular resolution of $\theta = 1''$ is desired at a wavelength of $\lambda = 2$ cm ($\nu = 15$ GHz), an aperture $D \approx 4$ km is required. To build a single large antenna of this diameter is impractical. A far more elegant solution is to effectively break the large reflector into an array of many small patches (antennas), each of diameter $d \ll D$, distributed over the desired aperture of diameter D. The basic element of such an array is a pair of antennas, an interferometer. The distance between a given pair of antennas is the antenna baseline b. The interferometer is sensitive to radio emission on an angular scale $\theta = \lambda/b$. Hence, the angular resolution of the array is determined by the maximum baseline $b_{max} = D$, the instrumental beam (§2.1) being $\Omega_{bm} \sim (\lambda/D)^2$. The field of view of the array is determined by the diameter d of the individual antennas: $FOV \sim \lambda/d$.

Most modern radio imaging arrays employ Fourier synthesis imaging. FASR will be no exception. The function of an interferometer is to multiply the signals measured at each antenna. This operation is performed in a device called a correlator. A given interferometer measures a single Fourier component—an amplitude and a phase—of the Fourier transform of the radio brightness distribution within the field of view of a single antenna at a spatial frequency b/λ. A given measurement of a Fourier component is referred to as a complex visibility. An array of N antennas distributed over a two-dimensional domain provides $N_{tot} = N(N-1)/2$ interferometers with baselines of varying length and orientation and, hence, N_{tot} visibility measurements. One can think of the ensemble of interferometers as constituting a sampling function, a field of delta-functions which multiplies the Fourier transform of the radio brightness distribution within the field of view. The sampling function is the auto-correlation function of the antenna locations. The measurement domain is referred to as the "*uv* plane", where *u* and *v* are the spatial frequency coordinates. The inverse Fourier transform of the sampling function $\mathbf{S}$ is referred to as the "dirty beam" $\mathbf{B}$. It is the point spread function (PSF) of the array. Fourier inversion of the ensemble of measured visibilities therefore yields $\mathbf{I}' = \mathbf{B} \star \mathbf{I} + \mathbf{n}$, where $\mathbf{I}$ is the true radio brightness distribution, $\mathbf{n}$ is instrumental noise, and $\star$ denotes a convolution. A variety of deconvolution and estimation techniques can be used to recover $\mathbf{I}$ from $\mathbf{I}'$.

It is worth pointing out that general purpose radio telescopes such as the VLA can exploit Earth rotation aperture synthesis. If a radio source is static in time—effectively the case for many cosmic radio sources—then the rotation of the Earth can be used to improve the sampling function. This is possible because the projected antenna array geometry, as viewed from a radio source, changes in time as the Earth rotates. Instead of sampling a single point in the Fourier domain, a given interferometer traces out an elliptical path in the Fourier domain time. In the case of solar observations, it is often not possible to use Earth rotation aperture synthesis because the solar radio emission varies significantly on short time scales: e.g., during a solar flare. Solar observations must therefore rely largely on the instantaneous sampling (snapshot imaging) provided by the array for transient phenomena, although Earth rotation aperture synthesis observations can be exploited to observe slowly varying phenomena.

4.2 FASR instrumental requirements

The instrumental requirements for FASR are determined by the scientific requirements, which have been addressed by the wider solar physics community in a number of workshops. The most recent of these was an international workshop at the NRAO in Green Bank, WV, in 2002. These requirements will be revisited periodically until construction of the instrument begins. In this section, we summarize current specifications and discuss the rationale for choices made in general terms. Specific choices are not justified in detail here.

1. *Imaging:* Radio emission from the Sun must be imaged with high dynamic range, fidelity, and angular resolution, with good sensitivity to both compact and extended emission. As discussed in the previous section, FASR will require good snapshot imaging performance, requiring a large number of antenna baselines, optimally distributed.

2. *Field of view*: A full disk imaging capability is desired up to a frequency of 18 GHz. This requirement is determined by the upper frequency limit

to which gyroresonance emission is expected to be relevant. A field of view of $\sim 10\ R_\odot$ is required at frequencies < 500 MHz, determined by the requirement that radio CMEs and related phenomena must be imaged.

3 *Angular resolution:* An angular resolution of $1''$ at a frequency of 20 GHz is required, and must be available whenever the Sun exceeds 30° in elevation. For a fixed array, the angular resolution scales linearly with frequency, yielding $10''$ at 2 GHz, and so on. This is believed to be comparable with the limit on angular resolution at radio wavelengths imposed by scattering in the solar corona (Bastian 1994).

4 *Frequency coverage:* The overall frequency range sampled by FASR is of critical importance. It must be sufficient to address each of the key FASR science areas described in §3. Coronal magnetography requires frequency coverage from 1–18 GHz; the physics of flares requires coverage from 0.5–24 GHz, or higher; the drivers of space weather require coverage from $\lesssim 50$–500 MHz.

5 *Frequency agility:* The cost of correlating roughly three decades of frequency bandwidth is very high and is, in any case, unnecessary so long as the broadband radio spectrum is fully sampled on a time scale commensurate with the phenomenon under study. FASR will therefore be *frequency agile*.

6 *Time resolution:* Radio spectra must be obtained at a sufficient rate to resolve the time scale on which phenomena evolve: 10 ms at decimeter wavelengths and 100 ms at centimeter wavelengths and meter wavelengths.

7 *Spectral resolution:* Radio spectra must be sampled with sufficient spectral resolution to resolve spectral features due to a variety of emission mechanisms: as high as 0.1% at decimeter wavelengths and 1% at centimeter and meter wavelengths.

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

9 *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 instantaneous frequency bandwidth of the data channels will be of order 1 GHz.

10 *Calibration:* Calibration of the instrument should provide an accuracy of 5% in the absolute flux calibration and an accuracy of $1''$ in absolute position at centimeter wavelengths. This can be relaxed to 10% and $5''$, respectively, at decimeter wavelengths.

These general requirements are reflected in Table 3.1. We now turn to a somewhat more detailed discussion of the FASR instrument.

Table 3.1. FASR Instrument Requirements

Frequency range	0.05–24 GHz
Frequency bandwidth	2×1 GHz per data channel
Frequency resolution	$<$ 300 MHz: 1%
	0.3–2.5 GHz: 0.1%
	$>$ 2.5 GHz: 1%
Time resolution	$<$ 300 MHz: 100 ms
	0.3–2.5 GHz: 10 ms
	$>$ 2.5 GHz: 100 ms
Number antennas	HFA: $\sim$ 100
	IFA: $\sim$ 70
	LFA: $\sim$ 50
Size antennas	HFA: 2 m
	IFA: 6 m
	LFA: LP dipoles/other
Angular resolution	$20''/\nu_{\rm GHz}$
Field of view	HFA: $8^\circ.5/\nu_{GHz}$
	IFA: $2^\circ.8/\nu_{GHz}$
	LFA: $\sim 70^\circ$
Polarization	IQUV
Absolute positions	$1''$
Absolute flux	5%

4.3 System design overview

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

FASR antennas will be designed to track the Sun every day from sunrise to sunset. 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 suggests that the antenna and front end electronics should be of a simple and robust design and that a minimum of signal processing should be done in the field. 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.

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 noise. This has two consequences: (1) the front-end electronics need not be cooled to cryogenic temperatures, as is commonly done with sensitive, general purpose radio telescopes like the VLA; (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 occur on short time scales, as implied in Table 3.1, and display narrowband structures. FASR must be designed to process such highly variable emission.

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 optimally support the total instrument bandwidth at low cost. FASR will therefore be composed of three separate arrays of antennas, each designed to support a sub-range of frequencies. The low-frequency array (LFA) will cover 50–350 MHz; the intermediate-frequency array (IFA) will cover roughly 300 MHz to 2.5 GHz; the high-frequency array (HFA) will cover 2.5–24 GHz. Several aspects of the instrument design from the antennas to the correlator are now discussed. Readers that are not interested in a moderately technical discussion are encouraged to skip the remainder of this section.

4.3.1 Antenna configuration. The number and configuration of antennas in each array is of critical importance. The criteria by which antenna configurations are assessed depend on the imaging problem at hand. Each of the arrays described above must image the Sun with high degrees of dynamic range and fidelity over roughly a decade of bandwidth with a fixed configuration. The FASR array configuration is therefore a challenging optimization problem, one that is presently under study.

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).

These considerations lead to a requirement that the angular resolution of the HFA is $1''$ at a reference frequency of 20 GHz, which requires a projected baseline of 3 km. To meet this requirement over a significant range of hour angle (source elevation $> 30°$) implies that a maximum antenna 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. 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.

The snapshot imaging capabilities of the instrument, and hence the instantaneous *uv* coverage, must be excellent. Work to date suggests that of order 100 antennas in the HFA, 70 in the IFA, and 50 in the LFA—yielding 4950, 2415, and 1225 instantaneous complex visibility measurements, respectively—will be needed to accomplish this goal. These will be configured in "self-similar" array configurations (Bastian *et al.* 1998; Conway 1998; 2000). The scale-free nature of self-similar configurations is ideal for imaging over wide frequency bands. An example of a self-similar configuration is one composed of logarithmic spirals (Conway 1998).

4.3.2 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.

The LFA will employ non-steerable, non-reflecting antennas: i.e., fixed log-periodic dipoles or Vivaldi-type antennas while the IFA and HFA will employ steerable, parabolic reflectors. The IFA will employ symmetric 6 m paraboloids. These have a field of view of $\sim$ 9°–1° from 0.3–2.5 GHz. The HFA will employ symmetric 2 m paraboloids, which have a field of view of $\sim$ 3.5°–0.5° from 2.5–18 GHz. Future studies will address the optimum choices for the antenna mounts and drives (IFA and HFA).

4.3.3 Feeds and front ends. Both the IFA and HFA will employ broad-band, dual-linear feedsfeed. The precise nature of the feeds—log-periodic dipoles, log-periodic zig-zags (e.g., Engargiola 2002), sinuous feeds, or variants thereof—requires a development and evaluation effort. 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.

FASR will employ tightly integrated broadband front end packages. Because the Sun is a highly variable source the signal must be attenuated by variable amounts. A switched step attenuator will be placed after the first low-noise amplifier. 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.

Given the relatively small size of the antennas and the simplicity of their front ends, the cost of each antennas is expected to be low.

4.3.4 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 radio frequency (RF) 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, although progress in broader bandwidth optical links is being monitored. 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 local oscillator at a frequency 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 local oscillator in this scheme.

4.3.5 Signal processing.

The RF signal observed by each antenna over its entire nominal frequency range will be transmitted in analog form to a central processing location via optical fiber. There, the desired frequency and bandwidth will be selected and the signal will be converted and digitized prior to further processing.

FASR will be designed to perform "low-dispersion" spectroscopy. A correlator that supports a large number of spectral line channels is not needed on scientific grounds. However, since, like most other modern radio telescopes, FASR will sample a relatively large instantaneous bandwidth, exposure to radio frequency interference (RFI) is a concern. RFI signals are typically narrowband ($< 0.1\%$) and can be very strong (up to 40 dB above quiet Sun levels at low frequencies). The system will require sufficient spectral resolution and dynamic range to isolate and remove sources of RFI in the band. It is therefore important to digitize the signal with a sufficient number of bits to ensure adequate dynamic range. It is expected that 8-bit sampling will be needed for frequencies below 2.5 GHz; 3 bits will likely be sufficient for frequencies > 2.5 GHz.

While alternative signal processing architectures are possible, FASR lends itself to an "FX-like" architecture wherein considerable signal processing will be applied to the signal from each antenna prior to correlation. 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.

If an FX-like approach is adopted, with frequency-domain signal processing performed in a station-based manner prior to signal correlation, the correlator itself can be relatively small. One-bit, two-level sampling, or two-bit, three-level sampling will likely be sufficient.

5. Operational Issues

An important goal of the FASR project is to "mainstream" the use of radio data by the wider solar physics and related communities. Much as the *Yohkoh* mission mainstreamed the use of SXR and HXR data, the SOHO mission mainstreamed the use of UV and coronagraph data, and the TRACE mission has mainstreamed the use of EUV data, FASR operations will be designed to provide users with the data and data analysis tools that maximize the utility of the data for the greatest number of users.

General purpose radio telescopes such as the VLA, the Very Long Baseline Array, the Giant Meterwave Radio Telescope, and others require a great deal of users. They must prepare detailed scripts for carrying out their observations, they must calibrate their data, and they must carefully image and deconvolve the telescope PSF from their maps. For this reason, radio astronomy has acquired the reputation of being unduly complicated. To achieve the goal of mainstreaming the use of FASR data requires shifting the burdens of data acquisition, calibration, imaging, and deconvolution from the user to facility operations. This goal, while ambitious, is necessary in order to allow users that have not been initiated into the craft of radio interferometry to nevertheless effectively exploit radio observations.

In considering this goal it is worth noting that distinct advantages lie in the fact that FASR, in contrast to a general purpose instrument, will be dedicated to a single radio source. This greatly simplifies daily operations and eliminates the need for user involvement in most observations. (It is quite likely, however, that while users would not be involved in routine FASR operations, users could nevertheless propose special-purpose observing modes.) There is cause for optimism in the fact that the NoRH and the NRH have both made significant progress in automating many operations functions and making data products available to the community in a relatively transparent manner. Given the breadth and diversity of the FASR science program, though, the difficulty of automating data calibration and pipelining imaging and deconvolution should not be underestimated.

6. Concluding Remarks

FASR is an ambitious project involving the national observatories, university partners, and international collaborators. The instrument is being carefully designed and optimized to exploit radio diagnostics of solar radio emission in order to measure a wide variety of physical parameters, many of them unique. FASR will therefore address an extremely broad science program and is expected to serve as a key research facility for solar radiophysics and the wider solar physics and space weather communities. Moreover, it is anticipated that FASR will contribute to forecasting and "nowcasting" of solar activity and space weather.

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