Toward a Frequency-Agile Solar Radiotelescope

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**Abstract.** For many years, solar radio observations have proceeded along two orthogonal axes: i) high resolution imaging at discrete wavelengths; ii) spatially unresolved spectroscopy at centimeter and decimeter wavelengths. Recently, progress has been made in exploiting both techniques in the form of imaging spectroscopy. The solar radio community has reached the consensus opinion that full exploitation of the radio spectrum to measure coronal magnetic fields in both quiescent active regions and flares, to probe the thermal structure of the solar atmosphere, to study energy release and particle energization in transient events requires a solar-dedicated frequency-agile solar radiotelescope, optimised for the purpose of imaging spectroscopy. In this paper we discuss just a few of the science highlights of such an instrument and introduce a "strawman" design.

1. Introduction

Solar observations in the radio part of the electromagnetic spectrum provide a unique perspective on virtually all phenomena in the solar atmosphere. Over the last twenty years the radio community has developed a detailed understanding of solar radio emission and its interpretation. The radio technology, image processing techniques, and understanding of radio diagnostics are now mature. A consensus exists among the international solar radio community, as expressed at an NSF and NASA supported Solar Radio Telescope Workshop held in San Juan Capistrano in 1995, concerning the future directions that must taken. It is therefore possible and timely to take advantage of the unique diagnostic po-
tential offered by the radio regime through the design and construction of an advanced solar-dedicated radiotelescope.

Here we highlight the more important capabilities of a proposed Frequency-Agile Solar Radiotelescope (FASR) and outline the outstanding science problems it will address. These include:

- Determining the quantitative structure of the coronal magnetic field by performing coronal magnetography in and near active regions.

- Determining the thermal structure of the quiet solar atmosphere from low-chromospheric to coronal heights with arcsecond angular resolution.

- Elucidating the energy distribution of energetic electrons associated with transient phenomena – flares, CMEs, and filament eruptions – through imaging spectroscopy with a high temporal cadence.

- Providing a robust proxy for the solar irradiance and a number of other solar features and emissions.

2. Radio Diagnostics

Radio emission in the wavelength regime spanned by the FASR – roughly 1-100 cm – is particularly rich in diagnostic potential. Both coherent and incoherent emission mechanisms occur in this wavelength range, as do both thermal and nonthermal emissions. Some radio emissions transition from optically thick to optically thin over this wavelength range, thereby increasing their diagnostic value. The key to tapping this diagnostic potential is to obtain high resolution radio brightness temperature spectra. Brightness temperature spectra can be obtained only by imaging at a large number of frequencies with sufficient spatial resolution to resolve the sources. While a number of emission mechanisms play a role in various solar phenomena, the dominant emission mechanisms and their diagnostic potential are briefly as follows:

- **Free-free radiation**: Dominant in most of the quiescent solar atmosphere, free-free radiation at radio wavelengths (where the Rayleigh-Jeans approximation applies) provides a simple linear thermometer for probing the thermal structure of the solar atmosphere. The relevant temperature range is \( \approx 8000 \) K to \( 4 \) MK. In the presence of magnetic fields, optically thin free-free radiation is weakly to moderately circularly polarized and constraints may be placed on the longitudinal component of the magnetic field in the upper chromosphere and corona.

- **Gyroresonance radiation**: Dominant in solar active regions, optically thick gyroresonance radiation provides a straightforward measurement of temperature as a function of coronal magnetic field strength. As its name suggests, gyroresonance radiation is due to the cyclotron resonance at the first few harmonics of the gyrofrequency, \( \nu_{Be} = eB/2\pi m_e c \approx 2.8B \) MHz, with \( B \) in gauss. The emission may be strongly circular polarized, and spatially resolved measurements of the spectral and polarization characteristics of the emission form the basis for coronal magnetography.
• **Gyrosynchrotron radiation:** Dominant during flares and other transient phenomena, gyrosynchrotron radiation provides numerous diagnostics of energetic electrons and the ambient medium. During flares, electrons are promptly energized to energies of 10–100 keV; an additional population of electrons may be accelerated to much higher energies ($\gg 1$ MeV) within a few seconds. Energetic electrons produce continuum emission at higher harmonics of the electron gyrofrequency, typically 5 to a few 10s of times $\nu_{Be}$. The emission is moderately circularly polarized, and again spatially resolved measurements of the spectral and polarization characteristics form the basis for quantitative measurements of coronal magnetic field strength and the energy distribution function.

• **Plasma radiation:** Dominant at decimetric ($\sim 10 – 100$ cm) and longer wavelengths, plasma radiation provides a sensitive means of detecting the presence of electron beams (type III bursts and variants) in the corona. Plasma emission provides good density and density-gradient diagnostics through its generation at the fundamental or second harmonic of the electron plasma frequency, $\nu_{pe} = \sqrt{n_e e^2/\pi m_e} \approx 9000 n_e^{1/2}$ Hz.

3. Science Objectives

Given the diagnostic potential of the decimetric and microwave regimes, an extremely broad program of science studies in both the corona and chromosphere will be supported by the FASR, due to its unique combination of high quality imaging and broad spectral coverage. Here we highlight several key topics.

3.1. Coronal magnetography

Quantitative knowledge of coronal magnetic fields is crucial to virtually all solar physics above the chromosphere, including the structure and evolution of active regions, flares, filaments, coronal heating, and CMEs. Considerable resources are devoted to the measurement of photospheric magnetic fields and extrapolation of the measured source surface into the corona. However, photospheric magnetograms are not perfect (saturation in sunspot umbrae, limitations on temporal, spatial or spectral resolution, ambiguities due to the physics of line-formation, etc.) and when extrapolated into the corona, such imperfections are magnified to an extent that is largely unknown, since there is currently no way to quantitatively check the results. It will help to have chromospheric field measurements using new infra-red (IR) techniques, but clearly it is important to have a technique for direct measurement of the magnetic field strength in the corona that can be used to complement measurements from lower heights—to guide and give a check on extrapolations, and to uncover new physics. An important goal of the FASR is to perform coronal magnetography of active regions.

There are two approaches to such measurements: (1) a well-established method that gives the 2D field strength at a single surface at the base of the corona; and (2) a still unproven method (e.g., Lee et al. 1997b) that exploits the 3D information present in the radio data to determine as much information about the 3D structure of $B$, $n$, and $T$ in the active region corona as possible.
Figure 1. A perspective view of a complex sunspot group (7 May 1991) in optical continuum is shown with field lines extrapolated into the corona using a nonlinear force-free extrapolation by Z. Mikić. The three surfaces are the calculated 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).

2D coronal magnetography Magnetography at the base of the corona is straightforward (Hurford & Gary 1986; Gary & Hurford 1994; Lee et al. 1997a). The outer boundary of an optically thick gyroresonant source is determined by its intersection with the chromosphere (cf. Fig. 1) and where, accordingly, the observed brightness temperature drops sharply. Thus the outer edge of the optically thick radio source at a given frequency defines a constant-field-strength contour on the base of the corona. As the frequency changes, so does the corresponding value of the field strength whose boundary is delineated. This technique is already routinely carried out with the VLA, but at limited numbers of frequencies corresponding to a few fixed values of $B$. FASR will measure magnetic strengths at the base of the corona running continuously from 200 to $> 2000$ G. As might be expected, the outer boundary of a source at a given frequency can be affected by other complications such as marginal optical depth due to unusual structure in temperature, density, or inclination of $\mathbf{B}$ in the active region. However, such unusual structure can easily be distinguished and corrected or avoided when the data are viewed not as a sequence of images at different frequencies, but rather as a spatially resolved set of gyroresonance spectra. The ease of this measurement will allow near-realtime coronal magnetograms to be produced throughout each observing day, allowing the observer to not only measure the magnetic field at the base of the corona, but to track its evolution through a period of hours and from day to day.
3D coronal magnetography  The radio measurements provide not just the outer boundaries of the surfaces shown in Fig. 1, but also the brightness temperature distribution over the surface within those boundaries. This represents additional information on the distribution of coronal temperature, density, magnetic field strength and orientation (e.g., Vourlidas, Bastian & Aschwanden 1997). We are aided in the interpretation of this information by the fact that the emission arises on clearly defined, nested surfaces (the various hatched surfaces shown in Fig. 1) that uniformly and monotonically range from low to high coronal heights as frequency decreases. This property of gyroresonance emission provides a very different perspective compared to an optically thin diagnostic such as X-rays, where all the emission along a given line of sight is integrated and projected onto the sky plane regardless of its height. The challenge of interpreting gyroresonance emission is to sort out the influences of the various parameters, which will require sophisticated modelling of the spatially resolved spectra. Obviously, we will be aided greatly in this goal by using complementary information from (i) magnetic field extrapolations (perhaps now based on three heights—at the photosphere [optical], chromosphere [IR], and base of the corona [microwaves]), and (ii) temperature and density constraints from soft X-rays, EUV, and other means.

Whether the ultimate goal of true 3D magnetography can be achieved cannot be answered at present, but if it is to be achieved it will require an instrument with the imaging quality and frequency agility of FASR; it cannot be accomplished with current radio facilities.

3.2. Thermal structure of the solar atmosphere

In weak field regions where thermal gyroresonance emission is largely absent, radio emission remains sensitive to thermal structure through thermal free-free emission. As is the case for observations in CO, microwave radiation is formed under conditions of LTE; the source function is therefore Planckian. For microwave observations, $h\nu \ll k_B T$ so the Rayleigh-Jeans approximation is valid, and the observed intensity is linearly proportional to the (line-of-sight weighted) kinetic temperature of the emitting material for optically thick sources. The optical depth is $\tau_{\nu} \propto \nu^{-2} n^2 T^{-3/2}$. By varying the frequency $\nu$ from 1–26 GHz, one samples the thermal state of optically thick plasma 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. We cannot discuss all possibilities here – however, by way of example we briefly discuss the capabilities of FASR in elucidating the structure of the quiet Sun atmosphere.

The chromosphere has been the subject of lively debate in recent years. It has become increasingly apparent 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 CO and microwave observations. In particular, observations of the CO molecule near 4.7 $\mu$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 demonstrate that the prevailing semi-empirical models include an over-abundance of warm chromospheric material (Bastian, Dulk & Leblanc 1996). Schematic multi-component models have been proposed that emphasize the pervasive cool component in the solar atmosphere (e.g., Avrett 1995; Ayres & Rabin 1996). Another approach has recognized that chromospheric dynamics play a critical role in understanding the structure of the chromosphere. Numerical models (Carlsson & Stein 1995), in which the chromosphere is permeated with a flux of dissipative waves, demonstrate that the mean physical conditions within the chromosphere may differ substantially from those derived from the same models by conventional non-LTE UV/EUV line diagnostics.

Modern chromospheric models require spatially and temporally resolved observations of the thermal state of the chromosphere on the relevant spatial and temporal scales. A key advantage of the CO lines is their narrow contribution function that allows fine vertical discrimination in the structure of the low chromosphere. The microwave contribution function (thermal free-free) is much broader and is therefore a cruder discriminant. However, CO dissociates at a temperature of 4000 K. It therefore provides the thermal “footprint” of the chromosphere. Spatially resolved microwave observations spanning 1–26 GHz will map the thermal structure of the solar atmosphere from chromospheric heights up into the corona. Microwaves are therefore a valuable complement to CO and other observations of the solar chromosphere.

The FASR design will allow us to sample the thermal structure of the chromosphere down to the height where \( T_e \sim 8000 \) K with a frequency-dependent angular resolution of 2.5–6”. FASR observations will 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.

### 3.3. Flares and coronal mass ejections

The FASR will, for the first time, allow full exploitation of the microwave/decimetric emission for flare studies. The possibilities are numerous and exciting:

- **Magnetic field in the flaring volume**: Microwave emission in flares is due to incoherent gyrosynchrotron emission from electrons with energies of several 10s to 100s of keV. The peak spectral frequency \( \nu_{pk} \) at a given location depends sensitively on the local magnetic field strength and the angle between the wave normal and the magnetic field vector. Joint observations of \( \nu_{pk} \) and the source polarization will allow the magnetic field strength and orientation to be inferred for the flaring source as a function of time. No other technique is available for this purpose.

- **Electron acceleration and transport**: The microwave spectrum is a powerful diagnostic of the details of the emitting distribution of energetic electrons. The optically thin part of the spectrum is sensitive to high energy cutoffs in the spectrum and to anisotropies in the distribution function. It is also worth pointing out that the relative timing of temporal features...
Figure 2. A model calculation of the gyrosynchrotron emission from a power-law distribution of energetic electrons trapped in an asymmetric coronal magnetic loop (a). Brightness temperature spectra are shown in panel (b). Snapshot maps of the brightness distribution at various frequencies are shown in the lower panels.

at different frequencies offers an additional diagnostic of acceleration and transport.

- **Location and properties of the energy release site:** Multitudes of type III and reverse drift type III bursts—resulting from bidirectional electron beams—accompany the impulsive phase of many flares (Aschwanden et al. 1995). While spectroscopic observations of classical and reverse-drift type IIIIs during flares have been performed, none have been imaged. The FASR will identify the location of these bursts, presumably intimately related to the primary energy release, and trace their trajectories both upward and downward in the flaring volume.

- **Chromospheric ablation:** In addition to diagnosing the magnetic field and the details of the energetic electron population, radio observations offer a means of probing the density and evolution (due, for example, to chromospheric ablation) of the ambient plasma by means of Razin suppression, the specifics of which depend on the density of the ambient plasma and the local magnetic field strength.

- **CME detection:** With support at decimetric wavelengths, the FASR may also be used for CME detection (Bastian & Gary 1997). The advantages of CME detection at radio wavelengths are: i) there is no occulting disk, so earth-directed CMEs will 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 possible nonthermal constituents. Owing to its frequency agility the FASR could provide a comprehensive observational picture of CMEs and associated phenomena over a wide frequency range. As such, the FASR will serve as a powerful tool for disentangling the complex relationship between CMEs, flares, filament eruptions, and radio bursts.

3.4. Synoptic measurements

Synoptic radio measurements are discussed in greater detail elsewhere in this volume (Schmahl & Kundu 1997). The 10.7 cm flux has been used for many years as a proxy for sunspot number and area, the emission in Ly$\beta$, Mg II, and EUV fluxes, and the total solar irradiance. Schmahl & Kundu (1995, 1997) have shown that multi-frequency measurements yield superior proxies for sunspots and irradiance.

In addition to providing well-calibrated multifrequency observations of the Sun over many years, one can envision many other synoptic studies with an instrument like the FASR. For example, with high-resolution, spatially resolved maps at each frequency, synoptic studies of the gyroresonance component of the radio emission and hence, the coronal magnetic field, could be performed. A second example is a multifrequency synoptic study of the still-mysterious polar brightenings (see Shibasaki, this volume).

Such observations require accurate and stable calibration over long periods of time. The FASR will be calibrated against cosmic standards. Atmospheric effects will be monitored and removed, perhaps using total power monitoring against the Sun.

4. Instrumental Requirements

The primary goal is to design and construct an instrument that fully exploits solar microwave emission as a diagnostic of physical processes on the Sun. To this end, a number of instrumental requirements have been identified:

1. Imaging: The sources of 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. A dynamic range of order 1000:1 and angular resolution of $\approx 1''$ at a frequency of 20 GHz are considered reasonable goals.

2. Broadband spectroscopy: The brightness temperature spectrum as a function of position is required for both decimetric and microwave phenomena. Hence, spectroscopic coverage over the frequency range of 300 MHz to $\gtrsim 26.5$ GHz with a spectral resolution of $\lesssim 5\%$ is needed.

3. Polarimetry: Observations in both the right- and left-hand senses of circular polarization are needed to form the Stokes I and V polarization parameters.
4. **High time resolution**: Brightness temperature spectra must be acquired at a rate sufficient to resolve the timescale on which the phenomenon of interest evolves. The most demanding requirement is imposed by the impulsive phase of flares, which will require a time resolution of < 1 sec.

5. **Large field of view**: In the interest of maximizing observing efficiency and in matching the capabilities of many full disk spectrographs and imagers, a full disk imaging capability is desired at most frequencies.

6. **Good absolute positional accuracy**: Instruments in most wavelength bands now possess an angular resolution ranging from less than 1 arcsec to several arcsec. Quantitative cross-comparisons between various wavelength regimes will require absolute source positions to a similar accuracy.

7. **Upgradability**: The instrument should be designed with future enhancements in mind. Examples include support of very high-time- and high-frequency-resolution observations of decimetric phenomena and the extension of frequency coverage to millimeter wavelengths.

8. **Easy access by the solar community**: The instrument should not place the burden of reduction on the user. All reductions should be performed on-site and a wide variety of data products should be made available for immediate and open use by the community at large.

5. **The FASR Design**

These requirements lead us to propose the following strawman design. High-angular-resolution imaging requires an instrument that employs Fourier synthesis imaging using an interferometric array of antennas. The requirements of high dynamic range and image fidelity, and of high sensitivity to a wide range of angular scales require a large number of antennas to properly sample the Fourier (or u-v) plane. Preliminary simulations suggest \( \approx 40 \) antenna elements, providing measurements of \( \approx 800 \) Fourier components instantaneously. An angular resolution of \( \approx 1'' \) at a frequency of 20 GHz requires a maximum antenna baseline of \( \approx 3 \) km while good sensitivity to extended emission will require adequate numbers of short antenna baselines. It is anticipated that frequency synthesis techniques will also be exploited (e.g., Bastian 1989), perhaps in the form of spatial/spectral image reconstruction (Komm, Hurford & Gary 1997). Logarithmic antenna spacings will accommodate frequency synthesis, and allow identical u-v coverage and angular resolution at selected frequencies. For a factor 1.5 spacing of antennas along each arm, for example, each factor of 1.5 in frequency will have identical u-v coverage, e.g. frequencies 3.3, 5, 7.5, 11.25, 16.9, and 25.3 GHz will all have identical u-v coverage on a subset of antennas.

The requirement of full disk imaging at most frequencies requires the use of small antenna elements. The strawman design calls for apertures of 2 m. On the other hand, the need for good absolute calibration implies a need for astronomical calibration; i.e., sufficient sensitivity is needed to compare the source position with that of known cosmic reference sources. This, in turn, implies a need for large, sensitive antennas. Hence, in addition to many small antennas,
the strawman design calls for at least one large antenna. The construction of one or more new 25 m antennas would be prohibitively expensive. An affordable alternative is to refurbish existing antennas—e.g., one or more of the two 27 m antennas at Owens Valley, the three 25 m antennas at Green Bank, or one or more 25 m antennas at the VLA site. These will be used to calibrate the instrument against cosmic standards and could also support high-resolution decimetric spectroscopy, and perhaps nighttime observing.

The requirement of broadband spectroscopy in the decimetric and microwave bands suggests a frequency-agile design. The technology for the detection, transmission and amplification of broadband microwave signals is mature, and off-the-shelf components are available at low cost in several bands of interest (e.g., 1-8 GHz, 8-18 GHz, 18-26.5 GHz, etc.). A match to commercially available microwave bands is therefore desirable, and an initial core operating frequency of 1-26.5 GHz is called for in the strawman design. Both high- and low-frequency extensions are feasible: to 300 MHz at low frequencies, and up to 40 GHz and/or the 80-115 GHz band at high frequencies.

The need for measurements of the total and circularly polarized radiation requires the use of dual-polarization feeds, receivers, and data transmission elements.

High time resolution may appear problematic in view of the large number of baselines and the broadband frequency coverage required—to process a bandwidth of 1-26.5 GHz for an array of 40 antennas (or 780 baselines) instantaneously would require a very large correlator. However, the entire spectrum need not be sampled instantaneously and the frequency resolution and rate at which spectra are acquired depends on the phenomenon of interest. The high
flux levels from the Sun allow an extremely fast sampling rate (~10 msec) with good signal to noise. Thus, the strawman design assumes that 500 MHz wide sections of the total bandwidth will be sampled sequentially; i.e., that frequency multiplexing will be performed. The 500 MHz IF bandwidth would itself be coarsely divided into 16 channels of 32 MHz bandwidth to provide the necessary spectral resolution and to prevent bandwidth smearing of the correlated signals. With the wide instantaneous IF bandwidths (> 500 MHz) now available, the entire 1-26 GHz band would be covered with ~50 samples in <1 sec. In other words, during flares, a set of 50 maps could be produced in less than 1 s.

Finally, we come to operational considerations. It is anticipated that the instrument will produce a large number of data products of great value to the research and space environment forecasting communities. These will be available rain or shine, and include:

1. Real-time precision flux spectra of the sun as a star.
2. Near real-time data cubes that display the brightness temperature in two dimensions from chromospheric to coronal heights.
3. Near real-time coronal magnetograms that would provide the magnetic field strength at the base of the corona in active regions.
4. A real-time catalog of flares - their locations, morphology, and a number of indices characterizing their radio spectrum and its evolution.
5. A real-time list of prominence eruptions and CMEs.

Of course, many research projects will require complete and detailed analyses of the data. For example, flare studies will require deconvolved maps for every frequency and integration time. These reductions will be largely automated, but will likely be performed offline and then archived. Users will be able to access the archive in a flexible way. Sophisticated users may wish to work with raw data. The means will be provided to do so.

While a broad program of science will be supported by routine operation of the facility, some users may wish to perform specialized observations (e.g., extremely high-time- or high-spectral-resolution studies). Every effort will be made to design the instrument and its operation for maximum flexibility.

6. Summary

It is now possible to design a powerful solar-dedicated radio telescope to perform broadband imaging spectroscopy in the decimeter and centimeter wavelength bands. Such a telescope would attack a broad range of scientific problems, from the ground, at modest cost. The instrument concept outlined above represents a distillation of many conversations and ideas from members of both the radio community and the broader solar community. These ideas were studied in some detail at an NSF and NASA supported Solar Radio Telescope Workshop, held in San Juan Capistrano, CA in 1995, and attended by about 40 US and international experts in solar radio physics. The Frequency-Agile Solar Radiotelescope concept thus represents a consensus opinion on the question of which direction groundbased solar radio astronomy can and must go in the near future.
The proposed instrument represents a major improvement on current radio facilities by providing the following capabilities:

- It will be solar-dedicated.
- It will provide imaging far superior to that of any current instrument.
- It will perform broadband spectroscopy—a spectrum will be available for each resolution element in the full-Sun field of view.
- It will provide “ready to use” data products to the community at large for both basic research and forecasting purposes.
- It will be a unique instrument that will provide an entirely new view of the Sun, with the potential for many new discoveries.

References

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Group Discussion

Ayres: A comment and a few questions: the comment is a caution concerning the interpretation of thermal Bremsstrahlung. While the emissivity is linearly
dependent on T, the opacity can be exponentially dependent on T when the gas is partially ionized. Thus, if there are steep temperature gradients, a small change in T can impose a large change in opacity, and therefore carry τ = 1 to a much different temperature. Detailed modeling is what is needed, as you have been conducting already. Questions: (1) what is the influence of the atmosphere in the 0.3–26 GHz range? (2) Are there any diagnostic lines in the interval? (3) How will you deal with the enormous data volume?

Bastian: First, in response to your caution, let me point out that over the frequency range being contemplated for the frequency agile solar radio telescope, the opacity is completely dominated by thermal free-free Bremsstrahlung. It is only at submillimeter and perhaps millimeter wavelengths that we would have to worry about rapid changes in the opacity resulting from temperature-induced changes in the ionization. As for your questions: (1) the atmosphere will have very little effect on the observations for frequencies less than 10 GHz, or so. It does become a nuisance at higher frequencies and strategies will have to be devised to calibrate out the antenna-based phase fluctuations introduced by the atmosphere over each antenna. Three possibilities have been discussed: (i) rapid switching between the source and a calibrator; (ii) self-calibration (which will mostly be used for observations of flares); (iii) total power monitoring (which relies on the correlation between system temperature fluctuations – due to the varying sky opacity – and phase fluctuations). This last possibility is actively being explored for application to the Millimeter Array. (2) While it was suggested back in the late-1960s that intermediate-n hydrogen recombination lines, and those of certain ions (e.g. O VI), might be detectable at millimeter and centimeter wavelengths, several searches have yielded no detections. Calculations show that the pressure and (where the magnetic field is strong) Zeeman broadening are so extreme as to render such lines too broad and shallow to be detectable. (3) While the data volume from an instrument like the proposed telescope will be large, it won’t be extreme – it will be comparable to that of today’s VLA.

Leka: You mentioned measuring the magnetic field strength at the base of the corona. How well are the heights of formation of the emission sources known?

Bastian: That’s a good question. The microwave measurement yields the temperature of the emitting material as a function of magnetic field strength and projected position in active regions. The height where a given temperature occurs in the corona is unknown, a priori. However, we do know that the base of the corona corresponds to that height where the temperature drops rapidly to chromospheric temperatures, which manifests itself as a break in the microwave spectrum. Assuming the height of the base of the corona is uniform in active regions, stereoscopic techniques may be used establish the height. Realistically, however, the base of the corona is a “rumpled” surface, so the height measurement would represent an average height. Ultimately, a close interplay between observations of this kind and various magnetic field extrapolations will be necessary.