Solar Imaging Radio Array (SIRA): A multi-spacecraft mission

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ABSTRACT

The Solar Imaging Radio Array (SIRA) is a mission to perform aperture synthesis imaging of low frequency solar, magnetospheric, and astrophysical radio bursts. The primary science targets are coronal mass ejections (CMEs), which drive shock waves that may produce radio emission. A space-based interferometer is required, because the frequencies of observation (<15 MHz) are cutoff by the ionosphere. SIRA will require a 12 to 16 microsatellite constellation to establish a sufficient number of baselines with separations on the order of kilometers. The microsats will be located quasi-randomly on a spherical shell, initially of diameter 10 km or less. The baseline microsat, as presented here, is 3-axis stabilized with a body-mounted, earth-directed high gain antenna and an articulated solar array; this design was developed by the Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center (GSFC). A retrograde orbit at a distance of ~500,000 km from Earth was selected as the preferred orbit because the 8 Mbps downlink requirement is easy to meet, while keeping the constellation sufficiently distant from terrestrial radio interference. Also, the retrograde orbit permits imaging of terrestrial magnetospheric radio sources from varied perspectives. The SIRA mission serves as a pathfinder for space-based satellite constellations and for spacecraft interferometry at shorter wavelengths. It will be proposed to the NASA MIDEX proposal opportunity in mid-2005.

Keywords: coronal mass ejections, solar radio bursts, radio astronomy, microsatellites, aperture synthesis

1. INTRODUCTION

For frequencies less than the ionospheric cutoff (~10-15 MHz during the day), only space-based radio observatories can observe the sun and other extra-terrestrial radio sources. To date, high resolution imaging at these frequencies has not been possible; most of the radio observations have been made by single, spinning spacecraft with wire boom antennas or by single, 3-axis stabilized spacecraft with rigid mast antennas. Extensive studies of solar, planetary, and other radio sources have been made by the International Sun-Earth Explorer-3, Voyager-1 and -2, Galileo, Ulysses, Geotail, Wind, Cassini, and other spacecraft missions, but none of these efforts can produce an image of a radio source. Their data are restricted to, at most, the flux density, polarization, mean source direction, and modeled angular source radius as a function of frequency and time. The NASA STEREO mission will launch in 2006, and the two STEREO spacecraft will permit the triangulation of the centroids of radio sources using the mean source directions from the 2 spacecraft. This will enhance the tracking of radio sources as they propagate outward from the Sun, but the detailed structure of the radio sources will remain unknown.

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Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing,
edited by G. J. Komar, J. Wang, T. Kimura, Proceedings of SPIE Vol. 5659
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.578736

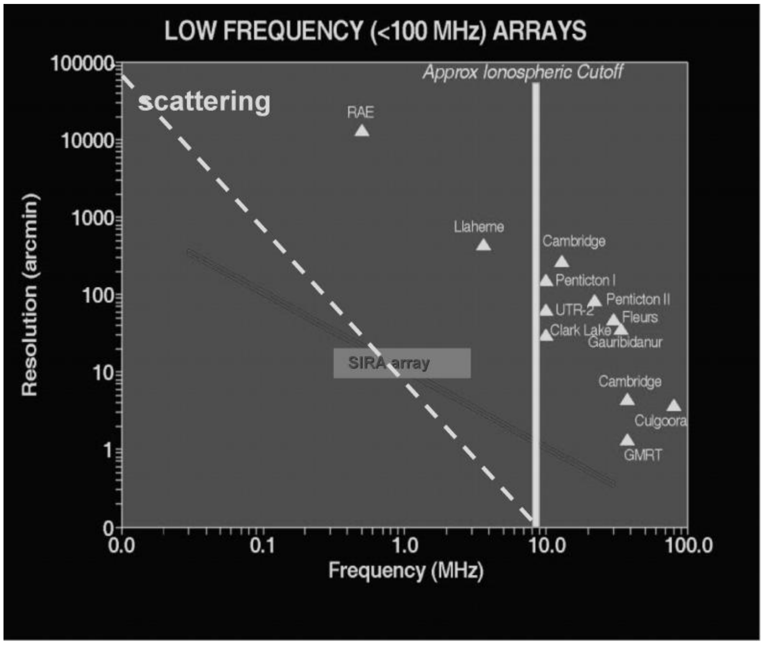

Figure 1: Theoretical angular resolution of the SIRA array, the Radio Astronomy Explorer satellite of the early 1970's, and a number of ground-based radio observatories plotted versus observing frequency. The dashed line represents typical observable source sizes due to interstellar and interplanetary scattering, both of which vary significantly across the sky. Interplanetary scattering is strongest in the sunward direction.

Low-frequency radio imaging is the logical next step, and the technology is ready for such a radio imaging mission. Microsatellite constellations can be used to conduct aperture synthesis imaging of low frequency radio sources in the solar corona, inner heliosphere, and terrestrial magnetosphere with high angular resolution (see Fig. 1). In this paper, we describe such a mission, the Solar Imaging Radio Array (SIRA).

2. SIRA SCIENCE GOALS

The study of the nature and evolution of solar transient phenomena is essential to understanding the Sun-Earth connection. Phenomena such as solar flares, filament eruptions, fast mode shocks, and CMEs are manifested by distinct types of non-thermal radio bursts. The SIRA mission will image these radio bursts at frequencies corresponding to 2 to 200 solar radii from the Sun to reveal their spatial and temporal evolution and to permit remote sensing of coronal and interplanetary density and magnetic field structures between the sun and Earth. The observations are complementary to white light (coronagraph/all-sky imager) observations because the mechanisms responsible for radiation in the two bands are different and because coronagraphs apparently do not image the CME-driven shock.

The primary solar-terrestrial science goals of the SIRA mission are:

- Image and track the propagation of coronal mass ejections in the interplanetary medium to improve understanding of their evolution, to distinguish unambiguously between Earth-directed and non-Earth-directed CMEs, to establish a metric for their "geoeffectiveness", and to predict their arrival times at Earth and other planets for space weather forecasting purposes.
- Image large-scale interplanetary magnetic field topology and density structures, such as coronal streamers, coronal holes, and the heliospheric current sheet, to improve and extend existing coronal and solar wind models of the inner heliosphere that relate to CME propagation.
- Enhance understanding of particle acceleration in flares and in shocks driven by CMEs and provide new insights into the radio emission mechanisms.
- Provide global imaging of the terrestrial magnetosphere illuminated by terrestrial radio emission to better understand the response of the magnetosphere to the impact of major space weather events like CMEs.

2.1 CMEs and type II radio bursts

Fast CMEs drive shocks in front of them as they propagate out of the corona into the interplanetary medium. The shocks accelerate electrons, which stream away from the shock, exciting electrostatic plasma waves[1]. According to the generally-accepted theory, the plasma waves decay into electromagnetic (radio) emissions at the fundamental frequency (f_p) and the second harmonic frequency ($2f_p$) of the plasma electron oscillations. These radio waves are detected remotely by spacecraft or terrestrially-based radio receivers; they are known as type II solar radio bursts. As illustrated in Fig. 2, this radio emission serves as a precursor to the CME leading edge as it propagates away from the Sun.

In addition to direct imaging of the shock-associated type II radio emission, there is an indirect method of observing CMEs using radio bursts. This method of mapping and tracking will work best during solar maximum when there can

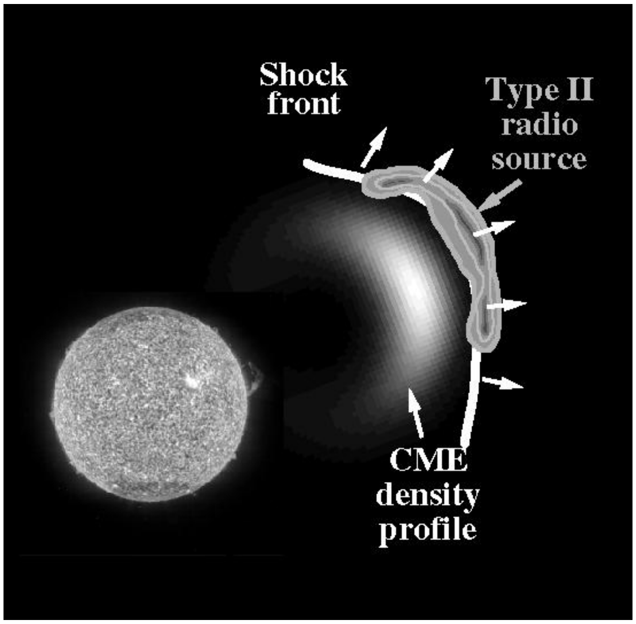

Figure 2: Illustration of a type II radio burst image coincident with the CME driven shock and the CME density profile.

be tens of intense kilometric fast-drift (type III) radio bursts per day. During the 1 to 4 days required for a CME to travel from the sun to 1 AU there will be many behind-the-limb type III bursts. A CME density enhancement will occult bursts occurring behind it, permitting the CME to be seen by the reduction of radio intensity. Furthermore, this method accurately measures the density profile in the CME since the density N is given by the observed frequency f_o of occultation [N (in cm^{-3}) = (f_o (in kHz) / 9)^2] — no assumptions are needed about column density between source and observer. As illustrated schematically in Fig. 2, this will provide the first large-scale picture of where the CME-driven shock lies relative to the CME piston material as it propagates through the interplanetary medium. Since both the density profile and radio emission will be measured by the same instrument, ambiguities and difficulties typically involved in comparing radio and white-light images are eliminated.

2.2 Mapping of Interplanetary Density Structures

SIRA will map the interplanetary density structures inside 1 AU by the direct and indirect imaging techniques described above. By combining images at different frequencies we will construct snapshots of density structures, such as extensions of coronal streamers and the heliospheric current sheet, throughout the inner heliosphere. During the active phase of the solar cycle type III radio bursts occur frequently and many such snapshots will be combined to follow the evolution of these structures.

2.3 Particle acceleration and Solar Energetic Particle (SEP) events

SEP events are accelerated by coronal and IP shocks and possibly by CME-related magnetic reconnection[2]. Intense SEP events present dangerous conditions for spacecraft and astronauts. Radio data from the Wind spacecraft show that most intense SEP events have characteristic 100 kHz - 14 MHz fast-drift radio emission[3]. These complex type III bursts have attracted attention because of uncertainty about the SEP acceleration source. SIRA imaging will permit association of the complex radio features with structures in the corona, leading to an improved understanding of SEPs and possible early warning of their arrival at 1 AU.

During solar maximum, the CME rate is about half a dozen per day. Only a small fraction of CMEs are involved in the production of geomagnetic storms or major solar energetic particle (SEP) events. Type II radio bursts observed in the outer corona (1-20 MHz) and large SEP events are associated with fast and wide CMEs and the shocks that they produce at 1 AU[4]. Imaging of the type II events will provide an indication of the shock direction and a more accurate interpretation of its speed. Combining these data, we can identify the 1-2% of CMEs that are SEP-effective out of the thousands of CMEs that occur.

2.4 Terrestrial magnetospheric response

The primary "geoeffective" disturbances that originate from the sun are fast solar wind streams and coronal mass ejections. The fast wind streams emanate from coronal holes and produce recurring geomagnetic storms with a 27-day periodicity. The non-recurring (and currently less unpredictable) geomagnetic storms are caused by CMEs, which pose the greatest danger to ground-based and space-borne technological systems. CMEs interacting with Earth's magnetosphere can result in geomagnetic storms capable of damaging satellite and electric utility systems and disrupting communications and GPS navigation services. The radiation hazard associated with solar disturbances can also pose a threat to astronauts.

Space weather involves two basic and important problems: first, predicting, well in advance, <u>when</u> a disturbance will arrive at Earth and, secondly, predicting the <u>geoeffectiveness</u> of a disturbance. Connections between solar and

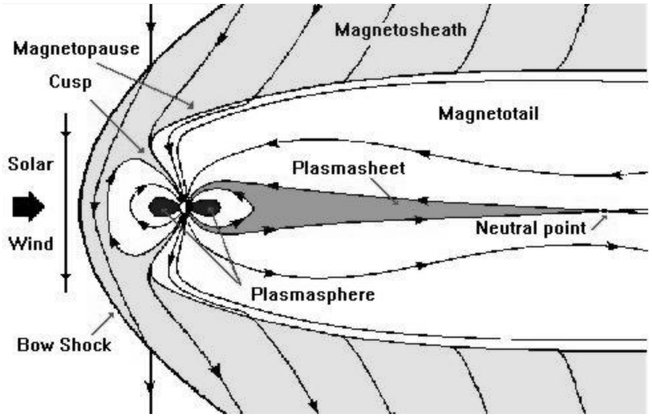

Figure 3: Components of the terrestrial magnetosphere. Sharp density gradients are effective at redirecting natural terrestrial auroral radio emission (AKR), resulting in an outline of the substructure of the magnetosphere in the radio image.

terrestrial events have been studied almost exclusively by assuming a propagation velocity from the sun to Earth. It is, however, very difficult to determine the speed and therefore the transit time of a disturbance from observations made near the sun. Furthermore, speeds observed near the sun can be significantly different from the speed of propagation in the interplanetary medium. As a result, a predicted Earth arrival time based on coronagraph images can be in error by a day or more. Clearly, what is needed is a means of tracking the solar disturbance through interplanetary space. The imaging and tracking of CMEs by the SIRA mission will provide a key link in solar-terrestrial relationship studies. Type II burst images provided by SIRA will enable accurate (to within hours) predictions to be made, up to days prior to a CME arrival at Earth.

At frequencies below a few hundred kHz, Earth's naturally-occurring radio emissions —Auroral Kilometric Radiation (AKR), trapped continuum, and emission at twice the *in-situ* plasma frequency (2 f_p) — will delineate regions of near-Earth space with strong gradients in the plasma and magnetic fields (see Fig. 3). At Earth's bow shock, 2 f_p emission is generated nearly continuously by electrons back-streaming along interplanetary magnetic field (IMF) lines tangent to the bow shock[5]. Since the IMF is constantly changing orientation and hence its contact point, imaging of the source region will trace a locus of points just upstream of the bow shock surface. Deeper within the magnetosphere, the AKR and trapped continuum are scattered by density irregularities in the dayside cusp, magnetosheath, and magnetotail, essentially "lighting up" the entire magnetosphere[6]. SIRA will produce high signal-to-noise radio images of the terrestrial magnetosphere precisely when the most interesting solar wind-magnetosphere interactions, such as magnetic reconnection, are taking place.

2.5 Astrophysics science goals

The SIRA mission will produce high-sensitivity, high resolution radio images of the entire sky at frequencies below 15 MHz. Many physical processes involved in the emission and absorption of radiation are only observable at low radio frequencies. For example, the coherent emission associated with electron cyclotron masers, as seen from the giant planets, Earth (AKR), and several nearby stars, is not only expected to occur and be detectable elsewhere in the galaxy but to be ubiquitous. Incoherent synchrotron radiation from fossil radio galaxies will be detectable by SIRA, revealing the frequency and duration of past epochs of nuclear activity. The multi-frequency, all-sky radio images produced by SIRA will allow the spectra of known galactic and extragalactic objects to be extended to much lower frequencies. This will provide unique information on galactic evolution, matter in extreme conditions, and life cycles of matter in the universe. It is also likely that unexpected objects and processes will be discovered by SIRA. Indeed, one of the cornerstones of the SIRA mission is the high potential for discovery.

3. SIRA MISSION DESCRIPTION

3.1 Basic requirements for SIRA mission

The SIRA mission will consist of 12 to 16 microsatellite buses that will be almost identical (Fig. 4). (A possible difference, for example, would be if only three of the microsats were instrumented to transmit timing signals to the constellation.) Communication with each microsat will consist of uplinks from and downlinks to the ground; inter-microsat communication will be limited (as described below) so that the loss of one or more microsats does not impair the scientific mission. The minimum science mission requires 10 microsats to provide a sufficient number of baselines for useful observation. (Note: the number of interferometric baselines for N satellites is N*(N-1)/2.) We will propose a prime mission lifetime of two years, with a total lifetime goal of four years.

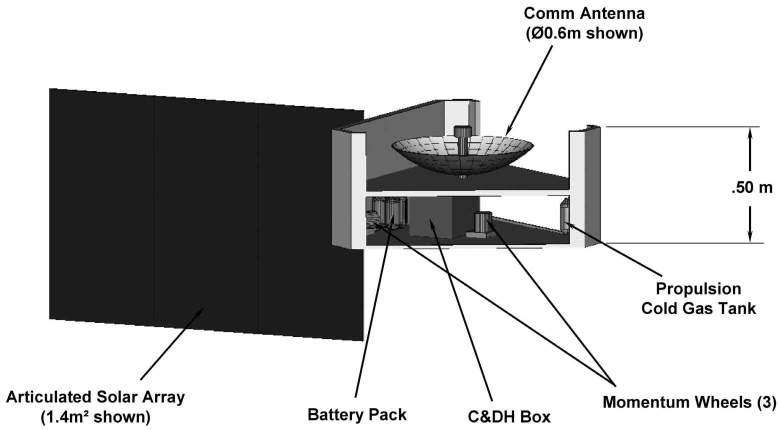

Figure 4: IMDC SIRA microsatellite with solar array deployed.

The spacecraft orbit proposed for this mission is a “retrograde” orbit around Earth at a distance of approximately 500,000 km. Such an orbit appears to orbit Earth in the direction opposite to the orbit of the moon. These orbits have been shown to be stable with minimal evolution of the constellation. The relatively close distance to Earth, as compared to an L1 halo orbit, facilitates the downlink from each of the microsats. Furthermore, it provides observations of the magnetosphere from all azimuthal perspectives. The orbit will be inclined by ~18º relative to the ecliptic to minimize eclipses.

Launch into this orbit would likely require the capability of a Delta II (Fig. 5a). A lunar flyby will be used to provide a rapid insertion into the desired orbit. An additional propulsion stage will likely be required to complete the orbit insertion, after which the microsats would be deployed from their carrier (Fig. 5b). As described in the IMDC Flight Dynamics presentation, the transfer time to mission orbit is 7 days with the lunar gravity assist. Orbital parameters are launch C3 of -0.1 km2/s2, transfer injection C3 of 0.135 km2/s2, mission orbit injection delta-V of 416 m/s, inclination to ecliptic plane of 18 deg, initial orbit radius of 495,000 km, initial period of 40.1 days, final orbit "radius" of 475,000 x 515,000 km, and final period of 40.2 days.

The microsats will be deployed into quasi-random locations on a spherical shell of 10 km diameter. There will likely be a minimum separation constraint imposed to prevent an excess number of short baselines. Further into the mission, the diameter of this shell may be increased up to 50 km.

Because of the data volume, an X-band downlink will be required (at 8 Mbps). High gain antennas of either the dish or phased-array type will need to be pointed Earthward during the downlink. The data will be downlinked sequentially from each of the microsats. The total amount of science data collected per day will be at least 20 GB. This is the quantity of data that could be dumped to one ground station during a 6 hour interval with approximately 1 hr allowed for transitions from 1 microsat to the next. The receivers are capable of generating more data, so we will either reduce the number of frequencies or transmit less than 100% of the data collected to reach the 20 GB limit. If two ground stations are available, then SIRA would observe at 16 log-spaced frequencies with 15 MHz as the highest frequency; this would generate almost 40 GB of science data per day. On-board data storage should be provided to retain approximately 2 days of data (~6 GB/microsat), in case a downlink cannot be made. In that case, the scientifically more desirable data would be downlinked during the next window.

The science and housekeeping data will be forwarded to one or more science centers with a delay of no more than 4 hours after reception at the ground station. The primary science center will likely be located at MIT, in association with Haystack Observatory. A second center may be located at GSFC or at a partnering institution. Quick look data will be generated at the science center(s), images will be made available on the SIRA web site, and data will be distributed to users in a timely manner.

3.2 Science Instruments

The basic instrumentation required to acquire the radio data is two dipole antennas and two receivers per microsat. Each dipole antenna will consist of two 5m stacer BeCu monopoles mounted on opposite sides of the microsat. The two dipoles will be mounted at a 90º angle to each other. Mounting must be done in a manner that reduces the base capacitance to 100 pf or less. Each monopole and mount will weigh ~1 kg; 4 monopoles/mounts are required per microsat. Knowledge of the orientations of the dipole axes to ±2 deg (total) is required.

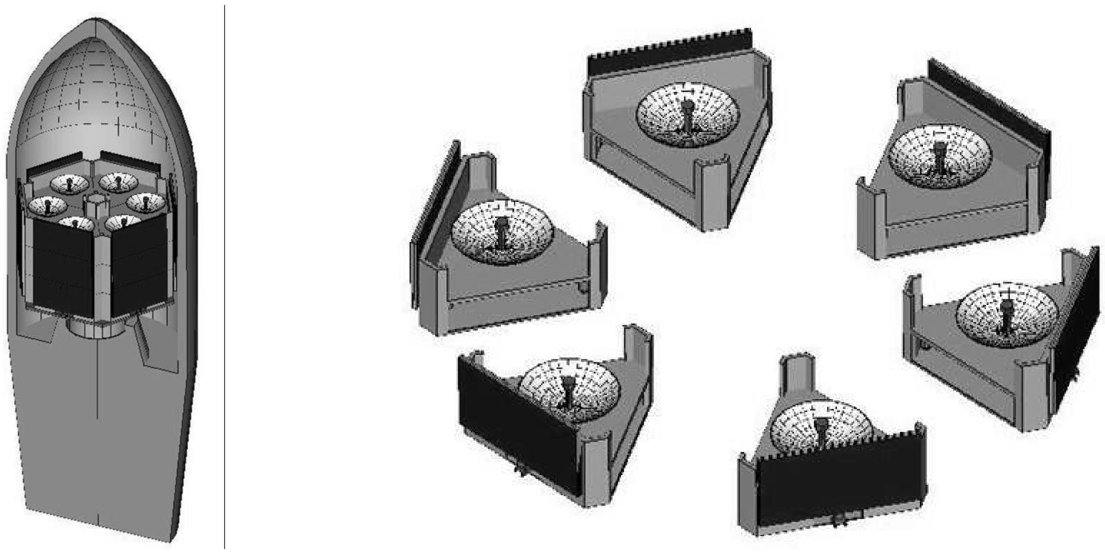

Figure 5: (a) IMDC SIRA microsats inside Delta II fairing; (b) Layer of 6 SIRA microsats separating during deployment.

Connected to each dipole will be a lightweight, low-power radio receiver programmed for interferometric data acquisition. A typical mode of operation will be to sequentially scan ~16 frequencies logarithmically-spaced in the frequency interval from 30 kHz to 15 MHz. The data will be 2-bit Nyquist sampled for bandwidths of one percent of the frequency. Each frequency would be sampled for one second or more before stepping to the next frequency. For 16 microsatellites and 16 frequencies with 15 MHz as the highest frequency, continuous science data for 24 hours would comprise 38.2 GB.

It is worthwhile to consider the constellation as the instrument, which facilitates understanding a number of requirements that interferometry imposes on the mission. Only when the data from the entire constellation are on the ground and processed will there be images of scientific value. To accomplish this, the relative ranges (baselines) of the microsats and the absolute orientation of the constellation must be known. The relative ranges must be determined to ~3 m, which is ~0.15 of a wavelength at 15 MHz. This ranging activity would need to be done at least once per day. On short time scales, the constellation may be considered to be a rigid body, defined by a single orientation. Its range from the ground station should be known to about 300 m accuracy. The constellation orientation will be determined either by ranging to individual microsats at the edges of the constellation or by using star trackers. It is desirable to know the absolute orientation of the (rigid) constellation to 0.5 deg; additional accuracy can be derived from post-processing of the data. During intervals between microsat ranging and orbital configuration determination, the relative and absolute positions of the microsats will be determined and maintained in a ground-based model. This model will be used to determine when individual microsats should be maneuvered to maintain their locations on the shell.

There are three timing criteria that must be met by the microsats operating as an interferometer. Absolute time tagging of the data to 0.1±0.01 sec is required. For aperture synthesis, we require phase coherence and bit stream (relative timing) alignment. The phase stability requirement will depend on the highest observing frequency and the longest coherent integration we plan to use. Typically, we need to insure that phase changes during the longest integration times will be less than a radian at the observing frequency. (We can solve for a long-term phase drift after correlation, but we need to keep the phase difference less than a radian during correlation to prevent significant reduction in fringe amplitude.) Assuming an upper frequency of 15 MHz and a maximum integration time of 100 seconds, we could require fractional frequency stability for the array of about 10^{-10}, which can be provided by high-quality crystal oscillators. The requirements for SIRA are less demanding, because this stability requirement applies to the differences between the oscillators on the different spacecraft. If we phase lock these oscillators to a common reference signal from one of the spacecraft, then the individual oscillators only need to be stable on time scales shorter than the phase lock loop time constant. The relative motions between spacecraft need to be modeled at the 3 cm/s level to keep Doppler offsets between the spacecraft from causing frequency shifts greater than one part in 10^{10}. At this differential drift rate, the inter-satellite ranges change by hundreds of meters per day, so they can be easily measured. Note that the GSFC

IMDC mission design assumed an approach that could be implemented with low cost oscillators and “continuous” updating via a VHF signal from a “master” microsatellite.

The timing accuracy required for the bit stream alignment depends on the bandwidth $\Delta\nu$ that we want to correlate. The downconverted and Nyquist sampled signals from each spacecraft must be aligned to within $1/(2\,\Delta\nu)$ before correlation. The largest bandwidth corresponds to the highest frequency; a 1% bandwidth for 15 MHz corresponds to 3 μsec. It is possible that we would use larger bandwidths at some times, so the required relative timing accuracy for bit stream alignment is 1 μsec.

We have addressed the following observation requirements in the preceding paragraphs: attitude control, antenna alignment, relative ranging, absolute position and orientation, absolute timing, relative timing, and phase coherence. In general, these are the same constraints that would be imposed on a ground-based radio interferometer, with the useful difference being that the longer wavelengths of space-based interferometry relax the magnitude of the constraints.

4. SIRA DATA ANALYSIS

The SIRA aperture synthesis data reduction has much in common with ground-based imaging observations at higher frequencies; however, a major challenge is the requirement to image the entire sky at the same time. This is necessary because individual radio antennas (dipoles) of reasonable size have very low directivity at these frequencies, which is the motivation for using an interferometer array. Consequently very strong radio sources will create sidelobes in directions far from their positions, and high dynamic range imaging will require that the effects of strong sources be removed from all sky directions, not just from the region immediately adjacent to the sources. This in turn requires an array geometry which produces highly uniform aperture plane coverage in all directions simultaneously, a requirement that no previous interferometer array has had to meet. A quasi-random distribution of antennas on a single spherical surface was found to provide excellent aperture plane coverage in all directions with a minimum number of antennas.

For SIRA, cross-correlation of the signals will be done on the ground in five steps. First, the data streams from all receivers will be aligned in time using knowledge of the array geometry. This will be done for each of a set of appropriately spaced positions (phase centers) on the sky. Second, the data streams associated with each phase center will be Fourier transformed to produce spectra. The time span of data used for the transforms will be less than the coherence time. Third, each spectrum will be examined for evidence of interference, and suspect frequency channels removed. Fourth, amplitude calibration will be applied to each spectrum. Finally, the spectra associated with each phase center will be cross-multiplied to produce the cross-power spectrum for each baseline. The cross-power spectrum contains the real and imaginary parts of the cross-correlation function, or equivalently, the baseline fringe amplitude and phase. The computing power required to cross-correlate all data in less than the observing time (~3 GFLOPS) can be obtained from a small cluster of workstations.

Phase calibration of the array is provided by a carrier generated by one of the satellites, to which all satellite oscillators are locked. Amplitude calibration is provided by 1) periodically injecting a known calibration signal into the signal path between the antennas and low frequency receivers, 2) comparison with known astronomical sources at the high end of SIRA’s frequency range, and 3) comparison with ground-based observations of solar bursts using antennas of known gain. The theoretical array sensitivity at 3 MHz is ~200 Jy in 5 seconds.

Based on imaging simulations, we expect to obtain a dynamic range of 10^2-10^3 for relatively compact sources (< 100 beams in size), depending on frequency. For very extended sources or the lowest observing frequencies the dynamic range will still be a few tens, which is entirely adequate for imaging strong, rapidly evolving sources. To verify the very-wide-field imaging performance of the SIRA mission, we created simulated visibility data for a number of radio sources in different directions and for a specified array geometry. These data were combined into a 3-D (u,v,w) visibility data file. Errors applied to the data were calculated from the galactic background plus the predicted coherence losses[7]. To improve the dynamic range of the image, we first removed the strongest sources in the data set by using only the highest amplitude data points. This allows strong sources to be readily located and modeled. Once subtraction of the strongest sources has reduced the residual visibility amplitudes to near the expected noise level, the remaining data points are restored and the initial field can be deconvolved. Additional tests were done to verify the ability of this

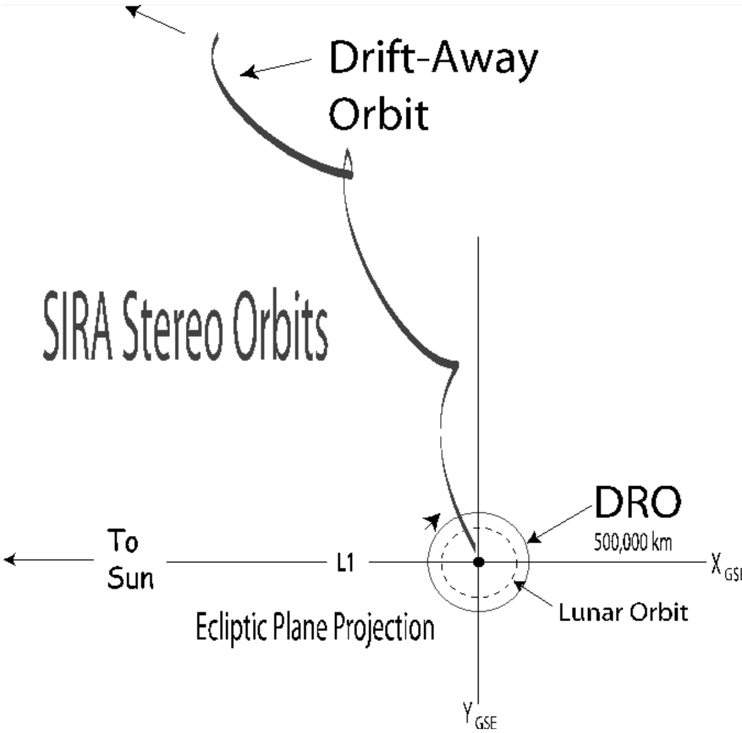

Figure 6: SIRA *Stereo* orbits: distant retrograde (DRO) and drift away orbits provide stereo viewing of solar transient radio burst images.

array to image structure in angularly large interplanetary transients. Nevertheless, more work is needed to fully understand the imaging performance on the largest angular scales.

Aperture synthesis imaging of very wide fields requires 3-D Fourier transforms, but regions of limited angular size (over which the effects of sky curvature are small) can be imaged with separate transforms in which one dimension is much smaller than the other two[8]. This approach lends itself to parallel processing. For the SIRA mission, the imaging problem is most difficult at the highest frequency (15 MHz) where the synthesized beam is smallest (~4 arcmin). We plan to make 1024 x 1024 pixel images with 50 arcsec pixels, so each image will cover an area of 14° x 14°. Thus, ~200 images are needed to cover the entire sky. Each image will require a 16 pixel Fourier transform in the "radial" direction to allow for sky curvature over the largest scale structure to which the data are sensitive. We will divide each image into ~100 smaller areas which will each be deconvolved with the appropriate synthesized or "dirty" beam[9]. All clean components are subtracted from the data for each field and each field is transformed again to produce residual images. This continues until no sidelobes remain. For intense solar bursts, snapshot images will be obtained without iterative processing.

5. ROLE OF SIRA AS A TECHNOLOGY PATHFINDER

Of the many space missions being proposed with more than a dozen satellites, SIRA is among the easiest and least expensive to develop. The radio receivers are simple, light weight, low power, low cost instruments that do not constrain the microsats. The mission takes place in the moderate radiation environment of space beyond the magnetosphere. Requirements for spacecraft pointing and constellation control are easily met. Consequently, SIRA represents the opportunity to implement a constellation with a dozen or more spacecraft on a MIDEX budget.

SIRA is also a pathfinder for space-based interferometry. Because the mission observes at the longest wavelengths of the electromagnetic spectrum, all aspects of interferometric design become easier. The inter-microsat ranging accuracy requirement is 3 m. The required constellation baselines are sufficiently long that there is no need for autonomous formation flying: spacecraft positions can be telemetered to the ground, where the needed maneuvers are determined and uplinked to the microsats. Nevertheless, the mission operations for SIRA would exercise all of the required functions relevant to a more demanding, shorter wavelength interferometric array in space.

With the conclusion of a successful SIRA mission, it would be appropriate to consider more advanced radio imaging missions. One possibility would be a SIRA *Stereo* mission, where two SIRA constellations would be inserted into separate orbits so that one is in a distant retrograde orbit around Earth, while the other is in a heliocentric 1 AU orbit, gradually drifting away from Earth (see Fig. 6). Each of the two constellations would have 16 or more microsatellites, arranged on a spherical shell to optimize the distribution of interferometric baselines. The shell diameter and other constellation parameters would be similar to the first SIRA mission. Since the drift-away constellation requires a data relay bus with a high gain antenna, a relay bus for the DRO constellation provides commonality. Data processing onboard the relay bus would reduce the visibility data to images with high frequency (~10 kHz) and high time (~5 sec) resolution, permitting reduction of the downlink data rate and enhanced monitoring of source evolution close to the Sun.

The images would be available to the user community within hours of arrival on the ground, allowing quick interaction with other NASA Sun-Earth Connection missions and ground-based solar observatories.

REFERENCES

1. S. D. Bale et al., “Observation of Topside Ionospheric MF/HF Radio Emission from Space,” Geophys. Res. Lett., 26, 2331, 1999.
2. H. V. Cane, W. C. Erickson, and N. P. Prestage, “Solar flares, type III radio bursts, coronal mass ejections, and
3. energetic particles,” Geophys. Res. Lett., 8, 1285, 2002.
4. R. J. MacDowall et al., “Long-duration hectometric type III radio bursts and their association with solar energetic particle (SEP) events,” Geophys. Res. Lett., 30, 8018, doi:10.1029/2002GL016624, 2003.
5. N. Gopalswamy et al., “Large solar energetic particle events of cycle 23: A global view,” Geophys. Res. Lett., 30, 8015, doi:10.1029/2002GL016635, 2003.
6. M. J. Reiner et al., “Terrestrial 2f(p) radio source location determined from WIND/GEOTAIL triangulation,” Geophys. Res. Lett., 24, 919, 1997.
7. J. K. Alexander, M. L. Kaiser, and P. Rodriguez, “Scattering of terrestrial kilometric radiation at very high-altitudes,” J. Geophys. Res., 84, 2619, 1979.
8. R. P. Linfield, “IPM and ISM coherence and polarization effects on observations with low-frequency space arrays,” Astron. J., 111, 2465, 1996.
9. T. J. Cornwell and R. A. Perley, “Radiointerferometric imaging of very large fields - the problem of noncoplanar arrays,” Astron. Astrophys., 261, 353, 1992.
10. D. A. Frail, N. E. Kassim, and K. W. Weiler, “Radio imaging of 2 supernova-remnants containing pulsars,” Astron. J. 107, 1120, 1994.