PROPOSAL COVER PAGE

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Name of Submitting Institution: NASA/GSFC **Congressional District:** 5

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AO Signature and Date: original signed by A. V. Diaz 9/8/2003

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[3] ... Proposal Title (Short and/or Full)

Short Title:	Solar Imaging Radio Array
Full Title:	Microsatellite radio interferometry: A concept study for the Solar Imaging Radio Array (SIRA) missions

[4] ... Proposed Start/End Date

Start Date:	01/01/2004

End Date:	12/31/2004

[5] ... Themes

(1) Sun-Earth Connection (2) Structure and Evolution of the Universe

[6] ... Predecessor Information

Predecessor Information:	None

[7] ... Summary

SIRA, the Solar Imaging Radio Array, will consist of one or more microsatellite constellations designed to image radio sources in the solar corona and heliosphere using aperture synthesis interferometric techniques. In this Space Science Vision Mission concept study, we focus on SIRA Stereo, a mission with two constellations of ~16 microsatellites each, providing stereoscopic images of radio bursts in the outer solar corona, inner heliosphere, and terrestrial magnetosphere. Because these radio bursts occur at frequencies below the ionospheric cutoff (~10 MHz), the observations must be made from space. One constellation will be in Earth orbit, the other in a STEREO-type drift-away orbit, which will gradually increase the stereo viewing perspective of solar bursts. These stereo images will permit direct 3-D localization and tracking of shocks (type II radio bursts) driven by coronal mass ejections (CMEs) and of solar flare electrons (type III radio bursts) as a function of time from near the sun to 1 AU. Imaging of the CME-driven shock front is important for understanding and predicting the space weather effects of CMEs, whereas imaging of the more frequent type III bursts will contribute to the study of intense solar energetic particle events. Imaging of the magnetosphere will permit viewing magnetospheric boundaries in reflected radio emission and monitoring its dynamic response to space weather events. We also discuss a SIRA MIDEX mission that would serve as a pathfinder for SIRA Stereo, as well as for other constellation and space-based interferometry missions, because of the relatively limited constraints necessary for long wavelength radio interferometry. SIRA MIDEX will be the first mission to image the heliosphere (and the celestial sphere) with high angular resolution at frequencies below the ionospheric cutoff; no current or near term mission has the capability to do this imaging. The radio images are intrinsically complementary to white-light coronagraph data, such as those of the Solar Dynamics Observatory (SDO), and can play a vital role in the NASA Living with a Star program. Stereoscopic imaging, as provided by SIRA Stereo, will directly locate radio sources in three-dimensions, greatly enhancing the science return and increasing space weather prediction accuracy.

[8] ... Cage Code, Duns, TIN

Cage Code:	25306
DUNS Number:	
TIN Number:	30005004

[9] ... Carrier

Is this an investigation on sounding rocket, a balloon, or an airplane? :	No

[10] ... Institution Type

Institution Type:	NASA Center

[11] ... Research Category

Research Category:	Instrument and Mission Development

[12] ... International Proposal

International Participation &	Yes (One of the SIRA Space Science Vision mission collaborators is from a foreign institution. He will participate in the mission definition on a no-

Description:	exchange-of-funds basis. We will adhere to all ITAR requirements.)

[13] ... US Government Agency Participation

U.S. Government Agency Participation:	Yes (The following SIRA VM proposals participants are affiliated with government agencies: R. MacDowall, N. Gopalswamy, M. Kaiser (all NASA/GSFC), D. Jones and P. Liewer (both JPL), and K. Weiler and N. Kassim (both Naval Research Lab.). In addition, funds are designated for use by the NASA/GSFC Engineering Directorate (Code 500) staff. The total full-cost accounted dollar amount requested for their participation is $253,500 out of the total request for $304,000.)

[14] ... Program

Program Selection:	Study Case 07: Solar Imaging Radio Array (SIRA)

[15] ... Data1

Use of Astronauts:	No

[16] ... Data2

Use of Nuclear Power:	No

[17] ... Budget

Type	Year 1	Total
Direct Labor	$127,800.00	$127,800.00
Other Direct Costs - Subcontracts	$99,300.00	$99,300.00
- Consultants	$0.00	$0.00
- Equipment	$0.00	$0.00
- Supplies	$1,300.00	$1,300.00
- Travel	$0.00	$0.00
- Other	$0.00	$0.00
Indirect Costs	$60,900.00	$60,900.00
Other Applicable Costs	$14,700.00	$14,700.00
Subtotal - Estimated Costs:	$304,000.00	$304,000.00
Less:Proposed Cost Sharing - Cost Sharing:	$0.00	$0.00
Budget Total	**$304,000.00**	**$304,000.00**

Continue

Edit Proposal

Table of contents & NRA compliance list (see items in red)

Summary of Personnel and Work Efforts

For the calendar year 1/01/2004-12/31/2004:

0.2 FTE - Robert MacDowall (PI)

0.6 FTE - all Co-Is
- 0.1 FTE - Michael Kaiser
- 0.1 FTE - N. Gopalswamy
- 0.1 FTE - Dayton Jones (JPL)
- 0.1 FTE - Kurt Weiler (NRL)
- 0.2 FTE - Michael Reiner (the Catholic University of America)

0.2 FTE - GSFC Flight Dynamics (orbital analysis, constellation stability, etc.)

0.3 FTE - GSFC Code 500 (mission design)
======
1.3 FTE - Total

In addition to the funded personnel listed above, 12 collaborators will provide scientific and technical input to the concept study at no cost to NASA. An educational component of the study concept activity will be managed by M. McGrath, University of Colorado.

<u>*Scientific/Technical/Management Section*</u>

1. SIRA *Stereo* mission summary

Vision Missions – As called for in the Space Science Vision Missions NRA, an appropriate candidate for vision mission status must have “the proper balance between innovation and the likelihood of the mission’s feasibility.” For the time frame beyond 2013, technological innovation will permit implementation of a Solar Imaging Radio Array (SIRA) mission that is far more capable than the one identified in the Sun-Earth Connections (SEC) 2003 Roadmap. This visionary mission, which we call SIRA *Stereo*, will use two widely-separated microsatellite constellations to obtain stereoscopic observations of solar and interplanetary radio emissions that have critical space science and space weather connections. Miniaturization at the component and satellite levels will permit launching the 32 or more microsatellites needed with a single launch vehicle. Advanced processing hardware will permit the necessary aperture synthesis calculations to be completed on-board, so that only processed images will be downlinked, permitting a substantially higher image acquisition rate.

SIRA was selected as a Space Science Vision Mission in recognition of its unique mission capabilities and their strong connections to all of the SEC Roadmap themes. In the SEC Roadmap (see Figure 1), the SIRA constellation mission identified for possible launch in the 2013-2028 time frame is a single constellation in a distant retrograde orbit around Earth. Such a SIRA mission can be implemented as a near-term MIDEX mission and will be proposed for the next MIDEX opportunity. In as much as a single SIRA constellation is one of the simplest constellation missions and one of the least-constrained space-based interferometry missions, it makes excellent sense to launch such a pathfinder mission at the earliest opportunity. A recent mission design analysis at the NASA Goddard Space Flight Center (GSFC) Integrated Mission Design Center (IMDC) confirmed that this mission can be built and flown within a MIDEX cost cap. In this proposal, we refer to this near-term mission as SIRA MIDEX. Funding for the SIRA MIDEX mission design and proposal effort will be obtained from sources other than this concept study.

Science goals – Microsatellite constellations can be used to conduct aperture synthesis imaging of low frequency radio sources from the Sun, inner heliosphere, and terrestrial magnetosphere with high time and frequency resolution. Primary SIRA *Stereo* science goals are to:

- understand the 3-D structure of coronal mass ejections (CMEs) and their associated shocks and quantify their propagation and evolution from the Sun to 1 AU
- enhance space weather prediction capabilities using time-sequenced radio images of CMEs, shocks, and other radio sources, and
- observe and quantify the global magneto-

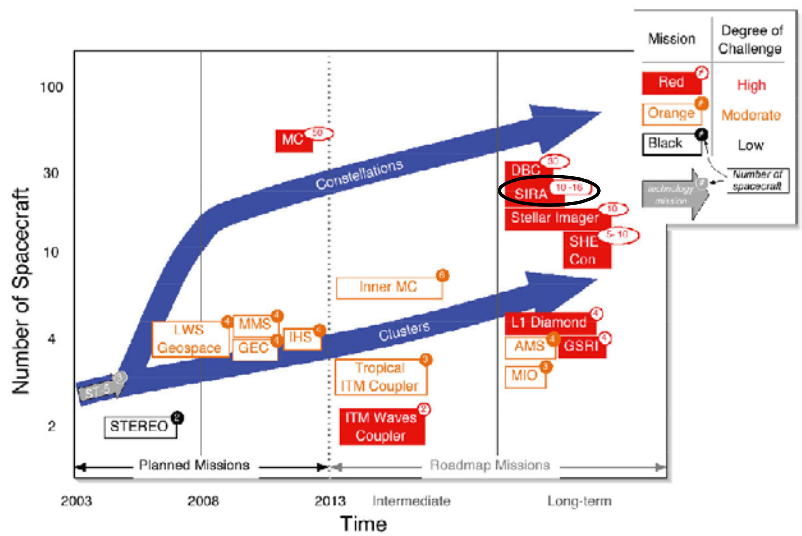

Figure 1– SIRA finds itself in the company of some significantly more challenging long-term, multispacecraft missions (SEC Roadmap 2003-2028). Given the simplicity of the SIRA microsatellites, we are confident that the degree of challenge for SIRA MIDEX is equal to or less than MMS or GEC.

spheric response to CMEs, high speed streams, and other space-weather-effective events from an external perspective

Using two constellations, SIRA *Stereo* will be able to fulfill all three of these goals simultaneously. (Depending on its location, SIRA MIDEX may only be able to fulfill one goal at a given time.) SIRA *Stereo* will also image the low-frequency (<15 MHz) radio universe at high angular resolution from a low noise environment far from Earth, very likely leading to important new discoveries in astrophysics.

NASA/SEC Relevance – SIRA *Stereo* is a visionary mission in the lineage of near-term Living With a Star (LWS) and other SEC missions. Using two microsatellite constellations, it will provide stereoscopic low-frequency radio observations that are critical to NASA Sun-Earth Connection goals and objectives. 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.

A major space weather goal of SIRA *Stereo* is accurate prediction, days in advance, of the arrival of CMEs at Earth, so that preventive actions can be taken. Radio imaging will provide improved prediction capability relative to Wind Waves or STEREO Waves radio data. In addition, SIRA *Stereo* will image Earth's magnetospheric response to such solar disturbances, providing a unique global view of the magnetosphere from the outside. In each of these cases, observations made from two separate perspectives will provide unique information not available to a single constellation mission. For example, in the case of a CME impacting the magnetosphere, one SIRA *Stereo* constellation will image the impact from an ideal location ahead of Earth in its orbit around the Sun, while the other near-Earth constellation will be well placed to observe CME-induced changes in the magnetosphere illuminated by the changing magnetospheric radio emissions.

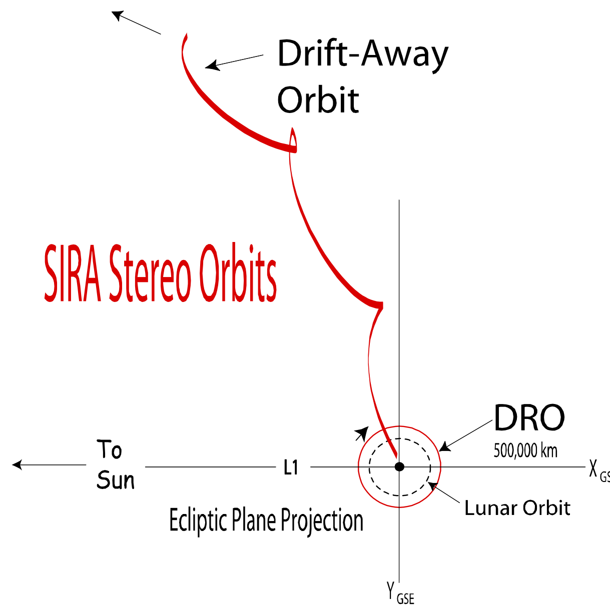

Figure 2 – One SIRA Stereo constellation is in a DRO near-Earth orbit, the other in a drift-away orbit, to provide a stereo perspective of solar radio emissions.

Science return vs. other missions – SIRA MIDEX will be the first mission to produce high resolution images of solar and terrestrial radio emissions at frequencies < 15 MHz; SIRA *Stereo* will be the first mission to produce stereoscopic images that permit 3-D localization of the radio sources. No current or scheduled mission can obtain these radio images. 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.

Mission design – The two SIRA *Stereo* constellations will be inserted into separate orbits so that one is in a "distant retrograde orbit" (DRO) around Earth with the other in a heliocentric 1 AU orbit, gradually drifting away from Earth (see Figure 2). Each of the two constellations will have 16 or more microsatellites, arranged on a spherical shell to optimize the distribution of interferometric baselines. The shell radius will be 5 to 25 km, which will be varied as appropriate throughout the mission. Since the drift-away constellation requires a data relay bus with a high gain antenna, we plan to use a relay bus for the DRO constellation for commonality.

The instrument payload for each microsatellite consists of 2 radio receivers (~30 kHz to 15 MHz), each attached to a short 10m dipole antenna. Onboard data processing will 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 stereo images will 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.

Concept study goals – The principle goals of the SIRA *Stereo* concept study are:

1. document all primary and secondary science objectives of the SIRA *Stereo* mission
2. describe advances over previous missions, interaction with concurrent missions, and mapping to future missions
3. investigate preferred synthesis techniques for mitigating propagation effects
4. investigate on-orbit data processing for improved operations
5. investigate various orbit options for the SIRA *Stereo* constellations
6. investigate and describe payload, satellite, deployment, and launch vehicle options
7. investigate automation of navigation (NAV) activities, orbit determination, and other operations
8. investigate communication requirements and ground station issues
9. develop science data processing and analysis software requirements
10. describe development, validation, and demonstration approaches for SIRA *Stereo*
11. describe maximization of "resilience" by statistical redundancy, adaptability, etc.
12. address all safety issues relating to SIRA *Stereo*

The results of these separate tasks will sharpen understanding of a subset of possible future missions for scientific and programmatic planning within OSS.

Concept Study Team – The SIRA *Stereo* mission concept study is a collaboration of Goddard Space Flight Center, Jet Propulsion Laboratory, and the Naval Research Laboratory, with co-investigators and collaborators from numerous universities, including Catholic University, University of Maryland, UC Berkeley, and from scientific institutions outside the U.S. An educational component of the concept study will be directed by M. McGrath at the University of Colorado. We plan to make use of the GSFC IMDC to resolve several key questions about the SIRA *Stereo* mission (see §7).

2. Scientific and Technical Background

Transient disturbances traveling through interplanetary space generate radio emissions at characteristic frequencies of the plasma. The solar radio emissions observable by the SIRA missions are *type II* radio bursts generated by shocks from flares and/or CMEs, *type III* radio bursts produced by suprathermal electron beams usually associated with solar flares, and *moving type IV* radio bursts generated by ejected plasma from filament eruptions. The radio frequencies associated with the evolution of solar disturbances range from several gigahertz to a few kilohertz, decreasing with the height of the disturbance in the solar atmosphere. The higher frequency emissions occur very close to the sun where the electron density and plasma frequencies are high, while lower frequency emission occurs in the less dense regions far from the sun.

Ground-based radio telescopes have had the capability for nearly three decades to image solar emissions using the technique of aperture synthesis. The top image in Figure 3 (Gopalswamy et al. 1987) shows an example of radio isointensity contours from solar thermal emissions with a superposed non-thermal type III source to the southeast, as observed by Clark Lake at 50 MHz. Because Earth's ionosphere prevents observations at frequencies below about 15 MHz (height above sun ~1.5 R_S), tracking solar disturbances from the Sun to the vicinity of Earth is the domain of space-based radio observations.

Spinning spacecraft with dipole antennas, such as the Wind spacecraft, provide radio observations as shown in Figure 3b (source direction and a source radius for a given intensity distribution model, but no information on the structure of the source). Only a constellation mission like SIRA MIDEX or SIRA *Stereo* can provide images of radio sources at frequencies below the ionospheric cutoff (Figure 3c).

SIRA MIDEX represents the initial effort to make such space-based observations. It will produce the first low frequency, high resolution, time-sequenced radio images of the solar corona and interplanetary disturbances such as shock-driven coronal mass ejections (CMEs). The more advanced SIRA *Stereo* mission will provide the first *stereoscopic* radio imaging and improved tracking of transient disturbances in the solar corona and interplanetary medium, which are critical for understanding many aspects of solar-terrestrial interaction and space weather. Its capability to observe the same phenomena from two different perspectives, with higher temporal and spectral resolution, will make possible triangulation of source locations .

In addition to solar observations, the SIRA missions will image Earth's magnetospheric response to such solar disturbances, providing a unique global view of the magnetosphere from the outside.

The SIRA missions use aperture synthesis, an interferometric technique where data from a large number of baseline lengths and orientations are combined to produce images with an angular resolution comparable to that of a single aperture the size of the entire interferometer array. This is the basis of ground-based arrays such as the VLA and VLBA and the VSOP space VLBI mission, and results in many orders of magnitude improvement in angular resolution.

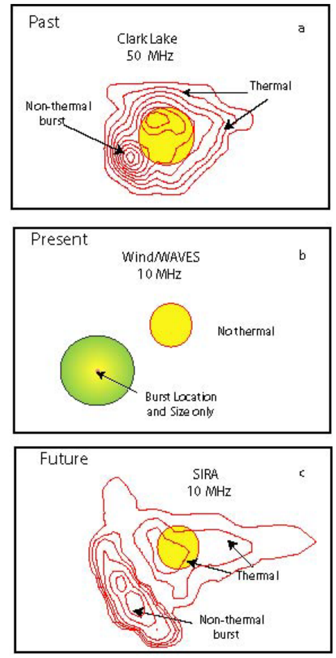

Figure 3 - (a) Image from the ground-based Clark Lake Radio Telescope. (b) 10 MHz data from Wind/Waves mission (single spacecraft). (c) Simulated SIRA 10 MHz image (multi s/c).

A basic SIRA constellation consists of ~16 identical small satellites with dipole antennas and low frequency radio receivers, distributed in a spherical array ~5 to 25 km in radius. The desired size of the array is determined by a fundamental limit to angular resolution created by scattering of radio waves in the interplanetary and interstellar media. However, the scattering limit is a strong function of direction and observing frequency. To allow for this, it will be possible to vary the size of the array during the mission to increase or decrease the maximum angular resolution. The spacecraft locations on the sphere must be distributed so that a wide range of baselines occurs.

The constraints on such long-wavelength radio imaging missions are not nearly as severe as for optical interferometry; for SIRA, the relative satellite position needs to be known only to ~3 m. Furthermore, the instrumentation itself is very simple – radio receivers and dipoles. Consequently, a basic, single constellation SIRA MIDEX mission can and should fly well before 2013. Such a mission will serve as a pathfinder for development, deployment, and operation of more complex and constrained constellations. It will also be an excellent pathfinder for SIRA *Stereo*, as well as other space-based, free-flyer interferometry missions.

3. Primary science goals

The top-level solar-terrestrial physics goals of the SIRA *Stereo* mission are:

- Image stereoscopically, triangulate, and track the transport of CMEs in the interplanetary medium to improve understanding of their evolution and propagation, to distinguish unambiguously between Earth-directed and non-Earth-directed CMEs, to establish a metric for their "geoeffectiveness", and to predict their Earth arrival times for space weather forecasting purposes.
- Image and triangulate 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 by stereoscopic observations of the radio source regions.
- Provide global imaging of the terrestrial magnetosphere illuminated by terrestrial radio emissions to better understand the response of the magnetosphere to the impact of major space weather events like CMEs.

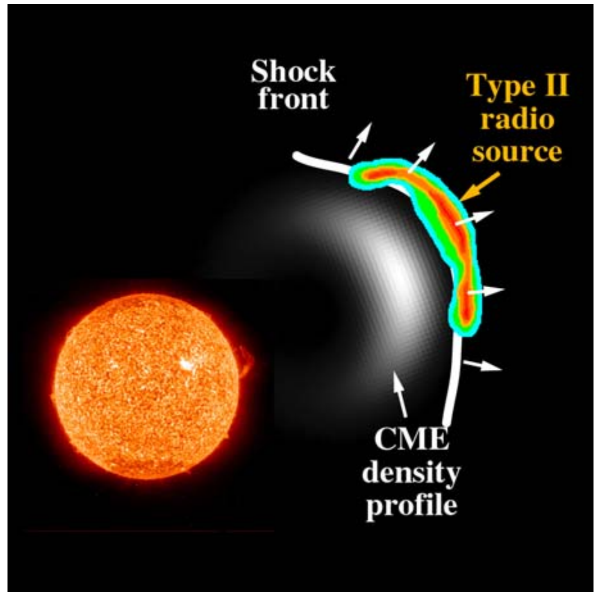

Figure 4 – Conception of SIRA image of CME density profile and shock-associated Type II radio emission.

3.1 CMEs

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 coronal mass ejections (CMEs) are manifested by distinct types of non-thermal radio bursts. The SIRA missions will image these radio bursts at low frequencies to reveal their

SIRA *Stereo* Traceability Matrix

Science objectives	Implementation	Science return	Strategic alignment
Track CMEs; predict space weather	Time-sequenced 3-D localizations of CMEs	Tracking & s.w. predictions for 50 CMEs (2 yrs)	NASA 2003 Strategic Plan Goal 5 and Space Science 2003 Strategy – Sun-Earth Connection Objective 3: Understand the origins and societal impacts of variability in the Sun-Earth system.
Map interplanetary structures; apply to CME propagation	Time-sequenced 3-D localizations of type III burst sources	Trajectories of ~1000 type III radio bursts (location vs. distance) (2 yrs)	
Understand particle acceleration	Images of shock & SEP associated radio bursts	Locations & radio intensities for all relevant bursts	
Monitor magnetospheric response to space weather	Images of magnetospheric radio sources for quiet & active intervals	Large-scale displacements of magnetosphere boundaries for all magnetic storms	

spatial and temporal evolution, and to permit remote sensing of coronal and interplanetary density and magnetic field structures between the sun and Earth.

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 be tens of intense kilometric 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. The CME density enhancement will occult bursts occurring behind it, permitting the CME to be seen by the reduction of radio intensity. This indirect method of mapping and tracking can also be applied when the CME is far from the sun where white-light coronagraphic imaging may not be possible. Furthermore, this method accurately measures the density profile in the CME since the density is precisely given by the observed frequency of absorption — no assumptions are needed about column density between source and observer.

As illustrated schematically in Figure 4, 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 emissions will be measured by the same instrument, ambiguities and difficulties typically involved in comparing radio and white-light images are eliminated. Furthermore, for SIRA Stereo, one constellation may observe the CME head on, while the other observes it in profile. This may help to clarify the relationship between the CME and the shock.

During solar maximum, the CME rate is about half a dozen per day. This amounts to nearly 7000 CMEs during the current solar cycle (up to 2002). Only a small fraction of CMEs are involved in the production of geomagnetic storms or major solar energetic particle (SEP) events. The 1-14 MHz type II radio bursts (as observed by Wind Waves) and large SEP events are asso-

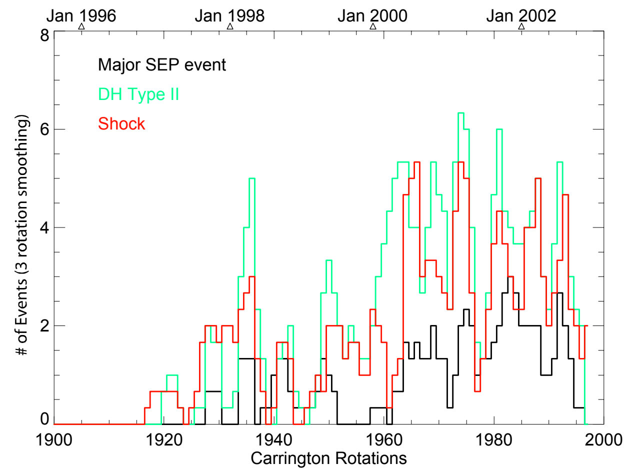

Figure 5 – Time correlation of shocks at 1 AU, type II bursts observed by Wind/Waves, and major SEP events (Gopalswamy et al., 2002).

ciated with fast and wide CMEs and the shocks that they produce at 1 AU (Figure 5). 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. SIRA Stereo will further enhance such determinations by triangulating source locations.

3.2 Mapping of Interplanetary Density Structures and Topology

Both SIRA missions will map the interplanetary density structures inside 1 AU by the direct and indirect imaging techniques described above, although the two perspective observations of SIRA *Stereo* will provide substantially improved 3-D mapping and source localization, in addition to substantially higher frequency and time resolution. 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.

3.3 Particle acceleration and SEP events

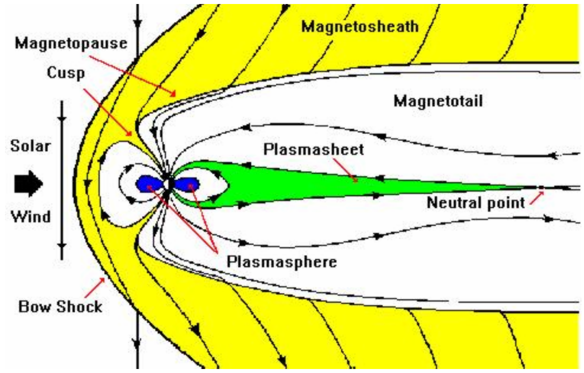

Figure 6 – Schematic drawing of magnetosphere; radio waves will be refracted at density gradients.

SEP events are accelerated by coronal and IP shocks and possibly by CME-related magnetic reconnection (Cane et al., 2002). Intense SEP events present dangerous conditions for spacecraft and astronauts. Wind Waves radio data show that most intense SEP events have characteristic 100 kHz - 14 MHz radio emissions (MacDowall et al., 2003). These complex type III bursts have attracted attention because of uncertainty about the SEP acceleration source. SIRA imaging will permit association of the complex features radio with structures in the corona, leading to an improved understanding of SEPs and possible early warning of their arrival at 1 AU.

3.4 The Terrestrial 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 unpredictable) geomagnetic storms are caused by CMEs, which pose the greatest danger to ground-based and space-borne technological systems and to astronauts. Space weather involves two basic and important problems: first, predicting, well in advance, when a disturbance will arrive at Earth and, secondly, predicting the geoeffectiveness of a disturbance.

Connections between solar and 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 tracking of CMEs by the SIRA missions will provide a key link in solar-terrestrial relationship studies.* With SIRA MIDEX, and especially with SIRA *Stereo*, the accuracy and timeliness of predictions will be significantly improved over what is currently possible using type II burst data from the Wind spacecraft. Type II burst images constructed in near-real-time by SIRA *Stereo* 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 (2fp) — will delineate regions of near-Earth space with strong gradients in the plasma and magnetic fields (see Figure 6). At Earth's bow shock, 2fp emission is generated nearly continuously by electrons back-streaming along interplanetary magnetic field (IMF) lines tangent to the bow shock (Reiner et al. 1997). 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 (e.g., Figure 7; Alexander and Kaiser 1977).

While AKR and continuum are quasi-continuous sources of emission, a distinct component of the AKR is now known to occur only

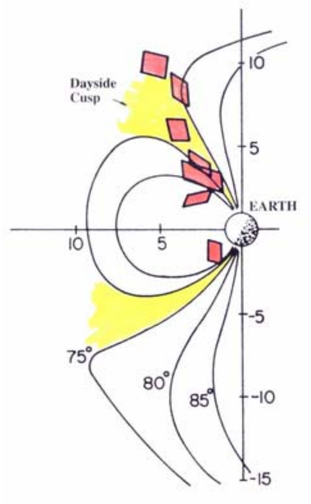

Figure 7 — Magnetospheric emission (AKR) near 200 kHz scattered off of density irregularities. This defines the day-side cusp; the SIRA missions will provide frequent imaging of such magnetospheric structures.

with southward turnings of the IMF (Desch 1996) and the onset of magnetic substorms (Anderson et al. 1996). Both SIRA MIDEX and SIRA *Stereo will produce high signal-to-noise images of the terrestrial magnetosphere precisely when the most interesting solar wind-magnetosphere interactions, such as magnetic reconnection, are taking place.*

4. Secondary science goals

Both SIRA missions will produce the high-sensitivity, high resolution radio images of the entire sky at frequencies below 15 MHz. SIRA *Stereo* will provide greater sensitivity given the location of one constellation far from terrestrial noise sources. 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 *Stereo*, revealing the frequency and duration of past epochs of nuclear activity. It is also likely that unexpected objects and processes will be discovered by SIRA *Stereo*. Indeed, one of the cornerstones of all of the SIRA missions is the high potential for discovery.

All-sky radio survey - The multi-frequency, all-sky radio images produced by SIRA *Stereo* 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. All of these issues are part of NASA's strategic goals. In addition, objects unseen at higher frequencies are almost certain to be found, resulting in the discovery of new phenomena. This is another NASA strategic goal, and a most exciting aspect of the SIRA *Stereo* mission.

In addition to its very high potential for discovery, the SIRA *Stereo* mission will address several key issues in NASA's SEU science area, including: 1) understanding the evolution of galaxies, 2) the exchange of matter and energy among stars and the interstellar medium, and 3) testing physical theories and revealing new phenomena. In each case, the key contribution of SIRA *Stereo* will be unprecedented angular resolution and sensitivity in a nearly unexplored frequency range. This gain in resolution and sensitivity will enable SIRA *Stereo* to detect and resolve individual objects anywhere on the sky and determine their low frequency spectra from imaging at multiple frequencies.

5. Data analysis and distribution

In this section, we describe the basic elements of data processing, focusing on the SIRA MIDEX mission. This data analysis pipeline has much in common with ground-based aperture synthesis observations at higher frequencies.

Array Configuration – Among the challenges of imaging the sky at low radio frequencies is the need to image the entire sky at the same time. This is necessary because individual radio antennas of reasonable size have very low directivity at these frequencies (which is the motivation for using an interferometer array in the first place). 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.

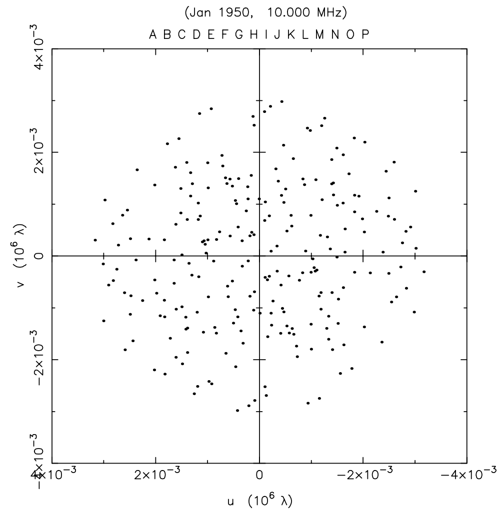

Figure 8 – Distribution of baselines in the aperture plane viewed from one perspective; all viewing angles have similar uniform u-v plane coverage.

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. An example of the aperture plane (u,v) coverage provided by a 16-satellite spherical shell is shown in Figure 8.

Cross-correlation – For SIRA MIDEX, 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. For SIRA *Stereo*, onboard data processing will be used to produce images, which are then compressed and downlinked. One of the concept study tasks is to develop detailed requirements for this onboard processing.

Sidelobe Suppression – Prior to cross-multiplication, all spectra will be multiplied by a combination of Gaussian and cosine functions to filter the frequency response of the array. This greatly reduces the delay beam sidelobes.

Interference Suppression – The delay-beam technique for suppressing interferometer response to emission far from the nominal phase center will fail for narrow-band signals. The most obvious source of narrow signals is terrestrial transmitters (see Figure 9). This problem is minimized by a combination of observing frequency selection, a high dynamic range receiver, ionospheric shielding, spectral data editing prior to cross-multiplication, and distance from Earth.

Calibration – 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.

Sensitivity and Dynamic Range – The array sensitivity at 3 MHz is ~200 Jy in 5 seconds. The coherence time limits imposed by fluctuations in the solar wind do not prevent useful imaging even at the lowest frequencies (Linfield 1996).

Based on our 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.

Imaging Simulations – To verify the very-wide-field imaging performance of the SIRA missions, we created simulated visibility data for a number of radio sources in different directions and 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 coherence losses as predicted by Linfield (1996).

To improve the dynamic range of the image we first remove 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 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.

Imaging wide fields - 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 (Cornwell & Perley 1992). This approach lends itself naturally to parallel processing. For the SIRA missions, 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,

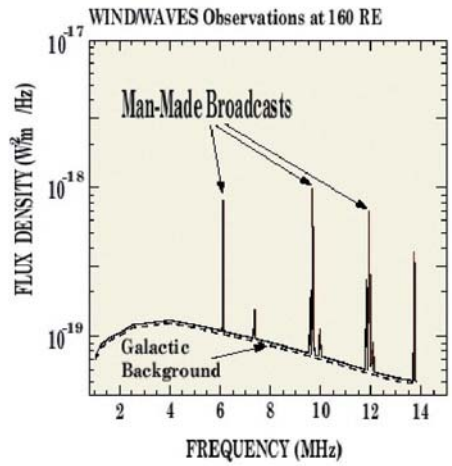

Figure 9 — Terrestrial interference observed by the WAVES instrument on the WIND spacecraft 10^6 km from Earth. At this distance 93% of the measurements above 6 MHz are within 3% of the galactic background. Interference from Earth will not be a major problem for SEC observations by the SIRA missions.

~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 (*e.g.,* Frail, Kassim, & Weiler 1994). 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.

Data Distribution & Archiving – All images and other data will be distributed on the Web as soon as available and archived at the NSSDC in a timely manner.

6. SIRA MIDEX Mission Implementation

Feasibility vs. innovation - The SIRA MIDEX mission design is reasonably well understood, based on design activity at GSFC over the last year, including a design run at the GSFC IMDC in August 2003. Two earlier MIDEX proposals submitted by the Jet Propulsion Laboratory for similar missions have also contributed to a good understanding of the trade space. In most ways, SIRA MIDEX serves as a baseline for SIRA *Stereo*; therefore, we present that mission design here to convey the feasibility of SIRA *Stereo*. Note the following significant differences between the two missions, which will be key elements in the SIRA *Stereo* concept study:

- 2 constellations vs. 1 constellation, which has significant effects on launch and mission operations requirements
- significant onboard data processing
- data relay bus vs. independent microsatellite downlinks
- additional data and science analysis to interpret stereo observations and convert them to 3-dimensional maps

We anticipate that these issues can be fully resolved with technology available prior to 2013.

6.1 SIRA MIDEX Mission design

Major elements of the SIRA MIDEX mission, which serves as a precursor for SIRA *Stereo* in many ways, include:

- 16 microsatellites
- 2 digital receivers per microsat
- crossed dipoles (10 m)
- frequency range ~30 kHz – 15 MHz
- imaging at ~16 frequencies
- DRO located ~500,000 km from Earth
- constellation radius ~ 5-25 km
- relative intersatellite ranging accuracy ~ 3 m
- daily data rate ~ 38 GB (16 satellites, 2 dipoles, 1% bandwidths, 2-bit sampling; can be reduced by duty cycling)
- mission life = 2 years (minimum)
- Streamlined mission operations and data systems approach

The DRO orbit represents a stable orbit sufficiently distant from Earth to reduce terrestrial radio interference, which can be reached at low launch and insertion energies. Using a segment of a periodic Earth-return orbit that arrives tangent to the DRO 8 months after launch at a point opposite the Sun, a small maneuver captures the SIRA carrier spacecraft with its 16 microsats. The microsatellites are then sequentially deployed by springs and maneuvered to positions on the order of 5 km from the carrier. This activity might require one month. We anticipate that the shell radius might be changed within the range of 5 to 25 km later in the mission. Ranging measurements from the ground, star tracker data, and intersatellite ranging are used to position the microsats accurately.

Maintenance of the relative array geometry requires measurement and control of each microsat position to within ~10% of the constellation radius. This will require each microsat to support a ΔV of 10 m/sec over a 2-year mission. An intersatellite fixed-tone ranging system will measure the relative positions to 3 m. For determining the array orientation, a combination of ranging, star tracker, and intersatellite range data will permit localizing the microsats to 10 m in an inertial frame.

6.2 Instrument design

The science instrument for SIRA MIDEX is the entire array of sixteen satellites operating together as an interferometer. Each SIRA microsat has two radio receivers, one for each dipole antenna, designed to receive signals in the range 0.03 to 15 MHz. Observing frequency, bandwidth, sample rate, and phase switching are controlled by the spacecraft processor, and can be changed by command. Each receiver digitizes a bandwidth of up to 150 kHz with 1 or 2-bit Nyquist sampling and can handle a very wide range of input levels. The receiver design is based on commercially available components. No new development is required. The dipole antennas are each 10 m long, using self-deploying beryllium -copper tape technology.

6.3 Spacecraft Implementation

The SIRA MIDEX mission is designed to be redundant at the system level: all microsats communicate directly to the ground, so no single spacecraft failure will be catastrophic. A schematic of a SIRA MIDEX microsat is shown in Figure 10. In this implementation, the only deployables are the monopoles that make up the orthogonal dipole antennas and a solar array extension (if required for adequate power). Communication with the ground station requires rotating each microsat to point the high gain antenna at Earth.

Stacked spacecraft as they would fit inside the fairing of a Delta 2925H-10 are shown in Figure 11. During the transfer orbit, the stack is spin stabilized to maintain thermal control of both the payload and the small bipropellant orbit insertion system.

After deployment (see Figure 12), the microsat attitude control provides for 3 axis stabilization. The solar array covered side of the spacecraft is directed sunward. The science pointing requirements are very simple: control and knowledge of dipole antenna directions to ~2 deg per axis. Small-scale motions can be ignored. The attitude control system consists of 3 reaction wheels, 4 cold gas thrusters, and a star tracker.

6.4 Spacecraft Operations

Once the telemetry stream has been established with a microsat, routine data acquisition begins. Once or twice per day, data are down-linked from the constellation. Periodically, each microsat is commanded to determine the range to the other microsats using the fixed tone ranging system. The absolute ranging measurements are used to determine when stationkeeping maneuvers should be performed.

6.5 Communications

For SIRA MIDEX, X-band uplink and downlink are the likely communication frequency bands. SIRA *Stereo* could take advantage of higher performance downlink capability. We will do a detailed analysis of the application of Ka band communication for SIRA *Stereo* and its consequences for enhanced science. We will also consider various options for ground stations.

6.6 Mission Operations

Clearly, it is necessary to design mission opera-

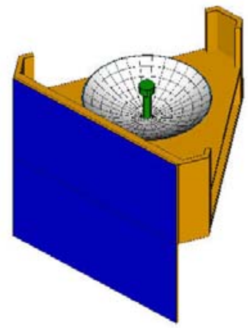

Figure 10 – Microsat extended solar array (blue) and fixed high gain antenna are shown.

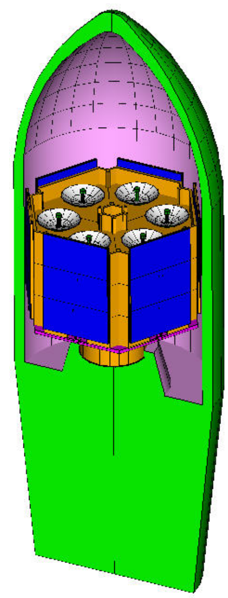

Figure 11 – Spacing is allocated for 18 microsats in the Delta 2925H-10 fairing.

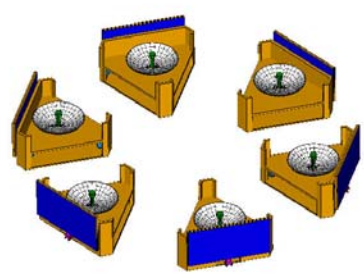

Figure 12 – Six SIRA microsats from one layer separate during deployment.

tions so that the task costs and resources do not scale with the number of spacecraft. To simplify mission operations for SIRA MIDEX, all calculations will be made on the ground; however, automation will be applied wherever prudent. More advanced software systems should permit station-keeping for SIRA *Stereo* to be done autonomously. Mission operations scheduling for all SIRA missions must be very efficient – array-based rather than spacecraft-based.

6.7 Data Analysis

For all SIRA missions and for SIRA *Stereo* in particular, the data processing pipeline is one of the most complex aspects of operations. Without careful analysis and implementation, it could become a major cost driver. The amount of software development required is considerable. In as much as many of the problems are similar to those of the proposed Low Frequency Array (LOFAR), we will work together with the LOFAR consortium to develop the needed software (www.lofar.org). The challenge for SIRA *Stereo* is enhanced because the major portion of the data processing pipeline will be onboard and, consequently, more difficult to change after launch. During the SIRA *Stereo* concept study, we will quantify the requirements for science data processing for that mission.

7. SIRA *Stereo* Concept Study and Products

The major product of the concept study is the final report, which will be provided in presentation and document format.

Statement Of Work (SOW) and Final Report - The final report will include thorough documentation of each of the following areas. Proposal team members who will make major contributions are indicated in parentheses (initials to save space, full listing in Sect. 8):

1) prioritized description and development of all science objectives, primary and secondary (MA, SB, TB, JLB, MD, WF, NG, GH, DJ, MK, NK, JL, PL, RM, MR, CS, KW)

2) detailed description of relationships to preceding and concurrent missions and ground-based observatories (TB, JLB, NK, JL, DO, CS, KW) and mapping of the scientific and technology results of the SIRA missions to future interferometry and constellation missions (MA, SB, NG, MK, PL, MR, CS)

3) investigation of preferred data processing techniques for mitigating effects of scattering and refraction, including the addition of additional satellites in the constellation (TB, JLB, DJ, DO)

4) investigation of on-orbit data processing by the data relay bus for improved operations and science results (GH, MK, RM, DO, MR, ES)

5) investigation of all reasonable SIRA *Stereo* orbits (GSFC flight dynamics group, NG, DJ, MK, RM)

6) analysis of payload, satellite, and launch vehicle options, including cost savings from miniaturization and options for international contributions that might reduce the cost to NASA (WF, DJ, MK, RM, KW). Investigation of deployment options, with emphasis on methods that have been used successfully (GSFC engineering directorate)

7) investigation of automation of NAV activities, orbit determination, and other segments of the various mission options (GSFC engineering directorate, MK, JL, RM)

8) investigation of communications requirements (possible use of Ka band) and ground station issues (GSFC engineering, DJ)

9) analysis of the science data processing and analysis software requirements to minimize development costs (NG, GH, DJ, NK, MR, ES, KW)

10) description of a development pathway for validation of advanced concepts which can be tested and used by SIRA (GSFC engineering, DJ, MK, RM)

11) analysis of methods to be used to maximize the "resilience" of SIRA *Stereo*, such as redundancy, networks, and operations (GSFC engineering, DJ, RM, KW)

12) analysis of safety issues relating to the launch and operations of SIRA *Stereo* (GSFC engineering, MD, DJ, MK, RM)

Schedule - The PI will have primary responsibility for scheduling the above activities to ensure that all are available for the final report. Most of the activities will be worked in parallel, with the goal of completing each item as soon as possible during the study year. A detailed schedule will be generated to permit assessment of progress in completing the studies. As a guideline, the equivalent of more than 1 task must be completed per month. Considerable attention will be given to acquiring written reports from the teams working on each item as soon as the studies reach a useful level of completion. The PI will be responsible for overseeing this on-line documentation library to facilitate the efficient completion of the final report.

Use of GSFC IMDC - We request a voucher to do mission design work for this study at the GSFC IMDC. This group has already worked on SIRA MIDEX and is familiar with the SIRA concept. Specific goals of that design run are:

- Determine the mass, volume, and power requirements for 32 SIRA *Stereo* microsatellites and the necessary launch vehicle
- Determine the most efficient insertion technique into the 2 distinct orbits
- Quantify the requirements for the data relay bus and integrate it into the launch, cruise, and deployment scheme
- Determine downlink requirements for various frequency bands
- Assess requirements for autonomous constellation control
- Estimate mission operations costs for a nominal mission of 2 years + 2 years extended mission

Study success metrics – The following methodologies will represent our approach to analyzing and documenting findings on the above major characteristics in the Final Report. At the start of the proposed activities, a detailed schedule will be developed to map the available personnel to the reporting areas. The Principal Investigator will review the progress in all areas on a bi-weekly basis in a regularly-scheduled telecon. As results become available, they will be posted to the SIRA web site and notification of the updates will be emailed to team members and others who have indicated an interest in SIRA. Comments will be solicited and fed back into the analysis. A draft of the Final Report will be prepared approximately 10 months into the project year. It will be made available on the SIRA website for comment. *The final draft will be reviewed by external reviewers for completeness and accuracy.*

Risk analysis methodology – To identify sources of risk and determine relative risk for alternative mission approaches, we will follow the ISO 9001 certified procedures identified in GSFC's NPG 8000.4 Risk Management Procedures and Guidelines. We will identify a contact person in the Office of Safety and Mission Assurance to guide us through the risk analysis process.

Education and public outreach (EPO) – SIRA MIDEX and SIRA *Stereo* are ideal missions for involving students and the public. Images of "objects" that blast outward from the Sun and reach Earth in an hour (type III electrons) or a few days (CMEs and type II shocks) are Sun-Earth Connection observations that have not been available previously. For both missions, we intend to collaborate with a broker-facilitator group to maximize the impact of SIRA EPO.

Although it is premature to work out the EPO details for a mission to be launched after 2013, we can do significant EPO in the course of the SIRA *Stereo* concept study. Several university classes will engage in a mission design effort for SIRA *Stereo* in parallel with the effort by the science team and the GSFC IMDC. This effort will be lead by Mike McGrath at the University of Colorado, as follows:

1. Baseline the SIRA mission specification as the class project for a ASEN 4148/5148 Spacecraft Design class at CU/Boulder, with telecast-

ing to U. Maryland and Catholic University.

2. Designate academic, government and industry mentors to act as resources, including the SIRA science team and GSFC technical staff.

3. Student teams each produce a concept study report that covers the entire mission design. There is a mid-term peer and a final Conceptual Design and Cost Review presentation

4. A group of students will be selected from the class to further develop the designs for the mission. The draft of the final report will be in place in early October 2004, with a presentation to NASA in early November 2004.

Students involved in these courses will have the experience of participating in a significant spacecraft mission design in both classroom and laboratory environments. We also intend to capture as much of this "process" as possible for inclusion in the education section of the SIRA web page. Lessons learned will be applied to future educational activities by the SIRA EPO team. The concept study will benefit substantially from this EPO effort, both because of the discipline required to present an organized development scenario to the students and because of alternate ideas brought forth in the student-based design efforts.

As an outreach activity, the SIRA *Stereo* concept study process will be highlighted on the SIRA webpage as it progresses. A capability will be included for the public to email questions, which will be answered by the Co-Is and Collaborators. We will also arrange for monthly Net-meeting presentations by the PI or a Co-I.

8. Management and science team – The PI will be responsible for completion of all aspects of the concept study and final report. Regularly scheduled telecoms and meetings with co-investigators and collaborators will be used to determine the rate of progress. The detailed responsibilities of the team members are indicated above and in Table 2. The significant number of collaborators will provide the concept study with a wide range of scientific and technical expertise at a low cost to NASA.

Table 2 -SIRA Stereo Concept Study Team Members

Name	Init.	Institution	Responsibility (letters refer to §7)
Marcus Aschwanden	MA	Lockheed	Collaborator; 1, 2
Stuart Bale	SB	UC Berkeley	Collaborator; 1, 2
Timothy Bastian	TB	NRAO	Collaborator; 1, 2, 3
Jean-Louis Bougeret	JLB	Obs. Paris	Collaborator; 1, 2, 3
Michael Desch	MD	GSFC	Collaborator; 1, 12
William Farrell	WF	GSFC	Collaborator; 1, 6
Nat Gopalswamy	NG	GSFC	Co-I; science lead, 1, 2, 5, 9
Gordon Hurford	GH	UC Berkeley	Collaborator; 1, 4, 9
Dayton Jones	DJ	JPL	Co-I; JPL lead, 1, 3, 5, 6, 8, 9, 10, 11, 12
Michael Kaiser	MK	GSFC	Co-I; management liaison, 1, 2, 4, 5, 6, 7, 10, 12
Namir Kassim	NK	NRL	Co-I; LOFAR/NRL contact; 1, 2, 9
Joe Lazio	JL	NRL	Collaborator; 1, 2, 7
Paulett Liewer	PL	JPL	Collaborator; 1, 2
Robert MacDowall	RM	GSFC	Principal investigator; oversight, 1, 4, 5, 6, 7, 10, 11, 12
Michael McGrath	MM	U. Colorado	Education coordinator
Divya Oberoi	DO	MIT	Collaborator; LOFAR/MIT contact, 2, 3, 4
Michael Reiner	MR	Catholic U,	Co-I; editor, 1, 2, 4, 9
Edward Schmahl	ES	U. Maryland	Collaborator; 4, 9
Chris St. Cyr	CS	GSFC	Collaborator; 1, 2
Kurt Weiler	KW	NRL	Co-I; NRL/SIRA lead, 1, 2, 6, 9, 11

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Facilities and Equipment

Computer and other facilities at the Goddard Space Flight Center, the Jet Propulsion Laboratory, and the Naval Research Laboratory are adequate for purposes of this concept study. No requests for equipment are made in this proposal.

NOT INCLUDED IN THIS DISTRIBUTION:

CVs for PI, Co-Investigators, and Collaborators

Current and Pending Support (as needed)

Center Director, Co-I, and Collaborator Letters of Commitment

Budget Details (incl. Proposing Institution Budget)