HERO: A SPACE-BASED LOW FREQUENCY INTERFEROMETRIC OBSERVATORY FOR HELIOPHYSICS ENABLED BY NOVEL VECTOR SENSOR TECHNOLOGY

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Abstract

HeRO (Heliophysics Radio Observer) is a proposed hybrid ground and space interferometric instrument. The space segment (HeRO-S) covers low frequencies, 100 kHz – 20 MHz, and is composed of 6 free-flying CubeSats equipped with vector sensors. The ground segment (HeRO-G), covers higher frequencies, 15 MHz – 300 MHz. HeRO will explore conditions and disturbances in a key region of the heliosphere, from two to tens of solar radii, using interferometric observations of solar radio bursts at frequencies that do not reach the ground. This will provide precise positions and basic structural information. The morphology of CME shock fronts will be traced via type II burst emissions, and heliospheric magnetic field geometries will be probed by measuring precise trajectories of type III bursts. Refraction in the heliospheric plasma on large and intermediate scales will be investigated throughout large volumes via the frequency dependence of accurate interferometric positional data on bursts. The data will also be information rich with high resolution in time, frequency and spatial position, and high SNR, creating fertile ground for discovery of new phenomena.

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1 Introduction

The Sun, our star, is a powerful source of non-thermal radio emission. Solar radio bursts provide insight into the Sun's magnetic field, coronal processes, and the solar wind. A wide range of spacecraft and ground-based instruments monitor the Sun at radio wavelengths as well across the electromagnetic spectrum in order to understand heliophysical processes. These observatories also contribute to forecasting potentially dangerous space weather that can wreak havoc on navigation, communications, and power grids. This paper describes HeRO (**He**liophysics **R**adio **O**bserver), a hybrid ground and space instrument to map and track type II and III solar radio bursts as they propagate from the solar corona out into the interplanetary medium. HeRO will be capable of tracking type II and III radio bursts with unprecedented spatial resolution through the use of multi-baseline radio interferometry from 300 MHz to 100 kHz. This paper describes HeRO's science goals (Section 2), mission design (Section 3), and expected performance (Section 4). The advantages of a vector sensor antenna for the space portion of HeRO is discussed in Section 3.3.

2 HeRO Science

2.1 Science Objectives

The solar corona, the solar wind, and the interplanetary medium are natural laboratories for fundamental plasma physics. HeRO will take advantage of these natural laboratories to address three science objectives:

1. Determine the location, shape, and properties of coronal and interplanetary shocks
2. Determine the site and conditions for efficient particle acceleration
3. Trace open magnetic fields along which energetic particles propagate

These three objectives can be addressed by remote observation of type II and III radio bursts across frequency (and corresponding solar distance) with high temporal and spatial resolution. Figure 1 shows that HeRO (composed of ground-based HeRO-G and space-based HeRO-S) will track solar radio bursts from the corona (1.03 R_{Sun}) to 0.5 AU (90 R_{Sun}).

2.2 Type II and III Radio Bursts

When the shock wave from a coronal mass ejection (CME) accelerates already-energized electrons present in the ambient plasma, the resulting type II emission reflects the morphology and motion of both the shock front and the CME, as well as the geometry of the local magnetic field. These type II bursts occur a few times per month, radiating both at the fundamental and the second harmonic of the local plasma frequency. As the

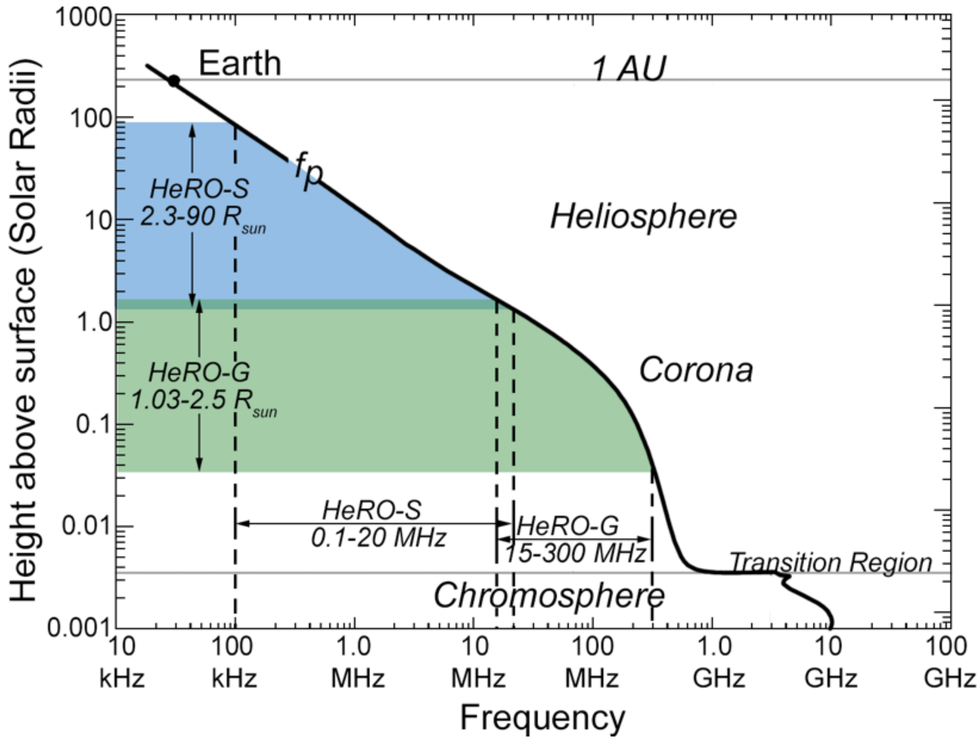


Figure 1: Plasma frequency as a function of solar distance. The green shaded portion of the plot shows HeRO-G coverage. The blue shaded area shows HeRO-S coverage. HeRO (HeRO-S + HeRO-G) covers 100 kHz – 300 MHz in frequnecy and 1.03 – 90 R_{Sun}.

disturbance propagates outward into lower density plasma the emission drifts from higher to lower frequency, with typical timescales of minutes to hours. Note that some diffuse type II-like bursts may be due to gyrosynchrotron emission, rather than plasma emission, although this remains speculative [Bastian, 2007; Pohjolainen et al., 2013].

Type III bursts are brief, lasting seconds to minutes, but are much more common than type IIs. Magnetic reconnection events accelerate energetic electrons across a broad range of heliocentric distances, resulting in fast-moving 'beams' of electrons propagating along magnetic field lines at appreciable fractions of the speed of light. These beams radiate at the fundamental and second harmonic with a broad distribution of starting frequencies, drifting rapidly to lower frequencies.

The burst phenomena to be studied by HeRO are initiated close to the solar surface and propagate far out into interplanetary space. We are interested in tracking both type II-producing shock waves and type III-producing electron beams along this full range of distances, for different reasons. For type II bursts, we follow the evolution of the radio-emitting regions (objective 1), due to electron acceleration and which are presumably the sites of ion acceleration as well, to better understand how the shock parameters (speed, Mach number, magnetic field geometry) affect the conditions of efficient acceleration (objective 2). We are interested in the entire lifecycle of the shock, in particular the 'hot spots' of particle acceleration at its front or flank, from the time the radio emission first develops in the low corona, transits the mainly-closed-field regions below the 'source surface' [Culhane et al., 2014], enters the solar-wind-dominated region, and then sweeps through ever larger portions of the heliosphere.

For type III bursts, we are mainly interested in defining the radio-emitting electron beam trajectories throughout their lifetimes. By remotely measuring the precise emission location as the type III burst propagates outward, the magnetic field line along which the electron beam is propagating can be mapped. A full understanding of these events, and the answers to the science questions posed, demands observations spanning the full range of frequency from event initiation to the limits imposed by the plasma frequency at the HeRO-S orbit. In practice, this means from a few hundred MHz to 100 kHz. Consequently, HeRO is designed to operate across this full range simultaneously, with no gaps, from 100 kHz to 300 MHz. Because the radio emission is due to plasma emission, there is a one-to-one correspondence between emitting frequency and distance from the Sun, shown graphically in Figure 1.

2.3 Spot Mapping

Using radio interferometry techniques, HeRO measures the location of type II and type III burst emissions with 20 to 2000 times better accuracy than current space-based instruments, depending on frequency, and with both improved precision and wider frequency coverage than current ground-based instruments. This supports the production of detailed spot maps comprising collections of precise centroid locations vs. frequency and time. Such spot maps have been shown (e.g. in Chen et al. [2015]) to delineate complex, fine-scale spatial structure well below the apparent size of individual sources. This capability is new, unique and scientifically powerful in the context of the science objectives posed in Section 2.1.

Spot maps are frequency- and time-dependent centroid positions valid when the source morphology is dominated by a single, point-like source. This is expected to be the case with solar radio bursts as long as the time-frequency cells are small. Accordingly, both HeRO-S and HeRO-G arrays are designed such that they span comparable physical extents of 10 km, corresponding to an accuracy of interferometric phase calibration requirement of 2° and an interferometric signal-to-noise ratio (SNR) of 30. Precise relative calibration benefits from the ability to form closure quantities, requiring a minimum of 3 antennas for phase and 4 for amplitude. The HeRO-S design with 6 antennas provides 10 phase and 9 amplitude closure quantities, and adequate constraints for detecting and modeling simple non-point-like sources in addition to measuring centroid positions. HeRO thereby maintains the required angular precision across the entire 100 kHz to 300 MHz range. To support the scientific goals, HeRO-S and HeRO-G must present a 2D array configuration projected into the solar direction at all times. Furthermore where the structure being observed has an angular extent comparable to or larger than the interferometer fringe spacing, a range of baseline orientations and lengths permits source size to be estimated. HeRO-G stations are designed with true imaging capability, while the 6 HeRO-S spacecraft provide 15 baselines for this purpose.

3 HeRO Design

HeRO is a hybrid instrument composed of a ground-based component for frequencies above the ionospheric cut-off (15–300 MHz) and a space-based component covering lower frequencies not accessible from the ground (100 kHz–20 MHz). Both components operate simultaneously to form a single instrument with frequency coverage from 100 kHz–300 MHz. Both HeRO-S and HeRO-G will make use of the spot mapping technique described in Section 2.3. HeRO could have been implemented entirely on a space-based platform, but data storage and clock stability requirements for the higher end of the HeRO frequency band would have made the spacecraft unnecessarily complicated and costly. Instead, the requirements for HeRO-S were simplified by setting the frequency upper limit at 20 MHz (maintaining overlap with HeRO-G). Position knowledge, sampling rate, and data rate requirements are significantly relaxed at 20 MHz vs. 300 MHz, reducing the cost and complexity of HeRO-S.

Both HeRO-S and HeRO-G will record raw voltage data to their respective ring buffers. When an event is identified, either by autonomous triggering (HeRO-G) or by ground-in-the-loop examination of dynamic spectra (HeRO-S), the portion of the buffer containing the event will be frozen and flagged for download or collection. The buffer size on both HeRO segments is sufficiently large for multiple events to be saved while continuing to use the remaining memory in ring buffer mode. HeRO-G events will be used to flag relevant data in the HeRO-S ring buffer and vice versa.

3.1 HeRO-S

HeRO-S(pace) comprises a flock of 6 identical 6U (30 x 20 x 10 cm) CubeSats, each with antenna, receiver, position and timing synchronization, precision clock, and memory management. For interferometry of solar radio bursts, the 6 spacecraft are positioned such that the baselines range from 0.5-10 km, in an optimized 3-D arrangement. For transient objects such as solar radio bursts, traditional aperture synthesis based on evolving baseline projections is not possible, but 'snap-shot' interferometry nevertheless allows precision metrology of centroids for single, compact sources, from which spot maps can be generated as a function of time and frequency.

HeRO-S uses a vector sensor as its antenna. The directivity of the Lincoln Laboratory Vector Sensor (VS) (Section 3.3) provides the capability to determine the direction of arrival and the polarization sense of incoming waves, allowing spatial and polarization steering of the antenna beam or nulling of interference sources. This allows HeRO-S to adaptively suppress noise from Earth-derived sources by an estimated 30 dB compared to conventional methods, such that solar radio bursts will dominate the result [Knapp et al., 2016a]. Without such nulling capabilities, avoidance of strong terrestrial emissions of both natural and artificial origin would require deployment to a distant location such as a Lagrange point or lunar orbit, severely constraining downlink rates. Positioning HeRO-S above the plasmapause minimizes plasmaspheric masking and distortion over the entire 0.1-20 MHz frequency range while remaining close enough to the Earth for efficient high data rate communication.

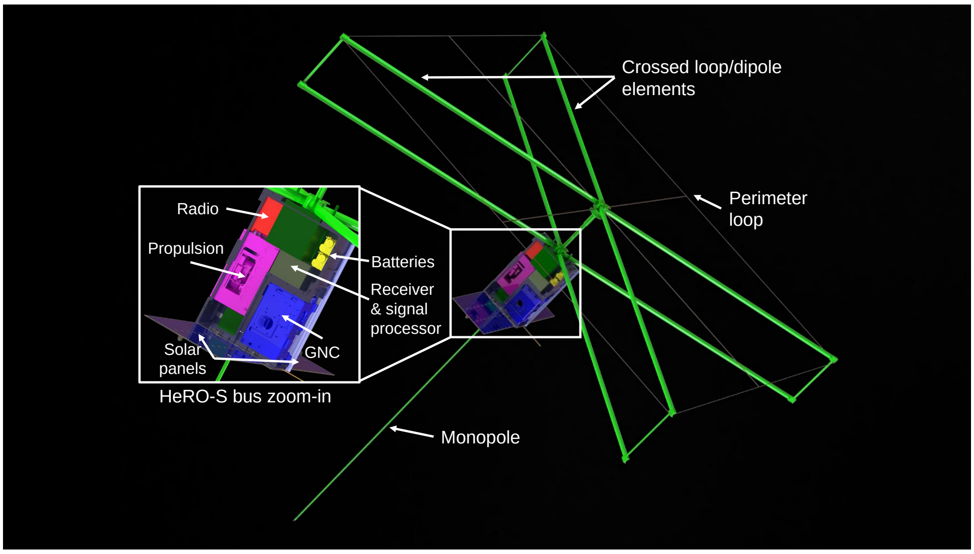


Figure 2: The 6U HeRO-S spacecraft. The vector sensor is composed of two crossed loop/dipole arms, a perimeter loop around the tips of the loop/dipoles, and a monopole. False colors are used to highlight key subsystems.

HeRO-S CubeSats will fly in loose formation in an elliptical, slightly skewed geosynchronous (S-GEO) orbit. The S-GEO orbit provides the benefits of a GEO orbit while never transiting the crowded GEO belt. Requirements for stationkeeping of the spacecraft are not stringent. Knowledge of relative spacecraft position is sufficient to establish array coherence, and can be refined to high accuracy by the interferometry itself. Position knowledge to 1/10–1/16 of a wavelength is generally considered sufficient for interferometric baselines, so HeRO-S's position knowledge requirement is 1.5-1 m at 20 MHz — well within the capability of standard ranging systems. Each spacecraft carries a chip-scale atomic clock for precision timing. Each HeRO-S spacecraft will have a small electric propulsion system for initial orbit adjustment, stationkeeping, reaction wheel desaturation, and disposal at end of life. The stationkeeping requirements for the S-GEO orbit are minimal ($\sim$64 m/s ΔV).

HeRO-S will observe the sun for 16 hours per day and store raw voltages in a ring buffer which can hold up to 32 hours of data. During the remaining 8 hours, when the Earth and plasmasphere are between the HeRO-S flock and the Sun, HeRO-S will downlink data that has been flagged as containing an event based on ground-in-the-loop examination of summary dynamic spectra from each node. HeRO-S will take advantage of a large dedicated X-band ground station to downlink decimated raw data for correlation on the ground rather than attempting to cross-correlate in space and downlink the visibilities. Retaining the raw data enables iterative tuning and adjustment of the correlation process for a particular observation, and allows iterative estimation of instrumental calibration parameters. In this respect, the data from both HeRO-S and HeRO-G will allow more processing flexibility than the visibility-only data that is produced by most major observatories.

HeRO-S will be calibrated using a stable NIST-traceable noise diode or comb generator, depending on the specific calibration. The calibration signal will be injected into the six antenna inputs [Dicke, 1946; Meloling et al., 2015] to determine channel-to-channel gain and phase differences as well as the absolute gain of the receiver system. The VS antenna element gains as a function of angle are measured by rotation of the spacecraft while observing a known reference such as a ground-based source. Traditional radio interferometry techniques like self-calibration will be used in post-processing on the ground after correlation. To suppress self-electromagnetic interference (EMI), all HeRO subsystems are selected for low noise and are shielded. Several spacecraft subsystems, including propulsion and communication, are turned off during data acquisition. The EMI spectrum is evaluated throughout development and the affected frequency ranges affected are constrained where EMI cannot be eliminated entirely.

3.2 HeRO-G

HeRO-G is the ground-based component of HeRO (15–300 MHz). HeRO-G is composed of two geographically separated 'stations', each of which contains 25 HeRO-G nodes with UV coverage optimized for solar observing (Figure 3b). Together, the two HeRO-G stations will provide 16+ hours of solar observation per day. The HeRO-G nodes are based on the RAPID (**R**adio **A**rray of **P**ortable **I**nterferometric **D**etectors) node design [Lind et al., 2013, 2015]. RAPID is currently under development at MIT Haystack Observatory in collaboration with Cambridge University. Each RAPID node is physically independent, equipped with a high performance direct digitization receiver, hot-swappable solid state disk (SSD) storage, precision clock, solar and battery power, and optional wireless interconnection.

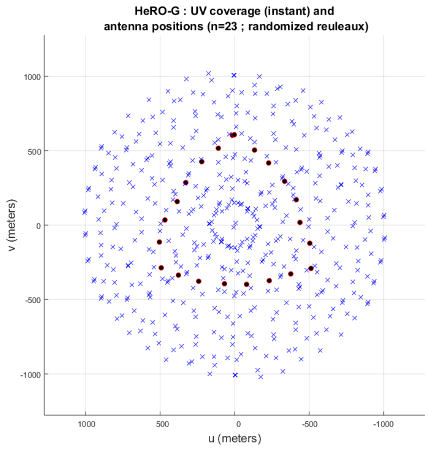
Each HeRO-G node will use a variant of the SKALA antenna [de Lera Acedo et al., 2015] for 50–300 MHz (Figure 3a) and a simplified LWA antenna [Ellingson, 2011] for 15–50 MHz. Both antennas will operate simultaneously using a common base. Raw voltage signals from HeRO-G antennas are captured, filtered, decimated, compressed, and time-tagged before being transferred to the solid state drive (SSD) ring buffer in the HeRO-G base unit.

Three connected inner HeRO-G nodes in a vector sensing configuration serve as a triggering system that semi-autonomously identifies solar bursts from their compact, transient, and spectrally narrow features and their angular location relative to the solar position. A successful detection causes raw data to be retained locally and a trigger to be sent to the outlying, unconnected nodes via Iridium or other satellite provider. The trigger informs the other nodes to mark this data for retention and notifies the operator of automatically detected events. Data are collected manually by swapping the solid state disks and transferring them to a centralized cloud computing facility. This is performed no less frequently than once per month, or when the buffer fills to a threshold capacity. Triggering thresholds will be set so that the buffer does not overflow too quickly.

3.3 Vector Sensor

A vector sensor is composed of three loops and three dipoles with a common phase center that capture the three components of the magnetic field in addition to the electric

(a) HeRO-G field unit with SKALA antenna.



(b) Antenna positions and instantaneous (u,v) coverage for HeRO-G station

Figure 3: HeRO-G field unit (a) and HeRO-G station layout (b). There are 25 HeRO-G units per station, arranged in a randomized Reuleaux triangle (red dots) to achieve uniform (u,v) plane filling (blue x). Baseline lengths range from 100 m – 10 km.

field 3-vector [Nehorai and Paldi, 1994]. The six elements of the vector sensor allow a complete characterization of incident electromagnetic fields, including full polarization measurement. In the HeRO-S deployable vector sensor, two crossed elements simultaneously provide loop and dipole modes [King, 1959; Robey et al., 2016]. A perimeter loop provides the third loop antenna along with mechanical stability, and a monopole provides the sixth element. The HeRO-S vector sensor, shown in green in Figure 2, is stowed in a 1U volume (10x10x10 cm) and deployed in two stages. The loop/dipoles are 4 m long, the monopole is 2 m long, the horizontal loop area is 8 m^2 and the two vertical loops are each 1 m^2 [Robey et al., 2016]. Further discussion on vector sensors for astronomical applications can be found in Knapp et al. [2016a], Robey et al. [2016], Knapp et al. [2016b], and Volz et al. [2016].

4 HeRO Performance

4.1 Sensitivity

Figure 4 compares HeRO sensitivity with type II and III burst intensities. Even for a single-baseline, HeRO-S and HeRO-G have sufficient SNR to detect and characterize nearly all expected type II and III bursts over their entire frequency range. More baselines will further improve performance. HeRO's instrumental noise floor is set by the galactic sky noise except at the lowest frequencies. Comparing HeRO's sensitivity or system-equivalent flux density (SEFD, solid black curve in Figure 4) to an average spectrum of a type III burst (dotted red curve), a signal-to-noise ratio (SNR) of at least 30 is maintained across all frequencies.

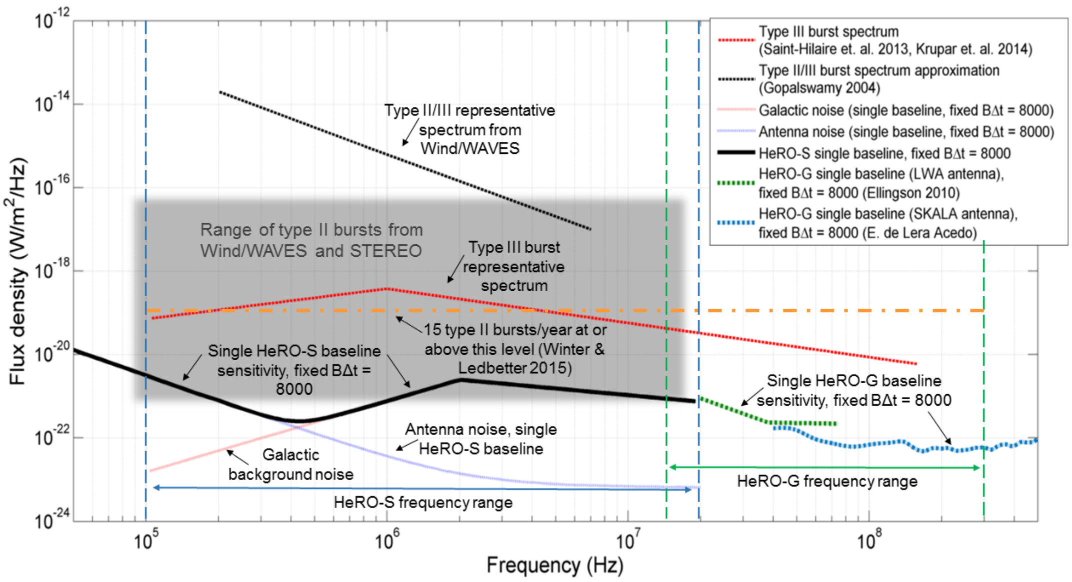


Figure 4: HeRO Sensitivity compared with expected solar radio burst flux. A single baseline of HeRO-S or HeRO-G will detect type II and III solar bursts over several decades of intensity and frequency. Shown for comparison are an average type III burst spectrum, scaled to an occurrence rate of 3 bursts per day (red); the range of type II bursts recorded by Wind/WAVES and STEREO over several years (gray box); the intensity of both type II and type II bursts observed by Wind/WAVES (black dashed); HeRO-S SEFD (solid black), the quadrature sum of antenna noise (purple) and galactic background (red) assuming a time-bandwidth product BΔt= 8000; HeRO-G SEFD for LWA antenna (green) and SKALA antenna (cyan). HeRO-G sees substantially less galactic noise than HeRO-S because of the limited field of view.

Not shown in Figure 4 but of significance is Auroral Kilometric Radiation (AKR), which is due to the electron cyclotron maser instability above the Earth's auroral ring. Generally occurring below 500 kHz, AKR is narrowly beamed into frequency-dependent hollow cones aligned with the magnetic field direction in the source region [Mutel et al., 2008; Menietti et al., 2011], is highly variable, and exhibits modulation with dayside emissions being weaker and less frequent. Time occupancies at the peak frequency of ∼300 kHz are in the 20–40% range [Panchenko et al., 2009]. Fortunately, AKR is strongly beamed away from the equator, is weaker and less frequent during the dayside HeRO-S observations, and is weakest during solar maximum. Any radiation reaching HeRO-S at 6R$_{Earth}$ will appear compact, on the order of 1°, and can be nulled by the VS.

4.2 Angular Resolution

HeRO's astrometric precision is defined in terms of a 'spot', i.e. a datum with position, flux, polarization, time and frequency values at a specific location in this 6D space. Spot position accuracy for a single baseline in one dimension is determined by the fringe spacing θ

$$\theta = \frac{\lambda}{B} = \frac{103\ arcmin}{\nu_{MHz}},\ B_{max} = 10\ km \tag{1}$$

multiplied by the phase error expressed as a fraction of 2π. This is given by $(2\pi \cdot \mathrm{SNR})^{-1}$, which will vary depending on the radio flux density. For the specified SNR of 30 corresponding to a phase error of 2°, the spot location precision will be

$$\theta = \frac{\lambda}{B \cdot 2\pi SNR} = \frac{0.6\ arcmin}{\nu_{MHz}} \tag{2}$$

This corresponds to 0.03 arcmin at 20 MHz and 6 arcmin at 100 kHz. These accuracies refer to relative measurements between observations nearby in time and frequency, delineating scientifically meaningful structures in the sources. Modeling indicates that 6 CubeSats (15 baselines) meet requirements for all expected sources, while as few as 4 (6 baselines) can locate features with degraded accuracy. HeRO's angular resolution performance is summarized in Figure 5.

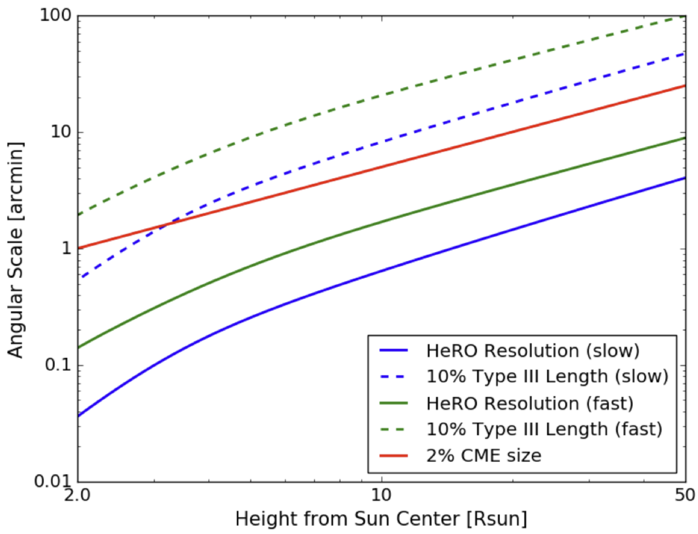


Figure 5: For type II bursts, HeRO-S requires centroid position accuracy <2% of the CME size (red line) [Gopalswamy and N., 2010]. For type III, HeRO requires 10% of the length of the electron beam based on a burst duration measurement [Alvarez and Haddock, 1973]. Green and blue dashed and solid lines compare modeled accuracy for slow and fast bursts [You et al., 2007].

5 Conclusions

HeRO, alone and in concert with existing and planned observatories, will significantly enhance our understanding of the solar corona, the dynamic interplanetary medium and magnetic field, and particle acceleration processes. In addition to performing ground-breaking heliophysics on its own, HeRO will directly support the in situ measurements of Solar Probe Plus (SPP) and Solar Orbiter (SO) during their cruise phases and close approaches to the Sun.

If HeRO were to launch in early 2022 near the next predicted solar maximum, HeRO expects to witness 20-40 radio-loud CMEs [Winter and Ledbetter, 2015] and to capture ⅔ of them in its one-year life — a sufficient sample to reveal the underlying physics. Type III radio bursts occur much more frequently, providing a sample of many hundreds to thousands of type III events. HeRO will track type II and III bursts with unprecedented angular and spectral resolution over half of the Earth-Sun distance. HeRO represents a major improvement in angular resolution capability, particularly at low frequencies (HeRO-S). As such, there is strong potential that HeRO will observe previously unknown phenomena in addition to addressing its primary science objectives.

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