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Abstract

The radioheliograph is an extensive array of antennas operating on the principle of aperture synthesis to produce images of the Sun. The image acquired by the telescope results from convoluting the Sun's true brightness distribution with the antenna array's directional pattern. The imaging quality of the radioheliograph is affected by a multitude of factors, with the performance of the "dirty beam" being simply one component. Other factors such as imaging methods, calibration techniques, clean algorithms, and more also play a significant influence on the resulting image quality. As the layout of the antenna array directly affects the performance of the dirty beam, the design of an appropriate antenna configuration is critical to improving the imaging quality of the radioheliograph. Based on the actual needs of observing the Sun, this work optimized the antenna array design and proposed a two-dimensional low-redundancy array. The proposed array was compared with common T-shaped arrays, Y-shaped arrays, uniformly spaced circular arrays, and three-arm spiral arrays. Through simulations and experiments, their performance in terms of sampling point numbers, UV coverage area, beam-half width, sidelobe level, and performance in the absence of antennas are compared and analyzed. It was found that each of these arrays has its advantages, but the two-dimensional low-redundancy array proposed in this paper performs best in overall evaluation. It has the shortest imaging calculation time among the array types and is highly robust when antennas are missing, making it the most suitable choice.

Full Text

Preamble

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A Novel Two-dimensional Low-redundancy Array Design for Solar Radio Imaging

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Abstract

A radioheliograph is an extensive antenna array that operates on the principle of aperture synthesis to produce images of the Sun. The image acquired by such a telescope results from convolving the Sun's true brightness distribution with the antenna array's directional pattern. While the performance of the "dirty beam" is one factor affecting imaging quality, other elements such as imaging methods, calibration techniques, and CLEAN algorithms also play significant roles. Since the layout of the antenna array directly affects dirty beam performance, designing an appropriate antenna configuration is critical for improving radioheliograph imaging quality.

Based on the actual requirements of solar observation, this work optimizes antenna array design and proposes a two-dimensional low-redundancy array. We compare this proposed array with common configurations including T-shaped arrays, Y-shaped arrays, uniformly spaced circular arrays, and three-arm spiral arrays. Through simulations and experiments, we analyze and compare their performance in terms of sampling point numbers, UV coverage area, beam half-width, sidelobe level, and performance under antenna absence. While each array type has its advantages, the two-dimensional low-redundancy array proposed in this paper demonstrates the best overall performance. It achieves the shortest imaging calculation time among all array types and exhibits high robustness when antennas are missing, making it the most suitable choice.

Key words: instrumentation: interferometers – methods: observational – techniques: interferometric

1. Introduction

A solar flare originates from the rapid release of magnetic energy in the solar corona, which accelerates high-energy electrons and enhances electromagnetic radiation across nearly the entire spectrum. As the most hazardous form of solar eruptive activity (Bastian et al. 1998), the energy release process of a solar flare stems from magnetic reconnection in the low corona flare region. Understanding the magnetic field structure and evolution of flare eruptions represents the core issue in solar flare physics research.

Microwave bursts, which vary in frequency, originate from plasma radiation, cyclotron radiation, and synchrotron radiation, carrying physical information about the magnetic field structure and high-energy electrons in the flare region (Dulk 1985). They can be used to diagnose the distribution and evolution of magnetic fields in the flare region, as well as the acceleration and transport of high-energy electrons. A radioheliograph is a fundamental tool for conducting regular solar radio observations, providing high spatial, temporal, and frequency resolution of flare eruption regions, and has consequently gained increasing recognition within the academic community.

The radioheliograph enables real-time solar observation through aperture synthesis imaging, with the core challenge in its construction being the design of a reasonable antenna array. Unlike typical radio sources, the Sun is an extended and variable source with a large dynamic range, requiring the radioheliograph to possess both high dynamic range and excellent instantaneous imaging capabilities. This places stringent demands on antenna array design. According to the principle of aperture synthesis imaging, the true brightness distribution of a radio source convolved with the dirty beam produces a dirty image. The dirty beam and the sampling function of the antenna array are Fourier transform pairs (Taylor et al. 1999). The arrangement of antenna positions determines the distribution of the sampling function (i.e., dirty beam) on the UV plane. Therefore, antenna array configuration is a key factor affecting both imaging quality and the speed of dirty image generation.

Additionally, the distribution of sampling points from all baselines formed by the antenna array on the UV plane is called UV coverage, which has a decisive impact on radioheliograph performance. Short baselines are more sensitive to large-scale structures, while long baselines affect small-scale details. Consequently, high-quality radio imaging observations require a well-designed and efficient antenna array.

Antenna array arrangement requires consideration of two main aspects: first, ensuring signal collection quality by optimizing parameters such as UV coverage, sidelobe level, and sensitivity; second, using limited resources to avoid excessive baseline redundancy in complex calculations while achieving high-performance imaging. Depending on different scientific objectives and requirements, antenna array arrangement often necessitates a compromise solution (Thompson et al. 2017).

Early radioheliographs employed two primary array types: T-shaped and Y-shaped arrays. The T-shaped array features a simple structure and rectangular UV coverage, with relatively straightforward imaging and calibration algorithms and no interpolation error, leading to its widespread use in early radioheliograph construction. Examples include the Nancay Multifrequency Radioheliograph (NRH, Condon et al. 1998), Nobeyama Radio Heliograph (NoRH, Nakajima et al. 1985), and Siberian Radioheliograph (Lesovoi et al. 2017). However, the T-shaped array has significant drawbacks, including greater baseline redundancy (exceeding 50%) compared to other arrays with the same number of elements.

The equilateral Y-shaped array is widely used in radioheliograph construction, such as in the Very Large Array (Condon et al. 1998), due to its excellent scalability and outstanding UV coverage performance. Nevertheless, this array type also has limitations. Since antennas are distributed in specific directions, creating a hexagonal UV coverage pattern, resolution is relatively low in some directions, and imaging and calibration algorithms are more complex.

In recent years, the solar physics community has begun applying several new antenna array configurations, namely three-armed spiral, circular, and Reuleaux triangle arrays (Keto 1997). The three-armed spiral array has received considerable attention due to its Gaussian baseline distribution and lack of redundancy, providing a larger field of view and frequency coverage than T-shaped and Y-shaped arrays. It is used in the Mingantu Spectral Radioheliograph (MUSER, Yan et al. 2009) and the Expanded Owens Valley Solar Array (Perley et al. 2011). However, these distributed arrays are relatively complicated, requiring a larger surface area for antennas, and their irregular UV coverage pattern leads to greater computational imaging requirements. Circular ring and Reuleaux triangle arrays provide the most uniform UV coverage and, under the same maximum baseline condition, achieve higher resolution without redundancy. However, their uneven sampling point distribution makes gridding time-consuming, and these arrays cannot be extended or scaled. The newly built Daocheng Solar Radio Telescope (Lu et al. 2022) uses a uniform circular array.

Overall, the advantages and disadvantages of common antenna array arrangements are apparent, and it is challenging to satisfy all requirements—such as low baseline redundancy, excellent UV coverage, and fast image processing—in practical applications. Therefore, designing new arrays that balance imaging observations and calibration calculations while achieving scientific goals is crucial. This paper proposes a novel two-dimensional low-redundancy array design that effectively resolves the conflict between antenna number and computational requirements. This design simultaneously reduces imaging computational costs while providing high-quality imaging. Section 2 introduces the calculations involved in the two-dimensional low-redundancy array. Section 3 conducts simulation analyses of commonly used arrays and the minimum redundancy array for imaging performance. Section 4 summarizes the entire paper.

2. Two-dimensional Low-redundancy Array

Optimizing antenna array design aims to achieve sufficient, uniform, low-redundancy UV coverage using as few antenna elements as possible. This approach enables relatively high spatial resolution by designing a minimum redundancy linear array (MRLA, Moffet 1968). As shown in Figure 1, the MRLA can be represented as $\{0,\ 1,\ 4,\ 6\}$. It comprises only four antennas, yet its baseline length is equivalent to a uniform linear array with six antennas.

For a one-dimensional linear array, the definition of redundancy is (Ishiguro 1980):

$$R = \frac{C_n^2}{L}$$

where C_n^2 represents the permutation and combination of array elements, n represents the number of array elements, and L represents the longest continuous baseline. Leech (1956) indicated that for $n \leq 11$, the optimal redundancy range of MRLA is $1.217 \leq R \leq 1.332$. When $n > 11$, the resulting redundancy of the antenna array would be insufficient to reach within that range, thus denoting the array as a low-redundancy linear array (LRLA, Ruf 1993). An LRLA is widely used in the radar field, and many algorithms have been developed specifically for obtaining an LRLA, including cyclic difference, simulated annealing, particle swarm optimization, and others (Lee & Pillai 1988; Ruf 1993; Camps et al. 2001).

An LRLA can comprehensively cover all possible baseline lengths within a maximum baseline interval. A two-dimensional low-redundancy array can be constructed by "multiplying" any two LRLAs, providing full coverage of a rectangular area on the UV plane and enabling two-dimensional radio imaging. This array ensures complete UV coverage and achieves higher spatial resolution by obtaining a relatively large number of sampling points and UV coverage area. In this paper, we implement this array as follows: (1) Construct an LRLA arrangement a_i with n_1 antennas and longest baseline L_1 in the x-axis direction, where $i = 1, 2, \ldots, n_1$, such that the spacing s between any two antennas in a_i satisfies $s \in [0, L_1]$ and can cover all possible array element spacings. (2) Construct an LRLA arrangement b_j with n_2 antennas and longest baseline L_2 in the y-axis direction, where $j = 1, 2, \ldots, n_2$, such that the spacing s between any two antennas in b_j satisfies $s \in [0, L_2]$ and can cover all possible array element spacings. (3) After forming these two matrices, we perform a Cartesian product to obtain a two-dimensional matrix denoted by (a_i, b_j), where each row represents an antenna's position along the x-axis and each column represents the position along the y-axis. This matrix is the desired low-redundancy array containing $n_1 \times n_2$ array elements, with each antenna's position marked as (a_i, b_j). Figure 2(c) shows the 7×7 arrangement of the resulting two-dimensional low-redundancy array.

The array is characterized by redundancy and no voids in UV coverage. Such an array enhances both signal strength and system reliability because redundant baselines take multiple measurements of the same point, which can be combined to improve the signal-to-noise ratio. Additionally, even if some antennas fail, the array can still obtain information about that point from other antennas. The UV coverage without nulls allows for more complete sampling and avoids problems such as aliasing during interpolation (Meurisse & Delmas 2001).

Assuming x_i represents the LRLA arrangement of n_1 elements on the x-axis, where $i = 0, 1, \dots, n_1 - 1$, and d is the minimum distance between elements along the axis, while y_j represents the LRLA arrangement of n_2 elements on the y-axis, where $j = 0, 1, \dots, n_2 - 1$, and d is the minimum distance between elements along the axis. The total number of elements in the resulting two-dimensional low-redundancy array is $n_1 \times n_2$. If the positions of any two antenna elements in the two-dimensional low-redundancy array are (x_i, y_j) and (x_k, y_l), then their corresponding spatial frequency sampling points in the (u, v) plane are given by:

$$(u, v) = \left(\frac{(x_i - x_k)d}{\lambda}, \frac{(y_j - y_l)d}{\lambda} \right)$$

Since the set $\{|x_i - x_k|\}$ can cover any integer in the interval $[0, L_1]$, the set $\{x_i - x_k\}$ can cover any integer in the interval $[-L_1, L_1]$. Similarly, the set $\{y_j - y_l\}$ can cover any integer in the interval $[-L_2, L_2]$. Therefore, the set $\{(x_i - x_k, y_j - y_l)\}$ can cover any integer in the region $([-L_1, L_1], [-L_2, L_2])$. Consequently, the sampling area of the two-dimensional low-redundancy array on the (u, v) plane is a rectangle $([-L_1 \cdot d/\lambda, L_1 \cdot d/\lambda], [-L_2 \cdot d/\lambda, L_2 \cdot d/\lambda])$, providing no voids in UV coverage and thereby eliminating any unsampled "blank areas."

3. Comparison and Analysis of Antenna Arrays

We developed a Python program to simulate and test the performance of the two-dimensional low-redundancy array. For comparison, we simultaneously calculated parameters for various array types including T-shaped, Y-shaped, circular, and spiral arrays. During calculation, each array had the same shortest baseline and 49 antennas. The layout, UV coverage, baseline histogram, and beam sidelobe level of each array are shown in Figures 2–5. For quantitative analysis, we compared these array types across several metrics: longest baseline, number of sampling points, UV coverage area, full width at half maximum (FWHM) of the beam, and sidelobe level, with results listed in Table 1.

The number of sampling points refers to UV sampling points obtained by the antenna array. For an array of N antenna units, the number of baselines is $N(N-1)/2$ without redundancy, yielding $N(N-1)$ sampling points due to conjugate symmetry. When the number of antenna elements is fixed, more sampling points indicate lower redundancy and produce more sampling data, which can improve image reconstruction. Regarding sampling points, the circular and spiral arrays have the highest numbers at 2352 and 2256, respectively, with neither having redundant baselines. The Y-shaped array has 1632 sampling points, while the T-shaped array and the two-dimensional low-redundancy array have relatively fewer sampling points at 1120 and 1224, respectively.

Radio interferometry arrays typically have multiple baselines of varying lengths and directions, offering different orientations and resolutions. More detailed celestial images can be obtained by combining signals from different baselines. In radio astronomy observations, baseline length depends on the scale of the studied celestial object and scientific objectives. Longer baselines are employed for high-resolution observations, particularly crucial for GHz-range radioheliographs focused on solar disk features, where higher resolution is desired. It should be noted that to compare actual heliograph resolution, the longest baseline calculated for the T-shaped array here refers to the longest baseline involved in the mapping calculation, not the longest baseline in the array's actual physical position. Comparing longest baselines across arrays reveals that the spiral array exhibits the greatest baseline length, followed by the Y-shaped array and the two-dimensional low-redundancy array.

UV coverage area refers to the UV sampling distribution that all baselines of the antenna array form in the UV plane. Similar to the number of sampling points, UV coverage area is a vital parameter characterizing antenna array quality and affecting imaging performance. In this context, UV coverage area specifically denotes the distribution of UV sampling points across all baselines within the UV plane. It is crucial to emphasize that UV coverage area does not correspond to a physical "area" but represents spatial sampling distribution. In snapshot mode, larger UV coverage area means more sampling points and better imaging effect. Additionally, when applying fast Fourier transform (FFT) for mapping, we want sampling points located on a regular grid; irregular sampling points require gridding. Figure 3 shows that the UV coverage of the T-shaped and two-dimensional low-redundancy arrays is regular. The Y-shaped array performs best regarding UV coverage area at 59.32% among tested arrays. The two-dimensional low-redundancy array and T-shaped array follow at 47.26% and 43.4%, respectively, while other arrays range between 41.32% and 34.32%.

A radio telescope beam's FWHM is critical for determining system resolution. As FWHM decreases, system resolution improves. Effective hardware configurations are necessary to minimize the half-power width, and simulation tests demonstrate that the spiral array provides the best resolution with an FWHM of $24'' \times 24''$. In contrast, the half-power width of the T-shaped, Y-shaped, and two-dimensional low-redundancy arrays is approximately $36'' \times 36''$. The circular array provides the poorest FWHM at $72'' \times 72''$.

Antenna array performance can be evaluated through sidelobe level, which represents signal strength received in directions other than the main beam. In the context of radioheliographs, sidelobe level primarily reflects undesirable dirty beam effects on resulting dirty maps. Lower sidelobe level indicates reduced false information in the dirty beam, producing a cleaner dirty map that is easier to recover. The data show that the spiral array exhibits the lowest sidelobe level, followed by the circular array, two-dimensional low-redundancy array, T-shaped array, and Y-shaped array.

This analysis demonstrates that no single antenna array can achieve optimal performance across all indicators. In practical scientific applications, one must carefully consider antenna layout performance parameters and select the most suitable scheme based on specific requirements. For high-precision imaging demands, antenna configurations with long baselines may be required; for large angular scale observations, configurations with shorter baselines may be needed (Kale 2017). While the arrays mentioned above present various advantages and disadvantages, none achieves optimal performance across all four indicators. The spiral array exhibits relatively good comprehensive performance, but high-frequency observations suffer from an abundance of short baselines and lack of long baselines. Moreover, despite its higher number of sampling points, the spiral array has limitations in UV coverage area, leading to poor image quality. The Y-shaped and two-dimensional low-redundancy arrays exhibit relatively good overall performance, but thorough examination of their performance is necessary, particularly concerning image quality—a crucial factor for radioheliographs.

4. The Influence of Array Configuration on Imaging

We subsequently performed imaging simulations of the above arrays to study their influence on image inversion and discuss the impact of antenna absence on imaging. To better understand array influence, we conducted an in-depth study of imaging performance.

4.1. Imaging with Different Array Configurations

In simulation experiments, each array had a fixed antenna number of 49. For solar observation, the field of view should exceed one solar radius, i.e., larger than $1.2R_{\text{sun}}$ (1152), requiring a minimum baseline less than 107.4λ.

During imaging simulation, we implemented conventional methodologies. We sampled the sky model (shown in Figure 6(a)) using different array configurations to obtain visibilities, then applied direct Fourier transform to the visibility function based on aperture synthesis imaging principles to create dirty images. To better assess array configuration impact on imaging, we opted for natural weighting with no tapering and chose not to utilize the CLEAN algorithm.

Weighting involves assigning more or less weight to visibilities based on their location in the UV plane. Emphasizing long-baseline visibilities improves image resolution, whereas emphasizing shorter baselines improves surface brightness sensitivity. Tapering refers to smoothing image edges by reducing weight of visibilities at large distances from the image center. To better reflect array formation effects on imaging, we preferred natural weighting and no tapering for imaging simulation. To comprehensively analyze array impact on imaging, we evaluated performance by assessing the standard deviation of profile residuals, root mean square (RMS) of the point-spread function (PSF) away from the 90% central peak, dynamic range, and average imaging computation time.

To calculate the standard deviation of profile residuals, we selected a slice passing through two bright sources in the image and a profile at the same position as the sky model. This standard deviation measures the difference between the sky model and dirty maps. Figure 7 illustrates slice profiles of dirty maps compared to the sky model. The “RMS of PSF away from the 90% central peak” refers to RMS of PSF values at positions or distances away from the 90% central peak of the PSF. This measurement characterizes imaging system performance by indicating how much a point source’s light spreads as one moves away from its central position. A smaller RMS value indicates a more focused and narrower PSF, while a larger value suggests a less focused PSF. Dynamic range is a key metric quantifying the spread or range of intensities within an image, often used to assess image quality and contrast. Here, dynamic range is defined as the ratio of peak intensity to the absolute value of the deepest minima in the image. We compared imaging computation time by measuring the duration from visibility to dirty map generation, conducting 100 tests to ensure accuracy and taking the average value.

Figure 6 depicts snapshot imaging results for various array configurations using the sky model shown in (b)–(f). These figures reveal that several configurations can achieve relatively good imaging results for the sky model. Notably, the Y-shaped array and two-dimensional low-redundancy array exhibit good imaging effects, enabling better reflection of image details. Conversely, the three-arm spiral array presents relatively poor imaging results. Under fixed minimum baseline conditions and fixed observation angular scales, the spiral array’s longest baseline is the greatest among configurations, but the array has relatively shorter baselines, resulting in reduced image clarity compared to other configurations.

Table 2 compares imaging parameters for different array configurations. Analysis reveals that the Y-shaped array has the lowest standard deviation at 13,778, followed closely by the two-dimensional low-redundancy array at 13,963, while the spiral array has the largest standard deviation at 16,445. The spiral and circular arrays exhibit the lowest RMS values at 7.4 and 6.02, respectively. The highest dynamic range value is also achieved by the Y-shaped array at 12.26, followed by the T-shaped array, with the two-dimensional low-redundancy array next at 9.08 and 8.05, and the smallest being the spiral array at 6.03.

The two-dimensional low-redundancy and Y-shaped arrays provide the fastest computation time from visibility data to dirty images, taking 2.3 s and 2.5 s, respectively. In contrast, the Y-shaped array and spiral array require the longest computation time, taking 3.7 s and 3.9 s, respectively.

Currently, GPU applications in imaging processes have revolutionized data processing efficiency and quality. Notably, cuGridder stands out as a GPU-based CUDA C program that significantly accelerates radio interferometric imaging by parallelizing key workflow steps, resulting in superior performance compared to traditional CPU and GPU libraries (Liu et al. 2022). Furthermore, implementation of a high-performance imaging pipeline for MUSER data processing harnesses GPU technology to meet massive observational data processing requirements, enhancing both processing speed and image quality (Mei et al. 2018). Additionally, advancements such as Hybrid Gridding and Convolution-Based FFT Pruning (Muscat 2021) illustrate innovative modifications to existing techniques, demonstrating substantial acceleration in radio interferometric image synthesis while maintaining high output quality, thus highlighting the key role of GPU technology in advancing radio astronomy imaging capabilities.

4.2. The Influence of Antenna Shortage on Imaging

Assessing the impact of antenna shortages on image inversion reveals the overall stability of antenna array operation. Given that antenna damage or malfunction is inevitable during telescope usage, missing one antenna results in the loss of $N-1$ sampling points, with corresponding holes in UV coverage that negatively impact imaging. A significant number of missing antennas can severely degrade imaging quality.

Given the unpredictable nature of antenna damage during routine observation, we employed a random selection method to repeat experiments with 1–30 missing antennas, conducting 100 repetitions for a total of 3000 experiments for analysis. We focused on comparing residual standard deviation of profiles and PSF RMS, with corresponding change curves shown in Figure 8.

In both figures, the two-dimensional low-redundancy array does not have the best performance, but its robustness is the strongest as the number of missing antennas increases. Antenna absence has less effect on two-dimensional low-redundancy arrays than on other arrays. These findings suggest that the influence of antenna loss on the two-dimensional low-redundancy array is relatively small. We attribute this to the relatively even distribution of baseline numbers and similar redundancy at each sampling point, which effectively suppresses errors. When the number of elements is not large, the two-dimensional low-redundancy array demonstrates strong robustness and is more suitable.

5. Conclusion

Antenna placement plays a critical role in determining the distribution of complex visibility points on the UV plane. Therefore, optimizing antenna array design equates to optimizing the distribution of these points on the UV plane. The distribution of UV points directly affects essential parameters such as sidelobe distribution, size, and beamwidth of the dirty beam, making antenna array optimization crucial for ensuring quality radio images. Consequently, antenna array design optimization is essential for achieving high sensitivity and resolution solar images within the desired frequency band. Generally, regular antenna configurations are used in radioheliograph array design to improve image quality. This study comprehensively considers various factors including baseline redundancy, UV coverage, and comprehensive aperture processing speed to improve imaging quality and real-time imaging speed, proposing and designing a two-dimensional low-redundancy antenna array. The antenna array is then compared and analyzed with common types such as T-shaped, Y-shaped, uniform circular, and three-arm spiral arrays. The specific results obtained from this comparison and analysis are as follows.

First, the UV coverage area of the two-dimensional low-redundancy antenna array is merely 12.26% smaller than that of the Y-shaped array, which has the maximum coverage area, and is 5.85% larger than the spiral array. Across all array configurations, parameters such as sampling points, beamwidth, and sidelobe level are moderate. Second, the two-dimensional low-redundancy antenna array has an advantage in calculation time during imaging simulation. The standard deviation of profile residuals is similar to that of the Y-shaped array, as is the dynamic range, meaning imaging quality is second only to the Y-shaped array. Third, the two-dimensional low-redundancy antenna array exhibits good stability, showing lower standard deviation than other array configurations. Due to its relatively even distribution of baseline numbers and similar redundancy at each sampling point, the effects of antenna failure on the two-dimensional low-redundancy array are minor, and errors can be effectively suppressed. Fourth, however, the RMS of a two-dimensional low-redundancy array is notably large, indicating higher sidelobe levels. These elevated sidelobe levels present challenges during deconvolution due to computational demands and risk of divergence. Addressing these challenges in practice may involve implementing more complex deconvolution algorithms and utilizing advanced mathematical and computational techniques to ensure lower sidelobe levels and achieve more accurate scientific outcomes (Kogan 2000).

In summary, the two-dimensional low-redundancy antenna array is desirable due to its strong robustness and high imaging quality when the number of array elements is limited. For radioheliographs striving for high-resolution imaging, fully dense UV coverage is not achievable due to limited antenna numbers. Hence, investigating antenna array arrangements for achieving satisfactory UV coverage is of great significance. In future studies, we will further explore the causes and correction methods of position errors in antenna arrays, investigate the effects of positioning errors on radioheliographs, and consider correction methods to further enhance radioheliograph performance.

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