Solar polar orbit radio telescope for space weather forecast

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Abstract. Radio emission from density plasma can be detected at low radio frequencies. An image of such plasma clouds of the entire inner interplanetary space is always a wanted input for space weather forecast and ICME propagation studies. To take such an image within the ecliptic plane may not fully explore what is happening around the Sun not only because of the blockage of the Sun, also because most of the ICMEs are propagating in the low-latitude of the Sun, near the ecliptic plane. It is then proposed to launch a solar polar orbit radio telescope to acquire high density plasma cloud images from the entire inner interplanetary space. Low radio frequency images require a large antenna aperture in space. It is, therefore, proposed to use the existing passive synthetic aperture radiometer technology to reduce mass and complicity of the deployment system of the big antenna. In order to reduce the mass of the antenna by using minimum number of elements, a zero redundant antenna element design can be used with a rotating time-shared sampling system. A preliminary assessment study shows the mission is feasible.

Index Terms. Radio telescope, solar polar orbit, space weather forecast.

1. Introduction

The study of solar coronal mass ejections (CMEs) and their propagation into the interplanetary space is a very hot topic within the past ten years (Pick et al., 2005; Gopalswamy, 2003; Gonzalez-Esparza, 2003; Liu, 2005). The main reason is that CMEs are the main source affecting our planet via space weather. Excepting the background solar wind, the Earth- space environment is generally quite stable and provides a safe environment for human technology facilities, such as man made satellites, and international space station. While the interplanetary condition changes, the geo-space environment is disturbed by magnetospheric and ionospheric storms (Yu, 2002; Tsurutani, 1999; Afraimovich, 2001). Free particles gather and move together to form a space current during the storms. At a certain space region, the flux of charged particles increases dramatically (Baker, 1998). Once a satellite runs into this region, the onboard electronics may be charged and discharged. In many cases, the electronics may fail to function normally or can even be destroyed completely. These events are called the space weather events analogous to imitate disastrous weather events on the surface of Earth.

Although the interplanetary CME or plasma clouds are vital to geo-space storms is little progress in monitoring or observing them after they left the surface of the Sun. What we would like to see, in fact, is the movement after it left the Sun, and track it all the way before it reaches Earth. Based on many observations it is known that CMEs will take 1-2 days to travel from the Sun to the distance of 1 AU (Gonzalez-Esparza, 2003; Schwenn, 2000; Robbrecht, 2005). Therefore, we have plenty of time to give a forecast once we can monitor it. We can also predict how serious the storm will be by looking at the density of the clouds.

To monitor the interplanetary CME or plasma clouds by radio wave frequency that matches the density or plasma frequency, two approaches can be taken. The first approach is to observe emission of the CME at two separate points, like a stereo, and retrieve the location of the emission source where the plasma clouds is. The second approach is to take an image of the entire inner interplanetary space within 1 AU from above the pole of the Sun.

In this paper, we present results of a preliminary feasibility study of a solar polar orbit radio telescope (SPORT) that aims at taking images of CME plasma clouds. The paper mainly concentrates on the concept design of the telescope. It is an extremely thinned array using only a few elements but with a physical aperture of 150 meters.

2. Requirements for solar wind monitoring

We must use the low-frequency band to monitor the interplanetary CMEs. But in order to take an image, the lower frequencies become an obstacle for high spatial resolution since they require very large antenna apertures that cannot be

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realized in space. Therefore, before proceeding, the observation frequency band must be discussed.

Table 1 shows the plasma density of CMEs at different distances from the Sun calculated using inversed square law together with plasma frequency.

Table 1.

Distance	0.1AU	0.3AU	0.5AU	0.7AU	1AU
Density cm^{-3}	3.0×10^8	2.6×10^7	6.69×10^6	2.05×10^6	26.7
f_p(Hz)	1.73×10^8	5.1×10^7	2.59×10^7	1.43×10^7	5.17×10^4

We take 15 MHz as our design input in all our discussions here after. It is obvious that this frequency cannot be used to observe the Sun from the ground, due to Earth's ionosphere.

If an image covers the entire inner interplanetary space across 2 AU, and the resolution cell is 0.1 AU × 0.1 AU, the antenna beam width must be rather narrow. A number of antenna aperture sizes with corresponding different orbit aphelion are listed in Table 2.

Table 2.

Orbit Aphelion	1AU	1.5AU	2AU	2.5AU	3AU
Beam width (deg)	5.7	3.8	2.86	2.29	1.91
Antenna aperture (m)	200	300	400	500	600

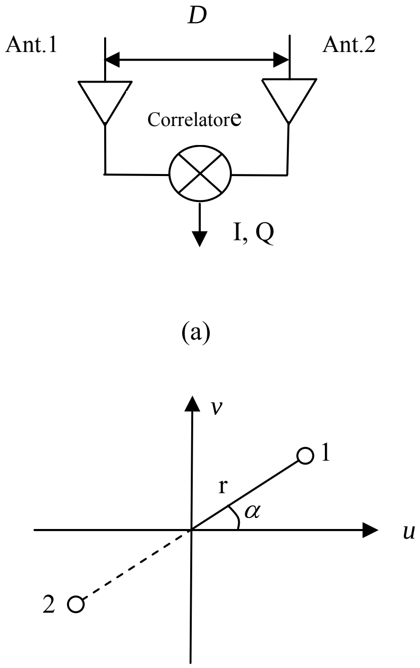
It is very clear that realizing such a physical antenna aperture in space is very difficult. It is possible to use synthetic aperture technology in replacement of the conventional technology.

An elliptical solar polar orbit is preferred. It should have its aphelion over the north pole of the Sun since most of the ground stations on Earth are on the northern hemisphere. When the telescope is flying around the aphelion of the orbit, it can gain a very long observation time. However, the perihelion should not be too close to the Sun to avoid engineering challenges on spacecraft thermal control. To balance this, we propose to have an orbit parameter of the mission as follows: solar inclination angle ~90 deg.; aphelion 1-1.5 AU; perihelion 0.5-0.7 AU; and the long axis of the orbit ellipse should be pointed to the north pole of the ecliptic plane within ±15 degrees.

3. Basic principle of synthetic aperture radiometry

A black and white image can be expressed by spatial frequency after performing a Fourier transformation. Details of the image are reflected in the high spatial frequency band and large scale contrasts of the target are reflected in the low spatial frequency band. The principle of the synthetic aperture technique is to measure the spatial frequency (SF) image of the target directly and take an inverse Fourier transform to get the original one. The SF sampling is carried out by a pair of antennas with a correlator multiplying the output voltages they receive. This device is shown in Fig. 1 (a).

The distance (D) between two antennas forms the baseline. In two-dimensional cases, the direction of the baseline also plays an important role. The output of this device provides two sampling points in the SF domain (-the UV-plane), as shown in Fig. 1 (b), where r is the length of the baseline, representing the direction of the baseline. The measurement in fact was done only once. The second point is obtained as if the baseline was rotated by 180 degrees.



(a)

(b)

Fig. 1. The two figures show: (a) spatial frequency sampling device, and (b) sampling points on the UV-plane from one baseline.

It is necessary to have the whole UV plane be covered before a Fourier transformation is taken. Therefore, more samples have to be taken with different baselines. The main difference to form a synthetic aperture array from an ordinary array is that during the measurement, one antenna element can be used multiple times, or so-called shared by many baselines. This is because the target is in the far field, and the sampling can be taken at any position in the location arrangement.

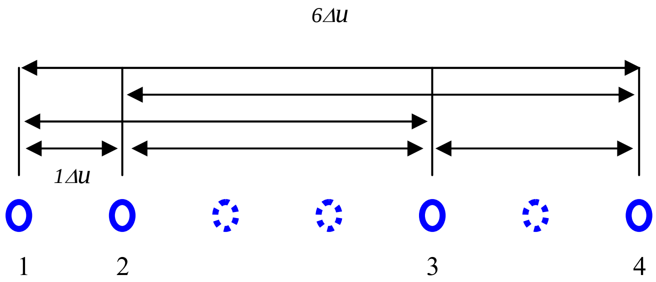


Fig. 2. A schematic of a zero redundant one-D thinned array is shown.

Fig. 2 shows an example of a one dimensional array with 4 elements forming 6 baselines from 1 Δu to 6 Δu continuously, where each element has been reused three times. The center of each baseline has been slightly shifted horizontally. But as explained above, it will not affect the image at all if the object is in the far field.

4. Conceptual design of SPORT

If an array has N elements, using the above principle, the maximum number of baselines that can be reached is

$$C^2_N = N(N-1)/2 \qquad (1)$$

If we need a 20 X 20 cell image, we then need 20 X 20 samples in the SF domain too; 400 sampling points on the UV plane represent 200 different sampling baselines. From equation (1), we have $N(N-1)/2 >= 200$, which yields N =21. This is to say, if we can reach a zero redundant design, a 21-element array will fulfill our requirement. The positions of these 21 elements will be distributed in a plane and the maximum distance from the two far most ones is 150 meters, which will sample the longest baseline and represent the highest spatial frequency. This 150 meters aperture is in fact equivalent to a 300 meters antenna aperture if a conventional technology is used. This is because in the SF sample, we have both amplitude and phase. The number of unknowns is the same as in the original domain.

The time-shared sample scheme is based on the polar coordinate. The samples are all taken at different modules of baselines, no matter where their directions are. The zero-redundant optimization aims to reach an as evenly distributed baseline module as possible between 1 Δu to $C^2_N \Delta u$. Once a group of samples are taken, the whole system rotates by a small angle and takes the second group of samples, and so on. After 180 degrees rotation, the sampling points will cover the whole UV plane completely but in a polar coordinate system. Then we interpolate them into a rectangular coordinate system and carry out the Fourier transform.

The CME plasma clouds are traveling in the interplanetary space less than 1000 km/s, i.e. ~0.024 AU/hour. Therefore, if the whole telescope rotates 1 rotation/hour, or 2 images per hour, there is almost no effect on the quality of the image.

To get a 20 X 20 cell image within 2 AU, we need 10 evenly distributed baselines to sample in one dimension and to rotate them. In order to reach this, we actually need only 5 element antennas since $C^2_5=10$. To take a double redundant, we could consider a telescope system with 8-10 elements in total. This is a feasible number to be realized in space.

Another good aspect with a rotating telescope is hidden in the spacecraft engineering side. A rotating system is stable and easier to control than a 3-axis stabilized system or a multi-spacecraft formation flying system.

The spacecraft of SPORT should provide a supporting system to deploy 8 to 10 antenna/receiver elements and rotate them during observation. A conceptual drawing is shown in Fig. 3.

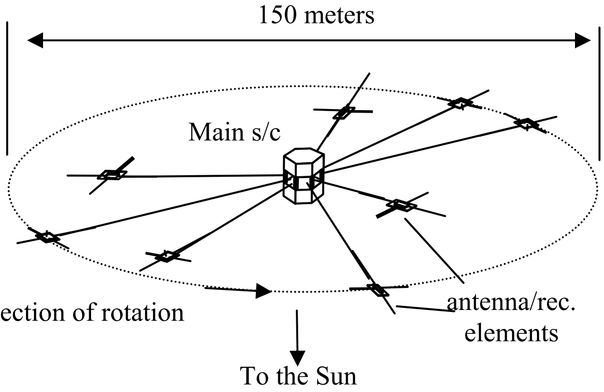


Fig. 3. A Conceptual design of Solar Polar Orbit Radio Telescope is shown.

The antenna/receiver elements are stowed inside the spacecraft during the launch and cruise phase. Once it is in the observation orbit, they are deployed from the spacecraft slowly under the constraints of maintaining a fixed center of gravity at the spacecraft. The antenna/receiver elements are connected with the main spacecraft by thin and non-conducting strings. They all provide themselves power with solar cells and keep the attitude stable by a gravitational boom during rotation. The receivers get synchronized beacon from the main spacecraft wireless and send digitized receiving signals back by microwave link. The total weight of an antenna/receiver element can be well controlled within 2 kg.

Due to the sampling theory, the maximum distance between any adjacent sampling points should be less than the maximum sampling interval, or $1\Delta u$. It can be roughly calculated by $\Delta u = R / C^2_N$, where R is the radius of the rotating aperture, N is the number of antenna/receiver elements. Take R = 75, N = 8, we have $\Delta u = 2.67$ m. This means that within half of a revolution, we must take $n = \underset{\cdot}{\Delta} R / \Delta u = 88$ measurements. The integration time of each sample is then no more than 20 seconds. We leave half of the time for communication between the element and the main spacecraft. The integration time of each correlation measurement is then 10 seconds, which is quite feasible for a good sensitivity quality of the radiometry measurement.

Optimization of the element positions in a plane is aimed to obtain evenly distributed baseline lengths, while maintaining the center of gravity close to the geometrical center of the system. It turns out that they are distributed within the plane as shown in Fig. 3. Note that the optimization solution is not unique.

4. Conclusions

Solar wind and CME plasma clouds monitoring is very important due to its application to space weather forecast. There is no space mission that currently covers this important area. In this paper, we have described, conceptually, a solar polar orbit radio telescope mission that aims to solve the long-term problem. This paper proposes the following:

1. Observing at the solar polar region and looking downwards, is a very effective way to have a very clear picture of the interplanetary CME plasma clouds.

2. It is possible to observe the CME plasma clouds up to 0.5 AU and even further at radio wavelength.

3. Using the synthetic aperture radiometry technique can help to overcome the difficulties deploying a very large antenna aperture for taking an image over the entire inner interplanetary space.

4. Using time-shared sampling and zero-redundant baseline optimization techniques can further thin the array more than existing current synthetic aperture schemes.

5. The present conceptual design has provided a feasible engineering path to realize this mission.

Acknowledgements. The authors thank the Chinese National High Technology Program for its support of this pre-study.

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