Solar Phys (2009) 259: 255–276
DOI 10.1007/s11207-009-9404-z

STEREO SCIENCE RESULTS AT SOLAR MINIMUM

Multipoint Observations of Solar Type III Radio Bursts from STEREO and *Wind*

M.J. Reiner · K. Goetz · J. Fainberg · M.L. Kaiser · M. Maksimovic · B. Cecconi · S. Hoang · S.D. Bale · J.-L. Bougeret

Received: 16 December 2008 / Accepted: 18 June 2009 / Published online: 11 July 2009

STEREO Science Results at Solar Minimum
Guest Editors: Eric R. Christian, Michael L. Kaiser, Theresa A. Kucera, O.C. St. Cyr

M.J. Reiner
The Catholic University of America, Washington, USA

K. Goetz
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, USA
e-mail: goetz@space.umn.edu

M.J. Reiner (✉) · J. Fainberg · M.L. Kaiser
NASA Goddard Space Flight Center, Greenbelt, MD 20071, USA
e-mail: michael.reiner@nasa.gov

J. Fainberg
e-mail: joseph.fainberg@nasa.gov

M.L. Kaiser
e-mail: michael.l.kaiser@nasa.gov

M. Maksimovic · B. Cecconi · S. Hoang · J.-L. Bougeret
LESIA, CNRS, UPMC, Université Paris Diderot, Observatoire de Paris, 5 Place Jules Janssen, 92190 Meudon, France

M. Maksimovic
e-mail: milan.maksimovic@obspm.fr

B. Cecconi
e-mail: baptiste.cecconi@obspm.fr

S. Hoang
e-mail: song.hoang@obspm.fr

J.-L. Bougeret
e-mail: Jean-Louis.Bougeret@obspm.fr

S.D. Bale
Physics Department, University of California, Berkeley, CA, USA
e-mail: BALE@sunspot.ssl.berkeley.edu

Abstract The twin STEREO and the *Wind* spacecraft make remote multipoint measurements of interplanetary radio sources of solar origin from widely separated vantage points. One year after launch, the angular separation between the STEREO spacecraft reached 45°, which was ideal for locating solar type III radio sources in the heliosphere by three-spacecraft triangulation measurements from STEREO and *Wind*. These triangulated source locations enable intrinsic properties of the radio source, such as its beaming characteristics, to be deduced. We present the first three-point measurements of the beaming characteristics for two solar type III radio bursts that were simultaneously observed by the three spacecraft in December of 2007 and in January of 2008. These analyses suggest that individual type III bursts exhibit a wide beaming pattern that is approximately beamed along the direction tangent to the Parker spiral magnetic field line at the source location.

Keywords Solar radio emissions · Intrinsic radiation characteristics

1. Introduction

The most conspicuous radio emissions from the Sun at low frequencies are the type III radio bursts, which are generally associated with solar flares that occur in active regions. These radio emissions result when electron beams from active regions are injected onto the open magnetic field lines in the interplanetary medium, along which they propagate at high speeds away from the Sun. The radiation from these interplanetary radio sources is generated at the plasma frequency f_{p} and/or its second harmonic $2f_{\mathrm{p}}$, which depends directly on the value of the plasma density in the region of the radio source [*i.e.*, $f_{\mathrm{p}}(\mathrm{kHz}) = 9\sqrt{n}(\mathrm{cm}^{-3})$, where n is the plasma density]. Since the interplanetary plasma density decreases with increasing distance from the Sun, the radio sources for a given solar event are generated at lower frequencies as the electron beam propagates farther from the Sun. This feature has been previously used to spatially track these radio sources and, consequently, their underlying electron beams through interplanetary space, thereby revealing the underlying global spiral magnetic field topology (Fainberg, Evans, and Stone, 1972; Reiner and Stone, 1986).

One drawback of this approach is that the density decrease along the path of the electron beam is not precisely known at the time or location of any given type III event. Hence a global interplanetary density model generally has to be assumed for tracking individual type III bursts through interplanetary space. A way out of this dilemma was possible for the continuous radio emissions observed for type III radio storms, where dynamic parallax, caused by the solar rotation, was used to locate the radio source at consecutively lower frequencies (Bougeret, Fainberg, and Stone, 1984). Those results, obtained without the assumption of an interplanetary density model, confirmed the underlying spiral magnetic field topology. However, that technique cannot be used for tracking individual type III radio bursts, since their temporal durations are much too short. Triangulation measurements from two or more widely separated spacecraft can be used for tracking single type III bursts. Such measurements were previously made using the radio instruments on the IMP-6, RAE, and *Helios* spacecraft and more recently using the matched radio receivers on the *Wind* and *Ulysses* spacecraft (Fitzenreiter *et al.*, 1977; Weber *et al.*, 1977; Reiner *et al.*, 1998). A different way for tracking type III radio bursts was recently provided by the *Ulysses* spacecraft, which observed the type III radio bursts from far above or below the ecliptic plane (Reiner, Fainberg, and Stone, 1995). A problem with the previous multispacecraft or high-latitude observations was that the relative orbits of the spacecraft were such that they provided only rare opportunities for tracking type III bursts. By contrast, the two STEREO spacecraft, which have identical radio receivers, were specifically designed to provide dedicated stereoscopic measurements of solar transient phenomena. A further asset is provided by the *Wind* spacecraft, which is located between the STEREO spacecraft and which provides a third triangulation observation.

By locating solar radio sources in the interplanetary medium, the triangulation measurements enable one to derive the intrinsic radiation characteristics of the radio sources such as the brightness temperature, the angular size of the source from different perspectives, and the intensity of the emitted radiation in different directions (the beaming pattern). These derived intrinsic characteristics of radio sources can provide a better understanding of both the nature of the generation mechanism of the radio waves and information on how these waves propagate from the source region to the observer. Radiation beaming is a characteristic feature of all solar and interplanetary radio sources. However, quantitative information about the beaming patterns for solar radio sources is somewhat limited, owing primarily to the lack of multipoint observations from intercalibrated radio instruments on two or more spacecraft. The most comprehensive investigation to date is that of Bonnin, Hoang, and Maksimovic (2008), who derived the average latitudinal and longitudinal beaming pattern for some 1000 type III bursts measured by the matched receivers on the *Wind* and *Ulysses* spacecraft, assuming that the radio sources were located on spiral magnetic field lines originating from the associated flare sites.

The matched pair of radio receivers on the STEREO spacecraft, further complemented by the intercalibrated radio receivers on the *Wind* spacecraft (all located in the ecliptic plane), provide the first opportunity to make quantitative three-point measurements of the longitudinal beaming patterns for *individual* solar radio sources; it is necessary to have at least three widely separated measurements since the radiation beaming pattern is a curved surface. Furthermore, in this case the actual location of the radio source can be deduced from the three-spacecraft triangulation. In this paper, we present preliminary results for locating type III radio sources in the interplanetary medium from three-spacecraft triangulation and for deducing the intrinsic beaming patterns, measured for two type III radio bursts that were observed when the STEREO angular separation was about 45°, as viewed from the Sun.

2. Instrumentation

The NASA/STEREO mission was launched on 26 October 2006. The twin spacecraft, STEREO A and STEREO B, were inserted into heliocentric orbits near 1 AU, with STEREO A leading Earth and STEREO B trailing Earth. The two spacecraft are separating at a rate of about 45° per year, as viewed from the Sun. The near-Earth *Wind* spacecraft, which was launched in November of 1994, has been continuously monitoring the Sun from L1 since 2004 (Bougeret *et al.*, 1995).

The SWAVES radio experiment on STEREO consists of a suite of instruments that measure the electromagnetic radiation and *in situ* plasma waves for solar-related phenomena (Bougeret *et al.*, 2008; Bale *et al.*, 2008). A similar suite of radio instruments exists on the *Wind* spacecraft. All three spacecraft have super-heterodyne receivers; those on STEREO extend to 16.025 MHz, whereas those on *Wind* extend to 13.625 MHz. Each of these spacecraft have radio source direction-finding capabilities. The *Wind* spacecraft, which has a 100-m-long dipole antenna in the spin plane and about a 10-m-long dipole antenna perpendicular to the spin plane, achieves the direction finding by synthesizing the signals from these two antennas. The STEREO spacecraft, each with three orthogonal 6-m-long monopole antennas, achieves the direction finding by measuring the auto- and cross-correlations between consecutive pairs of antennas.

3. Analysis of Type III Radio Bursts from STEREO and *Wind*

3.1. 7 December 2007 Type III Event

This type III radio burst was associated with a B1.4 X-ray flare that reached maximum intensity at 04:39 UT on 7 December 2007 and with a optical subflare that was observed at S05°W06° (*i.e.*, near the central meridian). The onset of the type III burst observed at the three interplanetary spacecraft occurred at about 04:40 UT. The associated dynamic spectra showing this type III burst, as observed at each of the three spacecraft, are illustrated in Figure 1. These spectra show that, as is typical for type III radio bursts, the onset time of the burst occurs later with decreasing frequency, owing to the propagation of the underlying electron beam from the Sun at speeds of about $0.3c$, where c is the speed of light (Fainberg and Stone, 1970; Dulk *et al.*, 1987). Thus, because of the decreasing local plasma density, the radio source and the underlying electron beam are located farther from the Sun at decreasing frequency.

At the time of this event, STEREO B was located downstream from Earth, 21.6° to the east of the Sun – Earth line and at 1.027 AU, and STEREO A was located 20.8° to the west, ahead of Earth, at 0.967 AU. The total separation angle between the two STEREO spacecraft, from the Sun, was 42.4°. The locations of the three spacecraft are also indicated in Figure 1. This wide angular separation is ideally suited for making triangulation measurements to locate the type III radio source at any given observing frequency.

There are only a few frequency channels that are common between STEREO and *Wind*. An excellent choice, for this initial investigation, is the frequency channel at 425 kHz for STEREO and at 428 kHz for *Wind*, which are identical frequencies to within the bandpass of the respective receivers (3 kHz for *Wind* and 25 kHz for STEREO). At this relatively low frequency, the type III burst has a relatively long duration, and the corresponding radio source is sufficiently far from the Sun to make its location in the interplanetary medium quite obvious.

To achieve the triangulation, we must determine the angular directions of the radio source from each of the observing spacecraft. For the spinning *Wind* spacecraft, the arrival direction of the radiation from the radio source, at any observing frequency, is readily deduced from an analysis of the intensity modulation patterns observed in the signals measured on each of the dipole antennas (Manning and Fainberg, 1980). For the three-axis stabilized STEREO spacecraft, the arrival direction of the radiation is deduced from an analysis of the auto- and cross-correlations measured between consecutive pairs of antennas, which are rapidly switched electronically from one pair of antennas to another. The approach taken here is to deduce the source direction angles from a simultaneous fit of the nine measurements of the auto- and cross-correlations, acquired essentially simultaneously, to the theoretical antenna equations, for each of the STEREO spacecraft (Ladreiter *et al.*, 1995; Cecconi and Zarka, 2007; Cecconi *et al.*, 2008).

Results of our direction-finding analysis at 425 kHz from the three spacecraft are shown in Figure 2 for the 7 December 2007 type III event. For each spacecraft, the lowest panel gives the relative intensities of the signals, in dB/10 units for STEREO and in log(sfu) units for *Wind*, as a function of time. This intensity – time profile is typical for a type III event and corresponds to a single injection of electrons at the Sun. It consists of a rapid rise to a maximum intensity, followed by a longer exponential-like decay. The middle panels in Figure 2 display the derived radio source azimuthal angles observed from each of the spacecraft, with positive angles corresponding to a source lying to the west of the spacecraft – Sun line and negative angles to the east of the spacecraft – Sun line. Finally, the upper panels show the

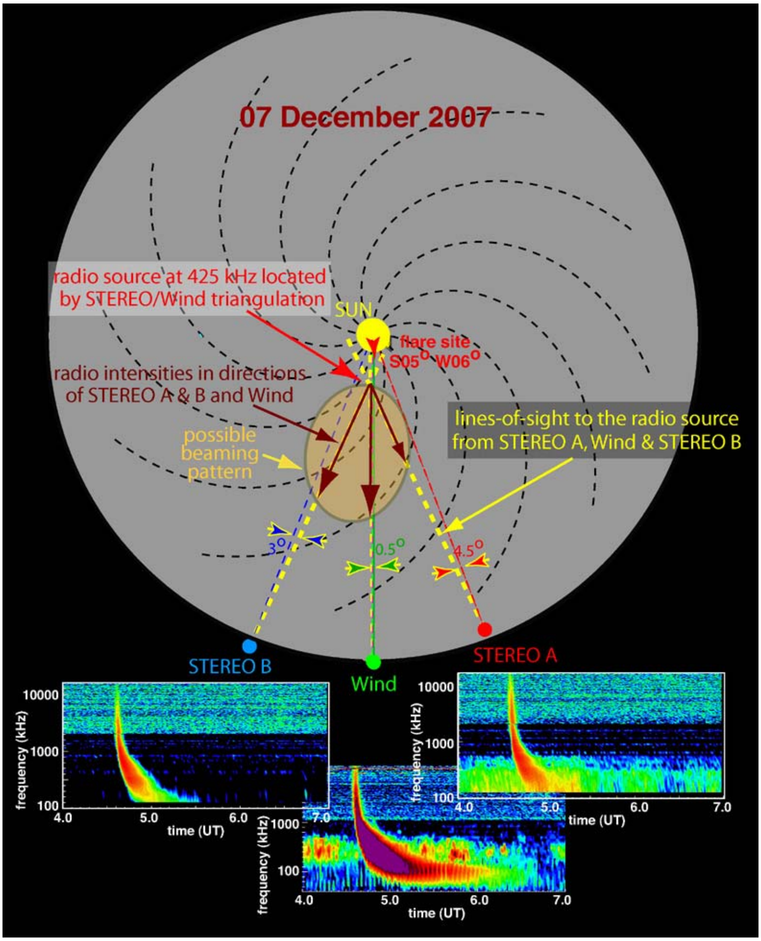

Figure 1 The locations of the STEREO and *Wind* spacecraft relative to the Sun on 7 December 2007, as observed from above the ecliptic plane. Dynamic spectra, from 04:00 to 07:00 UT, showing the type III burst observed essentially simultaneously at about 04:40 UT by STEREO A and B and by *Wind* are also presented. These spectra represent the intensity (color) of the radio emissions plotted as a function of frequency (vertical axis) and time (horizontal axis). The frequency extends from 100 kHz to 16.025 MHz for STEREO and from 40 kHz to 13.625 MHz for *Wind*. The yellow dashed lines are the line-of-sight directions from each of the spacecraft, determined from the direction-finding analyses at 425 kHz. The radio source is located at the intersection of these three line-of-sight directions. The brown arrows represent the relative intensities (flux densities) observed in the direction of each of the spacecraft, after the effects of the $1/R^2$ falloff of the radiation intensity was taken into account. The tan elliptical pattern represents a possible 2D radio source beaming pattern that is consistent with these observations.

derived radio source colatitudinal angles, measured with respect to the ecliptic plane (corresponding to a colatitude of 90°). From this analysis, we also deduce an angular size of the radio source. However, for the relatively low signal-to-noise levels on the STEREO spacecraft, this source parameter is not particularly well determined, and so we do not display or consider it here.

Because of its greater sensitivity and signal-to-noise ratio and because each direction determination is derived from a nonlinear least squares fit to 24 data points acquired during

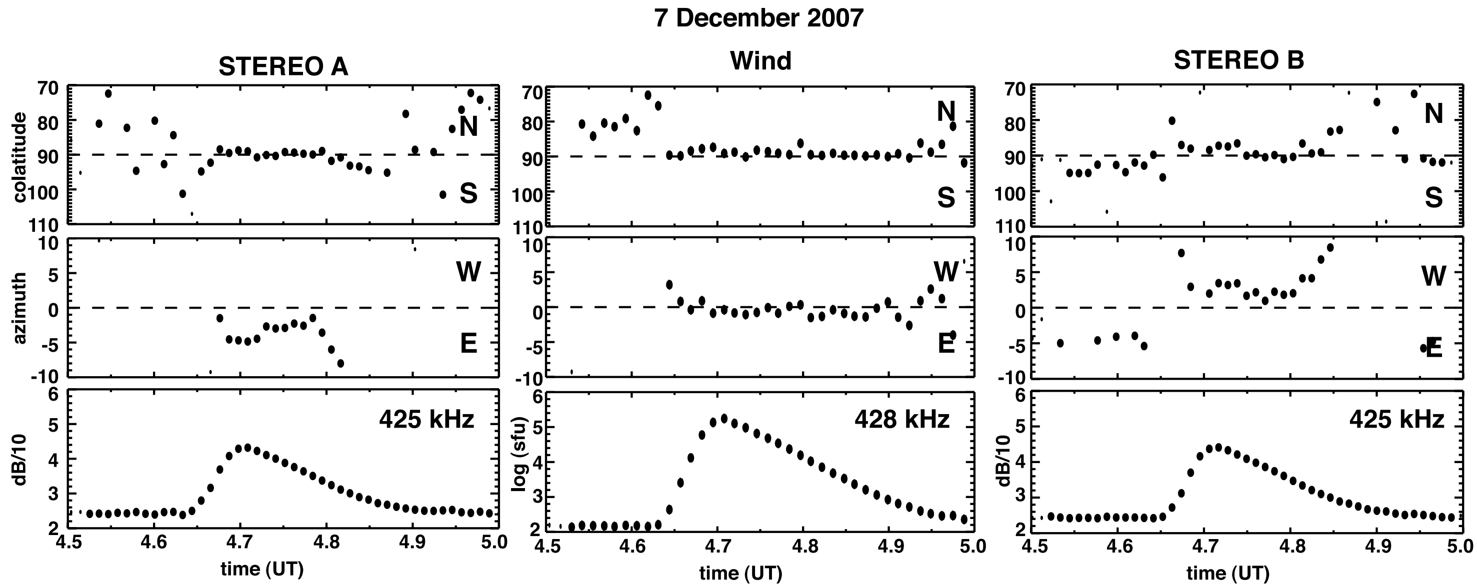

Figure 2 Results of the direction-finding analysis at STEREO A and B and at *Wind* at 425 kHz for the 7 December 2007 solar type III radio burst. The topmost panels are the derived colatitudinal angles of the radio source relative to the direction of the ecliptic plane (90°). Lower (higher) values correspond to the source lying north (south) of the ecliptic plane. The middle panels are the derived azimuthal angles of the radio source; positive (negative) values correspond to the source lying to the west (east) of the spacecraft – Sun line. The lower panels are the derived source amplitudes, in units of log(sfu) for *Wind* and dB/10 for STEREO. These amplitudes have not yet been corrected for the different distances of the radio source to each of the spacecraft. The intensity – time profile for this event exhibits the typical shape of a single-component type III radio burst.

the 3-second spacecraft spin period, the results for the direction finding at *Wind* are expected to be the more precise. The azimuthal and colatitudinal angles in Figure 2 derived at *Wind* for this event are seen to be quite steady across the entire duration of this type III burst profile. From previous experience with locating both solar and planetary radio sources from *Wind*, we have determined that these derived source directions are accurate to one degree or less. By contrast, the signal-to-noise ratio for the short antennas on STEREO is significantly lower and, although the measurements are essentially simultaneous, there are only nine independent measurements. Consequently, these source direction angles are less well determined from the nonlinear least squares fit. Furthermore, for STEREO the direction-finding analysis depends on accurately knowing the effective electrical lengths and effective electrical axes of each of the three monopole antennas. It is difficult to assess how accurately these antenna electrical parameters have been determined from the various modeling efforts (Rucker *et al.*, 2005; Bale *et al.*, 2008). We estimate that the derived source direction angles from the STEREO spacecraft have an uncertainty of one or two degrees.

For both the STEREO and *Wind* direction-finding results presented here, we take the average of the source direction angles measured near the peak of the burst at each spacecraft, where the signal-to-noise ratio is maximum. The direction-finding results shown in Figure 2, at 425 kHz, indicate that the azimuthal angles of the radio source were relatively small for this event. The average azimuthal angle, measured near the peak of the type III burst at STEREO A was $-4.5°$ from the Sun – STEREO A line. The source azimuth was $-0.5°$ from the Sun – *Wind* line and was $+3°$ from the Sun – STEREO B line. The colatitudinal angles measured at each spacecraft were all near 90°, implying that the radio source was very close to the ecliptic plane. Since these results indicate a source located essentially in the ecliptic plane, we consider here only the 2-D triangulated source locations.

The measured azimuthal angles are displayed by the (yellow) lines of sight in Figure 1. By assuming straight-line propagation of the radiation, the intersection of these three lines of sight then gives the location of the centroid of the radio source in interplanetary space. Specifically, this three-spacecraft triangulation implies that the radio source at 425 kHz, for this type III event, was located at about E2° and at a heliocentric distance of 0.2 AU ($43 R_{\odot}$) from the Sun. The clear advantage of this technique is that it directly gives the location of the radio source, without the need to make any assumptions about how the interplanetary plasma density decreases from the Sun.

The intensities shown in the bottom panels of Figure 2 cannot be directly compared since they are expressed in different units for STEREO and for *Wind*. To express all the intensities in common solar flux units, we intercalibrated the STEREO and *Wind* intensities by directly comparing type III bursts that were observed when all three spacecraft were close together. This intercalibration technique is described in the Appendix.

Although this intercalibration technique permits us to express the intensities observed at each spacecraft in common solar flux units, these measured solar flux units are not the intensities intrinsic to the radio source. The reason is that radiation intensity is expected to fall off with distance approximately as $1/R^2$ as it propagates from the source to the observer, and the distance from the radio source to each of the three widely spatially separated spacecraft is different. However, having located the radio source by the three-spacecraft triangulation, the $1/R^2$ distance corrections for the flux densities measured at each spacecraft can be made. In this way, we deduce the intrinsic flux density at the source, observed in the direction of each spacecraft. This enables us to make the first three-point measurement of the intrinsic beaming pattern of the radio source for an individual type III event.

Using the measured distances from the radio source to STEREO A, *Wind*, and STEREO B, which are estimated to be 0.82, 0.83, and 0.87 AU, respectively, to make the $1/R^2$ propagation distance corrections and using Equations (A.1) and (A.2) to intercalibrate the fluxes

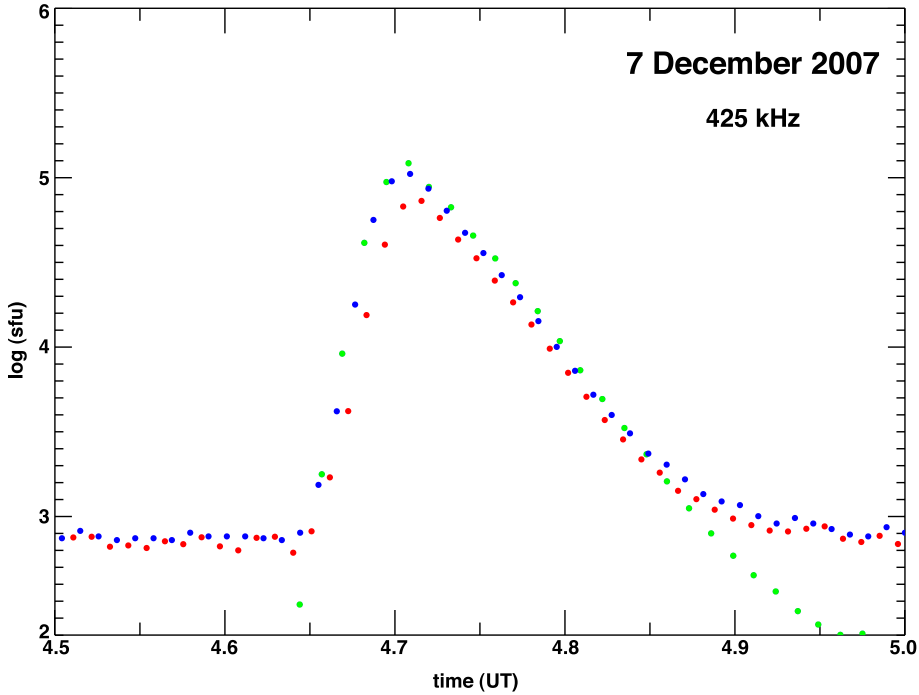

Figure 3 The derived intrinsic flux densities observed at STEREO A and B and at *Wind* on 7 December 2007 at 425 kHz. The flux density at *Wind* is given as the green points; the red (STEREO A) and blue points (STEREO B) are the derived flux densities at the two STEREO spacecraft in units of log(sfu). The algorithms in Equations (A.1) and (A.2) were used to determine the flux densities at the STEREO spacecraft, and the corrections for the $1/R^2$ falloff of the radiation intensity in propagating to each spacecraft was also made.

on all three spacecraft, we present the calculated intrinsic flux densities at the radio source, as observed in the direction of each spacecraft, in Figure 3. On this plot, no corrections were made for the different travel times of the radio waves from the source to the three spatially separated spacecraft, so the different onset times reflect the differences in the radiation propagation times to each spacecraft. The differences in the peak intensities are interpreted as resulting from the intrinsic beaming pattern of the radiation from the radio source. (Note that these intensities are here plotted on a log scale, so the actual intensity differences are greater than they appear.) In each case, comparing the flux densities measured at the peak of the bursts, observed at each spacecraft, we find that the derived intrinsic flux densities observed in the directions of STEREO B ($10^{5.02}$ sfu), *Wind* ($10^{5.05}$ sfu), and STEREO A ($10^{4.86}$ sfu) are in the ratio of 0.93, 1.0, and 0.65, respectively – with the flux in the direction of *Wind*, which was the largest of the three, arbitrarily normalized to unity. These relative flux densities are represented by vectors (of arbitrary length units) in Figure 1. As indicated by the simple elliptical pattern chosen to fit these vectors, these measurements suggest a relatively broad beaming pattern of the radiation from this radio source at 425 kHz. It also suggests that the maximum of the beaming pattern may be approximately directed along the spiral magnetic field line at the location of the radio source (Fitzenreiter, Fainberg, and Bundy, 1976; Weber *et al.*, 1977).

It is clear from this analysis that since the beaming pattern of the radiation is a curved surface, at least three independent spacecraft observations, as was the case here, were nec-

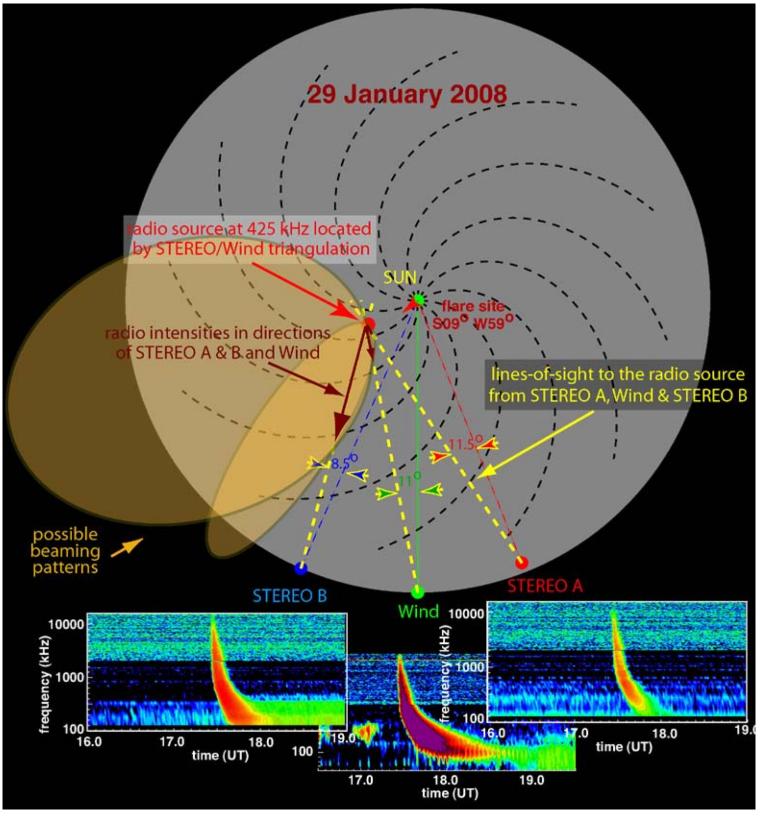

Figure 4 The locations of the STEREO and *Wind* spacecraft relative to the Sun on 29 January 2008, as observed from above the ecliptic plane. The dynamic spectra, from 16:00 to 19:00 UT for STEREO and from 16:30 to 19:30 UT for *Wind*, showing the type III burst observed essentially simultaneously at about 17:45 UT by STEREO A and B and by *Wind*, are also presented. The yellow dashed lines are the line-of-sight directions from each of the spacecraft, determined from the direction-finding analyses at 425 kHz. The radio source is located at the intersection of these three line-of-sight directions. The brown arrows represent the relative flux densities observed in the direction of each of the spacecraft, after the effects of the $1/R^2$ falloff of the radiation intensity was taken into account. The tan elliptical patterns represents possible 2D radio source beaming patterns that are consistent with these observations.

essary to determine its overall shape. It is also clear that the wider the separation of the spacecraft, the greater the angular extent of the beaming pattern that is sampled by these measurements.

3.2. 29 January 2008 Type III Event

A relatively intense type III burst, observed at the three interplanetary spacecraft at about 17:45 UT on 29 January 2008, was associated with a B1.2 X-ray flare that reached maximum intensity at 17:34 UT. LASCO EIT and STEREO EUV images indicate that this type III burst originated from an active region located near the east limb of the Sun. Dynamic spectra of this radio event, observed at each of the three spacecraft, are illustrated in Figure 4. As also indicated on that figure, at the time of this event STEREO B was located downstream from Earth, 23.5° to the east of the Sun – Earth line and at 1.0015 AU, and STEREO A was located 21.6° to the west, ahead of Earth, at 0.967 AU. The total separation angle of the two STEREO spacecraft, from the Sun, was 45.2°.

As for the 7 December 2007 event, for this far eastern event we located the radio source in the interplanetary medium from the three-spacecraft triangulation measurements at their common frequency of 425 kHz. The results of the direction-finding analysis from each of the spacecraft is shown in Figure 5, in the same format as in Figure 2. This type III event also exhibits the typical intensity – time profile for a single-component type III event, consisting of a rapid rise to a maximum intensity, followed by a longer exponential-like decay – implying a single injection of electrons from the Sun. As before, the middle panels in Figure 5 display the derived source azimuthal angles observed from each of the spacecraft. The radio source for this type III event is clearly located far to the east of the spacecraft – Sun line from each of the observing spacecraft, consistent with this event originating near the eastern limb of the Sun. This far eastern location of the radio source is also suggested by the fact that the intensity is significantly smaller at STEREO A than at STEREO B, which is expected to be closer to the radio source. The azimuthal angle observed from *Wind* exhibits a slight drift toward the central meridian over the duration of the intensity – time profile. This is typical for eastern type III bursts and results from proximity effects owing to the finite size of the radio source and of the underlying electron beam (Reiner and Stone, 1989; Reiner, 2001). This small azimuthal drift is not so clear in the STEREO data, most likely because of the reduced signal-to-noise ratio.

For this event, the average azimuthal angle of the source measured near the peak of the burst from STEREO A was −11° from the Sun – STEREO A line, −11.5° from the Sun – *Wind* line, and − 8.5° from the Sun – STEREO B line. The colatitudinal angles were again all near 90°, implying that this radio source was also close to the ecliptic plane. The line-of-sight directions corresponding to these measured angles are shown by the yellow lines on Figure 4. In this case, the triangulated source at 425 kHz was determined to be located at E64° and at a heliocentric distance of 0.19 AU ($37R_{\odot}$) from the Sun, that is, at a similar heliocentric distance as for the 7 December event. The distances from the radio source to STEREO A, *Wind*, and STEREO B were estimated to be 0.98, 0.92, and 0.85 AU, respectively.

Using this source location, we can convert the intensities in the lower panels of Figure 5 to the intrinsic flux densities observed in the directions of each of the spacecraft, by applying the intercalibration algorithms given in the Appendix and by correcting for the $1/R^2$ falloff of the radiation intensity. The results are shown in Figure 6. In this case, the flux densities at STEREO B ($10^{5.60}$ sfu), *Wind* ($10^{5.22}$ sfu), and STEREO A ($10^{4.63}$ sfu) are in the ratio of 1.0, 0.42, and 0.11, respectively, where here we have arbitrarily normalized the amplitude at STEREO B to unity since it had the largest value. These relative intensities are again represented by vectors of arbitrary length units, directed to each observing spacecraft, in Figure 4. Since only the edge of the beaming pattern is sampled for this far eastern event, a number of different beaming patterns can be found that are consistent with the observations. Two simple possibilities, which have maxima in different directions, are shown. Thus, although the overall beaming pattern is not well determined by the three-spacecraft measurements, these results provide a better understanding of how rapidly the intensity of the radiation decreases near the edge of the type III radio beam.

4. Discussion and Conclusion

With the intercalibrated radio receivers on the widely separated STEREO and *Wind* spacecraft, we have been able for the first time to make dedicated triangulation measurements

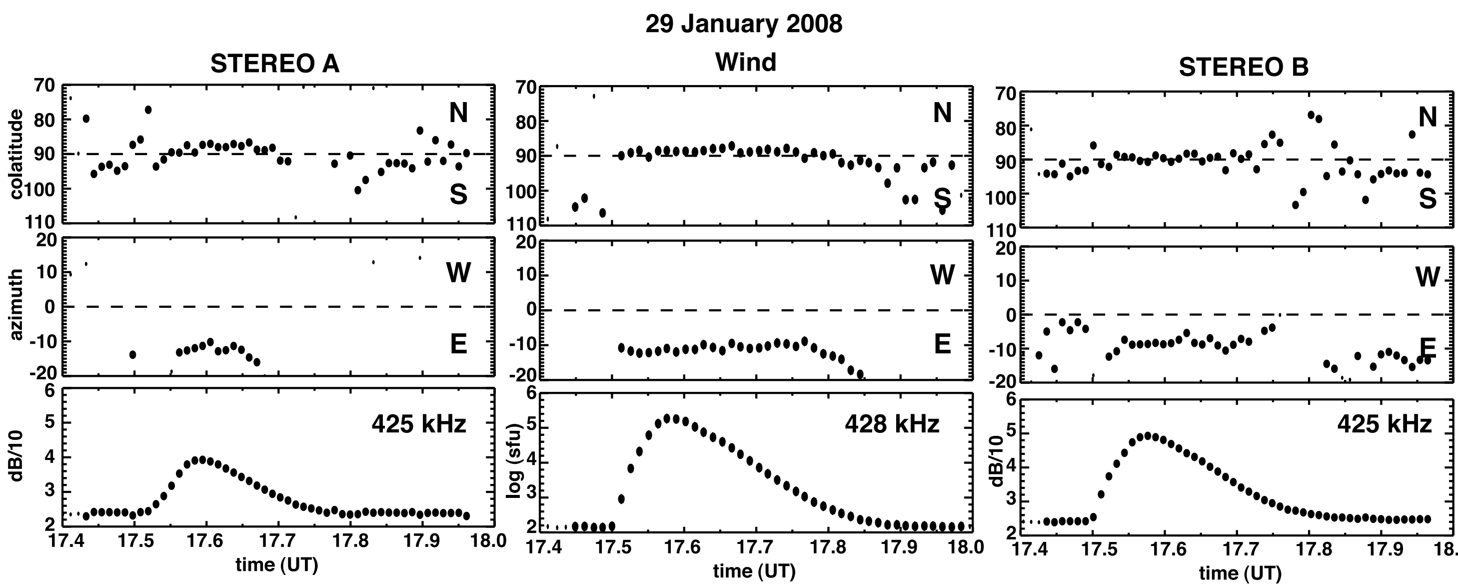

Figure 5 Results of the direction-finding analysis at STEREO A and B and at *Wind* at 425 kHz for the 29 January 2008 solar type III radio burst. The topmost panels are the derived colatitudinal angles of the radio source relative to the direction of the ecliptic plane (90°). Lower (higher) values correspond the source lying to north (south) of the ecliptic plane. The middle panels are the derived azimuthal angles of the radio source; positive (negative) values correspond to the source lying to the west (east) of the spacecraft – Sun line. The lower panels are the derived source amplitudes, in units of log(sfu) for *Wind* and dB/10 for STEREO. These amplitudes have not yet been corrected for the different distances of the radio source to each of the spacecraft.

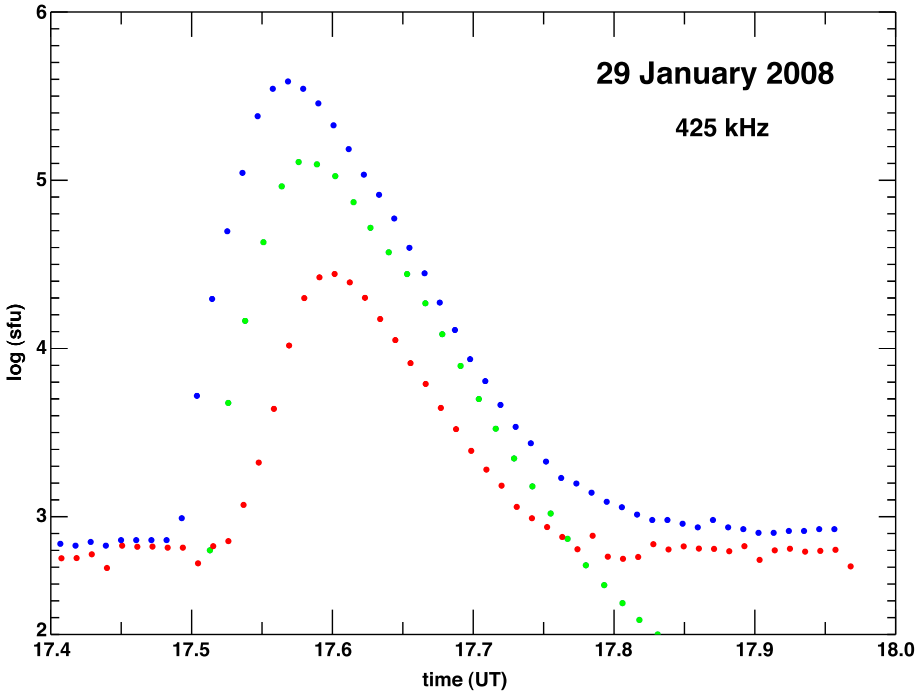

Figure 6 The derived amplitudes observed at STEREO A and B and at *Wind* on 29 January 2008 at 425 kHz. The flux density at *Wind* is given as the green points; the red (STEREO A) and blue points (STEREO B) are the measured amplitudes at the two STEREO spacecraft in units of log(sfu). The algorithms in Equations (A.1) and (A.2) were used to determine the flux densities at the STEREO spacecraft, which have been the corrected for the $1/R^2$ falloff of the radiation intensity in propagating to each spacecraft.

that directly locate radio sources in the interplanetary medium, without the necessity of assuming an interplanetary density model or other assumptions such as that the radio source must lie along a spiral field line from a flare site. We have focused here on using these source locations to obtain information on the intrinsic beaming pattern observed for individual solar type III radio bursts. During this period of solar minimum, there was a paucity of intense type III radio bursts that were observed simultaneously from all three spacecraft. However, an advantage of solar minimum is that those type III bursts that were observed were well-isolated events. In principle, this makes it easier to deduce the intrinsic properties of these events. Nevertheless, we would have preferred to have more events to better reveal the beaming characteristics at consecutively wider spacecraft angular separations, and also to have obtained a larger statistical sample of bursts that may yield additional insights into the details and intricacies of the beaming patterns for type III radio bursts. With our present relatively small sample of bursts and with our limited three-point observations, we can of course determine only the global aspects of the radiation beaming patterns. The global type III beaming patterns deduced here must be considered as including the effects of the finite source size and effects from the scattering of the radiation in the interplanetary medium as it propagates to the observer.

We can combine the results for the beaming patterns derived for the type III bursts observed in December of 2007 and January of 2008, described in Sections 3.1 and 3.2, to deduce information on the global characteristics of the type III beaming pattern over a very

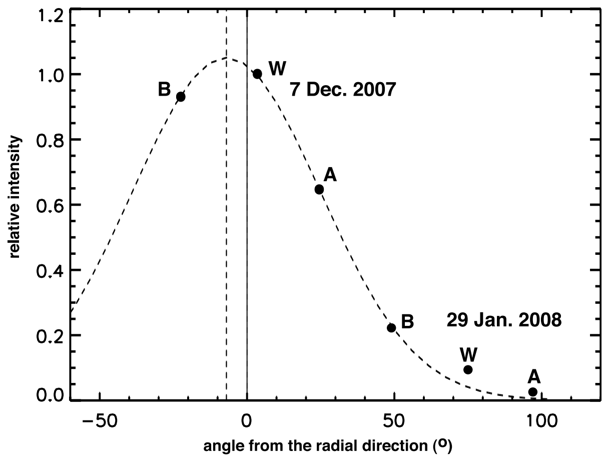

Figure 7 Relative beam intensity as a function of angle from the radial direction through the source location. The dashed vertical line is the spiral angle expected for a source located at about 0.2 AU.

wide angular range. We have plotted in Figure 7 the relative intrinsic intensities of the radiation as a function of the angle to each spacecraft, measured from the radial direction through the triangulated source locations given in Figures 1 and 4. We have fit a Gaussian to the first three points, which are the relative flux densities at each spacecraft measured for the 7 December 2007 radio source as given in Section 3.1. A Gaussian centered along the radial direction clearly does not provide a good fit to these relative intensity measurements. A good fit (dashed curve) is obtained for a Gaussian shifted eastward from the radial direction by about 7°. Since the value of the absolute flux density varies dramatically from one type III radio burst to another, for any given radio event we are at liberty to scale the three relative flux density measurements by any desired factor. In Figure 7, we have therefore decreased the three spacecraft measurements for the 29 January 2008 event, given in Section 3.2, by a scale factor of 0.22. We see that these points then line up reasonably well with the Gaussian beaming pattern fit to the 7 December event, except that the observed beaming may not decrease quite as fast as the Gaussian at these larger angles from the radial direction. Nevertheless, these results indicate that the global beaming pattern for type III radio bursts may be reasonably well represented by a Gaussian that is skewed toward the east, as would be expected if the radiation were beamed along the Parker spiral magnetic field lines. For the Parker spiral corresponding to a solar wind speed of 400 $\mathrm{km\,s^{-1}}$, the deviation of the angle tangent to the spiral from the radial direction is about 10° at about 0.2 AU, which is close to the angle deduced from the results in Figure 7. Interestingly, we have previously used such a skewed Gaussian beaming pattern in modeling the radiation from the finite type III source region (Reiner and Stone, 1989).

Although we have generally found that the temporal variations of the type III burst intensity profiles, viewed from the widely different perspectives provided by the STEREO and *Wind* spacecraft, were remarkably similar even in the small details, there are also notable exceptions. One example is the type III burst observed on 23 May 2007, whose intensity profiles are shown in Figure 8. At that time, the angular separation between the STEREO spacecraft was only about 7°. To better compare these three amplitudes, we have in this case arbitrarily shifted the event times such that the initial rise time is the same for each burst. As before, the STEREO amplitudes were converted to sfu using Equations (A.1) and (A.2). For this burst, although the initial rise and first peak intensities are identical, as observed from STEREO A and B, the second peak and the decaying portion of this burst exhibits significant systematic differences – while the peak time and shape of the intensity profile are

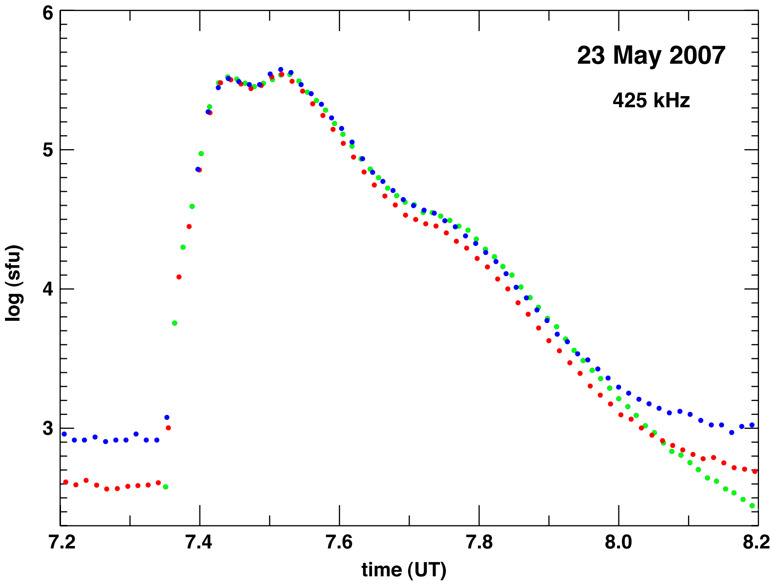

Figure 8 The derived flux densities observed at STEREO A and B and at *Wind* on 23 May 2007 at 425 kHz. The flux density at *Wind* is given as the green points. The red (STEREO A) and blue points (STEREO B) are the measured amplitudes at the two STEREO spacecraft in units of log(sfu). The algorithms in Equations (A.1) and (A.2) were used to determine the flux densities at the STEREO spacecraft, which have been corrected for the $1/R^2$ falloff of the radiation intensity in propagating to each spacecraft. We have arbitrarily shifted the event times such that all three bursts have the same onset times.

the same, the overall intensity observed at STEREO A is clearly lower than that observed at STEREO B. The *Wind* burst profile coincides with that at STEREO B. The slightly lower intensity observed from STEREO A is also not constant with time or intensity; it is lower by about 0.25 dB at the peak and by about 1.25 dB over the latter part of the decaying portion of the burst. We do not yet have an explanation for these systematic differences. For this event, the radio source centroid does drift to the west during the second portion of the burst, from W1° to about W3° as view from *Wind*. If anything, we would have expected that this would have increased, not decreased, the intensity at STEREO A. Perhaps there is some blockage of the radiation as it propagates to STEREO A by intervening high-density interplanetary structures. Alternatively, the beaming pattern may not be a smooth function, such as indicated by the (oversimplified) elliptical representations presented in Figures 1 and 4. The type III beaming patterns may have a more complex shape that is related to the plasma density variations and structures in the interplanetary medium. Clearly, more analysis is required on many more bursts to better understand the origin of such intensity differences.

The results presented here are preliminary in several aspects. *i*) We have considered only 2-D triangulation. This was justified in these cases because the colatitudinal angles for the radio sources were very close to 90°. Our triangulation techniques are being generalized to 3-D triangulation, which is a little more complicated. *ii*) The actual derived source direction angles depend to some extent on the relative effective electrical lengths of three monopole antennas. We are not yet sure that we have the "best" values for the electrical lengths for the individual antennas, which of course are different for each STEREO spacecraft. *iii*) The intercalibration between STEREO and *Wind* is also a little unsatisfactory at present. We are currently studying ways to improve on that intercalibration and to extend the technique to frequencies that are not common to the STEREO and *Wind* receivers, as well as to include the effects of possible temperature dependencies. Given our present estimates of the uncertainties in the derived STEREO azimuthal angles, at this stage the preciseness of the triangulated source locations, for the two examples given in Sections 3.1 and 3.2, have to be considered as being somewhat fortuitous. *iv*) We are also studying new ways to improve the stability of the direction-finding fitting procedures. *v*) Finally, we are studying different techniques for achieving the background subtraction that is necessary for obtaining accurate source directions for some of the weaker type III bursts observed from the STEREO spacecraft.

In all these analyses, we have assumed that the radiation intensity falls off as $1/R^2$ as it propagates from the radio source region to the observing spacecraft. Although this is clearly expected for a point source, the type III radio sources observed at these low frequencies are relatively large, with typical angular width measured from the spacecraft being 10° to 20°. Consequently, the assumption of a $1/R^2$ fall off may not be quite correct for these finite source regions. Further studies of the intensities observed from these three-point observations should provide further insights on this issue. Whereas we have corrected the flux densities derived for the different distances from the triangulated source locations to each spacecraft, we have not examined in detail here the differences in the radio propagation times. The study of these propagation time differences will be the subject for a future paper.

Acknowledgements The STEREO/WAVES and *Wind*/WAVES experiments are a collaboration of NASA Goddard Space Flight Center, the Observatoire of Paris – Meudon, the University of Minnesota, and the University of California, Berkeley. The French part of SWAVES was supported by CNES and CNRS.

Appendix

To measure the radiation beaming patterns and other intrinsic properties of type III radio bursts, it is necessary to first intercalibrate the radio receivers on all three spacecraft: STEREO A and B and *Wind*. The solar flux units ($1\ \text{sfu} = 10^{-22}\ \text{W}\,\text{m}^{-2}\,\text{Hz}^{-1}$) corresponding to the voltage outputs of the *Wind* spacecraft receivers were previously determined from pre-launch measurements of the dipole antenna lengths, from the measured antenna and antenna base impedances, and from a number of other quantities such as the receiver internal gains and reference voltages. The absolute calibration for the STEREO receivers can be achieved in the same way (Eastwood *et al.*, 2009). However, this case is a little more challenging because for the short (6 m) monopole antennas on the STEREO spacecraft the electrical lengths and effective direction angles of the individual antennas are significantly modified by the presence of the conducting spacecraft body. The electrical parameters of the individual antennas for STEREO A and B have been estimated from rheometry measurements on a scale model of the spacecraft and from computer modeling (Rucker *et al.*, 2005; Bale *et al.*, 2008). For example, although the physical length of the three monopole antennas on each STEREO spacecraft is 6 m, the electrical lengths of the antennas is only about 1 m, and that value differs somewhat for each of the three orthogonal antennas. Similarly, the effective antenna direction angles are displaced significantly from the physical antenna orientations. These effective antenna parameters must be accurately known for each of the monopole antennas for determining the flux density of the observed radio sources and for deducing the direction of arrival of the incident radiation. Furthermore, since any given (electrical) monopole antenna is generally not aligned perpendicular to the incoming wave from the radio source, the full direction-finding analysis must be performed to correctly derive the flux density of the source.

To compare the STEREO receiver outputs to *Wind*, the raw telemetry values must first be converted to physical voltage units. The technique for doing this is well established and has been used on many previous space missions, including *Wind*. For the STEREO receivers (Maksimovic, 2007), there is known to be a slight dependence on the ambient temperature and on the different power converters used. For this initial investigation, we used the ground calibration tests that were performed just before launch and that used the in-flight power converters, and we ignored any temperature dependencies. This initial calibration then gives the dB voltage values, shown in the bottom panels of Figures 2 and 5, from the raw telemetry values.

Since inaccurate values for the absolute calibrations of the measured fluxes observed at the STEREO and *Wind* spacecraft may lead to erroneous conclusions about the spatial variations of the intrinsic source parameters, such as the radiation beaming pattern, we must also accurately intercalibrate the physical radio source intensity units measured at STEREO A and B to those measured at *Wind*. The approach that is adapted here is to directly intercalibrate the STEREO receiver voltage outputs to the flux densities measured by the well-calibrated receivers on the *Wind* spacecraft by comparing type III radio bursts observed when all three spacecraft were close together. This method has the advantage that it does not depend critically on the uncertainties in the measured values of the antenna and antenna base capacitances and other electrical parameters that determine the voltage output of the receivers on STEREO. However, the method does depend on having accurate values for the relative electrical antenna lengths and orientations. In principle, this technique guarantees that the correct relative flux densities will be measured between STEREO and *Wind*.

It would have been desirable to perform the STEREO – *Wind* intercalibration near the beginning of the STEREO mission when all three spacecraft were very close together, as this would guarantee that any given type III radio source would be observed from exactly the same perspective at each spacecraft. It is unfortunate that the STEREO radio receivers were not switched to the present direction-finding configuration until 3 May 2007, about six months after launch. Consequently, we can only use type III radio events observed after that time to intercalibrate STEREO and *Wind*. The first intense type III event was observed on 19 May. By that time, the STEREO spacecraft were already separated by about 7°, relative to the Sun. We have found that even for this small separation angle between the STEREO spacecraft, small but significant differences were often observed in the radiation characteristics of some of the type III radio sources, such as shown in Figure 8. However, since the radiation beaming pattern is known to be very broad, it is expected that these differences will be minimal for type III sources located near the central meridian from where the radiation is beamed more or less directly to the three relatively close observing spacecraft. More significant differences are expected, and are often observed, for the measured beaming characteristics for sources that lie significantly to the east or west of the central meridian, when only the edge of the beaming pattern is generally observed. Thus it is best to avoid using far eastern or far western events for the three-spacecraft intercalibration. This requirement severely limits the number of type III bursts that can be used for the intercalibration, since most of the bursts observed during this time period were far eastern events that originated from active regions near or beyond the eastern limb, as viewed from Earth. Fortunately, at least the radio sources corresponding to the initial parts of the 19 and 23 May 2007 type III events were located very near the central meridian. We have therefore chosen these bursts to intercalibrate STEREO and *Wind*. These were the only intense radio sources that were found to lie near the central meridian during this time period.

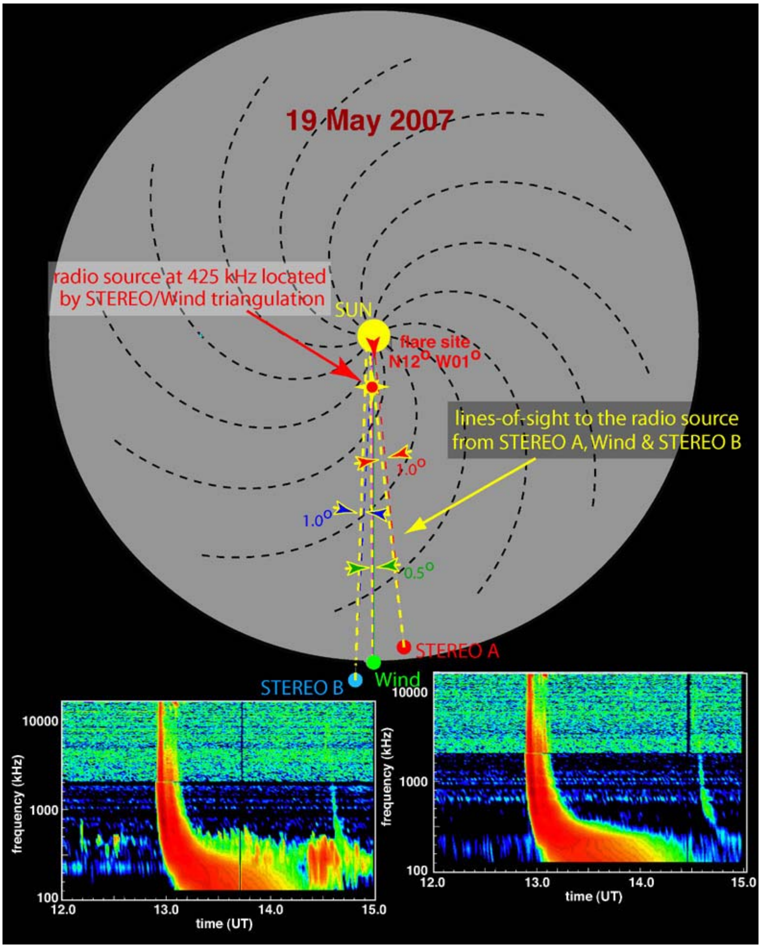

Figure 9 The locations of the STEREO A (red), STEREO B (blue), and *Wind* (green) spacecraft relative to the Sun on 19 May 2007, as observed from above the ecliptic plane. Dynamic spectral representations of a type III burst, observed essentially simultaneously at about 13:00 UT by STEREO A and B, are also shown. The frequency range extends from 100 kHz to 16.025 MHz and the time from 12:00 to 15:00 UT. (Note that STEREO B, being on the night side of Earth also observed some bursty AKR radio emissions from Earth, centered at about 300 kHz.) The yellow dashed lines are the line-of-sight directions to the radio source at 425 kHz from each of the spacecraft. These directions were derived from the direction-finding analyses for this type III radio burst. The actual radio source location at this frequency is the intersection of these three line-of-sight directions.

The intense type III radio burst observed at about 13:00 UT on 19 May 2007 was associated with a B9.5 soft X-ray flare, with maximum intensity at 13:02 UT. It occurred in the solar active region NOAA 0956 at about N12°W01° (*i.e.*, at the central meridian). The two dynamic spectra in Figure 9 show that this type III burst was viewed essentially simultaneously at the STEREO A and B spacecraft in the frequency range from below 100 kHz to 16.025 MHz. The complexity and long duration of this burst suggest that it was the result of several distinct injections of electron beams into the interplanetary medium (Cane *et al.*, 1981; Bougeret *et al.*, 1998; Reiner *et al.*, 2000; Reiner, Kaiser, and Bougeret, 2001).

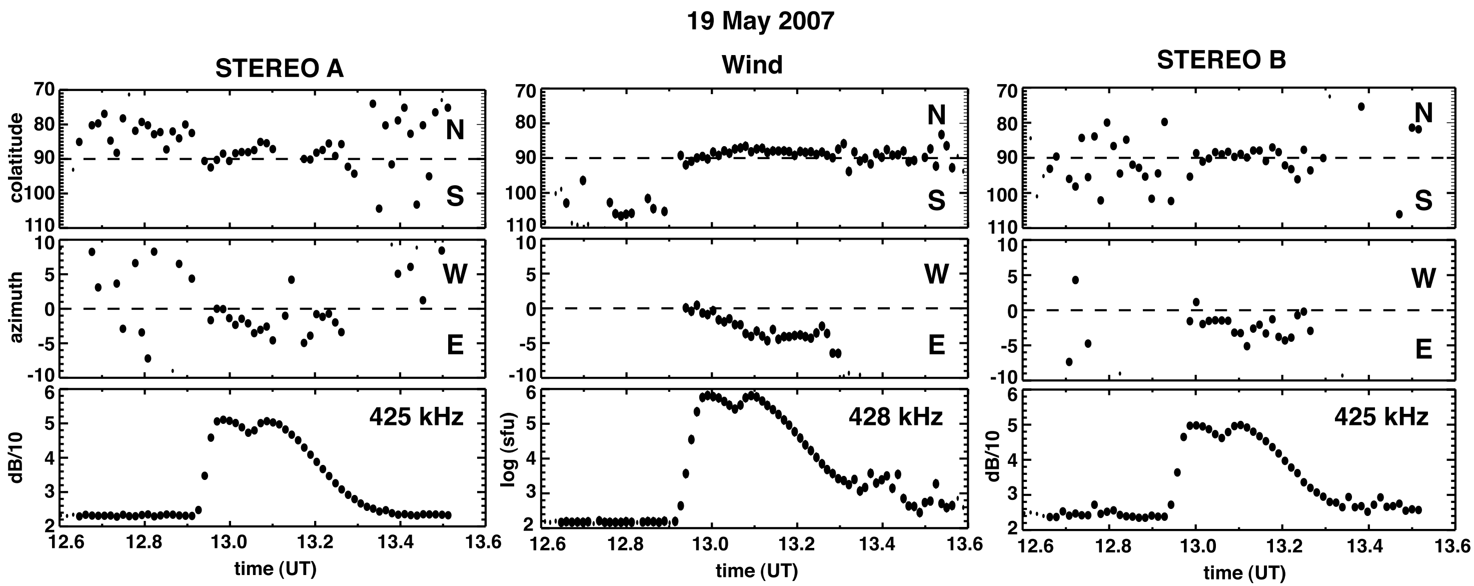

Figure 10 Results of the direction-finding analysis at STEREO A and B and at *Wind* at 425 kHz for the 19 May 2007 solar type III radio burst. The topmost panels are the derived colatitudinal angles relative to the direction of the ecliptic plane (90°). Lower (higher) values correspond to the radio source lying north (south) of the ecliptic plane. The middle panels are the derived azimuthal angles of the radio source; positive (negative) values correspond to the source lying to the west (east) of the spacecraft – Sun line. The lower panels are the derived source amplitudes, in units of log(sfu) for *Wind* and dB/10 for STEREO. These amplitudes, observed at the three spacecraft, have not yet been corrected for the different distances of the radio source to each of the spacecraft.

The direction-finding results for the 19 May event, observed by each of the three spacecraft at their common frequency of 425 kHz, are shown in Figure 10. All three spacecraft observed this radio source to be located slightly north of the ecliptic plane. The azimuthal angle of the source associated with the *initial* part of the burst, which is of interest here, was located to within 1° of the central meridian. The average of these derived azimuthal angles, measured during the first peak of this complex type III burst, are displayed by the (yellow) lines of sight in Figure 9. The radio source, located at the intersection of the three lines of sight, is clearly near the central meridian and at a heliocentric distance of about 0.2 AU.

As is the case here, the azimuthal angles for type III radio bursts often vary significantly with time over the duration of the burst; the source associated with the second peak of the 19 May event was located at an angle of 3.5° east of the central meridian from *Wind*. These temporal variations can be due to the finite size of the radio source region, to multiple electron injections, and/or to scattering of the radiation in the interplanetary medium (Reiner and Stone, 1989; Reiner, 2001). Further analysis of the time variations of the radio source azimuths and the corresponding triangulated source locations will be presented elsewhere.

Having located the radio source in the ecliptic plane by the three-spacecraft triangulation, on Figure 11a we display the three derived amplitudes, which were corrected for the different distances from the source to each spacecraft, by assuming a $1/R^2$ falloff of the radiation intensity. (Note that STEREO B was at a heliocentric distance of about 1.057 AU, while STEREO A was at 0.96 AU at this time.) The distances from the radio source to STEREO A, *Wind*, and STEREO B were estimated to be 0.75, 0.79, and 0.85 AU, respectively. The flux densities shown in Figure 11a are given as log of solar flux units for *Wind*, whereas the results for the STEREO spacecraft are simply expressed in the output voltage units in dB/10. Note that the STEREO A and B amplitudes are essentially equal after the $1/R^2$ distance effects are taken into account, indicating that, after the initial calibrations, the STEREO A and STEREO B receivers are well matched. To facilitate comparison of the different burst profiles, on this figure we have arbitrarily shifted the event times such that the rise time is the same at each of the three spacecraft.

The way that we achieve the intercalibration between STEREO and *Wind* is to simply map the dB values measured at STEREO to the corresponding measured solar flux values from *Wind*. We do this by requiring that the flux densities measured during the rising portions and at the initial peaks of the 19 and 23 May 2007 type III bursts (in Figures 8 and 11), associated with the radio sources located near the central meridian, should give the same flux density at each spacecraft, to within the measurement uncertainties. Figure 12 shows the relationship between the STEREO dB values and the *Wind* solar flux values determined for the initial component of these two type III events. A linear relationship is expected since $\log(\mathrm{sfu}) \propto 2\log V \propto \mathrm{dB}/10$, where V is the voltage measured on the antenna. Specifically, the linear relationships for STEREO A and B that provides the desired mapping were found to be

$$\log(\mathrm{sfu})_{\mathrm{STEREO\,A}} = 1.072(\mathrm{dB}/10)_{\mathrm{STEREO\,A}} + 0.423 \tag{A.1}$$

for STEREO A and

$$\log(\mathrm{sfu})_{\mathrm{STEREO\,B}} = 1.086(\mathrm{dB}/10)_{\mathrm{STEREO\,B}} + 0.365 \tag{A.2}$$

for STEREO B. These equations then allow one to convert the STEREO dB measurements directly in solar flux units that, by construction, are consistent with the flux densities measured at *Wind*, without requiring knowledge of the antenna impedances or the measured

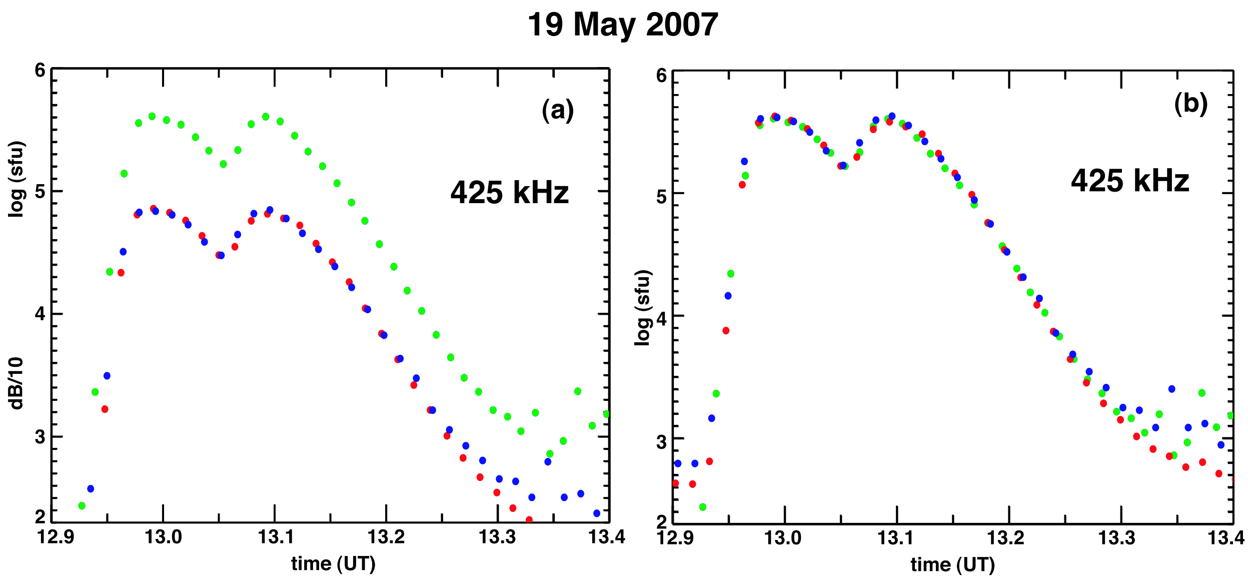

Figure 11 The derived amplitudes for the type III radio burst observed at STEREO A and B and at *Wind* on 19 May 2007 at 425 kHz. (a) The flux density at *Wind* is given as the green points, in units of log(sfu). The red (STEREO A) and blue points (STEREO B) are the measured amplitudes at the two STEREO spacecraft in units of dB/10. Note that the amplitudes at STEREO A and B are nearly identical, indicating a well-matched pair of receivers on STEREO A and STEREO B. (b) The flux densities at all three spacecraft, where the algorithms in Equations (A.1) and (A.2) were used to determine the flux densities at the STEREO spacecraft, after these flux densities had been corrected for the $1/R^2$ falloff of the radiation intensity in propagating to each spacecraft. Note that the intensity of the first peak of this complex type III burst, whose source is located near the central meridian, is the same for all three spacecraft (by construction). Also note that there are some slight, but significant, differences in the flux densities measured after the first peak at the three different spacecraft, even though the angular separation between the STEREO spacecraft was only 7° at that time.

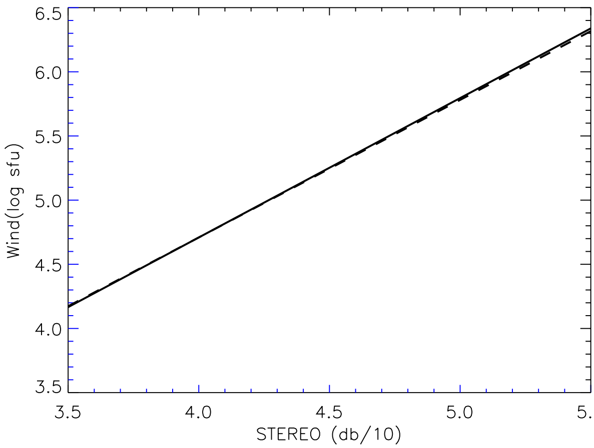

Figure 12 The intercalibration of the measured flux densities between STEREO A (solid) and B (dashed) and *Wind*. These data were obtained from the measured amplitudes at the initial peaks for the type III bursts observed on 19 and 23 May 2007.

reference voltages on STEREO. Applying Equations (A.1) and (A.2) to the STEREO amplitudes in Figure 11a, we obtain the flux densities at the three spacecraft shown in Figure 11b. These three amplitudes are clearly identical during the rising portion and at the initial peak of this type III burst, indicating that the STEREO and *Wind* receivers are now properly intercalibrated. Figure 8 shows similar results for the 23 May 2007 type III burst.

Note that although the rising portions and initial peaks exactly coincide (by construction), there are already some, relatively minor, but significant, differences in the second peak and in the decaying portion of the burst in Figure 11b, even for this small angular separation among the three spacecraft. Figure 8 gives an even more striking example. There obviously is no way to simultaneously match the two peaks of these bursts at all three spacecraft.

Having successfully intercalibrated the STEREO and *Wind* radio receivers, we can now proceed with some confidence to compare the flux densities for different type III events that were simultaneously observed for widely different angular separations of the STEREO spacecraft, such as given in Sections 3.1 and 3.2.

References

Bale, S., Reiner, M.J., Bougeret, J.-L., Kaiser, M.L., Krucker, S., Larson, D.E., Lin, R.P.: 2008, *Space Sci. Rev.* **136**, 529.

Bonnin, X., Hoang, S., Maksimovic, M.: 2008, *Astron. Astrophys.* **480**, 419.

Bougeret, J.-L., Fainberg, J., Stone, R.G.: 1984, *Astron. Astrophys.* **141**, 17.

Bougeret, J.-L., Kaiser, M.L., Kellogg, P.J., Manning, R., Goetz, K., Monson, S.J., Monge, N., Friel, L., Meetre, C.A., Perche, C., *et al.*: 1995, *Space Sci. Rev.* **71**, 231.

Bougeret, J.-L., Zarka, P., Caroubalos, C., Karlický, M., Leblanc, Y., Maroulis, D., Hillaris, A., Moussas, X., Alissandrakis, C.E., Dumas, G., Perche, C.: 1998, *Geophys. Res. Lett.* **25**, 2513.

Bougeret, J.-L., Goetz, K., Kaiser, M.L., Bale, S.D., Kellogg, P.J., Maksimovic, M., Monge, N., Monson, S.J., Astier, P.L., Davy, S., *et al.*: 2008, *Space Sci. Rev.* **136**, 487.

Cane, H.V., Stone, R.G., Fainberg, J., Steinberg, J.L., Hoang, S., Stewart, R.T.: 1981, *Geophys. Res. Lett.* **8**, 1285.

Cecconi, B., Zarka, P.: 2007, *Radio Sci.* **42**, RS2003.

Cecconi, B., Bonnin, X., Hoang, S., Maksimovic, M., Bale, S.D., Bougeret, J.-L., Goetz, K., Lecacheux, A., Reiner, M.J., Rucker, H.O., Zarka, P.: 2008, *Space Sci. Rev.* **136**, 549.

Dulk, G.A., Goldman, M.V., Steinberg, J.L., Hoang, S.: 1987, *Astron. Astrophys.* **173**, 366.

Eastwood, J.P., Bale, S.D., Maksimovic, M., Goetz, K., Kaiser, M.L., Bougeret, J.-L.: 2009, *Radio Sci.* doi:10.1029/2009RS004146.

Fainberg, J., Stone, R.G.: 1970, *Solar Phys.* **15**, 433.

Fainberg, J., Evans, L.G., Stone, R.G.: 1972, *Science* **178**, 743.
Fitzenreiter, R.J., Fainberg, J., Bundy, R.B.: 1976, *Solar Phys.* **46**, 465.
Fitzenreiter, R.J., Fainberg, J., Weber, R.R., Alvarez, H., Haddock, F.T., Potter, W.H.: 1977, *Solar Phys.* **52**, 477.
Ladreiter, H.P., Zarka, P., Lecacheux, A., Macher, W., Rucker, H.O., Manning, R., Gurnett, D.A., Kurth, W.S.: 1995, *Radio Sci.* **30**, 1699.
Maksimovic, M.: 2007, Calibration of flight models 1 & 2 of STEREO/WAVES, LESIA, Meudon, Internal Report.
Manning, R., Fainberg, J.: 1980, *Space Sci. Instrum.* **5**, 161.
Reiner, M.J.: 2001, *Space Sci. Rev.* **97**, 129.
Reiner, M.J., Stone, R.G.: 1986, *Solar Phys.* **106**, 397.
Reiner, M.J., Stone, R.G.: 1989, *Astron. Astrophys.* **217**, 251.
Reiner, M.J., Fainberg, J., Stone, R.G.: 1995, *Science* **270**, 461.
Reiner, M.J., Kaiser, M.L., Bougeret, J.-L.: 2001, *J. Geophys. Res.* **106**, 29989.
Reiner, M.J., Fainberg, J., Kaiser, M.L., Stone, R.G.: 1998, *J. Geophys. Res.* **103**, 1923.
Reiner, M.J., Karlický, M., Jiřička, K., Aurass, H., Mann, G., Kaiser, M.L.: 2000, *Astrophys. J.* **530**, 1049.
Rucker, H.O., Macher, W., Fischer, G., Oswald, Th., Bougeret, J.L., Kaiser, M.L., Goetz, K.: 2005, *Adv. Space Res.* **36**, 1530.
Weber, R.R., Fitzenreiter, R.J., Novaco, J.C., Fainberg, J.: 1977, *Solar Phys.* **54**, 431.