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Same-Beam Tracking with the Proposed DSN Array Using a Calibration Signal from Multiple Sources Simultaneously

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The accuracy of tracking measurements using very long baseline interferometry (VLBI) is seriously limited due to angular and temporal separation between the calibration and spacecraft measurements. Same-beam interferometry, in which the calibration source is in the same primary beam as the spacecraft being observed, eliminates temporal effects and, because of the reduced angular separation between the calibrator and the spacecraft, considerably reduces calibration errors.

With the current measurement methods, this requires having a suitable calibration source with enough signal strength within the primary beam of the antennas used for the interferometry measurements. Normally such sources are not available because of the low density number of suitable strong calibration sources. However, there are many more weaker calibration sources, and it may be possible to use a combined signal from a number of weaker sources within the primary beam of the antennas if a single strong source is not available within the primary beam at any time. The probability of having enough combined total signal increases considerably if we accept using multiple calibration sources. The expected accuracy of a tracking measurement using a signal from multiple calibration sources should be similar to the accuracy expected with a single calibration source within the beam, if the total combined signal from the individual weaker sources is similar to the desired single source.

An important point that is worth noting here is that if we want to take advantage of utilizing same-beam interferometry for accurate spacecraft tracking most of the time, then the diameter of the DSN Array antennas should be limited to as small a value as practical to give a large field of view. This will enable having suitable calibration source(s) within the primary beam of the antennas. Considering practical aspects, it appears that the diameter for a DSN Array antenna should be limited to a maximum of about 12 m.

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I. Introduction

There are a number of factors that limit the accuracy of spacecraft angular position measurements made using very long baseline interferometry (VLBI). VLBI measurements are used to determine the relative angular position of a spacecraft with respect to a compact calibration radio source, and therefore one of the factors determining the accuracy is knowledge of the exact position of the calibration source. This can be improved considerably by making multiple measurements. Other principal reasons for errors in accuracy, apart from signal-to-noise ratio (SNR) for the measurements, are variations in propagation path lengths for the signals arriving at the VLBI antennas, instrument changes due to temporal and spatial (angular) separation between the measurements of the reference source and the target spacecraft, and knowledge of the exact observing geometry of the antennas with respect to the source (Earth orientation, locations of the VLBI antennas and their axes of rotations, etc.). Using a calibrator in the same primary beam as the spacecraft allows simultaneous observations of the calibrator and the spacecraft, and minimizes angular separation between the calibrator and target, reducing effects due to lack of knowledge of the exact geometry of the observations. This is normally referred to as same-beam tracking or in-beam interferometry for tracking. It minimizes major calibration errors and, therefore, provides a potential approach for very accurate relative angular position measurement accuracy.

Same-beam tracking requires that the calibrator have sufficient signal strength to provide enough SNR in each observation to allow such measurements. Therefore, it depends on the availability of a suitable calibrator within the antenna primary beam. For the DSN Array [1], which has a 70-m equivalent G/T, where G is antenna gain and T is system temperature, in the initial build, a VLBI compact source of at least about 1 mJy is required for the calibration.

Current plans for the DSN Array [1] call for building sensitivity equivalent to a 70-m antenna, expressed as G/T, at each of the three DSN sites, using small antennas. It is estimated that using antennas with sizes less than 12 m in diameter increases the array cost because of the increased cost of electronics. With antennas larger than about 18 m in diameter, the cost of the antennas starts dominating the array cost. For a given sensitivity, the cost of an array as a function of antenna size has a broad minimum, and it is in the range of 12 m to 18 m in diameter. For spacecraft-tracking measurement purposes, antennas with smaller apertures seem to be favored. This is because smaller antennas have larger primary beams, which increases the probability of having a suitable calibration source in the primary beam of the antennas while pointing at the spacecraft, thus enabling accurate spacecraft-tracking measurements. Therefore, we will assume here that the DSN Array would use 12-m antennas.

The probability of having a suitable calibration source of sufficient strength (flux density $\sim$1 mJy, where a jansky (Jy) $= 10^{-26}\ \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{Hz}^{-1}$, required for spacecraft angular position calibration) in a 12-m antenna primary beam at 8.4 GHz (X-band) for tracking applications using VLBI is $\gtrsim$20 percent [2]. Since the spacecraft is a moving target in the sky, by scheduling the measurements at appropriate times, it may be possible to ensure having a suitable calibration source within a primary beam. However, it will be progressively harder to schedule such observations as a spacecraft's destination moves farther away from Earth, especially to Jupiter and beyond. This is because the angular motion of the spacecraft (say, per day) in the plane of the sky starts becoming less important as compared with the primary beam of the antenna. Therefore, it is important to avoid depending on motion of the spacecraft's angular position in the sky to schedule the observations.

If a strong enough calibration source is not available in the primary beam of the antennas and we wish to make a spacecraft position measurement using same-beam interferometry, then it should be possible to use a combination of many less strong sources in the beam for the calibration of spacecraft position, and it may be possible to do so at any time with the DSN Array using 12-m antennas as array elements.

II. Concept

If a compact enough radio source with adequate signal strength (a flux density, say, of >1 mJy) is not available within the same primary beam of the 12-m antennas at X-band as the spacecraft for spacecraft-tracking measurements employing same-beam interferometry, then it may be worth considering using combined signals from several discrete sources in the beam to make the measurement. A similar approach has been used in radio astronomy by Garrett et al. [3]. What is required is enough total flux density from all the calibration sources within the primary beam to be at least as much as that desired from a single source that could be used for the calibration. Each of these weaker sources should be stronger than a certain minimum flux density so that it can be detected in the overall available observing time to determine its flux and position/structure (say, $\sim$100 μJy), although this can be done in advance of a spacecraft observation pass. Furthermore, each of these sources should be compact, on the scale of the spacecraft angular measurement accuracy desired, for use as a calibrator; otherwise, measurements with just one baseline are not enough, and also the complexity of the analysis increases. Normally with the way we currently make such measurements, all sources except the strongest one contribute to confusion in the measurements of the strongest source. However, if we know the flux density and position (structure) of each source whose combined signal is to be used, then in the calibration process we can use an image of the region (containing these sources) instead of what is done normally, namely, using the position of a single source. Extended sources are quite often used for calibration purposes in radio astronomy, especially in "self-calibration" applications, and multiple sources can be viewed as an extended source with multiple discrete components. The accuracy of a spacecraft angular position measurement using this approach will depend on the accuracy of the image used for the calibration.

III. Requirements

Same-beam tracking measurements using combined signals from multiple sources will require accurate knowledge of the positions and flux densities (structures) of all the calibration sources. However, we can do that in advance, as mentioned earlier. This may work as follows: First, find out the rough positions and structures of individual sources using the DSN Array or Very Large Array (VLA) or some similar instrument, and then make VLBI measurements to find their positions/structures accurately. Multiple combiners at each VLBI site will be required, but that is not a limitation since we are already planning multiple combiners (perhaps 16) at each site for the DSN Array.

For correlating VLBI signals from multiple sources, we may have to generate a phased array signal for each source at each VLBI site based on geometry and initial calibration of the antennas at the site. Then the phased array signals from various combiners (beams) from each site have to be brought to the correlator, where cross-correlation signals can be generated for each source using the corresponding combiner signals from each site. This will increase the signal bandwidth to be transported and the correlation requirements to N times over what is required for one source, where N is the number of sources used for the calibration.

The array signal processing should be capable of phasing each beam of the array separately over the entire signal bandwidth, 0.5 GHz per antenna intermediate frequency (IF). This is not an additional requirement because this capability is also required for phasing of the telemetry signals over the full bandwidth from each of the multiple spacecraft in the beam simultaneously.

We are going to use the entire IF bandwidth of 500 MHz for each IF signal for the radio sources, but the spacecraft signal may be narrowband if the broadband telemetry is not implemented. Even if broadband telemetry is used for the spacecraft measurements, there may still be errors due to different bandpass shapes for the signals from the antennas in the beam-former sum. To eliminate this source of error, bandpass corrections may be important. This could be easily done prior to VLBI observations by using a strong nearby calibration source and calibrating the bandpass for each antenna and then using that for correcting the bandpass effects for each antenna signal before combining in the beam combiner.

IV. A Possible Methodology for Making the Same-Beam Tracking Observations

The phase referencing measurements for determining positions and flux densities of calibration sources down to 100 μJy may take a few hours (roughly 8 to 10 hours) of VLBI observation using a system having a bandwidth of 500 MHz and sensitivity equivalent to a pair of 70-m antennas making VLBI measurements. In terms of signal-to-noise ratio considerations, the amount of time could be reduced if we increase the system bandwidth, but from the point of view of determining the structures of sources, it may still be desirable to have as much spatial frequency (UV) coverage as possible.

One possible way to determine positions and fluxes of all the calibration sources in a primary beam is by using phase referencing VLBI observations of the sources in the beam with respect to a catalog source nearby. First, determine the position of the strongest source in the primary beam, using standard phase referencing observations, and then use the position of this source to determine accurate positions of other weaker sources in the beam, using longer integration and assuming the same variations for the instrument and atmosphere for all the other sources in the beam. It means there should be at least one source of enough signal strength within the primary beam of the antennas to make phase-referencing measurements with respect to a nearby known catalog calibrator in a short enough period that atmospheric and instrumental phase variation are not important for the phase referencing. Once that is done, longer integrations can be used for other weaker sources by using this as a reference source and assuming the same phase variations for all the sources in the field. This implies a minimum field of view (maximum antenna element size) for a given overall sensitivity. For a 70-m equivalent G/T at each of the two VLBI sites using 500 MHz over all bandwidths, this requires about a 0.3-mJy source for phase-referencing observations using a 100-s integration. Based on the source count [4], to have at least one 0.3-mJy source per beam would require a minimum beam size of about 120 sq. arcmin (at X-band) or a maximum diameter for antennas of about 12 m. This suggests that, if we want to use this approach, the maximum size of DSN array antennas should not exceed about 12 m in diameter, assuming a coherence time of about 100 s.

An initial, approximate estimate based on radio source count from Fomalont et al. [4] suggests that at any time there should be a flux density of at least about 1 mJy in sources stronger than 100 μJy in a primary beam of a 12-m antenna at X-band. However, it is not clear what fraction of this will be in sources compact enough to use for calibration purposes.

It should take only a few minutes of observing time for the DSN Array (with two stations, each with a 70-m equivalent sensitivity) to actually measure a spacecraft position relative to the calibration sources, assuming 1 mJy of signal from suitable calibration sources in the primary beam of the antennas.

It is possible that some of the 1-mJy flux density in the area of a 12-m antenna primary beam is from sources that are not suitable for the calibration. This is because at such low flux densities (0.1 mJy) the contribution to the radio source count may be increasing from star-forming galaxies, which may be extended sources, instead of from active galactic nuclei, which normally are compact sources. However, even if only half of this signal is from sources compact enough to be suitable for calibration, it may still be all right because it should still be possible to keep the calibration measurement's required observing time to $\lesssim$10 minutes by increasing the signal bandwidth to 1 GHz. A bandwidth of 1 GHz could be achieved by using both polarization signals, each having a bandwidth of 500 MHz, as is being considered for the DSN Array.

The accuracy of a spacecraft position measurement using multiple calibration sources in the primary beam of the antennas should be similar to that of a phase-referencing measurement with a single calibration source of strength equal to that of the total of the flux densities from all the sources used in the calibration process.

V. A Possible Demonstration

It may be worth looking into the possibility of demonstrating this (measuring a spacecraft angular position employing same-beam interferometry and using multiple calibration sources in the array-element beam) with DSN 34-m antennas. This may require choosing an appropriate observing epoch when a spacecraft is close to a group of suitable calibration sources such that all the sources are within the area of sky covered by a primary beam of the 34-m antennas at X-band. Alternatively, we could use a compact source in place of a spacecraft for testing the basic idea of using multiple calibration sources for calibrating a spacecraft position.

Initially we could use only one 34-m antenna at each VLBI site and later employ multiple antennas at each VLBI site for the demonstration experiments. Using multiple antennas at a VLBI site would require using multiple phased-array combiners at that site to take care of delay smearing of the signals for each target direction or devising some other method (such as using multiple narrow bandwidths at each site or transporting multiple data sets to the VLBI correlator) to take care of this aspect.

Another aspect that needs studying is the availability of calibration sources (especially in the 0.1- to 1-mJy flux density range) and their compactness. The number density of sources down to about 0.01 mJy at X-band is known from deep survey observations by Fomalont et al. [4] and others. However, the compactness of these sources for our application is not known and needs to be determined. We are pursuing this aspect with proposals to do test observations using the Very Long Baseline Array and/or the DSN.

VI. Conclusion

An approach for spacecraft angular position measurement at any time with the DSN Array using calibration sources in the same beam (same-beam tracking) has been described. It may take some development work initially to implement this, but we expect it to work.

In the beginning, this approach may be employed only in limited cases because of the effort required to make the image of the field containing the calibration sources for the desired part of the sky and because of the larger data bandwidth and correlation requirements, but as time goes by, these costs should come down due to Moore's law.

First, we should figure out the radio-source number count down to 100 μJy (or so), see how much total useful signal (flux density) is available for calibration purposes in a 12-m antenna primary beam, check if that is adequate, and then proceed further.

An important point that comes from the above discussion is that, to utilize same-beam interferometry to achieve high accuracy for angular measurement of spacecraft position for navigation, the size of the DSN Array elements should be as small as possible. Considering practical aspects (minimizing the array cost), it appears that the antenna diameter should be limited to a maximum of about 12 m.

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