Spacecraft Tracking with the SKA

D.L. Jones[a] *

[a]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA,
dj@sgra.jpl.nasa.gov

The possibility of using the SKA for occasional support of scientific space missions should be considered, along with all other science goals, in the design of the array. The benefits of higher data rates from distant spacecraft during high priority, short duration mission phases can be dramatic, while the technical requirements on the SKA to allow this capability are very few. The most fundamental requirement is coverage of the primary downlink frequencies for deep space missions. Additional benefits can result from real-time high precision angular position measurements of spacecraft. Such measurements allow spacecraft navigation with reduced errors and reduced risk, but require at least some long (thousands of km) baselines.

1. INTRODUCTION

Why use the SKA to track spacecraft? This is not generally considered to be a part of radio astronomy, after all. However, there are multiple precedents for the temporary use of radio astronomy facilities to support scientific space missions, including the use of the VLA during Voyager's flyby of Neptune [1] [7], and the combining of signals from the Parkes 64-m antenna with those from the Deep Space Network (DSN) station at Tidbinbilla [2]. In each of these cases, the goal was to increase the science return from a unique opportunity and a large investment by society in these science missions. Independent of the capabilities of future dedicated spacecraft tracking networks, there will always be situations where additional sensitivity can have a dramatic effect on the scientific value of a mission during short-term, high priority activities. For this reason the ability to track scientific spacecraft with the SKA is important for maximizing the benefit that society gets from its over-all investment in scientific activities.

The same argument can be (and has been) used to justify observing time for radio astronomy experiments on dedicated spacecraft tracking antennas when their sensitivity, frequency coverage, or geographic locations provided a significant increase in the value of the observations. Considering the cost of large radio arrays, whether intended primarily for radio astronomy or for spacecraft tracking, it seems only prudent to allow flexibility for the occasional use of all existing arrays combined. The potential beneficiaries of this flexibility will include deep space missions of NASA, ESA, JAXA, FSA, and other space agencies. Even though the SKA may be used only occasionally for spacecraft tracking support, these occasions are likely to be highly visible and to have great public appeal.

2. TYPES OF SPACE MISSIONS

Planetary exploration missions operate over a huge range of distances and data rates. Many are not constrained by telemetry downlink data rates, but often those at the greatest distances or carrying the most advanced sensors are. Limited sensitivity for telemetry downlink can also have important indirect effects on mission design. As an example, consider a mission to sample the atmosphere of one of the outer planets.

The traditional way to design such a mission is to use an orbiting or fly-by spacecraft to relay data from the atmospheric probes (parachute or balloon suspended, gliders, etc.) to Earth.

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But going into orbit usually requires a very large fuel payload, and flybys tend to stay within sight of any given location on a planet for only brief periods. If scientific data from the atmospheric probes could be received directly on Earth, no data relay would be needed, a single-point failure for the whole mission would be eliminated, and data could be obtained from an arbitrary number of probes on the Earth-facing hemisphere for up to half the planetary rotation period. Figure 1 illustrates the increase in data rates that could be obtained on Earth by using the SKA.

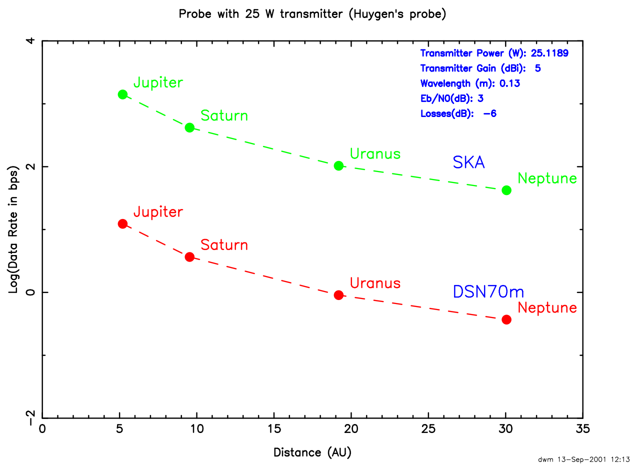

Figure 1. Telemetry downlink data rates to Earth from an atmospheric/surface probe similar to the Huygens probe on the Cassini mission, for each of the outer planets. With the SKA, data rates up to a kb/s can be obtained, while the current DSN 70-m antennas can provide only a few bits/s at best. Figure produced by D. Murphy at JPL.

The potential benefits of SKA spacecraft tracking extend beyond simply obtaining more data from science missions of the type being flown today. New mission concepts, such as large numbers of small, short-lived planetary probes (landers, rovers, or sub-surface penetrators), live video from cameras on planetary balloons or aircraft, constellations of hundreds of tiny in-situ magnetospheric probes, or solar-powered missions beyond the orbit of Mars can only be proposed if the on-board telecommunications hardware is extremely small, light, and low power. More collecting area on the ground is the only way to make innovative missions like these possible.

An additional benefit of using the SKA is that the wide range of baseline lengths required for imaging also provides real-time astrometric position measurements using phase delays. Phase delay is a more sensitive astrometric observable than the group delay currently used for spacecraft position measurement on single DSN baselines. By combining phase-referencing techniques using in-beam reference sources (made possible by the high sensitivity of the SKA) and a large SNR spacecraft signal, it will be possible to routinely determine plane-of-sky spacecraft positions to better than 0.1 milliarcsecond. This angular precision corresponds to a linear distance of less than one km at the distance of Saturn.

3. CURRENT AND PREDICTED DSN CAPABILITIES

The most sensitive current facility for spacecraft tracking is the NASA Deep Space Network, which consists of one 70-m antenna and several 34-m antennas at each of three sites (California, Australia, and Spain). These antennas are being upgraded to operate at frequencies of 32 GHz in addition to the traditional 2.3 and 8.4 GHz bands. It has been recognized for some time that the sensitivity of the DSN needs to be increased by a large factor to properly support future missions. In fact, even some current planetary missions can send back only a small fraction of the data obtained by their instruments due to the limited downlink data rates available.

Two options for increasing DSN downlink capability are being developed: optical communications and large arrays of radio antennas. Optical telecom has the potential to support extremely high data rates, but also has some serious disadvantages: It requires highly accurate and stable pointing of the spacecraft optical system, which precludes use during critical entry, descent, and landing mission phases, or from small unstabilized platforms like balloons or parachute-supported atmosphere probes, or from any type of low gain antenna during a spacecraft emergency. It also requires multiple large ground telescopes (for weather diversity) or dedicated orbiting telescopes for telemetry reception.

As a result of these difficulties, radio is likely to remain the dominant medium for spacecraft telemetry support for the foreseeable future. In support of future radio telecom the DSN plans to build an array of approximately four hundred 12-m diameter antennas at each of their three sites during the next decade. This will provide about an order of magnitude increase in sensitivity over the existing 70-m DSN antennas. However, it is worth noting that this will still be an order of magnitude below the sensitivity of the SKA. Consequently even if the DSN arrays are built before the SKA, there will still be opportunities for the SKA to make very significant contributions to the scientific data return from high priority missions.

4. REQUIREMENTS FOR TELEMETRY RECEPTION

The relevant SKA specifications to enable this type of observing are coverage of the major deep space telemetry downlink frequencies (2, 8, and 32 GHz), coverage of the ecliptic region of the sky, and the availability of a beamformed (summed, with no time averaging) output signal from the inner part of the array. Note that we never want to use the correlator output directly for telemetry reception. We want a vector sum of the (properly aligned) antenna voltages as the basic output, not cross-products. A continuous data stream is needed, since gaps in telemetry data cannot be recovered through additional observing. This is a contrast with normal radio astronomy observing, where all data bits are equal!

There are two scenarios where use of the SKA may be justified - to support very high data rates that enhance the science return during short-duration mission phases (e.g., live video from an airplane in the Martian atmosphere), or to support low data rates from probes that could not otherwise send data directly to Earth at all (e.g., figure 1). These two extremes require different operating modes. For high data rates the SNR of the spacecraft will be large, and real-time signal combining can be done with beamforming hardware alone using algorithms such as SUMPLE (see figure 2); there is no need for a full cross-correlator in this case.

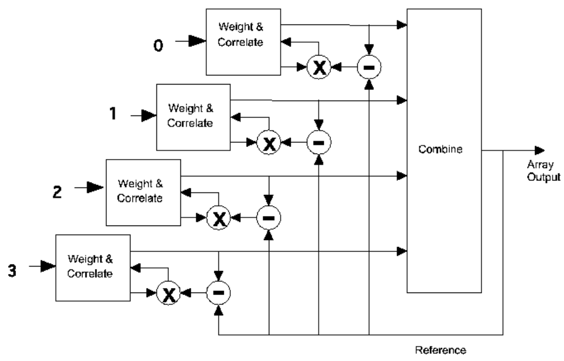

Figure 2. SUMPLE architecture for spacecraft telemetry reception [6]. This is an iterative approach in which each antenna is correlated with the sum of the N-1 other antennas. Experience shows that stable delay and phase solutions are obtained rapidly. No traditional N(N-1)/2 baseline cross-correlator is required. The architecture complexity scales linearly with the number of antennas being combined.

For the low SNR case, it will be necessary to phase the inner part of the SKA using nearby radio sources and a correlator in the usual way, and supply the resulting antenna gain solutions to the beamformer (see figure 3).

5. REQUIREMENTS FOR ANGULAR TRACKING

The ability of connected-element interferometers to provide nearly instantaneous sky posi-

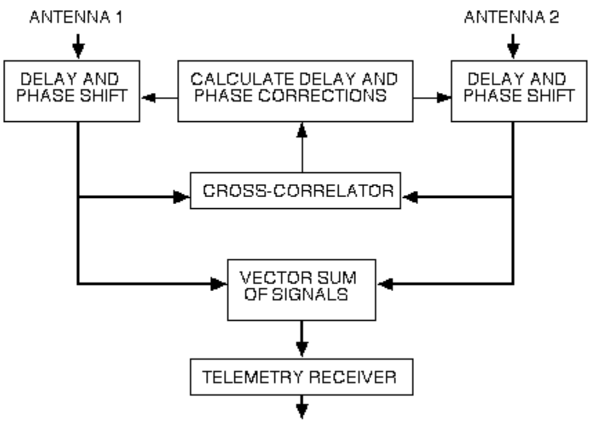

Figure 3. One possible beamformer architecture for low-SNR spacecraft telemetry reception, adapted from [5]. An arbitrary number of antenna signals can be combined with this approach. Note that the correlator output is used only to determine delay and phase corrections needed for coherent signal summing. The output is a vector sum of the input signal voltages, not a cross-correlation product.

tion measurements represents a new capability for spacecraft navigation. Currently the plane-of-sky position of a spacecraft must be deduced from radial (Doppler and range) measurement using a model of the spacecraft trajectory (gravitational field of the solar system). This requires relatively long tracking passes and is susceptible to errors in the model used. Alternatively, VLBI can be used to determine sky positions when a spacecraft transmits a special set of widely-spaced signals to allow group delay measurements. This special mode interrupts normal telemetry transmissions.

Unlike current spacecraft tracking networks that have only single very long baselines, the SKA will have a very large number of baselines covering a wide range of spacings. Although motivated by imaging requirements, this type of array configuration also allows astrometric measurements based on phase delay instead of group delay. Phase delay measurements allow either greater astrometric precision, or similar precision with shorter baselines compared to group delay measurements. The astrometric error from phase delay measurements is related to the ratio of baseline length to the observing frequency, while for group delay this is the baseline length over the bandwidth of the observations. The SKA will have large fractional bandwidths, but this will not reduce the group delay error because the narrow spacecraft signal bandwidth will be the limiting factor.

Another advantage of a connected-element interferometer like the SKA is the speed with which positions measurements can be made. This can be critical during the hours just before a spacecraft arrives at a target, particularly if aerocapture or atmospheric entry is going to be attempted. In addition, the SKA will be able to subdivide or re-use its large collecting area, through sub-arraying or multibeaming (for phased array concepts). This will permit all astrometric measurements to be made in a fully differential mode in which angularly nearby reference sources are used to correct errors caused by imperfect modeling of atmospheric and ionospheric delays or residual baseline offsets. The one remaining significant error source for differential astrometry, phase offsets cause by partially resolved structure in the reference source(s), can be removed because the SKA will be able to produce good, high resolution images of any reference source it observes.

6. UNIQUE ASPECTS OF SKA SUPPORT

In is likely that SKA support of science spacecraft will be infrequent but extremely valuable. The main goal is to allow occasional significant increases in the quantity of (very expensively obtained) data from scientific space missions to be obtained. The fact that the SKA can do this and simultaneously provide accurate plane-of-sky spacecraft positions for navigation is a unique new combination of capabilities.

The large A/T of the SKA can also be used for indirect support of science for space missions. A clear example is atmospheric or ring occultation experiments, where the increased SNR provided by the SKA will allow useful data to be obtained over a much wider range of optical depths.

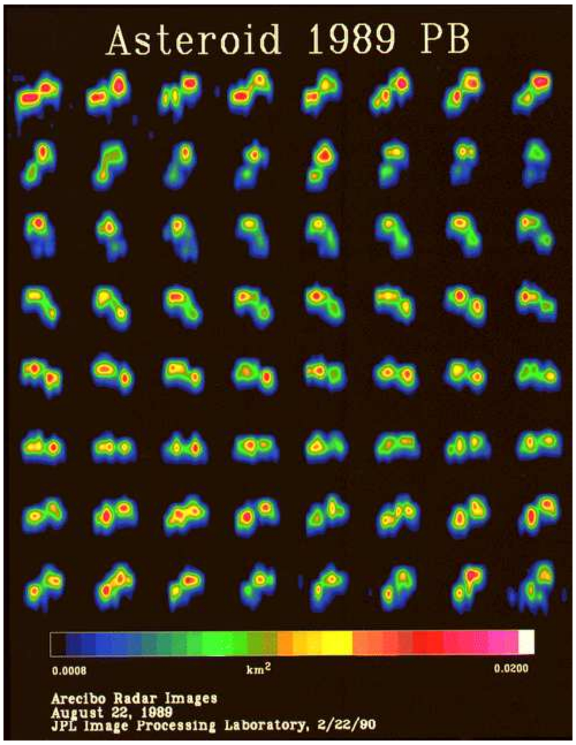

Figure 4. Radar images of an asteroid [4]. The resolution of images like these could be improved by an order of magnitude or more by using the SKA to receive radar echos.

Another area where ground-based collecting area could be particularly valuable is planetary radar (see contribution by Butler, this volume). While not a space mission, this scientific activity addresses many of the same issues of planetary geology and evolution as flight projects do. Planetary radar experiments tend to be SNR-limited (except for radar imaging of very-near-Earth asteroids), so an increase in sensitivity for echo reception would be very valuable. Targets include planets and moons out to the distance of Saturn and Titan, comets, and asteroids. The frequencies used for planetary radar observations are 2.3 and 8.5 GHz.

Radar measurements of the trajectories, sizes, and spin vectors of near Earth asteroids are essential for determining their future orbits accurately, and thus evaluating their potential harzard to Earth. Figure 4 shows an example of delay-Doppler asteroid imaging with the Arecibo planetary radar system. A bi-static radar system using the SKA for reception would significantly increase the available SNR of radar measurements.

The imaging capabilities of the SKA can be applied to radar observations by using the angular resolution of the SKA to resolve the ambiguities that plague traditional delay-Doppler radar imaging. This will permit radar imaging with better angular resolution than the SKA can provide directly [3].

7. EXAMPLES

Examples of the enhanced science return that higher telemetry data rates can enable are easy to think of: movies instead of single images, high resolution mapping and spectra instead of low resolution, mapping of entire planets instead of targeted observations. At the other extreme, critical short-lived mission phases like atmospheric entry, descent, and landing can only use low-gain antennas because of rapid and unpredictable spacecraft motions. In this situation the ability to receive even very small quantities of real-time data could be critical for diagnosing problems. We have learned from past experience how damaging it can be to have no telemetry at all during a critical mission event that resulted in failure. The same applies for a spacecraft emergency during any phase of a mission - the ability to get some data over low-gain spacecraft antennas can be immensely valuable for diagnosing problems and working out recovery procedures.

The flexibility of SKA observing implies that it should be possible to support spacecraft tracking and navigation in a co-observing mode. For example, while looking in the direction of a spacecraft, and array and correlator can be simultaneously used for large scale survey programs. The correlator would operate in its normal imaging mode; all special-purpose signal processing would be done independently by a beamformer.

8. CONCLUSIONS

The public invests in astronomy, and other scientific programs, for the excitement of exploration and discovery and for the chance of answering fundamental questions about the universe and our place in it. Like astronomy, planetary exploration addresses very fundamental questions of broad public interest. To maximize the scientific return from the significant investments in planetary science missions, we need to send as much data back to Earth as possible. This is particularly true for missions with short duration, high priority data-taking phases (e.g., atmospheric or surface probes on Venus, Europa, Io, or other hostile environments). The SKA has the potential to greatly increase the data return from such missions. This is true independent of plans to build dedicated radio arrays for spacecraft tracking or for optical communications, as dedicated tracking arrays are unlikely to come close to the sensitivity of the SKA and optical communications are not possible with low gain antennas or through opaque atmospheres. Occasional use of the SKA for telemetry reception during unique opportunities will contribute dramatically to the total increase in our scientific knowledge and to the public's interest in the SKA.

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