Spacecraft Telecommunications

T. Joseph W. Lazio1 and Sami Asmar1
1Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA; Joseph.Lazio@jpl.nasa.gov

Abstract. There is a long history of radio telescopes being used to augment the radio antennas regularly used to conduct telemetry, tracking, and command of deep space spacecraft. Radio telescopes are particularly valuable during short-duration mission critical events, such as planetary landings, or when a mission lifetime itself is short, such as a probe into a giant planet’s atmosphere. By virtue of its high sensitivity and frequency coverage, the next-generation Very Large Array would be a powerful addition to regular spacecraft ground systems. Further, the science focus of many of these deep-space missions provides a “ground truth” in the solar system that complements other aspects of the ngVLA’s science case, such as the formation of planets in proto-planetary disks.

1. Introduction

In addition to the multitude of astronomical applications described elsewhere in this volume, the next generation Very Large Array (ngVLA) could provide valuable benefits in other fields such as the telecommunications with robotic spacecraft on scientific missions throughout the Solar System. There have been many cases of radio astronomical telescopes participating in and enabling planetary missions by augmenting the receiving capabilities of traditional spacecraft tracking facilities, with notable examples including the VLA’s participation in Voyager 2’s flyby of the planet Neptune (Figure 1, Layland & Brown 1985) and the use of the Green Bank Telescope to track the descent of the Huygens probe to the surface of Titan and enabling the Doppler Wind Experiment (Folkner et al. 2006). The sensitivity and frequency coverage of the ngVLA has the potential to exceed considerably that of any existing or planned dedicated spacecraft radio tracking facility. This contribution is focused on the relevance of the ngVLA for potential NASA missions, but, with the increasing number of space agencies conducting deep space missions,1 the ngVLA could be of benefit to many space agencies for increasing the science return from their space missions.

1 In addition to NASA, the European Space Agency (ESA), the Japanese Aerospace Exploration Agency (JAXA), the Indian Space Research Organization (ISRO), and the Roscosmos State Corporation for Space Activities (Roscosmos) send robotic spacecraft into deep space, and potentially Korean and United Arab Emirates will do so in the future.
2. Scientific Context

Historically, NASA’s most demanding application for highly sensitive ground receiving stations has been planetary science missions, in which spacecraft have been sent to other bodies in the solar system, often at distances of multiple astronomical units from the Earth. Increasingly, however, heliophysics and astrophysics missions have begun to demand similarly sensitive ground receiving stations. For instance, the Solar TErrestrial RElations Observatory (STEREO) mission has two spacecraft, one in an Earth-leading
orbit and one in an Earth-trailing orbit, that are approximately 1 au distant\textsuperscript{2} and the Parker Solar Probe\textsuperscript{3} will dip to within a few solar radii of the Sun (i.e., travel to approximately 1 au from the Earth). In order to reduce interference from the Earth and operate in a stable environment, many astrophysics missions (e.g., Planck, Spitzer Space Telescope, Kepler, James Webb Space Telescope) are being launched into orbits such as Earth-trailing orbits or Earth-Sun Lagrange 2 point halo orbits.

In this landscape, the ngVLA would complement NASA and ESA’s network of deep space antennas by providing additional sensitivity for short-duration, high priority events. NASA’s Deep Space Network (DSN) is a network of 34 m and 70 m diameter antennas at three longitudes around the world that provides routine collection of telemetry data (a.k.a. “downlink”) from spacecraft beyond geosynchronous orbit; ESA has three 35 m antennas at similar longitudes with similar functionality. However, it is standard practice to consider augmenting these antennas during mission critical events, such as the entry, descent, and landing of a spacecraft on another planet. Such augmentation provides resiliency for the mission; for instance, for the Doppler wind experiment on the Huygens probe to Titan, the receiver on-board the Cassini spacecraft was not configured correctly and only the data from Earth-based radio telescopes assured the success of that experiment (Folkner et al. 2006). In addition, with its higher sensitivity, the ngVLA may enable the collection of additional data.

Table 1 compares the relative performance of the current DSN antennas (DSN 810-005 Modules 101, 104) with that potentially achievable with a fraction of the ngVLA, using the antenna gain at two standard deep space communications bands, X band (receiving at 8.24 GHz) and Ka band (receiving at 32 GHz); a 34 m antenna operating at X band is taken to be the reference. For the ngVLA, only the Core Array (Carilli 2018), consisting of 94 antennas of 18 m diameter, is considered; the antennas are assumed to have an efficiency of 65\%. While the actual performance of the ngVLA may differ from that shown in Table 1, it is clear that even a fraction of the full ngVLA offers substantial improvements. All other things being equal, the relative performance of Table 1 is equivalent to the signal-to-noise ratio achieved on the downlink signal, as the DSN antennas have system temperatures of approximately 20 K and we assume similar values for the ngVLA antennas. In turn, signal-to-noise ratio translates approximately linearly to downlink data rate; alternately, the higher sensitivity can be considered additional margin against unexpected events. We now discuss a few examples of mission concepts that could benefit from having extremely high sensitivity ground receiving stations.

The Visions and Voyages for Planetary Science in the Decade 2013–2022 Decadal Survey describes two New Frontier\textsuperscript{4} mission concepts that would necessarily be short-lived. The Saturn Probe concept would deploy a probe into Saturn’s atmosphere to measure its structure and composition. While the materials used to construct such a probe may have improved since the construction of the Galileo probe (Young et al. 1996, and references within), the Saturn probe would suffer the same eventual fate, crushed under the rising pressures as it descends. The Venus In Situ Explorer concept would land on the surface of Venus in order to sample the composition of the crust.

\textsuperscript{2}At the time of writing, the STEREO-B spacecraft is not operational.
\textsuperscript{3}At the time of writing, scheduled for launch in 2018 August.
\textsuperscript{4}NASA’s medium-class missions, with a cost cap of approximately $1 billion.
Again, while material properties and thermal control systems have improved since the construction of Soviet Venera landers, the surface of Venus is such a harsh environment that a lander will have a necessarily finite lifetime.

The *Ice Giants Pre-Decadal Survey Mission Study Report* considers flagship-class mission concepts to Uranus, Neptune, or both. Four mission architectures were studied in detail, with three of the four including an atmospheric probe. (Two architectures involved an atmospheric probe for Uranus, one for Neptune.) The expected lifetime of such a probe in the atmosphere of either planet is approximately 1 hr.

During the last perihelion passage of Comet 1/P Halley, a figurative armada of spacecraft were sent to conduct close fly-bys of its nucleus. Because of the high relative velocities between the Earth and a long-period comet such as Halley, the durations of the fly-bys were short. Inspired by both the success of the spacecraft that flew by Halley and the recent discovery of the first interstellar object (2I/2017 U1 'Oumuamua, Meech et al. 2017), there is active consideration of what kind of mission concept or concepts might be possible to enable a similar encounter. While the relative velocities could be even higher than in the case of the Halley encounters, the potential science return from a close encounter with an interstellar object would likely be significant.

These mission concepts are intended to be illustrative only, and specific instruments have not been selected. Nonetheless, the higher data rates enabled by the use of the ngVLA could enable more capable instruments (e.g., higher resolution mass spectrometers). Further, these example mission concepts are certainly not an exhaustive list of all possible short-lived mission concepts, but they illustrate how high-priority missions might nonetheless be short-lived and benefit greatly from additional sensitivity such as could be provided by the ngVLA.

An additional benefit of the ngVLA may be for use during spacecraft emergencies. It is standard practice to include low-gain antennas on deep space spacecraft for the purposes of enabling communications even if the spacecraft’s attitude is unknown or uncontrolled. Low-gain antennas have the obvious benefit of a wide field of view at the cost of sensitivity. The received signal from a spacecraft in “safe mode” would most likely be (much) weaker than planned from its high-gain antenna, for which the ngVLA’s high sensitivity could be of benefit in capturing engineering data and understanding the problem with the spacecraft.

| System                  | Relative Performance |
|-------------------------|----------------------|
|                         | X band   | Ka band  |
| DSN 34 m                | 1.0      | 11.7     |
| DSN 70 m                | 4.3      | ...      |
| DSN 4 × 34 m            | 3.7      | 46.8     |
| ngVLA Core Array (94 antennas, 18 m diameter) | 17.1 | 248 |
3. Design Considerations

The primary requirement for the ngVLA to receive spacecraft telemetry is for it to have frequency coverage of the allocated space-to-Earth downlink bands (Table 2). The relevance of the ngVLA is immediately obvious, as its planned frequency coverage encompasses all of the frequency allocations.

| Name | Telemetry (Downlink) (space-Earth) (GHz) |
|------|-----------------------------------------|
| S band | 2.29–2.30 |
| X band | 8.40–8.45 |
| Ka band | 31.8–32.3 |

Two additional bands warrant comment. There is a space-to-Earth allocation in the K band (25.5 GHz–27.0 GHz). This band is allocated for spacecraft with orbits that take them no farther than $2 \times 10^6$ km from Earth. This distance includes the Earth-Sun L2 point, which is used increasingly by astrophysics missions such as the James Webb Space Telescope. While such missions would also benefit from high sensitivity, they have regular telemetry requirements, which are more likely to be met by NASA’s DSN (or ESA’s Deep Space Antennas). However, should such a spacecraft enter “safe mode,” the ngVLA could assist with the recovery of the spacecraft.

There is also an allocation in the ultra-high frequency (UHF) portion of the radio spectrum used for spacecraft-to-spacecraft communications (“proximity links”). This band is not within the ngVLA’s frequency coverage, and the SKA1-Mid or a similar facility would be more appropriate.

Like pulsars, spacecraft are point sources, and full field interferometric synthesis is not required. Beamforming suffices. In general, the requirements for pulsar beamformed observations would be sufficient for spacecraft telemetry reception, with the added benefit that spacecraft signals are typically quite narrow band relative to astronomical sources. A specific concern with the legacy VLA for both pulsar observations and spacecraft telemetry was the “waveguide switch cycle,” which resulted in a 1.5 ms data gap every 50 ms (Deutsch 1982; Hankins 1999); modern digital electronics and fiber optic transmission should obviate this particular concern.

4. Conclusion

In conclusion, the ngVLA would be well suited for occasional use of high priority space missions, particularly those with intrinsically short lifetimes. Not only can these missions be considerable investments by a space agencies (with costs in excess of $1 billion), the science motivations for them often complement the larger ngVLA science case. Most notably, the planets in our solar system form the end states of the protoplanetary disks that the ngVLA will image and only by studying both will we understand planet formation and evolution.
Acknowledgments. We thank D. Jones, L. Deutsch, and R. Preston for helpful discussions and guidance on this topic. Some of the information presented is pre-decisional and is intended for informational purposes only. Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Carilli, C. L. 2018, “Next Generation Very Large Array Memo No. 47: Resolution and Sensitivity of ngvla-revB,” http://library.nrao.edu/public/memos/ngvla/NGVLA_47.pdf

Deutsch, L. J. 1982, “The Performance of VLA as a Telemetry Receiver for Voyager Planetary Encounters,” Telecommunications and Data Acquisition Prog. Report, TDA PR 42-71, 1982 July–September (Jet Propulsion Laboratory, California Institute of Technology: Pasadena, CA) pp. 27–39

Deep Space Network Telecommunications Link Design Handbook, DSN No. 810-005, Module 104, Rev.J, 2018 January 12, JPL D-19379 (Jet Propulsion Laboratory, California Institute of Technology: Pasadena, CA) https://deepspace.jpl.nasa.gov/dsndocs/810-005/

Deep Space Network Telecommunications Link Design Handbook, DSN No. 810-005, Module 101, Rev.F, 2015 August 5, JPL D-19379 (Jet Propulsion Laboratory, California Institute of Technology: Pasadena, CA) https://deepspace.jpl.nasa.gov/dsndocs/810-005/

Folkner, W. M., Asmar, S. W. Border, J. S., Franklin, G. W., Finley, S. G., Gorelik, J., Johnston, D. V., Kerzhanovich, V. V., Lowe, S. T., Preston, R. A., Bird, M. K., Dutta-Roy, R., Allison, M., Atkinson, D. H., Edenhofer, P., Plettemeier, D., & Tyler, G. L. 2006, “Winds on Titan from ground-based tracking of the Huygens probe,” J. Geophys. Res., 111, E07S02; doi: 10.1029/2005JE002649

Hankins, T. H. 1999, “Pulsar Observing at the VLA,” in Synthesis Imaging in Radio Astronomy II, A Collection of Lectures from the Sixth NRAO/NMIMT Synthesis Imaging Summer School, eds. G. B. Taylor, C. L. Carilli, & R. A. Perley, Astronomical Society of the Pacific Conference Series, Vol. 180 (Astronomical Society of the Pacific: San Francisco, CA) p. 613

Ice Giants Pre-Decadal Study Final Report, Solar System Exploration Directorate, Jet Propulsion Laboratory for Planetary Science Division, Science Mission Directorate, National Aeronautics and Space Administration, June 2017, JPL D-100520

Layland, J. W., & Brown, D. W. 1985, “Planning for VLA/DSN Arrayed Support to the Voyager at Neptune,” Telecommunications and Data Acquisition Report 42-82, Jet Propulsion Laboratory, California Institute of Technology

Meech, K. J., Weryk, R., Micheli, M., et al. 2017, “A brief visit from a red and extremely elongated interstellar asteroid,” Nature, 552, 378; doi: 10.1038/nature25020

Vision and Voyages for Planetary Science in the Decade 2013–2022, Committee on the Planetary Science Decadal Survey, National Research Council (National Academies Press: Washington, DC) ISBN: 0-309-20955-2

Young, R. E., Smith, M. A., & Sobeck, C. K. 1996, “Galileo Probe: In situ Observations of Jupiter’s Atmosphere,” Science, 272, 837; doi: 10.1126/science.272.5263.837