NASA SPACE COMMUNICATIONS AND NAVIGATION SUPPORT TO PLANETARY PROBE MISSIONS

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ABSTRACT[1]

In 2006 the National Aeronautics and Space Administration (NASA) formed the Space Communications and Navigation (SCaN) office with the charter of integrating NASA's space communications capabilities into one seamless system. SCaN has recently emplaced an architecture for this "Integrated Network." The Integrated Network will comprise the assets of the Deep Space Network (DSN), the Near Earth Network, and the Space Network (which includes the Tracking Data Relay Satellite System). Users of the Integrated Network will be able to plan support services using a integrated service portal, providing the same planning and service interface for all of SCaN's network capabilities.

Since the DSN is a critical piece of many planetary probe missions, the plans for the Integrated Network are of interest to this community. As implementation of the Integrated Network progresses, NASA will continue to engage this and other science mission communities to ensure the appropriate services are maintained and that the service interfaces are made easier and more streamlined. This paper, which may be viewed as part of this engagement, explains the overall plan for the Integrated Network, the top-level plans for its component capabilities, and the goals for the interfaces between the Integrated Network and the mission community.

In parallel with the development of the Integrated Network, NASA has instituted several new policies and guidelines concerning the use of the various SCaN assets. These are intended to help mission designers plan appropriate and efficient use of Integrated Network assets. An example is the guidance for the use of single DSN 34m antennas for routine deep space mission operations. There has been some confusion over these policies and guidelines. This paper is meant to help mission designers understand them as well as the rational behind them.

1. NASA SPACE COMMUNICATIONS TODAY

NASA's Space Communication and Navigation (SCaN) office was formed in 2006 to manage NASA's space communications assets. Today, these assets consist of three space communications networks. The Deep Space Network (DSN) is probably most familiar to the planetary probe community as this is the network that NASA uses to communicate with and help navigate missions in deep space. In fact, the DSN supports all NASA missions that venture beyond geosynchronous orbit (GEO).

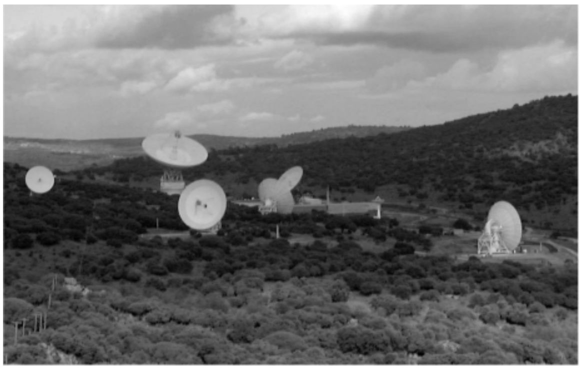

Fig. 1. DSN Antennas near Madrid, Spain

The Space Network (SN) comprises NASA's Telecommunications and Data Relay Satellite System (TDRSS). The SN's GEO satellites relay communications to and from spacecraft in orbits below GEO. The SN is capable of data rates up to 300 Mbps and is the main link with the International Space Station (ISS).

1 The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Fig. 2. TDRSS Satellite

The Near Earth Network (NEN) consists of ground stations in many places around the Earth. Some of these are owned and operated by NASA while others are contracted from commercial entities. The NEN primarily supports missions in low Earth orbit (LEO). The NEN's 18m antenna at White Sands, New Mexico, is the networks most capable and supports missions as far away as the Moon.

Fig. 3. Svalbard, Norway, antennas used by the NEN

Each of these three networks has serviced its respective mission community for many years. As such, each has evolved its own unique systems, processes, and interfaces. While some aspects of each network are governed by the physics of their challenges (e.g. the DSN has large antennas and the SN has high data rates), many aspects could clearly be made common.

SCaN's challenge, working with the experts in the three networks, is to identify and develop these areas of commonality. The result is what NASA is calling the "SCaN Integrated Network."

2. THE SCaN INTEGRATED NETWORK

Fig. 4 shows the architecture of the SCaN Integrated Network [1]. Three of the four "fingers" in the diagram actually contain most of the assets of the three current NASA communications networks. The term "network" has been replaced by the term "element" to help emphasize the point that there will be only a single NASA network when the transition is completed in 2018. The elements contain the systems, processes, and interfaces that are uniquely determined by the physics as mentioned above.

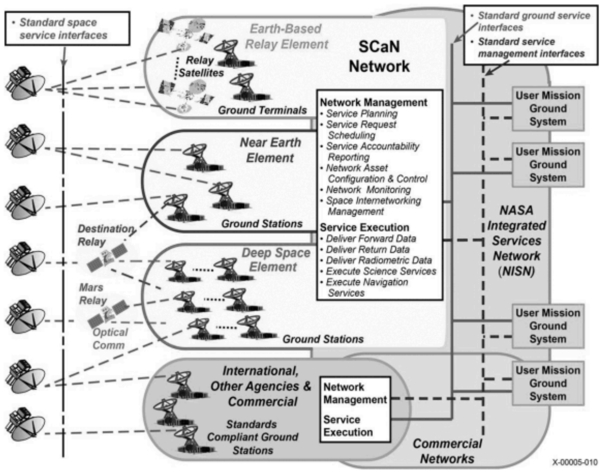

Fig. 4. The SCaN Integrated Network Architecture

The three "elements" interface to the mission user community through the NASA Integrated Services Network (NISN).

The key concept in the Integrated Network is the use of standard services that will be provided to the users. These services (which include telemetry, radiometrics, and timing) will be defined in such a way that users can obtain them from any of the elements essentially interchangeably – as long as the physics of space link allows this of course. For example, a mission with a spacecraft in LEO will be able to request and receive services from any of the three "elements" using the same user interface.

SCaN maintains a "service catalog" [2] that defines the standard services available from the three NASA networks today. As these transition to the SCaN Integrated Network, the service catalog will be updated as necessary to reflect this integration and to help the users plan for these services.

In many cases, these standard services will also be international standards and will be available with little or no change using tracking assets from other nations. This is being worked though the Interagency Operability Advisory Group (IOAG) [3] which comprises membership from most spacefaring nations. The IOAG maintains an international service catalog for those services that will be available through interoperability and cross support among assets from its member agencies. The detailed work of defining the interfaces for these services is accomplished through the Consultative Committee for Space Data Systems Standards (CCSDS) [4], an international body under the auspices of the International Standards Organization (ISO.)

The user interface for the SCaN Integrated Network will be through a “service portal” which will be designed to simplify the user experience – especially when requiring services from multiple SCaN elements. Deep space missions, by the way, often require services from NEN (or similar) assets today to support launch and early orbit operations before deep space assets can acquire and track the spacecraft. Though this phase of the mission is very short, it is critical and coordinating the additional tracking stations is often a difficult task.

There are four main goals being developed for the SCaN Integrated Network:

1) Reduce lifecycle costs of the SCaN communications assets
2) Reduce the effort required for users to obtain services from SCaN
3) Make it easier for NASA communications assets to infuse new technologies
4) Ensure the quality of SCaN services increases

The first goal is clear. If areas of similarity among the three elements can be implemented with common systems and processes, it should be possible to lessen development, operations, and maintenance costs.

Goal 2 is mostly aimed at missions that make routine use of multiple networks today. However, there should be benefit to all users.

Goal 3 is critical to providing increased capabilities as space missions evolve with time. For example, if all the elements in the SCaN Integrated Network use a common software-based receiver, then adding a new modulation type would require only a single development rather than three.

Goal 4 is particularly important for users to understand. SCaN will do nothing that will adversely impact the services it provides to missions. SCaN will be making many changes to the NASA networks, but in the end, the services that are provided to missions will be at least as good as they are today.

3. DSN PLANS IN THE INTEGRATED NETWORK ERA

The DSN has embarked on a project to add 34m beam waveguide (BWG) antennas so that by 2019 each of its three sites will have the ability to back up critical services performed by its 70m antennas [5]. In particular, four 34m antennas will be able to be arrayed to provide approximately the same downlink performance as a 70m antenna at X-band (8.4 GHz). One 34m antenna at each site will have a new 80 kw X-band transmitter so that it can provide the uplink performance of a 70m antenna (which is equipped with a 20 kw X-band transmitter).

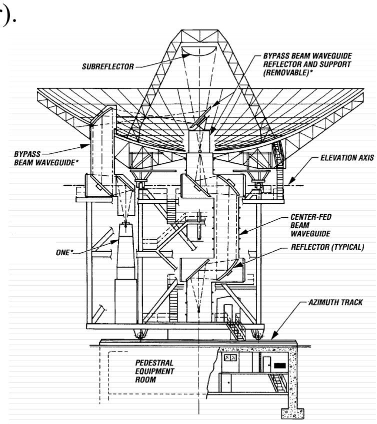

Fig. 5. DSN 34m BWG Antenna

This means the 70m antennas will no longer be single points of failure. However, it does not mean missions can design to this as their routine baseline capability (see Section 5).

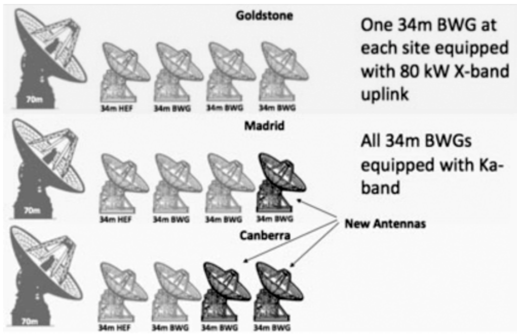

Fig. 6. DSN Architecture ~2020

In addition, all the new 34m antennas will be equipped with Ka-band (32 GHz) receivers. Ka-band is intended to be the new workhorse frequency for deep space missions. Ka-band downlink offers two advantages over X-band downlink.

First, because of the narrower beamwidths, Ka-band offers a substantial performance increase for the same size spacecraft antenna and the same transmitter power. The advantage is typically between four and six dB – or about a factor of four – and already assumes typical spacecraft pointing accuracy as well as various losses for antenna efficiency and atmospheric attenuation at Earth. Mission designers can take this advantage in increased data rates, decreased spacecraft transmitter power, decreased spacecraft antenna aperture, or fewer required DSN tracking hours.

Second, there is ten times as much radio spectrum allocated to deep space research at Ka-band as at X-band – 500 MHz. This means that higher data rate missions can be supported more easily at Ka-band than at X-band. It also means that more spacecraft can be located at the same target because of the higher availability of non-interfering channel assignments that can be made.

The DSN 70m antennas are not equipped with Ka-band receivers. In fact, there were several technology demonstrations of Ka-band systems on the 70m antennas performed in the 1990s. These showed that it was feasible to add Ka-band, but that it would be complex and possibly expensive. Since the 34m antennas can be arrayed to provide substantial performance at Ka-band, the need to add Ka-band to the 70m antennas is lessened and there is no plan to do so at the moment.

The Goldstone Solar System Radar has also been improved. Today, it has a resolution of slightly better than 4m – assuming, of course, the targeted object is close enough to be detected. This has already resulted in some of the most stunning images of near-Earth objects, such as this series of images of the object 2005 YU55, which came closer to Earth than our own Moon in November 2011 [6].

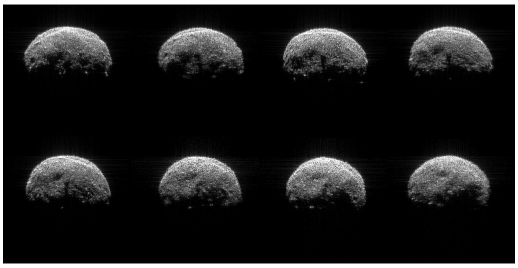

Fig. 7. Goldstone radar images of 2005 YU55

As the other two SCaN networks are upgraded, the DSN is likely to become the beneficiary of new capabilities. This is because of the trend toward implementing common systems among the networks. For example, the SN is currently being upgraded. Some of its new capabilities include new error correcting codes (e.g. low density parity check codes) and new radio frequency modulation types (e.g. 8 phase shift keying). If things go according to plan, these capabilities will then be easier and less expensive to add to the DSN where they will translate into additional performance gains for deep space missions.

4. SOME POLICIES FOR USING DSN ASSETS

The DSN is a very capable network that can do many things very well. However, it also has to support many user missions. Today, the DSN tracks approximately 30 different spacecraft in any given month and, in addition, performs many direct science observations.

There are no hourly operations fees for NASA missions that use the DSN. (The cost to missions of other agencies depends on agreements they have put in place with NASA.) Without such fees, there has to be some other mechanism to ensure the DSN does not become overloaded while still providing required services to all its customer missions.

Hence, NASA has instituted policies on the use of DSN assets. These policies have been emplaced for the good of the larger mission community. The policies are meant to guide user planning of DSN services and not to serve as a hindrance to any missions or mission classes. In all cases, the DSN provides assistance in the design of user missions through its Mission Commitments Office. The goal is to make every mission successful.

4.1 Use of single 34m antennas for routine operations

If a mission were allowed to use all the antennas at a give DSN site whenever it was in view, that would severely restrict the ability of the DSN to track multiple simultaneous missions.

This simple observation leads directly to the NASA policy of designing missions to be supported by single 34m antennas for routine operations.

Notice that this policy deals only with routine operations. For non-routine operations, additional antennas or 70m support can be planned. These operations would include tracking through spacecraft critical events such as trajectory change maneuvers (TCMs), planetary orbit insertions, science flybys, and entry, descent and landing (EDL).

4.2 Use of Ka-band for data rates over 1 Mbps

Once again, the intent is to track many spacecraft efficiently with a fixed number of DSN antennas. Communications using Ka-band is approximately four times as efficient as communications at X-band. This means only ¼ the tracks are required on average, leaving the antennas more time to track other missions.

The choice of 1 Mbps as the threshold stems from the fact that, after application of a rate 1/2 error-correcting code and BPSK modulation the spacecraft signal takes up a bandwidth of close to 8 MHz, which is the maximum routine channel size NASA recommends for deep space X-band. This constraint allows a reasonable number of spacecraft to coexist using X-band without undue mutual interference.

Since signal bandwidth is the underlying constraint that leads to this policy, a mission with a design for a higher data rate that can still fit in this bandwidth should work with NASA and the DSN if a waiver is desired.

For data rates less than 1 Mbps, the user can select either X-band or Ka-band.

4.3 Constraints for the use of Ka-band

Even though there is 500 MHz of bandwidth allocated to deep space research at Ka-band, NASA does not want to see this used up by only a few large missions. Ka-band is NASA's growth area band – but it has to last a long time. It will be our workhorse frequency band until optical communications is firmly in place and used by most missions.

Hence, Ka-band use is, by policy, restricted to 60 MHz channels, according to Space Frequency Coordination Group (SFCG) recommendation [7]. (The SFCG [8] is an international body that coordinates radio frequency use in space.) In addition, users with data rates greater than 20 Msps are required to use a spectral-efficient modulation scheme with a bandwidth to symbol rate ration (B/R_s) of no more than 0.5. One method of achieving this is the use of Gaussian Minimum Shift Keying (GMSK).

The DSN currently does not have receivers that are optimized for GMSK-modulated signals, so there will be a an additional signal loss of approximately 0.5 dB. SCaN has a long-term plan to add GSMK demodulators to all the NASA networks, but there is no plan in place for the DSN at this time.

4.4 Redundant coverage for certain critical events

This is not as strictly enforced as the other policies – but it highly recommended as a sound engineering practice.

By their very nature, critical events are "critical." For many of these (including TCMs, orbital insertions, and EDLs) loss of communications with a spacecraft can result in loss of the mission. Even in the case where a mission cannot be recovered through use of the communications link, this link is often the only source of information for determination of the cause of mission failure. This is invaluable information for all subsequent missions.

For these reasons, NASA recommends that at least two tracking stations can view a spacecraft during these kinds of events.

Some of these events will need to be supported through 70m services. The DSN plan for 34m array backup to the 70m antennas will likely make planning these events easier in the future.

5. SUPPORT TO PLANETARY PROBE MISSIONS

The DSN has supported many planetary probe missions during its 49-year history. It will continue to do so in the era of the SCaN Integrated Network.

5.1 Spacecraft communications up to planetary orbit – routine operations

As mentioned in Section 4, routine operations will be facilitated with single 34m DSN antennas. However, this is not a big constraint – at least for probe missions, since the routine phases of these missions (mostly cruise) generally do not have high data rate requirements.

Uplink is also not a constraint. Uplink data rates to deep space missions are usually constrained by the demodulator in the spacecraft transponder rather than by the physics of the link. Also, if needed, a mission could make use of the 80 kw X-band uplink that will be available on at least one 34m antenna at each DSN site.

Table 1 shows the approximate data rates that are possible today and in the 2020 time frame under various conditions. Columns 3 and 5 in particular show the kind of performance that can be expected with a single DSN 34m antenna at X and Ka-band respectively.

Missions are already flying today with Ka-band transmitters in the 100-Watt range. NASA has also developed a 180-200 Watt transmitter that, in fact, provided the technology used on several currently operating missions.

	Distance (AU)	Today (Mbps)			2020 (Mbps)	
DSN Configuration		34m X-band	3 x 34m X-band	34m Ka-band	3 x 34m Ka-band	3 x 34m Ka-band
Spacecraft Configuration		3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/2 LDPC code	3m antenna 180 W transmitter 1/2 LDPC code
Venus (Closest)	0.3	80.0	240	320	960	1728
Venus (Farthest)	2.4	1.3	3.8	5	15	27
Mars (Closest)	0.6	20	60	80	240	432
Mars (Farthest)	2.6	1.1	3.2	4.26	13	23.01
Jupiter	5.4	0.247	0.741	0.99	2.96	5.33
Saturn	10.1	0.071	0.212	0.28	0.85	1.52
Uranus	19	0.020	0.060	0.08	0.24	0.43
Neptune	30.3	0.008	0.024	0.03	0.09	0.17

Table 1. Space to Earth link performance

5.2 Spacecraft communications up to planetary orbit – critical events

For non-routine communications, it is possible to use multiple arrayed DSN 34m antennas and the 70m antennas. Table 1 gives a good indication of the kind of performance one could expect.

Of course, the actual performance depends on the nature of the critical event. The table is a good indicator for target encounters where a spacecraft high gain antenna will be pointed toward the Earth. For TCMs and EDLs, the spacecraft might be using a low gain antenna resulting in much less data rate – but in these cases there is usually not a requirement for high data rate.

5.3 Probe communications through a relay

Table 1 also is a good indicator of the link performance one would expect between a probe relay spacecraft and the Earth. If the probe is short-lived, then one could argue that that this phase of the mission is a critical event and therefore could use multiple 34m antennas. If probe operations were to be long term, then one would again be restricted to a single 34m antenna.

In most cases, probe communications through a relay spacecraft will be limited by the probe-to-relay link, which is not the subject of this paper.

5.4 Probe Direct to Earth communications

In the case were there is no relay spacecraft, probe operations will be direct to Earth. In this case, one has to also take into account the fact that the probe will likely be using an omnidirectional antenna and might also have local atmospheric losses.

Assuming a probe antenna with essentially no gain, communications performance is nearly frequency-independent, at least in a vacuum. Direct-to-Earth data rates for various probe distances were calculated for the IPPW meeting in 2006 [9]. They assume a probe with a 25W X-band transmitter and a 4 dBi antenna. The results shown in Table 2 are based on these calculations and modified to show the expected performance for the currently planned DSN configuration. We have shown a column for arraying a DSN 70m antenna with four 34m antennas. This is a possible DSN configuration the 2020 time frame for each site. This may be possible for short periods of special scientific interest. All these numbers are approximate – they are based on a model of Jupiter's atmosphere, including atmospheric absorption for a probe at a depth of 10 Bars assuming a 45° zenith antenna angle of transmission from the probe.

Ground Antennas	DSN 34m	DSN 70m	DSN 70m + 4 34m's
Venus (0.3 AU)	2.75 kbps	11 kbps	22 kbps
Venus (2.4 AU)	45 bps	180 bps	360 bps
Mars (0.6 AU)	725 bps	2.9 kbps	5.8 kbps
Mars (2.6 AU)	37.5 bps	150 bps	300 bps
Jupiter	8.75 bps	35 bps	70 bps
Saturn	2.5 bps	10 bps	20 bps
Uranus	0.75 bps	3 bps	6 bps
Neptune	0.25 bps	1 bps	2 bps

Table 2. Direct-to-Earth link performance

There may be some rare instances where a probe mission might require S-band communication with the DSN. The challenge here is that the deep space S-band has been encroached by the terrestrial and satellite S-band communities to the point where one can no longer rely on interference-free passes. S-band uplink, for example, is no longer possible at the DSN Madrid site.

NASA does not recommend the use of deep space S-band communications for new missions. If this is desired, we suggest working directly with NASA and the DSN to see what is still possible.

5.5 Mission navigation

All the radiometric data types that are used today for DSN missions will be available in the era of the SCaN Integrated Network. These include Doppler, ranging, and angular measurement (mainly ΔDOR) [10].

Ranging and Doppler data are gathered using the communication links and would mostly, therefore, come through the use of single 34m antennas. However, if additional accuracy is required for a mission, periodic short-term use of multiple 34m antennas of the 70m antennas would still be possible since these would be non-routine.

ΔDOR measurements require multiple antennas to provide the terrestrial baseline. Once again, if these are not required too often, they can be viewed as non-routine operations and planned within the NASA policies. It is also possible to use non-DSN antennas to obtain part of all of these measurements.

5.6 DSN science measurements

Many probe missions make extensive use of radio science. Such measurements can be used to characterize planetary atmospheres, winds, and gravity fields.

In general, these measurements require the most sensitive DSN receivers and the most signer-to-noise performance. In fact, the DSN uses a special radio science receiver (RSR) to obtain these measurements.

Since these measurements are typically of short duration at specific times in the mission, they can be planned using 70m tracking if needed. It is also possible to use the deep space S-band for radio science experiments even though it is strongly discouraged for communications, due to ever increasing terrestrial spectrum interference.

Radio science measurements can (and often are) accomplished using non-DSN facilities. Radio observatories are often ideal for this. The DSN RSR can be transported to many of these facilities if needed, given adequate preparation time.

6. CONCLUSIONS

NASA SCaN has begun integrating NASA's three space communication networks: The DSN, SN, and NEN. This will not impact the quality of services that the DSN supplies to planetary probe missions. Since the mission interfaces to SCaN (and hence the DSN) will be streamlined as part of the process, it is even possible that mission-associated DSN effort and cost could be reduced.

As SCaN proceeds with implementation of the Integrated Network, we will continue to reach out to the user community for advise and review. We encourage everyone who is a user or potential user of these networks to get involved and help us all succeed. For non-NASA users, the appropriate channels for this involvement include the various international for a including the IOAG, the SFCG, and CCSDS.

Although the DSN stands ready to be a part of every planetary probe mission, there are restrictions on the use of DSN assets. These policies are in place to ensure that the DSN will have the ability to support many simultaneous missions of many kinds.

We encourage anyone contemplating a probe mission that will use the DSN to begin working with the SCaN Customer Interface Office as soon as possible in the life cycle of the mission. It is really never too early to begin this process. SCaN and the DSN have processes in place to help mission managers and principal investigators plan for future DSN usage.

We expect the SCaN Integrated Network and the new NASA policies concerning the use of the DSN to enable easier transition to new capabilities and technologies in NASA's space communications infrastructure in the future – including the introduction of operational optical communications.

REFERENCES

1. Liebrecht, P., Schier, J., Bhasin, K., Bibyk, I., Butler, M., Hudiburg, J., Tai, W., Shames, P., "NASA's Space Communications Integrated Architecture," AIAA SpaceOps 2010, Conference April 25-30, 2010 Huntsville, Alabama

2. "Space Communications and Navigation (SCaN) Network Service Catalog, Version 2", NASA Document No. SCaN-SERVICE CATALOG, at URL https://scanngin.gsfc.nasa.gov

3. Interagency Operations Advisory Group (IOAG) web site, http://www.ioag.org/

4. Consultative Committee for Space Data Systems (CCSDS) web site, http://public.ccsds.org/default.aspx

5. L.J. Deutsch and R.A. Preston, "The Future of NASA's Deep Space Network and Applications to Planetary Probe Missions", Transactions of the 7th International Planetary Probe Workshop, June 2010

6. M.W. Busch, L.A.M. Benner, M. Brozovic, P.A. Taylor, M.C. Nolan, C. Magri, J.D. Giorgini, M. A. Slade, J.S. Jao, C.G. Lee, F.D. Ghigo, W.F. Brisken, J.L. Margot, S.P. Naidu, E.S. Howell, L.M. Carter, and M.K. Shepard, "Shape and Spin of Near-Earth Asteroid 308635 (2005 YU55) From Radar Images and Speckle Tracking", to appear in the Transactions of Asteroids, Comets, and Meteors, 2012.

7. Efficient Spectrum Utilization for Space Research Service, Deep Space (Category B), for Space-to-Earth Links in the 31.8-32.3 GHz Ka-Band, Recommendation SFCG 27-1R1, Space Frequency Coordination Group, June, 2011.

8 Space Frequency Coordinaton Group (SFCG) web site, https://www.sfcgonline.org/home.aspx

9. D. Abraham, L. Deutsch, R. Preston, and B Geldzahler, "Evolving the Deep Space Network: Implications for Planetary Probes", International Planetary Probe Workshop, June 2006.

10. J. Border, G Lanyi, and D. Shin, "Radiometric Tracking for Deep Space Navigation," in Advances in the Astronautical Sciences: Guidance and Control 2008, Vol. 131, Drews ME and Culp RD (eds), Univelt: San Diego, 2008; 309-328.