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A Growth Path for Deep Space Communications

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Increased DSN receiving capability far beyond that now available for Voyager is achievable through a mix of increased antenna aperture and increased frequency of operation. In this note we consider a sequence of options: (1) adding mid-sized antennas for arraying with the existing network at X-band; (2) converting to Ka-band and adding array elements; (3) augmenting the DSN with an orbiting Ka-band station; and (4) augmenting the DSN with an optical receiving capability, either on the ground or in space.

Costs of these options are compared as means of achieving significantly increased receiving capability. The envelope of lowest costs projects a possible path for moving from X-band to Ka-band and thence to optical frequencies, and potentially for moving from ground-based to space-based apertures. The move to Ka-band is clearly of value now, with development of optical communications technology a good investment for the future.

I. Introduction

The Deep Space Network (DSN) configuration which supported the encounter of Voyager with Uranus is the most sensitive and capable receiving instrument for deep space communications assembled to date. Even so, more data could have been gathered by the Voyager's instruments had a more capable link been available to transport that data to Earth. Other instruments are available now that could (if permitted) drive the communications link toward significantly increased capability. Is there a good technology pathway to follow to achieve significant growth in capability? We examine that question in the following and conclude that indeed, the development of Ka-band now, and research work leading toward optical/visible-band communications for the not too distant future, are both elements of that pathway. The material presented here is not brand new, having been adapted from results available in our references, but it is examined from a substantially different perspective.

The top level characteristics of the DSN and its relationship to its flight mission customers have developed along a well established philosophy of steady dependable service and continuous evolutionary growth of capabilities (Long Range Plan for the Deep Space Network (JPL Internal Document), Jet Propulsion Laboratory, Pasadena, California, October 1984). That philosophy is accommodated here, by building upon the existing infrastructure, including DSN capabilities and DSN and flight mission operating strategies. The DSN of 1986 provides support to spacecraft operating at X-band (8 GHz) and S-band (2 GHz) from three communication complexes spaced approximately equally in longitude about the Earth so that continuous coverage can be available if spacecraft events justify it. Each of the three complexes provides essentially the same capability as any other, so that the scheduling of spacecraft events is dependent only upon specifics of the trajectory and not upon network constraints. The parameters of the communication link are chosen such that there is at all times a very high confidence (90–95% or more) in achieving adequate communication. Variational tolerances of equipment performance and weather-dependent effects are included here.

Improvements to DSN capabilities have been incremental, built upon the existing features and adding new ones as needed for the next flight mission. Old features get discarded only when old in-flight missions dependent upon them cease to function. New features are examined and justified for their value to forthcoming missions, as compared to costs for other ways of achieving comparable mission objectives. For the purposes of this report, we consider the incremental cost to NASA of providing a significantly increased communications link capability for the "next" mission by means of a few tightly constrained pathways. Features of the 1986 DSN and of the current-design spacecraft are assumed to be available without added cost. High-confidence 24-hour coverage is assumed to be required.

II. Options for Growth

Options for communication growth examined here are of two types–increase the ground receiving aperture, or increase the communication frequency band used. Other parameters, such as spacecraft power, transmitting aperture, etc., are held constant at values which are presumed reasonable. The frequency bands of interest are the same as those examined by Dickinson (Ref. 1), who compared costs of X-band, Ka-band, and Optical communication for a fixed total data volume. According to the study done in the late 1970's of the Large Advanced Antenna Station (LAAS) (Haglund, H. H., et al., Large Advanced Antenna Station Status Report (JPL Internal Document No. 890-74), Jet Propulsion Laboratory, Pasadena, California, August, 1978), large receiving apertures at X-band are best achieved via arraying of moderate sized antennas of 30- to 40-meter diameter. The effective aperture is a function of the number of antennas employed. The successes at Voyager encounter demonstrated the utility of arraying in fact, as well as theory. We presume the same will hold at the higher frequency regimes as well.

Increasing the frequency band of operation improves the communication performance by narrowing the transmitted beam, thus delivering a larger fraction of the power to the receiving aperture, assuming all else is fixed. This requires a concomitant improvement in the precision with which the transmitted beam is pointed at Earth, thus imposing a requirement on spacecraft design that we cannot really deal with here. Thus it is assumed for this examination that the spacecraft attitude control is retained precisely enough for the body-fixed X-band (8.4 GHz) transmission, and that greater precision as needed is provided by the communication subsystem itself. For Ka-band (32 GHz), the increased precision of pointing is a factor of four as compared to X-band. An array feed solid state power amplifier with electronic beam steering, or a beam waveguide mirror system, is believed capable of this pointing refinement if it is provided with adequate knowledge of the true spacecraft attitude. The pointing of the optical (560 THz) transmission beam must be more than three orders of magnitude more precise than that for X-band. It has frequently been argued that the required pointing can be accomplished, again by beam waveguides, i.e., by steering the mirrors of the transmitting optical telescope, which are now much smaller and lighter than the comparable microwave components. We presume this to be the case, but retain a concern which will appear in the uncertainties of the cost-performance curves to be displayed.

The baseline capability against which other options are to be compared is that of the 1985-86 vintage DSN 64-meter antenna, operating at X-band as it did to support Voyager. The reference spacecraft transmits at X-band via a 10-watt Traveling Wave Tube Amplifier (TWTA), and a 4.5-meter aperture. This is the same spacecraft configuration as that selected as optimum by Dickinson, and the antenna represents the largest non-furlable aperture which can be carried in the Shuttle payload bay. Assuming TWTA efficiency of about 40%, the raw spacecraft power into the transmitter is about 25 watts. This combination supports a 26 kbps data rate from Saturn, which is available 24 hours per day via the three complexes of the DSN.

III. Option Cost Comparisons

Individual cost and performance estimates which make up the curves (Fig. 1) of cost vs communication growth are taken largely from Dickinson (Ref. 1). For these curves, the fixed parameter is raw spacecraft power into the transmitter, which is approximately 25 watts for both the X- and Ka-band cases in the reference report, and also set here at 25 watts input to the optical transmitter with assumed 8% efficiency. The spacecraft transmitting apertures for these curves are the same as those in the reference study: 4.5-meter antenna for microwave transmission and the 28 cm OPTRANSPAC telescope for optical. The parameters varied are the receiving aperture and the frequency band.

A. X-Band Curve

The zero-point for all curves is the capability of the DSN's current 64 meter antenna in conjunction with the referent X-band spacecraft. These antennas are currently being upgraded to become high efficiency 70-meter antennas, thus adding 2 dB in X-band communications performance. This upgrade will be completed by 1988, at a basic cost of $30M (±10%) (McClure, D. H. (JPL Private Communication) also Stevens, R., FY85 C of F Antenna Projects (JPL Presentation to NASA-OSTDS) Jet Propulsion Laboratory, Pasadena California, May 16, 1985). Further increases in X-band capability are available through arraying with an arbitrarily large number of 30- to 40-meter antennas a la the LAAS study results (Haglund, H. H., et al. Large Advanced Antenna Station Status Report (JPL Internal Document #890-74), Jet Propulsion Laboratory, Pasadena, California, August 1978). The aperture efficiency and system temperature of these antennas would be the same as that of the upgraded large antennas. The 40-meter antennas at last look were priced at $10M (assume ±10%) each, including all electronics needed for operation and arraying (Stevens, R., Report: Use of VLA and Japanese 64m vs Temporary New DSN Implementation for Voyager Neptune Encounter Support (JPL Internal Document IOM #RS84-7051D), Jet Propulsion Laboratory, Pasadena, California, October 29, 1984). This figure is consistent with the engineering estimates contained within the LAAS study, adjusted as necessary for the intervening cost inflation. Approximately half of this figure represents the steel and concrete of the radio telescope itself, while the other half is the electronics, control, and support equipment necessary to make the antenna a functioning entity. Expanding the three complexes symmetrically results in the X-band curve as shown.

B. Ka-Band Curve

The Ka-band version of the referent spacecraft uses a 5 W array feed power amplifier with the 4.5 m antenna. Raw spacecraft DC power is again approximately 25 W for the expected efficiency of this amplifier. Operation of this spacecraft communications link into the 70-meter provides a data rate of 117 kbps, when the 70-meter has been enhanced for Ka-band operation. Link margin for this rate was set to provide 90% confidence of successful communication. Cost of this capability is the $30M for the basic 70-meter upgrade, plus $25M (±20%) for their Ka enhancement, plus $59M (±$12M) for the first Ka-band capable spacecraft (Ref. 1). With this completed, the 70-meter is expected to be approximately 55% efficient at 32 GHz. Increments to this capability are assumed to be available in the form of 40-meter antennas which are 70% efficient at a cost of $12.5M (±20%) each, or for a 25% surcharge over their X-band counterparts. With these characteristics, each 40-meter aperture adds 48 kbps to the communications capability. The Ka-band curve shows the cost-performance path for symmetric growth of the three DSN complexes at Ka-band via these 40-meter arrayable modules.

C. Space-Based Ka-Band Point

The triangle indicated as H79 shows the approximate performance and cost of the 28-meter Ka-band Orbiting Deep Space Relay Station (ODSRS) as derived from Hunter (Ref. 2). That receiving system had a G/T performance which was 6 dB above that of the 64-meter X-band capability. Overall link performance is indicated on Fig. 1 at 3 dB to account for the 3 dB lower efficiency, and hence lower output from the transmitter of the Ka-band spacecraft. The total cost of the ODSRS as perceived in 1979 was $400M, including design, implementation, launch and on-orbit assembly, and 10 years M&O. Of that figure, $120M was supposed to include three Shuttle launches, plus the Orbital Transfer Vehicle needed to place the ODSRS at Geosynchronous altitude. Shuttle launch costs are currently carried as $140M per full cargo bay (Ref. 1), while the upper stage itself should cost on the order of $60M, consistent with the now-defunct STS-Centaur (Ref. 1). Thus an updating of the launch/installation cost entry would raise it from $120M ('79) to $480M ('86). The remaining cost elements, totaling $280M ('79), are items subject to general price inflation which is a net 55% over these years, for an adjusted cost of $440M ('86), with big uncertainty. Total ODSRS cost would be on the order of $920M (±20%) in 1986. The cost indicated on Fig. 1 includes the ODSRS plus $59M for the first Ka-band user spacecraft.

D. Ground-Based Optical Curve

Ground-based optical is evaluated assuming a user spacecraft with a 28 cm transmitting telescope and a 2 watt laser transmitter, consistent with raw spacecraft power of 25 watts and efficiency of 8%. Lasers currently exist with this efficiency, but at lower power levels (Ref. 3). The unit receiving aperture is assumed to be 10-meters, the same as the Keck Telescope to be built in Hawaii, but of substantially lower optical imaging quality. To counteract cloud blockage, the receiving apertures must be at least triplicated and spatially diversified in each longitude. (An alternative is added on-board storage and time diversity.) It is believed that in quantity, these 10-meter photon buckets would cost much less than the reported $70M cost of the Keck Telescope. Total capability cost for any specific level is the sum of the first-user spacecraft cost of $88M (±$16M), plus the ground receiving system costs for the collecting aperture. Lesh (Ref. 4) has recently calculated performance of this spacecraft-ground combination for both daylight and dark sky conditions while examining cost tradeoffs of size and surface quality for the ground receiving telescope element. To meet our requirements for continuous availability, link design for daylight conditions is appropriate. According to these calculations, a 10-meter collecting aperture with a surface quality adequate to provide 16 dB communications growth over the reference X-band system could be acquired for unit cost of $25M. To that figure we should add an overhead of about $5M for facilities, utilities, and interfacing into the remainder of the DSN's machinery, which is assumed to be available to support the optical receiving telescope as it does the radio ones today. Because of the analogy approach to these costs, an uncertainty of 2 dB (+60%/-40%) seems appropriate here. Total nominal cost for one optical subnet enabling a 16 dB communications growth thus is $270M, for three-point diversity in each of the three longitudes of the Network. Arraying these apertures provides the growth path shown. Smaller or lower quality telescopes can be used at somewhat lesser cost, as indicated by the dashed segment of the optical curve in Fig. 1.

E. Space-Based Optical Points

The orbiting optical DSS, as portrayed in early presentations of the 1985 study (Dickinson, R. M., Review of Ka-Band Study Task Results (JPL Presentation), Jet Propulsion Laboratory, Pasadena, California, March 22, 1985), can provide 761 kbps from a 130 mw laser with 28 cm transmitting telescope into an orbiting 20-meter photon bucket (LDR-type). Assuming that the transmitting laser power can be scaled upward to 2 watts, consistent with raw spacecraft power of 25 watts and efficiency of 8%, the overall communications capability becomes 26.5 dB above the X-band reference. Estimated cost of this orbiting receiving system was $300M, including $140M for the single Shuttle launch, on-orbit assembly, and installation on a space station (Dickinson, R. M., Review of Ka-Band Study Task Results (JPL Presentation), Jet Propulsion Laboratory, Pasadena, California, March 22, 1985). We have added another $140M to the installation costs as a rough estimate for the cost of placing it on a Geostationary platform instead of into low orbit. The first user spacecraft cost of $88M (±$16M) for development and integration of the optical transmitting subsystem is also included in the $530M cost denoted as OP85 on Fig. 1. Indicated uncertainty in cost is about 2 dB (+60%/-40%). As compared to the Ka-band ODSRS, the significantly lower cost is due in part to the smaller size, and in part to the assumed existence of a fully functioning Geosynchronous Space Platform which will provide real-estate and utilities to the optical DSS.

The orbiting optical DSS as finally described by Dickinson (Ref. 1) consisted of a 4.5-meter diameter photon bucket, which would also be Space-Station mounted. This reduction in size eliminated most of the on-orbit assembly work and cut launch charges to one-third of a Shuttle bay. It also lowered the communications performance by 13 dB by virtue of the reduced collecting area. Estimated cost of this device was $145M (+$62M/-$40M), as installed on a space station in low Earth orbit. To achieve full-time coverage for a using spacecraft in deep space, we must either assume the existence of a second station in low orbit and half rotation away, or assume the existence of another station at Geosynchronous altitude and allocate a premium for transporting the optical receiver to the higher location. We have chosen the latter path, and have added another $100M to the installation costs for this purpose. The first user spacecraft cost of $88M (±$16M) is also included in the $330M (+60%/-40%) cost point denoted as OP85' on Fig. 1.

Taking Fig. 1 in its entirety, the envelope of lowest costs follows a path from X-band to Ka-band with modest levels of arraying, and thence to optical frequencies. Space-based elements, unrealistic as free-flyers for microwave frequencies, also appear of value for optical frequencies with the assumed economies of residing on an established Geosynchronous Space Station Platform.

IV. Concluding Remarks

With time, it is expected that both the Ka-band and optical transmitter efficiencies will improve, thus moving these curves to the right, and perhaps lowering their costs at the same time. The X-band curve should be reasonably stable. The fuzziest thing on these curves is the ground-based optical, with both performance and cost very uncertain. Concern exists as well in the ability to accurately and stably point the very narrow optical beam. Both Ka-band and optical pathways show significant promise for future growth in communications capability. The technology for Ka-band is almost in hand, and it should be pursued vigorously to exploit that promise. Optical communication technology makes an excellent investment for a slightly more distant future.

References

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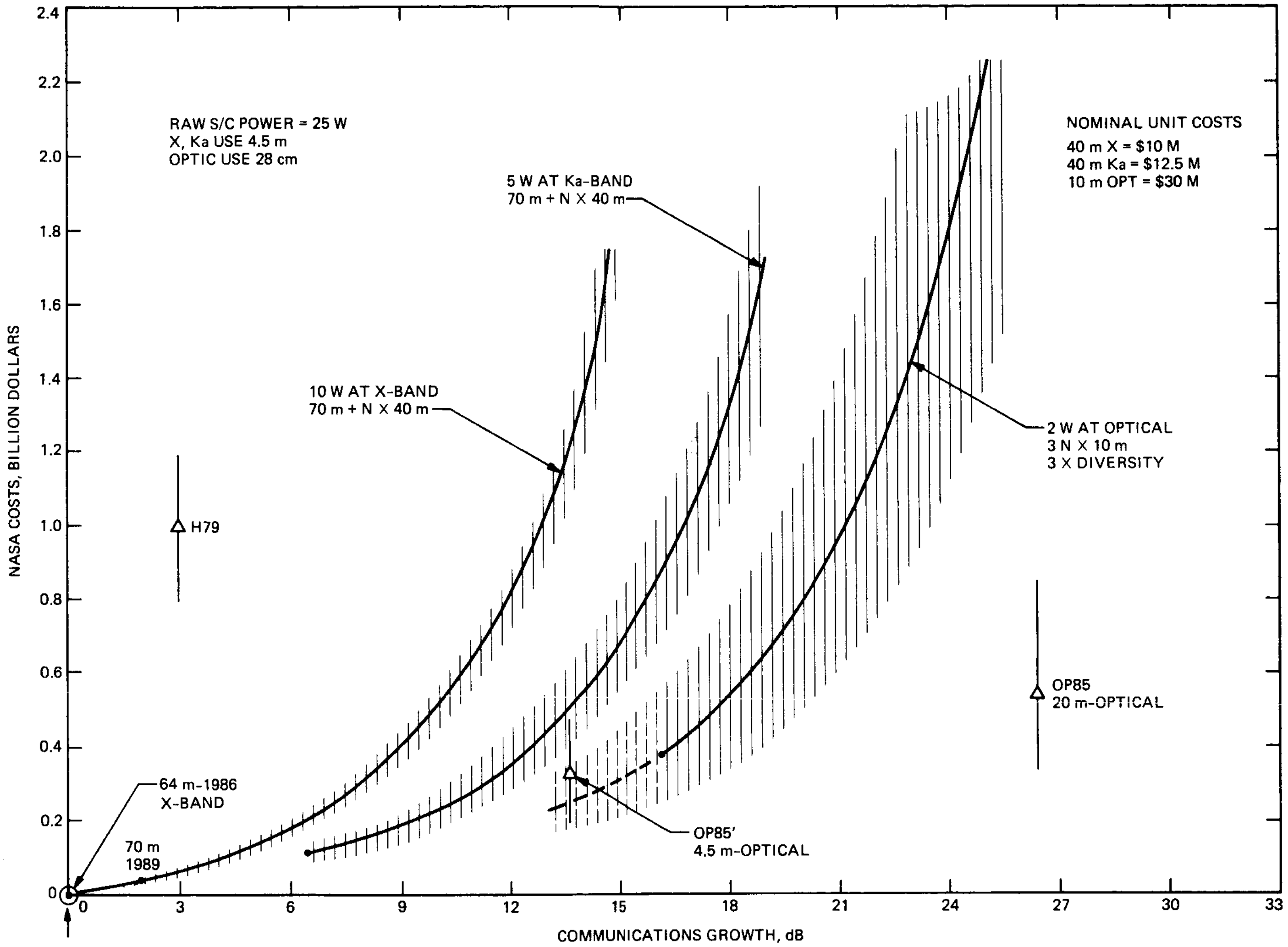

Fig. 1. Cost-performance comparison curves