TMO Progress Report 42-138 August 15, 1999

Comparative Deep-Space Link Performance

J. W. Layland[1]

Over the past decade and more, there has been continuing technology investment for improving telecommunications-link performance at the currently operating frequency of 8.4 GHz (X-band) and enabling larger improvements possible with 32-GHz (Ka-band) and visible light channels. A snapshot of comparative performance was presented in a 1996 study [2], leaving a number of open areas to be further explored. Since that time, a Ka-band telecommunications road map has been devised, and there have been substantial changes to the underlying technology. These items are accommodated in this repeat look at the comparative link performance, and inferences are drawn for development and technology investment.

I. Introduction

A recent report and presentation of a telecommunications road map was created with reference to three representative spacecraft telecommunications subsystem designs for the three communication bands of interest—8.4 GHz (X-band), 32 GHz (Ka-band), and optical communications—with approximately equal call upon spacecraft resources [1].[2] The ideas that follow and the related charts grew from curiosity about what would change, if anything, in these results if the spacecraft resources were forced to be identical across the three bands. That answer turned out to be essentially “nothing” but led to exploring the “what if” for changes to the resource level allocated for telecommunications. One objective in that exploration has been to find insight into areas for potentially fruitful technology development. An interpretation of the results appears in Section VII, “Inferences for Development and Technology.”

The assumed situation for the link design is identical to that of the road map [1], except for the spacecraft configuration. When the other factors are held constant, the telecommunications-link performance is proportional to the transmitted power and to the square of the diameter of the transmitting aperture. Spacecraft resources (power and mass) applied to telecommunications also depend upon the power transmitted and upon the size of the transmitting aperture. Although the real world is known to be a collection of discrete objects, defined by accumulated investments in technology and device development, the following analyses operate under the assumption that the resource values can be approximated as a continuous function of the pertinent parameter(s). For application to a real-world design, the continuum result is approximate and must eventually be rectified to a nearby realizable value.

The RF data set behind this is partly the various antennas and transmitting elements from the advanced communications benefit study (ACBS) [2] and partly antennas described in Sercel’s power antenna

---

[1] Communications Systems and Research Section.

[2] C. D. Edwards, “NASA’s Deep Space Telecommunications Roadmap,” viewgraph presentation to NASA Code-S (internal document), Jet Propulsion Laboratory, Pasadena, California, January 22, 1998.

report[3] plus element parameters for some recently launched spacecraft, such as Cassini and the Mars missions. The optical elements were taken from the ACBS, the Deep Space Systems Technology Program (X2000) design,[4] and the Space Infrared Telescope Facility (SIRTF) telescope design.[5] Additional reference points, both RF and optical, were extracted from presentations at the Visions Workshop[6] of the Deep Space Communications and Navigation Systems Center-of-Excellence (DESCANSO), held in May of 1998, and subsequent updates. Details for the parametric models appear in the Appendix.

II. Performance Trades

For a given desired link performance, transmitted power can be traded for transmitting aperture to achieve a target design. But increasing the power usually means increasing the mass of the power subsystem, be it solar panel (and battery) or radioisotope thermoelectric generators (RTGs), and of the other power and thermal handling elements. The ultimate resource limit is the capability to deploy the spacecraft mass at its destination, and the trades between telecommunications mass and power become trades between mass allocated to the transmitting aperture and mass allocated to the power-handling elements. During the ACBS effort, the power density for a solar-power system at Mars was estimated at about 7 W/kg,[7,8] and a similar value was thought to pertain to current RTGs for outer planet use. New development underway for the advanced radioisotope power system (ARPS) has a similar power-density target with a smaller module size.[9]

In the following discussion, the stated power density of 7 W/kg will be used to combine telecommunications subsystem mass and power into an overall metric for spacecraft resource usage stated in kg. Having done that, the transmitter-versus-aperture trades are worked parametrically to identify the locus of best performance-versus-resource usage. Figure 1 is representative of these trades, showing traces for a metric proportional to the effective isotropic radiated power (EIRP) while the total resource metric is held constant (at one of four values in this figure) and antenna diameter varies from zero to its maximum. There is an implied assumption that the spacecraft pointing is good enough not to seriously degrade the EIRP and that the mass of the pointing system itself is not strongly driven by the precise pointing for the larger antennas. The monotone rising trace follows the peak in the trade space for this figure. Note that the optimum is not sharply defined and finding discrete values in the neighborhood of any given point should not be hard.

The results of this appear in Figs. 2 and 3, which show (on a log scale) the data volume return in MB for a 5-h contact, as a function of incremental spacecraft resources (in kg). The choice of the 5-h-contact time follows the choice made for the telecommunications road map presentations. The assumed situation for the link design is identical to that in Edwards' material, and performance values, rather than being separately calculated, are scaled from the 34-m performance values in the road map [1]. The implied assumptions are that data transport is proportional to EIRP and that pointing losses are not significant. The parameter space covers (1) operation with or without a safe-mode broad-beam (low-

---

[3] J. Sercel, *Power Antenna Technology* (internal document), Jet Propulsion Laboratory, Pasadena, California, August 1994.

[4] C.-C. Chen, *X2000 Optical Communications Subsystem: Baseline Design Document for Europa-Orbiter Mission* (internal document), Jet Propulsion Laboratory, Pasadena, California, August 1998.

[5] *SIRTF Baseline Observatory Design*, Rev. A (Green Book), JPL D-12375 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 29, 1995.

[6] "DESCANSO Visions Workshop," viewgraph presentations (internal document), Jet Propulsion Laboratory, Pasadena, California, May 1998.

[7] D. McGee, personal communication, Avionic Equipment Section, Jet Propulsion Laboratory, Pasadena, California, May 14, 1995, and April 29, 1996.

[8] R. Bennett, personal communication, Flight Systems Section, Jet Propulsion Laboratory, Pasadena, California, July 1996.

[9] "ARPS—Advanced Radioisotope Power System," viewgraph presentation (internal document), Jet Propulsion Laboratory, Pasadena, California, 1998.

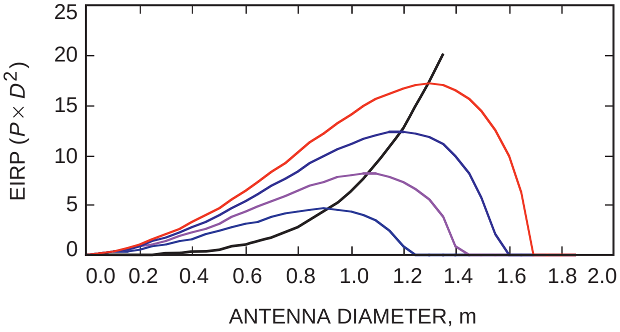

Fig. 1. The optimized EIRP trend versus the antenna diameter.

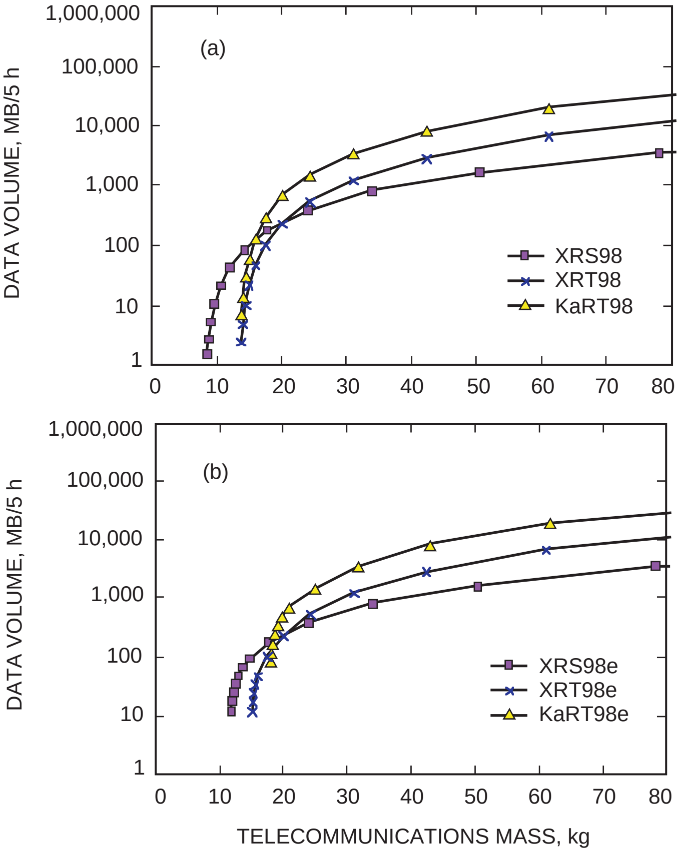

Fig. 2. Performance traces with currently available telecommunications transmitting components: (a) downlink and (b) downlink with a safe-mode communications channel.

gain) communications requirement, (2) power efficiencies consistent with today's spacecraft (1998/1999) or consistent with expectations for 2005, and (3) use of X-band, Ka-band, or optical communications. For the RF bands, configurations include a solid-state power amplifier (SSPA) coupled with a rigid antenna, a traveling-wave tube amplifier (TWTA) with a rigid antenna, and a TWTA with a (forecast) inflatable antenna; there is also a comparison with use of the 70-m-diameter DSN receiving antenna.

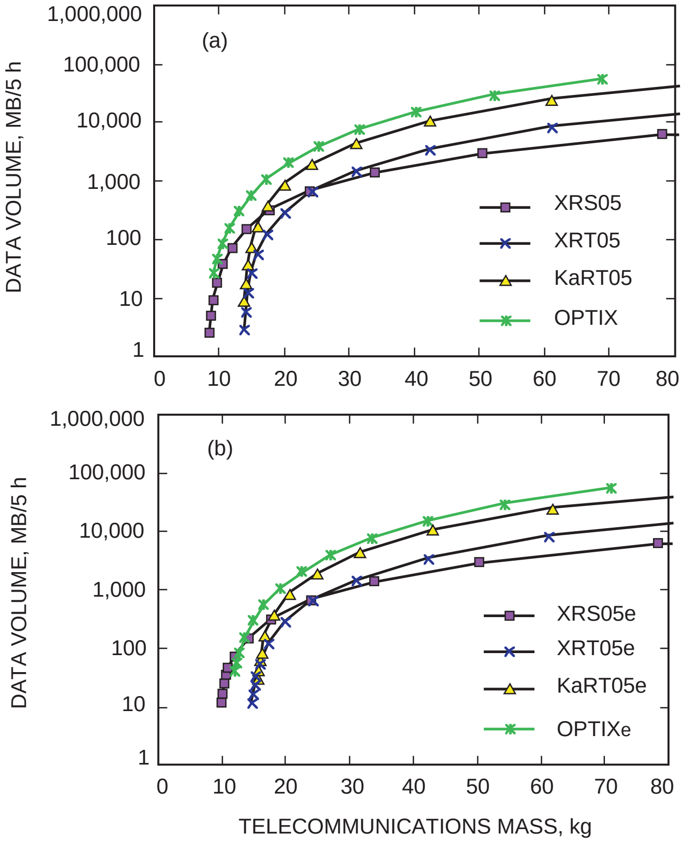

Fig. 3. Performance traces from Fig. 2 amended by parameters for power amplifier devices to be available in 2005: (a) downlink and (b) downlink with a safe-mode communications channel.

Figures 2 and 3 are in pairs that differ by inclusion of an emergency communications capability and are the same in other respects. The plot labels combine the following elements to identify the actual configurations: "X" denotes X-band, "Ka" denotes Ka-band, "RS" denotes a rigid antenna and a solid-state power amplifier, "RT" denotes a rigid antenna and a tube-type amplifier, "OPTIX" denotes the optical configuration, "98" denotes present day technology, "05" denotes 2005 technology, and "e" denotes an associated emergency communications link. (As an example, XRS98 denotes X-band via a rigid antenna with a solid-state power amplifier in today's technology.) In these figures, the x-axis is the resource usage on the spacecraft, in kg, while the free parameter for calculation is the transmitting aperture. The y-axis displays the corresponding link transport capacity in megabytes (MB) for a 5-h pass, the same performance metric used in the road map study [1]. For reference, a net average rate of 44 kb/s corresponds to a transport capacity of about 100 MB/5 h.

III. Basic Link Performance—Current Capabilities

Figures 2(a) and 2(b) present the performance with currently available telecommunications transmitting components. Traces are shown for tube-type power amplifiers at X-band and Ka-band and for X-band solid-state amplifiers; in all cases, they are representative of existing flight elements. A corresponding trace for a Ka-band solid-state amplifier is not shown as it would differ little from that for X-band, due to the lesser efficiency of current Ka-band devices. The antennas are assumed to be rigid in form, with parameters consistent with existing antennas, as modeled in the Appendix. Figure 2(a) shows only the primary downlink data return and telecommunications resource values. At high-end resource usage, the return data volume for the Ka-band tube-type link exceeds that for X-band by about 4.5 dB, while the return for the X-band tube-type link exceeds that for the X-band solid-state link by 4 to 5 dB. This clear distinction holds only for links capable of rates on the order of 500 kb/s (from Mars). As the resources allocated to telecommunications decrease from that level, the performance traces begin to converge or cross over. At the very low-end resource allocation (giving rates of a few kb/s from Mars), the X-band solid-state link requires the least telecommunications resources at any given data-return level. At in-between levels, the telecommunications performance versus resource metric is indecisive.

IV. Link Performance With a Safe-Mode Communications Requirement

Figure 2(b) is a parallel to Fig. 2(a) except that an added requirement for a safe-mode or emergency communications channel is added to provide for limited communication when precise pointing is not available. The need for a safe-mode communications channel is a matter of some debate, as the current trend toward intelligent autonomous spacecraft would seem to eliminate the need. On the other hand, few if any past missions have flown successfully without resorting to use of their safe-mode communications channels at some time in their flights.

A safe-mode communications capability can be provided through a low-power X-band downlink (at least 5 W) and a broad-beam (7-dBi) antenna. This value assumes the use of the DSN's 70-m antenna for reception and could be low; a cautious mission designer could be well advised to direct the use of 20 W or more for the safe-mode X-band power. Even so, the impact on the figures as drawn using the 5-W figure should show clear indication of the changes that result from the safe-mode communications requirement. Trying to do the safe-mode communications at Ka-band or optical frequencies would require a much higher emitted power level to counter the higher channel and equipment losses. For estimating the link performance at X-band, the transmit power is given a lower bound of the 5 W while the mass added for the low-gain antenna is negligible. For the optical channel, the full tiny X-band package must be added with a penalty of about 5 kg while, at Ka-band, some parts of the RF equipment can be shared, leaving a residual 2 kg needed to provide the low-power X-band capability. It is assumed that power can be off for the safe-mode channel when the main high-rate link is in operation and off for the main link when the safe-mode channel is needed.

Comparing this figure with its counterpart shows that little change results from imposing the safe-mode communications requirement at the high-performance end. At the low end, the resource advantage for X-band solid state over the tube type has somewhat diminished, thanks to the lower bound on required power, and, in the lower end of the indecisive region, there is a cross-over in the traces for the X-band and Ka-band tube-type amplifiers.

V. Forecast Link Performance—2005 Era

Figures 3(a) and 3(b) amend the performance traces from Figs. 2(a) and 2(b) by adopting parameters for power amplifier devices that are consistent with those already under development and that have reasonable assurance of being available for flight in the 2005 era. All device efficiencies have increased from their 1998 values, especially for Ka-band. The trace for Ka-band solid state is not shown but would fall approximately 3 dB above the X-band solid-state trace were it to be included. Characteristics of the rigid antenna family are assumed to be unchanged from current values, but the option is expected to be available for an inflatable antenna analogous to those currently under development. A plausible optical channel has been added assuming the use of a 10-m-diameter "photon bucket" for reception. At the high-performance end, this optical channel shows about a 2-dB apparent advantage over the Ka-band, rigid antenna, tube-type configuration. Among the RF configurations, Ka-band shows about a 5-dB advantage over X-band using the tube-type amplifiers and about a 3-dB advantage with solid state. Similarly, the X-band tube type retains a 3-dB advantage over X-band solid state. Other aperture options for the RF channel will appear in later figures. At the low-performance end, the resource advantage goes to the solid-state amplifiers, at either frequency, and to the optical option.

When the safe-mode communications element is added for Fig. 3(b), no change is apparent at the high-performance end, but there is an increase in minimum resource requirement at the low-performance end. X-band solid state continues to offer the minimum resource configuration with data rates of a few kb/s, and adding an optical channel appears to provide substantial increases in data return for a modest increase in allocated spacecraft resources.

VI. Forecast Link Performance—Other Configurations

There are a number of other configurations, including 70-m antennas or spacecraft inflatable antennas, that have been mentioned in the foregoing paragraphs but not yet presented in figures. We could continue in the present style, showing pairs of figures, but these are all very similar in appearance, making it hard to extract useful information. As an alternative, consider Fig. 4, wherein the apparent telecommunications-related mass has been fixed at a large value (here 40 kg) and the corresponding link performance calculated

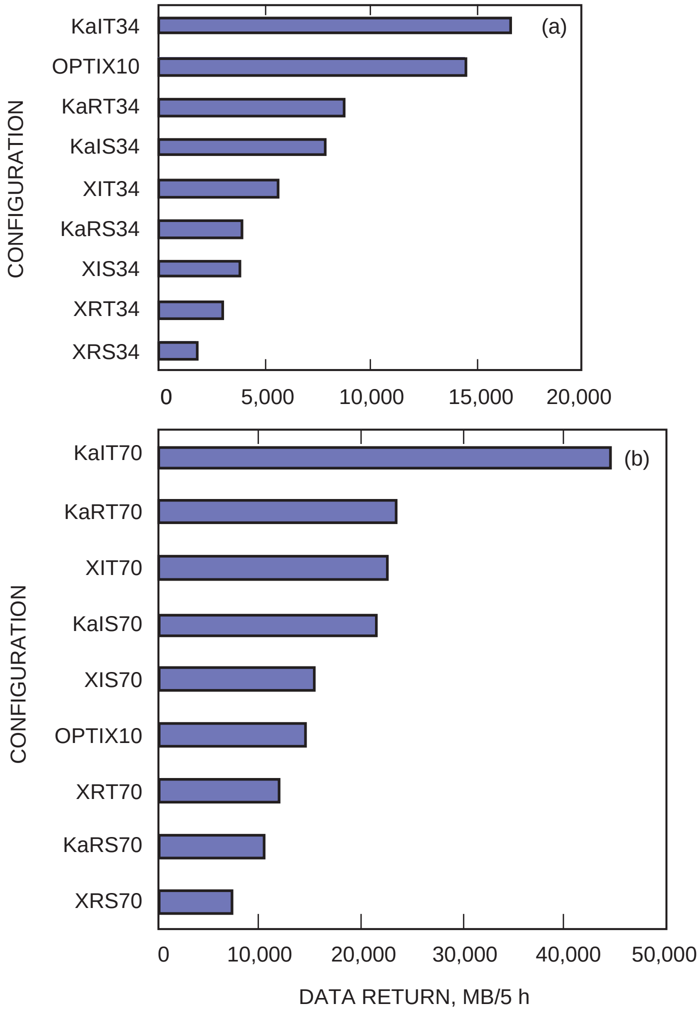

Fig. 4. Forecast downlink data volume for various antenna configurations: (a) 34-m antenna and (b) 70-m antenna.

for each of the various configurations of interest. As in prior figures, this is the performance at the best balance between mass and power. Figure 4(a) presents the 34-m reception; Fig. 4(b) presents the 70-m reception; and the optical 10-m configuration is included in both for convenient reference. Slices similar to those in Figs. 4(a) and 4(b) could be calculated at other values for the telecommunications mass, to or beyond practical limits, but the message embedded in the figures should not change. For high-link performance, we should seek value in Ka-band with the TWTA and with the low-mass inflatable reflector technology. In these figures [and Figs. 5(a) and 5(b)], the previously defined identification elements apply as well as the following: "IT" denotes an inflatable antenna with a tube-type amplifier, "IS" denotes an inflatable antenna with a solid-state amplifier, "34" denotes 34-m antennas, "70" denotes 70-m antennas, and "10" denotes the 10-m optical configuration.

The same approach also can be applied at the other end of the performance spectrum, except that the slice should be taken at a fixed low value of link data volume, and the corresponding telecommunications mass should be calculated for each of the interesting configurations. Figures 5(a) and 5(b) display the telecommunications mass according to configuration, with a performance slice taken at 10 MB/5 h, or about a 4.5 kb/s average. For the low level of link performance represented in these figures, there is little difference between frequency bands, but the rationale for the SSPAs at either band is clear. With the side information that the X-band SSPAs are readily available products while the others are still developmental, these figures offer rationale for selection of the X-band SSPA for low-performance applications or for work to improve it. Adding the requirement for emergency communications increases the mass requirement for any of the configurations but does not noticeably change these preferences.

VII. Inferences for Development and Technology

The foregoing figures offer some guidance as to top candidates for technology targets. These are stated with the assumption that the Spacecraft Transponding Modem (STM) development is completed as planned, since it is common to the various RF systems considered. Consistent with the foregoing

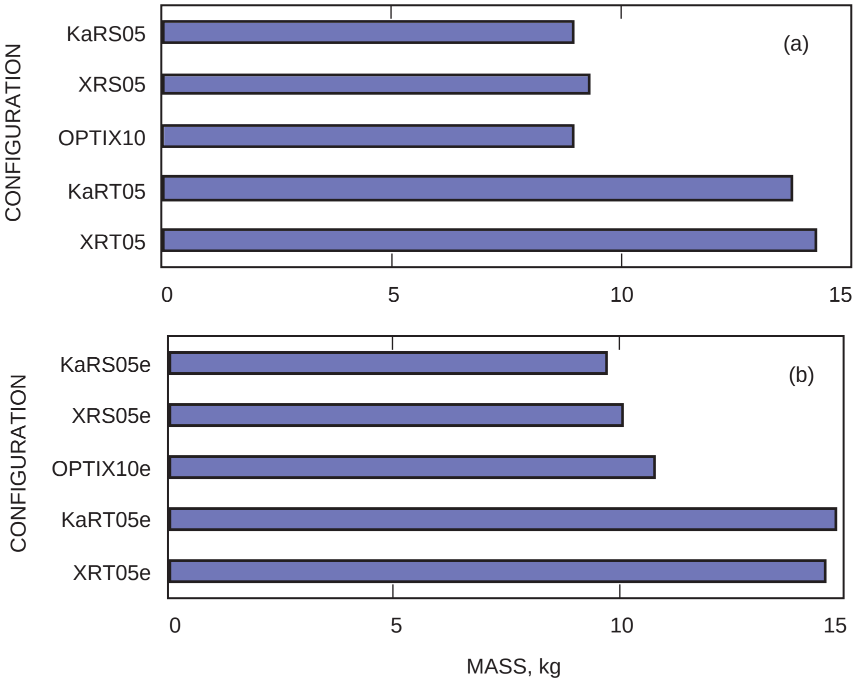

Fig. 5. Basic telecommunications mass with (a) low direct performance requirements and (b) safe-mode communications and low direct performance requirements.

discussions, the top candidates are (1) X-band SSPA efficiency for a range of 5 to 25 W, (2) efficient Ka-band TWTA for a range of 10 to 40 W, (3) low-mass (inflatable) antenna systems for diameters of 3 to 6 m, with an included vernier pointing capability, (4) safe-mode/emergency communications with low mass/power (embeds a low-power X-band SSPA and STM), (5) automation or some other operations concept that allows freedom from auxiliary communications for small spacecraft, and (6) optical communications overall development and improved efficiencies for the lasers and optical detection devices.

There are many other improvements worthy of pursuing, such as a lower noise temperature for Ka-band receiving, the efficiency of X-band TWTAs, the mass of the spacecraft microwave plumbing, the efficiency of 70-m Ka-band reception, coding and data compression, etc. Most of these developments currently are under way.

VIII. What Next?

Having espoused a parametric view of the telecommunications system elements and their performances, there are a number of tempting "what-ifs" that can reasonably be played out. One that should be done is the estimation of the uncertainties in the fit between the model and reality. Another tempting option is the forecasting of the technologies further into the future, say 2012. Both of these are left for future work.

Acknowledgments

The work reported here reflects information and insights gained from many people at JPL. Some of these are indicated by footnotes and references throughout the article. Special thanks go to Stan Butman, Chien Chen, Bob Clauss, Chad Edwards, Hamid Hemmati, Richard Horttor, Anil Kantak, Faiza Lansing, Jim Lesh, Anthony Mittskus, Ron Pogorzelski, Dan Rascoe, Charles Stelzried, Miles Sue, Laif Swanson, and Keith Wilson for valuable input to the foundation of this work.

References

[1] C. D. Edwards, Jr., C. T. Stelzried, L. J. Deutsch, and L. Swanson, "NASA's Deep-Space Telecommunications Road Map," *The Telecommunications and Mission Operations Progress Report 42-136, October–December 1998*, Jet Propulsion Laboratory, Pasadena, California, pp.1–20, February 15, 1999.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-136/136B.pdf

[2] H. Hemmati, K. Wilson, M. K. Sue, L. J. Harcke, M. Wilhelm, C.-C. Chen, J. R. Lesh, Y. Feria, D. Roscoe, F. Lansing, and J. W. Layland, "Comparative Study of Optical and Radio-Frequency Communication Systems for a Deep-Space Mission," *The Telecommunications and Data Acquisition Progress Report 42-128, October–December 1996*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–33, February 15, 1997.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-128/128N.pdf

Appendix

Parametric View and Basis

For the purposes of the calculations described in the main text, the resource requirements of the spacecraft telecommunications subsystem are assumed to be approximated by a low-complexity function of the output power and the transmitting aperture. The locus of the best balance between power and aperture then can be derived analytically. For power, the aggregate of consumed power plus device mass grows slightly faster than linearly with output power, and its variable part appears reasonably well approximated as $k \times P^e$, where P is the output power and k and e are parameters to be defined.

The parameter e would be unity if the multiple elements needed for high power could be connected with no fan in/fan out or combining losses. But reality intervenes and places e into the range of 1.15 to 1.3 for current devices. The suggested model value of $e = 1.25$ appears to fit the family of SSPAs in the ACBS [2], while the parameter k is pegged to match the power and efficiency characteristics of specific amplifiers. For the antenna aperture, the unit mass seems to be well approximated by a cubic $a + b \times D + c \times D^2 + d \times D^3$, where D is the transmit aperture and a, b, c, and d are parameters adjusted to match the family of antennas. Specific choices for these parameters will be presented shortly.

Given this form for the transmit power and aperture, the locus of best balance can be described by

$$k \times P^e = \frac{b \times D + 2 \times c \times D^2 + 3 \times d \times D^3}{2 \times e}$$

To generate the figures in the main text, both the performance values and the mass of the transmitting aperture were calculated as a function of D and then displayed as a function of combined resource usage.

Values for the parameters a, b, c, d, and k were chosen to fit through "real" systems where available. For the rigid antennas, the reference set includes the Advanced Communications Technology Satellite (ACTS) (3.3 m, 29 kg), Voyager (3.7 m, 43 kg), and Cassini (4 m, 56 kg), as well as the smaller antennas of the ACBS. The chosen approximation is $M = 0.5 + 0.7 \times D + 0.8 \times D^3$ for the rigid antennas. Figure A-1 displays this approximation in context with the stated values for real antennas. The same model values are assumed for both current and near-term forecast rigid antennas as this is a relatively mature technology. The real advance should come with the availability of low-mass inflatable antennas, such as are currently in development. Reference values for the inflatable antenna follow from Sercel's power antenna document[10] at the high end and from target values for current design efforts by John Huang at 1 and 3 m.[11] The chosen approximation becomes $M = 1.3 + 1.1 \times D^2$ for the inflatable antenna family. It should be acknowledged that this is not a formal least-squares product, but a heuristic fit through a very sparse data set.

Power amplifiers require resources in the form of both power and mass. The Mars Pathfinder X-band SSPAs each weigh 1.6 kg and when active consume 57 W DC to provide 12.5 W of RF,[12] giving a net efficiency of 22 percent, with power-handling capacity (input) of about 30 W/kg. Recent efforts

---

[10] J. Sercel, op. cit.

[11] J. Huang, personal communication, Spacecraft Telecommunications Equipment Section, Jet Propulsion Laboratory, Pasadena, California, December 8, 1997.

[12] R. P. Scaramastra, personal communication, Spacecraft Telecommunications Equipment Section, Jet Propulsion Laboratory, Pasadena, California, May 27, 1999.

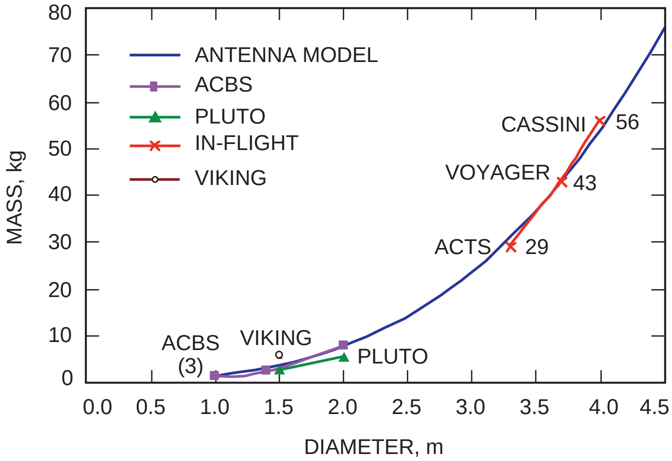

Fig. A-1. Rigid antenna parametric model and reference values.

have demonstrated an amplifier with 15 W at 27 percent efficiency,[13] which has been used to represent the current X-band SSPA family. For this and other configurations, a power-source density of 7 W/kg has been assumed. At Ka-band, the archetype is the Deep Space 1 (DS 1) Ka-band SSPA with 14 percent efficiency and a 2.5-W output.[14] This is modestly improved from values for the Ka-Band Link Experiment (KaBLE) SSPA. Shifting to the near future, a projected laboratory demonstration X-band SSPA should offer 20-W RF at 45 percent efficiency from a 1.6-kg package. This again shows a power-handling capacity of about 30 W/kg. The reference is less clear for Ka-band development, but 5 W at 35 percent is thought to be plausible, given successful device development.[15] When a TWTA is used, there is a minimum to mass and power drain, but the unit mass is almost independent of power output. The mass and efficiency of the current Cassini TWTAs were used as the 1998 performance: efficiency at 45 percent (X-band) and 35 percent (Ka-band) with a 5-kg mass. Future growth in efficiency to 60 percent (X-band) and 45 percent (Ka-band) were used for the forecast 2005 cases. The total requirements for the spacecraft system also include other elements, e.g., 5 kg for bits and pieces of microwave plumbing, brackets, etc., plus 10 W and 1 kg for the STM. Actual current values for these elements can be much higher, as, for example, in the Mars Global Surveyor (MGS) configuration.[16]

A parametric descriptor for the optical communications terminal was created in a similar fashion. The technical basis includes the four point designs of the ACBS [2, Table 10] and two variants of the X2000 30-cm design for the Europa mission, without its extra radiation shielding. Another reference value is provided by a recently completed Small Business Innovative Research (SBIR) development of a 30-cm optical communications telescope with a mass of 6.5 kg. To extend this to larger aperture sizes, the SIRTF design “green book” offers a reference point at 0.85 m, taking 35 kg for the precision telescope itself, with an estimated addition of 10 kg for the barrel baffle.[17] Telescope design requirements for SIRTF appear similar to those for an optical communications terminal, and both respond to a need to minimize mass.

---

[13] A. Mittskus, personal communication, Spacecraft Telecommunications Equipment Section, Jet Propulsion Laboratory, Pasadena, California, February 12, 1999.

[14] Ibid.

[15] Ibid.

[16] S. A. Butman, personal communication, Communications Systems and Research Section, Jet Propulsion Laboratory, Pasadena, California, December 1997 and May 1999.

[17] *SIRTF Baseline Observatory Design*, op. cit.

Comparing the larger of the ACBS designs with the two X2000 design points, one sees a shift toward a potentially more robust design with more functionality and increased mass and power, especially for the final X2000 design, as described by Chen.[18] The preliminary version of the X2000 30-cm design was utilized in [1]. Some elements of the "final" design point can be set aside as being special to the Europa context, bringing it closer to the "preliminary" value. Specific items include the accelerometers (3 kg), a thermal radiator (4.2 kg, scaled with laser power/heat), and a portion (7.4 W) of the power estimate for the control function (this reduces that element to its value in the ACBS designs).

With these as reference, the chosen approximation for the optical telescope mass becomes $M = 9 \times D + 40 \times D^2$, where D is the diameter in meters. The correspondence between the parametric view and the reference data points may be seen in Fig. A-2. The chosen approximation is clearly a compromise between competing design strategies.

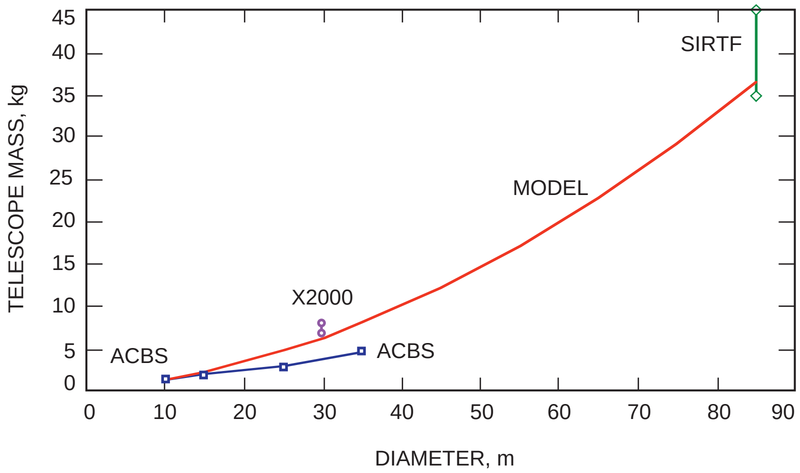

Fig. A-2. Optical telescope model and reference elements.

The net efficiency of the transmitting laser subsystem is taken to be 10 percent, per the X2000 design, but to achieve this, the actual conversion efficiency must be about 15 percent to accommodate losses in the power conversion and power allocated to thermal control. The approximate mass and power consumption of the laser subsystem and other electronics is derived from a combination of the ACBS design series for low-power terminals and the X2000 design at higher power (e.g, 3 W). Not including the telescope and its mountings, the approximate model for the laser communication package includes a base of 4.5 kg and 14 W, plus a variable element of 1.3 kg per laser W and 9.5 source W per laser W.

This optical-system model is nominal only and is a compromise between competing design viewpoints. Taking an aggressive approach to design of the optical system that extrapolates from the ACBS designs only and largely ignores the SIRTF and heavier X2000 Europa design points, the high-performance end would perform +2 dB better than the nominal optical values and +4 dB better than the Ka-band 34-m results. Becoming cautious and basing the model parameters on those of the X2000 "final" Europa design and also the heavier SIRTF figures results in an optical link performance that is 3 dB below that of the nominal optical values and 1 dB below Ka-band 34-m performance.

---

[18] C.-C. Chen, op. cit.

It is worth noting the current work toward an optical communications unit for X2000 delivery 2 is proceeding with design goals that are much smaller, lighter, and less power hungry than the smallest of the ACBS designs.[19] This is to be achieved in part by depending upon the main spacecraft for control processor functions and for thermal control and disposal of excess heat. If this development is successful, it promises a bright future for optical communications.

---

[19] "Optical Communications Subsystem," "DSST Future Deliveries Program: Performance Requirements (Goals) and Specification," Intranet Material (internal document), Jet Propulsion Laboratory, Pasadena, California, November 1998.