optical Communications for Extreme Deep Space Missions

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Abstract

A recent study of deep space telecommunication systems was performed in support of NASA's Mission to the Solar System planning activity. The results of this study show that high bandwidth communications (greater than 1 Mbps) are feasible at high-value planetary targets provided there are investments in the ground and spacecraft communication infrastructure. These targets include Mars, Jupiter, and Neptune. Optical communications is a key enabling technology for achieving the higher data rates. This work was then extended to consider solutions to extreme deep space (beyond 100 AU) communications. Communications data rates between 10 and 100 Kbps should be achievable from as far as 1,000 AU within 25 years. The technologies, infrastructure enhancements, and resulting performance capabilities are discussed in this paper.

Key Winks: Optical communications, Laser communications, Deep space communications

1. Introduction

There has been much interest lately in the development of a long range plan for telecommunications within our solar system. Part of the interest stems from a NASA Office of Space Sciences (OSS) planning activity to develop a *roadmap* for the *Mission to the Solar System*. The Jet Propulsion Laboratory (JPL) has been leading this effort for NASA, The roadmap has been synthesized over the past six months with participation from a cross section of the American science community as well as technologists from NASA field centers, academia, and U.S. industry. The roadmap covers robotic exploration for the period of time from now until the year 2020.

NASA realizes that solar system exploration will be an international activity. Foreign space agency plans for planetary missions have been factored into the roadmap activity. There will likely be an international planning activity that will follow NASA's acceptance of the roadmap recommendations.

In addition to developing a set of

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recommendations to NASA for missions in response to specific scientific questions, the roadmap team examined several of the key enabling technologies. One of these is telecommunications. The focus of the roadmap activity was on space missions within the solar system. However, the work that was performed in the telecommunications area can be extended to far outer planet and longer-distance missions as well.

The Mission to the Solar System roadmap considered many aspects of the telecommunications challenge. The team considered the networking aspects of operating many spacecraft (sad landers, rovers, ...) on a single target body using communications relay satellites orbiting around those bodies. The team also examined the challenge of providing a low cost, low mass, high performance communications capability between the surface elements and a relay satellite. The team spent most of its energy predicting the performance, as a function of time, for the *trunk lines* - the main communications channels between the target bodies and the Earth, rather than the local links between such things as landers and their local relay satellites. The trunk lines represent the hardest problem to solve for outer planet missions and beyond. Two radio frequency bands (X-band and Ka-band) were considered as was optical communications[1]. This paper deals only with performance estimates and technology developments considered for the optical communications options of those trunk lines.

The roadmap analysis included an examination of the key technologies required for the trunk lines and their probable availability over the next 25 years. Analyses were performed for three target body communications orbiters: Mars (2.5 AU), Jupiter (6 AU), and Neptune (30 AU.) The results showed that in the time frame of the roadmap, we could expect communication bandwidths of more than 1 Mbps at each of these targets - with much greater capabilities at Mars. Such large bandwidths were considered essential to provide a telepresence for the science community and the general public during the exploration, and to lay the infrastructure for subsequent piloted missions.

This work was then extended to cover communications capabilities out to 100 AU and 1,000 AU in the same period of time. The results indicate that it will be possible to support data rates of 10 to 100 Kbps from missions at 1,000 AU within 25 years,

?. Technology Predictions

In order to estimate communications link performance over the next 25 years, one must predict the evolution of critical communications technologies. This is an imperfect exercise. It is also, at the moment, not cost constrained.

The technologies listed below are not meant to represent all relevant technologies - only those that are seen as enabling for the main communications trunk links.

?.1 Wavelength

Current optical communications work for deep space links is concentrated at a wavelength of 1.064 µm. By the year 2005, it is expected the technology for communication at 0.53? µm will be available for flight. This will allow an incremental jump in performance.

2.2 Spacecraft Lasers

The efficiency of solid state flyable lasers is assumed to increase from its current value of about 10% to better than 30% over the next 25 years. At the same time, the radiated power is predicted to increase from 3 W to 20 W.

2.3 Low Mass and Cost Space Terminals

JPL has been working on the challenge of creating a low mass and low cost communications terminal for deep space missions using optical communications technologies. Although none of these terminals have flown in space yet, several prototypes, including the Optical Communications Demonstrator (OCD)[2] have been tested in the laboratory. The OCD terminal has an optical aperture of 0.1 m.

Figure 1 shows an engineering model for a deep space optical terminal. It has a mass of about 8.5 kg and a power consumption of 30W. Such a terminal could be available for experimental flight as early as next year.

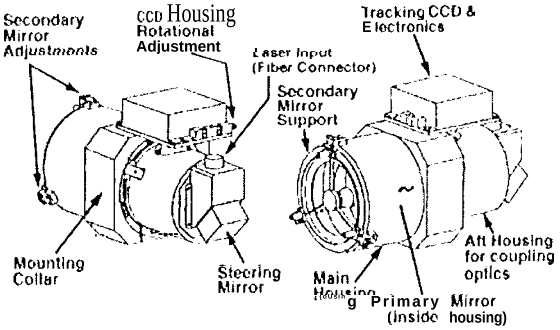

Figure 1, Deep space optical flight terminal

More advanced versions, that integrate the optical communications instrument with a science imaging system, could be ready for flight by 2000. These would have a mass of about 10 kg and consume approximately 35 W of power.

2.4 Earth Receive Apertures

“There is currently no operational capability for deep space optical communications. Demonstrations have been performed using modified astronomical observatories[3,4].

By the year 2000, there could be a limited ground-based optical communications capability to support demonstrations in deep space[5]. These stations could have a 10m non-diffraction limited receive aperture. This would be more than enough to support hundreds of kilobits of communications from Saturn-like distances in the near-term.

in order to make this capability truly operational, several copies of the 10m terminal would be built to achieve both continuous coverage with deep space targets and spatial diversity to combat the effects of Earth's weather. At least three, and maybe as many as five such stations would be needed to support operational deep space missions[6]. These could be in place by **'2005,**

By **2010,** the Earth receive capability could be increased either by building larger ground-based apertures, or by placing the terminals in Earth orbit[7,8].

2.5 Receive Filters

Current state-of-the-art for receive system detection filter bandwidth is about 10 Å. Over the next 25 years, this should decrease to better than 1 Å through the use of technologies such as the Faraday Anomalous Dispersion Optical Filter[9]

2.6 Detectors

Currently, all optical communications demonstrations with deep space have utilized avalanche photodiodes (APDs) to measure incoming photons. By the year 2015, solid state photomultiplier tubes (SS-PMTs) should be available.

2.7 Pointing

Just as in the case of RF communications, the pointing of both the spacecraft and Earth terminal apertures is also critical to the performance of the link for optical communications.

The first deep space missions to use optical communications will likely have a cooperative pointing system. In this case, a laser beacon signal will be sent from the Earth station, After acquisition, the two terminals will track each other's signal to achieve a closed-loop pointing.

By 2000, a spacecraft system that finds the optical image of the Earth could allow sufficient pointing accuracy to eliminate the need for an Earth terminal beacon for signal acquisition. More sophisticated systems that use star trackers and other on-board sensors could allow even better open loop pointing by 2005.

By 2010, such on-board autonomous pointing systems could be further improved by using non-mechanical fine-steering techniques for the spacecraft terminal.

3. Analyses for Mission to the Solar System

Using the technology projections above, link performance estimates were developed for three target-body orbiters: a Mars orbiter, a Jupiter-orbiter, and a Neptune-orbiter. It was assumed that the largest launch vehicle available for this exercise was a Delta III. The analysis was performed at five year intervals beginning in 1995 (present capability) and ending in 2020,

For each year, six link performances were calculated, Two of them were optical links based on aggressive and conservative estimates for the technology evolution. The other four were aggressive and conservative projections for both X-band and Ka-band[1]. The results are shown in Figure 2.

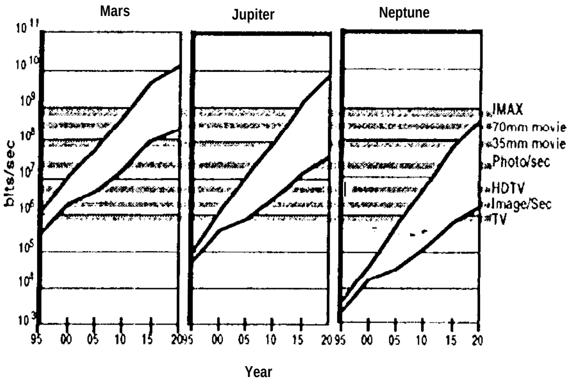

Figure 2. Mission to the Solar System capabilities projections for trunk lines

The areas in the graphs are bounded by the best aggressive case on the top and the best conservative case on the bottom. All three graphs eventually use optical communications to bound the areas as time progresses.

The horizontal lines through the graphs represent the capability that would be required to support real time communication of various common data types. These range from broadcast quality television (USA NTSC) to IMAX high resolution motion pictures. Aggressive compression technology was assumed for all of these data types.

The Neptune communications orbiter was, by far, the most challenging. It requires a Delta III launch vehicle and an RTG to supply sufficient power for the link. Optical communications provides the only option for 1 Mbps communications bandwidth in this time frame.

The basic conclusion for the Mission to the Solar System roadmap exercise is that a capability at least as good as commercial broadcast television could allow the public to participate in exploration of the entire solar system if there is enough investment in both flight and ground infrastructure.

4. Extensions to Far Deep Space Missions

All the same assumptions about the availability of key technologies remain valid for the farther, "out of the solar system", link performance calculations. In addition, since there is no target body to orbit for these missions, the spacecraft mass limitations for the communications system that had been imposed to allow for orbit capture and maintenance for the three planetary cases above can relaxed. This extra mass margin could go toward generating more spacecraft power, providing twice as much available communications electrical power from RTGs (150 W) beginning in 2010," This makes the link performance estimates look better in comparison to the Mars, Jupiter, and Neptune cases than one might expect from the inverse square distance loss.

An additional radio frequency technique considered for both the 100 AU and 1,000 AU missions was arraying of X-band and Ka-band ground antennas. Allowing for a 0.3 dB combining loss by 2020, an array consisting of a 70m and four 34m antennas (the planned configuration of all three Deep Space Network complexes by 2020) would have performance slightly better than a single 94m antenna. Since continuous coverage. is not likely to be a requirement for such missions, such large amounts of ground resources can be applied for short periods of time.

The results of the aggressive analyses are shown in tabular form in Table 1, together with the assumptions on available technologies. The conservative case differs from the values shown in two main ways: the RF spacecraft antennas are assumed to be fixed, 1.5m dishes, and the optical technology items are assumed to mature ten years later. in references 10 and 11, similar calculations are performed 10 estimate the communications performance of a 1,000 AU mission for X-band and optical systems. The results are comparable t() those presented here for the 2010-2015 time when one accounts for the differences in assumptions.

Figure 3 shows these results graphically in the same form as in the previous section. The areas in the graphs are bounded by the best of the aggressive and conservative results for each year. As shown in Table 1, the upper (high performance) envelope of these long-distance links is dominated by the optical system performance after the year 2005.

	Technology Area	1995	2000	2005	2010	2015	2020
Common	Spacecraft System Power	75	75	75	150	150	150
X-band	Transmitter Efficiency	50 %	53 %	56%	59 %	62%	65%
	RF Transmit Power (W)	20	32	33	70	74	78
	Spacecraft Antenna Diameter (m)	3	6	6	10	10	15
	Ground Antenna Diameter (m)	70	70$	82	82	88	94
	T sys (K)	30	20	20	20	20	20
	Ground Aperture Efficiency	65%	65 %	65%	65 %	65%	65%
	Coding	Turbo	Turbo	Turbo	Turbo	Turbo	Turbo
	Data Rate @ 100 AU (bps)	7.63E+02	7.32E+03	1.04E+04	6.11 E+04	7.50 E+04	2.03E+05
	Data Rate @ 1000 AU (bps)	7.63E+00	7.32E+01	1.04 E+02	8,11 E+02	7.50E+02	2.03E+03
Ka-band	Transmitter Efficiency	30 %	34 %	38 %.	42 %	46%	50%
	RF Transmit Power (W),	10	15	20	44	48	51.5
	Spacecraft Antenna Diameter (m)	1.5	3	6	6	10	15
	Ground Antenna Diameter (m)	70	70	82	82	88	94
	Tsys (k)	40	30	30	30	30	30
	Ground Aperture Efficiency	50 %	50%	50%	50 %	50%	50%
	Coding	Turbo	Turbo	Turbo	Turbo	Turbo	Turbo
	Data Rate @ 100 AU (bps)	7.13 E+02	5.70E+03	4.18 E+04	1.04 E+05	3.64E+05	1.02E+06
	Data Rate @ 1000 AU (bps)	7.13E+00	5.70E+01	4.18E+02	9.19E+02	3.23[	8.89E+03
Optical	Wavelength (A),	1.064	1.064	0.532	0.532	0.532	0.532
	Laser Efficiency	12%	20%	15 %	20 %	25 %	30%
	Laser Power (W)	3	5	5	10	20	20
	Spacecraft Telescope (m)	0.3	0.3	0.5	0.5	1'	1
	Receiver Location	ground	ground	ground	Earth orbit	Earth orbit	Earth orbit
	Filter Bandwidth (Å)	10,	3	1	1	1	1
	Detector Type,	APD	APD	APD	APD	SS-PMT	SS-PMT
	Ground Receiver Efficiency	56 %	56 %	56 %	56%	56%	56%
	PPM alphabet size	1024	1024	1024	1024	1024	512
	Data Rate @ 100 AU (bps)	1.00 E+02	1.00E+03	4.00 0E+04	4.00E+05	9.00E+06	7.00E+07
	Data Rate @ 1000 AU (bps)	1.00E+00	1.00 E+01	4.00E+02	4.00 E+03	9.00E+04	7.00E+05

Table 1.
Aggressive 100 AU and 1,000 AU capabilities projections for communications orbiters for X-band, Ka-band, and optical systems

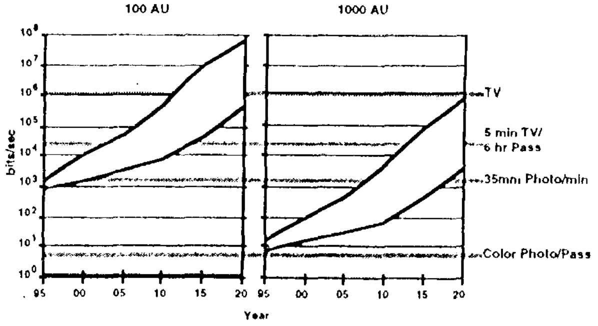

Figure 3. Capabilities projections for communications from missions at 100 and 1,000 AU

4. Conclusions

The calculations performed here indicate that, even in the near term, communications capabilities from fat outer solar system missions (up to 1,000 AU) are sufficient to support meaningful science and even public involvement. With today's technology, missions using kilobit data rates can be supported at 100 AU. Within 20 years, this capability will exist for missions at 1,000 AU. With an aggressive program of communications technology and infrastructure development, even greater capabilities will be possible - up to supporting real time broadcast quality television from 100 AU and many minutes of television-quality video each day from 1,000 AU. Optical communications will play an important part in this technology evolution.

Acknowledgment

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