TECHNOLOGY, DATA BASES AND SYSTEM ANALYSIS FOR SPACE-TO-GROUND OPTICAL COMMUNICATIONS

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A tract

Optical communications is becoming an ever- easingly import@ option for designers of space- round communications links, whether it be for ernment or commercial applications. **In this paper** th technology being developed by NASA for use in %-to-ground optical communications is presented. N t, a program which is collecting a long term data as of atmospheric visibility statistics for optical agation through the atmosphere will be described. ally, a methodology for utilizing the statistics of the atmospheric data base in the analysis of space-to- nd links will be presented. This methodology takes account the effects of station availability, is useful n comparing optical communications with rowave systems, , and provides a rationale for the blishing the recommended link margin.

reduction

Communications demands for spacecraft are r-increasing and the technology required to satisfy th se link demands often dominates the architecture of th spacecraft structures. This has been true for some e on military and NASA missions, and more recently as become a driver for many proposed commercial llite networks. Accordingly, NASA has been eloping optical communications technology so that fu re missions can satisfy those demands with much impact on the space platforms, or the launch icles required to lift them off the Earth's surface. tu dies, technology development, systems design and loyment planning for this technology have been erway at NASA's Jet Propulsion Laboratory for the ast 16 years [1].

In this paper the optical communications space minal technology being developed to address these lications will be described. Next, a program to her detailed statistics on the cloud-cover outages for ce-to-ground links will be described, including the a distributions that have been produced from those a. Finally, a link analysis methodology that utilizes a from this collection program will be discussed. Th s methodology will allow system designers to use the uncertainties in the link parameters, including atmospheric cloud-cover attenuation, to determine and justify the required signal margins for their links.

NASA Technology Development Program

The centerpiece of the NASA spacecraft. technology development is the Optical Communications Demonstrator (OCD) program [2]. This program is developing an engineering model of a flight terminal capable of returning kbps to Mbps from the planets, or Gbps from high-Earth-orbit to the ground. The system uses a "minimum-complexity" architecture that uses only one detector array and one fine steering mirror to accomplish beacon signal acquisition, tracking, transmit beam pointing, and transmit/receive coalignment (with point-ahead to accommodate cross velocity). Tracking of the beacon signal is accomplished by using a windowed sub-frame readout from the detector array.

Figure 1 shows a sketch of the entire communications terminal, The system consists of a single transmit/receive telescope, a fiber-optic coupled transmit laser assembly, and a separate control processor. All of the optics are located in the telescope assembly. A coarse pointing gimbal assembly is not needed except in mission applications where separate pointing of the terminal relative to the spacecraft is required. The telescope aperture size is 10 cm.

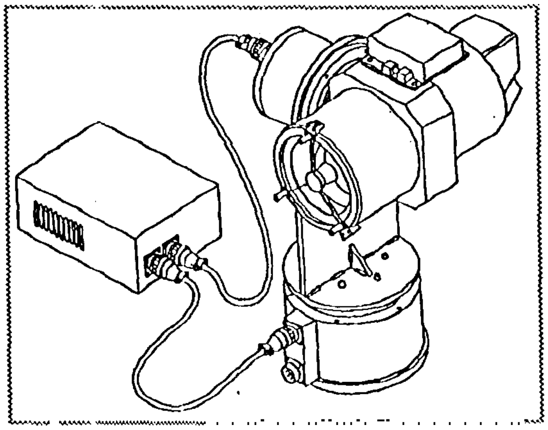


Figure 1. Diagram of the Optical Communications Demonstrator

The OCD is currently under development and is to undergo system-level testing in early 1996. Current estimates of the complete system mass and power (excluding the coarse-pointing gimbal) are 8 kg and 30 W.

For lower-altitude Earth-orbit applications, a smaller space terminal is being considered [3]. Like the OCD, this terminal will track an uplink beacon signal using a single tracking detector and a single fine steering mirror. Unlike the OCD, the system has no separate transmit-beam point-ahead. The transmit aperture is just under 1 cm in diameter, producing a broad enough beam to more than cover the point-ahead offset.

This terminal contains a 2-axis steering mirror that directs the received beacon signal through a dichroic filter and focuses it onto a quadrant tracking detector. Electronic signals from the tracker are used to keep the steering mirror properly oriented. Also contained on the unit is a laser diode emitter and anamorphic optics to circularize the output beam. The resulting transmit beam reflects off the dichroic filter, then the steering mirror, and is sent back in the direction of the beacon. It is expected that this terminal will have a mass of only about 3 kg and a power consumption of 11 Watts. It is capable of returning 1 Gbps or more from a 1000 km orbit to a 1-meter ground telescope with more than a 20 dB link margin.

The final element in the trilogy of optical communications space terminal technologies is an even smaller unit designed for short-range or lower data rate applications. Such applications include 500 km links to the ground at data rates less than about 50 Mbps, or space-to-space links of a few km at rates up to a few 100 Mbps. Unlike the above systems, this terminal contains no fine steering at all. The equivalent aperture diameter is approximately 0.5 mm, producing a wide enough transmit beam to cover the attitude uncertainty of most low Earth orbit mapping spacecraft. A small coarse pointing gimbal would be required to point the terminal relative to the spacecraft attitude. The estimated mass and power consumption for this terminal are 1.5 kg and 8 Watts respectively.

Atmospheric Visibility Monitoring Program

The performance of space-to-ground optical communications links is strongly influenced by the atmospheric conditions in the vicinity of the ground receiving station. The most significant impact comes from the attenuation (and occasional extinction) due to clouds. Some data exists on average clear weather vs cloudy weather probabilities [4]. However, to completely characterize an optical link, one would really like to have a detailed probability model for the cloud-induced optical signal attenuations.

Recognizing this, JPL began several years ago to develop and deploy a set of three atmospheric visibility monitoring observatories [5]. These observatories contain autonomously-operated 30 cm telescopes that measure the intensity of bright stellar sources on the ground and from those measurements determine the attenuation of the signal due to the atmosphere. Each of the observatories measures the stellar intensity through a set of 5 spectral filters; two narrowband filters centered at 532 mn and 860 nm, respectively, and three astronomical wideband filters known as the "I", "R" and "V" filters. A third narrowband filter centered at 1064 nm is also included, but the sensitivity of the system detector must be upgraded before it can be used.

The observatory equipment is housed in a roll-off roof dome to protect it during storms. A weather instrument tower monitors weather conditions and closes the dome when conditions (rain, snow, high wind, excessive humidity) exceed trigger levels. During these times, the observatory bookkeeps the condition as infinite atmospheric attenuation. Each observatory has a stored star catalog and when conditions permit, opens its dome and searches for stars in its list. If a star is not observed, the atmospheric attenuation is again bookkept as atmospheric extinction. When a star is located (using its precision telescope pointing mount), intensity measurements are made through the several spectral filters. After compacting measurements on one star, the system moves on to the next. Measured stellar intensities, as well as observatory status data are collected and stored on the observatory's computer hard disk. Once each day each observatory establishes connection with JPL via telephone line and its stored data is returned to a central JPL computer for processing.

The three observatories have been developed and deployed in the field. One is located at the JPL Table Mountain Facility (TMF), a 7500 foot elevation site near Wrightwood, CA (about 20 minutes northwest of San Bernardino). The second has been installed at an observatory facility at the top of Mt. Lemmon, Arizona. The third has been set up on the hilltop behind JPL in Pasadena, CA. Although placed in an operational mode in the spring of 1995, budgetary deficiencies have delayed final system checkout until the beginning of Fiscal year 1996. After checkout, the system will be relocated to the Goldstone tracking network complex in the desert near Barstow, CA.

Data from the set of observatories, primarily the TMF and Mt. Lemmon sites, have been collected for the past year. These data have been processed into cumulative probability distributions of atmospheric attenuation. A typical plot of such a distribution is shown in Figure 2. This particular plot shows the visibility statistics in the 860 nm narrowband filter for the Table Mountain Facility observatory. The horizontal axis is zenith atmospheric attenuation in dB and the vertical axis is the probability that the atmospheric attenuation was less than or equal to the corresponding value of attenuation on the horizontal axis. Similar plots have been obtained for the other filter bands and on the other observatories.

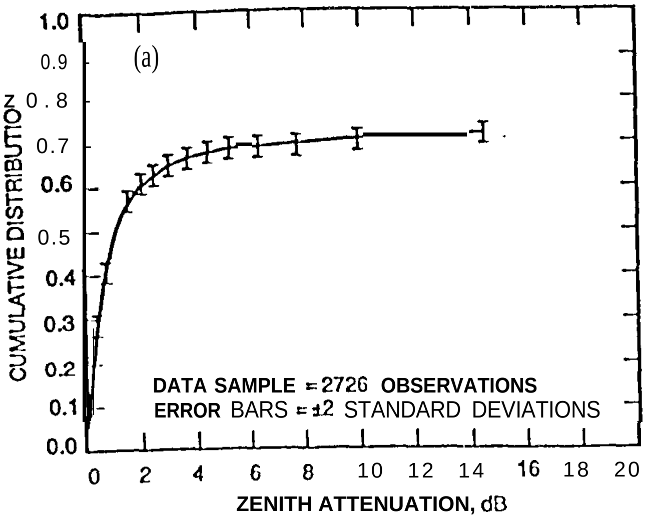


Figure 2. Cumulative probability distribution for the TMF observatory, 860 nm filter.

These plots represent the marginal (single station) probability statistics. The reason for developing three observatories and deploying them in a widely dispersed locations is to allow the collection of visibility statistics for a spatially -diverse network (joint probability statistics). It is known that if three stations, each with 70% availability are located in independent weather patterns, the probability that at least one of those stations is cloud-free (attenuation below some reasonable value) is 97%. The system described above was developed and deployed for the purpose of making measurements to validate these statistics. Current funding limitations have delayed the development of the software to produce such joint distributions for the time being.

Space-to-Ground Link Analysis Methodology

When most people calculate the performance of a communications link, they usually combine all the gains and losses in the link and then compare the resulting calculated received power with a known level required to produce some baseline performance. Any residual power is described as margin. Most link designers are comfortable with margins of 3-6 dB, depending on the particular application. But the reason one designs in margin into a link is really to cover the uncertainties that the designer has in that link design. If the parameters values are very uncertain, a much larger margin is required. If the parameter values have very little uncertainty, a large margin results in an excessively overdesigned (and usually unnecessarily expensive) system. Thus, a methodology for combining the uncertainties in the link parameters to assess the required margin is necessary. For most links, optical links particularly, atmospheric uncertainties must also be considered. Additionally, the impact of link availability (due to weather outages), and the magnitude of the atmospheric attenuation must also be evaluated.

The plot in Figure 2 shows a clear trade space available to the system designer. If one wishes to claim a low value of atmospheric attenuation, the link availability (probability that the link attenuation is less than or equal to that value) will be very low. Alternately, if one wishes to have a high (say 60 %) availability, a larger link atmospheric attenuation must be accommodated, It is also important to recognize that "link availability" and "link attenuation uncertainty" are two distinct, although interrelated, things. It is not fair to say that for the conditions depicted in Figure 2 the uncertainty in the weather attenuation is 10 or 20 dB if the station is being classified as a 50% availability station. If one requires the station to be available all the time, then the weather-induced attenuation uncertainty is very large. But, if one says 50% availability, then only the variations in attenuation during the clearest half of the possible tracking time should be included.

With these thoughts in mind, a methodology for including the effects of parameter uncertainties, with particular attention given to weather-related attenuation uncertainties, has been formulated. The starting point is the data collected by the visibility monitoring program, Figure 3 depicts a representative cumulative distribution curve for a reception site. On the curve a design value of zenith attenuation (α) has been chosen. (Note that this is the zenith attenuation. When using this procedure, the value of α must be increased when analyzing links at larger zenith angles. It is recommended that the path-length increase corresponding to the largest expected zenith angle be used.) Corresponding to the value of zenith attenuation is a nominal probability (P_α) that the attenuation is less than or equal to that value, We interpret P_α as the "availability" of the station. (Here we assume that if the attenuation exceeds α, the station is unavailable.) We also see that there is an uncertainty region or confidence interval established for P_α. This uncertainty, rotated in the α direction, represents the uncertainty ($\Delta\alpha$) in the design value of zenith attenuation.

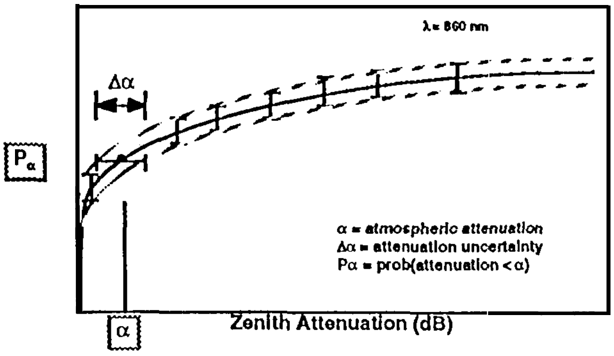
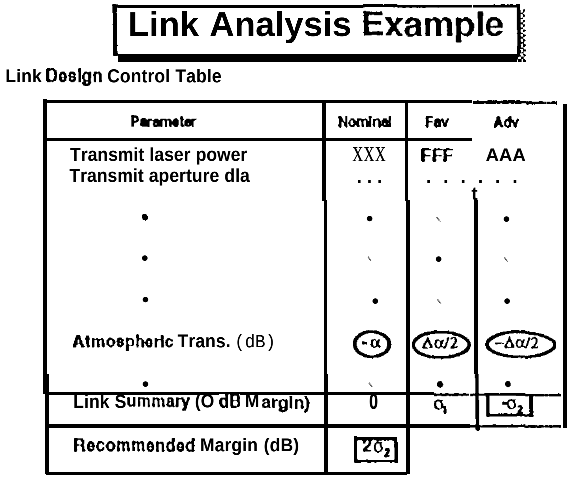


Figure 3. Representative site cumulative atmospheric. visibility distribution.

Next, we go to a Design Control Table for the link as depicted in Figure 4. Here we enter the nominal values of the link parameters, including the nominal attenuation value α (adjusted for zenith angle). We also enter the favorable and adverse tolerances for each of the link parameters, including $-\Delta\alpha/2$ for the favorable and $+\Delta\alpha/2$ for the adverse uncertainties in α. (We also take into account the anticipated probability distribution for the uncertainty of each parameter value). Now, working with the nominal parameter value column, we design the link for a O dB margin. At this design point we then combine the uncertainties in the adverse tolerance column (RSS'ing the random uncertainties and adding the static ones) to come up with an overall adverse uncertainty (σ_2) for the link.



Link Analysis Example

Link Design Control Table

Parameter	Nominal	Fav	Adv
Transmit laser power	XXX	FFF	AAA
Transmit aperture dia	...	...	...
•	•	•	•
•	•	•	•
•	•	•	•
Atmospheric Trans. (dB)	$-\alpha$	$\Delta\alpha/2$	$-\Delta\alpha/2$
•	•	•	•
Link Summary (O dB Margin)	0	σ_1	$-\sigma_2$
Recommended Margin (dB)	$2\sigma_2$		

Figure 4. Sample Design Control Table

Once the value of σ_2 has been determined, it becomes a basis for establishing the required link margin. How much confidence is required by the designer depends very much on the particular application. However, having a quantified basis for specifying that margin is a very important design practice. In our example, let us assume that we wish to provide a $2\sigma_2$ margin for uncertainties. This would give a 98 % confidence that the link would be closed with positive margin within the design uncertainties.

The above calculation is valid only when the station is available (i.e. when the weather produces α dB of zenith attenuation or less). We must now perform a statistical analysis that includes the effects of weather availability. To do this we will assume a spatially-diversified reception network and we will use the "Expected Data Volume" or EDV as the metric.

To do this, let us consider a set of N "candidate" stations all capable of viewing the space terminal when under cloud-free conditions. Then, the probability that m of those stations are "available" due to cloud statistics is

$$P_N(m) = B(N,m)\,(P_\alpha)^m(1-P_\alpha)^{N-m}$$

where B(N,m) is the binomial coefficient "N choose m". The probability that at least one of the stations is "available", P_N, is given by

$$P_N = \sum P_N(m) = 1-(1-P_\alpha)^N$$

where the sum is from m=1 to N.

This is the "joint availability" of the network to receive a downlink signal is everything is constant. In practice, things change; for example, the Earth rotates or the space vehicle passes over different regions, Let us assume that the total pass (data downlink) time is T seconds and that during that time, there are K disjoint segments of time t_k during which time there are N_k candidate stations. In other words, during the first interval of length t_1 there are N_1 candidate stations, the next interval of length t_2 there are N_2 candidate stations, and so on. We continue this until $t_1+t_2+\cdots+t_K = T$. Let us also assume that when at least one station is available, then we can reliably transmit data at a rate R (the rate used in the design control table). Then, the Expected Data Volume over the T-second interval is given by

$$EDV = R \cdot \sum t_i P_{N_i}$$

where the sum is over the K disjoint intervals making up the T seconds,

The EDV is the metric for determining the capability of the link. It is proposed that this measure and the underlying methodology be used when making comparisons between proposed RF and optical communications links. The EDV takes into account the effects of both weather availability and the uncertainties in the atmospheric attenuation.

The above methodology is, of course, only an approximation, based on certain simplifying assumptions for the link analysis. Most of these assumptions have been on the pessimistic side concerning that actual link performance. There are a number of refinements that could be implemented, albeit with corresponding increases in the difficulty of the calculations. Recall that we have taken the "adjusted value of α" which corresponds to the largest expected zenith angle. A more accurate model would include the effects of varying the zenith angles over the pass. Second, we have essentially bisected the weather probability distribution curve into an "available' and a "not available" region. In effect, we have quantized the cumulative probability distribution using binary quantization. A more accurate model would use more quantization levels to characterize that distribution and its associated probability values. Finally, we have assumed that if one station is available, the link at data rate R is established, But, with high probability, more than one station will be available at any one time and, in fact with a non-negligible probability, all of them will be available at the same time. Having multiple simultaneous reception stations available means that in principle, the data rate could be increased, resulting in a higher Expected Data Volume. No effort has been made to take this into account here.

Conclusions

We have discussed the trio of optical communications space terminal technologies being developed by NASA for future mission applications. This set includes the OCD which is nearing engineering model development completion, the smaller high data rate terminal for Earth-orbit-to-ground applications, and an even smaller terminal for specialized applications. We then described a program for collecting detailed statistics on atmospheric visibility. Finally, we presented a methodology for perfoming optical communications space-to-ground link analyses that includes the impacts of weather availability and atmospheric attenuation uncertainties. This methodology should prove useful when comparing the performance of RF and optical communications systems.

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