Analysis of Telescope Site Selection for Optical Deep Space Network[1,2]

Sabino Piazzolla[1], Farid Amoozegar[2], Robert Cesarone[2]

University of Southern California (IMSC)[1]
Los Angeles, CA 90007
piazzoll@sipi.usc.edu

Jet Propulsion Laboratory[2]
California Institute of Technology
Pasadena, CA 91109
(818) 354 -7428
Farid.Amoozegar@jpl.nasa.gov

Abstract—The successful design of an Optical Deep Space Network (ODSN) greatly depends on the selection of optimal telescope sites. At the highest system level, there are two main factors to consider in the design of a global optical communications network for deep space applications: telescope size (i.e., aperture size) and the distance between stations. The size of the individual telescope aperture needs to be selected based on mission needs (e.g., maximization of received photons per bit). At the same time, because of weather effects and Earth rotation, a number of telescopes have to be placed within certain distances around the Earth in order to achieve global coverage. The distance between the adjacent telescopes is driven by other secondary factors, which are basically derived requirements from: 1) outage tolerance; 2) continuity in data stream; 3) operational cost; and 4) minimal requirements on the spacecraft payload design. To perform properly, ground stations must be placed on high-altitude peaks (for better visibility and high atmospheric transmission) around the Earth. However, the scarcity of peaks, along with geopolitical issues, may cause difficulties in the selection of the telescope sites in a global network. In an optical deep space link, the characterization of the atmospheric channel requires great attention. In fact, cloud opacity is the first evident impairment to the successful closure of a space-to-ground (and vice versa) optical link. Likewise, aerosol distribution in the atmosphere can significantly increase the optical thickness of the atmosphere with a detrimental attenuation of the laser signal. Moreover, an optical communication/tracking network must operate during daytime, and in this case, an increase of background sky radiance can dramatically affect the receiver performance by increasing system noise.

In this paper, therefore, we present an analysis of site selection for an optical deep space network as performed by the ODSN study group at JPL. Given a set of mission requirements, we illustrate how the high-level requirements, along with the properties of the atmospheric channel, can be used to determine the site selection and the architecture of an ODSN. Moreover, we characterize candidate sites for a global optical network and their possible suitability for global architectures such as the linear dispersed optical subnet (LDOS) and cluster optical subnet network (COS).

TABLE OF CONTENTS

1. INTRODUCTION 1
2. DATA RATE/BER OF A MISSION 3
3. TELESCOPE SITE LOCATION 4
4. NETWORK CONTINUITY AND PEAKS 5
5. SUMMARY AND CONCLUSION 7
REFERENCES 8
BIOGRAPHY 9

1. INTRODUCTION

NASA's Deep Space Network (DSN), which for the past four decades has successfully supported deep space exploration missions, is today facing new challenges as it enters a new paradigm in its architecture, network configuration, service-oriented approach, and public involvement. Besides these challenges, the DSN is facing in the foreseeable future the need for an interplanetary backbone connecting its terminal local area networks distributed over the planet. Keeping in mind the goal to optimize a handful of link parameters, such as coverage, continuity, and cost, the requirement of increasing the rate of the data return from deep space, has led NASA to consider

[1] 0-7803-8155-6/04/$17.00© 2004 IEEE
[2] IEEEAC paper #1268, Version 2, Updated November 8, 2003

three technological solutions for the future of the DSN: **1)** migration of the existing DSN facilities toward Ka-band, **2)** small antenna arrays, and **3)** free space optical communications. Interestingly, among the above three technological solutions for the future DSN, NASA's strategic planning for optical communications is a new historical avenue, due to the philosophical and technological distance from RF, which has greatly served NASA for deep space exploration until now. As a future mission, NASA has already planned that by 2009 the first optical communication deep space link will be demonstrated on a Mars mission. NASA's increasing attention to optical communication led to the creation of a JPL ODSN study group, whose aim is to analyze architectural and technological issues for the future DSN in the optical range.

A future NASA ODSN poses new challenges in terms of mission requirements, mitigation of weather effects, life cycle cost, and optimization of antenna (telescope) surface. The dynamical interaction among (some) ODSN parameters and (some) logistics, environmental, and technological variables is summarized in Fig. 1.

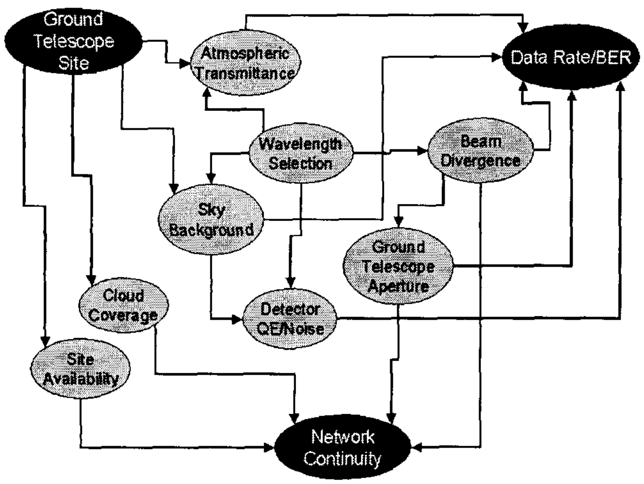


Figure 1 - Flowchart illustrating the dynamics among the main ODSN parameters

Note that in Fig. 1, we list three main parameters of the ODSN as being the data delivery capacity and accuracy (Data Rate/BER), the continuous Earth coverage (Network Continuity), and the proper location of the nodes (i.e., optical communication telescopes) of the network itself (Ground Telescope Site). The Data Rate/BER is clearly influenced by the amount of signal photon flux collected by the aperture of the Ground Telescope Site. This signal flux depends upon, among other factors, the angular spread of the laser beam and the atmospheric transmittance experienced at the receiver. Both atmospheric transmittance and laser beamwidth are related to the selected transmitter (spacecraft) wavelength, which also determines the number of sky background photons that during daytime operation contribute to increase the noise level at the detector level.

The amount of sky background photons collected by the detector is also determined by the receiver field of view which is related to effects of the atmospheric turbulence. comprehensive analysis of atmospheric turbulence effects will be presented in a later work. To ensure the continuous coverage of the Earth from deep space, despite its rotation, it is necessary to distribute a number of ground telescopes around the globe. Today NASA's DSN only requires three radio-telescope hubs (ground station complexes) to successfully operate the network. The DSN stations (located at 120 degrees of separation around the Earth (Goldstone, California; Madrid, Spain; and Canberra, Australia)) allow continuous coverage of the Earth from deep space. However, in the case of the future ODSN, the scenario will require a different geographical and logistical approach. Since the laser transmitter beamwidth from space can (usually) cover a limited area (footprint) on Earth it is necessary that the ODSN consists of a number of ground stations located around the Earth as a linear distributed optical subnet (LDOS) [1], Fig. 2. The idea behind LDOS is to have the spacecraft always pointing at a visible station belonging to the LDOS. When either the line of sight is too low on the horizon (20 degrees of elevation) or is blocked by atmospheric related conditions (i.e., clouds, low transmittance, etc.) the spacecraft beam is switched to a different station (or network node) by pointing to the adjacent optical ground station. Of course the adjacent station must be located in a geographical area where the atmospheric conditions are uncorrelated (or better, anti-correlated) with the previous station in order to optimize network continuity.

Figure 2 - Example of LDOS (star=telescope) and COS (circle=hub) architectures for optical deep space network (ODSN)

To simplify both the spacecraft re-pointing process and the network hand-off between stations, another network architecture has been proposed. The clustered optical subnet, or COS [1], consists of a number of optical hubs (three or more) distributed around the Earth, with the difference that each hub is composed of more than one ground station (*e.g.*, two or three). Each ground station of a hub (circle in Fig. 2) is located in a geographical area having (dry) weather pattern that is uncorrelated (or better anticorrelated) to the other stations to optimize the overall hub availability having at least one station with clear line-of-sight with the spacecraft (Fig. 2).

Of course, the location of the ground telescope is critical to the assurance of network continuity operation and is directly linked to the Data Rate/BER performances. As stated earlier, cloud coverage at the ground station has to be as low as possible to minimize link blockage, and it must be somehow predictable for program station operation. Moreover, at the ground station, the link must experience the highest atmospheric transmittance and lowest sky background possible during daytime. All of the previous atmospheric conditions are optimized when the optical ground station is located at high altitude because in this way the signal atmospheric path is reduced and so its interaction with the atmosphere. Moreover, local microclimatic conditions that usually generate low clouds are not influential at high altitudes (usually more than 2000 m), with the consequence of reducing the overall cloud coverage at the station. At the same time, the ODSN network continuity requirements demand a regular distribution around the Earth of peaks that may accommodate potential ground stations. Unfortunately, the global scarcity of potential telescope sites around the Earth and their uneven distribution (along with ever-present geopolitical implications) makes their identification even more complex for the design of a global ODSN.

Therefore, in this work we describe an analysis and methodology that can be used to identify possible peak candidates for a future ODSN. Our approach is as follows. First, we define a baseline optical deep space mission. By determining characteristics of an optical communication payload on the spacecraft and using a link budget, we calculate the photon flux reaching the Earth. Then, modeling the atmospheric effects along the atmospheric profile, we determine the atmospheric losses, the background photon noise, and the receiver performance at different peak altitudes, which helps in identifying the optimal peak elevation for an individual ground station in an ODSN. Finally, we study the global distribution of the Earth's peaks and landmass elevation at the required altitude, and we introduce determined conditions about the required low cloud coverage. Results from this last step will help selecting the telescope sites for the ODSN and analyzing the advantages of LDOS versus COS (or vice versa). The above three analytical steps are respectively discussed in Section 2, 3, and 4. In Section 5, we present a summary and conclusion of this investigation with indications of future work.

2. DATA RATE/BER OF A MISSION

The long-term objective of the ODSN is to provide ground support for solar system exploration. In doing so, a practical and logical step is to base the ODSN analysis and site selection strategy around a specific mission and use it as a reference model to begin the point design. In a study published by JPL in 1994 [1], the reference mission was based on a Pluto mission with 30 AU distance. Today, instead, the reference mission should be selected more considering these following factors. **1)** Due the relevance of the study of the red planet, the ODSN should select the Mars communication network architecture as the guideline for future ODSN analysis in order to provide a more complete synergy with various network element factors and to comply with new mission concepts. **2)** The ODSN should comply with the paradigm shift in autonomous spacecraft flying in formation, or clusters. **3)** The ODSN should understand the important role of other intermediate stages, or [define or write out IP] IP-based missions in space with new protocols for space network, and the concepts of space servers and on-board storage locations. **4)** There is a need for seamless connectivity of users to the network for ease of network operations. In a future vision, the Mars network will serve as the building block for the larger space network.

Therefore, a first natural choice for a reference mission for the ODSN is to understand how it may support a Mars mission. To design the ODSN as a support for a Mars mission, the next logical step is to derive an initial link budget based on the requirements, and then to analyze how the telescope aperture and the telescope location (via the atmospheric transmittance and daytime sky radiance noise) may affect the link budget itself. Specifically, the mission is required to provide a link at 1 Mbps, with uncoded bit error rate of 0.001 at the largest distance of separation between Mars and Earth of 2.4 AU. The spacecraft laser has 5 W of average power, and the wavelength selected is λ = 1064 nm. (Another possible option is to consider 1550 nm for the laser wavelength.) The modulation used is M-ary Pulse Position Modulation (M-PPM) with M = 256, which corresponds to a 31-ns pulse. The spacecraft telescope has an aperture of 30 cm diameter with a linear obscuration of 10%. Transmitter loss was set to be 1.42 dB (72% of the laser power). Given these data we run a link with results as summarized in Table 1

Because we did not restrict the ground telescope to a specific site (and therefore to a specific atmospheric condition) in the link budget of Table 1 it does not indicate any atmospheric loss. Concerning the receiver, we supposed an optical loss of 2.21 dB (60% transmission), and we normalized the receiver aperture of 1 m in diameter with linear obscuration of 20% to better describe the photon/flux per telescope aperture at detector of a telescope on the Earth. Losses of non-ideal synchronization and pulse amplitude were also added. Table 1 shows that in these conditions photon flux is 10.45 photons per pulse at the detector. To complete the information on link performance, a brief characterization of the receiver is necessary. Because our intent in this paper is to consider a general detection case, we hypothesized a photodetector of quantum efficiency of 50%. Thermal noise is then not considered, which can be an appropriate hypothesis in the case of a cryogenic receiver with low noise amplification [2]. Noise from photodetector dark counts is also not considered (photodetector dark counts are greatly reduced when the photodetector is cooled to cryogenic temperature [3]).

TABLE 1:LINK SUMMARY			
Bit Rate: 1.0 Mbps Modulation: PPM (M = 256) Range: 3.59E8 km BER: 0.0010			
LINK BUDGET			
Transmitter Power	5.0 W average	31 ns slot time	61.08 dBm
Optical Transmitter Losses	72 % transm		-1.42 dB
Transmitter Gain	30.0 cm aperture	5.98 μr beamwidth	117.67 dB
Pointing Losses			-2 dB
Space Loss	3.59E8 km	2.4 AU	-372.54 dB
Atmospheric Transmission	100.0 % transm.	No Atmosphere	0.0 dB
Receiver Telescope Gain	1.0 m aperture	20% Obsc.	129.40 dB
Optical Receiver Losses	60 % transm		-2.21 dB
Non-ideal bit synch. adjustments			-1.0 dB
Pulse amplitude variation adjustments			-1.0 dB
Peak Signal Power at Detector	10.45 phot/pulse	0.06262 nW peak	**-72.03 dBm**

3. TELESCOPE SITE LOCATION

Earth's atmosphere affects the optical signal from deep space in two ways. First, of course, when the optical signal goes through the atmosphere, it is absorbed. The longer the path through the atmosphere, the lower is the atmospheric transmittance. Therefore, the higher the telescope's (Roger, why telescope's...it is not a living being??) altitude is, the higher the atmospheric transmittance. Moreover, the larger the observation zenith angle, the lower is the atmospheric transmittance. Second, during daytime, the sunlight scattered by the atmosphere will cause a number of unwanted photons to be collected by the telescope aperture, increasing the noise level at the receiver and badly affecting the receiver performance (BER) itself. Again, sky radiance is dependent on the sunlight's path through the atmosphere. Moreover, sky radiance depends on the concentration of aerosol suspended in the atmosphere, and finally it depends on the Sun-Earth-Probe angle (SEP) separation. To guarantee the largest continuity of the data delivery, it is recommended that the SEP angle be as low as possible. In our study we assume a SEP of 5°. Also in order to limit the number of stations deployed by the ODSN, an optical communication telescope must be able to observe the sky at a large zenith angle (low elevation angle). In our study, therefore, we set this limit at 70° of zenith angle.

A good baseline for the ODSN is to require that the ground stations work in the worst conditions for transmission and sky radiance (except the case of overcast sky where the link cannot be closed at all) that correspond, from our assumptions above, to the case of 70° from zenith of observation angle and 5° of separation from the Sun during daytime (one should notice that star and planet irradiances in the field of view of the telescope during daytime are much less than the sky radiance and therefore is possible to ignore them without loss of accuracy).

The MODTRAN simulation program [4] was used to describe values of sky radiance and atmospheric transmittance at different altitude over the Earth. The simulation considers altitudes between 0.5 and 3.5 km, Fig. 3. The simulation refers to an atmospheric profile typical of mid-latitude region, with the rural aerosol model having its boundary layer starting at 0.5 km. Two cases of aerosol concentration are indicated: clear sky (visual range of 23 km at the bottom of the boundary layer) and hazy (visual range of 5 km at the bottom of the boundary layer). Keeping in mind that the aerosol concentration decreases exponentially starting at the beginning of the boundary layer, Fig. 3 shows that at 2 km of altitude, transmittance and radiance are independent of the aerosol concentration at the boundary layer. In Fig. 3, the dashed line describes the case of a rural aerosol model with a visual range of 5 km (hazy sky) at the bottom of the boundary layer. The continuous line is for visual range of 23 km (clear sky) at the bottom of the boundary layer.

Using transmittance and radiance data indicated in Fig. 3 and the link data in Table 1, we ran a number of simulations. To calculate the link margins at different altitudes, using the

FOCAS link simulation program of the Optical Communication Group at JPL. The link margins were calculated for two telescope diameter apertures, 5 m and 10 m (linear obscuration of 20% for both apertures), and due to detrimental effect of atmospheric seeing, a field of view of 40 µrad was considered. Finally, an optical filter of bandwidth of 0.1 nm was selected to restrict the flux of sky background photons. The simulation results are compared in Fig. 4 against a safety margin of 6 dB that we set for this deep space link.

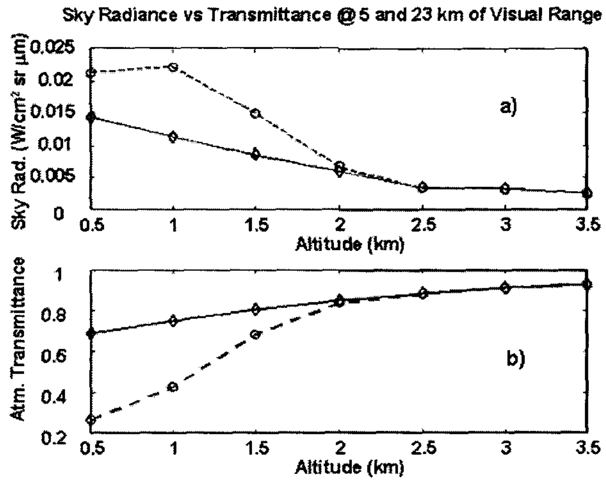


Figure 3 - a) Sky radiance at 1064 nm for a telescope at 70° zenith angle and with a 5° SEP angle. The sky radiance is shown for varying altitude. The dashed line describes the case of a rural aerosol model with visual range of 5 km (hazy sky) at the bottom of the boundary layer. The continuous line is for visual range of 23 km (clear sky) at the bottom of the boundary layer. **b)** Atmospheric Transmittance at 1064 nm for a telescope at 70° zenith angle for varying altitude. The different lines relate to atmospheric conditions as in a).

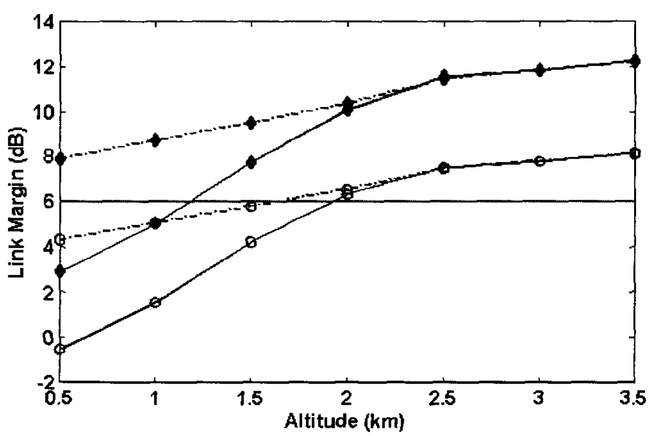


Figure 4 - Link Margins for a Mars-to-Earth link as indicated in Table 1 at different altitudes. The margins are calculated for a 5-m (circles) and 10-m circular apertures (diamonds) for clear (dashed line) and hazy (solid line) atmospheric conditions as shown in Fig. 3.

Not surprisingly, Fig. 4 indicates that the telescope of larger aperture may meet the requirements of the link at lower Earth altitude (i.e., lower atmospheric transmittance and larger sky background radiance). Particularly, in the worst atmospheric condition (hazy sky, solid line in Fig. 3), we found that a 10-meter (indicated by diamonds in Fig. 3) aperture telescope may be located at 1.2 km in order to have the link closed with the 6 dB margin. Conversely, a 5-meter aperture (indicated by circles in Fig. 4) can satisfy the link requirements at 1.9 km for hazy sky. As we expected, around 2.5 km, approximately the ending of the aerosol boundary layer, performances for hazy sky and clear sky are equivalent.

From examination of Fig. 4, one can see that there are obvious compromises between aperture size and site altitude. Of course, the deployment of a smaller-aperture telescope has its own advantages, mainly related to the economical standpoint [5,6]. At the same level, the scarcity of peaks available at higher altitude may also make it easier to find a lower altitude point that can house a large-aperture (e.g., 10-m) telescope for deep space optical communications. Moreover in the design of a global ODSN, the dichotomy of the problem "telescope aperture vs. site altitude" is even more critical. In fact, in a global ODSN, each single telescope must be located with precise coverage requirements that depend on the location of all the ground stations in the ODSN itself.

4. NETWORK CONTINUITY AND PEAKS

In a global ODSN, in principle the sites selected need to meet most, if not all, of the following conditions.

1) Latitude in proximity of the equator to better track spacecraft in the solar system ecliptic. In this work we consider the latitude range of ± 40°.
2) Longitude according to the architecture requirements, in our case according to LDOS or COS requirements.
3) Sites must have a minimum mutual view period of 4 hours with at least one other site, to allow smooth hand off of the operations.
4) Absence of geopolitical issues for site locations outside the United States.
5) Close to pre-existing facilities for easy installation and operation.
6) Low time duration (year long) cloud coverage with fairly constant and predictable weather.
7) High altitude for high atmospheric transmittance and low sky radiance, as derived in Section 3 of this work.

Considering the results obtained in Section 3, we derived the baseline that when selecting a site for a 5-m aperture telescope, an optimal site altitude would be 1.9 km, while for a 10-m aperture the requirement can be relaxed to 1.2 km. Unfortunately, there is an overall scarcity of high-elevation land on Earth, as indicated in Fig. 5. Overall, only the 7.5% of the Earth is above 1 km, 3.2% is above 2 km, and 1.38% is above 3 km. The latitude restriction of ±40° of the Earth surface dictated by the above selection criterion **2)**, further restricts the landmass availability as 3.5%, 1.2% and 0.76% respectively for altitude above 1, 2, and 3 km. Furthermore, geopolitical restrictions imposed by selection criterion **4)**, and the fact that the peaks are not regularly distributed in the Earth's landmass, greatly limit the availability of candidate sites for a global ODSN.

As a first approach to analyze the global availability of global peaks, we elaborated a digital topographic map of Earth with resolution of 2 km × 2 km. The Earth surface to be analyzed was restricted in the latitude interval [-40, +40] and longitude interval [-180, 180]. Moreover, to better view the potential ODSN site distribution, we divided the Earth altitude in three interval ranges as 0-1 km, 1 –2 km, 2 –3 km, 3-4 km and larger than 4 km. Results of this altitude level division of the Earth surface are presented in Fig. 6.

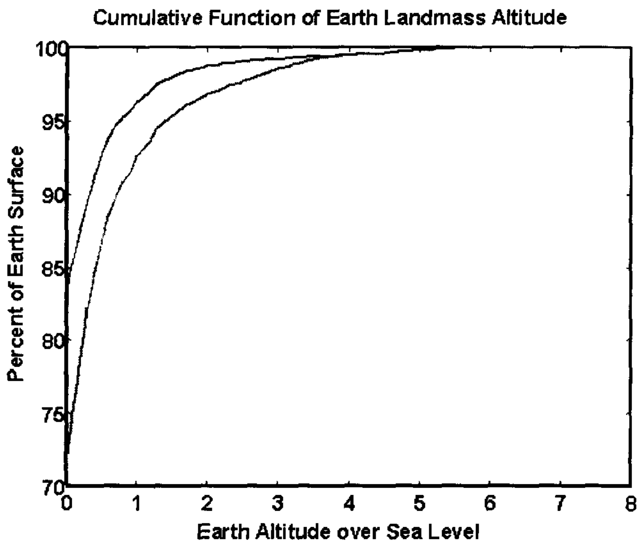


Figure 5 - Cumulative distribution function of Earth's landmass. As a reference, one should notice that only 7.5% of the Earth is above 1 km, 3.2% is above 2 km, and 1.38% above 3 km when considering the entire globe (red curve). Restricting the available landmass within latitude ± 40° (blue curve), we have only 3.5%, 1.2% and 0.76% of Earth above altitudes of 1, 2, and 3 km, respectively.

Analyzing Fig. 6, a number of useful indications can be deduced for the construction of an ODSN. For instance, if the LDOS design approach is going to be taken for the global ODSN architecture, there is large area of Earth, mainly defined by the Pacific Ocean that lacks available peaks. In that case, a sure stop for a station in the LDOS must to be Hawaii, where incidentally there are already a number of astronomical telescope housed on high-altitude peaks (e.g., Mauna Kea, Mount Haleakala). At the same time, Australia (where incidentally there is already a DSN radio-antenna complex), is relatively poor in high-altitude areas. Mainly, these locations, all within in the first range of 1-2 km of elevation, are concentrated in the center of the continent (Alice Springs) or close to the east cost of the continent. This scarcity of peaks in Australia can hamper the possible design of COS with a possible hub in this continent as previously suggested in the literature [1]. However, a more definitive answer to this last problem can come only after a careful evaluation and measurements of the sky background radiance and atmospheric transmission at candidate sites in Australia.

However, as also stated by selection criteria **6)**, the altitude of the station of the ODSN, is not the only atmospheric/environmental requirement.

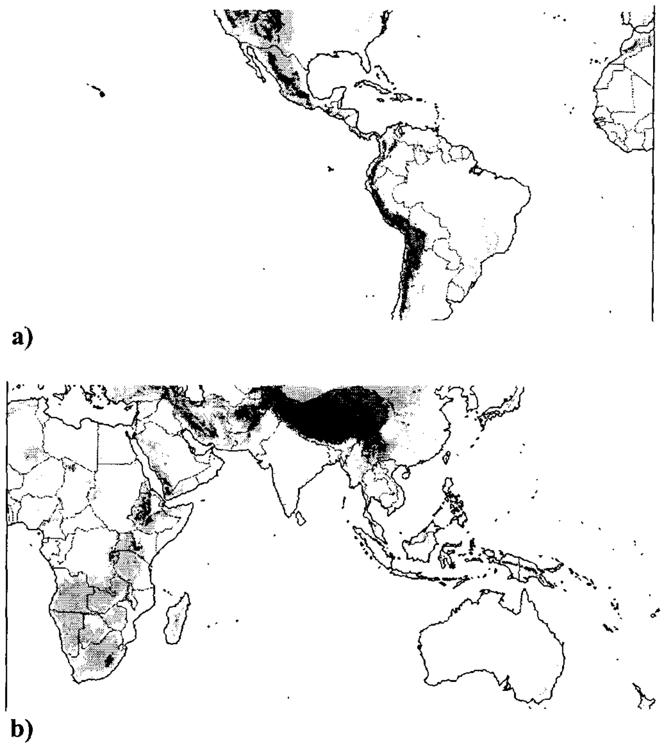


Figure 6 - Depiction of Earth landmass altitude at different ranges, as 0–1 km (white), 1–2 km (green), 2–3 km (blue), 3–4 km (red), more than 4 km black. **a)** Earth map in the latitude range [-40°, 40°] and longitude range [-180°, 0°]. **b)** Earth map in the latitude range of [-40°, 40°] and longitude range of [0, 180°].

The location of the network station must be in an area where the cloud coverage has minimal impact on the operation of the network itself. Therefore, a more powerful indication on the site suitability for belonging to the ODSN can be made after simultaneously considering cloud coverage statistics of the area and peak availability. To characterize the atmospheric channel and global cloud coverage, a number of resources are actually available to the scientific community. International agencies, institutions, and programs have made available weather and cloud coverage data from around the globe. For instance, the International Satellite Cloud Climatology Project (ISCCP) [7] is one source for weather data that can provide information for the selection of sites with optimal cloud coverage. ISCCP extracts and elaborates data from a multitude of weather satellites, e.g., Geostationary Operational Environmental Satellite (GOES), METEOSAT, GMS, INSAT, as well as NOAA polar-orbiting satellites. Another source of atmospheric data is the National Climatic Data Center (NCDC), which can provide surface observation data from observation sites distributed all around the globe [8]. To better explain the study approach for joint correlation of low cloud coverage and higher altitude peaks, we first present in Fig. 7 the cloud coverage in the section of Earth of interest for the ODSN using data from ISCCP.

The Earth map in Fig. 7 is within latitude range [-40°, 40°] and longitude range [0, 180°] and the map resolution is 2.5° × 2.5°. The figure indicates in color-coded fashion the annual average of cloud coverage in percent in the region of Earth of interest for the ODSN. Clearly, for ODSN site selection it is required average cloud coverage duration as low as possible.

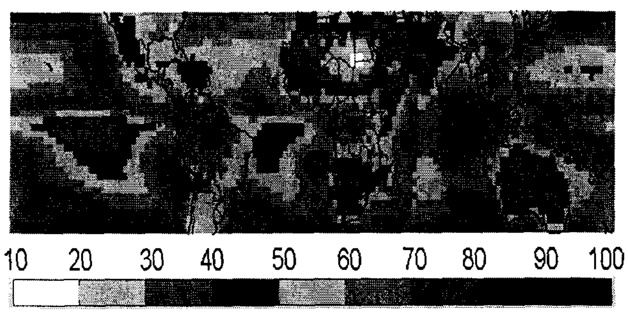


Figure 7 - Average annual statistics of cloud coverage. The cloud coverage percent duration is color coded according to the indication of the horizontal color bar.

While the map in Fig. 7 may indicate regions of favorable cloud coverage for the installment of optical telescopes for deep space communication, it does not convey any information about the site/area altitude. However, one can further reduce the search for ODSN sites around the Earth, by introducing the simultaneous selection criteria of low cloud coverage (less than 50%) and altitude higher than 1 km (other more restringing conditions about cloud coverage and altitude can be also be used). Results from this last operation are shown in the maps of Fig. 8, which indicate the locations on Earth that satisfy the simultaneous conditions of elevation in the range larger than 1 km and average annual cloud coverage less than 50%.

Results of this last operation of simultaneous selection of areas with the most advantageous cloud coverage and landmass altitude are shown Fig. 8. Figure 8 gives us more precise indications about the possible locations for ODSN and its possible architectural solutions. Starting from the Eastern Hemisphere as depicted in Fig. 8 a), beside Hawaii, other candidate areas are the southwestern United States and the Andes region (including northern Chile, southern Peru, and portions of Ecuador, and. Unfortunately there is a lack of available sites east of these regions in both North and South America. Proceeding eastward, we can observe a number of candidate sites in the northern African continent and southern Spain. Southern Africa and eastern Africa (especially close to the horn of Africa) may also be regions of interest. A number of interesting region are located in the Middle East and Arabian peninsula. Unfortunately, after the a region west of Pakistan and the Karakorum, moving eastward, (according to this first analysis) there is a great scarcity of peaks available in the map, except for the region around Alice Springs in the Australian Outback, and on the Australian east coast itself.

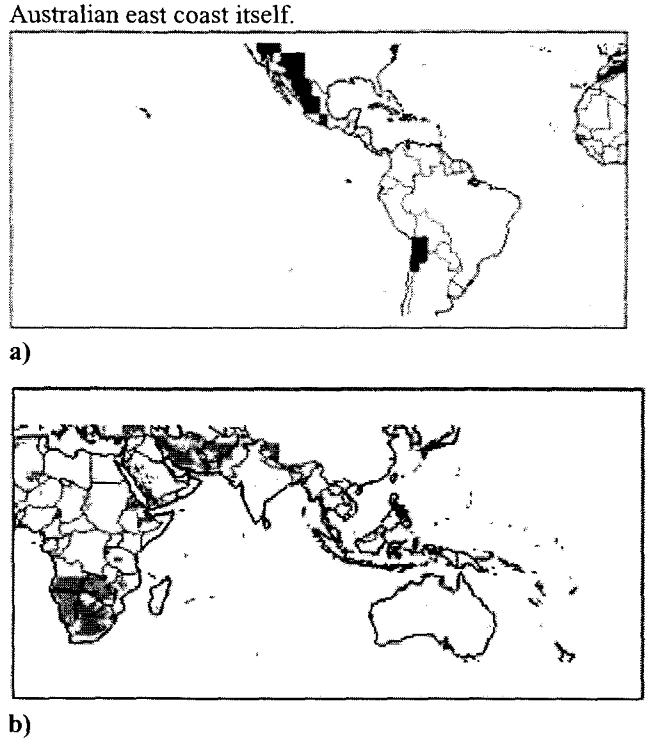


Figure 8 - Locations on Earth that satisfy the simultaneous conditions altitude larger than 1 km and average annual cloud coverage less than 50%. **a)** Earth map in the latitude range [-40°, 40°] and longitude range [-180°, 0°]. **b)** Earth map in the latitude range of [-40°, 40°] and longitude range of [0°, 180°].

5. SUMMARY AND CONCLUSION

In this work, we have proposed a first practical methodology for the selection of potential sites for a global ODSN. In our approach, we first baselined a possible deep space mission and its requirements in terms of BER, link margin, and data rate, and a few design figures (i.e., modulation, spacecraft and ground telescope optical transmission, etc). Then, to study link performance, it was supposed in our link scenario that we considered the worst case of optical signal interaction with Earth (i.e., 5^o of SEP angle, 70^o of observation zenith angle, and 2.4 AU range). It was demonstrated that at different altitudes on Earth, link performances differ greatly, and also that for different telescope apertures, there are different requirements of Earth altitude in order to successfully close the link. Next, we projected our study from single telescope location to a global ODSN, and we demonstrated that high altitude requirements, jointly with those of global cloud coverage, greatly restrict the landmass availability to house ODSN ground stations.

However, a number of issues must be further explored and amplified to have a more precise answer to the problem of ODSN site selection. For instance, we limited the deep space mission requirements to a minimum 5^o SEP angle separation. Conversely, to extend the duration of link coverage during a mission, the SEP angle requirement can be further reduced. Consequences of a smaller SEP angle separation will be a larger background sky radiance captured by the ground station, and a larger noise in the receiver. A direct consequence of a noisier receiver is that our minimum altitude per station requirement will be raised and fewer sites will be suitable for the ODSN use.

This work analysis can be further improved by providing a more precise model of the receiver channel. For instance, we did not consider effects of thermal noise in the receiver, or other noise factors deriving by the detector dark counts. In other cases, a Poisson channel may be more representative of the receiver statistics. In any case, a precise modeling of the receiver channel can provide better information on the BER statistics and therefore the necessary signal photon flux that can satisfy the link requirements. As demonstrated in Section 3, from these requirements we can derive the ground station diameter and/or the altitude of the ODSN stations.

Considering the meteorological activity of Earth, we introduced in our analysis a methodological approach to use global information on the cloud coverage. However, to further perfect this analysis it is also necessary to consider diversity statistics [9]. In fact, to optimize Earth coverage, one of the principles of the ODSN is that at least two stations may be contemporarily seen by the spacecraft pointing towards Earth. In this case, the positioning of the stations with respect to each other cannot be done without considering weather diversity.

Finally, in our report we did not consider the action of atmospheric turbulences. As known, Earth turbulence badly affects the signal both on the downlink and the uplink in a number of ways. One of the most evident effects of turbulence is the spreading of the received signal focused on the photodetector with a consequence of net loss of power [10]. Again, to limit effects of atmospheric turbulences, the ground station should be located higher in altitude (i.e., less turbulent atmospheric path for the uplink and downlink signal), which again may further raise the threshold of minimum altitude for ODSN ground stations and the related available sites. Implications of atmospheric turbulence effects on the deep space downlink analysis and on the global ODSN will be analyzed in a future work.

Acknowledgment: The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
The research has been funded in part by the Integrated Media Systems Center (IMSC), a National Science Foundation Engineering Research Center, Cooperative Agreement No. EEC-9529152.

REFERENCES

[1] K. Shaik et al., "Ground Based Advanced Technology Study (GBATS); Optical Subnet Concepts for the DSN," Jet Propulsion Laboratory, Pasadena, CA, D-11000, Release I, (JPL internal document) August 5, 1994.

[2] K. W. Kobayashi, J. E. Fernandez, J. H. Kobayashi, M. Leung, A. K. Oki, L. T. Tran, M. Lammert, T. R. Block, and D. C. Streit, "A DC-3 GHz Cryogenic AlGaAs/GaAs HBT Low Noise MMIC Amplifier with 0.15 dB Noise Figure," *1999 IEDM Conference.*

[3] M. Moszynski, W. Czarnacki, M. Szawlowski, B. L. Zhou, M. Kapusta, D. Wolski, and P. Schotanus "Performance of Large-Area Avalanche Photodiodes at Liquid Nitrogen Temperature," *IEEE Trans. on Nuclear Science*, Vol. 49, No. 3, June 2002.

[4] A. Berk, L.S. Bernstein, and D.C. Robertson, *MODTRAN: A Moderate Resolution Model for LOWTRAN 7*. Air Force Geophysics Laboratory Technical Report GL-TR-89-0122, Hanscom AFB, MA.

[5] F. Amoozegar, R. Cesarone, and S. Piazzolla, "Performance Analysis and Comparison of Clustered and Linearly Dispersed Optical Deep Space Network," *Proceedings of RCSGSO Meeting*, Pasadena, CA, 2002.

[6] L. Stepp, L. Daggert, and P. Gillett, "Estimating The Costs of Extremely Large Telescopes." *Proc. SPIE*, 4840, 2002.

[7] W.B. Rossow, F. Mosher, E. Kinsella, A. Arking, M. Desbois, E. Harrison, P. Minnis, E. Ruprecht, G. Seze, C. Simmer, and E. Smith, "ISCCP Cloud Algorithm Intercomparison." *J. Climate Appl. Meteor.*, 24, 1985, 877–903.

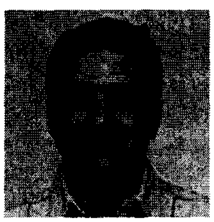
[8] S. Piazzolla and S. Slobin, "Statistics of Link Blockage Due to Cloud Cover for Free-Space Optical Communication Using NCDC Surface Weather Observation Data," SPIE Meeting, San Jose, CA, 2002.

[9] S. Piazzolla, S. Slobin, and E. Amini, *Cloud Coverage Diversity Statistics for Optical Communications in the Southern United States.* Publication 00-13, Jet Propulsion Laboratory, Pasadena, CA, November 30, 2000.

[10] A. Biswas, and S. Piazzolla, "Deep-Space Optical Communications Downlink Budget from Mars: System Parameters," *JPL IPN Progress Report.* PR 42-154, April–June 2003, Jet Propulsion Laboratory, Pasadena, CA, pp. 1–38, August 15, 2003.

BIOGRAPHY

Sabino Piazzolla *received his Diploma of Laurea in Electrical Engineering from University "La Sapienza" in Rome. While working for Alenia Spazio as in the microwave system group he participated in a number of international space program as ERS1, ITALSAT, SARX, etc. He received his MSEE and PhD from University of Southern California where he is currently researcher at the Integrated Multimedia Systems Center (IMSC) while he is collaborating with the Optical Communication Research Group at JPL. His fields of interest are Microwave, Optical Communication, Optical Computing, Optical Storage, and Atmospheric Optics. He is also currently lecturer at the University at Southern California and University of California Los Angeles.*



Farid Amoozegar *received his Ph.D. degree in Electrical Engineering with a minor in Optics and Applied Math from the University of Arizona in 1994. He served as a lecturer at the University of Arizona for two years and joined Hughes Aircraft in 1996. While at Hughes, he worked on a number of programs, including Teledesic, Thuraya, ICO, and Spaceway, and he participated in analysis, development, and integration and test of different digital communication payloads utilizing phased array systems. He joined the Jet Propulsion Laboratory in October 2002 in the Communications System and Research Section. His areas of interest are wireless communications, multi-sensor multi-target tracking, and free space laser communications. His current projects include Optical Deep Space Network architecture study, Ka-band system engineering, and phased array systems.*

Robert Cesarone *is with the Jet Propulsion Laboratory, California Institute of Technology. He is currently involved in program management, strategy development and long range planning at the Jet Propulsion Laboratory. His activities specifically involve telecommunications and mission operations, including development of architectural options for the Deep Space Network, NASA's network for tracking interplanetary spacecraft. He has held his present position since September 1991 and has been employed at JPL since 1977. Prior to his current assignment he has held a number of positions within the Voyager Navigation Team, in particular that of lead trajectory and maneuver engineer for the Voyager 2 flybys of Uranus and Neptune. Prior to his arrival at JPL, he attended the University of Illinois, where he received a B. S. in Mathematics in 1975 and an M. S. in Aeronautical and Astronautical Engineering in 1977. Mr. Cesarone has authored 34 technical and popular articles covering the Voyager Mission, trajectory design, gravity-assist and space navigation and telecommunications. He is an associate fellow of the American Institute of Aeronautics and Astronautics, a member of the World Space Foundation and a recipient of the NASA Exceptional Service Medal.*