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The mitigation of Atmospheric Impacts on Free Space Optical Communications

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Abstract— Clouds are key driver in the performance of free space optical communication (FSOC) systems. Clouds are composed of liquid water and/or ice crystals and depending on the physical thickness can produce atmospheric fades easily exceeding 10 dB. In these more common cases, impacts on FSOC systems may be severe. On the other hand, there are times when cloud fades may be as low as 1 or 2 dB as a result of thin, ice crystal based cirrus clouds. In these cases, the impacts on FSOC communication collectors may be limited.

The ability to characterize the distribution and frequency of clouds are critical in order to understand and predict atmospheric impacts. A cloud detection system has been developed and applied to produce high resolution climatologies in order to investigate these impacts. The cloud detection system uses geostationary, multi-spectral satellite imagery at horizontal resolutions up to one kilometer and temporal resolutions up to fifteen minutes. Multi-spectral imagery from the visible wavelengths through the longwave infrared is used to produce individual cloud tests, which are combined to produce a composite cloud analysis. The result represents a high spatial and temporal resolution climatology that can be used to derive accurate Cloud Free Line of Sight (CFLOS) statistics in order to quantify atmospheric effects on optical communication systems.

The Lasercom Network Optimization Tool (LNOT) is used along with a mission CONOPS and the cloud database to find configuration of geographically diverse ground sites which provide a high availability system.

Keywords: ***optical communications, lasercom, clouds, availability.***

I. INTRODUCTION

Strategies to support high-availability laser communications for future missions from space to Earth are increasingly receiving attention. Such missions will generate an ever increasing amount of data that must be transferred to ground locations on Earth. As an alternative to the current use of radio communications, deep space to ground optical communications will provide a higher bandwidth to transfer these data with smaller power mass and power consumption subsystems. However, optical communications may be interrupted by the presence of cloud cover. Typical clouds have optical fades that far exceed three dB. Therefore, it may not be feasible to include enough link margin in the link budget to prevent a link outage. It should be noted that some cirrus clouds may have optical fades less than three dB when averaged over many minutes. However, an optical communications link directed through the sky may encounter "knots" or areas within thin cirrus that may far exceed three dB. Therefore, a mitigation strategy ensuring a high likelihood of a cloud-free line of site (CFLOS) between a ground station and the spacecraft is needed to maximize the transfer of data and overall availability of the network.

One strategy to address this problem is the use of "ground station diversity," in which multiple stations have the potential to receive communications when other sites are cloud-covered or unavailable due to geometric visibility limitations. For this report, a ground station is considered "available" for communication when it has a CFLOS at an elevation angle to the spacecraft terminal of approximately 20° or more. The network is "available" for communication when at least one of its sites is "available." An additional metric for the Percent Data Transferred (PDT) can be computed that determines the amount of mission data transmitted to a ground site based on the network cloud-free availability, data rates/storage, and data volume. The Laser Communications Network Optimization Tool[i] (LNOT) is used to compute the optimal configuration of sites based on a specific scenario (i.e., Deep Space to ground), a long-term record of high resolution clouds, and other constraints like minimum elevation angle from the ground to the spacecraft.

The availability of a communication link between a spacecraft and a ground station network depends on many factors, including the number and location of the sites in the network and the orbit of the spacecraft, which together determine the elevation angle of the link and the path length of transmission through the atmosphere. Typical meteorological patterns cause the cloud cover state at stations within a few hundred kilometers to be correlated. Consequently, stations within the network should be placed far enough apart to minimize these correlations, maximizing the probability of CFLOS. This requirement may lead to the selection of a station that has a lower CFLOS than sites not selected, but that is less correlated

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with other network sites. The stations also need to be close enough to each other to maintain continuous access with the spacecraft as its position with respect to the ground changes with time. LNOT performs this analysis on a high-performance computing platform, using a long-duration cloud analysis to mitigate against the inter-annual variations in clouds over the globe.

The cloud database used by LNOT is a state-of-the-art, high-end, and validated cloud analysis that was developed based on Geostationary meteorological satellite imagery (the U.S. Geostationary Operational Environmental Satellites [GOES], Europe's Meteosat Second Generation [MSG], and Japan's Multi-functional Transport Satellite [MTSAT]) for the period 1995 to the present over the continental United States and Hawaii, and for 2005 to the present over portions of the world where existing NASA and ESA ground sites exist today (e.g., NASA's Deep Space Network [DSN]). For polar ground sites, one would need to integrate cloud data available from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) sensors and the European Meteorological Operational (MetOp) satellite systems. The spatial resolution of all existing cloud data is 4 km and is available at temporal resolutions as high as 15 minutes. This allows trade studies using LNOT for different optical communication scenarios such as LEO, Lunar, L1, L2, and Deep Space.

II. TECHNICAL APPROACH

A. Satellite Data

The analysis period presented here extends from 2005 - 2010. Note that our database of satellite images for CONUS and Hawaii stretches from 1995 to present, while the database for our OCONUS regions of interest are 2005-2010. The data for regions in the western part of CONUS and Hawaii are from GOES-West, while the data for South America and the eastern part of CONUS come from GOES-East. MTSAT provided the data for the Far East regions. Data for regions in Europe and Africa and for the Middle East and central Asia regions are from Meteosat Second Generation (MSG). For the period of interest, satellite data for CONUS and Hawaii are at 15 min resolution while the resolution for all OCONUS regions is at 1 hour resolution.

GOES imagers have five bands: visible (0.6 μm), shortwave infrared (SWIR; 3.9μm), water vapor (6.7 μm), longwave infrared (LWIR; 10.7 μm), and split window (11.2 μm). We replaced the water vapor channel, which is not used for cloud detection, with the reflectivity product during the day and the fog product at night (see below and section 2.3 for more detail on these products). The spatial resolution of the visible band is 1 km and that for the other bands is 4 km. For our purposes, the 1 km data is resampled to 4 km resolution so that it is comparable to the other bands. The MTSAT which covers the Far East has five bands very similar to the GOES satellites and are used in the same way as GOES. The MSG satellite has over 10 bands, however, only the similar bands to that of GOES and MTSAT are used in our cloud detection algorithm.

B. Clear Sky Background

Our cloud analysis techniques for the GOES data are described in detail by Alliss et al.[1]. All cloud tests consist of comparing satellite image values to dynamically computed clear sky background (CSB) values pixel by pixel in the regions of interest. The CSB is discussed below and main cloud test algorithms (albedo, LWIR, fog, and reflectivity) are discussed in section 2.3.

The CSB is defined as the amount of radiation emitted and/or reflected from a surface that reaches a satellite sensor when no clouds are present. The CSB varies spatially and temporally and is influenced by the radiative properties of the surface material, surface temperature, terrain height, soil moisture, and solar illumination angle. Because of these variations, the CSB must be calculated for each region separately, on a pixel by pixel basis, as a function of the above-mentioned factors to generate accurate cloud masks. For example, if the albedo test used a fixed threshold for typical differences between the observed and calculated CSB albedos for all locations, then false cloud detections would be likely over naturally highly reflective regions such as White Sands, NM or the salt flats of northern Chile.

Four CSBs are estimated in the CMG: albedo, reflectivity, LWIR, and fog[1]. The CSB is calculated for each pixel by using data from clear times over the previous 30 days at a given analysis time (e.g., 1400 GMT). This approach provides sufficient clear sky data and reduces the effect of diurnal and seasonal cycles of temperature and illumination, in particular, on the calculated CSB. The database from which clear times are determined includes not only the satellite imagery, but also ancillary surface and ship observations collected by the National Weather Service (NWS), World Meteorological Organization (WMO), and at several telescope observatories in South America.

The albedo CSB is calculated by identifying the darkest 10 % of albedo values from the previous 30 days of visible images. The selected albedo values are averaged to define the CSB for each pixel. The reflectivity CSB is determined only during the day and when snow cover is not likely present. Like the albedo, the darkest 10 % reflectivity product values from the previous 30 days are selected and averaged to generate the CSB.

To develop the fog product CSB, the warmest 10 % of LWIR values for the pixel over the previous 30 days are selected. The corresponding fog product values are then averaged to give the fog CSB. Note that the procedure used to generate the fog product CSB differs from that used to generate the albedo and reflectivity products in which clear pixels are chosen based on the albedo and reflectivity values themselves. Both fog product extremes indicate clouds and the selection of the 10 % warmest or coldest values will not provide the

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needed information; therefore, the two-step process is used for the fog product CSB.

The LWIR CSB is determined as the average of the difference between the LWIR temperature from the satellite for a given pixel and the LWIR CSB temperature estimated from a linear regression model. The regression model is developed with data from clear sky pixels that are used as prototypes. These prototype pixels are selected by a series of tests that find pixels with a high probability of being clear, even without the benefit of any of the cloud tests. The coefficients of the regression model for twelve predictors are fit with the data from the prototype pixels. The predictors include satellite data, time, terrain, and regional observations such as cloud cover and air temperature from the NWS and WMO. The LWIR regression model estimates the clear sky LWIR brightness temperature for each pixel. The LWIR residuals are the differences between the regression model temperatures and the measured imager LWIR temperatures. The warmest 10 % of the LWIR residuals are averaged to determine the LWIR residual CSB that is used in the LWIR cloud tests.

C. Cloud Tests

The CSB values and the satellite data are compared in four main cloud tests in the CMG: the LWIR test, the albedo product test, the fog product test, and the reflectivity product test. The LWIR test is applied at all times of the day, unlike the albedo, reflectivity, or fog product tests. A pixel is considered to be cloudy if the LWIR CSB for a given pixel exceeds the LWIR from the satellite by the threshold value or greater. This test cannot easily detect fog/low clouds at night because the cloud top temperatures are very similar to the surface temperatures. It is unlikely that clouds will radiate in the LWIR at temperatures greater than 300K. A pixel is deemed clear if the LWIR temperature is greater than 300K, even if the LWIR cloud test indicates that it is cloudy.

As mentioned above, the detection of fog and low stratus clouds at night is difficult with the LWIR. The fog product test is a multi-spectral test that compares values of the fog product calculated as the difference between the LWIR and the SWIR brightness temperatures[2,3,4]. The temperature differences result mainly because clouds observed in the SWIR have an emissivity that is 20%-40% lower than clouds observed in the LWIR[5]. Therefore, at night, liquid stratiform (low) clouds appear colder in the SWIR than they do in the LWIR. Typical T_{LWIR}-T_{SWIR} for fog and low stratus are approximately 2 K or larger[6]. The fog product can also detect ice clouds, which are highly transmissive and therefore appear warmer in the SWIR. Typical values for ice clouds are T_{LWIR}-T_{SWIR} are approximately -5 K or lower[6]. The daytime SWIR is dominated by reflected solar SWIR and therefore, the fog product is only useful at night.

The albedo test, which uses visible data, is applied when the solar zenith angle is below 89^o. This test will detect clouds if the pixel is more reflective than the albedo CSB and the difference is greater than a predefined threshold for that pixel. If the difference between the calculated albedo and the CSB is less than the threshold, the pixel is deemed clear. The albedo test may falsely detect snow as clouds.

The shortwave reflectivity product is implemented during the day to decide if a pixel is cloudy or if the surface is snow-covered. This product indicates the amount of reflected solar SWIR detected and is derived by removing the thermal component from the SWIR[5,6]. Water clouds are highly reflective in the SWIR while ice clouds are poorly reflective in the SWIR. As a result, water clouds appear as bright white and poorly reflective ice clouds and snow appear as dark gray or black in the resulting images. The reflectivity product, then, can easily distinguish between low clouds and snow cover. The reflectivity test is only applied when and where snow cover is likely and can override a false cloud detection for snow cover indicated by the albedo test. To ensure that high ice clouds (which also appear dark in the reflectivity test) are not present, the LWIR test must not indicate the presence of high clouds for a pixel to be considered clear.

With the CSB and satellite data, the CMG performs the multispectral tests to accurately distinguish between clouds and clear skies. During the day, for example over southern the Canary Islands (Figure 1), the LWIR and albedo products are used to detect clouds with the resulting mask accurately showing the presence of clouds around the summit of Tenerife. At night when low clouds cannot be adequately detected by the LWIR, the fog product is vital to developing accurate cloud masks. In fact, in a cloud scene from Hawaii (Figure 2), the low clouds over the land would not have been detected without the fog product.

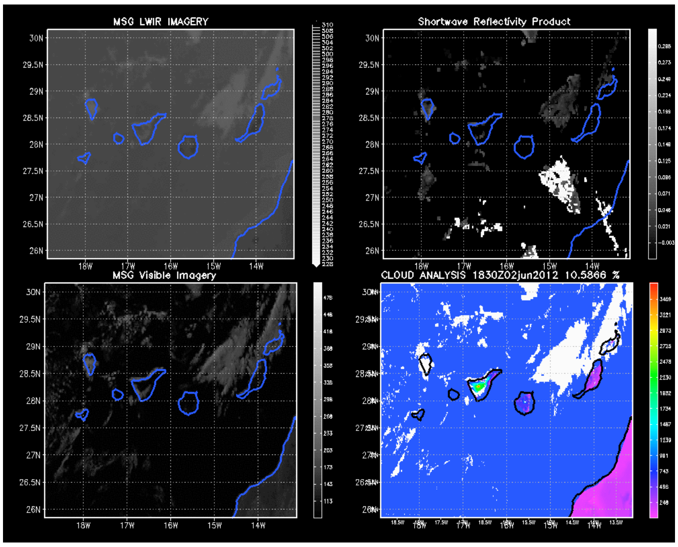

Figure 1: A sample cloud scene during the day for southern Italy and Sicily. The image on the left is the LWIR image from MSG during the day. The image in the center is the corresponding visible image from MSG. For these two images, the lighter grey images indicate clouds. The cloud

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mask on the right shows clouds as white and was generated with the CMG.

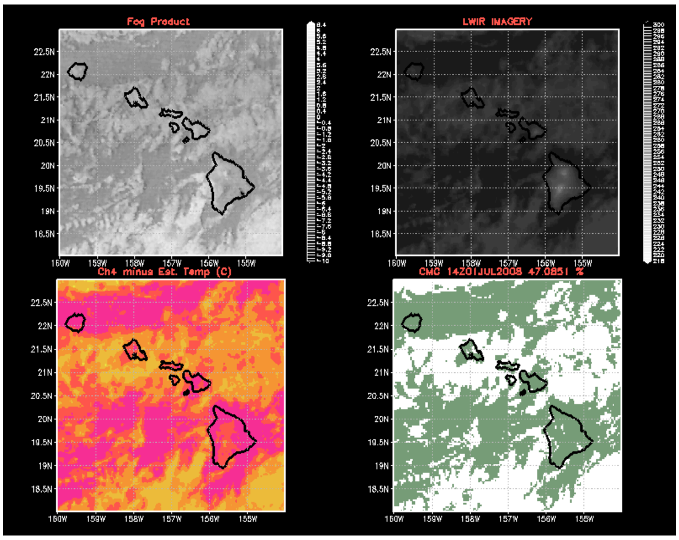

Figure 2. Fog Product (upper right), LWIR imagery (upper left), longwave infrared modeling (lower left), and composite cloud test (lower right) of a nighttime scene over Hawaii.

III. LASERCOM NETWORK OPTIMIZATION TOOL (LNOT)

The goal of optimization in developing a network of ground stations for optical communications is to achieve the highest availability for the network, i.e., the greatest percentage of time during which at least one ground station can communicate with the probe, with the fewest number of stations in the network. Not only must the cloud fractions at each site be considered, but also their location with respect to one another must be considered. Selecting stations with very low cloud fractions all in the same area, say within several hundred kilometers of one another, will result in low availabilities. In such a case, the low availability results because the stations could not see the probe a large percentage of the time because of the probe's movement with respect to the earth. If stations whose cloud patterns are highly correlated are selected, the availability may also be reduced because when one station is cloudy and thus unavailable, one or more of the other stations is likely to be the same. However, widely separated ("geographically diverse") stations will tend to be less correlated and because they would be positioned over a wide region of the globe, availability would be expected to be higher than the scenarios outlined above.

The process of finding an optimal ground station network is a discrete optimization problem. With over 420,000 pixels in our cloud database for the regions considered in this study, the search space must be reduced to be practical. JPL provides some constraints on the locations of the stations such as they must be within ±41° latitude; elevation angle of the probe with respect to the station must be greater than 20° for each pixel to be considered; minimum station altitude of 2 km (we also do tests for 0 km and 1 km); or the sites must be selected from a list of sites of interest. Even with these constraints, the database is too large to search exhaustively for the network with the maximum availability. Therefore, the optimization algorithm must be able to find the desired networks by searching only a small fraction of the network configuration space.

The optimization process we employ will seek a balance between what we call "locality" and "robustness". Locality refers to the idea that good network configurations are close together in space. This feature lets the algorithm make progress in selecting stations. If we did not have the locality feature, the n^{th} guess would be no better than the first guess. On the other hand, it is desirable that the algorithm not get trapped in local extrema in the configuration space. This feature is known as robustness. Our optimization process represents a tradeoff between locality and robustness in two distinct stages. In the first stage, the algorithm searches widely over the entire configuration space, sacrificing some locality in favor of robustness. Once the algorithm arrives in the vicinity of the solution, the second stage begins. In the second stage, some robustness is sacrificed in favor of locality as the algorithm finds the best configuration in the neighborhood of the last configuration found by the first stage. The limited robustness found in the second stage is not of concern because we assume that the optimal solution is nearby when we begin the second stage.

A typical optimization run evaluates more than 40 million networks. At the end of the optimization process, we further evaluate the availability of the ten best networks found by considering detailed line of sight calculations that take into account ground station locations, effects of parallax between the GOES imager and the probe, the elevation angle of the probe, and the cloud amount in a 2400 km^2 area centered on each station. To make these calculations, the position of the probe with time must be known. We assume that the probe is at 0^o inclination to the ecliptic, with a radius of 1.5237 AU (Astronomical Units; 1 AU= 149,597,870 km). This orbit is similar to that for Mars and is much faster to calculate than an elliptical, inclined orbit. Along with availabilities, we calculate complete network status at every 15 min time step, intra-network correlations, serial correlations, and outage distributions. This tool is referred to as the Lasercom Network Optimization Tool (LNOT) and is used in all analyses documented in section 4 below.

IV. RESULTS

A. Low Earth Orbit (LEO) Scenario

LNOT was used to determine the performance of a LEO Scenario using the specifications described above for 2005-2011. The CFLOS analysis for the LEO Scenario is similar to that for the other scenarios for most candidate sites. However, as was discussed in Section **Error! Reference source not found.**, the cloud database used by LNOT was developed using geostationary meteorological satellites. Geostationary

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satellites provide excellent coverage of tropical and mid-latitude regions, but do a poor job in high-latitude regions because of the oblique look angles. Since LEO satellites have significantly more geometric access time to high latitude stations, it is important to consider high-latitude sites for a LEO optical communications system. Therefore, in the absence of satellite-derived 15-minute cloud data for high-latitude sites, a cloud analysis was developed from surface observations for three sites: Svalbard, Norway; Fairbanks, Alaska; and McMurdo Station, Antarctica. Cloud reports providing the skydome cloud amount are available every 3-6 hours for each of these sites. These data were analyzed for their temporal statistics. Their statistical correlations were computed based on the time of year and time of day. These parameters were used to interpolate between the 3-6 hour cloud observations to create a cloud database with one-hour resolution, which could be used by LNOT similar to the cloud data for the non-polar regions. The resulting one-hour cloud database has the same statistical properties (e.g. temporal correlations, average cloud amount) as the original coarser cloud data from surface observations.

A list of 16 candidate sites for LEO ground stations was created from NASA, ESA, and JAXA sites, astronomical observatories, and International Laser Ranging Service (ILRS) sites:

- Canberra DSN Complex (Australia)
- Madrid DSN Complex (Spain)
- Table Mountain Facility (California, USA) (NASA)
- Goddard Space Flight Center (GSFC) (Maryland, USA) (NASA)
- White Sands Complex (WSC) (New Mexico, USA) (NASA)
- Tenerife Observatory, Canary Islands (ESA)
- JAXA Earth Observation Center (Japan)
- Hartebeesthoek, South Africa (ILRS)
- Matera, Italy (ILRS)
- Mt. Haleakala, Hawaii, USA (ILRS)
- McDonald Observatory (Texas, USA) (ILRS)
- New Norcia (Australia)
- La Silla Observatory (Chile) (ESO)
- Guam Ground Station (NASA)
- Svalbard Ground Station (Norway)
- Fairbanks Ground Station (Alaska, USA)

McMurdo Station in Antarctica was included in initial analysis. However, it was later determined that terrestrial fiber links from McMurdo were insufficient to support the LEO Scenario, and McMurdo was removed from consideration. The final list includes two polar sites (Svalbard at 78.9 N latitude and Fairbanks at 64.8 N latitude) and 14 non-polar sites.

The LEO Scenario requires data to be dumped at least once every three orbital revolutions with a high probability (e.g. 95%) as described Section 3.1.1.2. LNOT was used to compute the PDT for this scenario, and to determine how many ground stations might be required to achieve 95% PDT. The PDT was computed for the LEO Scenario using a process similar to that of the other scenarios, as follows. Using the seven years of cloud data and the position of the satellite, LNOT dynamically tracks the data collected (in Gb), the data stored onboard the satellite, and the data sent to the ground. For each hour in the cloud database, LNOT determines whether there is CFLOS from the satellite to any ground station. It also determines the amount of time during that hour the LEO satellite has access above 20° to any ground station. In the LEO Scenario, this geometric access time is measured in minutes, not hours. If a site has CFLOS to the satellite, data is sent at the specified data rate (10 Gb/s), and the data buffer is reduced by the amount of data sent. The amount of data sent when the line-of-sight (LOS) is cloud-free is equal to the product of the number of minutes of geometric access greater than 20° and the data rate. For example, if there are four minutes of cloud-free access to a station during an orbital revolution, the satellite can send 2.4 Tb of data (10 Gb/s × 240 seconds) to that ground station. If no site has CFLOS to the satellite during the current hour of data processing, the amount of data in the onboard buffer is increased by 500 Gb (12Tb per day divided by 24 hours) to simulate another hour of data collection. If the onboard buffer is full, the oldest data is purged, and the amount of data lost is recorded. The PDT is computed at the end of the simulation as the amount of data successfully sent to the ground divided by the amount of data collected by the satellite.

The LEO Scenario differs from the other scenarios in that sites gain and lose access to the satellite very quickly. A site in the mid-latitudes typically has a LOS above 20° to a LEO satellite such as Aqua for a few minutes per satellite pass. Polar sites have somewhat more contact time per orbit, as well as more orbits with access above 20° per day. Therefore, a high-latitude site has the potential to provide great value to a network of LEO ground stations. Taken collectively, the seven example sites shown in Figure 3 below provide an average of about 125 minutes per day of contact above 20° to the LEO satellite. However, geometric access is only part of the calculation. To successfully transmit data at optical wavelengths, the satellite must have cloud-free access to the ground station. When the effects of clouds are included, this time is reduced to an average of about 60 minutes of cloud-free access per day. The entire volume of data collected in a day (12 Tb) can be sent to the ground in 20 minutes of cloud-free access time. However, the satellite can only store data from three orbits (~4.5 hours of data), and therefore must transfer data to the ground at least once every three orbits to avoid exceeding the storage limit and losing data. Therefore, while the entire amount of data stored onboard the satellite can be transferred in less than five minutes (duration of a typical LEO contact), data will be lost when no site has CFLOS on three successive LEO orbits. With the seven sites in this scenario, the LEO satellite always has access above 20° to one or more sites at least once every three orbits. However, there are times when clouds obscure the LOS during the LEO passes, resulting in lost data.

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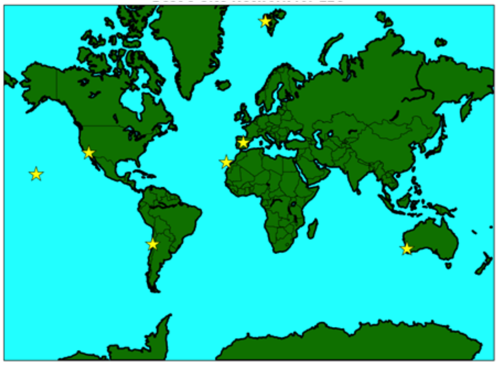

Figure 3: Optimal seven-site network configuration for the LEO Scenario.

The top performing LEO ground station networks were identified by exhaustively computing the performance of all the possible combinations of the 16 candidate sites for networks consisting of 3-15 sites. These PDT calculations were performed for combinations of non-polar sites only, as well as mixed polar and non-polar networks. This analysis indicates a seven-site network nearly achieves the objective of 95% PDT using both polar and non-polar sites, with a PDT of 94.8% for the top network (Figure 3). In fact, a seven-site network of only non-polar sites produces a similar PDT of 94.4%, despite having only about two-thirds the amount of geometric access time as the best seven-site network that includes Svalbard. While Svalbard provides very good geometric access to the LEO satellite, the cloud analysis indicates it is a very cloudy site, which negates much of its geometric benefit. Conversely, several of the non-polar sites only provide a few minute of geometric access per day, but have a very high probability of being cloud-free. Fairbanks rarely shows up in the top networks. It is located at a relatively high latitude, but at 64.8°, its geometric access time is significantly less than Svalbard at 78.9°. Additionally, Fairbanks is very cloudy, leading to the conclusion that it is not a very attractive high-latitude site for an optical ground station. McMurdo Station, with performance statistics similar to Svalbard, is an attractive site, but it was removed from final consideration due to the limitations of its terrestrial communications.

Figure 4 shows the cumulative distribution of the monthly PDT for the top seven-site network of ground stations for this scenario. The PDT is greater than 88% for all months during 2005-2011, and the overall PDT for this LEO Scenario is 94.8%. Figure 5 shows the cumulative distribution of the amount of data transferred daily from LEO to the seven-site ground station network. The data indicate that at least 10 Tb of data is sent to the ground on 90% of the days during 2005-2011. This analysis indicates that a globally distributed set of ground stations can be used to receive very large amounts of data from a LEO satellite, making cross support very attractive. High-latitude sites such as Svalbard increase PDT slightly when compared to strictly non-polar networks, but are not necessary to achieve high performance from a LEO mission.

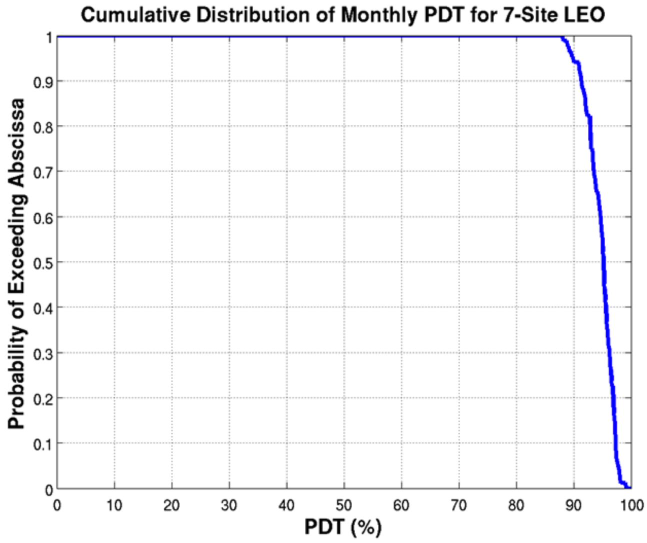

Figure 4: The cumulative distribution of the monthly PDT for the period 2005-2010 for the optimal seven site network.

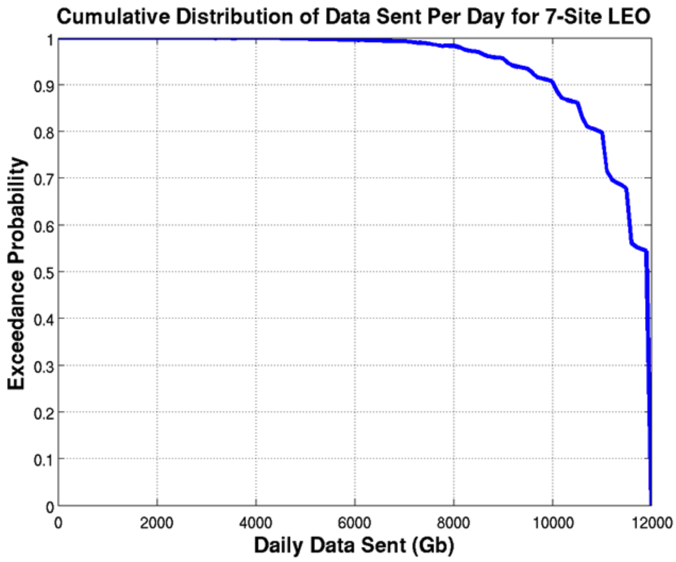

Figure 5: The cumulative distribution of the amount of data successfully sent to the ground by the LEO satellite for the seven site network of ground stations.

B. Lunar Scenario

The moon scenario refers to an optical communications system from a lunar orbiting satellite to ground station on the Earth's surface. This scenario is of particular interest since the NASA Lunar Laser Communications Demonstration (LLCD) is currently in preparation for a 2013 launch. Much of the scenario description is drawn from LLCD experience, as well as extrapolation to potential future lunar missions. The space terminal of LLCD is called the Lunar Lasercom Space Terminal (LLST) and the ground terminal is called the Lunar Lasercom Ground Terminal (LLGT).

The first criterion for a free space optical link is geometric line of site from the spacecraft to a ground terminal. As with other scenarios, the optical link quality is affected by the ground

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station elevation angle, with lower elevations reducing the link capabilities. For all lunar orbiting spacecraft, the first obvious requirement is line of sight to the moon itself; thus, lunar elevation angles will be consistent for all missions in this scenario analysis. Orbit-specific information further refines the scenario, though this information will vary from mission to mission.

LNOT was used to run a lunar scenario similar to that of NASA's LLCD project. To show the value of interoperability between the United States and European assets, two sets of site configurations were evaluated. The first consisted of a Haleakala (NASA) and Tenerife OGS (ESA) configuration, and the second was a four-site network containing Haleakala (NASA), Table Mountain Facility (NASA), Tenerife (ESA) and Hartebeesthoek, South Africa (ESA). As indicated in the concept of operations above, a site was considered available for communication when the lunar probe was at least 20 degrees above the horizon and a CFLOS existed. Table 1 below shows the mean PDT for the period 2005-2010. The mean PDT for both Haleakala and Tenerife individually exceed 80%. As a two site network, the PDT is approximately 97.4%. This increase is due to a combination of cloud de-correlation and the geographic separation between the two sites in terms of the total visibility time to the moon. When TMF and Hartebeesthoek are added to the two-site network, the PDT jumps to approximately 99.6%. The meteorological diversity between these sites is responsible for the high performance, almost guaranteeing that at least one site is available. Figure 6 shows the Cumulative Distribution Function (CDF) of the monthly PDT for individual sites as well as the two and four site configurations. Haleakala and Tenerife are the best performers individually, and the four site network produces only a low probability of PDT less than 95%. The lunar scenario is an excellent example of where cross support can enhance performance of optical communications.

Table 1: PDT (%) for Lunar Scenario for the 2005-2010 period.

Haleakala (NASA)	Table Mountain Facility (NASA)	Hartebeesthoek (ESA)	Tenerife OGS (ESA)
81.0%	68.6%	64.7%	84.4%

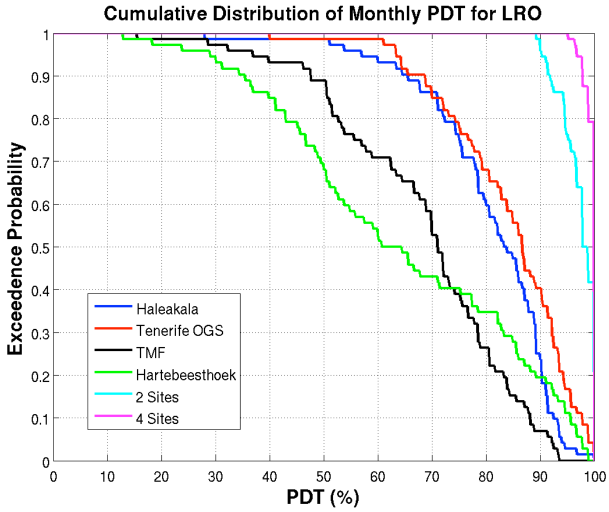

Figure 6: CDF of PDT for the four individual sites and the two- and four-site networks for the Lunar (LRO) scenario.

C. *Deep Space Scenario*

LNOT was used to determine the performance of a representative deep space scenario using the specifications described above for the period 2005-2010. This period of time represents approximately three Mars orbits around the Sun. This analysis provides a good representation of the performance that might be expected. The Deep Space Scenario differs from the other scenarios (e.g., L1 and L2) in that the distance of the satellite from Earth varies considerably through time. This factor impacts the data rate, since the data rate is proportional to $1/r^2$, where r indicates the range of the satellite to Earth. As stated in the Basic ConOps section, the Deep Space Scenario is designed such that the entire data storage from a Mars orbiter can be emptied in one pass. Specifically, at its closest range of 0.42 AU, the amount of data collected per day is 1.1 Tb, and the data rate is assumed to be 260 Mb/s. Using these specifications, an entire day's data can be transmitted in 73 minutes, or in just over one hour. As the range increases, and hence the data rate decreases, the daily data volume is scaled proportionately, so that an entire day's data can always be transmitted in 73 minutes, no matter the range. This assumption allows the computation of PDT to be independent of the range of the Mars orbiter.

As in all space-to-ground optical systems, the performance is a function of many factors, and the trade space may be vast. The analysis in this section demonstrates the impacts of the main performance driver—the number of ground stations. Increasing the number of ground stations improves the probability of having a cloud-free site at any given time, while also providing sites around the globe to ensure geometric line-of-sight from at least one site to the satellite at all times. The nine example candidate ground sites for the Deep Space Scenario are displayed on a map in 6. They include four NASA sites (Table Mountain Facility, Haleakala, Canberra DSN ground station, and Madrid DSN ground station), four ESA sites (the Tenerife OGS, Hartebeesthoek in South Africa,

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New Norcia in Australia, and a site in Chile), and one JAXA site in Japan. Using the six years of cloud data and the position of the satellite, LNOT dynamically tracks the data collected (in Gb), the data stored onboard the satellite, and the data sent to the ground at hourly resolution. At each hour, LNOT determines whether there is at least a 20° elevation angle to the satellite and whether there is CFLOS from the satellite to any ground station. If there is, data is sent to Earth at the specified data rate, and the onboard data buffer is reduced by the amount of data sent. If no site has CFLOS to the satellite, the amount of data in the buffer is increased. If the buffer is full, the oldest data is purged, and the amount of data lost is recorded. The PDT is computed at the end of the simulation as the amount of data successfully sent to the ground divided by the total amount of data collected by the satellite.

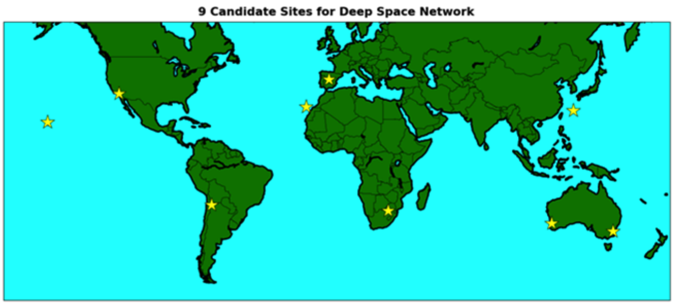

Figure 7: Candidate ground stations used for the Deep Space Scenario.

In this analysis, the PDT is calculated for ground station networks of 1 – 9 sites. Each particular combination of ground stations is chosen to maximize its global coverage (longitudinal diversity). For example, the 3-site network is comprised of Haleakala (156.3 West Longitude), Tenerife OGS (16.5 West), and New Norcia (116.1 East). Figure 8 shows the PDT of each network size. The result accounts for the variable data rate and data volume, since the scenario is defined such that one day's data is sent in one hour (by proportionately scaling both the data rate and data volume with range). For this scenario, a single site (Tenerife) provides a PDT of greater than 90%. This large PDT is possible because it only takes about 1 hour to transmit an entire day's data. Since a single site is visible to Mars for 8-12 hours per day, there is a high likelihood of having at least one hour of CFLOS on 90% of days for a ground station with good cloud-free statistics. When a second site is combined with the first site, such that the two sites provide longitudinal as well as cloud diversity, the PDT is increased to near 99%. Three or more sites produce values of PDT of well above 99%.

By reducing the data volume proportionately with the data rate, the data requirements are easily met with three sites.

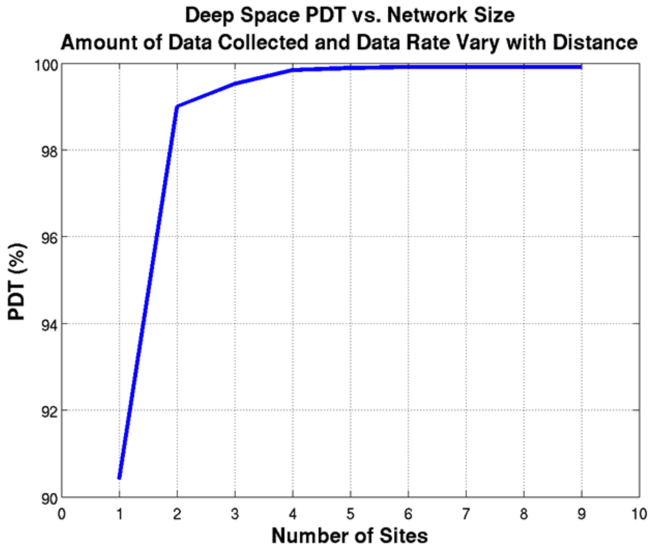

Figure 8: Overall PDT for the Deep Space Scenario for 1-9 site networks of ground stations for six different data rates.

At closest range, the assumption is that the entire data storage is emptied in one pass. As the range increases, and hence the data rate decreases, the data volume will be scaled proportionally. If there is geometric line-of-sight, and CFLOS, and the assumptions about the weather and atmosphere are within specification for the entire pass, then the data is downlinked successfully. If not, then some or all of the data must be scheduled for downlinking at another Earth station. It is assumed that there will be enough ground stations that under geometric and CFLOS conditions, the data will be downlinked within the required time, e.g., 24 hours.

V. Summary and Conclusions

Free space optical communications (FSOC) has hits challenges on many fronts, however, the viability of this technology from an atmospheric standpoint is not a limiting factor. The Lasercom Network Optimization Tool (LNOT) is a powerful risk mitigation tool along with a historical climatological cloud analysis to identify sites that would maximize the performance of a FSOC link given a mission conops and scenario. Geographic diversity of ground sites is the key factor no matter the mission scenario. Since clouds are highly correlated over short distances, separating sites by as little as 100's of kilometers to as much as 10,000 kilometers is desirable depending on the conops (LEO, Lunar, Deep Space, Geostationary). LNOT has shown that through proper placement of ground sites, high availability is possible, however, decisions on real time switching between sites in an operational scenario are addressed through other mitigation techniques such as short term cloud forecasting.

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