Preliminary Assessment of the Atmospheric Optical Channel at Goldstone (CA)

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Abstract—A number of criteria need to be considered for site selection of a deep space optical link receiver station. Some of the factors used to identify suitable locations include whether site conditions are favorable in the atmospheric optical channel, geographical convenience of the location, and (possible) existing facilities (e.g. roads, power, communication networks etc.). Recently, NASA/JPL has been conducting studies to evaluate whether the NASA’s Deep Space Network (DSN) Goldstone, California site is a viable candidate location for an optical deep space communications downlink station. Some reasons in considering Goldstone are quite evident: 1) the existing facilities would ease the integration of an optical ground station into the DSN; 2) it is conveniently near a NASA center (Jet Propulsion Laboratory or JPL); and 3) it is located in a desert region with possible high Cloud Free Line of Sight (CFLOS) statistics. Evaluating location suitability requires characterization of the atmospheric optical channel of the site, namely atmospheric loss and clear sky turbulence statistics. A suite of sensors has been installed at Goldstone to collect the necessary data to produce these statistics. The instruments include a sun-photometer, seeing monitor, and a dust particle profiler. This work presents initial results based on the data gathered at Goldstone to provide a preliminary assessment of the atmospheric optical channel and its implication on the data throughput for a hypothetical optical deep space mission.

Keywords—optical communications, atmospheric channel, Goldstone, telescopes, atmospheric loss, clear sky turbulence.

I. INTRODUCTION

Among the new NASA future objectives, there is one of increasing manifold for higher downlink data rates from spacecraft in deep space to better support the demanding high capacity data return needs of upcoming science, exploration, and human missions. In order to accommodate these requirements, optical communication has been a subject of renewed interest and investigation. Beside the flight section and its related technology challenges (e.g. laser and photo detector technology, sub-micron pointing, etc.), the ground segment of future optical deep space networks has its own importance and criticality to implement future NASA optical communication missions. For example, one of the first things to consider when design/deploying a future optical ground station network is to identify candidate sites [1]. One may initially consider that a proper location for an astronomical telescope (e.g. high mountain top, high CFLOS, low clear air turbulence) should also be suitable to house an optical communications ground station. However, the scarcity of high elevation locations along with their lack of integration with already existing NASA networks such as the deep space network (DSN), and the associated high cost to install a ground station at new locations different from the already existing NASA infrastructures has stimulated a preliminary study to understand the optical channel performance at an already operational NASA facility. A location of great interest is Goldstone, California, which is one of the three nodes of the DSN (other two are in the proximity of Madrid (Spain) and Canberra (Australia)). The current DSN ground stations operate over a large band of RF (namely from S-Band to K-Band), therefore a large effort was concentrated during previous years to characterize the RF atmospheric channel in these locations. Similarly, this effort presents some preliminary data and initial characterization of the atmospheric optical channel at Goldstone. Particularly, Sect. II will present a statistical characterization of the atmospheric loss at the site. Sect. III will discuss about clear air turbulence at Goldstone. Sect. IV will present how dust concentration at a location can affect atmospheric loss and telescope performance. Finally, Sect. V will summarize conclusion and future work. It should be noted that the experiments presented in this work were initiated at different stages during the year 2010 and this activity is foreseen to be ongoing for a number of years in order to build a solid statistical representation of the atmospheric channel. Therefore the work presented herein will discuss initial findings and a preliminary assessment of this statistical characterization.

II. AVAILABILITY AND ATMOSPHERIC LOSS

The DSN Goldstone complex is located in the California part of the Mojave desert, which is situated in an high plateau around 1.1 Km above sea level. Goldstone is renowned to house a number of large area antenna including the 70m diameter antenna that has served NASA missions for more than forty years. Goldstone also includes a number of more recent 34m antennas, including one termed DSS-13 that is mainly dedicated to radio-astronomy and the support of a number of other research applications. In the course of our
investigation we utilized the area around the DSS-13 antenna (termed Venus station) to deploy a number of instruments (to be described later on in this paper) for the characterization of the atmospheric optical channel.

Being in the center of a desert region, the Goldstone weather is very dry with relatively low cloud coverage and scarce vegetation which causes highly variable dust concentrations in the air. Cloud coverage is one of the main figures of merit in telescope site selection because clouds act as an opaque obstacle along the optical link line of sight which impairs the ability to close the link. According to a JPL/NASA sponsored study it was found that the estimated annual cloud free line of site is on average 66% over six years [2]. These CFLOS statistics were compiled from satellite imagery, and it is very encouraging for optical communication because it is comparable to that of high elevation sites dedicated for astronomical observations. Monthly average statistics for Goldstone are illustrated in Fig. 1, which shows that site availability varies from a minimum of 44.5% in February to a maximum of 85.6% in June. This dependence of the CFLOS on month of the year suggests that a successful geographical diversity strategy can already greatly increase ground station network availability, such as having a station located at Goldstone and another at a location with an anti-correlated weather pattern [3].

Other atmospheric effects that impact optical link quality are atmospheric loss and daytime sky radiance [4]. Atmospheric loss is the consequence of absorption and scattering that an optical beam experiences while propagating through the atmosphere. Daytime sky radiance is the diffuse radiation originated by atmospheric scattering of solar radiation. Sky radiance is captured by the ground station receiving aperture, and it manifests itself as noise background which negatively impacts receiver performance [4]. To characterize these two atmospheric variables, a sun-photometer was deployed at Goldstone on April 2010 (this Goldstone sun-photometer belongs also to a worldwide instrument network, called AERONET, that is dedicated to monitoring global aerosol distributions [6]). The sun-photometer is essentially a small telescope that tracks the Sun.

Every 10-15 minutes the instrument points directly at the Sun and reads the related spectral irradiance over a number of wavelength channels centered at 340, 380, 440, 500, 675, 870, 1020, and 1640 nm. These readings are used to derive atmospheric optical depth, equivalently atmospheric optical loss, at the wavelengths of interest. Sky radiance measurements are taken the instrument away from the Sun line of sight. Variation of aerosol concentrations in the air and other atmospheric constituents are reflected in variation atmospheric loss and sky radiance data as measured by the sun-photometer. Moreover, by an elaboration of the sun-photometer data, proper algorithm are able to identify if the measurement was taken in presence of the clouds or it was cloud free. Several years of data will be needed in order to produce reliable statistics of atmospheric loss and sky radiance. Since the sun-photometer makes substantially more measurements of atmospheric optical depth than sky radiance during each day, there is enough data for optical depth only available at this that we can use to provide an initial assessment of atmospheric loss at Goldstone for the period April 2010 - February 2011. Fig. 2 provides a representation of the atmospheric loss cumulative distribution function (CDF) for all the operational wavelengths of the instrument. The statistics are based on what AERONET terms "data level 1.5", in which measurements made during cloudy conditions are removed. The results presented are the loss in decibel units that a beam experiences while propagating through the atmosphere from the ground up. Table 1 summarizes atmospheric loss values for each wavelength at select CDF probabilities of 10%, 50% and 90%. The statistics are in good agreement with theory in which the largest loss is experienced at UV wavelengths such as 340 and 380 nm in relation to the infrared wavelengths of 870, 1020 and 1640 nm.

<table>
<thead>
<tr>
<th>MONTH</th>
<th>PROBABILITY</th>
<th>GOLDSTONE 1997-2003: CLOUD FREE LINE OF SIGHT</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.2</td>
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<tr>
<td>2</td>
<td>0.4</td>
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<td>3</td>
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<td>4</td>
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<td>12</td>
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<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Atmospheric Loss at Goldstone (in dB) at 10%, 50% and 90% of the CDF for the wavelengths observed by the sun-photometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAVELENGTH</td>
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</tr>
<tr>
<td>10% CDF</td>
<td>2.91</td>
</tr>
<tr>
<td>50% CDF</td>
<td>1.08</td>
</tr>
<tr>
<td>90% CDF</td>
<td>3.38</td>
</tr>
</tbody>
</table>
To further validate our findings, atmospheric loss values at Goldstone were simulated using the radiative transfer model software MODTRAN [7] to make a quantitative comparison against the sun-photometer measurements. The parameters used to model conditions at Goldstone include setting the boundary layer to begin at 1.1 Km corresponding to the Goldstone elevation, and applying the desert environment aerosol model with an associated wind speed of 3.3 m/s corresponding to the average wind speed at Goldstone based on long term wind speed in situ measurements. The concentration of aerosols in the stratosphere was described by the 'background stratospheric' model that is typically used to represent aerosol concentrations at higher altitudes. A second run was also performed to simulate a lower bound of the atmospheric loss by modeling an atmosphere free of aerosols at the boundary layer. All MODTRAN results are reported in Fig. 3, which are in agreement with the statistics presented in Table 1. The variation in the experimental data for cloud free line of sight atmospheric loss are well bounded by the simulations corresponding to the desert aerosol model (90% of the CDF of the atmospheric loss) and the aerosol free model (10% of the CDF). Since the MODTRAN results are such an excellent match with the measured data over this large spectrum, one can derive that this method can be used to predict atmospheric loss at wavelengths different from those measured by the sun-photometer, such as those more commonly used for optical communications (e.g. 1550nm or 1064nm).

Due to an insufficient amount of sky radiance data for this same time period, we will delay the report of our findings until more robust statistics can be compiled.

III. CLEAR AIR TURBULENCE

Randomness in atmospheric refractive index values originates from clear air turbulence. The effects of clear air turbulence are several, and they manifest themselves on a downlink beam as variation in time in signal irradiance (scintillation), variation in time of the angle of arrival, phase distortion, and deviation from a diffraction limited spot size at the receiver focal plane.

For a statistically homogenous and isotropic atmosphere, the measure of uncertainty in the refractive index is given by the refractive index structure function between two different points (\(R_1\) and \(R_2\)) given by

\[
D_n(n(R)) = \langle [n(R_i) - n(R_j)]^2 \rangle = 2C_n^2R^{2/3}
\]

where \(n(R_i)\) is the atmosphere refractive index at \(R_i\) [8], while the symbol \(\langle \rangle\) stands for the averaging operator. The parameter \(C_n^2\) is termed refractive index structure coefficient which is the measure of turbulence strength: the stronger the turbulence the larger the value of \(C_n^2\). The refractive index structure coefficient depends on temperature, pressure, and the coefficient of the temperature structure function itself [8]. The refractive index structure coefficient varies along the atmosphere vertical profile, and the degree of the turbulence effect is represented by the atmospheric coherence length, \(r_o\), defined as

\[
r_o = 0.423k^2 \sec(\theta) \int C_n^2(h)dh \right)^{3/5} (m)
\]

where \(\theta\) is the angle as measured from zenith for slant path in the atmosphere, \(k\) is the beam wavenumber at the wavelength of operation, and \(h\) is the altitude.

The atmospheric coherence length is related to the astronomical seeing \(S_e\) as

\[
S_e = \lambda / r_o
\]

which is the measure of angular extension of the full width half maximum of the point spread function at the focal plane of an optical system due to clear air turbulence. Because the astronomical seeing is much larger than the diffraction limit, the turbulence effect requires an increase in the telescope system field of view in order to capture the full downlink signal but at the expense of a much larger amount of undesired sky background noise [4].

Largest values of \(C_n^2\) are usually confined in the boundary layer in proximity to the ground where the temperature gradient and atmospheric pressure are largest. As the altitude increases the values of \(C_n^2\) rapidly decrease in an exponential fashion. Therefore the variation of the refractive index structure coefficient in the ground layer must be recorded daily to properly characterize site turbulence. Measurements were made at Goldstone using a ground scintillometer, which consists of two transmitting LED discs and receivers. The transmitter and receiver were separated by a distance of 800m and measurements were taken near the DSS-13 station [9] continuously over the course of one week during the summer of 2009, the results are illustrated in Fig. 4.

![Fig. 3 Comparison of measurement of atmospheric loss measurements made at Goldstone with MODTRAN modeling.](image-url)
The data clearly shows how the daily variation of $C_n^2$ is synchronized with the Sun cycle, with local minima occurring around sunset when the Sun zenith angle is around 85 degree and after dawn when the Sun zenith angle is around 70 degree.

And when the Sun reaches its peak at noon, $C_n^2$ assumes the largest values. The refractive index structure coefficient is associated with the atmosphere thermal gradient. Around sunset and dawn, the thermal gradient along the atmosphere profile is reduced along with the $C_n^2$ values. While at noon, the thermal gradient is at a maximum due to the temperature difference between the ground and atmosphere so the effects of clear sky turbulence are more pronounced because of the larger $C_n^2$ values. The same data represented in Fig. 4(a) was then binned by time of day in increments of one minute to examine the variation in average $C_n^2$ values over the course of a summer day, see Fig. 5. The figure indicates that values are bounded from low $C_n^2 = 3E-16$ (m$^{-2/3}$) around sunset and high $C_n^2 = 3E-14$ (m$^{-2/3}$) around noon. To infer the astronomical seeing (i.e. the integrated effects of clear air turbulence through the atmospheric profile) from these ground layer measurements is not a straightforward task. One needs not only measurements taken at ground level but also at higher altitudes. However, a number of $C_n^2$ profile models that describe the variation of $C_n^2$ from the ground layer to the top of the troposphere exist in literature [10]. Among them, an adaptation of the CLEAR1 model was one that fitted the best for Goldstone. The CLEAR1 model was originally produced to describe the clear air turbulence in the high desert of New Mexico at a ground layer of 1230 m. To describe the daily variation of clear air turbulence, it was assumed that the vertical profile of $C_n^2$ Goldstone was proportional to the CLEAR1 model. The CLEAR1 model proportionally constant was given by the ratio of $C_n^2$ value at the ground layer measured at Goldstone and the $C_n^2$ ground value of the CLEAR1 model. The proportionality constant was derived for each realization $C_n^2$ at Goldstone during the day, according to Fig. 5, and using Eq. 2 and Eq. 3, the it was calculated the astronomical seeing.
The derived average daily variation in astronomical seeing at Goldstone is presented in Fig. 6. The astronomical seeing in the figure refers to the zenith and a wavelength of 500nm according to the general convention used in astronomy.

One can observe in Fig. 6 that Goldstone nighttime seeing is on the order of 2 to 3 arcsec (as), while the maximum of 4 to 5 arcsec is reached at noon. The minimum seeing is observed around sunset (0.5 as) and after dawn (1.5 as). In summary, astronomical seeing values follow a cyclical trend: (a) starting with largest seeing at noon, (b) decreasing to a minimum before sunset, (c) rising after sunset to a peak, (d) decreasing during the night, (e) increasing before dawn to a peak, (f) decreasing to a local minimum after dawn, and finally (g) increasing again up to noon.

A nighttime scintillometer was deployed at Goldstone to verify this model. The instrument determines the atmospheric coherence length (and then the astronomical seeing) by measuring the fluctuation in centroiding position of a star image (usually Polaris) at the focal plane of a CCD imaging system. Average values of nighttime astronomical seeing for the period Jan-Feb. 2011 are reported in Fig. 7 in time steps of one minute. The average measured seeing at Goldstone is between 2 and 2.3 arcsec, which are in agreement with the modeling results provided in Fig. 6. It should be noted that data in Fig. 7 were taken during the winter time, while data in Fig. 6 is representative of summer time. Future investigations will provide the characterization of nighttime seeing during the summer as well.

**IV. DUST CONCENTRATION**

As mentioned earlier, the Goldstone facility is located in a desert where the environment is characterized by scarce vegetation and the concentration of aerosol is dominated by dust that is transported by local wind speeds. Dust concentration affects the operation of an optical ground station because light is scattered by dust aerosols, which means a beam propagating through the atmosphere will suffer additional loss. Since sunlight is also scattered by dust, the amount of sky background radiation may increase which would negatively impact receiver performance [2]. Finally, ground telescope mirrors will be susceptible to contamination due to dust accumulation which increases unwanted background radiation originated by the Sun irradiance (stray light) and scattered by the mirror surface itself with further degradation of the performance of the receiving system [11].

A particulate profiler was deployed at Goldstone to measure dust concentration levels. The instrument measures the amount of light scattered by particles suspended in the air. The light is generated by a local laser diode the detected amount of scattered light is converted into a measure of the particle concentration. The instrument is able to record at every minute the counts of dust particles per liter binned by particle size such as 0.3, 0.5, 0.7, 1.0, 2.0, 3.0, 5.0, 10 µm.

Measured dust concentration levels at Goldstone during the period August 2010-Nov. 2011 are illustrated in Fig. 8. The data shows that dust concentration can vary up to two orders of magnitude for particles of size 0.3 µm, and as expected lower dust concentrations for larger sized particles. Cumulative distribution functions of the particle bin sizes are indicated in Fig. 9.
Mie scattering theory states that the light scattered effects by aerosols (dust) are larger when the size of the particle is comparable to the wavelength considered. Moreover, Mie scattering effects are increased with higher dust concentration levels. To better understand the relation between dust concentration and atmospheric loss at a given wavelength, correlation coefficients were calculated over a matrix formed by the particle profiler dust size and the wavelengths observed by the sun-photometer. First, we time synchronized the measured atmospheric loss and particle count datasets together. Then for each wavelength, we compute the correlation coefficient for each dust size bin and atmospheric loss, results are summarized in Fig. 10.

A good degree of correlation is found between atmospheric loss at 340, 380, 440, and 500 nm when the dust size is of the order 0.3 and 0.5 \( \mu m \). For the larger dust sizes such as 0.7, 1.0, 2.0 and 5.0 \( \mu m \), the correlation is much higher with atmospheric loss in the near infrared wavelengths of 870, 1020, and 1640 nm. Because dust concentration in a desert region is dependent on wind speed, this initial analysis prompts further investigation in the future on whether wind speed is also correlated with aerosol concentration and atmospheric loss. If a model can be produced from such a correlation, it can be able to predict atmospheric loss at a given wavelength of interest (also those not covered within the sun-photometer range) and during time when the sun-photometer is also not working (meaning daytime or nighttime).

To characterize the effect of dust contamination at Goldstone, five small mirrors were placed on different locations on the DSS-13 antenna structure to monitor dust deposition over time. Accumulation of dust increases mirror roughness thus changing the bi-directional reflectance distribution (BRDF) value of the mirror surface.
Fig. 11 BRDF variations in time over five mirrors at Goldstone.

Effects of an increase in mirror BRDF (dimensionally sr⁻¹) are most prominent during the daytime because additional background light is introduced to the telescope system from stray light, which follows as

\[ L_\lambda = I_\lambda BRDF(SA)T_\lambda \]  

(4)

where the spectral background radiance \( L_\lambda \) is usually indicated in W/cm²sr/μm, \( I_\lambda \) is the spectral irradiance of the Sun (dimensionally W/cm²/μm), SA is the angle between line of sight and Sun, and \( T_\lambda \) is the atmospheric transmittance. The mirrors’ BRDF was measured daily for a two-week period using a scatterometer/reflectometer [12]. The data are presented in Fig. 11 showing an increase in the mirrors BRDF of up to three orders of magnitude as dust accumulated over time, with the exception of Mirror-4. This is due to the fact that Mirror-4 was mounted facedown and therefore less prone to collect dust. Theoretical models were used to convert the BRDF to a contamination rate [13] yielding a rate of 0.033% dust deposition coverage per hour, which is consistent with published data at other observatories [14]. Dust deposition rate is an important parameter to consider because it helps determine how frequently the primary mirror needs to be cleaned given different operational scenarios and the required stray light tolerances to uphold receiver performance.

V. CONCLUSION AND FUTURE WORK

In this work we presented an initial assessment of the atmospheric optical channel at the DSN location of Goldstone in California. In particular, we reported preliminary findings on atmospheric loss, clear air turbulence, and effects of dust concentration. Atmospheric loss measurements obtained with a sun-photometer offered statistics in favor of the site, especially in the near infrared channels supported by the instrument. The CDF plots in Fig. 2 show that 90% of the measurements at wavelengths 870, 1020, and 1640 nm have an associated atmospheric loss of 0.27, 0.2 and 0.19 dB or less, respectively. Furthermore, the data over the broadband range of the sun-photometer were in agreement with theoretical prediction and simulation data that we obtained using MODTRAN software. The simulations modeled the aerosol distribution of Goldstone by implementing the built-in ‘desert model’ at a given wind speed that is representative of the measured site average. We then examined the correlation of atmospheric loss and the dust distribution in the atmosphere, which were obtained with a particle counter instrument. The results yielded good correlation between dust size, its concentration, and atmospheric loss at the wavelength of operation. This finding suggests further investigation of a possible method to predict with some degree of accuracy atmospheric loss and dust concentration. Future work may include using measurements from the particle profiler to build different models describing the aerosol (dust) concentration in the atmosphere as input for MODTRAN simulations of the atmospheric loss. This approach is of great interest because the sun-photometer provides only daytime readings (when the Sun is visible), and this method could be used to extend assessment of the atmospheric loss during nighttime. In regards to clear sky turbulence, we measured cyclical variation of the refractive structure coefficient at the ground turbulence layer. We extrapolated the daily variation of the astronomical seeing at Goldstone using existing models found in literature, and there was good agreement between the model and site instrument measurements for nighttime seeing. Note that this is considered a partial confirmation as we have yet to validate the extrapolation method with daytime seeing measurements. Therefore, one of the objectives of future work is to complete our understanding of the astronomical seeing at Goldstone by measuring both daytime and nighttime seeing, and synchronizing these data with ground layer turbulence readings over an extended period of time. We will report additional progress as more data becomes available with our ongoing efforts in gathering measurements. We will also provide daytime spectral radiance findings at a later date when enough data has been accrued to compile meaningful statistics.

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REFERENCES


