COSMO Large Coronagraph Site Evaluation and Selection

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1 INTRODUCTION

1.1 Scope

This document describes the analysis and comparison of two possible locations for the COSMO Large Coronagraph (LC) Facility. This analysis considers many factors including: environmental, technical and cost. This analysis focuses on the LC Facility and not the other instruments of the COSMO Observatory. Additionally this document does not include any analysis on the site locations for potential international collaborators.

Section 2 introduces the concept design for the observatory structures. Section 3 briefly introduces the two sites, and Sections 4 - 7 analyze important environmental, technical and cost metrics. Section 8 provides a summary of these analyses and the recommended site selection.

1.2 Analysis Topics

This site analysis focuses on several key elements of an observatory site. These include:

1) Sky brightness
2) Aerosol content
3) Clear time fraction
4) Atmospheric seeing
5) Environmental conditions
6) Volcanic and seismic activity
7) Existing infrastructure
8) Permitting
9) Space availability
10) Cost

1.3 Considered Sites

There are many potential sites for the COSMO LC Facility. A survey of all possible sites would require resources that are beyond those available for this project. Our approach is to rely heavily on site evaluation data collected by others and to severely restrict the site search.

The first 4 items in the above list of elements to consider for the LC facility describe atmospheric conditions. They are listed in order of importance for the COSMO Large Coronagraph. The most important quality for the LC site is the sky brightness.

The DKIST project conducted a site survey (Hill et al., 2004) which included testing the sky brightness at six candidate sites (Big Bear, CA; Haleakala, HI; La Palma, Canary Islands; Panguich Lake, UT; Sacramento Peak, NM; San Pedro Martir, Mexico). Of those sites, Haleakala had the best sky brightness by far. Haleakala has a long history of quality coronal observations. Sky brightness measurements taken at Haleakala between 1955 and 2002 show no discernible change in the sky brightness with time (Labonte, 2003).

Mauna Loa is another site with a long history of quality coronal observations. HAO has operated a coronagraph there continuously since 1965. Using data from the Mk4 coronameter, Elmore (2007) showed that the sky brightness at Mauna Loa was \( \sim 0.5 \times 10^{-6} \) per airmass at 775nm during the years 2004 to 2006.

Haleakala and Mauna Loa are demonstrably two of the best sites for coronal observations in the world. For this reason, and in the interest of saving time and money, we have chosen to conduct a site evaluation and site selection rather than a site survey, and restrict the possible choices of the COSMO facility to:

1) Haleakala, Maui
2) Mauna Loa, Hawaii
1.4 APPLICABLE DOCUMENTS

1.4.1 HAO Documents
- COSMOLC-RQ-1000 (Science Requirements Document)
- COSMOLC-RQ-1001 (Concept of Operations)
- COSMOLC-RQ-6000 (Instrument Science Requirements Document)
- COSMOLC-DE-7002 (Optical Design Description)
- COSMOLC-RQ-6012 (Enclosure and Site Requirements Document)
- COSMOLC-DE-7100 (Mechanical Design Description)

1.4.2 NOAA Documents
- Mauna Loa Geotechnical Report
- GMD Banned Construction Materials List_Jan2014
- Environmental Assessment of MLO

1.4.3 External Documents
- MLSO Site Characteristics – Yasukawa, Hill, Andrulis, Schnell
- COSMO Technical Note #19, Rev #1, Steven Tomczyk (Aug 9, 2013) HAO Shabar Instrument and Observations
- NOAA Geotechnical Engineering Exploration for NOAA Observatory Mauna Loa Hawaii (Buchler, Willis and Ratliff, Denver, CO)
- NOAA – Environmental Assessment of Mauna Loa Observatory
- DKIST SPEC-0149 (Haleakala Environmental Spec)
- Nelson, P.G., “An Analysis of Scattered Light in Reflecting and Refracting Primary Objectives for Coronagraphs”, COSMO Technical Note #4,
2 BUILDING CONCEPT

The requirements on the observatory site and buildings are detailed in COSMOLC-RQ-6012 (Enclosure and Site Requirements Document). These requirements will not be duplicated here. They will be mentioned as appropriate in the analysis sections below.

For reference, the current building concept is shown in Figure 1 and the expected footprint in Figure 2. Both of these figures represent very preliminary designs and are shown here only for reference. For more detail on the building design see COSMOLC-DE-7100 (Mechanical Design Description). The dome building is divided into an observing floor and a laboratory area (not shown) underneath. To enter the observing floor an observer must enter through a vestibule which acts as a clean room entrance. This room will contain clean-room garb and related equipment. The control building is divided into three rooms. There will be a server room, an observer station room, and a general purpose work room. The size of this building and these three rooms will be refined, but Figure 2 shows a reasonable layout.

![Figure 1 - Large Coronagraph Facility and Control Building concept.](image)

Figure 1 - Large Coronagraph Facility and Control Building concept. The background image was taken at Mauna Loa for context, but does not represent the exact location for the observatory. A cross section of the dome is shown to detail the interior of the observing floor.
3 SITE DESCRIPTIONS

The following sections provide an overview of the two considered locations as well as some of their advantages and disadvantages. These advantages and disadvantages will be discussed in further detail in later sections of this document.

3.1 MAUNA LOA, HI

The Mauna Loa site would be located nearby the existing HAO operated Mauna Loa Solar Observatory (MLSO). The preference is for a location within the area currently used by the National Oceanic and Atmospheric Administration (NOAA). The observatory is approximately 46 miles from downtown Hilo at an elevation of 3,353m above sea level. The background sky brightness and overall cleanliness levels of the area are excellent.

Mauna Loa is considerably less developed than Haleakala though basic facilities are available (such as power and paved road access). High-speed data links capable of handling the data produced by the COSMO suite of instruments are currently not available.

The land at Mauna Loa was deeded to the government in 1957, prior to tighter regulations regarding environmental impact, etc. As a “grandfathered” site, the construction of the COSMO complex will not require as extensive (or expensive) a permitting process as Haleakala.

Mauna Loa is an active volcano. The Mauna Loa site is located on an 1832 lava flow with a fairly dark brown/black color. Because the lava flow is so new there is virtually no vegetation for many kilometers around the site, and this reduces aerosols such as pollens and bugs. The barrenness and remoteness of the site also means there are few birds or other animals. The impact of the dark rock on seeing is evaluated in a following section. Drawbacks of being on an active volcano include high levels of seismic activity, oc-
casional noxious gas plumes, and the potential for the observatory to be overrun by a new lava flow. The lava issue has been mitigated by NOAA though the construction of a large chevron diversion, nearly half a kilometer on a side. The proposed COSMO Large Coronagraph Facility lies slightly outside the existing berm. The berm will need to be pushed to the East to protect the COSMO LC facility.

![Figure 3 - Satellite image of the NOAA/MLSO site showing the potential location of the new LC Facility as well as the current MLSO facility.](image)

### 3.2 Haleakala, HI

The observatory at Haleakala is located near the summit of the Haleakala volcano, 24 miles from the Maui offices of the Institute for Astronomy in Kula, HI (38 miles from downtown Kahului). Its elevation is 3,054m above sea level. Haleakala has erupted 3 times in the last approximately 900 years. It is far less likely to erupt than Mauna Loa, but it is not considered dormant.

Haleakala is a very highly developed site with many institutions being represented (the largest being the Air Force observatory). As the most highly developed site it has ample facilities such as power and data communications. It also has a very limited number of sites available for development. Breaking new ground on Haleakala is extraordinarily difficult due to environmental impact regulations and other local concerns. For this reason the site for COSMO is restricted to previously developed sites. The only identified site not in use and large enough is the Mees Solar Observatory site.

The Mees Observatory site is over 70 feet in the E-W and 40 feet in the N-S directions. The existing building and dome would have to be demolished. A drawback to the Mees site is the proximity of the DKIST (shown in Figure 4 and Figure 5). DKIST is extremely large: the main dome peaks at ~49m above Mees and is nearly 30m wide, and it casts a large shadow. The DKIST will cast a shadow on the Mees site around solstice. This is discussed further in 4.3.1.
The ground at Haleakala is light brown/red volcanic rock in a semi-decomposed state. Some low brush and grasses sparsely populate the area. The ground rock is home to an endangered species of bird which makes its home in the rock crevices (part of the reason breaking new ground is difficult). There are also flying insects which make nests in the rock and these could interfere with the observations. This is discussed further in Section 4.2.

The K-cor and ChroMag instruments that are also part of the COSMO suite of instruments would also need to be located at Haleakala. The ZLO site provides one option.
4 ATMOSPHERIC CONDITIONS

4.1 Sky Brightness

Sky brightness is an important site characteristic for the COSMO LC facility because the sky background can degrade the quality of coronal observations through increased photon noise. The total background is a combination of light scattered by the atmosphere and instrument. The COSMO Large Coronagraph requirement is to achieve a sky plus instrument scattered light level of less than 5 parts per million (ppm) at 1074nm. A lower level of sky brightness will leave a larger portion of the scattered light requirement to be allotted to the instrument.

The sky brightness was also an important consideration for the Daniel K. Inouye Solar Telescope (DKIST). For this reason, Sky Brightness Monitors (SBMs; Lin and Penn, 2004) were developed to evaluate the sky brightness of the DKIST sites. The SBM, Figure 6, is an externally occulted coronagraph that simultaneously obtains images of the un-attenuated sky surrounding the Sun, and the solar disk though an ND4 (10^-4 transmission) filter. The images are obtained successively through color filters with passbands centered in the continuum at 450, 530 and 890nm with the fourth centered at the 940nm water absorption band. SBMs were deployed to six prospective DKIST sites including the Mees Observatory at Haleakala. For this study we did not re-deploy the SBM to the Haleakala site, but rather acquired the raw data collected for the DKIST site survey and performed an independent analysis. To evaluate Mauna Loa, we obtained a SBM from the DKIST project and deployed it at the Mauna Loa Solar Observatory (MLSO). MLSO was not part of the DKIST site survey.

One important aspect of these data is that they were collected at different times, by different observers, and mounted to different pointing platforms. Because the observing staff at the two observatories maintained different working hours, there is the potential for a systematic bias in the data. To correct for this, each data set was normalized to the actual hours of observation. The MLSO data were obtained by an

Figure 6 - The SBM instrument at Mees Observatory on Haleakala.
SBM mounted to a guided spar. At Haleakala the SBM was on a clock-driven (non-guided) equatorial mount that occasionally lost tracking. This resulted in the MLSO data being of slightly more uniform quality.

Both data sets were screened for obviously bad data. Data from the two sites were analyzed with identical software that was developed at HAO based on the methods described in Lin and Penn (2004) and Penn et al. (2004). The calibration and data analysis are described in more detail in Tomczyk and Elmore (2015). The effective height for the data shown here is approximately 5 \( R_{\text{sun}} \).

After removing obviously bad data, these results are based on: for Haleakala, 9530 measurements on 150 days from 10 Feb 2004 to 27 July 2006 and for MLSO, 18546 measurements on 293 days from 11 June 2006 to 21 June 2007. After processing and calibration, median values of the sky brightness were computed in half hour bins throughout the day. Figure 7 shows the median sky brightness in ppm vs local time for both sites. The top curves show the observed brightness; the U-shape is due to the increase in sky brightness while looking through more atmosphere towards the horizons. The bottom curves show the brightness per unit air mass (using a plane-parallel atmosphere model). Both sites show darker skies early in the morning and a degradation later in the day. This is probably due to late-day upslope winds bringing organic aerosols from the coastlines.

![Figure 7 - Median sky brightness in half-hour bins vs. local time for the two sites. The U-shape of the upper curves shows the influence of airmass on the data. The lower curves have been corrected for airmass using the plane parallel atmosphere approximation. The blue, green, red and black curves represent the 450, 530, 890 and 940nm passbands respectively.](image-url)
The 890nm data at MLSO are consistent with the analysis of sky brightness in the Mk4 coronameter data (Elmore, 2007) which showed that the sky brightness at Mauna Loa was ~0.5×10^6 per airmass at 775nm during the years 2004 to 2006.

Table 1 summarizes the results for the two sites and shows the mean and median sky brightness computed over the day. There is not much difference between the mean and median values at each site. In the blue, Mauna Loa shows only slightly lower sky brightness, but that difference increases with wavelength.

The conclusion of this analysis is that both sites show excellent sky conditions, especially in the near-IR. They both meet the COSMO requirement. MLSO has darker skies.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Haleakala (median)</th>
<th>Haleakala (mean)</th>
<th>Mauna Loa (median)</th>
<th>Mauna Loa (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>3.72</td>
<td>3.67</td>
<td>3.21</td>
<td>3.25</td>
</tr>
<tr>
<td>530</td>
<td>3.06</td>
<td>2.97</td>
<td>2.39</td>
<td>2.45</td>
</tr>
<tr>
<td>890</td>
<td>1.23</td>
<td>1.19</td>
<td>0.74</td>
<td>0.80</td>
</tr>
<tr>
<td>940</td>
<td>1.08</td>
<td>1.02</td>
<td>0.55</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 1. Mean and median sky brightness per airmass in ppm throughout the day at the two sites.

### 4.2 Aerosol Content

Aerosols can be categorized into two broad constituents. First, there are the microscopic particles of soot and other air-borne particles that are too small to resolve in the telescope but cause an increase in the level of sky brightness. The second category is large particles that are resolved by the coronagraph including flying insects and floating organic materials (air-borne seeds, pollen, etc.).

Large aerosols are especially problematic for several reasons. They are very bright when viewed near the sun, so they can significantly increase the photon noise where they are present. Also, they move around in the FOV on timescales that are short compared to the polarization modulation time. This causes intensity to polarization crosstalk that can severely compromise the polarization measurements. In addition, they are a source of particles that can compromise the cleanliness of the coronagraph objective lens.

The sky scattering varies with wavelength as $\lambda^{-\gamma}$. Pure Rayleigh scattering is caused by air molecules or particles smaller than 0.002µm and results in a $\gamma$ of 4. Lower values of $\gamma$ indicate the presence of larger particles, since Mie scattering is almost independent of wavelength.

The SBM data, discussed in Section 4.1, was used to determine the exponent of the wavelength dependence of the sky brightness. Figure 10 shows the median values in half-hour bins of the fitted exponent, $\gamma$, throughout the day for the two sites. It shows that MLSO has a significantly higher $\gamma$ for most of the day. This indicates that there are fewer aerosols at MLSO than at Haleakala. The range of the wavelength exponent observed at Haleakala in this study is roughly consistent with the value of 1.5 obtained in the study of Penn, Lin and Schmidt (2004) and the value of 1.88 obtained from the DKIST site survey (Hill et al., 2004). The mean and median values for the two sites are summarized in Table 2.

The higher exponent for MLSO explains the result in Section 4.1 that the sky brightness difference with Haleakala increases at higher wavelengths. That MLSO has lower aerosol content is probably related to the fact that MLSO sits on a 1832 lava flow and there is virtually no vegetation and associated pollen or bugs in the vicinity of the observatory. The lower values of the exponent at MLSO later in the day are consistent with aerosols being carried to the observatory by the upslope conditions. The level of vegetation and degree of human activity is greater at Haleakala. This result is also consistent with the airborne particle measurements conducted at both sites which are discussed in Section 5.1.
Figure 8 - Exponent of the wavelength dependence of the sky brightness. The plotted values are median values in half-hour bins.

<table>
<thead>
<tr>
<th></th>
<th>Haleakala (median)</th>
<th>Haleakala (mean)</th>
<th>Mauna Loa (median)</th>
<th>Mauna Loa (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponent</td>
<td>1.63</td>
<td>1.55</td>
<td>2.11</td>
<td>2.26</td>
</tr>
</tbody>
</table>

Table 2. Mean and median values of the exponent over the day for the two sites.

### 4.3 CLEAR TIME FRACTION

Cloud cover has a direct impact on the number of hours the Sun can be observed and therefore affects all aspects of COSMO’s scientific mission. To evaluate the average cloud coverage at each site we reference the excellent site survey conducted by the Global Oscillation Network Group (GONG) project (Hill et al., 1994) which included both Haleakala and Mauna Loa. In this long-term comprehensive survey, an Eppley Laboratories normal incidence pyrheliometer with a ~5.7 degree FOV was deployed on clock-driven equatorial mounts. Table 3 below shows a summary of that report for Haleakala and MLSO:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Haleakala</th>
<th>Mauna Loa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey start date</td>
<td>7/12/1985</td>
<td>25/5/1989</td>
</tr>
<tr>
<td>Survey end date</td>
<td>18/12/1991</td>
<td>16/9/1993</td>
</tr>
<tr>
<td>Days in data set</td>
<td>2203</td>
<td>1576</td>
</tr>
<tr>
<td>Fraction of clear time for entire period (&quot;Ca&quot;)</td>
<td>55.65</td>
<td>58.07</td>
</tr>
<tr>
<td>Fraction of clear time after removal of instrumental downtime (&quot;Cw&quot;)</td>
<td>64.43</td>
<td>64.98</td>
</tr>
<tr>
<td>Fitted intercept of site transparency power spectrum</td>
<td>-9.33</td>
<td>-9.74</td>
</tr>
<tr>
<td>Fitted slope of site transparency power spectrum</td>
<td>-1.34</td>
<td>-1.52</td>
</tr>
<tr>
<td>Average extinction coefficients</td>
<td>0.0943</td>
<td>0.0930</td>
</tr>
<tr>
<td>Standard deviation in extinction coefficients</td>
<td>0.0158</td>
<td>0.0263</td>
</tr>
</tbody>
</table>

Table 3 - Summary of GONG site survey data from Hill et al., 1994.
As can be seen, both sites are very similar with only about 0.5% difference in clear time fraction after correction for instrument down time. A review of these data indicates that both sites would be acceptable for the observatory.

4.3.1 Shadowing from the DKIST

The DKIST is a very large telescope in close proximity to the Mees observatory. Not taken into account in the GONG survey is time lost due to shadowing of the Mees site by the DKIST dome. To estimate this, we performed an approximate calculation. It models the DKIST as a rectangle that has its southernmost edge 15.9 degrees of due east in azimuth from the southernmost edge of the current Mees dome (see Figure 5) and that the DKIST is 49m tall. Figure 9 shows a calculation of the resulting hours lost to shadowing. The total time lost during the year would be about 67 hours. There are additional concerns about degraded seeing while the Sun is above the DKIST and possible glint from the DKIST dome. These are difficult to assess. The penalty from shadowing on clear time fraction at the Mees site is a few percent.

Figure 9 - Hours lost to DKIST shadowing of Mees Observatory.

4.4 Seeing

The spatial resolution requirement on the Large Coronagraph is 2 arcsec at 1074nm along the solar limb during median seeing conditions through less than 4 airmasses. The achieved spatial resolution of the LC will be limited by both the telescope/instrument optical design and the ambient seeing conditions at the facility’s location. The two of these components when added in quadrature must meet the 2 arcsec requirement.

The current optical design (see COSMOLC-DE-7002 Optical Design Description) achieves a nominal design of ~0.3" during a full scan of the 1083 spectral line (1082.4nm – 1083.6nm). This line was analyzed for convenience as it represents the long edge of the spectral bandpass of the Large Coronagraph and Filtergraph system. The results will be similar at 1074nm, where our requirement is specified. However this ~0.3" nominal resolution ignores the expected degradation due to optical manufacturing imperfections as well as mechanical alignment errors. A full analysis of these effects is described in
COSMOLC–DE–7002 (Optical Design Description). Figure 10 shows the summary plot of spatial resolution at 1083 resulting from a Monte Carlo analysis. Using the 80% probability as our benchmark, we determine the telescope and instrumental performance is 1.1″. This derives a median atmospheric seeing requirement of 1.67″. As the atmospheric seeing is dependent upon height, this requirement can be used to determine the required height to which the observatory must be constructed. This will directly affect the cost of the observatory.

![Performance Probability Analysis](image)

**Figure 10 - Expected instrumental spatial resolution of the Large Coronograph and Filtergraph optical design**

High-order adaptive optics (AO) only functions over very small fields of view, and therefore such systems are inappropriate for the Large Coronograph (which has a large 1° FOV). Although active tip-tilt systems have been demonstrated to reduce the impact of seeing over large fields, these systems are currently not planned.

4.4.1 An Introduction to $C_N^2(h)$:

In the theory of turbulent seeing, the atmosphere is described as a layered structure where the effects of turbulence on telescope seeing are described by a refractive index structure parameter $C_N^2(h)$, where $h$ is the height above ground. The Fried parameter ($r_o$), which describes the size of the isoplanatic patch, is related to $C_N^2(h)$ by:

$$
r_o(H) = \left( 16.7 \lambda^2 \int_H^\infty C_N^2(h) dh \right)^{\frac{3}{5}} \quad [1]
$$

The Fried parameter ranges from ~1 to 20cm scales at typical observatory locations. When the Fried parameter is small compared to the aperture of the telescope, the seeing is given by $\varepsilon_{\text{fwhm}} = 0.98 \lambda / r_o$ (radians). Combined with equation [1], we get:
\[ \varepsilon_{\text{fwhm}}(H) = 5.25 \lambda^{-1/5} \left( \int_{H}^{\infty} C_N^2(h) \, dh \right)^{3/5} \]  

Near the surface, \( C_N^2(h) \) is expected to decrease with height as a \( h^{-4/3} \) (Wyngaard, 1971). Then from Eq. 2 we would expect that the seeing will improve only as \( H^{-1/5} \). This very weak dependence of the seeing with height means that raising the height of the telescope to improve the seeing will be a costly proposition.

### 4.4.2 Seeing at Haleakala

The information presented here about seeing at Haleakala is taken from the DKIST site survey, with our gratitude. The DKIST survey used several methods to estimate the seeing: sonic anemometers, SHABAR arrays, and SDIMM instruments. For the purposes of this site evaluation, we will concentrate on the SHABAR data.

Figure 11 shows the height variation of \( C_N^2 \) measured at Haleakala using the SHABAR instrument (from the ATST ‘Haleakala Turbulence and Wind Profiles used for Adaptive Optics Performance Modeling’ RPT-0030). Also plotted in Figure 12 is the expected \( h^{-4/3} \) dependence. The figure shows that over the range of interest for the COSMO telescope \( C_N^2(h) \) drops off as \( h^{-4/3} \) or slower.

![Figure 11 - Values of \( C_N^2 \) measured at Haleakala using a SHABAR instrument, from the DKIST site survey.](image)

This weak dependence of seeing on height above the ground is further documented in Figure 12 taken from the DKIST Site Survey Report (Hill et al., 2004). It shows \( r_o \) vs. height for three sites including Haleakala. Note that the difference between the mean and the median seeing is significant. The implied skew in the distribution makes direct comparison of the two sites more difficult.

Additionally, from approximately April to September, the sun will rise above the DKIST structure as viewed from the Mees Observatory location. The heat radiating off of the dome could degrade the seeing.
4.4.3 Seeing at Mauna Loa

The DKIST site survey did not include Mauna Loa, and therefore we constructed a SHABAR array and deployed it at MLSO in December of 2012. The details of this deployment and analysis can be found in Tomczyk (2013). The Mauna Loa SHABAR was of a completely different design than the Haleakala one. The analysis for the Mauna Loa data was an independent implementation of the analysis described in Hill et al. (2004) and Hill, Radick and Collados (2003). The differences between the instruments and analysis warrant caution when comparing the results from Haleakala and Mauna Loa presented here.

The Mauna Loa results are based on two years of data taken with the Mauna Loa SHABAR instrument between December 11, 2012 and Nov 11, 2014. The variation of $r_o$ vs. height for Mauna Loa is shown in Figure 13. The mean and median values are very consistent and fall somewhere between the mean and median values for Haleakala shown in the red curves of Figure 12. The median and mean seeing results vs. height for Mauna Loa are shown in Figure 14 for wavelengths of 530, 656 and 1083nm.
Figure 14 - Height dependence of the median and mean seeing at MLSO. Blue, green, and red correspond to wavelengths of 530, 656, and 1083nm respectively.

Figure 15 - Height dependence of the median seeing at MLSO at 1083nm. The required seeing of 1.67" is denoted by the dashed line. This will be met at a height of 13.4m above the ground.

Figure 15 shows the median seeing at Mauna Loa at 1083nm. The figure shows that the COSMO LC requirement can be met if the entrance aperture of the telescope is at a height of 13.4m above the ground.

Similar to Haleakala, the seeing at Mauna Loa is only a weak function of height. Raising the height of the COSMO telescope much above this height will result in diminishing returns. Caution should be exercised in comparing the measurements at Haleakala and Mauna Loa given the differences in instruments and analysis.
5 ENVIRONMENTAL CONDITIONS

Environmental conditions can have a great influence on an observatory. In addition to affecting the quality and quantity of observations it can also present engineering challenges. Systems must be designed to handle expected temperature ranges, precipitation amounts as well as ambient wind and seismic activities. The level of cleanliness is especially important for COSMO since dust is an important source of telescope scattered light.

5.1 CLEANLINESS

Cleanliness of the primary lens or mirror in an internally occulted coronagraph is extremely important because dust is often the dominant source of instrument scattered light. The DKIST report on the scattering from the primary mirror by Hubbard (2002) concluded that “Scattering due to dust contamination of the primary mirror would appear to be the most serious stray-light concern for coronagraphic observations. The accumulation of dust on the primary quickly overwhelms the effects of surface microroughness from the polishing process”. Also, the analysis by Nelson (2006) of scattering from the lens objective of the COSMO LC predicts that it will be dominated by scattering from dust contamination.

These predictions are supported by at least two observations. The first is the instrument scattering in the Mauna Loa Mk4 coronagraph, illustrated in Figure 16 (from Elmore, 2007). It shows that scattering from dust contamination increases with time at all heights in the corona, and is reset to low values by periodic washing of the objective lens. The effective wavelength is 775 nm. Note that the COSMO LC requirement is 5 ppm scattering at 1.1 \( R_{\text{sun}} \) at a wavelength of 1 micron. A similar result has been obtained with the Coronal Multi-channel Polarimeter (CoMP) instrument behind the OneShot coronagraph at Mauna Loa, shown in Figure 17. The CoMP measurements include the sky background and are taken at a height of 1.2 \( R_{\text{sun}} \). They show that the CoMP/OneShot meets the COSMO requirement, but only when the lens has been recently cleaned. Upward departures from the linear trends in Figure 17 are due to days when the sky brightness is high. Note that the dust on the surface of both the MkIV and CoMP objective lenses were/are blown off with compressed air on a daily basis. A similar record of coronagraph scattering from dust at Haleakala is not available.

Since scattering by dust and light collected both scale as the area of the lens, these results can be expected from the 1.5m objective lens of the COSMO LC with the same dust distribution.

Based on the empirical evidence one can expect that the Mauna Loa site is clean enough that the COSMO scattered light requirement can be met so long as the objective lens is kept in a pristine state of cleanliness. This has driven our approach to pressurize the COSMO LC dome with HEPA filtered air of sufficient pressure to prevent outside dust particles from entering through the aperture of the dome. Extreme care will need to be taken that human interaction with the telescope will not contaminate the environment inside the dome. The inside of the dome will need to be treated like a clean-room environment.
Figure 16 - Instrument scattering plus coronal contribution measured in the Mk4 coronagraph (from Elmore, 2007). The coronal heights are color coded. The effective wavelength is 775 nm. The drop in scattering is associated with washing the objective lens.

Figure 17 - Measured instrument and sky background from the CoMP instrument at a height of 1.2 R\textsubscript{sun} and a wavelength of 1074nm.
Despite the empirical evidence, particle measurements at both sites are important to compare the relative cleanliness of the two sites, and to inform our cleanliness strategy focused on maintaining a pristine state of cleanliness of the COSMO LC objective lens.

The measurements for our cleanliness study come from two sources. For Mauna Loa, the particle measurements were made with a Particle Measuring Systems model LasairII. They consist of 3000 measurements taken over a period of 45 days in 2012. Data were obtained for particle sizes of 0.3, 0.5, 1.0, 5.0, 10.0 and 25.0 microns. The cleanliness measurements are described in greater detail in COSMO Site Cleanliness Report (COSMO Technical Note #26, Tomczyk, 2015).

For Haleakala, the particle measurements were taken as part of the DKIST site survey. They were obtained with a Met One Model GT-321 and consist of 8106 measurements taken over the course of nearly two years, 2003 and 2004. The data were obtained at a cadence of 10 minutes and the particle bins were 0.3, 0.5, 1.0, 2.0 and 5.0 microns. The data were taken and stored along with the sky brightness data. These data were analyzed by the DKIST project and presented in the DKIST Site Survey report (Hill et al., 2004). The results for Haleakala presented here are from an independent analysis of the Haleakala particle data.

Figures 18 and 19 show the histograms of the particle measurements for the two sites for the various particle sizes. The median values found here for Haleakala are 20-30% higher than reported by DKIST. This is a good level of agreement given that there were two independent analyses of the data. Median values should probably not be used due to the large variation in actual particle counts. The data from Mauna Loa show significantly less particle counts than for Haleakala, especially for the larger particles. This is important, given that larger particles scatter much more strongly than smaller particles.

Figures 20 and 21 show the raw data (top) and the mean particle distributions (bottom) for the two sites. Power laws have been fit to the distributions and the resulting fits are shown on the plots. The particle distributions are very different for the two sites: the Haleakala distribution is flatter than for Mauna Loa, having an exponent close to -2 while the Mauna Loa exponent is approximately -3. Since the Haleakala measurements have been made for particles only up to 5 microns in size, the power law exponent is less well determined and should not be used to estimate particle densities for particles > 5 microns.

The airborne particle distribution is quantified in terms of Cleanliness Class or just Class. It is historically measured in units of particles per ft$^3$ for particles ≥ some diameter. The cleanliness standard is defined by Federal Standard 209E. The Cleanliness Class is defined as:

$$\frac{\text{# particles}}{\text{ft}^3} \geq 0.5 \text{ microns} = \text{Cleanliness Class} = N_c .$$

For example, a Class 10,000 cleanroom has 10,000 particles per ft$^3$ ≥ 0.5 microns. The measurements presented above indicate that the environment at Haleakala and Mauna Loa are extremely clean, corresponding approximately to Cleanliness Class 10,000 for Haleakala and 2500 for Mauna Loa. These are conditions normally associated with clean rooms.

That high quality coronal observations have been obtained at these sites over the years is directly related to the cleanliness of these sites.
Figure 18 - Histograms of the particle counts for Haleakala.
Figure 19 - Histograms of the particle counts for Mauna Loa.
Figure 20 - For Haleakala, Top: raw particle counts vs. time. Bottom: mean cumulative particle distribution.
Figure 21 - For Mauna Loa, Top: raw particle counts vs. time. Bottom: mean cumulative particle distribution.
5.2 Temperature

Currently the Large Coronagraph Facility is required to perform scientific observations between 0 and 20 degrees Celsius. At Mauna Loa, the data from 2012 (which includes nighttime data) shows that 99% of the measured time falls in this range. The survival temperature range extends down to -10°C, and no data was recorded beyond this range. These data are shown in Figure 22.

Figure 22 - Distribution of temperature in 2012 at Mauna Loa. Data is compiled from the Earth System Research Laboratory, NOAA using data from 2012.
At Haleakala, data from the Western Regional Climate Center, shows that on average 1.2 days per year fell below 0°C between 1949 to 2006, and never below -10°C. Additionally, the average temperature, even in the winter is a reasonable >10°C. Figure 23 shows the monthly average temperature from 1957 – 2015. Neither location has temperature expectations that impact the LC Facility.

![Average Monthly Temperature data for Haleakala](image)

**5.3 Precipitation**

Figure 24 shows the hourly accumulations of precipitation at Mauna Loa in 2012. The total precipitation of 149mm in 2012 is negligible. Low amounts of precipitation is strongly beneficial for maximizing observing time.

Using data from the Western Regional Climate Center, Figure 25 shows the monthly average precipitation on Haleakala. This is significantly greater than at Mauna Loa, however it is still low enough to not greatly impact observing time. On average 80% of days in a year saw less than 2.5mm of rain.
The maximum (hourly averaged) wind speed recorded at Mauna Loa in 2012 was 17.5 m/s with an average velocity of 5.1 m/s in 2012. Figure 26 shows the distribution of wind velocities as measured in 2012. Our observatory HEPA system is currently specified to prevent any wind from entering the observatory that has a velocity < 10 m/s. This data shows that 90% of the time the wind speed is under this threshold.
Other data has shown this to be as high as 95% of the time. Regardless, wind speed at Mauna Loa will not substantially impact observing time.

Using data presented in the DKIST site survey, at Haleakala the average wind speed is 4.5 m/s, with approximately 90% of measured data showing wind speeds below our 10 m/s threshold. Figure 27 shows wind data from DKIST RPT-0030 for good seeing conditions. Thus both locations have suitably low wind velocities.

![Figure 26 - Distribution of wind speeds in 2012 at Mauna Loa](image1)

![Figure 27 - Wind velocity distribution (number of occurrences versus wind speed in m/s) from the DKIST RPT-0030. This data only includes times with good seeing.](image2)
5.5 SEISMIC

Mauna Loa is an active volcano. The recent volcanic activity is actually beneficial as the lack of vegetation and its associated pollens, bugs and aerosols improves the cleanliness of the area (Section 5.1). The site is protected by a large chevron diversion that would re-direct small and moderate lava flows away from the site. This chevron would have to be altered and push outwards to accommodate the COSMO LC location. MLSO has been operating for approximately 5 decades at this location without major incident.

A study by DKIST (SPEC-0149) of expected seismic levels at Haleakala led them to design requirements for up to a 3g load. This study would have to be adapted for COSMO, but it provides a reasonable expectations baseline. This value, as well as the quantity and experience of other observatories on the site gives us confidence that seismic issues at Haleakala will not be a significant issue.

6 PERMITTING AND ENVIRONMENTAL STUDIES

6.1 PERMITTING

The legal process of obtaining construction and operation permits on the Hawaiian Islands can be challenging. In particular, the DKIST facility experienced numerous unexpected delays and costs during this process. Streamlining this process for schedule and cost concerns is of high priority for the COSMO LC.

To achieve this goal, conversations were initiated with the National Oceanic and Atmospheric Administration (NOAA) who currently use a parcel of land on Mauna Loa that is owned by the federal government. HAO currently owns and has operated an observatory on this land parcel known as the Mauna Loa Solar Observatory for the past 50 years. Due to this history, HAO has a long-lived positive relationship with NOAA. As this land is federally owned, the permitting process is substantially reduced.

6.2 MATERIAL USABILITY

One challenge for construction on Mauna Loa is the need to avoid any materials that would influence NOAA’s atmospheric monitoring activities. To ensure this, NOAA has published a list of banned construction materials (GMD Banned Construction Materials List_Jan2014). HAO has constructed a previous observatory (MLSO) at the site, and has not been negatively impacted by these restrictions.

6.3 ENVIRONMENTAL IMPACT

Legal requirements to perform an Environmental Assessment (EA) or a more detailed Environmental Impact Statement (EIS) can be a scheduling and cost challenge for a new observatory. At the Mauna Loa site, the NOAA NEPA officer has determined that as the square footage of the LC facility is <5000 sq. ft. the COSMO LC would qualify for a categorical exclusion from doing an EA or EIS according to the National Environmental Policy Act (NEPA). This step was particularly costly and time consuming for the DKIST project on Haleakala and therefore represents a strong incentive to use the Mauna Loa site. Additionally, NOAA has previously performed an Environmental Assessment at Mauna Loa and determined no adverse impacts would be caused by a similar project. This assessment (Environmental Assessment of MLO.pdf), while unnecessary for COSMO, is still reassuring.

The COSMO project will try to minimize the visual impact of the COSMO observatory.

6.4 GEOTECHNICAL STUDIES

As part of any construction effort, a geotechnical study should be undertaken to analyze any geologic impacts on construction. This could include necessary construction tasks to prepare the site or fortify it for potential seismic events. A geotechnical study was undertaken by NOAA at a nearby location on their same land parcel. This study will prove a valuable reference to construction efforts on Mauna Loa. This report can be found in Mauna Loa Geotechnical Report.pdf. As Haleakala is the home of other astronomical instruments, it is likely similar studies have been performed there.
7 ACCESS AND INFRASTRUCTURE

7.1 ROAD ACCESS

The Mauna Loa site would require the construction of a short access road to the observatory. The main road can be seen in the very top left corner of Figure 3. The access road would be constructed from this road to the LC Facility. The Haleakala site would likely not require additional road construction.

7.2 DATA COMMUNICATION

The current data transfer capacity will be insufficient at Mauna Loa and will need to be upgraded. This would require the installation of additional data lines from Mauna Loa to Hilo.

7.3 MLSO

HAO currently operates MLSO at the Mauna Loa site which houses two of the main instruments (ChroMag and K-cor) of the suite of COSMO instruments. Building the Large Coronagraph at another location would possibly cause the eventual relocation of MLSO to the LC to avoid duplication of staffing, data servers, etc. This would cause significant disruption of scientific progress with ChroMag and K-cor. This move would also be an additional cost. Additionally, our observatory staff at MLSO will likely prove valuable during the LC construction effort. Their knowledge of the area, expertise in operating astronomical instruments, and convenient location would prove valuable during the construction effort.

8 SUMMARY

Both Haleakala and Mauna Loa are excellent sites for coronal observations and both are acceptable as sites for the COSMO LC. Each site has strengths and weaknesses. These are summarized in Table 4 which shows the evaluation metrics for the COSMO site.

Overall the Mauna Loa site has a small advantage in sky brightness, aerosol content, cleanliness and clear sky fraction. These alone are not sufficient to determine the location of the COSMO.

A strong motivation for Haleakala is the superior infrastructure (roads, data lines, possible collaborating observatories, etc.). The popularity of the Haleakala site has resulted in limited space available for development. The COSMO LC facility would need to be constructed at the Mees Observatory site, and the spar facility housing the K-Cor and ChroMag would need to be located at the ZLO site or other suitable place. The Mees site will undergo shadowing by the DKIST at certain times of year and the proximity of the DKIST may also degrade the seeing. The recent history with the DKIST construction highlights the difficult permitting process associated with the Haleakala site.

Mauna Loa has poorer infrastructure but simplified permitting owing to the status of the NOAA parcel as federal land. The volcanic activity on Mauna Loa is the most concerning aspect of constructing at that site, but has been mitigated by the construction of a diversion berm above the site.

Considering all these factors, we rank Mauna Loa as the preferred site for the location of the COSMO facility.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mauna Loa</th>
<th>Haleakala</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky Brightness</td>
<td>~0.9ppm at 940nm</td>
<td>~1.4ppm at 940nm</td>
</tr>
<tr>
<td>Aerosols</td>
<td>$\gamma \sim 2.3$ (fewer airborne particles)</td>
<td>$\gamma \sim 1.6$</td>
</tr>
<tr>
<td>Seeing</td>
<td>1.67″ at 15m height</td>
<td>Mean seeing is acceptable, but median seeing is not. Difficult to compare with data from Mauna Loa.</td>
</tr>
<tr>
<td>Observing Time</td>
<td>65.0%</td>
<td>64.4%</td>
</tr>
<tr>
<td>Hours lost to shadow</td>
<td>0</td>
<td>67</td>
</tr>
<tr>
<td>Cleanliness</td>
<td>Class 2500 equivalent</td>
<td>Class 10,000 equivalent</td>
</tr>
<tr>
<td>General Environmental Conditions</td>
<td>Benign temperatures, wind, etc.</td>
<td>Benign temperatures, wind, etc.</td>
</tr>
<tr>
<td>Volcanic Activity</td>
<td>Higher risk of seismic events and magma producing eruptions.</td>
<td>Some seismic events possible, but risk is much smaller</td>
</tr>
<tr>
<td>Permitting</td>
<td>Expedited process through NOAA. Some restrictions on materials.</td>
<td>Historically difficult and costly</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Requires upgrade to data lines. However no need to relocate operating COSMO instruments (ChroMag and K-Cor)</td>
<td>More developed.</td>
</tr>
<tr>
<td>Available Building Space</td>
<td>Space is available</td>
<td>Limited to ZLO And Mees existing footprints</td>
</tr>
</tbody>
</table>

*Table 4 - Summary of evaluation metrics for site selection. Green boxes represent significant advantages*