Trade Study Summary for Reflecting vs Refracting
Primary Objectives for the COSMO Large Coronagraph

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Abstract:
This trade study presents a summary of several COSMO Technical Notes in an effort to evaluate the relative performance of reflecting vs refracting coronagraphs. Both large aperture and very low instrumental scattered light are required to measure Gauss-level line-of-sight integrated magnetic fields with scientifically interesting spatial and temporal resolutions. For example, a 1.5m telescope observing with a few arc second spatial resolution and a 10-minute cadence would require the background light to be approximately 5ppm of the disk-center brightness. Traditional coronagraphs use refracting objectives up to half a meter in diameter, yet all modern large-aperture telescopes are reflectors. The requirement for a very low level of scattered light, however, strongly favors a large refracting singlet. Our investigations have concluded that a 1.5m refracting coronagraph is feasible with modern glasses and technology.

1) Introduction:
This report compares the relative merits of reflecting and refracting designs for a meter-class, internally-occulted coronagraph. We summarize the optical design developed for each. The apertures are assumed to be 1.5m. Both telescopes are designed with a 1-degree full field-of-view (FOV) as a requirement to fulfill COSMO’s synoptic mission. Since f/number is a significant cost driver, it was separately minimized in each design. f/5 was found to be optimal for a refractor, but reflectors could go as low as f/3. We analyzed both f/3 and f/5 reflectors. The baseline designs are given below.

1.1) Refracting Telescope:
Figure 1 below shows the configuration for the refracting design. The primary lens is a 1500mm diameter x 150mm thick un-coated singlet made from Corning standard-grade HPFS 7980 fused silica. The front surface is roughly six times the curvature of the rear
surface and has an aspherical component approximately 120λ in amplitude. The figure was optimized for 1075nm light (Fe XIII) for best image quality at the limb of the sun. The image quality (spot size) was analyzed for f/ ratios ranging from 3 to 8. Figure 2 plots the RMS and geometric spot size at prime focus for the solar limb as calculated by ZEMAX relative to the Airy disk diameter. It shows there is a sharp knee between f/4 and f/5 where the spot quality starts to degrade rapidly. At f/5, the RMS spot size equals the Airy diameter, though the Strehl ratio is only 0.45. A low Strehl ratio is not a problem since the geometric radius of the spot size is still much less than an arc second. Figure 3 shows the spot diagrams at the solar limb for both 1.075 and 1.43 µm. The 1.43µm spot required re-focusing the telescope by 69mm. The dispersion data for HPFS 7980 were provided by Corning. Chromatic aberration is discussed further in a later section.

A extensive Finite Element Analysis (FEA) study was conducted and is available as COSMO Technical Note². That study looked for degradation in image quality due to gravity and vacuum loading as well as stress-induced birefringence. The study found that a lens with a 10:1 aspect ratio and f/7 could support a vacuum load without degrading image quality. An f/5 lens, however, is thinner at the edges and will not support a vacuum without significant loss in image quality. Under its own 422kg weight, an f/5 lens deflects by approximately 5 microns at its center, increasing the spot diagram diameter by about 40%.³ For the anticipated 1-2 arc second spatial resolution of COSMO, this is not an issue.
The Swedish Vacuum Telescope (SVT)\textsuperscript{4} and the Large Earth-based Solar Telescope (LEST)\textsuperscript{5,33} both conducted extensive studies of thermal loading and stress in large fused silica windows, and found both could be reasonably controlled.

1.2) Reflecting Telescope:

The choice of f/number for the reflecting design is not simple, and both f/5 and f/3 are considered. f/3 was found to be the lowest reasonable f/ number when considering scattered light (described below). f/3 has a 20\% size advantage over f/5 but produces a very hot image at the occulter (1250x normal solar flux). This increases the potential for seeing from a hot occulter. An f/3 telescope would also have greater polarization cross-talk. Figure 4 shows our f/3 design. An un-obsured off-axis design is used to prevent diffraction from introducing stray light into the coronal FOV. A second off-axis parabola eliminates aberration introduced at the primary (Figure 5). The off-axis angle is limited by the requirement that the occulter at prime focus doesn’t vignette the folded beam. The size and location of the secondary is fixed only by practical considerations;

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{The f/3 reflecting telescope configuration.}
\end{figure}

a longer focal length would require a longer telescope tube and larger optics, whereas a shorter focal length would require a greater off-axis pointing angle from the primary to prevent vignetting. No comparison in the trade study was a strong function of the secondary focal length, so this parameter space was not explored in detail. Note the secondary optics are quite large themselves; the secondary and re-imaging optics (shown
as a simple ZEMAX ‘paraxial’ lens) are both 60cm in diameter for both f/3 and f/5 designs.

To avoid vignetting the coronal FOV, the solar image must be under-occulted at prime focus by an amount equal to the radius of the coma. Occulting is completed at a second occulting disk (not shown) in an image plane where coma has been fully corrected by the secondary. Under-occulting at the prime focus allows disk-intensity light to fall on the secondary. At f/3 approximately 8% of the disk light reaches the secondary, which limits the increase in the total scattered light to that amount (assuming equally cleaned mirrors). Figure 5 below shows the spot diagrams for the reflector at prime focus, and after correction by the secondary:

![Spot Diagrams](image)

Figure 5: The spot diagrams for a reflector at prime focus (a) and after correction by secondary (b). The circles represent the Airy disks (seen as a small point in the center of a)). The left square is 40 arc seconds on a side. The right square is 1 arc second on a side and shows near-perfect correction by the secondary. The image is at the solar limb.

1.3) Common issues:
If a 4096x4096 mosaic camera were used, the pixel size would be 0.88 arc seconds and the spatial resolution for both designs would be camera-limited. The f/5 designs will have approximately 2100 Watts on the occulter (55W/cm²), and an f/3 reflector would have 153W/cm². The occultor will have to be actively cooled, obscuring a portion of the FOV. Longer f/ ratios will reduce the fractional area obscured by the cooling plumbing. Residual temperature gradients will cause ‘telescope seeing.’ The tube in the refractor can be sealed and filled with helium. This has been shown to reduce telescope seeing to nearly vacuum telescope performance and is used in telescopes such as THEMIS and SOLIS. “Active occulting” (active control of the occultor radius and/or position) may be required to reach the lower corona. Such mechanisms favor longer focal ratios which provides more space at prime focus (due to larger a solar image).

2) Scattered Light:
The most critical issue in a coronagraph is the level of instrumental scattered light. COSMO Technical Note No.4 presents an extensive analysis of this complex topic. Technical Note No. 1 (1) demonstrates that high levels of scattered light dramatically impact the ability to make B-field measurements in the corona and this is difficult to overcome by increasing telescope aperture. Scattered light is primarily generated by the main objective (and the secondary in the case of a reflector), which are the only optical
elements in the telescope which receive disk-intensity light. In a reflecting telescope, scattering comes from microroughness of the mirror substrate, imperfections in the coating, and dust (contamination) of the mirror. Refractors have microroughness from two surfaces, contamination, inclusions in the glass, Rayleigh scattering, index inhomogeneities, and ‘striae’. A summary of each issue, in approximate order of importance, is given below:

2.1) Dust Contamination:

Figure 6 below shows the total scattered light (instrument + sky) in the Mk4 coronagraph at the Mauna Loa Solar Observatory (MLSO) for a time period of approximately 2 years. The different symbols represent elevations in the corona from 1.15 to 2.5 $R_\odot$ from disk center. The large drops in the intensity indicate dates where the objective was removed from the telescope and thoroughly cleaned. The cleaning at the beginning of 2006 was the best in this period, with the resulting scattered light at 1.15 $R_\odot$ of only 7ppm (2.5ppm at 2.5 $R_\odot$). All of these data are measured at 775nm.

![Figure 6: Scattered light from MLSO's Mk4 coronagraph](image)

It is important to note that scattering calculations are independent of telescope aperture; if one could obtain a lens of equal polish quality and levels of inclusions in a larger diameter, it is realistic to expect the same performance shown above (at the same site, etc.).

Figure 6 directly demonstrates that dust contamination is the dominant source of scattered light in the Mk4. After the 2006 cleaning, the scatter at 1.15 $R_\odot$ was 7ppm, and the scatter at 2.5 $R_\odot$ was 2.5ppm. As Figure 9 will show, the scattering from microroughness would drop by at least an order of magnitude over this range. The factor of ~3 observed is consistent with scattering from dust. It is important to note that the Mk4 is located on Mauna Loa, HI on a 1935 lava flow. There is no vegetation or loose soil in the area of the observatory, making it one of the cleanest sites in the world. The Mk4 lens is more
than 25 years old, is continually flushed with HEPA-filtered air, and is blown off with an
air gun every morning to remove larger pieces of detritus. With daily air dusting, the rate
of scatter increases by approximately 19ppm/year. If we assume the scattering is due to
dust, Mie theory predicts a factor of ~2 lower scattering for 1075nm.

Haosheng Lin has suggested using the variation in air mass over the day as a way of
calculating the scattering due to the atmosphere only. On a good day MLSO sees a sky-
only brightness of approximately 0.5ppm/(noon-equivalent air mass) at 775nm and 1.15
R₆. This will be lower at 1075nm due to wavelength scaling. The K-corona has a
brightness of approximately 1ppm at 1.15 R₆ and drops off rapidly with height.

2.1.1) Modeling Dust:
Dust is typically modeled as dielectric spheres, the scattering from which can be
calculated using Mie scattering theory. As Figure 7 below shows, the forward-scattering
peak (due to diffraction around the particles) grows in height as the 4th power of the
diameter. Since the highest angle of interest in scattering for a coronagraph with a 1º
FOV is 0.75º, this forward peak dominates the scattering. As a result, the largest particles
are by far the most significant. Rayleigh scattering only applies for particles much
smaller than the wavelength and does not apply here.

![Figure 7: Scattering by particles on a lens as calculated by Mie theory (courtesy of Thomas Germer, NIST Optical Technology Division).](image)

Figure 7 shows the Differential Scattering Cross-section (DSC), which is the scattered
power per steradian per incident light intensity for individual particles. To calculate the
scattering in a telescope, we need the Bi-directional Scattering Distribution Function
(BSDF). The BSDF is the power scattered per steradian per incident power. The DSC
can be converted into a BSDF if there is a distribution model for the number of particles
per unit area on the objective. The ‘standard’ distribution is the MIL-STD 1246C:

\[
N(D) = 10^{0.926 \left[(\log_{10} D) - (\log_{10} \mu m)^2\right] - 10.968} \mu m^{-2} \tag{1}
\]
For a given cleanliness class ($X_c$), the quantity $N(D)$ describes the total number of particles of diameter ($D$) and larger. The minimum diameter of particle in the 1246C standard is defined at $1\mu$m, and the largest diameter is equal to the cleanliness class in $\mu$m (in a $X_c=200$ distribution, the largest particle present is $200\mu$m). This size distribution can be combined with measured accumulation rates to predict scatter as a function of time. The data in Figure 6 can be fit fairly well assuming a 0.000072%/hour accumulation rate, an 0.001 initial fractional coverage, and an air dusting which removes all particles $20\mu$m and higher. It is unknown how air dusting actually affects the distribution, or what level of cleanliness is obtained with Mk4’s periodic cleanings. These data can be fit with different accumulation rates depending on these assumptions.

The Modeled Integrated Scattering Tool (MIST)$^{13}$ can calculate the expected BSDFs for the telescope given the particle distribution. The BSDFs can be numerically integrated over the solar disk (including limb darkening) to predict the level of scattered light in the coronal FOV. In the lens calculation, the surface inside the tube is assumed to be cleaned to the 0.0001 coverage level, and only the outside surface accumulates dust. The mirror calculation assumes a “double-interaction” model where the effects of the particles’ mirror image is considered. Those results are shown below.

The lowest curve in Figure 8 is shown only for reference; it matches the measured rate of increase seen in the Mk4 data with the assumed rates and initial coverage plus an air dusting which removes all particles $20\mu$m and higher. Note that dusting (in this model) reduces the scattering by more than a factor of 10.

We could not find long-term air cleaning data for reflectors. Since aluminum coatings are conductive and softer than glass, it is not clear that air cleaning would scale similarly. The top two curves form the relevant comparison. They show that for equal contamination levels the mirror-based telescope produces approximately 4 times higher scattered light than a lens-based design. Since a mirror folds both forward and back
scattering into the ‘top’ 2π half-sphere, one might expect a factor of 2. The forward-scattering peak, however, is several hundred times brighter (at our low angles) than the back-scattering peak, so this simple argument doesn’t hold. The forward-scattering peak does scale like the particle area squared, so a particle plus its image could be expected to scatter 4 times more light, at least at low incident angles. Why this factor remains at near normal angles is wrapped up in the details of the coherent interference effects between the particle and its image. It is not an exact factor, and has weak dependence on the optical constants of the lens glass, the mirror material, its coating (AlO₂, for example), and the reflection and transmission coefficients of all of the above. MIST can use both Bobbert-Vlieger theory\textsuperscript{14} (an exact model limited to particles of comparable size to the wavelength) and perturbation theory for larger particles in calculating the DSCs and BSDFs. These agree within 10% at 1μm particle sizes.

The relative performance of a reflector to a refractor is almost completely insensitive to the nature of the real particle distribution; if the DSC for a single particle on a mirror produces 4 times higher scattering than the same particle on a lens, then by linear superposition any distribution of particles produces the same factor of 4 difference. Although real-world detritus are not perfect dielectric spheres, the scattering from real scatterers should scale the same way and these calculations should accurately predict the real relative performance of reflectors and refractors.

Calculating the actual absolute levels of scattering from dust is extremely difficult; contaminants differ from site to site, real size distributions and optical constants are unknown, and models can only approximate the actual shapes real-world dust at best.

2.1.2) Dust Control & Cleaning:
Placing the objective in a stream of HEPA-cleaned air has proven effective in the Mk4 coronagraph. As a result, we plan to refine this method for COSMO. For a reflecting design the entire optical path would be closed with only the entrance aperture open to the outside environment. HEPA-filtered air would wash over the mirror (to help control its temperature), and leave the telescope through the aperture. The volume of the air would be relatively large to ensure adequate velocity to prevent dust from entering the telescope through the aperture. The air would be temperature controlled to minimize seeing as the air leaves the telescope.

To implement this strategy for a refractor, a ‘snorkel’ must be put on the end of the telescope tube. For the outward flow to be uniform over the aperture, this snorkel should be 2-3 times the aperture diameter in length.\textsuperscript{15} We envision the snorkel as a tube which is extended through the dome slot, and thus prevents the need for a larger dome. The tube would probably contain air plenums and also hold the main lens cover on its end. The reflector clearly has an advantage in avoiding these mechanical complications.

Even with an air flushing system, it is likely that the objective will require regular cleaning. Refracting coronagraphs have proven durable under regular cleaning for decades. Careful procedures combined with the inherent hardness of glass make cleaning lenses safe.
The durability of reflective coatings under daily cleaning has not been evaluated in any reference we could find. Aluminum is soft, and removing particulate contamination inevitably degrades the coating’s quality. The mirror may require re-coating more often than equivalent celestial telescopes. The cleanability can be improved by using a hard overcoating. In such a case, silver should be considered as the mirror’s material as its higher reflectivity would reduce mirror heating and therefore seeing. Though overcoatings are more difficult to strip and re-coat, this may be feasible.

Unexpected weather, such as sudden rain storms or accidental exposure to condensation conditions will require close monitoring. Direct exposure to liquid water would demand cleaning the objective. It is unclear whether a mirror can be cleaned after such an exposure and meet our scattering requirements without re-coating.

2.2) Light scattering from microroughness
Before there was “super-polish”, there was “coronal-quality.” Ever since Lyot, the polish quality of a coronagraph’s objective lens has been understood as crucial. Once again, the reader is referred to COSMO Technical Note No.4 for a more detailed description of the issue. Only a brief summary is presented below:

![Graph](image.png)

**Figure 9:** Comparison of scattering due to 1nm RMS microroughness and class 200 & 300 MIL-STD1246C contamination (for a lens).

A BSDF for microroughness can be calculated in MIST for both reflecting and refracting surfaces. As before, this can be integrated over the solar disk to give the scattered light level in the coronal FOV. The result is a level of scattered light which rises steeply as one goes lower in the corona. By contrast, scattering from dust is almost flat over a coronagraph’s FOV. This is illustrated in Figure 9. As a consequence, microroughness could easily dominate scattering in the low corona. For reflectors the situation is much more serious. Reflectors produce 10 times more scattering than a lens for a given RMS
surface roughness, even after considering the scatter from both surfaces of a lens (See Figure 10 below). This means that the ratio of scattered light from microroughness to dust for a reflector is 2.5 times higher than for a refractor. Surface roughness could easily become a dominant source in reflectors even at 1.1R\(_0\).

![Scattered light brightness in corona for 1nm RMS](image)

**Figure 10: Comparison of scattered light for a mirror and lens with 1nm RMS finishes.**

The data in Figure 10 are calculated using a slope for the 2-D surface roughness power spectral density (PSD) of 2.3\(^{16,17,18,19}\) and scale factor to match the 1nm RMS specification over a spatial frequency band of 0.0005 to 100µm\(^{-1}\). The scaling factor and slope can be used with the MIST to calculate a BSDF. These data are integrated over the solar disk to obtain the level of scattered light in a telescope’s image plane for any height in the corona. From these data conclude that the Mk4 lens polish is probably a 1-2nm RMS lens or better.

There is some debate in the community about the likely PSD slope. Despite this, some simple conclusions can be made: As in the case of scattering from dust, where the factor of \(-4\) was independent of the distribution, the factor of 10 for microroughness is independent of the RMS roughness or PSD slope. Polishing a mirror to have a \(-3\) times lower RMS roughness would make a reflector equal to a refractor for this contribution. The extent to which polishing can help is limited, however, by the fact that coatings have a roughness which is independent of substrate quality, and their contribution may be on the order of 6ppm at 1.1R\(_0\). Coatings are discussed in the following section.

In a reflector with a 1nm RMS finish, we expect approximately 25ppm scattering at 1.1R\(_0\) from microroughness. Assuming the particulate contamination level shown in Figure 6 for Mk4, we would expect no better than about 30ppm at 1.15 R\(_0\). In this example, scattering from microroughness is comparable to dust in a reflector at 1.1 R\(_0\).
2.3) Mirror coatings (reflectors only):
Coatings always make the scattering worse. The most direct evidence of this is a simple comparison of the Total Integrated Scatter (TIS) from a surface with what is predicted from the measured roughness. TIS is measured by shining a laser beam at a surface and measuring the total amount of scattered light using an optically integrating “Koblentz sphere”. This sphere is actually a hemisphere which collects all the light scattered in the $2\pi$ half-sphere above a surface and directs it to a single detector. Two small holes in the sphere allow the probing laser beam to enter the sphere and the specularly-reflected beam to escape. This is an old and mature technology. Scattering theory predicts that:

$$TIS(\text{in reflection}) = \left( \frac{4\pi \sigma}{\lambda} \right)^2 \quad [2]$$

where $\sigma$ is the RMS roughness. Many authors\textsuperscript{20,21,22,23,24} have taken samples and measured their surface roughness using three or four different methods, including TIS. Almost all authors observe the same result: the RMS roughness derived from TIS is typically 2-3 times larger than from profilometers (optical profilers, AFMs, Talystep stylus measurements, etc.) Said another way, the scattered light is 4-9 times higher than what one would expect from PSD data of the surface. Other authors\textsuperscript{25,26,22} have examined this effect by measuring TIS using very small laser beams which are scanned across the mirror surface. What they observe is a ‘background’ level of scatter which is consistent with other RMS measurements, but large local peaks which dominate the total scatter. An example is shown in Figure 11.

![Figure 11: Position-resolved TIS measurement showing point defects\textsuperscript{26}.](image)

These defects appear to be unrelated to substrate flaws, but are rather a property of the coating itself.\textsuperscript{20} There is no way to predict the level of defects which one might expect in preparing a 1.5m telescope, since it certainly depends on the details of the coating procedure used. In any case, even a 50% increase in scatter is a serious problem. It cannot be assumed that a ‘standard procedure’ for coating the mirror will produce
adequate results, or that substrate microroughness will fully define the level of scattered light due to mirror quality.

2.4) Inclusions (refractors only):
Historically coronagraph lenses have been made as thin as possible. One of the main reasons for this is to reduce the total number of inclusions in the bulk of the glass. Inclusions are primarily trapped air bubbles, but may also include such things as pieces of metal (typically platinum from the walls of the melt tank) and solid impurities from the raw material. Like particulate contamination on the surface, inclusions scatter light. Unlike most common dust, some of the inclusions can be very large; air bubbles can be up to 1mm in diameter in some materials. Figure 12 below shows the scattered light contribution at 1.1 $R_0$ for a single inclusion vs inclusion diameter (calculated using MIST).

Note that these data are valid at almost all elevations as Figure 9 shows the scattering from particles is nearly flat across the entire FOV. If the goal is to have less than 1ppm total scattering from inclusions, the data in Figure 12 show that we could tolerate only ten inclusions of 2mm diameter in the 425kg of glass which make up the 1.5m lens. We can tolerate 100 inclusions of 0.3mm diameter, 1,000 inclusions of 0.1mm diameter, or 10,000 inclusions of 0.05mm diameter and so on.

Fortunately, the telecommunications industry has driven the development of high-purity fused silica. Corning manufactures standard-grade 7980 fused silica in 60” diameter by 8” thick boules as a standard process. Typically, smaller optics are harvested from this large blank. COSMO would simply use an entire standard boule. Corning has made many measurements of the inclusion levels in these boules and has quoted that an entire boule is likely to yield less than 20 inclusions ranging in size from 0.10mm - 0.25mm diameter.
Corning 7980 is not tank-melted, and thus does not contain metallic contaminants. It is made by a massive deposition process called “flame hydrolysis:” silicon tetrachloride gas is oxidized by reaction with water (H\textsubscript{2}O) in an oxyhydrogen flame and the resulting ‘soot’ is accumulated. All inclusions are gaseous, and typically round. At the levels quoted from Corning, inclusions are not expected to be an issue.

2.5) Rayleigh Scattering (refractors only):
An important loss factor for optical fibers is scattering from impurities. These have been reduced to such a low level in fused silica that the dominant loss is Rayleigh scattering. The level of scattering loss at IR wavelengths is ~0.3dB/km of glass! Though significant for optical fibers, this is incredibly low by historical standards. Extrapolating data measured\textsuperscript{27} at visible wavelengths to 1075nm, one can calculate that the scattered light contribution at 1.1 R\textsubscript{o} is on the order of 5x10\textsuperscript{-11}. Rayleigh scattering is not an issue.

2.6) Index variations (refractors only):
All glasses have inhomogeneities in their index. Corning has measured the index variations in their 7980 fused silica boules using a 24” Zygo interferometer at 633nm. The central region is the worst part of the boule, but is still under 3.3ppm in homogeneity. Except for a peak at the boule center, all of the variations are at low spatial wavelengths.\textsuperscript{28} These long-wavelength variations have been modeled as a gradient-index model in ZEMAX. A ray-tracing analysis shows the increase in spot size is still less than 1 arc-second. Most of this will probably be corrected by local polishing of the optic. To look at “scattering” due to this index variation, ZEMAX can perform a FFT analysis of the PSF which takes into account the coherent interference of the rays passing though the lens. As expected the PSF is broadened by the variations (as indicated by the ray-tracing analysis), but no significant increase in the wings of the PSF are observed. Thus, index variations are not expected to be an issue.

2.6.1) Striae (refractors only):
A special class of index variations are called striae shown in a ‘shadowgraph’ picture below.

![Figure 13: Striae in a standard optical glass like BK-7 (a sample which failed QC).](image)

Striae are typically formed by a combination of incomplete mixing of materials in a melt tank and convective currents which are then frozen when the melt cools. They usually have a sheet-like topology which causes large phase distortion when viewed edge-on, but almost none when viewed normally to the sheet. They are of particular concern because their spatial scale is a few mm to cm, which is exactly the spatial scale required to scatter
into the angles of interest for a coronagraph. The smaller the blank, the lower the level of striae, which is another reason coronagraph lenses of traditional glasses have been made as thin as possible.

Fortunately, high-purity fused silica is not made by mixing components in a melt tank, but is deposited in layers from an extremely pure single-source gas. The ‘deposition’ process also tends to make any layering perpendicular to the optical axis of the blank. Corning has represented to us that 7980 has “no striae”. They are not expected to be a problem with fused silica glass.

3) Polarimetry:
Telescope optics introduce cross-talk among the different Stokes parameters of the solar light. This is examined in detail in COSMO Technical Note No. 3(29) Polarization in refracting telescopes (I to V coupling) is up to 100 times lower than in reflecting telescopes, depending on mirror coatings and the levels of stress-induced birefringence in the lens. Despite this, many researchers have found these telescope signatures can be removed in calibration and by looking at several wavelengths in the line profile to a level which is adequate for COSMO’s science mission.30 Telescope polarization is not expected to be an issue for either design.

3.5) Stress-induced birefringence in a refracting objective:
Birefringence introduced though stress from external mechanical sources, or simply by the lens’s own weight, is perhaps more problematic than other polarization signatures in that it can be time-varying. This has been analyzed in COSMO Technical Note No. 2.(2) The level of stress-induced polarization was found to be very small relative to other sources. In addition, time-varying signatures can be modeled and subtracted from data. This is common in telescopes with double-mirror turrets (such as the Dunn Solar Telescope (DST) and the SVT). Stress-induced birefringence is thus not expected to be an issue.

4) Wavelength Coverage & chromatic aberration:
Reflecting telescopes have no chromatic aberration and have excellent wavelength coverage. A simple singlet refractor has neither of these properties, and the chromatic aberration is particularly bad in a low-f/number telescope. Like coma from a reflecting primary, chromatic aberration in a refractor can be corrected by a secondary optic. This has been successfully done in many solar telescopes, such as the Evans Coronagraph, the Mk4, and the SVT.31 Correcting chromatic aberration is not always required. 1075 and 1083 nm could be simultaneously observed without a corrector or refocusing and still maintain a 4 arc second RMS spot size. Narrow-band measurements (with a spectrograph or Lyot filter) only require a minor re-focusing of the telescope to regain normal image quality. The aberration will cause full-intensity blue light to spill around the occulter, and one has to take care to reject this intense out-of-band light. This is present in most internally-occulted refracting coronagraphs (like the Mk4) and is routinely controlled. The benefit of this spilled light is that it can be used for guiding. If there is a requirement for simultaneous measurement of many wavelengths with optimal resolution, then a chromatic corrector can be added.
Wavelength coverage is also affected by absorption in a refractor’s fused silica primary. Unlike chromatic aberration, this cannot be corrected. The Science Advisory Committee met and discussed which coronal emission lines are critical to COSMO’s science goals. Three lines are considered essential: the Fe XIII lines at 1074.5 and 1079.8 nm and the He line at 1083.0nm. An additional goal would be the Si X line at 1.43µm. Corning’s standard-grade 7980 fused silica contains OH ions which have broad absorption bands, particularly in the IR part of the spectrum. These have been accurately measured, and the transmission for 1074.5, 1079.8, and 1083.0nm is between 99.8 and 99.9% per cm. The transmission for 1.43µm is slightly worse at about 98.5% per cm. With an average lens thickness of 10.8cm, the net transmission for 1.43µm is 85% or about 8% equivalent loss of aperture.

5) Telescope seeing & thermal issues:
Even though COSMO is not intended to operate near the diffraction limit, telescope seeing is a potentially serious issue because of seeing-induced polarization cross-talk. This occurs when seeing causes the polarization state at any given point in the image plane to vary with time. Because the amplitude of any given stokes parameter (I,Q,U, or V) is the result of a linear combination of sequential measurements, any change in the field between the measurements can cause an erroneous polarization signal. This can be minimized by taking measurements faster than the seeing changes (up to ~kHz frequencies) or by using “multi-beam” instruments which measure several different polarization states simultaneously.

An f/5 telescope has an image at prime focus which is 450 times brighter than normal sunlight. With a 1.5m aperture, the occulter will see about 2,000W of power on a 7cm diameter image. Active liquid cooling of the occulter will be required, and the plumbing for this will obscure a portion of the FOV. Inevitably some part of the occulter will be at a different temperature from ambient, and this could cause telescope seeing. In a refracting telescope, the telescope tube can be filled with He. He has a (n-1) which is an order of magnitude lower than air and a much higher thermal conductivity. This has been shown to dramatically decrease telescope seeing.6 In a reflector, hot gas rising from the occulter could interfere with the light beam reflected from the secondary, which is very near by (see Figure 4).

Temperature gradients in lenses and windows are a potentially serious issue which has been studied for decades. Significant advances have been made in understanding and controlling temperature gradients. The single greatest advance has been the availability of fused silica. It has a lower thermal coefficient of expansion (TCE), higher modulus of elasticity, lower solar absorption, and a much lower stress-optical constant than glasses like BK-7. This lowers its susceptibility to thermal stress by a factor of 12. Combined with shadowing the lens cell from direct sunlight, temperature control of the cell and controlling the temperature of the air surrounding the lens, temperature gradient issues can be effectively controlled.33

Dust will have a fractional area coverage on the primary of approximately 10^-3. Even if the dust is %100 absorptive, this is only %0.1 of the light. As a result, the heating of the objective will dominated by the absorption of optic. In a reflector the absorption is in the
coating. This will be on the order %8 for aluminum and %2 for silver. In fused silica, the power is absorbed in the bulk of the glass, and this is caused mainly by impurities (like OH). Absorption in fused silica is expected to be on the order of a few percent. HEPA-filtered air would be used to reduce heating as much as possible in both designs. It is unknown how much heating in either design would impact telescope performance.

6) Telescope Structure:
A refracting telescope is insensitive to all rotations of the objective lens in lowest order. In-plane translations of the lens are actively compensated by the telescope guiding. The only degree-of-freedom (DOF) to be controlled is the focal length. This allows the use of a simple tube for the structure – no Serrier-type construction is required. The tube would be hermetically sealed from the primary to just after the occulting assembly to keep dust out. The tube would be purged with He to improve seeing. The walls would have an active thermal blanket and probably house the air plenums for feeding the air washing system at the objective. A retractable tubular sleeve around the main tube would provide the ‘snorkel’ for dust control. The nominal design puts the instruments in-line on the optical axis, which increases the overall length. It is possible to place an instrument package piggy-back on the main tube with folding mirrors.

The lens will require a handling cart and an elevator to bring the lens up to a level where it can be installed and cleaned in the horizontal position (lens on-edge). Once installed and sealed to the telescope tube, removing the lens should be rarely done, if ever.

A reflecting telescope requires a corrector to compensate the coma from the primary. Both primary and secondary mirrors are off-axis parabolas, making the image quality sensitive in first order to all 6 DOFs of each optic. There are couplings, however, which give the system fewer than 12 DOFs to be controlled. Translation in the primary, for example, can be compensated by an equal translation of the secondary – this is one of the operating principles behind the classic Serrier-strut construction. With couplings, there remain at least 6 independent DOFs which must be controlled. A classic Serrier-strut construction would interfere with the folded beam path. A modified Serrier construction would have to be devised, and this was not done for this study. A standard hexapod mounting for the secondary would be desirable to aid in setting up and maintaining alignment. This should be integrated into the Serrier structure to reduce the overall length of the telescope. This structure would be enclosed by an independently supported cowling to isolate the optics from dust and allow for the HEPA-air flushing. The overall weight would be higher due to these structures, the weight of secondary optics (60cm diameter) and the weights of the mirror cells. For a f/5 1.5m primary, the overall ‘tube’ would be on the order of 1.7m wide by 2.5m tall. A 60cm Ritchey-Chrétien telescope could be used to reduce the beam size after the secondary in a relatively compact manner (in place of the paraxial lens shown Figure 4). This would provide several meters of space on top of the telescope for instrumentation. The instrumentation chain is potentially longer because a secondary solar image must be formed for final occulting. An f/3 design is possible, and this could reduce the overall length of the telescope. Potential issues with a faster design have already been described.
An additional requirement of the reflecting telescope is an on-site coating chamber and handling equipment to transport the mirror safely on a routine basis. Protected silver is probably the best option for cleaning, reducing telescope seeing, distortion of the primary, and telescope polarization. The feasibility of a silver coating chamber on site has not been investigated.

7) Cost:
The scattering performance due to microroughness is worse for a reflector, but this can be compensated by applying a 3-4 times better RMS finish to the mirrors. This is likely to be more expensive and may not be necessary if the scattering is dust-dominated. “Standard” coating techniques for the mirror may not be sufficient if scattering below 10ppm is required.

If the noise is dominated by scattering from dust as expected, the reflector’s ~4 times higher sensitivity can be compensated by doubling the aperture (from 1.5 to 3m). The two secondary optics would be 1.2m in diameter, and the dome would also have to be correspondingly larger. This would clearly be much more expensive than a refractor with the equivalent noise performance.

The coating equipment for the mirror will be expensive, and there’s no corresponding component in the refractor.

8) Summary:
The table below summarizes all of the issues considered in this study. The results are color coded such that green represents an advantage, red a disadvantage, and yellow an issue in which neither design has a significant advantage or the advantage is negligible in the context of COSMO’s science requirements.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Reflector</th>
<th>Refractor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic optical design</td>
<td>Two off-axis parabolas, large secondary optics, and a double-occulting system. Many internal DOFs to control. Hard mirror overcoating desirable.</td>
<td>Uncoated bi-convex singlet, one side aspherical. On-axis tubular design. Requires chromatic corrector if broad-band measurements are required.</td>
</tr>
<tr>
<td>Image quality (spot size)</td>
<td>Very sharp focus after secondary correction which is achromatic.</td>
<td>Sub-arc-second image at limb at prime focus meets requirements.</td>
</tr>
<tr>
<td>Instrumental scattered light due to dust</td>
<td>Approximately 4 times higher than refractor for equal contamination. Scatting from dust is expected to dominate.</td>
<td>Demonstrated sub-10ppm scattering at 1.15 $R_\odot$. 5ppm appears plausible.</td>
</tr>
<tr>
<td>Instrumental scattered light due to</td>
<td>10 times higher than refractor for the same</td>
<td>Approximately 2.5ppm at 1.1 $R_\odot$ with 1nm RMS</td>
</tr>
</tbody>
</table>

Figure 14: Summary of results
<table>
<thead>
<tr>
<th>Feature</th>
<th>Reflector</th>
<th>Refractor</th>
</tr>
</thead>
<tbody>
<tr>
<td>microroughness</td>
<td>surface finish. 0.3nm finish required to meet 5ppm target.</td>
<td>finish.</td>
</tr>
<tr>
<td>Dust Control</td>
<td>Requires separate cowling on structure. At least two surfaces to maintain.</td>
<td>Requires snorkel, one surface to maintain.</td>
</tr>
<tr>
<td>Cleaning the objective</td>
<td>Regular cleaning of mirror degrades coating. Frequent re-coating may be required.</td>
<td>Lenses proven durable under regular cleaning for decades.</td>
</tr>
<tr>
<td>Instrumental scattered light from coatings</td>
<td>Potentially a very serious problem. Can increase scattering by several fold over microroughness.</td>
<td>-na-</td>
</tr>
<tr>
<td>Instrumental scattered light from inclusions</td>
<td>-na-</td>
<td>Below the ppm level with levels quoted by Corning.</td>
</tr>
<tr>
<td>Instrumental scattered light from Rayleigh Scattering</td>
<td>-na-</td>
<td>Negligible in fused silica.</td>
</tr>
<tr>
<td>Instrumental scattered light from index variations</td>
<td>-na-</td>
<td>Has minor effect on the PSF, but does not add background in corona.</td>
</tr>
<tr>
<td>Instrumental scattered light from striae</td>
<td>-na-</td>
<td>An issue with glass other than fused silica.</td>
</tr>
<tr>
<td>Telescope polarization</td>
<td>Cross-coupling between Stokes parameters higher, but can be calibrated or otherwise removed.</td>
<td>Very low. Dominated by birefringence of bulk glass and stress-induced birefringence.</td>
</tr>
<tr>
<td>Wavelength coverage</td>
<td>Covers entire spectrum into the deep IR</td>
<td>Has absorption bands with 15% loss at 1.43 µm. Chromatic corrector needed if broad-band measurements are required.</td>
</tr>
<tr>
<td>Image sensitivity to thermal variation</td>
<td>Larger number of DOFs to control may require better thermal control. Distortions in primary not self-correcting.</td>
<td>Self-correcting to lowest order. Some temperature control required, but demonstrated in other telescopes.</td>
</tr>
<tr>
<td>Telescope structure</td>
<td>Folded beam geometry requires taller structure with independent strut and cowling construction. Higher weight.</td>
<td>Double-walled tube provides adequate support for objective. Tube doubles as dust cowling. ‘Snorkel’ required for dust control.</td>
</tr>
<tr>
<td>Cost</td>
<td>Same noise performance in dust-dominated regime requires an aperture 2x larger.</td>
<td>Relatively simple telescope structure.</td>
</tr>
</tbody>
</table>
9) Conclusion:
The primary factor in the effectiveness of the COSMO telescope will be the level of instrumental scattered light. The refractor is ~4 times less sensitive to dust and ~10 times less sensitive to microroughness. Coating quality could be a serious issue in reflectors. Better polishing can reduce scatter from microroughness, but scatter from dust and coatings cannot be reduced. Reflectors have an advantage in wavelength coverage, and this has a minor impact at 1.43\mu m. This is more than compensated by lower levels of scatter in the refractor. Other wavelengths relevant to the COSMO science requirement are not affected. Except for its large size, the refracting telescope is a well proven technology for internally occulted coronagraphs.

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1 Tomczyk, Steven, “Measurement errors in coronal magnetic field parameters,” COSMO Technical Note No. 1, Sept. 2006
3 A simple pressure servo could be used to help support the weight of the lens (0.3 psi max. overpressure). An FEA analysis shows this would reduce this effect dramatically. See reference 33 for details.
4 Scharmer, G.B., private communication
7 Jean Arnaud, private communication.
9 Inclusions could have a similar signature. The level of inclusions in the Mk4 has not been measured, however the lens is very thin and inclusions are not expected to introduce significant scatter.
10 Haosheng Lin, Institute for Astronomy, HI. Private communication.
13 Developed by Thomas Germer at NIST’s Optical Technology Division, Gaithersburg, MD. MIST is available for free download at the NIST web site.
15 This number must be confirmed with a computational fluid dynamics model.
17 Church, E.L., “Fractal Surface Finish,” (Applied Optics 27, No. 8, 15 April 1998.)
18 Duparre, et. al., “Surface characterization techniques for determining the root-mean-square roughness and power spectral densities of optical components,” (Applied Optics 41, No. 1, 1 January 2002.)
27 Thomas Germer, NIST Optical Technology Division, private communication.
28 These data are proprietary to Corning, but can be conditionally provided upon request.
29 Elmore, David, “Polarization in reflecting and refracting coronagraphs,” COSMO Technical Note No. 3
30 Jeff Kuhn and Haoehng Lin, Institute for Astronomy, private communications.