A Compact Full-disk Solar Magnetoagraph Based on Miniaturization of the GONG Instrument*

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Abstract

The design of compact instruments is crucial for the scientific exploration by smaller spacecraft such as CubeSats and deep space missions, as these missions require minimal instrument mass. In this proof-of-concept study, we demonstrate the miniaturization of the Global Oscillation Network Group (GONG) instrument. GONG instruments routinely produce full-disk maps of the Sun’s photosphere using the Ni I 676 nm absorption line, measuring Doppler shifts and magnetic fields. To miniaturize the GONG optical design, we propose replacing the bulky Lyot filter with a narrow-band interference filter. We validate this concept through numerical modeling and proof-of-concept observations. Finally, we propose a simple optical design for building a compact version of GONG.

Unified Astronomy Thesaurus concepts: Solar magnetic fields (1503); Solar instruments (1499); Space weather (2037); Interferometers (805); Michelson interferometry (1045); Optical phase shifting interferometry (1171); Polarimetry (1278); Radial velocity (1332); Space observatories (1543); Helioseismology (709)

1. Introduction

Accurate mapping of solar surface magnetic and velocity fields is crucial for several reasons. It allows us to: (a) characterize large-scale spatiotemporal patterns related to the solar cycle and interpret them in terms of solar dynamo models (Charbonneau 2010; Hathaway 2015), (b) make force-free extrapolations to model the global corona, (Mackay & Yeates 2012; Wiegelmann & Sakurai 2012), (c) track the evolution of magnetic flux in solar active regions in relation to flares and CMEs (Shibata & Magara 2011; van Driel-Gesztelyi & Green 2015). However, from Earth-based observatories or any single vantage point, we can only see one side of the Sun. Solar rotation eventually allows us to see the far side, but by that time the solar surface magnetic flux has already evolved (Sheeley 2005). A single vantage point also limits our space-weather modeling capabilities due to constrained information about surface boundary conditions, which impacts the accuracy of model predictions of the coronal and heliospheric magnetic field and solar wind parameters (Pevtsov et al. 2020). Additionally, the limited view of the solar polar regions from the ecliptic prevents us from mapping high-latitude flows and magnetic fields, which are important for solar dynamo studies.

Obtaining full-disk measurements from different vantage points, such as from Lagrange points (L4, L5) and/or polar orbits, can provide valuable information about solar magnetic and velocity fields and aid in understanding solar activity through better-initialized models (Gibson et al. 2018). The Polarimetric and Helioseismic Imager (PHI, Solanki et al. 2020) onboard Solar Orbiter (SoLO) mission (Müller et al. 2020), which observes the Sun from an orbit inclined to the ecliptic plane, is a current example of this approach. However, accessing these new vantage points can be costly, and it is desirable to have compact and lightweight instruments to obtain the observations. While there are other compact instrument designs, such as the magneto-optical filter (MOF) and tunable Fabry–Perot (FP) concepts (Cacciani & Fofi 1978; Berrilli et al. 2011). MOFs have very limited wavelength tunability which prohibits their use in the presence of large spacecraft velocities relative to the Sun. Also, MOFs require strong magnets and high temperatures for their operation, which can challenge magnetic cleanliness and temperature stability requirements. The wavelength tuning of a FP passband can be technically challenging when sampling narrow photospheric spectral lines, especially faced with large and changing spacecraft velocity relative to the Sun. Nonetheless, the PHI instrument onboard SoLO demonstrates the feasibility of a tunable solid FP in space. However, a low-voltage electro-optic tuning of a Michelson interferometer, as we suggest for the compact GONG design here, offers a simpler and lower-cost solution for line-of-sight Doppler and magnetic field measurements.

In this paper we present a concept for miniaturization of the GONG instrument (Harvey et al. 1996; Harvey & GONG Team 1998). In particular, we present proof-of-concept
results through numerical modeling and sample observations at a GONG engineering site. Finally, we propose a simple optical design for building a compact version of the GONG instrument (which we call C-GONG, henceforth).

2. Brief Description of the GONG Instrument

The GONG is a geographically distributed, ground-based network of six identical instruments designed to continuously observe the Sun’s photosphere (Harvey et al. 1996). It was designed for helioseismology, a technique that utilizes acoustic waves that propagate throughout the Sun, to measure its internal structure and dynamics (Ulrich 1970; Leibacher & Stein 1971).

The basic operating principle of GONG is described in detail elsewhere Brown (1981), Evans (1981), Shepherd et al. (1993), Harvey et al. (1996). In summary, GONG uses a wide-field polarizing cube Michelson interferometer (Title & Ramsey 1980) to perform phase-shifting interferometry (de Groot 2011) and measure Doppler shifts and Zeeman splitting of the solar spectral line. The advantage of GONG’s measurement technique is that the interpretation of the detector output in terms of magnetic and velocity signals is relatively straightforward (Equations (2)–(5) below).

In practice, the path difference of the Michelson interferometer is tuned across a single fringe period, in three steps of $2\pi/3$ radian step-size, causing the cosine-squared fringe pattern of the interferometer to modulate the intensity of a solar absorption line, which is isolated spectrally by means of a narrow-band filter. The resulting intensity on the detector is modulated depending on how the fringe over-laps the line profile. The phase of this modulation is proportional to the wavelength position of the solar absorption line.

In GONG, the phase-stepping of the Michelson interferometer is performed by means of a continuously rotating half-wave plate (RHWP). The intensity on the detector, $I(t)$, is then modulated according to the angle of the RHWP, which is given by the rotation rate, $\omega$, of the RHWP and time, $t$, at which the intensity is sampled:

$$I(t) = I_0 [1 + M \cos(4\omega t - \phi)]. \quad (1)$$

By sampling the modulated intensity signal at three Michelson phase-steps, $2\pi/3$ radians apart, one can determine, $I_0$, the mean intensity, $M$, the modulation amplitude, and $\phi$ the phase of the modulated signal. Of these, the $I_0$ and $M$ are related to the average spectral window brightness and equivalent depth of the spectral line, respectively, while $\phi$ is proportional to the Doppler shift of the line.

The expressions for phase, $\phi$, and modulation amplitude, $M$, in terms of the three measured intensities, $I_1$, $I_2$, and $I_3$ can be written as:

$$\tan \phi = \sqrt{3} \frac{I_2 - I_3}{I_2 + I_3 - 2I_1}, \quad (2)$$

and

$$M = \frac{\sqrt{3}(I_2 - I_3)^2 + (2I_2 - I_1)^2}{3I_0}, \quad (3)$$

where, $I_0$, is simply the average of the three intensities. The Doppler velocity, $v$, is related to the measured phase shift of the spectral line, $\delta\phi$, as follows:

$$v = c \frac{\delta\phi}{\phi_0}, \quad (4)$$

where, $c$ is the speed of light and $\phi_0$ is the nominal phase difference corresponding to the optical path difference between the two arms of the Michelson interferometer.

To measure the line-of-sight (LOS) magnetic field, one simply subtracts the velocity of the left- and right- circularly polarized, Zeeman-split $\sigma$ components of the spectral line. The velocity difference is directly proportional to the LOS magnetic field, given by the expression:

$$B_{\text{LOS}} = \frac{0.5\Delta v}{4.67 \times 10^{-13} g_{\text{eff}} \lambda_0 c}, \quad (5)$$

where, $\Delta v$ is the Zeeman splitting in velocity units (in ms$^{-1}$), $g_{\text{eff}} = 1.42$ is the effective Landé $g$-factor for the Ni I line, $\lambda_0 = 6767.8$ is the rest wavelength (in Å), and $c$ is the velocity of light (in ms$^{-1}$). For these values we get the relation, $B_{\text{LOS}} = 0.37$ $\Delta v$ in Gauss.

To illustrate the standard GONG instrument modular setup and its scale we show an image of an actual GONG instrument in Figure 1.

3. Miniaturization Concept for GONG

The key concept to make the current GONG design compact is to replace the prefilter and a rather bulky Lyot filter (Lyot 1944; Evans 1949) with an equivalent narrow-band interference filter. Such filters were not available when GONG was designed. The purpose of the narrow-band filter is to isolate the target solar absorption line from the rest of the spectrum. For reference, in Figure 2 we show the transmission profile of a two-cavity interference filter of passband $\sim$1 Å (the solid curve) together with the profile for the three-element wide-field Lyot filter of similar passband used in the GONG instrument (the dotted curve). This replacement not only reduces the system length (and volume) but also reduces the mass of the system, which is a crucial design parameter for deep space missions.

However, replacing Lyot filters with interference filters comes with a small compromise. This is because wide-field Lyot filters have a much larger acceptance angle than thin-film interference filters. This has two effects: (i) the passband of the interference filter shifts toward shorter wavelengths with increasing angle of incidence, and (ii) the acceptance angle of the system is reduced, as a consequence of blueshift
mentioned in (i), and hence a slower optical beam, than in the case of Lyot filter, would be necessary.

However, these two effects can be mitigated as follows. The passband shape and its wavelength shift with angle-of-incidence is a smooth function which can be modeled quite accurately using laboratory measurements. This field dependence can be calibrated using sunlight itself, i.e., by feeding the instrument a spatially (or disk) averaged solar light, for
Figure 3. Results of numerical simulations are shown here. Top panel shows spectral profiles of the solar absorption spectra (NSO FTS atlas spectra) and the instrumental transmission profile, i.e., a product of narrowband interference filter and Michelson transmission profiles, at one of the three path difference setting of the Michelson interferometer. Middle panel shows the simulated measurements of the magnetic and velocity field of the full disk of the Sun. Bottom panel shows the scatter plots between the “ground truth” GONG observations and simulated measurements.
example, by means of a small-angle optical diffuser. Since every pixel in the detector field-of-view is fed the same disk-averaged solar spectrum, any measured phase variations across the field-of-view are attributed to the instrument systematics and calibrated out during post-processing of the data.

The second effect of throughput limitation is more benign, since GONG is not a photon starved instrument. This is because the amount of solar radiation through a rather large passband (~1 Å) interference filter is dominated by the continuum radiation, which is quite large relative to a typical detector pixel full-well charge capacity. Calculations show that typical exposure times of a few milliseconds are enough to fill the full-well of typical detectors, when using interference filters. Thus, using a slower optical beam (relative to the Lyot case) with an interference filter is an acceptable trade-off. This implies that such a design would sacrifice angular resolution in lieu of the compactness. One could think of possible alternatives to preserve the angular resolution such as by locating the narrow-band interference filter ahead of the telescope aperture. However, this could have implications for the thermal oven design as the size of narrow-band filter would be now as large as the aperture itself, hence the total mass attributed to narrow-band filter would increase. As a second alternative, one could use a telecentric beam configuration for the filters with an intermediate focus, however, this also increases the system complexity and length. In summary, as mentioned above the compactness would typically come at the price of lower angular resolution.

Another key concept to make GONG design compact is to use a liquid crystal variable retarder (LCVR) instead of a rotating half-wave plate for tuning the Michelson interferometer’s path difference. This allows one to avoid a moving mechanism in the instrument design and the LCVR can be integrated into the Michelson optics package to save space.

Using these miniaturization concepts we propose a simple optical design for building a compact version of GONG or C-GONG, in Appendix.

3.1. Proof of Concept: Numerical Modeling

**Instrument Model:** To verify the concept of C-GONG we made a simple numerical model of the GONG instrument based on Equations (1–5). The instrument model was made as follows:

Let \( I(\lambda), P(\lambda), T(\lambda) \) be the wavelength transmission profiles of the solar absorption line, narrow-band prefitter and Michelson interferometer, respectively. These profiles are obtained as described below, and are sampled on a uniformly spaced wavelength grid, spaced 2 mA apart.

1. \( I(\lambda) \) is approximated with the quiet Sun disk-center solar reference spectrum from the NSO Fourier Transform Spectrometer (FTS) atlas (Braught 1982; Neckel & Labs 1984; Hinkle et al. 1995). A wavelength range of ±10 Å centered on the absorption line used by GONG, i.e., Ni I 6768 Å, was selected. The solid curve in the top panel of Figure 3 shows an example of \( I(\lambda) \).
2. \( P(\lambda) \), transmission profile for the narrow-band interference filter is given by the following equation (Smith 2008):

\[
P(\lambda) = T_{\text{max}} \frac{1}{1 + \left( \frac{2(\lambda - \lambda_0)}{\Delta\lambda} \right)^2},
\]

where, \( \lambda_0 \) is the central wavelength of the passband and \( \Delta\lambda \) is the full-width at half maximum (FWHM) of the interference filter, which was set to 1 Å here. Further, \( n \) is the number of cavities in the interference filter, for which we have used \( n = 2 \). The dashed curve in the top panel of Figure 3 shows the profile of \( P(\lambda) \).
3. \( T(\lambda) \), the Michelson interferometer’s wavelength transmission profile as functions of phase delay, \( d\phi \), is given by:

\[
T(\lambda, d\phi) = 0.5[1 + \cos(2\pi\Delta\lambda/\lambda + d\phi)],
\]

where, \( \Delta\lambda \) is the nominal optical path difference (OPD) of the Michelson interferometer used in GONG (\( \Delta\lambda = 1.5 \text{ cm} \)). The dotted curve in the top panel of Figure 3 shows an example of \( T(\lambda) \) for \( d\phi = 0 \).

We then simulate the three intensity measurements, needed to derive wavelength shift of the spectral line, as follows:

\[
I_i = \sum_{\lambda} I(\lambda)P(\lambda)T(\lambda, d\phi_i),
\]

where \( d\phi_i = i\pi/3 \), for \( i = 0, 1, \text{ and } 2 \) respectively. Using these three modeled intensities together with Equations (2–5), we can derive the Doppler shift of the spectral line. This process is repeated twice, once each for the left- and right- circular polarized \( \sigma \) components. The wavelength shift between the two Zeeman \( \sigma \) components is proportional to the longitudinal magnetic field, which is given by Equation (5).

While \( P(\lambda) \) and \( T(\lambda) \) are fixed according to the instrument design parameters, the input solar spectrum \( I(\lambda) \) needs to be varied according to realistic solar velocities and magnetic fields. Next, we describe how a reference “ground-truth” is established and used for generating \( I(\lambda) \) in our simulations.

**Input Ground-truth:** We use a full-disk Dopplergram and magnetogram, observed by GONG, as the “ground-truth” input for the line-of-sight velocity, \( V_{\text{LOS}} \), and magnetic field, \( B_{\text{LOS}} \), on the Sun. For each pixel \((x,y)\), we first take the atlas spectrum, \( I(\lambda) \), and Doppler shift it in wavelength according to the \( V_{\text{LOS}}(x,y) \) value. Thus, we have a Doppler shifted spectrum, \( I^D(\lambda,x,y) \), where \( \Delta\lambda_D \) is the Doppler shift in wavelength. We then apply Zeeman shift to \( I^D(\lambda) \) and produce two spectra corresponding to the two \( \sigma \) components, according to the \( B_{\text{LOS}}(x,y) \) value. Thus, at each pixel \((x,y)\) two input spectra can be represented as, \( I^{D,\sigma}(\lambda) = I(\lambda + \Delta\lambda_D + \Delta\lambda_D) \).
where $\Delta \lambda_H$ is the half of the wavelength separation between centroids of the right- and left- circularly polarized $\sigma$ components, and is given as $\Delta \lambda_H = 4.67 \times 10^{-13} \lambda_0^2 g_L B_{1,\text{LOS}}$, where $\lambda_0$ is the central wavelength of the spectral line and $g_L$ is the Landé splitting factor.

Using these synthesized spectra as input, and applying Equation (8), we simulate six measured intensities per pixel, three for each $\sigma$ component. Using these intensities with Equations (2)–(5) we deduce output magnetic and velocity values, $B_{1,\text{LOS}}^{\text{out}}(x, y)$ and $V_{1,\text{LOS}}^{\text{out}}(x, y)$, for each pixel. The simulated output maps of magnetic and velocity field are shown in the middle panel of Figure 3.

**Simulated Output:** The comparison of input “ground truth” with output “simulated” maps is shown via scatter plots in the bottom panels of Figure 3. As expected, we find a good correlation between the input and output values of the velocity and magnetic field. A small scatter of $\sim 20$ ms$^{-1}$ in the simulated Doppler maps and $\sim 10$ Gauss in the simulated magnetic maps is due to the wavelength shift of the filter passband with the field angle, which is not corrected for in our simulations. We plan to do a detailed modeling of these systematic effects in future work. For now, our simulations show the feasibility of replacing a Lyot filter with a narrow-band interference filter of similar bandwidth.

**Limitations:** It should be noted that these are ideal simulations with no instrumental errors and sources of noise. In real measurements the imperfections of the optics, measurement errors, noise sources and atmospheric seeing are typically present.

We also note that in our simulations here, we ignored the spectral line shape variation across the solar disk which occur due to line-of-sight effects as well as the presence of different solar features across the disk. However, such line shape variations mostly affect the line depth and width and hence, affects mostly the modulation amplitude, $M$, as given in Equation (3). Wavelength shifts are derived from the phase measurements and are thus not expected to show significant differences if realistic spectra are used in the simulations. We plan to explore this further in future studies. Also, we ignore the large scale Doppler signals, such as due to solar rotation, because we wanted to emphasize the sensitivity to small Doppler variations across the disk.

4. Proof-of-concept: Observations

For an observational demonstration of the proof-of-concept we replaced the Lyot filter at the GONG Boulder engineering site with a pair of narrow-band interference filters, placed in tandem. The demonstration setup is shown in Figure 4. A lens shown on the right collimates the primary solar image (not shown here) through a neutral density (ND) filter, two narrow-band filters, a linear polarizer, a Michelson cube interferometer and the rotating half-wave plate (HWP). Following the HWP, an imaging lens makes a solar image onto the camera (not shown here). Since we did not have a dual-cavity filter, we used two single-cavity filters in series to emulate one, which was needed to get a much cleaner spectral isolation of the solar absorption line. The interference filters were housed in temperature-controlled cells to maintain their spectral band-passes aligned relative to each other. Temperature tuning of the two bandpasses was accomplished by using a field spectrograph and the solar absorption line itself. The bandpass of the available filters was $\sim 1.7$ Å. Finally, we made some test observations using our proof-of-concept setup at the GONG site in Boulder, Colorado, USA. Using these full-disk...
observations we derived a ten-minute average magnetogram and a one-minute average Dopplergram. A quick comparison of these observations was done with other simultaneous observations from the GONG network. These comparisons are described in the next section.

4.1. Comparison of Magnetograms:

A solar full-disk magnetogram was obtained on 25 April 2018, by using the measurements taken with the proof-of-concept setup shown in Figure 4. We compare these observations with a simultaneous magnetogram obtained by GONG site at Big Bear, California, USA. A side-by-side comparison of the two magnetograms is shown in the top panel of Figure 5. The gray scale maps display the line-of-sight magnetic flux density, scaled to saturate at ±50 Gauss. The black/white shades represent the longitudinal field pointing toward/away along the line-of-sight. An active region designated as NOAA Active Region No. 12706, was present near the center of the solar disk. A magnified view of this active region is displayed in the middle panels of Figure 5, saturated at ±100 Gauss. A quantitative comparison of the signals in the two middle panels is shown by a scatter-plot in the bottom panel of the Figure 5, which shows a good one-to-one correlation, especially given the fact that the two observations are made under different atmospheric conditions at two distinct sites.

4.2. Comparison of Dopplergrams

A full-disk Dopplergram, derived from both our test observations and those from the GONG Big-Bear, California site, is displayed in the top panels of Figure 6. The Doppler map in the top-left panel exhibits faint concentric rings, referred to as fringes, on the surface of the solar disk. These fringes arise due to imperfect optical coatings of the Michelson interferometer and their calibration is well understood and is addressed in Toussaint et al. (1995). However, the required optical setup for these calibrations, including a Michelson entrance pupil mask and the imaging of the East and West solar limbs, was not available in our proof-of-concept configuration. As such, we are only able to make qualitative comparisons and acknowledge this limitation.

It should also be noted that the concentric fringe pattern is not visible in the magnetograms displayed in the top left panel of Figure 5. This is because, magnetograms are essentially a difference measurement of two Doppler signals, measured in right and left circularly polarized light, respectively. Hence, such a concentric fringe pattern, present in both polarization states, is mostly subtracted, leaving behind only the shifts due to the Zeeman effect. This happens because the fringe period is much larger as compared to the Zeeman splitting. Nevertheless, we should bear in mind that any optical design of a standalone compact-GONG instrument would need to include a GONG-like calibration scheme. This means a rotating wheel mechanism mounted with calibration optics would be needed to allow for in-flight calibration capabilities.

Now, coming back to the comparison of Doppler signals, we focus on the middle panels of Figure 6 where a region (marked by white rectangle in top panels) is shown side-by-side. This region is chosen because the solar supergranular flow pattern, which is predominantly horizontal, becomes prominent in the Dopplergrams near the solar limb. This makes feature comparison easier. The one-to-one correspondence between the supergranular flow structures can be easily seen in the middle panels. The lighter/darker shades in the gray scale map represent plasma flows away/toward the observer. Even though not fully calibrated for systematic instrumental effects, as mentioned above, we make a scatter-plot comparison between the maps shown in the middle panels. This scatter-plot in the bottom panel shows a broad agreement between the two maps, which is expected to become much better when instrumental effects, such as the concentric fringe pattern, are properly calibrated and removed.

5. Discussion and Conclusions

We have studied a miniaturization concept for GONG whereby we propose to replace the bulky Lyot filter with a narrow-band interference filter. In summary, the proof-of-concept observations and our numerical modeling demonstrates that using interference filters in place of Lyot filters is a viable alternative that leads to a miniaturization of the GONG instrument design.

Utilizing narrow band interference filters allows one to save on mass and volume and thus design a compact version of the GONG instrument. State-of-the-art interference filters with passband as narrow as ~0.1 nm can be commercially obtained (Martínez Pillet et al. 2011). It should be noted, however, that the feasibility of obtaining such narrowband filters critically depends upon the filter diameter. The interference filters are very small as compared to the Lyot filter in size, only a few millimeters in thickness. Such filters have previously flown in space instruments and are typically constructed with hard coatings on radiation-resistant transparent substrates (Scherrer et al. 1995, 2012).

While interference filters are compact, the acceptance angle of a wide-field Lyot birefringent filter (Lyot 1944) is much higher than a comparable interference filter. For example, for a 1-degree deviation from normal angle of incidence the passband of a field-widened (Title & Ramsey 1980) Lyot filter shifts only ~20 mÅ, whereas for a high refractive index coating (n = 2.0), the corresponding shift for an interference filter would be ~230 mÅ. Thus, using an interference filter would require a slower optical beam and a good calibration of the wavelength response of the instrument with field angle.
However, the advantages of a narrowband interference filter over a Lyot filter, namely, much smaller size (mass/volume reduction) far outweigh the acceptance angle disadvantage, which can be accurately calibrated and modeled in the laboratory as well as in-flight.

Accurate spectral calibration of the narrowband interference filter and the Michelson interferometer in the laboratory can be done by measuring the wavelength transmission profile, its variation across the clear aperture, and its thermal and angular drift coefficients. Using this data one can build an accurate end-

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**Figure 5.** Top row: Full-disk magnetograms from the C-GONG (left) and and GONG Big Bear, California, site (right). The color map saturates at ±50 Gauss. Middle row: A magnified view of the active region near the disk center marked by the white rectangle. The colormap saturates at ±100 Gauss. Bottom panel: A scatter plot between the magnetic signals in the panels shown in the middle row.
to-end model of the instrument. An in-flight calibration scheme could consist of feeding the instrument with a disk-averaged solar spectrum and making Doppler and magnetic measurements. Since, the instrument is fed the same average solar spectrum the measured variations across the detector plane represent systematic biases due to instrumental effects alone. Such disk averaging of the input light can be accomplished by inserting a small-angle optical diffuser plate in the collimated

Figure 6. Top row: Full-disk Dopplergrams from the C-GONG (left) and and GONG Big Bear, California, site (right). The color map saturates at $\pm 5 \text{ km s}^{-1}$. Middle row: A magnified view of region marked by the white rectangle in top panels. The colormap saturates at $\pm 5 \text{ km s}^{-1}$. Bottom panel: A scatter plot between the Doppler signals in the panels shown in the middle row.
beam and also rotating the spacecraft in roll axis during the averaging.

Additional simplification in the GONG design is also possible by replacing the rotating half-wave plate (RHWP) with an electrically tunable liquid-crystal variable retarder (LCVR). Using a LCVR avoids the complication of using a mechanical system for precision rotation of the wave plate, such as in GONG, hence reducing the complexity and cost in the design. LCVRs for space application have been demonstrated recently by the SoLO mission (Alvarez-Herrero et al. 2015).

In Appendix, we propose a simple optical schematic for building C-GONG. The key ideas suggested are using a compact light-feed or telescope as a front-end, a narrow-band interference filter for spectral isolation of the spectral line, and an electro-optic (LCVR) tuner for the Michelson interferometer. Of course, variants of the proposed setup can be thought of, for example, the Galilean telescope can be replaced with a slightly longer Keplerian design or folded Schmidt-Cassegrain optics. The interference filter can be integrated into the Michelson oven assembly to save space and the beam-splitter feeding the guider Sun-sensor can be placed before the Michelson entrance.

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### Appendix

#### Optical Design Concept for Building C-GONG

##### A.1. Design Parameters

We propose here a simple optical design concept for building a compact GONG. The top level specifications for the concept design are given in Table 1, and are very similar to GONG. In principle, the design can be adapted to different spatial resolution or field-of-view requirements, however, such changes will impact the overall dimensions and mass. Figure 7 shows an optical ray-trace with key components labeled. Sunlight enters the instrument through an entrance window, W1, which could be a broad-band filter made of radiation resistant glass to reject unwanted solar light into the system. This is done to provide protection to other components in the system from ultraviolet damage and minimize stray light and solar heating. Detailed design for building such entrance windows are known from previous missions, such as SOHO/

| S. No. | Parameter                        | C-GONG | GONG |
|-------|----------------------------------|--------|------|
| 1.    | Angular resolution              | 5"     | 5"   |
| 2.    | Pixel sampling                  | 2.5 pix^{-1} | 2.5 pix^{-1} |
| 3.    | Detector (FoV)                  | 1 k x 1 k (0/6) | 1 k x 1 k (0/6) |
| 4.    | Pixel size (microns)            | 9      | 14   |
| 5.    | Wavelength                      | Fe i 617.3 nm | Ni i 676.8 nm |
| 6.    | Telescope aperture diameter     | 4.5 cm (required) | 2.8 cm |
| 7.    | Angular magnification           | 5途   | 4途   |

MDI, SDO/HMI and SoLO (Scherrer et al. 1995, 2012; Solanki et al. 2020).

Next, a Galilean telescope made from the lenses L1 and L2 renders a collimated beam through the narrow band prefilter, PF and Michelson Assembly via a folder mirror, FM. The entrance aperture of the telescope is depicted as 4.5 cm in the ray trace (larger than 2.8 cm requirement in Table 1) to allow a flexible design, i.e., if one needs a higher angular resolution. For example, one can aim for a 3 arc-sec resolution by choosing a suitable larger format detector with smaller pixel size.

A fold mirror, FM, is mounted to a piezoelectric tip-tilt actuator as a part of C-GONG image stabilization system that can provide fine pointing for the solar images. The imaging lenses L3, L4, and L5 make a full-disk image of the Sun, simultaneously onto a camera sensor and a solar position sensor (SPS) via a beam-splitter. A neutral density filter, ND, is used to control the illumination level onto the limb sensor. The selection of left- or right- circularly polarized light is done via a LCVR retarder, LC1 together with the polarizer, P1.

The Michelson interferometer assembly consists of the following components. A solid polarizing cube beam-splitter with appropriate optical path difference, Δ, between the two arms with end mirrors, M1 and M2, is placed between two crossed polarizers, P1 and P2. The quarter-wave plates (QWP) placed near the end mirror, M1 and M2, rotate the plane of polarization by 90°, as described in Harvey et al. (1996).

A second LCVR placed at the exit port of the Michelson assembly, LC2, performs the function of tuning the Michelson’s path difference by changing the retardance of the LCVR, electro-optically. This LCVR based tuning avoids a physical mechanism such as the rotating half-wave plate in the GONG instrument, and also saves space by optically integrating with the Michelson cube. Since the LCVRs and the Michelson cube need to be in a stable temperature environment, the entire assembly would need to be placed inside a thermally insulated oven with active temperature control. The narrow-band filter, PF, can also be integrated optically with the Michelson assembly for thermal reasons, however, we show it separately.
here as it may require independent adjustment of tilt angle and temperature.

A.2. Calibration Scheme

To enable in-flight instrument calibration a multi-aperture calibration wheel driven by a stepper motors mounted with calibration optics can be placed between L2 and PF (or after L2, if PF is located inside Michelson housing). The calibration wheel can have following optics:

1. Diffuser plate: for scrambling the incoming light such that each pixel on the detector is illuminated by a mean spectrum of the solar disk. Further, to average out the solar rotation profile one can roll the spacecraft during integration. Any systematic pattern in the derived B and V measurement represents the instrument biases due to angular effects as well as the instrument imperfections.
2. Dark: An opaque mask to block the light for taking dark frames.
3. Flats: Diffuser plate above also provides a flat-field intensity to the camera.
4. Circular polarizer: To calibrate the 1/4 and 3/4 wave retardance voltages of the LC1.
5. Focusing lenses: To correct for focus drifts due to thermal changes in the instrument focus.

A.3. Angular Blue-shift of Filter Passband

The angular magnification of the collimated beam in the instrument due to the telescope optics is a design parameter that affects the amount of passband shift of the NBF. The passband of the filter shifts toward the blue according to the formula:

$$\lambda(\theta) = \lambda_0 \sqrt{1 - \left(\frac{n_0}{n_r}\right)^2 \theta^2},$$  \hspace{1cm} (A1)

where, \(\theta\) is the angle of incidence (AOI), \(\lambda_0\) is the central wavelength of the filter passband at normal AOI, \(n_0\) is the refractive index of the external medium and \(n_r\) is the effective refractive index of the filter (we use \(n_r = 2\) and \(n_0 = 1\)).

In the current concept design a 5\times angular magnification would lead to an angular blueshift of 367 mA, when using Fe I 6173 line. While the spectral line would still be inside the passband the SNR would be reduced due to lower transmission away from the center of the transmission profile. This means that the center of the solar disk would have a higher SNR than the limb. This is certainly undesirable and can be mitigated or reduced in one or more different ways, as listed below:

1. Offset the filter passband by deliberately tuning the temperature of the filter (the passband shifts toward red with increasing temperature) such that the central transmission wavelength of the filter profile is shifted slightly red-wards with respect to the solar spectral line. This way one can limit the spectral line from getting too far away from the central peak of the transmission profile, even for the limb pixels.
2. Use a slightly broader passband filter at the cost of a lower SNR (due to a larger amount of solar continuum transmitting through).
3. Reduce the angular magnification in the optics to 3\times. This would result in a slightly longer (∼100 mm) focal distance between the Michelson and the camera, while the overall dimensions can still be kept the same. In this case the angular blueshift at the edge of FOV is reduced to ∼132 mA.
4. For modest telescope apertures, such as 2.8 cm, one can think of incorporating a NBF (of diameter 3 cm) in front of the telescope aperture i.e., between W1 and L1, or design it as part of W1 itself. In this case there would be

Figure 7. An optical design concept for building a C-GONG.
no angular magnification and maximum angular blueshift at the edge of FOV is reduced to $\sim$15 mA.

### A.4. Mass Estimate

Based on the scale of the optical ray-trace shown here, we estimate the overall dimensions of the C-GONG to be easily accommodated inside $40 \times 20 \times 10$ cm$^3$, comparable to an 8U CubeSat. A 1U unit is defined as $10 \times 10 \times 10$ cm$^3$ size with typical mass of 1.33 Kg, as a rule of thumb. However, latest specifications (CubeSat Design Specification (CDS) Revision 14.1) allow for up to 2 Kg per 1U unit. Thus, optimally an 8U design for C-GONG would be limited to about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass. As an upper limit, however, the biggest CubeSat of 12 U size for C-GONG would mean 24 kg limit, about 16 Kg mass.

While an exact mass estimate is difficult to assess without making a real instrument design. If we consider a breakdown of mass estimate in terms of various components, such as given in Table 2, where we have taken typical values based on existing designs and material density/volume estimates, we get a total of about 17 kg, which is very close to our baseline estimate above. Thus, for a C-GONG with the top-level specifications given in Table 1, we may consider a 20 Kg mass limit with a 10 U configuration providing $\sim$25% margin, and an upper limit of 24 Kg with a 12 U configuration providing $\sim$50% margin. In a future paper, we plan to present a prototype design based on the C-GONG concept with more robust estimates, and provide a detailed trade-off study of the key design parameters.

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### Table 2

| S. No. | Item | Mass Estimate (kg) |
|-------|------|-------------------|
| 1     | Electronics (Sun sensor, tip-tilt mirror, camera, LCVR, temperature and motor control) | 2 |
| 2     | Computer (Processor board and data storage) | 1 |
| 3     | Optics (Lenses, filter, LCVRs, entrance window, Micheleison) | 2 |
| 4     | Mechanics (Mounts for camera, optics, base-plate, side covers, front door, Micheleison housing) | 5 |
| 5     | Tip-tilt mechanism (mirror, piezo stage, mount) | 2 |
| 6     | Thermal insulation (blankets, heaters, sensors) | 1 |
| 7     | Calibration mechanism (wheel, motor, mount) | 2 |
| 8     | Camera head | 2 |