Validation and Testing of the CROBAR 3D Coronal Reconstruction Method with a MURaM Simulation

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Abstract

I report on validation and testing of a novel 3D reconstruction method than can obtain coronal plasma properties from a single snapshot perspective. I first reported on the method in 2021, and I have since named it the Coronal Reconstruction Onto B-Aligned Regions (CROBAR) method. The testing and validation are carried out with a cube from a MURaM 3D MHD simulation, which affords a coronal-like “ground truth” against which the reconstruction method can be applied and compared. I find that the method does quite well, recovering the “coronal veil”—like features recently reported from the MURaM simulations and allaying concerns that these features would thwart recovery of valid 3D coronal structure from a limited number of perspectives. I also find that a second perspective between ~45° and 90° does significantly improve the reconstructions. Two distinct channels with soft-X-ray-like temperature response (peaking above 5 MK) would suffice for CROBAR’s optically thin observables A suite of AIA-like EUV passbands, with good coverage in the 3–8 MK range, is also well suited to CROBAR.

Unified Astronomy Thesaurus concepts: Active solar corona (1988); Solar corona (1483); Solar coronal loops (1485); Astronomy data analysis (1858); Solar magnetic fields (1503); Astronomy data modeling (1859); Computational methods (1965); Solar extreme ultraviolet emission (1493); Solar x-ray emission (1536)

1. Introduction

The solar corona is inherently 3D, and it is our premier observing ground in the natural world for full 3D magnetohydrodynamics—the magnetic field and hydrodynamics are fully qualified participants, the range of scales exceeds anything we can simulate on computers or in a laboratory, and our position in the solar system gives us a front row seat. It is also crucial for understanding Earth-affecting space weather. Despite this, essentially all of our observations are 2D line-of-sight integrated images. Furthermore, the number and complexity of coronal structures result in considerable line-of-sight confusion, which makes it impossible to simply identify emission from one part of the image with a single plasma structure. A means of reconstructing the 3D structure of the corona from these 2D images is therefore critical.

In Plowman (2021), I reported on a new method that can reconstruct 3D coronal plasma properties even from a single perspective. The method works by fitting emission profiles, as functions of field-line arc length, to a set of volume-filling field-aligned regions. As a result, the method has been named “Coronal Reconstruction Onto B-Aligned Regions,” or CROBAR.

The initial paper described the method and showed an initial application to some data from the Solar Dynamics Observatory Atmospheric Imaging Assembly (SDO/AIA; Lemen et al. 2012; Pesnell et al. 2012), as a proof of concept. The reconstructions shown there used only the AIA perspective for the reconstruction and a potential field for the field-aligned structure. A subsequent comparison with observations from the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008) sufficed to show the plausibility of the technique, albeit hampered by the limits of the potential magnetic field extrapolation.

In this paper, I show a validation of the field-aligned region reconstruction approach using a 3D MHD simulation from an MPS/University of Chicago Radiative MHD (MURaM; e.g., Rempel 2017; Cheung et al. 2019) simulation as a synthetic “ground truth.” A recent paper using this simulation (Malanushenko et al. 2022) has pointed out some shortcomings of the traditional coronal loop approach when it comes to recovering 3D coronal plasma structure using a limited number of structures. Specifically, the traditional coronal loop approach assumes that the corona consists primarily of a small number of isolated monolithic flux tubes and that the properties of these flux tubes can be reconstructed using optically thin observations from only two or three vantage points without reference to any other source of information about the volume being observed, essentially using standard tomography. However, the simulations discussed by Malanushenko et al. (2022) indicate that these structures are much more numerous, are more complex in their profiles, and fill a large part of the volume. Therefore, additional structural information is required to constrain their properties. This information can be provided by our understanding of the magnetic field, which is what CROBAR aims to do.

CROBAR has some parallels and grows out of a coronal-loop-like approach, so it may be reasonable to wonder whether it is not subject to these limitations. However, I believe that CROBAR largely avoids the concerns expressed in Malanushenko et al. (2022), for the following reasons:

1. CROBAR is not a “blind” inversion. The magnetic field provides the “skeleton,” which is fleshed out by the field-aligned regions. The fundamental physical assumption it relies on, which Malanushenko et al. (2022) does not invalidate, is that the plasma in the corona is mostly forced to follow the coronal magnetic field, and the field structure is largely determined by a boundary value
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2. The CROBAR B-aligned regions fill the entire volume, rather than being just a handful of loops on top of a static (or empty) background. There are also a large number of them, and they are individually quite small, which enables them to fit complex structures that they would not individually be able to (provided that they are spaced tightly enough to resolve said structure).

3. The cross-sectional shape of the regions follows and deforms as a function of arc length, again following the field structure. This can allow CROBAR to replicate the "coronal veil" appearance described by Malanushenko et al. (2022).

Indeed, some of the same concerns raised in Malanushenko et al. (2022) motivated the development of these features in what ultimately became CROBAR. In this paper I focus on how well CROBAR performs at recovery of volume emission information when given a magnetic field and one or more optically thin emission images. That is, I use the magnetic field in the MURaM simulation to compute the skeleton on which the field-aligned regions are built. The intention is to isolate each component of the validation (in this case the emission structure) and verify correct function in isolation. I leave the other major component (refinement of the magnetic field extrapolation based on the residuals of the emission structure) to a future paper, even though I have already implemented a basic version of this component based on a linear force-free field. Covering both of these topics simultaneously would result in a long and unfocused paper.

I now give a brief discussion of the MURaM simulation.

1.1. MURaM Simulation and Technical Considerations

I use the same coronal MURaM simulation also reported in Cheung et al. (2019) and Malanushenko et al. (2022); however, I use a somewhat earlier time in the simulation (the time of the snapshot may be referenced by its unique index of 100,000) during which the volume is less active. The CROBAR approach is less likely to be suited to times of strong plasma dynamics when the field alignment of the plasma is less certain and the field is less likely to be force-free (the frozen-in condition is unlikely to be satisfied at such times).

CROBAR assumes that the field-aligned structure is simple and representable by a small set of functions inspired by 1D hydrostatic loop models. It also uses force-free magnetic fields, where the currents are always parallel to the magnetic fields. These are both widely known to break down, for example, during a flare. If there is significant time variation in EUV images or magnetograms over a period of the radiative cooling time (hours to minutes, depending on temperature), CROBAR’s output should not be expected to be valid. At other times, however, CROBAR should work, and it should also help to provide initial and final conditions for those highly dynamic intervals where it cannot represent the corona well. CROBAR can also provide a starting point for future, more sophisticated modeling efforts with applicability deeper into such highly dynamic intervals.

This time interval in the simulation still contains the complex structures pointed out by Malanushenko et al. (2022) and shows the sort of complexity associated with solar active regions. It is important to note that there are some differences with a typical solar active region, however:

1. The region is significantly smaller than the long-lasting active regions most often the focus of solar physics research, at roughly $100 \times 50 \times 50$ Mm, or fewer than 200 pixels across as viewed by SDO/AIA. Many active regions are several times this size in linear extent.

2. The boundary conditions are periodic, so that the region behaves as if it has an identical clone of itself on each side rather than being relatively isolated.

3. The simulation performs a number of approximations to deal with aspects that are too computationally demanding to incorporate (such as extremely high Alfvén wave speeds in some regions) and assumes that the chromosphere is LTE.

For more discussion of the details of the simulation, see Rempel (2017), Cheung et al. (2019), and Malanushenko et al. (2022). Figures showing the appearance of the simulation will be shown in connection with the reconstructions, as the narrative develops.

2. CROBAR Methodology and MURaM Forward Modeling

2.1. Magnetic Field Skeleton and B-aligned Regions

As previously mentioned, this paper treats only the plasma emission part of the problem. The emphasis is on whether field-aligned emission can reproduce coronal emission at all, regardless of the quality of the magnetic field skeleton. There is little point in covering the refinement of the magnetic field skeleton before this question has been addressed, as Malanushenko et al. (2022) have illustrated. Therefore, I use as the skeleton the magnetic field contained in the MURaM simulation rather than (for example) attempting to use and refine a linear force-free field. I intend to address that topic in a future paper, and I have already carried out some work in that direction with promising results.

I traced 10,500 field lines through the volume, using the MURaM field vectors. Of those initial points, 10,000 were at the photosphere level and their location was randomly chosen with a weight based on the vertical field strength at the photospheric level. The other 500 initial points were uniformly distributed through the volume and then traced in both directions until they reached the photosphere or the edges of the cube. The tracing was done with the 2/3-order Runge–Kutta scheme included in scipy’s integrate.solve_ivp method. I removed field lines from the set that were too short in either height (less than 1 voxel, 0.064 Mm) or overall length (less than 8 voxels, 0.512 Mm). This is referenced to the voxel grid used for associating points in the volume with field lines, which was chosen to have 0.064 Mm grid size in each direction (i.e., the three orthogonal spatial directions, x, y, and z), rather than the $192 \times 192 \times 64$ km$^3$ grid resolution used in the MURaM simulation. This choice was made to ensure full resolution of the simulation and also because the computational load of CROBAR is light. The voxel grid used by CROBAR therefore has just under 1 billion voxels, requiring 3 GB of RAM (2 GB for the array indicating the loop ID of each voxel, and 1 GB for the array indexing its length along the loop).

Images of the seed points for tracing field lines and the vertical field component at the nominal photospheric level
(8 Mm, 125 voxel heights; compare Rempel 2017) are shown in Figure 1. The boundary conditions are at least nominally periodic (the left edge of the simulation is identified with the right edge and the top with the bottom), and I wanted to maximize the number of complete field lines (footpoint to footpoint), so I shifted the cube 128 voxels to the left compared to its usual presentation, placing the negative polarity at cube center. This makes nearly all loops in the cube complete, since most large-scale connections in the cube are between the positive polarity/ies and the negative polarity/ies. I also padded the cube on the top and bottom (using the periodic boundary conditions) by 32 pixels, in a further effort to avoid edge effects. The field-aligned regions used for the reconstruction are shown in Figure 2, using both a projection through with the voxels of 1 in 20 of the regions set to 1 and a set of orthogonal slices through salient locations in the cube.

A brief description of how CROBAR determines the regions shown in Figure 2 is as follows: CROBAR labels each field line with a sequential index number. The field-aligned regions are determined by dividing the volume into voxels and assigning each voxel the number of the field line it is closest to. This is described in more detail in the first paper. The section panels of Figure 2 simply show the number assigned to each voxel in a slice of the voxel cube with a colorful palette. This is all that is necessary to produce a section of the regions. Note that the section figures do not show field direction.
orthogonal cross sections; this would be a complex 3D surface. What they show are planar sections along the principal axes of the cube. Similarly, the projection figures are summed through a cube made from the index number cube by setting every 20th index number (0, 20, 40, etc.) to one and the rest to zero.

The padded voxels mentioned above are omitted from the reconstruction, since they contain incomplete field lines. Similarly, I noticed a small edge discontinuity in the cube at 128 voxels (roughly $-24$ Mm in $x$ in Figure 2), so I only used the right-hand side (rightmost 256 voxels) of the cube for the reconstructions; emission from voxels outside the resulting 49.152 x 49.152 x 41.152 Mm subsection of the MURaM cube is set to zero in both the forward modeling and the CROBAR reconstructions. Emission from outside this subsection will not be shown in subsequent figures.

2.2. Optical Depth and Related Considerations

One part of the forward and inverse modeling that is essential to consider is the transition from optically thin emission to optically thick in whatever part of the solar spectrum is being observed. Although coronal emission is generally described as optically thin, at some point it transitions to being optically thick; otherwise, we could see through the solar disk in these passbands!

This is complicated by the simplifying assumptions made in the MURaM simulations. Real-world physical processes occur at higher spatial resolution than is computationally feasible, even on a supercomputer—see Rempel (2017). This results in artifacts where the simulation cannot resolve the real physics. For example (Section 2.3 of that paper), a spatial resolution of a few kilometers is required to resolve the transition region where the radiative-loss rate peaks, but the resolution of this simulation is 64 km, which is much coarser than a few kilometers. As a result, the abrupt changes across the transition region are not realized on a fine enough scale and appear to be tens of kilometers across rather than a few. This region of high density and significant emission is therefore much thicker than it is on the real Sun.

While necessary for computational tractability, they result in high-density cusps at the base of the observing region, which can appear to dominate the emission, unlike real solar passband images. CROBAR does not accurately reproduce these, which leads to issues with the reconstructions. To avoid these issues, I set a minimum height cutoff of 2.5 Mm above what I take to be the photospheric height, which in turn is 8 Mm (125 voxel heights) above the base of the simulation. Above this height, I approximate optical depth attenuation with a local extinction factor $e^{-\tau(z)}$ (compare Mok et al. 2016), where $\tau(z)$ is proportional to the vertical integral of the density. Naturally, this is inexact for nonvertical lines of sight. The constant of proportionality is set so that optical depth unity occurs at a column density of $3 \times 10^{19}$ cm$^{-2}$.

These issues might also suggest that CROBAR is not as readily suited to passbands or lines that have a significant contribution from nonoptically thin emission at the footpoints, although I expect that such difficulties can be mitigated with further refinement and iteration (or use of Differential Emission Measures (DEMs), as described in Plowman 2021). This is not simply a question of where the temperature response function is large, however; because emission is proportional to temperature response times density squared ($R(T)n^2$), one must also consider the density where optically thick emission becomes
significant. The condition results in the following inequality:

$$R(T(\tau = 1)) < R(T(\tau \ll 1)) \frac{n(\tau \ll 1)}{n(\tau = 1)}^2$$

(1)

if the emission from optically thin temperatures $T(\tau \ll 1)$ is to dominate over the optically thick emission $T(\tau = 1)$. If the ideal gas law holds and the pressure scale height is large, this becomes

$$R(T(\tau = 1)) < R(T(\tau \ll 1)) \frac{T(\tau = 1)^2}{T(\tau \ll 1)}^2.$$  

(2)

In other words, the $R(T)$ at optically thin temperatures must be greater than at $\tau = 1$ temperature by a factor of the square of the temperature ratio $T(\tau \ll 1)/T(\tau = 1)$. This may have underappreciated implications for the temperatures of other features observed in the corona, such as the moss. The temperature of the most visually apparent features at low heights may be much cooler than the shape of the temperature response function alone would indicate.

2.3. Forward Modeling of the MURaM Cube

The temperature response function for this exercise was the power law with index 2 mentioned in Plowman (2021). This is the ideal response function for this purpose because the emission profile of each region is a function only of pressure and dependence on specific details of the region’s temperature profiles is minimized (see Equations (10) and (11) in Plowman 2021). The linearity assumption is therefore most nearly satisfied. As Plowman (2021) noted, this kind of response function can be synthesized from a DEM, and it is also very similar to some relatively low temperature X-ray response functions such as from the Hinode X-Ray Telescope (XRT; Golub et al. 2007) or Yohkoh Soft X-Ray Telescope (SXT; Tsuneta et al. 1991). I have also noticed that they tend to look quite similar to images from SDO AIA 335 Å (Lemen et al. 2012), suggesting that a large fraction of coronal emission comes from temperatures where that passband has a scaled power-law index of 2. This is a potentially interesting result (it might be thought that the peaks of AIA 335 Å [Lemen et al. 2012] would make it look significantly different than the power-law response, but the temperature response alone is not enough to determine a loop emission profile, as the discussion at the end of Section 2.2 demonstrates), which I intend to investigate further. For this paper, use of the index 2 power law means that the reconstruction performed is of the plasma pressure. A second reconstruction of a power-law temperature response with a different index can be used to recover the plasma properties if desired, as Plowman (2021) describes, but I will defer detailed investigation of that topic to a later paper.

For the reconstructions in this paper, I will consider viewpoints of 0° (overhead) alone, 0° + 60°, and 0° + 90° (90° corresponds to a typical limb view of the region). Those are each shown in Figure 3, along with an equivalent overhead view with the SDO AIA 335 Å temperature response function (the latter shows more "cusp" low-lying emission than the T² channel, more so than with real AIA 335 Å data, so I expect that those features are due at least in part to the simplifying assumptions of MURaM previously mentioned).

Each of these views of the MURaM cube will also be shown alongside the reconstructions.

Figure 3 also shows a longitudinal slice through the region, illustrating that this emission contains interesting structures like those noted by Malanushenko et al. (2022). For example, the apparent pair of loops running from [10,5] to about [45,0] in the overhead view is shown in coordinate [6,5] to [10,10] in the cross section to be a much more complicated composition of features evocative of Rayleigh–Taylor plumes—two or three connected horizontal structures at around 6 Mm in height along with a pair of vertical structures. Similarly, the compact bright loop-like structure running from about [15,−17] to [37,−17] is revealed to be a hollow shape reminiscent of the “koppa” features mentioned by Malanushenko et al. (2022).

3. CROBAR Results

For the CROBAR profiles I assumed an RTV-like (Rosner et al. 1978) profile with an apex temperature of 2.5 MK and an exponential pressure profile with a scale height of 60 Mm MK⁻¹ (150 Mm for 2.5 MK apex temperature), although because I use the $T^2$ power law for the temperature response only the pressure profile affects the results. I also allow the loops to be asymmetric in their emission profile (see also Section 4 of Plowman 2021), with separate coefficients controlling the left and right sides of the loop, which are averaged at the midpoint (given a symmetric overall emission profile of normalized arc length $l$, an asymmetric profile $f_\text{a}(l)$ can be produced from it by $f_\text{a}(l) = c_l l^l(l) + c_r(1-l)^r(l)$; $c_l$ is the coefficient controlling the left side of the loop, and $c_r$ is the coefficient controlling the right side of the loop). Field-aligned regions can have very different geometry at their endpoints, and I prefer to let the observations dictate this behavior rather than imposing symmetry.

CROBAR is built around a $\chi^2$ minimization, which requires a specification of measurement errors or equivalent. In this case the measurement errors are typically the shot noises in the EUV or X-ray observations, so I assume that the errors are proportional to the square root of the forward-modeled intensities, with the constant of proportionality set so that the median error level in the overhead data is 5%. I also added a small amount of $l^2$ norm regularization (2 × 10⁻⁵), enough to smooth the results but not enough to have a significant effect on the goodness of fit. The reduced $\chi^2$ goodness-of-fit parameters with respect to the images were 0.51 for 0° alone, 1.49 for 0° + 60°, and 1.75 for 0° + 90°. The lower $\chi^2$ values for 0° reflect that synthetic data are easier to fit, due to being only one perspective. This is likewise the case for 0° + 60°, since its two perspectives are more similar.

And now, the reconstruction results. I performed a single-viewpoint reconstruction using only the overhead view, a two-viewpoint reconstruction using the overhead and 60° views, and a two-viewpoint reconstruction using the overhead and limb (90°) views. These multiviewpoint reconstructions are easily done in CROBAR’s framework by simply stacking the forward matrices, data vectors, and error vectors. Figure 4 shows the overhead view of all of these reconstructions, Figure 5 shows the 60° view, Figure 6 shows the 90° view, and finally Figure 7 shows the latitudinal slice also shown in Figures 3 and 2.

Overall, the results look quite good to my eyes. Even the single-perspective snapshot reproduces most of the structures seen in integrated emission and many of them seen in the snapshot. This could likely be improved with an
experimentation with the scale height of the field-aligned regions and allowing them to vary from one region to the next. The two perspective reconstructions are even better, with most structures in both the slice and the integrated emission being recovered. This includes the complicated “veil”-like structures pointed out by Malanushenko et al. (2022), which are best shown in the latitudinal slice (Figure 7)—e.g., the curved structure at [10,−17] and the vertically elongated structure running from [15,−12] to [25,−17]. The overhead and 90° reconstruction reproduces the slice best, but this is no surprise considering that it samples the vertical stratification best. To compare how well the different selection of perspectives constrains the volume emission as a whole, I performed an estimate of goodness of fit for the resulting cubes based on a per-voxel (rather than the image level per pixel values reported earlier) $\chi^2$ deviation using the following formula:

$$\chi^2_E = \frac{1}{N} \sum_{ijk} (E_{\text{MURaM}}(i, j, k) - E_{\text{CROBAR}}(i, j, k))^2 / \sigma(i, j, k)^2,$$  

(E stands for emission and $(i, j, k)$ are the indices of the cubes—for this expression, I bin down the CROBAR output so it matches that of the MURaM cube). For the weights, or “errors,” $\sigma(i, j, k)$, I use the following:

$$\sigma(i, j, k)^2 = E_0 E_{\text{MURaM}} + \sigma_0^2,$$  

(4)

where $E_0$ and $\sigma_0$ (the noise floor) are both 20% of the mean value of $E_{\text{MURaM}}$. This makes the minimum “error” equal to 20% of the mean value of the MURaM emission, the mean “error” 28%, and the relative “error” decreases (square root scaling) with increasing per-voxel emission.

Equation (4) is derived by analogy to the errors in many detectors (e.g., CCDs): there is a Poisson (e.g., “shot” noise) term whose size scales with the square root of the signal (in this case the emission) and a constant (e.g., “read” noise) uncertainty term. The first of these contributes the $E_0$ $E_{\text{MURaM}}$ term in the equation, while the second contributes the $\sigma_0^2$ term. While the analogy to read and shot noise may not
be a precise match here, the optically thin observations that the reconstructions are based on are driven by it. Moreover, it nicely encapsulates that brighter features should be given higher priority (though not in proportion to their brightness) and that there is a threshold ($\sigma_0$) below which errors in dim features are not significant. With $E_0 = \sigma_0$, the read noise and shot noise are equal when the emission level is equal to $\sigma_0$.

By this metric, the overhead-only reconstruction scored 9.6, the $0^\circ$ and $60^\circ$ reconstruction scored 5.7, and the $0^\circ$ and $90^\circ$ reconstruction scored 5.0. A second perspective is therefore roughly twice as good by this metric than a single perspective, with $90^\circ$ being slightly better than $60^\circ$ in quality.

In addition to the direct comparisons in emission slices and projections and the quasi-$\chi^2$ figures just mentioned, Figure 8 shows scatter plots for each set of inputs. Each shows a slope of 1, with $90^\circ$ having the smallest spread and $0^\circ$ having the most, as would be expected and consistent with the other comparisons. The horizontal streaks are expected given the resolution.

Figure 4. CROBAR reconstruction of the MURaM $0^\circ$ emission. The top left panel shows original MURaM emission, the top right panel shows CROBAR reconstruction using only the MURaM $0^\circ$ emission, the bottom left panel shows CROBAR reconstruction using MURaM $0^\circ$ and $90^\circ$ emission, and the bottom right panel shows CROBAR reconstruction using the MURaM $0^\circ$ and $60^\circ$ emission. Each panel has an identical color scheme, including minimum and maximum level.
limits of the reconstruction. The figure shows the square root of the emission rather than the emission itself; since we are using the index 2 power law, the square root of the emission is the plasma pressure, so Figure 8 shows direct recovery of a plasma parameter (arguably the most important one) of the simulation.

4. Discussion, Implications, and Conclusions

I have demonstrated that CROBAR can reproduce the complex structures seen in the MURaM simulations reasonably well, provided a valid magnetic skeleton for its $B$-aligned regions. Even a single perspective can obtain usable results, and two perspectives are significantly better. This is despite concerns (Malanushenko et al. 2022) that the “veil”-like nature of these structures (and presumably the real corona that MURaM attempts to model) might frustrate attempts to recover them using a limited number of perspectives. However, I would argue that, despite their complex appearance in cross section, we can expect these veil-like structures to still be governed by the field-aligned (or nearly field-aligned) condition: gradients of the plasma properties (e.g., temperature and density) and emission along the field direction are small and can be represented by a small number of degrees of freedom through much of the volume. CROBAR’s success in recovering this emission from the MURaM simulation is an indicator of the
validity of this expectation. It also possesses the resolution and performance to resolve the complexity of the field-perpendicular structure. Being volume-filling is also an essential property of any decomposition that attempts to recover these structures, and CROBAR’s field-aligned regions possess this property as well.

Figure 6. CROBAR reconstruction of the MURaM 90° emission. The top left panel shows original MURaM emission, the top right panel shows CROBAR reconstruction using only the MURaM 0° emission, the bottom left panel shows CROBAR reconstruction using MURaM 0° and 90° emission, and the bottom right panel shows CROBAR reconstruction using the MURaM 0° and 60° emission. Each panel has an identical color scheme, including minimum and maximum level.
Figure 7. Latitudinal slices of the CROBAR reconstruction and MURaM emission. The top left panel shows original MURaM emission, the top right panel shows CROBAR reconstruction using only the MURaM 0° emission, the bottom left panel shows CROBAR reconstruction using MURaM 0° and 90° emission, and the bottom right panel shows CROBAR reconstruction using the MURaM 0° and 60° emission. Each panel has an identical color scheme, including minimum and maximum level.
4.1. Implications for Coronal Missions Away from the Earth—Sun Line

Although CROBAR can provide 3D information from just a single perspective, the results shown here point out the importance of additional viewpoints and quantify the improvement from adding another viewpoint. They also indicate that both 60° and 90° as additional perspectives provide similar improvements. This suggests that a “drifter” spacecraft, moving from ~45° to 90° over its lifetime, could provide a similar degree of reconstruction quality to one that was “parked” (e.g., at a Lagrange point) over its entire lifetime. This would be similar to the orbits of the STEREO spacecraft. Orbits like that of Solar Orbiter, while usable for science work, would be less desirable from a space weather standpoint owing to inconsistent temporal coverage.

Most coronal space observations have focused on EUV lines or passbands with relatively low temperatures and narrow temperature coverage. However, some of the considerations discussed in Section 2.2 indicate that these are not the best suited to the coronal 3D reconstruction problem. Instead, a passband with a temperature response that is a power law (or at least monotonic), peaked at high temperatures (hotter than the plasma being observed), is ideal. This suggests an X-ray imager (a la Yohkoh SXT or Hinode XRT) or perhaps a relatively broadband EUV imager if a suitable wavelength window can be found. The other option would be to use DEMs, although that requires more lines/passbands (more complexity, weight, and telemetry) and must still include lines or passbands with high temperature response. That said, I have seen surprisingly promising results applying CROBAR to AIA passbands such as 335 Å and 171 Å, or the STEREO passbands (STEREO does not have much in the way of high-temperature coverage; see comment below). I am still investigating this, and it will be the topic of a future publication. I am also investigating application of CROBAR to data from Solar Orbiter (García Marirrodriga et al. 2021), particularly the SPICE spectrograph (SPICE Consortium et al. 2020), and expect this will also be the topic of a future publication.

The short version of the above two paragraphs is that an “optimal” cost/benefit deep space mission to take advantage of CROBAR would include either an imager with soft-X-ray-like temperature response functions (two distinct channels) or an AIA-like instrument with at least five channels and high-temperature coverage at least as good as what’s provided by the 335 Å and 94 Å channels (these are essential for AIA to cover the critical temperature range from $10^{5.4}$ to $10^{6.8}$ K, where many active region field lines have their temperature peaks). It should also observe from roughly 60° (as little as 30° may be workable, but this remains to be tested). No spacecraft has done this to date; STEREO is the closest, but its high-temperature coverage is not well suited to CROBAR and the life span of the remaining spacecraft is highly uncertain.

4.2. Conclusions and Next Steps

The utility of CROBAR as a starting point, giving a 3D emission structure corresponding to a coronal volume from just one or two vantage points, is substantial. It provides a viable path forward for future improvement: with it we can refine and optimize our models of the field with guidance from coronal emission observations, we can add refined models for the field-aligned emission in accordance with modelers, and we can experiment with adding more detailed physics to the framework as opportunity and insight present themselves. Without it, we had been limited to speculating about how our 2D images connect to the actual 3D volume.

This paper has focused on testing for the field-aligned reconstruction concept against the MURA M simulations, but I have already found significant success with initial implementation of the refinements just mentioned in the context of real solar data. I have already implemented a basic tunable field model, in the form of a nonlinear force-free-field, and applied it to CROBAR reconstructions with AIA and STEREO data with very promising results. These will be covered in an upcoming publication. A version of the code will be uploaded to a public repository along with that subsequent publication; in the meantime, the code can be provided on request.

The analysis in this work was carried out in Python, making use of NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), AstroPy (Astropy Collaboration et al. 2013, 2018), and SunPy (The SunPy Community 2020). I would like to acknowledge Matthias Rempel for providing the MURA M cube and Anna
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