Space Weather Prediction Through the Observation and Modeling of Coronal Magnetism

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Final Report

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The overarching motivation for this work is the need to predict the geoeffectiveness of interplanetary coronal mass ejections (CMEs). This is a complex problem, requiring an understanding of the magnetic structure that leaves the Sun in a CME, of how it propagates through and interacts with the solar wind, and of how it impacts the Earth's magnetosphere and couples with the upper atmosphere. We focused on the weak link in the very beginning of this chain: what is the internal magnetic structure of the CME?

The goal of our project was to develop a new methodology for assimilating coronal magnetic diagnostic data into magnetohydrodynamic (MHD) models in order to establish not only the magnetic structure of the source region of coronal mass ejections (CMEs), but also the global field into which it erupts. Our project name is **Data-Optimized Coronal Field Model**, or **DOCFM**.

The unique aspect of our method is that it directly incorporates coronal polarimetric data into magnetic models of the 3D coronal field. Such models are generally done as a boundary problem, drawing upon measurements of the solar surface magnetic field. However, these require often critically limiting assumptions about the nature of coronal currents as the models are otherwise under-constrained. Magnetic currents and the related property of magnetic helicity are fundamental to the structure and eruptivity of solar magnetic fields (Pariat et al., 2015; Dalmasse et al., 2015; Fan, 2016; 2017; 2018a; Raouafi et al., 2016; Janvier et al., 2016; Chintziglou et al., 2017; Fan and Liu, 2019). The DOCFM challenge has been to determine how to use measurements in the corona itself – in particular coronal polarimetry -- to improve specifications of the coronal magnetic field.

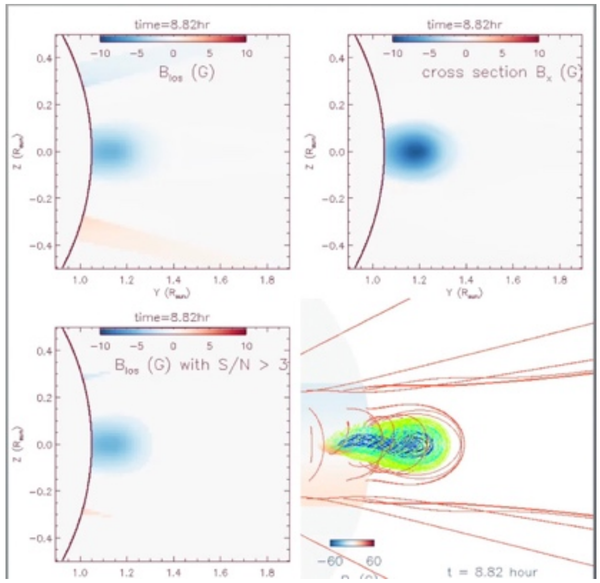

Figure 1. MHD simulation of a magnetic flux rope (Fan, 2017) illustrates the capability of the COSMO telescope (Tomczyk et al., 2016) for making measurements in circularly polarized light that may be directly inverted to yield line-of-sight magnetic field strength in the corona (Fan et al., 2018). The left-hand column shows line-of-sight magnetic field inverted from synthetic COSMO circular polarization data, with (top) and without (bottom) noise taken into consideration. The top right image shows the ground truth line of sight field, and the bottom right shows sample field lines for the flux rope.

1. Measuring the magnetic field

The first challenge was to make polarimetric measurements and demonstrate their sensitivity to coronal magnetic fields. To this end, we used observations taken with the unique Mauna Loa Solar Observatory Coronal Multichannel Polarimeter (CoMP) instrument to develop and constrain models of coronal magnetism. CoMP obtains measurements of the Stokes polarization states that include total intensity (I) and linearly-polarized light magnitude and direction ($L^2=Q^2+U^2$, Azimuth). Circularly-polarized light (V) requires a bigger aperture than the 20cm CoMP, which is a prototype for the planned Coronal Solar Magnetic Observatory (COSMO) large coronagraph. That 1.5 meter telescope will be capable of obtaining unprecedented global circular polarization measurements that can be directly inverted to yield line-of-sight magnetic field strength (**Figure 1;** Tomczyk et al., 2016; Fan et al., 2018).

We also make use of a suite of forward-modeling SolarSoft IDL codes (FORWARD) to convert analytic models or simulation data cubes into coronal observables, including Stokes polarization parameters (I, Q, U, V) directly comparable to CoMP observations. Our primary goal was to develop automated implementation for forward modeling the synthetic equivalents of CoMP data from an initial potential field source surface (PFSS) global field and spherically-symmetric density distribution, using only date as input. Not only did we complete the goal as set, but we also added the capability of automatically synthesizing CoMP data based on the Predictive Science Inc. (PSI) MAS MHD simulation cubes available online (Gibson et al., 2016).

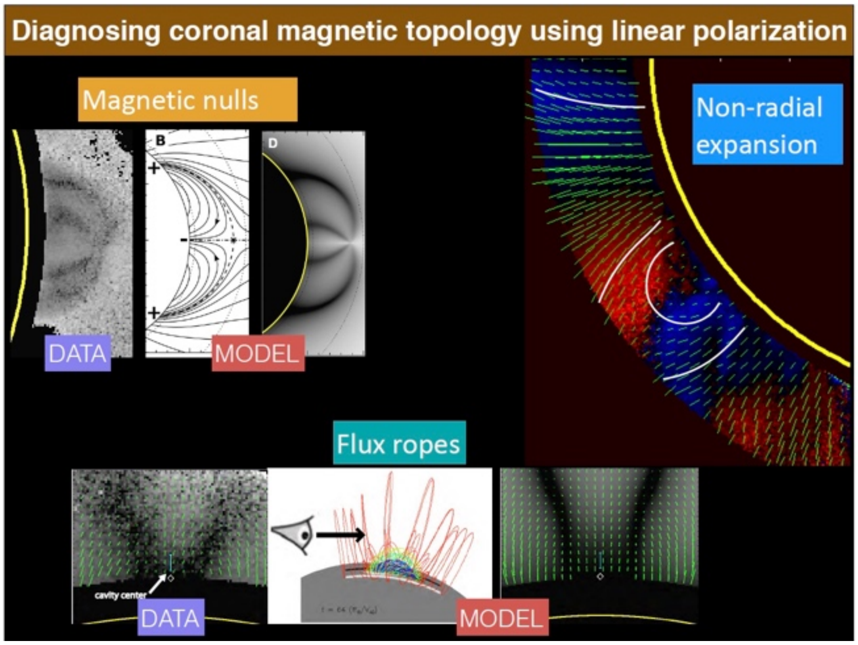

Figure 2. Observations of solar features as observed in CoMP linear polarization demonstrate characteristic topological signatures. Shown are magnetic nulls within coronal pseudostreamers and non-radial expansion (Gibson et al., 2017), and magnetic flux ropes (Bak-Steslicka et al., 2013). Linear polarization data are from the CoMP telescope, the model magnetic fields shown in the middle, and forward-modeled linear-polarization data on the right. See also Gibson (2015).

2. *Modeling the magnetic field in pseudostreamers*

Using FORWARD and CoMP data in combination with magnetohydrodynamic models, we considered how various magnetic configurations appeared in coronal linear polarization measurements (**Figure 2**). We identified CoMP data regions of interest, including cavities and pseudostreamers, that showed sensitivity to coronal magnetic fields (Jibben et al., 2016, Gibson et al., 2017).

Pseudostreamers are common coronal structures that appear at the solar limb as streamers bordering magnetically open regions of the same polarity. They are locations prone to sympathetic eruptions and sources of a hybrid kind of solar wind with properties intermediate between slow and moderately fast wind. The pseudostreamer magnetic topological skeleton, and in particular the magnetic X-point at their cusp, imprints a clear signature in linear polarization that can be used to distinguish pseudostreamers from the larger helmet streamers or two nearby streamers (**Figure 2**, top left).

Gibson et al. (2017) analyzed one pseudostreamer observed by CoMP on April 18, 2015 and found that the observed expansion factor was significantly larger in the CoMP observations than expected from a potential field extrapolation with possible implications for the solar wind speed and the inferred location of the X-point was higher than the height in a PFSS model. To verify if these findings were common to all pseudostreamer topologies, we extended this analysis to more than thirty CoMP pseudostreamers, for which we identified the magnetic nulls and computed the expansion factor. Our goal was to understand if there are systematic differences between these observations and predictions of a potential field model.

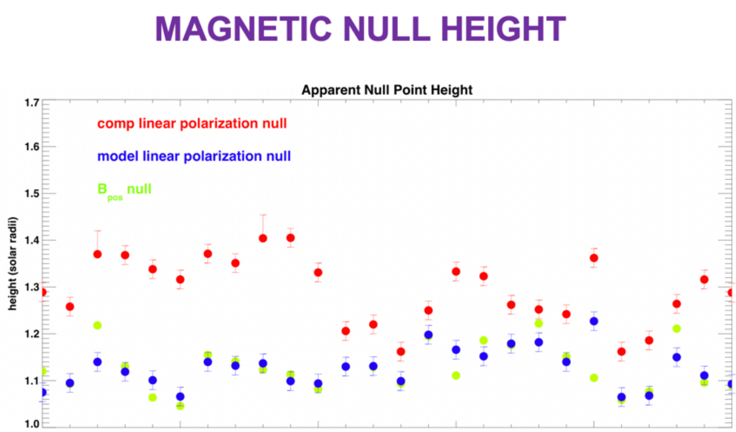

Figure 3. Comparison of pseudostreamer null heights found in observations and models. The red and blue dots represent the height of the null point inferred from the L/I maps for CoMP and PFSS extrapolations, respectively. The green dots give the height of the X-point in the plane-of-the-sky in the PFSS magnetic field maps. De Toma et al., *in preparation*, 2020.

We selected the pseudostreamers based on their appearance in CoMP images. Specifically, we looked for streamers that harbored two coronal cavities and had the typical 3-lobes signature in linear polarization. Magnetograms from the HMI instrument on the SDO satellite and extrapolations obtained with the IDL SolarSoft PFSS package developed by M. DeRosa and incorporated into FORWARD were then used to confirm that the selected streamers were pseudostreamers, i.e. that these structures had two regions of the same magnetic polarity at their boundaries and an X-point at their cusp.

One of our stated goals was to establish density/temperature model dependence on field line topology and strength. To this end, we developed a simple hydrostatic model, with two different densities assigned to open and closed magnetic field lines, and used this to compute the density-weighting on the linear polarization line-of-sight integral in FORWARD. The expansion factor from observations and models was based on the method designed by K. Dalmasse to compute linear polarization expansion factor assuming local variation of the magnetic field and circular cross-section flux-tubes (see Gibson et al., 2017).

We found that CoMP observations systematically indicate magnetic null heights in pseudostreamers that are higher than those predicted by extrapolations of the photospheric magnetic field (**Figure 3**). In particular, the height of the magnetic X-point was higher in the observations than in models for all cases, indicating that PFSS extrapolations systematically underestimate the height of the 2D null point and confirming the previous result found in Gibson et al., 2017. This difference in height is likely due to the currents present in pseudostreamer structures that are neglected in PFSS models. However, the linear polarization expansion factor near the flanks of the pseudostreamers did not show a clear trend and varied significantly with height, at least at the heights covered by the CoMP field-of-view. These results indicate that the larger expansion factor found for the case of April 18, 2015 is not a common feature of pseudostreamers. This finding is consistent with the analysis of Karna et al. (2019a) that showed that the expansion factor is not a robust discriminator between potential and non-potential models.

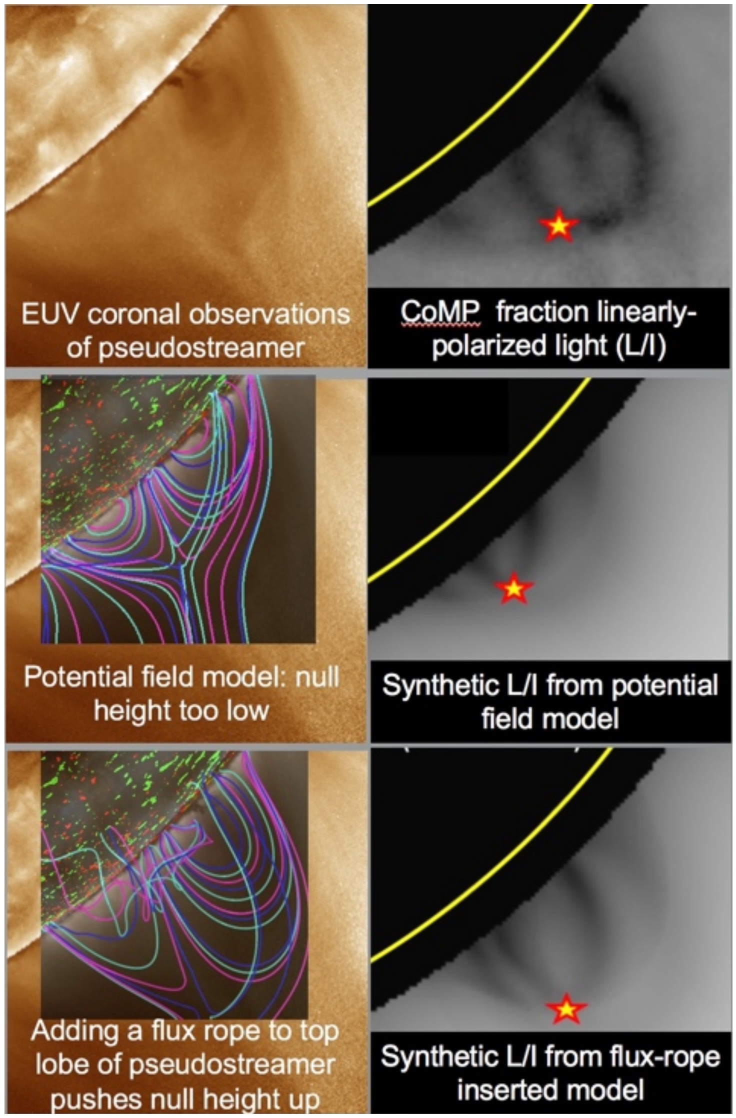

Figure 4. Analysis (Karna et al., 2019a) demonstrating that CoMP observations can be used to diagnose non-potentiality, and to guide models in adding currents in a manner that reproduces the signatures of magnetic topology (e.g., magnetic null height) observed by CoMP.

Karna et al. (2019a) then applied the flux-rope insertion technique to the pseudostreamer of Gibson et al. (2017). By varying model parameters (axial and poloidal magnetic flux) a set of magnetic models were created and investigated using topological characterization (Tassev and Savcheva, 2017). We weighted the plasma with the open vs. closed field hydrostatic density models and used FORWARD to synthesize CoMP-like linear-polarization data. We demonstrated that adding a flux rope to the upper lobe of the pseudostreamer (where a prominence cavity is visible) resulted in a larger closed field region, higher magnetic null point, and stronger magnetic expansion, and overall better matched the linear polarization measured by CoMP (**Figure 4**). In addition, Karna et al (2019b*)* demonstrated that the continued energization of this magnetic flux rope led to a CME from this region, as was observed.

3. Goodness-of-fit criteria

The magnetic null height manifestation in synthetic vs. observed linear polarizations represents one example of a means to distinguish and ultimately optimize models to match observations. Dalmasse et al. (2016) experimented with different goodness-of-fit (GOF) measures, including likelihood and log-likelihood characterizations. We also examined the effect of combining different groupings of the Stokes parameters (I, Q, U, V) of CoMP-like data within the GOF measure, and demonstrated that degeneracy in parameter space can be reduced by including both linear and circular polarization.

Beyond this, one of our stated goals was to consider how complementary data assets might be incorporated in future to improve GOF measures. Gibson et al. (2016) presented a broad range of coronal observations that depend upon coronal magnetic fields that have been include in the FORWARD code distribution. For example, FORWARD-modeled radio emission also presents an avenue for future observational constraints (McCauley et al., 2017). CoMP observations of line-of-sight velocity clearly demonstrate flow along coronal cavity axes that might also be used as a constraint on GOF (Bak-Steslicka et al., 2016).

A particularly interesting development has been the addition of capability to synthesize UV coronal polarimetry to FORWARD. In collaboration with Silvano Fineschi of the University of Torino and Jie Zhao of Purple Mountain Observatory, we explored the complementary properties of IR forbidden and UV permitted line observations for constraining the coronal magnetic field (Raouafi et al., 2016; Zhao et al. 2019). In particular, in the UV, the linear polarization observations are sensitive to line-of-sight magnetic field strength as well as direction (**Figure** 5).

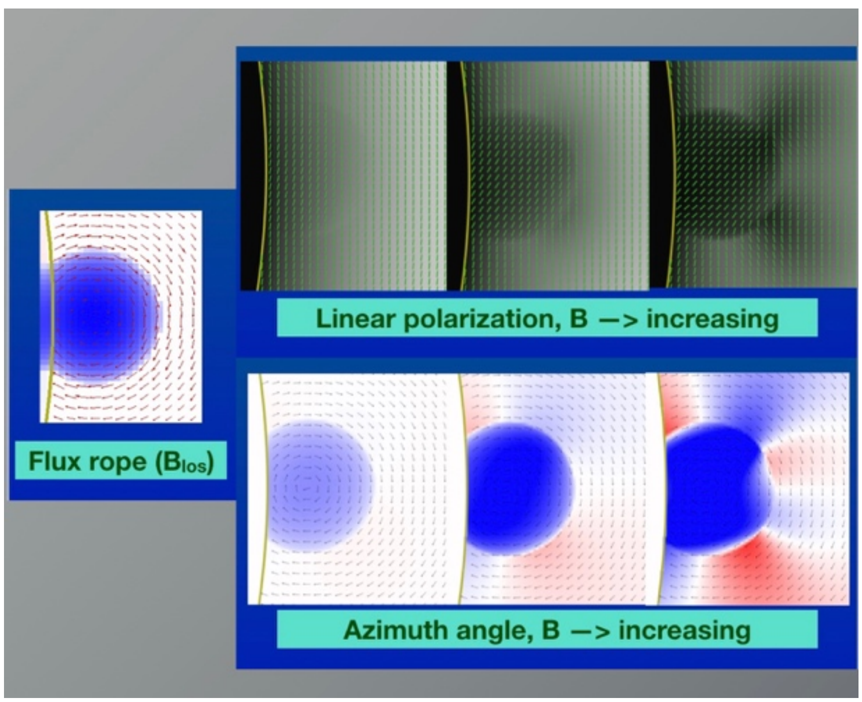

Figure 5. UV linear polarization magnitude and Azimuth angle are directly related to the line-of-sight magnetic field, showing stronger signal with increasing field strength for a forward-modeled magnetic flux rope (Zhao et al., 2019).

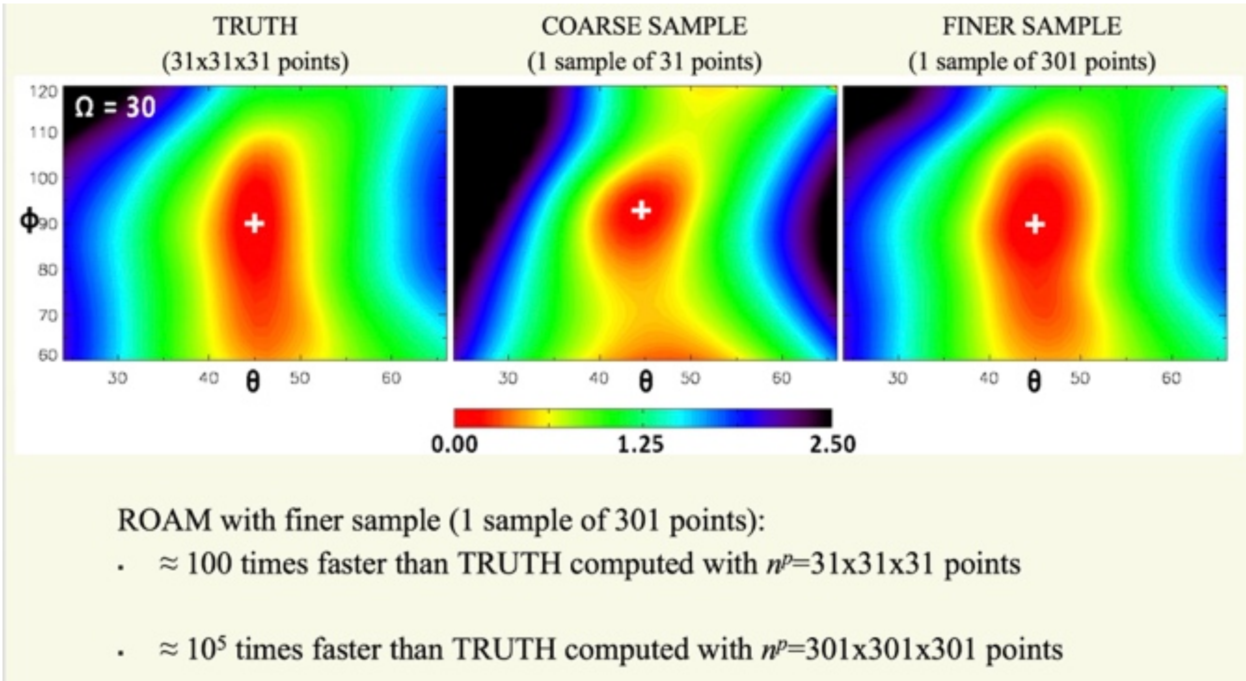

Figure 6. By sparsely sampling parameter space and interpolating, the Radial-basis-functions Optimization Approximation Method (ROAM) achieves orders of magnitude increases in speed vs. a full grid search of parameter space (Dalmasse et al., 2016).

4. Testing the DOCFM framework

Our ultimate goal is to draw all of the above strands together as part of a forward-fitting technique to model the coronal magnetic field in as automated as possible a fashion. To this end, we developed and applied global minimization techniques and advanced statistical methods, demonstrating how they may be used to obtain a best fit between inserted flux rope model and synthetic data.

Dalmasse et al. (2016) developed a new, fast and efficient, optimization method for model-data fitting: the Radial-basis-functions Optimization Approximation Method (ROAM). Model-data fitting was achieved by optimizing a user-specified log-likelihood function that quantifies the differences between the observed polarization signal and its synthetic/predicted analog. Speed and efficiency were obtained by combining sparse evaluation of the magnetic model with radial-basis-function (RBF) decomposition of the log-likelihood function. The RBF decomposition provided an analytical expression for the log-likelihood function that was used to inexpensively estimate the set of parameter values optimizing it. Using a synthetic test bed of a coronal magnetic flux rope, we tested ROAM and showed that it achieved orders of magnitude increases in speed vs a full grid search of parameter space (**Figure 6**).

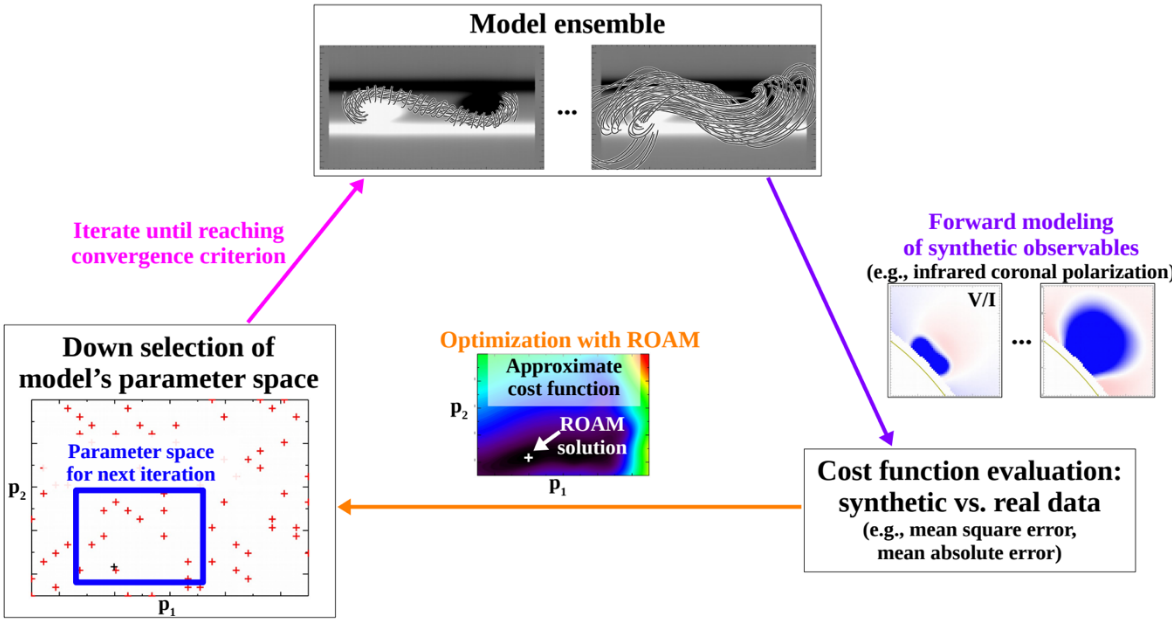

Figure 7. The DOCFM framework.

A test of the full DOCFM framework was presented in Dalmasse et al. (2019), illustrating our general approach to model-data fitting which combines a parametrized 3D generative model with forward modeling of coronal data (**Figure 7**). Our test utilized the parametrized flux rope insertion method and infrared coronal polarimetry where synthetic observations were created from a known "ground truth" physical state, along with an iterative version of ROAM. We showed that this framework allows us to accurately retrieve the ground truth 3D magnetic field of a set of force-free field solutions from the flux rope insertion method.

5. Next steps: towards predictive capability

We are currently investigating the possibility of exploiting CoMP and COSMO observations for mapping and studying the accumulation and release of coronal free magnetic energy, with the goal of developing a new tool for identifying "hot spots" of coronal free energy such as those associated with twisted and/or sheared coronal magnetic fields. This project is being undertaken in collaboration with NCAR SOARS summer undergraduate, Marcel Corchado-Albelo. In the submitted paper Corchado-Albelo et al. (2019), we have applied forward modeling of infrared coronal polarimetry to three-dimensional models of non-potential and potential magnetic fields. From these we defined a quantitative diagnostic of non-potentiality that in future could be calculated from a comparison of infrared, off-limb, coronal polarization observations and the corresponding polarization signal forward-modeled from a potential field extrapolated from photospheric magnetograms. Our work confirms the capacity of polarization measurements for diagnosing non-potentiality and free energy in the solar corona. We are currently extending this research to global models of the energized corona, in collaboration with DOCFM collaborator Duncan Mackay.

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