VCMass: A Framework for Verification of Coronal Mass Ejection Ensemble Simulations

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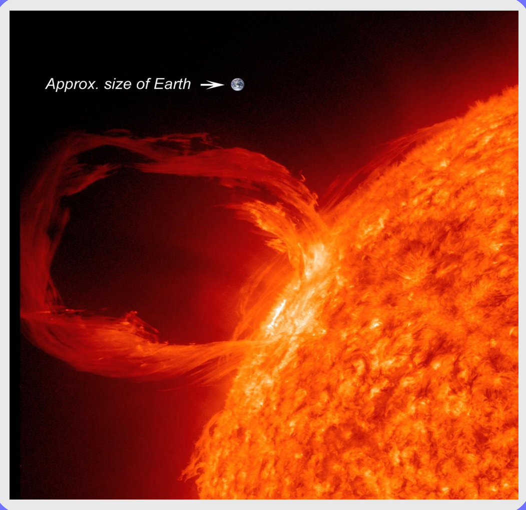
What is Space Weather?

Space weather is the description of the environmental conditions in our solar system and its effects on planetary bodies and spacecraft. The dominant factor in determining space weather is the Sun, as it produces both the solar wind, a constant stream of charged particles, as well as high energy events such as solar flares or coronal mass ejections. These events have dramatic effects on Earth and man-made satellites, which provides immense importance to their prediction.

Coronal Mass Ejections

Coronal mass ejections (CME) are events that occur when magnetic field lines on the Sun reconnect. This accelerates giant plasma clouds into interplanetary space. The biggest CME on record is the Carrington Event from 1859 that generated auroras as far south as the Sahara and damaged telegraph lines worldwide. It is estimated that a similar event today would cause up to $2.6 trillion in damages in North America alone and the resulting power outage could last for up to 2 years.



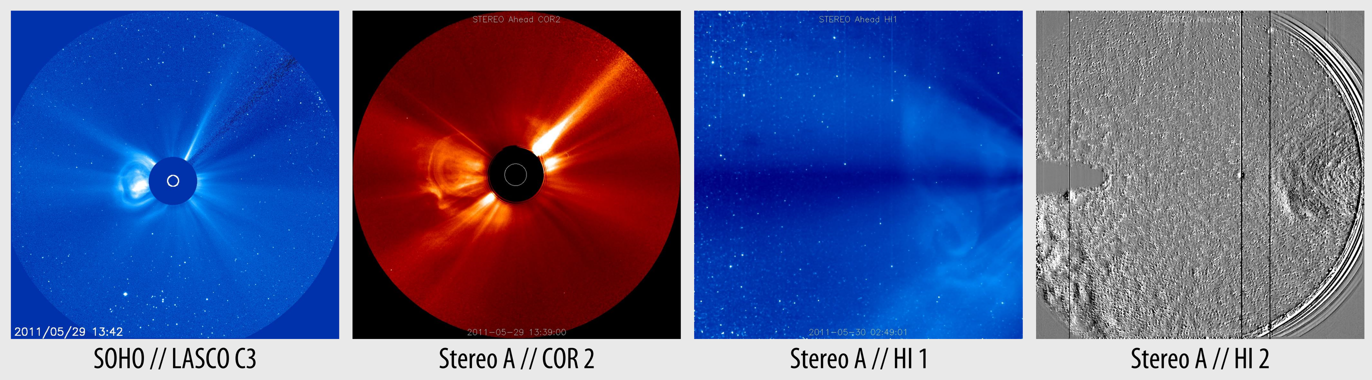
Our framework

Space weather analysts can use our framework to compare ensemble runs that are produced to predict the evolution and propagation of CMEs. Ensembles are necessary as the initial conditions are manually selected, thus introducing measurement errors. Through comparison of these ensemble parameters, the analyst can gain a deeper understanding of the CMEs, a field that is not yet well understood in general.

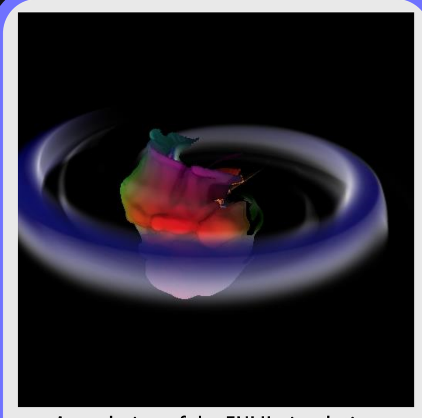
Data

We utilize three groups of data sets in our framework:

1. Imagery collected from coronagraph and heliographic images aboard the SOHO and STEREO A and B spacecraft.
2. Ensemble simulations of the CME that produce 4D volumetric data containing many data fields (e.g., particle density or temperature). Each simulation's initial condition is based on 4 parameters derived from approximating the CME on the imagery using a cone: location (longitude and latitude), velocity, and opening angle.
3. Ground truth measured data of CMEs that impact Earth or a spacecraft in the solar system equipped with appropriate measurement devices.



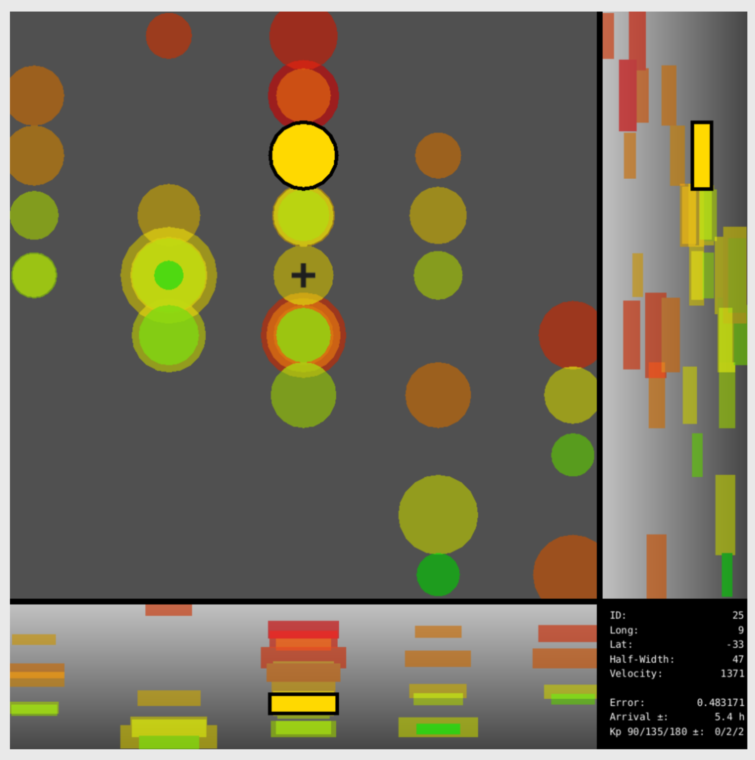
The coronagraph imagers and heliospheric imagers that are used retrieving the simulation parameters and producing image-based comparisons



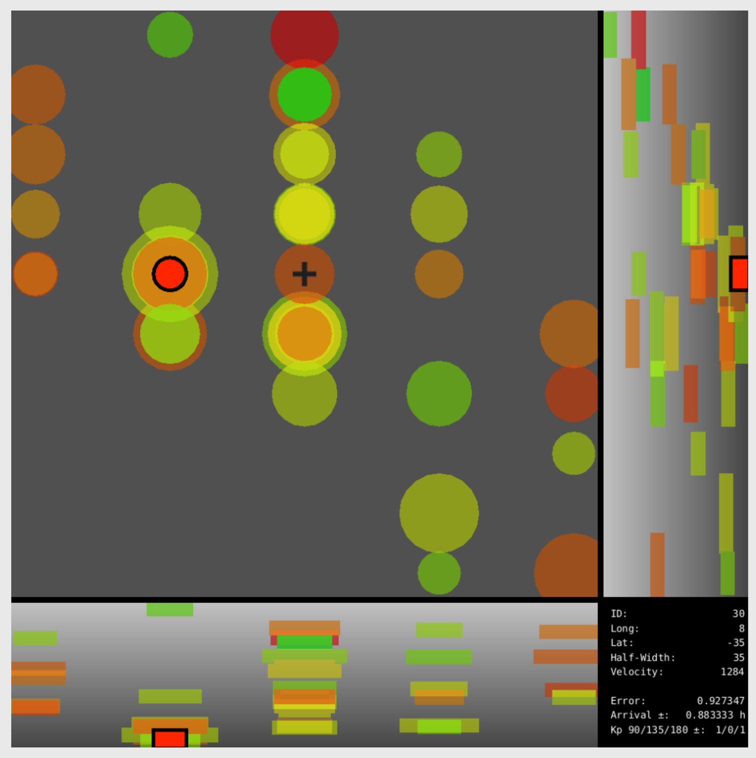
A rendering of the ENLIL simulation

Ensemble Selection View

Using the Ensemble Selection View, the analyst has a direct overview over all ensemble members. The main view shows the longitude and latitude on the horizontal and vertical axis and the opening angle using the size of the glyph. The color coding depends on the chosen error metric. The error metric can either be ground truth data (arrival time, or magnetic field directions) or derived from a time-dependent error, for example an image-based comparison between the satellite imagery and the simulation. The other views show the projection into longitude/velocity and latitude/velocity respectively.



The Ensemble Selection View coloring glyphs by ground-truth arrival times

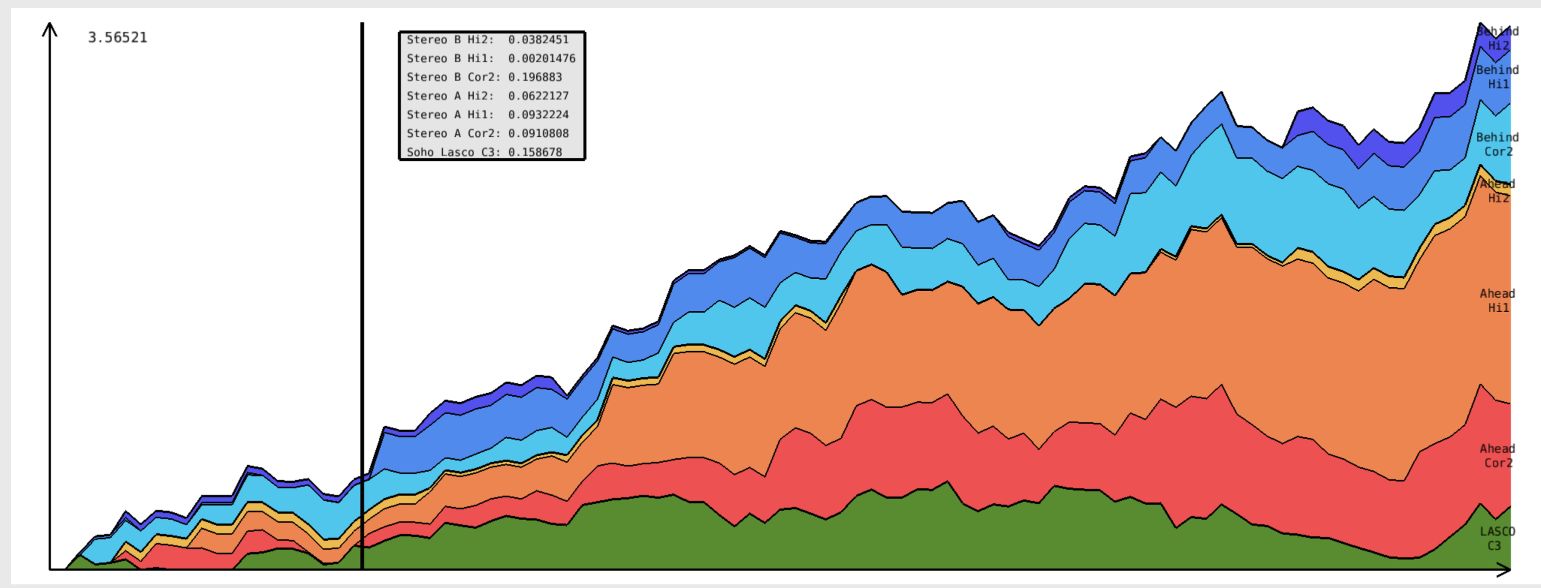


The Ensemble Selection View coloring glyphs by a derived time-dependent error value

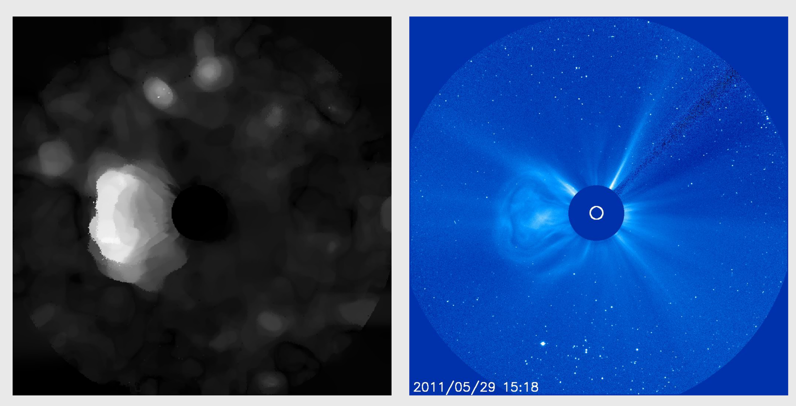
Timeline View

After selecting an ensemble member in the Selection View, the Timeline View shows the evolution of the time-dependent error for the particular member. The algorithm used for computing the error is deliberately held flexible. Currently, we are experimenting with an approach that uses optical flow analysis and a perceptual difference metric to compare a rendering of the simulation data with the satellite imagery for each timestep of the simulation.

The Timeline View allows the analyst to gain a deeper understanding of the error's composition by inspecting each instrument and satellite separately. The color scheme is chosen to maintain a mental registration; a primary color is selected for each spacecraft, and it's instruments use a perceptually close variation of that color.



The Timeline View shows the evolution of the time-dependent error along simulation time. The error can be shown in three ways. First, the total error is shown as a single line. Second, the error is grouped by satellite and shown as a stacked graph. Third, the error for each instrument and each satellite is shown as a stacked graph

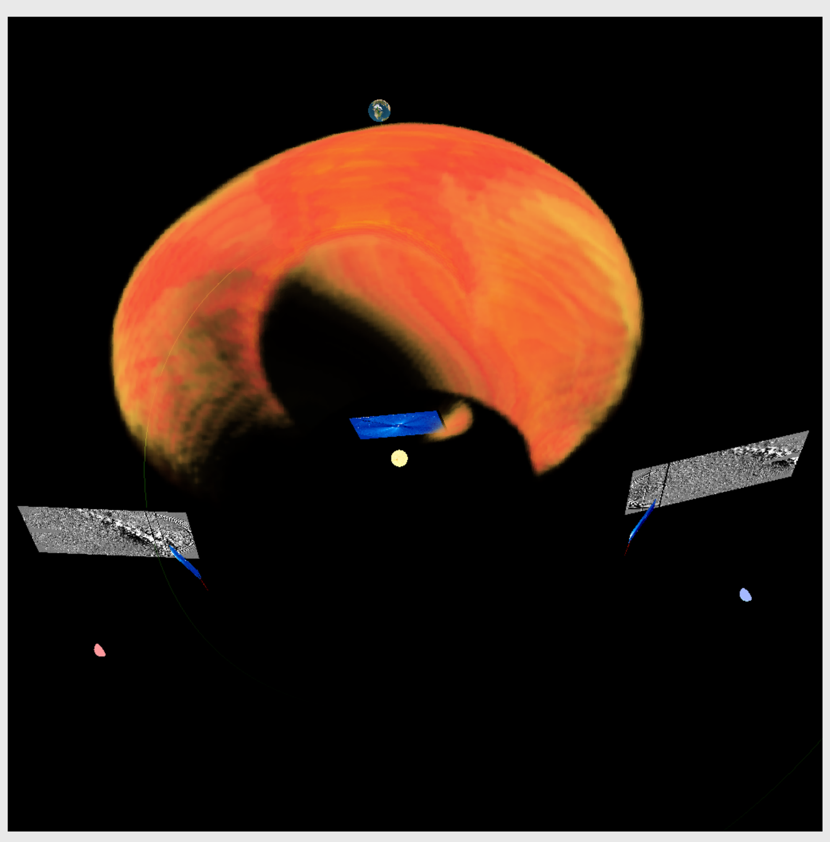


One way of generating the time-dependent error is using image-based, optical flow analysis. By comparing the optical flow between subsequent satellite images (shown here) and the rendering, a perceptual measure of agreement is derived.

Rendering View

Selecting a specific time in the Timeline View loads the appropriate timestep of the simulation in the Rendering View. This view shows the rendering of the CME embedded with planetary bodies as well as the fields of view of the involved instruments. This interactive visualization allows the analyst to inspect the 3D structure of the CME, a task which they cannot perform with their current tools. By using a prototype of our framework, collaboration partners already detected structures in the CME that were previously unknown to the solar physics community.

The simulation is stored in a spherical coordinate system. To circumvent resampling artefacts, we perform the volume rendering in spherical coordinates as well. Each sample on the ray is transformed into spherical coordinates, which are used for the lookup. This technique allows both for an adaptive sampling scheme, as there is more data available closer to the origin, as well as a more accurate interpolation based on SLERP interpolation.



The satellite imagery, as well as the location of planetary bodies and spacecrafts, is embedded into the 3D volume rendering of a selected timestep. Shown here is the timestep right before the CME hits the Earth in the top. All 7 instruments are shown using projective texturing.

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