SECCHI 3D Reconstruction Efforts at NRL

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With inputs from:
R. Howard, J. Newmark, J. Cook, P. Reiser
Currently pursuing three approaches for 3D reconstructions of CMEs and coronal structures (plumes, streamers, etc).

- Parametric modeling (RayTrace)
  *Thernisien, Howard*

- Tomographic modeling (Pixon)
  *Cook, Newmark, Reiser*

- Hybrid Approach (Pixon w/ ARM)
  *Reiser*
RayTrace

• Models the brightness (total and polarized) produced by Thomson electron scattering from an arbitrary electron density distribution.

• The input electron density distribution can be either a 3D data cube or an analytic description.

• The output is a 2D image that simulates the observation in a white light coronagraph (user-defined).

• The observer location, image spatial resolution, the orientation of the density model and the instrumental vignetting function are arbitrary.

• Key contacts:
  Thernisien (raytrace), Patel (GUI), Howard, Vourlidas.
RayTrace Frontend

- Image Resolution
- Observer Position
- Electron Density Position
- Movie Making
- LOS Integration Step
- Model Parameters
- Start Raytracing and Display

From Thernisien et al. 2004
RayTrace Visualization

- Example of a fluxrope visualization in RayTrace.

**Electron Density Positioning**

- Positioning with trackball
- Data image background can be used in order to match structure position

*CME model positioned with GUI and corresponding LASCO/C3 simulation.*

*From Thernisien et al. 2004*
CME Models Currently Implemented

- “2D” Loop
- Spherical shell
- Cylindrical shell
- “Ice Cream Cone”
- Graduated cylindrical shell (GCS)
  - Since the GCS model is a reasonable simulation of a flux-rope CME, we have used it to investigate the appearance of a CME as a function of STEREO separation angle.
  - Parameters are
    - The angular size in the two directions
    - Thickness of the shell
    - The height of the leading edge
    - The orientation of the structure in the corona
    - The radial electron density distribution
Spherical Shell
“Flux Rope” Calculated in 3 Orientations
“Horizontal” Flux Rope

• We present views of the horizontal flux rope as a function of angle from the observer’s viewpoint
  – A halo CME is 0 degrees
  – A limb CME is 90 degrees
• The SECCHI COR2 vignetting function as been applied
Horizontal “Flux Rope”
RayTrace Summary

• We have simulated the effect of the STEREO orbit separation on the appearance and the ability to reconstruct the 3D geometry
• Spherical Shell, Loop, Cone and Graduated Cylinder give recognizable differences
• Stereo separation angles of <20 degrees show little to no stereo effect.
• Polarized Brightness (pB) images have little effect on CMEs at the limb, but considerable effect at large angles from the plane of the sky.
• Complementary to 3D inversion and MHD techniques.
• Could provide constraints to the MHD models.
Tomographic Modeling

• Strategy:
  – Apply 3D tomographic electron density reconstruction techniques to solar features (mainly CMEs).
  – Utilize B, pB, temporal evolution from 2/3 vantage points.
  – Construct (time dependent) 3D electron density distribution.

• Focus:
  – Use theoretical CME models and existing LASCO observations to identify the range of conditions and features where reconstruction techniques will be applicable.

• Goal:
  – Provide a practical tool that will achieve ~daily CME 3D electron density models during the STEREO mission.

• Key contacts:
  – J. Newmark, J. Cook, P. Reiser
Key Aspects

• **Renderer:**
  - Physics (Thomson scattering), tangential and radial pB, total B, finite viewer geometry, optically thin plasma.

• **Reconstruction Algorithm:**
  - PIXON (Pixon LLC), Pina, Puetter, Yahil (1993, 1995) - non-parametric, locally adaptive, iterative image reconstruction.
  - Chosen for speed (<$10^9$ voxels): small number of iterations, intelligent guidance to declining complexity per iteration. Sample times: $32^3$ ~15 min, $64^3$ ~1 hr, $128^3$ ~6 hrs (1 GHz PC).
  - Minimum complexity: With this underdetermined problem, we make minimal assumptions in order to progress. Another possibility is forward modeling

• **Visualization:**
  - 3D electron density distribution, time dependent (movies), multiple instrument, multiple spacecraft, physics MHD models.
3D Reconstruction: CME model (J. Chen)
Three Orthogonal Viewpoints

Figure 5. IMAGES Visualized from Principal Viewpoints
Column Density, Infinite Geometry

Logarithmic \([4.00 \times 10^4, 2.00 \times 10^3]\) electrons \(\text{cm}^{-2}\)
3D Reconstruction: CME model (J. Chen)
Three Ecliptic Viewpoints

Figure 5. IMAGES Visualized from Principal Viewpoints
Column Density, Infinite Geometry

Logarithmic $[4.00e+14, 2.00e+19]$ electrons cm$^{-2}$

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3D Reconstruction: CME model (J. Chen)
Two Viewpoints

Figure 5. IMAGES Visualized from Principal Viewpoints
Column Density, Infinite Geometry

Logarithmic \([4.00 \times 10^{14}, 2.00 \times 10^{19}] \) electrons cm\(^{-2}\)
Limitations

- Limited viewpoints, underdetermined solution. Introduction of third vantage point helps with some objects.
- Limited overlap region of multiple viewpoints. Objects outside one field of view. Intensity contributions from seen by only one telescope.
Hybrid (ARM) Modeling

• Recently we started exploring a 3rd approach to electron density reconstruction.
  – Namely, to incorporate a priori knowledge to the tomographic method (Additional Regularization Method (ARM)).
  – For example, we “know”
    - that electrons should be distributed smoothly along LOS,
    - that the emission should be positive,
    - that the large scale envelope of the CME should be symmetric.

• Paul Reiser tested the effect of several constraints on synthetic data
A Priori Knowledge

Let’s add two constraints:

1. Electron Density Distribution is Smooth

\[
\text{MINIMIZE} \quad P(I) = \chi^2 + \lambda_s P_s(I) \quad \text{Eq. 2}
\]

where \( \lambda_s \) is an adjustable parameter and \( P_s(I) \) is a Penalty function which increases as electron density smoothness decreases.

2. Axial Symmetry

\[
\text{MINIMIZE} \quad P(I) = \chi^2 + \lambda_s P_s(I) + \lambda_\phi \sum_{\text{all voxels}} \left( \frac{\partial I}{\partial \phi} \right)^2
\]

But

- Problem is underdetermined
  (\( 2N^2 \) equations, \( N^3 \) unknowns)
- Solutions are noisy
Hybrid Modeling w/ Axial Symmetry

x view (CCD)  y view (CCD)  z view

"True" density

PIXON reconstruction

Tikhonov reconstruction

Tikhonov reconstruction with axial regularization
Another Example - Unmatched Scenes

What to do when one viewpoint contains additional structure?

Apply axial symmetry regularization only in the voxels shown here.

\[
\text{MINIMIZE} \\
\mathcal{P}(I) = \chi^2 + \lambda_s \mathcal{P}_s(I) + \lambda_\phi \sum_{\text{shell voxels}} \left( \frac{\partial I}{\partial \phi} \right)^2
\]
Unmatched Scenes- ARM Result

Figure 6: Half shell with blob

"True" electron density

PIXON reconstruction

Tikhonov reconstruction with masked axial regularization
Conclusions

- Useful 3D reconstructions are achievable!
- Parametric modeling is easy to implement, fast, and intuitive. It can be directly linked to MHD models. Unlikely to match observations in detail.
- Tomographic techniques achieve better agreement with observations. Time-consuming, error analysis is difficult/complex.
- Incorporation of a priori knowledge in tomographic reconstruction shows great promise. Minimization subject to “magic” selection of parameters (different for each reconstruction). Still time-consuming.
- Tomographic reconstructions are significantly improved with the addition of a third viewpoint (LASCO continuing operation is extremely important).
- Application to SECCHI will require substantial effort and collaboration; we appreciate all help on scientific preparations.
- Web Site: http://stereo.nrl.navy.mil/ (follow link to 3D R&V). This contains past presentations and all necessary details to test reconstruction methods on our sample problems.
Backup

Backup Slides

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Views From STEREO-A and -B
The SECCHI suite consists of 5 telescopes to observe CMEs from their birth at the solar surface through the corona and into the inner heliosphere.

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<th>Telescope</th>
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<th>COR2</th>
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<td>He II 30.4 nm</td>
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Science - Examples

- Geometric figures - uniform density, no background
- Polar Plumes - hydrostatic equilibrium solution of density vs. height, tube expansion, statistics.
- Equatorial streamers - projection of current sheets, effect of AR’s, compare to 3D reconstruction using tie points (Liewer 2001), density enhancements vs. folds.
- CME’s – Use models to prepare for SECCHI, effect of viewpoint angles, velocity, polarization, structure evolution, etc. CME models include time dependence
  - J. Chen – CME, no background
  - P. Liewer – CME + background – not yet studied
  - Z. Mikic – CME, K corona evolution
  - S.T. Wu – CME - not yet studied
- Questions: How to isolate CME? Assume subtraction of F+minimum K corona, but how to handle time dependent K corona? Why we want to: decrease complexity, eliminate structures of equal or greater brightness
3-D Reconstruction Using the Pixon Method

• The problem is to invert the integral equation with noise:

\[ D_n(x) = \int d^3r H_n(x, r)n(r) + N_n(x) \]

• But there are many more model voxels than data pixels.
• And the reconstruction significantly amplifies the noise.
• All reconstruction methods try to overcome these problems by restricting the model; they differ in how they do that.
• A good first restriction is non-negative \( n(r) \).
  \[ \Rightarrow \text{Non-Negative Least-Squares (NNLS) fit.} \]
• Minimum complexity (Ockham’s razor): restrict \( n(r) \) by minimizing the number of parameters used to define it.
• The number of possible parameter combinations is large.
  \[ \Rightarrow \text{An exhaustive parameter search is not possible.} \]
• The Pixon method is an efficient iterative procedure that approximates minimum complexity by finding the smoothest solution that fits the data (details: Puetter and Yahil 1999).
• New modification: Adaptive (Hierarchical) Gridding
“Flux Rope” Calculated in Total B and pB
Evolution of Vertical “Flux Rope” as a Halo