Differential Emission Measure Reconstruction with the Solar-B X-Ray Telescope

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Abstract. Two of the main considerations in the design of the Solar-B X-Ray Telescope are temperature coverage and discrimination. We describe how these factors enter into the design of XRT, as well as the methods we have developed for producing estimates of emission measures. We analyze model DEMs to evaluate our ability to reconstruct DEMs.

1. XRT Design and Temperature Measurements

Two of the main considerations in the design of the Solar-B X-Ray Telescope (XRT) are temperature \( T \) coverage and temperature discrimination. In order to meet the instrument’s scientific objectives by the observation of the solar corona, XRT is required to be able to distinguish plasma structures across \( 6.1 < \log T < 7.5 \), with a temperature resolution of \( \Delta (\log T) = 0.2 \). These requirements affect many aspects of the telescope’s design, such as the channel selections (focal plane filters), the X-ray optical resolution, the white-light rejection, and the quality of the mirror polish.

In addition, procedures for estimating plasma temperatures and emission measures are required in order to interpret the observations and address the scientific goals. The purpose of this study is to evaluate one portion of the XRT objectives: the quality of \( T \) and emission measure (EM/DEM) reconstruction with XRT. In particular, DEM reconstruction is investigated for its quality versus the number of channels used and the \( T \)-range imposed.

The temperature sensitivity of XRT is determined by many factors. Some of the more relevant design elements are (1) the reflectance of the telescope as a function of incoming photon energy; (2) the transmission of the entrance aperture prefilters and the focal plane filters as a function of energy; and (3) the response of the focal plane detector as a function of energy.

A schematic of the XRT telescope is shown in Fig. 1. The telescope is a grazing-incidence annular mirror, with a nominal average grazing angle of 0.9 degrees. For a given mirror design, the main factor governing the temperature sensitivity is the mirror surface composition. Three mirror coatings (silicon, nickel, and iridium) with various energy cutoffs were considered. For the XRT mirror, iridium was chosen as the coating best suited to meet the mission requirements. A plot showing the telescope X-ray throughput versus wavelength is shown in Fig. 2.

The entrance aperture prefilters serve to reject visible light from entering the instrument, and also thereby decrease the heat load, while transmitting more
Figure 1. The Solar-B/XRT flight design.

Figure 2. XRT mirror response function.
than 70% of the X-rays from 2–60 Å. The prefilters are 1200 Å Al on a 2500 Å polyimide substrate.

The focal plane (FP) filters are included to further reduce the visible light reaching the focal plane detector, and to provide variable passbands at soft X-ray wavelengths for plasma diagnostics. The nine FP filters (see Table 1) are designed to have different low-temperature cutoffs; this provides the primary means for meeting the requirement on temperature discrimination. The relatively large number of available analysis filters also helps to constrain DEM reconstructions for observed coronal plasma.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Material</th>
<th>Nominal Thickness</th>
<th>Measured Thickness</th>
<th>Substrate</th>
<th>Material</th>
<th>Thick./Trans.</th>
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<tr>
<td><strong>Entrance:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>thin-Al/poly</td>
<td>Al</td>
<td>1200 Å</td>
<td>—</td>
<td>polyimide</td>
<td>2500 Å</td>
<td></td>
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<td><strong>Focal Plane:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>thin-Al/mesh</td>
<td>Al</td>
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<td>1720 Å</td>
<td>mesh</td>
<td>74.5 %</td>
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<td>thin-Al/poly (1)†</td>
<td>Al</td>
<td>1283 Å</td>
<td>1490 Å</td>
<td>polyimide</td>
<td>2800 Å</td>
<td></td>
</tr>
<tr>
<td>thin-Al/poly (2)†</td>
<td>Al</td>
<td>1283 Å</td>
<td>1520 Å</td>
<td>polyimide</td>
<td>2618 Å</td>
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<tr>
<td>C/poly (1)†</td>
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<td>6000 Å</td>
<td>polyimide</td>
<td>1000 Å</td>
<td></td>
</tr>
<tr>
<td>C/poly (2)†</td>
<td>C</td>
<td>6079 Å</td>
<td>5500 Å</td>
<td>polyimide</td>
<td>2520 Å</td>
<td></td>
</tr>
<tr>
<td>Ti/poly (1)†</td>
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<td>2345 Å</td>
<td>2100 Å</td>
<td>polyimide</td>
<td>4000 Å</td>
<td></td>
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<td>2345 Å</td>
<td>2200 Å</td>
<td>polyimide</td>
<td>2522 Å</td>
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<td>10.2 µm</td>
<td>—</td>
<td>100 %</td>
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<tr>
<td>medium-Al</td>
<td>Al</td>
<td>12.5 µm</td>
<td>12.7 µm</td>
<td>—</td>
<td>100 %</td>
<td></td>
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<tr>
<td>medium-Be</td>
<td>Be</td>
<td>30 µm</td>
<td>27.8 µm</td>
<td>—</td>
<td>100 %</td>
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</tr>
<tr>
<td>thick-Be</td>
<td>Be</td>
<td>1.0 mm</td>
<td>1.12 mm</td>
<td>—</td>
<td>100 %</td>
<td></td>
</tr>
<tr>
<td>thick-Al</td>
<td>Al</td>
<td>25 µm</td>
<td>29.4 µm</td>
<td>—</td>
<td>100 %</td>
<td></td>
</tr>
<tr>
<td>white-light</td>
<td>SiO₂</td>
<td>2.5 mm</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

† For these filters there is both a primary and a spare.

The focal plane detector is a 2k × 2k back-illuminated CCD with 1′0 pixels. XRT will have 2.5× better spatial resolution than the Solar X-ray Telescope (SXT) on Yohkoh (another grazing-incidence imaging telescope for soft X-rays). This ratio is the same as that between TRACE and SOHO/EIT — the improvement is illustrated by Fig. 3. In full-disk mode the effective improvement is a factor of 5. Note that the improvement of XRT relative to SXT exists in all of the soft X-ray channels, and that XRT also has an EUV channel using the thin Al on mesh filter. The latter will have resolution comparable to that of SXT because the XRT is diffraction-limited.

As pointed out many years ago (Craig & Brown 1976), there are limitations to the ability to determine a source temperature distribution of a hot plasma by spectroscopic means. The main limitation is a fundamental one: the flatness of the emission kernel due to the Boltzmann width $e^{-\epsilon/kT}$. This makes the spectrum relatively insensitive to the DEM, and makes the inversion problem poorly-determinable. We therefore do not expect any significant improvement
in temperature discrimination in XRT relative to SXT. However, the improved spatial resolution will likely provide views of more nearly isothermal plasma, thereby improving the effectiveness of the diagnostics.

The net throughputs of the XRT and SXT telescopes in two sets of similar filters are displayed in Fig. 4 as the effective area versus wavelength. In comparison to SXT, XRT shows a significantly greater effective area, and extended response at both short and long wavelengths. Although it is not shown here, XRT will also have better temperature coverage than GOES/SXI.

2. Iterative Forward Modeling of DEMs

We wish to find the “best” fitting DEM for a given set of observations in several spectral channels. Here we consider a set of XRT images taken of an active region (AR). We assume that the structure of the AR loops is unchanged during the time it takes for XRT to accumulate all of the images. Before processing,
In this section, we discuss how we estimate the DEM in a given pixel. Our procedure produces an iterative least-squares fit to the observations using a DEM represented by a spline with evenly spaced knots in log($T_e$) space. For the set of observations (all $c$) in pixel $i$, we solve the simultaneous equations

$$O_{ic} = \int Q_i(T) I_c(T) \, dT,$$

where $O_{ic}$ is the observation of the $i$-th pixel in spectral channel $c$, $Q_i(T)$ is the differential emission in the $i$-th pixel, and $I_c(T)$ is the instrumental response function for channel $c$ for an emission measure that is independent of $T$. With the forward modeling approach, we assume a DEM, apply Eq. (1), and compare the predicted observations for each filter with the real observations. The optimal DEM spline is found using IDL mpfit routines from Craig B. Markwardt.† These routines use the non-linear least-squares method based on the MINPACK-1‡ routines.

A basic problem with the forward modeling approach is determining the relevance of the best-fit solution. The XRT focal plane science filters are distinguished by the amount of transmission at long wavelengths (low energy photons). Towards shorter wavelengths (higher energy photons), the transmissions of all of the focal plane filters approach unity. It is easy to see that these filters do not form an “orthogonal” basis set for temperature and emission measure determinations. There are likely to be multiple nearby minima that have substantially different DEM($T$) curves. To address this issue we expand our nominal set of observations into 100 different Monte Carlo realizations by adding random noise,

†http://cow.physics.wisc.edu/~craigm/idl/idl.html
‡http://www.netlib.org/minpack/
consistent with the photon noise, to the observations. The best least-squares fit to each of the realizations is then determined. Our confidence in the fit is measured by the fluctuations in the fits about the median best fit.

3. Results

To assess the efficacy of DEM reconstruction, we have applied the DEM software to XRT observations simulated using known input DEM models and compared the results for the derived DEMs with the models. In this paper, we discuss a selection of three analyses that illustrate the quality of DEM reconstruction that can be achieved with XRT.

In each of the following cases, a nominal observation is calculated for a given DEM model, and then the procedure samples the observation 100 times by including random photon noise at the 3% level. The distribution of calculated DEM curves (relative to the known DEM model) indicates the accuracy and robustness of the analysis method, as discussed in the previous section. We

Figure 5. Fitting single-$T$ DEMs. In these plots, $\log T_{\text{model}} = (a) 6.1; (b) 6.4; (c) 6.7; (d) 7.0$. The model DEM is shown as a solid line; the grayscale shading indicates the density of 100 Monte Carlo estimates; and the diamonds indicate the median fit.
have indicated the median member of each set of realizations as an estimate of the model DEM.

**Single-\(T\) DEMs** We started off by investigating the simplest case, that of an isothermal region, which is characterized by a single-temperature emission measure. In Fig. 5 we provide four “single-\(T\)” DEM fits. Here we fit the signals of several model isothermal regions of different temperatures: \(\log T = 6.1, 6.4, 6.7,\) and 7.0. Each plot shows the input delta function DEM over the temperature range of 5.5–8.0 \(\log T\) (solid line), the 100 Monte Carlo realizations in each temperature bin as fitted over this same range (grayscale), and the median of all realizations for each temperature bin (diamonds). For each plot all nine filters are used and the assumed error is 3 %.

Figure 5 demonstrates that the emission measure of an isothermal region can be fitted with good accuracy. In particular, we observe that each single-\(T\) DEM fit successfully locates the signature temperature of the region by placing most of the power in the temperature bin corresponding to the impulse of the delta function, with a smaller amount placed in the adjacent bins. In addition, we note that XRT’s ability to find the correct \(T\) is independent of the temperature of the observed plasma; that is, each of these DEM fits is equally good. Recall that the fitted DEM is a spline curve through several knots; although this is not the best function for fitting a delta function, our results are still quite good.

Another interesting observation is that although the peak of each fit is well-placed, its median value consistently falls somewhat lower than the input value of the original DEM. We tentatively attribute this to conservation of the original EM (the fit model must reduce power at the peak in order to place power in adjacent bins). However, we plan to investigate this question more thoroughly.

**“Real” AR DEM and the Value of Many Channels** The corona is known to be highly inhomogeneous in temperature, density, and magnetic field — the isothermal approximation is often inadequate for describing the optically thin solar atmosphere across length scales comparable to the span of an XRT pixel. The actual DEM distribution in an active region is thus expected to include material across a wide temperature range. We analyzed our DEM procedure using a realistic DEM model that is included in the CHIANTI database (Young et al. 2003, and references therein). This model of an active region DEM (CHIANTI file “active_region_os6.dem”) was derived by K. P. Dere from observations of the Sun (Dupree et al. 1973) by the scanning spectrometer on OSO-6 (Huber et al. 1973).

Figure 6 suggests how well the input DEM can be reconstructed as a function of the number of observing channels used. In Fig. 6a, four XRT channels have been used to perform fits. The figure shows the model AR DEM (solid line with two humps), the distribution of fitted DEMs (grayscale), and the median values of the 100 DEM runs (diamonds). The DEM is fitted over the log temperature range 5.5–8.0 and 3 % noise is assumed. These relatively thick XRT filter channels determine the presence of the hotter peak of material, as indicated by the convergence of the median fit to the model DEM curve, but fail to detect the cooler material. The narrow uncertainty bands indicate that the fits are robust or, in the words of one author, “reliably bad”.
Figure 6. Fitting a “real” AR DEM. Increasing the number of channels increases the goodness of the reconstruction.

In Fig. 6b, the same model is fitted with eight XRT channels; that is, we have included thinner filters in the analysis. It is obvious that the fitted DEMs more accurately reproduce the model DEM curve across the entire temperature range. Even though the uncertainty bands are not as constrained as in Fig. 6a, they adequately indicate the presence and temperature of the cool component. To achieve good results in DEM reconstruction with XRT data, it is thus important to have observations in many (independent) channels.

Effects of Temperature Range The DEM estimate can become even more accurate as we vary the temperature domain of the fitting procedure. In Fig. 7 we provide two DEM fits over different temperature ranges, but using the same set of eight filters. Each plot shows the model DEM over the temperature range of $5.5 - 8.0 \log T$ (solid line), the 100 Monte Carlo realizations in each temperature bin within the specific temperature range chosen for the fit (grayscale), and the median of all realizations for each temperature bin (diamonds). The temperature range for the DEM fit is $5.5 - 8.0 \log T$ in the first plot and $5.7 - 7.5 \log T$ in the second. For both plots the assumed error is 3%.

Figure 7 shows that the choice of temperature range for a DEM fit affects the quality (accuracy and precision) of the fit. This suggests that there might be an optimal temperature range over which to fit the DEM, at least for a given set of filters. While the relationship of temperature range (and of filter set) to quality of fit is not an obvious one, this question clearly requires further attention.

4. Conclusions

The XRT instrument is well-designed for temperature coverage and discrimination. Software has been produced to make DEM estimates using XRT data, and the analysis described in this paper has led to increased knowledge of XRT’s abilities. Isothermal plasma is identified correctly throughout the temperature
Figure 7. Fitting to “real” AR DEM is affected by temperature range. Estimate DEM over log $T = (a)$ 5.5–8.0; and (b) 5.7–7.5. The model DEM is shown as a solid line; the grayscale shading indicates the density of 100 Monte Carlo estimates; and the diamonds indicate the median fit.

range of the instrument. Multithermal DEMs can also be reliably estimated with a sufficient number of independent channels (approx. six or more), while an insufficient number of channels can lead to “reliably bad” estimates. It is also apparent that the choice of temperature range for the solution method can influence the results. Further research will investigate the nature of this influence.

References