Characterizing the Temperature Discrimination Capability of the X-Ray Telescope (XRT / Hinode)

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0. Abstract

The X-Ray Telescope (XRT) is one of the instrument packages on-board the *Hinode* satellite observatory. This instrument can image the full solar disk, or a smaller area, in each of nine broadband X-ray passbands, with a resolution of about one arc-second, using a modified Wolter-I grazing-incidence telescope. With the inclusion of a coronal spectral model (as a function of temperature), thermal diagnostic analysis can be performed across a temperature range of log T = 5.5 to ~8.0. Using the method of Singular Value Decomposition (SVD), we present an analysis to characterize the temperature discrimination abilities of the XRT passbands when used as a set--- this analysis is independent of DEM solution methods. We consider how the temperature diagnostic capability is uneven across the useful temperature range. This information could be useful in designing thermal studies to increase the robustness of the temperature solutions, and in interpreting XRT data with physical models.

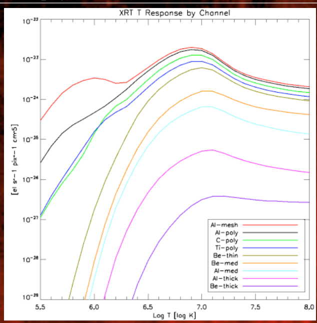


Figure 1. XRT temperature responses in x-ray passbands. Channel names correspond to selection of the diagnostic filters.

1. Introduction

The temperature response functions of the XRT passbands are broad and overlapping (Fig.1). These functions combine the instrument channels' effective areas with a model of solar emission. The units are "CCD signal (electrons) per second per EM", where EM is the columnar emission measure and goes approximately as n_e^2 for a collisionless plasma such as the solar atmosphere. The *differential* emission measure DEM is the temperature *(T)* distribution function satisfying Eq.1 for the observation I_c in channel *c* with temperature response $R_c(T)$.

$$I_c = \int R_c(T)\, \mathrm{DEM}(T)\, dT \qquad \text{[Equation 1]}$$

A set of XRT observations can be used to solve the inversion of Eq.1 and thus derive the DEM, giving temperature and emission measure information about the observed solar plasma. However, the ability of XRT to "resolve" similar temperature profiles is subject to some complications:
- the inversion is ill-posed;
- the formal errors must be propagated; and
- the DEM is often solved for more free parameters (i.e., temperature bins) than there are channels, making the problem under-constrained.

Therefore, the ability to perform *T* diagnostics is sensitive to the ability to distinguish between similar observations. In this poster, we investigate XRT's temperature discrimination capability by looking at the separation of observation vectors as a function of the plasma T observed.

2. Method

The XRT temperature response functions can be thought of as a linear mapping R'_{cT} between an "observation" vector of dimensionality $N_{channels}$ (equals the number of channels in a single set of observations) and a "DEM" vector space of dimensionality N_T, where N_T is the number of *T* bins spanning the solution range (Fig.2). For this analysis, we chose N_T = 26. (It is not uncommon to choose bins of width 0.1 dex, and this nicely covers our range of log*T* = 5.5 to 8.0. We desire detail in our results, and we do not need to actually solve the under-constrained inversion problem in this analysis.)

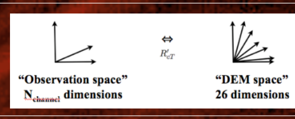


Figure 2. Response functions as a linear mapping between an "observation" vector space and a "DEM" vector space.

The thought experiment for this analysis:
- Two areas j and k within the XRT FOV.
- Isothermal temperatures (T_j, T_k) and DEMs (DEM_j, DEM_k).
- Observations (x_j^c, x_k^c) in multiple x-ray channels with index c = {1…$N_{channels}$}.
- Uncertainties on observations (σ_j^c, σ_k^c).

The Question: Is the observation vector $x_j^c \pm \sigma_j^c$ equivalent to, or distinguishable from, the vector $x_k^c \pm \sigma_k^c$? (For every pair of T_j, T_k.) The quantification of this answer provides a map of XRT's temperature discrimination capabilities.

Details to be considered:
- XRT's digitized measurements have a dynamic range of ~ 2000x.
- XRT's exposure control has a dynamic range of > 10,000x.
- For the coolest temperatures, a DEM might not be observable in both the thinnest and thickest filters (i.e., saturation or zero counts).
- For large measurements, uncertainty is dominated by counting statistics.
- For small measurements, we estimate a minimum uncertainty of 5 DN. (This may be generous. The error calibration of XRT is work in progress.)

How we quantify separation between two observation sets: Δ_{jk}
- If one wished to examine the difference between two measurements in just one channel c1, where the observation pair is $x_j^{c1} \pm \sigma_j^{c1}$ and $x_k^{c1} \pm \sigma_k^{c1}$, one would look at their difference relative to their mutual error σ_{jk}^{c1} :

$$\delta_{jk}^{c1} = (x_j^{c1} - x_k^{c1}) / \sigma_{jk}^{c1}, \text{ where } \sigma_{jk}^{c1} = [(\sigma_j^{c1})^2 + (\sigma_k^{c1})^2]^{1/2}.$$

- If $\delta_{jk}^{c1} < 1$, then the two measurements are likely the same.
- If $\delta_{jk}^{c1} \geq 2$ or 3, then the two measurements are likely to be different.

- To quantify the vector separation across all the channels at once, we sum this quantity in quadrature over the channels:

$$\Delta_{jk} = (1/81) * \{ \textstyle\sum_c [(x_j^c - x_k^c) / \sigma_{jk}^c]^2 \}^{1/2}$$

- Note that this is equivalent to a chi-square comparison of a dataset with a model, except that we are comparing two datasets with each other.
- The factor of (1/81) normalizes the scale of Δ_{jk} to match that of δ_{jk}^c for a dataset with 9 XRT channels (the baseline set for thermal diagnostics):
- If all nine values of δ_{jk}^c are ~ 1, then Δ_{jk} ~ 1;
- if all nine values of δ_{jk}^c are ~ 3, then Δ_{jk} ~ 3; et cetera.
- Note that smaller data sets are "penalized" by this normalization--- unused channels are effectively treated as if their respective values of δ_{jk}^c = 0.

What we did:
- For the set of 26 isothermal temperature bins in the XRT response range, we evaluated Δ_{jk} for every combination pair of isothermal DEMs.
- Figure 3 illustrates a few of these DEM pairs that were evaluated.
- Figure 4 illustrates the mapping of our results.

3. Results & Discussion

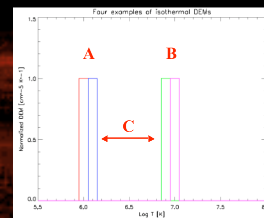


Figure 3. Four examples of the 26 "isothermal" DEMs. Called "isothermal" because they are much narrower than the response curves. Note that these 26 DEMs are also the coordinate axis vectors for the 26 dimensional "DEM space". Furthermore, 3 examples of DEM pairs are labeled {A, B, C} and can be found in Figure 4.

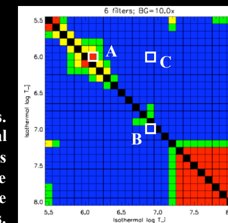
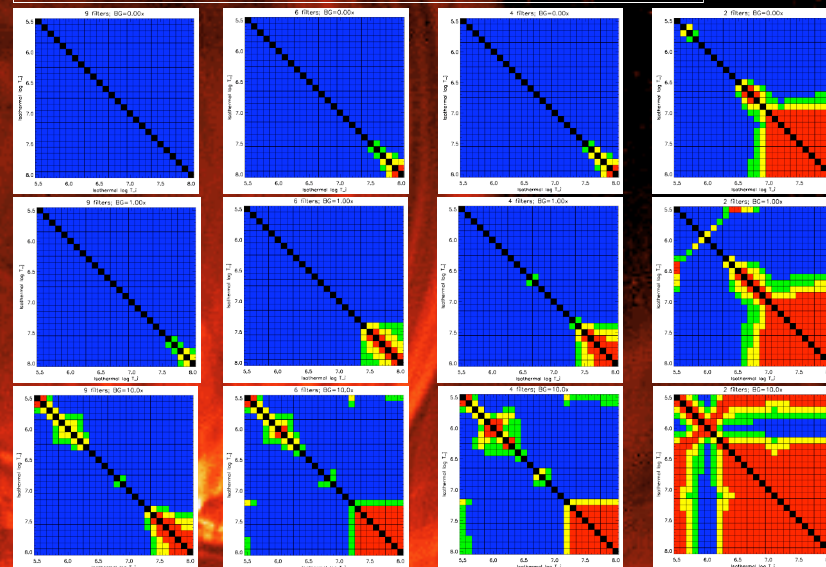


Figure 4. An example of the graphical plots with which we present our results. Shown is a color-coded symmetric matrix of Δ_{jk} results for all pairs of isothermal DEMS, where j,k run from log T = 5.5 to 8.0 in 26 bins. The 3 coordinate points labeled {A, B, C} correspond to the 3 DEM pairs shown in Figure 3. The meaning of the color codes is given in Table 1 (below), and they indicate the confidence level at which XRT can distinguish that pair of temperatures.

What's the difference between these plots?:
- Temperature discrimination generally improves with increasing number of channels. We analyzed Δ_{jk} for the baseline set of 9 single-filter channels, and for sets of 6, 4, and 2 filters.
- In practice, it is difficult to find isothermal plasmas in the corona along a line of sight. Even techniques of background subtraction are tricky to get right. Therefore we also analyzed Δ_{jk} with extra background emission measure distributed across the temperature bins, to confuse the signals. The level of background emission measure we applied is expressed as a multiple of the emission measure contained in the "isothermal" DEMs.

Table 1: Confidence levels for Δ_{jk}

$\Delta_{jk} = 0$
$0\,\sigma \leq \Delta_{jk} < 1\,\sigma$
$1\,\sigma \leq \Delta_{jk} < 2\,\sigma$
$2\,\sigma \leq \Delta_{jk} < 3\,\sigma$
$3\,\sigma \leq \Delta_{jk}$



- 9-filters={See Figure 1}. 4 filters={Al-mesh,C-poly,Be-thin,Be-med}. 2 filters={Al-mesh,Al-poly}.
- 6 filters={Al-mesh,Al-poly,C-poly,Be-thin,Be-med,Al-thick}.

- A conclusion of this analysis is that filter sets can optimized to focus on selected temperature ranges, allowing a reduction in the amount of telemetry required.
- However, these results should be used with caution, since the DEMs were highly idealized. The temperature discrimination of XRT for more realistic, multithermal DEMs will require more sophisticated, thorough analysis.

Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and the NSC (Norway).