Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 57 (2016) 1286–1293
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Seeing the solar corona in three dimensions

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Received 7 March 2015; received in revised form 29 May 2015; accepted 30 May 2015
Available online 7 June 2015

Abstract

The large availability and rich spectral coverage of today's observational data of the solar corona, and the high spatial and temporal resolution provided by many instruments, has enabled the evolution of three-dimensional (3D) physical models to a great level of detail. However, the 3D information provided by the data is rather limited as every instrument observes from a single angle of vision, or two at the most in the case of the STEREO mission. Two powerful available observational techniques to infer detailed 3D information of the solar corona from empirical data are stereoscopy and tomography. In particular, the technique known as *differential emission measure tomography* (DEMT) allows determination of the 3D distribution of the coronal electron density and temperature in the inner corona. This paper summarizes the main technical aspects of DEMT, reviews all published work based on it, and comments on its future development and applications.

Keywords: Corona; EUV; Tomography

1. Introduction

The solar corona can be observed in white light, EUV, X-ray, and radio wavelengths. Being the corona optically thin in these spectral ranges, its images are two-dimensional (2D) projections of the 3D emitting structure. Detailed knowledge of the 3D distribution of the fundamental plasma parameters of the solar corona ($\mathbf{B}, N_e, T_e$) is highly desirable to advance its modeling. Stereoscopy and tomography are powerful observational techniques of the corona, that allow to infer quantitative 3D information. An excellent introduction to solar stereoscopy can be found in Inhester (2006). A recent general review on both techniques covering all the spectral ranges listed above can be found in Aschwanden (2011), with a strong focus on stereoscopy. In this review we specifically focus on *differential emission measure tomography* (DEMT) in a more extensive fashion, updating on all published work in the field at the moment of writing this article.

Minnaert (1930) originally developed the scattering theory of the photospheric white light (WL) by the free electrons of the corona, that allows to infer the 3D distribution of the coronal electron density from WL images. van de Hulst (1950) was the first to perform a global corona reconstruction using eclipse images and assuming full azimuthal axi-symmetry, an assumption firstly relaxed by Leblanc et al. (1970). It was Altschuler and Perry (1972) who developed the first actual solar rotational tomography (SRT) using coronagraph data. A good review on WL SRT can be found in Frazin (2000) and Frazin and Janzen (2002), who developed a robust, regularized, positive method for tomographic inversion of the coronal density from time series of WL images. Later on, Frazin et al. (2005) first introduced the concept of DEMT, a technique

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http://dx.doi.org/10.1016/j.asr.2015.05.047
0273-1177/

which uses time series of EUV images to determine the 3D distribution of the coronal local-DEM (or LDEM).

DEMT was developed by Frazin et al. (2009), and firstly applied by Vásquez et al. (2009) to study the 3D structure of coronal prominence cavities. The technique consists of two steps. In a first step the tomographic inversion of time series of full-sun EUV images is performed, to find the 3D distribution of the EUV emissivity in each filter band of the telescope. In a second step the emissivities found for all bands in any given coronal location are used as a constraint to infer the LDEM. Finally, moments of the LDEM are taken, as a result of which global 3D maps of the coronal electron density and temperature are produced.

In this review we summarize the main aspects and applications of the DEMT technique. Sections 2 and 3 describe and illustrate the two steps of DEMT, Section 4 is a review of published results using the technique, and Section 5 summarizes its main characteristics and future prospects for its development and application.

2. The tomographic model of the corona

To perform the EUV tomography, the inner corona volume in the height range 1.00–1.25 $R_\odot$ is discretized on a $25 \times 90 \times 180$ (radial × latitudinal × longitudinal) spherical grid. Due to optical depth issues (analyzed in detail in Frazin et al. (2009)) and EUV signal-to noise levels (which depend on the particular filter), the results are reliable typically in the height range from 1.03 to 1.20 $R_\odot$.

For each filter band of the EUV telescope separately, time series of full-sun EUV coronal images covering a complete solar rotation are used to find the 3D distribution of an emissivity-type quantity known as the *filter band emissivity* (FBE). The FBE of each EUV filter is the integral over wavelength of the coronal spectral emissivity multiplied by the passband of the filter. The intensity in each pixel is a line-of-sight integral of the FBE. The intensities of all pixels of all images can be arranged in a single very large column vector, as well as the FBE in every cell (or voxel) of the tomographic grid. In this way, both vectors are linearly related through a very large non-square sparse projection matrix, that depends on the geometry of the observations. Both the projection matrix and the pixel intensity vector are known, and the problem is to find the FBE vector. This poses a non-invertible linear problem for each band separately, which is the tomographic problem.

In the case both instruments the *Extreme ultraviolet Imaging Telescope* (EIT) on board the *Solar and Heliospheric Observatory* (SoHO), and the *Extreme UltraViolet Imager* (EUVI) on board the *Solar TErrestrial RElations Observatory* (STEREO), the number of EUV bands that can be used for DEMT is 3. In the case of the *Atmospheric Imaging Assembly* (AIA) on board the *Solar Dynamics Observatory* (SDO) the number of bands is increased to 6.

The 3D distribution of the FBE is found by solving a global optimization problem, and the FBE distribution that best reproduces the intensities observed in all the pixels of all the images is determined. A thorough technical explanation of all aspects of the inversion can be found in Frazin et al. (2009), and discussions on the uncertainties involved can be found in Vásquez et al. (2009, 2010, 2011) and Nuevo et al. (submitted for publication).

Based on reconstructions using data of the EUVI instrument, Fig. 1 shows a summary of the EUV tomography step. The first column shows (from top to bottom) images in the bands of 171, 195 and 284 Å. These images are just one sample from the time series actually used to perform the tomography. For each band, the second through fourth columns show, in a color scale, projected spherical cuts of the tomographic FBE at 1.035, 1.085, and 1.135 $R_\odot$, respectively. The last column shows the respective synthetic images calculated by integrating the tomographic models along the line-of-sight. The black streaks seen in the reconstructions near some of the active regions are artifacts caused by the Sun's temporal variability.

To evaluate the accuracy of the tomographic model, the synthetic images can be quantitatively compared to the corresponding data images. An example of this, based on data from the AIA/SDO instrument, is shown in Fig. 2 from a tomographic reconstruction of the solar corona in the bands of 171, 193, 211, and 335 Å (from top to bottom).

The black rings in the images shown in Fig. 2 correspond to pixels with projected radius in the range 0.98 to 1.025 $R_\odot$. This near-limb data is not actually used for the tomographic inversion, as the emission along their corresponding line-of-sights can be affected by optically thick emission (Frazin et al., 2009). For each pair of images, the relative difference between the synthetic and observed values is below 0.1, 0.2 and 0.3 for about 35, 60 and 75% of the pixels, respectively. The same level of agreement holds for off-limb or on-disk pixels considered separately. The tomographic model provides then a quite detailed and reliable description of the average state of the global corona during the reconstructed period.

EUV tomography can currently be applied from only one or two (in the STEREO era) point-of-view. With such limited simultaneous information the temporal resolution of the technique is of the order of half solar rotation (or about two weeks). Of course, this is the most important limitation of the technique, which is then suitable for studying structures that are stable during their observed transit.

Thus far, all published work on DEMT has only used static SRT. However, time-dependent SRT based on Kalman filtering techniques has been applied to white light (WL) images of the corona (Butala et al., 2010). The type of detail and dynamics captured by EUV images is quite different to those seen in WL images. While for WL data time-dependent SRT has been shown to improve the reconstructions to some extent, it is not clear what benefits would be obtained with EUV images.