Chapter 3

The Michelson Doppler Imager on SOHO

The Michelson Doppler Imager (hereafter referred to as MDI) is an instrument designed to probe the interior of the Sun by measuring the photospheric manifestations of solar oscillations[1]. The MDI observables include line and continuum intensity, magnetic field strength, and line-of-sight (Doppler) velocity. Although it is possible to use intensity images of the Sun for the purposes of time-distance helioseismology — in fact, the first ever application of the method was made with intensity images (Duvall et al., 1993) — the technique has been more commonly applied to velocity images. A *Dopplergram* is an image where the value of each pixel is a measurement of the line-of-sight velocity of the surface of the Sun. The rest of this chapter briefly describes the MDI instrument and the production of Dopplergrams.

3.1 The SOHO Spacecraft

The Solar and Heliospheric Observatory (SOHO) is a spacecraft constructed, launched, and operated under the joint auspices of the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). SOHO

[1]For a more detailed description of the MDI instrument see Scherrer *et al.* (1995) and the MDI Web site at `http://soi.stanford.edu/`.

was launched in December, 1995 and placed in a halo orbit about the Earth-Sun L_1 Lagrange point. From this vantage point (about 1.5×10^6 km sunward of the Earth), SOHO has an uninterrupted view of the Sun, and a small and slowly changing spacecraft-Sun velocity.

SOHO carries a payload of a dozen instruments[2], which can be divided into three broad categories (Domingo and Fleck, 1995): remote sensing of the solar atmosphere, *in situ* measurement of the solar wind, and helioseismology.

The spacecraft was designed for an initial mission duration of two years, but with sufficient on-board fuel for up to six years. The instruments and spacecraft components were designed and tested for a six-year lifetime as well. At the time of this writing, the spacecraft continues to operate, almost four years after launch. Most of the observations used in this dissertation were made between May, 1996 and June, 1998, at which time flight engineers lost contact with SOHO. They were able to reacquire spacecraft control only after several months of painstaking effort, so there is a considerable gap in the helioseismic record.

SOHO is three-axis stabilized, with the means to control the pointing, roll angle, and orbital motion quite accurately. When operating with its full capabilities, the spacecraft has its optical axis pointing at the center of the Sun, with an accuracy of better than 10 arcseconds over six months and 1 arcsecond over fifteen minutes. The roll of the spacecraft is maintained such that the Sun's axis of rotation is always contained in the spacecraft XZ plane; in practical terms, this means that the effective position angle[3] of MDI images is always zero. The roll error is less than 1.5 arcminutes over fifteen minutes.

3.2 MDI

SOHO offers an unprecedented opportunity for helioseismologists because of the uninterrupted observation, the lack of intervening atmosphere, and the relatively long

[2]Further information about SOHO and its instruments can be found on the World Wide Web at `http://sohowww.nascom.nasa.gov/`.

[3]See also appendix A.

observation time. MDI, along with the other helioseismology instruments on SOHO, has been designed to take advantage of that opportunity.

MDI is based on a modification of the Fourier Tachometer technique (Brown, 1980; Evans, 1980). A refracting telescope feeds sunlight through a series of filters onto a charge-coupled device (CCD) camera. The optical elements in the filter system include the front window, the blocker, the Lyot filter, and two tunable Michelson interferometers.

The fixed filters have bandpasses centered on the nickel (Ni) absorption line at 6768 angstroms, which is formed near the middle of the photosphere. The front window bandpass has a full width at half maximum of 50 Å, and also efficiently blocks infrared radiation. It is the only filtering element which is not located inside the temperature-controlled oven. The second element in the filter system, the blocker, has an 8 Å bandpass. The Lyot filter, the third of three fixed elements, is a wide-field, temperature-compensated design (Title and Rosenberg, 1981) with a bandpass of 465 mÅ. The combination of the fixed filters has a transmission bandpass of 454 mÅ.

The light in this frequency band then passes through the two tunable Michelsons, which are the heart of the filter system. The two Michelsons have sinusoidal bandpasses with periods of 377 mÅ and 189 mÅ and are operated as analogs of birefringent elements. The bandpass can be positioned, or tuned, simply by rotation of half-wave plates. In this way it is possible to make spatially resolved images, called *filtergrams*, in a narrow (94 mÅ) bandpass anywhere in the vicinity of the Ni 6768 line.

3.2.1 MDI filtergrams

In normal operation, filtergrams are obtained at five tuning positions which are 75 mÅ apart, spanning the 377 mÅ tuning range. All of the standard observables are computed from these sets of five filtergrams. The filtergrams are labelled F_0 through F_4 according to their central spectral frequency: F_0 is nearly in the continuum, F_1 and F_4 are centered in the wings, and F_2 and F_3 are centered about the core of the Ni 6768 line at disk center. The Doppler velocity is given by

$$v_{LOS} = c\frac{\Delta\lambda}{\lambda}, \tag{3.1}$$

where v_{LOS} is the component of the velocity along the line of sight, c is the speed of light, λ is the wavelength of the absorption line, and $\Delta\lambda$ is the Doppler shift. In the case of MDI, the line shift is measured from the light intensity in the four filter bands F_1 through F_4:

$$\begin{aligned} x &= (F_1 + F_2) - (F_3 + F_4) \\ \alpha &= \begin{cases} x/(F_1 - F_3), & x < 0; \\ x/(F_4 - F_2), & x \geq 0 \end{cases} \end{aligned} \tag{3.2}$$

The MDI onboard processor then calculates the velocity from α using a lookup table that was contructed from simulations using parameterized solar line profiles and measured transmission characteristics.

3.2.2 Observing modes

In normal operation, MDI can make Dopplergrams with a one minute cadence without interruption. In practice, the amount of data that can be returned to Earth is limited by telemetry constraints. The basic observing mode is known as the Structure program. In this mode, the onboard processor computes vector-weighted averages of the 1024×1024 pixel Dopplergrams to reduce them to 192×192 pixels. One of these lower-resolution images is transmitted each minute.

The Dynamics program runs during a two- or three-month continuous timespan each year. During this time, MDI is able to send one full-disk (1024×1024) Dopplergram per minute, along with selected other observables. In addition to this continuous coverage, full-disk images are recovered for an eight hour period of each day. These short periods are known as campaigns. About once per month, there are opportunities for extended campaigns of three to five days. For this work, images were used from three Dynamics periods: June and July, 1996; April and May, 1997; and

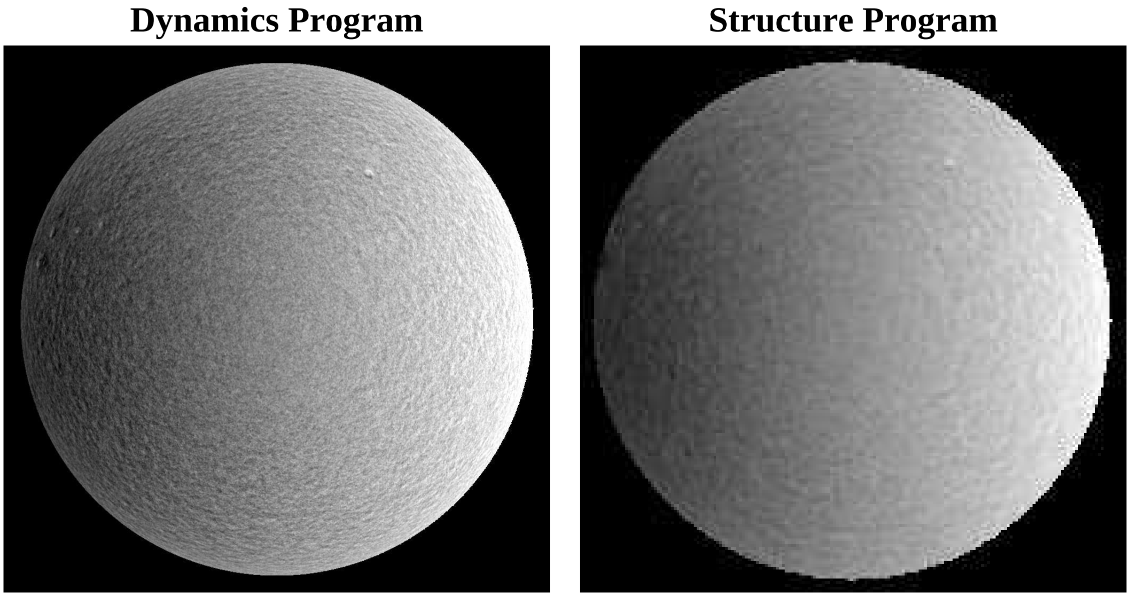

Figure 3.1: Typical Dopplergrams from MDI. The left-hand figure is a Dopplergram from the Dynamics program (full 1024×1024 pixels) and the right-hand figure is a Dopplergram from the Structure program (192×192 pixels). Dark pixels represent motion towards the observer, and light pixels away from the observer. Note the gradient across the image due to the solar rotation.

January, 1998.

During Dynamics programs or campaigns, it is also possible to record Dopplergrams in high-resolution mode. In this mode the spatial resolution is increased by a factor of 3.2 by taking magnified filtergrams of a restricted region of the solar disk.

Figure 3.1 shows a typical Dynamics and a typical Structure Dopplergram. Dark pixels represent velocites toward the observer, and bright pixels velocities away from the observer. The most prominent feature of the Dopplergrams is the gradient from east to west (left to right) across each image. This velocity is about 2000 m/s at the solar equator. Superimposed on this large-scale gradient are patterns which correspond to convection cells on various scales, and the solar five-minute oscillations. It is easy to see the difference in spatial resolution between the two Dopplergrams. Another, less obvious, difference is the fact that the Structure image has been cropped to remove a few pixels near the limb.

In practice, an image cannot be captured every minute. Some images are lost due to instrument calibration and spacecraft manoeuvres, telemetry gaps, and cosmic ray hits to the onboard storage memory. For this work, the effective duty cycle is about 95% on average.

The work included in this thesis will concentrate on data from the full-disk Dynamics and Structure programs. The images from the Dynamics program offer two principal advantages over the images from the Structure program: they have a higher spatial resolution (2 arcsecond pixels, which corresponds to a solar size scale of $0.12°$ at disk center); and they allow observation closer to the limb, since the Structure images are cropped before transmission to the ground. On the other hand, the Structure images (10 arcsecond pixels, or $0.6°$ scale at disk center) are made continuously, interrupted only for spacecraft maintenance maneuvers or other anomolous events. Furthermore, the decreased spatial resolution can be an advantage from a computational point of view. I will make a few more comments on the relative advantages and disadvantages of the two observing modes in the following chapter, which explains the details of the data analysis procedures.