PERFORMANCE OF A STABILIZED FABRY-PEROT SOLAR ANALYZER

D. M. Rust and T. Appourchaux
The Johns Hopkins University Applied Physics Laboratory
Johns Hopkins Road, Laurel, Maryland 20707 USA

F. Hill
National Solar Observatory*, P.O. Box 26732
Tucson, Arizona, 85726, USA

ABSTRACT. A unique solar lineshift analyzer described by Rust, Burton and Leistner (1986) has been used at the Sacramento Peak Observatory to study solar oscillations. Operation of this "Stablized Solar Analyzer" (SSA) depends on the electro-optic effect in crystalline lithium niobate, the substrate of the solid Fabry-Perot etalon. Voltage on the etalon shifts the passband by $\sim 4.5 \times 10^{-4}$ Å/V. The etalon has a passband of 0.175 Å at 6102.7 Å. The stabilization system uses a tunable diode laser to relate the Fabry-Perot passband to the D2 line of atomic Cs 133, at 8521.46 Å. This system reduced instrumental noise to less than $\Delta\lambda/\lambda = 10^{-9}$ over a six-hour interval.

1. INTRODUCTION

The instrument described here was developed to measure solar magnetic fields and surface velocities. Called the Stable Solar Analyzer (SSA), it has been used at the Vacuum Tower Telescope of the Sacramento Peak Observatory to record the spectrum of the solar oscillations. The instrument is to be further developed for long-term observations at several ground observatories and for eventual operation aboard a spacecraft, such as the ESA/NASA Solar and Heliospheric Observatory (SOHO). The ground-based program will also serve to test the SSA, in preparation for unattended operation in space.

The key component of the SSA is a lithium niobate Fabry-Perot etalon. Lithium niobate is a highly transparent material whose index of refraction changes in proportion to voltage applied parallel to its crystallographic c-axis. Our etalon is used as a filter in a simple imaging system; the passband is cycled over $\pm$ 0.1 Å to detect Doppler and Zeeman shifts in a Fraunhofer line in the usual way (Rust, 1985a).

Two etalons have been polished and tested at the CSIRO National Measurment Laboratory in Australia (Rust, Burton and Leistner, 1986). At JHU/APL, the etalons are mounted in temperature-controlled cham-

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bers, stabilized with a diode laser and placed in service at the APL Solar Observatory (Rust, Kunski and Cohn, 1986).

Work began on the SSA in December, 1983. Work in 1984 focussed principally on instrument definition and on research with key components, i.e., electro-optic light modulators, optical filters, and telescope design (Rust, 1985a, b). Test data taken in October, 1985, at the Sacramento Peak Observatory showed an rms noise of 80 cm/s in the $k - \omega$ diagram in the five-minute band, after six hours of observation.

2. SENSITIVITY TO VOLTAGE

The tuning curve was measured in the laboratory by a number of techniques, but we thought it would be instructive to measure it with the same setup used for solar observations. While applying a 300 V (peak-to-peak) square wave to the etalon, we used the multiple diode array detector at the Vacuum Tower Telescope to record the intensity at the center of the sun. It is constant from frame to frame when the passband is offset by exactly equal amounts redward and blueward of the Fraunhofer line under observation. We used the Ca I line at 6102.7 Å.

To establish the voltage tuning curve, we tilted the etalon and offset the voltage until the frame-to-frame flicker disappeared. As shown in Figure 1, wavelength variation and offset voltage are parabolic functions of tilt angle. The curve labeled Theoretical was calculated by formula (3) below and scaled by the tuning parameter determined in the laboratory: 4.5×10^{-4} Å/V. The error bars on it result from uncertainties in the laboratory measurements of the tuning parameter. The solar observatory determination of the tuning parameter is in good agreement with the laboratory determinations.

3. SENSITIVITY TO OFF-AXIS RAYS

Lithium niobate is a uniaxial birefringent crystal with $n_0 = 2.3$ and $n_e = 2.2$. The crystallographic c-axis, where $n_e = n_0$, coincides with the optical axis of the SSA, and there is no on-axis effect of the birefringence on the passband. For off-axis rays, we need to take the birefringence into account:

$$n_0(\theta') = n_0 \;\; : \;\; n_e(\theta') = (\cos^2\theta'/n_0{}^2 + \sin^2\theta'/n_e{}^2)^{-1/2} \qquad (1)$$

where θ' is the off-axis angle inside the $LiNbO_3$. For small angles we may write:

$$n_e(\theta) = n_0 \times \left[1 + \frac{n_e{}^2 - n_0{}^2}{2n_e{}^2}\,\frac{\theta^2}{n_0{}^2}\right] \text{ with } \theta \simeq n_0\theta' \qquad (2)$$

On the sun, $\theta < 0.005$ rad, and the separation between the two transmitted wavelengths is so small that we can approximate the filter profile by that of a single-index etalon. We take the off-axis wavelength shift dellambda as the center of gravity of the two rings:

$$\frac{\Delta\lambda}{\lambda} = -\alpha(X^2 + Y^2) - \beta(X^2 + Y^2) \qquad (3)$$

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where α is the usual off-axis shift coefficient, $c\theta_0{}^2/2\,n_0{}^2$, and β is the birefringent effect, $c\theta_0^2\,(n_0^2 - n_e^2)/4n_0^2\,n_e^2$. θ_0 is the solar angular radius and c is the speed of light. X and Y are the reduced solar angles:

$$\theta = \theta_0 (X^2 + Y^2)^{1/2} \tag{4}$$

Although the effect of birefringence on the filter profile is negligible, there is a substantial addition to the off-axis shift. In our case, $\alpha = 0.56$ km/s and $\beta = 0.023$ km/s with $\theta_0 \simeq 15'.15$.

4. STABILIZATION

The passband is referenced to the Cs 133 D2 line at 8521.26 Å. The setup consisted of the stabilized diode laser described by Rust, Kunski and Cohn (1986), the Fabry-Perot etalon in a thermally controlled housing, a detector for the laser light transmitted by the etalon, a lock-in amplifier to detect the modulated component of the transmitted signal, and a high-voltage amplifier to apply correction signals.

The wavelength of the diode laser light was modulated at 3 kHz, so we observed an intensity modulation in the beam passed by the etalon (after tilt-tuning it to 8521.26 Å). The lock-in amplifier was synchronized with the 3 kHz modulation and produced a signal whose amplitude was proportional to the modulation and the wavelength offset and whose sign depended on whether the selected passband was redward or blueward of the mean wavelength of the laser. The servo loop strove to keep this signal near zero. The integration time was 30 ms.

Figure 2 shows the power spectrum of the passband peak wavelength position after a 5.82 h run. The low frequency variation was caused probably by room temperature variations that may have changed the tilt of the etalon. The noise in the 5-min band is 7.35 $m/s/\sqrt{Hz}$. Integrated over the whole run, it is 5 cm/s.

We also tested another stabilization scheme, one which took advantage of the red-to-blue cycling used in real solar measurements. We used the laser light reflected by the etalon to follow both wavelength and tilt angle variations. (A Fabry-Perot etalon used in reflection gives a pattern of dark fringes complementary to the bright fringes seen in transmission). We detected the reflected beam with a large, position-sensing diode (UDT PIN SC-50) and chopped at 3 Hz between offsets 0.1 Å apart. At a servo integration time of 10 s, the noise in the 5-min band was 22 $m/s/\sqrt{Hz}$, for a 10 h run. It is about three times higher than in the first scheme due to the fact that the absorption fringe was only five percent below the continuum formed by the off-axis rays.

5. COMPENSATION FOR SOLAR ROTATION

As described by Rust, Burton and Leistner (1986), Doppler shifts due to solar rotation can be offset somewhat by operating the etalon at a tilt from the sun-center-to-telescope ray. With the etalon tilted 22 arcmin to the west of sun center, the dynamic range that must be devoted to the

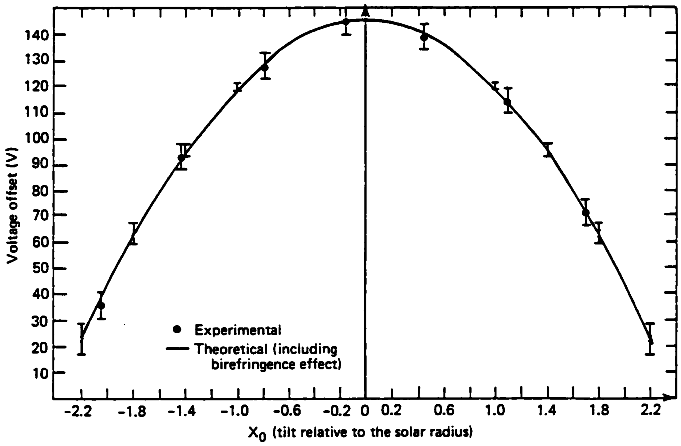

Fig. 1 Voltage required to recenter the etalon passband on the spectral line at 6103Å after a tilt X_0. The error bars on the experimental curve reflect the least signal differences detectable with the instrumentation.

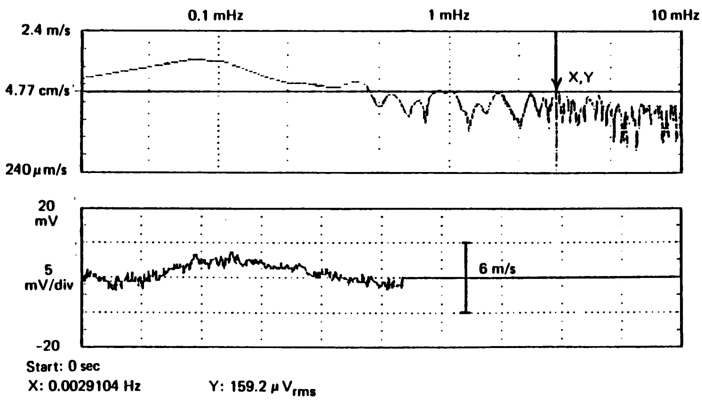

Fig. 2 (Top) Power vs. frequency and (bottom) offset vs. time of the Fabry-Perot passband peak wavelength position. Arrow shows power at (X, Y), i.e., at ω = 2.91 mHz. The rms noise (Y = 159.2 μV) is equivalent to 4.77 cm/s, i.e., $\Delta\lambda/\lambda$ = 1.59 × 10^{-10}.

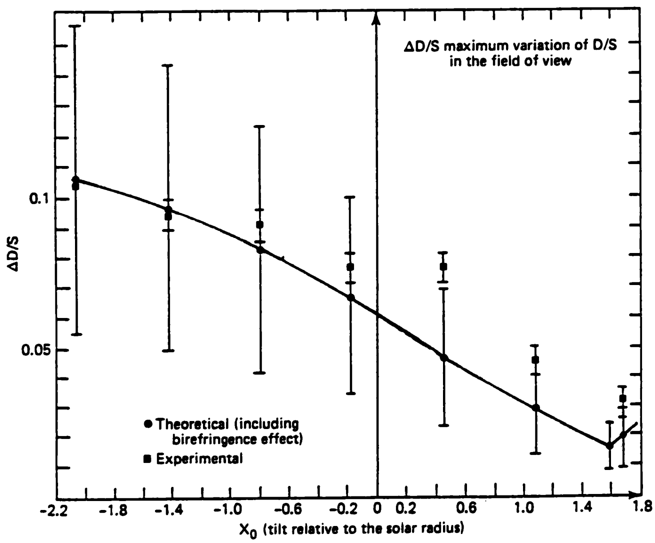

Fig. 3 Maximum apparent range of non-oscillatory lineshifts on the sun versus etalon tilt. The spread of values in D/S on the experimented curve reflects uncertainties caused by fringe patterns in the CCD.

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solar rotation should drop from 4 km/s to 1 km/s. Figure 3 shows our measurements of the maximum apparent range of non-oscillatory lineshifts on the sun vs. etalon tilt. The shifts are stated in terms of the difference D between between red and blue wing signals divided by the sum S of these. There is good agreement between the measurements and the calculations, labeled Theoretical. The large error bars on the calculated points are due to the uncertainties in the width of the solar line, its depth and the width of the filter passband. The range of D/S was reduced less than expected. Some of the apparent lineshifts may have been due to interference fringes in the CCD detector.

6. RESULTS OF SOLAR OBSERVATIONS

For 10 days in February, 1986, at the Vacuum Tower Telescope of the Sacramento Peak Observatory, we obtained full-disk observations of the solar oscillations. The oscillation spectra were degraded by internal "seeing" in the telescope or jitter in the guiding and possibly by thermal drifts in the filter passband since it was not servoed to the laser beam at that time. Nevertheless, Hill, Rust and Appourchaux (1987) obtained useful data on the subsurface rotation rate.

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