N89-15864

Display paper presented at the Max '91 Workshop of the American Astronomical Society Solar Physics Division meeting, Kansas City, MO June 6 - 10, 1988.

SOLAR VECTOR MAGNETOGRAPH FOR MAX '91 PROGRAMS

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ABSTRACT

A new instrument for measuring solar magnetic fields is under construction. Key requirements for any solar vector magnetograph are high spatial resolution, high optical throughput, fine spectral selectivity and ultra-low instrumental polarization. An available 25-cm Cassegrain telescope will provide 0.5 arcsec spatial resolution. Spectral selection will be accomplished with a 150-mÅ filter based on an electrically tunable solid Fabry-Perot etalon. Filter and polarization analyzer design concepts for the magnetograph are described in detail. The instrument will be tested at JHU/APL, and then moved to the National Solar Observatory in late 1988. It will be available to support the Max '91 program. The magnetograph is being constructed at the Center for Applied Solar Physics, which is supported by the Air Force Office of Scientific Research University Research Initiative grant AFOSR-87-0077.

INTRODUCTION

The principal objective of the Center for Applied Solar Physics (CASP) is to improve solar activity observations and prediction techniques through an interdisciplinary program of instrumentation development and fundamental research on solar magnetic fields. Design and fabrication of a solar vector magnetograph is the keystone of the program, which began in January, 1987. This report summarizes activities on the VMG program. Other reports from the CASP program are available on request.

In early 1987, Rust, Appourchaux and Harris (APL/JHU preprint 87-24) studied a number of VMG design options, specifically as they relate to an instrument for operation in space. The proof-of-concept magnetograph now being assembled at APL will be operated at the Sacramento Peak Observatory, under a joint agreement with the National Solar Observatory. The major optical and electronic components for the VMG have been obtained and are described in the following paragraphs.

TELESCOPE AND CAMERA

The first optical element in the CASP magnetograph is a 25-cm reflecting telescope of the Ritchey-Chretien design, which allows a large field of view although the telescope is very compact (~ 60 cm long). The telescope is evacuated to eliminate the effects of internal seeing. We have established that this telescope forms near diffraction-limited (0.7 arc-second) images and that the custom relay optics for the VMG will convey the solar images to the electronic camera image plane without degrading the resolution.

To map the magnetic fields, we will use a 576 x 384-pixel CCD (charge-coupled device) camera and image collection system made by Photometrics, Inc. in Tucson, Arizona. This system has proven to be the key element in our optics evaluation program. The CCD camera allows rapid quantitative evaluation of diffraction patterns, scattering, image scale, beam deflection, etc. For example, Figure 1, made with an image processing and color hardcopy unit, clearly shows the first diffraction ring and the scattered light pattern around the image of a single point light source. The large dynamic range of the system is evident since the amplitude of the scattered light (green and red areas) is less than one thousandth of the central (white) peak of the diffraction pattern.

The CCD camera readout time will determine the cadence of the observations. Ten readouts of the CCD will be required to collect the electrons needed for a signal-to-noise ratio of unity in a longitudinal field of 10 G (Figure 2). Readout times average 2 s for the whole CCD. Thus, 10 G sensitivity can be obtained in 20 s.

POLARIZATION ANALYSIS

Construction of solar vector magnetic field maps requires precision polarimetry (1:10,000) in narrow (~ 0.15 Ångstrom) bands in the solar spectrum. The CASP magnetograph (Figure 3) is built around an electrically tunable APL-developed Fabry-Perot filter and a polarimeter concept developed at the Space Sciences Laboratory, NASA Marshall Space Flight Center. The polarimeter is especially designed to eliminate crosstalk between the relatively strong line-of-sight magnetic field signal and the much weaker transverse field signal. Crosstalk is caused by unavoidable imperfections in the retardance and positioning of the polarizing elements. The MSFC study suggests that low crosstalk polarization analysis can best be achieved by using a removable achromatic quarter-wave retarder followed by a rotating polarizer.

To minimize instrumental polarization, we use components which are rotationally symmetric about the optical axis. In particular, the magnetograph will be fed by a Cassegrain telescope mounted on a spar rather than one fed by a coelostat or other mirror system.

The polarization of the incident light is expressed in terms of the four Stokes vectors. These are derived from the intensities transmitted by the polarization analyzer (quarter-wave plate plus prism) as it is configured to pass various combinations of linear and circular polarization. A Glan-laser prism is used as the linear polarization analyzer because of its excellent extinction ratio. It is mounted in a programmable precision rotating stage. An HN38 dichroic polarizer is attached to the prism to further increase the contrast ratio between the blocked and transmitted senses of polarization.

A second quarter-wave plate is attached to the rear of the Glan-laser prism to yield circularly polarized light and thereby minimize modulation of the beam intensity by subsequent polarizing components, such as folding mirrors. Provision is also made for mounting a pair of wedge prisms to compensate for beam deviation caused by the polarization analyzer.

All elements of the polarimeter, including a newly developed liquid-crystal polarization rotator, have been procured and shown to conform to our specifications. Tests of the overall polarimeter sensitivity will be started in July, 1988.

FABRY-PEROT FILTER

Our F-P filters are constructed at the National Measurement Laboratory in Australia from a thin wafer of lithium niobate polished to 40 - 50 A flatness. The accepance angle of a lithium niobate etalon is five times that for an air-spaced etalon; that is, for the same spatial and spectral resolution, an air-spaced etalon would have to have five times the area of the lithium niobate etalon. The advantage over a birefringent filter is almost as great because of the long path length required by the birefringent filter.

In lithium niobate, application of an electric field induces a change in the refractive index for light propagating along the optic axis. We use this property to tune the filter. The tuning requirements of the solar magnetograph are modest. Typical spectral lines are only 0.2 Å wide, and +/- 500 V will tune the filter through 0.4 Å.

Comparison of the off-axis behavior of a Fabry-Perot etalon with the Doppler shifts due to solar rotation shows that, if the etalon is operated at an appropriate tilt from the suncenter-to-telescope ray, the Doppler shifts from solar rotation can be closely matched (cancelled). Thus, the etalon provides a passband that is at once narrow and correctly positioned on the spectral line everywhere in the field of view.

Last year, we conducted an extensive series of tests of Fabry-Perot filter elements. We tested the filter's ability to withstand voltage cycling equivalent to ten years' operation and to survive the vibration of a shuttle launch. No deterioration was found. Similarly, the filter withstood bombardment by energetic protons.

We have one 75-mm F-P filter in hand. CSIRO is making another and they now have two ready for coating. At least one should be ready for delivery in August.

In collaboration with investigators from Washington University, we measured the performance of a small-aperture commercial acousto-optic blocker filter and studied a large-aperture device suitable for solar imaging. On the basis of this study, we concluded that such a filter can be built but it requires a developmental effort that is outside the scope of CASP's interests. The acousto-optic filter is now being developed with APL Independent Research and Development funds.

IMAGE MOTION COMPENSATION

The pointing stability required for the relatively long exposures anticipated with the 25-cm telescope will be achieved with an image motion compensation system based on binary correlation. The heart of the system is a sequential binary correlation (SBC) algorithm for computing the solar image offset based on images obtained by the 32 x 32 Reticon photodiode tracking array. A relay mirror position is updated at a 50-Hz rate as the sensed image is compared with a periodically updated reference image. The algorithm can operate well even when only solar granules are in the 10 x 10 arc-sec Reticon field. That is, high contrast features are not required for successful operation.

K. Strohbehn and P. K. Murphy tested the SBC algorithm at APL using solar granulation data obtained by R. B. Dunn at the Sacramento Peak Observatory. Their trials showed that the fast binary registration can give nearly the same results as conventional, slower, grayscale registration. The SBC algorithm introduces rms pointing errors of ~ 0.02 arc-second, which is considered negligible. Strohbehn has implemented the SBC algorithm in custom hardware for the VMG and is scheduled to complete testing of it this summer.

BALLOON-BORNE VECTOR MAGNETOGRAPH

Because of the fine structure of the solar magnetic fields, the full power of a VMG can be realized only when the blurring effect of turbulence in the Earth's atmosphere can be eliminated. This can be accomplished eventually with a space platform or high altitude balloon. Opportunities for a space mission may arise only in the distant future, but because of the Max '91 program, prospects for a balloon flight are much brighter.

Numerous studies have shown that a one-meter class telescope is needed to achieve the short exposure times and high resolution needed to answer the most fundamental questions about solar magnetism. We are now studying how to mate a one-meter telescope to the VMG focal plane instrumentation and fly it on a long-duration balloon mission. First results are very encouraging since balloons are now able to carry instruments up to six meters in length and up to 2000 pounds weight. We believe that the VMG fed by a one-meter telescope can be ready to participate in the Max '91 programs.

Although a balloon-borne telescope program cannot achieve all the scientific objectives of a long-duration space mission, such as the Optical Solar Laboratory, the contribution of a one-meter instrument to the Max '91 program will be enormous, particularly in vector magnetography where even a flight as short as five or six hours would likely revolutionize our understanding of the structure and evolution of magnetic fields in active regions. A fifteen-day flight would certainly capture many flares and make a major breakthrough in flare research.

ACKNOWLEDGEMENTS

Dr. Kim Strohbehn and Dr. Patricia Murphy of APL designed and implemented the correlation tracker. John Townsend and Benjamin Ballard are developing the computer programs needed to handle solar data. Robert Moore and Harry Zink performed systems analyses and major component evaluation. Gary Starstrom is designing the magnetograph structures on the APL Computer-Aided Design equipment. The 25-cm evacuated telescope was furnished by the High Altitude Observatory of the National Center for Atmospheric Research. Support for the Center for Applied Solar Physics is provided by AFOSR Grant 87-0077.

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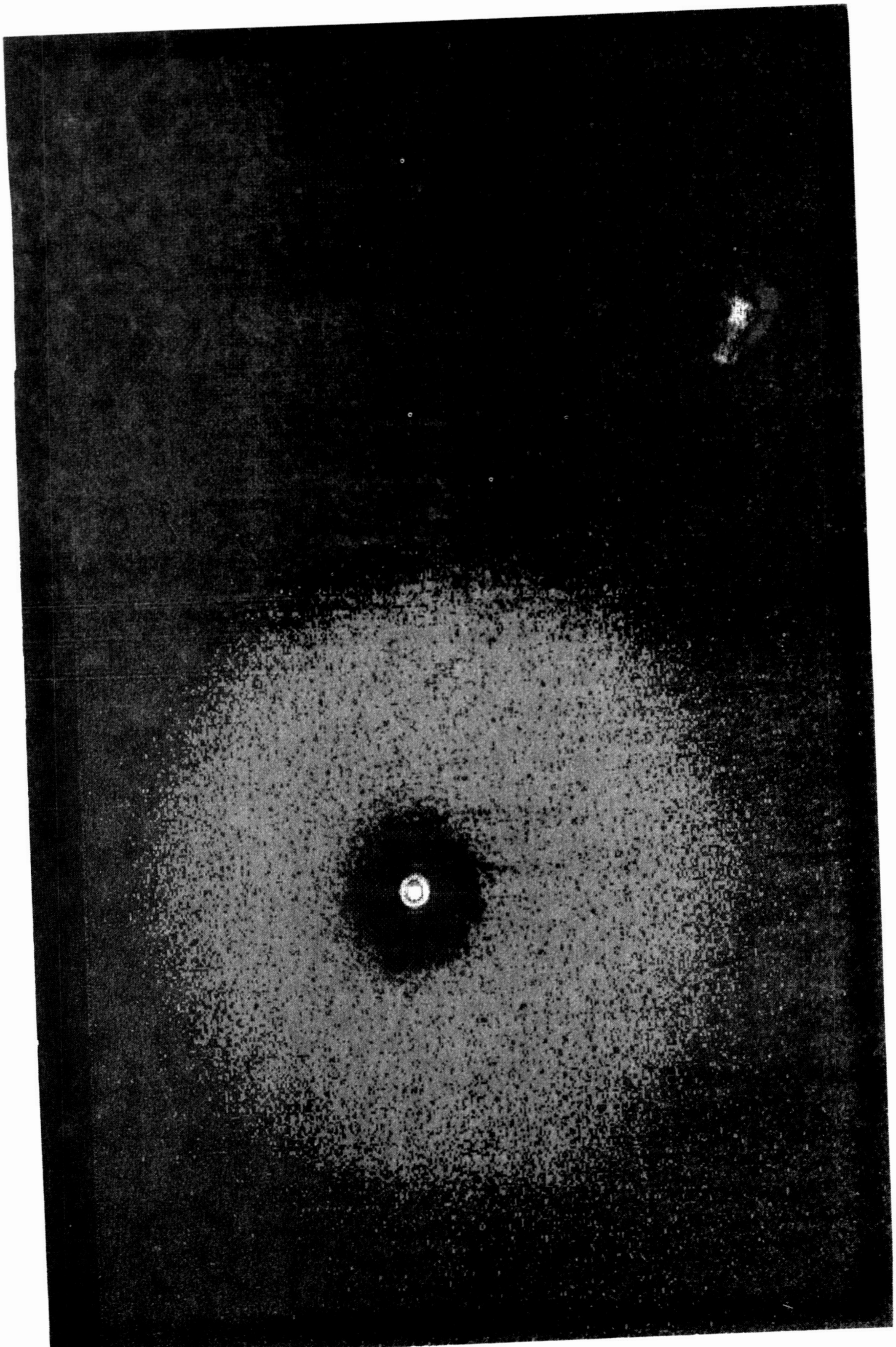

Figure 1. Image of a point light source obtained through the vector magnetograph optics. The peak and the first diffraction ring (white) and scattered light (green and red areas) are clearly shown.

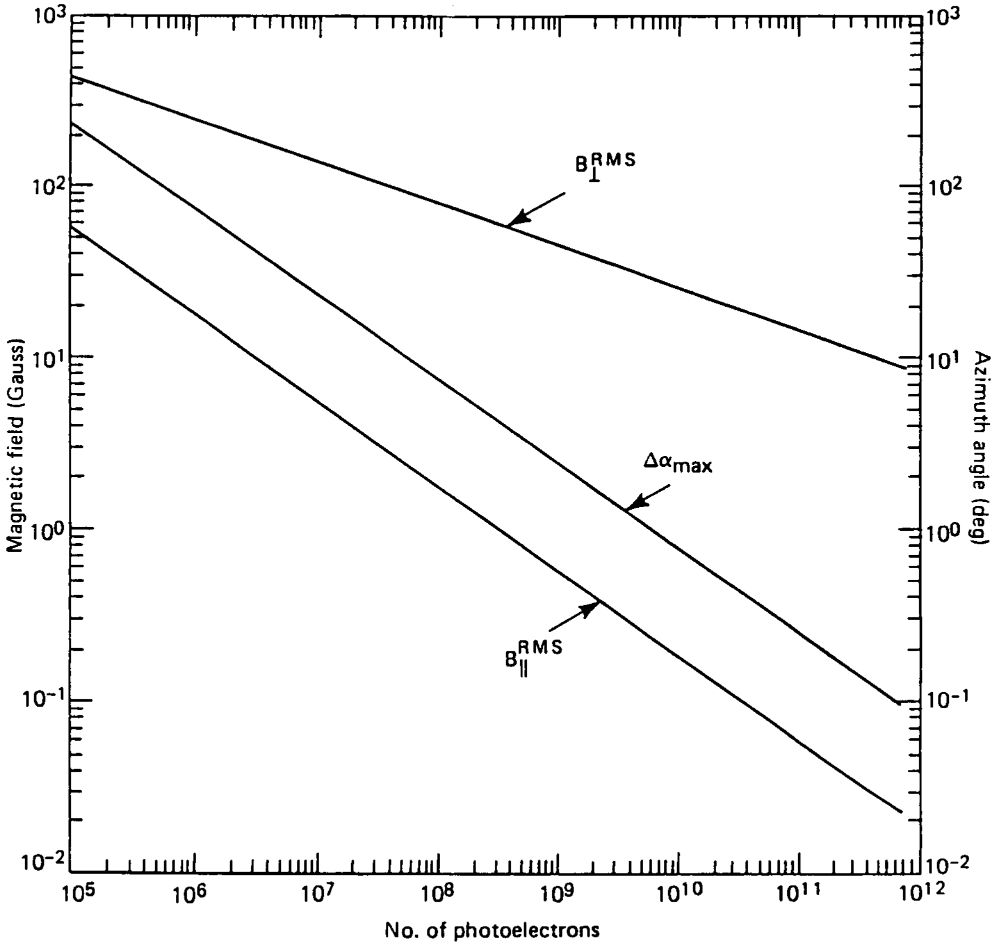

Figure 2 Errors on the measurements of $B_\parallel$, $B_\perp$ and α. These curves were computed assuming a line width $\Delta v_0 = 0.15$Å, a depth $P = 0.5$, and a Landé factor $g = 1.5$. The quality factor Q was assumed to be about 2. $\partial^2 p/\partial v^2|_{v=0}$ was assumed to be about 1. The magnetic field taken to compute $\Delta\alpha_{max}$ is $B_\perp = 300$ gauss.

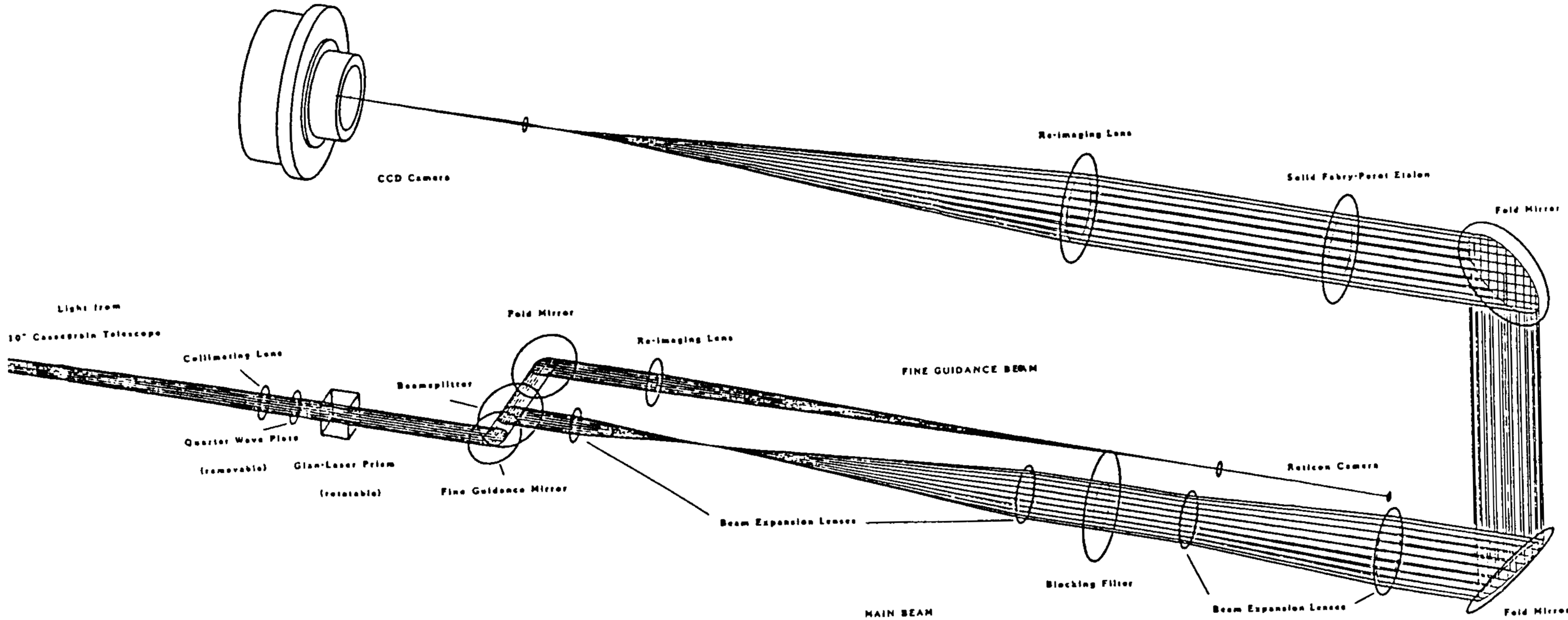

Figure 3. Principal optical components of the CASP vector magnetograph.

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