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NEW INSTRUMENTS FOR SOLAR RESEARCH

New instruments have been installed at observatories in New Mexico and California for measuring solar magnetic fields and surface velocities. The magnetic fields provide the energy for all eruptive and accelerative processes on the Sun, and the surface velocities reveal the dynamics of the solar interior. Early detection of emerging magnetic fields may give several hours' warning of impending solar flares and interplanetary shocks. The new instruments incorporate several technical innovations, including a lithium niobate filter for high spectral resolution. With this filter, circular and linear polarization and Doppler shifts are measured in solar spectral lines to yield estimates of the magnetic field vector in active sunspot regions. A program of daily measurements is planned for study of the current peak in the 11-year solar cycle.

INTRODUCTION

Solar research has grown steadily at APL over the past decade, building on an already strong foundation in ionospheric, magnetospheric, and space plasma physics. This work has focused on the causes of violent solar activity (such as flares) and their effects at the Earth, which often disturb radio communications and spacecraft operations.

Recognizing the need for better instrumentation to study the Sun, the Air Force Office of Scientific Research asked the Laboratory to establish a Center for Applied Solar Physics (CASP). The Laboratory established CASP in late 1986 as an interdisciplinary program of instrument development and fundamental research on solar activity. In this program, we hope to make significant improvements in our understanding of how flares occur and how to predict them. We believe that optical instruments to better reveal the structure and evolution of the Sun's magnetic fields (from which flares draw their energy) will eventually allow the flares to be understood and forecast.

The emergence of fresh magnetic flux on the Sun clearly triggers flares when a marginally stable magnetic configuration exists. An eruption follows that blows open the magnetic arcades above the active region. Reconnection of the disrupted fields causes intense heating to 100 million degrees. The growing flare emits X rays that affect radio wave propagation at Earth. In addition, a shock wave explodes into interplanetary space and, depending on the magnetic fields it encounters, may strike Earth two to three days later.

Fast protons are emitted with energies up to 1 GeV. These solar energetic particles will pose a serious radiation hazard for astronauts when they venture outside the protective shield of the Earth's magnetosphere. Early detection of emerging solar magnetic fields may give several hours' warning before a major flare onset, so that astronauts and ground-based operators of unmanned spacecraft will have adequate time to take protective action.

INSTRUMENT PERFORMANCE OBJECTIVES

A major undertaking of CASP is beginning to bear fruit—the design, construction, and operation of a solar vector magnetograph (VMG) that will provide unique data on the sunspot regions where flares originate.[1]

The magnetograph was designed to measure all three components of the solar magnetic field with a sensitivity of 50 to 100 G and a spatial resolution on the Sun of about 700 km (1"). The instrument is beginning to approach these performance goals.

During these years of maximum solar activity (1989 to 1991), vector magnetograms will be obtained each day from the VMG that is installed at Sacramento Peak, New Mexico, a site that enjoys clear skies during most of the year. The data will have unprecedented quality because of the high sensitivity and high spatial resolution of the new VMG and because of the good image quality at the site. Vector magnetograms at other sites are generally obtained at approximately 5" resolution, which corresponds to about 3500 km at the solar surface. Image quality at Sacramento Peak is frequently better than 2"—justifying 1"/pixel resolution. And because the VMG can be operated every day, we expect to capture data at 0.5"/pixel on days with exceptional observing conditions.

It is important to achieve the highest resolution possible because active regions, which will be the principal targets for the VMG, are composed of magnetic flux tubes only 0.1" to 1.5" (70 to 1000 km) in diameter. The strength of the fields in these tubes is probably 500 to 1500 G (0.05 to 0.15 tesla). We will study the structure and evolution of those fields. Present ideas to describe such fields are founded principally on lower resolution observations. Such ideas as flux emergence, flux cancellation, and magnetic stress need to be tested by VMG observations. We must determine how active regions evolve toward increasing complexity and higher potential energy; we must determine if it is true that highly sheared, stressed magnetic configurations presage flares and if the sheared magnetic fields are the reservoirs of flare energy.

Interpretation of VMG measurements is not a straightforward process. The output of the instrument is a series of measurements of the Stokes polarization vectors

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HOW SOLAR MAGNETISM AND ATMOSPHERIC MOTION IS MEASURED

Atoms in the solar atmosphere emit radiation in very narrow spectral bands, called lines. Where the atmosphere is moving up or down, the apparent wavelength of the atomic emission lines will be decreased or increased, respectively, according to the Doppler principle, which states that the apparent change in wavelength of the emission from a moving source is proportional to the velocity of the source with respect to the viewer. By measuring changes in the wavelength of a solar spectral line, one can infer how fast the atoms in the atmosphere are moving up or down.

Atoms in a magnetic field will have their spectral line emission changed because the field raises the energy of some atoms and lowers the energy of others, depending on each atom's orientation to the field. The presence of magnetic fields in the solar atmosphere may be inferred from measurements of the polarization in the atomic spectral lines. Where the solar atmosphere has a magnetic field, the lines will split into two or more polarized components. If the magnetic field direction is strictly parallel with the line of sight, the split components will be circularly polarized; if the field is perpendicular to the line of sight, the split components will be linearly polarized. There will be a central component at the natural atomic wavelength (corrected for Doppler shift), and it will be polarized in the direction of the field. There will also be two offset components whose linear polarization will be at angles of 90° to the field direction. All the spectral components are measured by the vector magnetograph and are expressed in terms of the four Stokes polarization parameters: I (intensity), Q (linear polarization at 0°), U (linear polarization at 45°), and V (circular polarization). The magnetic field strength may be inferred from these parameters, using the theory of the formation of spectral lines in a stellar atmosphere.

at several wavelength steps across an atomic absorption line in the solar spectrum. In relating such measurements to the magnetic fields on the Sun, one must consider how the radiation is formed and how idealized measurements are degraded by imperfect optics and smearing in the Earth's atmosphere. To address these questions, we created a computer model to simulate the output of the magnetograph, taking into account its limited spectral resolution and that the pixels may sample regions that are not uniformly filled with magnetic structures. Some results of the model are shown in Figure 1.

The model of the solar atmosphere used to compute the curves in Figure 1 is the result of many years of development at the High Altitude Observatory in Boulder, Colorado. It provides solutions to the radiative transfer equations[2] that describe the solar spectrum in the presence of a magnetic field. We have simulated the measured response of the instrument and find that the response of the VMG can be roughly predicted over a wide range of fields. But the definitive calibration connecting our Stokes measurements to the solar fields will have to be determined by comparisons with other measurements and with more sophisticated theoretical models.
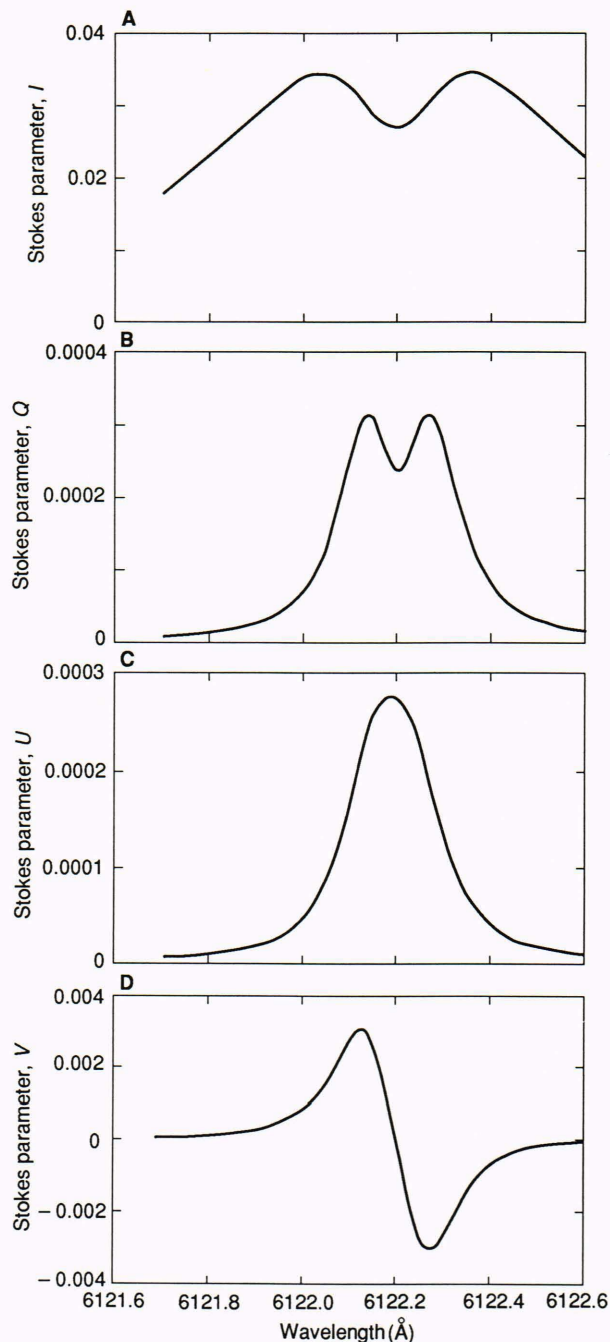

Figure 1. Simulated profiles of the Stokes parameters, which represent intensity (*I*), linear polarization (*Q* and *U*), and circular polarization (*V*) as functions of wavelength near the calcium line at 6122.2 Å in the solar spectrum. The profiles take the instrument's spectral response into account and show the magnetograph response to a 1000-G magnetic field at 30° to the line of sight.

PERFORMANCE OF THE SOLAR VECTOR MAGNETOGRAPH

The APL solar VMG (Fig. 2) was installed in a 6-m dome at the National Solar Observatory at Sacramento Peak in April 1989, for the joint use of scientists from APL, the Air Force Geophysics Laboratory, and the National Solar Observatory. First light was achieved in May
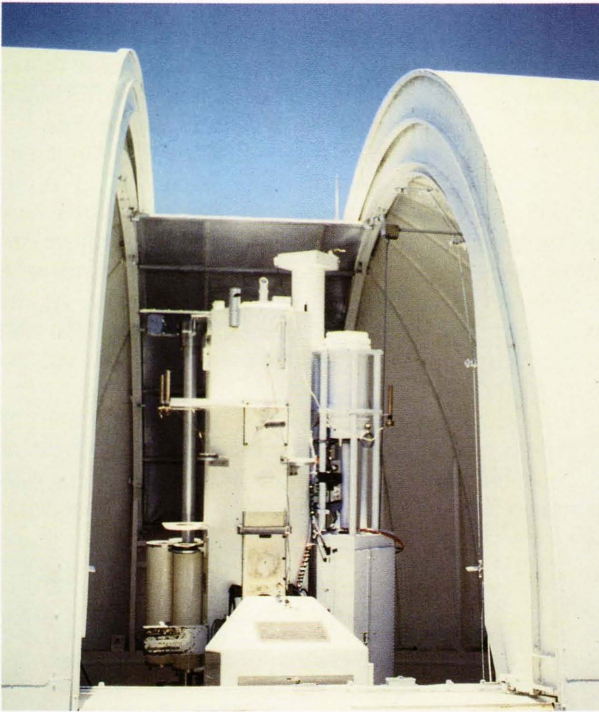
Figure 2. The APL Solar VMG (rightmost telescope) installed in the Hilltop Dome of the Sacramento Peak Observatory in Sunspot, New Mexico. The upper part is the vacuum 25-cm Cassegrain telescope. The lower part is the magnetograph optics housing.

Figure 3. John O'Byrne and Kim Strohbehn testing the vector magnetograph at APL prior to its shipment to New Mexico.

1989, and the instrument began regular production of vector magnetograms in October. Two of the authors (O'Byrne and Sterner) are on long-term assignment in New Mexico to develop observing routines and to take advantage of the current peak in solar activity.

The observatory is 9200 ft above sea level, resulting in a fairly severe environment. In winter, temperatures fall below 0°F, and summer temperatures reach 90°F. On many days, the temperature changes by more than 10°F/h. Therefore, active thermal controls are required to forestall passband shifts in the optical filters and in other sensitive optical and electronic components.

The mountaintop environment is also especially hazardous to electronic equipment. In August, a nearby lightning strike damaged some line drivers and other components despite our efforts to protect against such an eventuality. Before the next round of summer thunderstorms, we plan to replace all long electrical cables with optical fibers.

The largest optical element in the CASP magnetograph is a 25-cm reflecting telescope of the Ritchey–Chrétien design, which allows a large field of view, even though the telescope is very compact (about 60 cm long). Air is evacuated from the telescope to eliminate the effects of internal turbulence. We have established that this telescope and the specialized magnetograph optical train form near-diffraction-limited images (about 1″) on the charge-coupled device (CCD) camera that serves as the image sensor.

Research Support Instruments, Inc., of Baltimore designed and fabricated the magnetograph support structure. The structure was delivered at the beginning of April 1989, and underwent initial functional, stiffness, and alignment tests at APL before shipment to Sacramento Peak. A cement pier was poured near the APL Solar Observatory, and the magnetograph was mounted on it and guided on the Sun (Fig. 3). During these tests, it was discovered that the pointing drives would bind at some solar angles. A redesigned mechanism was supplied and, after some further adjustments at Sacramento Peak, the drives have worked well.

The structure supporting the magnetograph optics must be very rigid because the relative gravity vector varies as the telescope follows the Sun across the sky. Flexure in the mechanical housing should be limited to an amount that would shift the image on the detector by 0.25 pixel during a 15-min observation sequence. Reducing the flexure to the required level proved to be one of our most difficult tasks. The telescope at the front of the instrument (which weighs over 50 kg) had to be cantilevered, with its center of gravity about 1 m from a pivot point. The original structure shown in Figure 2 was not rigid enough. A set of crisscross straps eventually reduced the flexure to an acceptable level.

Several months were required to program the VMG control computer, which is built around a Motorola 68020 microchip. The computer controls the CCD camera and commands several other microprocessors that

control the polarimeter, focus, and filter settings. Simultaneously, the computer must also gather all engineering and solar data. Much of the software development was done by John Townsend and Kim Strohbehn at APL before the instrument was shipped to New Mexico. The software was completed on site, and by October it had evolved into an easy-to-use, semi-automatic operating and data-analysis system. Use of the flexible Forth language greatly facilitated the process.

Before shipment, all of the optical and electronic elements underwent extensive testing at APL. Despite these tests, which showed that the optical system was able to operate near the design resolution limit, the first images through the instrument were disappointing. The problem was finally tracked down to an error in the assumed focal length of the telescope and a resultant error in the focal length of the lens that transfers the solar image from the telescope focal plane to the magnetograph. It overfilled the secondary optics, and the advantage of having a relatively large telescope was lost. Installation of a shorter focal length lens solved the problem.

Solar field measurements require precision polarimetry. Our polarimeter is especially designed to eliminate crosstalk between the relatively strong line-of-sight magnetic field signal (which is carried by circularly polarized light) and the much weaker transverse field signal (which is the linearly polarized component). In a break with previous practice, the waveplate for detecting circular polarization is completely removed from the beam when the linear measurements are made.

The key element for isolating the linearly polarized component of the sunlight is a rotating prism. Knowledge of the prism's orientation to within 0.1° is required. We built a system that automatically repositions the prism to an accuracy of 0.1° whenever necessary. In addition, two optical wedges were mated to the prism and adjusted until the beam wobble caused by the prism rotation was less than 2″. (Beam wobble will cause spurious polarization signals.) The small remaining residual beam wobble caused by the rotating prism will be removed by a beam-motion compensation system.

Working with the Commonwealth Scientific and Industrial Research Organization, a Division of Applied Physics in Australia, we developed custom lithium niobate Fabry–Perot filters[3] that provide the needed narrow spectral bandwidth and large throughput. The filters are made from thin wafers of lithium niobate polished to a root-mean-square flatness of 0.0025 wavelength, or about 15 Å. 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 select the precise wavelength in the solar spectrum to be sampled. We tested the filter's ability to withstand operation equivalent to 10 years of use and to survive the vibration of launch, should the opportunity arise to put a VMG in space. No deterioration was found. The filter also withstands bombardment by energetic protons.

The lithium niobate filter is in a large temperature-controlled housing designed by Jim Cloeren of the APL Communication, RF, and Optical Systems Group. The design is derived from those used in the precision clocks

in the Space Department's navigation satellites. The filter has proved to be quite stable, an important property considering that a passband shift of only 0.1 Å would mimic the wavelength shift of the strongest magnetic fields and velocities we ever expect to encounter on the Sun.

The width of the filter passband is 0.17 Å, but a narrower filter will improve the signal levels. A 0.15-Å filter will be installed in July 1990. Figure 4 shows how definition of the profile of the magnetically sensitive calcium line at 6122 Å in the solar spectrum improves with a narrower filter and with two filters in series. As the figure indicates, a major source of unwanted light and consequent loss of signal is leakage from adjacent orders of the filter.

The lithium niobate filter has a free spectral range of 3.25 Å; that is, transmission bands (orders) occur at 3.25-Å intervals. Blocking the unwanted orders with commercially available filters has proved to be a prob-
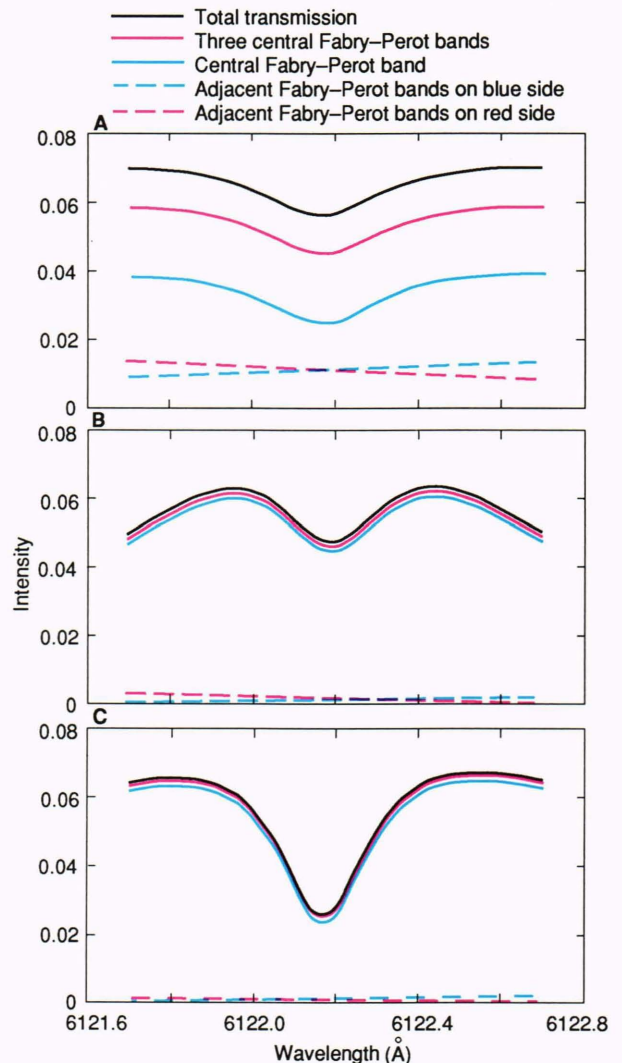

Figure 4. Comparison of spectral line profiles. **A.** Profiles after passage through the 0.17-Å filter and a 3.5-Å blocking filter. **B.** Profiles expected with the 3.5-Å blocker, a 0.17-Å Fabry–Perot filter, and a 1.1-Å cleaved mica blocker. **C.** Profiles expected with a 2.5-Å blocker and two lithium niobate filters (0.15- and 0.11-Å) in series.

lem. When used at their full aperture, thin-film filters of the required narrowness (2 Å) often show broader profiles than are indicated by manufacturers' specifications. Use of two Fabry–Perot filters with incommensurate spacing (different free spectral ranges) seems to be the best solution. At present, the magnetograph is operated with an added 1-Å cleaved-mica blocker, which gives a contrast nearly as high as two lithium niobate filters, but at a reduced overall light level.

Narrower filters impose longer exposure times, so a potentially high resolution image can be smeared by solar "seeing" (which is caused by turbulence in our atmosphere). The required image stability can be restored with an image motion compensation (IMC) system, to be installed in June 1990. Our original approach to this was to implement a sequential binary correlation algorithm[4] for computing the offset of each solar image relative to a reference image. An image-relaying mirror was to tilt as necessary to keep the target region fixed as each new image was compared with the reference. When this system was tested with a solar image at the APL Solar Observatory, it was only about half as fast as required to remove the image motions and was hampered by high detector noise. We are compensating for the lack of an IMC system by cross-correlating images during post-observation processing.

We are building a new IMC system that is derived from the fast Fourier transform IMC recently developed at the National Solar Observatory. This system can use our optical train, and operation at the requisite high rate has already been demonstrated. We expect to install the Fourier transform device in June 1990. It should improve the magnetic signal levels and further sharpen the images.

A second approach is under development. It uses an innovative integrated motion-detection chip that incorporates the detector array, amplifiers, and all the logic needed to produce analog signals that show instantaneous image motion. Integrated devices of this type have recently been developed at The Johns Hopkins University Electrical and Computer Engineering Department, and they show very fast response characteristics and a remarkable freedom from noise.[5]

INITIAL RESULTS

Figure 5 shows the first magnetogram obtained after installation of the improved blocking filter. The upper panel shows a small group of sunspots on 28 October 1989 in a false color scale. The lower panel shows the magnetic fields, with upward-directed fields in blue and downward fields in red and yellow. Regions with no fields are green. Several classic features of sunspot magnetism are easily seen: The fields are strongest in a large leading (westernmost) sunspot, and the polarity of the big spot is opposite that of the following spots. Areas of positive and negative fields, sometimes called invisible sunspots, extend beyond the dark sunspot areas themselves. Far from the sunspots, the fields (yellow in Fig. 5) outline a cellular network that is caused by convection at the solar surface. The image is not sharp because of uncorrected atmospheric turbulence.
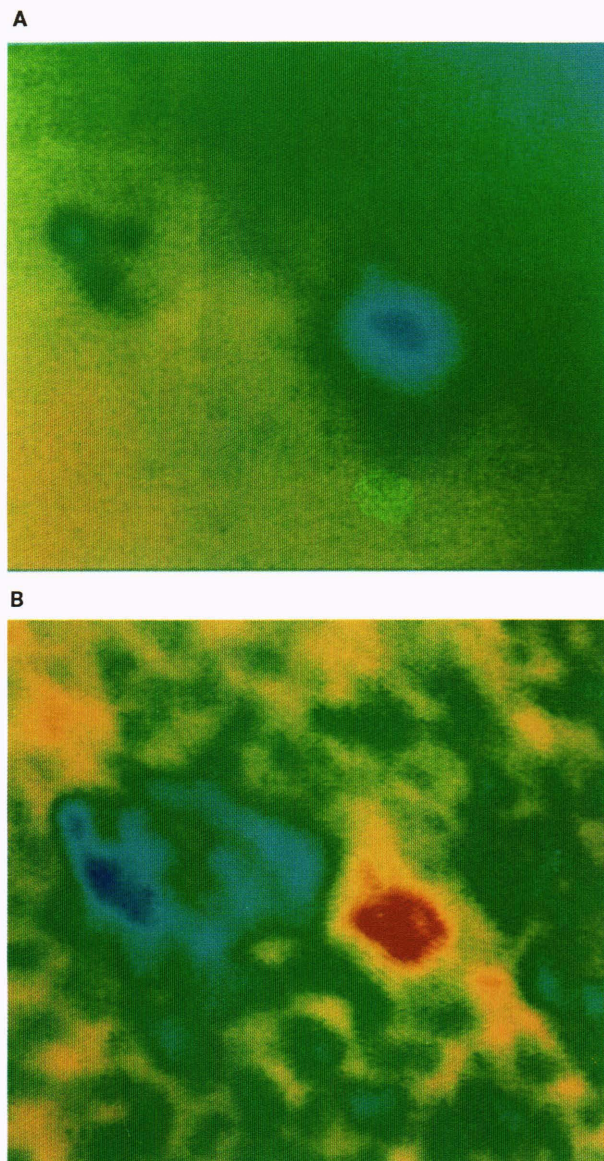

Figure 5. Sunspots and magnetic fields recorded on 28 October 1989. **A**. The sunspot picture is derived from the Stokes *I* parameter. **B**. The magnetic field is derived from the Stokes *V* polarization parameter. The field of view is about 100,000 km^2. Negative magnetic fields are shown in red (strong) and yellow (weak); positive fields are blue.

A better series of observations was obtained 9–12 November 1989 (Fig. 6), and in it we can follow the growth and initial decay of a large spot group from which over 40 flares erupted. We know that the origin of most of the flares was in the regions where the positive and negative fields came in closest contact. The area covered by the spot group peaked on 10 November at about 0.1% of the total area of the solar disk.

Figure 6 shows only the line-of-sight component of the magnetic fields. It is the easiest to measure, and the new observations are not unique. More interesting is the field component transverse to the line of sight (Fig. 7), which generally gives a signal only 1/100 as strong. The
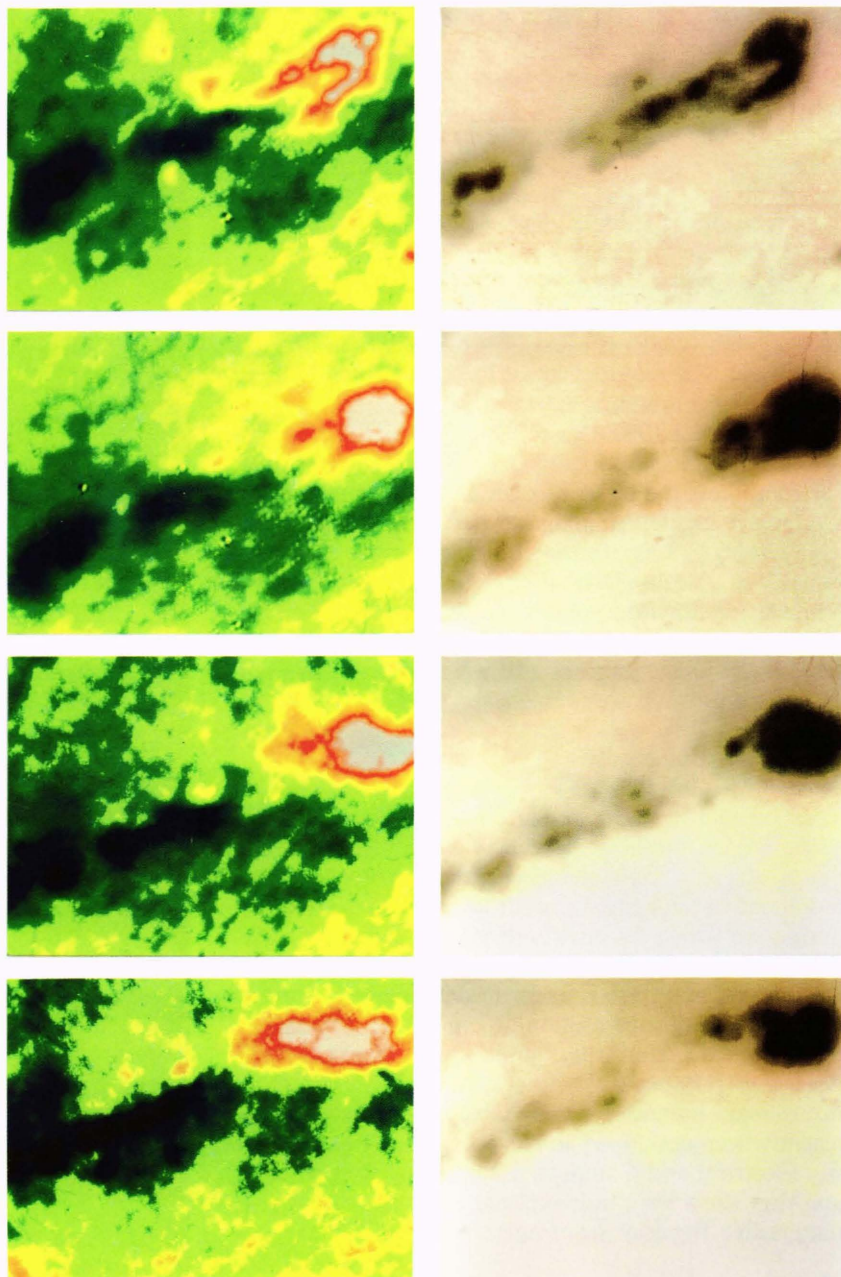
Figure 6. Daily sunspot pictures (left) and magnetic fields (right) inferred from measurements of the *I* and *V* Stokes parameters for 9–12 November 1989. These images show (top to bottom) the evolution of the active solar region and the variable quality of the data, which is caused by varying atmospheric conditions at the observatory.

transverse component is not only more difficult to detect, it is more difficult to visualize. In Figure 7, each short stripe represents the direction and magnitude of the magnetic field projected on the solar surface. To avoid hopeless clutter, data are shown for only 1 pixel in 10. The figure shows that there are strong transverse fields in the regions where flares usually occur, as earlier measurements at lower resolution have shown.[6]

The preliminary data shown here will have to be calibrated and studied in detail and in conjunction with photographs of the flares in order to gain new scientific insight, but already they show the potential of the VMG. The data are now being analyzed at Sacramento Peak with the facilities of the National Solar Observatory and at APL with those of the Space Physics Group.

OTHER ACTIVITIES OF THE CENTER FOR APPLIED SOLAR PHYSICS

Besides its usefulness for measuring magnetic fields, the lithium niobate Fabry–Perot filter also makes possible very accurate measurements of Doppler shifts in solar spectral lines. At the same time as the solar measurements are being accumulated, the filter can be tuned to a standard wavelength reference, such as a stable laser, so that the absolute wavelength of the solar line can be determined. One of our filters is incorporated in the Stable Solar Analyzer (SSA), an instrument designed to measure the solar surface oscillations.[7] The oscillations can be used to reveal the subsurface structure of the Sun, just
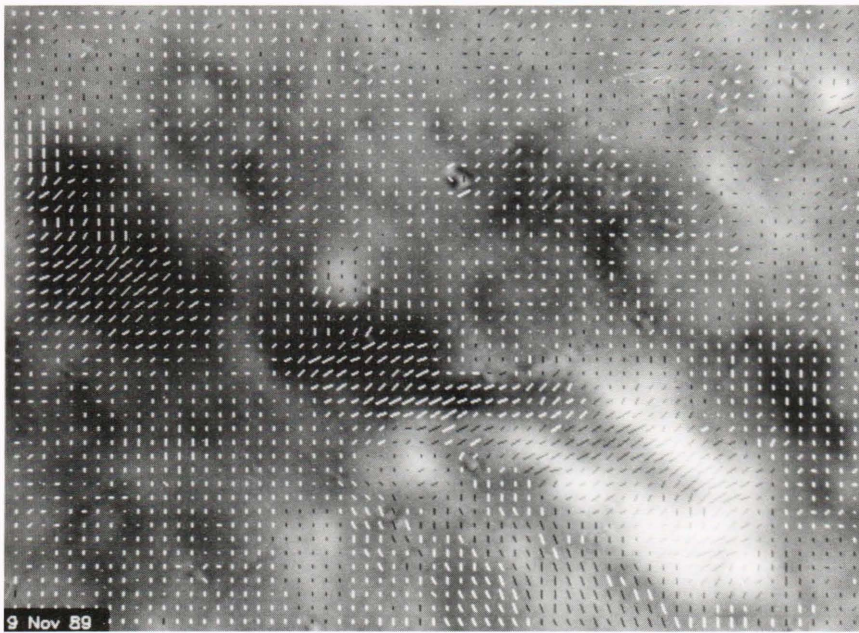
Figure 7. A map of the transverse fields obtained from the *Q* and *U* Stokes parameters as measured in a solar active region on 9 November 1989. The transverse component of the field is shown by the short line segments. The longitudinal (line-of-sight) component is represented by white and black areas for positive and negative fields, respectively.

as waves from earthquakes are used to probe the interior of the Earth; this is the new science of helioseismology.

An observational program in helioseismology is being conducted with the SSA at the Mt. Wilson Observatory, near Los Angeles. One objective of the program is to provide data for better understanding of the origins of solar magnetic activity. To carry out the helioseismological program, the SSA must make measurements of Doppler shifts that correspond to velocities of only 10 cm/s. The stability of the lithium niobate filter, when it is locked on an atomic wavelength standard, is just sufficient to achieve this sensitivity.[3] So far this has been demonstrated only in the laboratory. The SSA program at Mt. Wilson is intended to establish the requisite sensitivity in an observatory setting, a much more difficult task.

The optical path in the SSA is quite straightforward. Unfocused sunlight from the 60-ft tower at Mt. Wilson is relayed by a fast guider mirror through an infrared absorber and a 2-Å thin-film filter to the lithium niobate filter. Next, the solar image is focused on the CCD detector by a single lens. A shutter consisting of two liquid-crystal light valves controls the exposure rate. The shutter and the readout cadence are controlled with reference to a time signal that provides the precise time base needed for helioseismological observations. The SSA has an integrating servo system that locks the filter to a stabilized laser line with 2×10^{-10} precision in percentage wavelength change.

Solar observations were obtained in 1989 with a 1024 × 1024-pixel CCD camera and digital computer provided by Mt. Wilson. The quality of the observations was marginal until an improved blocker filter was installed and the earlier mechanical shutter was replaced with the liquid-crystal device. Figure 8 shows early observations of the Doppler shifts resulting from solar rotation. The figure lacks detail, indicating that the sensitivity is still
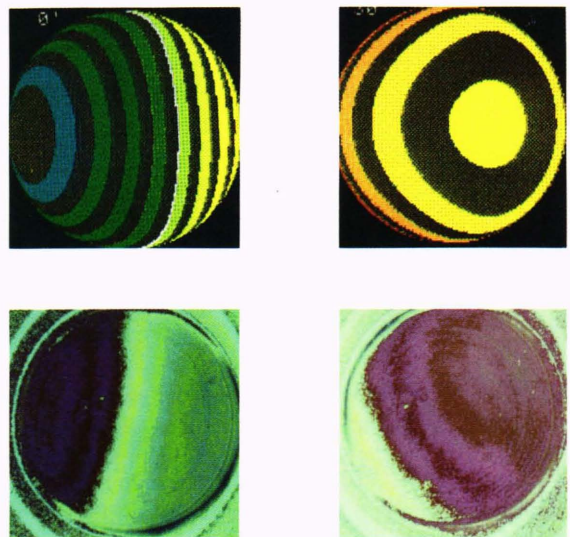

Figure 8. Comparison of the observed contours of equal apparent Doppler shift on the solar disk and contours computed from a model. Contours of equal apparent velocity on the solar surface are shown as computed (top) and recorded (bottom) at the Mt. Wilson Observatory. When the Fabry–Perot filter is tilted by about 30′ relative to the solar beam, much of the rotation velocity can be removed before recording, thereby reducing the dynamic range requirement. The images on the left have no tilt; the Fabry–Perot was tilted to make the images on the right.

below the sensitivity achieved by other technologies. We intend to install a cleaved-mica blocker filter, as in the VMG, to improve the sensitivity.

Reduction of helioseismological data requires substantial computer resources, usually several hours on a Cray XMP or similar computer for each day's observations. The Mt. Wilson observations are being examined at APL and at the University of Southern California. We hope

to make the process more economical and convenient for a small research group by using the APL-developed QUEN computer[8] for the most time-consuming calculations.

The CCD camera at Mt. Wilson requires several seconds to record and store each image. This may seriously degrade the data, because the noise from brightness and focus variations caused by turbulence in the Earth's atmosphere increases as the interval between observations increases. It is better to record images separated in time by less than 0.04 s, so that spurious image changes are small. Consequently, in the summer of 1989 we switched to a video camera with a fast frame grabber and recorded data at 30 images per second. The frame grabber was interfaced with an IBM PC/AT that also controls the SSA electro-optics and records engineering data.

PLANS FOR THE FUTURE— A BALLOON-BORNE MAGNETOGRAPH

Because of the small scale of the solar magnetic field elements, the full power of a VMG can be realized only when the blurring effect of turbulence in the Earth's atmosphere is avoided. This means that the instrument should be operated on a gondola carried near the top of the atmosphere by a balloon, or outside the atmosphere on a space platform. Opportunities for a space mission may arise only in the distant future, but prospects for a balloon flight are much brighter. A balloon could carry a VMG and a 90-cm telescope to altitudes over 30,000 m, where the solar images would be perfectly sharp. On a long-duration balloon flight, there would be opportunities to study the magnetic field evolution associated with many flares. An electronic camera and data processing system for operating the VMG at balloon altitudes is being assembled.
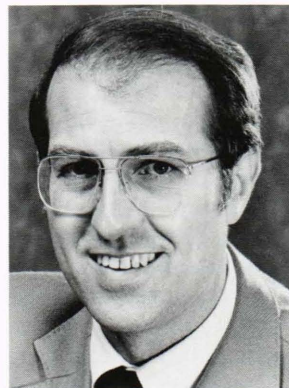
CONCLUSIONS

Forecasts of flares and space environment conditions will be more important than ever when man again ventures outside the magnetosphere to return to the Moon and start for Mars. The National Aeronautics and Space Administration made a huge effort during the Apollo lunar program to be aware of and to protect the astronauts from the hazards of solar disturbances. President Bush's Moon/Mars Human Exploration Initiative for the 1990s will require an even better effort than the 1960s program because of the longer periods of astronaut exposure. We hope the APL VMG can show how to give useful warnings of flares. Besides that, the scientific problems that may be addressed with the solar VMG and the SSA range from the physical understanding of solar flares to the internal structure of the Sun. In addition, observational experience with these instruments may suggest applications and new refinements for the electrically tunable, lithium niobate Fabry–Perot filter.

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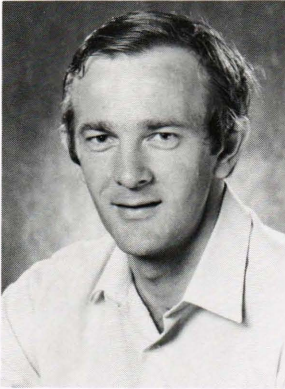
JOHN W. O'BYRNE was born in Sydney, Australia, in 1959. He received his B.S. in physics in 1981 and completed a Ph.D. in physics (astronomy) in 1986, both at the University of Sydney. His Ph.D. project involved the development of an optical interferometric system to monitor the effects of atmospheric turbulence on stellar images. As a research associate during 1986–87, he expanded this work with the development of a microthermal temperature measurement system and contributed to the optical and mechanical design of the modern stellar interferometer under construction by the Sydney astronomy group. Dr. O'Byrne is also interested in teaching astronomy and conducted astronomy courses for adults in Sydney. He came to APL in 1988 as a research associate in the Space Physics Group, joining the VMG project with responsibilities for the development, testing, and observational program of the instrument.
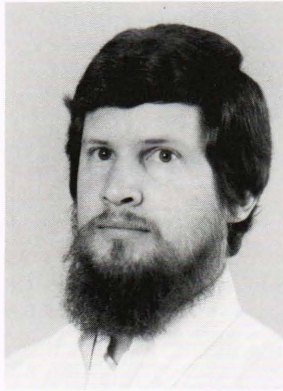
RAYMOND E. STERNER II was born in Washington, D.C., in 1952. He received a B.S. degree in mathematics and physics from Andrews University (1974), an M.Sc. degree in radiation health from The Johns Hopkins University (1980), and an M.S. in computer science from The Johns Hopkins University (1984). He worked at the Johns Hopkins Radiation Oncology Center from 1977 to 1982, helping to develop both patient treatment techniques and treatment-planning software. Since 1982, Mr. Sterner has been a member of the Submarine Technology Department's Remote Sensing Group and has been working with image processing and the spectral analysis of ocean wave video imagery. He received a Janney Fellowship in 1987 to study collisions between galaxies as an explanation of some luminous arcs in galaxy clusters, and has been granted observation time on the Hubble Space Telescope to study one such arc. Since May 1989 he has been involved in the development of the JHU/APL Solar Vector Magnetograph at the National Solar Observatory at Sunspot, New Mexico.