DAVID M. RUST, RYSZARD KUNSKI, and RALPH F. COHN

DEVELOPMENT OF ULTRASTABLE FILTERS AND LASERS FOR SOLAR SEISMOLOGY

A unique instrument has been developed to measure solar magnetic fields and suface velocities. With this Stable Solar Analyzer, a ground-based research program at the new APL Solar Observatory and at the National Solar Observatory is helping to understand the subsurface convection cells of the sun and the structure of surface and subsurface magnetic fields. The Analyzer will see eventual operation aboard a spacecraft, probably the ESA/NASA Solar and Heliospheric Observatory. The Analyzer is based on a crystalline lithium niobate Fabry-Perot filter that is used with a stabilized laser, which provides an absolute wavelength reference. A laser/Fabry-Perot combination has attained a wavelength stability of two parts in 10^{10} over a six-hour interval.

The APL Solar Observatory serves as a laboratory where we can test components of solar instruments that may someday fly in space. A Zeiss telescope, declared surplus by NASA at the conclusion of the Orbiting Solar Observatory Program, provides a stable beam of sunlight for use either on the telescope itself or on a fixed optical bench. With a lens in the beam, we can study the solar image. Often an unfocused beam is used instead so that the response of filters and detectors can be studied more easily (Fig. 1).

WHY STUDY THE SUN?

The sun has spots caused by magnetic fields that buoy up from the interior. The number of visible spots fluctuates between zero and several hundred on an 11-year cycle, but no one understands why. The spots and their magnetic fields affect the earth's climate and the space environment,[1] but the controlling forces are in the solar interior, and we know very little about what happens there.

THE SOLAR OBSERVATORY

Wednesday, February 20, 1985, was one of those brilliantly sunny winter days that tempt you to skip the shuttle and walk to the Kershner Building in your shirtsleeves. But the open field between there and the shops always has a cold wind across it in winter, so I covered the shorter distance to the site for the APL Solar Observatory quickly. I was grateful that the walls of the observatory had already been raised and glass installed in the one, southward-looking window. There was no roof, but a silvery new dome, a small-scale version of the famous one at Mt. Palomar, was resting on four-by-fours nearby. The Zeiss telescope was waiting in the rigger's loft.

At noon, the shadow of a plumb bob line over the cement pier inside the observatory ran exactly from north to south. I traced its path on the steel plate capping the pier. The telescope would be aligned to the etched line. According to celestial reckoning, that will keep the image from wobbling as the telescope follows the sun through the sky each day.

As soon as the telescope was in place and fastened down, the crane shown in the picture lifted the dome and lowered it gently to close the 10-foot-hole in the roof. Later, a rainstorm revealed only a small leak, which stopped after the roof was tarred.

The APL Solar Observatory near the 60-foot satellite tracking antenna. The building houses a Zeiss telescope with a photoelectric guider. The telescope is mounted on a cement pier set 10 feet into the ground in order to limit vibrations. A PDP 11/23 computer has been installed at the observatory for data recording and instrument control.

D. M. R.

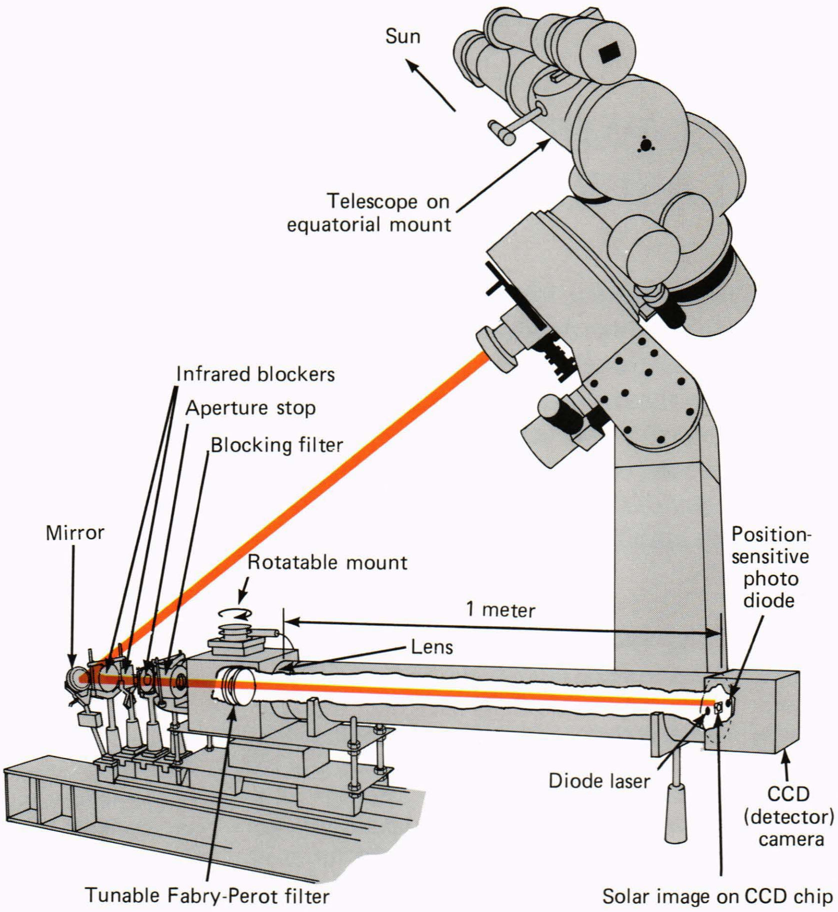

Figure 1—A schematic diagram of the observatory instrumentation as presently installed. Unfocused sunlight is directed by the Zeiss telescope to an optical bench where a mirror redirects the light, shown in color, through filters to a lens that forms the image at the camera (right). The diode laser stablization system sits astride the camera.

The instruments being developed at the APL Solar Observatory will probe the interior of the sun by the new science of helioseismology—the study of solar quakes. What is revealed will certainly tell us a great deal about the forces of convection and rotation below the surface.

THE MUSIC OF THE SPHERES

Figure 2 shows how, in 1970, giant waves were detected at the sun's surface. An instrument that measures the local surface velocity was scanned rapidly back and forth for several hours.[2] When the velocity at each point along the scan line was plotted against time, large areas were found to be oscillating in phase. Similar oscillations had been detected 10 years before the work illustrated in the figure, but no one had realized how large the oscillating areas were. Several more years passed before the implication of this observation was realized; namely, if the oscillations can remain in phase over a large area and for a long time, they must be global resonances. Observations by Deubner[3] and theoretical models by Ando and Osaki[4] and Ulrich and Rhodes[5] established, in 1975, that the music of the spheres is ringing clearly in the sun. There are ten million modes of vibration, some examples of which are shown in Fig. 3. All of them are global, pulsing back and forth and around the sun at the speed of sound. Something sets them off—we do not know what—but at the surface they resonate for days. These sunquakes last for a long time because the solar gases have practically no viscosity. Waves that are emitted toward the interior of the sun may persist for years, so lossless is the cavity of that celestial sphere.

The sound waves probe the interior with a speed that varies with frequency, and it is this dispersion of the waves that creates so many resonances, the pattern of which can be used to chart density and temperature at all depths down to one-twentieth of a solar diameter.[6,7] Also, waves that travel in the same direction as the rotating internal gases have a different wavelength than waves that travel against the rotation. This splitting can be used to determine how fast the inside of the sun is turning.[8]

Some fundamental questions about stellar structure and the puzzling shortage of neutrinos from the sun's core may be understood through measurements of the waves that pass closest to the core. Therein lies a challenge to the solar physicist. To detect them, he must measure velocities at the surface as small as 30 centimeters per second, and he must not allow his velocity meter to drift by more than one part in a billion per month.

LOOKING FOR THE RESONANCES

When any gas is moving toward or away from the observer, the apparent wavelength of the atomic lines

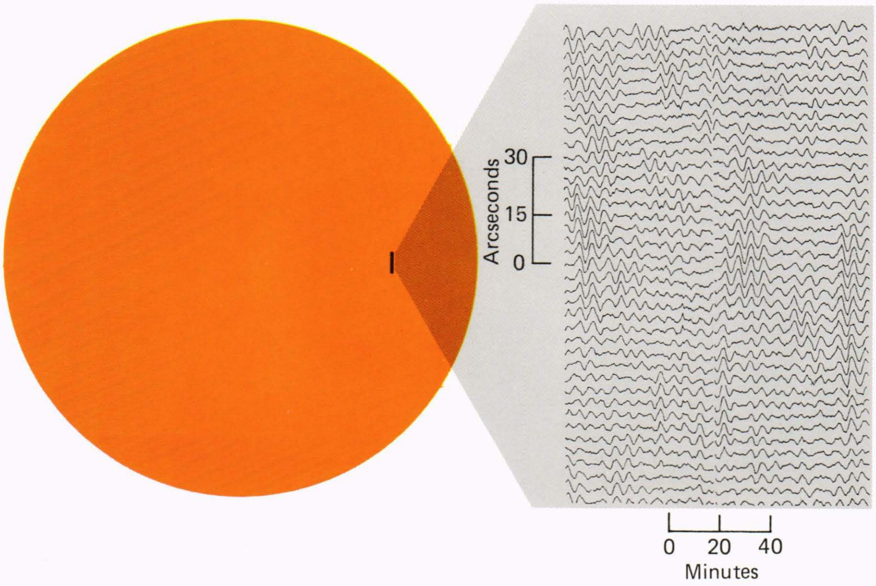

Figure 2—At each point on the solar surface, the gases move up and down regularly with periods of about five minutes. These traces of surface velocity versus time show how the gases sometimes oscillate in phase over large areas of the solar disk. The subject of helioseismology was born with the realization that the oscillations represent global acoustic resonances.

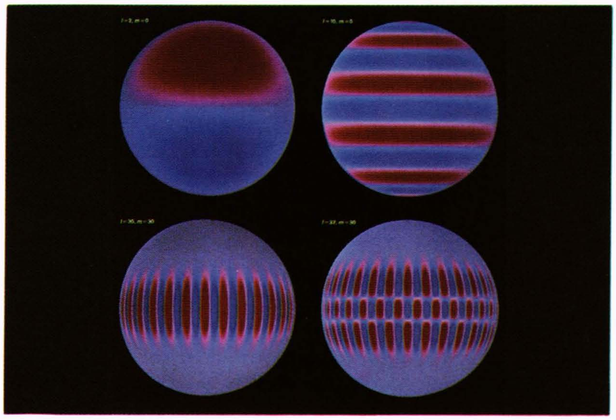

Figure 3—Global oscillation modes. The surface motion is represented by blue for up and red for down. The colors would be reversed 2-½ minutes later. The spheres represent the patterns one would see if the sun oscillated in only a single mode at a time. In reality, there are 10 million simultaneous modes of oscillation. (Figure courtesy of J. W. Harvey of the National Solar Observatory.)

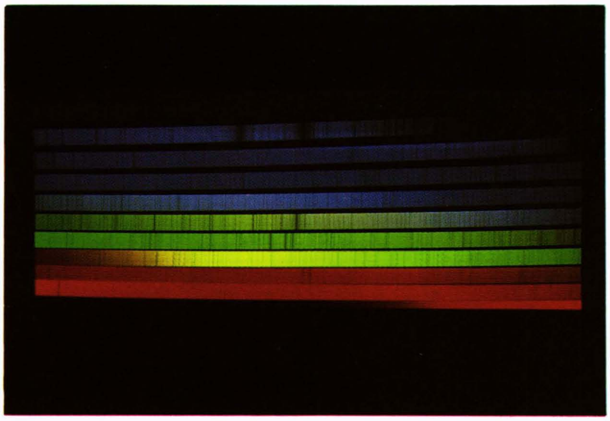

Figure 4—The solar spectrum. The voids, called Fraunhofer lines, are caused by the absorption of light by atoms in the surface gases. Almost all the elements known on earth have been identified in the sun by their characteristic absorption patterns. (Photograph courtesy of Sacramento Peak Observatory.)

it emits will be shifted by the well-known Doppler effect toward the blue for approaching gas and toward the red for receding gas. The presence of the internal solar waves is revealed by motions of the gaseous surface just as earthquakes are revealed by the motion of the ground. The solar surface is a glowing gas whose spectrum (Fig. 4) is hatched by dark lines called Fraunhofer lines. They appear at the same wavelengths as the bright emission lines of gases that are heated in the laboratory.

A velocity meter for studying the solar oscillations uses filters placed just redward and blueward of an atomic line. When the line shifts in wavelength, there is a difference in the intensity recorded through the two filters. For suitably designed filters, the intensity difference is proportional to the velocity (Fig. 5). To measure a velocity of only 30 centimeters per second, an intensity difference of one part in ten thousand must be detected. In order to distinguish among the ten million global oscillation modes, one must achieve that precision at three-quarters of a million points on the solar image.

Fortunately, repeated measurements can be made for days and combined to attain the precision required for this helioseismology, although this is difficult to accomplish from terrestrial observatories where clouds and sunsets interfere with depressing regularity. Therefore, NASA and the European Space Agency are planning a Solar and Heliospheric Observatory (SOHO) that will carry instruments for helioseismology and other solar research into a halo orbit (Fig. 6) between Earth and the sun. SOHO will be launched in 1993, and we hope that the instrument being developed at the APL Solar Observatory will be aboard.

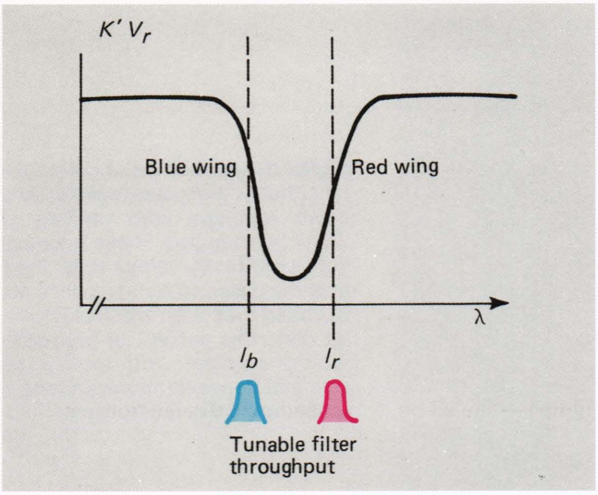

Figure 5—Velocities (V_r) on the solar surface may be inferred from sequential measurements of intensity (I_r and I_b) in the red and blue wings, respectively, of any Fraunhofer line in the solar spectrum. The tunable Fabry-Perot filter operates at 1 hertz, alternately passing 0.18-angstrom bands from the red and blue wings of the line. V_r is proportional to the displacement of the line $\Delta\lambda$, with the constant of proportionality (K') being dependent on the atomic line and filter profiles. The power spectrum of the oscillations as a function ($f(\omega)$) of the frequency is obtained by Fourier transformation of the observed velocities ($V_r(t)$).

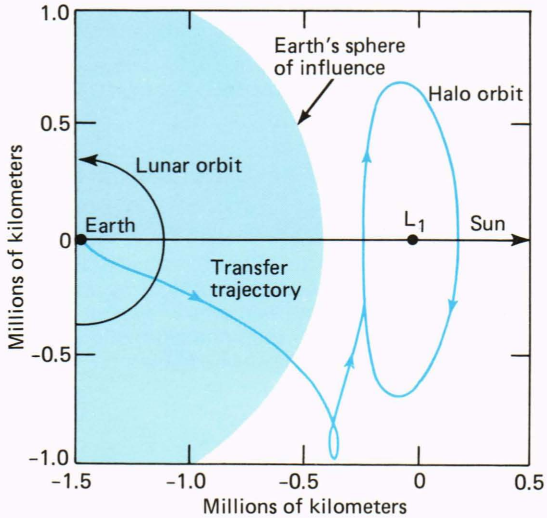

Figure 6—The Solar and Heliospheric Observatory will circle a point in space, called the first Lagrangian point (L_1), where the pull of earth's gravity equals that of the sun. Such a halo orbit is very stable, although occasional bursts from on-board rockets will be necessary to maintain it for several years.

TUNING INTO THE ATOMIC FREQUENCIES

In collaboration with the Applied Physics Division of the Australian National Measurement Laboratory of the Commonwealth Scientific and Industrial Research Organization, we have designed and fabricated a tunable filter from a 50-millimeter-diameter wafer of optical quality lithium niobate crystal. Two 75-millimeter crystals have also been obtained. Filters made from them will be completed soon and will provide higher light throughput and better resolution of solar features than does the 50-millimeter filter.

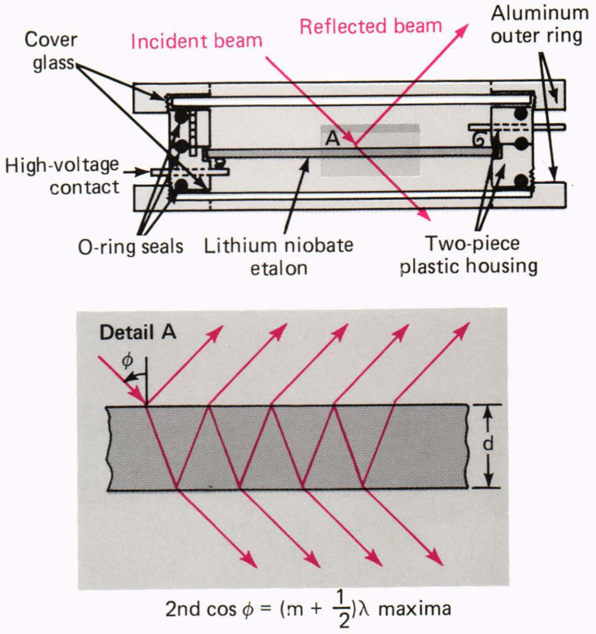

Figure 7—The Fabry-Perot etalon, 0.22 millimeter thick, mounted in a nitrogen-filled enclosure for protection of its silvered faces. Voltage is applied to the etalon by means of two spring contacts. The wavelength passed by the etalon is a linear function of applied voltage. It also depends on the thickness (d) and the index of refraction (n). For a given wavelength (λ), transmission maxima occur at discrete orders (m = 1,2,3, ...) as the angle of incidence (ϕ) is varied. Normally a series of rings appears, as shown in Fig. 8.

Lithium niobate is a highly transparent crystalline material whose index of refraction changes in proportion to voltage applied parallel to the c axis of the crystal. The advantage of using lithium niobate crystal is that, when the faces of a wafer of it are polished flat and parallel and are coated with a partially reflecting material, the resulting device acts as a Fabry-Perot filter whose passband position can be tuned by the application of voltage to the crystal faces.[9] The Fabry-Perot filter (sometimes called "etalon" from the French word for "standard") and its principle of operation are shown in Fig. 7.

The measured properties of the 50-millimeter Fabry-Perot filter are listed below. Figure 8 shows how the transmission of helium-neon laser light varies with angle. The picture can be used to measure the filter's optical qualities, as follows:

Thickness: 0.0222 centimeter
Free spectral range: 3.25 angstroms
Passband: 0.17 angstrom
Effective finesse: 18.6
Coating: silver (reflectance approximately 0.91)
Voltage sensitivity: 4 × 10^{-4} angstrom per volt
Temperature sensitivity: 4.8 × 10^{-2} angstrom per degree Celsius

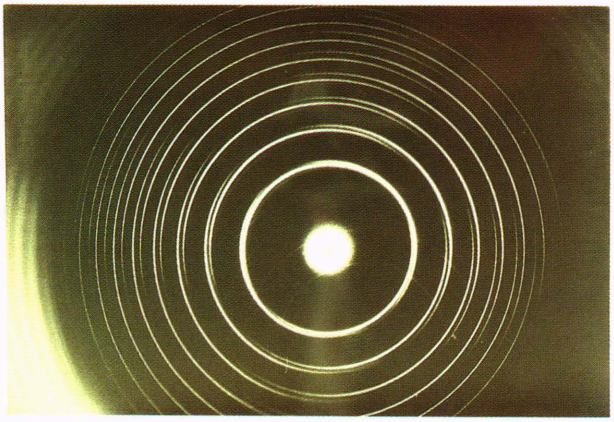

Figure 8—The classic Fabry-Perot rings seen when viewing an extended monochromatic light source through an etalon. They are altered by the properties of the lithium niobate crystal. Because the crystal is birefringent for off-axis rays, two sets of rings are seen. They have been separated with a polarizing filter placed over the camera lens.

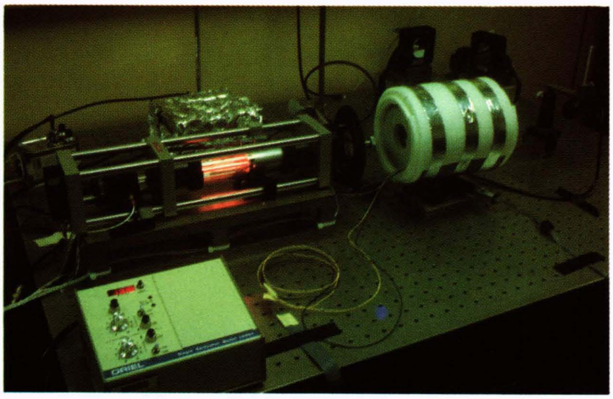

Figure 9—The stablility test setup. The beam from a helium-neon laser passes through the Fabry-Perot etalon enclosure (wrapped in a thermal insulation blanket) to a detector diode (right). Changes in the transmitted beam intensity due to temperature fluctuations were corrected to a precision of 3 × 10^{-9}. The laser is from the National Bureau of Standards and has a wavelength stability of 1 × 10^{-13}.

This etalon is a stable, compact, rugged, tunable filter that is capable of making very high precision measurements of Zeeman and Doppler shifts in solar spectral lines. It is the key component of the velocity meter that we call the Stable Solar Analyzer because of the laser system that it uses to achieve the stability required for recording the oscillations.

STAYING TUNED IN

The index of refraction of lithium niobate depends on temperature, so the wavelength passed by the etalon made from it also is sensitive to temperature. Temperature control of such a large optical element exposed to full sunlight is not possible at the ±40 microkelvin level that would be required to meet the SOHO performance goals. Therefore, a servo circuit was developed by the Space Department's Space Instrumentation Group to stabilize the etalon by applying a voltage to compensate for drift resulting from temperature and alignment changes. Figure 9 shows the laboratory test setup.

In the test, the wavelength passed by the unservoed etalon drifted because of variations in temperature, mechanical alignment, and supply voltage. The servo, which was a digital system programmed on a PDP 11/23 computer, established the validity of our tunable etalon approach to the SOHO stability requirements. With a stabilized helium-neon laser from the National Bureau of Standards providing the reference wavelength, λ, and with the test setup as illustrated in Figs. 9 and 10, the servo stabilized the passband of the etalon to three parts in a billion ($\Delta\lambda/\lambda = 3 \times 10^{-9}$).

Because the lifetime of the gas laser is limited, it is not a suitable frequency standard for a space-borne instrument. Therefore, a system for stabilizing diode lasers was developed for the Stable Solar Analyzer program by APL's Time and Frequency Systems Section. Diode lasers have not previously been used for spacecraft frequency standards, but they have the requisite properties: they are rugged, lightweight, and long-lived, and their frequency is easily modulated.

Our method of stabilizing the diode laser drew on many of the techniques developed earlier in a program to improve optically pumped cesium beam frequency standards. In the device made for the Stabilized Solar Analyzer, cesium-133 vapor at 40°C is held in a small glass cell. Part of the laser beam passes through the cell, as shown in Fig. 11. The amount of light passing through the cell depends on how close the laser's wavelength is to a cesium atomic line. Absorption is highest at precisely 8521.26 angstroms. Since the wavelength of the laser is proportional to the current applied to it, we were able to control the wavelength with a servo loop in which the laser current supply depends on the intensity measured by the detector at the end of the cell.

Two diode laser units have been made; we intend to measure their long-term stability by a heterodyne technique in which each laser is servoed to one of the two fine structure lines of the cesium D2 line. These lines are separated in frequency by 9.2 gigahertz so a detector illuminated by both lasers will see a beat frequency equal to 9.2 gigahertz, a frequency that can be measured to great precision with standard microwave techniques.

Our goal for the heterodyne system is to demonstrate that the wavelength of each laser can be maintained for several months at the 10^{-12} level of precision. For now, there is only the record (Fig. 12) of the servo error signal that shows that short-term open-loop frequency fluctuations of greater than 10^{-8} are reduced to approximately 10^{-9} by closing the loop. The signal is noisier between A and B in the figure because turning on the servo changes the average applied current and thus the laser temperature. About two minutes are required to establish a new equilibrium.

After stabilization, the beam from the diode laser passes on to the Fabry-Perot filter as shown in Fig.

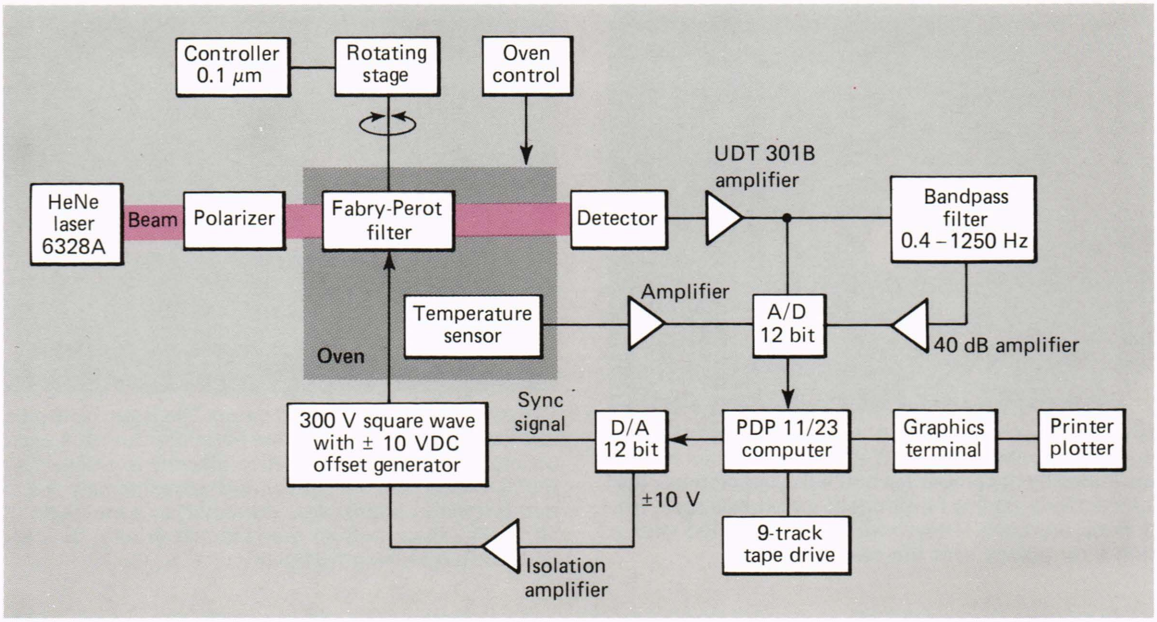

Figure 10—A block diagram of the test setup for the digital servo stabilizer. The rotating stage was used to calibrate the wavelength scale for the tests. The passband of the etalon was cycled through ±0.12 angstrom by application of a 300- volt square wave. The resultant alternate current signal at the detector was driven to zero by application of a small additional voltage as required.

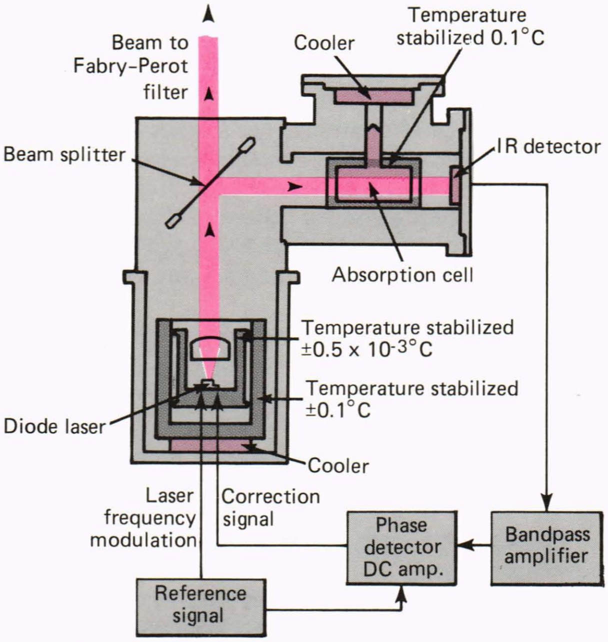

Figure 11—The stabilized diode laser provides a rugged and long-lived wavelength standard. The cesium vapor absorption cell is the atomic standard to which the diode laser is slaved. This diode laser system will provide a spacecraft wavelength standard that can be maintained at the 10^{-10} level of precision for several years.

11. The method of servo-controlling the etalon was changed from the digital scheme used earlier to an analog phase detection scheme because the digital servo demands too much of the computer's time when solar images are being recorded.

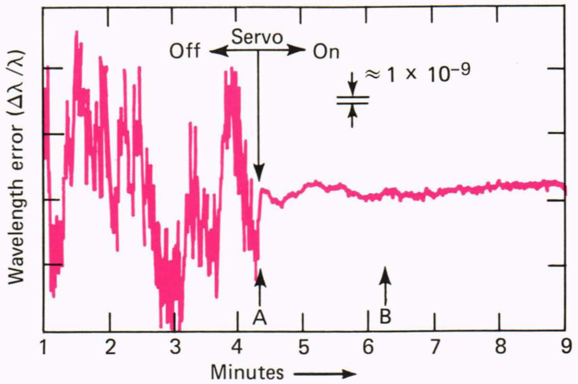

Figure 12—The short-term performance of the first of the stabilized diode lasers.

TRANSCRIBING THE NOTES

The minicomputer used for laboratory tests of the digital servo system has been moved to the solar observatory for data recording and instrument control. At a cadence of 1 hertz, the solar image as filtered by the lithium niobate etalon is transferred to the memory with 12-bit precision by a solid-state television camera. The camera, made by Photometrics, Ltd., uses half the 380 × 576 pixels (picture elements) of its solid-state chip for recording the image and half for storage of the previous image. The half-exposed, half-covered chip replaces a mechanical shutter because the exposure time depends on the interval between data shifts from the exposed side to the covered side. For our purpose it is instantaneous. The shift requires 1 millisecond, the exposure time with the 50-millimeter etalon is 100 milliseconds, and the digitization time for the stored image is 1 second.

By January 1986, the software for the solid-state television camera control and data storage was being debugged. The computer has been used with single detector diodes to measure the transmission of the Fabry-Perot filter and of several auxiliary filters. The techniques for tuning the filter in wavelength and for controlling its temperature in a real observatory environment were worked out. Finally, to take advantage of the instrumentation, even though the data recording system was not yet ready, we packed everything and spent two weeks with the instrumentation at the Sacramento Peak Observatory in Sunspot, N. Mex.

The results of the Sacramento Peak runs are shown in Fig. 13. Signal power (proportional to the square of the velocity) is plotted against temporal frequency and wavelength. There are three features of particular interest in this power spectrum. The first is the power at all frequencies for small wave number (left edge of the figure). This is instrumental noise, caused mostly by nonuniform sensitivity of the optical system for velocity at different points on the solar image. The second is the power at low frequencies for all wave numbers (bottom edge of the figure) that is due to convective motions on the solar surface and instrumental effects; it is a troublesome and hard-to-avoid noise that tends to obscure the oscillatory signal.

The third and most interesting feature of the velocity power spectrum is the series of ridges in the center of Fig. 13. They form along parabolic lines relating temporal frequency to spatial frequency. The presence of the ridges shows that, at a given frequency, only oscillations of a select family of discrete wavelengths are resonating in the sun.

The signal levels detected during the Sacramento Peak runs are consistent with the levels expected theoretically, considering the measured filter bandwidth, the aperture of the telescope, the detector efficiency, etc. Another run was made in February 1986; next, we plan to undertake regular observations at the APL Solar Observatory.

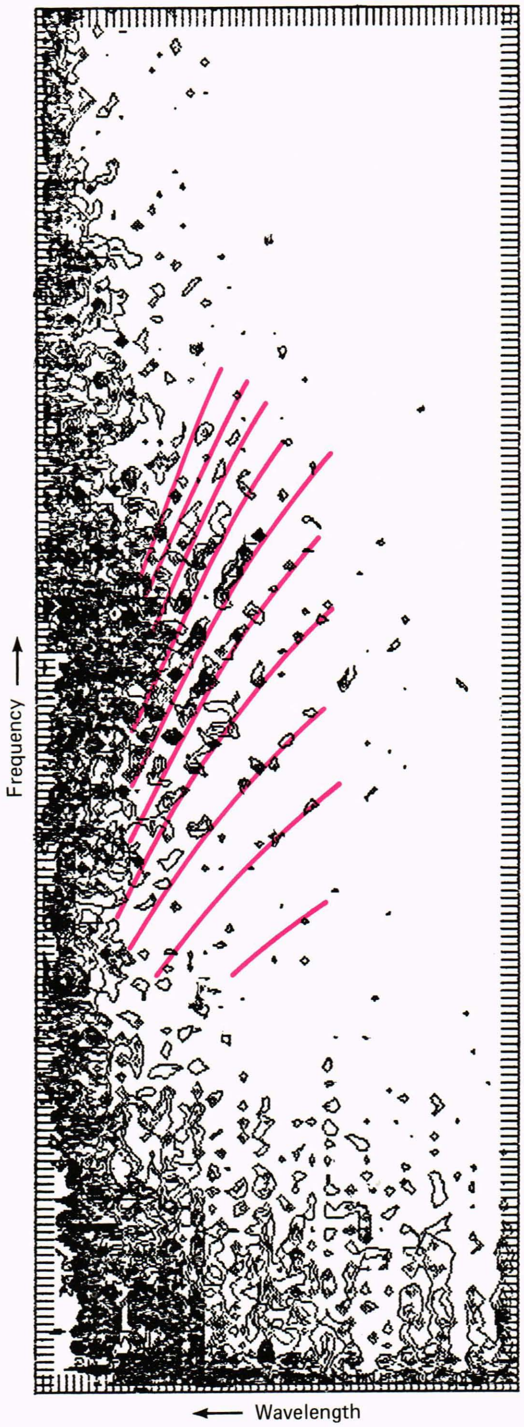

Figure 13—A power spectrum showing the ridges (center) that reveal the presence of stable global oscillations. Heavily contoured areas reflect the presence of long wavelength and low frequency instrumental noises. Data were obtained in October 1985 with the first etalon made for the Stable Solar Analyzer program. Theoretical positions of the ridges are shown by colored lines.

REFERENCES

[1] D. M. Rust, "The Solar Maximum Observatory," *Johns Hopkins APL Tech. Dig.* **5**, 188-196 (1984).

[2] S. A. Musman and D. M. Rust, "Vertical Velocities and Horizontal Wave Propagation in the Solar Photosphere," *Solar Phys.* **13**, 261 (1970).

[3] F. L. Deubner, "Observations of Low Wavenumber Non-Radial Eigenmodes of the Sun," in *Physique des Mouvements dans les Atmospheres Stellaires*, R. Cayrel and M. Steinberg, eds., Colloques Internationaux du CNRS, Paris, p. 259 (1975).

[4] H. Ando and Y. Osaki, "Non-Adiabatic Non-Radial Oscillations: An Application to the Five-Minute Oscillations of the Sun," *Publ. Astron. Soc. Japan* **27**, 581 (1975).

[5] R. K. Ulrich and E. J. Rhodes, Jr., "The Sensitivity of Non-Radial p-Mode Eigenfrequencies to Solar Envelope Structure," *Astrophys. J.* **218**, 521 (1977).

[6] J. W. Leibacher, R. W. Noyes, J. Toomre, and R. K. Ulrich, "Helioseismology," *Sci. Am.* **48** (Sep 1985).

[7] J. Christensen-Dalsgaard, D. Gough, and J. Toomre, "Seismology of the Sun," *Science* **229**, 923 (1985).

[8] R. K. Ulrich, E. J. Rhodes, Jr., and F. L. Deubner, "The Effect of a Radial Rotation Velocity Gradient on p-Mode Eigenfrequencies," *Astrophys. J.* **227**, 638 (1979).

[9] W. Gunning, "Double-Cavity Electrooptic Fabry-Perot Tunable Filter," *Appl. Opt.* **21**, 3129 (1982).

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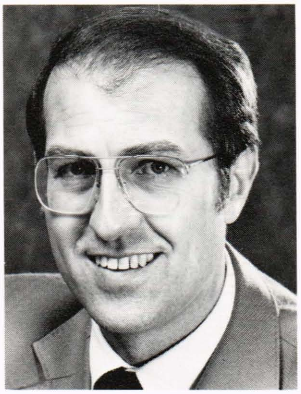

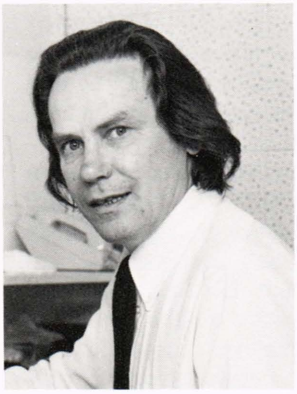

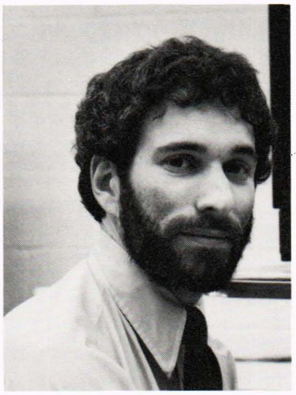

DAVID M. RUST was born in Denver, Colo., in 1939 and received a Ph.D. in astrogeophysics from the University of Colorado in 1966. Before joining APL in 1983, he was employed by American Science and Engineering, Inc., in Cambridge, Mass., and Greenbelt, Md., where he served as the Solar Maximum Mission Observatory Coordinator and as chairman of the Solar Maximum Year Study of Energy Release in Flares. Dr. Rust's specialties are in the physics of solar activity and in solar observatory instrumentation. He serves on the NASA Helioseismology Steering Committee. He is a member of the Principal Professional Staff at APL and head of the Solar and Interplanetary Physics Section of the Space Physics Group. He is also principal investigator for the Solar Maximum Mission Hard X-Ray Imaging Spectrometer data analysis and manager of the solar magnetograph project.

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Dr. Kunski was a member of the Polish National Committee of the International Union of Radio Science (URSI). He holds several patents on atomic frequency standards and is coauthor of a book on temperature stabilization of quartz frequency standards. His professional experience includes research on atomic spectroscopy and its application to atomic frequency standards at the National Physical Laboratory, Great Britain (1972); the National Bureau of Standards (1974-75), and University Laval, Quebec, Canada (1978-81).

He worked with Bendix Field Engineering from 1981 until joining the Time and Frequency Systems Section at APL as a subcontractor in 1983, where he continued his studies, under NASA sponsorship, of the research of atomic frequency sources, hydrogen masers, laser optical pumping in a cesium beam, and frequency stabilization of semiconductor lasers.

RALPH F. COHN was born in Willimantic, Conn., in 1955. He received a B.S. in electrical engineering from Tufts University in 1977 and an M.S. in ocean engineering from the University of Rhode Island in 1979. He joined APL in 1979, working for the Ocean Data Acquisition Program and concentrating on signal processing and oceanographic sensor design and testing. Since 1982, he has been a member of the Space Sciences Instrumentation Group, where he specializes in electro-optical instrumentation, image processing, and charged particle instrument development. He is also participating in the Milton S. Eisenhower Research Center's buried pipeline corrosion program, where he is involved in magnetometric and electrochemical measurements. Mr. Cohn is pursuing a Ph.D. degree in The Department of Materials Sciences and Engineering at the Johns Hopkins University.