AIAA 81-0204R

Coronal Observations from the Solar Maximum Mission Satellite

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The Coronagraph/Polarimeter on board the Solar Maximum Mission satellite operated successfully for over 6 months. This paper addresses first, the scientific goals and coronal observations obtained, and second, the instrument design and control. The coronal observations are discussed with particular emphasis on studies of evolutionary changes in the corona and of material ejected from the sun. The instrument design section describes some of the more unique features of the coronagraph. These include 1) an optical design incorporating an achromat objective lens resulting in 10-arc sec resolution in imaging and an instrumentally scattered radiance of less than $10^{-9} B_{solar}$, the mean solar disk radiance, and 2) an SEC vidicon detector, allowing integration on the low light levels of the corona. The instrument control section describes 1) the microprogram sequence controllers using the "algorithmic state machine" concept which control the vidicon camera and data acquisition, and 2) CORMAX, the program resident in the onboard computer used to command the desired observations. The computer control assures flexibility in the observing program to optimize observations of changing solar phenomena and allows rapid response to either SMM or ground-commanded solar flare alerts.

Introduction

THE sun reached the peak of its 11-yr activity cycle in late 1979. To take advantage of these few years of increased activity, and to apply experimental techniques unavailable to ground-based observatories, the Coronagraph/Polarimeter (C/P) was among the seven experiments chosen to be on the Solar Maximum Mission (SMM) satellite, launched into Earth orbit in February 1980. Study of results from earlier satellite coronagraph observations suggested that a number of areas of research should be emphasized with the new SMM instrument. These included 1) dynamics of the corona, especially the relationship of coronal transients (rapid changes in the corona) to the evolution of the corona, with observations lower in the corona than previously achieved; 2) magnetic field directions in the corona analyzed through the use of emission line polarization; 3) coronal manifestations of solar flares and eruptions of solar prominences with the capability of discerning cool prominence material from the high temperature corona using an H-alpha emission line filter; and 4) better discrimination between the electron and dust coronae using red to blue color differences.

Meeting the C/P scientific goals presented a number of technical challenges. Observation of the inner corona demand an optical and detector system able to reject instrumentally scattered light and respond to low light levels in the corona expected to vary by a factor of 10^3. Examination of the corona in different spectral bandpasses (for both the emission lines and the continuum corona) required both narrow-band and broadband transmission filters, commandable according to the observation desired. The control of the C/P necessitated great flexibility. While solar flares are short-lived, requiring an onboard alarm, the slower eruptive prominences and radio burst exciters were detectable only from the ground-based observatory networks, with alerts uplinked by ground commands to the spacecraft.

Data would be in the form of digitized images transmitted to ground stations. The allotted data transmission budget was stretchable provided the observations could be suitably tailored to the tape recorder dump schedule of the day. The C/P is unique in the variety and complexity of observational modes possible. The above-mentioned goals were achieved through the design of a versatile instrument, directed by microprogram sequence controllers and commanded from the ground by input to CORMAX, a program resident in the onboard computer. The operations were controlled from the Goddard Space Flight Center, from which response to the real time changes on the sun and collaborative programs with the other SMM instruments and solar optical and radio observatories around the world were directed.

The C/P instrument is described in detail by MacQueen et al.,[1] with the first papers of preliminary scientific results given by House et al.[2] and Wagner et al.[3] This paper presents a description of the examples from the coronal observations. A discussion of the instrument, in particular the optics and SEC vidicon detector, is followed by an explanation of the control aspects of the telescope.

Coronal Observations

A sample of the more than 25,000 frames obtained of coronal structures over the 6-month operational lifetime of the SMM C/P is shown in Fig. 1, taken on April 12, 1980. The coronal data are imaged on a vidicon in quadrants, 5.5 solar radii on an edge, rotatable around the sun. The figure shows the corona oriented such that solar northwest is up. A set of disks occults the solar disk and the inner corona out to half a solar radius above the limb (lower center of Fig. 1). The radiance levels of the corona vary from $10^{-7} B_{solar}$, the mean solar disk radiance, to less than $10^{-9} B_{solar}$ from the inner to the outer portions of the field of view (from 1.5 to 6.0 R_{solar} from sun center).

The structures (streamers) seen are the sum of radiation scattered by free electrons and dust particles in the line of sight. That the form of these streamers is dictated by the sun's magnetic fields is known, but the details of this control continue to be a subject of current research. Significant and new data concerning this problem are provided by the C/P Fe

Presented as Paper 81-0204 at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Mo., Jan. 12-15, 1981; submitted Feb. 25, 1981; revision received Jan. 25, 1982.

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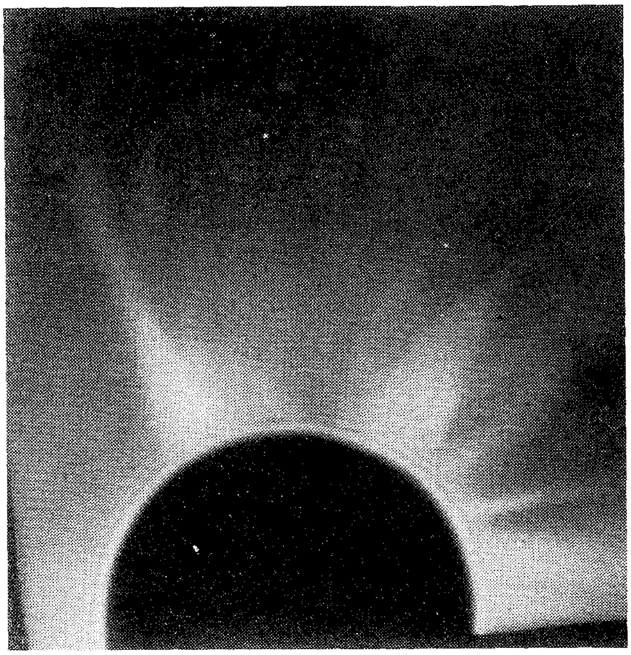

Fig. 1 The quiet solar corona at 2001 U.T. (Univeral Time), April 12, 1980.

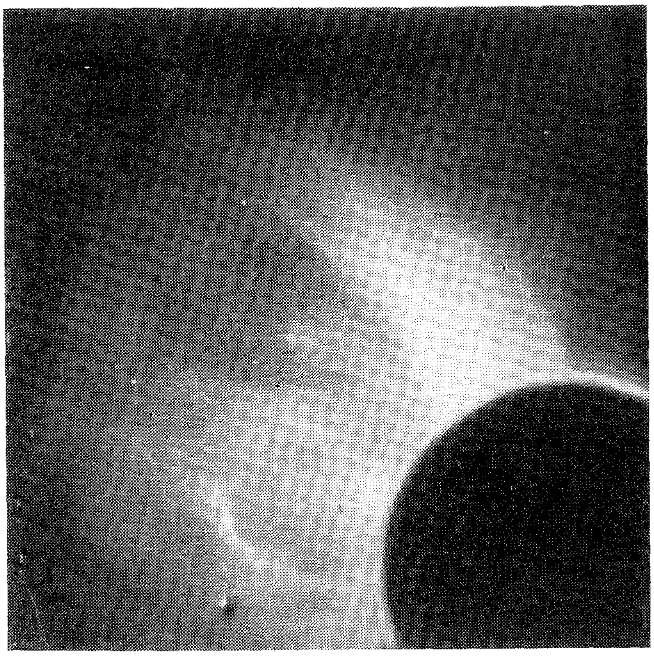

Fig. 2 An example of a coronal transient rising above the occulting disk at 1138 U.T. (Universal Time), May 5, 1980.

XIV green line measurements. This spectral line, at 5303 Å, originates at temperatures in excess of 1×10^{6} K. The direction of magnetic fields is reflected in the polarization measured in this line. In addition, the coronal data include both intensity and linear polarization information in distinct broad spectral bands in the red, green, and blue. These data permit an estimate of the electron density through separation of the unpolarized dust-scattered coronal component from the electron corona, and also, permit an estimate of the angle from the plane of the sky to the scattering region. The synoptic data are being used to construct a history of the long term evolution of the corona.

Of particular interest are the coronal transients, those events where a rapid change in the corona is observed. To date over 70 transients have been identified in the coronagraph data set; most often these events are seen as ejections of

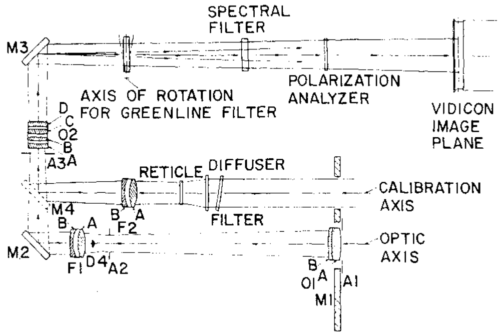

Fig. 3 Optical system diagram.

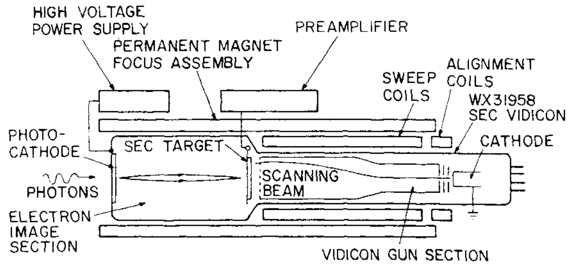

Fig. 4 Vidicon functional diagram.

material from the sun. These data will provide a better understanding of the overall energy processes involved in transients related to solar flares or eruptive prominences. Figure 2 shows one image of a sequence taken on May 5, 1980. The event is centered at 27°N on the west limb of the sun and consists of a complex structure of loops and knots of material moving outward. The leading edge motion corresponds to an outward speed of about 500 km/s; the bright knots are cool hydrogen material moving at about 300 km/s. The C/P is the first spaceborne coronagraph to make observations of the H-alpha emission of cool prominence material. Information on excitation mechanisms of the neutral hydrogen plasmoid emissions is also available by polarization analysis. Complete analyses for this and other transients are being carried out to give 1) the radiance of the electron corona and the H-alpha emission; 2) the polarization of the radiation (and with this an estimate of the angle between the plane of the sky and the structure); 3) the density of the transients; 4) the amount of neutral hydrogen ejected; and 5) combined with metric radio data, the magnetic field strength in such events.

On the average, 200 images of the corona were taken daily, with approximately 30 additional frames interspersed throughout the 15 orbits per day to ensure good calibration of the vidicon.

Instrument

Optical System

The C/P is the most recent version of a spaceborne externally occulted Lyot coronagraph.[4] The C/P optical system is shown in schematic form in Fig. 3. The rejection of stray instrumentally scattered light is of utmost importance in a coronagraph designed to measure both the near ($1.5R_{\text{solar}}$) and far ($6.0R_{\text{solar}}$) corona. One technique used to accomplish this rejection is through the choice of an achromatic objective lens (O_1). The color correction permits operation of the coronagraph at a wide variety of wavelengths. An accurate focus in each color of the bright-edged image of the external occulting disks (not shown in the figure) onto a smaller internal occulting disk (D_4) is possible. A singlet objective lens suffers from severe chromatism, and unless prevented by the use of a large internal disk, would permit higher levels of stray light to pass by the internal disk. The net result of the use of an achroma objective is to permit the instrument to achieve a low stray light level in all colors, and at the same time, allow an inner field vignetting considerably reduced over that needed in an broad bandwidth system.

The air-spaced doublet objective lens combines fused silica Suprasil I and cerium-doped F2G20. To minimize the scatter, the elements are polished to "coronagraph quality" finish and left uncoated. The glass chosen must also have a very low internal bubble content. Quantitative scattering tests were done on the eight available sets of objective lenses to select the best set for flight. The results showed that the total scattering was approximately two times greater than the singlet objective of the Skylab ATM coronagraph. This higher scatter is attributed to the combination of an inferior polish of the F_2, which is a softer glass, and the increased path length through the glass of a doublet over a singlet. Multiple reflections from the doublet surfaces produced ghosts, the effects of which were reduced by adjusting curvature and lens spacing so they could be occulted. For the SMM C/P the desire to examine the corona closer to the sun than ATM in widely-separated wavelength bands required making the objective achromatic; the two times higher stray radiance in the far field was an acceptable tradeoff.

SEC Vidicon

The Coronagraph/Polarimeter requires a detector of high spatial resolution and low light level response to adequately record images of the corona. The sensor chosen was a secondary electron conduction (SEC) vidicon (Westinghouse WX31958) with an S20 photocathode (see Fig. 4). The vidicon was optimized for C/P use by removing the suppression mesh; this increased the spatial resolution and improved the signal to noise. In order to further increase the signal to noise, the target readout beam was slightly defocused. A permanent magnet focus assembly was used instead of an electromagnetic coil, providing a relatively cool environment for the vidicon photocathode. The resolution achieved for a high resolution image (896×896 pixels) is 10 arc sec, each pixel being 6 arc sec. An average of every 2×2 pixels using onboard electronics provided low resolution images with a resolution of 14 arc sec. Clearly, the beam defocus has a significant impact, principally on the high and not the low resolution images.

An accurate calibration of the coronal radiance is fundamental to the determination of coronal densities and magnetic fields. The photometric integrity was ensured by the use of an inflight calibration system. A separate optical path (see Fig. 3) allowed light from the solar disk to pass through a set of calibration filters and impinge on the vidicon. The filters consist of a neutral density filter, an opal diffuser, and a reticle. The reticle displays three areas of different densities and a bar pattern modulation transfer function target. The attenuation of the solar disk radiance by the calibration filters was measured prior to launch using as standards the same High Altitude Observatory (HAO) opals as used on the ATM and ground-based HAO coronagraphs. Calibration programs were designed to monitor the vidicon response and uniformity with time. These data will be compared with the preflight measures of the reciprocity, uniformity, MTF, and dark current.

Instrument Control

Microprogram Sequencers

The operation of the SEC vidicon camera, the engineering and science data acquisition and storage, and interfacing with the spacecraft telemetry are all controlled by microprogram sequence controllers. A simplified block diagram of the C/P instrument (see Fig. 5) shows the sweep control sequencer (SCS) and data control sequencer (DCS). The SCS controls 1) the gun electron beam position during the erase and read modes of the target, 2) the switching of the beam and control grids, 3) the shutter during the expose mode, and 4) the flood

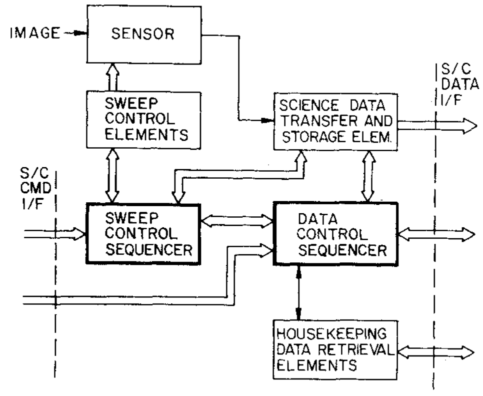

Fig. 5 Simplified coronagraph block diagram.

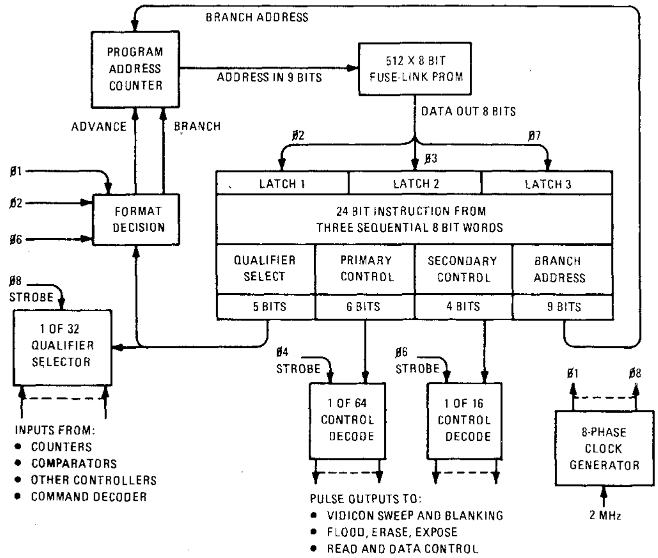

Fig. 6 SCS block diagram.

lamps during flood mode. The DSC controls the engineering data system (multiplexer, analog/digital conversion, and memory storage) which provides data at the serial engineering data port, and the science data (video sampling, analog/digital conversion, and scan line memory storage), which provide data at the serial science data port.

To accomplish the complex sweep generation and data processing algorithm of the vidicon system, the logic control architecture of a microprogram sequence controller was used. A microprogram sequencer is one in which control outputs are generated and branch decisions are made in a sequence of "states" or time periods. The sequence programs are stored in programmable read-only memories (pROM's). The three principal operations of the sequencers are to 1) retrieve instruction word from the pROM code, 2) generate outputs from the instruction word, and 3) test qualifier inputs to determine if a branch to another sequence must be made.

The algorithm to be performed by the "state machine" leads to the specification of the microprogram instruction for each state. Each instruction contains the qualifier code for that state followed by the output codes and branch address in the event that the qualifier requires a branch to another sequence.

The block diagram for the SCS is shown in Fig. 6. A 24-bit instruction is assembled and consists of the four fields shown in the figure. A digital multiplexer selects 1 of 32 inputs to be tested. If the qualifier is high (logic 1) the information in the branch address portion of the instruction is loaded into the program counter on the next pulse. Otherwise the program counter is just advanced one count; that is, the next state

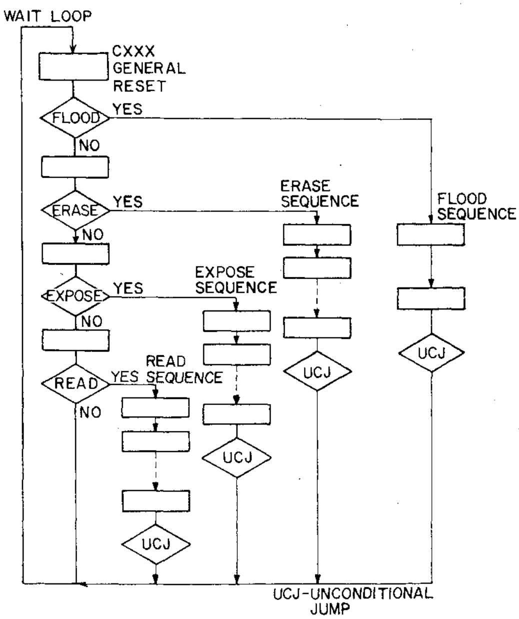

Fig. 7 Vidicon control sequences.

address is assumed to be the next pROM address in sequence. The SCS algorithm accomplishes four tasks: flood, erase, expose, and read, with the pROM consisting of 512 8-bit words. The details will not be presented, but the flow chart is shown in Fig. 7.

CORMAX

The C/P instrument observing modes are resident in the onboard computer (OBC). CORMAX operates from a set of tables uplinked every 12 h that contain information on the observational programs to be carried out and their time schedule. Tables with spacecraft sunrise and sunset times, solar flare level at which to initiate a flare program, exposure durations, tape recorder dump times, and other parameters are also uplinked. All the information is time-tagged and CORMAX checks every step in its logic with the spacecraft elapsed time to respond to the desired action.

The selected daily observing program is translated by CORMAX into specific operation of the mechanisms (aperture door, exposure shuttle, filter wheels, and calibration mirror), SEC vidicon, and tape recorder. CORMAX generates the commands, which are then sent by the OBC executive to a command stack. Groups of commands (up to 16 at a time) are then sent to the instrument via a remote interface unit.

CORMAX tables are generated following the SMM daily planning session where a consensus set of coronal and solar disk observations are planned. A DEC PDP 11/34 dedicated to C/P data retrieval, preliminary processing, and CORMAX table generation resides in the HAO C/P area of the experimenters operations facility at GSFC. A CORMAX simulator program in the PDP mimics the planned operations of CORMAX and verifies the tables to be uplinked for accuracy, completeness, and feasibility. The simulator enables the C/P planner to optimize the scientific data to be gathered during the orbits allotted by displaying graphic and tabular information in an interactive manner.

Conclusion

The scientific objectives of the SMM C/P have been well met by the versatility and flexibility of the instrument. The use of an optical design with an achromat objective lens and the selection of a calibrated SEC vidicon as a detector in space have been very successful in measuring the faint coronal radiance. The microprogram sequence controllers adequately manipulated the instrument functions to realize an optimum condition in data collection, while the computer control assured flexibility in the observing program to optimize observations of changing solar phenomena and allowed rapid response to either SMM or ground-commanded solar flare alerts.

Exciting and new scientific results from the C/P data are already being reported (House et al.[2] and Wagner et al.[3]). These include spectacular examples of plasma and radiative instabilities which appear in the cool material injected into the million degree corona (Fig. 2). Simultaneous cospatial radio and visible light observations of shock waves are finally permitting radio burst emission processes to be specified. Magnetic field orientations in the corona are now discernible through the use of emission line polarization measurements on 13-times ionized iron.

Acknowledgments

We wish to acknowledge the excellent programming of R. Reynolds and A. Stanger of HAO. We are indebted to Ball Aerospace Systems Division personnel for their detailed design and construction efforts, and particularly to D. Nelson, program manager. This work was supported by NASA under Contracts S55989 and S55989A. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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