FINAL REPORT

Vector Magnetograph Design

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Physics Department
University of Alabama in Huntsville

March 1, 1996

To: Solar Physics Branch
Space Sciences Laboratory
Marshall Space Flight Center

Contract NAG8-1112
NASA MSFC Solar Magnetograph
Final Report
Vector Magnetograph Design

This report covers work performed during the period of November 1994 through March 1996 on the design of a Space-borne Solar Vector Magnetograph. This work has been performed as part of a design team under the supervision of Dr. Mona Hagyard and Dr. Alan Gary of the Space Science Laboratory. Many tasks were performed and this report documents the results from some of those tasks, each contained in the corresponding appendix. Appendices are organized in chronological order.

Presentations:
Several presentations were given during the contract:

1. National Solar Observatory, Sunspot, NM
   January 30, 1995
   Presented Solar-B concepts

2. Presentation to Prof. Tsuneta, Dr. Ogawara, and others from NAOJ and ISAS
   March 29, 1995 at MSFC
   Presented design issues for the Solar-B magnetograph

3. National Astronomical Observatory of Japan
   July 17-20, 1996
   12 hours of lectures on the MSFC magnetograph design, polarimetry, and polarization aberrations. The outline was as follows:
   2 hour plus backup
b. Introduction to the Jones and Mueller polarization calculus.
3 hours basic

c. Polarimetry, measuring polarization elements and optical systems.
3 hours
included Japanese language viewgraphs

d. Polarization ray tracing.
4 hours
polarization of interfaces
Cassegrain telescope polarization

4. Marsnall Space Flight Center, Solar-B Review
March 4 & 5, with 8 Japanese astronomers in attendance

March 4, 1996
Solar-B Optical Design and Tolerance Analysis

March 5, 1996
Solar-B Optical Design Considerations

Tasks documented in Appendices:

Appendix 1 Solar-B Vector Magnetograph Specifications

Appendix 2 Notes from Meeting with Don Neidig,
National Solar Observatory, Jan. 30, 1995

Appendix 3 Optical Design Modification for 2x System for the EXVM Magnetograph

Appendix 4 Design Studies for Reflective Field Stops for Gregorian Telescope
Appendix 5  Radiation Hardened Doublet Design

Appendix 6  Meeting Summary from Trip to National Astronomical Observatory of Japan, Mitaka Japan

Appendix 7  Presentations from Prof. Tsuneta's Group on Solar-B Magnetograph Design

Appendix 8  Meeting Notes from Presentations by Prof. Tsuneta's Group on Solar-B Magnetograph Design

Appendix 9  My Presentation to Prof. Tsuneta's Group on the UAH/ Marshall Space Based Vector Magnetograph Design

Appendix 10 Development of Method for Generating a 2x Lens Magnifier

Appendix 11 Instructions for Developing a 2x Lens Design from a Thin Lens Starting Point

Appendix 12 Cassegrain Telescope

Appendix 13 Optimizing the Polarimeter Collimator Lens

Appendix 14 Solar-B Meeting Presentations, March 1996

Appendix 15 Solar-M Meeting Notes
### Solar-B Vector Magnetograph Specifications

Russell Chipman

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Correlation tracker:
Spectral band
Blocking

What is left over from beamsplitter?

Fabry-Perot Filter:
Aperture
Maximum ray angle
Telecentric beams, near image

140 mm (changed)
25 arcmin

CCD
Pixels
Image height
S/N
Readout
Temperature
Well depth
Quantum efficiency
Window (if required)

1024 x 2048
22 mm
> 700
12 bit
-30 degrees C
> 500,000 electrons
> 40%
BK7, 2 degree wedge, AR @ 630.2 nm
Appendix 2.

Notes from Meeting with Don Neidig, National Solar Observatory, Jan. 30, 1995

Points on SOLAR-B design
Need for space based free flier
Need for several other wavelengths for context
Would package with a very short wavelength imager
   60-100 angstroms
   small telescope will give sub arc sec resolution
   pick coronal line in EUV
   Hoover could build?

Advantages of our design:
   high spatial resolution
   Excellent polarization analysis

Our design will be criticized by HEO unless take full spectral lines
   at about 25 mA resolution, ours is 125
   Lockheed will propose 25 mA Lyot filter
Filling factor problem when don't have full line profile
Uncertainties from Doppler velocities and low spectral resolution

Our design will be criticized by Gene Parker (Guru) U of Chicago since 60 cm aperture
don't quite get to mean free path of photon in the photosphere.
100 cm does get to that scale.
How much less costly to do 60 cm vs. 100 cm

Orbiting solar observatory failed
   too fancy
   high resolution spectrographs
Gregorian with 45 degree reflection

Tracking space debris with a coronograph, looking within minutes of solar surface.
Should be able to see objects to mm scale
Fraunhofer diffraction pattern analysis

Rust built balloon instrument mostly unfunded.
Couldn't do it carefully.
Preliminary tests in NM didn't work on balloon.
Will it work at S. Pole?
Appendix 3.

Optical Design Modification for 2x System for the EXVM Magnetograph

A lens system was designed which when inserted in the magnetograph breadboard would increase the magnification by approximately a factor of two while leaving the image in the same place.

Later in April, 1995, lens mounts were finished and this 2x optical system was mounted in the EXVM magnetograph, aligned, and its operation tested.
Progress Report

Date: March 9, 1995

To: Dr. Mona Hagyard  
Marshall Space Flight Center

From: Russell A. Chipman  
Steve McClain  
University of Alabama in Huntsville

Re: Contract # NAG8-1112

Laboratory magnetograph optical design modification:

We have modified the optical design of the laboratory solar magnetograph in order to facilitate testing of the Fabry Perot filter. The modification entails the insertion of two lenses to act as a 2x converter between the first and second fold mirrors. The design reduces the system field of view and the invariant by (approximately) a factor of two. As a result, the marginal ray angle at the Fabry Perot has been reduced to 0.003757 radians from 0.006831 radians. This enables the Fabry Perot spectrum to be tested with smaller angles of incidence for a single field value. Note, however, that the system is not telecentric at the Fabry Perot. This did not prove possible of a design utilizing catalog lenses without more drastic changes to the remainder of the optical system. However, for testing at a single field value (or a restricted field of view) this non-telecentricity will not affect the testing of the Fabry Perot spectral performance.

The additional lenses are catalog Spindler Hoyer achromats. Their insertion do not require movement of any other elements in the magnetograph. The optical system remains sentially diffraction limited. Insertion of a field aperture before the Fabry Perot may be prudent so that the Fabry Perot does not act the field stop.

Specifically, the 2x converter consists of a 200 mm efl achromat (SH322271) placed 25 mm beyond the first fold mirror and a -50 mm efl negative achromat (SH325221) placed 0 mm lens. A complete CODE V optical system specification and analysis is available on request.

\[ \Delta \lambda \text{ at center } 79 \text{ mÅ}, \text{ shift over field } 250 \text{ mÅ} \]

\[ \text{was } 128 \text{ mÅ} \]
magnetograph w/2x
Y-FAN
1.00

1.00 RELATIVE
FIELD HEIGHT
(0.0408°)

-1.00

---

X-FAN
1.00

---

0.00 RELATIVE
FIELD HEIGHT
(0.000°)

1.00

-1.00

magnetograph w/2x

OPTICAL PATH DIFFERENCE (WAVES)  525.0 NM

SM  5-Mar-95
magnetograph w/2x

DIFFRACTION MTF

SM 5-Mar-95

DIFFRACTION LIMIT

0.0 FIELD (0.00°)

1.0 FIELD (0.04°)

WAVELENGTH WEIGHT

525.0 nm 1

DEFOCUSING 0.00000

SPATIAL FREQUENCY (CYCLES/MM)

MODULATION
magnetograph w/2x

Position 1, Wavelength = 525.0 nm

Global coordinates with respect to surface 1

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OPD = 0.000 Waves
Radiometry

Steve McClain
Department of Physics
University of Alabama in Huntsville
3/7/95

Source radiometry

Solar spectral radiance in wavelength:

Entire notebook is in MKS units
h=6.63 \times 10^{-34};
c=3 \times 10^8;
k=1.38 \times 10^{-23};
T=5000;
lamb0=630.2 \times 10^{-9};
band=0.0125 \times 10^{-9};
lamb0 = center of Fabry Perot bandpass
band = bandwidth of Fabry Perot
T = effective temperature of solar region at lamb0 (estimate)
L[\lambda] = 2 \cdot h \cdot c^2/\lambda^5 \cdot \exp\left[\frac{h \cdot c}{(\lambda \cdot k \cdot T)} - 1\right] \times (\lambda^2);

Solar radiance in detection band

\begin{align*}
L[\lambda_{\text{band}}] &= 3.36647 \times 10^3 \\
radiance &= L[\lambda_{\text{band}}] \cdot \text{band} \\
420.809 \\
\text{Radiance of sun in spectral band} \\
\text{= 420.809 } \text{W/m}^2 \text{sr}
\end{align*}

exitance = 3.1416 \cdot \text{radiance}
1322.01

Optical system radiometry

Etendue
image radius = hcy
marginal ray angle = umy
values from CODE V ray trace to image plane
hcy = 4.422 10^-3;
mum = 0.02456;
imagearea = 3.1416 (hcy)^2
0.0000614311
CODE V transmittance: quarter wave coatings assumed: 0.586
polarimeter and filters not modelled, guess transmittance = 0.2
transmittance = 0.1172
0.1172
etendue = transmittance 3.1416 imagearea (Sin[umy])^2
8
1.36407 10

**Flux onto detector**

flux = radiance etendue
5.74012 10
irradiance = flux / imagearea
0.0934399
irradiance in watts/m^2

**Detector radiometry**

pixelsize = 10.10^-6;
pixelarea = pixelsize^2;
Assumes square pixels
pixelpower = irradiance pixelarea
9.34399 10
quantumefficiency = 0.4;
detectedpower = pixelpower quantumefficiency
3.7376 10
power per pixel in watts
welldepth = 5 10^-5;
\[
\text{photon energy} = \frac{h c}{\lambda_0}
\]

\[
3.15614 \times 10^{-19}
\]

\[
\text{photon flux} = \frac{\text{detected power}}{\text{photon energy}}
\]

\[
1.18423 \times 10^7
\]

\[
\text{fill time} = \frac{\text{well depth}}{\text{photon flux}}
\]

\[
0.0422215
\]

\[
\text{fill time} = \text{time to saturate ccd pixel} = 42 \text{ milliseconds}
\]
Appendix  4.

Design Studies for Reflective Field Stops for Gregorian Telescope

Due to the Japanese interest in a Gregorian telescope with a reflective field stop, I attempted with Matt Smith's assistance to design one. We used a new optical design program from Optical Research Associates called Light Tools, which allows a nonsequential ray trace. A Fast Gregorian telescope was set up and we manually varied the parameters on a field stop, with the intention of reflecting all of the light outside of a circular field of view past the secondary and back out the front of the telescope. We came close to achieving this objective but our best design still sent some light into the telescope barrel inside the prefilter.

The enclosed figures document our design experiments.

The second set of figures explore using a plane mirror with a hole at the intermediate image to reflect the out-of-field light back out the front of the telescope.
NASA MSFC Field Rejecting Gregorian Telescope
NASA MSFC Field Rejecting Gregorian Telescope
NASA MSFC Field Rejecting Gregorian Telescope
NASA MSFC Field Rejecting Gregorian Telescope
Appendix 5.

Radiation Hardened Doublet Design

Alan Gary has made a compelling argument for using radiation hardened glasses in the optical design due to the levels of radiation at a 600 km orbit.

In response I have designed a series of doublets using various combinations of radiation hardened glasses. I am seeking a lens appropriate for the polarimeter collimator. I would like to find the glass combination which yields the best achromatic correction with good wavefront quality.

A large number of radiation glass pairs were tried. Each combination was optimized with the constraint that the back focal lengths be equal at 630 and 525 nm to minimize chromatic aberration. An achromatic doublet generally has a positive and negative focal length element. For these experiments, each glass pair (g1, g2) was optimized in four configurations listed in order of position from the image:

1. g1 positive fl, g2 negative fl,
2. g2 positive fl, g1 negative fl,
3. g1 negative fl, g2 positive fl,
4. g2 negative fl, g1 positive fl,

None of the lens optimizations gave good color correction for wavelengths below 480 nm.

The best pair of glasses was bk7g25 and kzfs4g20. This combination worked well in all four configurations.

Best configuration lens file z2(2)
Other good pairs of glasses were:
K5g20 kzfs4g20
gg375g34 kzfs4g20

Overall, this was a frustrating exercise because none of the lenses was particularly good. All had large chromatic aberration and poor wavefront over a .8 degree field with the stop 1.5 efl away.

I am convinced that two element lenses from radiation hardened glass will never work below 450 nm.

The figures in this section show the best doublet layout, the wavefront aberration (showing the large chromatic aberration and other aberrations), and two plots of the focal length.
TANGENTIAL

1.00 RELATIVE FIELD HEIGHT
(1.600°)

0.62 RELATIVE FIELD HEIGHT
(1.000°)

0.00 RELATIVE FIELD HEIGHT
(0.000°)

SAGITTAL

1.00

0.00

700.0 NM
630.0 NM
525.0 NM
390.0 NM

z2(2) bk7g5 kzfs4g20
1534

OPTICAL PATH DIFFERENCE (WAVES)

rac 24-Jun-95
$z2(2) \text{ bk7g5 kzfs4g20}$

1534

24-Jun-95

WAVELENGTH

FOCUS SHIFT

0.400

0.300

0.200

0.100

0.000

-0.100

-0.200

-0.300

-0.400
| 0.00  | 0.10  | 0.20  | 0.30  | 0.40  | 0.50  | 0.60  | 0.70  | 0.80  | 0.90  | 1.00  | 1.10  | 1.20  | 1.30  | 1.40  | 1.50  | 1.60  | 1.70  | 1.80  | 1.90  | 2.00  | 2.10  | 2.20  | 2.30  | 2.40  | 2.50  | 2.60  | 2.70  | 2.80  | 2.90  | 3.00  |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| FOCAL LENGTH | WAVELENGTH |
| 0.00  | 0.10  | 0.20  | 0.30  | 0.40  | 0.50  | 0.60  | 0.70  | 0.80  | 0.90  | 1.00  | 1.10  | 1.20  | 1.30  | 1.40  | 1.50  | 1.60  | 1.70  | 1.80  | 1.90  | 2.00  | 2.10  | 2.20  | 2.30  | 2.40  | 2.50  | 2.60  | 2.70  | 2.80  | 2.90  | 3.00  |
| 0.00  | 0.10  | 0.20  | 0.30  | 0.40  | 0.50  | 0.60  | 0.70  | 0.80  | 0.90  | 1.00  | 1.10  | 1.20  | 1.30  | 1.40  | 1.50  | 1.60  | 1.70  | 1.80  | 1.90  | 2.00  | 2.10  | 2.20  | 2.30  | 2.40  | 2.50  | 2.60  | 2.70  | 2.80  | 2.90  | 3.00  |
| 0.00  | 0.10  | 0.20  | 0.30  | 0.40  | 0.50  | 0.60  | 0.70  | 0.80  | 0.90  | 1.00  | 1.10  | 1.20  | 1.30  | 1.40  | 1.50  | 1.60  | 1.70  | 1.80  | 1.90  | 2.00  | 2.10  | 2.20  | 2.30  | 2.40  | 2.50  | 2.60  | 2.70  | 2.80  | 2.90  | 3.00  |
Appendix 6.

Meeting Summary from Trip to National Astronomical Observatory of Japan, Mitaka Japan
Meeting Report
National Astronomical Observatory, Mitaka, Japan

To: Marshall Space Flight Center
Solar Physics Branch

From: Russell A. Chipman, University of Alabama in Huntsville

Meeting Topic: Solar B instrument design
Meeting Date: July 17-21, 1995
Report Date: August 9, 1995

Organization of Meetings:
The meetings took place at the observatory offices in Mitaka. Prof. Tsuneta of Tokyo University Astronomy Dept. was in charge and set the agenda. Dr. Ichimoto of Tokyo University Astronomy Dept. and Dr. Akioka of the governments Communications Dept. in Ibaraki were significant technical contributors. A group of graduate students also attended and presented. Prof. Sakurai attended occasionally, and only had a few questions and comments.

I gave four lectures for a total of about 10 hours, three on polarization, one on the Marshall Solar B design. A copy of this presentation was sent to Mitaka in advance, and copies were distributed at my talk.

In return, for three afternoons, I was given a detailed presentation of the present Solar-B baseline design. This consisted of a total of about 8 hours of lectures and discussion. This covered the optical magnetographs and the spacecraft systems. An EUV telescope and x-ray telescope were mentioned, but not discussed in the presentations. I received copies of these presentations, and copies will be forwarded to the Solar Physics Branch. I also took copious notes on my computer during the talk, and you should receive a copy by email. These are detailed, but do not stand well alone. These real time notes should indicate the direction of the presentations I received, and complement the copies of viewgraphs.

Dr Serge Koutchme(?), of Paris, France was also concurrently at the observatory on separate business, but partook of many of the meetings.

Every day the group went together to lunch and dinner, and we had good opportunities to get to know each other.
Summary:

Prof. Tsuneta's design is being developed by graduate students, post docs, Dr. Akioka from another government lab, and by some small support from studies performed by companies. They have identified and understand the key problems, but have difficulty performing the detailed design. They lack clear procedures for resolving the most difficult but important design issues.

They have what they call a "baseline design", but Prof. Tsuneta knows several key issues remain to be resolved, before it can be considered an actual baseline.

They now have 1 1/2 years to prepare their proposal, and they don't have to compete with anyone. They are the only group which can get the solar magnetograph approved; the hurdle is to have a proposal which will be approved. Then the announcement of opportunity is straightforward.

NASA support is key to project approval. They find the US difficult to collaborate with. They are surprised by the competition between the US groups, and have some difficulty dealing with this. They wish we would collaborate more, and that they could get the combined best from the various US groups.

Their principal technical concern is pointing accuracy; they repeatedly stated that pointing accuracy is the principal factor which limits pointing accuracy. They currently seek a polarimetric accuracy of 0.001. They desire a much faster measurement cadence than MSFC has proposed. They are using a polarizing beam splitter, sending one beam through the birefringent filter, and the orthogonally polarized beam to an echelle Littrow spectrograph.

Mission objective: A systems approach to photosphere-coronal activity:
1. to reveal solar MHD phenomena,
2. the photosphere as the origin of coronal magnetic activities,
3. high resolution x-ray and optical observations,
4. hard and soft x ray features

Planned instruments:
1. Vector magnetograph, 0.1-0.2 arc sec resolution,
2. Echelle spectrograph/polarimeter,
3. x ray telescope, magnetic behavior in solar corona,
4. xuv spectrograph, coronal velocity field measurement.

Satellite:
600 km orbit
680 kg scientific package

Launch date:

They might get to launch in 2003 if the satellite is ready, and the infrared satellite scheduled for 2003 slips. Indications are the IR satellite might not be ready on schedule. Although this would be during the solar minimum, they are proceeding with this plan. There is some but not a lot of concern about getting the flight approved during minimum.

They put this question to MSFC through me
"Is there a problem with science output if we launch in 2004 or 2005?"
They feel the mission objective can be addressed with quiet sun, revealing fundamental processes. There are less events, but Skylab was launched at solar minimum. So the mission is oriented to the quiet sun. Based on your 20 years of experience, what is your answer?

Baseline design:
50 cm aperture Gregorian telescope
no prefilter
rotating retarder in primary hole before Gregorian focus
folding mirror, articulated
polarizing beam splitter cube followed by two channels:
a. Lyot filtergram based imaging channel
b. Littrow echelle spectrograph based high spectral resolution channel
Lytot filtergram channel:
Collimator
Beamsplitter
Blocking filter wheel
Choice of Lyot filter or interference filters
Shutter
Beam splitter
Camera lens
CCD #1

Littrow Echelle Spectrograph Channel
Relay lens
Scanning mirror
Blocking filter wheel
Slit
Littrow lens
Echelle grating
Shutter
CCD #2
25 mA resolution
1 m Focal length
Designed together with HEAO

Lack of Baseline Design:
Prof. Tsuneta expressed the following opinions regarding this design.
First, the design is far too complex, and ways must be sought to simplify the design. Prof. Tsuneta does not like the two CCDs, nor the beamsplitters in the imaging path (filtergrams).
Second, they do not know how to make some of the trade-off comparisons, particularly Cassegrain/Gregorian and Lyot/Fabry Perot. Reliability is the driving consideration, but is not easily quantified. Further, his group is not skilled at the detailed design of many of
the subsystems.
Third, without an acceptable baseline design, it will be difficult to get an Announcement of Opportunity (AO) out of ISAS.

Telescope:
Prof. Tsuneta's primary concern is contamination; spectral control and heat is the second most important problem. The satellite will require thrusters which create a dirty environment which may contaminate the optics. A prefilter is far forward and exposed to a large solid angle of space. Thus the prefilter may be expected to collect more contamination than an open primary mirror, since much of the material deposited on the prefilter would land first on the walls and baffles of the telescope. The primary mirror sees a smaller solid angle of space. The primary would be heated above the temperature of the walls, so much of the contamination might be moved from the primary to the walls. The idea of the conical field stop seems to have fallen out of favor, but a 45 degree folding mirror heat dump is under consideration.

Polarimeter:
The present design uses a rotating retarder, a folding mirror, and a polarizing beam splitter (PBS), with the light analyzed/divided and sent to the two instruments. They desired to place the retarder as far forward as possible, and placed it in the hole of the primary mirror. The analyzer is a polarizing beam splitter. They are proposing taking 12 measurements per 360 degree rotation of the retarder.

Filter:
Their baseline design incorporates a universal birefringent filter, but they remain open to a Fabry-Perot, especially since it has been demonstrated in space. They mentioned the difference in near band spectral rejection of the birefringent vs. Fabry-Perot design. Lockheed has proposed a filter using the SOUP design for the crystals and polarizers, but with different motors which operate in a sealed compartment driven by magnetic fields.
An important issue is how to perform a meaningful comparison of the birefringent vs. Fabry-Perot filter weighted toward reliability issues, but also considering stray light, tunability, and other engineering considerations.

Other:
Doppler compensation is considered essential. They intend to transmit up revised orbital elements every day. They plan to get simultaneous Doppler information from the Echelle spectrograph so a Doppler compensation can be made every 10 seconds or so.

My Comments to Prof. Tsuneta’s Group on the Baseline Design:
1. Polarizing Beam Splitter Cube
They had not looked at any coating designs for PBSs. They did not realize that high extinction ratios are not available with polarizing beam splitters, nor that the polarizing axis rotates with angle of incidence. Further, a PBS with broad spectral coverage may be difficult to accomplish. I recommended designing this element as soon as possible to demonstrate feasibility, then fabricating a witness sample for test.

2. Broad spectral range
The baseline design includes vector magnetograph measurements at 5250 and 6302 A as well as narrow band filtergrams from 6563 A down to 3900 A. I emphasized that although a system can certainly be designed to cover this spectral range, that I felt the cost would be much higher. I expect that nearly every component will require more design and analysis; that much more testing will be necessary; and the likelihood of significant problems or failure is much higher. This continuous additional effort that might be difficult to quantify, but that two or more many years of additional design and procurement effort might easily be expended over the design effort for a system restricted to 5000-6600 A.

Prof. Tsuneta’s Comments:
Prof. Tsuneta expressed interest in further collaboration with UAH/Marshall, particularly
for the polarimeter construction and calibration. He said the lectures were very helpful, and would help his group in the design of this system. He appreciated NASAs effort in arranging this opportunity.

Further Comments regarding NASA and US system:
"American research groups seem overly concerned with money".
"We are more affected by Washington politics than Tokyo politics, and therefore must pay a great deal of attention to Washington politics."
"There is so much competition between the US research groups, that it is difficult for us to collaborate with the US groups."
"We wish that somehow we could get the best from each of the various US groups, or that such would be proposed to us."
"For example, a birefringent filter from Lockheed, a spectrograph from the High Altitude Observatory, a polarimeter from NASA/UAH, etc."
Appendix 7.

Presentations from Prof. Tsuneta’s Group on Solar B Magnetograph Design

This appendix contains copies of the viewgraphs from a series of presentations I received at the National Observatory of Japan. For four days, members of Prof. Tsuneta’s group addressed a wide range of issues regarding the Solar-B Design.
The Solar B Magnetograph Design

Prof. Tsuneta's Group
University of Tokyo Tenmondai
National Observatory of Japan
Mitaka, Tokyo, Japan

Presentations:
July 11-14, 1995

Contents:

Solar B Mission Objectives
Dr. Sakao, Univ. of Tokyo

Solar B Telescope Optical Design
Ryouhei Kano, Univ. of Tokyo (graduate student)

Filtergraph Design
Y. Suematsu, Univ. of Tokyo

Solar B Spectrograph
Dr. M. Akioka, Hiraiso, CRL

Accuracy Issues in Solar B
Dr. Ichimoto, Univ. of Tokyo
連続講義のお知らせ

アラバマ大学物理教室のチップマン教授が日本を訪問します。チップマン教授は、偏光光学系と精密偏光測定の専門家で、今回、偏光の測定と解析について連続講義をしていたいただくことになりました。皆様奮って御参加下さい。

-- 偏光の理論と応用 --

Prof. Russel A. Chipman
(University of Alabama in Huntsville)

7月17日 14時～ (天文台講義室)
"Introduction to the Jones and Mueller polarization calculus"

7月18日 9時30分～ (コスモス会館会議室)
"The NASA/Marshall Solar Vector Magnetograph Design"

7月19日 9時30分～ (コスモス会館会議室)
"Porlarimetry, measuring polarization elements and optical systems"

7月20日 9時30分～ (コスモス会館会議室)
"Porlarization ray tracing"

世話人 一本(天文台) 常田(天文センター)
Mission Objectives

Observations from Yohkoh

"Dynamic" corona rather than static

Magnetic reconnection:
Playing essential roles in various-scale coronal activities including solar flares.

Next Solar Mission (Solar-B)

Photosphere as the origin of coronal magnetic activities

Systems approach to the corona-photosphere connection
→ reveal solar MHD phenomena

High resolution imaging observations of corona and photosphere with X-ray and optical telescopes

On-board Instruments:

- Optical Telescope:
  Vector magnetic measurement

- X-ray Telescope:
  Magnetic behavior in the solar corona

- XUV Spectrograph:
  Coronal velocity field measurement
### The Next Japanese Solar Mission

<table>
<thead>
<tr>
<th>Mission Objective</th>
<th>High spatial resolution observations of magnetic coupling between photosphere and corona as the engine of coronal/thermospheric MHD activities.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>Sun-synchronous orbit with $h \sim 600$ km</td>
</tr>
</tbody>
</table>
| Weight            | Scientific payloads and bus components: $\sim 680$ kg  
|                   | Thrusters: $\sim 170$ kg |
| Launch Timing     | Around the year 2004 |
| Mission Period    | More than 2 yr of sun-synchronous operation using thrusters.  
|                   | Extended operation in the post-sun-synchronous phase. |
| S/C Body Control  | X/Y: 0.02"/s (under study) |
| Image stabilization | X/Y: $\gg 0.02$"/s (possible use of a tip-tilt mirror) |
| Data Rec. Rate    | $\sim 500$ kbps |
|                   | $\sim 3$ Gbits / orbit |
| Data Rep. Rate    | $\sim 5$ Mbps (desired) |
太陽フレアは太陽系の中で最も激しい爆発現象の一つです。最大規模のフレアの場合は、メルトニン水素爆発の10億分の1のエネルギーを放出します。「ようこう」はフレアにおける磁気リコネクションの証拠を示すいくつかの謎を残しています。磁気リコネクション理論によれば、リコネクション領域から秒速2000km以上の高速ジェットが噴出するはずです。そのような高速ジェットをまだ見つかっていません。

さらに基本的な問題が残されています。フレアのエネルギー源が窓点近傍のコラナに蓄えられた磁気エネルギーであることはほぼ間違いありませんが、このエネルギーがどのように蓄えられたのか、まだわかりません。エネルギーの磁力線が光球プラズマの運動にわされるように蓄えられたのでしょうか？それとも、新たれた磁束管の浮上という形で、直接、対流層内部から排出されたのでしょうか？
こう進む。の歌や、絶望達磨を唱えた声

この像は、コロナの細胞がダイナミックに動き

違った動きで、この動きをうまくとらえてくれ

ました。たとえ同時に地上で撮影された光は

磁場写真に比べてみると、光はコロナの周

磁気的カップリングこそがコロナのダイナミ

ックスの鍵を解くための鍵を握っているとい

う印象を受けます。下図はその一例です。周

点（高圧－高圧の種類）のすぐ近くで、逆向

きの磁場（X線－白の種類）が異なりつつ、あ

ような異常が生じると、著しいウェットとフ

レアが発生します。しかし逆向きの磁場の発

因はまだわからていません。

このようにコロナ活動が光球コロナ間の

磁気的カップリングに支配されているのは、

ほぼ疑いありません。しかし、こう試着

のX線観測・地上の可視光磁場観測ともに空間

分解能が十分ではなく、核の光球コロナ

間の磁場構造が不明のままでした。SOLAR-

B衛星では、高空間分解能のX線・可視光同

時観測によって光は、コロナ間の磁場構造を

明らかにしました。コロナのダイナミックスの核

としての光球コロナ間の磁気的カップリングの

鍵をさがります。
Overview of Satellite System

System Characteristics

1. Attitude Control System

Close relationship between ACS and PIs

- Sub-arcsec pointing
  \((\sim \times 6\) higher stability than Solar-A)\)

- Active control (by a tip-tilt mirror) necessary?

- Signals between ACS and the optical telescope
  OPT -> ACS: solar rotation tracking (by feature tracking) ?
  ACS -> OPT: gyro signal for tip-tilt control ?
  Tip-tilt mirror as a part of ACS ?

2. Spacecraft Orbit

Scientific requirements <-> trade-offs with system requirement

- Sun-synchronous vs equatorial orbits
  merits and demerits (thermal control, weight penalty etc.)

- Use of thrusters (sun-synchronous orbit)
  Operation for post sun-synchronous orbit
  -> Mission design \((\text{extended/degraded mission})\)

- Radiation environment
  System impact (shielding, radiation-hardened devices, ... )
3. Telemetry

- Scientific requirements and data production rate
  
  **huge amount of data** \( (\geq 7 \text{ Gbits/orbit of raw data}) \)

- On-board data processing
  including Stokes demodulation and data compression etc.

- On-board data storage
  large volume DR & data buffers necessary

- **Telemetry downlink rate** \( (\sim 5 \text{ Mbps}) \)
  \(-\) Possible ?

4. Ground facilities (TBD)

- Data downlink at KSC and DSN
  
  Telemetry downlink rate / Use of X-band

- Data transfer between KSC/DSN and ISAS

- Data storage and processing
  
  (data compression at ground facilities ?)
<table>
<thead>
<tr>
<th>Att. control</th>
<th>Next Mission</th>
<th>Solar-A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short term</strong></td>
<td>X,Y: 0.2&quot;/s</td>
<td>X,Y: 1.2&quot;/s</td>
</tr>
<tr>
<td></td>
<td>Z: 45&quot;/s</td>
<td>Z: 5'/s</td>
</tr>
<tr>
<td><strong>Med. term</strong></td>
<td>X,Y: 0.4&quot;/min</td>
<td>X,Y: 7&quot;/min</td>
</tr>
<tr>
<td></td>
<td>Z: 1.5'/min</td>
<td>Z: 7'/min</td>
</tr>
<tr>
<td><strong>Abs. pointing</strong></td>
<td>X,Y: &lt; 1'</td>
<td>X,Y: &lt; 6'</td>
</tr>
<tr>
<td></td>
<td>Z: &lt; 2'</td>
<td>Z: &lt; 10'</td>
</tr>
<tr>
<td><strong>Active control</strong></td>
<td>maybe necessary</td>
<td>not necessary</td>
</tr>
<tr>
<td></td>
<td>(X,Y: 0.02&quot;/s)</td>
<td></td>
</tr>
</tbody>
</table>

**Orbit**
- **Orbit**: Sun-synchronous, polar LEO (h ~ 600 km)
- **Weight**: ~ 700 kg
- **Mission period**: > 1 yr

**Telemetry**
- **Data rec. rate**: ~ 500 kbps
- **Rec. data size**: ~ 3 Gbit/orbit
- **Downlink rate**: ~ 5 Mbps
- **Mission design**: several x 10 times larger

**New**
- Orbit
- Launch procedure

**New orbit design**

**New S/C system**

Large difference ii

~ x6 higher attitude control
Key Issues

- **Sub-Arcsec Pointing**

<table>
<thead>
<tr>
<th>X/XUV</th>
<th>OPT ?</th>
<th>0.2&quot;/s → 0.02&quot;/s (baseline target)</th>
</tr>
</thead>
</table>

  - Active image stabilization?

  Requirements: for 20" arcsec stability (c.f. HST: 7" arcsec)

  - Filter wheels : counter wheels necessary
  - Gyro : pulse weight 0.004" (c.f. Solar-A: 0.08"
  - Momentum wheels :
    - ball-bearing type
    - ... oil soak / wobble torque problems
    - magnetic-bearing type
    - ... really feasible? (under development)

- **Active Stabilization (by Tip-tilt mirror)?**

  - Sensor ? (limb sensor / correlation tracking / or else?)
  - Tip-tilt mirror feasible ?

- **Signals between ACS & Optical Telescope**

  - Rotation tracking (attitude control w.r.t. the Sun)
    OPT → ACS : feature tracking signal

  - Tip-tilt mirror control
    ACS → OPT : high precision gyro signal

  Tip-tilt mirror as a part of ACS?
Orbit Choices and Scientific Requirement

Scientific Requirements

- **High Spatial Resolution Observations**
  - Minimize thermal distortion
  - Constant thermal environment

- **Continuous Observations**
  - Observe solar activities in various timescales
  - Increase efficiency of observations
  - Pre- and post-flare activities

- **Minimize Doppler Effect due to Orbital Motions**
  Precise magnetic field measurements (line width $\sim 100\text{mÅ}$)

Orbit Choices

- Sun-synchronous orbit with $h\sim 600\text{km}$

- Sun-synchronous orbit is preferable for the scientific requirements

- Weight penalty / Radiation environment / Orbit lifetime

- Need more careful study (Other orbit ?)

Study Area

- Mission design for the post sun-synchronous orbit

- Most preferable orbit (height etc.)

- Launch sequence and initial operation
## Comparison between Sun-Synchronous and Equatorial Orbits

<table>
<thead>
<tr>
<th>Orbit (*)</th>
<th>Sun-Synchronous</th>
<th>Equatorial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observation</strong></td>
<td><strong>Continuous observation</strong> for ~ 8 months / yr</td>
<td>S/C night: ~ 40 min / orbit</td>
</tr>
<tr>
<td>Doppler shift ((\lambda = 5000\AA))</td>
<td>at most ~ 130 mA(_{\text{pp}})/orbit max: ~ 0.7 mA/10s</td>
<td>~ 250 mA(_{\text{pp}})/orbit max: ~ 1 mA/10s</td>
</tr>
<tr>
<td><strong>Thermal / power design</strong></td>
<td>Much easier than equatorial orbits</td>
<td>Not easy</td>
</tr>
<tr>
<td>Total S/C weight (net dry weight)</td>
<td>~ 875 kg (~ 700 kg)</td>
<td>(\leq 1.5) t (with thrusters) ((\leq 1.3) t)</td>
</tr>
<tr>
<td><strong>Launch</strong></td>
<td>Constraints on (i, h,) and (e)</td>
<td>Experienced (resources available) Thruster desired</td>
</tr>
<tr>
<td>Thruster (**)</td>
<td>Necessary; ~ 170 kg (fuel: ~ 125 kg, tank: ~ 45 kg) contamination?</td>
<td>Desired</td>
</tr>
<tr>
<td>Radiation environment</td>
<td>SAA + auroral zone significant contrib. of flares</td>
<td>SAA</td>
</tr>
</tbody>
</table>

(*) \(h = 600\) km, \(e = 0\) assumed  
(**) for 2 yr orbit lifetime
\[ \Delta \lambda \text{ Doppler} \]

Max. and Min. of Doppler

\[ \frac{d\Delta \lambda}{dt} \text{ Doppler} \]

Max. and Min. of Doppler Time Variation

Night Zone

Doppler Shift by Orbital Motion

\begin{align*}
\text{incension} &= 97.79 \text{ deg} \\
\text{eccentricity} &= 0.00 \\
\text{w} &= 90.00 \text{ deg} \\
\text{height} &= 600 \text{ km} \\
\text{wave length} &= 6303 \text{ A} \\
\text{time/orbit} &= 5801 \text{ sec} \\
\text{Night(max.)} &= 1322 \text{ sec}
\end{align*}

- S/C night appears for \( \leq 4 \text{ months} \)
- max. night interval: \( \geq 20 \text{ min} \ (\sim 23\%) \)
On-Board Doppler Compensation

Ground Support System

Data Upload every 3-7 days (TBD)

Table Upload

Orbit Timer

Orbital Elements, or Coeffs. of Polynomials

(stored in memory)

On-Board Doppler Estimation

$\delta \lambda$

Observing Table

$\lambda$

(target wavelength)

Accuracy of $\delta \lambda$: 20 m/s
Update cycle: < 10 s

(exec. immediately)

Passband Tuning (FLT)
CCD Read-Out Addr. Change (SPG)
On-board Data Flow

Telescope

(2048 x 2048 pixel CCD)

on-chip summation (2x2), limit image FOV

Stokes demodulation

Data compression (DPCM / JPEG)

(Loss-less / Lossy compression)

variable data size?

Data recorder

Telemetry

Ground stations (KSC / DSN)

Data Rate (preliminary)

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Raw data</th>
<th>Recorded data</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray</td>
<td>1.2 Gbit/orb (204 kbps)</td>
<td>396 Mbit/orb (66 kbps)</td>
</tr>
<tr>
<td>Optical</td>
<td>4.2 Gbit/orb (700 kbps)</td>
<td>1.9 Gbit/orb (322 kbps)</td>
</tr>
<tr>
<td>FLT</td>
<td>2.2 Gbit/orb (367 kbps)</td>
<td>1.0 Gbit/orb (169 kbps)</td>
</tr>
<tr>
<td>SPG</td>
<td>6.4 Gbit/orb (1.1 Mbps)</td>
<td>2.9 Gbit/orb (491 kbps)</td>
</tr>
<tr>
<td>TOT</td>
<td>384 Mbit/orb (64 kbps)</td>
<td>384 Mbit/orb (64 kbps)</td>
</tr>
<tr>
<td>XUV</td>
<td>384 Mbit/orb (64 kbps)</td>
<td>≥ 3 Gbit/orb (≥ 500 kbps)</td>
</tr>
<tr>
<td>Total</td>
<td>8.0 Gbit/orb (1.4 Mbps)</td>
<td>≥ 5 Mbps downlink rate</td>
</tr>
</tbody>
</table>
DR, Telemetry, and Ground Facilities

Requirements to Data Recorder

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Solar-A</th>
<th>Astro-D</th>
<th>Astro-E</th>
<th>IRIS</th>
<th>Solar-B(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REC</td>
<td>32 kbps</td>
<td>32 kbps</td>
<td>~ 200 kbps</td>
<td>~ 300 kbps</td>
<td>~ 500 kbps</td>
</tr>
<tr>
<td>REP</td>
<td>262 kbps</td>
<td>262 kbps</td>
<td>≥ 1 Mbps</td>
<td>~ 4 Mbps</td>
<td>~ 5 Mbps</td>
</tr>
<tr>
<td>Data/orbit</td>
<td>80 Mbit</td>
<td>128 Mbit</td>
<td>~ 1 Gbit</td>
<td>~ 2 Gbit</td>
<td>~ 3 Gbit</td>
</tr>
<tr>
<td>REP time</td>
<td>5min 20s</td>
<td>8min 32s</td>
<td>~ 10 min</td>
<td>10 min</td>
<td>10 min</td>
</tr>
</tbody>
</table>

(*) Preliminary. PI data only.

→ semiconductor memory for huge capacity
16 Mbit DRAM available? (high radiation-hardness)

Packet Telemetry?

• On-board packet interface?

• Packet downlink telemetry? → Real-time monitor in X-band?

Ground Stations

<table>
<thead>
<tr>
<th></th>
<th>current status</th>
<th>future plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSC S-band</td>
<td>max. 262 kbps</td>
<td>TBD (no high speed TLM available?)</td>
</tr>
<tr>
<td>KSC X-band</td>
<td>max. 262 kbps</td>
<td>TBD (&gt; 2 Mbps?)</td>
</tr>
<tr>
<td>KSC → ISAS</td>
<td>384 kbps</td>
<td>?</td>
</tr>
<tr>
<td>DSN S-band</td>
<td>max. 262 kbps</td>
<td>max 1.6 Mbps?</td>
</tr>
<tr>
<td>DSN X-band</td>
<td></td>
<td>no high speed TLM available?</td>
</tr>
<tr>
<td>DSN → ISAS</td>
<td></td>
<td>?</td>
</tr>
</tbody>
</table>

Concerns on DSN:

• low max. downlink rate?

• location adequate for sun-synchronous orbits?
Overview of the Solar-B Optical Telescope

Ryouhei Kano
Institute of Astronomy, The University of Tokyo
kano@sxt1.mtk.s.u-tokyo.ac.jp

1995 July 18-20
Mitaka, Tokyo
1. Optical Telescope Schematic

- 50cm to avoid the instrumental polarization
- Polarization analyzer
- Tip-Tilt mirror (TBD)
- Heat rejection cone or plane mirror
- 22cm

2. Overview of Optical Telescope

Ryouhei Kano
Univ. of Tokyo
Jan. 19, 95
Parameters of Optical Telescope

Aplanatic Gregorian

<table>
<thead>
<tr>
<th>Component</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>D=500 $\phi$, f=7500, F/15</td>
</tr>
<tr>
<td>Primary mirror</td>
<td>D0=500 $\phi$</td>
</tr>
<tr>
<td>Secondary mirror</td>
<td>D1=552 $\phi$, f1=2100, F/4.2</td>
</tr>
<tr>
<td>Distance between two mirrors</td>
<td>D2=220 $\phi$, m=3.57</td>
</tr>
<tr>
<td>Back focus</td>
<td>3000</td>
</tr>
<tr>
<td>Total focal length</td>
<td>7500</td>
</tr>
<tr>
<td>Plate scale</td>
<td>36 $\mu$m/arcsec</td>
</tr>
</tbody>
</table>

CCD 9 $\mu$m/pixel, 2048x2048 pixels

Focal Plane Package

<table>
<thead>
<tr>
<th>Component</th>
<th>F-value</th>
<th>PlateScale</th>
<th>FOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyot filter</td>
<td>F/18.56</td>
<td>0.2&quot;/pixel</td>
<td>400&quot;</td>
</tr>
<tr>
<td>Interference filter</td>
<td>F/37.13</td>
<td>0.1&quot;/pixel</td>
<td>200&quot;</td>
</tr>
<tr>
<td>Spectrograph</td>
<td>F/18.56</td>
<td>0.2&quot;/pixel</td>
<td>400&quot;</td>
</tr>
</tbody>
</table>

Aberration (F/18.56) 0.05" within the FOV
Airy Disc Diameter 0.50" @ 5000Å
<<<Aplanatic Gregorian System for the Solar Telescope>>> 

\[ D(0) = 500.0 \text{ mm} \quad \text{fl} = 7500.0 \text{ mm} \quad \text{bf} = 214.0 \text{ mm} \]
\[ W = 0.0 \text{ mm} \quad \text{dis} = -3000.00 \text{ mm} \]
\[ D(1) = 500.0 \text{ mm} \quad R(1) = -4200.11 \text{ mm} \quad K(1) = -0.95296 \]
\[ D(2) = 220.2 \text{ mm} \quad R(2) = 1406.15 \text{ mm} \quad K(2) = -0.36874 \]

Field = 0.00 arcmin / 0.00 dec

Secondary Mirror
Despace (mm) = 0.000 0.000 0.000
Tilt angles = 0.00 arcsec / 0.00 dec
Spot Diagram at 214.04
0.5° 斜入射
off axis

2ndary Mirror
副鏡 218 φ

Heat Rejection Mirror
熱除 200 φ TBD

Window

Primary Mirror
主鏡 532 φ

Aperture
開口 500 φ

SOLAR-B OPTICAL TELESCOPE
FRI JAN 27 1995 R. Kano
3. Focal Plane Package

- In order to reject most of light before Lyot filter
- To avoid the ghost

2ndary focus (above 544mm)

-59mm

7.5kg (オープンを除く)

1. Nikon設計(Ver 93.3.3)を採用
SPOT DIAGRAM

Lyot pass

DEFOCUS

-0.0200 (cm)  -0.0100  0.0000  0.0100  0.0200  RAY NO.

AIRY DISK

656 (nm)

589 (nm)

390 (nm)

486 (nm)
4. Tolerances (F/18.56.Lyot filter)  
Nikon report (ver 95.03.08) & MITSUBISHI report (ver 95.03)

<table>
<thead>
<tr>
<th>Component</th>
<th>Tolerance</th>
<th>Achievable accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary mirror (M1)</td>
<td></td>
<td><strong>gravitational distortion</strong></td>
</tr>
<tr>
<td>Decenter</td>
<td>+/- 70 μm C(i)</td>
<td>+/- 100 μm (gravity +/- 70 μm)</td>
</tr>
<tr>
<td>Tilt</td>
<td>+/- 7” C</td>
<td>+/- 30” (thermal +/-11”, gravity +/-10”)</td>
</tr>
<tr>
<td>distance between M1 and M2</td>
<td>+/- 450 μm S (stability)</td>
<td>+/- 50 μm (thermal +/- 29 μm)</td>
</tr>
<tr>
<td>secondary mirror (M2)</td>
<td>+/- 70 μm C</td>
<td>+/- 50 μm (gravity +/- 40 μm)</td>
</tr>
<tr>
<td>Decenter</td>
<td>+/- 15” C</td>
<td>+/- 30” (thermal +/-11”, gravity +/-10”)</td>
</tr>
<tr>
<td>Tilt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>distance between M2 and Col</td>
<td>+/-110000 μm S (stability)</td>
<td>+/- 70 μm D</td>
</tr>
<tr>
<td>Collimator (Col)</td>
<td>+/- 2200 μm C</td>
<td></td>
</tr>
<tr>
<td>Tilt</td>
<td>+/- 2’ C</td>
<td></td>
</tr>
<tr>
<td>Lyot filter</td>
<td>Tilt</td>
<td>+/- 5’ C</td>
</tr>
<tr>
<td>Camera (Cam)</td>
<td>Decenter</td>
<td>+/- 3000 μm C</td>
</tr>
<tr>
<td>Tilt</td>
<td>+/- 7’ C</td>
<td></td>
</tr>
<tr>
<td>distance between Cam and CCD</td>
<td>(stability)</td>
<td>+/- 110 μm D</td>
</tr>
</tbody>
</table>

Each tolerance is set to give the aberration of 0.13”, which is $1/\sqrt{14}$ of the Airy disc diameter.

(i) : The main term of the aberration = C; coma aberration, S: spherical aberration and D: defocus.
Max. angle = 120.0°  \( P_{\text{max}} = 3.8 \times 10^{-3} \)

Al. Coating

refraction index: \( n - ik \)

\( n = 0.77 \)
\( k = 6.1 \) for Al.
Filtergraph

Aim:
- High resolution diagnostics of physical condition (B, v, T) and structure (morphological) changes in the photosphere and chromosphere
- Connection of the photosphere and chromosphere with the corona

Current basic scheme:
Two channel filtergraph
wide band and narrow band

+ one CCD camera
The average quiet-Sun temperature distribution derived from the EUV continuum, the La line, and other observed bright lines are indicated.
Constraints from Detector

CCD:
format: 2k x 2k (KODAK?)
pixel: 9 µm x 9 µm
full well: 8.5 x 10^4

READ-OUT:
clock: 512 kHz – (1 MHz)
frame read time: 8 sec – (4 sec)

Field of View (FOV)
200" x 200", one pixel = 0.1" x 0.1"
400" x 400", one pixel = 0.2" x 0.2"

S/N:
shot noise: photo-electron^1/2

one exposure: 225 (0.45%),
for n = 5 x 10^4 e

sum of 20 exposure: 1000 (0.1%),
for n = 1 x 10^6 e
<table>
<thead>
<tr>
<th>Filter</th>
<th>Central wavelength (Å)</th>
<th>passband (Å)</th>
<th>Airy disk radius (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3933 (Ca II K)</td>
<td>chromosphere</td>
<td>2</td>
<td>0.17</td>
</tr>
<tr>
<td>4305 (g-band)</td>
<td>faculae</td>
<td>10</td>
<td>0.18</td>
</tr>
<tr>
<td>4500 (cont.)</td>
<td>photosphere</td>
<td>10-20</td>
<td></td>
</tr>
<tr>
<td>5670 (cont.)</td>
<td>photosphere</td>
<td>10-20</td>
<td></td>
</tr>
<tr>
<td>6563 (Hα)</td>
<td>flare</td>
<td>3</td>
<td>0.28</td>
</tr>
<tr>
<td>6690 (cont.)</td>
<td>photosphere</td>
<td>10-20</td>
<td></td>
</tr>
</tbody>
</table>
### Narrow band

#### Spectral Lines

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Diagnostics</th>
<th>UBF Passband (mÅ)</th>
<th>Airy Disk Radius (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg I 4571.1</td>
<td>T</td>
<td>50 (62)</td>
<td>0.194</td>
</tr>
<tr>
<td>Fe I 4705.0</td>
<td>B (g=2.5)</td>
<td>53 (66)</td>
<td></td>
</tr>
<tr>
<td>H I 4861.3</td>
<td>I, v</td>
<td>57 (71)</td>
<td></td>
</tr>
<tr>
<td>Mg I 5172.7 (b2)</td>
<td>T, B (g=1.75)</td>
<td>66 (82)</td>
<td>0.22</td>
</tr>
<tr>
<td>Fe I 5250.2</td>
<td>B (g=3.0)</td>
<td>68 (85)</td>
<td></td>
</tr>
<tr>
<td>Fe I 5576.1</td>
<td>v</td>
<td>77 (96)</td>
<td></td>
</tr>
<tr>
<td>Fe I 6302.5</td>
<td>B (g=2.5)</td>
<td>100 (125)</td>
<td>0.27</td>
</tr>
<tr>
<td>H I 6562.8  (Hα)</td>
<td>I, v</td>
<td>109 (136)</td>
<td>0.28</td>
</tr>
</tbody>
</table>
## Comparison: Fe I 5250 vs. Fe I 6302

<table>
<thead>
<tr>
<th>Formation Height (see remarks)</th>
<th>Fe I 5250</th>
<th>Fe I 6302</th>
</tr>
</thead>
<tbody>
<tr>
<td>higher</td>
<td>lower</td>
<td></td>
</tr>
<tr>
<td>( \rightarrow B ) weaker if filling factor = 1</td>
<td>( \rightarrow B ) stronger if filling factor = 1</td>
<td></td>
</tr>
<tr>
<td><strong>B-sensitivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>V-signal (weak):</strong></td>
<td>high (g=3.0)</td>
<td>high (g=2.5)</td>
</tr>
<tr>
<td>( B \times 10^{\text{-3}} )</td>
<td>( B \times 7 \times 10^{\text{-4}} )</td>
<td></td>
</tr>
<tr>
<td>( B^2 \times 8.1 \times 10^{\text{-7}} )</td>
<td>( B^2 \times 5.4 \times 10^{\text{-7}} )</td>
<td></td>
</tr>
<tr>
<td><strong>Q-signal (weak):</strong></td>
<td>( \pi )-comp: weakly blended in spot</td>
<td>( \sigma )-comp: weakly blended in spot</td>
</tr>
<tr>
<td><strong>Blend</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>( T )-sensitivity</strong></td>
<td>very sensitive</td>
<td>insensitive</td>
</tr>
<tr>
<td>( \rightarrow B ): atmospheric model depend</td>
<td>( \rightarrow B ): almost the same geometrical height</td>
<td></td>
</tr>
<tr>
<td><strong>Magneto-Optical effect</strong></td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td><strong>Nearby lines</strong></td>
<td>Fe I 5247.058 (g=2.0)</td>
<td>Fe I 6301.508 (g=1.67)</td>
</tr>
<tr>
<td></td>
<td>Fe I 5250.654 (g=1.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T-diag.: 5247.058/5250.654</td>
<td></td>
</tr>
<tr>
<td><strong>Remarks</strong></td>
<td>radius of Airy disk: 0.22 arcsec, for ( D_1=50 ) cm, ( D_2/D_1=0.45 )</td>
<td>radius of Airy disk: 0.27 arcsec, for ( D_1=50 ) cm, ( D_2/D_1=0.45 )</td>
</tr>
<tr>
<td><strong>T diagnostics</strong></td>
<td></td>
<td>accurate ( B ) measurement</td>
</tr>
<tr>
<td><strong>other useful lines nearby</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( h(\text{km}) )</td>
<td>QS</td>
<td>PL</td>
</tr>
<tr>
<td>5250.2</td>
<td>260</td>
<td>230</td>
</tr>
<tr>
<td>5247.1</td>
<td>266</td>
<td>236</td>
</tr>
<tr>
<td>6302.5</td>
<td>249</td>
<td>232</td>
</tr>
<tr>
<td>6301.5</td>
<td>337</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>Wide band filter</td>
<td>Narrow band filter</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>filter-type</td>
<td>e.g. interference, simple optics, high transmission</td>
<td>e.g. Lyot, complicated, low transmission</td>
</tr>
<tr>
<td>passband</td>
<td>2–20 Å</td>
<td>0.05–0.1 Å</td>
</tr>
<tr>
<td>image quality</td>
<td>high: short exposure</td>
<td>middle: long exposure, need several images</td>
</tr>
<tr>
<td>diagnostics</td>
<td>photosphere–T_min: Temperature, horizontal velocity, intensity oscillation, morphology</td>
<td>photosphere–chromosphere: vector B, vertical velocity, horizontal velocity (chromosphere), Temperature, morphology</td>
</tr>
<tr>
<td>Current choices</td>
<td>several filters (f wheel), FOV: 200”x200” (0.1”/pix), wavelength range: 3900–7000Å</td>
<td>one UBF, several lines, FOV: 400”x400” (0.2”/pix), wavelength range: 4500–6600Å</td>
</tr>
</tbody>
</table>
collimation

- FWHM
- wavelength change

P-filter

L-filter

pupil

telecentric

- spectral homogeneity
- FWHM broadening

birefringent \((n_0, n_e)\)

spheric ab.

+ defocus

\[
\Delta S = \frac{d(n_0 - n_e)^2}{2 n_0 n_e}
\]

\[
\frac{\Delta S}{2F} > \frac{(n_0^2 - 1) d}{8 n_0^4 F^3} \quad \text{(spheric ab.)}
\]
Lyot Filter Calcite: $d = 11.639$ (cm)
Aperture of Filter = 3.0 (cm)
Length of Filter = 40.0 (cm)
Index of Filter = 1.50

Field of View (arc sec)

Telescope Aperture (cm)

Collimated to Lyot Filter

Aperture of Filter = 3.5 (cm)
Length of Filter = 40.0 (cm)
Index of Filter = 1.50

Field of View (arc sec)

Telescope Aperture (cm)
Baseline Items (+) & Open Questions (-) for Fitergraph

+ Two channel (narrow and wide band)
+ filter type
  narrow band: one Universal Birefringent Filter
  wide band: several interference filters
+ wavelength range:
  narrow band: 4500 - 6600 Å
  wide band: 3900 - 7000 Å
+ passband:
  narrow band: 100mÅ at 6303Å
+ tuning accuracy (stability)
  narrow band: 0.5mÅ (0.5% S/N)
+ CCD camera: one 2k x 2k
+ CCD read-out clock: 512 kHz/pixel
+ filter location: inbetween collimator (not telecentric) and camera lens
- image scale: 0.1 or 0.2 arcsec per pixel?
- FOV: 200 or 400 arcsec?
- focusing method: glass plates of different thickness, linear stage?
- wide band: wavelength and passband?
- Temperature control: entire focal plane package or each instruments?
  - optical bench, UBF, blocking filters, lenses
- lines, OK?
  - narrow band: H I 6563, Fe I 6302, Fe I 5576, Mg I 5173,
    H I 4861, Fe I 4705, etc.
  - wide band: Ca II K 3933 (2 Å), G-band 4305 (10 Å), Hα (3 Å)
    continuum in 4500, 5670, 6690, etc.
- S/N: 0.5%, OK?
- CCD camera: Kodak?
- image registration: software or hardwired, method?
- flat fielding: how?
Ca II K, 3 A wide filter, La Palma, 14-June-1994, 13:36 UT.
Brandt and Simon observing. Tick marks are 1 arc second.
pixel = 0.4"

c.2"
c.1"
0.02"

D = 50, r
p = 0.85
λ = 930 Å
Stokes Polarimetry with Grating Spectrograph
Physics of Flux Tube
Precise Observation of Active Region Structure
Inversion of Stokes Profile

0.2" world -> Localized V and I
(Granulation, faculae .....)
Profile will be different from standard model
Ambiguity of interpretation for filter obs.

Stokes Profile with Grating Spectrograph

2. Basic Requirement
25mA resolution
0.2" / pix
Small Size (1 or 1.5 m length)
Light Weight
Simple Mechanism
(moving mecha. not Preferred)
CaK Observation with no grating rotation
3. K line observation

K-line Option

<No Grating rotation and one CCD>

K line => outside of CCD in case of n=79/mm
CCD: 2K by 2K (9 μ)

↓

Higher order with coarse grating

=> Small FSR => many orders overlap

<n=31.6/mm ruling>

· Many lines are observable without grating rotation
  3933, 3968, 4571, 5250, 6303 etc....

· FSR is 70 Å for 6303
  blend of 6233.6
more narrow blocking filter(<70Å)
### Performance

#### Case 1 (No Frame Integration and slow modulation)

**<Grating Optics>**
- Littrow type Echelle

**<Grating>**
- Grating Constant: 31.6 grooves/mm
- Braze Angle: 63.5
- Blank Materials: ULE or Zerodur
- Coating: Al

**<Spectrograph Optics>**
- F of Main Optics: 19
- f of Littrow Lens: 1000 mm

**<CCD Detector>**
- Pixel Number: 2K by 2K
- Pixel Size: 9 micron (=0.2")
- Full Well: 85,000
- S/N: 0.3 % (Photon Noise)

**<Performance>**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffraction Order</td>
<td>6303 CaK</td>
</tr>
<tr>
<td>Anguler Disp.</td>
<td>90</td>
</tr>
<tr>
<td>mA/pix</td>
<td>6.36*10^-4</td>
</tr>
<tr>
<td>Resolv. Power(mA)</td>
<td>14</td>
</tr>
<tr>
<td>Electron on CCD (1/S)</td>
<td>5*10^5</td>
</tr>
<tr>
<td>(in continuum)</td>
<td>9*10^5</td>
</tr>
<tr>
<td>(Depends on QE etc)</td>
<td>5*10^6</td>
</tr>
</tbody>
</table>

# Drift due to TE

- CTE = 0.7*10^-6/k
- $\Delta \lambda \sim 19$ pix/20°C
- CTE = 1*10^-6/k
- $\Delta \lambda \sim 1.5$ pix/20°C
### Observable Lines with Fixed Eschell SPG for Solar-B(Case1)

M.A March 1995

<table>
<thead>
<tr>
<th>m</th>
<th>λ - Range</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>6279 - 6307</td>
<td>Photospheric Magnetic</td>
</tr>
<tr>
<td></td>
<td>6301 / 2 (Fe I)</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>6279 - 6307</td>
<td>Photospheric Magnetic</td>
</tr>
<tr>
<td></td>
<td>6297 (Fe I)</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>5887 - 5913</td>
<td>Chromospheric Magnetic</td>
</tr>
<tr>
<td></td>
<td>5895 (D I)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Na I)</td>
<td></td>
</tr>
<tr>
<td>99</td>
<td>5709 - 5734</td>
<td>Photospheric Velocity</td>
</tr>
<tr>
<td></td>
<td>5713 (T I)</td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>5487 - 5512</td>
<td>Photospheric Magnetic</td>
</tr>
<tr>
<td></td>
<td>5501 (Fe I)</td>
<td>Largest V-Amp</td>
</tr>
<tr>
<td></td>
<td>5506 (Fe I)</td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>5487 - 5512</td>
<td>Photospheric Magnetic</td>
</tr>
<tr>
<td></td>
<td>5497 (Fe I)</td>
<td>Largest V-Amp</td>
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<tr>
<td></td>
<td>5501 (Fe I)</td>
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<tr>
<td>105</td>
<td>5382 - 5407</td>
<td>Photospheric Temperature</td>
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<tr>
<td></td>
<td>5394 (Mn I)</td>
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<td>8</td>
<td>5233 - 5256</td>
<td>Photospheric Magnetic and Temp</td>
</tr>
<tr>
<td></td>
<td>5250 / 47 (Fe I)</td>
<td>(Line Ratio)</td>
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<tr>
<td>112</td>
<td>5046 - 5069</td>
<td>Photospheric Temperature</td>
</tr>
<tr>
<td></td>
<td>5052 (C I)</td>
<td></td>
</tr>
<tr>
<td>115</td>
<td>4914 - 4936</td>
<td>Photospheric Magnetic</td>
</tr>
<tr>
<td></td>
<td>4912 (Fe II)</td>
<td>Photospheric Velocity</td>
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<tr>
<td>115</td>
<td>4914 - 4936</td>
<td></td>
</tr>
<tr>
<td>123</td>
<td>4595 - 4615</td>
<td>Photospheric Magnetic</td>
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<tr>
<td></td>
<td>4607 (Sr I)</td>
<td>Weak B (Hanle effect)</td>
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<tr>
<td>124</td>
<td>4558 - 4578</td>
<td>Photospheric Temperature</td>
</tr>
<tr>
<td></td>
<td>4571 (Mg I)</td>
<td>LTE, Temperature Min.</td>
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<tr>
<td>139</td>
<td>4065 - 4084</td>
<td>Photospheric Magnetic</td>
</tr>
<tr>
<td></td>
<td>4080 (Fe I)</td>
<td></td>
</tr>
<tr>
<td>143</td>
<td>3952 - 3970</td>
<td>Chromospheric Temp and Vel.</td>
</tr>
<tr>
<td></td>
<td>3968 (H)</td>
<td>(Ca II)</td>
</tr>
<tr>
<td>144</td>
<td>3925 - 3842</td>
<td>Chromospheric Temp and Vel.</td>
</tr>
<tr>
<td></td>
<td>3933 (K)</td>
<td>(Ca II)</td>
</tr>
</tbody>
</table>
# Observable Lines with Fixed Eschell SPG for Solar-B(Case2)

M.A March 1995

- **n=23.2 grooves/mm**
- **f=1217mm**
- **grating angle = 64.03°**
- **Width of CCD = 4.819mm**

<table>
<thead>
<tr>
<th>m</th>
<th>Range</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>6297.9-6304.0</td>
<td>6301/2 (Fe I)</td>
</tr>
<tr>
<td>139</td>
<td>5573.0-5578.3</td>
<td>5576 (Fe I)</td>
</tr>
<tr>
<td>144</td>
<td>5379.5-5384.7</td>
<td>5380 (C I)</td>
</tr>
<tr>
<td>151</td>
<td>5130.1-5135.1</td>
<td>5132 (Fe II)</td>
</tr>
<tr>
<td>190</td>
<td>4077.1-4081.0</td>
<td>4080 (Fe I)</td>
</tr>
<tr>
<td>197</td>
<td>3932.2-3936.0</td>
<td>3933 (Ca II)</td>
</tr>
</tbody>
</table>

- Photospheric Magnetic
- Photospheric Velocity
- Photospheric Temperature
- Photospheric Temperature
- Photospheric Magnetic
- Chromosphere
Case 2 (Fast Modulation with Continuous Rotating WP)

<Grating Optics>
Littrow type Echelle

<Grating>
Grating Constant 23.3 grooves/mm
Braze Angle 63.5
Blank Materials UI.E or Zerodur
Coating Al

<Spectrograph Optics>
F of Main Optics 19
f of Littrow Lens 1213 mm

<CCD Detector>
Pixel Number 758(x) x 244(λ)
Pixel Size 8.5 μm(x) x 19.75 μm(λ)
Spatial Scale 0.2''/pix (≈ 0.1''/pix)
Full Well 60,000
S/N 0.1% (Frame Integration)

<Performance>

<table>
<thead>
<tr>
<th></th>
<th>6303</th>
<th>CaK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffraction Order</td>
<td>123</td>
<td>197</td>
</tr>
<tr>
<td>Angular Disp.</td>
<td>6.51*10^-4</td>
<td>1.04*10^-3</td>
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<tr>
<td>mA/pix</td>
<td>25</td>
<td>16</td>
</tr>
<tr>
<td>Resolv. Power(mA)</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>Electron on CCD (1/S)</td>
<td>9.5*10^5</td>
<td>1×10^5</td>
</tr>
<tr>
<td>(in continuum)</td>
<td>(Depends on QE etc)</td>
<td></td>
</tr>
</tbody>
</table>
Observing Sequence
for Spectrograph

Demodulation

I  Q  U  V
Tip Tilt Mirror Consideration
M.Akioka (Hiraiso,CRL)

1, Requirements
< Image Stabilize >
Filter Obs. : 0.01 arcsec / 10 sec(?)
(SP G : Obs. : < 0.002 arcsec / several sec.)
(see Lite's sans comments on Jan.)

< Requirement for Tip Tilt Mirror >
Location 150mm far from secondary focus
diam. about 30mm
resolution of tilt angle 0.5 μrad
Drv. freq. ??? 10 or 20 Hz?

2, Tip-Tilt Mirror on Japanese Satellites
Used for Engineering Sat. for Laser Communications
(1)Laser Communications Experiments (LCE) of ETS-6 (by NASDA and CRL)
Communication Experiment between Satellite and Ground
Satellite Launch had troubled but experiments was successful

<Fine Pointing Mechanism>
Detector : Quadrant Detector
Mirror Actuator : Moving Coil Actuator
Pointing Accuracy : 2 μrad (system)
Now under development

**<Fine Pointing Mechanism>**

- **Detector**: Quadrant Detector
- **Mirror Actuator**: Low Voltage Piezo Stack
- **Pointing Accuracy**: $1 \mu \text{rad}$ (system with testing model)

3. Moving Coil Actuator for LCE
   - **Permanent Magnet + Coil**
     - **Response frequency**: about 300Hz
     - (in case of LCE with 1.5cm mirror)
     - **Resolution of mirror angle**: $0.87 \mu \text{rad}$ (with test model)
     - (depends on noise and sensor)
   - **Tracking range**: $\pm 0.4 \text{mrad}$
   - **Low Hysterisis**
   - **Two Axis module is easily available**
   - **Range for tilting is large**

4. Piezo Actuator for OISETS
   - **Stack of Low Voltage Piezo**
     - **Response frequency**: 2kHz
     - (Mirror Diam. = 20-30mm)
     - **Now under evaluation for Solar-B**
   - **Hysterisis**
   - **Higher response frequency**
   - **Smaller size**
5. Problem and future action
   - Evaluation of Mirror angle resolution for Piezo
     (for Open loop control with gyro signal)
   - Evaluation of Gyro performance for open loop
   - Error sensing for Closed Loop
   No good concept for error detection for closed loop control
   Limb sensing : Not enough resolution
   Correlation Track : No experience in space
   Sunspot Track : Limitation for target selection
Required Resolution
for T-T mirror

Secondary Focal Plane
0.28"/μm

0.006" = 0.21 μm

15 cm

Telescope
ムービングコイルタイプアクチュエータ

電流(コイル) $i$

磁界 $B$

トルク $T=Bl$ L

原油

原則図

アクチュエータ概念図

Moving Coil
LCE Optical Part

LCE Comm Element (PAM, LDs, APD)

Point/Track Control

4QD

AN

FPM

CCD

Telescope

GIM

第5 図 LCE 光学部のレイアウト
図5 精選尾系の外乱に対する応答
polarization accuracy and physical quantities

$B \leftrightarrow P$ relation

$$B_\| \sim \alpha P_v$$
$$B_\perp \sim \beta P_Q^{1/2}$$

$\alpha \sim 1.7 \cdot 10^3$, $\beta \sim 2.0 \cdot 10^3$ (for FeI6303Å, B in Gauss),

detection limit

$$\delta B_\| \sim \alpha \delta P_v$$
$$\delta B_\perp \sim \beta (\delta P_Q)^{1/2}$$

uncertainty

$$\Delta B_\| \sim \alpha \delta P_v \sim \delta B_\|$$
$$\Delta B_\perp \sim \frac{dB_\|}{dP_Q} \delta P_Q \sim \frac{1}{2} \beta P_Q^{-1/2} \delta P_Q \sim \frac{1}{2} \frac{\delta B_\|}{B_\|}$$

1. $\phi$: azimuth angle of $B_t$

$$\Delta \phi \sim \frac{\Delta B_\|}{B_\|} \sim \frac{1}{2} \left(\frac{\delta B_\|}{B_\|}\right)^2$$

2. $j$: electric current

resolvable element of $J$ for pixel size $dx$

$$j \sim \frac{1}{\mu_0} \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right) dx^2 \sim \frac{1}{\mu_0} \frac{\partial B_t}{\partial x} dx^2$$

$$\delta j \sim \frac{1}{\mu_0} \delta B_t dx \sim 4.1 \cdot 10^7 \delta B_t dx \text{ Amp.}$$

(B in Gauss, dx in arcsec)

$$\Delta j \sim \frac{1}{\mu_0} \Delta B_t dx \sim \frac{1}{2} \frac{\delta B_\|}{B_t} \delta j$$
3. $\varepsilon$ : energy element

$J$ along a coronal loop of length $l$

$$\varepsilon \sim \frac{1}{2} L j^2$$

$L = 2l(\log \frac{2l}{dx} - \frac{3}{4})$ : inductance

$$\delta \varepsilon \sim \frac{1}{2} L (\delta j)^2$$

$$\Delta \varepsilon \sim \frac{\partial \varepsilon}{\partial I} \Delta I = LI \Delta I$$

4. $E$ : total energy

(B.C. Low 1982, Solar Phys. 77, 43)

$$\Delta E = \frac{1}{\mu_0} \int \int_{x=0} dx \, dy \{ x(B_{z}^{ff} - B_{z}^{p}) + y(B_{y}^{ff} - B_{y}^{p}) \} B_{y}^{ff}$$

$B^{ff}$: force free field

$B^{p}$: potential field

$B^{ff} - B^{p} \rightarrow \Delta B_{t}$

$$\Delta E \sim \frac{1}{\mu_0} \int \int_{x=0} dx^2 y \Delta B_{t} B_{t} \sim \frac{L^3}{\mu_0} < B_{t} \Delta B_{t} >$$

$< >$: spatial average, $B_{t} \approx B_{t}$

$$< B_{t} \Delta B_{t} > \sim \frac{1}{2} \delta B_{t}^2 \sim \frac{\beta^2}{2} \delta P_{Q} \sim \frac{\beta^2 \delta P_{Q}}{2N^{1/2}}$$

$N$: total pix. number ($n^2 = (L/dx)^2$)

$$\Delta E \sim \frac{1}{2\mu_0} \beta^2 L^2 dx \delta P_{Q}$$

noise level

field of view
<table>
<thead>
<tr>
<th>$\epsilon = 1%$</th>
<th>$\epsilon = 0.3%$</th>
<th>$\epsilon = 0.1%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta B_t \ (G)$</td>
<td>17</td>
<td>5.1</td>
</tr>
<tr>
<td>$\delta B_t \ (G)$</td>
<td>200</td>
<td>110</td>
</tr>
<tr>
<td>$\Delta B_t \ (G)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_t=100G$</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>500</td>
<td>40</td>
<td>12</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
<td>6.0</td>
</tr>
<tr>
<td>$\Delta \phi \ ($deg.$)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_t=100G$</td>
<td>–</td>
<td>34</td>
</tr>
<tr>
<td>500</td>
<td>4.6</td>
<td>2.3</td>
</tr>
<tr>
<td>1000</td>
<td>1.1</td>
<td>0.34</td>
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</tbody>
</table>

表 1: accuracy of polarization and $B$

**Accuracy of Measurement**

For this error in $Q, Y$ or $V$

For 1 wavelength

---

**energy resolution for 200"x200" FOV**

---

1: spatial resolution, pol. accuracy and energy resolution
sources of polarization errors

polarization measurement:

\[ I'_1 = c_{i1} I + c_{q1} Q + c_{u1} U + c_{v1} V \]
\[ I'_2 = c_{i2} I + c_{q2} Q + c_{u2} U + c_{v2} V \]
\[ \vdots \]
\[ I'_N = c_{iN} I + c_{qN} Q + c_{uN} U + c_{vN} V \]

\[ I'_n \Rightarrow I, Q, U, V \]

error in \( I'_n \)\( s \) \( \leftrightarrow \) noise

error in \( c_{i,q,u,v} \) \( \leftrightarrow \) crosstalk by optics instrument

change of \( I \) \( \leftrightarrow \) image motion

1. noise
   a) photon noise \( \cdots \delta(Q, U, V) \sim \epsilon I \sim (ntE_Q/E_M)^{1/2} \)
   b) dark noise
   c) read noise

2. crosstalk by optics components
   a) \( I \rightarrow Q, U, V \) \( \cdots \delta(Q, U, V) \sim \delta c_i I \)
   b) \( V \rightarrow Q, U \) \( \cdots \delta(Q, U) \sim \delta c_v V \)
   c) \( Q \leftrightarrow U \) \( \cdots \delta(Q, U) \sim \delta c_{u,q}(U, Q) \)

3. image motions
   a) telescope jitter, drift \( \cdots \delta(Q, U, V) \sim \delta x \frac{dI}{dx} \)
   b) beam wobbling by Rot. WP \( \cdots \)
   c) time change of solar feature \( \cdots \delta(Q, U, V) \sim \delta t \frac{dI}{dt} \)
I → QUV

V → QU

Q ↔ U

image motion

Spurious linear polarization follows gradient.
<table>
<thead>
<tr>
<th></th>
<th>noise</th>
<th>crosstalk by optics</th>
<th>image motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>estimation</td>
<td>$\delta(Q,U,V) \sim \epsilon I$</td>
<td>$\delta(Q,U,V) \sim \delta c, I$</td>
<td>$\delta(Q,U,V) \sim \delta c_v, I$</td>
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<tr>
<td>spatial</td>
<td>random</td>
<td>fixed on device</td>
<td>fixed on device</td>
</tr>
<tr>
<td>distribution</td>
<td>detection limit</td>
<td>false $B$ even $B=0$</td>
<td>false $B$, assoc. $B$</td>
</tr>
<tr>
<td>effect on $B$</td>
<td>noisy weak filed</td>
<td>$c$ pattern</td>
<td>spot, mag. element</td>
</tr>
<tr>
<td>false $j$</td>
<td>random</td>
<td>devic pattern</td>
<td>assoc. above</td>
</tr>
<tr>
<td></td>
<td>trend $\rightarrow$ small effect</td>
<td>above features</td>
<td>above features</td>
</tr>
<tr>
<td></td>
<td>uniform $\rightarrow$ no effect</td>
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<tr>
<td>source</td>
<td>photon noise</td>
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<td>obliq. refl.</td>
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<tr>
<td></td>
<td>dark noise</td>
<td>dust on WP</td>
<td>error of WP</td>
</tr>
<tr>
<td></td>
<td>read noise</td>
<td>error in exp. time</td>
<td>obliq. trans. of WP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>etc.</td>
<td>etc.</td>
</tr>
<tr>
<td>calibration</td>
<td>impossible $\epsilon$</td>
<td>continuum $\delta c_i \leq \epsilon$</td>
<td>DC plage $\delta c_v \leq 3\epsilon$</td>
</tr>
<tr>
<td>demand</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

|               |               |                      |                               |                              |

表 1: characteristics of polarization errors
<table>
<thead>
<tr>
<th>NOISE</th>
<th>spatial distrib.</th>
<th>time variation</th>
<th>calibration SP,FL</th>
<th>to avoid</th>
<th>adopt SP</th>
<th>FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>photon noise</td>
<td>random</td>
<td>random</td>
<td>impossi.</td>
<td>integration</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>dark noise</td>
<td>random</td>
<td>random</td>
<td>impossi.</td>
<td>cooling</td>
<td>○</td>
<td>○</td>
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<tr>
<td>read noise</td>
<td>random</td>
<td>random</td>
<td>impossi.</td>
<td>slow A/D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CROSSTALK BY OPTICS**

| telescope refl.        | I ⇒ Q,U,V       | trend          | const            | possible coating   | △        | △  |
| folding mirror         | I ⇒ Q,U,V       | trend          | const            | no folding mirr.   | △        | △  |
| dust on WP             | I ⇒ Q,U,V       | irreg.         | vari.            | difficult          |          |    |
| fringe by WP           | I ⇒ Q,U,V       | irreg.         | vari.            | difficult          |          |    |
| exposure error         | I ⇒ Q,U,V       | uniform        | random           | possible           |          |    |
| inhomogeneity sensitivity | I ⇒ Q,U,V   | irreg.         | const            | possible           |          |    |
| ghost                   | I ⇒ Q,U,V       | irreg.         | slow var.        | difficult          |          |    |
| error of WP retard.    | V ⇒ Q ⇒ U       | uniform        | slow var.        | possible           | stable element | (O) (O) |
| error of WP setting    | V ⇒ Q ⇒ U       | uniform        | const.           | possible           | calibration | (O) (O) |
| imperfect. of Pol.     | V ⇒ Q ⇒ U       | uniform        | const.           | possible           | calibration | (O) (O) |
| oblique trans. to WP   | V ⇒ Q ⇒ U       | trend           | const.           | possible           | calibration | (O) (O) |
| non-uniform WP         | V ⇒ Q ⇒ U       | trend?          | const.           | possible           | calibration | (O) (O) |
| error in WP rot.       | V ⇒ Q ⇒ U       | uniform        | random           | difficult          | stable rot. | (O) (O) |
| CCD read out           | V ⇒ Q ⇒ U       | trend           | const?           | possible           | calibration | (O)    |

**IMAGE MOTION**

| atoms. scintillation   | I ⇒ Q,U,V       | sun             | random            | impossi.           | space     | ○  |
| WP wedge, tilt         | I ⇒ Q,U,V       | sun             | random            | imp. pos.          | oil bath  | △  |
| telescope jitter       | I ⇒ Q,U,V       | sun             | random            | imp. pos.          | Tip-Tilt mirr. | △  |
| solar change           | I ⇒ Q,U,V       | sun             | random            | imp. pos.          | fast modulation | (O) |

表 1: error sources

Which are dominant
Image motion
Beam splitter
Dust on waveplate
ghost brightness
calibration of crosstalk

polarization modulation:

\[
\begin{bmatrix}
I'_1 \\
I'_2 \\
\vdots \\
I'_N
\end{bmatrix}
= \begin{bmatrix}
1 + \Delta c_{i1} & c_{q1} + \Delta c_{q1} & c_{u1} + \Delta c_{u1} & c_{v1} + \Delta c_{v1} \\
1 + \Delta c_{i2} & c_{q2} + \Delta c_{q2} & c_{u2} + \Delta c_{u2} & c_{v2} + \Delta c_{v2} \\
\vdots & \vdots & \vdots & \vdots \\
1 + \Delta c_{iN} & c_{qN} + \Delta c_{qN} & c_{uN} + \Delta c_{uN} & c_{vN} + \Delta c_{vN}
\end{bmatrix}
\begin{bmatrix}
I \\
Q \\
U \\
V
\end{bmatrix}
\]

calibration = to know \(\Delta c_i, \Delta c_q, \Delta c_u, \Delta c_v\)

1. \(\Delta c_i: \ I \rightarrow Q, U, V\)
   - continuum at disk center \(\Rightarrow\) unpolarized
   \[
   \begin{bmatrix}
   I \\
   Q \\
   U \\
   V
   \end{bmatrix}
   = \begin{bmatrix}
   1 \\
   0 \\
   0 \\
   0
   \end{bmatrix}
   \rightarrow \Delta c_i(x, y)
   \]
   make observation

2. \(\Delta c_v: \ V \rightarrow Q, U\)
   - plage near disk center \(\Rightarrow\) \(V >> Q, U\)
   \[
   \begin{bmatrix}
   I \\
   Q \\
   U \\
   V
   \end{bmatrix}
   = \begin{bmatrix}
   1 \\
   0 \\
   0 \\
   0
   \end{bmatrix}
   \rightarrow \Delta c_v(x, y)
   \]
   - \(Q, U, V\) profiles \(\Rightarrow\) \(Q, U\): symmetric, \(V\): asymmetric
   \[(Q, U)_{\text{sym}} = f(\Delta c_v) \cdot V\]

3. \(\Delta c_{q,u}: \ Q \leftrightarrow U\)
   - penumbra near disk center \(\Rightarrow\) \(B_t //\) filaments
   - compare with well calibrated ground-based observation
image shift and $\delta I$

granulation contrast:

$$\delta I = \frac{dI}{dx} \delta x = 0.5 I \delta x \quad \Rightarrow \quad \frac{\delta I}{I} = 0.1\% \quad \leftrightarrow \quad \delta x = 0.002''$$

change of line profile:

inter granule, $T=T-280 K \quad V = 2.0 \text{km/s}, \quad \text{FeI}6303A$

$$\frac{\delta I}{I} = 0.1\% \quad \leftrightarrow \quad \delta x = 0.001''$$
requirement on image stability

assumptions:

- $\delta I/I = 0.1\%$ is produced by image shift of 0."001
- photometric accuracy — 0.1\% (SP) and 0.5\% (FLT)
- 0.75Hz for rotating wave plate (filter exp=0.33s)
- fullset of filter images taken in 10 sec
- no correction by tip-tilt mirror

<table>
<thead>
<tr>
<th></th>
<th>spectrograph</th>
<th>filtergraph</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>case 1</td>
<td>case 2</td>
</tr>
<tr>
<td>beam wobble</td>
<td>0.&quot;02</td>
<td>0.&quot;005</td>
</tr>
<tr>
<td></td>
<td>($\frac{1}{10}$ PSF)</td>
<td>($\frac{1}{10}$ PSF)</td>
</tr>
<tr>
<td>satellite drift</td>
<td>0.&quot;003/s</td>
<td>0.&quot;0005/s</td>
</tr>
<tr>
<td></td>
<td>(0.&quot;001/0.33s)</td>
<td>(0.&quot;005/10s)</td>
</tr>
<tr>
<td>jitter</td>
<td>0.&quot;001</td>
<td>0.&quot;005</td>
</tr>
<tr>
<td></td>
<td>at 1.5 and 3.0 Hz</td>
<td>at 0.1 ~ 3 Hz</td>
</tr>
</tbody>
</table>

$\Delta X \sim 0."015$

case 1: Polarized intensities are measured with the same pixel.

case 2: Image registration is made after observation.
time variation of intensity and \( \text{S/N} \)

1. change of granulation
   - contrast of granules: \( g = 0.2 \rightarrow 0.5 \)
   - width of boundary: \( x = 0.5 \rightarrow 0.2 \)
   - horizontal motion: \( v = 1 \text{ km/s} \)
     \[
     \Rightarrow \frac{1}{I} \frac{dI}{dt} = \frac{g v}{x} = 5.6 \times 10^{-4} \text{s}^{-1}
     \]
     \[
     \left( \text{0.1} \% \rightarrow 1.8 \text{ s} \right) \rightarrow 3.5 \times 10^{-2} \text{ s}^{-1}
     \]

2. five minute oscillation
   - \( v \) amplitude: \( \delta v = 250 \text{ m/s} \)
   - time scale: \( \delta t = 150 \text{ s} \)
   - \( dv/dt = 1.67 \text{ m/s}^2 \)
     \[
     \Rightarrow \frac{1}{I} \frac{dI}{dt} = 1.6 \times 10^{-4} \text{s}^{-1}
     \]
     \[
     ( \text{in FeI6303}\AA )
     \]

3. Doppler shift by orbital motion
   - max. rate of \( V \) change for polar orbit: \( d\lambda/dt = 0.084 \text{ mÅ/s} \)
     \[
     \Rightarrow \frac{1}{I} \frac{dI}{dt} = 3.8 \times 10^{-4} \text{s}^{-1}
     \]
     \[
     ( \text{in FeI6303}\AA )
     \]

integration time and \( \text{S/N} \)

flux budget \( \rightarrow N \sim 6 \times 10^5 \text{ electrons/s/pix} \)
   (for \( \Phi=50\text{cm}, 0.2 \times 25\text{mÅ pix., FeI6303}\AA, \text{QE}=0.4 \) )
     \[
     \Rightarrow \frac{\delta I}{I} \sim (N \cdot t)^{-\frac{1}{2}} \sim 0.0013 \times t^{-\frac{1}{2}}
     \]
## flux budget

+++++++ telescope throughput ++++++++  

<table>
<thead>
<tr>
<th>Component</th>
<th>Area (cm²)</th>
<th>Intensity (erg/photon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope aperture (50)</td>
<td>1963</td>
<td>1.96e+03</td>
</tr>
<tr>
<td>Sub mirror (22)</td>
<td>390</td>
<td>1.57e+03</td>
</tr>
<tr>
<td>Mirror (0.93x3)</td>
<td>0.804</td>
<td>1.27e+03</td>
</tr>
<tr>
<td>IR,UV cut filter</td>
<td>0.90</td>
<td>1.14e+03</td>
</tr>
<tr>
<td>Pol. modulator</td>
<td>0.95</td>
<td>1.08e+03</td>
</tr>
<tr>
<td>Beam splitter</td>
<td>0.45</td>
<td>4.87e+02</td>
</tr>
<tr>
<td>Solar intensity</td>
<td>5.88e-05</td>
<td>2.86e-02</td>
</tr>
<tr>
<td>erg/photon</td>
<td>3.15e-12</td>
<td>9.08e+09</td>
</tr>
</tbody>
</table>

+++++++ spectrograph (6303A) ++++++++  

<table>
<thead>
<tr>
<th>Component</th>
<th>Spatial sample (0.2x0.1)</th>
<th>Spectral sample (20.0)</th>
<th>lens (0.97x4)</th>
<th>mirrors (0.93x1)</th>
<th>Blocking filter</th>
<th>Grating efficiency</th>
<th>Quantum efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.00e-02</td>
<td>0.0200</td>
<td>0.885</td>
<td>0.930</td>
<td>0.50</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>1.82e+08</td>
<td>3.63e+06</td>
<td>3.21e+06</td>
<td>2.99e+06</td>
<td>1.49e+06</td>
<td>7.47e+05</td>
<td>2.99e+05</td>
</tr>
</tbody>
</table>

+++++++ filtergraph (6303A) ++++++++  

<table>
<thead>
<tr>
<th>Component</th>
<th>Spatial sample (0.1x0.1)</th>
<th>Passband width</th>
<th>lens (0.97x2)</th>
<th>Beam splitter</th>
<th>Blocking filter</th>
<th>Lyot transmission</th>
<th>Quantum efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00e-02</td>
<td>0.111</td>
<td>0.941</td>
<td>0.90</td>
<td>0.50</td>
<td>0.22</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>9.08e+07</td>
<td>1.01e+07</td>
<td>9.48e+06</td>
<td>8.53e+06</td>
<td>4.27e+06</td>
<td>9.38e+05</td>
<td>3.75e+05</td>
</tr>
</tbody>
</table>
flux = $6.0 \times 10^5$ electron/s/pix, # of states = 4

![Graph showing orbital motion and granulation motion with time in seconds and I/\delta I on the y-axis.](image)

- Full = $3 \times 10^5$ e$^-$
- $dt = 0.05, 0.50$ sec

---

flux = $6.0 \times 10^5$ electron/s/pix, # of states = 4

![Graph showing orbital motion and granulation motion with time in seconds and I/\delta I on the y-axis.](image)

- Full = $5 \times 10^4$ e$^-$
- $dt = 0.05, 0.50$ sec
beam wobbling by a rotating waveplate

\[ i : \text{ wedge angle} \]
\[ \alpha : \text{ tilt angle} \]

- **wedge**
  \[ n \sin = \sin(i + \delta \theta) \]
  \[ \delta \theta \sim (n - 1) \cdot i \]
  \[ \delta x_w \sim (n - 1) \cdot l \cdot i \]

- **tilt**
  \[ \sin \alpha = n \cdot \sin(\alpha - \theta) \]
  \[ \theta \sim \frac{1}{n}(n - 1) \cdot \alpha \]
  \[ \delta x_t \sim d \cdot \theta = \frac{1}{n}(n - 1) \cdot d \cdot \alpha \]

**parameters**

- image size: \( 1'' = 3.64 \cdot 10^{-2} mm = 36.4 \mu m \) (base line)
- location of WP: \( l = 21 cm \)
- wave plate: \( d = 2 mm, \quad n = 1.55 \) (quartz)

**tolerance of \( i \) and \( \alpha \)**

allowable image motion: \( 26x \leq 0''.002 \Rightarrow \delta x = 3.64 \cdot 10^{-5} mm \)

\[ i \leq 3.15 \cdot 10^{-7} rad = 6''.5 \cdot 10^{-2} \]
\[ \alpha \leq 5.13 \cdot 10^{-5} rad = 10''.6 \]

\* \( i \rightarrow 95 \text{ mA} \sim \frac{1}{50} \lambda \) parallelism of WP for 3cm diameter.
avoiding influence of the image motion

1. symmetric sampling
   cancel the I→Q,U,V crosstalk
   \[ 2 \delta x < \frac{1}{10} \text{PSF} \sim 0''02 \]
   * candidate mode for the spectrograph

2. compensate by tip tilt mirror
   \[ i = 10'' \rightarrow 2\delta x = 0''.154 \]
   rotation = 0.5 Hz \[ \rightarrow dx/dt \sim 0''.154 /s \]
   \[ \Rightarrow \frac{dx}{dt}/\delta x = 0''.154/0''.002 = 79 /s \]
   i.e. \[ \sim 100 \text{ Hz} \] is required for tip-tilt mirror.
   * Result changes with assumed parameters.
   * Detection of image motion may be a difficult problem.

3. cancel the wedge and tilt (for rot.WP)
   \[ \delta x_w + \delta x_t = 0 \rightarrow \alpha = -n \cdot \frac{1}{4} i = 2'.72 \]
   * 10''.6 accuracy is still required for the direction of rot. axis.
   * Interference fringe?

4. put WP in oil bath (for rot.WP)
   * This solves also fringe problem.

5. use LQVR
**fast system vs. slow system**
for polarization measurement

<table>
<thead>
<tr>
<th></th>
<th>fast system</th>
<th>slow system</th>
</tr>
</thead>
<tbody>
<tr>
<td>rot. wave plate</td>
<td>continuous (≈ 0.75 Hz)</td>
<td>step-wise (≈ 0.5 Hz)</td>
</tr>
<tr>
<td>CCD clock</td>
<td>fast (≈ 1 MHz × 2)</td>
<td>slow (0.5 MHz)</td>
</tr>
<tr>
<td>fullwell</td>
<td>≈ 5 \cdot 10^4</td>
<td>≈ 2 \cdot 10^5</td>
</tr>
<tr>
<td>shutter</td>
<td>frame transfer</td>
<td>mechanical shutter (?)</td>
</tr>
<tr>
<td>shutter timing</td>
<td>≈ 1 ms</td>
<td>-</td>
</tr>
<tr>
<td>exposure</td>
<td>≈ 80 ms</td>
<td>≈ 300 ms</td>
</tr>
<tr>
<td>accumulation</td>
<td>yes (≈ 60 times)</td>
<td>no</td>
</tr>
<tr>
<td>accuracy</td>
<td>0.1 %</td>
<td>0.3 %</td>
</tr>
<tr>
<td>sampling</td>
<td>16 pos. / rot.</td>
<td>4 or 5 position</td>
</tr>
<tr>
<td>duration for 1 set</td>
<td>≈ 5 sec</td>
<td>≈ 3-4 sec</td>
</tr>
<tr>
<td>total electron #</td>
<td>1 \cdot 10^6</td>
<td>1.1 \cdot 10^5</td>
</tr>
<tr>
<td>efficiency</td>
<td>100%</td>
<td>20 ~ 30 %</td>
</tr>
<tr>
<td>required image stability (without tip-tilt mirror)</td>
<td>&lt; \frac{1}{10} PSF ≈ 0.&quot;02</td>
<td>&lt; 0.&quot;003</td>
</tr>
<tr>
<td>wobble by WP</td>
<td>&lt; 0.&quot;003/s</td>
<td>≤ 0.&quot;0008/s</td>
</tr>
<tr>
<td>satellite drift</td>
<td>&lt; 0.&quot;001</td>
<td>&lt; 0.&quot;003</td>
</tr>
<tr>
<td>jitter</td>
<td>at 1.5 and 3.0 Hz</td>
<td>at 0.2~1 Hz</td>
</tr>
<tr>
<td>problems</td>
<td>compatibility with filter</td>
<td>0.3 % accuracy</td>
</tr>
<tr>
<td></td>
<td>fast clock</td>
<td>image stability</td>
</tr>
<tr>
<td></td>
<td>(flat fielding?)</td>
<td></td>
</tr>
</tbody>
</table>
classification of polarization measurement

1. mechanisms of polarization modulation

(a) rotating wave plate (continuous)
(b) rotating wave plate (stepping)
(c) wave plate wheel
(d) liquid crystal variable retarder

2. Modulation sequence

(a) take $I \pm Q, I \pm U, I \pm V$
(b) take 4 sets of $I_i = \frac{1}{2}(I + c_{qi} \cdot Q + c_{ui} \cdot U + c_{vi} \cdot V)$
(c) take more than 5 kinds of $I_i$
(d) take only $I \pm V$

3. onboard accumulation, make or not
**tradeoff between polarization modulators**

<table>
<thead>
<tr>
<th>modulator</th>
<th>mechanism</th>
<th>retardation</th>
<th>vector (Q,U,V)</th>
<th>efficiency</th>
<th>v-only</th>
<th>speed</th>
<th>mechanical disturbance</th>
<th>control</th>
<th>beam wobble</th>
<th>stability</th>
<th>reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rot.WP</td>
<td>λ/4</td>
<td>0.318, 0.318, 0.636</td>
<td>&lt;1.0(^1)</td>
<td>O</td>
<td>O</td>
<td>Δ(^2)</td>
<td>(O)(^3)</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>(continuous)</td>
<td>127°</td>
<td>0.511, 0.511, 0.511</td>
<td>&lt;0.8(^1)</td>
<td>△</td>
<td>X</td>
<td>O</td>
<td>Δ (O)(^3)</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Rot.WP</td>
<td>λ/4</td>
<td>0.354, 0.354, 0.653</td>
<td>1.0</td>
<td>△</td>
<td>X</td>
<td>O</td>
<td>Δ (O)(^3)</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>(stepping)</td>
<td>123°</td>
<td>0.547, 0.547, 0.547</td>
<td>&lt;0.837(^1)</td>
<td>△</td>
<td>X</td>
<td>O</td>
<td>△</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Turret</td>
<td>(\frac{1}{4}\times 2, \frac{3}{4}\times 4)</td>
<td>0.333, 0.333, 0.333</td>
<td>1.0</td>
<td>△</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>△</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>(\frac{1}{4}\times 2, 123°\times 4)</td>
<td>0.547, 0.547, 0.547</td>
<td>1.0</td>
<td>△</td>
<td>X</td>
<td>O</td>
<td>?</td>
<td>O</td>
<td>△(^4)</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>LCVR×2</td>
<td></td>
<td>0.577, 0.577, 0.577</td>
<td>1.0</td>
<td>O</td>
<td>O</td>
<td>?</td>
<td>?</td>
<td>O</td>
<td>△(^4)</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

1. Pure I cannot be obtained with 2 exposures due to Q->I crosstalk.
2. Continuously rotating WP requires precise shutter timing.
3. Continuously rotating WP causes image motions even during exposure.
   But image motion can be suppressed by putting the WP in oil bath.
4. LCVR is sensitive to temperature variation but the calibration seems not to be very difficult.
merits of the fast system:

- a high photometric accuracy
- small mechanical disturbance by the modulator
- the symmetric sampling reduces $I \rightarrow Q,U,V$ crosstalk caused by beam wobbling by the rotating wave plate by factor of 10
- quick modulation relaxes the requirement on satellite drift rate
- only limited frequencies of satellite jitter are responsible to the $I \rightarrow Q,U,V$ crosstalk
- controlling principle may be simple because the modulator can be a reference for both filter and spectrograph operations

demerits of the fast system:

- compatibility with the filter instrument
  - pure $I$ and $V$ cannot be obtained with 2 exposures
    $( Q \rightarrow I $ crosstalk $ )$
  - exposure of the filtergram should be shorter than twice of the spectrograph for $Q,U$-measurement and 4 times for $V$-measurement
  - precise timing is required for the mechanical shutter
  - image moves even during exposures
  - shutter by a moving slit may cause a different modulation phase in FOV
- fast clock of CCD and fast demodulator are required
modulation by a rotating waveplate

\[ 2I' = \left\{ 1 + R \sin\left(4\pi dn/\lambda\right) \sin \delta \cos 2\phi \right\} \cdot I \]
\[ + \left\{ \frac{1 + \cos \delta}{2} \frac{1 - \cos \delta}{2} \cos 4\phi \right\} \cdot Q \]
\[ + \frac{1 - \cos \delta}{2} \sin 4\phi \cdot U \]
\[ - \sin \delta \sin 2\phi \cdot V \]

\[ R = 2 \left( \frac{n-1}{n+1} \right)^2 \]: reflection index, \( n \): refraction index, \( d \): thickness
effective sampling for filter system

\[ \delta = 0.352, \quad \text{eff.} \times 2 \quad (Q, U, V) = 0.522 \ 0.522 \ 0.615 \]

\[
\begin{array}{cccccc}
\phi & c_i & c_q & c_u & c_v \\
39.38 & 0.015 & -0.538 & 0.306 & -0.785 \\
73.12 & -0.062 & 0.506 & -0.738 & -0.444 \\
106.88 & -0.062 & 0.506 & 0.738 & 0.444 \\
140.62 & 0.015 & -0.538 & -0.306 & 0.785 \\
\hline
\text{M.E.} & 0.038 & 0.522 & 0.522 & 0.615 \\
\text{M}_p & 0.513 & 0.960 & 0.891 & 0.790 \\
\end{array}
\]

\( M_p \) is defined by \( \sqrt{\sum_i m_{ip}^2} \), where \( m_{ip} \) are elements of the inverse matrix.

\[
\begin{bmatrix}
I \\
Q \\
U \\
V
\end{bmatrix} = 
\begin{bmatrix}
m_{1i} & m_{2i} & m_{3i} & m_{4i} \\
m_{1q} & m_{2q} & m_{3q} & m_{4q} \\
m_{1u} & m_{2u} & m_{3u} & m_{4u} \\
m_{1v} & m_{2v} & m_{3v} & m_{4v}
\end{bmatrix} 
\begin{bmatrix}
I'_1 \\
I'_2 \\
I'_3 \\
I'_4
\end{bmatrix}
\]
constraint on filter obs. from the continuously rot. WP

\[ Q \rightarrow I \text{ crosstalk: } \Delta I_{max} \sim 8.8\% \]

exposure limitation: \( \Delta t < 167 \text{ ms (Q,U)} \)
\( \Delta t < 333 \text{ ms (V)} \)

reduced efficiency: factor 0.64 for 45° exp.

shutter timing: \( \delta t < 4 \text{ ms (}\delta I = 0.5\%) \)

beam wobbling: \( \delta x < \frac{1}{10} \text{ PSF (during exp.)} \)
\( \delta x < 0."005 \text{ (between exp.)} \)

non-uniform phase: ?

\( \Rightarrow \) vector sampling determination

\( \Rightarrow \) flux budget of SP and FLT

OK for long \( \lambda \)

\( \Rightarrow \) not serious

\( \Rightarrow \) investigation of mech. shutter
\( (\delta t \sim 8 \text{ ms for SXT shutter}) \)

\( \frac{15}{\mu}\text{s}^\text{2} \)

\( \Rightarrow \) same with spectrograph

\( \Rightarrow \) image registration on ground?

\( \Rightarrow \) investigation of mech. shutter calibration scheme?
**tradeoff between locations of polarimater**  
*(case of rotating wave plate)*

<table>
<thead>
<tr>
<th></th>
<th>at pupil image (collimated)</th>
<th>at solar image (converging)</th>
<th>no image (converging)</th>
</tr>
</thead>
<tbody>
<tr>
<td>image motion by tilt</td>
<td>no</td>
<td>large</td>
<td>middle</td>
</tr>
<tr>
<td>&quot; by wedge</td>
<td>large</td>
<td>no</td>
<td>middle</td>
</tr>
<tr>
<td>plate inhomogeneity</td>
<td>insensitive</td>
<td>sensitive</td>
<td>middle</td>
</tr>
<tr>
<td>(I→Q,U,V cross talk)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>distance from primary</td>
<td>large</td>
<td>small</td>
<td>small</td>
</tr>
</tbody>
</table>
estimation of \( Q \rightarrow I \) crosstalk (I-ambiguity)

assumptions:

- LTE line formation
- magnetic field — 2000G, horizontal
- filter width — 100mA at 6000Å
- retardation of WP — 126.8°
- sampling around 45° and 135°
- exposure duration — 1°, 71°, 90°

<table>
<thead>
<tr>
<th>line</th>
<th>1°</th>
<th>71°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeI6303Å</td>
<td>-7.5</td>
<td>0.</td>
<td>2.5</td>
</tr>
<tr>
<td>FeI5506Å</td>
<td>-8.8</td>
<td>0.</td>
<td>2.9</td>
</tr>
<tr>
<td>FeI5250Å</td>
<td>-8.4</td>
<td>0.</td>
<td>2.8</td>
</tr>
<tr>
<td>FeI4442Å</td>
<td>-4.5</td>
<td>0.</td>
<td>1.5</td>
</tr>
</tbody>
</table>

consideration:

- Exposure duration of \( \sim 70° \) rotation reduces \( Q \rightarrow I \) crosstalk. Allow small I-ambiguity.
- Take vector magnetic field with 4 exposures always when accurate I is required from the scientific objective.
Lyot filter: FWHM, transmission, # of photon

flux budget for spectrograph and filtergraph
degradation of modulation efficiency

$$ME = \frac{1}{N} \sum_{i=1}^{N} |c_{pi} - c_{pi}|, \quad M_p = \sqrt{\sum m_{ij}^2}$$

sampling at 39.38°, 73.12°, 106.88°, 140.62°
rot. angle during exposure = $\Delta \phi$

\[
\begin{array}{ccccccc}
\Delta \phi & q & u & v & q & u & v \\
1.0 & 0.522 & 0.522 & 0.615 & 0.957 & 0.891 & 0.790 \\
10.0 & 0.509 & 0.509 & 0.611 & 0.982 & 0.914 & 0.795 \\
22.5 & 0.470 & 0.470 & 0.599 & 1.063 & 0.989 & 0.811 \\
45.0 & 0.333 & 0.333 & 0.553 & 1.503 & 1.399 & 0.877 \\
70.0 & 0.137 & 0.137 & 0.473 & 3.637 & 3.386 & 1.027 \\
90.0 & 0 & 0 & 0.391 & - & - & 1.364 \\
\end{array}
\]

consideration:

- If $\Delta \phi < 45^\circ$, S/N does not degrade more than factor 0.66
  $\rightarrow$ not very serious

requirement on the mechanical shutter

$\delta I/I = 0.5\%$ (40,000 electrons) $\rightarrow \delta \phi \sim 1.1^\circ$
rotation freq. = 0.75Hz $\rightarrow$ timing accuracy ($\delta t$) $\sim 4$ ms

consideration:

- Yohkoh SXT shutter $\rightarrow \delta t \sim 8$ ms $\rightarrow$ needs
- further study of shutter mechanism
- monitor timing and calibrate on data analysis?
\[ \delta = 0.250, \quad \text{eff.*}^2 (Q,U,V) = 0.318 \ 0.318 \ 0.637 \]

\[ \delta = 0.352, \quad \text{eff.*}^2 (Q,U,V) = 0.509 \ 0.509 \ 0.509 \]
3.1.1 グレゴリー望遠鏡

口径500mm、主鏡 f=100mm、副鏡 f=703mm、主鏡副鏡間距離3000mmのグレゴリー望遠鏡を考える。図のように光軸に平行な光線も、入射点が光軸から離れるに従って同心円状の直線偏光を示し、その大きさは周辺で約2×10⁻⁴程度になる。しかし、視野中心に於いてはMueller行列を平均すると単位行列となり、全体として疑似偏光は発生しない。また、視野の端（200°）に於いても平均したMueller行列の成分は、最大で10⁻⁷程度の大きさであり、疑似偏光はほとんど問題とならないであろう。

\[
M_{\text{max}} = 250.0 \text{ mm} \quad P_{\text{max}} = 2.2 \times 10^{-4}
\]
Meeting Notes from Presentations by
Prof. Tsuneta's Group on
Solar-B Magnetograph Design

During the Solar-B presentations I attempted to keep detailed notes of the speakers' comments. These notes are not intended to stand alone but to accompany the speakers' handouts. The purpose of the notes is to highlight the topics which the speakers emphasized, catch some information which might not have been presented quite the same in the notes, and to get a sense of some of the dialog which ensued.
Meeting notes on Solar B presentations to Russell Chipman
From Prof. Tsuneta's group
National Astronomical Observatory
Mitaka, Japan
July 18-20, 1995

Attendees include:
Dr. Tsuneta
Dr. Ichimoto
Serge Koutchme (spelling?), France

Tsu: U Hawaii, High Altitude Observatory, Lockheed, and German meetings have already occurred.
Purpose - free exchange on designs on baseline
develop baseline plan
Day 1  spacecraft and mission
2 spectrograph, and polarimeter; Ichimoto summary
3 polarization

Dr. Sakao Presentation  Spacecraft and Mission

- Hard x-ray person, spacecraft systems
Mission objectives
Result from Yohkoh
Dynamic rather than static corona
Magnetic reconnection role, including solar flares

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For solar-b.

Objective: systems approach to photosphere-coronal activity
reveal solar MHD phenomena
photosphere as origin of coronal magnetic activities
high resolution x-ray and optical
hard and soft x ray features

Plan
Vector magnetograph, 0.1-0.2 arc sec resolution
x ray telescope, magnetic behavior in solar corona
xuv spectrograph, coronal velocity field measurement

must have high resolution for optical and x ray

600 km orbit
680 kg scientific package
170 kg thrusters
launch 2004

2 year period of sun synchronous observation using thrusters
image stabilization 0.02"/sec, higher with tip/tilt mirror
data recording rate 500 kbps or 3 Gbps per orbit
downlink rate 5Mbps desired (under study)

serg: what about 10 km/sec orbital velocity
Sakeo: on-board Doppler compensation system
(RC mostly transverse)

Attitude control
sub arc sec for spacecraft body
6x higher that Yohkoh
instrument active control does not require active control?
Solar rotation tracking
disturbance: counter wheels needed for filter wheels

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sensor: gyro signal for tip tilt mirror control, experiments under way

Actuator: momentum wheels noise
type 1, ball bearing type, ... oil soak / wobble torque problem (HST)
type 2, magnetic bearing
need to suppress torque and noise
really feasible? Under study. Solve? Then 0.02"/sec in spacecraft body
otherwise need tip-tilt mirror, studying feasibility
Sensor? Limb sensor?

Spacecraft orbit
Scientific requirements
baseline sun synchronous (vs. equatorial)
then need thrusters to maintain
also thrusters at launch
Radiation environment worse in sun synchronous vs equatorial
Scientific considerations:
a. high spatial resolution observation
   minimize thermal distortion, constant thermal environment
b. continuous observation
   solar activities in various timescales
   more efficient observations
   pre and post flare
c. Minimize Doppler effect for 100 mA line width spectral measurements

orbit choice
Sun synchronous has weight penalty
1.3 tons equatorial
.85 in sun synch. including thrusters
8 months / yr observing vs 40 min night/orbit
Doppler shift 130 mA vs 250 mA
Thermal design much easier vs not easy
more experience in equatorial launch
no previous sun syn. launch from Kagoshima

thrusters
170 kg required vs desired

radiation load on electronics
more trapped electrons in 1 4 Mbit Dram per day
0 errors/ bit/day
0.002 Solar B
0.010 Solar B during flare

Doppler shift graphs shown at 600 km
causes 0.09 mA shift/sec
8 months no night
max. 20 min night per orbit ~23%

Telemetry:
huge amount of data
>7 Gbits/orbit, cannot downlink all
On board data processing including Stokes demodulation and data compression
Solar A "80 Mbit/sec
5 Mbit/sec downlink"

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On-board large volume data recorders and data buffers (using 16 Mbit DRAM?)
Downlink 5 Mbps? Possible?
Kagoshima has 10 min downlink window

RC: TRDS downlink?

On-board data flow
Telescope
may sum 2x2 pixels, usually limit FOV
Stokes demodulation
JPEG lossless data reduction
Data recorder
Telemetry
Ground Stations KSC/DSN?
Reduce 8 to 3GBit/sec

Data recorder req.
compare Solar A IRIS Astro-D Astro-E Solar-B
Solar-B has highest requirements

Packet telemetry?
On-board packet interface?
Packet telemetry? In x-band?

Ground Stations
KSC
s band current 262 kbps, future TBD
x band " 262
KSC to ISAS "384
DSN is Goldstone, Wallops, Madrid, Australia
262 plan to 1.6Mbps

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Spacecraft layout
current plan
Optical on main axis
X-ray one side
XUV other side
Bus module on each side
Thruster tanks
solar panels'

artist's rendering

Serg: optical aperture?
Sakao: studying best place for thrusters to minimize contamination to telescopes
also studying damage if off-axis sunlight focused inside telescope
studying need for telescope door

On board Doppler compensation
Data up-load every 3-7 days orbital element info (TBD)
calculate detailed orbital elements, polynomial coefficient
Orbit timer
On board Doppler estimation
Accuracy of delta lambda combined with target wavelength yields lambda + dlambda
perform passband tuning
CCD readout address change (for spectrograph)
update every 10 sec or faster

Serg: should include solar rotation elements
RC: 5 min oscillation Doppler correction
general laughter
mission objective can be addressed with quiet sun reveal fundamental processes less events more oriented to quiet sun

Tsu: Q to MSFC is their problem with science output if we launch in 2004 or 2005 MSFC best people to ask because we have 20 years of operation 2004 is near minimum 2002 is out of question 2003 is not the baseline, based on performance of IR telescope Skylab launched at solar minimum

Serg: tilt axis can correct 2 axis. What about spin? Tsu: largest effect at edge of FOV, 2d order, first two axes are first order team who builds telescope must have very close interaction with spacecraft builders

Sakao finish

Ryouhei Kano U Tokyo Grad Student

Optical Telescope Schematic Gregorian heat rejecting cone or plane mirror rotation retarder analyzer in primary hole tip tilt mirror

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Pol. BS
Lyot filter arm
Spectrograph arm

Telemetry.
Aplanatic Gregorian
50 cm
f/15 at image
CCD 9 micron/pixel
nose cone limits telescope length
Focal plane
Lyot filter f/18 0.2/pixel FOV 400"
Interference filter f/37 0.1"/pixel
Spectrograph f/18.5 0.2"/pixel
Aberration 0.05" at edge of FOV
Airy Disc 0.5" @ 5000A

Kano wrote ray trace program for mirrors
spot diagrams shown

Polarization analyzer
to avoid instrumental polarization, analyzing retarder inside primary
then folding mirror
then Polarizing beam splitter for analyzer

RC: stray light problem of retarder so far forward
critical surfaces seen by both primary and secondary
About 1.8 degree cone through retarder and beamsplitter

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Q. Secondary mirror position
Tolerance analysis
Primary: 70 micron decenter, 7" tilt
mirror separation 450 micron +-5
Secondary 70 micron decenter, 15" tilt
expect gravitational distortion of 40 microns (Mitsuchika (?) Co. quote)
collimator decentration 2200 micron, 2' tilt

Lyot, 5' tilt
Camera, 3000 micron decenter, 7' tilt
Each tolerance yields aberration of 0.13" or 1/Root14 of airy disk diameter
Main aberration terms, coma, spherical ab, defocus

Tsuneta: baseline plan, no prefilter, nothing over telescope aperture
Serg: protection of telescope coatings
Tsuneta: reflecting not refracting. If you have a cover, contamination problem is the same. Also distortion of full aperture window.
UV protection?
Heat rejection cone

50 cm primary
22 cm secondary

Tilted heat rejection mirror, flat, 45 deg.
Window on side of tube, 280 mm diam.
even with heat rejecting cone, the rays strike the barrel

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Focal plane package
BS sends light to two channels
Nikon studied BS and lens achromatization

Filter arm
Collimator
Lyot
Filter
BS to 2x arm with interference filter for high spatial resolution
shutter to select Lyot/Interference
Camera lens
CCD

Spectrograph
Littrow lens, Echelle grating
Field lens
Slit
1000 m spectrograph lens, double pass
70A band
order, greater than 100

Spot diagrams from Nikon for Lyot arm
390 -56 nm
mainly defocus

Mitsubishi structure study

instrumental polarization ray trace of crossed folding mirror
system
2 degree cone angle

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for aluminum ellipse map 0.38% polarizance, calculation for unpol. light
RC: this is diattenuation only, retardance often 5x larger

end of Kino's presentation

Tsuneta -- Daily summary

serious problems
1. Spatial resolution vs FOV
some want highest resolution
others want largest FOV at cost of resolution
assume 2000x2000
currently emphasize FOV more
since space telescope should emphasize resolution
RC: aliasing
Serg: telescope aperture, not optimum for radiometry, time cadence
too many photons, CCD limited, computer limited redundant

issue 2. Large secondary mirror
to get polarization analyzer in hole.
Also heat rejection system
4300-6563
6302 only for magnetograph?

Issue 3. Critical tolerances
3 m long system
need a refocus mechanism?
5 DOF mechanism for secondary? Don't like

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how can we relax critical tolerance.
RC: refocus mechanism increase tolerances about 10x removing
defocus limitation, now coma, SA limitation

initial option was Cassegrain. because of tolerances.

Issue 4: thermal design/ contamination
back side of primary is for heat dump, need large clean area for
radiation dump
bad place for retarder and tilt mirror
Nihon spacecraft not clean
how to protect from out-gassing?
Organic material exposed to solar UV may become black
Heat primary above ambient
but have no heater power
Historically, Nihon spacecraft have passive control
Can we continue observations after contamination?

How share tasks
Telescope Mitsubishi/Nikon, have made earth observing telescopes
Focal plane package US?
Small complaint - US people only talk about money
Mr. Suematsu's presentation

Spectrographs
Narrowband, Lyot, This talk
Wideband, Littrow,
Aim: high resolution diagnostics of physical condition and
structure, morphological, in photosphere and chromosphere
Connections with corona
Two channel filtergraph, one CCD

Graph of solar temperature and lines with altitude

Constraints of detector
2K x 2K Kodak
9x9 microns
85000 electrons/well
512 KHz readout (maybe 1MHz) at 12 bits
8 sec readout
FOV .1x.1" per pixel yields 200"x200" FOV
S/N 225 for one exposure
S/N 1000 for 20 exposure w/ 1,000,000 electrons

Wideband filters
3933 CaII 2A
4305 g-band 10A faculae
4500 continuum 10-20A photosphere
5670
6563
6690
Narrowband
4571  50 mA  .194 A Airy disk
4705
4861
5172
5250
5576
6302
6562.8 109 mA  0.28" Airy Disk

Comparison of 5250 vs 6302
5250 is Temp sensitive
since don't have full line profile, this causes more error
6302 less temp sensitivity

Compare narrow vs. wide band filtergraph
Wideband  interference filter, high transmission, short exposure
study temperature, horizontal velocity, intensity oscillations, morphology
Filter wheel
3900-7000 range
2-20 A passband

Narrowband
Lyot
<5% transmission, complicated, long exposure
lower image quality, need image averaging
study vector B
vertical and horizontal velocity
morphology

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Current choice: one universal birefringent filter, several lines wavelength range, 4500-6600 .05-.1 A passband

Beam at filter
Collimated
Telecentric
mention birefringent pol. ab of converging beam in calcite pupil in middle of Lyot filter

Show Stokes profile through Zeeman line
only observe blue and red wings, not measure line center

RC: why not scan FP while building up spectrum rather that taking all MSFC averages at one wavelength

Q: beamsplitter design
Q: wavelength range

Baseline:
collimated beam
4500 -6600A
3.5 cm aperture
40 cm length
ray angle f/30 in air

Lockheed filter

Open questions:
image scale 0.1 or 0.2
FOV 200 or 400"

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focussing method adjustment, linear stage
temp control, entire focal package or each instrument
Spectral lines
S/N 0.5% OK?
CCD Kodak?
Image registration: software or hardwired, method?
Gain equalization

example of Lockheed 3A filtergram CaII K
Lockheed FeI magnetogram and H alpha
4305 A Lockheed image

RC: Explanation of Aliasing if too few pixels
more pixels is better
Serge: error is related to intensity derivative
which is linear function in OTF domain
so maybe central obscuration helps

Dr. Akioka's presentation
Hiraiso, CRL (n of Tokyo on coast)

Spectrograph channel
Stokes polarimetry with Grating Spectrograph
Physics of flux tube
Precise observation of active region structure
Inversion of Stokes profile

Requirements.
25 mA resolution
0.2"/pixel

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small, 1 or 1.5 m
light weight, simple, no moving mechanisms
CaK observation with no rotation

Observing sequence
Slit FOV
Baseline:
sixteen analyzer positions per slit location
then move slit

Rotating retarder
Tip tilt mirror
PBS
Lens, Slit, scan mirror
blocking filter
Field lens and slit
Achromatic Littrow lens
Echelle Grating
Shutter
CCD camera

1 m EFL yields 25 mA

0.2 world -> localized V and I  (granulation will be different
from standard model)  (??)
Profile will be different from standard model
Additional information gleaned from full line profile,
temp, velocity fields
at 0.1", this may become important

Echelle order ~100

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Lens to adjust image size on slit

Want to observe CaK with no grating rotation

Current baseline parameters, designed together with High Altitude Observatory
23.3 lines/mm
63.5 deg blaze
Al coating
Diff order 123 for 6303 and 197 for CaK
Blocking filter wheel
25 mA / pixel

Another case
larger format CCD 18 mm
quicker readout, TI chip
758x244 pixels
continuous rotating retarder
31.3 grooves/mm
90th order 6303
144th CaK

problem for CaK line
transmission of PBS

RC: need PBS cube demonstration

Timing:
Reference clock
retarder encoder

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CCD triggers
Adders for Stokes demodulation
Image frame buffers

Status of tip-tilt mirror
Requirements.
Spectrograph needs 0.002 arcsec for several sec.
See B. Lites comments
Location, far from solar image, 150 mm
30 mm diameter
0.5 microrad resolution
10-20 Hz drive freq.
been used previously on Jap. satellite

Future action
Action may be available with requirements
but don't have design for sensing image jitter
considering gyro for spacecraft jitter and correlation tracker
tilt mirror may need to be open loop
limb sensing, not enough resolution
    partial sun, small field image
correlation tracking, no experience in space
sunspot tracking--limits target selection

gyro testing is ongoing

July 20, Mitaka, Third Day of Presentations
Dr. Ichimoto

"equations in notes"
Longitudinal polarization proportional to circular polarization

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Transverse to sqrt of linear polarization
Detection limit of field and uncertainty equations based on noise relation between B azimuth
resolvable element of current J
smallest element of energy resolution for 200" FOV
Polarization errors
I=W S
errors in I are noise
errors in W, crosstalk in instrument
Change of I, image motion

Photon noise
dark current
read noise

Crosstalk
I -> Q,U,V artificial polarization from unpolarized light
V -> Q,U circular to linear
Q <-> U orientation error

Image motion
telescope jitter/drift dI/dx delta_x alignment of images
Beam wobble from wave plate
Time change of solar feature delta_t dI/Dt time between images

Characterization of polarization elements
Noise limits detection limit on B
Optics crosstalk causes false B even when B is zero
Image motion gives false B around granulation, flare, sunspot features

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I,Q,U,V error
dust on waveplate, error in exposure time, gain, oblique reflection
calibration requirement
noise must be as small as possible
calibrate crosstalk better than epsilon
circular crosstalk should be 3 times smaller than epsilon,
intensity accuracy
image motion

ghost brightness varies with aim point on sun
calibration of crosstalk
1. Measure unpolarized continuum at disk center
2. Phage near center [I,0,0,V] yields circular to linear crosstalk
3. Q,U,V profiles, Q,U symmetric; V antisymmetric
4. Penumbra near disk center, Q <-> U
assume penumbra near disk center
compare with well calibrated ground based observations

Tsu: calibration wheel?
Tsu: Yohkoh filter wheel, already 10,000,000 rotations

granulation contrast
relation of image shift and polarization noise
0.1% intensity change at granule comes from 0.002" motion

Serge: granulation has very sharp steep boundary and field is strongest in small area between granules

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Change of line profile
Doppler shift due to 2/km line of sight motion
0.001 arc sec shift cause >0.1 dI

requirements on image stability

Tsu: do we really need 0.1%, this is what High Altitude
Observatory says they need

RC: analyzing image shift in the case of the Airy disk gives
limiting crosstalk present. Then if structures have 20%
contrast, multiply by 0.2
smallest possible uncorrelated areas in image.

Tsu: what about velocity field on sun? How long for objects to
move by 0.001"

Ichimoto:
Change of granulation
typical velocity field - 1/km/sec
(1/I) dI/dt 5x10e-4 /s

5 minute oscillation, not so important
(1/I) dI/dt 1.6x10e-4 /s

Integration time and S/N

Flux Budget

bind: need 7 sec to get 0.1% dI
but granulation changes in 2 sec

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each set of Stokes components should be measured in 1 sec, and repeated to build up accuracy
Only the part of the spacecraft jitter near the modulation freq of polarimeter affects the measurement.
(RC: The MSFC measurement profile has long power spectrum, very low freq response and susceptibility)

Beam wobbling by rotating waveplate
wedge effect, conical deviation
tilt of waveplate
(RC: rotating element at image eliminates beam wander)
with waveplate 21 cm from image 2mm thick waveplate, n=1.55
allowable image motion 0.002"
parallelism needed 0.0065 arc sec.
similar to parallelism needed for Fabry-Perot ideas:
1. Symmetric sampling, rotate through 16 positions in 360 degrees
2. Compensation by tilt mirror after calibration
3. Cancel the wedge versus tilt
4. Put waveplate in oil bath
5. Some other polarization modulator

fast vs slow polarization measurement
fast, continuously rotating waveplate
slow, stepwise rotation
fast CCD, frame transfer, 1 mS timing, 80 ms exposure, accumulate 60x
0.1 accuracy, measure 16 positions/per rotation, 1 data set in 5 sec, total electrons 10e6, acceptable wobble is .1 PSF
Tradeoff between polarization modulators
most critical, reliability, then speed

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Merit of fast system
high accuracy
symmetric sampling reduces beam wobbling
relaxes requirement on satellite drift
only limited frequencies of satellite jitter cause I -> Q, U, V
crosstalk

Problems
compatibility with filter instrument
pure I and V cannot be determined in 2 exposures
needs a shutter, frame transfer CCD is not available at full
2kx2k pixels
precise shutter timing
fast CCD clock and stokes modulation required

Alternative telescope/polarimeter configuration
use pickoff mirror at plane of intermediate image
primary
interm. Image
secondary
pickoff at interm image plane
crossed folding mirror
polarimeter

Tsu: this requirement for 0.002 arcsec image stabilization cannot
be measured with CCD, so there is no baseline
Trying to justify mission
You must examine this assumption.

Serg: separate problem of image subtraction from integrating
signal in analysis.
Still combined.

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Appendix 9.

My Presentation to Prof. Tsuneta's Group on the UAH/Marshall Space Based Vector Magnetograph Design

During my visit to the National Observatory of Japan I presented 12 hours of lectures on the MSFC magnetograph design, polarimetry, and polarization aberrations. The outline was as follows:

a. The NASA/Marshall Space-based Solar Vector Magnetograph Design. 2 hour

b. Introduction to the Jones and Mueller polarization calculus. 3 hours basic

c. Polarimetry, measuring polarization elements and optical systems. 3 hours included Japanese language viewgraphs

d. Polarization ray tracing. 4 hours polarization of interfaces Cassegrain telescope polarization

This Appendix contains the viewgraphs for a. The NASA/Marshall Space-based Solar Vector Magnetograph Design. The other notes are taken from corresponding chapters in my short course notes, and in the interest of brevity they are not included here.
The NASA/Marshall Space-based Solar Vector Magnetograph Design

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With Viewgraphs Contributed by:

Mona Hagyard
Alan Gary
Ed West
NASA Marshall Space Flight Center
Huntsville, AL
NASA MSFC Solar Magnetograph
Objectives

Present the NASA Marshall Space Flight Center Solar Vector Magnetograph optical design

Review the components of the optical system

Discuss design tradeoffs

Cassegrain vs. Gregorian

Fabry-Perot vs. Birefringent Filter

Design of Polarimeter

Status of the prototype EXVM Magnetograph

Instrumental Polarization
BACKGROUND

- **MSFC VECTOR MAGNETOGRAPH**
  - 22 YEARS IN OPERATION (1973 - 1995)

- **STUDY FOR AIR FORCE 1988**
  - SOLAR ACTIVITY MEASUREMENTS EXPERIMENT (SAMEX)
  - 30 cm VECTOR MAGNETOGRAPH, H-ALPHA TELESCOPE, XUV IMAGER

- **EXPERIMENTAL VECTOR MAGNETOGRAPH (EXVM)**
  - GROUND-BASED SAMEX CONCEPT

- **MSFC SPACE VECTOR MAGNETOGRAPH (MSVM)**
  - BASED ON EXVM DESIGN
  - BALLOON OR SATELLITE INSTRUMENT (MSVM -> SOLAR-B)
IMPORTANT FEATURES OF THE MSVM

- **LARGE FIELD OF VIEW**
  - 4.3 x 8.6 arcmin with 0.50 arcsec spatial resolution
  - 2.2 x 4.3 arcmin with 0.25 arcsec spatial resolution

- **OPTIMUM MAGNETIC SENSITIVITY**
  - Symmetric telescope with special coatings
  - Maximum linear polarization sensitivity
  - Minimum circular crosstalk
  - $1 \times 10^{-4}$ polarimetric accuracy $\Rightarrow$ 30 G transverse fields

- **HIGH TEMPORAL RESOLUTION**
  - ~ 5 minute cadence
  - Filter magnetograph
  - Special CCD camera
  - Versatile data acquisition system
AN ADAPTABLE DESIGN

- CASSEGRAIN ⇔ GREGORIAN TELESCOPE

- SPECTROGRAPH "ARM"

- MULTI-BANDPASS SEGMENTED PREFILTER
  - EXAMPLE: \( \lambda 6302 \pm 75 \text{ Å} \), \( \lambda 5250 \pm 75 \text{ Å} \), \( \lambda 6563 \pm 75 \text{ Å} \)
  - \( \lambda 5250 \pm 75 \text{ Å} \), \( \lambda 4508 \pm 75 \text{ Å} \), \( \lambda 4305 \pm 75 \text{ Å} \)

- 1X ⇔ 2X OPTICS

- 125 mÅ ⇔ 63 mÅ BANDPASS AT \( \lambda 6302 \)
MSVM Optical Design
Marshall Space Flight Center

Concept developed from a MSV Balloon Proposal for a 60 cm Telescope

Components:

Telescope: Symmetric Diffraction Limited 60cm Cassegrain with UAH Low Polarization Optical Coatings
Prefilter: Full Aperture Prefilter
Polarimeter: A 50mm Glan-Thompson Rotating Analyzer in a Collimated Beam
Image Motion Compensator: Spot Tracker and Articulated Folding Mirror which Follows the Polarimeter
Blocking Filters: Set of Insertable Narrow Band Interference Filters (2.5 Å)
Zoom Lens Optics: Dual Set of Optics: 1x for Large FOV and 2x for Diffraction Limit
Fabry-Perot Etalon: A 140mm Etalon in a Telecentric Beam with High Reflectivity Broadband Coating
Detector: A 1024 by 2048 (Active Pixels) Camera System
Marshall Space Flight Center

Vector Magnetograph

Proposed Instrument
Polarimeter

High polarimetric sensitivity, 1:4000

Rotating retarder polarimeter

Followed by additional polarizer for intensity control

Quartz quarter wave linear retarder

Large aperture Glan-Thompson polarizer

Six measurement sequence for Stokes vectors
Operational Modes

EXVM polarimeter

\begin{align*}
\omega & \quad \frac{\lambda_1}{4} \\
\omega & \quad \frac{\lambda_2}{4}
\end{align*}

Glan Thompson

Polaroid

\begin{align*}
\omega & \quad \frac{\lambda_1}{4} \\
\omega & \quad \frac{\lambda_2}{4}
\end{align*}

Rotating waveplate polarimeter

\begin{align*}
\omega & \quad \frac{\lambda_1}{4} \\
\omega & \quad \frac{\lambda_2}{4}
\end{align*}

Analyzer

Polarization

\begin{align*}
\omega_1 & \quad \omega_2 \\
Polarization & \quad I+Q \quad I+Q \quad I+Q \quad I+Q \\
& \quad 0 \quad 45 \quad 45 \quad 45 \quad 135 \quad 45 \quad 45 \quad 135 \quad 135
\end{align*}

Beam-splitting Stokes polarimeter
## Advantages

<table>
<thead>
<tr>
<th>EXVM polarimeter</th>
<th>Rotating waveplate polarimeter</th>
<th>Beamsplitting Stokes Polarimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="EXVM polarimeter diagram" /></td>
<td><img src="image" alt="Rotating waveplate polarimeter diagram" /></td>
<td><img src="image" alt="Beamsplitting Stokes Polarimeter diagram" /></td>
</tr>
<tr>
<td>$\lambda_1 \frac{1}{4}$ Polaroid</td>
<td>$\omega_1 \frac{\lambda_1}{4}$ $\omega_2 \frac{\lambda_2}{4}$ Analyzer</td>
<td>Non-polarizing beamsplitters</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$\omega_1$ $\omega_2$</td>
<td>Waveplate</td>
</tr>
</tbody>
</table>

| 1. No circular crosstalk | 1. Single detector | 1. Circular crosstalk should be small |
| 2. Single detector | 2. No rotating parts | |
| 3. Large field of view | | |
| 4. Polarization resolution designed for $1 \times 10^4$ | | |
Disadvantages (emphasis on linear polarization measurements)

<table>
<thead>
<tr>
<th>EXVM polarimeter</th>
<th>Rotating waveplate polarimeter</th>
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<td><img src="Image" alt="Beamsplitting Stokes Polarimeter diagram" /></td>
</tr>
<tr>
<td>$\lambda_{2}/4$</td>
<td>$\omega_1$</td>
<td>Non-polarizing beamsplitters</td>
</tr>
<tr>
<td>$\lambda_{1}/4$</td>
<td>$\omega_2$</td>
<td>$35/67$</td>
</tr>
<tr>
<td>Polaroid</td>
<td>Analyzer</td>
<td>$50/50$</td>
</tr>
<tr>
<td>Glan Thompson</td>
<td></td>
<td>$1\cdot V$</td>
</tr>
<tr>
<td>$1\cdot U$</td>
<td></td>
<td>$1\cdot U$</td>
</tr>
<tr>
<td>$1\cdot Q$</td>
<td></td>
<td>Waveplate</td>
</tr>
</tbody>
</table>

| Minor | 1. Large moving mass | 1. Wavelength or temperature dependent | 1. Non-polarizing beamsplitters limit wavelength range |
|       | 2. Some instrumental modulation IF following optics polarization sensitive $(k_1,k_2)$ AND retarder $\lambda_{2}/4$ imperfect | 2. Limited field of view | 2. Field of view dependent on beamsplitters |
|       | 3. Image motion at detector | 3. Fast axis misalignment errors | |
|       | 4. Possible image motion at detector | |
|       | |
|       | | | |


SCHEMATIC OF COMPENSATION WHEEL

COMPENSATION WHEEL

MOTOR

WHEEL GEAR

POLARIMETER GEAR

POLARIMETER

$r_2$
Prefilter options for the MSVM magnetograph

Design goal: Three wavelength bandpasses
   a. 15nm at 525nm
   b. 15nm at 630nm
   c. 15nm at 656nm

Options that are being studied:

1. Segmented multi-bandpass prefiltter

   Advantages
   a. Smaller thermal load on optics and polarimeter

2. Cold mirror coating on secondary (transmit infrared)

   Advantages
   a. No optical aberrations from full aperture prefiltter
   b. Smaller mass
Fabry-Perot Etalon

Tunable 0.125 Angstrom resolution (0.0125 nm)

Solid substrate, not air spaced. Rigid.

Electrically controlled, piezoelectric transducers

$4 \times 10^{-4}$ Angstrom/volt

Located at a telecentric image,

Identical spectral response over the entire field of view.
Fabry-Perot Filter

Rationale

1. Commensurate Spectral Resolution
2. High Etendue
3. Mechanically Simple
4. Rapid Tunability
5. Minimum Complexity

6. Minimum Polarization Sensitivity

Philosophy

1. Magnetic Sensitive Lines
2. Telecentric Configuration
3. Multiline Diagnostics
4. Maximum Sensitivity
5. Coarse Spectrographic Mode

Presentation

1. Spectral Capabilities
2. Finesse Selection
3. Measured Values for ET70
4. Spectral Bands 5250/6302

70-120 mÅ
>50%
PZT/3 Year Lifetime
0.2 msec/ Red-Blue / Orbital Doppler
Weight, Length, Cost, Temperature
Sensitivity, and Scattered light
Compatible with Polarimeter
Filter Widths
Measured Values

Queensgate ET70 Fabry-Perot Etalon
80 mÅ

Andover Blocker
2.5 Å

1. Delivered Filters Met Specifications
2. Confirms Manufacturing Capabilities with Required Specifications
Solar Spectrum

Minimum Three Blocker Configuration using Tilt Shifting for Wavelength Selection

5250 Å
Multiline Diagnostics of Magnetic Field

6302 Å
Photospheric Magnetic Field

6563 Å Hα
Zeeman Line Selection

The Selection of the 5250 Region for Fabry-Perot Filter Optimization

5250  Advantages
      Cleanest Multiplet Pair
      Pair for Temperature Diagnostic
      Optimization Allows the 6302 Region to be Accessible

5250  Disadvantages
      Slightly Lower Splitting (17%)
      Slight TiO Blend (5250.24) in Umbra Temperature Sensitivity (2x)

6302  Advantages
      Multiplet Pair
      Slightly Larger Splitting (17%)
      Nearby Telluric Lines Diagnostic for Ground Observations
      Higher CCD Quantum Efficiency (.4x)

6302  Disadvantages
      No Temperature Diagnostic Lines
      Not Optimum for Etalon Design
Fabry-Perot vs. Birefringent Filter

Fabry-Perot
- electrically addressable
- simpler optical system
- solid
- limited by scattering

Birefringent filter
- larger field of view
- many moving parts
- index matching, bubble formation in space
- optical quality of large pieces of calcite
Locating Filter at a Telecentric Image vs. a Collimated Pupil

Bandpass shifts to blue proportional to angle of incidence squared

Telecentric image,
spectral band is broadened
spectral band is the same for all image points

Collimated pupil
spectral band is minimum
spectral band varies over image
shifts to blue toward edge

Both have same bandpass when averaged over all rays

The larger the pupil/image, the narrower the bandpass
Large Field of View

Fast Readout

High Signal to Noise

Maximum Sensitivity

Frame-transfer CCD Camera

Large Pixel Array
MODIFIED MIT LINCOLN LABS CCD CAMERA

- 1024 x 2048 PIXELS
- 24\(\mu\) PIXEL SIZE
- 500 Ke WELL DEPTH
- QE = 65%
- 1 M-PIXEL/s READOUT AT EACH PORT
**MSVM CCD CAMERA**

*(MODIFIED MIT LINCOLN LAB AXAF CCD)*

- **ARRAY:** 1024 x 2048 PIXELS

- **WELL DEPTH:** 500,000 ELECTRONS \(N_w\)

  \[ S/N = \sqrt{N_w} = 700 \]

  \[- S/N = 10^4 \text{ REQUIRES 200 INTEGRATIONS} \]

- **EXPOSURE TIMES**

  - 0.24 S, 0.96 S in 1-X, 2-X 'OPTICAL CONFIGURATIONS'

- **READOUT TIME:** 0.26 S
TYPICAL TIMELINE AND DATA RATES: 1 X OPTICS

OBSERVING SEQUENCE

- Hα LINE CENTER
- Hα LINE WING
- λ 5250 PROFILE (I ± V AT 0, ± 90, ± 120 mÅ)
- I ± V WITH 20 INTEGRATIONS (1 G)
- I + Q, I + U WITH 200 INTEGRATIONS (40 G)
- λ 5250 PROFILE (I ± V AT 0, ± 90, ± 120 mÅ)
- Hα LINE CENTER
- Hα LINE WING
TIMELINE AND DATA RATES: 2 X OPTICS

- REDUCE $I \pm V$ INTEGRATIONS TO 10 (2 G)
- REDUCE $I \pm Q, U$ INTEGRATIONS TO 100 (60 G)
- TOTAL TIME = 6 MINUTES
- TOTAL DATA = 71.4 MB (200 kB/s)

10-TAPE EXABYTE CAROUSEL ≡ 50,000 MB CAPACITY

TAPE RECORDING AT 0.5 MB/s ⇒ 2.8 MINUTES (1 X)

2.4 MINUTES (2 X)
Polarimetry: Measuring Polarization Elements and Optical Systems

Russell A. Chipman
Associate Professor of Physics
University of Alabama in Huntsville
Huntsville, AL 35899
(205)895-6417 x318
Telescope

Aperture: 50 or 60 cm

Configuration:

Cassegrain with full aperture prefilter (shown)
or
Gregorian with reflective conical field stop

Aspheric mirrors:
Hyperboloids plus aspheric terms
will utilize NASA/Marshall large aspheric mirror fabrication facilities

Low polarization enhanced reflective coatings
NASA MSFC Field Rejecting Gregorian Telescope
NASA MSFC Field Rejecting Gregorian Telescope
Instrumental Polarization

Polarization sensitivity is compromised by nonnormal angles of incidence at surfaces before polarimeter

Larger angles of incidence cause larger polarization state changes

Particularly couple circular polarization into linear polarization

Seek to minimize instrumental polarization, particularly coupling of the generally larger circular component into linear polarization.

Subject of Polarization Ray Tracing talk
Polarization Aberration Analysis and Minimization

Mirrors and Lenses induce polarization aberrations

Polarization Aberrations reduce accuracy of polarimeter measurements

Accurate magnetic field measurement requires reduction of polarization aberrations

Tools for analyzing polarization aberrations:

- Polarization ray tracing
- Polarization aberration theory
- Polarization optical testing with imaging polarimeter

Polarization compensation:

- Low polarization design techniques
- Balancing polarization aberrations
Polarization Aberration Resuction in SAMEX Design

SAMEX Solar Magnetograph Study (1988)

Polarization Aberration Correction:

Designed with low angles of incidence
Coatings optimized for low polarization
Second order polarization aberrations balanced

Polarization Aberration Reduction:

Design had 1/1000 the instrumental polarization of equivalent Cassegrain telescope with aluminum mirror coatings at 5250 Å.
21.6 Telescope and Polarimeter Polarization Calibration

When system is assembled and aligned:

Illuminate with large number of precisely calibrated polarization states.

Determine exact response of system to arbitrary states on pixel-by-pixel basis.

Determine alignment of sequential images to 1/100 of pixel.

Incorporate into polarimeter data reduction routines.
SPECIAL SPACEFLIGHT QUALIFICATIONS

- "COOL" TELESCOPE OPTICS
  - REDUCED THERMAL PROBLEMS

- FABRY-PEROT FILTER
  - QUEENSGATE INSTRUMENT ON UARS/WIND II
  - HIGH TRANSMISSION ⇒ HIGH TEMPORAL RESOLUTION
  - MINIMUM POLARIZATION RESPONSE ⇒ 10^{-4} SENSITIVITY

- SIMPLE DESIGN
  - OPTICS (COMPACT AND UNCOMPLICATED)
  - SPECTRAL FILTER (MINIMUM NUMBER OF MOVING PARTS)
  - ACCESSIBLE FOCAL PLANE

- POLARIMETER TORQUE COMPENSATION
Additional Engineering Studies

Underway:

Mechanical design
Thermal analysis
Optical tolerance analysis
Low polarization coating design

Expecting Funding:

Low polarization coating prototype fabrication and test
Further polarization element refinement
How accurately can the transverse and longitudinal solar magnetic fields be measured?

Accuracy of Stokes vector measurements

Polarimeter accuracy

Instrumental polarization
Minimizing crosstalk between circular polarization and linear polarization in optical coatings.

Wavelength accuracy
Control of Fabrey-Perot etalon

Space-based wavelength calibration

Noise
Detector

Temporal fluctuations of solar irradiance
21.5

How is the standard deviation of the magnetic field measurements related to the following:

Detector noise

Accuracy of calibration

Polarimeter alignment

Telescope and folding mirror instrumental polarization

Calibration drift in orbit

Image mismatch, four corresponding pixels not having exactly the same instantaneous fields of view

Image motion during measurement

Averaging due to pixel size relative to small intense features,
Appendix 10.

Development of Method for Generating a 2x Lens Magnifier

A lens system was desired which when inserted in the magnetograph would increase the magnification by a factor of two, with a corresponding decrease in the field of view. The size of the image would remain the same, but the f/# of the light at the image would be increased by a factor of two. The entire primary mirror would still be used, but at one half the field of view. The Fabry-Perot would be illuminated with a telecentric beam the same size, but with half the angular bandwidth in each axis.

I realized that this 2x magnifier had the following paraxial implications. Consider first the chief and marginal paraxial rays which are tabulated in this appendix. Since the field of view has been reduced by a factor of two, we desire to reduce the height and angle of the chief ray by a factor of two from the front of the system through to the 2x magnifier. Exiting the magnifier, the chief ray should attain its initial values all the way to the image. This ensures the image size is unchanged. Similarly, the marginal ray height should be unchanged from the entrance to the system to the 2x magnifier. Following the magnifier, the marginal ray height and angles should be reduced to one half the initial values.

The system with the 2x magnifier will have one half the Lagrange invariant and one fourth the etendue of the 1x system without the magnifier.

Using these principals, I developed a graphical method on the y-ybar diagram to connect an incident beam with one half the chief ray, and an emerging beam with one half the marginal ray and find a family of thin lens solutions. One result was that there
were no one or two lens solutions to this problem. This explained the difficulties that Ron Eng and Mary Acree had been having in trying to optimize a 2x magnifier with two lenses.

I then developed one solution for the 2x magnifier using three thin lenses of focal lengths: 239 mm, -10 mm, and 33.5 mm. The attached paraxial ray trace shows that this system satisfies the 2x magnifier requirements. The "2x system to insert" table specifies the lens placements.