The Solar Bolometric Imager: Characteristics and Performance

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Overview

The Solar Bolometric Imager (SBI) is an innovative solar telescope capable of recording images in essentially total photospheric light. It has an angular resolution of ~5", sufficient to distinguish sunspots, faculae and enhanced network. These are the photospheric magnetic structures that so far are known to be linked most closely to irradiance variation.

The SBI detector is an array of 320 × 240 ferro-electric thermal IR elements whose spectral absorptance has been extended and flattened by a deposited layer of gold-black. The telescope is a 30-cm Dall-Kirkham design with uncoated primary and secondary pyrex mirrors. The combination of telescope and bolometric array provides an image of the solar irradiance with a flat spectral response between 0.28 \( \mu \text{m} \) and 2.6 \( \mu \text{m} \), over a field of view of 917" × 687", and a pixel size of 2.8". After a successful set of ground-based tests, the instrument is being readied for a one-day stratospheric balloon flight that will take place in September 2003. The observing platform will be the gondola previously used for the Flare Genesis Experiment project (FGE), retrofitted to house and control the SBI telescope and detector.

The balloon-borne SBI will provide the first bolometric maps of the photosphere, to evaluate the photometric contribution of magnetic structures more accurately than has been achievable so far, using spectrally selective imaging over restricted wavebands. More accurate removal of the magnetic feature contribution will enable us to determine whether other solar irradiance mechanisms exist besides the effects of photospheric magnetism.

The balloon flight will enable SBI to image over essentially the full spectral range accepted by non-imaging space borne radiometers such as ACRIM, making the data sets complementary. The SBI flight will also provide important engineering data to validate the space worthiness of the novel gold-blackened thermal array detectors, and to verify the thermal performance of the
Science Goals

The current models of the total solar irradiance variation show a 95% correlation with the changing projected areas of dark sunspot, bright faculae and network. However, it is still not known whether the photometric effect of sunspots, faculae and network is actually equal or simply proportional to the measured radiometric fluctuations. Uncertain broad-band photometric contrasts of spots, and especially faculae and network, currently present the main obstacle to improved modeling of total irradiance fluctuations. The bolometric contribution of faculae is currently uncertain by as much as a factor of two.

The SBI will provide the first opportunity to bolometrically image brightness variations at the solar photosphere. Its flat spectral response from the UV to the IR (like that of ACRIM) will directly provide the facular and network contribution to the total irradiance, and will complement the non-imaging space-borne radiometer measurements.

The 3 main objectives of the balloon-borne SBI are:

- To accurately measure (better than 10% per pixel) the bolometric contribution to the total solar irradiance of sunspots, faculae and enhanced network. Thus to help determine whether these structures can account for the rotational and 11-yr variability of the total irradiance, or whether other mechanisms highly correlated with their area variation might contribute significantly.

- To search for other lower level inhomogeneities in photospheric heat flux uncorrelated with the photospheric magnetic structures themselves, and possibly associated with large scale convective cells, meridional circulations, etc. Such inhomogeneities might prove more important over time scales longer than the 11-yr cycle.

- To provide important engineering data to validate the space flight-reliability of the novel gold-blackened thermal array detector and to verify the thermal performance of
Instrument Requirements

- Spectrally constant photometric response for optics and detector from 0.28 to 2.6 µm. This band pass contains ~ 96% of the total solar irradiance. The spectral response must be constant to better than ±10% over this spectral range.

- Repeatable, linear photometric response curve.

- The angular resolution in the NIR must be sufficient to resolve 10" structures. This is the characteristic size of the enhanced solar photospheric network, which is the smallest photospheric structure currently known to contribute significantly to the total irradiance variation.

- The telescope scattered light must be low enough to allow contrast measurements of better than ±10%.

- The balloon must fly at altitudes higher than 80 kft. (~ 24.5 km) to avoid molecular band absorption from the Earth’s atmosphere.

- Telescope and detector must be able to operate in a vacuum environment (pressure ≤ 4 mB) and within a temperature range from −50 °C to +70 °C.

- The telescope must be able to handle the solar heating.
Optical Design

ρ **Dall-Kirkham 30 cm Ø F/12.** This design is chosen to provide long focal length with a compact package, as required for a balloon flight.
  ρ Resolution: 0.2" at 0.28 µm, 2.2" at 2.6 µm.
  ρ Pixel size: 2.86 × 2.86 arcsec/pixel (for 50 × 50 µm pixels).
  ρ Field of view: 917" × 687" (for 320 × 240 pixels detector).

ρ **Primary and secondary made of bare (un-coated) pyrex.** Pyrex reflectivity has a good flatness across the required spectral range. The average reflectivity is ~ 4%.

ρ **Filter wheel with 5 selectable filters:**
  ρ 4 Inconnel-coated ND filters at or around ND 1. ND 1 is the calculated required attenuation to limit the total energy input on the detector to 1 mW/cm². Possibly during flight a slightly different attenuation will be required because of the different conditions at float altitude.
  ρ 100 Å band-pass filter centered at 3900 Å for Ca K observations.

ρ **Fused quartz vacuum window** on the detector.
ρ **Telescope materials and mechanisms are vacuum compatible.**

Schematic of the optical system.

Net optical system transmission, calculated from measured values for the individual components: two un-coated pyrex mirrors, one ND 1.0 filter, and one fused quartz detector window.
**Imaging Bolometer Characteristics**

- **Array of 320 × 240 Barium Strontium Titanate (BST) ferroelectric detector elements.**
  - Pixel size: 50 × 50 µm.
  - On-chip thermal regulation to BST Curie temperature (~ 30 °C).
  - Senses by pyroelectric and dielectric effects.
  - AC coupled \( \Rightarrow \) requires an optical chopper (Archimedes Spiral).
  - Maximum accepted input irradiance: 1 mW/cm².

- **Detector array covered with a thin film of gold black.**
  - Spectral absorptance of gold black films vary less than 1% from 0.2 µm to beyond 3 µm.
  - Spectral energy distribution absorbed radiation is redistributed by the gold black in form of thermal emission and is detected by the thermal IR BST imaging array.
  - The thin uniform coating retains ~ 70% of the original detector MTF.
  - The response of the resulting detector is uniform from UV to beyond 10 µm.

300-1600 nm percent hemispherical (diffuse + specular) spectral reflectance plot of the gold black film. The flat spectral response continues well beyond 10 mm. Courtesy Jose Rice, NIST Gaithersburg.

Gold-blackened Raytheon BST detector array with fused quartz window.
Photometric Precision

- Less than 1.5% non-linearity over a 45 dB dynamic range. It includes the irradiance level at the SBI solar plane.

- 1% RMS gain drifts measured over several hours with camera viewing uniform scene.

- 3 - 4% RMS day to day gain repeatability under a variety of illumination conditions.

Mean detector response (in a $50 \times 50$ box) as a function of illumination intensity over linear response range of detector output. Response becomes sub-linear for intensities (irradiance) greater than $\sim 1.4 \text{ mW/cm}^2$.

Camera

- Gold blackened array
- Chopper (rotating frequency = 60Hz)
- Archimedes spiral (shutter)
Observing Platform (gondola)

- **Same gondola previously used for the Flare Genesis Experiment project (FGE)**
  - Frame bolted together from standard aluminum angle. The structure is strong enough to support the 4400-lb weight of the instrumentation even under a design load of 10 g, and is rigid enough to allow stable pointing to at least 10".
  - Proven design: The gondola already successfully endured one test flight in New Mexico (1994), and two Antarctic Flights (Jan 1996: 21 days at float altitude, Jan 2000: 17 days). During the past 8 years the gondola and its subsystems have undergone many improvements and upgrades.

- **Alt-azimuth Telescope mount:**
  - Telescope mounted to the gondola on its elevation axis.
  - Azimuth pointing achieved by turning the gondola using a reaction wheel.

- **Pointing system:** Same as one used for FGE. Transition from lower accuracy to high accuracy pointing.
  - **Track state 1:** four photodiode sensors mounted at 90° intervals around the gondola for coarse orientation of the gondola in azimuth.
  - **Track state 2:** two linear position-sensors with cylindrical lenses, mounted parallel to elevation and azimuth. FOW: ±20°, accuracy ~ 0.25°.
  - **Track state 3:** 5 cm Ø refracting telescope projecting a 1cm diameter solar image onto a lateral-effect diode (LED). An aluminum disc at the center of LED occults 90% of the solar image to improve the sensitivity. FOW ±1°, accuracy ~ 0.05" RMS when Sun is at the center of LED.
  - An x-y motion stage moves the LED in the image plane of the guiding telescope to provide offset pointing of main telescope with respect to the Sun center.
  - Pointing accuracy: ~ 10".
  - Predicted jitter: ~ 1" RMS or better.
Two Main computers (ATX motherboard 1GHz Pentium III):
- Command, Control & Communications (CCC).
- Digital Acquisition Computer (DAC).

Computers and other commercial electronics housed inside 1 atm pressurized vessels.

Gondola powered only by batteries.

Images stored on board in four 20 GB hard drives (high shock type).

Communications to/from ground via redundant UHF radio links. (gondola always in line of sight).

Capability to send commands from the ground, as well as to run the instrument in fully autonomous mode.

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**SBI System**

- APV = CCC Pressure Vessel
- CCC = Command Control Computer
- MPV = MAX3 Pressure Vessel
- MAX3 = Subsystems Control Interface Processor
- RF = Up/Downlink transcievers
- MTU = Momentum Transfer Unit
- DPV = Digital acquisition computer Pressure Vessel
- FW = Filter Wheel
- GSE = Ground Support Equipment
- GUI = Graphic User Interface
- CIP = Consolidated Instrument Package (provided by NSBF)
- NSBF = National Ballooning Facility (NASA)
Telescope Mount With Passive Damping System

- Isolates high frequency jitter of gondola from telescope.
- Spring-mass-damper system.
- 2 cages (inner and outer) mounted on flex-pivot spring supports. A flex-pivot is a weak torsional spring but capable to sustain strong transversal and longitudinal forces.
- Oscillation passively damped with eddy current: A copper conductor moves between strong permanent magnets. The interaction between the electrons in the conductor and the external magnetic field generates a force opposite to the velocity of the conductor.
Flight Profile

1) **Launch:** Beginning September 2003 from Palestine (TX), at sunrise (~6:00 local time).

2) **Ascent:** Until gondola reaches float altitude threshold (~25.0 km). Pointing turned off. Duration: ~2 h, from ~6 am to ~8 am.

3) **Engineering & Calibrations:** Pointing calibration and stabilization. Focus calibration. Detector calibration. Acquisition of flat field. Duration ~1.5 h

4) **Observing program:** (from ~9:30 to ~11:35)
   - Acquire full disk mosaic in total light. 10 tiles. Each tile is the average of ~30 frames
   - Acquire full disk mosaic with Ca K filter (100 Å passband centered at 3900 Å).
   - Repeat the above.

5) **Noon occultation:** From ~11:35 to ~13:05 the Sun elevation is above 53° and the telescope is in the shadow of the gondola mezzanine. The observing program is interrupted and the pointing is turned off.

6) **Afternoon observations:** (~13:05 to ~18:10)
   - Turn pointing back on.
   - Redo focus calibration & flat field.
   - Resume observing program.

7) **Flight termination:** Stop observing program. Turn off pointing & stow telescope. Shut down computers & hard drives. Shut down power.

**Flight duration:** ~12 h 10 m

**Observations duration:** ~7 hours

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![Mosaic of the Sun](image)
Data Reduction

- Flat field correction & de-rotation.
- Form full disk images from mosaics. Optional: co-add frames taken in all repetitions during flight to reduce noise.
- Remove photospheric limb darkening.
- Measure photometric contrast of sunspots and calculate the deficit in total irradiance caused by their presence.
- Identify faculae and network from narrow band images. Measure their contrast and calculate the increase in total irradiance due to their presence.
- Remove sunspots, faculae and network from disk images and search for additional photometric inhomogeneities.

Data Products

- Full disk broad band images of the photosphere, with spectrally uniform response over the range 0.28 – 2.5 μm (~ 96% of the solar total irradiance), and an angular resolution of ~ 5".
  - Objective: 0.1% photometric precision relative to the mean disk intensity at each pixel
    ⇒ photometric contrast \( \text{Is/Ip} \) can be measured to better than 10% accuracy (\( \text{Is} = \) intensity of a structure, \( \text{Ip} = \) mean intensity of photosphere).
  - No requirement for absolute accuracy on time scales much longer than the duty cycle of recording one mosaic (tens of minutes).
- Narrow band images (100 Å band pass centered at 3900 Å) of the same scene showing bright magnetic structures with higher contrast than in wide band.
  - The above images will be used to:
    - Create maps of the photometric contrast, \( \text{Is/Ip} \), of spots, faculae and network, relative to the photosphere, in wide band light.
    - Search for other brightness inhomogeneities at the photosphere.
Sun imaged in total light on September 24, 2002. The images were obtained by overlapping 10 bolometric frames recorded with the SBI detector and telescope during ground test observations at APL. A) Mosaic before removal of the limb darkening. B) After limb darkening removal. Sunspots and faculae are clearly visible. Some artifact are also present. They are mostly due to imperfect flat fielding. The spatial resolution is about 5 arcsec. West is approximately towards the upper left corner and north towards the lower left corner.
Total light profile across a sunspot and a few faculae. The photometric signal is calculated relatively to the average disk intensity (as measured by the SBI bolometer). The different profiles correspond to relative intensities for a single frame (1/30th second integration), a 30 frames average (1 second), and a 300 frames average (10 seconds). The inset plot shows an expansion of the intensity scale of the right side of the scan (crossing two faculae). Weak intensity structures as small as 10\" in size of are clearly resolved. A comparison between the plots with different integration times shows little or no difference between the 1 second and the 10 seconds averages. The pixel to pixel RMS noise is 0.6% of the photometric signal for a single frame, 0.2 % for a 1 second exposure average, and 0.05% for a 10 seconds exposure average. The tests demonstrate that the SBI prototype can achieve the required precision of better than 10% already with a single exposure. A 1 second exposure is sufficient to resolve all the intensity structures thought to contribute to the total Solar irradiance.