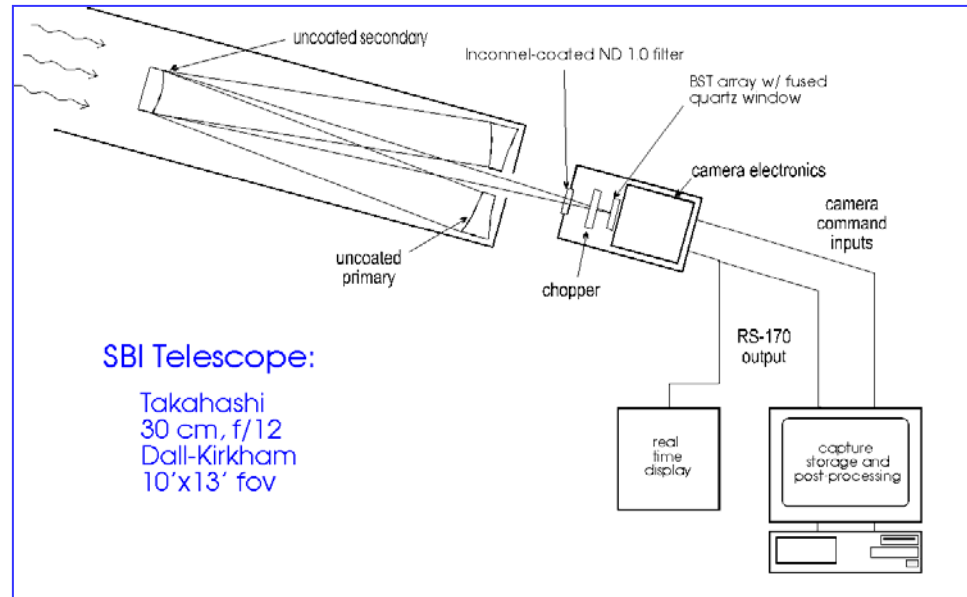


Total Light Imager with Flat Spectral Response for Solar Photometric Measurements



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Abstract

The Solar Bolometric Imager (SBI) is a novel solar imaging system optimized for studying mechanisms of total irradiance variation. Uncertain broad-band photometric contrasts of spots, and especially faculae and network, currently present the main obstacle to improved modeling of total irradiance fluctuations. After 20 years of effort, accurate contrasts remain elusive because the photometric response functions of conventional camera and telescope systems are highly wavelength dependent, and difficult to remove from measurements of structures having non-black-body radiance distributions. The SBI can provide the required data in a single image because it has the same spectrally “flat” (i.e. constant) photometric response as pyrhelimeters such as ACRIM over the wavelength range between approximately 0.28 μm and 2.6 μm , containing over 96% of the total solar irradiance. The prototype SBI system at CRI utilizes a 80,000-element uncooled thermal imaging array whose spectral absorptance has been flattened by gold-blackening. We use a 30 cm-aperture Dall-Kirkham design with bare glass primary and secondary mirrors to provide uniform spectral response, and to avoid solar heating and saturation of the imager. The image quality (<3” resolution over a 13’ X 10’ FOV) is very satisfactory for our purpose of accurately discriminating the total irradiance contributions of photospheric magnetic structures, such as spots, faculae and network from other possible solar heat flow inhomogeneities. We are currently redesigning the (commercial) camera electronics to improve calibration accuracy for an eventual balloon-borne experiment. We expect the improved accuracy provided by the SBI to significantly improve the constraints on possible slow changes in solar irradiance that may drive secular climate variations.

The Solar Bolometric Imager (SBI) will complement space-borne radiometer measurements with an ability to bolometrically image brightness variations at the solar photosphere

Science Goals:

- **Accurate (better than 10%) measurement of bolometric contribution of both sunspots and faculae (facular value is currently uncertain by as much as a factor of two)**
- **Removal of magnetic structure contribution from radiometer measurements to determine whether long-term variations occur by mechanisms other than the changing projected area of sunspots, faculae, and network**

SBI Specifications

• **Spectrally constant (ie 'flat') photometric response for optics & detector from 0.28-2.6 μ m (this bandpass contains ~96% of total solar irradiance)**

- Select optics for flat net system spectral response and image brightness control
- Bolometric imager: 320x240 ferro-electric array with spectrally flat gold-black coating applied by CRI

• **Repeatable, linear photometric response curve**

- Modify commercial 8 bit camera for ground-based prototype
- Develop custom 10-12 bit camera for eventual balloon-borne experiment

• **Angular resolution better than 5" at all θ 's (~spatial extent of smallest photospheric structures with measurable contribution to total irradiance)**

- Ground-based prototype telescope
 - 30 cm, F/12 telescope, 2.4" per pixel
 - 13' x 10' fov (~1/6 of solar disk)
 - evaluate scattering off uncoated telescope optics
- Minimize detector MTF degradation due to gold black coating

• **No solar heating issues**

Sensor Development

CRI has developed technique for deposition of gold-black on ferro-electric arrays

- 100% active pixel coverage
- no shorting of peripheral circuits
- thin uniform coatings that retain ~70% of original detector MTF
- flat spectral response from UV to beyond 10 μm

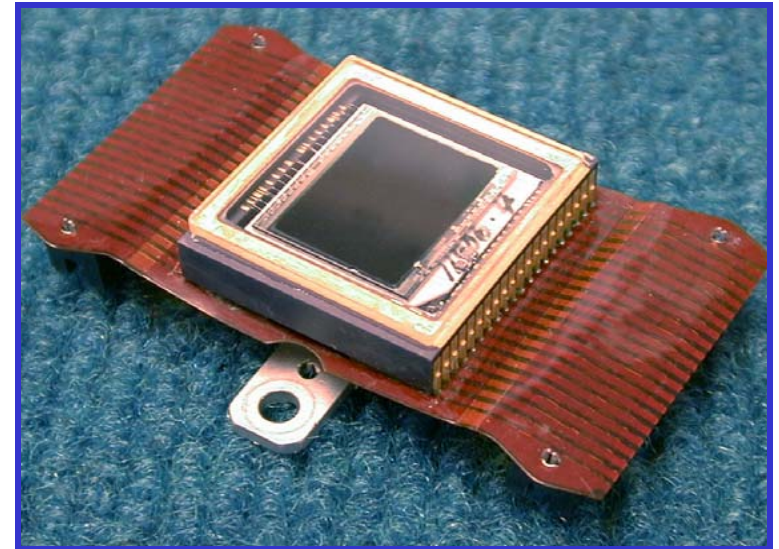
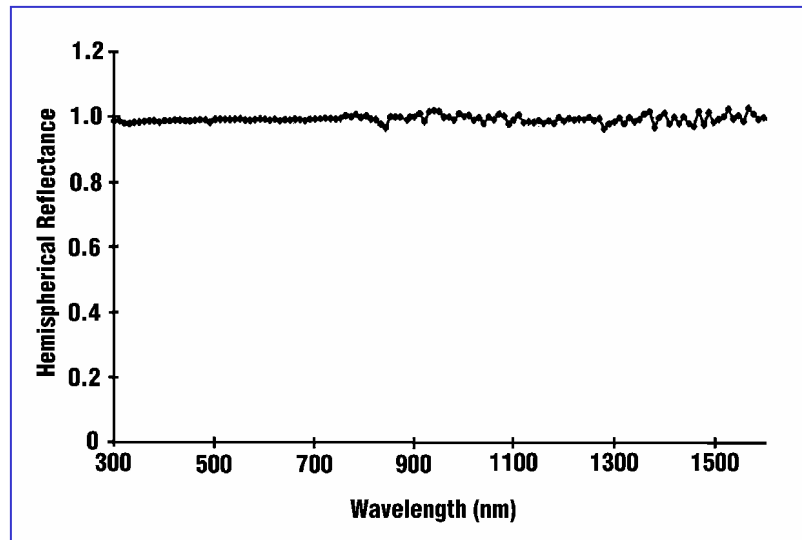


Figure Captions

Gold blacked detector array with fused quartz window (above)

300 nm-1600 nm hemispherical spectral reflectance curve (left). The flat spectral response of gold-black continues well out beyond 10 μm (Joe Rice, NIST Gaithersburg, private communication)

Optical Configuration

An optical configuration consisting of uncoated Pyrex primary and secondary mirrors with an Inconel-coated ND filter and fused quartz detector window was chosen to attain:

- flat system spectral response (+/- 7% variation between 280 nm and 2600 nm)
- attenuation of solar irradiance to levels acceptable to SBI detector (less than $\sim 1.4 \text{ mW/cm}^2$)

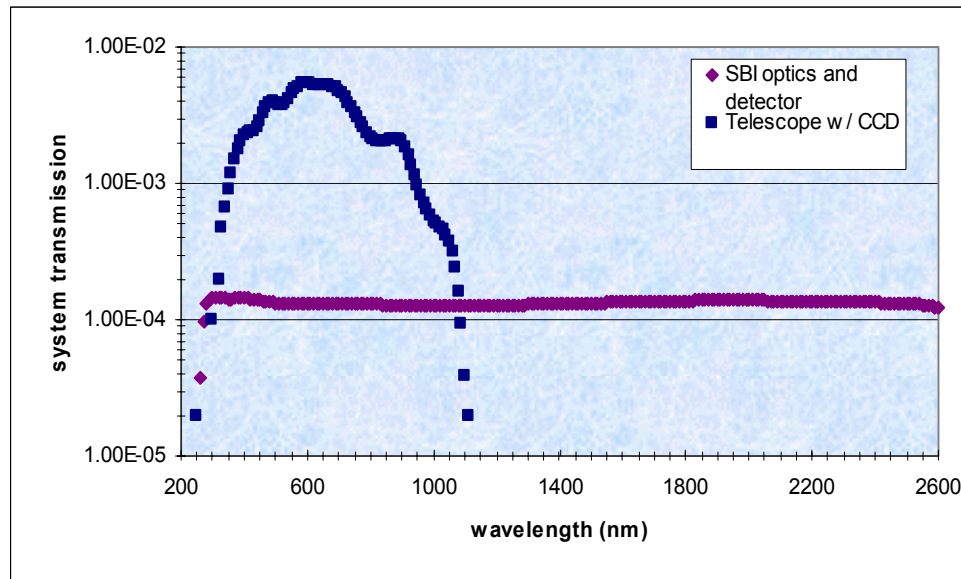
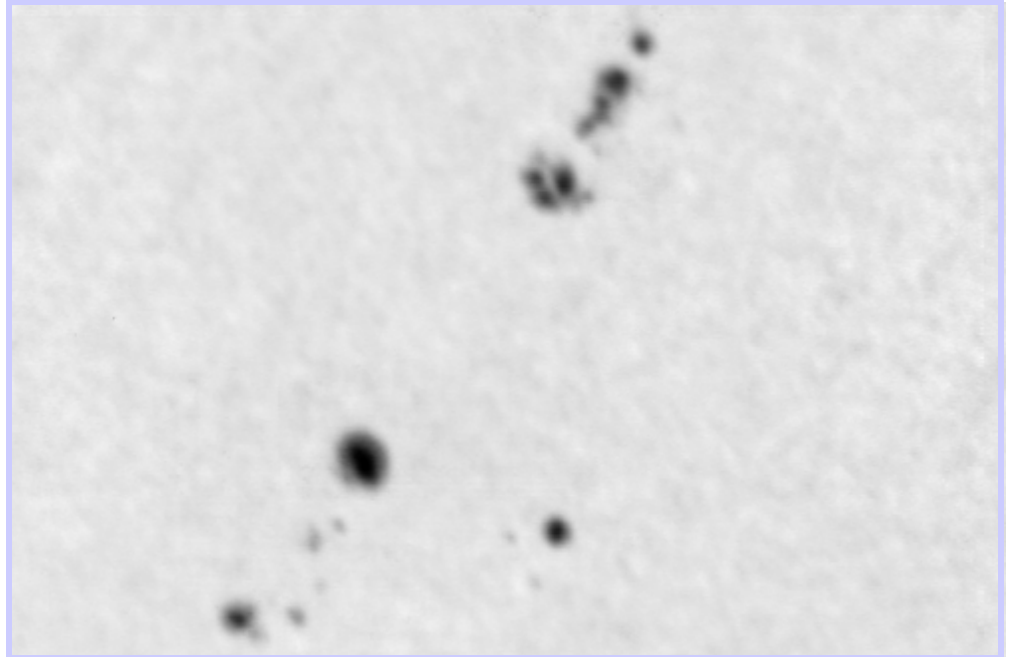
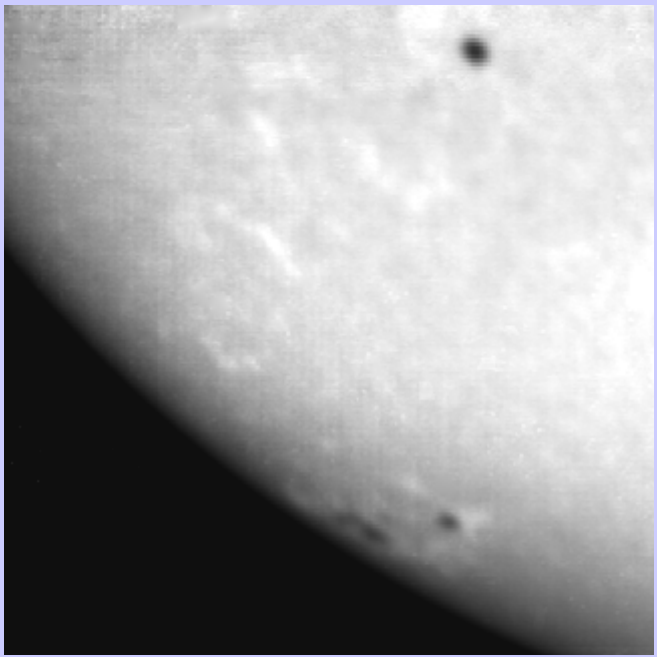


Figure Captions:

30 cm, F/12 commercial Dall-Kirkham telescope with bare Pyrex mirrors used for ground-based testing of the SBI concept (above).

SBI system spectral response compared against spectral response of typical telescope with Al-coated mirrors and CCD detector scaled by .01 for display purposes (left)

Observations with the Solar Bolometric Imager



Images of sunspots and bright faculae near the sun's limb (left) and of a sunspot group near the disk center (right); demonstrating the SBI's excellent image quality. The images were obtained with a gold-blackened ferro-electric detector array and the ground-based SBI prototype telescope on 9/13/99. Each final image consists of four captured images (each the average of 10 video frames) with the telescope pointed at four slightly different positions on the sun, individually flat-fielded, and then co-added. The scale on both final images is $\sim 5.5''/\text{mm}$.

Image Quality

- Larger sunspots (>15" dia.) measured with contrast $((I-I_0)/I_0)$ of 65%
- Small spots (~7.5" dia.) measured with contrast of ~40%
- Enhanced network structures (~15" extent) measured with S/N of 5:1

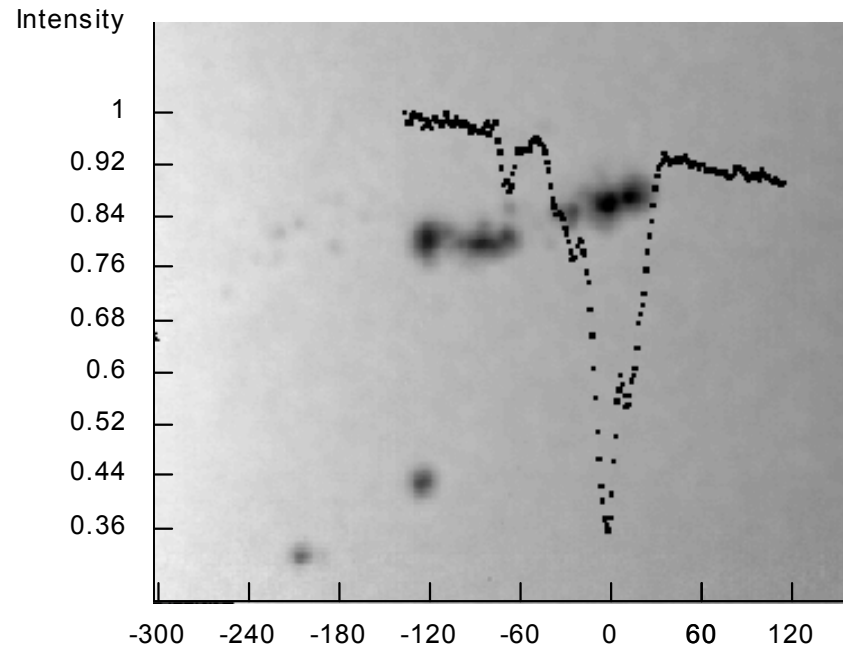


Image of sunspot group obtained with SBI on 11/22/99 with sunspot intensity overlay for darkest spot. The contrast obtained with the SBI is comparable to white light CCD images of the same structures on the same day from the Mees Observatory on Mauna Kea

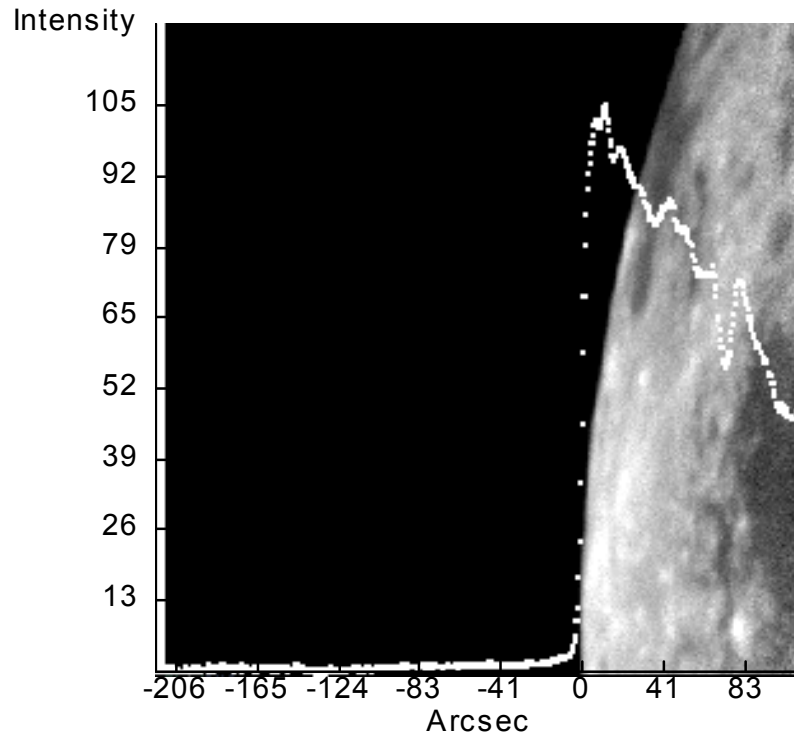
Scattering

Back surface reflections from the uncoated SBI telescope optics resulted in scattering no greater than in solar tower telescopes such as the McMath Telescope at Kitt Peak

- **1.5% scattering**
40'' off-limb

Stellar imagery shows no evidence for ghost images (due to backsurface reflections)

- **<2% (upper limit)**



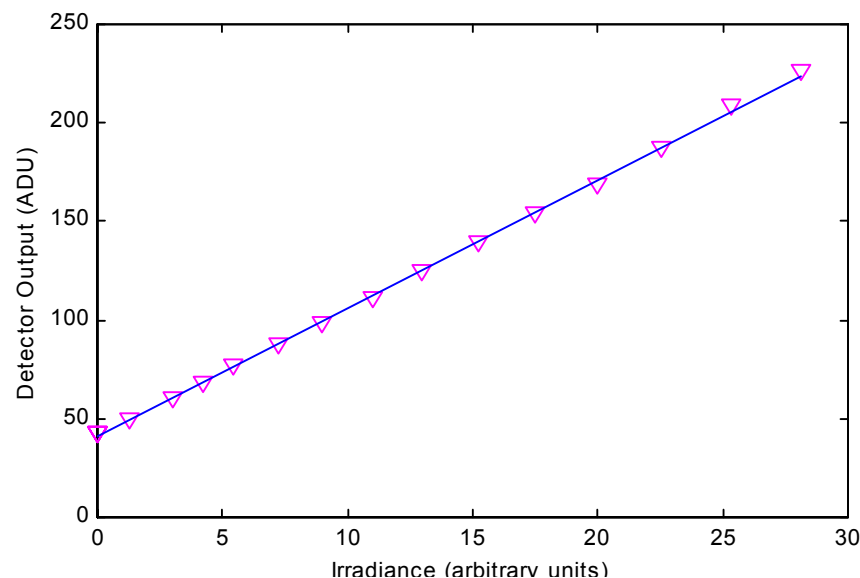
White light image of lunar limb obtained with CCD camera and SBI telescope with intensity profile overlay. By using the lunar limb we obviated the need for ND filters whose scattering may have reduced the accuracy of the scattering measurement

Photometric Precision

Less than 1.5% non-linearity with modified detector readout over a 45 dB dynamic range which includes the irradiance level at the SBI focal plane

1% RMS (2.3% pp) gain drifts measured over several hours of operation with camera viewing uniform scene

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



Mean detector response (in a 50x50 box) as a function of illumination intensity over linear response range of detector output. Response becomes sub-linear for intensities greater than those shown on plot (irradiance greater than $\sim 1.4 \text{ mW/cm}^2$)

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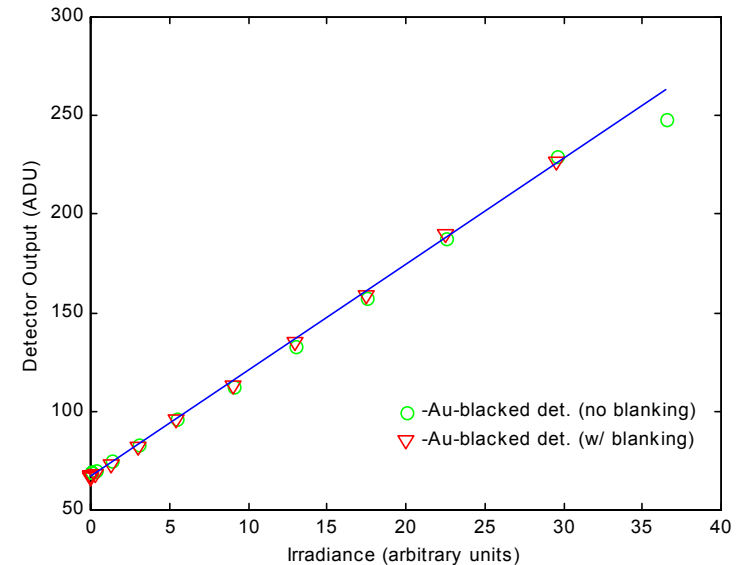
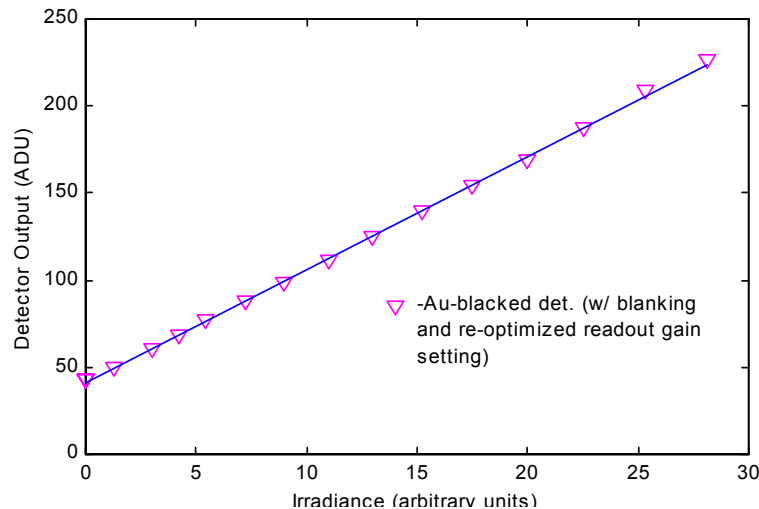


Figure Captions

Mean detector response (in a 50x50 box) as a function of illumination intensity over linear response range of detector output (above). Data were obtained with the array uniformly illuminated (no blanking), and with the array partially blanked off to simulate observation of the solar limb. Response becomes sub-linear for intensities greater than 30.

More detailed detector response curve with gain optimized for linear response regime (left)

Summary

The SBI's novel optical system combined with modifications made to a commercially available uncooled IR imager (the first such use for astronomical applications) has resulted in an instrument that meets all of our requirements for the study of mechanisms of total solar irradiance variation:

- flat spectral response from the UV through IR
- better than 3" angular resolution
- acceptable scattering (<2% 40" off-limb)
- linear and reproducible detector response
- negligible solar heating

Work continues on a camera utilizing the latest generation ferro-electric detectors for an eventual balloon-borne experiment. Balloon flight of the SBI is necessary to avoid the most serious atmospheric absorption bands due to water vapor and CO₂; useful measurements could be obtained from a short-duration flight, and the full potential of the SBI would be realized with a long-duration underflight of a spaceborne pyrhelimeter.