Long-Term Stability of the Photometric Calibration of the STEREO HI-1 Heliospheric Imagers

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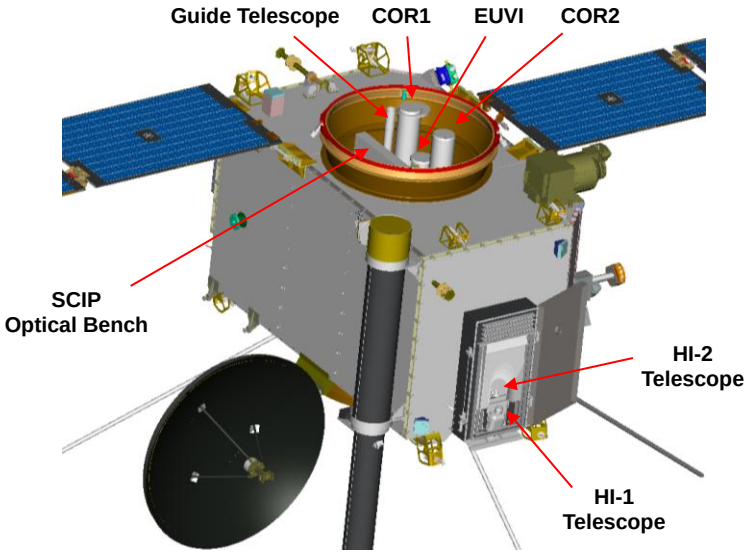
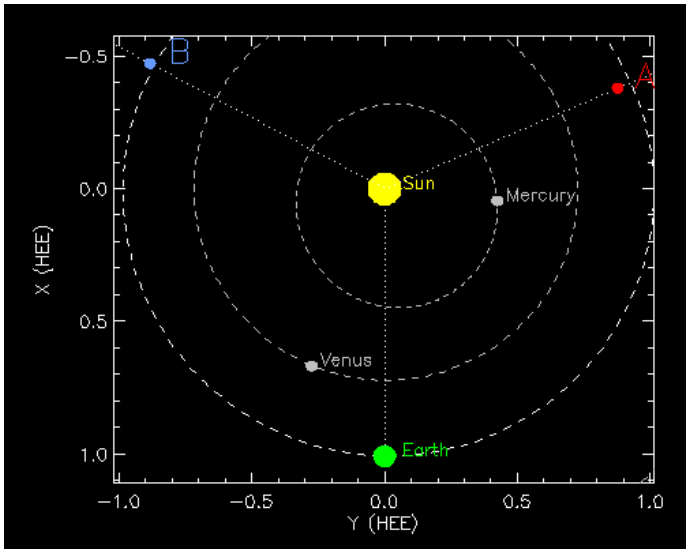
The STEREO Mission





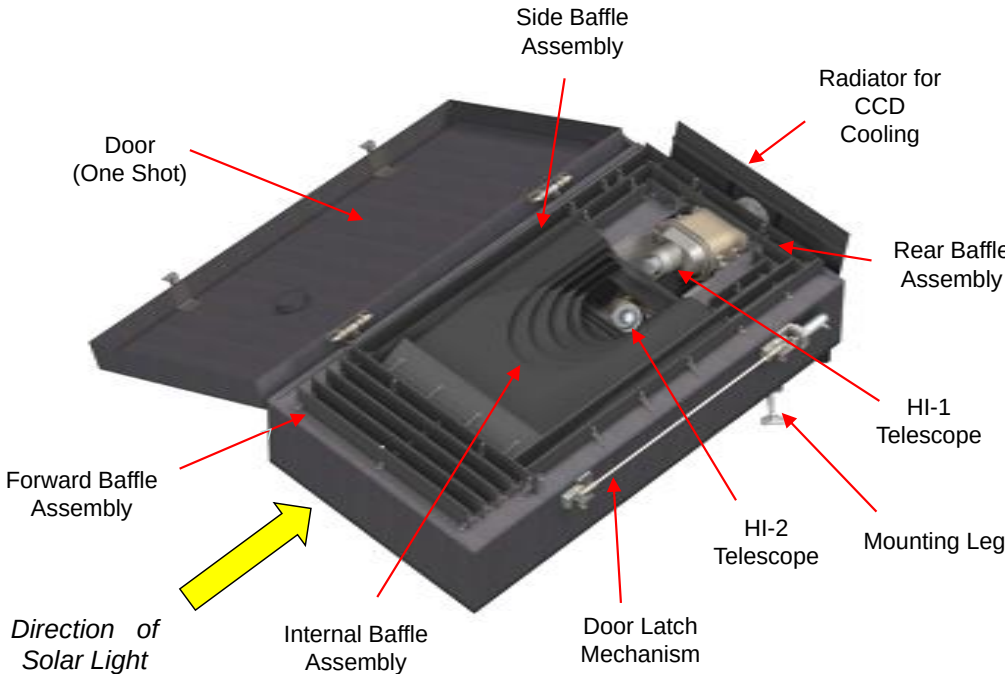
- SECCHI instrument suite (Howard et al, Space Sci Rev, 2008)
  - COR-1
  - COR-2
  - EUVI
  - **HI-1** and HI-2

- Launch 26 Oct ‘06
- STEREO-A h’centric insertion 15 Dec ‘06
- STEREO-B h’centric insertion 21 Jan ‘07
- Science operations began Mar 2007

The Heliospheric Imagers

- 2 deeply-baffled white-light imagers
  - Conventional refracting optics using rad-hard glass
  - CCD cooled to < -70ºC
  - Single-shot door / no other mechanisms

	HI-1	**HI-2**
Axis offset from Sun	14.0º	53.7º
FOV radius	20º	70º
Elongation range	4º – 24º	18.7º – 88.7º
	15 – 90 R_o	70 – 330 R_o
CCD pixel size	35"	2'
Science image array	1024 x 1024	1024 x 1024
Image bin size	70"	4'
Spectral band-pass	630-730 nm	400-1000 nm
Summed image cadence	40 min	2 hr
Brightness sensitivity	3 x 10^{-15} B_o	3 x 10^{-16} B_o
Stray-light rejection	3 x 10^{-13} B_o	10^{-14} B_o



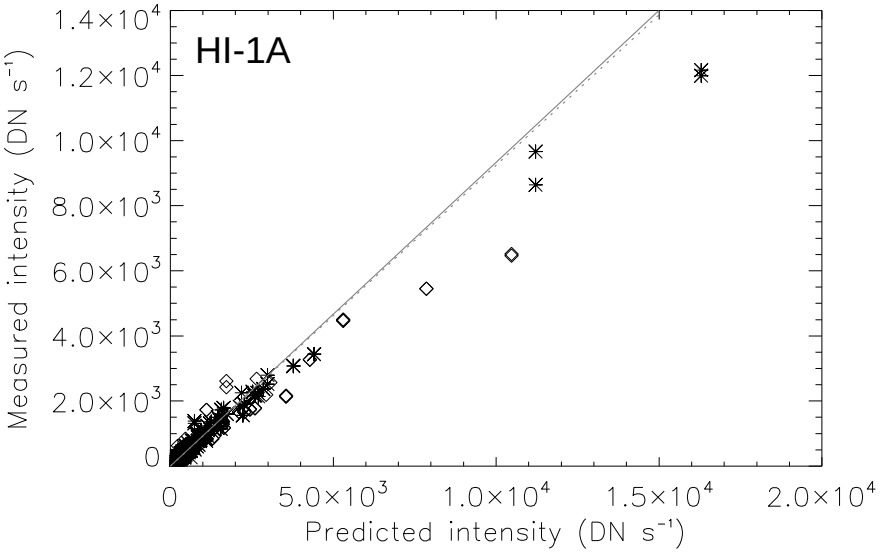
Eyles et al, Solar Phys. 2009

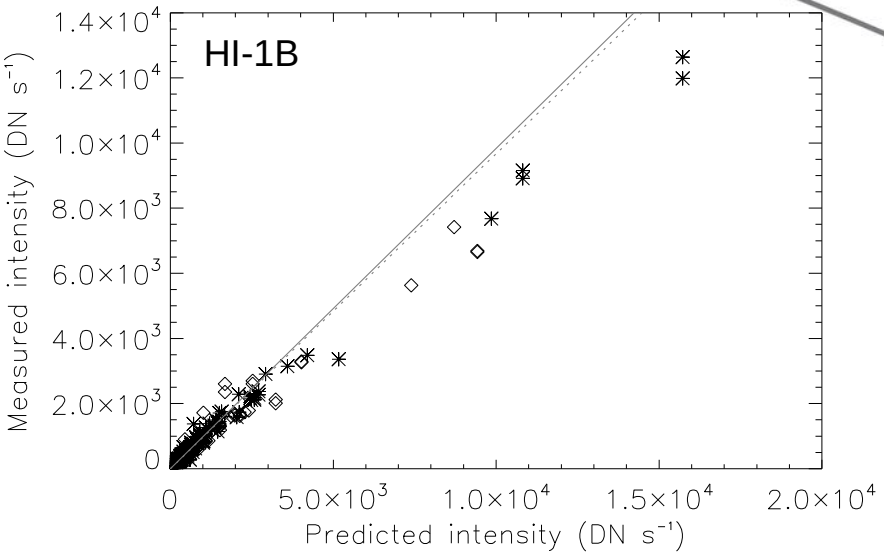
Initial Photometric Calibration of HI-1*

- Used data up to Dec 2008
- Observed intensity of well-isolated stars with R magnitude ≤ 12 within 100 pixel radius of centre of FOV measured by aperture photometry
  - Stars used listed in NOMAD catalogue (Zacarius et al, 2004) and are of known spectral type
  - Measured intensity calculated from at least 18 observations
  - Variable stars eliminated (top 25% of standard deviations)
- Predicted intensities calculated by folding standard stellar spectrum (Pickles, 1998) for spectral type through optimum model of instrument response function
  - $C_{pred} = (A/G) \int (\lambda/hc) S(\lambda) T(\lambda) QE(\lambda) d\lambda$ (in DN s^{-1})
    where A is aperture and G is camera electronics readout gain (e^- per DN)
  - Model of instrument response based on pre-flight calibration of filter responses, CCD manufacturer's QE data, glass transmission data, etc
- Plotted measured intensity versus predicted intensity for large population of stars

* Bewsher et al, Solar Phys. **264**, 433, 2010

Initial Photometric Calibration Results





- Fitted a straight line $I = \mu P$, where μ is a correction factor to give the calibrated response
  - Outliers at high intensities (due to saturation effects) have negligible effect on overall fit and value of μ
  - μ values close to 1.0
  - No significant difference in μ with spectral type – confirming validity of model of instrument spectral response

Initial Photometric Calibration Results *(cont)*

	Number of stars	μ value
HI-1A	903	0.93
HI-1B	541	0.99

- Residual deviation from 1.00 due to unknown systematics, e.g.
  - Absolute value of optics/filter transmission
  - Absolute value of CCD QE
  - Camera electronics readout gain
  - etc
- Also derived an improved large-scale flat-field correction from measured/ predicted response for stars crossing each pixel of image then averaging and smoothing.

Stability of HI-1 Photometric Calibration*

- Initial photometric calibration used data from Jan 2007 to Dec 2008
- Repeated the analysis for each complete orbit of STEREO spacecraft

	Orbit 1	Orbit 2	Orbit 3	Orbit 4	End Orbit 4
HI-1A	28 Mar 07	28 Feb 08	6 Feb 09	17 Jan 10	26 Dec 10
HI-1B	28 Mar 07	14 Apr 08	8 May 09	1 Jun 10	24Jun 11

	Orbit 1	Orbit 2	Orbit 3	Orbit 4	Overall
HI-1A	0.926	0.933	0.927	0.930	0.929
# stars	430	418	433	424	1705
HI-1B	0.998	0.987	0.989	0.993	0.991
# stars	387	384	455	417	1643

- Conclude that long-term stability of photometric response of HI-1 is better than 1%.

* Bewsher et al, Solar Phys. **276**, 491, 2012

Validity and Stability Flat-Field Correction

- Repeated the analysis for different regions of the FOV after applying the flat-field correction for HI-1A:

FOV Region	Orbit 1	Orbit 2	Orbit 3	Orbit 4	Overall
0 – 100	0.925	0.933	0.927	0.931	0.929
0 – 500	0.938	0.940	0.935	0.931	0.936
All	0.935	0.940	0.936	0.930	0.935
100 – 300	0.934	0.939	0.941	0.931	0.939
300 – 500	0.940	0.942	0.936	0.932	0.937
> 500	0.944	0.950	0.946	0.943	0.946

- Value of μ varies by ≤ 1% across 4 orbits for each FOV case
- Value of μ varies by < 2% between the different FOV cases
- Some indication that increases from centre of FOV to outer regions

Validity and Stability Flat-Field Correction

- Results for HI-1B:

FOV Region	Orbit 1	Orbit 2	Orbit 3	Orbit 4	Overall
0 – 100	0.998	0.986	0.988	0.993	0.991
0 – 500	1.002	1.001	1.001	0.997	1.000
All	0.999	1.000	0.994	0.992	0.996
100 – 300	1.011	1.014	1.014	1.009	1.012
300 – 500	1.001	0.998	1.002	0.997	0.999
> 500	1.004	1.004	0.999	0.999	1.001

- Value of μ varies by ≤ 1% across 4 orbits for each FOV case
- Value of μ varies by ≤ 3% between the different FOV cases
- No indication that μ increases from centre of FOV to outer regions

Conclusions

- From the start of mission science operations until the end of the 4th complete orbit (26 Dec 2010 and 24 June 2011 for STEREO A and B, respectively) the photometric response of the HI-1 instruments has remained stable to 1% or better.
  - Thernisien et al (2006) found LASCO-C3 degraded by 3.5% over 8 years of operation
  - Llebaria et al (2006) found LASCO-C2 degraded by 0.7% per year
- Value of μ varies by ≤ 3% between the different FOV cases, with ≤1% change over 4 orbits
- Updated overall values for μ and conversion to Mean Solar Brightness (folding through response a standard solar spectrum – Neckel and Labs, 1984)

	Initial μ value	Updated μ value	Initial B_o per (DN s^{-1} pix^{-1})	Updated B_o per (DN s^{-1} pix^{-1})
HI-1A	0.93	0.94	8.99×10^{-14}	8.89×10^{-14}
HI-1B	0.99	1.00	9.04×10^{-14}	8.86×10^{-14}