Characterizing Chromatic Effects in Small Star Trackers

Ryerson University

Sinclair Interplanetary

Tom Dzamba (tdzamba@ryerson.ca), John Enright (jenright@ryerson.ca), Doug Sinclair (dns@sinclairinterplanetary.com)

Full paper included in the conference proceedings (SSC16-P2-01)

1. Overview

- How does star color affect the design, calibration, and operation of star trackers?
- Key steps:
  - Build effective star catalogs (populate with the *right* stars)
  - Characterize performance of designs and specific sensors.
  - Correct bulk effect with per-star focal length offset.
  - Up to 15% RMSE error reduction in data collected from on-orbit sensors.

2. Motivation and Objectives

- Star trackers are sensitive to color of incident light. Two primary effects:
  - Dim stars harder to see due to a color dependent change in the size of the star image, and
  - Attitude determination affected by color dependent change in the position of the star.
- Paper presents strategies to characterize, validate, and optimize the performance of satellite instruments.

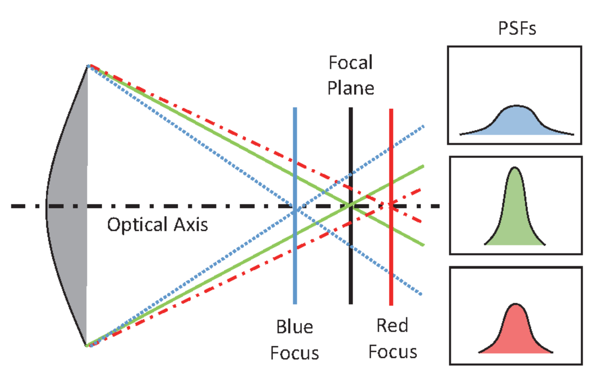

Figure 1: Axial chromatic aberration. On-axis effect that causes a color-dependent change in star size and shape.

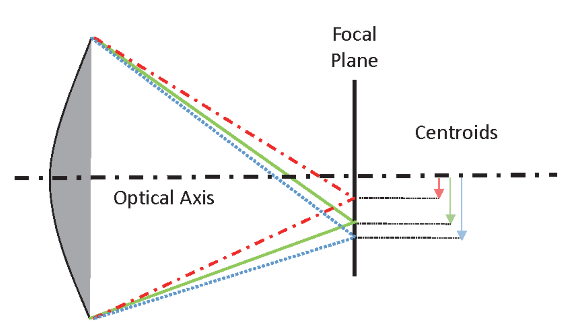

Figure 2: Lateral chromatic aberration Off-axis effect that causes a color-dependent change in star position

3. Stellar Spectra and Classification

- Stellar spectra are classified by:

  Type (O,B,A,F,G,K,M)/**subtype** (1-10), which denote the temperature of the star, and

  Luminosity (I-VII), a measure of the stars intrinsic brightness.
- Photometric systems (e.g., UBVRI) measure a star's irradiance in different spectral passbands.
- Color Indices (e.g., B-V) capture relative irradiance between passbands and can describe broad spectral features.

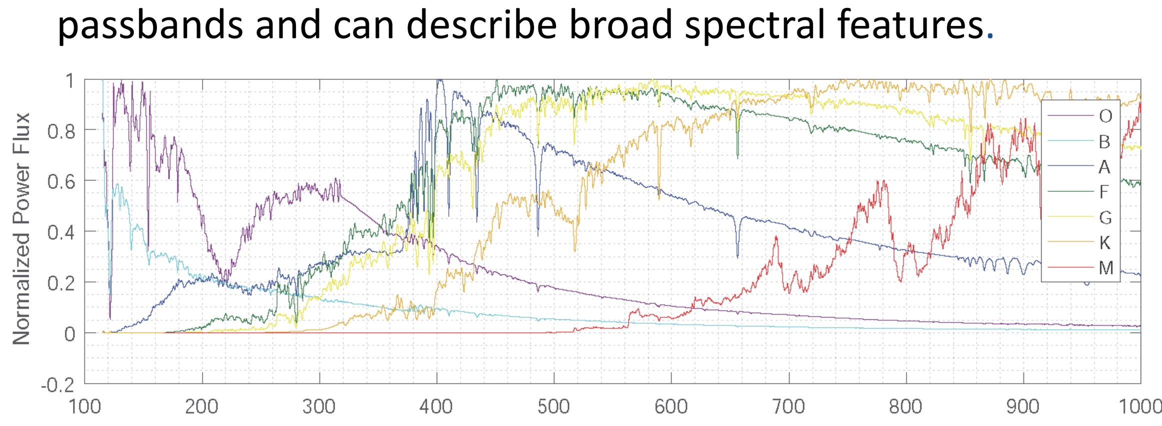

Figure 3: Example spectra for each Morgan-Keenan spectral type. Because star trackers are not spectroscopic instruments, only broad spectral features impact performance.

4. Star Catalogs

- Star catalogs are populated to ensure sufficient star detections in every scene.
- Predicting per-star sensor response is difficult prior to launch. Ground observations affected by seeing and reddening.
- Our approach calculates a composite magnitude that better represents observable star intensity (Figure 4).
- Predictions must include:
  - Spectral characteristics of the detector (QE)
  - Spectral characteristics of the lens (ACA, Focus)
  - Some measure of star brightness (e.q. Vmag)
- Orbital data can be used to refine predictions.

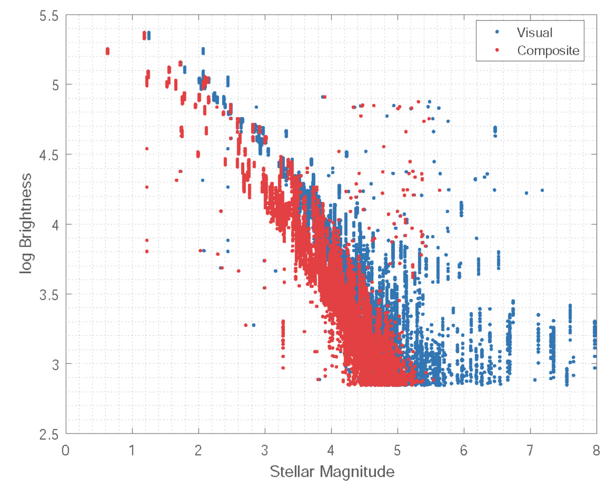

Figure 4: Effectiveness of composite stellar magnitude

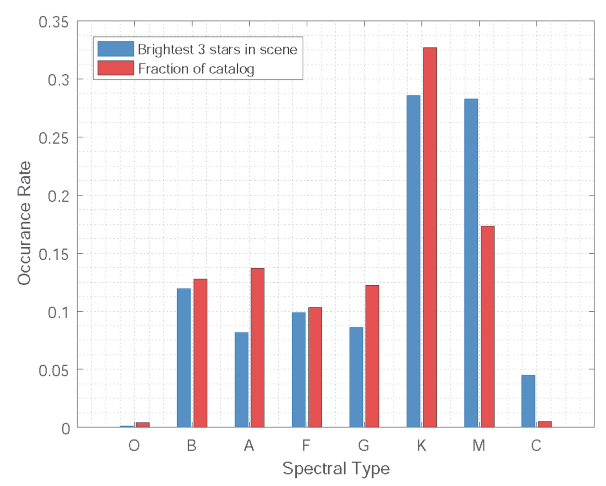

Figure 5: Occurrence rate of each MK spectral type.

5. Lens Characterization

- Chromatic aberration has two primary effects:
  - Image-level: change in star size and shape
  - Calibration-level: change in star position
- Knowing the magnitude of these effects is useful in many stages of star tracker design.
- Lab-based characterization compares response using a motorized gimbal, a broadband star source, and a set of 5 color filters (see Table 1).

Image-Level Analysis:

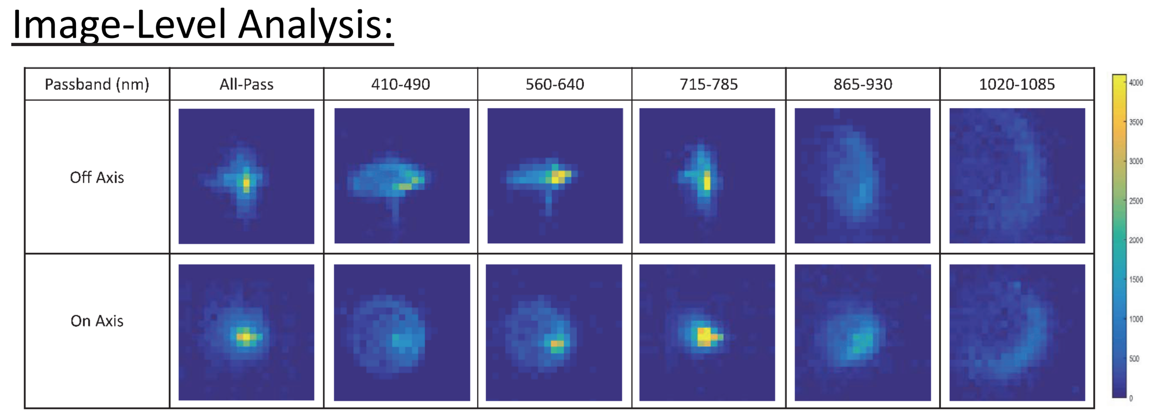

Figure 6: Examples of ST-16 star images in different colors and FOV positions.

- Figure 5 shows star images in different passbands.
  - Large changes in size and shape due to color and FOV.

Calibration-Level Analysis:

- Camera calibration of the ST16 is specified by 8 parameters.
- Numerical optimization used to identify best parameters.
- Camera calibration error (CCE) measures instrument performance. CCE defined by RMS angular error between known and measured star vectors.

5. Lens Characterization (cont.)

CCE chromatic dependence characterized by three trials:

1. **Broadband validation:** CCE of broadband calibration applied to narrowband data.
2. **Full recalibration:** new optimal set of all 8 parameters.
3. **Focal length only recalibration:** optimal f_L computed (using broadband values for other parameters).

Collection Passband (nm)	CCE (arcseconds)			δf_L (μm)
	Broadband Validation	Full Recalibration	f_L only Recalibration	
All-Pass	N.A.	5.14	N.A.	N.A.
410-490	25.45	5.28	5.40	-16.0
560-640	12.81	5.01	5.28	+6.30
715-785	6.83	5.24	5.38	+2.60
865-930	25.23	6.43	7.20	-15.4
1020-1085	61.65	8.85	12.27	-36.8

Table 1: ST-16 Chromatic Calibration Performance. Focal length accounts for most of the change in CCE's chromatic between passbands.

- No significant increase in CCE for full recalibrations, except for IR passbands.
- Large increase in CCE for narrowband data when using a broadband calibration.
- Focal length appears to account for most of the change.

6. Star Vector Error

- Using the computed change of the lens' focal length, δf_L, from Table 1, we can predict a net change in the focal length of the lens for any given star with a known stellar spectra.
  1. Convert the spectrum's energy flux to photon flux, $P(\lambda)$.
  2. Calculate the normalized photoelectric response, $\bar{D}(\lambda)$, by convolving $P(\lambda)$ with the detector's QE and normalize.
  3. Calculate the spectral focal length shift, δf_S, by convolving measured focal length shift of the lens, δf_L, with $\bar{D}(\lambda)$.
  4. Integrate δf_S to yield the net change in apparent focal length, Δf, for this spectrum.
- Yields a per-spectrum correction to the change in focal length due to chromatic aberration.
- Broadband spectra not available for most stars, but color indices are.
- Use reference spectra to map predicted focal shifts to V-I color indices (Figure 6).
- Fitting this trend enables lookup of focal shift with V-I color index.
- Yields per-star correction to change in focal length.

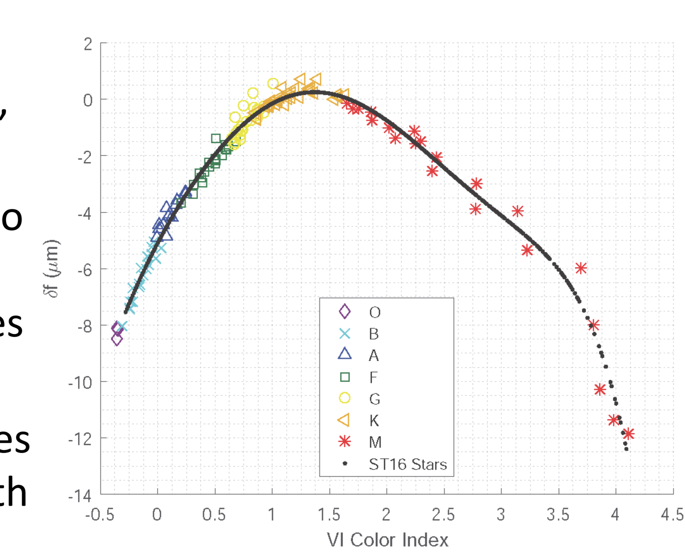

Figure 7: Net focal shift of all Pickles Stellar Atlas (PSA) stars, specified by VI color index. This enables per-star corrections to chromatic aberration, given the VI color index (available for most stars).

7. Results from On-Orbit Sensors

- To gauge the effectiveness of our proposed chromatic corrections, we compare residuals errors of on-orbit data with and without the per-star offsets to focal length.
- Figure 7 depicts the changes to typical on-orbit calibration.

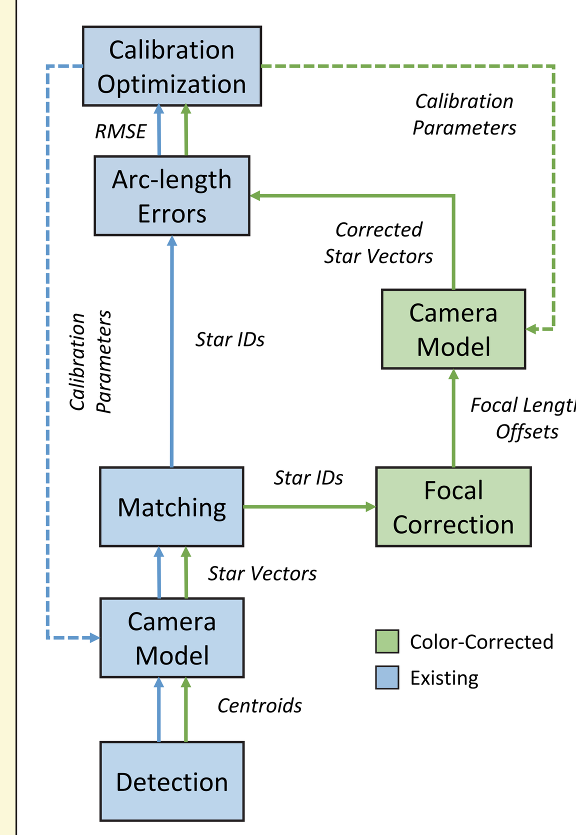

Figure 8: Comparison of monochrome and color-corrected on-orbit calibrations.

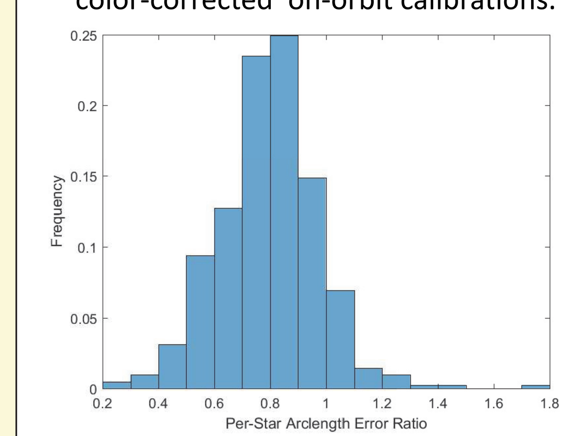

Figure 9: Mean arc-length error ratio calculated on a per-star basis (N≥10).

- Changes are simple: after matching, recalculate star vectors using star-specific focal lengths:

$$f_i = f_0 + \delta f_i$$

- Recalibration optimizes f_0 to minimize RMS errors in angles between stars.
- 12 datasets collected from 6 sensors (1 cal., 1 val., per unit).
- Error ratios between corrected and uncorrected residuals show significant effectiveness. (Table 2)
- Most sensors see improvements of 3-5% RMSE.
- Results strongly dependent on stars within the dataset.
- Secondary metric looks at the effect of correction on the mag. of the arc-length error. (Last column of Table 2).
- Fig. 8 shows change in mag. of arc-length error for unit 3.

Unit	Arc-Length Calibration	RMSE Ratio Validation	Improved Fraction
1	0.935	0.938	0.88
2	0.954	0.955	0.83
3	0.864	0.961	0.91
4	0.929	0.860	0.84
5	0.977	0.983	0.50
6	0.908	0.946	0.82

Table 2: Effect of Color-Corrected Calibration.

- Most stars see a decrease in error.
- Errors increase for a minority of stars. Perhaps inaccuracy in δf_i correction or coupling to stars position in FOV.

8. Conclusions

- Star spectra combine with lens characteristics to alter the brightness, placement and appearance of imaged stars.
- We have presented models that allow designers to:
  - Predict instrument response to particular stars
  - Correct for the most significant chromatic effect: wavelength-dependent shift in focal length.
- Depending on the set of stars in any particular batch of obs., corrections can yield RMSE reductions of up to 15%.
- Approach easily adaptable to different sensor designs.