

## 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.

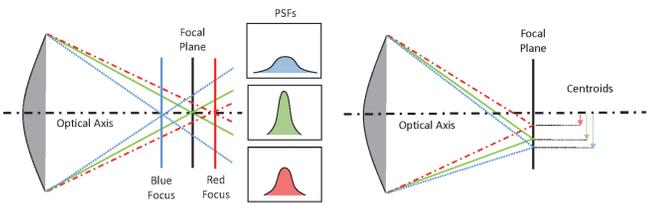


Figure 1: Axial chromatic aberration. On-axis effect that causes a color-dependent change in star size and shape.

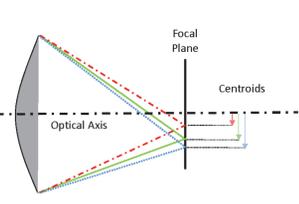


Figure 2: Lateral chromatic aberration. Off-axis effect that causes a color-dependent change in star position.

## 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.

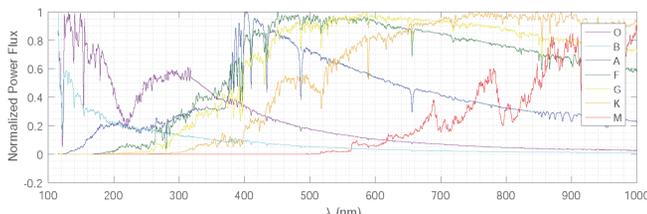


Figure 3: Example spectra for each Morgan-Keenan spectral type. Because star trackers are not spectroscopic instruments, only broad spectral features impact performance.

## 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.g. Vmag)
- Orbital data can be used to refine predictions.

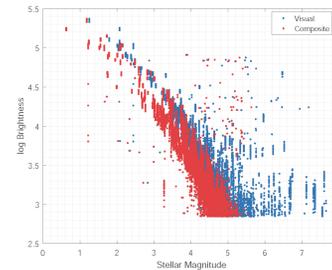


Figure 4: Effectiveness of composite stellar magnitude

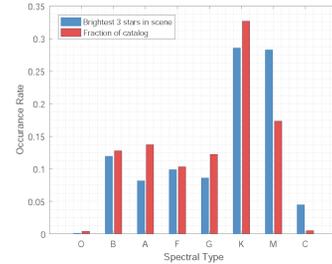


Figure 5: Occurrence rate of each MK spectral type.

## 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:

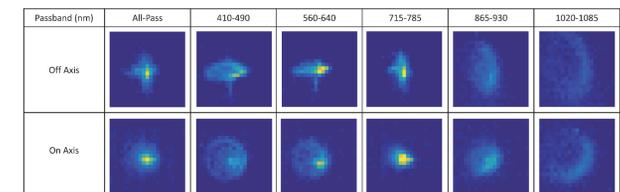


Figure 6: Examples of ST-16 star images in different colors and FOV positions.

- 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:

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

Collection Passband (nm)	CCE (arcseconds)			
	Broadband Validation	Full Recalibration	$f_L$ only Recalibration	$\delta f_L$ ( $\mu\text{m}$ )
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,  $\delta f_L$ , 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.
  - Convert the spectrum's energy flux to photon flux,  $P(\lambda)$ .
  - Calculate the normalized photoelectric response,  $\bar{D}(\lambda)$ , by convolving  $P(\lambda)$  with the detector's QE and normalize.
  - Calculate the spectral focal length shift,  $\delta f_S$ , by convolving measured focal length shift of the lens,  $\delta f_L$ , with  $\bar{D}(\lambda)$ .
  - Integrate  $\delta f_S$  to yield the net change in apparent focal length,  $\Delta f$ , 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.

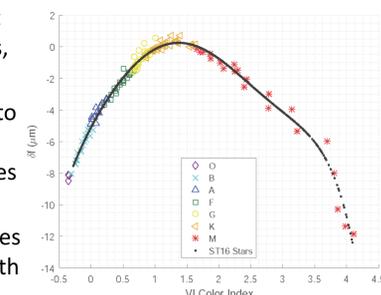


Figure 7: Net focal shift of all Pickles Stellar Atlas (PSA) stars, specified by VI color index. This enables per-star corrections to chromatic aberration, given the VI color index (available for most stars).

## 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.

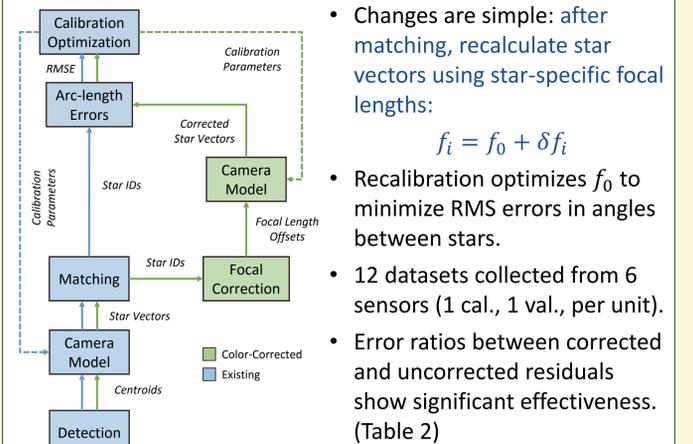


Figure 8: Comparison of monochrome and color-corrected on-orbit calibrations.

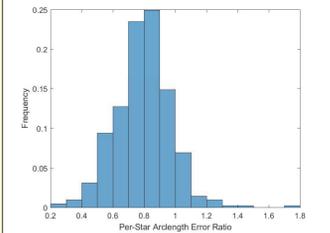


Figure 9: Mean arc-length error ratio calculated on a per-star basis ( $N \geq 10$ ).

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.

## 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.