Characterizing Chromatic Effects in Small Star Trackers

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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% RMS 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.
  - 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.

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., UBVI) 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.

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.

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 gimbals, a broadband star source, and a set of 5 color filters (Table 1).

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.
  1. Convert the spectrum’s energy flux to photon flux, \( P(\lambda) \).
  2. Calculate the normalized photoelectric response, \( \Phi(\lambda) \), by convolving \( P(\lambda) \) with the detector’s QE and normalizing.
  3. Calculate the spectral focal length shift, \( \delta f_{\lambda} \), by convolving measured focal length shift of the lens, \( \delta f_L \), with \( \Phi(\lambda) \).
  4. Integrate \( \delta f_{\lambda} \) 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.

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.
- Changes are simple: after matching, recalibrate star vectors using per-star focal length with.
  - Recalibration optimizes \( \delta f_L \) 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% RMS.
- 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.
- Most stars see a decrease in error.
- Errors increase for a minority of stars. Perhaps inaccuracy in \( \delta f_L \) 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 RMS reductions of up to 15%.
- Approach easily adaptable to different sensor designs.