Photometric Calibration for Wide-Area Space Surveillance Sensors

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Outline

• Introduction and Background
• Typical photometric techniques and calibration issues
• Photometric Bandpass conversions
• Comments on photometric reference catalogs
• Summary
Introduction

• Optical space surveillance sensors frequently operate with wide bandwidths
  – Lincoln Near Earth Asteroid Research (LINEAR) project: ~400 – 900 nm
  – Wide bandwidths maximize sensitivity

• Photometric calibration presents challenges:
  – Atmospheric variability
  – Poor quality reference catalogs
    Lack all sky coverage (e.g., Sloan Digital Sky Survey)
    Lack accurate photometry (e.g., USNO B1)
    Lack of faint calibration stars
  – Mis-match of star catalog and sensor bandpasses (color)
    Especially problematic for broad-band, unfiltered CCD images
    Requires color correction

• We address techniques for correcting existing star catalogs to sensor bandpasses and development of high quality all-sky photometric reference catalogs
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Typical Photometric Reduction Process

- **Data Collection**
  - Characterize the sensor
  - Obtain calibration data with science/search data

- **Image Calibration**
  - Bad pixels/cosmic rays/internal reflections
  - Dark/read noise
  - Flat field

- **Intensity Measurement**
  - Background estimation/subtraction
  - Signal estimation

- **Absolute Calibration**
  - Zero point estimation
  - Extinction correction
  - Color correction
Basic Photometric Correction

- Calculate zero-point, comparing catalog and image stars

$$Z_p = \frac{1}{N} \sum_{i=1}^{N} \left( -2.5 \log_{10}(i_i) - m_i \right)$$

- Apply zero-point to object of interest

$$m_T = -2.5 \log_{10}(i_T) - Z_p$$

Differences in the spectral response of the sensor and the star catalog require a color correction to be performed for accurate photometric calibration.
Two Absolute Calibration Schemes

• Differential or on-chip photometry
  – Use serendipitous stars in image
  – Requires accurate catalog magnitudes and good sky coverage with catalog

• All-sky photometry
  – map out extinction correction and color corrections over large part of sky with separate data collection of well-calibrated reference sources
  – Can achieve excellent calibration but requires very stable (spatially and temporally) atmosphere – only obtained on a small percentage of nights

\[ X \approx \sec z \]
\[ Z_p(X) = Z_p(0) + \Delta m(X) \]

\( z \) is zenith distance, angle from straight up
Reference Catalog Properties

- **USNO B1**
- **NOMAD/UCAC**
  - Poor photometric accuracy (~0.3 mag); non-standard photometric bandwidths

- **Landolt, Stetson**
- **Hubble Guide Star Photometric Catalog**
- **Sloan Digital Sky Survey (SDSS) Photometric Database**
  - Excellent photometric accuracy (< 0.05 mag); limited sky coverage

- **Pan-STARRS Photometric Catalog**
  - Does not exist yet; maybe by 2009-2010
USNO B1 Photometric Accuracy
USNO B1 Photometric Accuracy

Comparison of USNO B R band with Johnson–Cousins R band

RMS Scatter: 0.303838

Residual USNO B1 R - Synth USNO B1 R

Johnson–Cousins R magnitude (from Skiff–LONEOS catalog)
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Astronomical Bandpasses

$ugriz$ are Sloan Digital Sky Survey (SDSS) spectral bandpasses
• Empirical color transformations impractical for space surveillance sensors
  – Requires large amount of calibration star observations from sensor of interest
  – Requires accurate catalog magnitudes and color indices for calibration stars of interest

• Our method makes use of “synthetic magnitudes”
  – Calculated from high resolution stellar spectra (Pickles catalog)
  – Calculate for sensor bandpass and star catalog bandpasses

• Derive functional relationships between computed color indices
  – Provides color correction of catalog stars from catalog bandwidth to sensor bandwidth
  – Allows consistent use of sensor magnitude system
Color Correction Calculations

Star Catalog

multiply & integrate (all spectral types)

convert to mags

vega color reference

color terms (subtract)

linear or quadratic fit

multiply & integrate (all spectral types)

convert to mags

vega color reference

\[ l-r = c_1(u-r)+c_2(g-r)+c_3(r-i)+c_4(r-z) \]
Color Correction Residuals

~600 SDSS stars matched to LINEAR obs in one field

RMS Scatter = 0.0927916
Optimal Fit Scatter = 0.0804952
Color Correction Results

<table>
<thead>
<tr>
<th></th>
<th>analytically-derived color corrections</th>
<th>empirically-derived color corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINEAR vs SDSS_r</td>
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<td>0.107</td>
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<tr>
<td>no color correction</td>
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</tr>
<tr>
<td>with g-i color correction</td>
<td>0.093</td>
<td>0.080</td>
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<tr>
<td>with 4 term color correction</td>
<td>0.084</td>
<td>0.077</td>
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</tbody>
</table>

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LINEAR Imaging Data
Archived Images
LINEAR Imaging Data

- 4.5 years
- 1596 nights
- ~16,000 unique fields (1.98 square degrees each)
- ~32,000 square degrees covered
- ~1,200,000 “looks” (5 images each)
- 6.0 million images
- 30 Terapixels
- 58 Terabytes (uncompressed)
- ~419 SDLTs
- 44 disk drives (500 GB)

LINEAR Telescope
LINEAR Star Catalog

- Aperture photometry
  - 6 million images
  - ~40 million unique stars
- Use overlap between adjacent regions to find global photometric solution
  - 1% overlap between fields
- Global photometric solution
  - $5 \times 10^9$ measurements of star magnitudes
  - $5 \times 10^7$ free parameters
    - $4 \times 10^7$ star magnitudes
    - $6 \times 10^6$ zero-points
- Refer to spectrophotometric catalog
  - Sloan Digital Sky Survey
- Check against other star catalogs
  - Hubble Guide Star Photometric Catalog
  - Stetson Fields, etc.
Summary

- Four parts to photometric measurements
  - sensor characterization, image calibration, intensity estimation, absolute calibration
- Absolute calibration
  - More accurate photometric catalogs needed
    Possibly coming in 2009
  - Color corrections must be done carefully
- Algorithm derived to affect calibration of wide-bandwidth sensors using narrow-band catalog data to better than 0.1 magnitude
- Investigating generation of accurate photometric catalog using archived LINEAR data
USNO B1 Photometric Accuracy

Smoothed Residuals for synthetic USNO B versus Johnson–Cousins R

NOTE: Color corrections amount to 0.015 mag maximum
History of Photometry

- **Hipparchus (~130 BCE)**
  Divided visible stars into 6 brightness bins
- **Ptolemy (~140 CE)**
  Basic astronomical texts for 1400 years
- **Galileo (1610 CE)**
  First use of telescope, first extension beyond 6 categories
- **Pogson (1856 CE)**
  Brightness ratio of 100 == 5 magnitudes
- **Photographic Emulsions (late 1800s)**
- **Standardized Bandpasses (UBVRI...) (mid 1900s)**
- **CCDs (1980s)**
- **New bandpasses (ugriz) (1990s on)**
Color Correction Example for LINEAR

Synthetic Magnitudes derived from Pickles spectral atlas for LINEAR and SDSS bandpasses

\[ \text{LINEAR} = r + 0.08692(g - i) - 0.05797(g - i)^2 \]
Color Correction Verification - 1

Color Correction for LINEAR from SDSS

~600 SDSS stars matched to LINEAR obs in one field

RMS Scatter = 0.107433

Analytic fit
Color Correction Verification - 2

![Graph showing color correction verification between LINEAR and SDSS r (l-r) vs. SDSS g-i. The graph includes data points and lines for Analytical and Empirical fits.]
Color Correction Residuals

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Catalog Bandpasses

$ugriz$ are SDSS spectral bandpasses, $BVRI$ are Johnson-Cousins bandpasses.