Improving Photometric Calibration of Meteor Video Camera Systems

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Abstract

We present the results of new calibration tests performed by the NASA Meteoroid Environment Office (MEO) designed to help quantify and minimize systematic uncertainties in meteor photometry from video camera observations. These systematic uncertainties can be categorized by two main sources: an imperfect understanding of the linearity correction for the MEO's Watec 902H2 Ultimate video cameras and uncertainties in meteor magnitudes arising from transformations between the Watec camera's Sony EX-View HAD bandpass and the bandpasses used to determine reference star magnitudes. To address the first point, we have measured the linearity response of the MEO's standard meteor video cameras using two independent laboratory tests on eight cameras. Our empirically determined linearity correction is critical for performing accurate photometry at low camera intensity levels. With regards to the second point, we have calculated synthetic magnitudes in the EX bandpass for reference stars. These synthetic magnitudes enable direct calculations of the meteor's photometric flux within the camera band-

pass without requiring any assumptions of its spectral energy distribution. Systematic uncertainties in the synthetic magnitudes of individual reference stars are estimated at ~ 0.20 mag, and are limited by the available spectral information in the reference catalogs. These two improvements allow for zero-points accurate to $\sim 0.05 - 0.10$ mag in both filtered and unfiltered camera observations with no evidence for lingering systematics.
Keywords:
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1. Introduction

Meteor photometry is a fundamental and essential calculation for characterizing individual meteors and meteor showers. Measurements ranging from meteor shower fluxes to the mass of an individual meteor all require accurate measurements of the meteor's radiative emission, usually determined using the techniques developed to measure photometric fluxes of stars in telescopic observations. While this procedure is straightforward in principle, the practical considerations that go into the design of meteor camera systems add complications to the procedure. Many of these complications are rarely considered by meteor observers, which in turn introduces large systematic uncertainties and errors into their photometric measurements.

The first design consideration that greatly impacts the final photometry is an accurate understanding of the camera's response and linearity. Meteor video cameras are commonly set to have a non-linear, power-law response (parameterized by a power-law index γ) in order to increase their contrast and dynamic range. Any errors in mapping the raw camera counts back onto

a linear system (hereafter referred to as the linearity correction) will lead to large systematic errors in photometry that depend on the magnitude of the sources in question.

At the same time, meteor cameras are typically not equipped with the same astronomical filters utilized in the observations and determinations of the reference star magnitudes in order to maximize their sensitivity to meteors. A color correction to account for differences between the reference and detector bandpasses therefore must be included. Although the color term for a sample of reference stars can be calculated, that color term is not valid for meteors. Unlike the predominantly thermal/black-body spectral energy distributions (SED's) observed from stars, meteor SED's are typically dominated by emission lines either from its own metals or the atmosphere.

Without careful consideration for the linearity correction and color corrections of the video cameras used to observe meteors, any resultant photometry is potentially subject to large errors. Critically, these errors are highly non-linear in nature and vary on a meteor-by-meteor basis, which makes it difficult to predict their overall scale from the observational data alone. Given the foundational role meteor photometry plays in characterizing meteor showers subsequent calculations such as the masses of individual meteors or the mass index of a meteor shower may in turn be subject to severe errors.

In this paper, we discuss methods that the NASA Meteoroid Environment Office (MEO) has developed to address these potentially large systematic errors in meteor photometry. While the precise models we have determined are only directly applicable to the camera systems deployed by the MEO, most of the methodologies and tests discussed below can be modified to

accommodate the specific hardware and software utilized by other meteor video camera networks.

2. The MEO's All-sky and Wide-field Camera Networks

The MEO has two video networks which observe meteors nightly- the All-sky network and Wide-field network. Both camera networks utilize Watec 902H2 Ultimate charge-coupled device (CCD) cameras set with manual gains. These cameras are equipped with Sony EX-View HAD ICX828ALA CCD chips. The cameras deliberately set the γ parameter to "LO" and subsequently have a non-linear response that should correspond to $\gamma = 0.45$ based on manufacturer specifications.

Each of the All-sky cameras is equipped with a 2 mm $f/1.4$ fisheye lens. Half of the Wide-field cameras are outfitted with 17 mm $f/0.95$ Schneider XENON lenses and the other half use 17 mm $f/0.95$ Navitar lenses, producing a $22^\circ \times 16^\circ$ field of view. The video signal is read in through video capture cards on Linux computers using the `ASGARD` meteor detection software (Weryk et al., 2008; Brown et al., 2010). The camera data is read into computers using Brooktree or Sensoray 810 video capture cards. For both camera networks the cameras run at 30 frames per second.

In addition to the unfiltered camera systems, the MEO deployed a series of four photometric color cameras in June of 2015. These four Watec 902H2 Ultimate CCD video cameras are equipped with 17 mm $f/0.95$ focal length Navitar lenses, giving them an identical field of view as the Wide-field cameras. Each of these cameras is equipped with different standard Johnson-Cousins astronomical filters ($BVRI$) to provide photometric color

measurements of meteors. These four cameras work in tandem with the signal from one of the unfiltered Wide-field cameras, and record data in each of the four filters whenever `ASGARD` flags a detection in the unfiltered video feed regardless of the signal present in the color camera data themselves. The need to determine accurate photometric colors of meteors was one of the major drivers behind the MEO's effort to improve their camera calibration procedure.

3. The Scale of Calibration Uncertainties

Before discussing the results of the MEO's laboratory tests, it is important to discuss the level to which the current calibration paradigm is uncertain. We demonstrate this with a simple zero-point calibration model using reference stars observed in a single All-sky event, the data from which is shown in Figure 1. By default, `ASGARD` assumes the response follows a single power-law with $\gamma = 0.45$ across the entire dynamic range and uses R-band reference magnitudes from the SAO J2000 V4 catalog (Myers et al., 2001) to determine the calibration model.

As can be seen in these data, there is a clear segregation between the redder spectral types (e.g. K and M) and the bluer types (e.g. B and A). It is clear that redder stars (types K and M) and bluer stars (types B, and A) have significantly different zero-points than each other as well as average across all spectral types. This uncertainty amounts to ~ 0.5 mag in the zero-point across all stellar spectral types. Critically, this ~ 0.5 mag of uncertainty must be added in quadrature to every source observed in these video data, including the meteor. Because the photometric color of the me-

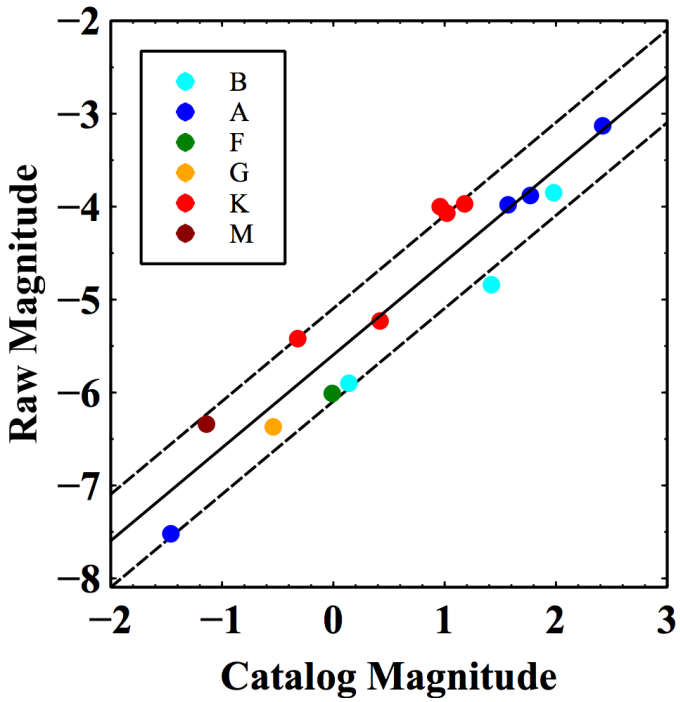

Figure 1: A zero-point calibration model for an All-sky camera observation that demonstrates the level of systematic uncertainty associated with the color correction. The raw magnitudes (y-axis) are taken in an unfiltered camera, whereas the reference magnitudes (x-axis) are derived from the R-band using the SAO J2000 V4 catalog. The different colors denote different spectral types. The solid line denotes the best-fit zero-point to all fourteen reference stars, while the dashed lines denote ± 0.5 mag around that model.

teor in question can vary significantly from the stellar SED's and is frequently unmeasured, systematic errors in the meteor's photometry may still persist even after attempting to account for this uncertainty using reference stars.

An inappropriate linearity correction can be an even larger source of uncertainty than the color term, because it scales with the level of illumination of the camera. Comparing the same meteor observed in two different cameras (with or without filters) could be subject to systematic offsets, as could observations of a single meteor at different times.

4. Linearity Correction

We performed tests of the camera linearity using two different experiments: one set used observations of a professional-grade chip chart in the Video Calibration Laboratory located at Marshall Space Flight Center. The other set of experiments utilized a an inexpensive setup consisting of an Arduino Uno programmable computer board and an off-the-shelf Light-Emitting Diode (LED). Because the LED tests are inexpensive ($\sim$ \$100 US of total equipment) and can be readily reproduced by other meteor camera networks, we will focus on those tests in this work.

The Arduino board was programmed to increase the duty cycle of the LED in 256 equal increments using pulse width modulation, which provides a repeatable standard light-source for which the performance of multiple cameras (or settings on an individual camera) can be directly compared. The LED's brightness levels spanned the full dynamic range of the Watec cameras, and the hardware and software utilized by our test camera system was identical to the deployed systems that are currently taking observations.

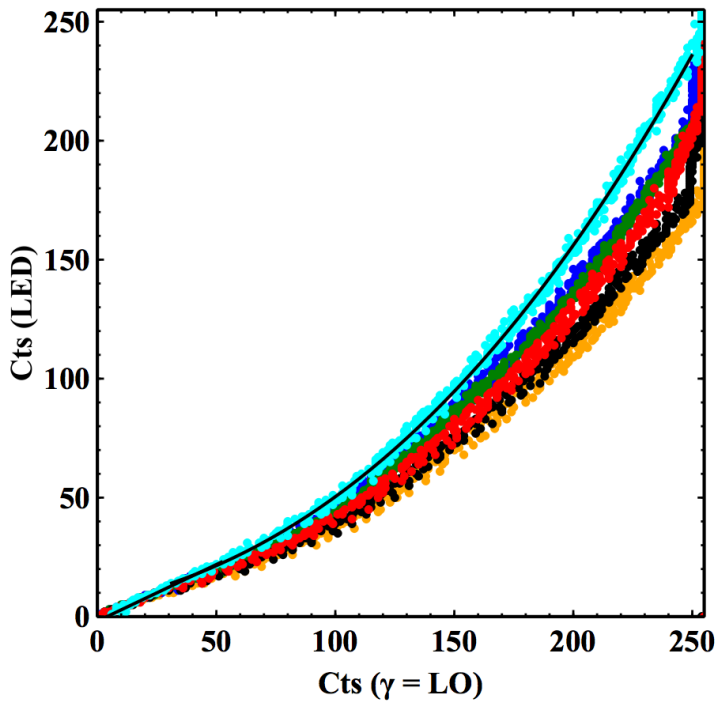

Figure 2: The uncorrected response of eight Watec cameras in the LED test. The x-axis shows the median pixel value within an aperture centered on the LED, and the y-axis is the relative intensity of the LED normalized to a maximum value 256. Each of the eight colors denotes a different camera. The solid black curve denotes the best fit affine + power-law fit to the cyan data points.

The linearity correction model was determined for eight Watec cameras in order to quantify variance in the camera-to-camera response.

The results of the LED tests for all eight cameras are shown in Figure 2. All of the cameras show consistent behavior of a linear response at low illuminations and a power-law response at higher intensities. Variations in each camera's gain account for the differences in the overall scaling and saturation limits of each curve. The transition between the affine and power-law components occurs at 30 counts in the uncorrected pixel values, corresponding to $\sim 10\%$ of the maximum pixel values. The power-law index is consistent with $\gamma = 0.45$, and the transition between these two functions occurs at pixel values of ~ 30 in the uncorrected data. Our fiducial linearity correction model is derived from the best-fit model to one of the eight cameras and takes the following parameter values

$$F'(F) = \begin{cases} 2.81 + 0.48 \times F & \text{if } F \leq 30 \\ 255 \times \left(\frac{F+83.19}{370.89}\right)^{1/0.43} & \text{if } F > 30 \end{cases} \tag{1}$$

where F' corresponds to the linearized number of counts in the camera and F denotes the counts in the raw image data. Applying this formula to the data from Figure 2 confirms that the transformed output of each of the eight cameras is linear, which ensures that this single formula can be applied to multiple cameras.

5. A Synthetic Reference Catalog

In order to circumvent the need for a potentially large and highly uncertain correction for the meteor magnitude from the detection bandpass into

the reference star's bandpass, we instead determine synthetic magnitudes for all reference stars in the EX bandpass (hereafter the EX-band)[1] . In detail, we combine our model of the EX-bandpass with the V-band magnitudes and spectral type information from the SAO J2000 V5 Catalog (Myers et al., 2015) to calculate model EX-band magnitudes for each of $\sim 300,000$ stars.

The EX-band was determined as the product of the quantum efficiency of the Watec's Sony EX-View HAD CCD chip (provided by the manufacturer), the wavelength-dependent transmission of the Navitar lens (also provided by the manufacturer), and the wavelength-dependent transmission of the atmosphere from Capak (2015). The assumed bandpasses for the $BVRI$ filters account for all three of these components as well as the bandpass of the filter itself using the standard Johnson bandpasses included in the `PySynPhot` software package developed by the Space Telescope Science Institute (Lim et al., 2015). All five resultant bandpasses are shown in Figure 3.

As stated above, the SAO J2000 V5 Catalog (Myers et al., 2015) includes spectral type information for all of its $\sim 300,000$ stars. We utilize the Morgan-Keenan spectral types from this catalog (column `'SpMK'`) whenever possible, as these spectral types include the luminosity class in the spectral type for those stars[2]. Spectral types without the luminosity class are identified for the rest of the stars in the column `'Sp'`. Roughly 40% ($\sim$ 120,000

[1]We name this bandpass after the Sony EX-View HAD CCD chip. The CCD chip is the primary driver of the camera's spectral response, and this particular CCD is utilized by other cameras than the Watec cameras tested in this work.

[2]As an example, the Morgan-Keenan spectral type of a Sun-like star would be "G2V" instead of simply "G2", where the "V" denotes the main-sequence luminosity class.

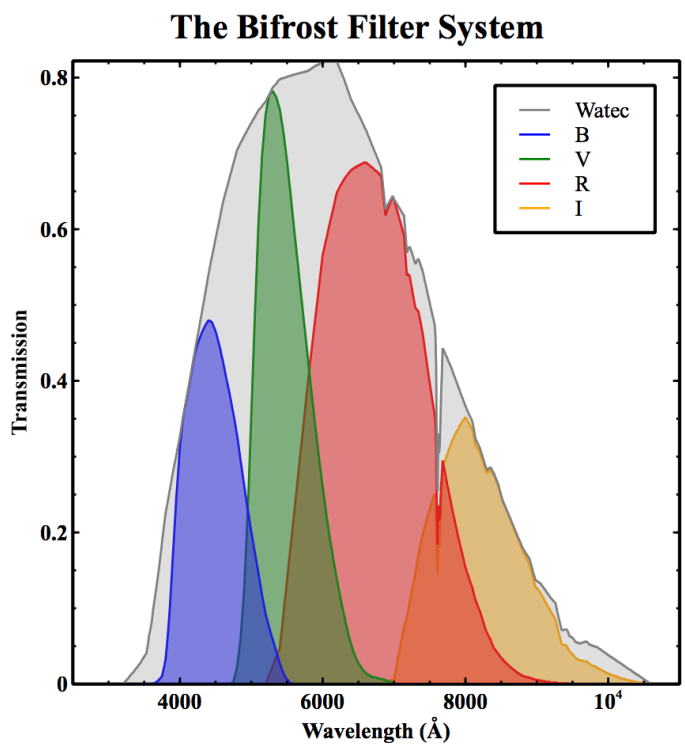

Figure 3: The assumed bandpasses for the unfiltered and color video cameras utilized by the MEO. The color bandpasses further include the transmission efficiency of their respective filters.

out of 300,000) of the stars in SAO J2000 V5 have the more informative Morgan-Keenan spectral types.

Synthetic $EX - V$ colors were determined for each spectral type using the `PySynPhot` software package (Lim et al., 2015) and the theoretical stellar atmosphere models of Gunn and Stryker (1983); Jacoby et al. (1984); Pickles (1998) included with `PySynPhot` corresponding to different spectral types and luminosity classes. We have also utilized the unpublished atlases of Bruzal and Bruzal-Persson-Gunn-Stryker included with `PySynPhot` to maximize the sample of spectral types for which we can determine synthetic magnitudes. All of the synthetic magnitudes were normalized to the SED of Vega in every bandpass. By doing these calculations in `PySynPhot` we are able to determine the absolute photometric flux of Vega in all five bandpasses, and our zero-point in the EX-band corresponds to a flux of $1.2 \times 10^{-5}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$.

Synthetic magnitudes were calculated for each source in the SAO J2000 V5 catalog by identifying all model colors whose spectral type included the spectral type of each star. For those stars without a Morgan-Keenan spectral type (e.g. "G2" instead of "G2V") this would include all available luminosity classes. The median color correction across all matching model colors was determined and applied to the reference star's V-band magnitude to determine its model magnitude in all of the other filters. Stars with unusual spectral types such as carbon stars, white dwarfs, or close binaries were not included in these calculations. We supplemented the SAO J2000 V5 Catalog in a nearly identical manner for stars without measured photometric B, R, or I-band magnitudes in order to ensure that the reference catalog was uniform across all five filters. Actual measurements superseded any magnitudes

determined using synthetic colors whenever available.

5.1. Testing the Validity of Synthetic Magnitudes Using CCD Observations

The synthetic magnitude procedure we have implemented cannot account for all of the observed and expected variations in stellar spectra, and these modeling deficiencies manifest themselves as systematic/intrinsic scatter in the photometric calibration model. Further tests are required to determine the level of systematic uncertainty this procedure introduces into the final photometric measurements of meteors as well as confirm that no additional measurement biases are present. In order to validate the synthetic magnitudes and estimate the systematic uncertainties associated with this modeling, we utilized observations of the sky with an Andor iKon 936 CCD camera (hereafter the Andor camera) equipped with a Nikon DX 18-55mm f/3.5-5.6GII AF-S Nikkor lens during the peak nights of the Perseid and Geminid meteor showers.

The Andor camera was deployed to observe the sky at a fixed altitude and azimuth continuously over an entire night with repeated 30 s exposures. The focal length of the lens was set to its maximum value of 55 mm, resulting in a field of view of $\sim 30^\circ \times 30^\circ$. In a single 30 s exposure, thousands of stars as faint as ~ 10 mag are detected. Synthetic magnitudes for the Andor bandpass (hereafter the A-band) were determined in the same manner as for the EX-band, albeit with different response curves for both the lens and camera chip. The bandpasses for the Andor and Watec cameras are shown in Figure 4. While the A-band and EX-band bandpasses are not identical in shape, they cover similar wavelength ranges and the peaks of their response curves are at similar wavelengths. These features indicate that trends measured in the

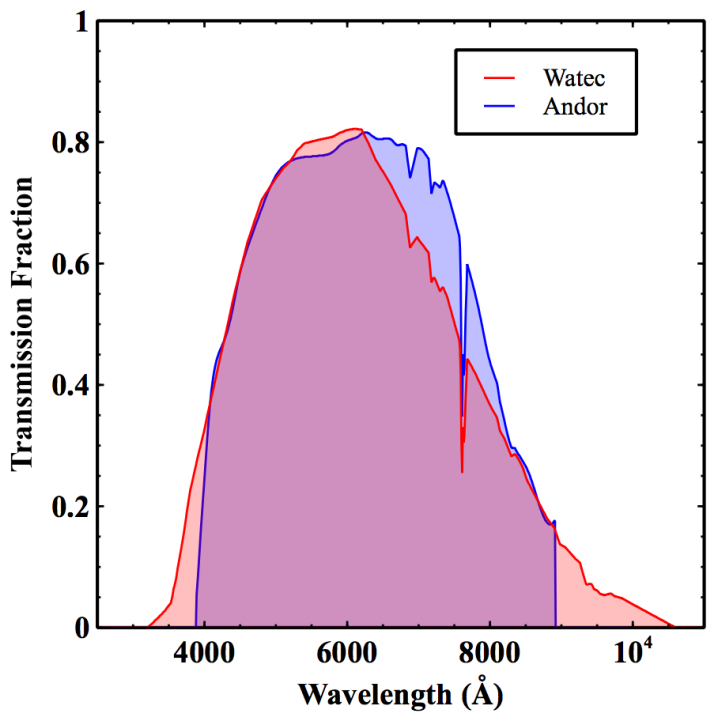

Figure 4: The assumed bandpasses for the Watec (EX, in red) and Andor (A, blue) cameras.

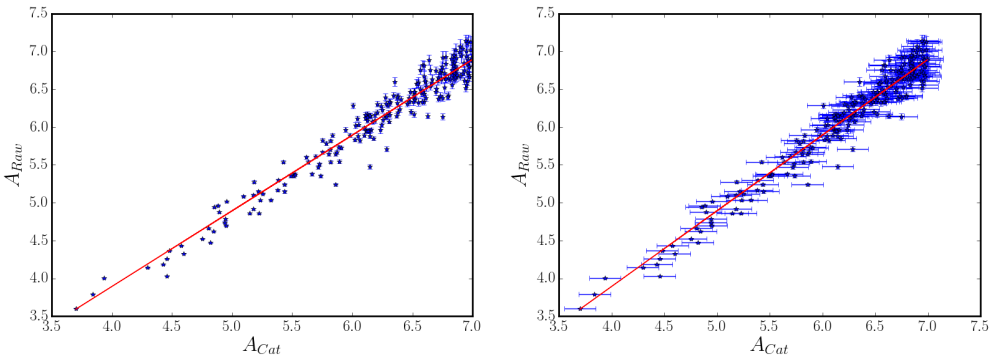

Figure 5: Zero-point figures for an individual 30 s observation of the sky using the Andor camera during the Geminid shower. *Left*: The raw magnitudes versus synthetic Andor-band catalog magnitudes, with the best-fit zero-point model overlaid in red. *Right*: The same data as the left plot with additional systematic uncertainty added to each stellar reference magnitude in quadrature. For this image the systematic uncertainty is estimated at 0.10 mag.

A-band can be safely assumed for the EX-band as well.

An example zero-point fit of the Andor observation data is shown in Figure 5, and demonstrates that a simple zero-point calibration model with intrinsic scatter is a good descriptor of the data. We estimate the systematic uncertainty associated with our synthetic magnitudes by adding additional uncertainties to the measured uncertainties in quadrature and repeat the zero-point calculation until we reach a reduced χ^2 value of 1. This procedure consistently resulted in a systematic uncertainty of $\sim 0.06 - 0.20$ mag per star. We therefore conservatively add 0.20 mag of systematic uncertainty in quadrature to the measurement uncertainties when performing stellar photometry regardless of the filter.

6. Photometric Performance

We now discuss the overall performance of our changes to the photometric calibration model using unfiltered (EX-band) and filtered observations of a single meteor event. The zero-point determinations for the unfiltered and color video camera systems are shown in Figures 6 and 7, respectively. The error bars in both plots account for uncertainties arising from both the aperture photometry statistics and the systematic uncertainty associated with the bandpass transformation, which are assumed to be 0.20 mag for every reference star. Unlike the zero-point model of Figure 1, there exists no evidence exists of significant color-dependent segregation in the reference magnitudes. In fact, there is no evidence for any intrinsic scatter in either plot not already accounted for by the calculated uncertainties.

The All-sky cameras are able to measure a zero-point with ~ 0.04 mag precision, the calibration data for which is shown in Figure 6. Critically, there exists no evidence for any intrinsic scatter in these data points not already accounted for in the error bars, which themselves account for the statistical uncertainties in the aperture photometry, with 0.20 mag of systematic uncertainty added in quadrature to address synthetic magnitude modeling deficiencies. The Wide-field calibration data, also shown in Figure 6, is able to measure a zero-point to the same level of precision. Tests of a more sophisticated zero-point + extinction model shows no statistically significant improvement in the fit when adding an airmass-dependent term to the calibration model.

The precision of the zero-points for this event in each filter are 0.10 mag in the B-band, 0.05 mag in the V-band, 0.03 mag in the R-band, and 0.04 mag

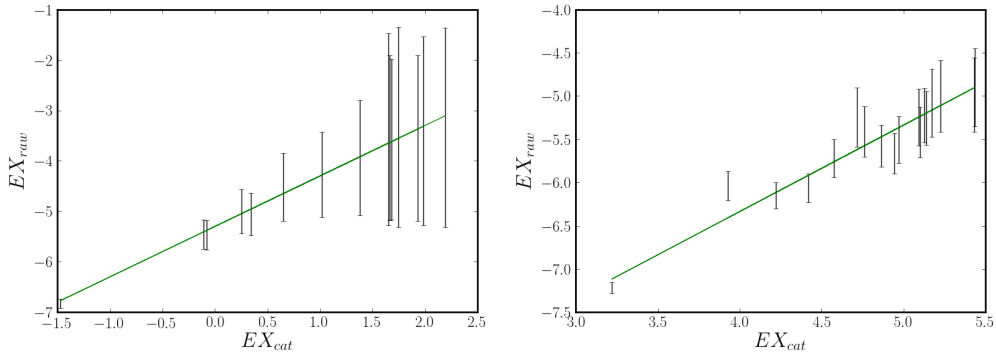

Figure 6: Zero-point calibration models for the unfiltered (EX-band) All-sky and Wide-field cameras. *Left:* The All-sky zero-point calibration model. *Right:* The Wide-field zero-point calibration model. In both sub-figures the raw magnitude is plotted as a function of the catalog magnitude, with the solid line showing the best-fit zero-point calibration model. The slope of the line is fixed to unity.

in the I-band. The reference star data and best-fit zero-point models for each color filter are shown in Figure 7. Again, there exists no evidence in any of the four filters of intrinsic scatter or color dependent segregation in the calibration model, and no statistically significant improvement exists to the calibration model by adding an extinction term.

7. Discussion and Future Work

The results of these lab tests demonstrate the importance of testing meteor camera setups in the laboratory prior to deploying them for meteor observations. Without incorporating the new linearity correction and synthetic magnitudes the systematic uncertainties on the zero-point were estimated at ~ 0.5 mag. Applying this calibration model to the meteor itself results in even larger but unquantified systematic uncertainties due to the unknown

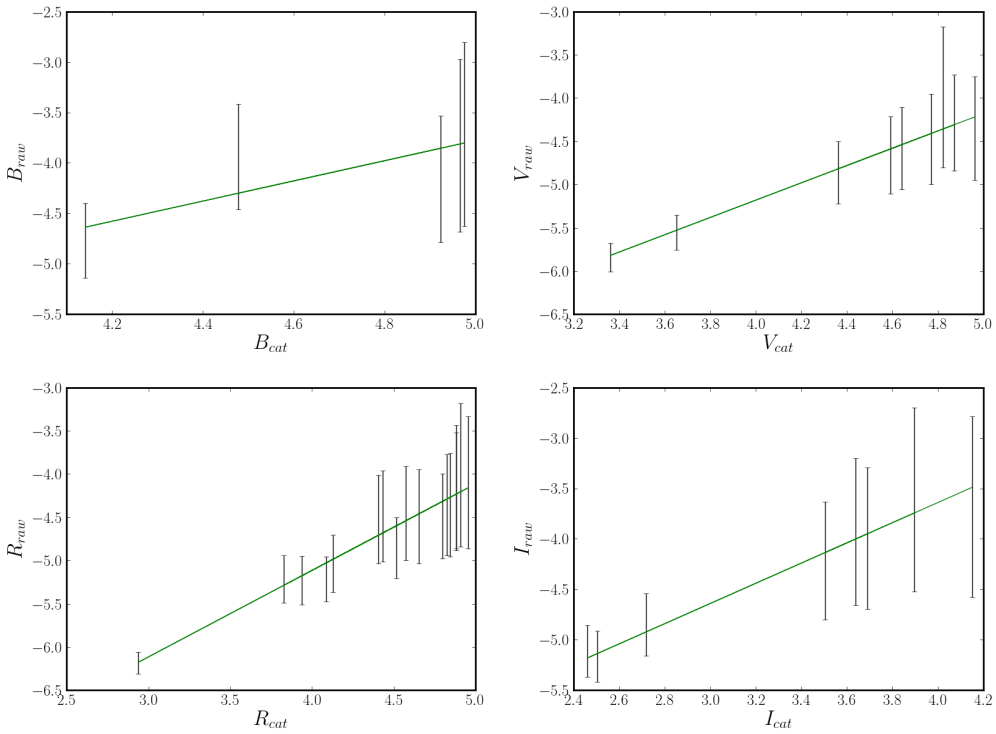

Figure 7: Zero-point calibration models for the filtered color cameras, which have an identical field of view as the Wide-field cameras. In all four sub-figures the raw magnitude is plotted as a function of the catalog magnitude, with the solid line showing the best-fit zero-point calibration model. The slope of the line is always fixed to unity. *Top Left*: The calibration model for the B-band, which has a precision of 0.10 mag. *Top Right*: The calibration model for the V-band, which has a precision of 0.05 mag. *Bottom Left*: The calibration model for the R-band, which has a precision of 0.03 mag. *Bottom Right*: The calibration model for the I-band, which has a precision of 0.04 mag.

photometric color of individual meteors as well as errors in the linearity correction being applied to the data. With these corrections in place the statistical uncertainty in the zero-point is reduced to $\lesssim$ 0.10 mag and shows no evidence for further systematic uncertainties. Although the absolute improvement in the zero-point uncertainty is significant enough on its own, the reduction of the systematic uncertainties in subsequent measurements such as meteor masses are essential to further improving meteor observations and source characterization.

We reiterate that the particular results presented here are specific to the MEO's combination of Watec 902H2 Ultimate video cameras, Sensorary/Brooktree video capture cards, and `ASGARD` meteor detection software. They should not be blindly applied to any other meteor video camera system. The general trends, testing procedures, and algorithms employed by this work are almost certainly applicable to other camera systems, but dedicated tests using systems that replicate deployed cameras as closely as possible are essential to confirming its performance and accuracy. Ideally, this battery of tests (or a variant thereof) is integrated into the commissioning phase of every meteor camera before deployment in order to ensure conformity with manufacturer expectations or to provide the opportunity for camera-specific calibration parameters. The `PySynPhot` package enables synthetic magnitudes to be calculated for an arbitrary bandpass, enabling meteor luminosities to be accurately measured in nearly any camera system whenever its bandpass can be assumed or measured.

While the changes to the MEO's photometry procedure discussed here have greatly improved both the accuracy and precision to which we can mea-

sure meteor magnitudes, further development and testing will enable even better performance. In particular, the MEO is currently developing experiments that will enable a direct measurement of the Watec camera bandpass. Our current implementation uses an assumed bandpass shape derived from the manufacturer's specifications. A more accurate model of the bandpass will reduce systematic uncertainties associated with the synthetic magnitude calculations. At the same time, future surveys and reference catalogs may provide more accurate SED's for the stars observed in the MEO's camera networks. Incorporating future spectroscopic data of reference stars into our procedure will further reduce systematic uncertainties on synthetic magnitudes below the level of ~ 0.20 mag that we have estimated. Finally, the MEO is currently developing and testing methods to correct for saturation in the cameras, which effectively extends the dynamic range of the cameras at the bright end. This development will be especially useful for the All-sky cameras, with saturated events corresponding to bright fireballs likely of public interest.

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