Anuenue: A New Tool for Studying Unresolved Objects

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ABSTRACT

The standard instrument for collecting photometry data on unresolved objects at the Maui Space Surveillance System is the Visible Imager, which is the science camera for the AEOS adaptive optics (AO) system. Being embedded in the AO system comes at a high cost. The Visible Imager is unable to collect light shorter than 700nm and the large number of optics in the AO system lowers the optical throughput to 25%.

The Anuenue instrument avoids these problems by being dedicated to collecting photometry of unresolved objects. It is located on the B29 rear Blanchard of the 1.2 m telescope at MSSS. It is capable of collecting data from 400 nm to 1000 nm at a variety of frame speeds. Even though it is located on a smaller telescope, it is expected to be more sensitive than the Visible Imager and capable of collecting more accurate data. We describe the instrument and possible missions.

1. INTRODUCTION

Small or distant objects are difficult if not impossible for ground based telescopes to spatially resolve. In these cases, techniques such as spectroscopy or photometry are needed to determine the properties of the object. Currently much of the photometry of unresolved objects at the Maui Space Surveillance System (MSSS) is done with the Visible Imager [2,3,5]. This is not a dedicated photometric instrument but instead the science camera for the AEOS telescope adaptive optics system. While the Visible Imager can be used to acquire non-resolved imagery, from which high-quality photometry can be extracted, its optimization for imagery results in some severe limitations including: low optical throughput, limited exposure times, and observations restricted to wavelengths longer than ≈700nm. We set out to build an instrument designed from the start to collect photometric data of unresolved objects. By doing so, we can increase the instrument's performance and expand its capabilities. One new capability will be to collect observations of objects in multiple filters which allows for the computation of object colors. With that concept in mind, the instrument was named Anuenue; Hawaiian for rainbow.

The MSSS 1.2m telescope was identified to be the most appropriate platform for the new instrument, as this telescope has been relatively underused recently and has available space to mount Anuenue on a semi-permanent basis. While the 1.2 m telescope is smaller than 3.6 m AEOS telescope, Anuenue will only have two optics before the instrument, rather than over 20 before the Visible Imager. This coupled with improved quantum efficiency of the detector, and lower dark and read noise, gives Anuenue a greater signal to noise ratio (S/N) for a given target and exposure time. This will allow for the collection of data on fainter targets or at a faster data rate.

2. INSTRUMENT DESIGN

Along with the requirement to be optimized for photometry, it was desired that Anuenue be a low-cost system. To reach this goal, we used an off-the-shelf camera and the vendor supplied software. There is a trade off between cost and flexibility when using vendor supplied software. Custom built software that will be ideally suited for our tasks, while we will have to learn how to operate vendor supplied software. In addition, vendor supplied software may not have all our desired capabilities.

Fortunately, the amateur astronomy community provides a ready market for CCD cameras, resulting in a dual trend of decreasing price and increasing sophistication for both the hardware and associated control software. These improvements in performance have led to an increasing trend of amateurs collecting professional-grade data and, occasionally, contributing to significant scientific discoveries.

After a review of the available instrumentation, we selected the Apogee Alta U47 camera, which comes bundled with MaxIM DL software. This software is scriptable and customizable and offers all of the major functionality that we desired. The Apogee Alta U47 uses a science grade E2V CCD47. This detector has 1024×1024 13 μmpixels. The CCD response spans the spectra range from 300 nm to 1000 nm and has a peak quantum efficiency of 95% at 550 nm. The detector has two gain settings with correspondingly different readout times: 12-bit at 2 MHz and 16-bit at 700 kHz. The read noise for these rates is 10 e^- RMS at 700 kHz or 2 ADU RMS at 2MHz. Exposure times can range from 30ms to 183 minutes; more than adequate for all of our tasks. Dark current is typically 0.1e^-/pixel/sec when the CCD is cooled to -20° C. The camera is cooled to 55°C below ambient by an air-cooled on-board thermo-electric cooler. The camera connects to the control computer via USB, which makes interfacing far less complex than using custom controller cards. The camera also has built in serial ports for the control of auxiliary equipment which in the case of Anuenue, this is a five element filter wheel built by Optec Inc. This filter wheel normally has a Bessel BVRI filter set with a clear filter for unfiltered observations. The filter wheel can be changed quickly and we also have a SILC filter set, which is also commonly used for satellite observations [7]. The time to switch between neighboring filters is 3.2 seconds.

The instrument is mounted on the rear-Blanchard of the B29 telescope of the 1.2m Telescope. The 1.2 m telescope is a unique mount, in that it has two 1.2m telescopes mounted on a common yoke. This allows for independent instrument packages to observe the same object, without resorting to beam splitters or dichroics which would limit the light going to each instrument.

The instrument package consists of a custom honeycomb optical breadboard with the optics mounted to the breadboard using standard hardware. A custom enclosure is mounted to the breadboard. The interior of the enclosure is painted flat black, while the outside is painted flat white. The use of a breadboard allows for optic mounts to be moved around to support future upgrades of the system, such as the addition or replacement of a camera.

Custom optics are needed to mate the beam from the telescope to the camera. The optics were designed to be near diffraction limited over the entire field and from 400–1000 nm. A fold mirror intercepts the beam coming from the telescope secondary and directs it onto the optical bench. Two lens assemblies refocus the beam onto the detector. The entire instrument package is shown in Fig. 1. The fold mirrors are coated with FSS-99, protected silver. This maximizes the reflectivity through most of the wavelengths, but at the cost of not being able to observe below 400 nm. This eliminates the possibility of U-band observations, but that was not thought to be that useful of a filter, since the CCD detector will have a low quantum efficiency in that band.

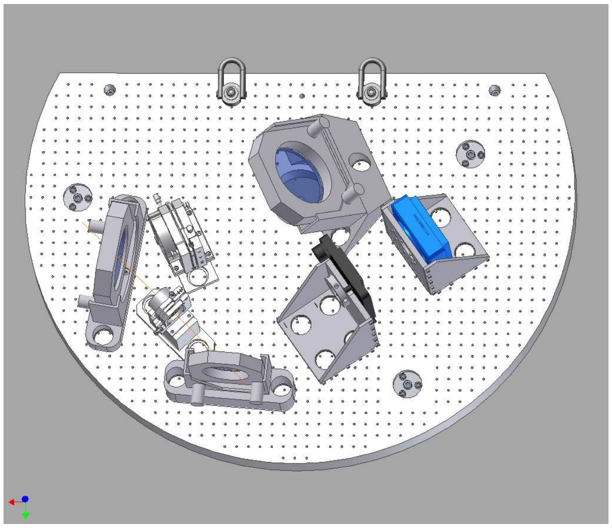

Fig. 1.— The instrument layout. The first mirror folds the beam from the telescope onto the optical bench. Then the beam goes through the first lens assembly, the 2nd fold flat, the 2nd lens assembly, the 3rd fold flat and then finally the filter wheel and the camera. Two hoist rings are installed at the top of the bench allowing for the easy removal of the instrument package, so that another instrument can substituted. It is not intended that Anuenue be removed frequently, but we wanted to ensure that it could be for specific missions.

3. CAPABILITIES

Anuenue has a field of view of approximately 1 arcminute. Since the system has no image correction hardware, the images will be seeing limited. Only very large man-made satellites such as the International Space Station and the Space Shuttle will be resolved by the instrument. Unresolved objects will appear as indistinct blobs, though Anuenue will be able to resolve multiple objects if they are separated by more than the size of the seeing disk (nominally $1''$.)

4. DATA REDUCTION

After subtracting bias and dark counts and at fielding the images, we use the DAOPHOT aperture photometry algorithm of Stetson[8] to extract net target signals. We have found that accurate photometric signals may be extracted by using a circular aperture 9 arcseconds in radius, which is large enough to include the entire source spread function even for slightly wind-jittered images. The reduction code program assumes that the brightest extended source of signal on the detector is that of the target of interest, and automatically centers the photometry aperture on the brightest source. An additional procedure determines if either the photometry aperture or the sky annulus is contaminated by star streaks and/or cosmic ray streaks. Given a sequence of images on a particular target, the data reduction process extracts a signal for each image and tabulates a list of exposure mid-point times, net target signals, and associated signal uncertainties.

The data reduction program automatically identifies images of the calibration stars, and uses the extracted signals to derive instrumental calibration coefficients. Calibration stars are taken from the list of Landolt [1,5]. These calibration coefficients provide the means to convert raw signals into exo-atmospheric magnitudes. Extracted net signals (counts/second) from each recorded image are denoted S_k, where k is an index spanning all calibration star images. The I-band magnitude of the kth calibration star measurement, I_k, is related to the net signal as follows:

$$I_k = -2.5\log(s_k) + Z - KX_k + \epsilon(R_{C,k} - I_{C,k}), \tag{1}$$

where Z is the zero-point, K the extinction coefficient, and ϵ the transformation coefficient. In equation 1, X_k denotes the air-mass of the measurement, $I_{C,k}$ the calibrated I-band magnitude for the photometric standard star [4], and $R_{C,k}$ the tabulated R-band magnitude. The first term on the right hand side of Equation 1 is often refereed to as the instrumental magnitude. The transformation coefficient, ϵ, accounts for the difference between the Bessel I-filter spectral band pass used by Anuenue and the Johnson I-filter band pass used by Landolt[5].

To derive the three calibration coefficients Z, K, and ϵ defined in equation 1, at least three photometric measurements of calibration stars must be made. However, in practice, deriving well-defined values for Z, K, and ϵ requires at 10-15 calibration star measurements, spanning a range of air masses, X_k, absolute magnitudes, $I_{C,k}$, and color differences, $(R_{C,k} - I_{C,k})$. We use a least-squares

Table 1. Anuenue Camera Properties

	12-bit Data	16-bit Data
Array Size	1024×1024	1024×1024
Readout Rate	2MHz	700 kHz

analysis procedure to find the best-fit values for the three coefficients. Specifically, the program finds the minimum of the chi-squared function,

$$\chi^2 = \sum_k \left[\frac{(I_k - I_{C,k})}{\Delta I_k} \right]^2 \tag{2}$$

with respect to the three variables Z, K, and ϵ. In equation 2, ΔI_k denotes the statistical uncertainty of the measured instrumental magnitude. During photometric conditions, Anuenue is capable of achieving very accurate calibrated photometry: residual differences, $(I_k - I_{C,k})$, are generally $\leq$0.02 for targets brighter than 12.5 magnitudes.

The atmospheric extinction coefficient, K, can vary on a nightly basis, and even during a single observing shift, because it depends on the variable properties the atmosphere above the observatory. This requires that calibration star measurements be taken concurrently with observations of any targets for which calibrated I-band magnitudes are desired. The coefficients Z and ϵ do not depend on the atmosphere, but may vary relatively slowly in time in response to instrumental and telescope sensitivity changes. For calibration star observations acquired between 2007 June 3 and 2007 June 19, the extinction coefficient varied between 0.03 and 0.26, with a median value of $\approx$0.06. The zero point and transformation coefficients derived during the same period were Z = 21.79 ± 0.04 and ϵ = 0.10 × 0.02.

After Z, K, and ϵ have been derived from calibration star measurements for a particular night, the calibrated I-band magnitude for any other target observed during that night may be calculated using Equation 1. Note that Equation 1 requires an estimate of the color difference $(R - I)$ for the target of interest, which may or may not be available to the observer. For objects reflecting sunlight, the $(R - I)$ value may be estimated by using the solar color index $(R - I)_{Sun}$= 0.34 [6]. This approximation assumes that the satellite reflects sunlight with the same albedo in both I and R spectral bands, and that other emissions that are not reflected sunlight may be neglected. Even if the actual target $(R-I)$ color difference were one whole magnitude different than that of the Sun, this approximation would still only introduce an inaccuracy of ≈ 10% in the calibration procedure.

5. CONCLUSION

We have developed the Anuenue photometer which is capable of producing high quality photometry of unresolved sources. The data produced will help answer questions on the composition, shape and state of unresolved satellites in both low Earth and geosynchronous orbits.

6. Acknowledgments

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7. References

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