The Gaia Catalogue Second Data Release and its Implications to Optical Observations of Man-made Earth Orbiting Objects

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ABSTRACT

The Gaia spacecraft was launched in December 2013 by the European Space Agency to produce a three-dimensional, dynamic map of objects within the Milky Way. Gaia's first year of data was released in September 2016. Common sources from the first data release have been combined with the Tycho-2 catalogue to provide a 5-parameter astrometric solution for approximately 2 million stars. The second Gaia data release, made public in April 2018, provides astrometry and photometry for more than 1 billion stars; a subset of which contains the full 6-parameter astrometric solution (adding radial velocity) and positional accuracy better than 0.002 arcsec (2 mas).

In addition to precise astrometry, a unique feature of the Gaia catalogue is its production of accurate, broadband photometry using the Gaia G-band. In the past, clear filters have been used by various groups to maximize likelihood of detection of dim man-made objects but these data were very difficult to calibrate. With the second release of the Gaia catalogue, a ground-based system utilizing the G-band filter will have access to 1.5 billion all-sky calibration sources down to an accuracy of 0.02 magnitudes or better. We discuss the advantages and practicalities of implementing the Gaia filters and its associated catalogue into data pipelines designed for optical observations of man-made objects.

1. INTRODUCTION

The space environment is populated with billions of dollars' worth of economic and military investments, is growing more crowded, and is home to increasingly smaller spacecraft. Fragmentations and collisions within this population lead to the production of small debris across Earth orbits that is becoming increasingly ubiquitous and difficult to track.

The National Aeronautics and Space Administration's (NASA) Orbital Debris Program Office (ODPO) is charged with providing measurement based statistical models and information about the Earth orbiting debris environment. Observations of man-made objects with altitudes near Geosynchronous orbit (GEO) are obtained primarily by using optical (visible) telescope assets. These assets use reflected light from the Sun to infer information about the objects' size and orbit. Bright objects are generally tracked by the Space Surveillance Network and information about these objects is made public in their associated catalogue. However, a population of small and dim debris objects exists outside of the catalogue and understanding the characteristics of these objects is necessary to model the environment accurately. In particular, optical observations of GEO debris are necessary to estimate the population's size and population density as a function of orbit.

To obtain an estimate for a detected object's size, many assumptions must be made. Common assumptions relate the object's photometric magnitude to a particular albedo, shape, and phase function. To minimize error, this magnitude should be calibrated to a standard photometric filter system. This allows for a meaningful comparison of debris observations made at an earlier time or by other telescopic systems.

By their nature, filters attenuate certain sections of the spectrum and reduce the sensitivity of the system. Since the objects of interest are inherently dim, observations characterizing the unknown debris population require maximizing the throughput of the filter system while maintaining photometric accuracy so that these dim objects can be detected and characteristics inferred.

2. PHOTOMETRIC CALIBRATION METHODS

Producing photometry that can be compared to previously obtained measurements requires considering the combined responsivity and current atmospheric conditions of the system being used. Contributing factors include the spectral response of the optical surfaces, the specifications of the detector, and the atmospheric extinction, which can attenuate signals as a function of wavelength.

The accepted calibration method to account for differences between systems and observing sites is to observe stable (non-variable) stars with well-known spectra. From this, an estimation of the atmospheric extinction (how much of the star's signal has been attenuated due to the atmosphere) and the system's zero point can be derived. The zero point is defined as: for a given bandpass (filter), the magnitude at which an astronomical source produces one analogue-to-digital unit (ADU) per second the detector is exposed. This number, therefore, provides a quick understanding of the systems' throughput or sensitivity to detect an astronomical signal at a given wavelength range.

Various stellar catalogues have been produced that provide these calibration sources, often located in specific or limited sections of the celestial sphere [1, 2, 3, 4]. Photometric calibration using these star fields requires periodically slewing the telescope off the target to observe the calibration source. This can be time consuming and atmospheric qualities can vary between the calibration source and the target, lowing the calibration accuracy.

Alternatively, all-sky catalogues have also been produced providing calibration stars down to a particular brightness limit, accuracy, and sky-coverage. Using these catalogues as references provides calibration sources within the same image as the target of interest, removing the atmospheric or time concern associated with using standard star fields.

Both of these methods require either making target observations using the same bandpass as the catalogued calibration source or accounting for the difference in spectral response between the two systems. Therefore, if calibrated photometry is a requirement, use of an astronomical filter that can be associated with a known stellar calibration catalogue is necessary. Additionally, if maximizing signal throughput but also maintaining the ability to produce calibrated photometry (as in the case for orbital debris observations) is a requirement, then select a broad-band, all sky, and accurately calibrated stellar catalogue.

3. THE GAIA SPACECRAFT: MISSION AND INSTRUMENTATION

The Gaia spacecraft is a European Space Agency mission launched in late-2013 as a follow-on to the previous Hipparcos mission. Its primary purpose is to survey astronomical objects in the Milky Way and create a dynamic, three-dimensional map of the detected objects. Its basic design concept consists of an array of charge coupled devices (CCD) across a focal plane that can provide x and y coordinates and various bands of photometry for a detected source as the spacecraft rotates and allows sources to scan across the focal plane.

Over its planned 5-year mission, Gaia will monitor over 1.5 billion sources (primarily stars), provide extremely precise photometry, and produce 6-parameter astrometric solutions for detected objects. These parameters are: the object's positional information, its rate of change in position, its distance, and its radial velocity (the speed of the object's motion towards or away from Earth). This information, combined with other standard photometric or spectroscopic observations, can provide information about a star's size, age, material composition, and other interesting properties, such as whether the star is native to the Milky Way. The Hipparcos mission obtained similar results but with fewer sources and precision. Gaia has already surpassed the Hipparcos' catalogue source count by two orders of magnitude.

Gaia is capable of producing photometry using three different bands: the G, G_{BP} and G_{RP}. The G-band produces a transmission curve (transmission vs. wavelength) similar to the quantum efficiency curve of a standard CCD.

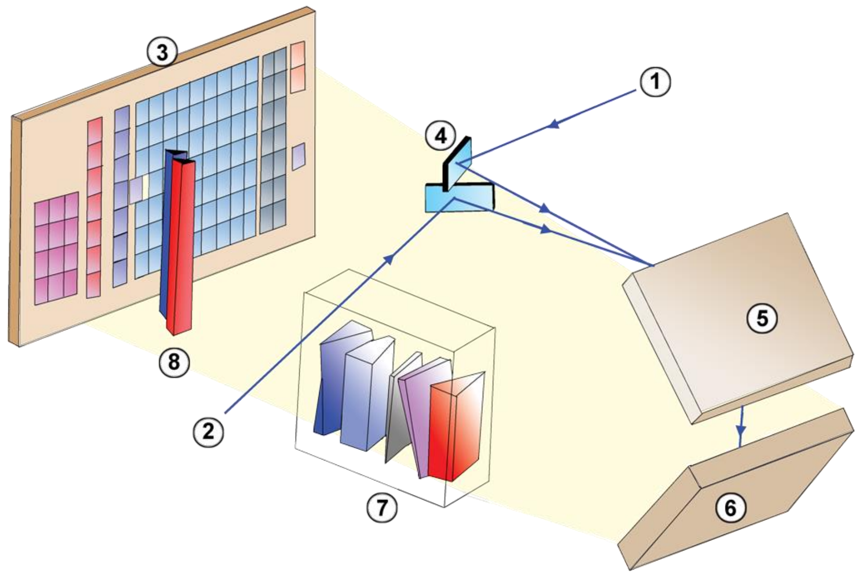

Fig. 1. The Gaia Focal Plane. 1: Incoming light from mirror M3. 2: Incoming light from mirror M'3. 3: Focal plane, containing the detector for the Astrometric instrument in light blue, Blue Photometer in dark blue, Red Photometer in red, and Radial Velocity Spectrometer in pink. 4: Mirrors M4 and M'4, which combine the two incoming beams of light. 5: Mirror M5. 6: Mirror M6, which illuminates the focal plane. 7: Optics and diffraction grating for the Radial Velocity Spectrometer (RVS). 8: Prisms for the Blue Photometer and Red Photometer (BP and RP). *Image credit: ESA - A. Short*

The G_{BP} and G_{RP} band photometry is produced via separate CCDs that use a series of prisms acting like broad-band filters. As the spacecraft rotates, the source's light scan across the G_{BP}-, G_{RP}- and G-focal planes so each source is correlated from chip-to-chip. As a result, high precision, multi-band photometry is produced near-simultaneously to the astrometric information.

In April 2018, Gaia released its second data release (DR2) which includes approximately 1.6 billion photometric sources with a G magnitude, and 1.3 billion sources with G_{BP} and G_{RP} magnitudes [5]. The typical uncertainties listed are 0.3 milli-magnitude (mmag) for G < 13 up to 10 mmag for sources of G = 20.

4. ADVANTAGES OF USING THE GAIA G-BAND FOR ORBITAL DEBRIS OBSERVATIONS

For orbital debris observations, as mentioned, it is often necessary to maximize the sensitivity of the photometric system since the objects of interest are, by their nature, difficult to detect. This is a combination of their small size and low albedo, which results in a low albedo-area product of the object's reflected light. Therefore, the strategy becomes an attempt to maximize the throughput of the system while simultaneously taking data using a photometric system that has been precisely calibrated.

Fig. 2 shows two common bandpass systems: Sloan Digital Sky Survey (SDSS) and the Johnson-Bessell filters. Current and historical observations have used either a modified Johnson R filter or the SDSS r′ filters. More recent observations of orbital debris using NASA's Eugene Stansbery Meter Class Telescope (ES-MCAT) have used the r′ to calibrate its photometry.

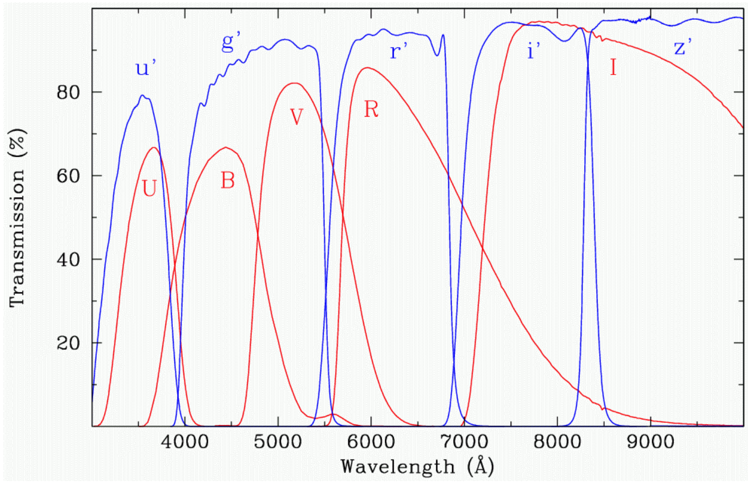

Fig. 2. Filter transmission curves for the Johnson-Bessell and the Sloan Digital Sky Survey filter system.
Image credit: Telescopio Nazionale Galileo

For comparison, the Gaia bandpass system can be seen in Fig. 3.

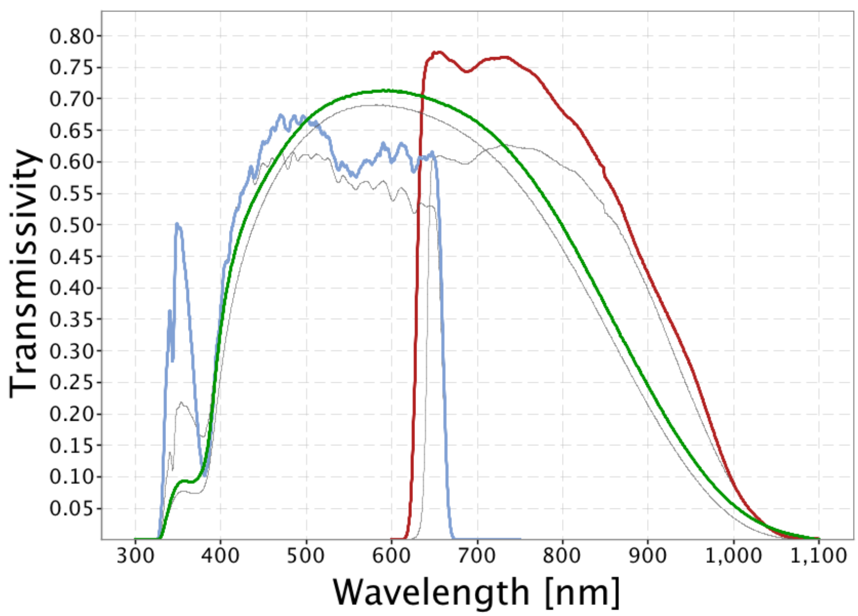

Fig. 3. The Gaia passband system. The colored lines represent the modified passbands that are representative of the colors released in DR2. The G-band curve is shown in green, the G_{BP} in blue, and the G_{RP} in red. The grey lines are the pre-launch estimations for the passbands.
Image Credit: Jordi et al 2010[6] and the ESA GAIA DR2 information page

Comparing the systems, it is quickly apparent that the Gaia G filter covers the broadest bandpass with its spectral throughput being very close to that of a standard CCD detector. To illustrate this further, Fig. 4 shows the throughput of the SDSS r′ compared to the Gaia G.

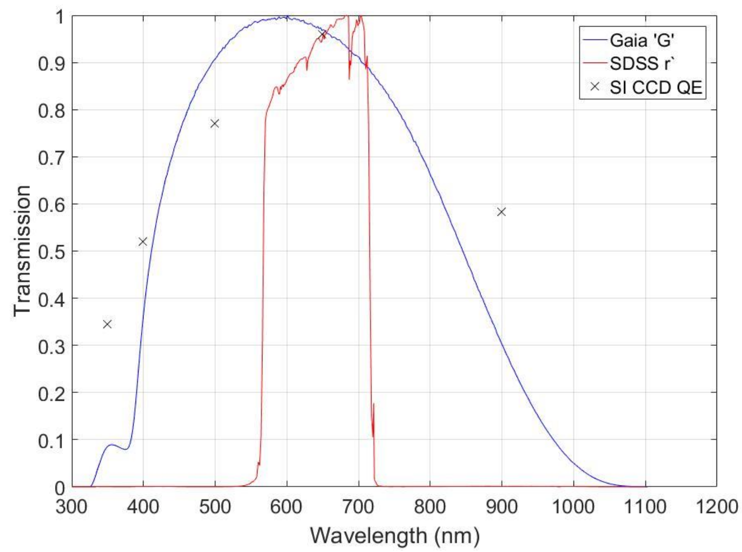

Fig. 2. The Gaia G-band transmission curve as compared to the SDSS r` filter and the quantum efficiency of a typical E2V Charged Coupled Device.

Summing the area under the two curves and applying the magnitude equation ($-2.5 \, Log \, (F_G/F_{r`})$), we find there is a 1.1 magnitude flux increase using the Gaia filter. This does not account for the object's reflectance spectra, the quantum efficiency of the various detectors, or wavelength specific attenuation of the atmosphere. These effects would need more precise characterization to understand the advantages possible with to specific system. In addition to the potential increased throughput using the Gaia system, Gaia provides the option for all-sky coverage which, as mentioned, does not require constant reslewing of the telescope, increasing the efficiency of the observations.

Implementing the use of the Gaia system can be accomplished in two ways. One method is to continue using standard filters such as the Johnson-Cousins or SDSS and to convert the standard stars' observed magnitude into the Gaia bandpass. This can be done via filter to filter conversions that are outlined in Jordi et al 2010 [6]. This method takes advantage of the all-sky nature of the catalogue such that in-frame calibrations can be done regardless of where one is pointing in the celestial sphere. It also allows for possibility of calibrating data that was previously obtained.

The second method, and the one more applicable towards optimizing orbital debris observations, is to develop a system-specific filter that can mimic the G bandpass after it is convolved with the detector's quantum efficiency curve. This provides the same advantages as the previous method but also takes advantage of the near-open band calibrated photometry, which is necessary to push down a system's detection limit. Because of the broadband nature of the G bandpass, developing a representative filter is not difficult to produce.

Integrating previous applications of the more standard filter systems' color-photometry to distinguish populations or materials within the Earth orbiting population with the Gaia G_{BP} and G_{RP} bands is also a subject of interest and will be the subject of a later paper.

5. CONCLUSIONS

The Gaia spacecraft has produced an all-sky calibration source with unprecedented photometric and astrometric precision. Estimates here show it potentially, could increase the sensitivity of a telescopic system by approximately 1.1 magnitudes while still providing comparable, exoatmospheric photometry between observations. In addition to the estimates produced here, which show theoretical applications of a system using a near-open filter system similar to the G-band, conversions of more standard filter systems can be found in Jordi et al 2010 which could allow for previously obtained data to be calibrated with in-frame sources. Potential also exists to extend previous work using color-color information to characterize on-orbit materials in the Gaia photometric system, but this will be the subject of future work.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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