Unmanned Aerial Systems for Variable Star Astronomical Observations

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Abstract Variable star astronomy (and astronomy in general) has two problems: a low altitude problem and a high altitude problem. The low altitude problem concerns ground-based observatories. These observatories are limited by inclement weather, dust, wind, humidity, environmental and light pollution, and often times being in remote locations. Ideal locations are limited to dry and/or high elevation environments (e.g., the Atacama Desert in Chile). Locations such as low elevation, rainy, and polluted environments are undesirable for ground-based observatories. These problems can be resolved by spacecraft operating above the degrading effects of the atmosphere, but come at a very high price (the high altitude problem). Additionally, maintenance is impossible with space-based telescopes (e.g., Kepler with its degraded performance due to the loss of reaction wheel control). One potential solution to the low/high problems may be to utilize an Unmanned Aerial Vehicle (UAV) carrying a telescope payload. A modest sized UAV could easily carry a telescope system payload high above the ground environment at a fraction of the cost of spacecraft. This could permit essentially round-the-clock operation in virtually any location and in any type of environment. This will become increasingly important to both professional and amateur astronomers who will need quick access to telescopes for follow-up support of new astronomical observatories such as the Large Synoptic Survey Telescope (LSST) and the Transiting Exoplanet Survey Satellite (TESS) which will continuously generate enormous amounts of data.

1. Introduction

A potential solution to the low/high problem of ground-based and space-based astronomical observatories is to utilize a "moderate-altitude system" that operates above the degrading effects of the near-earth environment but at a fraction of the cost of space-based assets. Such a moderate-altitude system is the Unmanned Aerial System (UAS). Unmanned Aerial Systems consist of multiple components or segments: an Unmanned Aerial Vehicle (UAV) segment, a ground-based UAV control and status segment, a ground-based "mission product" data collection and processing segment, and a ground-based segment for UAV payload control and status. An Unmanned Aerial Vehicle, commonly known as a drone, is an aircraft without a human pilot aboard, but controlled by humans from the ground control stations. The UAV would host an astronomical telescope payload, not unlike what is used at ground observatories. Figure 1 shows the high level system architecture of an Unmanned Aerial System operated as an airborne telescope platform.

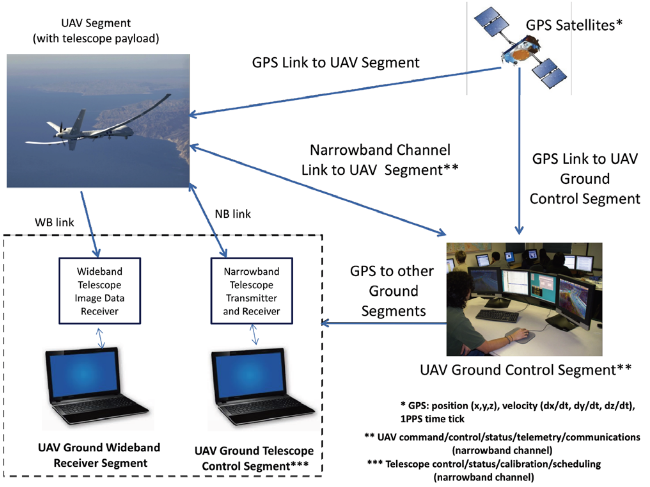

Figure 1. UAS System Architecture for Telescope Operations.

2. Background

Unmanned Aerial Vehicles (UAVs) have existed for many decades, but have achieved impressive technical advances in approximately the last 20 years. This is primarily the result of use of UAVs by the U.S. military since the terrorist attacks of September 11, 2001. These systems have been used for surveillance and intelligence gathering missions as well as delivery of weapons-on-target in Iraq, Afghanistan, Syria, and other war zones without endangering human pilots and aircraft crew members.

In addition to the military uses and applications, drones have become the vehicle of choice for many non-military, civilian, and commercial applications and have become a household word that most people are familiar with. As the drones continue to evolve technologically, they are becoming capable of carrying more advanced payloads on smaller platforms at decreasing costs. What would have been difficult, if not impossible, even a few years ago is now rapidly becoming feasible at affordable costs.

One application for Unmanned Aerial Systems that appears not to have been seriously addressed to-date is their use as medium altitude astronomical observation platforms. Optical and electro-optical payloads are relatively common on drones for ground surveillance and eyes-on-target military and intelligence applications. However, astronomical observation applications with the optics "pointing the other way" seems to have not received much attention. Both types of optical payload systems share common problems and solutions. This paper will address many of the issues of importance, from an engineering perspective, necessary to utilize Unmanned Aerial Systems for astronomical observations.

As previously mentioned, Unmanned Aerial Systems consist of various component segments. While the exact number

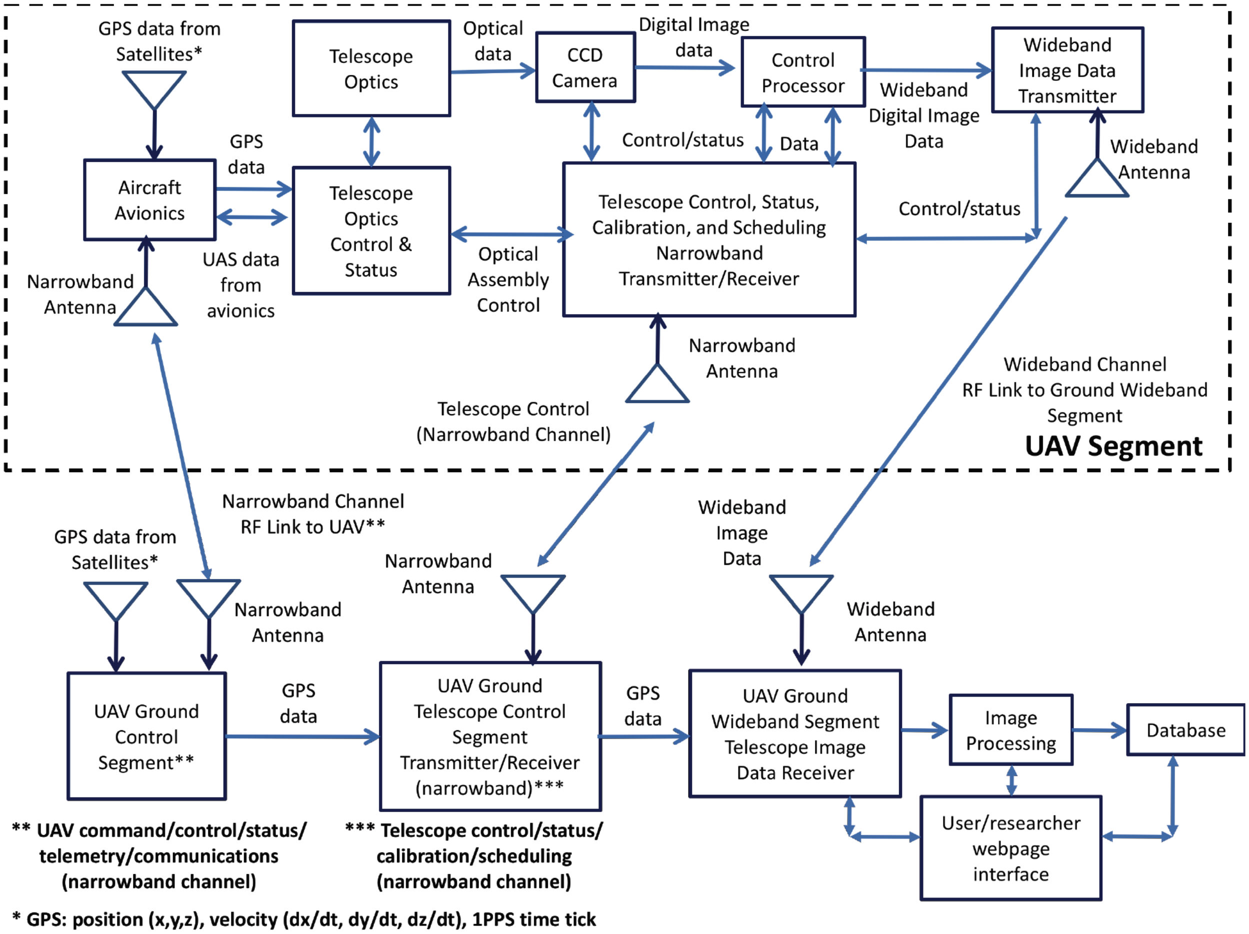

Figure 2. Detailed UAS System Architecture for Telescope Operations.

of segments depends upon the level of detail required, the overall system can be broken down into four major parts: an Unmanned Aerial Vehicle (UAV) segment, a ground-based UAV control and status segment, a ground-based mission product data collection and processing segment, and a ground-based segment for UAV payload control and status. Additionally, all segments rely upon GPS information, but this is not considered to be part of the UAS. This overview is shown in Figure 1. Below is the detailed description of each segment. However, most of the emphasis will be placed on the UAV segment since it is the astronomical observation platform of interest, with the other segments acting in supporting roles. The detailed UAS systems architecture for astronomical telescope operations is shown in Figure 2.

3. Instrumentation and methods

3.1. Unmanned aerial vehicle segment

The UAV airborne component or segment is the “housing” for the telescope payload in the same way that the ground-based observatory and spacecraft are the “housings” for ground-based and space-based telescopes, respectively. Although there are potentially numerous possible candidates for the airborne segment, one excellent example is the NASA Altair UAV (NASA 2015). The Altair, a high altitude version of the military Predator B, was specifically designed as an unmanned platform for both scientific and commercial research missions that require endurance, reliability, and increased payload capacity. Figures 3 and 4 show the Altair UAV in flight and on the ground with its payload bay open, respectively. The Altair has an 86-foot wingspan, a 36-foot length, can fly up to 52,000 feet with airspeed of 210 knots, and has an airborne endurance of 32 hours. Additionally, it has a gross weight of 7,000 pounds and can carry a payload up to 750 pounds (sensors, communications, radar, and imaging/telescope equipment). It incorporates redundant fault-tolerant flight control and avionics systems for increased reliability, GPS and INS (Inertial Navigation System), an automated collision avoidance system, and air traffic control voice communications for flights in National Airspace. Finally, it can be remotely piloted or operated fully autonomously.

3.1.1. Telescope optical system

The UAV telescope optical system would not be simply mounting a ground observatory type telescope in the aircraft (i.e., installing an AAVSOnet type telescope). This payload would necessarily incorporate adaptive and/or active optics. Adaptive optics is a technology used to improve the performance of optical systems by reducing the effect of incoming wavefront distortion by deforming a mirror in order to compensate for the distortion. Active optics is a technology used with reflecting telescopes which actively shapes the telescope mirrors to prevent deformation due to external influences such as wind,

Figure 3. The NASA Altair UAV in flight.

Figure 4. The NASA Altair UAV payload bay.

temperature, vibration, and mechanical stress. If the UAV segment is always flown at its maximum altitude of 52,000 feet, adaptive optics may not be needed since at that altitude it would be above all but a few percent of the earth's atmosphere (60,000 feet is above all but 1% of the earth's atmosphere). However, if flown at lower altitudes, adaptive optics may be necessary. Therefore, in order to account for all reasonable operational scenarios, it will be assumed that both adaptive and active optics are required (Wikipedia 2018).

Adaptive optics works by measuring the distortions in a wavefront and compensating for them with a device that corrects those errors such as a liquid crystal array or a deformable mirror. Deformable mirrors utilizing micro-electro-mechanical systems (MEMS) are currently the most widely used technology in wavefront shaping applications due to the versatile, high resolution wavefront correction that they afford. Active optics utilizes an array of actuators attached to the rear side of the mirror and applies variable forces to the mirror body to keep reflecting surfaces in the correct shape. The system keeps a mirror in its optimal shape against environmental forces such as wind, sag, thermal expansion, vibration, acceleration and gravitational stresses, and telescope axis deformation. These are all significant concerns in the UAV aircraft operational environment. Active optics compensate for these distorting forces that change relatively slowly, on the time scale of seconds, thereby keeping the mirror actively still in its optimal shape. Adaptive optics operates on shorter time scales (milliseconds) to compensate for atmospheric effects, rather than for mirror deformations. Adaptive optics and active optics can both be incorporated in the telescope optical path, since the former uses smaller corrective mirrors (secondary mirrors) while the latter is generally applied to the reflector primary mirror. Using both, atmospheric wavefront and aircraft environmental effects can be compensated for and corrected. Figure 5 illustrates generic adaptive optics architecture.

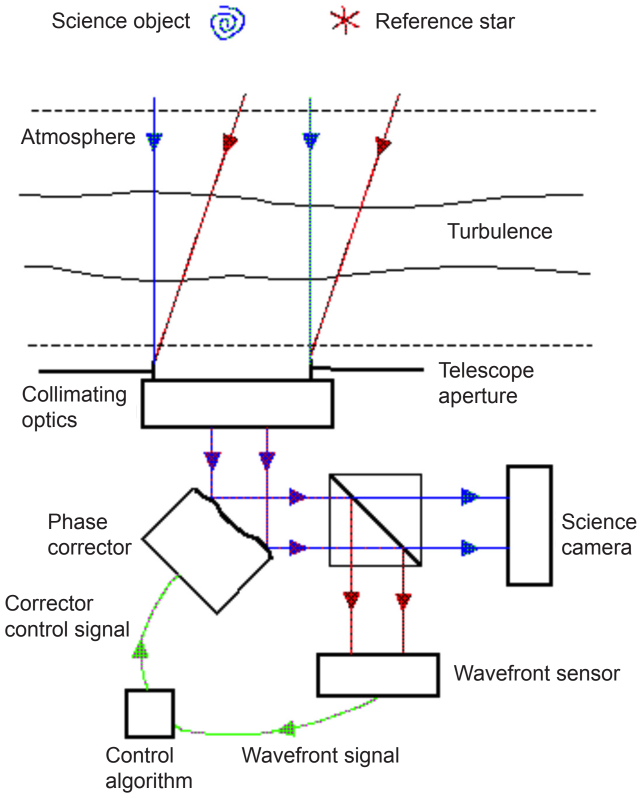

Figure 5. Adaptive optics architecture.

One of the most important issues for high altitude astronomical observations will be the use of guide stars as an optical reference for science imaging. Due to the continuous motion of the UAV, guide stars may be even more important than for ground-based observations. Since objects in science imaging may be too faint to be used as a reference for measuring the shape of optical wavefronts, bright guide stars in close proximity to the target stars need to be used. Since both the target and guide stars pass through the same atmospheric turbulence, the guide star can be used as a calibration reference source for the target star, thereby applying small corrections to the adaptive optics system. Additionally, since the UAV will necessarily use an optical window as the telescope "radome," the bright reference guide stars will be used to "calibrate out" the degrading effects of the optical window material (scratches, material imperfections, optical aberrations such as reflections, and so on).

In the situation where there are no useable natural guide stars close to the target star, artificial guide stars can be generated by using an onboard laser beam as the reference light source. Laser guide stars work by exciting atoms in the upper atmosphere, which then produce optical backscatter that can be detected by the onboard adaptive optics. The laser guide stars can then be used as a wavefront reference in the same way as a natural guide star. The weaker natural reference stars are still required for image position information (plate solving/pattern matching).

Two examples of optics payloads flown on high altitude aircraft are given in Appendix C.

3.1.2. Science image and data processing

The output of the adaptive/active optical system is optical data similar to most other telescopes, but presumably corrected for wavefront and UAV environmental degradations. As with other telescope systems, the optical data are immediately captured on a CCD camera, including any UBVRI (or other, Ha, for example) filtering that is required by the telescope user. The CCD camera output is digital image data which are then sent to the UAV telescope control processor. The control processor is the heart and brain of the telescope system since it coordinates all of the astronomical digital image data with the telescope control protocols being uplinked from the UAV telescope ground station.

As shown in Figure 2, the telescope control data, received from the ground, command the optics, receive optics performance status, perform optics calibrations (darks, flats, etc.), and schedule user activity (number/type/duration of images required, filter combinations, etc.). Additionally, the telescope control provides a feedback mechanism to the telescope optics control and status system (the UAV equivalent of a computerized telescope equatorial mount). This is also combined with the aircraft avionics data and the received UAV GPS data. The combination of these various inputs to the telescope optics keeps the optics stabilized against aircraft motion, vibration, shock, and acceleration as well as providing GPS data for "locating" the telescope as it flies its mission. The GPS provides x, y, and z position, dx/dt, dy/dt and dz/dt velocity, and a 1 PPS (pulse per second) time tick to synchronize all functions within the UAV telescope system as well as the overall UAV avionics system. All of the UAV telescope payload functions are controlled from the UAV ground telescope control segment via a narrowband channel RF (radio frequency) transmitter/receiver on the UAV segment.

Finally, the wideband digital image data (science images) from the telescope system are downlinked via an onboard wideband image data transmitter to the UAV ground wideband segment for further image processing as may be required. No wideband receiver is needed here since no wideband image data is uplinked to the UAV.

3.2. Ground-based UAV control and status segment

The UAV Ground Control Segment is used to control the UAV airborne segment. There are few, if any, direct interfaces with the telescope payload. The UAV Ground Control Segment acts as the aircraft "pilot" and air traffic control tower, similar to that for commercial or military aircraft operations. Instead of onboard human pilots and aircrew, all UAV flight operations are orchestrated remotely from the ground. The UAV has, at least in the case of the NASA Altair vehicle, redundant fault-tolerant flight control and avionics systems for increased reliability, GPS and INS (Inertial Navigation System), an automated collision avoidance system, and air traffic control voice communications for flights in National Airspace. It can be remotely piloted or operated fully autonomously. The Ground Control Segment interfaces with the UAV for command, control, flight status, operational telemetry, and voice/data communications. As a result, the UAV would appear as a normal commercial aircraft to national and international air traffic control systems.

3.3. Ground-based segment for UAV telescope payload control and status

Unlike the UAV Ground Control Segment which has little to do with telescope payload operation, the UAV Ground Telescope Control Segment handles all of the onboard telescope operations. These functions are similar to a ground based robotic telescope or perhaps satellite based telescope (but most likely considerably simpler then space assets). This UAS segment uses a narrowband communications channel to uplink telescope commands. This system performs telescope command, control, performance status, calibration, scheduling, and miscellaneous telescope payload overhead functions. This communicates directly with the UAV telescope control system on the aircraft as described above. The combination of the ground-based and aircraft-based telescope control system can be thought of as a distributed computerized equatorial mount for the airborne telescope. The UAV Ground Telescope Control Segment also receives GPS data, thereby keeping this segment synchronized with all the other UAS segments. Just as pilots "think" they are in the cockpit flying the aircraft, telescope users "think" they are operating a ground-based robotic telescope.

3.4. Ground-based wideband data collection and processing segment

The fourth UAS segment is the UAV Ground-based Wideband Data Collection and Processing Segment. This function again has nothing to do with the UAV aircraft operation, but is necessary for wideband image (science image) ground processing and post-processing. This segment utilizes a wideband RF receiver to acquire and process science data. Again, this segment receives GPS data to stay synchronized with the other segments, although in all likelihood only the 1 PPS timing information will be necessary. No RF transmitter is necessary in this segment since no wideband image data are sent back to the UAV. The processed/post-processed science image data are finally sent to astronomical databases for use by researchers, similar to the wide variety of astronomical databases currently in existence (e.g., Kepler, ASAS, ASAS-SN, NSVS, etc.).

4. Concept of operations and results

Based upon the UAS System architecture for telescope operations as presented above and shown in detail in Figure 2, a Concept of Operation (CONOPS) can be developed incorporating both the UAV flight parameters and telescope observation techniques. The CONOPS will include 1) UAV flight procedures necessary for telescope operation at altitude, 2) orbital scenarios, 3) optics calibration, and 4) telescope operation by the user/researcher. It will be assumed that the NASA Altair vehicle is used for this mission and flight procedures discussed below will reflect those of the Altair.

4.1. UAV flight procedures necessary for telescope operations at altitude

The UAV airborne segment of the overall UAS system, which carries the telescope payload to its operational altitude of 52,000 feet, can take off from any runway available as long as the UAV Ground Control Segment is in close proximity. The UAV and UAV Ground Control Segment do not necessarily have to be close to the UAV Ground Telescope Control Segment and/or the UAV Ground Wideband Segment telescope image data receiver, although there would be some advantages in doing so. The telescope payload would be dormant, powered down, and physically secured during all UAV takeoff (and landing) flight operations. As the UAV is climbing to altitude, the telescope payload bay would begin environmental stabilization procedures. These would include temperature and humidity control, mechanical vibration and shock damping, and condensation management (primarily when landing where extreme condensation can be a serious problem, even producing "rain" within the payload bay). Appendix A outlines mitigation procedures for controlling condensation.

4.2. Orbital scenarios

Upon reaching the desired altitude and after all equipment and the payload environment have stabilized, the UAV would be positioned into its operational "orbit." High altitude UAVs are typically flown in a long-duration loitering orbit around ground-based targets. Similar orbits would be used for astronomical observations. These operational orbits are typically long elliptical paths or four-sided "box" paths. The idea is to maintain the flight profile as straight as possible for as long as possible to minimize turning or banking maneuvers. With a 32-hour airborne endurance time, extremely long, stable flight paths should be possible.

After insertion into a stable operational orbit, the telescope payload will become operational. All telescope systems can be powered up, including all of the RF transmitters and receivers required to transmit and receive telescope commands to and from the ground segment as well as the wideband image transmitter for downlinking science images. At this point, telescope optics calibration can begin.

4.3. Optics calibration

Optics image calibration should be done when the UAV has reached operational altitude and the temperature and humidity inside the telescope payload bay have stabilized. In particular the CCD camera cooler should be allowed to stabilize prior to taking the image frames. Approximately 0.5 hour is the recommended time for payload stabilization. The optics calibration is similar to that performed with ground-based systems, i.e. bias frames, dark frames, and flat frames. Appendix B outlines calibration procedures based upon that recommended by the AAVSO. After calibration the telescope is ready for user/researcher operation.

4.4. Telescope operation by the user/researcher

The user/researcher would use the airborne telescope in a manner similar to that of a ground-based robotic telescope system such as AAVSOnet or iTelescope. Specifically, the users/researchers would access the telescope through a webpage that allows them to make reservations for time in the future, schedule various observing scenarios such as multiple short (time domain) images or long exposure images, UBVRI or other filter selection for imaging, manual optics calibration if desired, plate solving/pattern matching, focusing, and image download. Image processing by the user would then be done with appropriate personal software or access to analysis software such as VPHOT.

At the conclusion of an imaging session at altitude, the procedure for landing the UAV is essentially the reverse of the takeoff procedure. The telescope payload will be physically and mechanically secured, and powered down. Additionally, condensation control and mitigation will be started in order to protect the equipment from the adverse effects of condensation as the UAV decreases altitude. This is discussed in Appendix A.

5. Discussion and future directions

The implementation of moderate-to-high altitude UAVs carrying telescope payloads for astronomical observations appears not to have been seriously addressed to date as an application of rapidly advancing drone technology. This application allows observations to be performed above most, if not all, degrading atmospheric effects at a fraction of the cost of an equivalent space-based asset. Such an application can be realized with currently exiting scientific and technological resources at moderate cost. Full implementation of a system similar to that discussed above will require no new principles of physics nor advanced technologies that currently do not exist, i.e., needs nothing new to be discovered or invented. While new technologies would undoubtedly be helpful, nothing new is necessary.

Therefore, the current and future challenge will not be scientific or technological, but rather one of focused attention on solving the problem with adequate funding. This is almost always the hardest part of bringing new ideas to fruition. By combining private sector innovation with academic research capabilities and adequate capital resources from committed investors, Unmanned Aerial Systems for astronomical observation could become a reality in the near future.

6. Conclusions

One potential solution to the low/high problems may be to utilize an Unmanned Aerial Vehicle (UAV) carrying a telescope payload. A modest sized UAV could easily carry a telescope system payload high above the ground environment at a fraction of the cost of spacecraft. This could permit essentially round-the-clock operation in virtually any location and in any type of environment. This will become increasingly important to both professional and amateur astronomers who will need quick access to telescopes for follow-up support of new astronomical observatories such as the Large Synoptic Survey Telescope (LSST) and the Transiting Exoplanet Survey Satellite (TESS) which will continuously generate enormous amounts of data. Quick access to telescope systems that are not affected by environmental factors and enjoy very high duty cycles will become extremely valuable. Examples of optics payloads on two other high altitude aircraft are discussed in Appendix C.

7. Acknowledgements

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Additional thanks go to the author's coauthors of U.S. Patent Number 6559530 (Hinzel *et al.* 2003) who were involved in the development of Micro-Electro-Mechanical Systems (MEMS) technology. MEMS technology is critical for adaptive optics systems. Finally, the author wishes to thank the AAVSO for the publication of the *AAVSO Guide to CCD Photometry* (AAVSO 2014) which provides the complete procedure for accurate CCD photometry, including all of the calibration procedures.

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Appendix A: Condensation mitigation

For electro-optics systems, any residual moisture within the internal cavity or enclosure operated in the field and/or at altitude could produce disruptive condensation that fogs mirrors and lenses, which effectively could blind the equipment in critical situations. The other concern with condensation is corrosion, which is just as destructive because it can degrade performance and shorten system lifespan. Often used in commercial and military applications, electro-optics systems are mounted on aircraft, helicopters, missiles, or transported at high elevations where extremely low temperatures and air pressure can cause condensation even with minimal moisture present. With so much at stake, manufacturers of laser, imaging, camera, and other optical systems are increasingly mandating a nitrogen purge to wring the moisture out of enclosures and cavities before these systems are deployed to the field. However, this problem is still potentially serious when systems are operated at high altitude, even if measures have been taken during the manufacturing process to minimize the condensation problem. In a nitrogen purge, ultra dry nitrogen with a dew point of –70 degrees Celsius is introduced under pressure into an enclosure or cavity to remove moisture and create a much drier internal environment than standard desiccant can achieve. Nitrogen purging is accomplished through commercially available purging systems or ad hoc systems created by the engineers designing the product itself. The concept of a nitrogen purge is essentially to "squeeze" the internal components like a sponge to remove any residual humidity or moisture out of the system and then seal it up to keep the internal cavity moisture-free during its operational life.

It is a common misconception that the majority of the moisture in a sealed cavity or enclosure is contained in the empty volume of air. In fact, the majority of the moisture is contained in the hygroscopic materials, such as common internal plastic circuit boards or other plastic components within the enclosure. Hygroscopic plastics readily absorb moisture from the atmosphere and can release that moisture under temperature cycling and other environmental factors.

The internal electronics are the main culprit for much of residual moisture and must be remedied with a nitrogen purge. A nitrogen purge enters the cavity or enclosure through a single port and is pressurized to a pre-determined level before a valve opens and the gas flows back into the unit. There it passes a dew point monitor and displays the current dew-point temperature. The nitrogen is then vented to the atmosphere and a new cycle commences. This cycling continues until the equipment reaches the required dew-point level, at which point it automatically shuts off.

Appendix B: Optics calibration

Bias Frames: Bias frames should be done in a dark environment with the shutter closed. Exposure should be zero seconds or as short as possible. Approximately 100 images should be taken and averaged together to create a Master Bias.

Dark Frames: Dark frames should be done in a dark environment with the shutter closed, with exposure time as long or longer than the science images. Twenty or more images should be taken. If combining into a raw Master Dark use this only with science frames of the same exposure and do not use the Master Bias. If combining into a Master Dark, subtract the Master Bias from each, then average- or median-combine them all to create a Master Dark for use with science frames of equal or shorter exposure. Use this with the Master Bias in calibration.

Flat Frames: Flat frames should be taken with a uniform, calibrated light source within the telescope payload bay. The focus should be the same as that of the science images and exposure time should result in about half of the full well depth of the CCD. Ten or more images should be taken for each filter and averaged- or median-combined together. Subtract a Master Dark and Master Bias to create a Master Flat.

Appendix C: Optics payloads on high altitude aircraft

The application of UAS technologies and systems to variable star astronomical observations would not be the first time that optics payloads have been deployed on high altitude aircraft. Two notable examples are the military/homeland security systems which utilize what are termed Multispectral Targeting Systems (MTS) and the SOFIA system developed by NASA and the German Aerospace Center (DLR). SOFIA is the Stratospheric Observatory for Infrared Astronomy.

While the details of the military/homeland security MTS payloads are classified and not publicly available, some indication of this capability may be inferred from what is known about certain recent anti-terror operations utilizing the Predator B, Predator XP, Grey Eagle, and other high altitude systems. Figure 6 shows a typical MTS mounted on the underside of the Predator vehicle.

This system utilizes a 12-inch sensor turret weighing less than 60 pounds that sees in infrared and the visible spectrum and delivers intelligence in high-definition, full motion video. Its camera contains 4096 × 4096 pixels with a field of view of 11.4 × 11.4 degrees. Other MTS units have selectable fields of view, for example a wide FOV of 27.7 degrees, a medium FOV of 6.0 degrees, and a narrow FOV of 1.02 degrees. If it assumed that the Predator is operating at its maximum altitude of 52,000 feet and can clearly detect and track in real-time a human being who is approximately 6 feet tall and running at high speed, this will give an indication of the resolution that is operationally achievable. Undoubtedly, the actual classified performance would be significantly better than that.

Figure 6. Predator Multispectral Targeting System.

SOFIA is a multi-sensor platform flown in a modified Boeing 747 aircraft carrying a 2.7-meter (106-inch) reflecting telescope. The telescope consists of a parabolic primary mirror and a hyperbolic secondary mirror in a bent Cassegrain configuration, with two foci (the nominal IR focus and an additional visible light focus for guiding). The IR image is fed into a focal plane imager which is a 1024 × 1024 pixel science grade CCD sensor. It covers the 360–1100 nm wavelength range, has a plate scale of 0.51 arcsec/pixel, and a square field of view of 8.7 × 8.7 arcminutes. Five Sloan Digital Sky Survey filters—u', g', r', i', z'—and a Schott RG1000 NIR cut-on filter are available. The system f-ratio is 19.6 and the primary mirror f-ratio is 1.28. Telescope elevation range is approximately 23–57 degrees with a field of view of 8 arcminutes.

In addition to the telescope itself, SOFIA carries several science instruments, including a mid-IR Echelle spectrometer, a far-IR grating spectrometer, a mid-IR camera and grism spectrometer, a far-IR heterodyne spectrometer, a far-IR bolometer camera and polarimeter, and a mid-IR bolometer spectrometer.

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