Uncrewed Aerial Systems (UAS) for Astrophysics Research:
Rapid Followup of Observations from the Vera C. Rubin Observatory

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Abstract: Recently, **The Vera C. Rubin Observatory** produced the first images and with that a new era in astronomy and astrophysics has begun. The unprecedented scale, cadence, and level of data access provided by Rubin and the Legacy Survey of Space and Time (LSST) program will transform how humanity studies the dynamics of the universe. The data provided by this survey will enable the exploration of many of the most pressing questions from cosmology such as why the universe is expanding, the large-scale properties of the expansion, and the nature of dark matter and dark energy. Rubin will produce petabytes of data that will require followup observations in order to study in more detail the initial observations made. Professional observatories are in high demand with tight schedules and it often takes days to weeks for astronomers to prepare proposals for followup observations. This is where Uncrewed Aerial Systems (UAS) play a critical role. UAS are significantly more agile and can respond in minutes to alerts produced by Rubin for followup observations. A network of UAS can provide an around-the-clock resource for continuous observations. An example of UAS operations for followup observations for Galactic Supernova will be presented.

Introduction

Astronomy 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 which is the location of the Rubin Observatory). 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). Like their ground-based counterparts, spacecraft suffer from lengthy delays due to creating proposals and scheduling observations. Additionally, maintenance is impossible with space-based telescopes.

One potential solution to the low/high problems may be to utilize Uncrewed Aerial Systems (UAS) carrying a telescope payload. A modest sized UAS 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 followup support of ground-based astronomical observatories such as the Vera C. Rubin Observatory/Legacy Survey of Space and Time (LSST) camera. Every night, the Rubin Observatory/LSST will take thousands of images, one every 34 seconds. After three or four nights, it will have covered the entire southern sky and then start all over again. It will identify 6 million objects in our solar system, 17 billion stars in our galaxy, and 20 billion galaxies in the universe. After a decade, Rubin will have taken more than 2 million images and generated 500 petabytes of data. Due to its wide field of view and the thousands of images taken, Rubin will generate millions of alerts per night that can be used for followup observations. This is where UAS plays a critical role. An important example of followup observations by UAS is in support of the SuperNova Early Warning System (SNEWS).

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 Uncrewed Aerial System (UAS). Uncrewed Aerial Systems consists of multiple components or segments; an Uncrewed 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 Uncrewed 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 Uncrewed Aerial System operated as an airborne telescope platform.

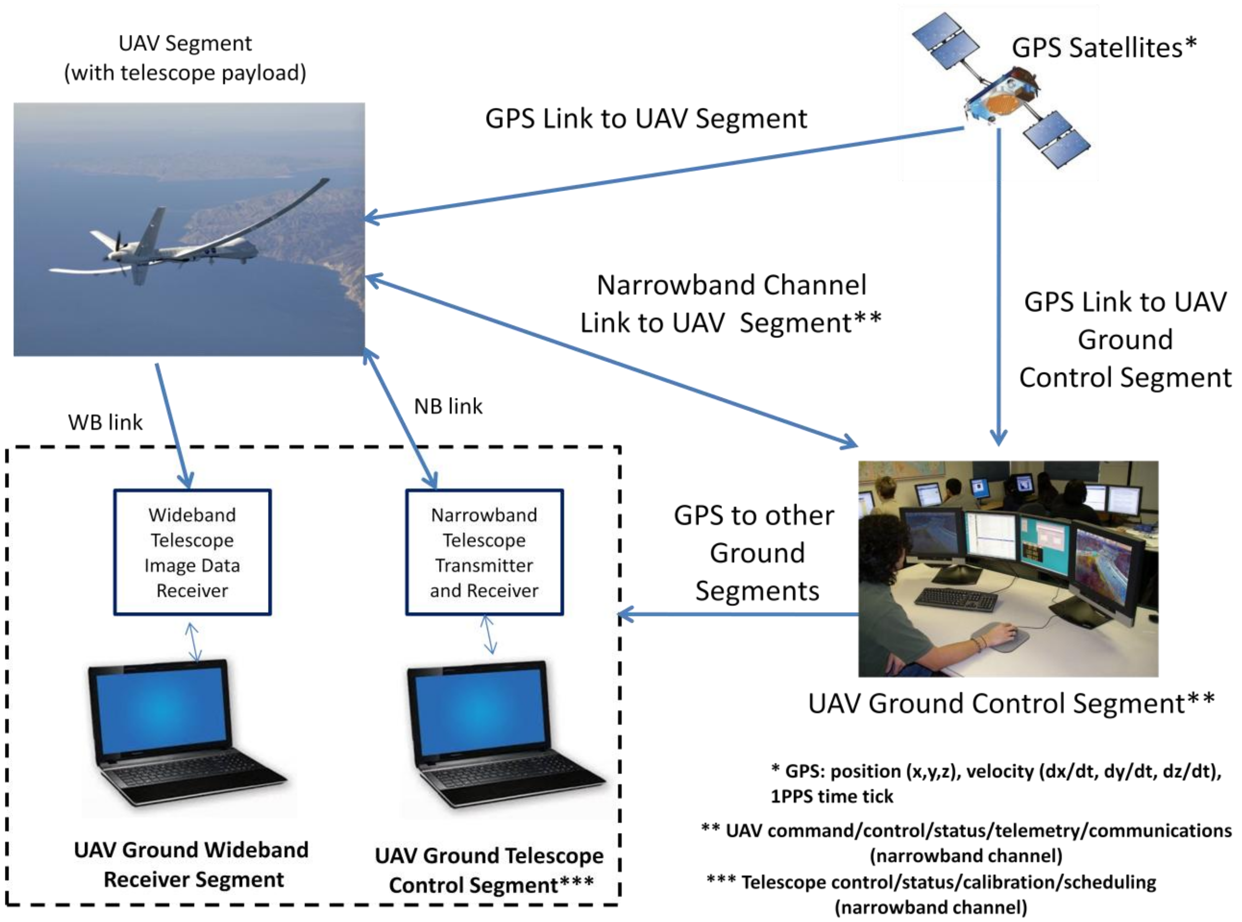

Figure 1: UAS System Architecture for Telescope Operations

1. Background

Uncrewed 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 for surveillance and intelligence gathering missions as well as delivery of weapons-on-target in 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 Uncrewed 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 Uncrewed Aerial Systems for astronomical observations.

As previously mentioned, Uncrewed Aerial Systems consist of various component segments. While the exact number of segments depends upon the level of detail required, the overall system can be broken down into four major parts; an Uncrewed 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 is shown in Figure 1 above. 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.

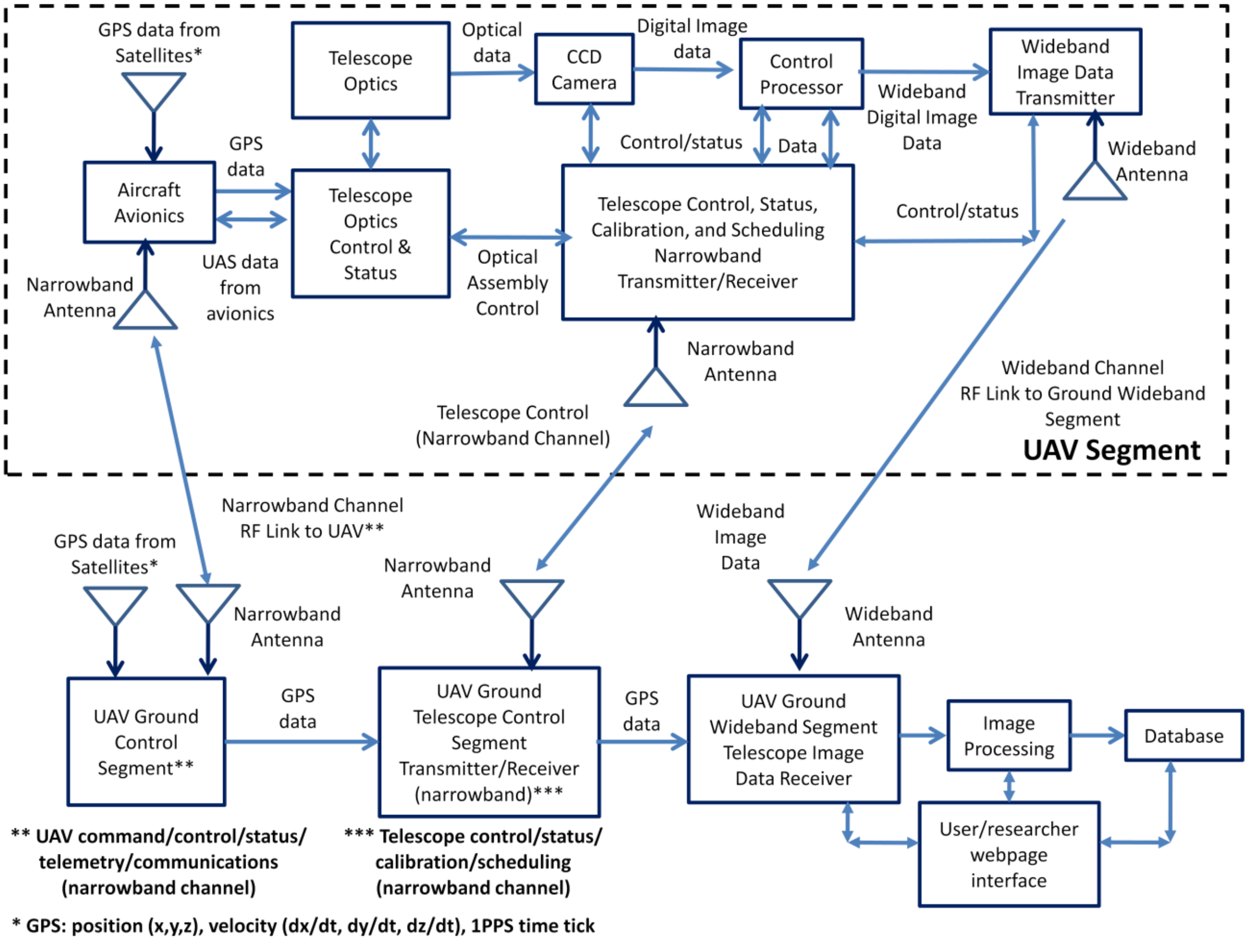

Figure 2: Detailed UAS System Architecture for Telescope Operations

2. Instrumentation and Methods

Uncrewed 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. 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 52000 feet with airspeed of 210 knots, and has an airborne endurance of 32 hours.

Additionally, it has a gross weight of 7000 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.

Figure 3: The NASA Altair UAV in Flight

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC05–0090–19 Date: April 20, 2005 Photo By: Tom Tschida

A satellite antenna, electro–optical/infrared and ocean color sensors (front) were among payloads installed on the Altair for the NOAA–NASA flight demonstration

Figure 4: The NASA Altair UAV Payload Bay

Telescope optical system**:** The UAV telescope optical system would not be simply mounting a ground observatory type telescope in the aircraft. 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, temperature, vibration, and mechanical stress. If the UAV segment is always flown at its maximum altitude of 52000 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 (60000 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.

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 later 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 a generic adaptive optics architecture.

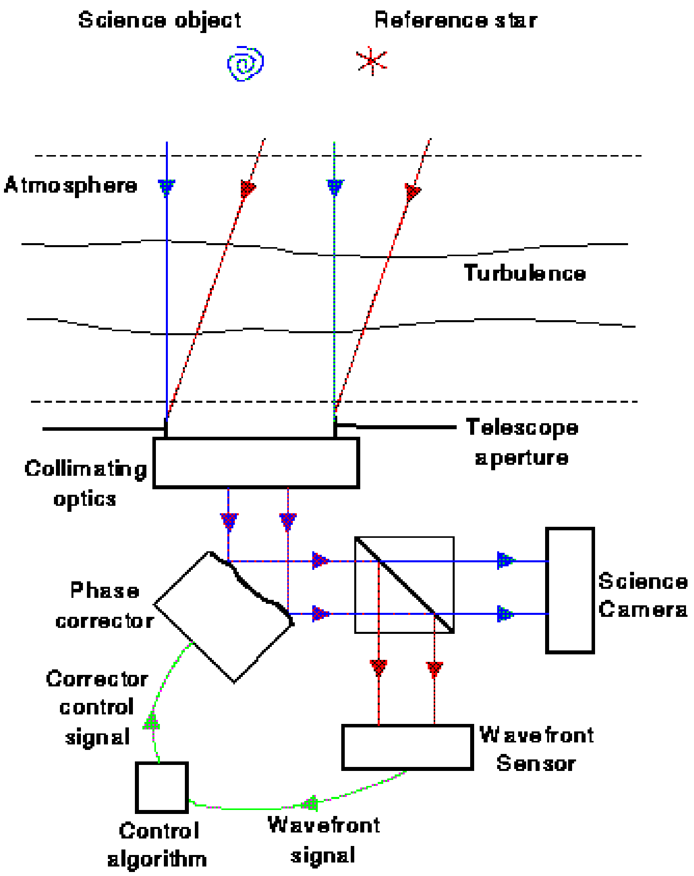

Figure 5: Adaptive Optics Architecture

One of the most important issues for high altitude astronomical observations will be the use of guide stars and/or stellar pattern matching fields 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, i.e., scratches, material imperfections, optical aberrations such as reflections, etc.

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).

There are multiple techniques that could be used in UAS for the telescope architecture. One creative approach is to use a design similar to the Rubin/LSST design. This is shown in Figure 6. The LSST utilizes an Active Optics System to optimize image quality by controlling the surfaces of three mirrors (M1, M2, and M3) and maintain the relative position of the three optical components (M1M3 mirror, M2 mirror, and the camera). The mirror surfaces are adjusted by control actuators. The primary mirror (M1) and the tertiary mirror (M3) occupy the same central position (M1M3) and the camera is positioned directly below the secondary mirror (M2) and aligned along the optical axis with it. The camera and M2 use actuators to facilitate optical positioning relative to the M1M3 mirror combination.

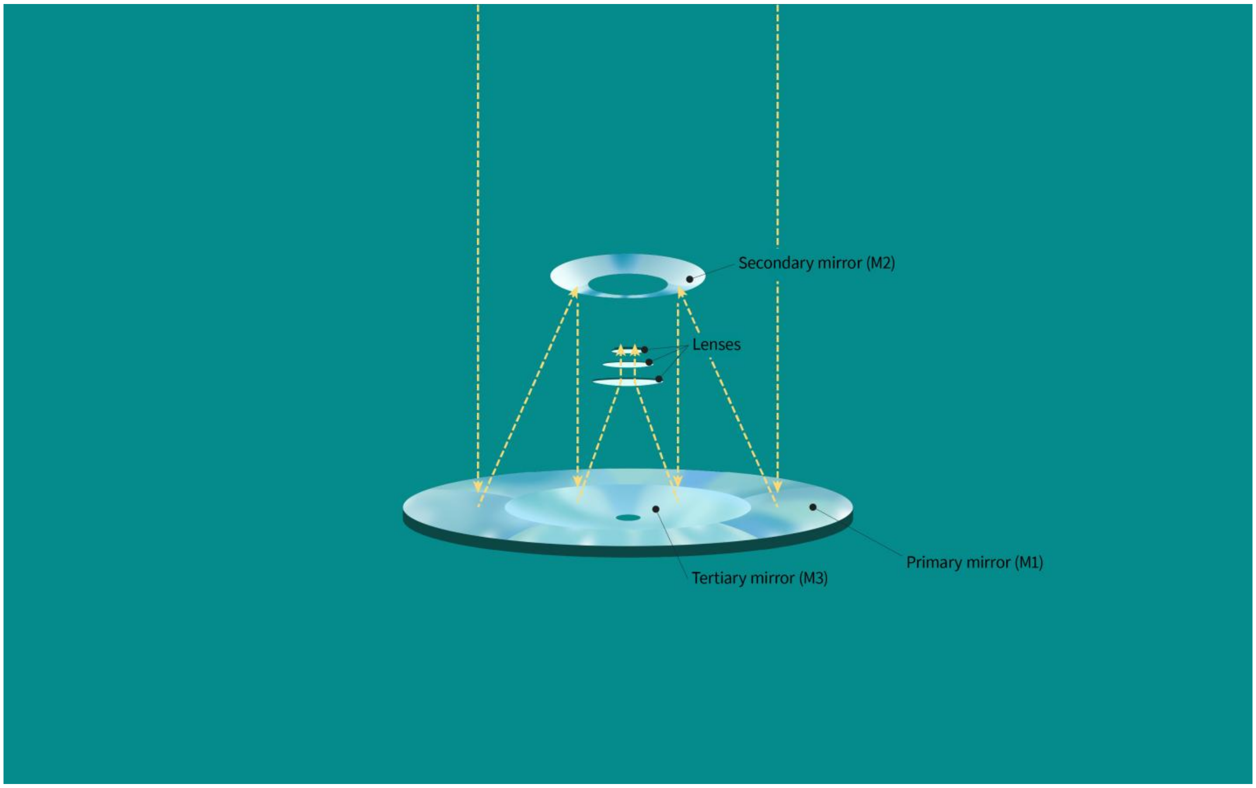

Figure 6: Telescope Architecture for UAS Based on the Rubin Design

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 is immediately captured on a CCD camera, including any UBVRI (ultraviolet, blue, visual, red, infrared) filtering that is required by the telescope user. The CCD camera output is digital image data which is 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, commands the optics, receives optics performance status, performs optics calibrations (darks, flats, etc.), and schedules 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 is 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.

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.

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.

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 is sent back to the UAV. The processed/post-processed science image data is finally sent to astronomical data bases for use by researchers, similar to the wide variety of astronomical databases currently in existence (e.g., Transiting Exoplanet Survey Satellite/TESS, All Sky Automated Survey for Supernova/ASAS-SN, Zwicky Transient Facility/ZTF, etc.). In the case of images generated by the Rubin Observatory/LSST, real-time alerts will also be transmitted so that the UAS can rapidly be airborne for follow-up observations.

3. 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.

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 52000 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 I outlines mitigation procedures for controlling condensation.

Orbital Scenarios:

Upon reaching the desired altitude and after all equipment and the payload environment has 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.

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 has stabilized. In particular the CCD camera cooler should be allowed to stabilize prior to taking the image frames. Approximately ½ 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 II outlines calibration procedures based upon that recommended by the American Association of Variable Star Observers (AAVSO). After calibration the telescope is ready for user/researcher operation.

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 (https://www.aavso.org/aavsonet).

Specifically, the users/researchers would access the telescope through a webpage or portal 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 the AAVSO VPHOT (https://apps.aavso.org/vphot/). In the case of images from the Rubin Observatory/LSST, the user/researcher could use the alerts generated when an image is taken, to request further images to be rapidly taken during the mission as long as requests do not conflict with other observing requirements. This could be orchestrated by the onboard and/or the ground-based UAS control capabilities.

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 I.

An example of UAS operations for followup observations:

An example of UAS operations for followup observations for Galactic Supernova is the SuperNova Early Warning System (SNEWS). When a massive star collapses at the end of its life, most of the binding energy is emitted in the form of neutrinos. These neutrinos emerge promptly from the stellar envelope over a timescale of seconds. If the star explodes, the burst of supernova photons does not become visible until hours later. We can therefore expect to observe the neutrino burst from a Galactic Supernova before we see the optical counterpart in the sky. Although a Galactic Supernova is rare and expected only every few decades, the next event will provide a unique opportunity to study these violent astrophysical phenomena. The observation of a neutrino burst can thus provide a warning for astronomers that the opportunity to get a rare glimpse at the collapse of a star, resulting in a supernova, may soon be presenting itself.

The neutrino burst is detected by a worldwide network of neutrino detectors buried deep underground to shield them from transient background radiation. These include KamLAND (Japan), HALO (Canada), and IceCube (South Pole). In addition, gravitational wave detectors like LIGO have sensitivity to asymmetrically-collapsing supernovae and can benefit from and contribute to such an alert. A neutrino detection alert message is immediately transmitted to any party that is in the SNEWS network for followup observations. This includes amateur astronomers and professional observatories such as the Rubin Observatory. With the alert information from the neutrino detector array, an estimated position of the neutrino outburst in the sky is determined and a plot generated. This is shown in Figure 7. The colored rings estimate the probability of the location of the neutrino source with the darker shades in the center being the highest probability and the lighter shades being lower probability. The black dots on the plot are the Milky Way as viewed edge-on. Given the fact that the various counterparts of a Galactic Supernova explosion, especially the optical counterparts, arrive on earth within a matter of hours, a rapid response is critical to followup observations in near-real-time. This is where the primary advantage of UAS comes into play. Upon detection of a neutrino burst from one or more neutrino detectors and the transmission of the detection alert, the UAS can be airborne and on station within minutes. At that point, the UAS will fly an elliptical, loitering orbit as previously described. Finally, as seen in Figure 7, even though an approximate location has been identified via the neutrino bursts, this nevertheless is still a relatively large area with millions of stars. The UAS, or multiple UAS, will still need to image numerous stars to derive a better position of the target of interest.

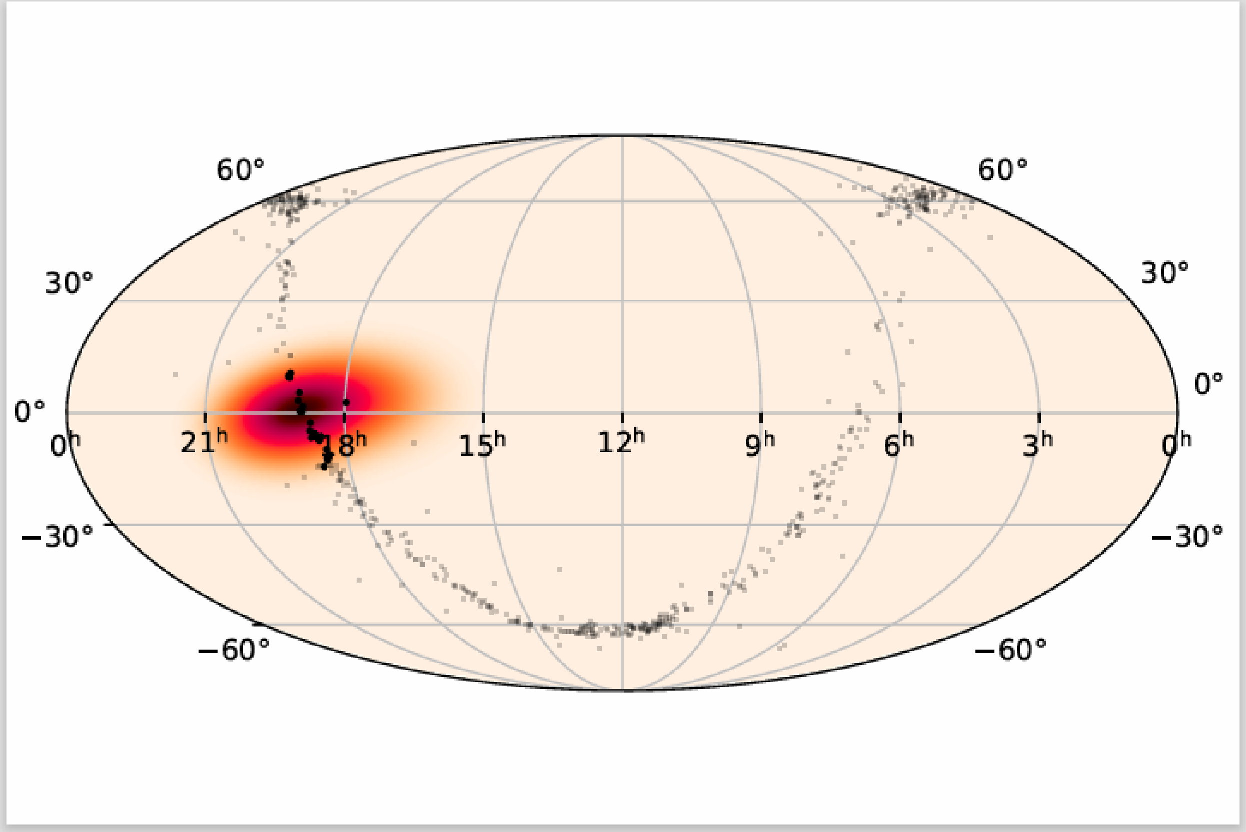

Figure 7: Galactic Plot of Supernova Neutrino Burst

4. 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. Uncrewed Aerial Systems for astronomical observation could become a reality in the near future.

5. Conclusions

One potential solution to the low/high problems may be to utilize an Uncrewed 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 followup support of new astronomical observatories such as the Rubin Observatory/LSST 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.

Acknowledgements

The author wishes to thank the AAVSO for the publication of the AAVSO Guide to CCD Photometry which provides the complete procedure for accurate CCD photometry, including all of the calibration procedures.

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Wikipedia: https://en.wikipedia.org/Active-optics. https://en.wikipedia.org/Adaptive-optics

Appendix

Appendix I: 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 II: 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 as 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 for each filter and averaged or median combined together. Subtract a Master Dark and Master Bias to create a Master Flat.