SWUIS-A: A Versatile, Low-Cost UV/VIS/IR Imaging System for Airborne Astronomy and Aeronomy Research

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ABSTRACT

We have developed and successfully flight-tested on 14 different airborne missions the hardware and techniques for routinely conducting valuable astronomical and aeronomical observations from high-performance, two-seater military-type aircraft. The SWUIS-A (Southwest Universal Imaging System – Airborne) system consists of an image-intensified CCD camera with broad band response from the near-UV to the near IR, high-quality foreoptics, a miniaturized video recorder, an aircraft-to-camera power and telemetry interface with associated camera controls, and associated cables, filters, and other minor equipment. SWUIS-A's suite of high-quality foreoptics gives it selectable, variable focal length/variable field-of-view capabilities. The SWUIS-A camera frames at 60 Hz video rates, which is a key requirement for both jitter compensation and high time resolution (useful for occultation, lightning, and auroral studies). Broadband SWUIS-A image coadds can exceed a limiting magnitude of $V = 10.5$ in <1 sec with dark sky conditions. A valuable attribute of SWUIS-A airborne observations is the fact that the astronomer flies with the instrument, thereby providing Space Shuttle-like "payload specialist" capability to "close-the-loop" in real-time on the research done on each research mission. Key advantages of the small, high-performance aircraft on which we can fly SWUIS-A include significant cost savings over larger, more conventional airborne platforms, worldwide basing obviating the need for expensive, campaign-style movement of specialized large aircraft and their logistics support teams, and ultimately faster reaction times to transient events. Compared to ground-based instruments, airborne research platforms offer superior atmospheric transmission, the mobility to reach remote and often-times otherwise unreachable locations over the Earth, and virtually-guaranteed good weather for observing the sky. Compared to space-based instruments, airborne platforms typically offer substantial cost advantages and the freedom to fly along nearly any ground-track route for transient event tracking such as occultations and eclipses.

1. INTRODUCTION

For decades, airborne astronomy and geophysical observations have proven useful adjuncts to ground-based and space-based instrumentation, particularly for optical and infrared studies [1]. Compared to ground-based instruments, airborne research platforms offer superior atmospheric transmission, the mobility to reach remote and often-times otherwise unreachable locations over the Earth, and virtually-guaranteed good weather for observing the sky. Compared to space-based instruments, airborne platforms typically offer substantial cost advantages and the freedom to fly along nearly any ground-track route for transient event tracking such as occultations and eclipses.

With Southwest Research Institute (SwRI) and NASA funding, we have developed the hardware and techniques for routinely conducting valuable astronomical and aeronomical observations from high-performance, two-seater military-type aircraft. A key advantage of these platforms over more conventional, larger airborne platforms (e.g., those based around KC-135/Boeing 707s and Boeing-747s) is a significant cost savings, often of order 10:1 per flight hour. Other key advantages include worldwide basing (obviating the need for expensive, campaign-style movement of specialized large aircraft and their logistics support teams), and ultimately faster reaction times to transient events. High-performance aircraft such as the F/A-18B also have the ability to reach higher altitudes and offer *unrestricted* pointing ability through all-sky canopies, important capabilities not available with other small airborne astronomical platforms such as the NASA Lear jet.

This development and demonstration project was accomplished with the Southwest Universal Imaging System – Airborne (SWUIS-A). SWUIS-A is a versatile and capable low-cost astronomical imaging system developed by our group beginning in 1997. We successfully flight-demonstrated SWUIS-A aboard both NASA WB-57 and F/A-18B aircraft (Fig. 1) flying out of Ellington Field at NASA's Johnson Space Center in Texas, and NASA's Dryden Flight Research Center at Edwards Air Force Base in California [2]. SWUIS-A is a simpler, broad-band visible-wavelength derivative of the NASA-funded SWUIS (Southwest Ultraviolet Imaging System) instrument that we have flown successfully aboard the Space Shuttle on STS-85 and STS-93 (see [3] for instrument description, and [4] for some initial scientific results).

A valuable attribute of SWUIS-A airborne observations is the fact that the astronomer flies with the instrument, thereby providing Space Shuttle-like "payload specialist" capability to "close-the-loop" in real-time on the research done on each aircraft research mission. Flight training for the two SWUIS-A payload specialists (authors Durda and Stern), funded largely with SwRI internal research grants, has included intensive FAA and NASA flight physicals, various aircraft systems training courses, altitude chamber training, aircraft egress and ejection seat training, water survival school, and aircraft certification check rides. We have also created and validated a detailed, 17-page instrument operations checklist (see `http://www.boulder.swri.edu/swuis/swuis.instr.html`), and have streamlined the process of astronomical and flight planning necessary to bring a SWUIS-A mission to a successful conclusion.

As noted above, 14 successful SWUIS-A missions have been flown to date. During each mission SWUIS-A performed flawlessly. These missions included five high-altitude flights in a NASA WB-57 to observe comet Hale-Bopp in mid-1997, a single mission in November 1998 aboard the USAF FISTA aircraft to study the Leonid meteor shower that year, and eight missions in NASA F/A-18B aircraft to perfect techniques for observing asteroid and planetary occultations over oceans where ground-based facilities cannot be based (see Section 3 below). Plans are in development to transition SWUIS-A to F-15, F-16 and U-2 aircraft as well, in part for their unique technical capabilities, and in part to broaden the available flight opportunities for research.

Figure 1. NASA Dryden F/A-18B aircraft 846 (left) and 852 (right). Authors Durda and Stern have successfully deployed SWUIS-A aboard these aircraft multiple times during our 1998–1999 Asteroid Occultation Demonstration Project (see Section 3).

2. DESCRIPTION OF THE SWUIS-A SYSTEM

SWUIS-A consists of: an image-intensified CCD camera with broadband response at visible wavelengths, high-quality foreoptics, a small video recorder, an aircraft-to-camera power and telemetry box with camera controls (called the PIB), a GPS position/time video encoder unit, and associated cables, filters, and other minor equipment (Figs. 2 and 3). An interconnect diagram of the major SWUIS-A hardware items is shown in Fig. 4.

SWUIS-A utilizes a Xybion Electronic Systems model ISS-750 intensified CCD camera that frames at video rates (60 Hz), which is a key requirement for both jitter compensation and the high time resolution needed for research such as occultation, lightning, and auroral studies. This camera has broadband response throughout the visible from roughly 400–900 nm, with a DQE of ~30% from 600–800 nm and a peak sensitivity between 750–800 nm (Fig. 5). For most astronomical work, the camera is mounted on a Bogen tripod mount firmly affixed to the top of the rear cockpit instrument glare shield. The Bogen mount allows precise pointing capability with outstanding image stability. The camera may be hand-held for applications requiring rapid or flexible target pointing. A precision digital inclinometer mounted on the camera allows highly accurate and repeatable target acquisition.

Figure 2. (Left) SWUIS-A flight hardware installed in the rear cockpit of a NASA F/A-18B. The SWUIS-A Xybion intensified CCD camera is mounted above the instrument glare shield on a Bogen bracket, allowing ALT/AZ pointing capability with image stability. The SWUIS-A camera control electronics and power interface box (PIB) is the white box mounted just forward of the stick, and is connected to the Xybion camera by the white cable harnesses. (Right) Author Durda preparing for takeoff to flight test the SWUIS-A system in a NASA F/A-18B (March 1999). The intensified CCD camera is visible with its light baffle installed on the foreoptic.

Figure 3. The SWUIS-A PIB installed in the rear cockpit of a NASA F/A-18B. Mounted just above the PIB is a Citizen LCD monitor used to verify camera pointing and to monitor image quality. The white cable connected to the top of the PIB carries camera power and control/video data. The cable connected to the left side of the PIB is routed to aircraft power and VTR connections on the right side of the cockpit.

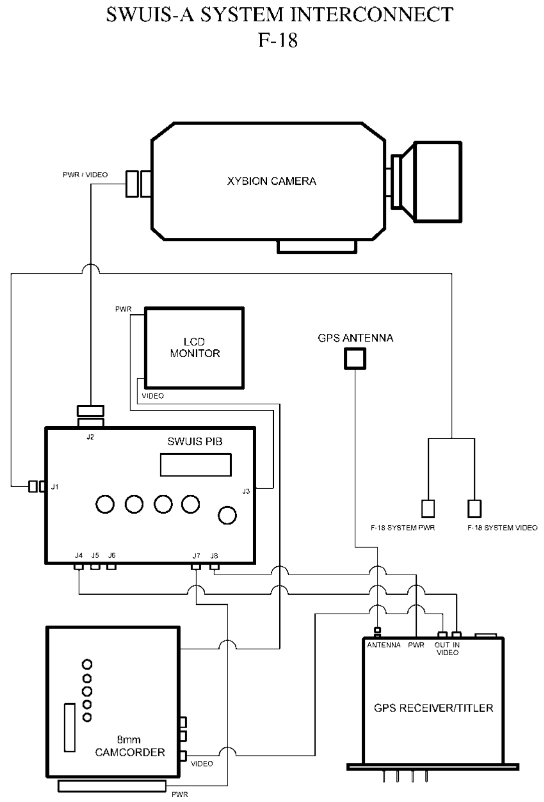

Figure 4. Interconnect diagram for the major SWUIS-A hardware elements. The F/A-18B configuration is shown.

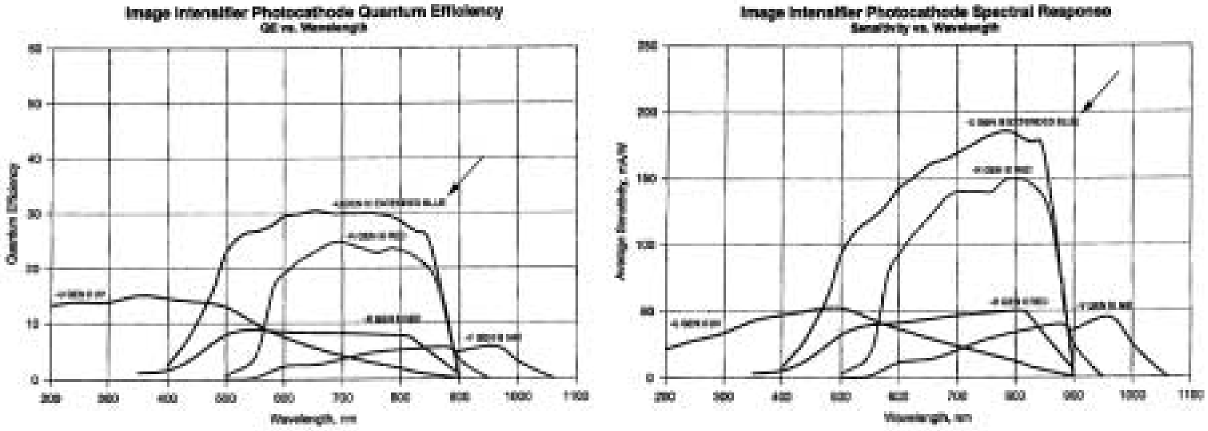

Figure 5. Detector Quantum Efficiency (left) and spectral response curve (right) of the Xybion Electronic Systems model ISS-750 intensified CCD camera utilized in the SWUIS-A system. The curves for the ISS-750 are the highest plotted here, labeled “GEN III EXTENDED BLUE” (indicated by arrows). This highly capable camera has broadband response throughout the visible from roughly 400–900 nm, with a DQE of ~30% from 600–800 nm and a peak sensitivity between 750–800 nm.

The primary SWUIS-A foreoptic is a fast 85mm f/1.4 lens, giving a wide field-of-view of 6.7º × 5.7º. With this foreoptic, SWUIS-A images can attain in dark sky conditions a limiting magnitude of $V = 9.5$ in single frames, and fainter than $V = 13.0$ in 10 sec integrations (after image frames have been co-registered to remove image drift and jitter due to aircraft motion and co-added to increase S/N; see Fig. 6 below). Along with pointing and instrument field of view selection, CCD intensifier gain, video gain, and other camera controls are available to the instrument scientist in the aircraft via a miniature LCD video monitor and the PIB, in order to maximize image quality in real-time.

SWUIS-A video data are recorded on a self-contained miniature SONY Hi-8mm video recorder for analysis after flight. Image data often can also be recorded on-board the aircraft; both of the NASA Dryden F/A-18B aircraft that we have utilized in the past are equipped with on-board Hi-8mm recorders mounted in equipment bays just forward of and below the cockpit. We process and analyze the recorded image data with Interactive Data Language (IDL) software routines, written and validated in-house at SwRI. The image reduction software, which we call “Betty2”, is an up-graded version of IDL software that our team developed to reduce and analyze SWUIS Space Shuttle image data, and was developed as a rapid data processing utility for initial assessment and full reduction of occultation data obtained with SWUIS-A. Betty2 allows one to pre-sum, co-register, co-add, and display SWUIS-A image sequence data. After hand-selection of stars on which image frames will be co-registered, image co-registration offsets are displayed as a function of time to confirm correct removal of image drift and/or jitter. The software also includes functions developed to measure the brightness variations in individual image frames at the pixel locations of specified stars, thus providing accurate, high time-resolution, background-subtracted aperture photometry of faint stars near the SWUIS-A detection limits. The SWUIS-A Betty2 image reduction and analysis software has been developed for portability and to operate on a laptop computer, allowing quick-look and preliminary data reduction capabilities in the field.

The advent of the satellite-based Global Positioning System (GPS) has revolutionized the ability of an observer to accurately determine their location anywhere on Earth, and now makes it possible for airborne observers to determine their time-variable location as accurately as stationary, ground-based observers. The SWUIS-A system utilizes a self-contained GPS receiver and video titler unit manufactured by Horita Corporation. The Horita GR-8/GPT-50 combined GPS receiver and titler unit stamps the input SWUIS-A video signal with GPS time and position information, and outputs the stamped video signal for recording on the video recorder. The unit is very small (4.4 × 15.2 × 14.6 cm), allowing its use in the cramped rear cockpits of fighter-type aircraft. The Horita GPS receiver/titler unit stamps *each* 1/60 sec SWUIS-A image data frame with accurate GPS time and precise aircraft location information, making it possible for us to accurately determine the geometric circumstances of SWUIS-A observations.

SWUIS-A hardware integration into NASA F/A-18B aircraft has typically taken between 3–6 hours, with integration times being reduced as both the SWUIS-A team and aircraft ground crews became more familiar with and streamlined the integration process. De-integration can be completed in as little as one half hour.

3. EXAMPLE SCIENCE: AIRBORNE OBSERVATIONS OF ASTEROID OCCULTATIONS

Occultations are a valuable and well-proven technique that planetary astronomers have developed to probe the solar system [5]. In an asteroidal occultation event, the light from a distant star is temporarily blocked out by an asteroid (within our solar system) that passes in front of the star, as seen from Earth. Hundreds of these events occur each year over all parts of the Earth. The main utility of asteroid occultations is their ability to determine the sizes, shapes, and (as a result of knowing the size and the brightness of the subject asteroid), its surface reflectivity. In effect, asteroidal occultations turn the impossible into the possible, by revealing the size and shape of asteroids, which typically have angular diameters of just a few milliarcseconds ($\sim 10^{-9}$ deg), and cannot be resolved in *any* telescope – including the Hubble Space Telescope. This is done by turning the problem from one of angular resolution into one of timing. In essence, one times the interval during which the star occulted by the asteroid disappears, and then converts that interval to a chord length in kilometers across the asteroid, knowing various geometrical circumstances of the event and the orbital motion of the asteroid (in actual practice, more precise modeling is required to achieve real precision). In addition to revealing sizes, shapes (with multiple observers), and reflectivities, asteroidal occultations have also detected asteroidal satellites and provided precise astrometric information that is used to refine asteroidal orbits.

The reduction of occultation data to yield the size and shape of an asteroid requires precise timing of the circumstances of the event and a careful determination of the observer’s location. For ground-based observers, both can be achieved in a straightforward manner: timing information is usually recorded from a radio broadcast time standard (station WWV) and the location information is accurately determined from topographic maps. Airborne observers have the added complication of a rapidly changing observing location and have had in the past to rely on less accurate means of determining the position of their aircraft at the time of the occultation event. NASA’s Kuiper Airborne Observatory, for instance, was equipped with an onboard Inertial Navigation System (INS), which used gyroscope-based instrumentation to measure changes in the aircraft position. Unfortunately, the INS can “drift” substantially once set, and can result in position errors of as much as several kilometers on a long mission, yielding significantly degraded resolution on the asteroid target as compared to data gathered by ground-based observers. The GPS system utilized by SWUIS-A and aboard other research aircraft has solved these problems.

With SWUIS-A, we set out to develop and demonstrate techniques for a low-cost, fast-response airborne occultation capability using NASA/Dryden Flight Research Center (DFRC) high-performance aircraft. Our Airborne Occultation Demonstration Project, which began in July 1998, was designed to produce flight occultation results from multiple events to prove this faster-cheaper concept in practice, and to determine its viability for more extended support as an operational science program in future years.

Toward this end, NASA’s DFRC made available a high-performance platform, the F/A-18B, and engineering support, ground, and flight crews. SwRI provided the SWUIS-A hardware, flight astronomers, and SwRI engineering support personnel to integrate SWUIS-A into an F/A-18B and fly a series of occultation observation, development, and test missions.

The SWUIS-A/F-18 system had to be: (1) tested for EMI/EMC compatibility in the flight environment; (2) tested for imaging performance and effective sensitivity as a function of aircraft speed and altitude (e.g., for boundary layer turbulence over the aircraft airframe) in order to determine the best F-18 observation speed and altitude; and (3) flown to then demonstrate the SWUIS-A/F-18 combined system performance in a series of 4–5 actual occultation missions to establish a track record and expand the SWUIS-A operational envelope. In 8 program flights, the major program operational objectives were successfully accomplished, including EMI/EMC checks, instrument sensitivity calibrations, aircraft ground track targeting, SWUIS-A star field pointing and target acquisition, and training of a second SWUIS-A operator. SWUIS-A performed flawlessly on all flights.

The Airborne Occultation Demonstration Project successfully concluded with the SWUIS-A observation of an occultation event involving the main belt asteroid 308 Polyxo, on the night of 9–10 January 2000. The 148 km diameter asteroid (estimated from the measured surface brightness of the asteroid; refining the exact size and shape was in fact the purpose of observing the occultation event) occulted the magnitude $V = 8.6$ star HIP 49999 along a path that crossed the southern United States. We deployed SWUIS-A aboard a NASA F/A-18B at a point along the predicted center of the asteroid’s shadow path near NASA’s DFRC, co-located with Edwards Air Force Base. SWUIS-A recorded a 12.047 sec occultation (Fig. 6) from above clouds that would have prevented a ground-based observation of the event at that location. SWUIS-A airborne data and ground-based data from 4 other locations along the path are currently being reduced to provide refined size and shape information for asteroid 308 Polyxo.

4. CONCLUSION

With initial systems development and operational trials of SWUIS-A behind us, we are now entering what we expect will be a vigorous operational research phase. Additional observations of asteroid occultations are planned, including events involving asteroid 45 Eugenia, which was recently discovered to have a small orbiting satellite [6]. Future SWUIS-A airborne missions aboard high-altitude aircraft, such as two-seater U-2s, will take advantage of the ability of the instrument to look near (and soon, even at) the Sun to search for Vulcanoids (a putative population of small asteroids circling the Sun inside Mercury’s orbit) and to observe breakup mechanics in Sun-grazing comets. On the horizon we see the possibility of using SWUIS-A to detect and track space debris that might pose a hazard to satellites, the Space Shuttle, and the International Space Station, and the application of SWUIS-A to the study of a wide variety of terrestrial aeronomical phenomena, including lightning and sprites, aurora, and ozone studies, and future studies of meteoroid showers, missile tests, and other phenomena of interest. We encourage interested users of SWUIS-A, including researchers, operational remote sensing users, and the education/public outreach community to contact the authors to discuss possible collaborative projects.

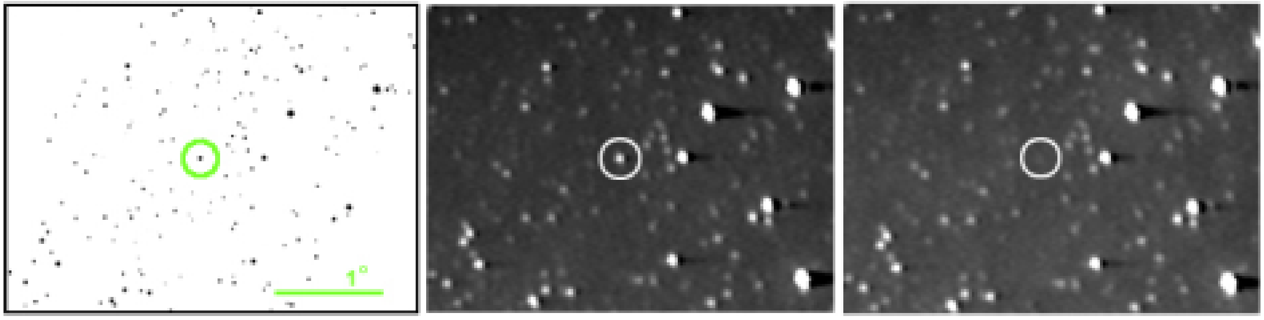

Figure 6. Star chart and SWUIS-A images of the star field from an occultation event involving asteroid 308 Polyxo. The chart on the left indicates the star HIP 49999, the 8.6 magnitude star occulted by Polyxo on 9 January 2000 (see `lunar-occultations.com/iota/asteroids/astrndx.htm`). The middle panel shows a 10-sec co-added SWUIS-A image taken before the occultation event, with the star visible at its normal brightness (for comparison, the two bright stars at the 2 o'clock position have magnitude $V \approx 6$–6.5). The panel on the right shows a 10-sec co-added SWUIS-A image taken during the occultation event (which lasted for 12 seconds), while the star was occulted by Polyxo. *The asteroid itself is faintly visible at magnitude 12.7.* These images were obtained by author Durda at an altitude of 41,000 feet from a NASA F/A-18B. An animated gif of these data may be viewed on the SWUIS-A web site at: `www.boulder.swri.edu/swuis/swuis.instr.html`.

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