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# Sensing Hazards with Operational Unmanned Technology: Cost Study of Global Hawk Unmanned Aircraft System Operations for High Impact Weather Observations, Final Report

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NOAA/Unmanned Aircraft Systems Program
Silver Spring, Maryland
January 2018

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**DEPARTMENT OF COMMERCE**

**Wilbur Ross**
Secretary

**NATIONAL OCEANIC AND**
**ATMOSPHERIC ADMINISTRATION**

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# EXECUTIVE SUMMARY

The Sensing Hazards with Operational Unmanned Technology (SHOUT) Project collected atmospheric measures using sensor payloads aboard high altitude, long endurance unmanned aircraft systems (UAS), such as the Global Hawk (GH) aircraft. Use of these measures at regional and global scales have consistently demonstrated positive forecast benefits for high impact weather events, such as hurricanes, tropical cyclones, and land falling Pacific storms. Furthermore, these measures have an important secondary scientific value as gap-fill, should anomalies occur in future satellite coverage.

While the scientific value of very high-resolution datasets obtained using UAS technology is gaining merit, cost is a driving force in determining the practicality of transitioning this technology to routine operations. Therefore, the SHOUT project has continued to analyze the costs of using Global Hawk for science observations and as satellite data-gap risk mitigation tool since 2014. This report expands upon previous cost studies; refreshes the Analyses of Alternatives ([AOA], NOAA 2012); explains operational availability of the platform and sensors; assesses the integrated system for operations; and adds to the lessons learned and best practices for the National Oceanic and Atmospheric Administration's (NOAA's) use of the High Altitude Long Endurance (HALE) UAS for routine operations.

The previous SHOUT cost studies (NOAA 2015b, 2016) suggested that a NOAA partnership with NASA to stand up one Block 10 Global Hawk aircraft, in addition to the Advanced Concept Technology Demonstration (ACTD) aircraft—Air Vehicle 6 (AV-6), was a viable option and could help NOAA to address the critical issue of potential satellite data gaps. With this action, NOAA gained the added flexibility of two reliable and mature aircraft readily available for research and operations. Additionally, several instrument payloads were evaluated during the Observing System Experiment (OSE) and Observing System Simulation Experiment (OSSE), which are discussed in greater detail within the final SHOUT Impact Study (Wick *et al.* 2018), before selecting the final payload. The selected SHOUT operational payload consists of the Airborne Vertical Atmospheric Profiling System (AVAPS), the High Altitude Monolithic Microwave Integrated Circuit (MMIC) Sounding Radiometer (HAMSR), the High-altitude Imaging Wind and Rain Profiler (HIWRAP), and, the Lightning Instrument Package (LIP). Although, two additional instruments: the Hurricane Imaging Radiometer (HIRAD) and the Scanning High-resolution Interferometer Sounder (S-HIS) remain on a secondary list for potential future integration, because they were previously integrated and flown on a Global Hawk.

During SHOUT 2016, the project made improvements to a) existing operational and research data ingest and archival strategies, as well as b) improvements to integration and visualization through the provision of several new real-time products by the instrument teams within NASA Airborne Science Mission Tool Suite (MTS), c) initial efforts to archive of data in the Meteorological Assimilation Data Ingest System (MADIS), and d) team coordination. These

activities made critical data available remotely, which improved operational scientific collaboration and reduced the number of deployed personnel.

The initial 2016 cost study results continue to support the NASA/NOAA partnership, as the 2016 El Niño Rapid Response (ENRR) and Hurricane Rapid Response (HRR) SHOUT missions demonstrated the ability to reduce response time as Global Hawk missions transitioned to more of an operational footing. Additionally, the flexibility and reliability of the aircraft also continued to improve. Hence, planning for the ENRR project took less than six weeks, and HRR demonstrated the ability to redeploy from the opposite coast in four days and be ready for operations. This operational model has supported several Concepts of Operation (CONOPS), including quick deployments to obtain observations of atmospheric rivers, Arctic weather, and hurricane operations. Also, in 2016, aircraft availability time increased from five to 11 weeks and responding personnel shifted to a rapid response framework.

Overall, these costs analysis indicate a reduction in costs per flight hour, which reflects positively on the year-to-year efforts taken to continually optimize personnel, as well as the platform, sensors, data management and CONOPS when operating from NASA's Armstrong Flight Research Center (AFRC) and Wallops Flight Facility (WFF). The final cost analysis (see Table ES-1) is based on the assumptions of 10 science flights over the 10 operational weeks, a three-sensor payload, and 870 GB total of data. The expected costs of platform, science and data management activities were roughly $2,248K, $1,163K and $329K respectively which broke down to $9,398, $4,863 and $1,376 cost per flight hour.

**Table ES-1.** Summary of a) platform costs at Armstrong Flight Research Center (AFRC) and Wallops Flight Facility (WFF) and b) summary of mission science and c) summary of data management costs. The costs summary assumes NASA Airborne Science Program base funding and in-kind contributions from the Space Act Agreement between NASA and Northrup Grumman Corporation.

| | | AFRC | WFF |
|---|---|---|---|
| a) | **Platform Costs** | | |
| | Total Costs | $2,248,120 | $2,953,343 |
| | Total Cost/Flight Hour | $9,398 | $12,346 |
| b) | **Mission Science Costs** | | |
| | Total Costs | | $1,163,443 |
| | Total Cost/Flight Hour | | $4,863 |
| c) | **Data Management Costs** | | |
| | Total Costs | | $329,219 |
| | Total Cost/Flight Hour | | $1,376 |

***The SHOUT Cost Analysis concludes that the Global Hawk UAS is operationally feasible and affordable for application to high impact weather events.*** Still, the project will continue to advance the automation of sensors and vehicle operations to further minimize costs.

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# LIST OF ACRONYMS

| Abbreviation | Description |
|---|---|
| ACTD | Advanced Concept Technology Demonstration |
| AFRC | Armstrong Flight Research Center |
| AMS | Aerosol Mass Spectrometer |
| AOA | Analysis of Alternatives |
| ATTREX | Airborne Tropical Tropopause Experiment |
| AV-6 | NASA ACDT Global Hawk, Air Vehicle 6 |
| AVAPS | Airborne Vertical Atmospheric Profiling System |
| CAST | Coordinated Airborne Studies in the Tropics |
| CIRA | Cooperative Institute for Research in the Atmosphere |
| CIRES | Cooperative Institute for Research in Environmental Sciences |
| COMSEC | Communications Security |
| CONOPS | Concepts of Operation |
| DMP | Data Management Plan |
| ECMWF | European Center for Medium range Weather Forecasting |
| ENRR | El Niño Rapid Response |
| GloPac | Global Hawk Pacific |
| GRIP | Genesis and Rapid Intensification Processes |
| GTS | Global Telecommunications System |
| HALE | High Altitude, Long Endurance |
| HAMSR | High Altitude MMIC Sounding Radiometer |
| HIRAD | Hurricane Imaging Radiometer |
| HIWRAP | High-altitude Imaging Wind and Rain Profiler |
| HRR | Hurricane Rapid Response |
| HS3 | Hurricane and Severe Storm Sentinel |
| HWRF | Hurricane Weather Research and Forecasting (non-operational Hurricane Research Division research variant) |
| IAA | Interagency Agreement |
| JPL | Jet Propulsion Laboratory |
| JPSS | Joint Polar Satellite System |

| Abbreviation | Description |
|---|---|
| LIP | Lightning Instrument Package |
| MADIS | Meteorological Assimilation Data Ingest System |
| MMIC | Monolithic Microwave Integrated Circuit |
| MTS | NASA Mission Tool Suite |
| NASA | National Aeronautics and Space Administration |
| NHC | National Hurricane Center |
| NOAA | National Oceanic and Atmospheric Administration |
| NWP | Numerical Weather Prediction |
| OAR | Office of Oceanic and Atmospheric Research |
| OMAO | Office of Marine and Aviation Operations |
| OSE | Observing System Experiment |
| OSSE | Observing System Simulation Experiment |
| QC | Quality Control |
| RL | Readiness Level |
| S-HIS | Scanning High-resolution Interferometer Sounder |
| SHOUT | Sensing Hazards with Operational Unmanned Technology |
| UAS | Unmanned Aircraft Systems |
| USAF | United States Air Force |
| WFF | Wallops Flight Facility |
| WISPAR | Winter Storms and Pacific Atmospheric Rivers |

# ABSTRACT

The Sensing Hazards with Operational Unmanned Technology Project collected atmospheric measurements using sensor payloads aboard the Global Hawk high-altitude, long-endurance unmanned aircraft system. The use of Global Hawk observations at regional and global scales have consistently demonstrated positive forecast benefits for high impact weather events, such as hurricanes, tropical cyclones, and land falling Pacific storms, but these observations also have an important secondary scientific value to fill potential gaps in future satellite coverage. Even though the technology is scientifically proven, costs are a driving force in determining the practicality of transitioning it to routine operations. The analyses of costs associated with using the Global Hawk for science observations and as a satellite data-gap risk mitigation tool have been ongoing throughout the project's lifecycle. Improvements made to existing data ingest and archival strategies, as well as to real-time data integration and visualization processes, resulted in cost savings and enhanced scientific collaboration. Furthermore, shifting staff to a rapid response framework resulted in a reduction in deployed personnel. Through this evolved Concept of Operations, the cost analyses indicated a reduction in costs per flight hour, which reflects positively on the year-to-year efforts taken to continually optimize personnel, as well as, the platform, sensors, and data management. Presently, the Global Hawk unmanned aircraft system is operationally feasible and affordable for application to high impact weather events. Meanwhile, the project continues to advance the automation of sensors and vehicle operations to further minimize costs.

# 1 INTRODUCTION

While National Oceanic and Atmospheric Administration (NOAA) is taking active steps to prevent gaps in polar-orbiting satellite observations, it is also working to take precautionary measures to mitigate the impact of a gap, should one occur. The Disaster Relief Appropriations Act of 2013 provided funds to investigate methods for reducing the impact of such a gap in data that is crucial for providing accurate weather forecasts affecting U.S. interests. One of these investigations involves the development and testing of a targeted observations project, using unmanned aircraft systems (UAS) to collect vertical atmospheric observations and other essential environmental information to assist in the prediction of high impact weather. This project, designed by the NOAA UAS Program Office, focuses on Sensing Hazards with Operational Unmanned Technology (SHOUT) to quantify the influence of UAS environmental data on high impact weather prediction and assess the cost and operational effectiveness of UAS to help mitigate the risk of satellite observing gaps.

## 1.1 SHOUT Project Objectives

The SHOUT project has two primary objectives:

1. Quantify the significance of unmanned observations to high impact weather prediction through data impact studies, using Observing System Experiments (OSE) based on unmanned observations collected during prototype operational field missions and Observing System Simulation Experiments (OSSE) based on expected unmanned observing capabilities.
2. Quantify the cost and operational benefit of unmanned observing technology for high impact weather prediction through detailed analysis of life-cycle operational costs and constraints, versus scientific benefit.

As the SHOUT project has continued to mature, other viable unmanned observing platforms, payloads, and strategies have been incorporated into the overall evaluation of UAS observing strategies for operational application. Coordination with high-altitude manned aircraft observing strategies is yet another related concept for operations that is being investigated.

The SHOUT project delivered periodic data impact analyses of Global Hawk UAS observations to address SHOUT Objective 1. These reports examined the results from data assimilation studies of Global Hawk observations into tropical cyclones and global Numerical Weather Prediction (NWP) models, conducted by NOAA, NASA, and Naval Research Laboratory scientists. Preliminary results from these efforts have demonstrated notable promise for High Altitude Long Endurance (HALE) UAS observations to improve high-impact weather forecasting (Wick *et al.* 2018), although the final analyses and conclusive results are forthcoming.

Through a parallel effort to address SHOUT Objective 2, the SHOUT Global Hawk Cost Study Reports (NOAA 2015b, 2016) examined four operational options based on standard aircraft costing. Independently, NASA made the decision that supports NOAA's recommended option, which is discussed later in this report.

## 1.2 Purpose of this Report

This report, one of two final SHOUT report deliverables, presents the progress of activities addressing SHOUT Objectives 1 and 2. An update to the 2015 data impact analysis of Global Hawk observations for tropical cyclone and other high-impact weather prediction will be provided in a separate report. This document represents the third, updated cost study of Global Hawk operations, which includes new information from the 2016 campaign and focuses on SHOUT Objective 2.

# 2 PLATFORM ANALYSIS: NASA GLOBAL HAWK AND ALTERNATIVES

The NOAA UAS Program and the Office of Marine and Aviation Operations (OMAO) have been collaborating with the Airborne Science Program of the NASA Earth Science Division since 2008 to demonstrate and evaluate UAS flying at high altitudes (*i.e.*, >50,000 feet) and low altitude (*i.e.*, < 18,000 feet) for scientific, environmental data collection. NOAA and NASA have both reviewed HALE platforms by conducting Analysis of Alternatives (AOA). NASA conducted theirs first in 2005, followed by NOAA in 2012, which followed the United States Air Force AOA Handbook (United States Air Force [USAF], 2010). Collaboration between NOAA and NASA began after the NOAA UAS AOA of Unmanned Aircraft System (UAS) Platforms (NOAA 2012) suggested the Global Hawk as the only viable platform for high altitude observations.

A variety of HALE operational specifications, and readiness levels (RLs) were explored in the NOAA AOA (2012) report, and were more recently reviewed by NASA in technology demonstrations (see Table 2.1). Of these, the Global Hawk was the only platform put into production by the U.S. Air Force and U.S. Navy.

After examining numerous platforms for SHOUT, including alternative fuel powered aircraft, the conclusion from the NOAA AOA (2012) and subsequent investigations (Smith and Nickol, 2016) is that the Global Hawk continues to be the only formal government Program of Record (in the HALE UAS category, in the form of the USAF Global Hawk, "RQ-4B", and the U.S. Navy's Triton, "MQ-4C") that possesses the necessary attributes to accomplish the given observational requirements for high-impact weather analysis and prediction (Table 2.1). Combined with its large payload capacity, the long endurance (*i.e.*, > 24 hours) and long range (*i.e.*, > 9,000 nautical miles) specifications of Global Hawk UAS offer increased capabilities for operational, targeted weather observing strategies over remote reaches of the open ocean. Furthermore, this platform possesses the highest RL of all investigated HALE UAS platforms.

**Table 2.1.** Operational specifications and readiness level (RL) attributes for several of the investigated HALE UAS options considered at the onset of SHOUT.

| HALE UAS Platform (Manufacturer) | Payload (lb.) | Endurance (h) | Cruise Speed (kts) | Range (nm) | Ceiling (ft.) | RL |
|---|---|---|---|---|---|---|
| Global Hawk (Northrop Grumman) | 1,500 | 31 | 335 | 11,000 | 65,000 | 9 |
| Global Observer (AeroVironment) | 400 | 168 | N/A | N/A | 65,000 | 5 |
| Phantom Eye (Boeing) | 600 | 240 | 150 | 28,800 | 65,000 | 4 |
| Zephyr (QinetiQ) | 13.2 | 2,160 | 54 | 117,300 | 70,000 | 5 |

Payload, endurance, and technology readiness attributes give the Global Hawk a significant advantage when it comes to logistics and supportability. Therefore, the NASA/NOAA team developed tailored Concepts of Operation (CONOPS), designed around these capabilities, to obtain upstream observations of developing storms to better predict downstream impacts with longer lead times.

As of June 2017, the most operational HALE UAS aircraft available for science research is the Advanced Concept Technology Demonstration (ACTD) NASA-modified Northrop Grumman Global Hawk aircraft, known as Air Vehicle 6 (AV-6). However, NASA is currently modifying one of the more capable Block 10 Global Hawks for future science missions. The modification of additional airframes into the NASA science configuration depends on available funding.

The use of UAS to extend the range and endurance of atmospheric observation missions is compelling, since using manned aircraft for Earth science observations limits range to a few thousand kilometers and approximately eight hours endurance unless very large aircraft with multiple crews are used. Even the longest range manned aircraft, such as the NOAA WP-3D Orion, have an endurance limit of 10–11 hours. Therefore, NOAA funded a recent study by Aeronautics Systems Analysis Branch NASA Langley Research Center (Smith and Nickol 2016) to update the initial NOAA AOA (2012) and examine the current state of the art for HALE UAS designs and their application to Earth science, with a focus on atmospheric observations to improve weather forecasting. Several notional UAS missions, including a NASA concept for a Next Generation HALE UAS specifically designed for Earth science missions, were analyzed and compared to current-day operations using manned aircraft. The study indicated a potential for future HALE UAS designs to attain global reach, possessing an endurance of days with payloads of greater than 1000 lbs. and, in the case of future solar-powered UAS, weeks or even months of endurance with smaller payloads. Development costs to potentially advance NASA's NexGen Concept Design to an Earth science platform was estimated by Tecolote Research, Inc. at $240M for one full scale flying prototype and $24M each for six production aircraft. Operation and support costs were estimated at $2,500 per hour. The cost estimate for a 24-hour mission covering the same distance as Global Hawk was $120,000. As an example, monitoring the track of Hurricane Georges in 1998 for eight days would have cost approximately $300,000 using Next Generation HALE UAS, accounting for a total of two flights, covering 120 hours at $2,500 per hour.

NASA acquired the Global Hawk at no cost; consequently, there are no development and acquisition costs to compare. However, for reference, Global Hawk operation and support costs are estimated to be $4,500 per hour, not including the science team, which is reviewed in detail in Section 3.3. Also, alternatives to Global Hawk, other than the Navy's MQ-4C Triton, are unlikely to be available within the next five years since there are no known pursuits of new HALE UAS designs for atmospheric observations. The MQ-4C Triton is a Northrop Grumman Global Hawk derivative with advanced automation features and the capability to fly in adverse weather conditions that could make it less costly to operate than Global Hawk, but with the trade-offs of a lower maximum altitude and less endurance.

In the absence of "Next Generation" HALE UAS specific requirements and funding from government organizations, it is also unlikely that a commercial company will create a suitable aircraft with sufficient payload capacity. While there are several promising avenues of research into solar- powered aircraft that could stay aloft for weeks or even months, the payload capacities are often less than 200 pounds. These aircraft will initially require some advanced technological developments to realize the system performance benefits. Sensors would need to be miniaturized, and alternatives to dropsondes would need to be developed to allow accurate atmospheric vertical profiling using remote sensing rather than *in situ* measurements that use consumable resources. If the use of dropsondes is deemed necessary, the system would need to be smaller and lighter than the current system to allow a useful quantity to be carried by a solar-powered UAS that may stay aloft for weeks or months. If that proves infeasible, then the solar-powered aircraft could still provide useful data from remote sensors, supplemented by dropsonde data from unmanned or manned non-solar-powered aircraft. Nevertheless, solar-powered UAS could provide useful platforms for smaller Earth science payloads. Beyond this, several other HALE platforms are currently being conceptualized, which would have alternative fuel options that may lead to operations at even higher altitudes (e.g., > 65,000 ft.) and with longer endurance (e.g., > 4 weeks). As UAS technology matures, future options will continue to be explored.

With regard to the latest evolution and trend to develop and launch small, mission-specific satellites, there is a need to compare the functions and costs of HALE UAS mission concepts to the use of existing and planned Earth science satellites. Comparisons will help to discern the type of objectives in which HALE UAS are more effective, or provide a complementary component to the overall observational needs and data collection strategies. A closer investigation into available satellite implementation schedules may guide future investment in Earth science research and enable an informed approach to determine where to direct resource allocations.

HALE UAS can provide missions where UAS are more effective and less costly than a satellite limited to remote observations and specific orbits. Furthermore, a Next Generation HALE UAS, custom-built for science missions, will be more effective and cost less than the NASA-modified Global Hawk. However, development and non-recurrent engineering costs required for a prototype would put this out of reach under the budget environment at the time of writing. Without government research and development funding, it is unlikely that a Next Generation HALE UAS capable of carrying large science payloads will be available within 10 years, leaving the Global Hawk as the only viable option for executing such missions. For smaller payloads, solar-powered HALE UAS offer great potential, and several prototype designs are under development by commercial companies.

## 2.1 Increasing Technology Readiness and Reliability of the Global Hawk

Previous field demonstrations of the Global Hawk were pivotal in increasing the technology readiness and reliability of the platform. The 2015 and 2016 SHOUT Global Hawk Cost Study Reports (NOAA 2015b, 2016) presented detailed information about each of these projects. The major goal of Genesis and Rapid Intensification Processes (GRIP) experiment conducted in 2010 (Braun *et al.* 2013) was to improve our understanding of the physical processes that control hurricane formation and intensity change, with specific emphasis on the relative roles of environmental and inner-core processes. A key focus of GRIP was the application of new technologies to address this important scientific goal, including the first use of NASA’s Global Hawk UAS for hurricane science operations. In 2011, the Winter Storms and Pacific Atmospheric Rivers (WISPAR) airborne campaign (Neiman *et al.* 2014) focused on improving scientists' understanding of atmospheric river evolution and used the Global Hawk to evaluate the operational use of HALE UAS for investigating these phenomena. Later, in 2012, the Hurricane and Severe Storm Sentinel (HS3) project used NASA’s Global Hawk to overfly tropical storms and hurricanes in the Northern Atlantic, Caribbean, and Gulf of Mexico basins (Braun *et al.* 2016). These flights helped improve scientists’ understanding of the processes that lead to the development of intense hurricanes. HS3 demonstrated successful deployment and operation of the Global Hawk from NASA ground control stations on both the U.S. East and West Coasts.

## 2.2 NOAA SHOUT Campaign

The first dedicated SHOUT field campaign, conducted during the summer of 2015, had the primary goal of data collection to determine the effect of Global Hawk observations on tropical storm forecasts, as well as, to explore the potential to support improvements to forecasts of high-impact Alaska weather events. SHOUT Payload selections were based on the potential to generate a positive forecast impact and included the Airborne Vertical Atmospheric Profiling System (AVAPS), High Altitude Monolithic Microwave Integrated Circuit

(MMIC) Sounding Radiometer (HAMSR), High-altitude Imaging Wind and Rain Profiler (HIWRAP), and Lightning Instrument Package (LIP) instruments, described in greater detail in Section 3.1. Additionally, new techniques developed to identify regions of greatest forecast uncertainty are based on ensemble NWP model forecasts, and employed to generate targeted observation strategies.

Key achievements during the campaign included the first operational assimilation of Global Hawk dropsonde data into the Hurricane Weather Research and Forecasting (HWRF) NWP model, an enhanced real-time data display, delivery of remote sensing data for use by forecasters at the National Hurricane Center (NHC), and successful deployment of the Global Hawk from the U.S. East and West Coasts. Furthermore, external collaboration efforts led to the acquisition of additional data to support SHOUT impact assessments collected during the Tropical Cyclone Intensity experiment (https://www.eol.ucar.edu/field_projects/tci) led by the Office of Naval Research.

# 3 ANALYSIS OF COMPONENTS FOR THE SHOUT CAMPAIGN

The optimization of Global Hawk UAS for use in NOAA operations was further developed in 2016 based on the 2015 and 2016 SHOUT Global Hawk Cost Study Report (NOAA 2015b, 2016), which included a recommendation for NASA/NOAA collaboration to continue for future Global Hawk operations. This collaborative effort makes the most efficient and cost-effective use of the aircraft by sharing resources, personnel, and scheduling. For example, when NASA stands up the more capable Block 10 Global Hawk aircraft while continuing operation of the predecessor ACTD AV-6 aircraft, NOAA will gain the added flexibility of two reliable and mature aircraft, readily available for research and operations from NASA Armstrong Flight Research Center (AFRC), NASA Wallops Flight Facility (WFF), and other sites using the Global Hawk Mobile Operations Facility.

NOAA’s SHOUT project investigates HALE UAS as a near-term satellite data gap mitigation tool. The platform, sensors, and strategic applications testing occurs in the same operational environment as manned aircraft and their corresponding sensor payloads. Support for the SHOUT project consists of a highly qualified and flexible workforce that includes NOAA Corps officers, government personnel, and skilled contractors.

## 3.1 Sensor Analysis

Based on requirements and budget constraints, several instrument payload combinations have been considered for integration onto the NASA Global Hawk UAS. As of the writing of this report, there were 36 instruments (Appendix A) that could potentially be integrated and flown onboard the aircraft, with others to follow. For SHOUT, all sensors selected for integration and evaluation were previously flown on this platform and have mature readiness levels (RLs) at or near level 8, which describes their use for system demonstrations in an operational environment for routine research data collection (Figure 3.1).

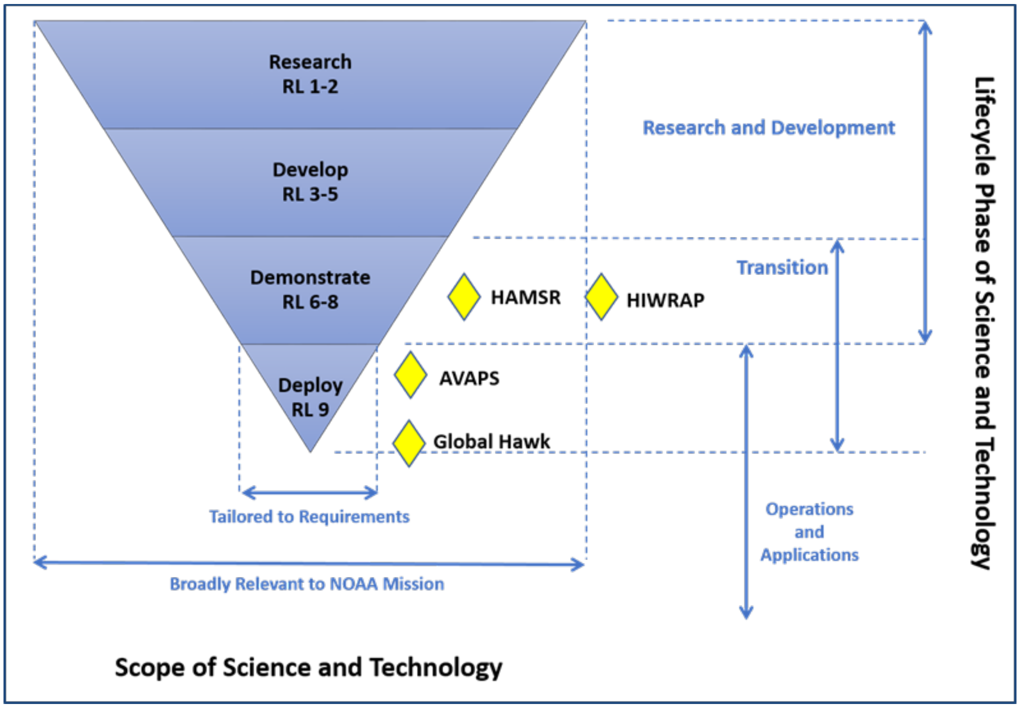

**Figure 3.1.** Readiness level (RL) of platform and payloads for the primary SHOUT instruments.

To investigate alternative options for the mitigation of negative impacts in the case of satellite system gaps (e.g., Joint Polar Satellite System [JPSS]) for high-impact weather forecasts, a key objective of SHOUT, a distilled list of payload options was generated. As part of the project, the evaluation of potential benefits contributed by each instrument occurred through a combination of OSE and OSSE studies. From this list, the payload combination selected and investigated for operational NOAA missions consisted of AVAPS, HAMSR, HIWRAP, and LIP instruments (Table 3.1). These four instruments contribute to monitoring and improving our understanding of atmospheric rivers, the formation and intensification of tropical cyclones, and winter storm reconnaissance through remotely sensed measurements of wind speed and direction, pressure, temperature, humidity, water vapor transport, and electric field.

A combination of science, logistic, and budgetary requirements helped prioritize the payload selection, which also included an evaluation of each instrument’s RL. Because each of the instruments has been successfully integrated and used on an AV-6 in previous projects and during a significant portion of the SHOUT campaign, they have all been qualified on the platform, which reduces future engineering efforts (Figure 3.2). Therefore, incorporation of these instruments onto the newer Block 10 Global Hawk aircraft, which has a similar configuration to the one used for the AV-6 aircraft should require minimal effort. However, a future version of this payload suite could feasibly incorporate additional instruments, due to the larger payload capacity available with the Block 10 Global Hawk. The total weight of the four selected instruments is approximately 837 pounds, which is well below the 1500-pound limit for the newer Global Hawk platform.

**Table 3.1.** SHOUT Project instrument payloads.

| Instrument Name | Sensor Type | Primary Observed Properties |
|---|---|---|
| Airborne Vertical Atmospheric Profiling System (AVAPS) | In situ | Direct profile measurements of pressure, temperature, humidity, wind speed, and wind direction |
| High Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer (HAMSR) | Remote/ Passive | Retrieved profiles of temperature, humidity, liquid water, and precipitation structure |
| High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) | Remote/ Active | 3-dimensional reflectivity and Doppler wind velocity fields in precipitation |
| Lightning Instrument Package (LIP) | Remote/ Passive | Detects nearby lightning and measures electric fields, electric field changes, and air conductivity |

Additional considerations, other than weight, are also important in determining the optimal payload configuration for SHOUT missions. These include operational altitude, center of gravity, fuel load, ferry time, proposed time on station, and electrical system loads with each sensor having its own tradeoffs for size, weight, and power. Aside from the finalized payload selected for operational evaluation aboard the Global Hawk during SHOUT, instrument payloads previously integrated and flown on the Global Hawk campaigns remained on a separate list of instruments (Table 3.2) considered for further investigation and future integration onto the Global Hawk for operational missions.

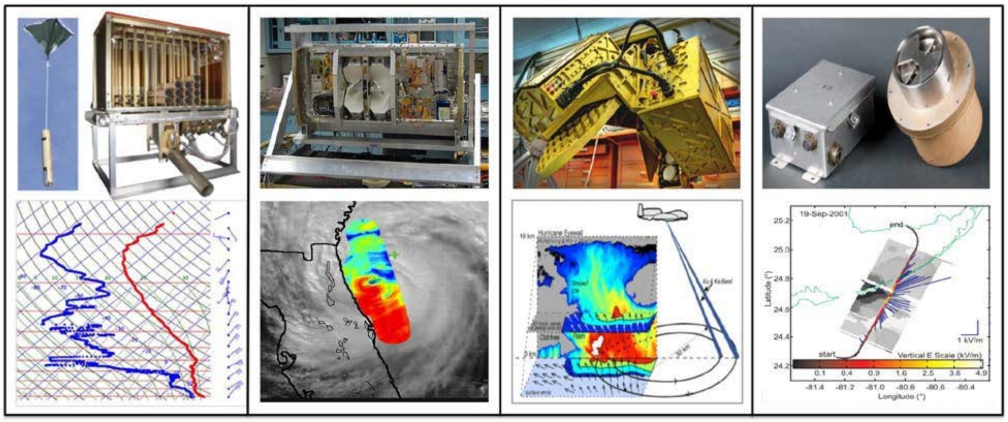

**Figure 3.2.** SHOUT payloads for high-impact weather observation. From left to right: Airborne Vertical Atmospheric Profiling System, High Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer, High-altitude Imaging Wind and Rain Airborne Profiler, and Lightning Instrument Package.

**Table 3.2.** Shout payloads for future, potential HALE UAS operational missions.

| Instrument Name | Sensor Type | Primary Observed Properties |
|---|---|---|
| Scanning High- Resolution Interferometer Sounder (S-HIS) | Remote/ Passive | Retrieved profiles of temperature and humidity in clear- sky conditions; Cloud-top temperature, cloud-top height, cloud optical depth, cloud drop effective radius, ocean surface skin temperature. |
| Hurricane Imaging Radiometer (HIRAD) | Remote/ Passive | Retrievals of surface wind speed and profiles of rain rate |

Designed primarily for research and development activities, many evaluated sensors are unique and vary in their degree of maturation. Use of more streamlined, operational variants of these sensors would act to minimize or eliminate post-flight maintenance, remove the need for ongoing involvement of the original Principal Investigator (except under extraordinary circumstances), and maximize real-time data transmission.

During the transition phase; however, some instruments would initially require more work and input from the original Principal Investigators, while others would require only minimal redesign. Such improvements are beyond the scope of this cost study. More detailed information about these sensors and the developmental history and use for each is in the 2015 and 2016 SHOUT Global Hawk Cost Study Report (NOAA 2015b, 2016).

## 3.2 Operational Analysis

During SHOUT 2016, the Global Hawk deployed for multiple high-impact weather targets of interest. This eventful campaign year created the needed opportunity to conduct a comprehensive operational and cost analysis, investigating the use of HALE UAS in an operational mode for satellite gap mitigation by providing atmospheric observations as input for NWP model forecasts. Use of the same operations and resulting datasets provided situational awareness to operational forecasters and helped to determine if the addition of this data might enhance existing input to NWP forecasts. During the 2016 campaign, the SHOUT team increased operational efficiency by establishing a “Rapid Response” capability, which released personnel from on-site operations when not actively monitoring a storm and recalled later in time for deployment and operations once conditions for a storm became imminent. Furthermore, for the first time, the team could turn around the aircraft in less than 24 hours during a back-to-back deployment series of three consecutive missions over Hurricane Matthew with a single maintenance crew.

### *3.2.1 Assessment of Project Planning*

A working knowledge of all roles and responsibilities was developed around NASA Global Hawk operations and implemented during SHOUT to successfully prepare the project to support operational planning, implementation, and post-mission efforts. Advanced preparation was required due to the collaborative nature of the teaming effort between NASA and NOAA and the long lead times for administrative actions. Many of the components of this project plan are condensed and captured in Table 3.3, which provides the information necessary to support and meet all program, science, and project requirements with the most efficient use of resources. It also highlights some of the challenges of planning an unmanned aircraft project, which has many unique considerations that are not common to manned aircraft projects. This plan was assessed and optimized for the SHOUT project operational and science goals.

**Table 3.3.** Summarized components of the SHOUT Project Plan.

| Project Planning Components | Details |
|---|---|
| Submission of Flight Requests with Aircraft Organizations | Requests for scheduling aircraft and instrumentation shall be submitted to the Airborne Science Program through Science Operations Flight Request System: https://airbornescience.nasa.gov/sofrs/ |
| Establishing Support Agreements | The collaborative projects between federal agencies are funded through an Interagency Agreement (IAA). |
| Project Scientists and Instrument Teams | Mission Science/Instrument Team staffing should be addressed early in the planning process. Funding non-NOAA Mission Science and Instrument teams, as well as the implementation of comprehensive data management plans, is accomplished through orders under the IAA. |
| Badging/ Access/ COMSEC | NASA facilities require each participant to be logged in to the Earth Science Projects Office database to ensure access and badging. Communications Security (COMSEC) briefings will be provided by the host facility Security Officer. |
| Coordination of Diplomatic/ ATC Clearances | Overflight and airspace clearances must be coordinated through the State Department. |
| Certificates of Authorization (COA) | The COA should be reviewed to be sure it is consistent with the project requirements, needs, and operations. |
| Coordination/ Development of Agreements with Host Organizations | Hosting agreements for deployment are covered under the IAA task orders. Agreements should include hangar space, laboratory and office space, weather support, weekend tower and field operations, chase aircraft (if required), and fuel arrangements. |

### *3.2.2 Mission Summaries from 2016 SHOUT Campaign*

Two separate deployments of the Global Hawk aircraft were conducted by the SHOUT project in the 2016 to collect observations in support of the data impact studies and to enhance the situational awareness of operational forecasters. These included a three-week deployment in February 2016, performed in partnership with the NOAA El Niño Rapid Response (ENRR) experiment to provide observations from synoptic-scale winter storms and atmospheric rivers in the Pacific Ocean, as well as a ten-week deployment in August–October 2016 focused on observations of hurricanes and tropical storms for the Hurricane Rapid Response (HRR) initiative in the Atlantic Ocean and Gulf of Mexico (Table 3.4).

**Table 3.4.** Science flight statistics from the SHOUT 2016 campaigns.

| SHOUT Campaign Component | Science Flights | Number of Dropsondes Deployed | Aircraft Availability |
|---|---|---|---|
| El Niño Rapid Response 2016 | 3 flights<br>71.0 flight hours<br>~ 30 sonde flight hours* | 90 | 02–22 Feb 2016<br>(21 days) |
| Hurricane Rapid Response 2016 | 9 flights<br>214.3 flight hours<br>215 sonde flight hours* | 647 | 28 Jul–10 Oct 2016<br>(75 days) |

*Sonde flight hours are atmospheric data hours recorded once sonde is launched from the Global Hawk.

During ENRR, the Global Hawk flew a total of 71.0 hours in three science missions (Figure 3.3) with the AVAPS, HAMSR, and HIWRAP sensors and dropped a total of 90 sondes to provide broad area measurements of atmospheric rivers and associated synoptic-scale storms over the data-sparse Eastern Pacific Ocean. Later in the year, and carrying the same payload, the HRR component of the 2016 SHOUT campaign (Figure 3.4) resulted in 214.3 flight hours across nine science missions.

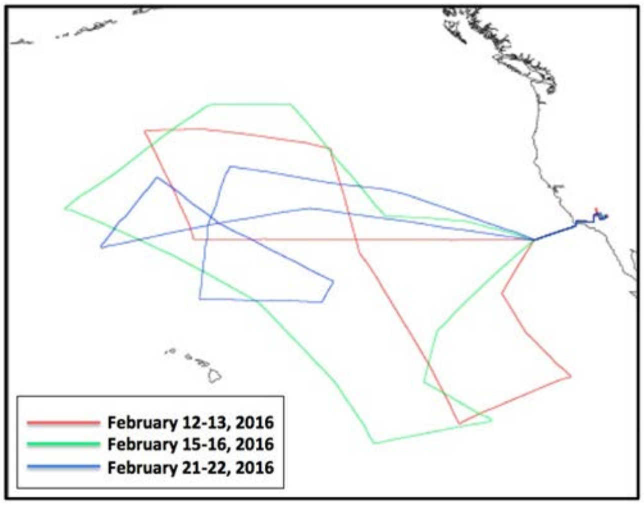

**Figure 3.3.** Global Hawk flight tracks during the 2016 SHOUT ENRR campaign.

The list of achievements grew even more (Table 3.5), adding an international collaboration with the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX), dual Global Hawk Operations Center operations during science flights, real-time dropsonde data ingest into the HWRF and European Centre for Medium-Range Weather Forecasts (ECMWF) NWP forecast models, and additional reduction to the on-site personnel requirements for mission planning and execution, among others. Furthermore, data from HRR was used by operational forecasters at NHC for situational awareness, analysis, and forecasting while coordination with manned aircraft for simultaneous operations (Figure 3.5). Also, for the first time, data from UAS was used by the NHC to upgrade a tropical cyclone to a hurricane (*i.e.*, Gaston); three consecutive flights (with a turn-around <24 hours) were launched for a land-falling hurricane (*i.e.*, Matthew; 73.2 science flight hours; 168 sondes dropped); and a record-setting 90 sondes were successfully dropped from AVAPS during a single mission (*i.e.*, Hermine). Out of 647 sondes dropped from AVAPS during HRR, 97 percent of the data was successfully transmitted in real time to the Global Telecommunication System (GTS), and 95 percent passed the HWRF and ECMWF quality control filters.

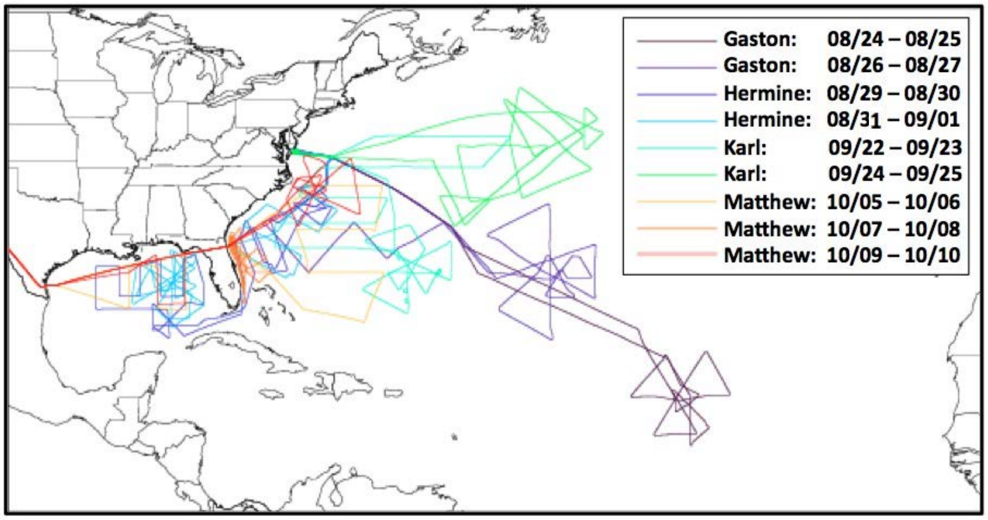

**Figure 3.4.** Global Hawk flight tracks during the 2016 SHOUT HRR campaign.

**Table 3.5.** Notable achievements from the El Niño Rapid Response (ENRR) and Hurricane Rapid Response (HRR) components of the 2016 SHOUT campaign.

| | ENRR | HRR |
|---|---|---|
| Multi-mission / Multi-aircraft coordination | ✓ | ✓ |
| International coordination | | ✓ |
| Increased aircraft, sensor, and crew “Operational Availability.” | ✓ | ✓ |
| Reduced personnel requirements and deployment footprint from previous campaigns | ✓ | ✓ |
| Dual Global Hawk Operations Center operations during science flights | | ✓ |
| Real-time data distribution established to support science flights from remote locations | | ✓ |
| Real-time dropsonde data distribution to Global Telecommunications System (GTS) | ✓ | ✓ |
| Real-time dropsonde data assimilation into operational NWP forecast model(s) | ✓ | ✓ |
| Real-time use of data for situational awareness, analysis, and forecasting by NOAA operational forecast center(s) | | ✓ |
| Real-time imagery distribution through the NOAA UAS Program Website | ✓ | ✓ |

For more information and a complete description of the operational objectives, flights conducted, and observations collected during both deployments, please refer to the supporting SHOUT Impact Study (Wick *et al.* 2018).

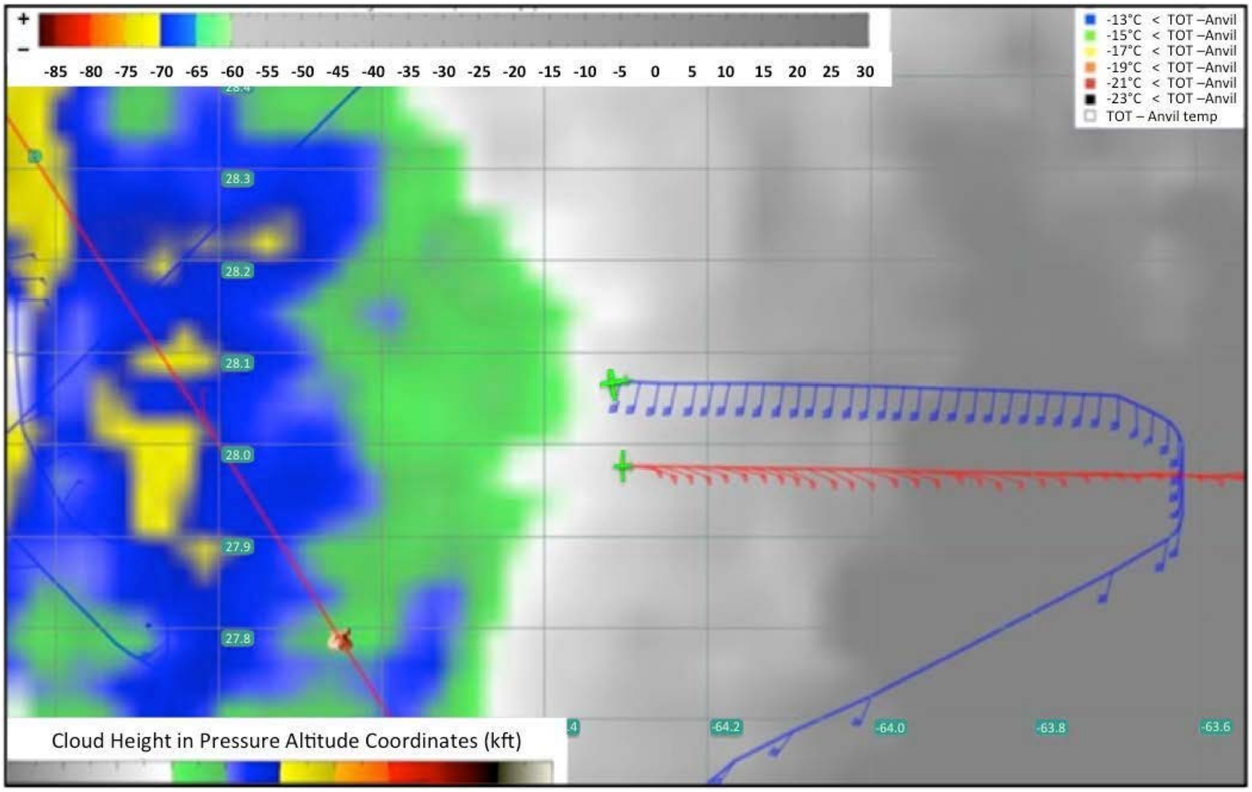

**Figure 3.5.** Screen capture from NASA's Mission Tool Suite (MTS) showing manned-unmanned Teaming applications during SHOUT. The Global Hawk AV-6 (red) is lined up with the manned WP-3 (blue).

### *3.2.3 Operational Availability and Assessment*

"Operational Availability" can be defined as the quantified degree to which a system is expected to be available and work properly when it is required (U.S. Department of Defense 1997). The operational availability of systems is crucial to an organization's ability to successfully execute missions while minimizing cost. Sustained operations cannot be accomplished without effective systems and proper support. Primarily through spiral development efforts, SHOUT improved the system and subsystem design of Global Hawk operations with effectiveness and supportability in mind. Over the course of the project, cost-effectiveness and mission readiness were enhanced through increased reliability, supportability, and remote (*i.e.*, "off-site") real-time access to operational scientific data to minimize personnel deployment footprint.

As the SHOUT systems evolved, from the early days of HS3, the RLs have advanced and the operational availabilities of the platforms and sub-systems have improved to above 90 percent with no 2016 missions aborted for platform or sensor malfunctions. That is, the platform and all sub-systems were operational over 90 percent of the time they were scheduled to be. Notably, the Global Hawk aircraft was able to perform back-to-back-to-back operations during Hurricane Matthew with the aircraft being returned to flight within 24 hours. Additionally, the AVAPS system's engineering improvements allowed for the full capacity of sondes (*i.e.*, 90 sondes) to be launched during hurricane events. To that end, the amount of sonde flight time was on par with the aircraft flight time for the HRR campaign and exceeded that from the manned aircraft, which employ more typical CONOPS. The sonde data also provided a secondary function of providing coincident *in situ* data to support and validate data from the other Global Hawk sensors and remote sensors. Conformational data will be critical in the acceptance and exploitation of sensor data for other, future uses.

Finally, due to the improved reliability and real-time distribution of remote sensor data via the NASA Airborne Science Mission Tool Suite (MTS) and other web-based resources, the collaborating sensor teams decreased deployed personnel by more than 30 percent. In fact, the HAMSR team had no need to deploy personnel for the final three flights of the Hurricane Matthew mission set, as they could monitor the sensor's status remotely while significantly saving on deployment costs. This type of real-time remote monitoring of sensor status and data output is critical to operational affordability, and it provides the additional benefit of an increased mission collaborative environment.

## 3.3 Data Management Analysis

The NOAA UAS Data Management Plan (DMP) was developed within the framework of the Environmental Data Management Committee (EDMC) for handling UAS instrumentation package data and covers acquisition, ingest, quality control, integration, visualization, and archiving (NOAA 2015a). Recommendations from that plan were used to prototype and demonstrate all phases of the UAS data lifecycle from real-time operations to post analysis and research (Figure 3.6) to maximize the value of the data collected through coordinated data management practices.

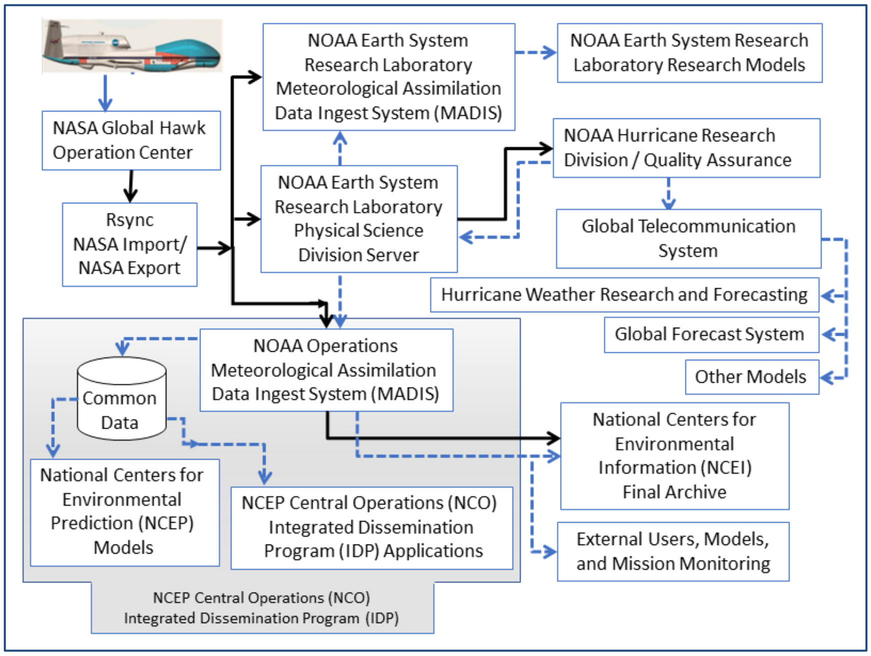

**Figure 3.6.** Global Hawk data flow and architecture.

Each of the four sensors in Global Hawk's payload (see Section 3.1) were individually developed, integrated, assessed, and documented in the NOAA UAS DMP. This included sensor specifications (Table 3.6) and core metadata to assist with data discovery, quality assurance, and to provide the potential for integration into value-added services, such as new data distribution and web-based visualization tools accessed using the NASA MTS and NOAA GTS. In addition to quick access links, these tools provided the capability for users to dynamically toggle on- and-off the various observation layers, adjust layer transparency, and visualize Global Hawk observations along with various satellite observations. Post flight, data was grouped and made available for further analysis allowing users to access previous observations.

**Table 3.6.** Summary of instrument data specifications for the Airborne Vertical Atmospheric Profiling System (AVAPS), High Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer (HAMSR), High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP), and Lightning Instrument Package (LIP) used during the SHOUT campaign.

| Instrument | Spatial Resolution | Raw Measurement Precision | Retrieved Parameter Precision |
|---|---|---|---|
| AVAPS Dropsondes | Horizontal: N/A<br>Vertical: (Depends on fall speed) | Pressure: +/- 1.0 hPa<br>Temperature: +/- 0.2 C<br>Wind: +/- 0.1 m/s<br>Humidity: +/- 7% | N/A |
| HAMSR | Horizontal: 2 km<br>Vertical: 1-3 km | TB: 0.1-0.6 K precision;<br><1 K accuracy | Temperature: 2 K<br>Water Vapor: 15%<br>Liquid Water: 25% |
| HIWRAP | Horizontal:1.6 km (6.6 GHz); 2.5 km (4 GHz) @ nadir from 20 km altitude | NEDT Brightness Temperature: 0.19-0.27 K | Wind Speed: 1-5 m/s |
| LIP | Horizontal: 5-10 km Vert: N/A | 5-10% V/m | (Ex, Ey, and Ez) at .1s |

During SHOUT 2016, the project made improvements to existing operational and research data ingest, and archival strategies, in addition to improvements to integration and visualization through the provision of several new real-time products by the instrument teams within MTS, initial efforts to archive of data in the Meteorological Assimilation Data Ingest System (MADIS), and team coordination. MADIS, a NWS operational system, provides near real-time data pathways to NOAA operational and research systems, as well as, the greater meteorological community is a potential pathway to operations and archive of Global Hawk observations. Once the Global Hawk data sets are fully realized in MADIS, users may access the data through MADIS interfaces or NOAA's Data Catalog (https://data.noaa.gov/). However, to view text, xml, or csv observations user will need to download the MADIS API (https://madis.noaa.gov/madis_api.shtml).

Real-time data sets were made available on the NASA MTS and SHOUT websites throughout the mission. Meteorological observations were placed into GTS, and the SHOUT NRD-94 'minisonde' in- situ data were assimilated into a variety of both operational and research NWP forecast models (Table 3.7). Because of the criticality of providing accurate input for such applications, especially into operational NWP models, heavy emphasis was placed on quality assurance and processing of all utilized observations.

**Table 3.7.** Summary of model data use from the National Oceanic and Atmospheric Administration (NOAA) Sensing Hazards with Operational Unmanned Technology 2016 campaign.

| NWP Forecast Model Name | Model Type: Operational - vs- Research | Domain Type | Source Nation / Institution |
|---|---|---|---|
| Hurricane Weather Research and Forecasting (HWRF) | Operational | Regional | U.S. / NOAA Hurricane Research Division |
| Coupled Ocean/Atmosphere Mesoscale Prediction System | Operational | Regional | U.S. / Navy |
| Navy Global Environmental Model | Operational | Global | U.S. / Navy |
| European Centre for Medium-Range Weather Forecasts (ECMWF) | Operational | Global | Europe (independent intergovernmental) |
| United Kingdom Meteorological Model | Operational | Global | United Kingdom |
| Hurricane Weather Research and Forecasting System - Research version | Research | Regional | U.S. / NOAA Hurricane Research Division |
| Weather Research and Forecasting Model - Advanced Research version | Research | Regional | U.S. /Pennsylvania State University and the National Center for Atmospheric Research |
| Fifth-Generation Mesoscale Model | Research | Regional | U.S. / Pennsylvania State University and the National Center for Atmospheric Research |

Project data is available from the following three web addresses:

- HS3 Project:
  https://espo.nasa.gov/hs3/data_products

- NOAA Meteorological Assimilation Data Ingest System (MADIS): https://madis.ncep.noaa.gov/madis_gapfillua.shtml
- NOAA SHOUT Preliminary Data Archive: https://www.esrl.noaa.gov/psd/psd2/coastal/satres/shout_prelim_data_archive.html

The final Data Management effort fell under four general activities:

1. UAS data lifecycle management, consisting of managing and maintaining data through various stages of the data lifecycle including data creation, real-time delivery for modeling assimilation and visualization, accessible storage for use in other tools and applications, and eventual archival for long-term preservation.
2. Research and investigation of existing visualization tools, providing guidance and recommendations going forward for real-time UAS data visualization within three distinct 'realms': 1) real-time field data tracking and collection, 2) real-time field data visualization for operational users, and 3) scientific visualization for data analysis, comparison, and assessment of impacts. Each visualization system will allow users to integrate other Earth system data synchronized in both time and space. Initial candidates will include existing NASA MTS, the NOAA Earth Information System, and the second generation of the NOAA Advanced Weather Interactive Processing System.
3. Development of real-time data visualization tools resulting from the output of task two.
4. Development and implementation of tools aiding UAS data discovery and accessibility to meet NOAA data management requirements.

There is a recognized need to further automate data distribution, processing, publishing, and archiving. This work will commence with the MADIS team using SHOUT Data sets as case studies to optimize the processes for NOAA operations. The first step in this effort enhances the quality control (QC) process applied manually by the research teams. Once the QC process reaches maturity, the algorithms will transition to MADIS, although responsibility for continued QC enhancements remains with the principal investigator. Following this transition, latencies will be reduced while preserving data pathways for user communities, providing for a more streamlined and reliable system (Figure 3.7).

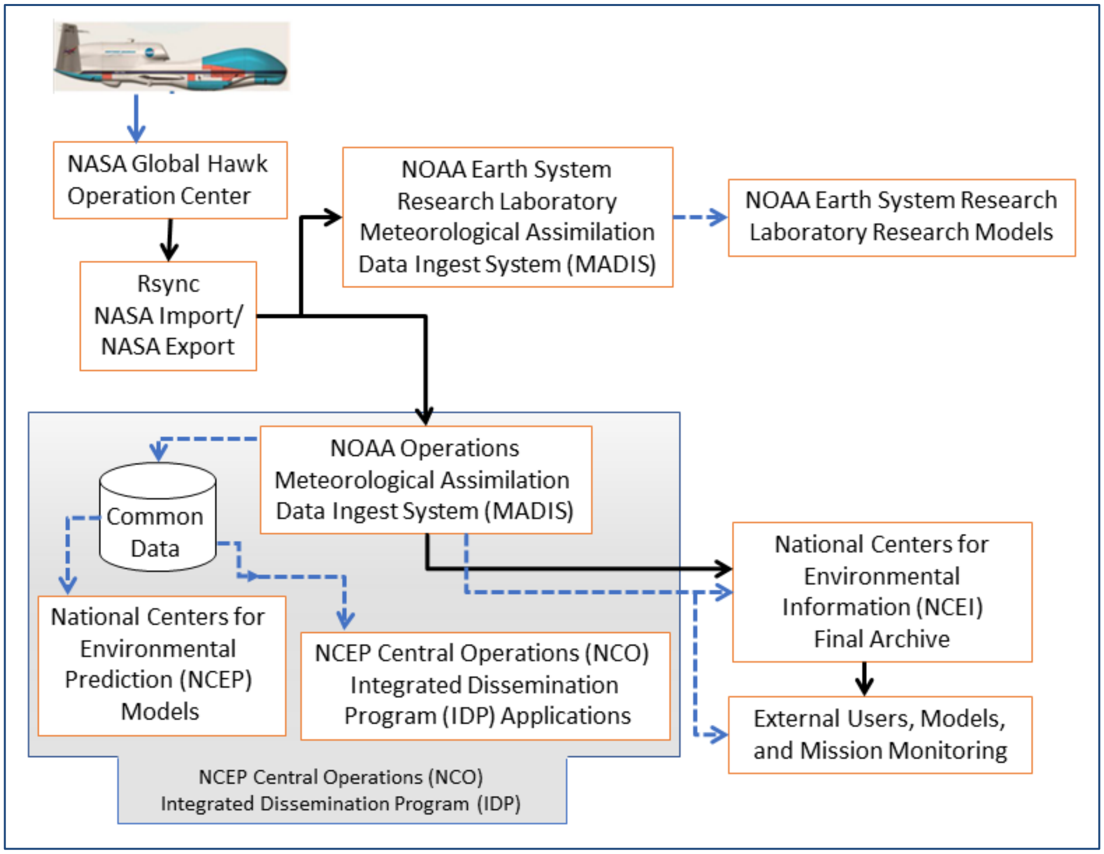

**Figure 3.7.** Optimized Global Hawk data flow and architecture.

# 4 COSTING ANALYSIS

The 2015 and 2016 SHOUT Global Hawk Cost Study Reports (NOAA 2015b, 2016) examines both startup and annual costing for operating a retired USAF Global Hawk UAS either in partnership with NASA or as an independent NOAA asset. The initial analysis detailed four basic options for NOAA's evaluation to implement a cost- effective and efficient transition of Global Hawk operations for high-impact weather events. Since the time that the preliminary SHOUT Global Hawk Cost Study report was released, NASA has decided to stand up the more capable Block 10 Global Hawk while maintaining the ACTD AV-6 aircraft. The decision reduced both program and operational risk, as the NASA and NOAA team will have two aircraft available for research and development.

In order to advance the operational model adopted during the HRR campaign, a rapid response model was employed to maximize the opportunity of capturing suitable scientific targets, reduce costs, and demonstrate what future potential operational deployments of the Global Hawk, as opposed to research campaigns, might look like. The aircraft and experimental teams were scheduled for an extended two-month period from August to September with the goal of conducting up to eight 24-hour flights studying high-impact targets. To avoid the prohibitive costs associated with deploying personnel for the full two-month period, the campaign was planned such that staff would only travel when a target was identified and would remain deployed only during the period of the missions. The goal of the rapid response model was to identify flight opportunities and deploy personnel 72 hours in advance of a potential mission. As illustrated in Table 4.1 the cost drivers for operations continue to be labor and travel. During SHOUT 2015, the actual window for operations was limited to a five- week period during the peak hurricane period (NOAA 2015b). This narrow operational window constrained the availability for operations to a smaller period than would be optimal for being mission ready for hurricane targets. In 2016, these figures were improved when aircraft availability time was increased to 11 weeks (NOAA 2016). Heightened availability was accomplished by reducing the number of science and instrument personnel required to support the mission during operations and reducing travel time in field.

## 4.1 Platform Analysis

The 2015 SHOUT Global Hawk Cost Study Report (NOAA 2015b) reflected analytically-based costs for aircraft stand-up and operations. The purpose of this cost report was to develop a reliable costing model for Global Hawk operations using cost and operational data spanning three consecutive campaigns including: SHOUT 2015, ENRR 2016, and SHOUT 2016 (Tables 4.1 and 4.2). The costing information for SHOUT 2015 estimated project costs for operations using three scenarios: 1) Operations from AFRC, 2) Operations from both AFRC and WFF, and 3) Operations from WFF. All three scenarios were five-weeks in duration with 10 operational flights. Estimates for operations were developed for both coasts. In the event the Atlantic hurricane season proved weak, project scientists would have the option to redeploy to the West Coast and attempt Pacific storms. However, in practice, the return to the West Coast to fly East Pacific Storms was no more successful. Since the SHOUT 2015 project was abbreviated due to a lack of suitable missions, these costs are extrapolated from the missions flown. The remaining funds supported both the ENRR and SHOUT 2016 campaigns.

Amounts associated with ENRR 2016 and SHOUT 2016 from WFF, operated primarily from WWF, are actual costs, whereas the SHOUT 2016 ARFC costs depicted are estimates for operations solely from AFRC. The information derived from (Tables 4.1 and 4.2) was useful for developing the subsequent two tables using the U.S. Office of Management and Budget ([OMB], 1992) Circular A-126 accounting methods. These two additional tables provide actual SHOUT costing numbers for use in estimating the cost of future Global Hawk campaigns from ARFC (Table 4.3) and those deployed to WFF (Table 4.4). Through the optimization of personnel, platform, sensors, data distribution, and CONOPS, the team improved on the mission success from previous years while significantly reducing costs. Additional cost improvements resulted from optimized manpower and travel logistics by maintaining rapid response capability while waiting for high-impact weather targets of interest to come into focus before initiating travel deployment of essential personnel.

**Table 4.1.** SHOUT costing information for operations spanning three consecutive campaigns from 2015 to 2016. The costs summary assumes NASA Airborne Science Program base funding and in-kind contribution from the Space Act Agreement between NASA and Northrup Grumman Corporation.

| | **Hurricanes (2015) 5-weeks** | | | **ENRR[**] (2016) 3-weeks** | **HRR[†] (2016) 10-weeks** | |
|---|---|---|---|---|---|---|
| | **Estimated AFRC[*]** | **Estimated Bi-Coastal** | **Estimated WFF[§]** | **Actual AFRC[*]** | **Estimated AFRC[*]** | **Actual AFRC/WFF[§]** |
| Flight Hours | 248 | 268 | 268 | 96 | (Combined hours for AFRC*/WFF[§]: 239.2) | |
| NASA/NOAA/NGC[‡] Reimbursable Labor | $485,483 | $485,483 | $485,483 | $312,628 | $736,834 | $786,834 |
| Travel (NASA/NOAA/NGC[‡]) Contractor Labor Overtime/Travel | $58,000 | $185,116 | $305,188 | $52,300 | $60,000 | $486,700 |
| Flight Hours | $973,500 | $1,072,000 | $1,072,000 | $563,510 | $964,800 | $964,800 |
| Shipping, Logistics | | $35,392 | $35,392 | | | $48,000 |
| Ames Information Technology Support (labor & travel) | $80,000 | $182,460 | $210,000 | $39,570 | $175,000 | $249,905 |
| KU Satellite communication | $108,615 | $108,615 | $108,615 | $52,835 | $83,490 | $83,490 |
| Miscellaneous AC Parts | $86,175 | $86,175 | $86,175 | | | |
| Earth Science Project Office | $178,000 | $178,000 | $178,000 | | | |
| AFRC[*] Information Technology Assessment | $10,470 | $10,470 | $10,470 | $10,000 | $10,000 | $10,000 |
| WFF[§] Support (Field Services Labor) | | $157,000 | $157,000 | | | $97,922 |
| Global Hawk OPERATIONS SubTotal | $1,980,243 | $2,500,711 | $2,648,323 | $1,030,843 | $2,030,124 | $2,727,651 |
| CM&O[**] (Overhead) 14.9% | $245,000 | $265,000 | $275,000 | $114,512 | $217,996 | $225,692 |
| TOTAL COSTS | $2,225,243 | $2,765,711 | $2,923,323 | $1,145,355 | $2,248,120 | $2,953,343 |
| TOTAL COST/ FLIGHT HOUR | $8,972 | $10,319 | $10,907 | $11,930 | $9,388 | $12,448 |

* Armstrong Flight Research Center (AFRC)

** Center Management and Operations (CM&O)

*** El Niño Rapid Response (ENRR)

**** Earth Science Project Office (ESPO)

† Hurricane Rapid Response (HRR)

‡ Northrop Grumman Corporation (NGC)

§ Wallops Flight Facility (WFF)

**Table 4.2.** The Actual SHOUT costing information for operational science missions and payloads spanning three consecutive campaigns from 2015 to 2016. The costs summary assumes NASA Airborne Science Program base funding and in-kind contribution from the Space Act Agreement between NASA and Northrup Grumman Corporation.

| | **Hurricanes (2015) 5-weeks** | **ENRR* (2016) 3-weeks** | **HRR** (2016) 10-weeks** |
|---|---:|---:|---:|
| Mission Science Labor | $75,000 | $45,000 | $72,000 |
| Goddard Science | $57,909 | – | – |
| Mission Science Travel | $90,000 | $36,000 | $65,000 |
| Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison | $58,000 | $25,000 | $75,000 |
| High Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer | $245,000 | $65,000 | $183,147 |
| High Altitude Wind and Rain Airborne Profiler | $329,739 | $180,000 | $200,000 |
| Dropsondes (for the Advanced Vertical Atmospheric Profiling System) | $450,000 | $330,000 | $453,296 |
| Advanced Vertical Atmospheric Profiling System | $169,290 | $124,500 | $115,000 |
| Lightning Instrument Package | $80,000 | N/A | N/A |
| TOTAL COSTS | $1,554,938 | $805,500 | $1,163,443 |
| TOTAL COST/ FLIGHT HOUR | $5,802 | $8,390 | $4,863 |

*El Niño Rapid Response (ENRR)

**Hurricane Rapid Response (HRR)

**Table 4.3.** The "Daily" and "Per Flight Hour" Global Hawk costs from NASA Armstrong Flight Research Center (AFRC) for operation of the aircraft only (does not include mission science or payload costs). The costs summary assumes NASA Airborne Science Program base funding and in-kind contribution from the Space Act Agreement between NASA and Northrup Grumman Corporation.

| | Cost Driver | Standard Rate | Quantity | Cost Estimate Per Day | Cost Estimate Per Flight Hour |
|---|---|---|---|---|---|
| DIRECT COSTS - VARIABLE | | | | | |
| Crew: | | | | | |
| Travel and Per diem (Domestic) | per traveler per day | $325.00 | 3 | $975.00 | |
| Maintenance (time/cycle based): | | | | | |
| Parts | per flight hour | $1,500.00 | 1 | | $1,500.00 |
| Contracts | per flight hour | $1,800.00 | 1 | | $1,800.00 |
| Engine Overhaul / Aircraft Refurbishment | included in Maintenance | $400.00 | 1 | | $400.00 |
| Fuel - Jet A | per gallon per flight hour | $4.25 | 1 | | $318.75 |
| Other: | | | | | |
| Communications | per flight hour | $348.00 | 1 | | $348.00 |
| DIRECT COSTS - FIXED | | | | | |
| All Labor - Full Burdened Base labor | per project day | $11,492.00 | 1 | $11,492.00 | |
| INDIRECT COSTS | | | | | |
| Admin/Operations overhead | per project day | $1,827.04 | 1 | $1,827.04 | |
| Depreciation | per project day | $767.00 | 1 | $767.00 | |
| Self-insurance costs | per flight hour | $3.83 | 1 | $3.83 | – |
| TOTAL COSTS (per day and flight hour) | | | | $15,064.87 | $4,366.75 |

**Table 4.4.** The “Daily” and “Per Flight Hour” Global Hawk costs for deployment from NASA Wallops Flight Facility (WFF). The costs summary assumes NASA Airborne Science Program base funding and in-kind contribution from the Space Act Agreement between NASA and Northrup Grumman Corporation.

|  | **Cost Driver** | **Standard Rate** | **Quantity** | **Cost Estimate Per Day** | **Cost Estimate Per Flight Hour** |
|---|---|---|---|---|---|
| DIRECT COSTS - VARIABLE |  |  |  |  |  |
| Crew: |  |  |  |  |  |
| Travel and Per diem (Domestic) | per traveler per day | $325.00 | 21 | $6,825.00 |  |
| Maintenance (time/cycle based): |  |  |  |  |  |
| Parts | per flight hour | $1,500.00 | 1 |  | $1,500.00 |
| Contracts | per flight hour | $1,800.00 | 1 |  | $1,800.00 |
| Engine Overhaul / Aircraft Refurbishment | included in Maintenance | $400.00 | 1 |  | $400 |
| Fuel | per gallon per flight hour | $4.25 | 75 |  | $318.75 |
| Airfield Fees (Wallops Flight Facility services, etc.) | per project day | $1,400.00 | 1 | $1,400.00 |  |
| Other: |  |  |  |  |  |
| Shipping / Transportation | per flight hour | $200.00 | 1 |  | $200.00 |
| Communications | per flight hour | $348.00 | 1 |  | $348.00 |
| DIRECT COSTS - FIXED |  |  |  |  |  |
| All Labor - Burdened Base labor | per project day | $11,492.00 | 1 | $11,492.00 |  |
| INDIRECT COSTS |  |  |  |  |  |
| Admin/Operations overhead | per project day | $3,224.00 | 1 | $3,224.00 |  |
| Depreciation | per project day | $767 | 1 | $767.00 |  |
| Self-insurance costs | per flight hour | $3.83 | 1 | $3.83 |  |
| TOTAL COSTS (per day and flight hour) |  |  |  | $23,711.83 | $4,566.75 |

Global Hawk affordability is further highlighted through an examination of the fuel burn rate. An examination of the fuel burn rate further highlights Global Hawk affordability. For example, the Global Hawk's use of 75 gallons per hour compared to the 750 gallons per hour used by the manned Hurricane Hunter aircraft, which affects the mission efficiency of long endurance platforms and reduces the percentage of aircraft transit time for 24 hours of on-station observation. The fuel burn rate became especially interesting during the ENRR Campaign, as three different types of manned (e.g., Lockheed WC-130 Hercules and NOAA G-IV) and unmanned (e.g., Global Hawk) aircraft were flying similar one hour to on-station transits for atmospheric sampling. The Global Hawk collected 65 hours of on-station time in three missions, while it took the WC-130 more than six flights and the GIV approximately 12 flights to attain the same amount of on-station time (Figure 4.1).

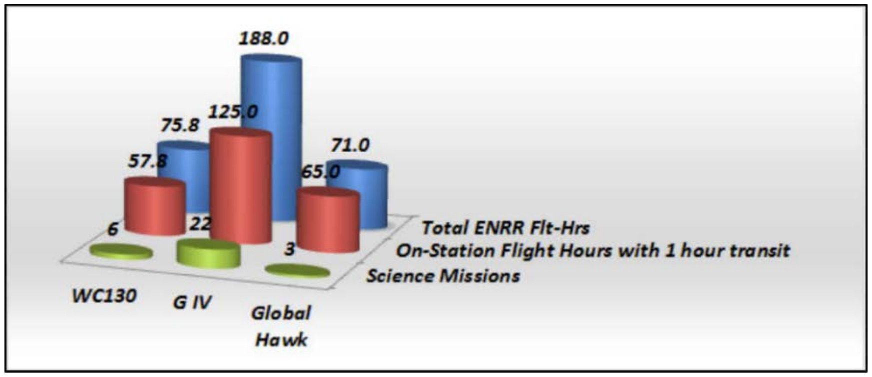

**Figure 4.1.** Manned and unmanned science missions, on-station flight hours, and total ENRR flight hours summary.

As the transit time of the aircraft increases, the number of flights required to have a 24-hour on- station time for the manned aircraft could reach double digits, while a 24-hour Global Hawk event could do so with one-two flights. This is important in aircraft analysis, as unscheduled maintenance often occurs with each additional mission. While the scale and scope of the ENRR missions were similar, the fuel consumption and carbon footprint of the manned aircraft were approximately 10 times greater than that of the unmanned aircraft (Figure 4.2).

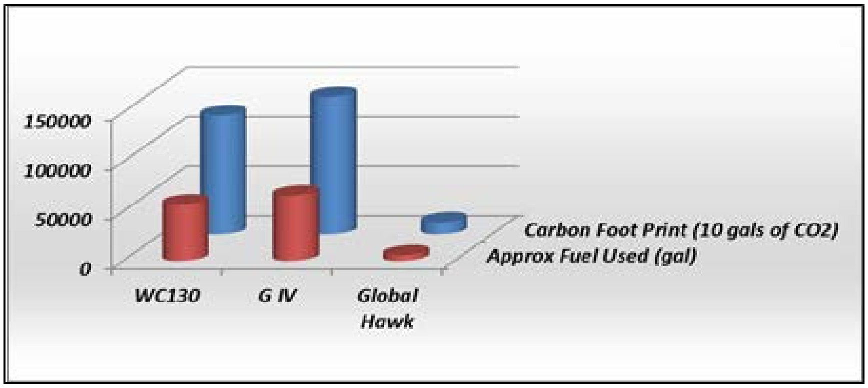

**Figure 4.2.** Manned and unmanned systems fuel used and carbon footprint during ENRR.

As of the writing of this report, the comprehensive figures with this data from the HRR missions were not yet available; however, preliminary information indicates a similar result when comparing the unmanned aircraft with its manned counterparts. While continuing to use these aircraft for environmental intelligence missions in pristine environments like the Arctic or Antarctic, minimizing the environmental impact and costs maximizes mission efficiency and effectiveness.

## 4.2 Mission Science Analysis

The mission science cost analysis is based on data collected over three campaigns. Mission science support and sensor costs were derived from the 2016 season information. The costs were developed based on 10 flights using 3 sensors (*i.e.*, AVAPS, HAMSR, and HIWRAP) and the associated dropsondes for a project over a 10 week period (see Table 4.5).

**Table 4.5.** Mission science cost analysis. The costs summary assumes NASA Airborne Science Program base funding and in-kind contribution from the Space Act Agreement between NASA and Northrup Grumman Corporation.

| | Cost Driver | Standard Rate |
|---|---|---|
| Mission Science Labor/Travel | 8 Mission Scientists | $137,000 |
| Payloads/Support/Labor | Labor/Support/Sensor | $573,147 |
| Dropsondes (for the Advanced Vertical Atmospheric Profiling System) | 675 Sondes | $453,296 |
| TOTAL COSTS | | $1,163,443 |
| Mission Science Cost/Flight Hour | | $4,863 |

## 4.3 Data Management Analysis

At a high level, data management costs consist of UAS data lifecycle activities beginning with data observation through long-term preservation efforts. Also included are research and development costs for real-time visualization tools and data discovery. The SHOUT UAS Program has managed these activities with support from the Cooperative Institute for Research in Environmental Sciences (CIRES) and Cooperative Institute for Research in the Atmosphere (CIRA). The majority of SHOUT 2015 data costs were establishing the Data Management architecture and initial network start-up, the SHOUT 2016 ENRR and HRR missions optimized the data management plan, and the SHOUT 2017 cost were for the final archiving of the 1,305 GB of SHOUT data with the total cost of $1,362K over three years (see Table 4.6). The budget reflects developmental efforts for the SHOUT data architecture and MADIS data archival.

**Table 4.6**. Summary of data management cost for the SHOUT campaigns. The costs summary assumes NASA Airborne Science Program base funding and in-kind contribution from the Space Act Agreement between NASA and Northrup Grumman Corporation.

| | **Hurricanes (2015)**<br>**5-weeks**<br>**AFRC*/WFF‡**<br>**3 Flights** | **ENRR**** (2016)**<br>**3-weeks**<br>**AFRC***<br>**3 Flights** | **HRR† (2016)**<br>**10-weeks**<br>**AFRC*/WFF‡**<br>**9 Flights** | **CLOSE- OUT (2017)**<br>**Boulder, CO** | **TOTAL DATA MANAGEMENT COST** |
|---|---|---|---|---|---|
| Data Management & Visualization (CIRA**) | $283,425 | $133,000 | $200,441 | $273,422 | $890,288 |
| - Manpower (~ Full Time Employee) | 1.25 (FTE) | 1.75 (FTE) | 1.75 (FTE) | 1.6 (FTE) | 1.6 (FTE) |
| Data Archiving (CIRES***) | $102,159 | $50,000 | $128,778 | $76,619 | $357,556 |
| - Manpower (~ Full Time Employee) | .33 (FTE) | .6 (FTE) | .6 (FTE) | .25 (FTE) | .5 (FTE) |
| Total Data Storage (MB) (6-8 GB / FLT) | 18,000 | 24,000 | 72,000 | | 114,000 |
| TOTAL COSTS Per Year | $385,584 | $183,000 | $329,219 | $350,041 | $1,361,844 |
| TOTAL COST / MB | $21 | $7 | $4 | | |

* Armstrong Flight Research Center (AFRC)
** Cooperative Institute for Research in the Atmosphere (CIRA)
*** Cooperative Institute for Research in Environmental Sciences (CIRES)
**** El Niño Rapid Response (ENRR)
† Hurricane Rapid Response (HRR)
‡ Wallops Flight Facility (WFF)

# 5 SUMMARY AND RECOMMENDATIONS

This Final SHOUT Cost Study Report updates the 2015 and 2016 Cost Study Reports (NOAA 2015b, 2016) and supports NOAA's transition to a testbed of Global Hawk UAS technology for satellite gap mitigation and a proposed operational system for high impact tropical, Arctic, and synoptic scale oceanic storm reconnaissance and forecasting. Because this will be an ongoing operational NASA activity with the availability of dozens of scientific payloads, NOAA will continue to evaluate the acquisition strategy and operation of HALE platforms with scientific instruments for NOAA missions. However, the SHOUT 2017 Cost Analysis concludes that the Global Hawk is operationally feasible and affordable for this application when compared to its manned counterparts.

While the cost drivers for operations continue to be labor and travel, aircraft availability time was almost doubled to 11 weeks in 2016. This year's real-world costing of flight operations was stable, and mission flexibility increased by establishing a rapid response capability as opposed to having personnel deployed, "waiting for the storm." Further cost reductions included reducing the number of science and instrument personnel required to support the mission during operations and reducing travel time in the field.

Based on current program plans, budgetary realities, and asset availability for the foreseeable future, the 2015 recommended "NASA/NOAA Option", in which NOAA continues to take advantage of NASA's decision to stand up a Block 10 Global Hawk at AFRC while maintaining AV-6 for operation, continues to be recommended. This approach gives NOAA the most powerful data collection capability for the lowest cost. Furthermore, by using NASA's excess capacity on the two Global Hawks made available after the SHOUT 2016 missions, the agency reduces risk while maintaining the most flexible, reliable, and maintainable option.

Items needing further action were expanded upon at the SHOUT Technical Interchange Meeting (TIM). These six items include:

- Continuing the HALE transition to operations planning, including the NWS' Capabilities and Requirements Decision Support process.
- Continuing to socialize and gain cultural acceptance of UAS and HALE operations throughout NOAA, including in Arctic Operations.
- Optimizing the hurricane observation strategy through the coordination of Global Hawk, GIV, P3, C130, satellite, and other reconnaissance missions to provide unprecedented coverage of observations for operational application.
- Streamlining the interagency agreement (IAA) process. (e.g., The "Rapid Response" component of these missions estimated roughly three months for the administrative process to have IAAs in place, which is the pacing item).

- Obtaining “file and fly” status access to airspace. (*i.e.*, Without the ‘file and fly” status, the FAA requires up to a 48-hour notice).
- Refining human factors for long endurance operations.

As the RL and operational availability of the Global Hawk and sub-systems have increased, operational costs have decreased, making the transition to operations of HALE platforms within NOAA to fulfill observational requirements more feasible. NASA’s East Pacific Origin and Characteristics of Hurricanes mission in 2017 will provide an opportunity for continued Global Hawk teaming. Moreover, the potential international Arctic mission in the Spring 2018 or 2019 would expand the operational envelope and reach of HALE platforms.

Finally, analysis to fully understand the cost drivers, especially manpower, persists. As such, the automation of sensors and vehicle operations continues to advance (e.g., the U.S. Navy’s MQ-4C Triton variant of the Global Hawk); the Naval CONOPS plans to use ground stations manned by a four-person crew, including an air vehicle operator, a mission commander, and two sensor operators; and the system, subsystems, and data distribution automation continues to optimize remote monitoring of systems and science, which will minimize the number of deployed personnel.

# ACKNOWLEDGEMENTS

Input for this report and the overall execution of the SHOUT project was made possible through the efforts of a highly qualified team of individuals possessing a variety of extensive, relevant backgrounds. First, from NOAA's Office of Oceanic and Atmospheric Research (OAR), the SHOUT project would not have been possible without guidance and oversight from the Principal Investigator and Director of the NOAA UAS Program, Robbie Hood, as well as the lead SHOUT Project Scientist, Dr. Gary Wick, a physicist in the Physical Science Division of the Earth System Research Laboratory. Also, Dr. Jason Dunion from the NOAA/AOML/Hurricane Research Division was a Co-PI and operational coordinator with the other science teams and platforms.

NOAA Corps Officers Captain Phil Hall and Commander Jon Neuhaus from NOAA's OMAO provided hands-on support and piloting expertise for the planning and execution of each SHOUT mission, while Alan Goldstein served as the Global Hawk Payload Manager during many of the joint NASA/NOAA Global Hawk missions. Additionally, Frank Cutler, the NASA Global Hawk Program Manager out of the Armstrong Flight Research Center (AFRC), also contributed greatly to the success of the SHOUT project with the experience and oversight that he brought to the team.

Project Managers Phil Kenul (TriVector Services, Inc.) and John "JC" Coffey provided support on behalf of Cherokee Nation Technologies. Also supporting the project, Dave Fratello, Lead Payload Systems Engineer for the NASA Global Hawk Project at AFRC; and key members from the NOAA UAS Program Office, Dr. Pete Black and John Walker, atmospheric scientists and members of the Science Assessment Team for the NOAA UAS Program Office.

Furthermore, the SHOUT project would not have been possible without the input, dedication, and support from the array of highly qualified payload instrument Principal Investigators and their associated teams: Dr. Shannon Brown from NASA's Jet Propulsion Laboratory (HAMSR), Dr. Gerald Heymsfield from the NASA Goddard Space Flight Center (HIWRAP), Terry Hock of the National Center for Atmospheric Research (AVAPS), Dr. Richard Blakeslee from the NASA Marshall Space Flight Center (LIP), Dr. Hank Revercomb from the University of Wisconsin (S-HIS), and Dr. Daniel Cecil from the NASA Marshall Space Flight Center (Hurricane Imaging Radiometer [HIRAD]).

Lastly, the SHOUT team is also extremely grateful to the large group of skilled individuals who supported the project from behind the scenes at NASA Armstrong Flight Research Center, NASA Wallops Flight Facility, Northrop Grumman's Global Hawk team, L-3's Global Hawk flight support, NOAA OAR, NOAA OMAO, and others who contributed to the success of each mission as pilots and mission scientists. Without the combined, coordinated efforts of these folks, SHOUT would not have been practicable.

# SOURCES FOR COSTING STUDY

This study is based on several years of experience executing flight operations with the NASA AFRC in close communication with all instrument PIs: AVAPS (Hock, National Center for Atmospheric Research), HIWRAP (Heymsfield, Goddard Space Flight Center), LIP (Blakeslee, Goddard Space Flight Center), HAMSR (Brown, JPL), S-HIS (Revercomb, University of Wisconsin), and HIRAD (Cecil, Marshall Space Flight Center). Original costing efforts and sources are listed in the 2015 and 2016 reports (NOAA 2015b, 2016).

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# APPENDIX A: AIRBORNE SCIENCE INSTRUMENTS USED ON THE GLOBAL HAWK

(Updated: November 2016)

**Instruments Integrated and Flown on Global Hawk:**

| | | |
|---|---|---|
| 1 | Focused Cavity Aerosol Spectrometer | Global Hawk Pacific (GloPac) |
| 2 | Nucleation-Mode Aerosol Size Spectrometer | GloPac |
| 3 | Ultra-High Sensitivity Aerosol Spectrometer | GloPac |
| 4 | Meteorological measurement System | GloPac, Airborne Tropical Tropopause Experiment (ATTREX) |
| 5 | Cloud Physics LIDAR | GloPac, Hurricane and Severe Storm Sentinel (HS3), ATTREX |
| 6 | Microwave Temperature Profiler | GloPac, ATTREX |
| 7 | OZONE | GloPac, ATTREX |
| 8 | Unmanned Aircraft System Chromatograph for Atmospheric Trace Species | GloPac, ATTREX |
| 9 | Unmanned Aerial System Laser Hygrometer | GloPac, ATTREX |
| 10 | Airborne Compact Atmospheric Mapper | GloPac |
| 11 | Lightning Instrument Package | Genesis and Rapid Intensification Processes (GRIP) |
| 12 | High-altitude Imaging Wind and Rain Profiler | GRIP, HS3, Hurricane and Severe Storm Sentinel (SHOUT) |
| 13 | Airborne Vertical Atmospheric Profiling System | GRIP, Winter Storms and Pacific Atmospheric Rivers (WISPAR), HS3, SHOUT |
| 14 | High Altitude MMIC Sounding Radiometer | GRIP, WISPAR, HS3, SHOUT |
| 15 | Scanning High-Resolution Interferometer Sounder | HS3 |
| 16 | Hurricane Imaging Radiometer | HS3 |
| 17 | Advanced Whole Air Sampler | ATTREX |
| 18 | Diode Laser Hygrometer | ATTREX |
| 19 | Fast Cloud Droplet Probe | ATTREX |
| 20 | Miniature Differential Optical Absorption Spectrometer | ATTREX |
| 21 | Solar Spectral Flux Radiometer | ATTREX |
| 22 | Picarro Cavity Ring Down Spectrometer | ATTREX |
| 23 | NOAA WATER VAPOR | ATTREX |
| 24 | Land, Vegetation and Ice Sensor | (solo, test) |
| 25 | Airborne Detector for Energetic Lightning Emissions | HS3 (2013) |
| 26 | HAWKEYE | ATTREX |
| 27 | Uninhabited Aerial Vehicle Synthetic Aperture Radar, Z-25 VERSION | NGC, Canadian Flt. 2014 |
| 28 | Digital Mapping System NADIR Camera | NGC Canadian Flt. 2014 |
| 29 | Aerosol Ice Interface Transmission Spectrometer (U.K.) | Coordinated Airborne Studies in the Tropics (CAST) / ATTREX |
| 30 | GreenHouse Observations of the Stratosphere and Troposphere (U.K.) | CAST / ATTREX |

## Instruments to be integrated on Global Hawk:

| | |
|---|---|
| 31 ER-2 Doppler Radar (Goddard Space Flight Center) | Hands-On Project ExperienceHOPE / East Pacific Origins and Characteristics of Hurricanes Quarter 3, Contract Year 2017 |
| 32 TM ANTENNA (Climate Data Support Initiative) | TM Technical Demonstration, Quarter 4, Contract Year 2017 |

## Instruments proposed for Global Hawk:

| | |
|---|---|
| 33 SNOW RADAR | (solo, test initially) |

## Situational Awareness Instruments, facility instruments on Global Hawk:

| | |
|---|---|
| 34 High Definition Visual CAMERA | GloPac + |
| 35 Global Hawk In-flight Turbulence Sensor (ACCELEROMETER) | GloPac + |
| 36 LIGHTNING DETECTOR | GRIP + |
| 37 LOW-LIGHT NOSE CAMERA | GRIP - ATTREX (no longer used) |
| 38 DAYLIGHT NOSE CAMERA | HS3 (2014) + |
| 39 IR NOSE CAMERA | SHOUT + |

## Situational Awareness Instruments Purchased, to be integrated on Global Hawk:

| | |
|---|---|
| -- WEATHER RADAR | Electronic testing complete; waiting for schedule and funding to install. |

## Instruments Funded for Global Hawk Development, on hold:

| | |
|---|---|
| -- AMS (MULTI-SPECTRAL) | Design completed for GloPac, but removed prior to integration. |
| -- Global Ozone Lidar Demonstrator (OZONE) | American Recovery and Reinvestment Act effort to include only design activity. Completed. |
| -- Glacier and Land Ice Surface Topography Interferometer-H (X-BAND SAR) | Jet Propulsion Laboratory needs funding for new fairing fabrication. |
| -- Tropospheric Wind Lidar Technology Experiment (WIND LIDAR) | Mechanical integration on aircraft halted due to structural issues |