A Decade of Weather Technology Delivered to America's Space Program by the Applied Meteorology Unit

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Abstract

The Applied Meteorology Unit (AMU) is a unique joint venture of NASA, the Air Force and the National Weather Service (NWS). The AMU develops, evaluates and transitions new technology and techniques to improve weather support to spaceport operations at the Eastern Range and Kennedy Space Center (KSC). Its primary customers are the 45th Weather Squadron (45WS) at Cape Canaveral Air Force Station (CCAFS), the Spaceflight Meteorology Group (SMG) at Johnson Space Center in Houston, TX, and the National Weather Service (NWS) Office in Melbourne, FL. Its products are used to support NASA's Shuttle and ELV programs as well as Department of Defense and commercial launches from the Eastern Range. Shuttle support has highest priority and includes landing sites elsewhere in the US and overseas.

This paper presents a brief overview of the AMU and how it is tasked by its customers to provide high priority products and services followed by a sampling of products delivered over the last ten years that are currently in operational use. Each example describes the problem to be solved, the solution provided, and the operational benefits of implementing the solution.

An Overview of the AMU

The AMU was established in 1991 based on recommendations from a “blue-ribbon” NASA advisory panel[1] and the National Research Council (NRC)[2]. In accordance with those recommendations it was co-located with the Air Force operational forecasters at CCAFS to facilitate continuous two-way interaction between the AMU and its operational customers. It is operated under a NASA, Air Force, and NWS Memorandum of Understanding (MOU) by a competitively selected contractor. The contract, which is funded and managed by NASA, provides five full time professionals with degrees in meteorology or related fields, some of whom also have operational experience. NASA provides a Ph.D.-level NASA civil service scientist as Chief of the AMU. The AMU Chief manages the AMU for the Government and participates actively in its technical work. The Air Force provides office and laboratory space adjacent to Range Weather Operations in the Range Operations Control Center. The NWS provides access to additional space at the Melbourne Florida NWS Office when required. Both Air Force and NWS personnel also collaborate with the AMU in its technical work.

The AMU is tasked by its customers through a unique, nationally recognized[3] process that is described in detail below. The tasks are limited to development, evaluation and operational transition of technology to improve weather support to spaceport operations and providing expert advice to the customers. The MOU expressly forbids using the AMU resources to conduct operations or do basic research. The AMU may be tasked to perform any or all of the following technology transition services

- Evaluating new technologies with the potential for immediate or near-term operational application
- Tailoring new or existing technologies to the specific requirements and capabilities of our customers and their infrastructure

- Assisting with the development of a concept of operations for effective use of new or existing technologies
- Developing training materials for the use of weather sensors, systems and techniques
- Assisting in the effective specification, acquisition, installation and testing of new weather systems and sensors

Examples of several of these kinds of work will be presented below.

Once the AMU has been assigned a task, the AMU Program Manager assigns a principal investigator and other team members as appropriate. The team prepares a task plan that describes the work to be done, the methodology to be used, the deliverables to be prepared and the task schedule. This plan is reviewed with the customer(s) who proposed the task to ensure that the task has been correctly understood and that the deliverables are what the customer wants. Monthly progress reports and quarterly technical reports are provided to all customers and the quarterly reports are posted to a publicly accessible website (http://science.ksc.nasa.gov/amu). The customer is usually directly involved throughout the design and development of the work. At every critical decision point during the execution of the tasking, the customer is involved in the decision making process. Finally, before the deliverables are formally presented the customer is given an opportunity to review a draft or beta test version of each. This interactive task execution process has also been nationally recognized as a "best practice"[4].

In cases where the AMU's work may be of general interest to the scientific community, an appropriate conference paper or journal article will be prepared. A complete bibliography of AMU publications may be obtained from the website. Including papers currently in press, the total number is approaching one hundred.

The AMU Tasking Process

The AMU may be tasked through any of three processes: formal prioritized tasking, option hours tasking, and mission immediate tasking. Formal prioritized tasking accounts for over 80 percent of the AMU's workload. Option hours tasking accounts for most of the remainder. Mission immediate tasking is rare, but can be of the highest priority when it occurs. Each tasking process is described below.

Formal Prioritized Tasking

Formal prioritized taskings are assigned by consensus of the AMU tasking group. The group consists of representatives from the Air Force, NASA and the NWS. A quasi-annual face-to-face meeting is convened at a location determined in advance by group consensus. About six weeks prior to the meeting, each of the three agencies submits proposals for taskings for the next 12 to 15 months. Each proposal includes at least the following

- A descriptive title
- A detailed technical description
- The operational benefit or requirement to be satisfied by undertaking the task
- A statement explaining why the AMU is the best organization to perform the work
- A list of deliverables and the customer(s) to whom they will be delivered
- An estimate of the AMU resources required to perform the work

After the proposals are received, the AMU contractor reviews them and makes its own independent assessment of the following

- The feasibility of the task
- The appropriateness of the task for the AMU
- The resources required to perform the task

Each proposal with the associated contractor review is provided to the three participating agencies for discussion and evaluation. Prior to the face-to-face meeting, email and telephone discussions take place to lay the groundwork for an efficient and effective face-to-face meeting.

The tasking meeting is designed to match the proposed work to the available resources. Inevitably, the sum of the resources required to do all of the proposed work exceeds the resources actually available. Unless proposals are modified or withdrawn, they must be prioritized and only those proposals with high enough priority to remain above a resource-determined “cut line” will be performed.

There are four phases of discussion at the meeting. In the first phase each agency presents its proposals and the group has the opportunity to ask clarifying questions. The goal of this phase is to ensure that every proposal is completely understood. The proposals are not critiqued or prioritized. Phase two provides each agency with the opportunity to critique the proposals and make suggestions for eliminating, modifying or combining proposals in order to get within the resource limitation. If phase two does not result in reducing the proposed workload to match the labor available, phase three begins in which the remaining proposals are ranked in priority order. The ranking is done by a consensus process with the possibility of a formal vote available as a backup if consensus cannot be reached. Since its inception, the AMU tasking process has always been able to achieve a consensus result, usually by additional modification or withdrawals of proposals to get within the resource limitation. The AMU contractor is an important contributor to finding ways of re-scoping and scheduling the work to maximize the opportunity to meet the requirements of all of our customers. After the proposals are ranked, the contractor presents a final analysis of the remaining tasks and advises where the cut line, if any, must be drawn. Phase four is the adoption of the tasks above the line as the formal prioritized work of the AMU for the following year.

Option Hours Tasking

Option hours tasking is available for work that was not accepted through the formal prioritized process or which is proposed between tasking meetings. A customer who is willing to pay for the service may request that their proposed task be undertaken using option hours. Under the terms of the AMU contract, the Government may buy up to two full time equivalents (FTE) (labor years) per year in addition to the five FTE base-funded by NASA. The use of option hours is subject to the following constraints

- The tasks must be consistent with the AMU MOU
  - May not undertake basic research
  - May not perform operational duties
  - Must relate to improvement of weather support to the Shuttle Program or national and commercial space program activities at the Eastern Range
- The tasks may not conflict with or impede the formal prioritized taskings
- The AMU must be the most appropriate facility for conducting the work

The Chief of the AMU, as NASA contract manager, makes the final decision as to whether a proposed option hours tasking is appropriate. If the tasking is approved the proposing organization provides the necessary funding to purchase the additional hours.

Mission Immediate Tasking

On rare occasions, the special expertise and experience of the AMU may be needed to assist the operational customers with a situation outside of their normal experience base under conditions where there is not time to go through either of the processes discussed above. This may happen, for example, during a launch countdown where unusual radar signatures are seen or remote sensing and *in situ* observations appear inexplicably inconsistent. Resolving the causes of these anomalies needs to be done immediately to assure success of the mission. The AMU Chief has the authority to assign a Mission Immediate tasking to the AMU if the following criteria are met

- The work does not constitute performing an operational role (because that would violate the terms of the MOU)
- The AMU has the necessary expertise to perform the work at the level of competence required
- The urgency of the situation precludes using the option hours process

• The scope of the work is small enough that any disruption or delay of other taskings will be small and transient.

A Decade of AMU Products

Although the AMU has been in operation for nearly thirteen years, this paper focuses on the last decade. Products from the first several years were presented in a 1995 paper by Ernst and Merceret[5]. The products described in this section are not a comprehensive listing, but they do provide examples of the three tasking methods described above and the various product types that typify the AMU's service to the American space program. Some of the products requested by the AMU customers include written reports, training, sensor analysis, display software, data ingest software, statistical analysis, climatological analysis, forecaster aids, numerical weather prediction (NWP) model evaluation and improvement, data quality control, and operator training, a few of which are described in this section. In it's nearly 13 years of operation, the AMU has completed 63 tasks, only a few of which are described here. Many of the task reports are available at http://science.ksc.nasa.gov/amu.

Forecaster Aids – Formal Prioritized Taskings

Anvil Forecast Tool: The 45WS and SMG identified thunderstorm anvil forecasting as one of their most challenging tasks when predicting the probability of a Launch Commit Criteria (LCC) violation or evaluating Space Shuttle Flight Rules (FR) due to the threat of natural and triggered lightning. In this case, the customers requested the AMU to develop a capability to display a thunderstorm anvil threat corridor on a satellite image[6]. The threat corridor is based on observed data from a rawinsonde or forecast data from an NWP model. The AMU delivered a product through which the forecaster can request the Meteorological Interactive Data Display System[7] (MIDDS) to generate an anvil threat corridor which is shown by dotted lines on the satellite picture (Figure 1). If thunderstorms are forecast to occur in the threat corridor, the time until the resulting anvils would approach close enough to violate launch or landing constraints[8] can be estimated from the dotted range rings on the threat corridor overlay. By developing this tool directly on MIDDS, the forecasters can use the capability in real-time on a system they use routinely in support of daily operations.

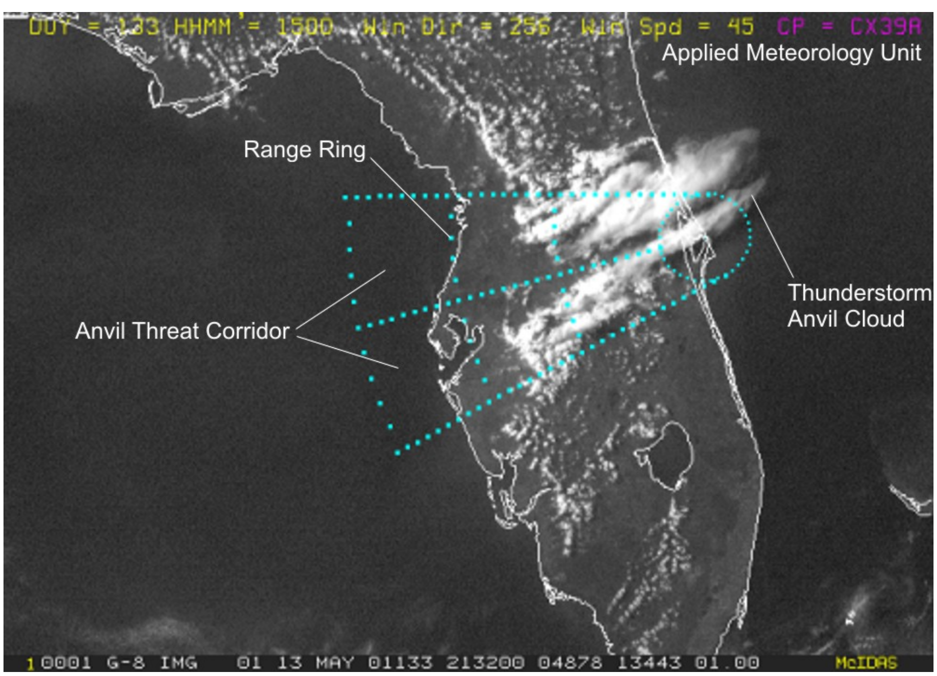

Figure 1. Anvil forecasting tool displayed on a MIDDS forecaster workstation

<u>Microburst Prediction Tool</u>: The 45th Weather Squadron wanted to improve their microburst forecast capability after a poorly forecast 65 Kt (33.5 m/s^{-1}) microburst event occurred at the Shuttle Landing Facility on 16 August 1994. The 45WS tasked the AMU to develop an application forecasters could use daily to better forecast these severe wind events. The AMU developed a RAOB-based Microburst-Day Potential Index (MDPI) that provides an estimate of the probability downbursts each day. The product is displayed on MIDDS in a manner similar to that shown in Figure 2. The MDPI performance includes a probability of detection of 97%, a false alarm rate of 28%, and a critical success index of 70%[9]. As with the anvil forecasting tool, the MDPI is executed and displayed on MIDDS giving the forecasters direct access to this product for daily operations support. The tool also displays the Wind Index (WINDEX) developed by the National Severe Storms Forecast Center (now Storm Prediction Center). In addition to the MDPI, The AMU developed related radar-based tools for nowcasting downbursts using cell trends.

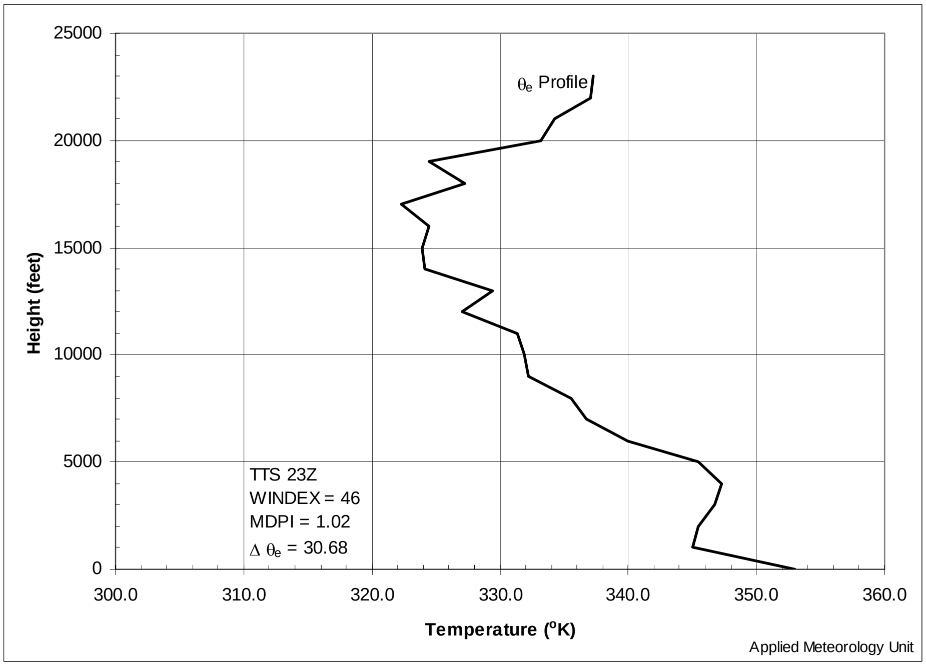

Figure 2. Example of MIDDS graphical MDPI/WINDEX display

Numerical Weather Prediction – Formal Prioritized Tasking

In an effort to improve NWP model capability, the AMU was tasked to improve the integration of local meteorological data sets into the analysis scheme for the Advanced Regional Prediction System (ARPS) NWP model. Most NWP models use national data sets but very few take advantage of any available local data. The KSC/CCAFS area has a high density of meteorological observations that could improve local short-term model forecasts if the data were assimilated properly into an analysis scheme. One example of a local data set integrated into ARPS is shown in Figure 3 which depicts the forecast radar composite reflectivity without using radar data from the Melbourne, Florida Weather Surveillance Radar-1988 Doppler (WSR-88D) (a) and with the WSR-88D data (b). It is clear that the data from the local radar produced forecast radar reflectivity in east central Florida which was much closer to the observed values as seen within white circles in Figure 3. The assimilation of local data sets is a continuous process that runs with the ARPS analysis scheme thereby providing forecasters with better NWP model guidance for every forecast cycle.

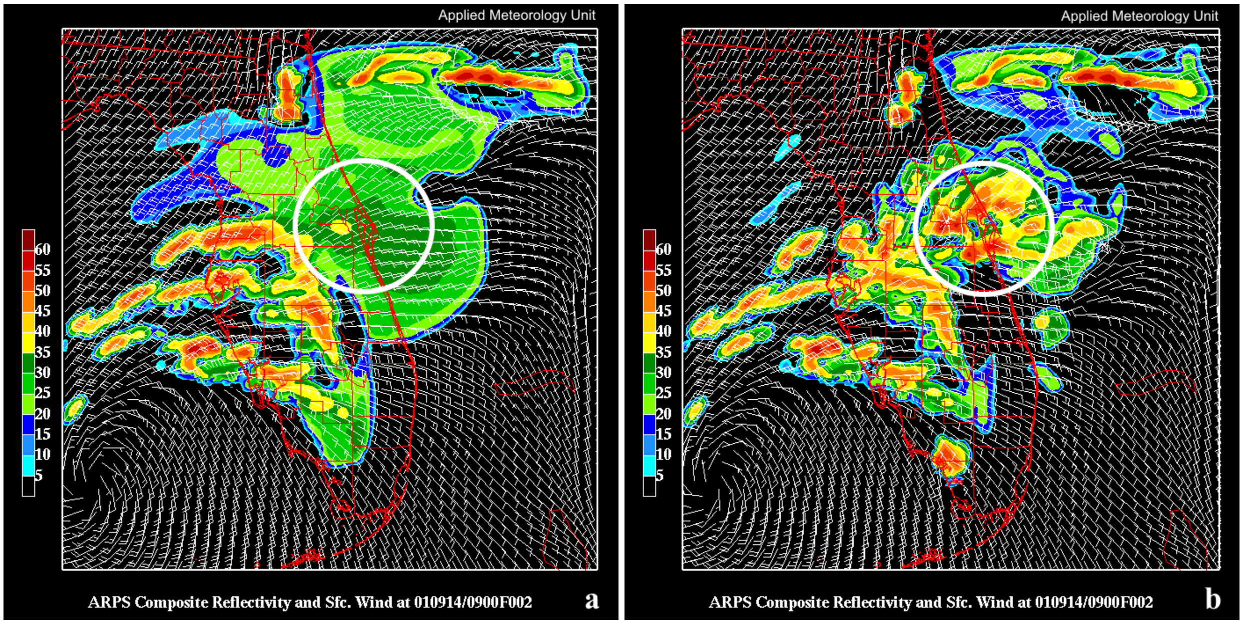

Figure 3. ARPS model showing forecast radar composite reflectivity without assimilating local radar data (a) and with local radar data (b)

Sensor Evaluation – Formal Prioritized Tasking

The networks of meteorological sensors in and around KSC/CCAFS play a critical role in support of space launch operations. Forecasters rely on the accuracy and consistency of these sensors to produce accurate forecasts. When the balloon-borne sensor system or Meteorological Sounding System (MSS) was to be replaced after about two decades of operation, the AMU was tasked to compare the data from the MSS with the new Automated Meteorological Profiling System (AMPS). The purpose of the AMU study was to determine the nature of relative humidity differences between the AMPS and MSS, and to evaluate the impact of any such differences on the diagnosis of tropospheric stability and thunderstorm forecasting indices[10]. Because local experience and thunderstorm forecast rules-of-thumb are based on a long history of stability indices computed from MSS observations, it was important that forecasters become familiar with any changes in the relative humidity data that may accompany the transition to AMPS and the resultant impact on the tools used for analysis and forecasting of thunderstorm activity.

Figure 4 shows the vertical profiles of average relative humidity from both sensors for the cool season (a) and the warm season (b). The initial AMU sensor comparison indicated forecasters could expect the atmosphere to appear less stable when diagnosed with AMPS than with MSS, assuming that their temperature profiles were equal. However, the AMU determined that AMPS and MSS stability indices computed from the warm-season dual-sensor profiles were statistically indistinguishable. This apparent paradox was resolved by evidence of a weak systematic temperature difference between AMPS and MSS that counteracts effects of the relative humidity difference on stability indices. As a result of this analysis the AMU was able to recommend that AMPS products be used without modification thereby providing the forecasters with a high level of confidence in the new system.

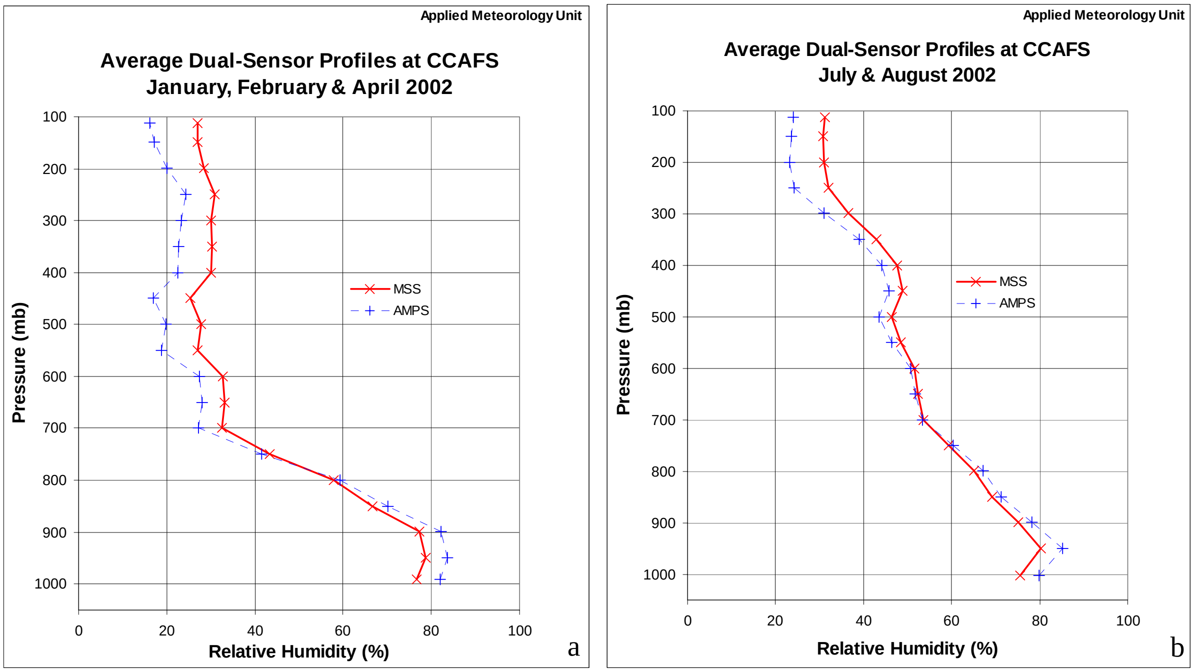

Figure 4. Vertical profiles of average relative humidity from the MSS (solid) and AMPS (dashed) sensors for twenty dual-sensor ascents taken in Jan., Feb. and Apr. 2002 (a) and vertical profiles of average relative humidity from the MSS (solid) and AMPS (dashed) sensors for twenty dual-sensor ascents taken in July and August 2002 (b)

Poorly Forecast Severe Weather Event – Mission Immediate Tasking

The AMU was tasked to analyze and evaluate a poorly forecast severe weather event that affected a major portion of Brevard County including Patrick Air Force Base on 13 August 1996. The severe weather event occurred during the warm season and therefore the task was levied as “Mission Immediate” to quickly ascertain why the event was not forecasted and what could be done to improve forecasting of similar events for the rest of the season. The primary purpose of the analysis was to evaluate relevant meteorological data from the event in order to glean lessons learned and to better understand the contributing factors that caused the damaging weather. From this analysis recommendations were derived to assist forecasters in recognizing these contributing factors more readily when they occur. Results and recommendations were provided for the benefit of future warning operations at both the 45WS and the National Weather Service in Melbourne (NWS MLB).

Space Shuttle Optical Imaging – Option Hours Tasking

The NASA/ KSC Weather Office tasked the AMU to: *“Identify and evaluate alternative methods for determining whether or not a sufficient number of Shuttle launch imaging cameras will have a field of view unobstructed by weather”*. This task was based on the finding from the Columbia Accident Investigation Board (CAIB) Report[11] for Space Shuttle return to flight. Since the CAIB Report dictated that the Shuttle could not return to flight before this capability was in-place it was imperative to quickly determine if it was possible to observe and forecast conditions allowing the cameras to have an unobstructed view of the Shuttle upon launch. The AMU determined what methods were available to mitigate cloud forecasting challenges.

Based on these results, the AMU was further tasked through the prioritized tasking process to develop a statistical model and forecast decision aid for the Space Shuttle Launch Weather Officer using both option hours and base-funded hours.

Summary

The AMU has been an outstanding example of interagency cooperation and effective, practical technology transition. Its success is due to at least five factors:

- Its unique customer-driven tasking process
- Continuous end-to-end customer involvement in task planning and execution
- Co-location of the AMU with an operational customer
- The range and depth of education and experience of the AMU civil service and contractor employees
- Flexibility in the tasking process, adapting task design, or even canceling tasks as lessons are learned during the task

These factors have led the AMU to a remarkable record of delivering operationally useful products on schedule and on budget for over a decade.

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8. See, *e.g.*, Lightning Launch Commit Criteria at the Eastern Range/Kennedy Space Center, W.P. Roeder, J. Sardonia, S. Jacobs, M. Hinson, A. Guiffrida and J. Madura, 37th AIAA Aerospace Sciences Meeting and Exhibit, 10-15 January 1999, Paper 99-0890, page 9.

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