Sam II – How We Did It

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SAM II is a very successful first-generation atmospheric research experiment developed for the Nimbus 7 observatory by the Langley Research Center. It came into existence within tight resource and short schedule constraints by a core project team of four engineers. Even though SAM II has been in orbit for over 14 years, it continues to meet scientific mission objectives. SAM II was recognized by the American Meteorological Society in January 1991–earning the Principal Investigator, Dr. M. P. McCormick, the Jules G. Charney Award for ". . . outstanding contributions to satellite sensing through development of solar occultation instruments for elucidation of the nature of Polar Stratospheric Clouds" which are central to understanding the heterogeneous chemistry that causes the Antarctic ozone hole.

Today's spiraling cost, long development schedule, and large resource estimates to develop new spaceflight instruments begs a close review of past concepts to determine if they are applicable today. This paper describes technical approaches and management techniques used during the period from 1973 to 1978, many of which fit within today's TQM initiatives.

We began relatively inexperienced and none of us knew any of the others when selected for the project. Only half of the team had flight hardware experience. All were GS11/12 engineers. Given the high visibility of the Nimbus program, the risks involved with development of a sophisticated, first-generation instrument, and the limited experience of the project team, Langley management could have micromanaged us to death. Instead, they accepted the risk and let us do our jobs without interference. They gave us the resources and the responsibility and we accepted the accountability for SAM II's success. They empowered us to speak with their authority in making real time decisions. Today, this is known as TQM.

Middle line managers helped us with technical advice, but we dealt with the upper managers for all management-related issues. They took a keen personal interest in SAM II and in our efforts. They visited the University of Wyoming (UWY) and Ball Aerospace on many occasions and knew our contractor counterparts. When asked, they even helped us with technical advice. They provided several analyses, including the Aliasing Error Analysis that we used in our instrument error budget.

They probably could have prevented us from making some mistakes, but wisely used restraint and correctly judged that in the final analysis, the experience gained from these mistakes would provide a greater long-term benefit than the temporary setbacks caused by them. And when we made mistakes, we accepted full responsibility without trying to pass the buck, and then worked twice as hard until we had the problem corrected. They offered virtually unlimited support as needed from the line organizations at the Center. The main benefit of the close relationship of the SAM II team with upper management was the tremendous boost in team morale derived from having their trust, confidence, support, and freedom to do things our way without interference.

Each SAM II team member maintained strong relationships with mentors, and each considers this relationship to have had a major positive influence on development of personal and technical skills necessary for SAM II success. We also strongly advocated and succeeded in getting our contractor and subcontractor to provide mentors for their young engineers.

Adherence to Phased Project Planning

Although we had no text to follow on phased project planning, we followed all the classical principles and covered all the bases that are contained in today's writings on project life cycles. These include: 1) establishing a clear set of science mission requirements and then converting these into instrument performance requirements during Pre-Phase A; 2) exploring potential instrument concepts that could deliver the necessary performance, lifetime and reliability during Phase A; 3) conducting technology surveys to select the most feasible candidate concepts, performing tradeoff studies to evaluate relative merits of candidate concepts, and evaluating technology state-of-the-art and performing risk analysis of candidate concepts in Phase B; 4) selecting a system and then subsystems concepts and quickly moving to the hardware phase by building an Engineering Model (EM) to do development testing to qualify selected concepts during Phase C; and finally, 5) fabricating, performance testing, and flight qualification testing of hardware during Phase D.

We could have written the current textbook on project life cycle principles. We moved to hardware quickly during Phase C/D and built an all-up Engineering Model that proved to be a major key to our success. The EM was thoroughly evaluated and tested, and many ProtoFlight Model (PFM) design refinements came from unforeseen problems during fabrication and testing or from failure to meet performance requirements during testing. The EM gave us a "test bed" that allowed quick evaluation of potential fixes without endangering flight hardware. All of our significant problems were quickly identified and corrected with permanent solutions using the EM hardware. Analyses are good tools, but the real proof of a design is in hardware performance. Also, the EM permitted testing beyond flight test limits, which helped to evaluate reliability, lifetime, and safety margin. Our EM testing was not constrained by QA issues, nor the number of test cycles–factors that must be strongly addressed with flight hardware.

Many design flaws were discovered during the EM fabrication and test phase. The most notable failure was that of the elevation gimbal flex pivots during vibration testing. This resulted in an elevation gimbal redesign, including development of an isolation grommet design that has been used by three subsequent solar occultation instruments.

Risk Management

Early in the SAM II project, we conducted a survey of the availability and status of technologies that would be required for successful development. We did not take a conservative technical approach and were willing to accept many new and unproven designs and approaches. In retrospect, we used extraordinary engineering judgment in accepting some high-risk approaches that succeeded and in rejecting others that in hindsight would have given us problems. Many of the high-risk designs and approaches that were selected probably would be questioned in today's conservative environment.

We identified and ranked risks and put considerable effort into reducing those that could cause catastrophic problems. For high-risk designs, we aggressively pursued a risk reduction program that usually included fabrication of test articles, qualification testing, life testing, evaluation of results, and assessment of residual risk. Decisions were not based on a "hunch" or even an "educated guess," but were based on doing a lot of risk/payoff homework, identifying the development required, and then conducting the necessary development program. The problems incurred were not as severe as one would expect from a first generation design, and this risk management approach played a major role in the SAM II success.

Strong Systems Engineering Approach

Another major key to the SAM II success was effective systems engineering. We believed that with effective systems engineering, the project management process would take care of itself. Ed Mauldin, as Instrument Manager, had the closest role to that of a Project Manager, but this can be described as a part-time job since his full-time responsibility was optics and radiometric engineering. His project management efforts mainly consisted of administrative tasks necessary to keep the books in order; reporting tasks to provide monthly MIC reports and status reviews to Langley Research Center and Goddard Space Flight Center management; and coordination activities such as planning for the design reviews.

Although picked to cover optics, electronics, mechanical, and control system disciplines, we used a systems approach for design and problem solving. Thus, an optimized design was developed that has changed very little in the SAGE, SAGE II, and SAGE III instruments that have followed. This strong systems engineering approach eliminated many potential problems and also formed a "checks and balance" relationship among team members where each forced the other to do homework in order to defend a design or problem solving approach to the other team members. We became interchangeable and looked out for all disciplines when only one of us was in the contractor's plant to review a design, discuss concerns and problems, or operate the instrument during a test. We were also blessed in having an outstanding systems engineer at Ball Aerospace.

Effective Schedule and Cost Control

Much of our success can be attributed to having an excellent working schedule. Although every subsystem of the SAM II instrument had unforeseen problems that were significant schedule drivers, the PFM delivery was shipped only two months after the originally contracted date. This included recovery from a flex-pivot failure during vibration testing that by itself caused a 30-week delay in the CDR and EM delivery. We actually recovered all but one month of lost PFM schedule, but then lost a month waiting for a high-quality sun in Boulder, Colorado needed to perform the final Baseline Systems Test.

Maintenance of this excellent working schedule can be attributed to Lillian Henry of the University of Wyoming, who developed her PERT and technical skills while working on Project Hawkeye at the University of Iowa. Lillian kept an up-to-date PERT schedule in front of us at all times. PERT was used to provide an efficient guide on how to get from here to there, not to point out that the contractor was failing to keep schedule. We had weekly reviews by teleconference (including Langley, UWY, and Ball teams) in which PERT was used as a tool to review all critical and near-critical path activities and conduct brainstorming to find efficient workarounds to minimize schedule slip when problems arose. For a significant period in the middle of the program, all subsystem paths were parallel critical due to implementation of workarounds. PERT activities were focused, people oriented, and broken out into daily increments until PFM delivery. PERT revisions were frequently made to reflect the current best assessment of the most efficient sequence of activities. We even included the Wyoming and Colorado first week of hunting season as a PERT consideration, since many of our contractors were avid hunters. PERT was used as a daily management tool as opposed to a monthly reporting tool.

Cost control was very simple by today's computerized Performance Measurement System (PMS) standards–yet very effective. When one of us visited UWY or Ball, one of our first activities was to meet with the Project Manager and review cost and schedule. We wanted to see which activities had been completed since our last review and which were in progress, with the names of individuals attached. We wanted to see how many

hours these individuals had charged to the SAM II account. Then, we personally went to the individual and asked to see results, such as analyses completed, drawings completed, fabrication completed, testing completed, etc. It did not take rocket scientists' skills to find the soft spots, and when these were found, we had meetings with the responsible supervisors and asked for (and received) explanations and remedial action. As shown in the table below, the system worked very effectively. Even without a PMS type system, our cost-to-complete proved reasonably accurate and we did not have any financial surprises.

COST AND SCHEDULE PERFORMANCE

SAM II PLAN

- Langley inhouse cost estimate: $2.4M
- Original budget (including contingency): $3.5M
- Original ProtoFlight Model delivery: 32 months after C/D start

SAM II ACTUALS

- Contract signed for: $2.177M
- Contract cost runout: $3.165M
- Contract cost overrun: $0.482M
- SAM II instrument total cost (11/9/77): $3.250M
- Delivery: 34 months after C/D start

Small Core Team

We operated as a small core team backed by technical experts from within the line organizations. Thus, we were a clearinghouse for all line organizations participating on SAM II, which permitted rapid response to contractor technical issues. We often used specialists for ad hoc support, and when we needed support, we were not required to go through line organization channels for approval. Some efforts only took a day or two–other efforts seldom took longer than a week or two. Significant problems, such as the flex-pivot failure, were attacked intensively with tiger teams. On these occasions, the focused activities led to quick and permanent solutions that allowed the project to move forward with a minimum of delay.

Our ad hoc team members, most of whom came out of research organizations, were eager to help us. We never had to persuade any of them to work on SAM II even though on most occasions they were very busy and had to push their regular activities aside. This approach resulted in a considerable manpower savings at the Center and a cost savings to the project.

Although strangers to each other when SAM II began, we immediately developed strong bonds and close personal relationships, and we remain lifelong friends. We spent many hours together professionally and socially. However, the close personal relationships did not stifle strong debates on the issues, for each of us was very outspoken as we aired our concerns in frequent team meetings. And these concerns were always taken as positive critiques as opposed to personal criticism. The fact that a mechanical engineer could grill an optical engineer on optics without the optical engineer taking it personally (and vice versa for other team members) testifies to the strong interpersonal relationships that existed among us.

Communication Barriers

Early in the SAM II development, we were faced with a very difficult situation regarding communication channels with UWY and Ball. Contractually, we could not deal directly with Ball since they were a subcontractor of UWY. Moreover, UWY could not perform an adequate subcontract monitoring role because the staff was very "thin" and totally immersed with their work, and UWY did not have experienced engineers covering all the necessary disciplines to perform an adequate monitoring role. To say that we performed a tight rope act would be an understatement.

Our relationship with UWY and Ball employed lessons learned from Project Hawkeye, a satellite developed by Langley with a contract to the University of Iowa with Ball Aerospace as a major subcontractor. First, we aggressively dealt with UWY to define a program that our team could feel comfortable with, and one which provided acceptable confidence of success. This included some tough negotiation in the early days regarding project staffing; we needed to assure ourselves that the UWY team possessed the necessary skills and enthusiasm. After these negotiations were completed, we nurtured our UWY relationships to remove communication barriers and instill mutual cooperation and support. After we had gained their confidence and trust, we followed the same approach with Ball, with the blessing of UWY. We strived from the beginning to develop a clear picture of where we were going and the approach we wanted to use to get there. The emphasis was always on what was best for SAM II. Personal gain was never in the forefront.

On many occasions, we let the contractor take credit for our ideas, which gave them great incentive to work with us, and then we rolled up our sleeves to help get the job completed. Although there were bumps from time to time, the three teams became one united team, all working together to do the best job for SAM II. Differences were resolved by the dedication of each team member and each organization to make the necessary sacrifices to do what would be in the best interest of SAM II.

Often, Government project teams perform a monitoring role in which technical experts are mainly used to evaluate contractor performance and to serve as consultants to help solve problems. We did not monitor our contractor and subcontractor counterparts, but worked side-by-side to share responsibilities in all phases of the project. We had a significant "hands on" role that included participating in design activities, qualifying hardware at Langley, writing procedures and performing tests at Ball, performing instrument problem troubleshooting, etc. We spent nearly as many hours in the clean room with the instrument as did the Ball and UWY engineers, and were treated more like Ball employees when in the plant than as "customers." UWY and Ball team members soon learned to respect us as being technical equals and all "us against them" barriers were removed. Good rapport with UWY and Ball had a great side benefit–we always had up-to-date information.

Using this concept, we were able to develop SAM II for a much smaller cost than would have been incurred if we had used the monitoring approach, since team technical manpower was significantly increased and very little energy was wasted in hiding agendas and playing the traditional Government vs. contractor game of staying at arm's length. A testimony to the success of our balancing act is the fact that we were able to curtail Ball and UWY feelings of meddling and micromanagement and were never seriously accused of these negative behaviors.

One of the Langley SAM II team members was in the contractor's plant almost continuously, eliminating the need for an on-site representative. These trips overlapped, so that status, issues and concerns of all instrument subsystems could be relayed by the departing team member to the arriving team member. At least one of us was always present during important events, such as subsystem and system checkout and performance and qualification testing. Don Hedgepeth lived in Boulder nearly the entire summer of 1976 helping with the EM assembly, checkout, performance testing and flight qualification testing. Ed Mauldin was once in Boulder for 30 days, waiting for a high-quality sun to run the final Baseline Systems Test. We also traveled with the contractor and subcontractor to vendor facilities to assess status and perform hardware inspections. This allowed an independent assessment of vendor-related issues.

Regarding change orders, we made clear from the beginning that unless the contractor saw a directive in writing from the Contracting Officer, comments heard in brainstorming sessions were not to be interpreted as directives. All directives went through the Contracting Officer to the prime contractor, UWY. Before a directive was issued, the Langley team reviewed it thoroughly with UWY until we were sure that the directive was clearly understood. We did not direct the subcontractor, Ball Aerospace, but they did receive similar directives from UWY.

Complementary Relationship with Principal Investigator

We were fortunate to have a very supportive Principal Investigator in Dr. Pat McCormick. Pat provided a clear and concise set of science objectives during Pre-Phase A. He provided a major support role in instrument concept development, such as data inversion simulations to establish instrument performance requirements. Pat helped us evaluate potential instrument concepts during Phase A and helped us conduct tradeoff studies during Phase B. We kept Pat informed of our progress, issues and concerns. He fully understood the engineering problems we faced, and provided relief when we were up against technology barriers in Phase C. Together, we refined the instrument concept during Phase C from a solar tracking instrument to a solar scanning instrument–a design that simplified the instrument and significantly improved the accuracy of data inversion. Neither the engineering team nor the science team would have arrived at this design independently, but the team's synergism resulted in an optimized instrument concept that is still used in current solar occultation instrument design. Both science and instrument teams had a relationship in which each trusted the other to give SAM II their very best effort. In short, Pat was our greatest supporter.

The Langley/Goddard Partnership

Today, new projects take the sister-center relationship between Langley and Goddard for granted. It did not start out that way. Traditionally, Goddard owned all requirements in their programs, including instrument performance requirements. An early Nimbus project manager at Goddard reminded us of the Golden Rule: "He who has the gold, rules." We did not accept this lopsided relationship and insisted on being treated as an equal partner. First, we worked diligently to define a boundary between centers, including explaining our responsibilities, authority, and development role. Then, we aggressively negotiated with Goddard until Langley ownership of the SAM II requirements and development approach was affirmed. Goddard retained ownership of spacecraft interface requirements and top-level mission requirements, such as spacecraft orbit parameters. Eventually, we were treated as peers and the inter-center relationship became unruffled.

Again, this illustrates how we insisted on principles now linked to TQM: those doing the work should be given the responsibility and authority to produce their products. The ground rules established then essentially remain in effect today for inter-center space flight development programs.

Spacecraft Interface

In the beginning, the Nimbus observatory consisted of nine sophisticated flight instruments that required a stringent adherence to the initial allocation of the limited spacecraft resources. These initial budgets were established on March 10, 1975, by the Nimbus Project Office at Goddard, which was less than two months after SAM II contract award. The controlling document was the Sensor Interface Requirements Document (SIRD). A five-phase delivery of interface materi-

als was required by the SIRD, with each phase requiring substantiation that an instrument could stay within its allocated resources. After March 10, Goddard required monthly review of all resources.

At one point very early in the program, Goddard had allocated all weight and power resources and had no contingency at all. One instrument was removed from the payload to recover contingency, but adherence to initial budgets continued. Thus, weight and power were major considerations in selection of technologies, design concepts, and parts used in SAM II. Despite not having an instrument configuration when the early resource allocation and tight resource constraints were placed, we were able to deliver SAM II within all spacecraft budgets.

The concepts used by a small core team to successfully develop the SAM II instrument, which has performed in orbit since October 1978, are summarized below. We could have mentioned other concepts, but did not want to risk obscuring the ones we felt were most important. Many of these concepts are now basic principles of TQM, but were chosen at the time because they simply made common sense:

- Management empowerment of the project team
- Adherence to Pre-Phase A, Phase A, Phase B, and Phase C/D principles
- Engineering model as early proof-of-design elements
- Attentive risk management
- Strong systems engineering approach
- Effective schedule and cost control
- Small core team backed by experts in the line organization
- Close-knit project team
- Removal of communication barriers with contractors
- Frequent visits to contractors
- Clear procedures for directing contractors
- Complementary relationship with the principal investigator
- Well-defined Langley/Goddard partnership
- Attentiveness to spacecraft interface
- Use of "lessons learned" from previous projects
- Mentor relationships