Cost Optimization and Technology Enablement
COTSAT-1

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ABSTRACT

Cost Optimized Test of Spacecraft Avionics and Technologies (COTSAT-1) is an ongoing spacecraft research and development project at NASA Ames Research Center (ARC). The space industry was a hot bed of innovation and development at its birth. Many new technologies were developed for and first demonstrated in space. In the recent past this trend has reversed with most of the new technology funding and research being driven by the private industry. Most of the recent advances in spaceflight hardware have come from the cell phone industry with a lag of about 10 to 15 years from lab demonstration to in space usage. NASA has started a project designed to address this problem. The prototype spacecraft known as Cost Optimized Test of Spacecraft Avionics and Technologies (COTSAT-1) and CheapSat work to reduce these issues. This paper highlights the approach taken by NASA Ames Research center to achieve significant subsystem cost reductions. The COSTAT-1 research system design incorporates use of COTS (Commercial Off The Shelf), MOTS (Modified Off The Shelf), and GOTS (Government Off The Shelf) hardware for a remote sensing spacecraft. The COTSAT-1 team demonstrated building a fully functional spacecraft for $500K parts and $2.0M labor. The COTSAT-1 system, including a selected science payload, is described within this paper. Many of the advancements identified in the process of cost reduction can be attributed to the use of a one-atmosphere pressurized structure to house the spacecraft components. By using COTS hardware, the spacecraft program can utilize investments already made by commercial vendors. This ambitious project development philosophy/cycle has yielded the COTSAT-1 flight hardware. This paper highlights the advancements of the COTSAT-1 spacecraft leading to the delivery of the current flight hardware that is now located at NASA Ames Research Center. This paper also addresses the plans for COTSAT-2.

1.0 INTRODUCTION

COTSAT-1 is a rapid prototype, low-cost spacecraft for science and exploration experiments, including remote sensing, and technology demonstration. The spacecraft platform is designed to accommodate low-cost access to space for variable remote-sensing payloads while maintaining an architecture that allows for future expansion to potential biological payloads. The platform may also accommodate other payloads and technologies with minimal redesign. COTSAT-1 is a ~250 kg small spacecraft that is base-lined to accommodate a remote sensing instrument as the primary payload. The primary objective for the COTSAT-1 mission is to rapidly deploy a spacecraft with a minimum six month reliable-performance period on orbit. The goal of COTSAT-1, as a technology demonstration unit, is to demonstrate drastic cost reduction in spacecraft design and to develop methods and technologies for maximizing reuse of developed spacecraft hardware, software and related technology.

2.0 COST STRATEGIES

The low developmental cost of the spacecraft platform, as compared to systems of similar capability, is primarily enabled by housing the bus and payload subsystems in a single-atmosphere, artificial environment[9]. This concept has been proven with the first man-made satellite, Sputnik, developed by the former Soviet Union. Other Soviet sealed environment spacecraft have been designed and flown successfully. This heritage design attracted the interest of ARC because of dramatic cost reduction possibilities.

Additionally, proper design of the software architecture for COTSAT-1 has proved to generate significant cost reduction through simplified development and integration time. The amount of software reuse is increased on COTSAT-1 by leveraging existing software libraries and device drivers already written for off-the-shelf electronics. In some cases, minor modifications to the open source or industry supplied software drivers were necessary to simplify integration or to add desired features. However this approach has still proven to be effective and significant in cost reduction, compared to a completely new development and testing effort.

2.1 Artificial Atmosphere

As mentioned previously, a key design characteristic of COTSAT-1 for cost reduction and reduced development time is the single-atmosphere (absolute), artificial environment which encompasses the vast majority of the satellite components. The sealed structure of COTSAT-1, shown in figure 1, is used to replicate an Earth-like atmosphere which provides a convective medium to aid in heat distribution. Two fans and four reaction wheels move air within the container to further promote an isothermal gaseous environment for electronics. This design makes feasible the incorporation of a wide array of pre-built hardware including Commercial Off-The-Shelf (COTS), Modified Off-The-Shelf (MOTS) and Government Off-The-Shelf (GOTS) hardware that might otherwise be unsuitable for the space environment. Hybridizing a single-atmosphere

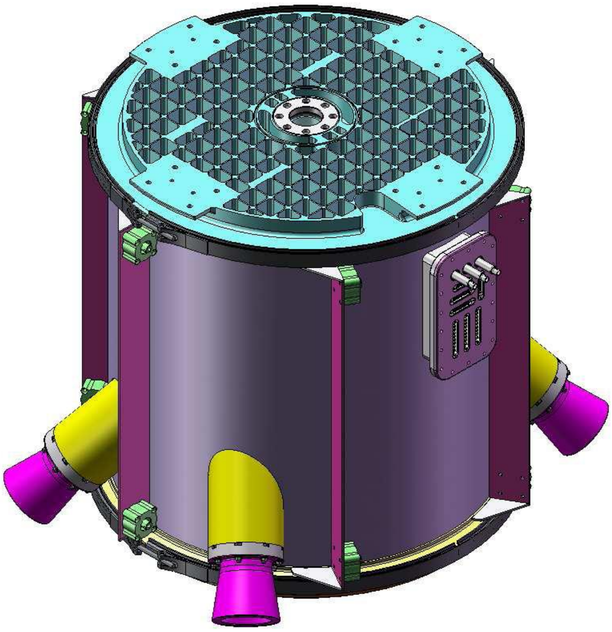


Figure 1: Artificial Atmosphere Container (AAC)

pressure vessel with current COTS technologies allows for subsystem cost reduction, in most cases, by several orders of magnitude. By using COTS hardware, the spacecraft program can utilize development and testing investments already made by commercial vendors. When inexpensive or suitable COTS hardware solutions are not readily available, subsystems are designed, developed, and/or augmented in-house at ARC. In-house developed hardware for COTSAT-1 includes the reaction wheel system, star tracker system and electrical power system. Indeed, COTSAT-1 makes extensive use of COTS, MOTS, and GOTS hardware to considerably save on development time and cost.

2.2 Bus

A key design element in the bus structure of COTSAT-1 is the modular platform upon which the bus is assembled. This structure allows for a logic-flow integration of components leading to ideal placement of electronics resulting in reduced electrical noise and power loss from long leads. Additionally, by mechanically separating the system into modules, subsystems can be more easily and quickly bench tested. The system is also built vertically, as pictured in figure 2. Because of this vertical design, in the event of an electrical problem the upper portion of the AAC can be lifted off and, by removing a limited number of fasteners, the problematic portion of the bus can be pulled for bench-top diagnostics. Not only does this feature prove useful for development when assembly and disassembly is frequent, but it is crucial should a problem arise at the launch site where every minute counts.

2.3 Software

The desired goal for the COTSAT-1 software architecture was to reduce development cost and to promote and maximize potential software reuse. This was achieved by generating a set of core software daemons for common spacecraft functions. The software architecture consists of modular, independent software daemons for each subsystem or capability such as the star tracker, the inertial measurement unit (IMU), the reaction wheels, the main executive, the communications system, the control system and the payload. Each software daemon is given a pre-determined priority level for the multitasking operating system. Major subsystem software daemons communicate via UDP/TCP. The modular software architecture allows for parallel development and testing before integration. The architecture also allows for subsystem reuse on future missions.

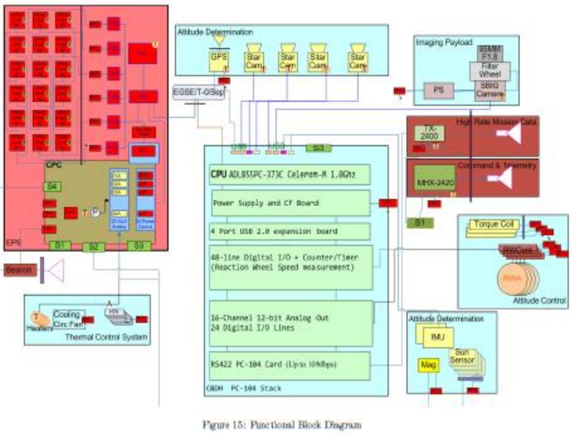


Figure 3 Block Diagram

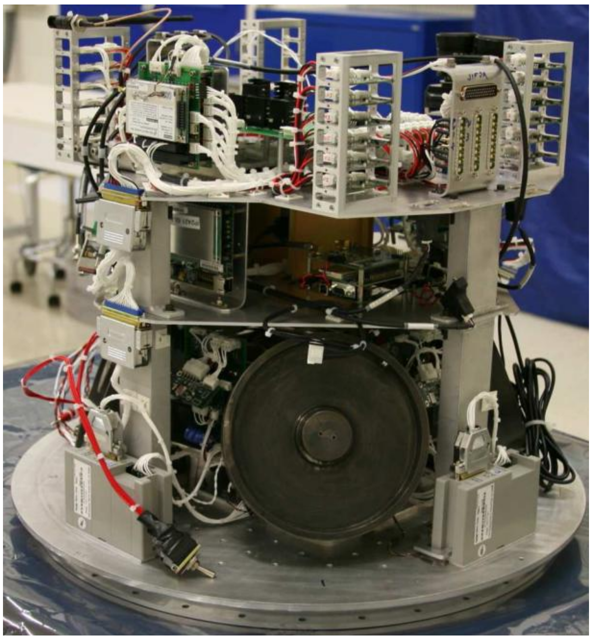


Figure 2: Modular Bus Structure

In addition to utilizing separate software daemons for major subsystems, the COTSAT-1 software also makes extensive use of dynamically loadable shared object libraries. Each module, for example the module to interface with the IMU, is compiled into a dynamic shared object library. The shared object libraries not only adhere to the modular design but also provide flexibility in software upgrades and simulation. They can also be used in Matlab/Simulink for simulation purposes. The procedure

allows for verification of the flight software functionality for debugging purposes and allows for testing system response with simulated environmental conditions [8]. By selecting GNU/Linux as the satellite operating system, COTSAT-1 was able to leverage upon a number of industry or open source community supported COTS hardware. Open source software libraries and community supported software programs were also leveraged to further reduce development costs and increase potential code reuse. Wilmot[1] notes that the adoption of standard open source GNU tools aids in establishing commonality between build tools and reducing dependency on proprietary tools, thereby increasing the potential software reuse and hence cost reduction. For example, task scheduling and prioritization on COTSAT-1 is implemented using Posix Threads (PThreads), a standard threading library. By using a POSIX compliant threading structure, the software will operate on any POSIX compliant system, preventing the software from becoming locked to a particular design. Additionally, the use of a standard library maximizes reusability and the generated code is more readily understood by other software developers, hence reducing training time and cost.

3.0 SUBSYSTEM LEVEL DEMONSTRATIONS & COST SAVINGS

As discussed above, both the versatile software and the sealed atmosphere allow for significant cost savings in many of the spacecraft’s other subsystems. COTS components can be integrated into the COTSAT-1 bus more easily than typical spacecraft. This not only reduces cost, but also enables the testing of technologies that would otherwise be too high-risk to be considered for utilization. The impact of this approach, while prominent of all aspects of the project, is perhaps most notable in the guidance, navigation and control (GNC) and the power subsystems.

3.1 GN and C

The GNC subsystem for COTSAT-1, which achieves three-axis attitude determination and control, is especially notable because it employs hardware and software that are entirely COTS or developed in-house at ARC.

Figure 4: In-house development of torque coils

For three-axis control, COTSAT-1 employs four reaction wheels and three magnetic torque coils. Nominal operations include the use of the reaction wheel system for three-axis pointing control with the torque coils used for wheel desaturation. The torque coils are also essential for initial stabilization of the satellite after launch and for detumbling the spacecraft. The torque coils, pictured during development in figure 4 to the right, may also be used to produce additional torques should the reaction wheel system become degraded during nominal operations. Both the reaction wheels and the torque coils were developed in-house at NASA Ames. In particular, developing the reaction wheel system configuration (as pictured in figure 5) at ARC has generated wheels at 10% of the cost for similar wheels, while still achieving the same performance characteristics and durability.

For attitude determination, COTSAT-1 relies on a star tracker system and an inertial measurement unit (IMU). The star tracker system comprises four monochrome machine-vision cameras and software developed in-house. The cameras are all controlled and powered via USB 2.0. The supporting hardware and software make it such that the number of operating cameras is variable. While a typical star tracker system may cost on the order of $1M, the ability to utilize COTS hardware reduces the cost to only a few percent of this. The cost and ease of integration of this architecture make it ideal for rapid production of future small spacecraft. [2]

The control system requires input from the attitude determination sensors and the reaction wheel system (control system actuators). Consistent with the

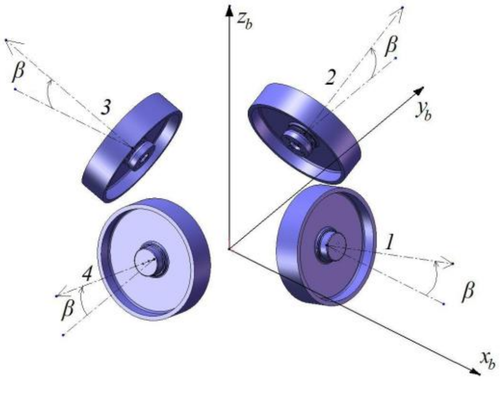


Figure 5: Reaction wheel configuration

software design architecture, each subsystem communicates with resource subsystems via UDP/TCP packets. The interface between the control system and the actuators is a data packet with a set of requested body torques. The control system actuator subsystem daemon transforms the requested body torques into individual low-level control commands which are sent to the actuator hardware. In the case of COTSAT-1, the requested torques are translated into voltage control signals for each reaction wheel.

The information exchanged between the control system and the attitude determination sensors is a quaternion describing the satellite attitude and satellite body rotational rates. The control system need not necessarily have information as to the actual source of the determined attitude information. Although the concept was conceived independently by the COTSAT-1 project, the design philosophy is similar to that of Graven et al.,[2] where the nature of the information exchanged stems directly from the physics rather than from the hardware devices present. The attitude control system simply assumes that the satellite has the capability of providing attitude information and rotational body rates at a minimum desired rate. For COTSAT-1 the attitude information is provided via an attitude estimator subsystem daemon. The COTSAT-1 attitude estimator is an extended Kalman filter, which utilizes body rate sensor information and regular star tracker quaternion updates. A USB MicroStrain IMU is used for body rate information. Although the MEMS IMU contains an integrated magnetometer for absolute orientation determination, magnetic fields generated from satellite components such as the reaction wheels is expected to interfere with magnetometer readings. As a result, the attitude control system for COTSAT-1 only utilizes the IMU for body rate information. Since the control system software daemon is separated from the attitude estimator subsystem, a change in the method to determine spacecraft attitude information will not require a change to the control system software modules. For instance, the attitude estimator could receive information from a different combination of attitude sensors such as a sun sensor, horizon sensor, or an IMU, yet the same basic attitude information in the form of a quaternion and body rotational rates would be supplied to the control system. By designing the system to accept a standard set of parameters related to the physics rather than directly from hardware sensor and actuator inputs/outputs, the ability to mix and match various hardware devices to provide the same capability is maximized. Similarly, the ability to reuse developed technology and subsystem modules for future missions is enhanced.

Figure 6: Solar Panels, Mounting Structure, and Configuration on COTSAT-1

3.2 Power Generation

The power generation system of COTSAT-1 is also remarkable in its extensive cost savings and novel design. The spacecraft is using COTS panels, as shown in the leftmost image of figure 6. The panels were originally intended for home power generation, and would not be suitable for operation in the harsh space environment as manufactured. With a few modifications, however, the system is achieving a reliable solar panel fit for space application for the cost of $10/watt compared to the industry standard of $500/watt to $1000/watt. For added sensory knowledge, six sun sensors mounted in three orthogonal directions were also added to the solar array assembly. The solar panel assembly consists of eighteen panels in a hexagonal configuration around the sealed avionics container, as shown in the rightmost image of figure 6. The panels are mounted in this position by structural support angles, shown in the center of figure 6, connected in turn to the longerons through vibration isolation mounts.

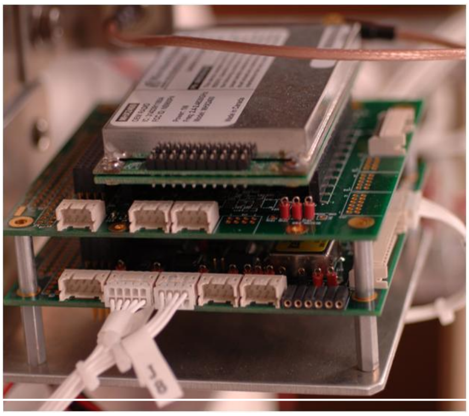


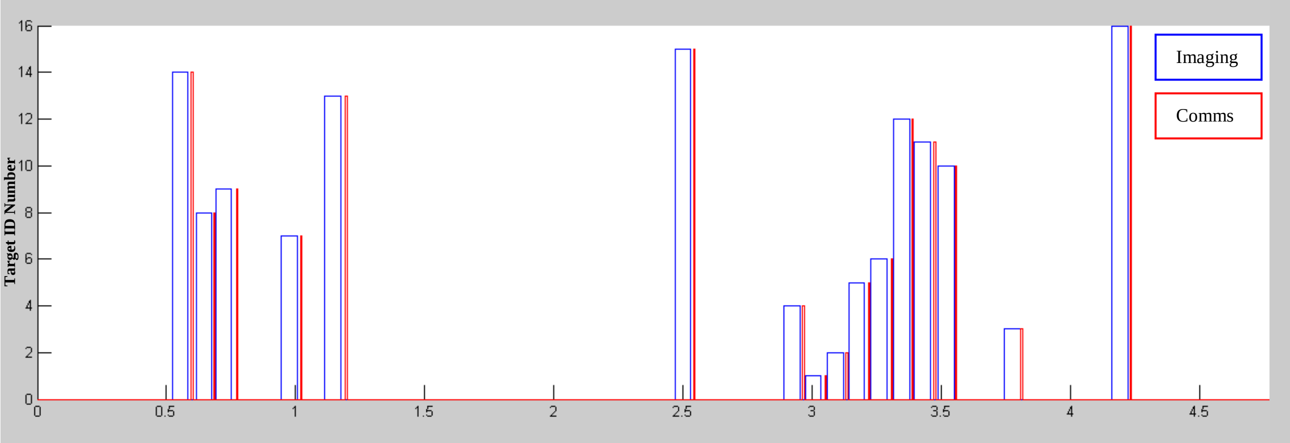
Figure 7 Central Power Converter

Single 40 and 50 watt panels were subjected to 19 g of vibration in both the longitudinal and vertical axes during initial tests. Both the glass substrate and the electrical connections survived during these tests. The panels were also tested in a thermal vacuum chamber and have been shown to keep the same level of performance between -70˚ C and +100˚ C. The solar panels, while rated at 40 to 50 watts on the surface of Earth, will be exposed to much more solar energy once they are above the atmosphere. Ultimately, the solar array will easily produce sufficient energy for COTSAT-1 for the entirety of the mission at a fraction of the cost of conventional assemblies.

4.0 OPERATIONS AUTONOMY

The on-orbit operations for COTSAT-1 are also designed to be minimally cost-intensive. This is achieved by reducing the amount of control needed during the mission and automating/scheduling as many operations as possible before launch. Tasks such as slewing, fine-pointing, filter selection, imaging, ground-tracking, communications, and any other predefined modes can all be scheduled and uploaded to COTSAT-1 at any time before or after launch. This schedule then determines virtually all on-orbit operations for the satellite, save emergency or safe modes, for the duration of the mission. The only action necessary from the ground station would then be data communications, acquiring and monitoring ephemerides, and creating and uploading new schedules to the spacecraft if necessary. New schedules would be necessary whenever the target plan changes or when the current ephemeris differs from the predicted ephemeris by some threshold value.

This automated scheduler was used to design a science mission using COTSAT-1. The baseline goal was to image 16 astronomical targets of particular interest with sufficient signal-to-noise ratio. The mission was designed with minimal risk: prioritizing targets, scheduling the most important targets first and as early as possible, and scheduling downlinks as soon after imaging as possible. The timeline in figure 7 below is a graphical display of actual output from the scheduler. It can be seen that for the input ephemeris, imaging constraints are met for target 14 first (the width of the blue bar denotes time scheduled for imaging) while target 1, which has scheduling priority, cannot be imaged until much later.



The red bars show that images of each target will be downloaded very soon after imaging is complete.

Seconds elapsed since emission epoch

Figure 8 Graphical output of mission operations

x 10^6

The scheduler works by integrating MATLAB with a custom built scenario in Satellite Toolkit (STK) software. Specific physical and operational rules and constraints are applied and any number of astronomical or surface targets can be programmed into the scheduler with weighted priority. Once the spacecraft ephemeris is known and applied to the STK scenario, the MATLAB software tool iterates and optimizes the operations schedule to image and download all targets as soon as possible. The output is actually a file that can then be uploaded to the spacecraft at any time. This file contains timestamps for the initiation and termination of all necessary spacecraft and payload operations pertaining to target capture and downlink. This process is visualized in figure 8 below. Ultimately, the software provides versatile, long-term scheduling that enables minimal active involvement on ground and quickly mitigates any unforeseen launch date slips or changes in ephemeris.

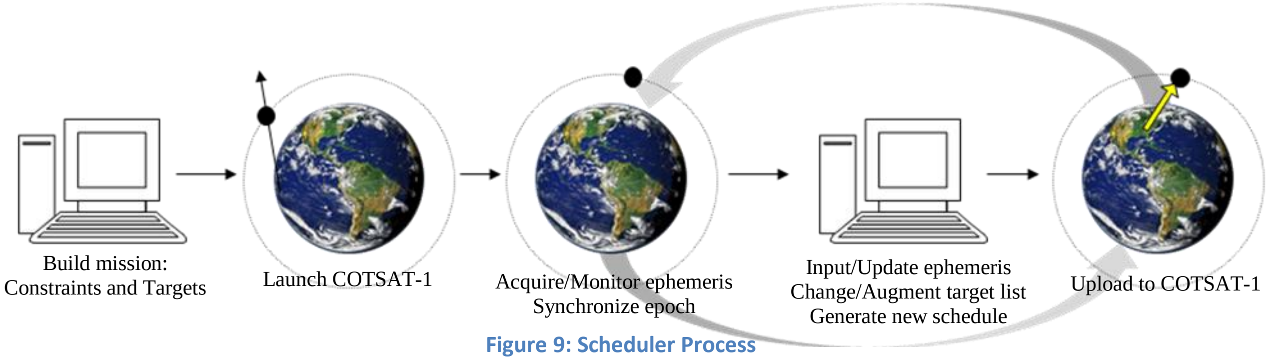


Figure 9: Scheduler Process

5.0 QUALITY ASSURANCE, DEVELOPMENT & TEST

While numerous measures are taken to lower the cost of COTSAT-1, Quality Assurance (QA) was still of prime importance. This project is a skunk-works type development activity where quality was integral to the project development rather than a separate function. Development was made by rapid prototyping and proof through testing while seeking minimal approval from a separate QA organization. Prior to component design or selection, the relevant personnel gathered and refined the requirements of the hardware and then brainstormed solutions that are consistent with the project approach of low-cost, off-the-shelf solutions[6]. The concept was further refined and brought back to the team for comments within minutes or hours. Additional QA approaches are listed below:

- Manufactured components were fabricated to flight standards and tracked to maintain flight integrity for the current and any potential future mission.
- Materials were kept in bonded stores or in a project area with restricted access.
- During both assembly and storage, Electrostatic Discharge (ESD) compliance was critical and enforced in the lab.
- Assembly of critical components was supervised by a qualified engineer with critical tasks being tracked by written assembly and test procedures.
- Any material or subsystems leaving the lab (e.g. for environmental testing) were tracked closely by project personnel.
- Any non-conformance was handled immediately and removed from the lab area when appropriate.

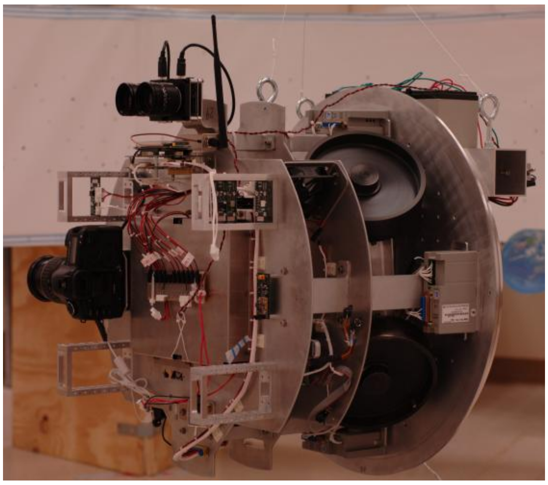


Figure 10: Dynamic Test Platform

- Articles tested to failure were retained for study.
- Verification and validation of components was done on-site at Ames in labs utilizing equipment required and suitable to conduct these tests.
- Vibration, thermal, vacuum and hydrostatic tests were performed on components.

The COTSAT-1 development philosophy was to be heavy on testing but still fast and responsive. The approach was to test early and often with the objective being “test as you fly, fly as you test” by the end of the project. The focus was on rapidly building/buying hardware, writing software, and testing it as soon as possible. Prototypes and test rigs were built early on in the project for the reaction wheels, the sealed container, the command and data handling system, the star trackers, solar arrays and the electrical power system. This focus was heavy on flat-sat laboratory tests where the various components are integrated and operated with flight software at various levels of development. Shown at the right in figure 9 is the third iteration of this flat-sat testing configuration. It consisted primarily of flight versions of hardware and software, including all of the components mentioned above as well as additional sensors. The flight version of the star tracker software and attitude estimation were both implemented, as well as a number of modules to control basic devices such as the IMU and reaction wheel. As of now, the final flight versions of the software have been verified on the proto-flight unit.

The concurrent development process has allowed the team to identify issues early and to develop performance profiles of the system as it moves though the development process. Specific tests required to demonstrate performance of higher risk components have been identified and are focused on as early in the development flow as possible allowing any shortcoming to be addressed early in the design cycle. This approach has lead to many interesting findings in developing the solar array configurations, software development, reaction wheel bearing selection and control system design.

6.0 CONCLUSIONS

The Cost Optimized Test of Spacecraft Avionics and Technologies project, COTSAT-1, has examined and demonstrated a number of cost reduction techniques for rapid spacecraft design. As presented in this paper, COTSAT-1 has adopted a number of design philosophies and industry technologies not currently widely accepted within the spacecraft design community. The primary enabling technology is the adoption of the artificial environment container, which further provides for a number of cost reduction techniques, such as the use of COTS technologies. Structural modularity is also critical in development and time savings. Open source software further expands the cost reduction techniques by promoting a wide array of software reuse and design architectures. Furthermore, adopting widely accepted standard interfaces such as Ethernet and USB promotes cost reduction by increasing the number of available off the shelf hardware and software solutions. Selecting widely adopted standard data interfaces additionally enables accelerated testing, prototyping and parallel development without necessarily having access to the host platform. WE are currently developing plans to develop a COTSAT-2. This vehicle will utilize the same approach of COTs and GOTs hardware and software. The major modification is the replacement of a hard shelled enclosure with a soft sided one. It is felt this will provide greater flexibility and further lower cost.

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