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ALTAIR™ : Millennium's DARPA SeeMe Satellite Solution Technical (R)evolution

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ABSTRACT

Millennium Space Systems ALTAIR™ "27U" satellite developed under DARPA's SeeMe (Space Enabled Effects for Military Engagements) program represents a game-changing spacecraft class addressing military, civil, and commercial needs, balancing extreme affordability, performance, and schedule responsiveness. DARPA's overarching requirement called for a 24-spacecraft constellation, with satellites flying in any orbit, at less than $500K cost each, and with readiness to launch 90 days after call-up. This paper discusses the design process and lessons learned during high-altitude balloon tests and full engineering-model spacecraft development to achieve both high performance and low cost. We describe the driving spacecraft innovations to successfully achieve DARPA's requirements. Innovations include payload performance, 3-D printed structure, GN&C/ACS Suite performance, communications system approach, Flight Software Implementation, Commercial-Off-The-Shelf (COTS) part usage, development & production approaches, and enabling constellation technologies. **The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government. Distribution Statement "A" (Approved for Public Release, Distribution Unlimited).**

INTRODUCTION

Millennium's ALTAIR™ satellite implements a low-cost, high-performance vision for spacecraft design, manufacture, launch, and operations. ALTAIR™ with a visible sensor payload was developed for the DARPA Space Enabled Effects for Military Engagements (SeeMe) program. In a SeeMe constellation, the ALTAIR™ spacecraft delivers 24/7 individual warfighter imagery using a small satellite network manufactured using state-of-the-art 3D printed composites and up-screened commercial-off-the-shelf (COTS) components to realize very low cost and high performance. The prototype spacecraft bus is pictured in Figure 1. The ALTAIR™ bus can support a wide range of payloads beyond SeeMe's optical sensors. For the tactical SeeMe mission, the highly agile "27U Cubesat" (36 cm x 36 cm x 37 cm) can slew at 10 degrees per second without any settling time, provide approximately 6 arcsec pointing accuracy, and directly communicate to and from a ground-located tactical radio. The basic SeeMe Operations Concept is illustrated in Figure 2. The specific SeeMe spacecraft bus masses 20 kg, can carry 25 kg of payload, provides approximately 27 W Orbit Average Power to the payload, and can fly in orbits between 200 and 350 km altitude at any inclination. However, the basic ALTAIR™ spacecraft can operate in any Low Earth Orbit (LEO) up to approximately 600 km altitude and can carry up to 50 kg payload mass. With modifications the spacecraft can fly in any orbit including high LEO, MEO, and GEO

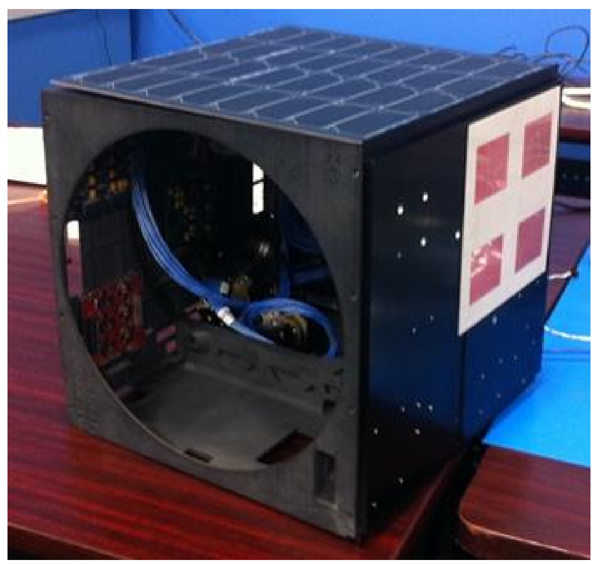

Figure 1: The functional prototype ALTAIR™ spacecraft bus configured for the SeeMe mission.

ALTAIR™ mission performance is payload dependent but offers a dollar-per-picture cost, significantly lower than traditional or current alternatives, by reducing total system costs combined with its innovative operations concept. The 27U spacecraft configuration is developed using industry standard CAD, and manufactured using

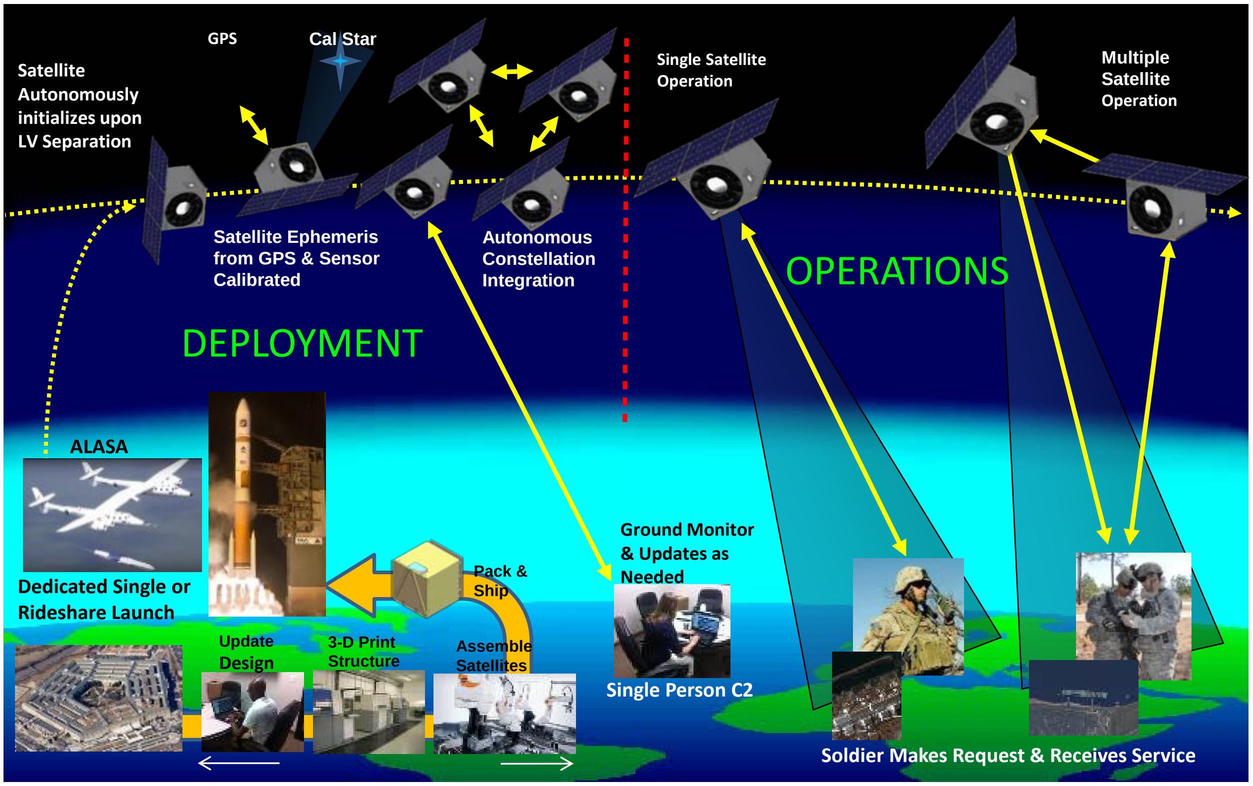

Figure 2: SeeMe Operations Concept as envisioned using ALTAIR satellites. 24 Satellites would be produced within 90 Days, launched on available rockets, autonomously initialize and operate to provide user services.

modern additive processing for rapid prototyping, flexible design, low-cost, non-continuous production based on mission requirements, desired payload configuration, and parts availability. The ALTAIR™ flight-control features a low cost, high-performance attitude sensor suite with actuators and advanced estimation & control algorithms to achieve high level pointing accuracy generally associated with mainline imaging missions. Existing tactical-compatible radios serve as uplink, downlink, and crosslink to reduce cost, minimize complexity, and enhance communications, providing as a cost-effective that achieves high data rates and effectively replaces traditional ground station control systems. Flight Software is coded directly from simulation models developed in a fast-prototype fashion. The spacecraft is constructed from COTS components to reduce cost and shorten production schedules. Technologies such as crosslinks, a network layer, and spacecraft autonomy enable very low cost constellations to achieve enhancement in persistence, latency, coverage, survivability, resiliency and other capabilities usually too cost and schedule prohibitive for traditional space systems.

ALTAIR™ implements approaches to spacecraft design, development, production, and operations which are user responsive to cost, schedule, performance and mission needs. The game-changer is fielding constellations of high performance satellites at one-to-two orders of magnitude below traditional costs, thereby fostering missions previously too cost prohibitive. ALTAIR™, based on SeeMe requirements, is a highly compact, modular, scalable, and reconfigurable spacecraft with agility and processing power to support demanding missions, while providing ultra-low-cost mission solutions. ALTAIR™ is a revolutionary product to serve the increasing demands of multiple users, missions, theaters, and CONOPS - on tightly constrained budgets and on operationally relevant timelines.

DESIGN PROCESS

Unlike more mainline satellite systems, Millennium relied on the fast-prototype spacecraft development approach through three distinct design cycles to produce a working functional prototype ALTAIR™ spacecraft. The ALTAIR™ spacecraft hardware, software, and ground system were all tailored to the DARPA SeeMe program goals and objectives. The overriding DARPA goal for SeeMe was to produce a satellite with real military utility for a price point less than $500K, regardless of production quantity. The fast prototyping systems engineering process typically builds a design from the bottom-up by assembling existing components into needed systems through short “Build, Test, Learn” iterative cycles, improving the systems capability and performance at each cycle until desired performance goals are met. Satellite design and performance are captured as system specifications for future production at the end of each development cycle. This process is shown schematically in Figure 3. Fast Prototyping is inherently a spiral development which can truly be faster, cheaper, better than traditional approaches, and more quickly converges to a functional product. Contrary to popular belief, if implemented properly, fast prototyping provides all the rigor expected of traditional requirements-based Systems Engineering approaches. Though fast prototyping works particularly well when applied to singular flight systems with minimal external interfaces like ALTAIR™, this approach may not be advisable for large system of systems with many external interfaces.

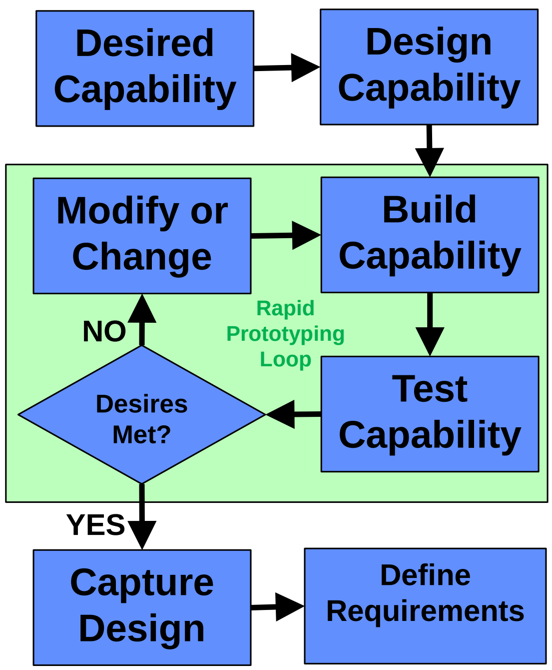

Figure 3: Rapid prototyping systems engineering process used to develop the ALTAIR™ spacecraft.

ALTAIR™ SATELLITE DESIGN SUMMARY

The basic ALTAIR™ spacecraft design is illustrated in Figure 4 along with its main features and benefits. The space vehicle is designed as a low-cost, high-performance, high-flexibility 3-axis controlled bus. The space vehicle for the SeeMe operations concept achieves the $500k price point regardless of quantity. ALTAIR™ can operate in any Low Earth Orbit up to 600 km, or with minor modifications beyond 600 Km. The 27U bus is 3D printed allowing extreme flexibility when accommodating payload designs that are <50 kg as well as different possible configurations. The compact, modular, flexible configuration bus is also designed for compatibility with several launch vehicles, such as DARPA ALASA, the ESPA Ring, Minotaur, EELVs, and others, including launch from the International Space Station. The modular, adaptable spacecraft was also designed for low-cost and non-continuous production using a software-defined-satellite methodology and production methods. The spacecraft implements and takes full advantage of software defined radios. The baseline spacecraft uses S-band and L-band radio frequencies, however, depending on the mission operations, the radios can be reprogrammed for new frequencies, waveforms, and data rates as required to serve different mission sponsors. ALTAIR™ also provides very high level pointing accuracy and agility by utilizing a low-cost, high-performance GNC suite not seen on other platforms for this price.

The ALTAIR™ flight-control system features low cost, yet high-performance attitude sensor suite with actuators and advanced estimation and control algorithms to achieve high level pointing accuracy. A COTS GPS receiver, Three-Axis Magnetometer (TAM), a rate sensor, an in-house developed star tracker, and exclusive algorithms for enhanced attitude processing provide geodetic pointing knowledge to better than 6 arcsec Circular Error Probability (CEP). Such exceptional pointing accuracy for this satellite class translates to geolocation & mapping precision under 10 m at 60° elevation angle and 300 km altitude. Four Honeybee Robotics CMGs, each with 100 mNm torque and 120 mNms momentum, coupled with singularity-free steering laws, allows rapid vehicle angular acceleration and speeds up to 10°/sec about any axis. Smooth, rate-matched slews up to 90 degrees can be executed in < 14 seconds for rapid target acquisition, with negligible settling time. Targets can be tracked with < 0.3 arc sec pointing stability per image frame. Torque coils integrated into the structure provide back-up attitude control and momentum desaturation capabilities.

Existing tactical radios serve as uplink, downlink, and crosslink to reduce cost, minimize complexity, and enhance user experience. This innovative approach effectively replaces large ground stations and control systems. The satellite communicates using full-duplex and TDMA technology to deconflict field users and crosslinking adjacent satellites to serve the maximum numbers of field users. The ALTAIR™ baseline implements a 1.6 Mbps payload data downlink. However, mission sponsors can select their desired downlink parameters and determine which mission design fits their need. The communications architecture can support up to 5 Mbps links on a wide range of frequencies using a software defined radio.

The ALTAIR™ satellite may be launched as a primary payload on a small launch vehicle, or alternatively as a secondary or rideshare payload. The compact baseline 27U spacecraft can be stored and transported to the launch site either conventionally or inert in a launch container, such as a Planetary Systems Corporation's (PSC's) Canisterized Spacecraft Dispenser (CSD). Upon on-orbit deployment, the satellite autonomously completes built-in-tests, self-calibrates, and reports readiness for its mission. The spacecraft ground segment control is through a typical personal computer or laptop connected to the same tactical radios as typical users, transmitting commands and receiving telemetry as required. The combination of highly agile ACS and constellation crosslinks supports at least 10 simultaneous user requests, passing unfulfilled collections to the next satellite as part of a larger constellation. Data and status are streamed in near real-time to users directly or through a crosslink for a transparent experience and delivery of imaging products within 90 minutes. The production, launch, deployment, and mission operations concept is illustrated in Figure 2.

DEVELOPMENT LESSONS LEARNED

When Millennium began developing the ALTAIR™ satellite for the SeeMe program, the SeeMe objectives of producing a 24 satellite constellation within 90 days to operationally provide high resolution imagery requested by individual soldiers using tactical radios within 90 minutes at a $500K price point per satellite seemed a daunting challenge. In the end, the biggest lesson learned is the highly positive result that we *can* produce very highly capable, operationally useful, inexpensive, small satellites singly, or in quantity, if we avoid the standard aerospace industrial base. Cubesat developers have known this for years, but the ALTAIR™ bus represents a significant, and unprecedented advance in size, capability, performance, and payload accommodations for military, science, and commercial applications at this low price point.

Another evident but important lesson is that there's nothing like testing to validate design, and field testing yields far more stressing conditions which more fully exercise your systems than laboratory testing ever will. The most relevant, and successful example is how Millennium used balloon testing (Shown in Figure 5) to test its satellite system operations concepts, hardware and software in short-duration flights. Balloon testing is

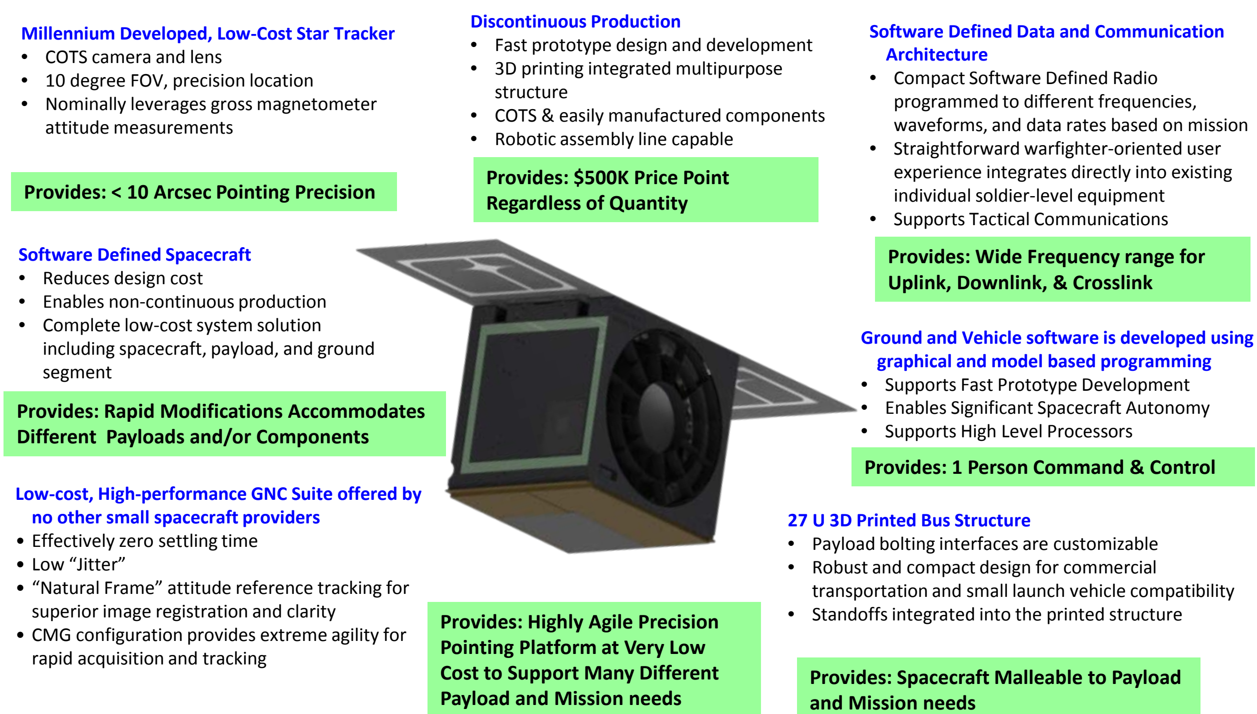

Figure 4: ALTAIR™ Spacecraft significant design features, benefits, and associated innovations seek to provide a small satellite with the capability of much larger and more expensive satellites at very low cost.

an effective tool for small spacecraft development.

There were numerous other lessons learned in Millennium's fast prototype development implementation, both positive and negative. In the end, the innovations brought to bear during SeeMe system development provided the tools needed to achieve the desired goals, objectives and final product. The most prevalent innovations and associated lessons learned will be discussed in the next sections.

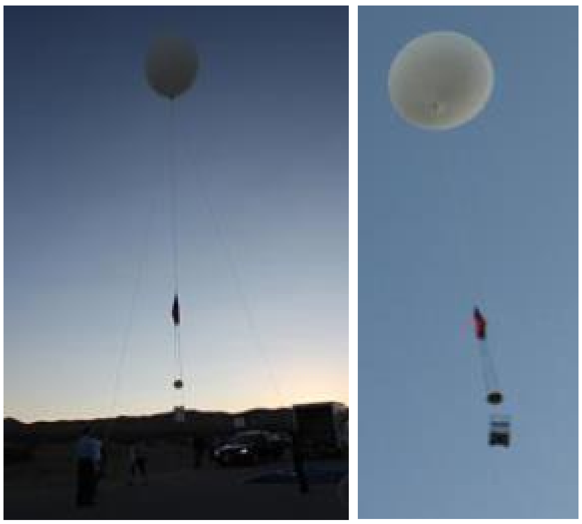

Figure 5: Balloon testing was an effective way to test small satellite technology and operations.

PAYLOAD PERFORMANCE

To provide a suitable imagery product, a highly sensitive sensor is needed. For the SeeMe mission, Millennium successfully worked closely with two optical payload providers. L3 Communications Integrated Optical Systems (IOS) provided a visual sensor using a traditional Ritchey-Chretien telescope design leveraging their Unmanned Aerial Vehicle (UAV) production line to meet cost and production goals. Lawrence Livermore National Laboratory (LLNL) developed an innovative compact monolith telescope which reduces sensor volume for similar performance. LLNL also provided a 1U scale prototype compact monolith telescope sensor for our balloon tests. The L3 and LLNL sensor concepts are illustrated in Figure 6. Both sensor providers met the desire for National Imagery Interpretability Rating Scale (NIIRS) 5+ imagery from 300 Km altitude with 0.5 m Ground Sample Distance (GSD) (0.7-1.2 m Ground Resolution Distance (GRD)) at nadir. Both sensor designs provided different innovative means to eliminate defocus and misalignment issues which often plague space telescope systems which must survive standard launch environments. By removing the active focusing mechanism, additional structure, and/or precise post-manufacturing calibration typically required of such sensors, lower cost and high production rates are achievable. As development progressed on these sensors, there was always a desire to increase aperture to improve performance while maintaining cost and production timeline targets. This desire was accommodated by moving from the original spacecraft sizing (30 x 30 x 30 cm) configuration to the final sizing, (36 x 36 x 37 cm). Any larger satellite configuration increased price.

Figure 6: The LLNL compact monolith and L3 Comm IOS Ritchey-Chretien telescope sensors.

3-D PRINTED STRUCTURE

Millennium decided to use 3-D printing for its ALTAIR™ satellite structure to provide a flexible, low-cost means to change satellite configurations, accommodate different payloads, and (if necessary) to easily accommodate different components during production. Early on, Millennium Space Systems selected CRP-USA, an Italian company with an American Subsidiary in Mooresville North Carolina, as the vendor for its 3-D printed structure. CRP-USA specializes in additive manufacturing and performs fast-turn part design and production for the NASCAR & Formula 1 automotive racing industry. Their WindForm™ series material is a high performance polyamide-based thermoplastic, carbon microfiber filled proprietary composite material used for rapid prototyping with a laser sintering process. We chose CRP-USA, and specifically the WindForm™ XT 2.0 material used in other space applications in various components and "space qualified" through the Montana State University's 1U PrintSat Cubesat & the KySat 2 1U Cubesat built by the University of Kentucky and Morehead State University. The 3-D printed structure using WindForm™ XT 2.0 material supports Millennium's rapid production approach. It accommodates flexible design, and low-cost, non-continuous production driven by the mission requirements, payload configuration, and/or alternative component selections.

Millennium, with CRP-USA's support, found 3-D printing for this class spacecraft extremely valuable and versatile. The ALTAIR™ spacecraft structure met low cost, flexibility, and versatility expectations. Configuration, structural, and thermal design can be tailored using 3-D printing, though Millennium has not yet taken full advantage of the possibilities this technology has to offer in the ALTAIR™ design. The full scale 3-D printed structure for the ALTAIR™ spacecraft is shown in Figure 7. The 3-D printing vision was to provide an "art-to-part" capability for rapid satellite production capability.

Figure 7: The ALTAIR™ Spacecraft 3-D printed structure.

GUIDANCE NAVIGATION & CONTROL/ ATTITUDE CONTROL SYSTEM (GNC/ACS) SUITE PERFORMANCE

The ALTAIR™ GNC system provides agility previously unavailable on even larger vehicles without enormous expense. HoneyBee Robotics provided miniature Control Moment Gyroscope (CMG) units setting a new standard in low-cost precision-pointing hardware. The ALTAIR™ CMG configuration provides extreme agility for rapid acquisition and tracking. CMGs provide torque capability well beyond the range of reaction wheels of comparable size and weight, allowing for ultra-rapid slews and minimal downtime between pointing objectives.

Coarse stand-by attitude knowledge is provided by the Three-Axis Magnetometer (TAM), Inertial Measurement Unit (IMU), and Global Positioning System (GPS) measurements. Specifically, the attitude system innovations include: 1) Hybrid magnetometer-star camera precision attitude determination; 2) Real-time attitude knowledge smoothing; 3) CMGs for high agility; and 4) Precision operations using globally stable momentum control.

The system provides 6 arc sec CEP geodetic pointing knowledge; smooth, 90 degree rate-matched slews executed in <14 seconds for rapid target acquisition, with negligible settling time; ground sites tracked with <0.3 arc sec pointing stability per image frame. The mature ALTAIR™ GNC/ACS design provides superior performance with several innovations offered by no other small spacecraft provider.

Hybrid Attitude Determination

ALTAIR™ implemented a novel Hybrid Attitude determination approach using star cameras and TAM to determine precise attitude down to 6 arsec. Coarse attitude determination using the TAM and IMU is globally convergent, and calibrates observable TAM biases, scale factors and non-orthogonalities, as well as gyro biases, scale factors, and alignments, to the achievable limit dictated by the latest 13 X 13 International Geomagnetic Reference Field (IGRF) magnetic field model update for the Earth. This approach provides assured backup attitude determination to aid safing and initial acquisition, and support fine attitude determination. Our magnetometer-based coarse attitude Kalman Filter is globally convergent, using the same techniques applied for fine attitude determination.

The precise attitude determination Kalman Filter algorithm estimates both attitude and gyro error terms, including bias, scale factor, and misalignments, with assured convergence from any initial state with regular updates from the star tracker. Standard Extended Kalman Filter algorithms can diverge in unpredictable circumstances, and are especially vulnerable to outlier data getting incorporated into filter updates. This filter formulation has been observed on-orbit with existing assets to re-converge even after instruments have provided transient bad data.

CMG Singularity-Free Momentum Management

In ALTAIR™, we implemented an attitude controller which is globally Lyapunov stable with wide stability margins. Traditional control approach create a non-minimal state representation, resulting in various ad hoc measures which must be taken to avoid integral windup, including saturation nonlinearities which can create transient control spikes, and means for resetting the controller in the event of anomalies. Our approach is a globally stable control, and is ideally suited for CMG actuation, particularly in the way ALTAIR™ uses the CMGs. Simulation results have surpassed our most optimistic expectations for unprecedented smooth vehicle motion. Slews are rate matched at both beginning and end using a simple and robust, yet near-optimal, slew trajectory algorithm, resulting in effectively zero settling time, maximizing system duty cycle for viewing ground sites. An example CMG rate envelope is shown in Figure 8. Slew trajectory rate matching at both the beginning and end of slews confers essentially zero settling time so that, once a slew is completed, the vehicle is immediately ready to perform the mission. Our algorithm is near-optimal, yet relatively simple, and provides performance generally found only on far more expensive vehicles.

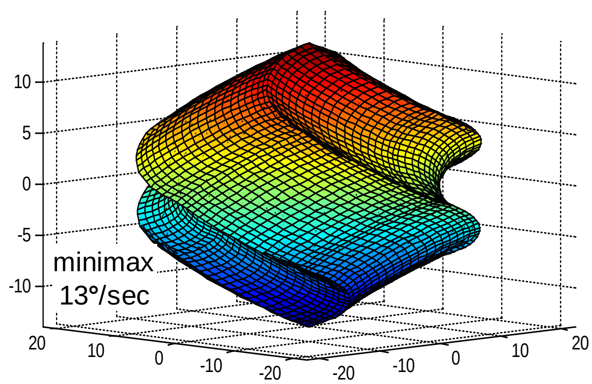

Figure 8: Example ALTAIR™ CMG rate envelope.

Post-Filter Attitude Smoothing

Standard attitude filtering relies on gyro rate data to reduce the state vector dimension, providing substantial additional throughput and isolating the filter performance from the various non-linearities in the dynamics and control loop. Millennium improvements on this post-filtering smoothing technique allow us to approach the theoretical limit in attitude knowledge, significantly enhancing geolocation capability.

Enhanced Momentum Unloading

The standard "H cross B" momentum unloading approach using electromagnetic torque rods or coils has the advantage it produces, instantaneously, the most rapid reduction in momentum possible. However, over the long term, this approach tends to drive the momentum vector near the local magnetic field line, where the torquers are unable to remove any momentum. Figure 9 shows one of our simulations where the traditional momentum unloading approach cannot unload bounded momentum, whereas the enhanced method handily unloads momentum with significant margin. We have developed a significant leap forward, enabling us to use smaller, less power-hungry torque coils to achieve the same unloading performance. Advanced torque coil firing strategy allows momentum maintenance at lower orbits than standard approaches.

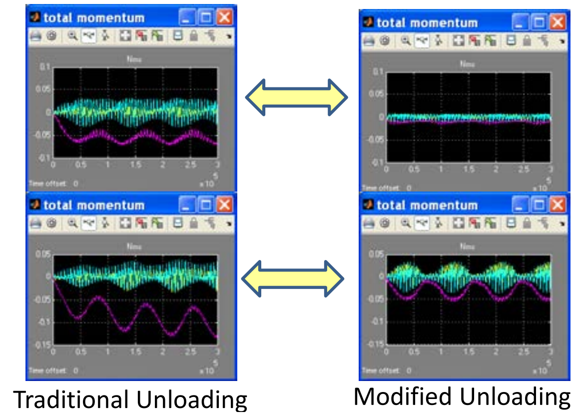

Figure 9: Modeling shows the enhanced momentum unloading is superior to traditional approaches.

Star Tracker

Originally, Millennium intended to implement a magnetometer-only attitude determination scheme for the ALTAIR™ satellite for simplicity and low cost. This approach would have worked, until potential users expressed interest in much higher precision pointing than anticipated. To meet the desired precision pointing, we moved to the hybrid magnetometer-star tracker solution. After an extensive survey of available star trackers, both domestic and foreign, we could not find a product which met our performance, cost, schedule, and production rate goals. As a result, we developed a star tracker in-house in order to provide the ALTAIR™ satellite with a low-cost solution which uses COTS parts, including procurement of a COTS lens with space heritage. The star tracker assembly in-house build uses precision optics, an innovative baffle design for superior stray light rejection, and robust algorithms for star identification and quaternion attitude estimation. The prototype Star Camera is shown in Figure 10. Star Tracker algorithms were developed guided by the open literature using MATLAB/Simulink, converted to flight software. The algorithms have successfully processed real star images taken with camera and yielding a 6 arcsec cross-axis accuracy.

Figure 10: Star Camera in test configuration.

COMMUNICATIONS SYSTEM APPROACH

The RF system ALTAIR™ satellite for the SeeMe mission was one of the most difficult problems to solve, but in the end a versatile solution was developed. The difficulty is in communicating with hand-held Tactical User sets as these radios typically are low power systems with zero-gain antennas. Initially we strived to provide a system with full coverage from the satellite on both the up and down links to maximize system performance. To close the ground links at low cost we had to compromise the system solution. First, we selected a versatile Software Defined Radio (SDR) which is a FPGA-based solution providing future operations flexibility. The selected SDR supports full range of frequencies and various waveforms. Second, for the SeeMe application, the radios use the Mobile Satellite System band (2485- 2500 MHz) with hemispherical coverage for low-rate requests of images, and the the Mobile Satellite System band (1610-1645.5 MHz) with a 60 Degree Beamwidth for high-rate downlink of images. Appropriate patch antennas designed to support these frequencies are incorporated into the ALTAIR™ SeeMe-configured spacecraft, and can be redesigned easily to be suitable for other user applications in the future. The basic Communications System Architecture is shown in Figure 11.

ENABLING CONSTELLATION TECHNOLOGIES

Three technologies implemented on the ALTAIR™ spacecraft were meant to significantly facilitate leveraging a low-cost satellite's ability to perform in a larger constellation. These technologies are crosslink communications, an associated network layer, and spacecraft autonomy.

Both spacecraft communications links are able to perform as crosslinks. However, the low-data-rate S-Band system is the primary crosslink intended to chain satellites together. The system operates as a First-In/First-Out (FIFO) for received user requests. If an individual satellite cannot handle a request it receives, the satellite can transmit the request to other satellites in range, and each satellite determines on its own whether the request may be addressed. The low rate crosslink communicates without needing to point the spacecraft. However, due to the communications performance compromises made, if the high data crosslink functionality is used, vehicle pointing is required.

To avoid link access conflicts, the S-Band Up/Downlink employs a TDMA Slotted ALOHA scheme. The ALOHA System has been implemented in various wireless and hardline communication systems in the past. The ALOHA system's simplicity leads to fewer collisions and less crosstalk between radios and ensures higher probabilities of messages being received, all at a lower cost over implementing various other complex messaging schemes. This attribute makes ALOHA perfect for SeeMe where mitigating user collisions on both the ground and space segments is imperative in order to obtain a high performance. For our application, each second is subdivided into 10 distinct 0.1-second intervals. These 10 slots are allocated as necessary to the spacecraft crosslink, the user requests, and the spacecraft request acknowledgements. The timing between intervals is synched on the ground and in space using GPS time.

To simplify the spacecraft and in turn constellation management, the ALTAIR™ bus was designed for completely autonomous operations. The ALTAIR™ spacecraft autonomously initializes upon Launch Vehicle separation, autonomously calibrates its own star cameras and the sensor payload if necessary, autonomously integrates itself into an established constellation, and performs all subsequent satellite maintenance and user operations support autonomously. Though the SeeMe satellites are designed with a high degree of autonomy, we do expect to provide a ground system to provide a back-up and alternative capability to positively command and control individual satellites as necessary. This capability was demonstrated in our first balloon test, and the ground control used in that test will evolve into the eventual spacecraft telemetry, command, and control system.

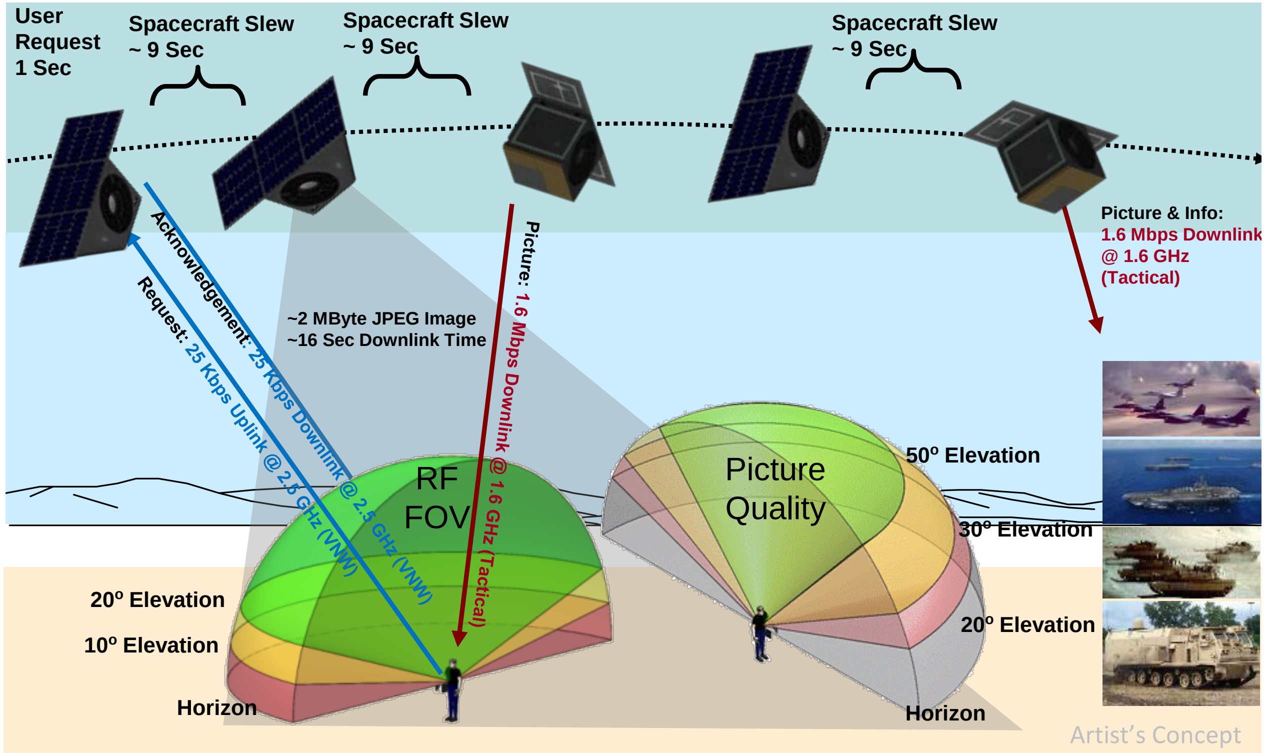

Figure 11: The ALTAIR communications architecture as envisioned for the SeeMe application.

During early constellation deployment, the satellite autonomously initializes upon launch vehicle separation and controls the start-up sequence. Specific component requirements such as reaction wheel spin-up are accounted for in initialization. When the satellite separates from the launch vehicle, separation switches open and the satellite power is turned on. The bus initialization sequence begins: the telemetry L-band transmitter is enabled to downlink telemetry to a single ground station if necessary, and the satellite optionally transmits state of health telemetry to the single-person ground station if desired. The GNC systems are then turned on; the magnetometer, GPS, and CMGs. Rough three-axis knowledge and the Sun are acquired. Initialization continues by acquiring ephemeris from GPS. Once the initialization is completed, the remaining subsystems are turned on. After several satellites deploy, the constellation can execute late deployment operations. During late deployment, the satellites autonomously integrate into the constellation by acquiring ephemeris from an almanac transmitted by other satellites already in the constellation as well as transmitting ephemeris data for itself. Upon initialization completion, the satellite becomes "operationally capable," meaning the satellite is ready to receive and execute requests from ground users.

The flight software incorporates top-level flight management providing complete autonomous vehicle control. This autonomy allows the vehicle to self-access and react continuously to maintain a positive state-of-health. Upon receipt of tactical ground requests, the flight software immediately processes and concludes the serviceability of the request. On comparison with other stored requests, the flight software determines whether or not to service the request. The high-fidelity GNC model integrated with the flight software implements the innovative control logic producing unparalleled attitude control. Furthermore, the GNC model is fully integrated with all other subsystems so the vehicle can autonomously respond to any condition. Top-level flight management was developed and fully integrated with all subsystems. If an on-orbit anomaly occurs, the satellite would autonomously slew to sun-point and attempt to reset the anomalous component or system. The satellite will attempt to reset the component a number of times before the satellite transmits to the ground segment the satellite needs help. If the satellite needs help, the ground segment will then manually try to troubleshoot the satellite's anomalous component or system.

FLIGHT SOFTWARE IMPLEMENTATION

ALTAIR™ implemented model-based Flight Software (FSW) design centered on a single system vehicle "model" and environment simulation coordinated with flight software functions. This "model" is developed in modeling tools (e.g., Matlab/SIMULINK, LabVIEW). This single, core model is then central to defining requirements, producing early development products tested against the subsystem requirements and evolved into real-time software running in multiple test environments including the actual flight processor and integrated avionics. Finally, the same software is run against the ground mission operations software and incorporated as part of ground software tools. Multiple testing environments coupled with model-based design supports shortened development cycles, early testing, and software implementation validation. Model-based design allows early software functionality implementation as well as allowing support to "late" requirements and the software adapted to evolving requirements. The software is tested relatively very early in development and continues to be tested in multiple environments throughout development. Having software supporting subsystem testing early in development also allows the subsystems to "shake out" the real requirements, not perceived ones. Coupled with strong software processes (change control, source control) this process is ideal for rapid development efforts. Advanced, automated source code generation tools increase efficiency by minimizing the tedious software coding tasks, and eliminating the need to "throw the design over the wall" to be coded by specialist programmers not familiar with the detailed working of the algorithms.

The ALTAIR™ flight management software was developed and fully integrated with all subsystems. An initialization phase autonomously controls each initialization sequence. Specific component requirements such as CMG spin-up are accounted for in the initialization sequence. Subsystem management software was developed, integrated, and/or updated to meet specific program requirements. With rapid prototyping and generally, Millennium has been able to leverage software development and specific modules from previous flight programs. The GNC software is also largely adopted from previous flight programs but includes the innovations previously discussed. Utilizing software across programs is a demonstration of modular software architecture flexibility. The software has both heritage and flexibility to incorporate important advances to improve performance and satisfy different mission requirements.

Application-specific software was developed for the SeeMe mission to receive a tactical request, process that request, and immediately assess request serviceability. Our simulations demonstrate the flight software can accurately service user requests. One simulation example is shown in Figure 12. A basic fault-management architecture was developed to limit the effort required for complete top-level integrated fault detection and recovery software. Most subsystems already monitor their own state-of-health and therefore most effort is consumed in integrating subsystem state-of-health with the top-level.

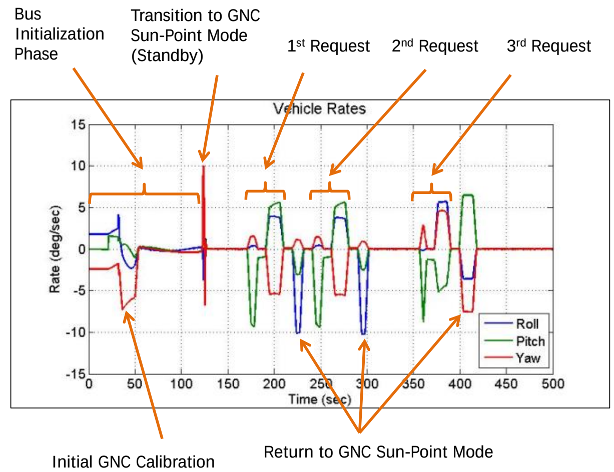

Figure 12: FSW Simulation of SeeMe operations.

COTS PART USAGE

Millennium Space Systems ALTAIR™ satellite system solution expands on Millennium's flight-proven Commercial-Off-The-Shelf (COTS) hardware up-screening processes, along with software-defined small satellite manufacturing using state of the art tool-free 3D printed composites to realize very low cost non-continuous production. Millennium has striven to use only COTS components in the ALTAIR™ satellite development. Alternatives to COTS were considered only when COTS products were not available and/or when another higher-value, low-cost, discontinuous production technique was available.

Millennium's COTS evaluation process was integral part of the fast prototype development process used to develop our ALTAIR™ spacecraft design. Various COTS suppliers were initially queried to determine parts relevant to small satellite production which could perform functionality traditionally assigned to standard satellite subsystems. Providers queried included traditional smallsat, cubesat, industrial, manufacturing, and automobile suppliers. Products were generally found on-line with their associated specification sheets. Parts were assessed and selected for maximum capability to the envisioned spacecraft capability. In some cases, DARPA desires for system-level SeeMe performance were decomposed to determine the necessary component performance specifications. When commercial parts could not serve a specific need, formal requests were made to available low-cost aerospace suppliers for specific capabilities. In general, these requests for information from even the low-cost satellite supplier industry could not meet DARPA cost

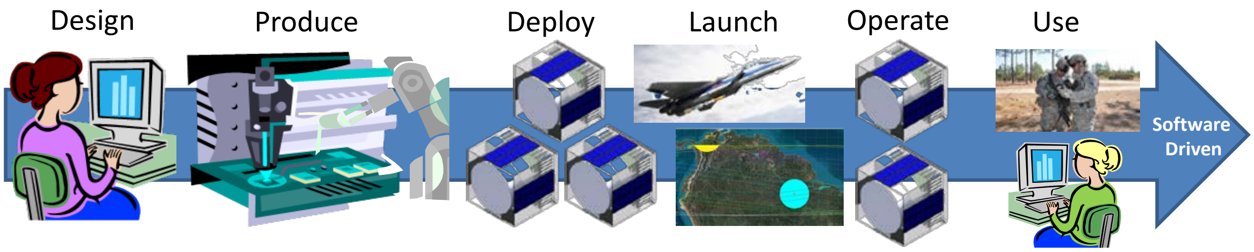

Figure 13: The Computer Defined Satellite vision for ALTAIR

and schedule goals for the SeeMe system. This situation forced a make-buy evaluation to determine whether COTS piece parts could be used to build a specific component meeting cost and schedule goals. In general, this “build-from-COTS-parts” approach worked when COTS components were not available. As the ALTAIR™ SeeMe satellite rapid prototype design matured, the original and alternative COTS component suppliers were again queried and the design database updated. More often than not, COTS suppliers improvement cycles are faster than our aerospace design cycles, so such updating frequently improves the satellite.

When we performed supplier surveys for all the anticipated subsystems, components, and parts we believed would be necessary for our ALTAIR™ SeeMe satellite, we set up some procurement ground rules for our program which our Responsible Engineering Authorities (REAs) for each subsystem enforced upon potential suppliers. Our ground rules stated for the suppliers were:

1) A minimum and fixed price for each component regardless of quantity

2) A 45 day delivery time maximum for all components

3) The ability to meet expected parts requirements for each component.

These rules kept us consistent with the DARPA SeeMe goals and our system engineering approach, whether a supplier was COTS, industrial, or a traditional Aerospace provider. Most traditional aerospace suppliers could not or would not meet our requirements. In general, COTS suppliers could meet our needs. We found COTS suppliers meeting our criteria for all components with the exception of the RF System and the Star Tracker. Over the remainder of the program, we continued refining our design, updated supplier options as necessary. We successfully developed a low cost star tracker in house exceeding our established SeeMe performance threshold and able to close in on the program goals for high performance.

DEVELOPMENT & PRODUCTION APPROACHES

Millennium Space Systems has striven to provide a paradigm shifting approach to DARPA’s desired Non-continuous production based on a new vision for software-defined spacecraft design, manufacture, launch, and operations. What we call the Computer Defined Satellite approach is conceptually cartooned in Figure 13. This approach is meant ultimately to provide a paperless “art-to-part” capability eliminating many processes between design and production, so many different payloads and hardware components could be accommodated to support rapid on-demand production. The Computer Defined Satellite database support goes beyond production to support deployment, launch, and operations as well. The Computer Defined Satellite approach is the means by which we intend to bring cost-effective discontinuous production to fruition. By having a baseline configuration combined with 3D printing technology, we are able to quickly accommodate different payloads, components, and/or orbits very quickly, reducing the design modification processes from months to days.

Millennium has defined the architecture for the Computer Defined Satellite approach and is working towards the vision. To date, we have migrated the ALTAIR™ spacecraft design to commercial web-based concurrent engineering databases. We have also started work on integrating different commercially available concurrent engineering tools to facilitate automated design updates from a baseline, automated ordering, and streamlined receiving, and parts management. The ALTAIR™ prototype spacecraft is used in time and motion studies to determine actual production procedures, travelers, and timelines. Tablets are used for paperless manufacturing management. Given that all parts arrive within 45 days of order, total per-satellite preparation work is under one man-day, and spacecraft assembly is well under one man-day. Figure 14 shows different assembly sequences, with each individual assembly sequence manually performed in under an hour. The spacecraft is designed to be robotically assembled should production rates ever justify such an infrastructure investment. Overall

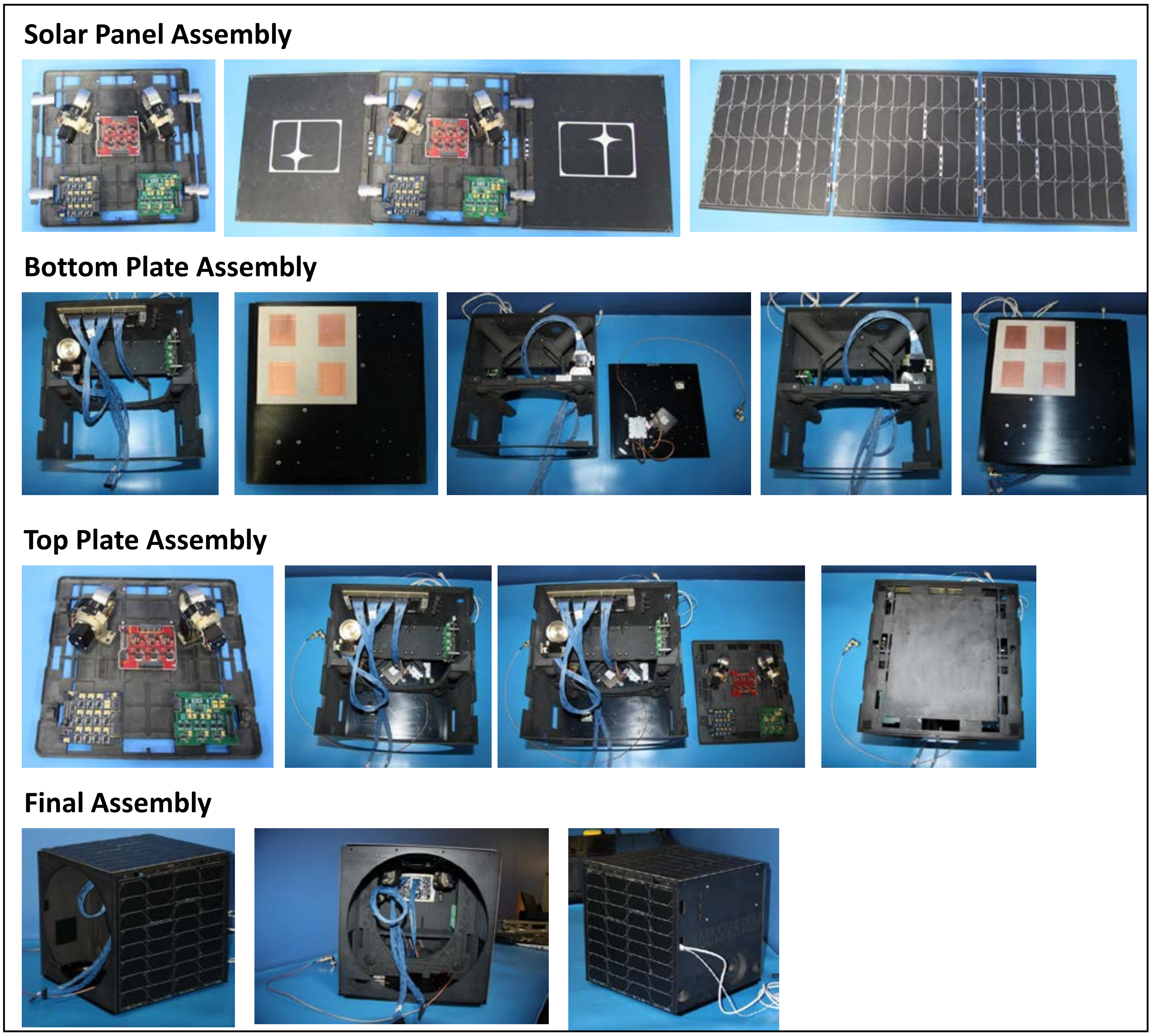

Figure 14: ALTAIR Spacecraft prototype used for production pathfinding time and motion studies.

ALTAIR™ satellite manufacturing can handily meet the discontinuous production goals DARPA desired where any number of satellites can be produced at the same price point *without* taking advantage of any learning curve.

SUMMARY

Millennium's ALTAIR™ Spacecraft as developed for the DARPA SeeMe program is an innovative, paradigm shifting approach based on a new vision for software-defined spacecraft design, manufacture, launch, and operations. By using COTS components wherever feasible, the ALTAIR™ spacecraft balances size, weight, power, agility, and lifetime to provide an optimized system while maintaining incredible payload design accommodation flexibility. Pretty much any payload compatible with the basic spacecraft volume envelope can be accommodated. We met SeeMe program goals by using COTS components and piece-parts, and achieving significant economy by keeping spacecraft bus hardware under approximately $100K.

The ALTAIR™ spacecraft is a 27U CubeSat-like design easily reconfigurable through Millennium Space Systems' software-defined approach, 3D printing, and standard and COTS hardware to accommodate changes, technology insertion, and alternate payload configurations. The satellite is specifically configured to minimize surface area and maximize payload, with ballast as necessary, for a minimum 45 day operational lifetime in low altitude orbits without propulsion, or fly as high as 600 Km altitude without modification for longer life. Meanwhile, empty volume is maximized to accommodate fixed or deployable payloads. Power is supplied by three solar arrays. The ALTAIR™ Attitude Control System uses standard hardware plus four CMGs to provide complete, precise, and agile three-axis control. The bus houses the command and data handling board, transceiver/crosslink, electrical power, thermal monitoring, attitude sensors, and CMGs. The command and data handling system is broken into three processor boards including a flight processor board, payload interface board, and communication board. The communication and data transfer architecture is negotiable and reconfigurable for desired mission operations.

The ALTAIR™ total system solution expands on Millennium Space Systems' flight-proven COTS hardware up-screening, heritage model-based software, and rapid prototyping to deliver a low cost and agile pointing payload platform. ALTAIR™ in its SeeMe incarnation, has the capability to provide 24/7 individual warfighter imagery using a software-defined small satellite network manufactured using state-of-the-art tool-free 3D printed composites and up-screened COTS components to realize very low cost, non-continuous production. The baselined ALTAIR™ design can be stored and transported inert in a canisterized spacecraft dispenser. Payload designs larger than the baseline require minimal engineering efforts for storage and transportation to the launch site. Upon deployment, the ALTAIR™ satellite completes built-in tests, self-calibrates the payload, and reports to the ground its readiness for the mission.

The ALTAIR™ spacecraft implements radically different approaches to spacecraft design, development, production, and operation. Millennium Space Systems' solution utilizes a software-defined answer to spacecraft development applying modern autocoded software development environments, CAD directly to 3D printing technology, COTS parts, and automated spacecraft testing and calibration. The methodology results in a highly compact, modular, scalable, and reconfigurable spacecraft with impressive agility, and ultra-low cost mission capable solutions. The ALTAIR™ system is a truly revolutionary product with the capability and costing to accommodate potential payloads and configurations over an extremely wide range to provide efficient solutions to various mission goals and architectures.

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