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ADAPTATIONS OF GUIDANCE, NAVIGATION, AND CONTROL VERIFICATION AND VALIDATION PHILOSOPHIES FOR SMALL SPACECRAFT

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Decades of experience developing increasingly capable and more complex spacecraft have resulted in a set of accepted practices and philosophies to verify and validate (V&V) guidance, navigation, and control (GN&C) subsystems. Until recently, small, low-cost spacecraft have had very simple or non-existent GN&C subsystems requiring minimal or no subsystem testing. As the next generation of small spacecraft take on more challenging GN&C requirements, the GN&C community is struggling with how to scale the subsystem V&V effort to produce spacecraft approaching the reliability of flagship-class missions while staying within the reduced resources of a small satellite project.For this paper, we will examine five aspects of GN&C V&V (requirements definition, software testing and analysis, hardware component testing, integrated vehicle testing, and in-flight V&V) and compare the V&V campaign of a flagship-class mission (Mars 2020) to that of two recent, successful CubeSat missions: ASTERIA and MarCO. Experiences from the development of these CubeSats yield valuable lessons learned and guidelines for future small spacecraft designers.

INTRODUCTION

In the early days of small spacecraft, including CubeSats, their guidance, navigation, and control (GN&C) subsystems were very simple. Most, such as QuakeSat, which was one of the first CubeSats to be launched in 2003, used a permanent magnet and hysteresis rods to damp out rates and align the spacecraft with the Earth's magnetic field.[1] Since then, the GN&C subsystems slowly advanced to the point where they now contain the same types of sensors and actuators that would typically be seen on a much larger spacecraft. The Radio Aurora Explorer (RAX), launched in 2010, also used a passive magnetic attitude control system, but had a sun sensor, magnetometer, and gyros for attitude estimation.[2] In 2013, the Bright Target Explorer was launched, which performs three-axis attitude estimation and control using a star tracker, magnetometer, coarse sun sensors, reaction wheels, and torque rods.[3]

As small spacecraft became more capable, they became more widely seen as able to perform more meaningful technology demonstrations or even science, which attracted the attention of larger institutions such as the Jet Propulsion Laboratory (JPL). As JPL began to develop its own CubeSats, it became evident that JPL was ill-prepared to balance the extremes of staying within the very limited schedule and budget constraints against the desire of delivering a product with flagship mission levels of reliability or probability of success.

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While this tug of war is inevitable and, in some sense, necessary, this paper aims to help guide future small spacecraft projects by presenting the GN&C verification and validation (V&V) approach of two successful JPL missions: Mars Cube One (MarCO) and the Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA). Note that this is a retrospective analysis of what occurred and the GN&C V&V processes were not consciously tailored prior to MarCO and ASTERIA. Also, this paper will not lay out the entire V&V process, but rather will extract examples of notable differences between these projects, each with a budget on the order of $10 million, and a JPL flagship mission such as Mars 2020 (M2020), with a budget of $2.1 billion.

For reference, the NASA Systems Engineering Handbook defines V&V in the following way:[4] "Verification of a product shows proof of compliance with requirements—that the product can meet each "shall" statement as proven though performance of a test, analysis, inspection, or demonstration (or combination of these)", while "Validation of a product shows that the product accomplishes the intended purpose in the intended environment—that it meets the expectations of the customer and other stakeholders as shown through performance of a test, analysis, inspection, or demonstration."

To describe the V&V process adaptations performed on ASTERIA and MarCO versus M2020, this paper will be split into six sections. First, this paper will first introduce these three missions by describing their overall mission objectives and GN&C subsystem design at a high level. Next, the requirements definition process will be described, which sets the key requirements to be verified during the V&V process. The next four sections split the V&V effort into software testing and analysis, hardware component testing, integrated vehicle testing, and in-flight V&V.

BACKGROUND

This section will briefly introduce the three projects that will be discussed throughout this paper and provide a high-level description of their GN&C subsystems.

The Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) is a 6U CubeSat designed to test pointing and thermal control technologies, perform opportunistic photometric observations of bright, nearby stars, and possibly detect exoplanets transiting these stars. The completed flight vehicle is shown in Figure 1. It was launched in August 2017 and was deployed from the International Space Station on November 2017.[5] Its attitude control subsystem (ACS) is the Blue Canyon Technologies (BCT) XACT unit, which contains three orthogonal reaction wheels and torque rods, a star tracker, gyros, magnetometer, sun sensor, and software to estimate and control the attitude. It also has a pointing control subsystem (PCS), which is able to further improve the pointing capability of the spacecraft, by using a piezo stage, which translates the payload imager to remove attitude errors and stabilize the image. Figure 2 pictorially depicts this two-stage control concept. ASTERIA has achieved the best pointing to date of a spacecraft of its size[6] and has detected a known transiting super-Earth 55 Cancri e.[7]

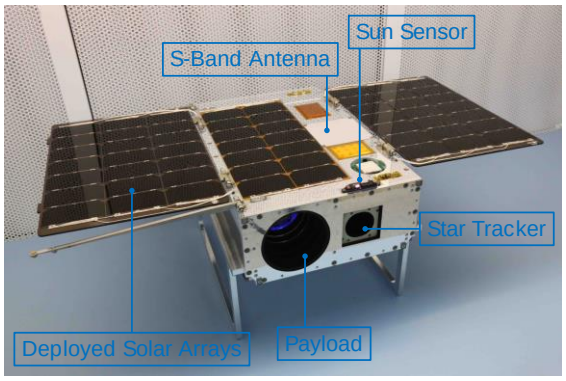

Figure 1. ASTERIA Spacecraft.

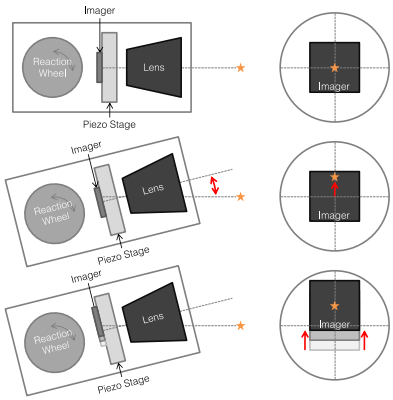

Figure 2. Two-Stage Pointing Control Architecture Cartoon.

The Mars Cube One (MarCO) mission consists of a pair of 6U CubeSats designed to perform a series of technology demonstrations for deep space missions, which culminated with the spacecraft performing a bent-pipe-relay service for the NASA Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) lander on November, 26, 2018, during its entry, descent, and landing (EDL) to the Martian surface.[8] The two spacecraft are shown in Figure 3. MarCO's technology development demonstrations all are aimed at supporting the InSight EDL and other deep space CubeSat missions. Amongst the demonstrations are the demonstration of viable CubeSat operations at ~1.4 AU (such as the power, thermal, communication, and attitude control subsystems), and the demonstration of the trajectory correction maneuvers required to execute a close Mars flyby in support of InSight's EDL. The ACS and propulsion unit use the BCT XACT and a Vacuum and Air Components Company of America (VACCO) Industries propulsion unit. MarCO's XACT unit contains three reaction wheels, a pair of coarse sun sensors, a star tracker, and a three-axis gyroscope and interfaces directly with the VACCO propulsion unit.[9]

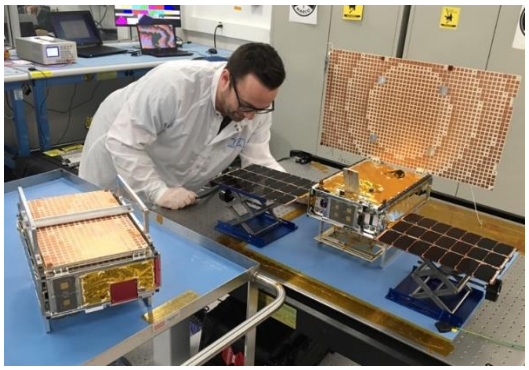

Figure 3. MarCO Spacecraft

The Mars 2020 (M2020) mission is JPL's next Mars rover, which has seven instruments that support the four main science objectives: (1) characterize the geology around the landing site, (2) seek preserved biosignatures of microbial life in rock samples, (3) collect and cache rock and regolith samples, and (4) prepare for humans, including the in-situ production of oxygen.[10] This mission is scheduled to launch in July or August 2020 and land on Mars in February 2021. Figure 4 shows the spacecraft during its cruise phase from Earth to Mars and Figure 5 shows the rover on Mars. For the sake of simplicity and serving as a better comparison to ASTERIA and MarCO, this paper will only discuss the GN&C pertaining to the cruise ACS of the M2020 mission. The ACS controls the spin-stabilized spacecraft using eight reaction control system (RCS) thrusters, eight digital sun sensors, and a star scanner with redundant sensors and electronics. This subsystem builds off of heritage from Mars Pathfinder, the Mars Exploration Rovers, and the Mars Science Laboratory.

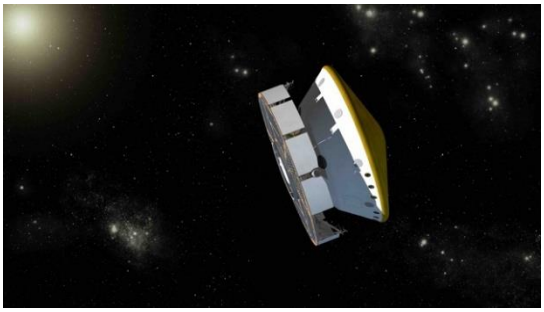

Figure 4. Mars 2020 Spacecraft During its Cruise Phase. Image Credit: NASA/JPL-Caltech.

Figure 5. Mars 2020 Rover Studying a Mars Rock Outrcrop. Image Credit: NASA/JPL-Caltech.

REQUIREMENTS DEFINITION

Defining requirements forms the backbone of the V&V campaign because each requirement becomes an item that must be verified during the V&V process. Ideally, the set of requirements that are defined are both necessary and sufficient to ensure the needs, goals, and objectives of the mission are met. While such an ideal may not be achieved in practice, it is something that is strived for during the requirements definition process. Requirements are typically defined throughout the Pre-Phase A, Phase A, and Phase B stages[4] and can take years to develop. By streamlining the requirements definition process, the entire V&V process is streamlined. Both ASTERIA and MarCO pared down the requirements definition process by performing an as-needed flow down. Instead of flowing down requirements from the level one (L1) requirements down through all of the various levels (e.g., L1 program, L2 project, L3 flight system, L4 subsystem, and L5 component requirements), requirements were only flowed down to the appropriate level.

One reason for not flowing requirements down to lower levels is due to the nature of the small satellite missions and the market of GN&C products. Since there are still a limited number of products on the market (though the market is growing) and ordering custom hardware may not be feasible due to budget constraints, often small satellite missions are conceived with requirements that fall within the capability of products already available on the market, eliminating the need to flow requirements down further. Also, since both ASTERIA and MarCO leveraged integrated, turnkey GN&C subsystems, it did not make sense to flow down requirements from the subsystem to the component level, considered the purview of the subsystem vendor.

Another reason is that it isn't as necessary given the small size of the team. One of the main purposes of requirements is to communicate important design decisions, ensuring that the system is built as expected and there are no surprises. However, there's little need to flow down requirements if it's just one person managing the entire GN&C subsystem. A single person managing all the subsystem requirements is feasible only because of the lower overall complexity of small spacecraft.

Figure 6 shows the 17 GN&C-related requirements from ASTERIA and how they flowed from the L1 pointing requirements. The figure does not show an ideal set of requirements—it is not—however, it does show how the requirements resemble the project personnel structure and important lines of communication. The requirements do not flow further down into the GN&C subsystem, but rather to other important system-level requirements such as mass and magnetic properties, payload performance, and software capability.

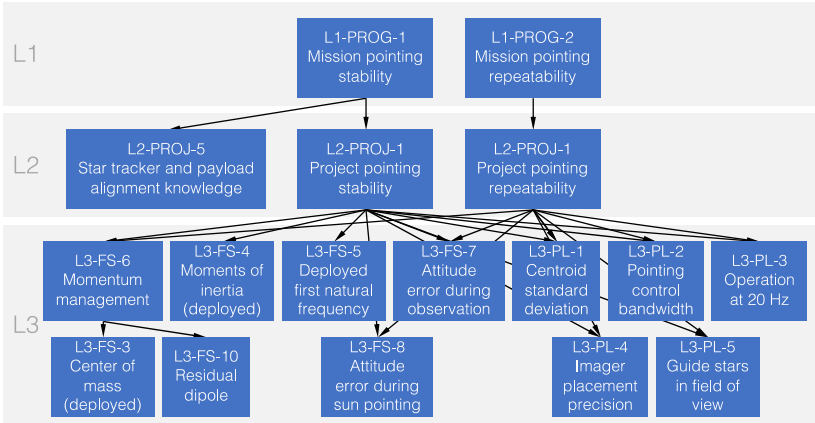

Figure 6. Example of Requirements Flow-Down on ASTERIA.

Similar to ASTERIA, MarCO has only 12 ACS and propulsion requirements. These specify the functionality and performance needed to satisfy the other subsystems. A formal flow-down of requirements was not created for MarCO's ACS and propulsion systems. For this mission, the driver is the technology demonstration focus of the mission. Additionally, the requirements primarily are quantitative, though many are qualitative or capture general functionality. For example, a requirement specifying that the system support 3-axis control using the RCS thrusters is primarily a software requirement, since 3-axis control is physically assured because of the need to desaturate reaction wheels using the RCS thrusters. Further, the requirement to be able to execute up to five TCMs does not specify the definition of a TCM, allowing multiple segments to comprise

each TCM. Consequently, this requirement does not govern the number of TCM thrusting events, but the need to navigate to Mars. Therefore, while the MarCO requirements each have specific denotations, the intent of each often spans a wider scope than the specified quantitative measure.

M2020, on the other hand, has many more requirements compared to these small satellite missions. M2020 has 31 L4 GN&C requirements, 51 L5 cruise ACS requirements, 17 L5 digital sun sensor assembly requirements, and 13 L5 star scanner assembly requirements. On M2020, it is important to flow down the requirements from the subsystem to the component level since each of the main components are delivered by different vendors (not as an integrated subsystem) and there are many more people involved with the design and delivery of hardware and software (typically one person per component/algorithm as opposed to one person for the entire subsystem).

The overall result of this as-needed requirements flow-down is fewer requirements, which comes with both positive and negative aspects. This achieves the goal of streamlining the V&V process since it means less process is necessary to verify the requirements. It also affords more flexibility throughout all mission phases since design and implementation details may be changed more easily. Fewer requirements also come with the negative aspect of more risk. For example, important requirements on components such as the radiation or thermal environment were often not levied upon vendors as dictated by schedule and budget. This as-needed flow-down is necessary to streamline the V&V process for small satellites and it really only works on smaller projects with lower overall spacecraft complexity.

GN&C SOFTWARE TESTING & ANALYSIS

The main purpose of performing software testing is to ensure the functionality and performance of the GN&C software as defined in the requirements. While analysis is separate from software testing, it is grouped together in this section since the two are closely related. Analysis can include items such as error budgets and gain/phase margins, which can be derived from simulations used to test the software.

On M2020, the cruise ACS software, which is written in C, is tested in a simulation environment, also written in C, which contains models of the dynamics, sensors, and actuators. Tcl scripts are used to test the software for various scenarios throughout cruise. Detailed error budgets were created from simulation results as well as analysis of telemetry from MSL. Final closeout of Cruise ACS requirements are performed on a hardware-in-the-loop simulation and on the flight vehicle. This was deemed necessary to sufficiently test the higher system complexity.

For ASTERIA, little was trimmed down in terms of the content of the software testing and analysis owing to the pointing requirements being vital L1s. Luckily, past work could be leveraged to reduce the workload on ASTERIA.[11] A time-domain simulation was developed in Simulink, which called the PCS flight software, written in C. One tricky aspect was that the ACS software needed to be simulated without access to the BCT-proprietary flight algorithms. An example of results showing the attitude and pointing error from a single simulation run are shown in Figure 7.

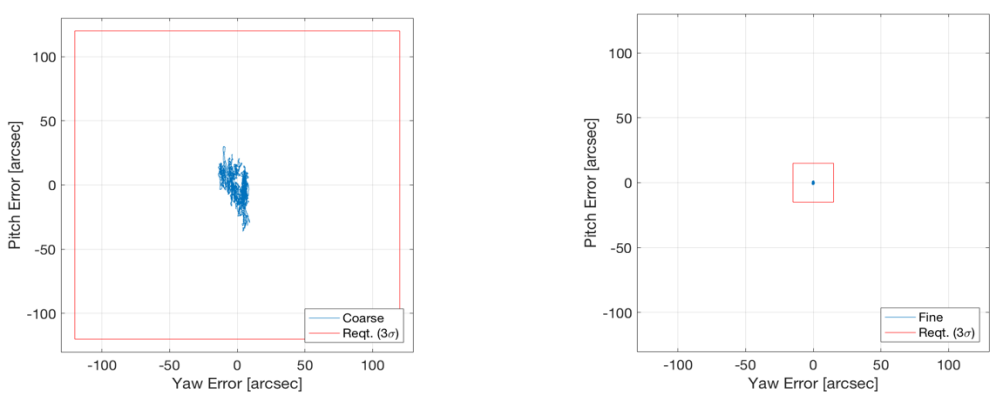

Figure 7. Example of ASTERIA Simulation Results Showing Attitude Error (Left) and Pointing Error (Right).

For the MarCO mission, in contrast, JPL did not perform any testing or analysis of the ACS software. Instead, the software was tested by BCT since their code is proprietary. As a part of the standard testing, which was also performed for ASTERIA's XACT, BCT performed regression testing, mission-specific simulations, and stability and control analyses. As an additional deliverable for MarCO, BCT provided results such as Monte Carlo simulations to assess the performance of thrusting maneuvers both for providing trajectory changes and for momentum dumping. Figure 8 shows one such example of the output data used by BCT for assessing the ability of the spacecraft to dump momentum from reaction wheels using the RCS thrusters over a range of initial momentum vectors equivalent to 20 deg/s tipoff rates in each axis of the fully-stowed configuration. In each of the 1900 cases, the momentum was autonomously brought to a level from which reaction wheels could control the spacecraft attitude within three minutes. This and other deliverables from BCT provided a method of assessing the software's ability to maintain safe control of the spacecraft without the need to release proprietary information and ultimately reducing the workload on JPL.

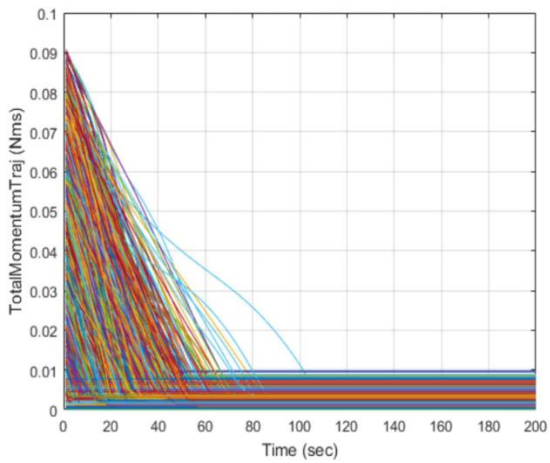

Figure 8. Momentum Dump Monte Carlo Performance – Provided by BCT in BCT Document 3ICD1356 Rev. D, March 1, 2018.

It is clear that software testing and analysis is essential to the success of a mission from a GN&C perspective. ASTERIA did not and could not compromise on the amount and rigor of the testing and analysis performed on the pointing control subsystem. For MarCO, and ASTERIA to a lesser extent, it made sense to subcontract out the testing and analysis of the attitude control subsystem given that BCT was providing a fully integrated subsystem. Doing so does result in its own set of complications, however. For example, since BCT performed testing and analysis, some system-level properties such as mass, inertia, and flexible modes needed to be provided to BCT. However, the hardware was delivered before these values were finalized. In the case of ASTERIA, the XACT was delivered and operated with older inertia estimates rather than the as-measured values in Assembly, Test, and Launch Operations (ATLO). While this is not ideal, these inertia errors were easily absorbed by the ample gain margins in the attitude controller. Like ASTERIA, MarCO's XACT was delivered based on estimated physical properties with a controller that would remain stable over an agreed upon set of uncertainty bounds for each physical property. While subcontracting this testing and analysis has enabled ASTERIA and MarCO to remain within programmatic constraints, it did complicate the typical subcontractor relationship due to system-level couplings.

GN&C HARDWARE COMPONENT TESTING

Typically, testing of the GN&C hardware is performed to verify L5 requirements levied upon each hardware component. This includes both functional and performance testing such as ensuring the hardware turns on, can be commanded, produces desired actuation or measurements within tolerance, stays within required power constraints, and survives and/or operates in the specified pressure, temperature, vibration, electromagnetic, and radiation environments. Since neither MarCO nor ASTERIA had L5 requirements to verify, hardware testing was not guided by the need to verify requirements. Instead the functionality, performance, and also phasing of hardware were treated as verification items for the tests performed.

Both ASTERIA and MarCO followed similar, parallel functional and phasing tests of the XACT. BCT performed many hardware tests prior to delivery, including laboratory phasing tests (magnetometer, torque rods, IMU, and sun sensor), night sky testing of the star tracker, and vibration and thermal testing of the entire unit. Also, radiation testing was performed on a similar XACT unit to characterize the radiation tolerance, which was beneficial for both ASTERIA and MarCO. After receipt of the XACT, some of the functional tests were either repeated or expanded upon. For example, both projects used JPL's Small Satellite Dynamics Testbed (SSDT) star field simulator[12] to test the functionality and phasing of the XACT star tracker. As shown in Figure 9, a star field was displayed on a small screen, which was imaged by the star tracker through a collimating lens. Various slews were tested at representative slew rates to demonstrate the ability of the star tracker to produce the expected quaternion and rate trajectory. ASTERIA also used the SSDT planar air bearing[13] to test the functionality and phasing of the XACT reaction wheels. Figure 10 shows the XACT on a mount allowing for testing of all three orthogonal wheels, which rests on an air bearing. When the wheels are actuated, the phasing of the wheels can be verified by ensuring that the vehicle begins to rotate in the expected direction. While the ASTERIA and MarCO projects performed a significant amount of functional testing to verify the design of the XACT, which had not yet flown in space at that time, future missions using the XACT can curtail the amount of function testing since there is already some confidence in the design, and focus on workmanship and phasing tests. Testing performed by each project utilizing a turnkey GN&C subsystem contributes to improving the subsystem for future missions, assuming that information on design bugs and improvement suggestions are fed back to the vendor and disseminated to future users.

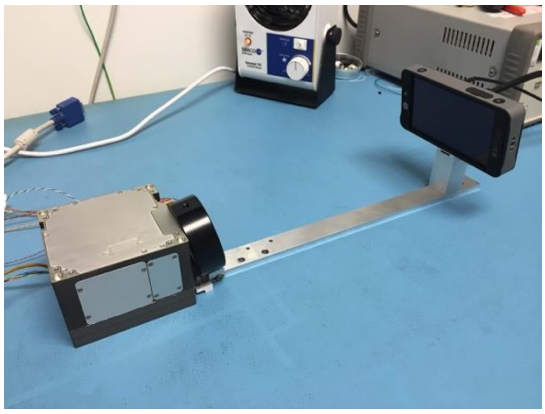

Figure 9. Star Tracker Functional and Phasing Test on ASTERIA's XACT.

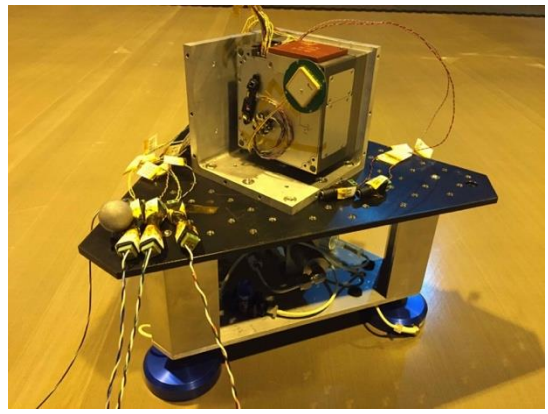

Figure 10. Reaction Wheel Functional and Phasing Test on ASTERIA's XACT.

In addition to the XACT, ASTERIA also tested the piezo stage, imager, and lens components, which are all a part of the pointing control subsystem. While component testing of imager and lens was performed, it was not relevant from a GN&C perspective. The piezo stage, on the other hand, was tested at a component level. A mass simulator was mounted on the piezo stage. Simple analog input/output testing using a signal generator and oscilloscope was performed to demonstrate the ability to move the piezo stage and remove hysteresis. A dynamic signal analyzer was used to measure the frequency response of the stage.

While there was nothing particularly different about the hardware tests on MarCO and ASTERIA versus what might be performed on a flagship mission, what is notable is what tests were included versus taken out. For example, on a larger mission, vendors will typically perform environmental tests such as vibration and TVAC testing on components before delivery. BCT did actually perform both vibration and thermal testing, but TVAC testing was not performed at the component level and was deferred to system-level TVAC testing. Similarly, PI did not perform any environmental testing on the piezo stage and therefore both TVAC and vibration testing were deferred until system-level testing. While this does increase the risk of uncovering problems later in time, it was necessary to meet time and cost constraints. Another notable difference is that meaningful phasing tests could actually be performed at the subsystem level since the XACT is really a complete subsystem and delivered as a unit to spacecraft integration. Larger missions typically procure individual components and integrate them, and therefore must perform phasing tests on the integrated flight vehicle to ensure the software, electronics, harnesses, and hardware are integrated as expected. With the

software and hardware all integrated into the XACT, phasing can be performed at the component level, as long as extra care is taken in inspecting the commands and mounting of the XACT within the flight system.

INTEGRATED VEHICLE TESTING

On M2020 and similarly other JPL flagship missions, there are multiple venues for performing integrated tests. The ones most relevant for GN&C testing are the Work Station Test Set (WSTS), Mission System Testbed (MSTB), and Assembly, Test, and Launch Operations (ATLO) venue. WSTS is a non-real-time, software-only simulation. It contains all of the flight software, along with GN&C models of the dynamics, actuators, and sensors to create a more complete software environment versus a standalone GN&C simulation. It also uses the Ground Data System (GDS), which allows for testing of commands and telemetry in a flight-like environment. The MSTB is similar to WSTS except it is a hardware-in-the-loop simulation. Usually engineering models (EMs) are used, though it is possible to use flight-candidate hardware. The software runs on an actual flight computer, which is connected to real electronics, sensors, and actuators. The actuator outputs feed into a real-time simulation of the spacecraft dynamics and sensor measurements. This venue is primarily used to test software and hardware interfaces that cannot be, or are better tested in this real-time environment with hardware. It is also used as a place to dry run procedures before being run in ATLO. ATLO is, for the most part, just like the MSTB, except that the actual flight vehicle is being used for testing. This venue is primarily used to test integrated hardware and software functionality and phasing.

Both ASTERIA and MarCO loosely followed this structure of venues for integrated vehicle testing. One big difference is that both of these small spacecraft projects did not include the WSTS venue. The main reason is that it takes significant amount of resources, which were not available, to develop and debug WSTS. Even if the resources were available to develop this venue, there would inevitably be WSTS-specific idiosyncrasies, which can impede the V&V process while not reflecting the behavior of the actual flight system. For example, the M2020 flight computer is big endian; however, since WSTS is run on a little-endian system, binary data from a WSTS run is stored with its byte-order reversed versus how it will be stored on the actual flight computer. The negative aspect of not developing a WSTS venue was increased demand for testing on the testbed and flight system, leading to many late-night test shifts. However, this was manageable given the small size of the ASTERIA and MarCO team. This is very different in a large team, where it would be impossible to have everyone vying for time on the MSTB or in ATLO, without WSTS, given the ratio of people to available testbed time. WSTS, once developed, can be inexpensively duplicated to accommodate as many users as needed to alleviate testing bottlenecks on MSTB and in ATLO.

MarCO and ASTERIA each had their own versions of the MSTB, simply referred to as a testbed, which were invaluable tools for testing prior to delivery and in flight. The MarCO testbed is shown in Figure 11. Both projects used a vendor-supplied simulation environment for the XACT called the Realtime Dynamics Processor (RDP). The RDP simulates the sensor inputs during testing based on the XACT's actuator commands as if the spacecraft were in space through a separate test connector on the XACT. On MarCO, there was an additional propulsion test unit, consisting of electronics provided by the vendor, that simulates the sensor readings and requires the appropriate heater loads for maintaining tank and plenum pressures.

Tests of representative maneuvers that would need to be performed in space were performed using the XACT and RDP. On MarCO, one scenario that was tested was to start with a tumbling initial state and achieve a stable Sun-pointing attitude. The expected tipoff rate upon deployment from the launch vehicle for MarCO was < 2 deg/s. To demonstrate robustness, the XACT was tested with an initial rate of 30 deg/s/axis as shown in Figure 12. This rate is higher than the reaction wheels' detumble capability, necessitating the use of thrusters to lower the system momentum. Immediately following the command to go to sun pointing mode, the XACT commands thrusters to counter the body rates. Thruster firing is indicated by the increase in thruster firing durations in the top two subplots and the effect is shown in the slowing of the body rotational frequency in the quaternion subplot. Once the system momentum is reduced to a level that the reaction wheels can control the spacecraft's rotation rate, the thrusters stop firing and the wheels spin up. The thruster firing durations do not drop to zero after they finish firing because the last value is stored in memory and returned throughout the rest of the test. This test demonstrated the functionality of the interface and the control software between the XACT and VACCO units as well as the ability for the attitude control and reaction control systems to manage the spacecraft's overall system momentum.

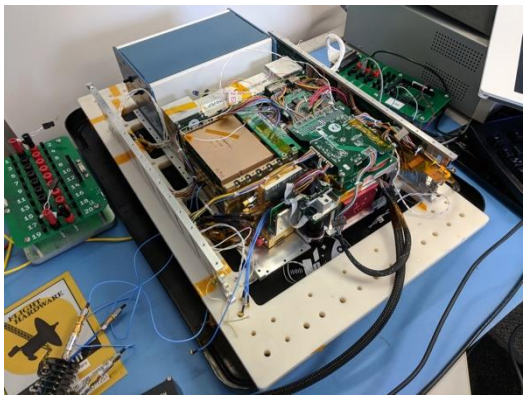

Figure 11. MarCO Ground Testbed.

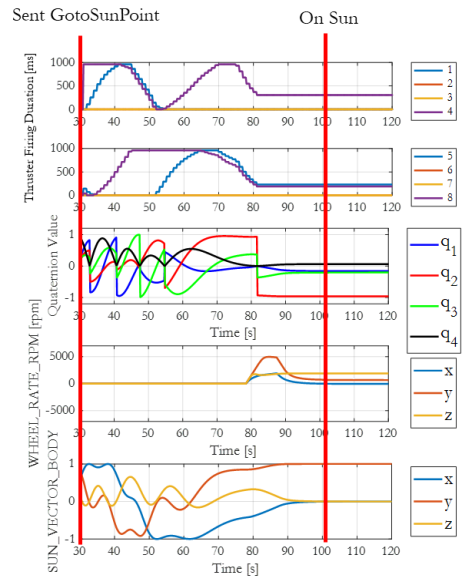

Figure 12. MarCO Testbed Test of XACT Achieving Sun Point from 30-deg/s/axis Initial Tipoff Rate.

On ASTERIA, the pointing control loop was tested for the first time with hardware in ATLO. This testing needed to be performed on the flight system since it was the only venue with a complete payload and optical ground support equipment. Simple tests were performed to verify the phasing of the imager and the piezo stage with respect to the imager, and delay of the piezo stage commands. Also, imager noise characteristics were measured to update the imager model.[14] The ground testing of the pointing control subsystem culminated in a closed-loop functional test (Figure 13) where a field of pinholes (emulating a star field) was imaged and stabilized by the payload. A fold mirror in the optical path emulated attitude errors. Figure 14 shows the "attitude error" produced by moving the mirror by hand and the pointing error with the piezo stage actively stabilizing the star field. Note that the attitude error is very "noisy" when the mirrors are actually being moved due to effects such as stiction. It is most obvious that the system is functioning properly when the mirror is not being moved: constant attitude error, but zero pointing error. This test proved the end-to-end functionality of the pointing control system hardware and software.

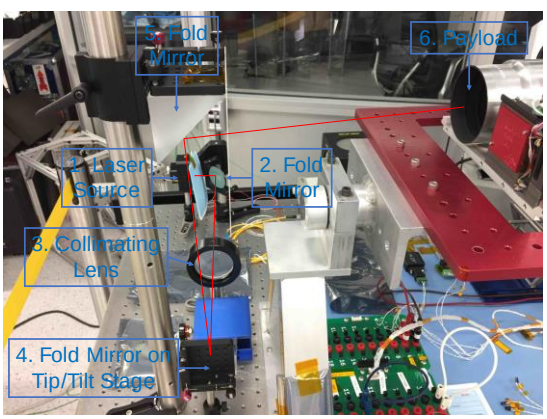

Figure 13. ASTERIA Payload Test Setup in ATLO.

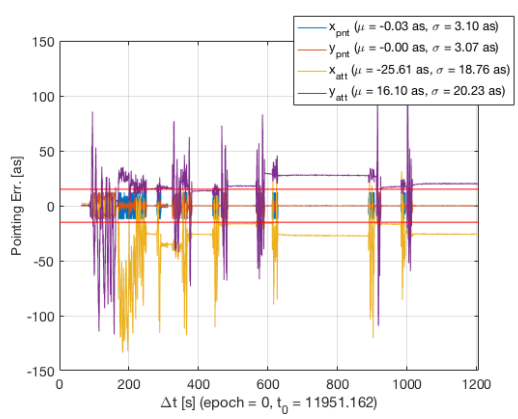

Figure 14. Attitude and Pointing Error in Closed-Loop Test on ASTERIA.

It is important to note that both ASTERIA and MarCO did not use a three-degree-of-freedom air bearing to test the attitude control. On ASTERIA, this idea was suggested throughout the project development as a

way to perform an end-to-end test of the attitude and pointing control subsystems together. It is often thought that CubeSats are small and it should be relatively easy to perform such a test. However, there are many issues to consider. For example, it is very tedious to position the center of mass at the center of rotation to reduce the effect of pendulum dynamics. Even if this is performed, the piezo stage moving on the order of tens of microns can shift the center of mass enough to cause significant disturbances, especially when considering attitude errors on the order of an arcsecond.[15] On MarCO, there are other considerations such as propellant slosh moving the center of mass and cleanliness issues for planetary protection and the thruster valves. All of these hurdles, not to mention the time and effort to set up such a test, resulted in not pursuing this path.

In addition to testing the functionality of the GN&C capability in isolation, mission scenario tests were also performed to test the system's ability to coordinate multiple subsystems via sequences to perform mission scenarios. On MarCO, one example was performing the bent-pipe relay with InSight to ensure that all of the software hooks were in place to operate in bent-pipe mode at the appropriate attitude. On ASTERIA, the main test was to perform an observation of a star field with the pointing and thermal control active while saving coadded images and downlinking telemetry on the next pass. On both projects, mission scenario testing exercised the fault protection systems to ensure that the fault monitors and responses were exercised as expected. Since these tests are of the whole spacecraft as an integrated system, they provide the most realistic assessment of the software and hardware's readiness to perform the mission.

IN-FLIGHT VERIFICATION & VALIDATION

Since both ASTERIA and MarCO are technology demonstrations, some GN&C requirements could not be considered verified until demonstrated in flight. The missions would not be deemed successful unless these requirements were demonstrated in space.

On ASTERIA, the L1 pointing stability (5 arcseconds RMS over 20 minutes) and pointing repeatability (1 arcsecond RMS from observation to observation) requirements were some of the mission's top requirements that were needed to be satisfied to declare mission success. Following an on-orbit calibration of the geometric parameters of the camera,[14] repeated observations of various star fields were performed. For nine observations of HD 219134, the pointing repeatability was 1 milliarcsecond RMS and the pointing stability was 0.5 arcseconds RMS over 20 minutes. This more than met the pointing requirements and is the best pointing stability achieved to date on a spacecraft of this size.[6] There were some sequencing missteps along the way, which were quickly diagnosed and fixed through the use of the ground testbed. Also, there were a couple flight software updates that were made to improve and expand the capability of the pointing control software. This ability to change software has been invaluable, especially as ASTERIA enters a new phase of the mission to perform new technology demonstrations that were not a part of the original mission.[16]

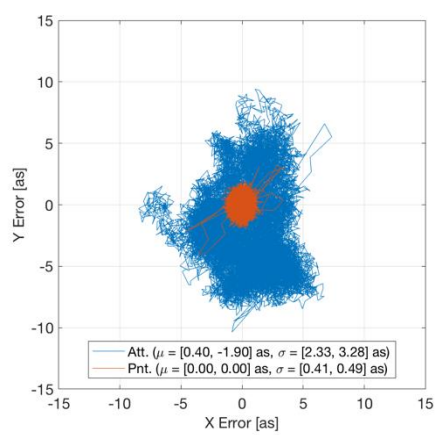

Figure 15. ASTERIA Attitude & Pointing Error for HD 219134 Observation.

One key item for MarCO to demonstrate in flight is a trajectory correction maneuver (TCM). It is impossible to demonstrate a TCM before launch, so the top-level requirement on MarCO that the spacecraft be able

to perform these maneuvers could not be met and the mission could not be deemed fully successful without a flight TCM. Although the interfaces were demonstrated for short periods during thruster checkout firings during ground V&V processes, the first TCM helped complete the V&V process for several requirements concerning the ability for the thrusters to maintain spacecraft attitude and to adjust the trajectory according to ground-commanded specifications. Figure 16 shows the angular error in body coordinates observed during the first TCM segment performed on MarCO-B. The attitude error is computed from the difference between the estimated spacecraft attitude and the commanded firing attitude. The angular error before the slew to the firing attitude is the same as that after the slew from the firing attitude, confirming that the spacecraft returned to its initial attitude for Earth communication. Importantly, however, is the behavior observed following the start of thruster firing. An initial transient of approximately 15 degrees is observed primarily towards the –X body direction. This transient behavior is a result of the controller firing thrusters with a set of physical parameters that do not perfectly match the spacecraft. The controller compensates over the next several seconds for the transient error, and small oscillations are visible with decreasing amplitude until the thrusters stop firing. The thrusters are not able to reduce the attitude error entirely over the duration of the burn, so the reaction wheels are used to return to the firing attitude as soon as the thrusters cut off. This TCM segment relied on the proper functionality of the attitude control and propulsion systems working in concert as part of a fully-integrated spacecraft. Commands from the ground were used to fire thrusters of the propulsions system according to commands from the attitude control system; the TCM validated in-flight the functional abilities of each subsystem and helped meet the requirement that MarCO perform the first CubeSat TCM and demonstrate necessary technologies for future missions.

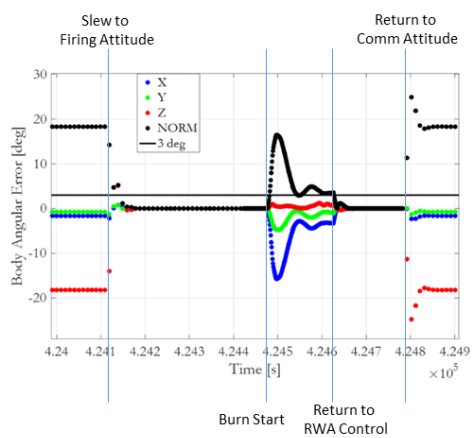

Figure 16. Angular Error from Commanded TCM Attitude of MarCO-B TCM1 Segment on 2018 Day of Year 141.

CONCLUSION

The successful achievement of the GN&C requirements on ASTERIA and MarCO are a testament to the overall GN&C V&V performed on these missions. Despite the stringent cost and schedule budgets, ASTERIA and MarCO were able to perform several in-space firsts for small spacecraft. Below is a summary of some of the conclusions made when analyzing the V&V performed on these two missions.

These are a few items that can be scaled down to fit within tight schedule and cost constraints:

- Flow-down of requirements. There is less of a need to flow down requirements to the component level if an entire subsystem is being procured. Requirements should capture important system-level interactions and will likely result in having the number of requirements be roughly proportional to the size of the project. Fewer requirements means less to verify, which affords more flexibility, but comes with increased risk.
- Number of simulation environments. Only one strong simulation is necessary. For ACS simulations on MarCO and ASTERIA, this turned out to be the hardware-in-the-loop simulation with

the XACT and RDP. On ASTERIA, there was only one PCS simulation. The RDP served as a flexible way to test the hardware and software of both the ground and flight XACT units.

- Fancier integrated tests. While tempting, tests such as three-degree-of-freedom air bearing tests should really be assessed in terms of cost versus benefit. Often there are a host of issues that need to be resolved, requiring more resources than originally expected. Also, hardware or software changes will need to be made to the system, making the test less representative of the flight environment and more of a functional demonstration. Often, there is a simpler way of performing a functional test of the control system.
- Procedures and procedure development. Time spent testing is of the utmost importance and should not be sacrificed to create, scrub, and polish procedures. However, documenting all testing performed is still very important.

These are a few items that should not be scaled down:

- Testing of essential GN&C verification items
    - Performance. Overall performance is typically predicted in simulation and/or analysis. Component-level performance is typically measured during component testing.
    - Functionality. Hardware and software interfaces via commands and telemetry are ultimately tested on the flight vehicle.
    - Phasing. Ensuring the correct polarity of all sensors and actuators must be performed on the flight system.
    - Timing. The delay of sensors and actuators should be known either through measurements, which is preferred, or through analysis.
- Ability to defer development and testing. It is inevitable that development and testing will be pared down to fit within schedule and cost constraints. Being able to do this after delivery or during flight operations is important.
    - Being able to update flight software in flight is a key enabling feature for fixing issues not caught during ATLO and for handling unknown unknowns.
    - There is no need to test every command and piece of telemetry. Focus on testing essential ones prior to delivery.
    - Having a testbed enables testing to continue after the flight vehicle is delivered.
    - Ensure arbitrary commands can be sent to vendor-provided hardware. This eases the burden of needing to implement all commands. Plus, there may be undocumented commands that may come in handy during operations.

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