Production of Flight Instruments for Multi-Satellite Constellations

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Recent National Academy of Science Decadal Surveys in space and Earth-science have called for simultaneous, distributed multi-point measurements in and from space, requiring constellations of small spacecraft. Small satellites have demonstrated their utility for enabling high-quality science measurements and observations. NASA missions have leveraged advances in sensor miniaturization, technology innovations, and new small satellite mission architectures to enable meaningful measurement-based scientific investigations that operate on small satellites and that are responsive to science objectives described in National Academy of Science Decadal Surveys. The advent of high capability small spacecraft enables consideration of science missions involving multiple small spacecraft, constellations of a few or many for simultaneous distributed in situ observations or remote observations from a variety of viewpoints. The central challenge for fielding instrumented space-flight constellations is to provide the required multiple sets of fully verified and calibrated instrument hardware, software, and operational processes from within a one-off project-based scientific space flight culture. Although there are numerous commercial entities providing "off-the shelf" spacecraft and avionics, the challenge lies in the multi-unit production of the uniquely targeted instrumentation necessary to perform the specific measurements required for a particular science investigation. Traditionally, the cost of such instrumentation has represented a significant portion of the hardware cost for a mission and posed the highest risk area for implementation. A shift in paradigm from large science platforms to constellations of smaller satellites drives the challenge to build instruments in a quasi-production environment. This paper describes key aspects of, and challenges encountered in the development program for the successful production of instruments for the Fast-Plasma Investigation (FPI) instrument suite of 64 flight plasma spectrometers and supporting electronics on the NASA Magnetospheric Multiscale (MMS) 4-satellite constellation mission. Although the MMS mission was not composed of small satellites, there are key aspects of the instrument production that apply directly to constellations of small satellites.

I. Introduction

In NASA's Heliophysics Division, science mission concepts involving multiple (few to dozens spacecraft have been prominent among recommended moderate and large class missions in each of the two most recent National Academies Press Decadal Surveys[1,2]. Several of these concepts have either flown (e.g., MMS[3], Van Allen Probes[4]) or are under development (e.g., Geospace Dynamics Constellation[5]), while others (e.g., Magnetospheric Constellation[6]) have yet to be developed. Other high-value multi-spacecraft Heliophysics science missions have been selected through NASA's Explorer Program (e.g., Themis[7], HelioSwarm[8]). Heliophysics is not unique among space-based science

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mission disciplines in the drive toward multi-spacecraft missions. A successful example in the Earth Science Division is CYGNSS[9].

Platform multiplicity requires smaller platforms and instruments, given launch volume and mass constraints. Therefore, the scientific need for multiple observation points drives a need for small instruments on multiple small platforms. We focus here on the multiplicity aspect, based on our experience in developing the Fast Plasma Investigation (FPI) for flight on NASA's Magnetospheric Multiscale (MMS) mission[10]. During 2005 through 2015, the MMS mission undertook a development where 4 complex identically-designed observatories (integrated spacecraft and instruments), each comprised of 9 different instrument types, were produced over a 5-year period from instrument suite Critical Design Review (CDR) to launch (reference Figure 1).[3] Of those instrument types, the Fast-Plasma Investigation (FPI) suite, implemented by a consortium led by the NASA Goddard Space Flight Center (GSFC), provided 8 similar instruments (4 Dual-Electron Spectrometers (DES) and 4 Dual-Ion Spectrometers (DIS)), and 1 redundant Instrument Data Processing Unit (IDPU) per observatory, for a total of 32 dual spectrometers (64 electrostatic analyzers) and 4 IDPUs.[10] A significant aspect of the instrument development and deliveries was the fact that the 16 DIS instruments were developed, built and tested by Meisei Electric Co. Ltd. in Japan.

Each mission will have its own drivers for constellation implementation. For example, the scientific driver for MMS' four-spacecraft configuration was the requirement to measure 3D spatial gradients of in-situ quantities based on the linear Taylor series approximation. For this, four observation points arranged near the points of a tetrahedron are required. Gradients are derived from differences among measurements at the four closely-spaced observatories. The in-situ quantities (electric and magnetic fields; electron & ion integral moments: densities, average velocities, pressures) and their spatial gradients comprise all[11] the terms in the Vlasov equation[12], a form of Newton's 2nd Law that governs the physics of collisionless plasmas. The scientific target of MMS is collisionless magnetic reconnection[12], a fundamental plasma process that occurs in highly localized spatial regions, re-orders global magnetic topologies, and is a central process responsible for dynamic space weather near Earth and elsewhere. The multitude of plasma instrumentation required for FPI on each MMS spacecraft was driven by a need for speed. Localized reconnection regions typically move with the background plasma at high speed in the spacecraft frame of reference and high time resolution is required to capture details of small reconnection sites as they convect past the observation points. Plasma moments are derived as integrals over 3D (velocity space) particle distribution functions that require 3D (full sky) field of view. Spacecraft spin, traditionally used to acquire such 3D view is too slow (3 rpm) in this case, so many multi-channel sensors were employed as described in (4). Since the 3D plasma gradient measurements depend on assembling measurements from multiple sensors on each spacecraft to form plasma measurement sets, and on differencing those sets among the four spacecraft, FPI was challenged with achieving and maintaining excellent accuracy and precision in addition to the large number of flight units to be developed. Though MMS is not comprised of small-spacecraft, and the multiplicity of MMS platforms is modest, that of the FPI instrumentation is representative of larger constellations of smaller spacecraft envisioned in recent decadal surveys.

With any need for science observations on more numerous small platforms, there is a resulting need to implement production-like strategies for scientific instruments wherever possible to successfully execute these types of missions. This is challenging in a unique, self-contained scientific space flight project development environment. Commercial development and production entails multiple stages from Proof-Of-Concept (POC) to Engineering Validation Test (EVT) to Design Verification Test (DVT) to system Verification and Validation test (V&V) to Production Validation Test (PVT), and finally to mass production (MP). In industry, the EVT through the PVT stage can entail from 5 to 500 units depending on the complexity, volume and cost of the hardware. In addition, all or some of the listed stages may be skipped or combined depending on the industry, the product and the size of the company. Although this approach is prohibitive in cost and development schedule, and to some extent not relevant for scientific space flight instruments for a single mission where foreseeable production quantities are smaller (< ~100), there are elements that can be incorporated into the traditional approach for scientific space flight instrument development at various stages and to different extents. For single-instrument builds, the typical approach is to progress from an Engineering Model (EM) demonstrating proof-of-concept through an Engineering Test Unit (ETU) for design verification and validation, including environments, to the final Flight Model (FM).

Traditionally, space flight instruments are developed in single to small quantities, not requiring methodologies and processes associated with commercial production. Consequently, no equivalent to multiple DVT and PVT units described above had been completed prior to FPI's scheduled builds of the 32 instruments and 4 IDPUs. Instead, commercial processes were employed for the fabrication of mechanical parts and production of Printed Circuit Board Assemblies (PCBAs) and some best practices from commercial production were implemented for the production of the final FM instruments where applicable and feasible.

Commercial industry has made significant advances in the low (10s) to mid (1000s) volume production of instrumentation for space flight in the areas of telecommunication terminals (e.g., SpaceX, Eutelsat, Maxar, Amazon),

optical imagers (e.g., Planet, Maxar, BlackSky, Airbus), radars (e.g., Iceye, Airbus, Synspective, Maxar, Capella Space, Umbra, BlackSky) and optical hyperspectral spectrometers (e.g., Planet, Orbital Sidekick, BlackSky). These are driven more by commercial benefits of telecommunication and Earth imaging data than by the need for very high scientific quality. Some scientific missions, specifically MMS, require highly accurate and precise instruments. Each mission places unique and possibly stringent requirements and constraints at every step of the instrument development and production.

The purpose of this paper is to provide insight into key elements of commercial production that could be fruitfully applied to the concurrent production of numerous similar scientific space flight instruments, based on the experiences and observations from the successful MMS FPI instrument suite production. The paper is organized along the flow of a development and production project from requirements in Section II, parts evaluation and proof-of-concept in Section III, design and design verification in Section IV, production preparation and readiness in Section V to production, test and calibration in Section VI. In addition, it provides commissioning and operations observations in Section VII as these pose their own unique challenges for constellation missions with multiple similar instruments. Finally, conclusions are provided in Section VIII.

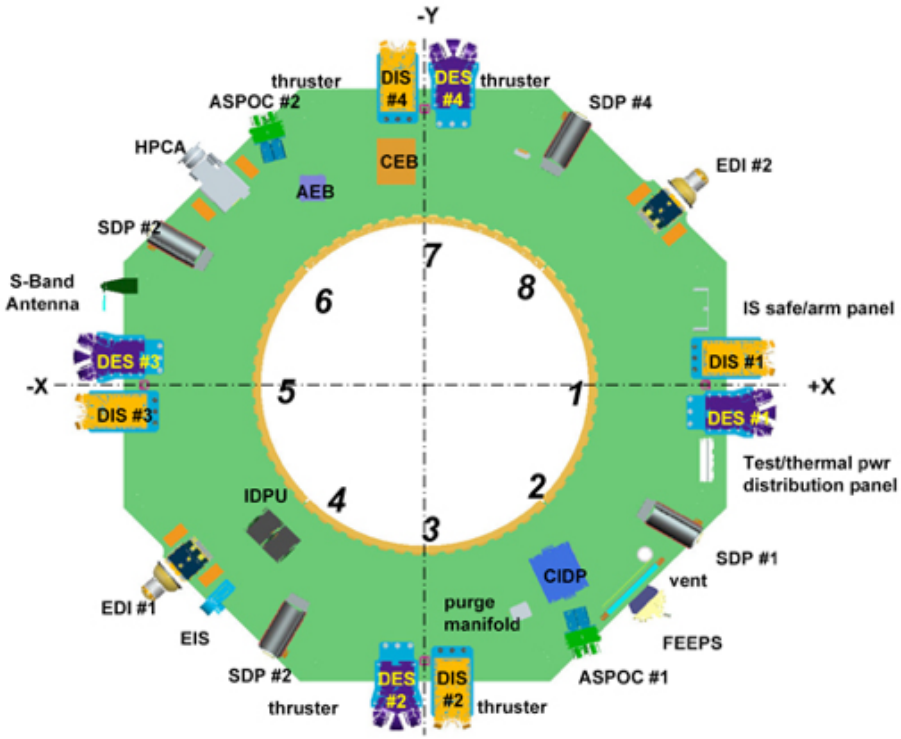


Figure 1. MMS instrument payload.

II. Key production element #1: Requirements

The two key drivers for space-flight science instrument requirements are scientific performance and environmental conditions to be encountered during launch and on-orbit. The former is typically negotiable in the formulation phase, while the latter is imposed by storage, launch and operational conditions. Both require clear specification prior to design and production of the critical ETU. Mission science leadership is needed to limit the required instrument performance to that which is necessary to accomplish the mission science objectives. The natural inclination of instrument scientists and engineers to strive for the best possible performance in a particular context can and does lead to "mission creep" that can be costly and distracting as team members strive to satisfy goals in addition to requirements or to satisfy a set of evolving requirements. Too often, consideration of what an instrument could do as opposed to what it must do, plays an outsized role in requirements definition. Consider the requirements for a magnetospheric constellation (MagCon) mission as envisioned by Kepko[6] for an example. MagCon calls for 36 small spacecraft, each equipped with a magnetometer, ion and electron plasma spectrometers, and an energetic particle

sensor, and comprising an element of a flight formation that spans a large 2D segment of the geomagnetic tail once-per-orbit when the orbit apogee is on the night side. The primary scientific advances promised from MagCon derive from the large-scale formation that provides many simultaneous and dispersed observations, together providing time series of synoptic snapshots of Earth's magnetotail under various dynamic and quiescent conditions. Instrument performance requirements in this case are modest compared to modern space plasma instrument capabilities. Any temptation to optimize instrument performance beyond that required in such a case would be counterproductive and would present tangible risk to the central challenge of delivering the many modest-performing instruments that the mission requires. Appropriate and stable instrument performance requirements should be defined sufficiently early that the ETU, which serves as the verification unit for the design, performance, and environmental ruggedness, as well the pathfinder for the FM final design and production, is well-founded. In contrast, a mission like MMS required highly precise and very well cross-calibrated electron and ion spectrometers to achieve the scientific objectives.

When producing a sizeable number of FM instruments, it is important to include specific requirements for manufacturability as an integral part of the early engineering requirements development. When manufacturability requirements are incorporated early in the ETU development, the ETU verification process, in addition to identifying required functional changes, also identifies opportunities to correct unnecessary complexities in disassembly/reassembly processes to ensure efficient and successful manufacture of the FM instruments. Manufacturability is critical, as errors owing to overly complex manufacturing processes can quickly erode budget and schedule in a multi-unit production. Many parts of the DES and DIS instruments on FPI/MMS were specifically designed with this in mind. As an example, the curved electrostatic analyzer electrodes have fragile coatings so they can be damaged from handling and at the same time must be assembled together with very tight tolerance. To accomplish this with more ease and repeatability, tooling features where imbedded in the parts, and tools were designed for efficient and safe handling and assembly of the parts. Further, precision alignment was implemented as an integral part of the design to avoid costly alignment procedures during assembly.

III. Key production element #2: Parts Evaluation and Proof of Concept

A. Parts Evaluation

Careful and appropriate parts evaluation of critical parts is essential in any scientific instrument or other product that push the boundaries of physics and/or technology capability, to ensure successful, cost efficient and reliable development and production. This seems logical but is often missed or intentionally skipped due to limited time and budget and reluctance to invest early to realize cost savings later in the production phase of the project. Parts evaluation entails, but is not limited to:

- Due diligence evaluation of vendors, parts design and parts fabrication.
- Capability, performance, limitations, and unexpected behaviors.
- Variability in performance.
- Reliability.
- Radiation tolerance.
- Aging and conditioning (if needed).

The following describes three examples of parts-driven issues encountered on FPI/MMS late in the development and production that had a significant impact on schedule and cost. Had more investments in the early phases of the project been possible, a more thorough parts evaluation would likely have uncovered some if not all of these issues. This would have made the later project execution faster and less costly. Fortunately, it was possible to overcome and/or correct the issues and deliver excellent instruments resulting in a highly successful mission. Naturally, there is no guarantee of uncovering all limiting parts performances and all possible parts issues. There may be challenges that are simply outside the knowledge or foresight of any team. However, thorough parts evaluation and measurements in context of the application is highly advisable as it will always increase knowledge leading to a reduction in the risk of design issues and an increase in the likelihood of finding parts issue early in the development instead of late in the production.

The first example pertains to capabilities and behaviors of charge sensitive amplifiers used in the detection system of the instruments. The DES and DIS instruments each have two 16-channel detection systems with tightly packed charge sensitive amplifiers.[10] A change in the charge sensitive amplifier part selection was identified and required late in the design of the ETU instruments to meet the science requirements. Such a late change to a new part with somewhat unknown behavior makes thorough investigation of the new part even more critical. The new amplifier exhibited a mix of performance limitations and unexpected behaviors that were not uncovered during parts evaluation but instead

were discovered during the performance testing of the ETU DES. The issues revolved around device grounding, device output drive behavior and capability, channel-to-channel output-to-input crosstalk and resulting cyclic re-triggering amongst the 16 channels, and non-linear fold-back behavior in the amplifier threshold control. These behaviors were critical to understand and manage in the design to achieve successful operation of 16 densely spaced channels. It required 4-5 months of debugging to get to the root cause of the issues on the ETU. The design changes had to be proven out on the ETU using band-aid modifications to the extent possible and had to be implemented directly into the FM design without full design verification. The risk was accepted as root causes were clearly understood after the debug effort. This type of situation can be avoided by: 1) making sure required parts performance is identified early, by thoroughly evaluating what is truly required instead of relying on heritage implementations, ensuring early and correct selection of critical parts, and 2) spending more effort and cost to clearly understand the capabilities and behaviors specific to the critical parts of the instrument before finalizing the instrument design. For this example, thorough due diligence evaluation of the part vendor, design, and fabrication together with detailed investigation and testing of the part in a dense multi-channel context would reveal many if not all such issues, resulting in a proper ETU instrument design. Often, in the development of a space flight science instrument, this is done only to a very limited extent due to the practice of applying heritage as much as possible. This leads to a mind-set of 'already understanding' the parts and system, as they are similar with what has been used and done before. However, every instrument has its uniqueness that will require quite specific parts operation and sub-system design to work and perform as required.

In addition, since 32 of these parts were used in each of the 16 DES and 16 DIS instruments, and the charge detection threshold was critical to instrument performance and calibration, parts variability was critically important to meeting the science requirements. Individual control of 32 charge detection thresholds in 32 instruments across 4 spacecraft is undesirable and operationally costly and untenable. Therefore, a characterization, evaluation and binning effort was undertaken late in the project just before the FM production to ensure uniformity in threshold within each instrument. This resulted in outstanding science performance uniformity within each instrument but came at a cost of a lot of extra work for the team at a critical time in the project. In this case also, early investment in parts evaluation is a much better and less costly solution.

The second example pertains to parts reliability in relation to the application for high voltage opto-couplers used in the high voltage power supplies of the instruments. Each DES instrument uses 12 and each DIS instrument uses 6 high voltage opto-couplers for a total of 288 of these parts that have to reliably switch voltages of up to 4.1 kV and 5.8 kV at a rate of 4.27 kHz and 0.85 kHz with a slew rate of 55 V/μs and 30 V/μs for DES and DIS, respectively, for the duration of the mission.[10] Previous missions had flown up to 48 of these parts and this was used as the basis for flight heritage and adequate reliability. This, however, is not an adequate basis to demonstrate the required reliability. Flying 288 of these parts, for a mission life of 29 months and meeting the MMS mission reliability requirements, requires a Mean Time To Failure (MTTF) of 7742 years for the part, which is not demonstrated by the previous flight of 48 parts. For this part, thorough due diligence evaluation of the part vendor, design and fabrication together with detailed investigation and testing of parts reliability is critical. This was not done to the extent necessary early in the project partly because it was not fully realized how demanding the reliability requirement was and how much stress the part would have to withstand in terms of high voltage switching and temperature cycling between orbital perigee and apogee. During FM instrument testing failures of this part started to manifest, leading to a significant investigation effort. Root cause was narrowed down to design and manufacturing issues for the part to be able to reliably withstand the high voltage switching in combination with the temperature stress of the application. This led to a large undertaking to identify and replace weak parts based on parts test data from the vendor, a large instrument screening test to screen out weak parts that would fail early, binning of instruments with weakest remaining parts on one spacecraft, and operational changes to minimize instrument temperature cycling and keep the opto-couplers at near-constant temperature. This ensured a highly successful science mission for MMS far into extended mission life. However, it required a significant undertaking late in the project that could possibly have been avoided by careful evaluation of the actual reliability requirements unique to FPI on the MMS mission rather than relying on flight heritage. This should then have led to more rigor early in the project in evaluating the parts in relation to the required reliability by more extensive due diligence investigation of the parts design and fabrication, and parts test data evaluation. It would likely have revealed the parts issue so action could have been taken before the start of ETU design.

The third example pertains to aging and conditioning of Micro-Channel Plates (MCPs) used in the detection system of the instruments. It is well-known that the gain of MCPs change over time as charge is generated from the MCPs by incoming particles. This is most prevalent in the beginning and eventually flattens out over time in operation[13]. Therefore, it is normal to condition the MCPs by extracting a certain amount of charge before installation in the FM instruments. For the 16 DES instruments in FPI, a total of 50 sets of MCPs (32 + 18 spares) had to be conditioned. When conditioning a large number of MCP sets, the duration of the conditioning becomes highly important for cost and schedule. MCPs could not be procured early enough in the build process to complete the

preconditioning process required for a flattened gain. Therefore, a compromise was made between how much to invest in preconditioning hardware, cost and instrument performance. The decision was made to have a single fully automated vacuum charge extraction facility that was able to precondition two sets of MCPs at a time. In the remaining time available, this allowed an extraction of ~0.1 C out of the desired 1.0 C. This mitigated the steepest part of the gain falloff but required frequent (roughly once per month) adjustments in MCP voltage during flight to compensate for the gain change over time on orbit. This complexity could have been significantly reduced if the MCPs could have been procured earlier, or a larger preconditioning setup had been developed. Again, early investment in parts procurement, evaluation and handling is a much better and less costly solution.

B. Proof-of-Concept

Performing a good proof-of-concept goes hand in hand with early parts evaluation, with the purpose of ensuring that the design can work within the boundaries of physics as well as parts technology limitations. It is essential that proof-of-concept includes critical aspects of the design to be implemented. As an example on FPI/MMS, the charge sensitive amplifier had to work in an implementation where 16 of them were tightly packed on a circuit board requiring much better grounding, power supply design, output-to-input isolation and output load design than in an application allowing a more sparse layout. The proof-of-concept, unfortunately, was performed with only two charge sensitive amplifiers well-spaced on a circuit board. This led to the incorrect understanding that the dense 16 channel design would work as designed. The outcome and resolution is described above in Section III.A.

In contrast the electrostatic sub-system of the instruments went through very thorough proof-of-concept early on, as it was known to be highly challenging to implement well. It was therefore very well understood, and the ETU design performed exactly as expected.

Again, early investment in thorough and proper contextual proof-of-concept for critical aspects of the instrument is a much better and less costly solution especially for a project that undertakes production of multiple instruments.

IV. Key production element #3: Design and Design Verification with an ETU

Technology Readiness Level (TRL) is how NASA assesses the maturity of an instrument concept and the ability of an instrument project to be implemented, where TRL-6 establishes the threshold for an instrument to begin the flight build implementation. TRL-6 is defined as a flight-like equivalent hardware compliment that meets functional, performance, and ruggedness requirements in relevant environments.[14] In the MMS/FPI implementation, this unit of hardware is called the engineering test unit (ETU), which is equivalent to a commercial DVT unit.

In some instances, space flight instrument proposers with constrained development budgets have made the decision to forgo the ETU to save money or time and to go straight into production, or the ETU is treated as more of a proof-of-concept Engineering Model (EM) platform that ends up not being flight-like. This strategy represents a formula for disaster should design issues be identified during initial testing of the first FM article, or well into the environmental test campaign. At that stage of the project, the team is in place and the marching army costs represent an order of magnitude increase over the savings achieved by elimination or abbreviation of an ETU. This scales to higher proportions for a higher number of required FM units. Also, depending on the issue and required recovery time, schedule margin can be eroded significantly.

A second aspect for the ETU is the criticality of maintaining configuration control of the design implementation used for the verification test. If a design is tested and verified, but there were undocumented design changes in the tested article, the ability to reproduce the hardware configuration for the flight build can be significantly compromised.

Instrument End-to-End testing (to the extent possible) is critical for the demonstration of instrument performance prior to integration onto the observatory due to limitations for testing at the observatory-level. The ETU provides a pathfinder to demonstrate critical instrument performance representative of the flight hardware. In the case of JUNO mission to Jupiter, the Johns Hopkins University/Applied Physics Laboratory (JHU/APL) Jupiter Energetic Particle Detector Instrument (JEDI)[15] ETU was subjected to a thorough calibration test across all elemental species using a calibration source which was available at the NASA Goddard Space Flight Center. The subsequent 3 flight instruments were only tested at a subset of elements across the spectrum (using capabilities at the JHU/APL laboratory) to verify linearity as compared to the flight-like ETU. A high-fidelity pedigree and thorough calibration of an ETU can represent a potential for significant cost and schedule savings in the production phase if less sophisticated calibration facilities can be used for the flight builds. Critically, the ETU can provide a high fidelity “gold-standard” for isolating and resolving problems encountered during all subsequent flight article testing and operations.

Although great strides in development had been accomplished by the time of the MMS FPI instrument CDR in May 2010, the DES ETU, required to be ready for delivery by CDR was delayed. Recovery and turn-around efforts

were undertaken and completion of the ETU was accomplished 5½ months after CDR. During ETU design verification testing several design issues were discovered (one of which is briefly described above) that prevented the DES ETU from meeting performance requirements. Ultimately, after 5 months of debug and design change development, the DES design was verified with a modified ETU. Several of the findings and resulting design changes on DES also applied to the DIS and were incorporated by the DIS development team. The design changes were "band-aided' into the ETU and rolled directly into the FM design due to a trade between limited time and resources versus risk, perceived as being reasonably low due to the debug effort leading to full root-cause understanding. This turned out to be the right decision. However, the right solution is to spend more time on parts evaluation and proof-of-concept earlier in the project. After this, the instrument proceeded into production with all instruments (16 DESs and 16 DISs) and 4 IDPUs being delivered on time. Though this retrenchment on the ETU was expensive and painful at the time, the alternatives of either cancellation or entering the multi-unit build without a fully verified and documented ETU were both unacceptable. The ultimate value of the ETU for FPI was huge despite its early design issues.

V. Key production element #4: Production Preparation and Readiness

A key element to the implementation of multi-unit space flight hardware entails definition and implementation of processes and work methods that are thorough, rigorous, practical and smart. These are inherently to be defined and developed prior to initiation of the flight build. The optimal time is therefore early and hand in hand with the ETU development and verification.

A. Data Management and Configuration Control

Data generation begins in the proposal stage and accelerates through both the development, production, test and operational mission phases. Early investments in capable data management and configuration control systems are good investments when done in context of the size and scope of the project and mission. This is needed for but not limited to:

1. Drawings
2. Documents (requirements, specifications, procedures, processes etc.)
3. Work order authorizations
4. Production data including genealogy tracking and production progress
5. Risks
6. Anomaly and failure reports and resolution
7. Software (both ground test and flight software)
8. Test and calibration data
9. Final instrument end item data packages
10. Mission housekeeping and science data

Effective data management and configuration control can help to avoid costly issues ranging from significant design, production and test mistakes to loss of critical calibration or science data. At NASA GSFC, an excellent configuration management system is in place that covers 1-3 and 5-6. In addition, gold standard software configuration management systems are in place and each mission has carefully implemented systems for mission housekeeping and science data storage and management. All of these were extensively utilized on MMS/FPI.

Solutions for number 4, production data, are widely implemented in commercial production due to the high-volume, whereas it is hard if not impossible to justify the expense for building just one or two unique instruments. However, when producing tens of instruments as for FPI, production data tracking becomes critical while a full-fledged production data system is still too costly to implement. This is an example where low-cost processes and tools can advantageously be implemented that deliver the intent of full-fledged systems. On FPI, genealogy tracking, production tracking, and progress reporting were all implemented as fundamental parts of the production processes using simple tools implemented in Excel. This brought good practices of production management to the project at a low cost and provided a critical element to successfully managing the production.

Handling of test and calibration data is essential both during production and for commissioning and in-flight calibration. For FPI, a data server with geo-diverse backup in a different building was implemented to ensure proper data storage and retention. In addition, and critically, it enabled data automation during testing which provides significant cost savings as further described in Section V.E.

Typically, when an instrument is delivered for a mission an End Item Data Package (EIDP) is delivered together with the instrument. For a single instrument, this has typically been in the form of all documents delivered as a

collection of electronic copies on some form of media together with a cover document specifying all the files. This is, even for a single instrument, cumbersome, labor intensive and challenging to handle for the receiving party. With tens of instruments, it becomes impractical. In the case of FPI, a more efficient approach was developed utilizing the fact that all documentation was readily available in the configuration management system and all test and calibration data was readily available and organized on the project data server. An overview EIDP document was implemented in Excel providing all production, test and anomaly information as well as top level performance specifications and all calibration data with hyperlinks to every single piece of documentation pertaining to each instrument in the configuration management system and to all test data for each instrument on the data server. This way the EIDPs were put together in a cost-effective manner without duplication of data and data storage, and the recipient could easily and efficiently get a quick overview and access detailed documentation and test data.

B. Production and Test Facilities

When undertaking a production of multiple instruments in an environment used to building single unique instruments it is important to properly and honestly assess the facilities in which the production and testing will take place. To be successful and not introduce unnecessary stress and mistakes, the facilities need to be set up to realistically support the expected volume of hardware and associated ground support equipment and staff. Even for a small-scale production, it is important that production facilities are set up for and can support parallel assembly activities and a flow of instruments in different assembly phases. This should be factored into the process at an early stage, or the production can become very slow, stressful and disorganized at best or grind to a halt and result in critical mistakes at worst. For FPI the production facility was set up to handle the progression of up to four instruments in parallel. At the same time, it could handle incoming inspection of mechanical parts and circuit boards.

The test facilities are equally important. For FPI, the Printed Circuit Board Assembly (PCBA) and electrical sub-system test stations and facilities were set up with a very high degree of automation, as described in Section V.E, for handling a steady flow of items under test.

Regarding both environmental testing required for flight qualification and end-to-end scientific measurement calibration, the required equipment is typically cost-prohibitive for a single scientific flight project to own. The challenge that results is that any ability to meet scheduled deliveries depends on timely reliable availability of these specialized facilities. Consequently, it is relevant to consider the benefit versus cost of acquiring dedicated facilities for targeted needs. Transport of flight hardware to external facilities adds additional handling risks and cost that need to be weighed in the decision process. For test and calibration of the final FPI instruments, a test facility with two vacuum chamber e-beam test stations was implemented also with a high degree of automation to allow testing and calibration of two instruments in parallel with minimal staff. Finally, for environmental testing, a dedicated Thermal VACuum (TVAC) facility was implemented that also allowed testing of two instruments at a time. EMI/EMC testing was made more efficient by performing many tests in dedicated project laboratories using portable EMI/EMC equipment. Only the test that had to be done in a radio anechoic chamber was performed in shared institutional facilities on the first flight article for qualification. In contrast, efficiency for vibration testing was achieved by using both internal and external shared vibration test facilities.

C. Processes, Procedures and Tools

Thorough and well thought out processes and procedures are important to implement a single scientific space-flight instrument. However, they become much more critical when producing multiple instruments, as do managerial, information and data tools that facilitate and document the production. Again here, many things successfully and efficiently implemented in commercial production can be adapted to small-scale production in a single-build environment. When these things are worked into how the project operates from the beginning, the production will become more cost effective, the team will be more production oriented, and both the number of encountered issues and the time required to resolve them will be less.

Integrated Master Schedules (IMS) and Earned Value Management (EVM) are two essential tools employed in assessing progress and performance for NASA projects. Key milestones are derived from the IMS and correlated with costs from the associated Work Breakdown Structure (WBS) elements monthly, where earned value is calculated/determined. Although these tools provide metrics for evaluation of overall project performance, from a day-to-day management perspective the tools do not necessarily provide a concise assessment of production progress and areas that require more attention.

For FPI, processes were implemented for efficient hardware and data handling, for production tracking, for testing, test data analysis and test reporting, for progress tracking and reporting, and for anomaly reporting and resolution. In addition, a detailed assembly and test process flow was implemented for every sub-system as well as for every completed flight article. Detailed procedures were implemented for all assembly and test work based on the

ETU assembly and test run. Finally, everything was operated using electronic documentation and tools with a mix of institutionally available and custom tools. For the MMS FPI project, genealogy and production tracking were implemented as fundamental parts of the production processes using simple tools constructed in Excel as shown in Fig. 2. This brought good practices of production management to the project at a low cost and provided a critical element to successfully managing the production. It enabled the ability to easily identify production status, holes, or issues. The matrix in Fig. 2 was an extremely helpful aid for FPI and was used daily throughout the FM production and test execution.

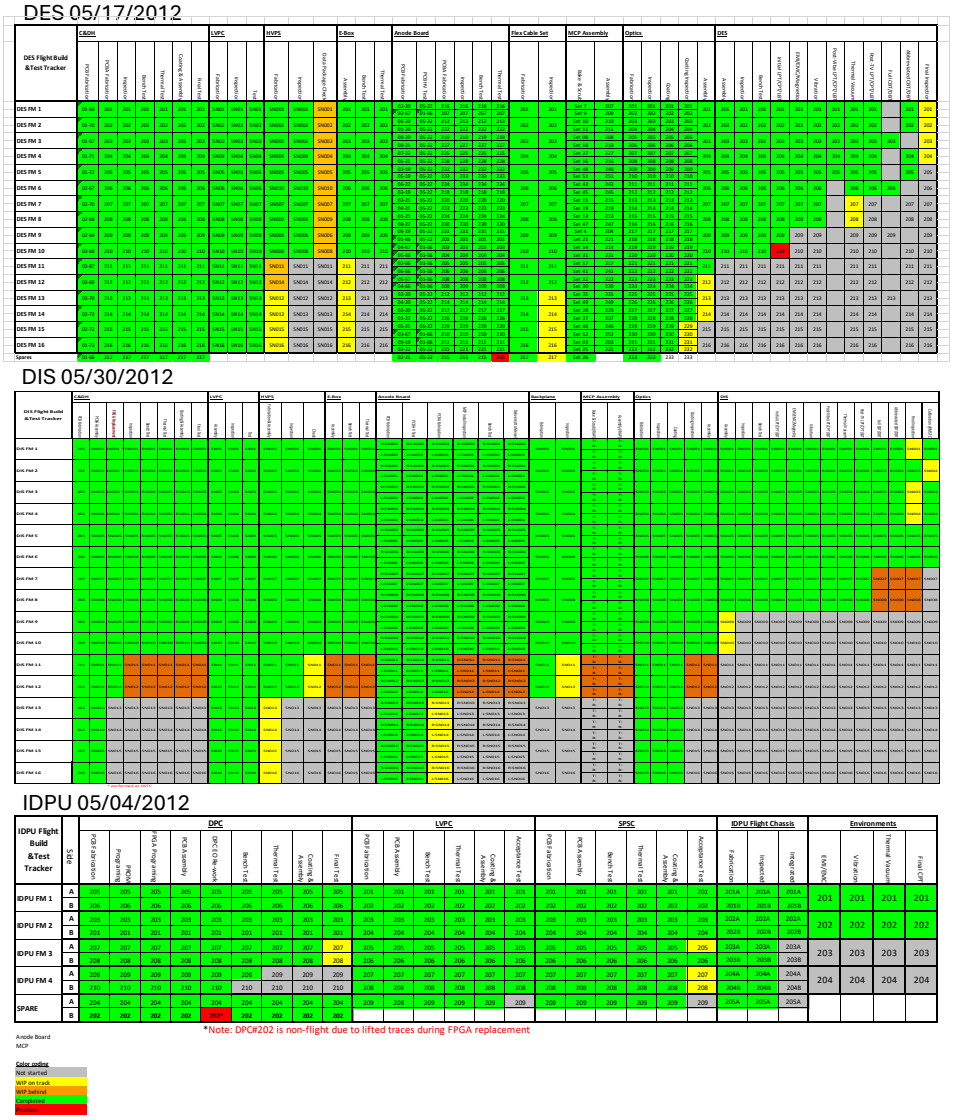


Figure 2. DES, DIS, & IDPU hardware tracking tool.

D. Training of Production Team

For commercial volume production, the manufacturing engineers get involved during build and test of the DVT units and training of the production team takes place as a lead-up to the PVT unit production where final details are incorporated. That approach is not feasible with a low to moderate volume production of scientific space-flight

instruments. However, the general approach can still be beneficially replicated. For FPI, several steps were taken in this direction. The assembly team was trained during ETU assembly with concurrent implementation of assembly procedures. The training was then continued into the first 4 units of the 16-unit dual spectrometer build with full engineering support. This enabled an overall more efficient production run. The key was to allow training to continue into the FM production build to get enough hands-on training time with full engineering support.

For the testing, the engineering test team that performed ETU testing transitioned onto the FM testing for the entire production run which meant they were fully trained by the time of the production run. This was made possible without any addition of staff by heavy use of test and data automation as described in the next sub-section.

E. Test and Data Automation

Test automation is essential for successful and cost-efficient production of multiple instruments. For the DES of FPI alone there were 68 PCBAs, 16 high voltage power supply sub-systems, 50 sets of MCPs, and 16 DES instruments to test. This would not have been feasible without a high degree of automation. In addition, test automation promotes consistency and greatly reduces human error. The development of test automation does cost more for the project in its earlier phases, but this money is well-spent to substantially reduce cost later in the project. For FPI, fully automated test stations were implemented for all PCBA, sub-system, and MCP testing. One PCBA, the detection system anode board, required complicated simultaneous connections to 16 charge injection probes. To make this accurate, repeatable and easy for the operator to accomplish, a special probing test fixture was developed that enabled easy installation of the anode board into the test station and easy engagement of all 16 probes. Specialized test fixtures were also made for the high voltage power supply, MCPs, and instruments all with a focus of making testing more accurate, repeatable, safe, and effective. For the testing of the instrument, a robotic fixture was implemented inside the TVAC chamber so each instrument could be efficiently tested with the e-beam at all instrument look angles without time-consuming chamber breaks. Significant test station and test fixture design as well as software development was required but was well worth the investment due to the quantity of items to be tested.

Test automation alone is not enough to ensure efficiency. The vast amount of data from the testing will quickly overwhelm the team if not handled appropriately. For DES on FPI, all test procedures were automated and programmed into the test stations and all produced test data was automatically stored by the test station onto the data servers together with meta-data and proper directory setup. This enabled the use of automated data processing, saving a large amount of data analysis time. For DES, this was even taken a step further with auto-generation of test reports based on a developed test report template and automated data processing results summary and graph generation. In this way the bulk of each test report only had to be written once for each different item. All subsequent test reports were auto generated, reviewed and annotated as needed. This removes a very large amount of manual labor for the engineers and, importantly, moves their focus onto the evaluation of the results instead.

F. Anomaly Recording, Reporting and Resolution

Anomalies are unavoidable on any space-flight scientific instrument build but can vary in number. When producing multiple instruments, the number of anomalies will be higher. It is critically important to be able to handle this larger volume in an efficient manner or it will overwhelm the project and grind the production to halt. On FPI, an anomaly recording, reporting and resolution process geared towards rapid reporting and resolution was implemented over time. It was not fully matured at the start of production but rather evolved during the production of the first four FM instruments. Streamlining the process gained efficiency and the ability to continually move the production forward in parallel with anomaly resolutions.

VI. Key production element #5: Production, Test and Calibration

The preparations for production readiness were described in the previous section. These if done well can lead to successful and cost-efficient production of the scientific instruments. The successful production, test, and calibration of the FPI instruments for MMS is described in the following as an example of how this can work out.

A. Production

As mentioned earlier, a small-scale DVT unit production run is typically used in the commercial production sector to develop the production facilities, instrumentation, processes and procedures and to conduct initial training of manufacturing engineers and technicians. Final production readiness and validation is accomplished on a small- to

medium-scale PVT production run. This is not fully feasible or affordable for a small-scale scientific instrument production. However, the intent of this process can still be implemented. This was done for the FPI instruments for MMS.

For a scientific flight project, it is customary and typical to build one ETU to verify and qualify the design and then proceed to building the FM instrument with, hopefully, only minor design changes. For a small-scale production like the 16 DES instruments for FPI on a limited budget it was not feasible to build more than one ETU. Also, it is not clear that it would have provided significant benefits in this specific case due to significant design issue encountered on the ETU. If this had not been the case, 2-3 ETUs would have been beneficial as it would have provided for more assembly training and provided units to allow more efficient test development in parallel. In general, for a small-scale production of tens of instruments, we recommend building at a minimum one but preferably a few ETUs depending on the size, complexity, and cost of the instrument.

In the DES and IDPU cases, the assembly facilities were already fully implemented before the production of the ETU. This allowed training of the production team in the actual FM production facility so that all processes and procedures could be appropriately evaluated and streamlined in preparation for the FM production in the actual production setting. Optimization of design for manufacturing for the FM was a critical output from the ETU. Further, the FM production procedures were implemented, and initial training of the manufacturing team was conducted during the ETU build.

For the final FM production, the instrument design was well optimized for manufacturing, but training had to continue with the first 4 out of 16 FM units. In essence, the first 4 FM units acted as PVT units ironing out production issues and mistakes as they manifested themselves through the production and subsequent test. The essential element here is to not assume the team is ready for full scale production based on assembly and test of one to a few ETUs. It is critically important to continue close collaboration between the development and production team and treat the first several FM units with a strong training and production validation focus, as issues and mistakes in the remaining population of FM units can become much more costly to the project.

Although rigorous processes, procedures and training may be in place, for a quasi-production environment there typically remains a significant amount of repetitive touch labor. Human nature dictates that complacency can take place where critical assembly steps are performed from memory, versus following detailed assembly procedures and work orders. In addition, heritage conventions that would apply in most cases, but are counter to the instrument design and implementation needs in specific and critical areas of the design, can further end up driving the team to incorrect assembly if complacency takes place or if new assembly and/or quality assurance staff is added to the team during production. One example in the case of the FPI DES was the sudden use of polymeric staking of high voltage cables inside the sensor head where the MCP is located to comply with a heritage cable support requirement. Staking can contaminate the MCPs by outgassing, and was specifically designed out for that reason with mechanical clamping support and an approved slight violation of the heritage support requirement. The assembly change found its way into the assembly in the middle of the production flow due to addition of new staff and was not discovered until it had been implemented in four FM units. This forced a long and costly life-time test of a set of pristine and potentially contaminated MCPs to prove the MCPs had not been severely contaminated and could be used as is. This is but one of several cases that were observed. In each case, the team stood down to focus on re-training and the importance of process discipline. Such painful delays, in the midst of a constrained schedule, were nevertheless found to be worthwhile investments on behalf of project success.

B. Sparing

Sparing philosophy is a key element in the risk posture a project is willing to undertake. There is no one-size-fits-all. An approach based on the complexity and cost of a specific subsystem or element is required. In the case of FPI, there was only one set of spare PCBAs for each instrument type (DES and DIS) that was fabricated and tested (6.25% sparing), where a more conservative approach would have required one spare set of PCBAs per every 4 instruments of each type (25% sparing). This approach was based on both cost and resource constraints and resulted in a higher level of risk, where a failure late in the project timeline could have had an impact to the launch date for the MMS mission. Sparing of 10-15 % should be a minimum, with a more robust strategy based on the complexity of an element/component requiring significant touch labor for build, test and calibration, where a failure would result in a significant impact to the delivery schedule. This is not unique to electrical parts. In the case of mechanical parts and detectors (e.g., MCPs) that are fragile, a sparing philosophy would be based on % yield and attrition due to handling during assembly and test. For FPI DES, there were 18 spare MCPs for a build requiring 32 MCPs (56% sparing). This allowed for performance-based parts selection and significant failure/handling attrition.

FPI chose to not have any fully built spare DES or DIS instruments due to cost, time and resource constraints. This again led to a higher risk where a safer risk posture would have been a 12.5%-25% sparing (2-4 spare instruments for 16 total instruments of each type).

Sparing needs to be carefully considered and saving cost by reducing spares may in fact not be the best investment in the long run for the project and mission.

C. Testing

In commercial production, test facilities and test stations are usually implemented separately for design verification testing with DVT units and for testing of the final product where the latter test infrastructure is validated through the PVT units. This is not feasible or affordable in small-scale production of space flight scientific instruments. The same test facilities and test stations will often have to be used for both the ETU and FM units. In addition, the final FM units need, not only to be performance-tested (as is often the case for many commercial products), but also require environmental testing and scientific calibration.

For DES on FPI, initial development of test infrastructure and test stations was undertaken leading up to ETU assembly and during ETU assembly. Further refinement took place based on the findings from the ETU testing and were implemented during the production of the first few FM units. Dedicated facilities and test stations were implemented for all parts, PCBA, sub-system and instrument test and calibration as well as for environmental TVAC testing to ensure the FM production volume could be efficiently managed, qualified, and precisely tested. In contrast, common institutional test facilities were used for vibration testing and EMI/EMC testing.

Parts (MCP), PCBA, and sub-system test stations were fully automated including auto-generation of test reports to efficiently handle the volume of units (50 MCPs, 68 PCBAs and 16 high voltage power supplies) with a small team. This allowed for thorough testing of batches up to 4 PCBAs per day with a focus on evaluation of test results rather than hardware, test, and data handling logistics.

Initial instrument Limited Performance Testing (LPT) was performed before environmental testing in the same test facility as the final test and calibration described below. A dedicated TVAC facility was implemented to allow thermal vacuum qualification of two instruments in parallel in one TVAC chamber. This enabled enough instrument volume to pass through efficiently while it minimized the amount of complicated chamber and thermal controls, thereby keeping the staffing requirements low. A significant portion of the TVAC testing was also automated and safety auto-shutdown features where implemented for all critical safety aspects of the test.

Final post-environmental instrument Comprehensive Performance Test (CPT) and calibration were conducted in in the same dedicated test station facility, with two e-beam vacuum chambers, as the pre-environmental LPT. Each chamber contained a robotic test fixture allowing mostly automatic testing of all instrument look angles without chamber breaks. Due to the high degree of automation, each test station only required staffing with one test engineer and two instruments were continually tested in parallel with only two test engineers present. The system was set up for fully automated testing but, owing to the nature and value of the high-precision scientific instruments and also to the decision to have no complete spares, it was chosen to always staff the test stations.

Overall, a very efficient test program and test infrastructure can be and was assembled. To accomplish this, efforts must be started early. Up-front investments in proper facilities, test automation, and data handling are critical to ensure significant cost savings and minimize risk during the production stage.

D. Calibration

Ground calibration is always easier and more accurate than in-flight calibration due to the ease of access to the instrumentation and the controlled nature of a laboratory environment. Therefore, any calibration that can be performed on the ground and then applied to the flight environment should be performed before launch. In the case of FPI, the dynamic range of the instrument, coupled with the large number of instruments, and large number of parameters to be characterized made it impractical to individually measure and calibrate every operation point under vacuum with a stimulating (e-beam) particle source.

Rather, we used several strategies to ensure the full range of parameters are calibrated on the ground with a comparably smaller set of physical lab measurements:

1. **Dimensional Reduction:** Some parameters are only dependent on a single variable. For example, the efficiency of the MCP declines at higher incidence energies. The gain of the MCP is affected by the incident angle of the particle. Each of these parameters simultaneously affects how a particle will be counted, but they *do not affect each other.* In such a case, the energy falloff does not need to be measured for all angles and the angular gain variation does need to be measured for all energies.

2. **Fitting to Models:** Many instrument parameters closely follow model mathematical distributions (e.g. a Gaussian approximation to the shape of an energy or angle pass band). In such cases, we do not need to measure every single data point in the parameter space, but rather just those required to quantify to specified accuracy, the smaller number of parameters that form the underlying mathematical model, in addition to performing surveys to identify significant departures from the model. This enables substantial reductions in the number of input data points to be measured.
3. **Requirement Driven Calibration and Testing:** Vacuum beam testing, as with processes described in previous sections, was largely automated. A user needed to choose a small number of test-parameters and the bulk of the testing executed automatically over the course of minutes to hours. Upon conclusion of a test, the output is comprised of a graphical test summary, properly indexed and stored data files, and a pass/fail test report that responds to the relevant requirements. In this way, the test and calibration of the sensors are specifically designed to quantitatively demonstrate that the instrument meets its requirements.

E. Handling of Unexpected Issues Late in Production and Post-Delivery

Contingency work and associated facility requirements sometimes appear. As mentioned in Section III.A, an issue manifested itself on MMS FPI with the large volume of high voltage opto-coupler parts used in the DES and DIS instruments. The issue was realized late in the project, after FPI flight articles had been completed. It was decided to move forward with delivery of the instruments to the four spacecraft while root-cause investigation proceeded to enable overall progress with plans for recovery as needed. Since all instruments had been built and integrated, it was further determined that replacement of all the suspect parts was impractical both from time and cost perspectives, and due to non-availability of alternative parts. After establishment of root-cause, the instruments were cycled off spacecraft and into initial rework, for selective replacement based on indicative parts data for the worst parts, followed by an extended TVAC infant mortality screening test for all the instruments, and further rework if needed with subsequent re-verification test. This together with on-orbit operational thermal changes ensured a highly successful science mission for MMS far into extended mission life. However, it required a significant logistical undertaking late in the project that had to be implemented for efficiency and managed very tightly. The key takeaway here is that a project needs to be able to adapt and find smart solutions for how to handle such late-breaking issues with limited cost and schedule impact.

Reliability analysis indicated that an operational exposure of 1500 hours with 64 thermal cycles would weed out a statistically reasonable number of parts with conditions that could lead to infant mortality and early FPI failures. The FPI “SuperSuite” test was devised and twice-executed where in each test, 16 dual spectrometers supported by two IDPU ETUs were simultaneously subjected to 1500-hour, 64-cycle thermal-vacuum tests. Two instruments (one DES and one DIS) experienced infant mortality failures. This test, while critical to the success of FPI on MMS required long-term 24/7 commitment of a thermal vacuum facility and its operators in addition to instrument team members. Facility depth, team resiliency and project adaptability proved critical to FPI and MMS at that juncture.

VII. Key production element #6: Operations and Commissioning

MMS is not just a set of four independent satellites with independently operating instruments. Rather, a strict formation is maintained because the science requires all instruments on all satellites to be coordinated. This requires precise and careful orchestration of all operational actions that the spacecraft takes. To accomplish this, several operational strategies were utilized to improve efficiency and allow scientific accuracy to be achieved within a limited time and budget.

A. Automatic Data Ranking

MMS gathers far more data than it can ever expect to downlink. While all of the low-resolution survey data are telemetered to the ground, only about 5% of the high-resolution burst data are downlinked. This becomes an even larger concern as constellation sizes grow and instruments gain resolution and, at the same time, ground station capabilities do not expand at similar rates.

To help mitigate this problem, MMS uses an Automated Burst Selection (ABS) system to automatically rank and prioritize data. Each instrument suite on MMS provides a set of trigger data numbers (TDNs) that represent how scientifically interesting a given 10 second interval is. These TDNs are combined to form an overall indicator that is used to order the data for downlink. In this way, highly interesting data are preserved and ensured eventual downlink to the ground.

B. Scientist In the Loop (SITL)

The final selection of MMS burst data to be downlinked is made on the ground by the SITL[16], a rotating human member of the MMS science team who performs prompt surveillance of the slower-cadence TDNs and science data products. A highly compressed ground processing system was developed and data are processed within hours of downlink, with a series of summary plots provided for examination by the SITL, including initial rankings and rationales provided by the ABS system. This enables an efficient process that is executable within the allocated time window. Rotation among science team members ensures a diversity of points of view in selecting data to address the central MMS science target of collisionless magnetic reconnection.

The critical elements applicable to missions that generate more data than can be downlinked are 1) clear definition of the data necessary to accomplish mission objectives and 2) a strategy to identify and prioritize for transmission data so-defined, while discarding non-essential data as required by limited downlink capacity. The MMS SITL system depends on infrastructure both on the ground (communication, data management & display, SITL console interaction, coordination with MMS Science Working Group and Operations) and in-flight (burst data memory storage, automatic data ranking). While the SITL approach has been highly successful for MMS, a larger share of the data selection decision-making could, in future instances, be delegated to in-flight algorithms and computational resources.

C. Automated Operational Sequences

As each MMS spacecraft houses 26 instruments, the commanding quickly becomes intractable if each command is considered independently. MMS therefore makes extensive use of automated operational command sequences that reduce the operational complexity for a given orbit. For example, FPI calls a single Ramped Calibration command that ramps up high voltage simultaneously on 8 power supplies, and then performs a series of calibration activities in a round-robin fashion on each spectrometer[10].

D. Aiding Commissioning and Calibration with Ground Test Data

To commission and later calibrate a large number of instruments in-flight, it helps to maximally leverage ground calibration. FPI was subjected to an extensive ground calibration of each sensor[10], providing a well-defined baseline in flight. While it was not possible to know the precise operating performance of each sensor after it had undergone spacecraft integration, storage, and launch, and was operating in a new environment, that well-defined baseline enabled a quick, efficient, and well-calibrated transition to science operations. In commissioning, an automated script performed a calibration sweep at the HV setting expected from ground calibration, along with calibration sweeps at plus/minus delta HV to look for deviations from ground calibration. In this way, many sensors could be quickly and efficiently calibrated, and optimal operating points defined without the need to conduct a full search through the available parameter space.

Each FPI sensor is subject to having its Micro-Channel Plate (MCP) High-Voltage (HV) periodically adjusted to account for downward gain drift over time. Routine calibration is performed throughout the mission, comparing calibration sweeps at both the current MCP HV and the current MCP HV plus an incremental delta. Comparison of these two sweeps enables a binary choice to either continue operating at the current MCP HV or to increase the MCP HV by the increment for optimal performance. This simple binary choice allows for efficient routine calibration maintenance of all 64 spectrometers.

VIII. Conclusion

The advent of high capability small spacecraft enables consideration of science missions involving constellations of a few or many spacecraft that provide simultaneous spatially distributed in situ or remote observations. Individual missions can and will place unique, sometimes stringent requirements and constraints at every step of the development and production. For such missions it is imperative that targeted early financial investments be included to mitigate technical and programmatic risks. For example, the FPI, developed for NASA's MMS mission and launched in 2015, required 64 plasma electrostatic analyzers, each with supporting detectors, front-end electronics, and high voltage generation, in addition to 4 supporting instrument data processing units. The FPI development experience for MMS was as unique as the mission itself and, while not necessarily typical of multi-instrument flight development programs, it offers a single example. FPI represents a multi-instrument build of unprecedented numbers for NASA's Heliophysics Science Division. There is great motivation to accommodate multi-spacecraft, implying small spacecraft in many cases, missions across NASA's Science Mission Directorate.

We have described the FPI experience in the context of six Key Production Elements that we were able to employ (or not) through the instruments' development. Those are: 1) early definition of clear and limited requirements, 2) early parts evaluation and proof of concept, 3) early design and design verification with an ETU, 4) early production preparation, 5) production, test and calibration, and 6) early consideration of automation in, and leveraging of ground test data for commissioning and calibrated operations. The concept that repeatedly rises to the top, given clear science requirement definition, is the need for early investments of selected critical human and financial resources. These are required to lay groundwork in IT, parts review/test, process development & verification, along with manufacturability-focused ETU development & verification, and consideration of automation in all appropriate processes including manufacturing, assembly, instrument test, calibration, commissioning and science operations.

The FPI on MMS has performed extremely well on-orbit meeting the hopes of its scientific stakeholders. Not all multi-instrument projects will face either the specific challenges that we encountered, or enjoy the specific advantages that were available during the FPI development. The experiences described here represent this team's approach to a single instance of adapting commercial-like processes into a stand-alone project-based development environment.

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