D. EXECUTIVE SUMMARY

Understanding the detailed physics of reconnection, turbulence and particle acceleration is at the forefront of magnetospheric and, more broadly, space and astrophysical plasma physics. With its unique integrated instrument set and comprehensive supporting theory and modeling program, our Magnetospheric Multi-scale (MMS) proposal—Solving Magnetospheric Acceleration, Reconnection, and Turbulence (SMART)—focuses on reconnection and addresses all of the science objectives set forth in the Phase A Concept Study Guidelines.

The SMART payload contains a proven complement of instruments to ensure the highest quality measurements ever made in the Earth’s magnetosphere. These include the most accurate electric field instruments ever flown, which combine double probes, spacecraft potential control, and an Electron Drift Instrument. Electron and ion analyzers will measure 3D plasma distributions in <30 ms, the highest time resolution ever achieved. Spacecraft potential control also provides the only proven method to accurately measure low energy electrons and ions. Added to this is the highest time resolution ion composition instrument ever flown that can accurately measure minor ions at the magnetopause.

This report describes only the “Optimized Payload” of our original proposal as it offers significant enhancements through added payload mass. A proprietary study by Orbital Sciences Corporation, verified by the GSFC flight dynamics group, shows that, by launching into an orbit with a 400-km altitude perigee, using on-board propulsion to raise perigee to the desired 1250 km, and delaying the inclination change from 28° to 10° until apogee reaches 25 R_E, the instrument mass can be increased while maintaining ample reserves.

The multinational, multi-institute SMART team is experienced with multiple instrument suites and has extensive, successful flight histories. The team provides technical depth and ample, experienced staff for the fabrication, test, calibration and integration activities that four spacecraft entail, with robust schedule reserves. A team of skilled theorists and modelers has defined the measurements needed to ensure closure on these objectives. The SMART instrumentation has optimum performance in all parameter ranges and is flight-proven to a very high level.

Science Objectives. The primary focus of the SMART science is reconnection and associated processes. Our understanding of reconnection hinges critically on the kinetic physics which allows reconnection to take place. Does the breaking of the frozen-in field condition arise because of inertial effects or anomalous resistivity and turbulence? Recent measurements and simulations indicate that electrons demagnetize at the electron skin depth, but that the scale for ions depends on the presence of a guide field. These are also the scales for the narrow current sheets at the center of the reconnection process. The scales are small—of the order of 1 km for the electron inertial scale at the magnetopause—and the SMART instrument suite has the requisite resolution to distinguish these small scales. In the anomalous resistivity picture of reconnection, the strong currents developed during reconnection produce high-frequency waves that evolve into a variety of non-linear structures, scattering electrons and providing the dissipation needed for reconnection. By coupling detailed distribution function measurements with comprehensive electric and magnetic field measurements, the SMART payload will distinguish between the contributions of anomalous resistivity and particle inertial effects by evaluating the dissipation associated with each.

A major objective of the SMART investigation is to determine what influences where magnetic reconnection occurs at the magnetopause. Does reconnection proceed only for oppositely directed magnetic fields (anti-parallel reconnection) or for any angle (component reconnection)? For the former, the geometry of the solar wind magnetic field and that of the Earth’s field predict the reconnection location. For the latter, a range of locations is possible, but even within that range component reconnection is thought to be suppressed for high plasma[]. The SMART investigation combines measurements of boundary conditions (such as flow velocity and magnetic field direction) with measurements in the diffusion region to determine differences in the electron current structure and predicted reconnection rate. This comparison will distinguish between competing models for the location and local conditions for reconnection.

A complementary issue is finding where magnetotail reconnection occurs. In the magnetotail, the magnetic field is essentially always anti-parallel across the magnetotail cur-
rent layer, but questions remain about the relative importance of bursty reconnection occurring on smaller scales as compared to substorm reconnection over larger regions. These questions also relate to what determines the location of tail reconnection. SMART will answer these questions by directly observing magnetotail reconnection.

The temporal evolution of reconnection remains unresolved: Is reconnection a continuous process with multiple locations or is it a bursty process? Steady reconnection rates are predicted to be about 0.1 of the Alfvén speed upstream from the diffusion region. Non-steady reconnection such as flux transfer events (FTE) may arise from flows that lead to convection of the reconnection site. SMART’s high time resolution measurements of reconnection rates and detailed flow measurements near the reconnection current layer will distinguish between these two types of reconnection.

Various magnetic structures are generated by reconnection. Flux ropes, plasmoids, and FTEs have all been observed, but without multi-point measurements on the key spatial scales, our understanding of the formation and evolution of these structures is limited. For example, accurate composition measurements in the presence of high proton fluxes (a unique capability of SMART) coupled with detailed field measurements and precise low energy ion cutoff data from multiple spacecraft will determine whether FTEs are launched by bursts of reconnection or other processes.

The MMS secondary objectives of particle acceleration and turbulence have elements related to reconnection. Among these are the roles of electric fields in particle acceleration and the temporal and spatial properties of turbulence at the magnetopause and in the magnetotail.

Key to the success of the SMART science plan is the coupling of theory and observation. The observing plan is optimized to elucidate the key factors that distinguish between competing models. The instrument team will work closely with the theory team to ensure that measurements are placed in the appropriate theoretical context.

Technical Approach. The SMART instrument suite and mission design have been developed to achieve high-resolution measurements within targeted regions of space where reconnection occurs. The instrument suite comprises three groups: Hot Plasma, Fields, and Energetic Particles. Each group has significant heritage to minimize risk and enhance scientific return.

The Hot Plasma complement consists of a Fast Plasma Instrument (FPI) and a Hot Plasma Composition Analyzer (HPCA). They are supported by the Active Spacecraft Potential Control (ASPOC) system, which keeps the spacecraft near the plasma potential by emitting a weak beam of ions. FPI’s fast electron and ion arrays provide, independent of spacecraft spin, the time resolution needed to resolve the small, moving reconnection diffusion region. Each spacecraft carries eight FPI electron and ion sensors, which can electronically deflect the look direction to give 4 steradian coverage. The HPCA uses a unique radio frequency technique to accurately measure minor ions in the presence of high proton fluxes. This new capability will significantly enhance our understanding of the role of various ion species in the reconnection process.

The FIELDS complement consists of analog and digital fluxgate magnetometers (AFG and DFG), a search-coil magnetometer (SCM), spin-plane and axial double-probe electric field instrument (SDP & ADP), and an electron-drift electric field instrument (EDI). The SDP, along with the ADP, provide full 3D electric field measurements. For the most accurate measurement possible, each ADP boom is deployed to 9.5 m, requiring a spacecraft spin rate of ≤3 rpm. ASPOC and EDI are the key to accurate E and B measurements. Cluster has clearly shown that ASPOC greatly reduces double-probe errors. However, for reconnection, double-probe errors need to be <1 mV/m. This requires accurate inflight calibration of the double probes in a variety of plasma conditions. Using $\mathbf{E} \cdot \mathbf{B} = 0$ and $\mathbf{v} \times \mathbf{B}$ analysis to remove double-probe errors has been proven inadequate. EDI provides the only flight-tested technique for this inflight calibration. In addition, the extremely low-magnitude reconnection magnetic fields require measurement accuracy to <1 nT. EDI has proven to be invaluable on Cluster for accurate determination of magnetometer spin-axis offsets. Only inflight cross-calibration with EDI can provide the needed E and B accuracy.

The SMART energetic particle detector (EPD) system consists of an Energetic Ion Spectrometer (EIS) with composition determination and a Fly’s Eye Energetic Particle Sen-
sensor (FEEPS) for high-time-resolution 3D measurements. EPD provides comprehensive measurements over an extended energy range of electrons and ions (by species).

For the best resolution measurements of the very localized, microscale physics of reconnection, we will use a burst data scheme whereby high resolution data from each instrument are continuously sent to the Central Instrument Data Processor (CIDP), which selects the best events for transmission to the ground. Each instrument also sends lower resolution data to the CIDP to provide Fast Survey mode (40% of the orbit) and Slow Survey mode (60% of the orbit) data when lower resolution is sufficient.

Most of the SMART instrument designs are copied from past missions, need little or no modification, and will move directly to qualification model (QM) development. Those few instruments which have new components require prototype development before moving to QM production. During QM development, final design issues will be resolved so that the QM can be used without modification as the basis for the flight models (FM). During QM fabrication, instrument software and ground support equipment (GSE) will be developed and tested. The QM will undergo functional, performance, and environmental testing. At QM completion, a design review will be conducted to develop the FM manufacturing plan. The FM will be manufactured using procedures established during the QM phase. Once the FM units are completed the QM will be refurbished to be the flight spare.

The instrument suite will be integrated and tested before delivery for spacecraft integration. The first flight suite will be integrated at SwRI, on a spacecraft vendor provided structure so that payload compatibility issues can be resolved without impacting spacecraft integration. The second through fourth suites will be shipped directly to the spacecraft vendor, removing the need for each investigation team to ship flight hardware twice before spacecraft integration. At the spacecraft vendor facility, a subset of the suite integration and testing will take place before spacecraft integration.

Calibration of the entire instrument suite is critical to achieving the scientific objectives. The SMART team will perform detailed, rigorous calibration of the first unit of each type. Subsequent units will have reduced calibration, more sparsely spanning the full range of measurements. To ensure good intra-calibration between similar sensors, all like sensors will be calibrated at the same facility. On orbit, the space environment will be used to maintain calibration over time between both like and unlike sensors across the four spacecraft.

SMART requires IRAS (along with ground tracking) to provide vector spacecraft separations to an accuracy of only 1% of range after the fact. There is no requirement for on-board data synchronization among spacecraft; the data need only be synchronized to 1 ms after the fact. The IRAS is required to transmit 8-bit data-quality words from each spacecraft to the others every 10 s with less than 3-s latency for burst mode triggering.

SwRI will lead the SMART team in developing and implementing a system compliant with the Mission Assurance Requirements for MMS, including a Product Assurance Implementation Plan. All teams are experienced with NASA flight programs and have processes for all aspects of quality assurance.

The SMART Science Operations Center at LASP is responsible for mission planning and scheduling. During weekly telecons with key team members the observation plan will be reviewed and an operations schedule produced. Issues addressed during the telecons will include data mode (fast/slow-survey) allocation and burst-mode trigger algorithms. Following these telecons, instrument command sequences will be generated and forwarded to the Mission Operations Center at GSFC, where they will be checked and then uploaded to the spacecraft.

The SMART team is committed to making data available to the entire scientific community as quickly as possible. Our data processing plan combines distributed processing at the instrument Co-I sites with rapid production of merged data products at SMART’s central Science Data Center at LANL, where the full data set will be archived and accessible on-line to the community.

The SMART mission design fits within resources and maximizes the encounters with reconnection regions. The mission has three phases, each with different regions of focus. The primary target of Phase 1, beginning on the dusk flank magnetopause, is the dayside magnetopause reconnection region. The MMS spacecraft will sample the low latitude magnetopause over a period of approximately 6 months. Phase 2 focuses on the near-Earth neutral line and starts when the spacecraft reach the dawn flank magnetopause. The
spacecraft apopees are then raised in steps to 25 $R_e$ followed by orbit inclination reduction from 28° to 10°. The orbit then sweeps across the magnetotail over a period of three months and continues to sweep until it returns to near noon at 1 year, 4 months into the science mission. The Phase 3 orbit, focusing on both the dayside magnetopause and the magnetotail, is achieved by a lunar swing-by, which increases the perigee to 12 $R_e$ and maintains apogee at 31 $R_e$. At the end of phase 3, the 2 year primary science mission is complete.

**Management Plan.** Unlike previous missions where one payload is developed for one spacecraft, MMS requires the production of large numbers of sensors and support systems for multiple spacecraft, all within cost and schedule caps. The SMART team has significant experience delivering multiple copies of flight hardware and will meet the management challenges presented by MMS with a tailored set of processes optimized for a production program.

The SMART team organization is designed to be as simple as possible commensurate with the tasks to be performed. The team is led by the PI, Dr. James L. Burch, and is organized around major investigations with a single point of contact for each. The investigation team leads will report to the PI and PM. The teams developing components of each investigation will report to their team leads. This approach results in simple, clear lines of reporting and accountability. The payload team leads are highly experienced; the key institutions have proven track records and have worked together on missions such as IMAGE, ACE, and Cluster.

The SMART management approach draws on experience from the IMAGE and New Horizons missions. Web-based tools will be used to facilitate tracking and management of all project-related activities at the SMART team institutions. For schedule development and tracking as well as cost development and reporting, we will use Primavera Project Planned Enterprise (P3e). This system was set up based on our Work Breakdown Structure (WBS). The WBS is combined with an organizational breakdown structure to track cost and schedule performance accurately at all levels. Other management tools include the DOORS database for requirements management, the Action Item Management System for tracking reviews and action item closure, and the SwRI Risk Management System (RMS) for tracking risk as the project develops.

Milestone dates in the SMART schedule are derived from the NASA required delivery dates for the four payloads and chosen to provide ample schedule margins, particularly for the first payload. Investigation leads used these for schedule development for their various elements. The master schedule in P3e for the payload was built directly into the WBS including the investigation delivery dates, milestone review dates, integrated payload test dates, and spacecraft I&T support. The investigation teams have added detailed activities, resources, and interdependencies to form a complete investigation schedule. From P3e the investigation leads can obtain chart outputs, resource loading reports and cost reports for use in planning. The investigation schedules are linked to the CIDP, GSE and I&T schedules. Each month, the investigation leads will update the master schedule with actual costs and other resource usage, actual work accomplished, and tasks completed. From the updated schedule, the PM can obtain reports such as earned value, cost variance, estimate to and at completion, and schedule slack trends.

The SMART team will use a tailored version of the MMS Continuous Risk Management (CRM) Plan. The SMART CRM uses SwRI’s RMS web-based tool instead of PRIMX but is essentially the same as the MMS CRM plan in all other respects and is completely compatible with NASA Risk Management Procedures and Guidelines. Risks are continuously identified (by any team member), reviewed, classified, entered into the RMS, updated, and reported monthly. Every risk has at least two mitigation plans, and each plan has a mitigation trigger date. This process will continuously assess and attack risks during all phases of the MMS mission.

Because foreign hardware contributions play a key role in the SMART payload, we have carefully considered the risk associated with their funding. Although it is expected that these contributions will be funded by their governments, to reduce risk the SMART team has implemented a full cost policy under which foreign and US institutions are treated in an identical fashion in terms of management, schedule, and cost. Those contributions (material and labor) that did not have funding guarantees as of the submission of the CSR are included within the SMART suite cost cap. Both
schedule and cost reserves were identified for these contributions. During Phase B, there will be an aggressive effort to secure full funding commitments for the foreign hardware. As funding commitments are obtained, they will be reallocated first to restore the EIS instrument Phase C/D costs (see J.1.3.1) and then used to increase the cost reserves.

Design reviews for the SMART team will include milestone reviews, peer reviews, and technical interchange meetings. We expect all milestone reviews to be managed by the NASA Integrated Independent Review Team with a formal RFA process for all milestone reviews.

The SMART team will submit monthly reports to NASA and also after peer and milestone reviews. Monthly reports will include technical, resource, risk, and schedule status reports. We also expect to meet with NASA on a quarterly basis to present technical progress, schedule status, and risk status for both individual instruments and overall payload.

Cost Plan. The cost plan meets the total funding constraints of the AO and provides all required cost data from all participating organizations on the anticipated costs for all phases of the MMS mission. The SMART team is committed to NASA’s cost containment priorities. All team members have provided conservative estimates with sufficient technical and business reserves, consistent with the proposed reserve management strategy.

The total SMART project costs were reevaluated using a discrete-estimate, bottoms-up approach, including full-cost accounting estimates from participating NASA and other Government-funded centers. Since the original proposal submission, continued planning has refined and clarified the detailed requirements, improving and reconfirming the SMART cost realism. Cost reserves were allocated to work breakdown structure (WBS) elements based on an assessment of cost growth risk. These Concept Study efforts further mitigate potential technical and cost uncertainties.

The SMART total mission cost to NASA, including NASA and other Government-funded centers, and all reserves is $139,750K in RYS ($122,228K in FY03$). SMART costs have been rigorously scrubbed, and are well supported by a high-fidelity cost plan and reserve allocation.

Education and Public Outreach, Technology Plan, and Small Disadvantaged Business Plan. The SMART Education and Public Outreach (E/PO) activities will combine new initiatives with proven techniques -- all inquiry-based and aligned with national science standards. Activities will focus on a mission website, teacher training, educational software, and science videos for regular venues as well as planetariums. Across all activities, we will create three new initiatives: Micro to Macro, What Changed? and Songs of Space. The last of these will make SMART science approachable for the non-scientist by making changes that the MMS spacecraft measure. During Phase B, we will evaluate the feasibility of adding a small (<200 g, <1 W) student-developed high energy solid state detector to the payload.

The E/PO products, to the extent possible, will be made accessible to blind and other disabled learners through consultation with accessibility experts. Distribution of student modules, museum exhibits, planetarium and television shows will be coordinated with ongoing, successful distribution programs.

Nearly all of the technology for the SMART payload is flight proven with heritage from previous similar missions. Improvements which are being made to ensure the best possible measurements include the novel HPCA instrument and improved SDP wire boom deployers. These improvements are scientifically important, but are not expected to result in significant commercialization opportunities.

SwRI will involve both Small Disadvantaged Businesses (SDB) and Minority Institutions in the SMART program. SwRI will also work with the SMART team at universities and government centers to ensure active participation of SDB’s and students from Minority Institutions, who will be involved in a variety of programs to acquire hands-on experience while completing their education.

Conclusion. The SMART suite of science driven instruments provides the most complete set of measurements of reconnection ever made, at low risk and within the cost cap. By combining high resolution measurements of all key parameters with a closely coupled theory and modeling program, the SMART approach will yield a detailed physical understanding of how reconnection takes place.