NASA's Magnetospheric Multiscale (MMS) Mission

2015 University of North Dakota Space Studies Colloquium

Craig Tooley - MMS Project Manager
NASA Goddard Space Flight Center

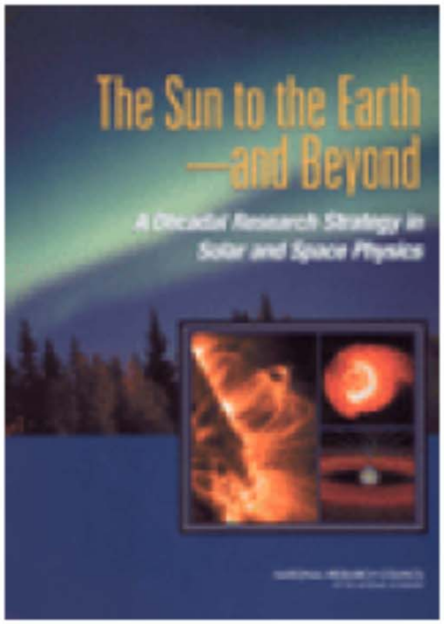
Today's Presentation

- Who your speaker is
- The purpose of the MMS mission
- The Spacecraft we built to execute the mission
- How the development was executed
- The launch and operation of the mission
- Status of the mission now
- Questions & discussion

Your Speaker Today – Craig Tooley

- BSME from University of Evansville 1983
  - Co-op Engineer at Regional Power Plant & GE Plastics Factory
- MSME From University of Maryland 1990
- Employed by NASA at the Goddard Space Flight Center since 1983…
  - Primarily have worked as engineer, systems engineer, and as a manager on numerous Space Shuttle payloads and missions, including Hubble Space Telescope servicing missions.
  - Deputy Project Manager for original Triana (later renamed DSCOVR) mission. Also Lead Engineer for the new Upper Stage required for *planned* Shuttle launch of Triana.
  - Project Manager for the Lunar Reconnaissance Orbiter (LRO), launched in April 2009 and now in its 5th year of lunar operations
  - 1st Project Manager for the Joint Polar Satellite System (JPSS) Flight Segment, the next generation of NOAA/NASA weather and climate satellites which replaced the NPOESS Program.
  - **Project Manager for the MMS mission since May 2011**

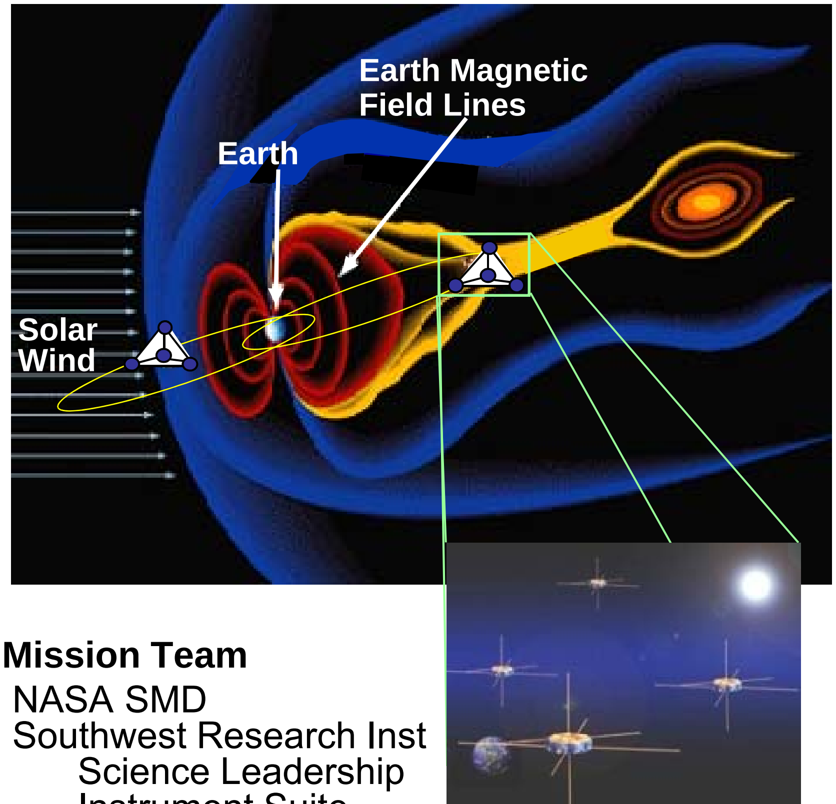
Why MMS? - Solar and Space Physics Decadal Survey Highest Priority



National Academy of Sciences Decadal Survey in Solar and Space Physics, 2002

Moderate	1	Magnetospheric Multiscale	Four-spacecraft cluster to investigate magnetic reconnection, particle acceleration, and turbulence in magnetospheric boundary regions.
	2	Geospace Network	Two radiation-belt-mapping spacecraft and two ionospheric mapping spacecraft to determine the global response of geospace to solar storms.
	3	Jupiter Polar Mission	Polar-orbiting spacecraft to image the aurora, determine the electrodynamic properties of the Io flux tube, and identify magnetosphere-ionosphere coupling processes.
	4	Multispacecraft Heliospheric Mission	Four or more spacecraft with large separations in the ecliptic plane to determine the spatial structure and temporal evolution of coronal mass ejections (CMEs) and other solar-wind disturbances in the inner heliosphere.
	5	Geospace Electrodynamic Connections	Three to four spacecraft with propulsion for low-altitude excursions to investigate the coupling among the magnetosphere, the ionosphere, and the upper atmosphere.
	6	Suborbital Program	Sounding rockets, balloons, and aircraft to perform targeted studies of solar and space physics phenomena with advanced instrumentation.
	7	Magnetospheric Constellation	Fifty to a hundred nanosatellites to create dynamic images of magnetic fields and charged particles in the near magnetic tail of Earth.

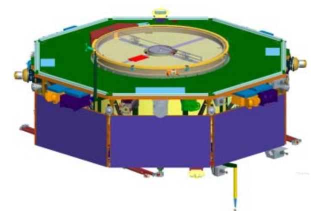
MMS Mission Overview



Science Objectives

Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere

- Temporal scales of milliseconds to seconds
- Spatial scales of 10s to 100s of km



Mission Description

- 4 identical satellites
- Formation flying in a tetrahedron with separations as close as 10 km
- 2 year operational mission

Orbit

Elliptical Earth orbits in 2 phases

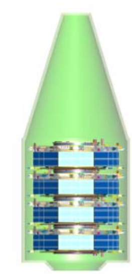
- Phase 1 day side of magnetic field 1.2 R_E by 12 R_E
- Phase 2 night side of magnetic field 1.2 R_E by 25 R_E

Significant orbit adjust and formation maintenance

Instruments

Identical *in situ* instruments on each satellite measure

- Electric and magnetic fields
- Fast plasma with composition
- Energetic particles
- Hot plasma composition



Spacecraft

- Precision spin stabilization (~ 3 rpm)
- Magnetic and electrostatic cleanliness

Launch Vehicle

- 4 satellites launched together in one Atlas V

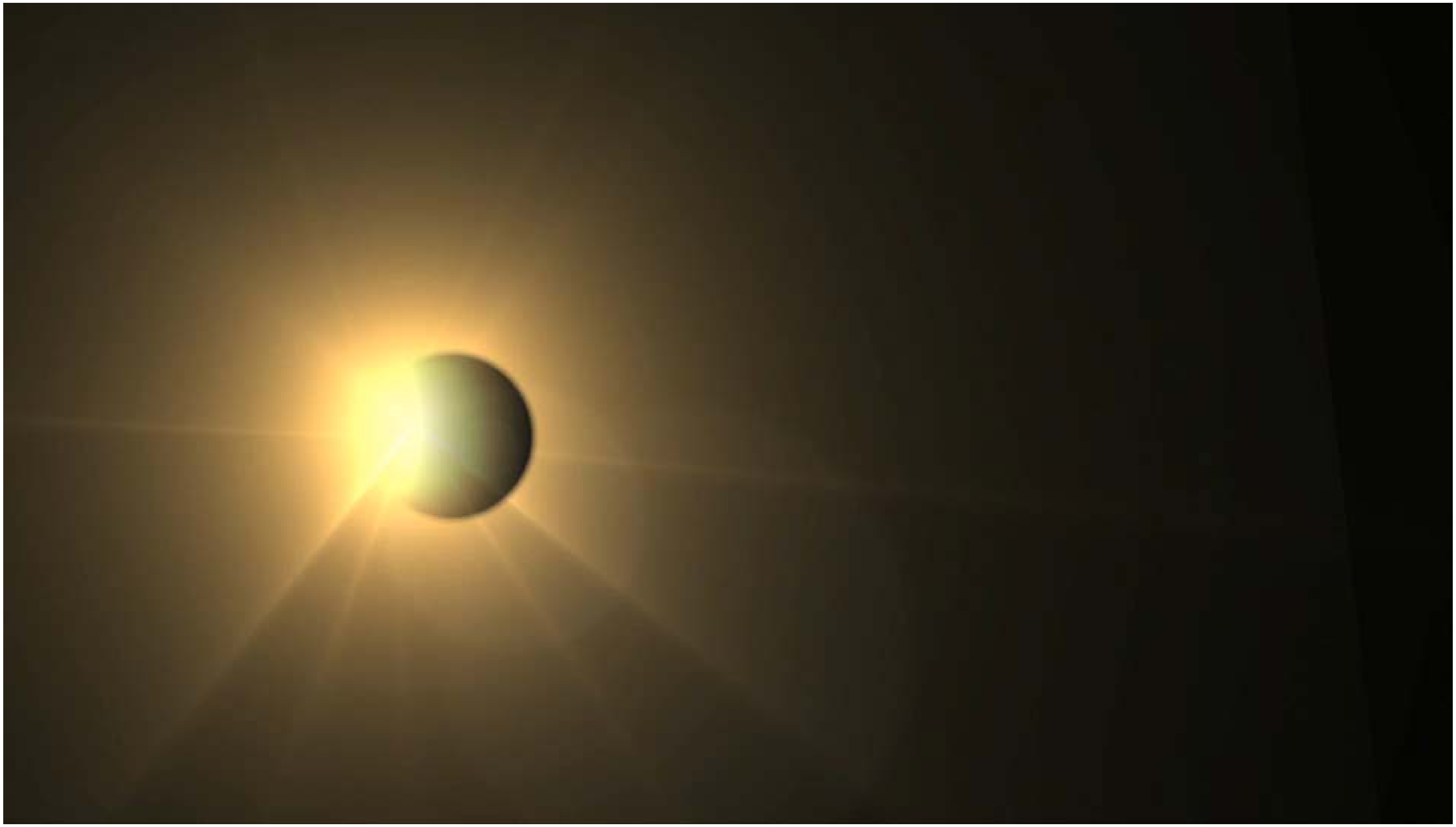
Mission Status

- Launched 3/18/2015 – Commissioning ongoing

Mission Team

- NASA SMD
- Southwest Research Inst
  - Science Leadership
  - Instrument Suite
  - Science Operations Center
  - Science Data Analysis
- NASA GSFC
  - Project Management
  - Mission System Engineering
  - Spacecraft
  - Mission Operations Center
- NASA KSC
  - Launch services

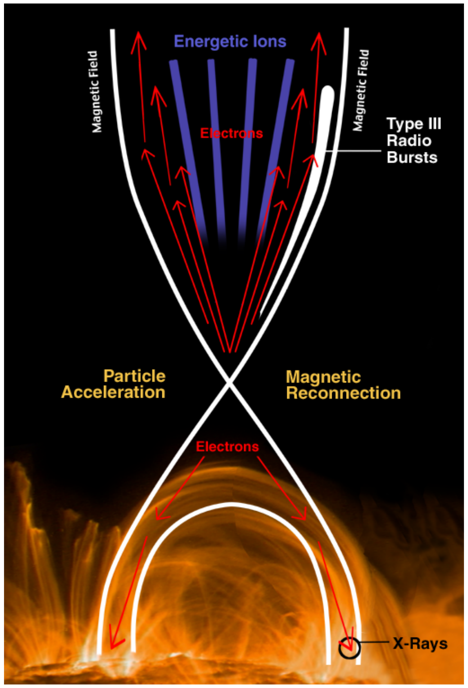
NASA MMS Mission Trailer Video

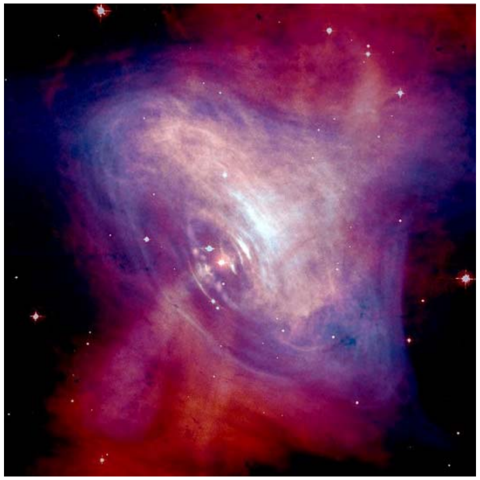


Universal Process of Magnetic Reconnection

Throughout the universe, we find that magnetic energy is explosively released in a fundamental, but poorly understood process called "reconnection."

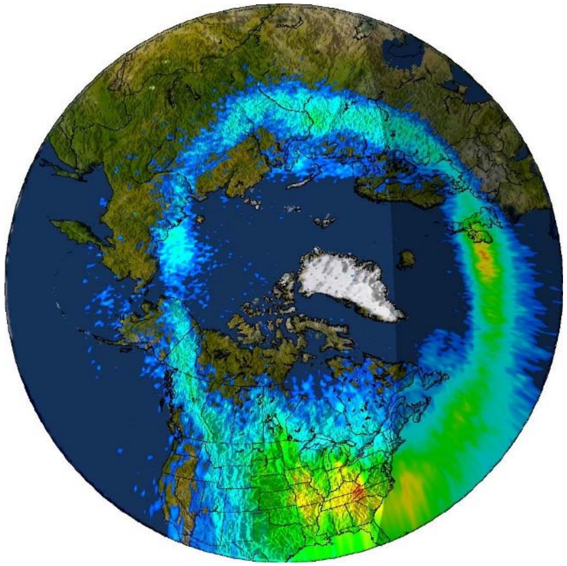
Solar Flare





Jets in Crab Nebula

Aurora



Reconnection plays an important role in heliophysics (solar flares,magnetic storms,aurora), astrophysics (magnetar flares, accretion disks) and laboratory plasma physics (sawtooth oscillations in Tokamaks).

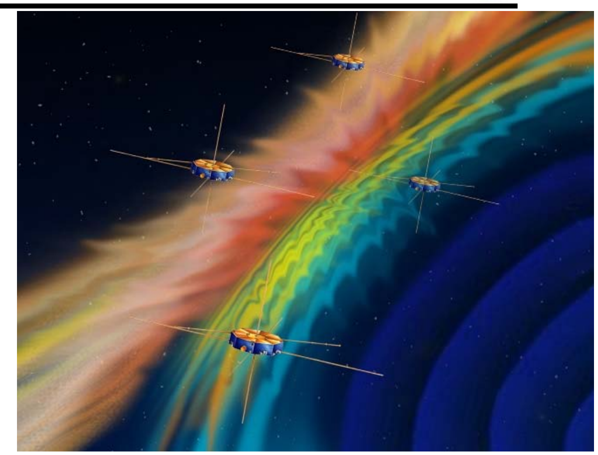
MMS Science Overview

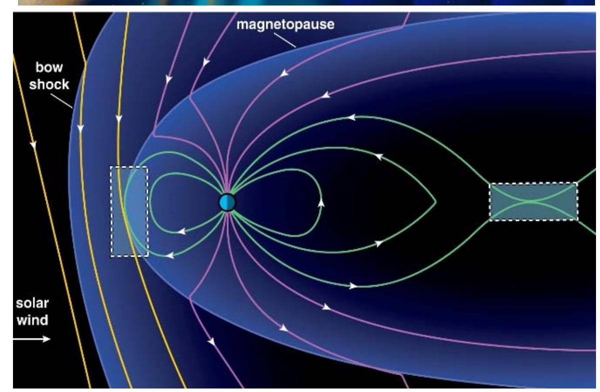
Scientific Objective: Understand the microphysics of magnetic reconnection by determining the kinetic processes occurring in the electron diffusion region that are responsible for collisionless magnetic reconnection, especially how reconnection is initiated.

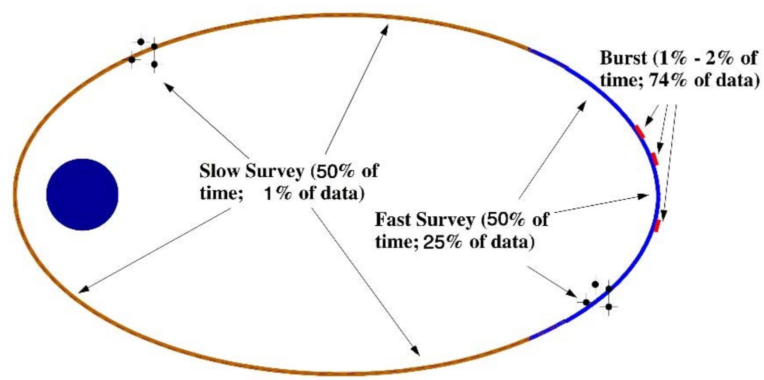
NASA's Polar and ESA's Cluster missions have advanced the science of reconnection at the MHD and ion scales. However, probing the reconnection process itself requires detailed measurements at the electron scale with spatial and temporal resolutions far higher than achieved by Polar or Cluster.

Measurement Strategy: Obtain 3D samples of *plasmas, E and B fields, waves and energetic particles* with four-identically instrumented spacecraft separated by distances spanning the ion and electron scales (~100 km down to 10 km at the dayside magnetopause and ~ 100 km to 30 km in the neutral sheet of the geomagnetic tail).

Challenges: Obtain 3D plasma distributions at 150 ms (ions) and 30 ms (electrons) compared to 4 s and 2 s, respectively on Cluster. Separate O^+ and protons at the magnetopause for the first time. Obtain accurate 3D Electric Field measurements. Select the optimum 2% of the total high-rate data for transmission to the ground. Operate the mission as an in-situ laboratory with scientists-in-the-loop during the entire mission.





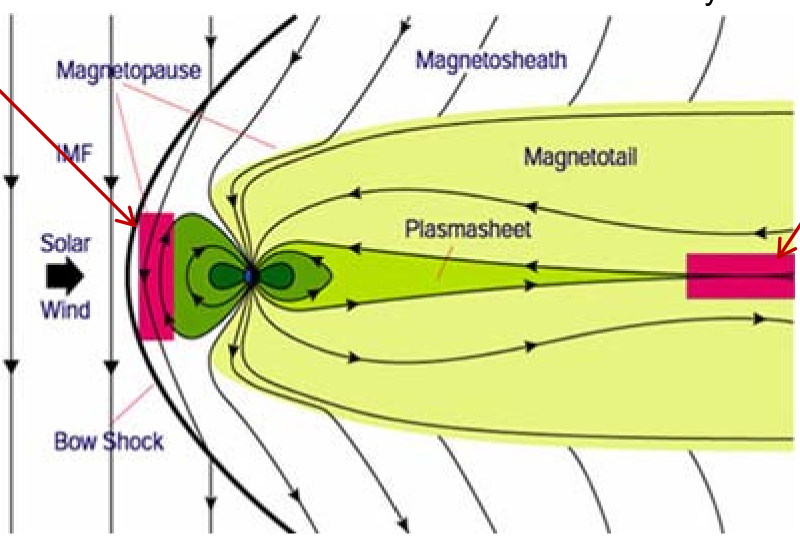


Where MMS Explores Magnetic Reconnection

Magnetic reconnection occurs in two main regions of Earth's magnetosphere: (1) the dayside magnetopause and (2) the night side magnetotail. MMS will employ a two-phase orbit strategy to explore each of these regions in turn

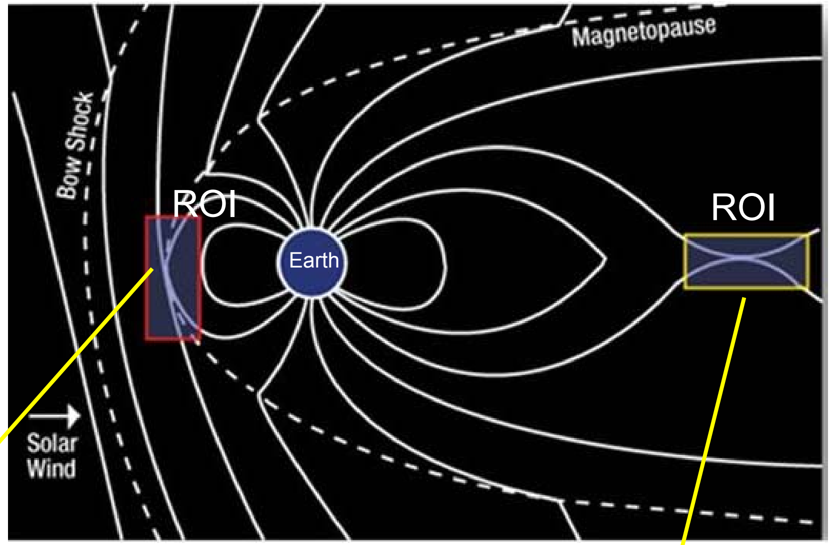
In **Phase 1,** MMS will probe reconnection sites at the mid-latitude dayside magnetopause. Here the interplanetary magnetic field (IMF) merges with the geomagnetic field, transferring mass, momentum, and energy to the magnetosphere. The solar wind flow transports the merged IMF/geomagnetic field lines toward the night side, causing a build up of magnetic flux in the magnetotail.

In **Phase 2**, the MMS constellation will investigate reconnection sites in the night side magnetotail, where reconnection releases the magnetic energy stored in the tail in explosive events known as magnetospheric substorms and allows the magnetic flux stripped away from the dayside magnetopause by the solar wind/magnetosphere interaction to return to the dayside.

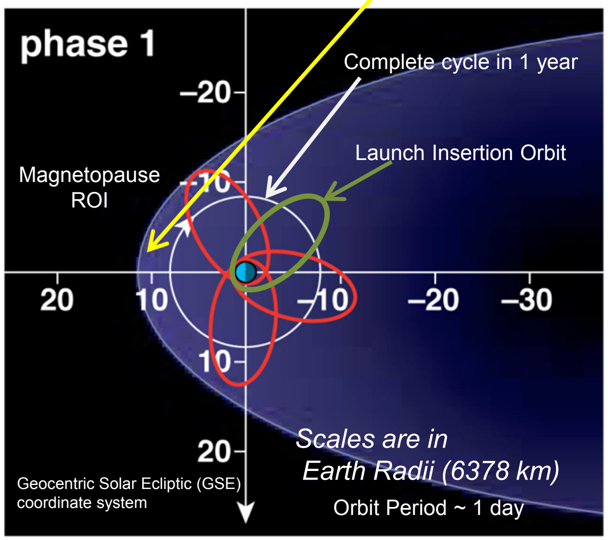


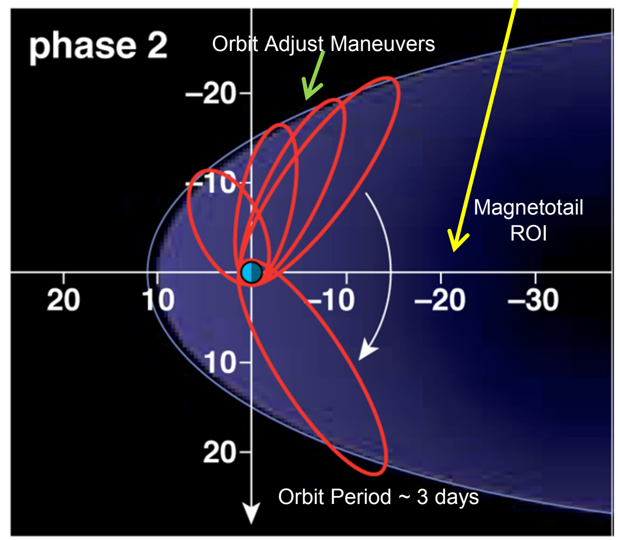
Flying MMS- Orbits & Regions Of Interest (ROI)

- The 4 MMS Observatories are launched into a elliptical orbit (red) which moves through the magnetopause boundary ROI as the Earth orbits the Sun. Shown in Geocentric Solar Ecliptic (GSE) coordinates.
- MMS Observatories will be maneuvered into a higher orbit the second year which will pass thru the magnetotail ROI
- On-board GPS and ground tracking data will be used in conjunction with closed-loop maneuver executions to maintain required spacecraft tetrahedron formations. Formation accuracy maintained to 100m.

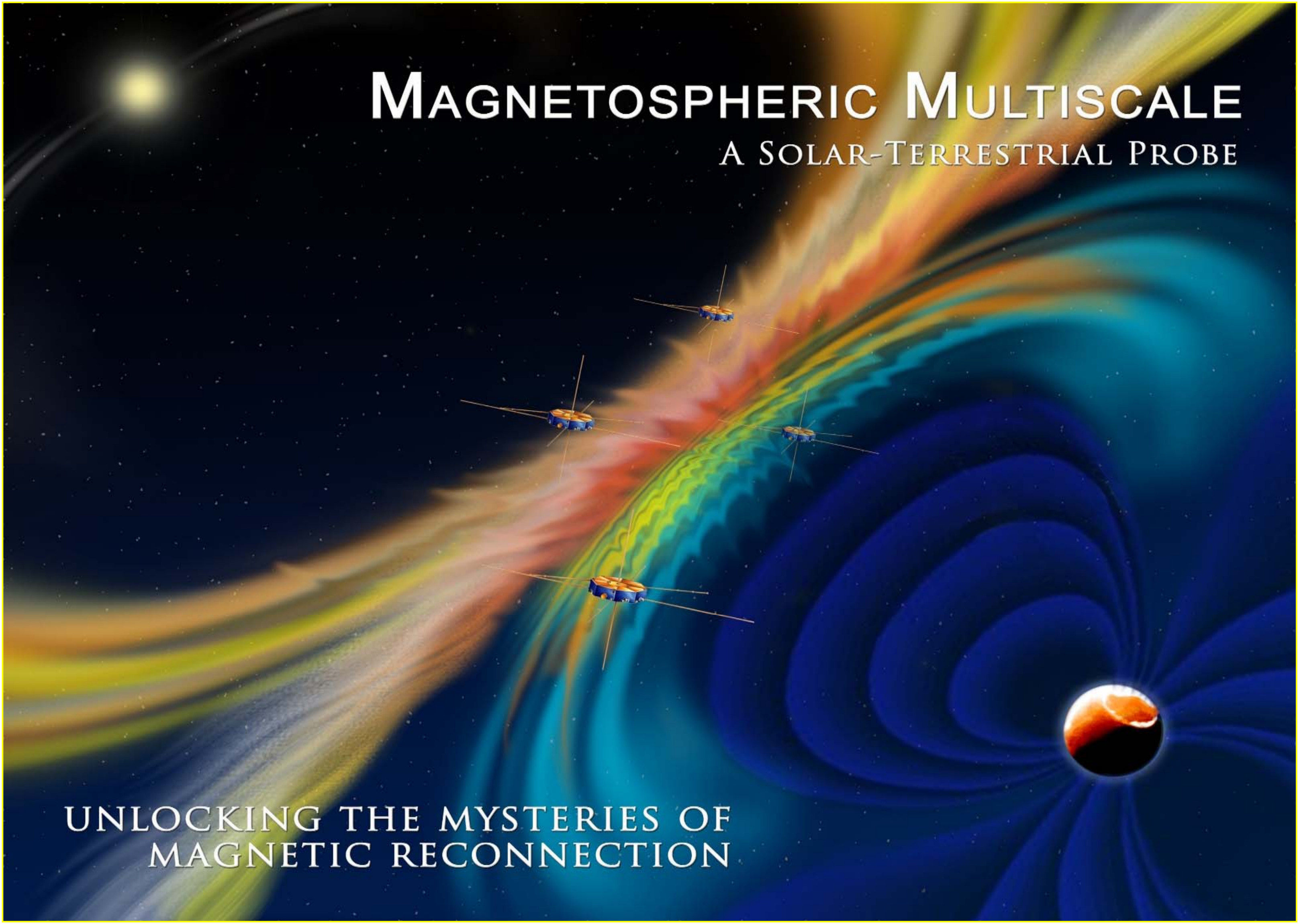


Sun ←





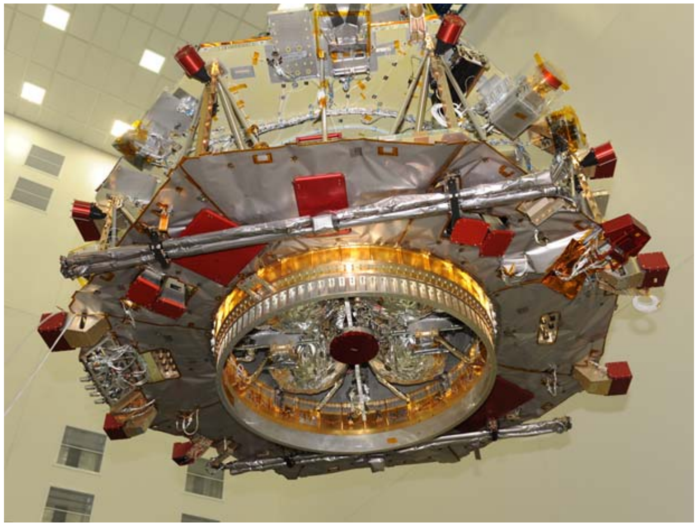
MMS Mission Simulation Video



The MMS Observatory

Four Identical Observatories

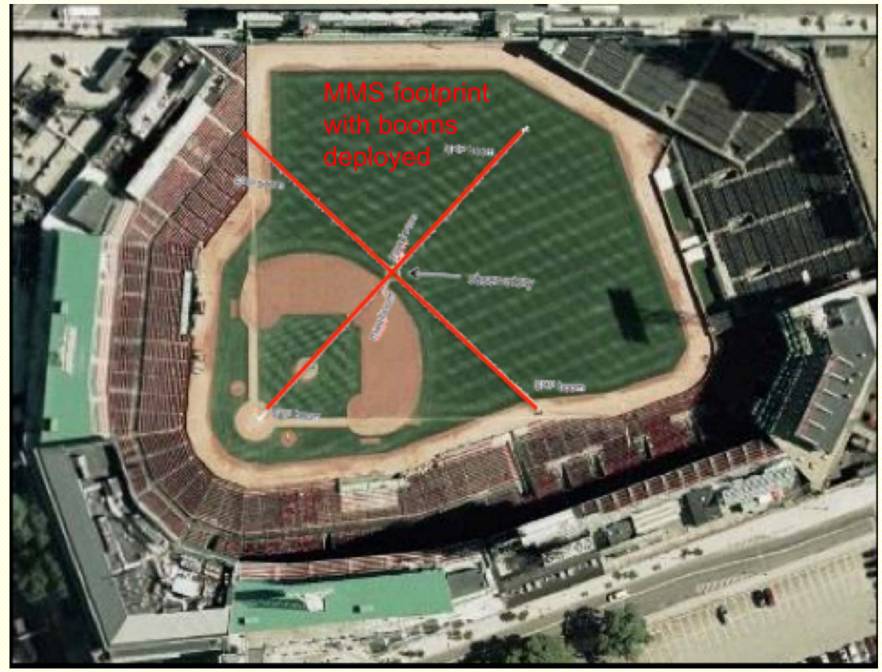
Observatory #1 - Mass Properties Test & Balancing

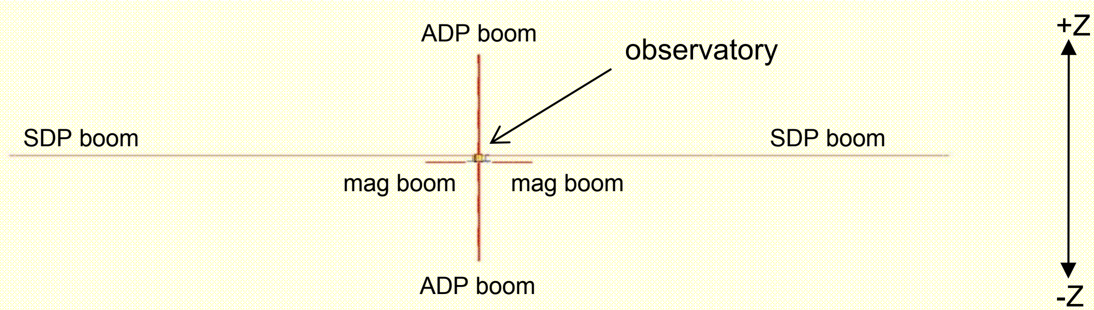


Observatory #1 - Lift Prior to Orbital Debris Shield Installation

MMS Observatory Characteristics	
Mass	1353 kg/2983lb wet (410 kg N_2H_4) each
Size	1.23m x 3.7m (48.4” x 145.5”) with booms stowed
Stack Height	4.9m (16.1’)
Spin Rate	3 rpm (7.3 max rpm- SDP deploy)
ACS(3σ)	Spin axis 2-5^{o} of ecliptic N within 0.5^{o} & spin phase =/- 0.1^{o}
Propulsion:	1lbf axial (4) & 4lbf radial (8) thrusters
Spacecraft Processor	ColdFire processor @ 40 MHz/SpW & RS422 Interfaces
Science Data Storage	96 Gbyte CIDP MMM storage, 2% Tx, stores: [38hr Burst Mode+68hr Fast Survey + 68hr Slow Survey]
Communication System	S-band 2101.25MHz Rx/2281.9 MHz Tx, LHCP, 8W Tx, Rates: 125bps-2Kbs Rx/ 2.5 Mbps max Tx. Use GN,SN.DSN
Power	DET solar array system, 368W orbit average Phase 2
Magnetics	< 1 amp/m^2 dipole moment & AC currents < 4 mA 20KHz.
Electrostatics	< 0.5V to chassis (0.9 nA/cm^2 assumed).
Key enabling attributes	Precision formation flying of 4 observatories with separations of 10 km. GSFC built weak signal GPS receiver Navigator provides orbit determination with accuracy of 100 m while flying up to 140,000 km above the GPS constellation. On-board Accelerometer allows closed loop formation flying maneuvering of spinning observatories

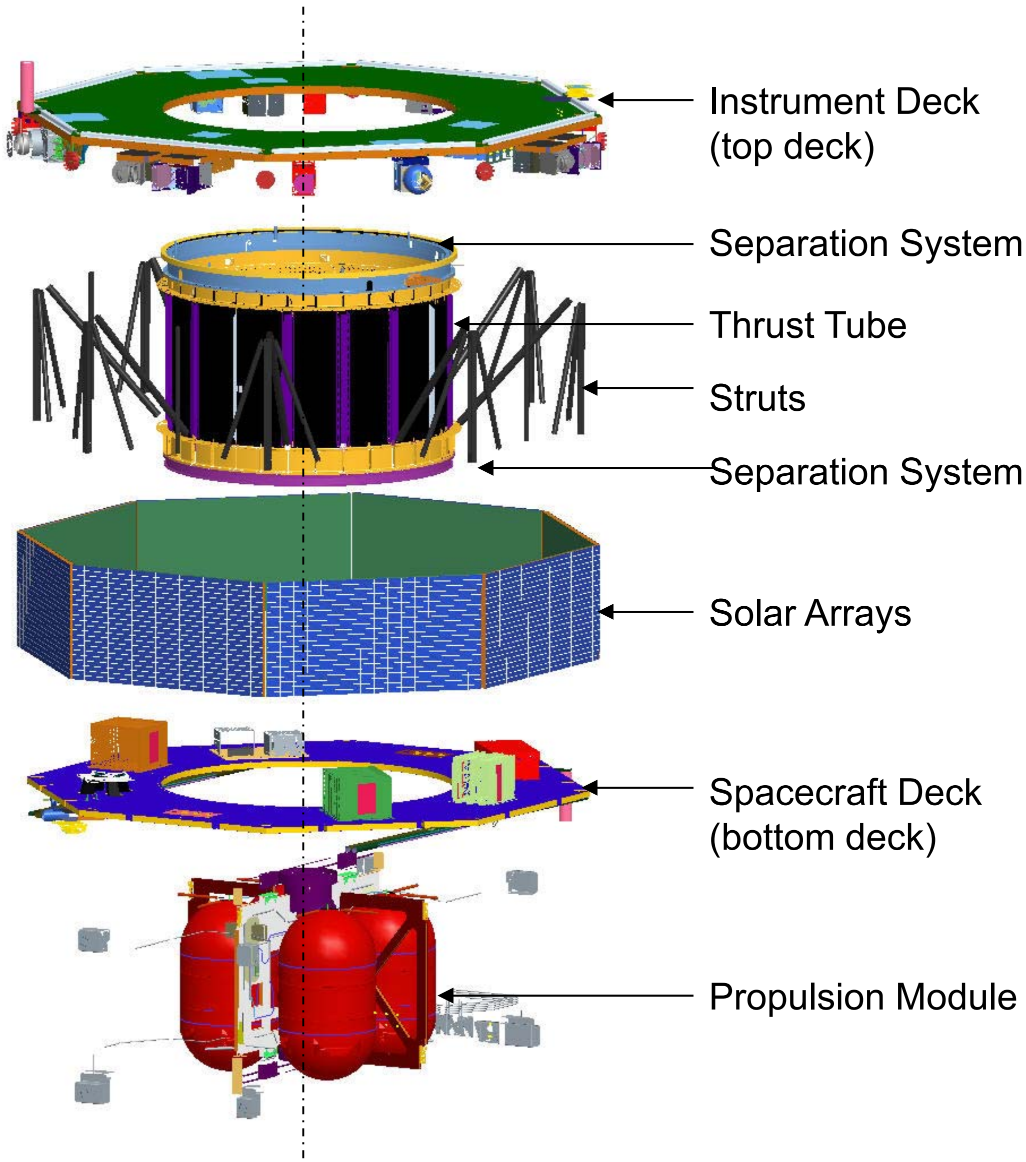
MMS Deployed Booms – to scale

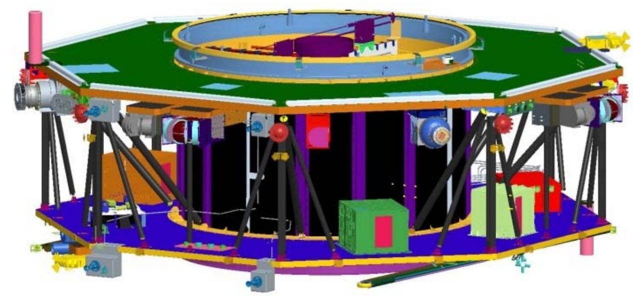


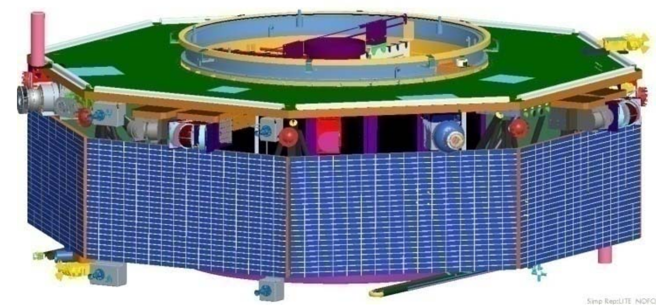


MMS Observatory Layout

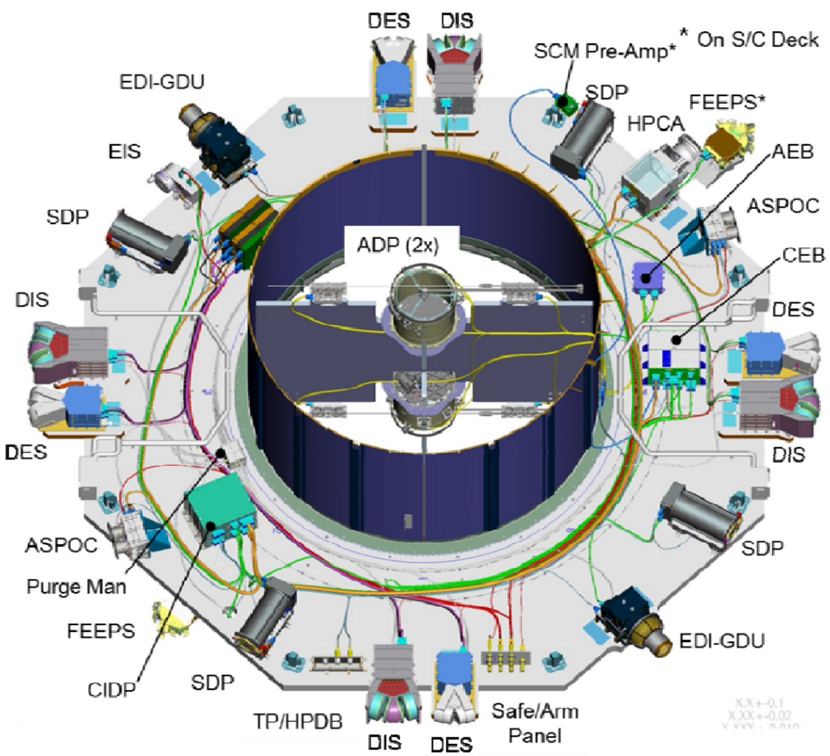
Modular Design for Ease of Integration



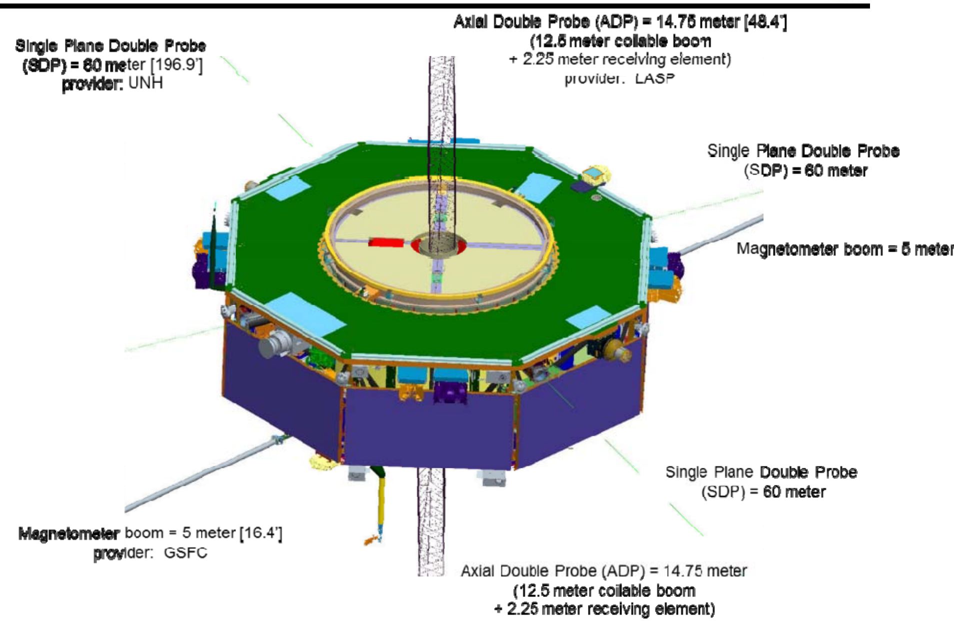




MMS Science Instruments



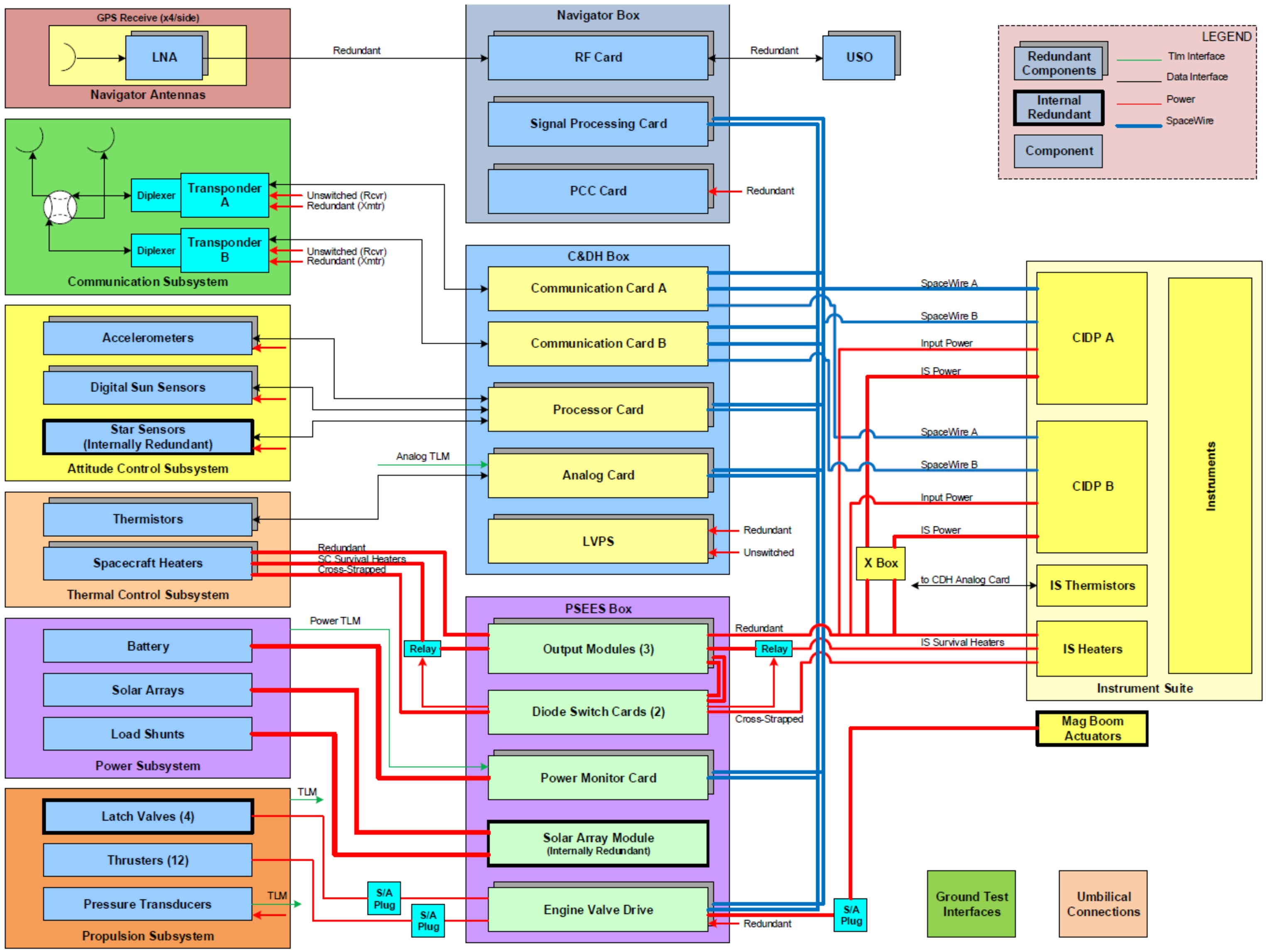
View looking up at inner side of an MMS Instrument Deck with Spacecraft Deck, Tanks, and solar arrays not shown



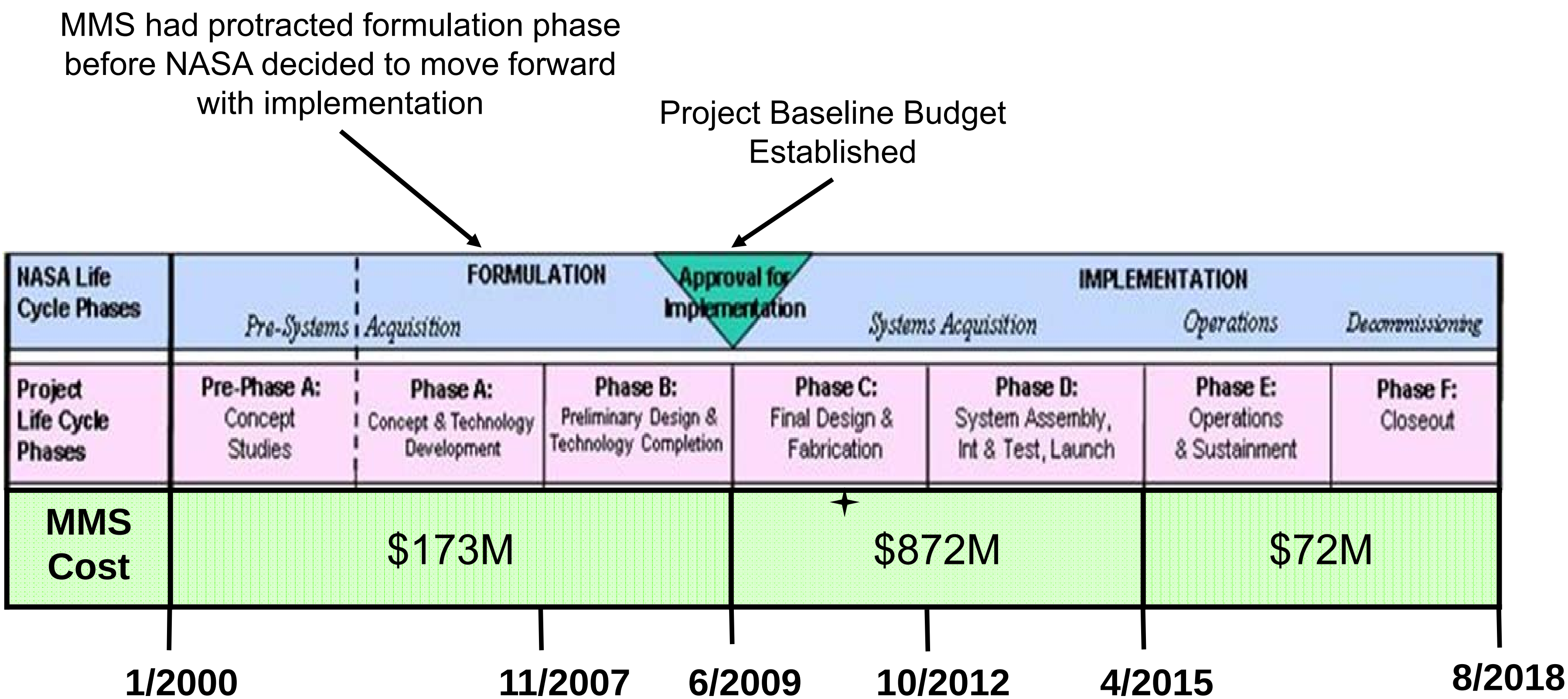
MMS Instruments

ADP - Axial Double Probe/UNH-LASP (8)
AFG - Analog Flux Gate Magnetometer/UNH-UCLA (4)
ASPOC - Active Spacecraft Potential Control/IWF Austria (8)
CEB - Central Electronics Box (Fields)/ UNH (4)
CIDP - Central Instrument Data Processor/SwRI (4)
DES - Dual Electron Spectrometer/Meisei Japan (16)
DFG - Digital Flux Gate Magnetometer/UCLA/IWF Austria(4)
DIS - Dual Ion Spectrometer/GSFC (16)
EDI/GDU - Electron Drift Instrument/ GunDetector Unit/ UNH-IWF (8)
EIS - Energetic Ion Spectrometer/APL (4)
FEEPS - Fly's Eye Energetic Particle Sensors/Aerospace (8)
HPCA - Hot Plasma Composition Analyzer/SwRI (4)
IDPU - Instrument Data Processing Unit (FPI)/GSFC (4)
SCM - Search-Coil Magnetometer (mounted on boom)/UNH-LPP France (4)
SDP - Spin-Plane Double Probe/UNH/KTH Sweden/LASP (16)

MMS Observatory Block Diagram



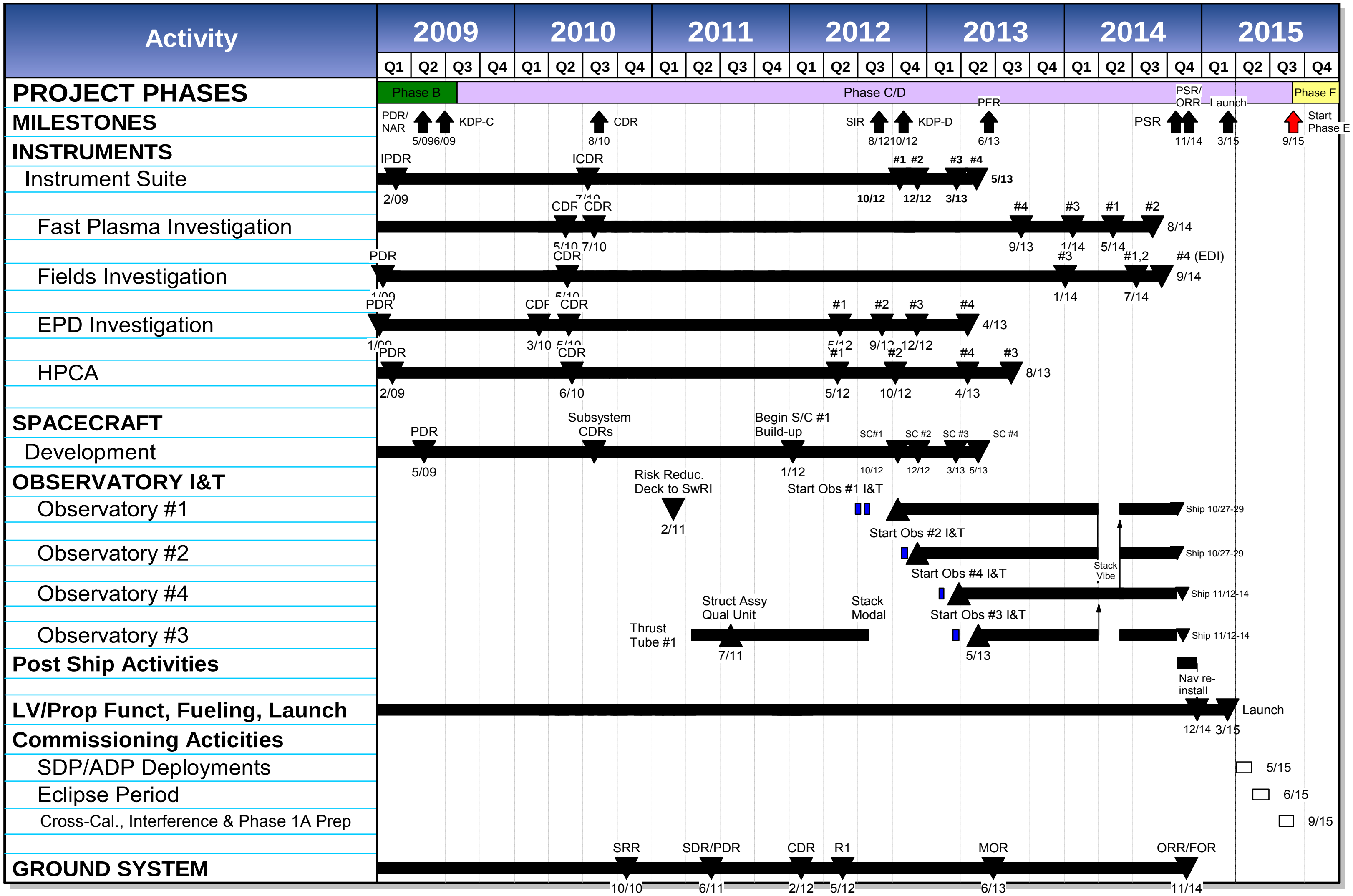
MMS Project Lifecycle



- **<u>Lifecycle Cost includes:</u>** All labor and overhead (civil servant and contractor), all equipment and hardware ,testing, launch vehicle procurement, ground systems and operations, and science data analysis.
- **<u>The MMS Mission was executed (thus far) on-budget and on-schedule</u>** with the caveat (*there is always a caveat!)* that the mission had a ~ $34M overrun (3%) beyond NASA's baseline budget due to the impacts of the Federal Government Shutdown. Total cost is $1.1B

Executing the MMS Project

History via Gantt Chart



Executing the MMS Project
The Most Important Element for Success

MMS TEAM AT NASA GODDARD

MMS Project Execution

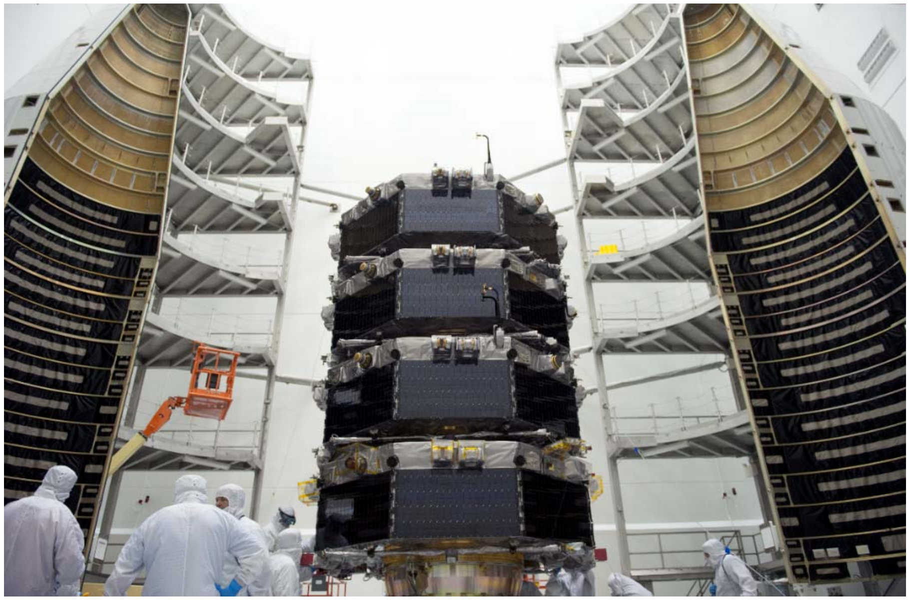
Who built it and are now flying it

MMS is an in-house NASA Goddard mission, meaning a Goddard team of civil servants and contractors built and tested the spacecraft, integrated the instruments, and operates the mission. Southwest Research Institute was selected as the Instrument Suite provider and lead a team with members many different institutions who together built the 100 MMS instruments, integrated them as a suite to the MMS Observatories, and operate them on-orbit.

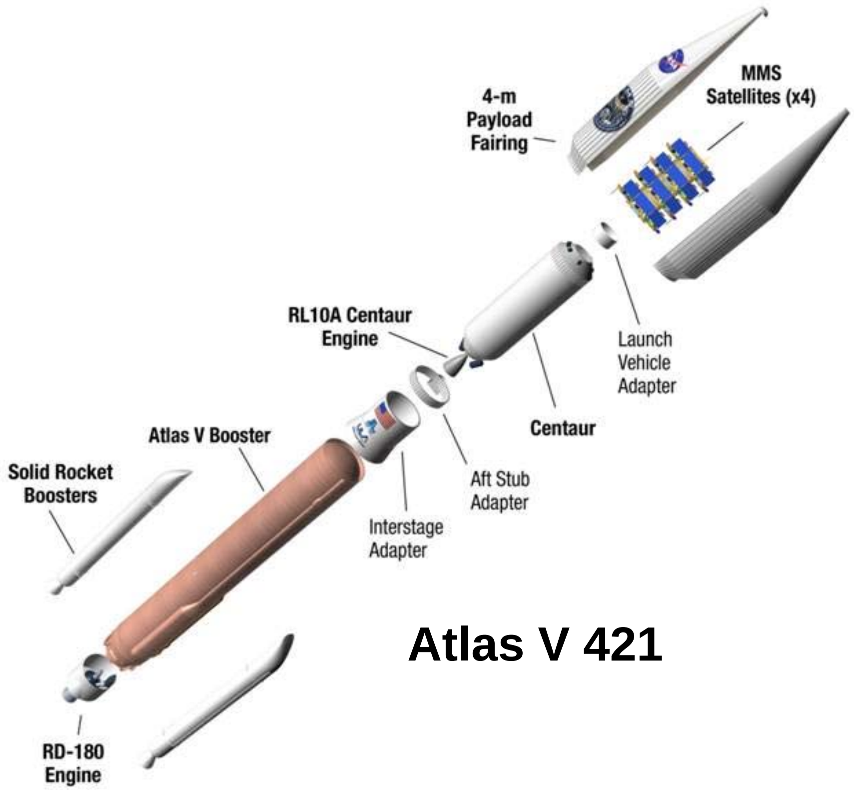
Launching MMS
Payload Processing at Launch Site

After the completion of integration and environmental testing at NASA Goddard MMS began a four month launch site campaign preparing for launch on the Atlas V rocket at CCAFS in Florida.

MMS Team performing stacking and final check-outs at AstroTech Payload Processing Facility


MMS Observatories being encapsulated in Atlas 4m Fairing

MMS at the Launch Pad



Atlas V 421

MMS at SLC 41 Launch Pad

Launching MMS
Launch Day

Separation of MMS #1 from Centaur

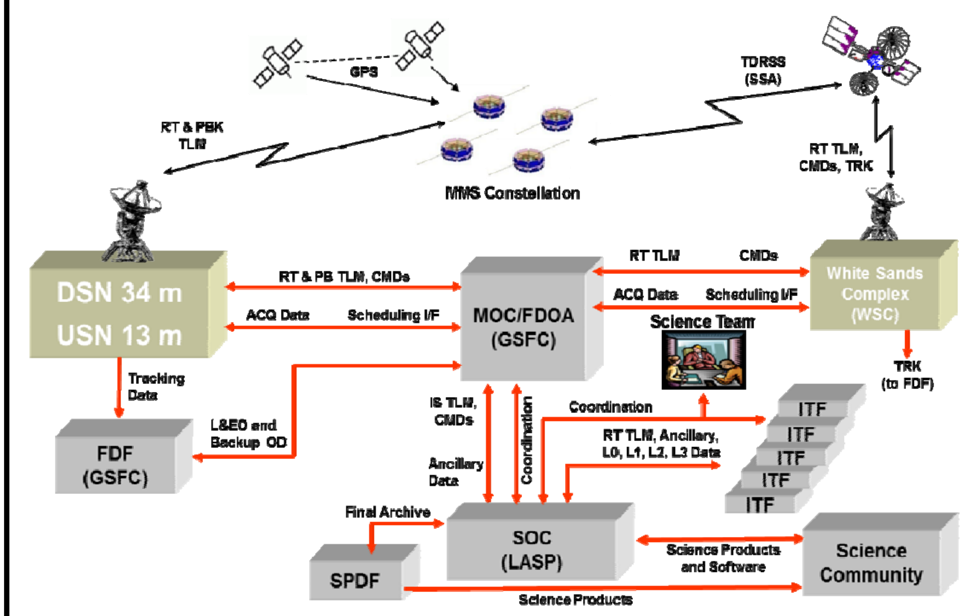
MMS Launch

MMS Launch Video

Mission Operations - Flying MMS

MMS Spacecraft and overall mission operations are controlled from NASA Goddard while the Instrument Suite is controlled from the Payload/Science Operations Center at LASP in Boulder Colorado. LASP in turn coordinates with the individual instrument teams at their institutions.

MMS Mission Operations Center (MOC) at NASA Goddard

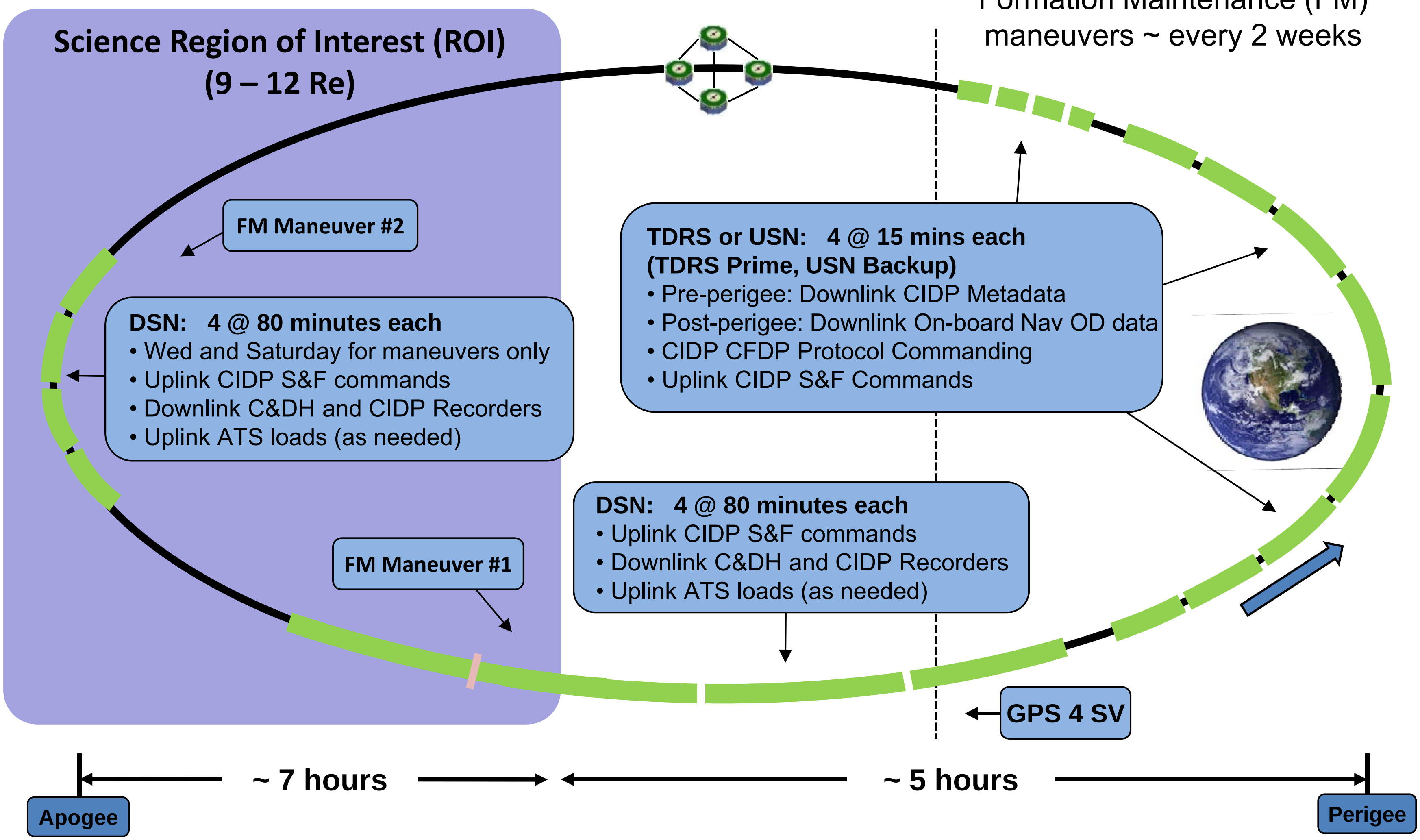


MMS Ground Operations System

Flying MMS

Typical Orbit (day) in the life during 1st year

Phase 1: ~ 1 day orbit period
Formation Maintenance (FM)
maneuvers ~ every 2 weeks



MMS Status Post Launch

- The MMS mission is in its 5th week of flight operations. The mission is proceeding extremely well! 4½ more months of commissioning activities remain ahead of us, then we enter the science region-of-interest.
  - Instrument activation and calibrations are proceeding on schedule with no significant instrument problems.
  - Boom deployments have been in progress for the past 3 weeks and will be completed in a week.
  - All spacecraft systems are performing perfectly. Of particular note are:
    - The simultaneous nutation-precession-spin controller and the PWM closed loop thruster control systems are exceeding expectations in their accuracy.
    - The Navigator weak-signal GPS system is significantly exceeding its performance requirements. Tracking more GPS SV and performing on-board orbit determination at higher than expected altitudes.
    - Power and thermal systems are exhibiting robust performance and will yield revised power margins that will enable additional science operations.

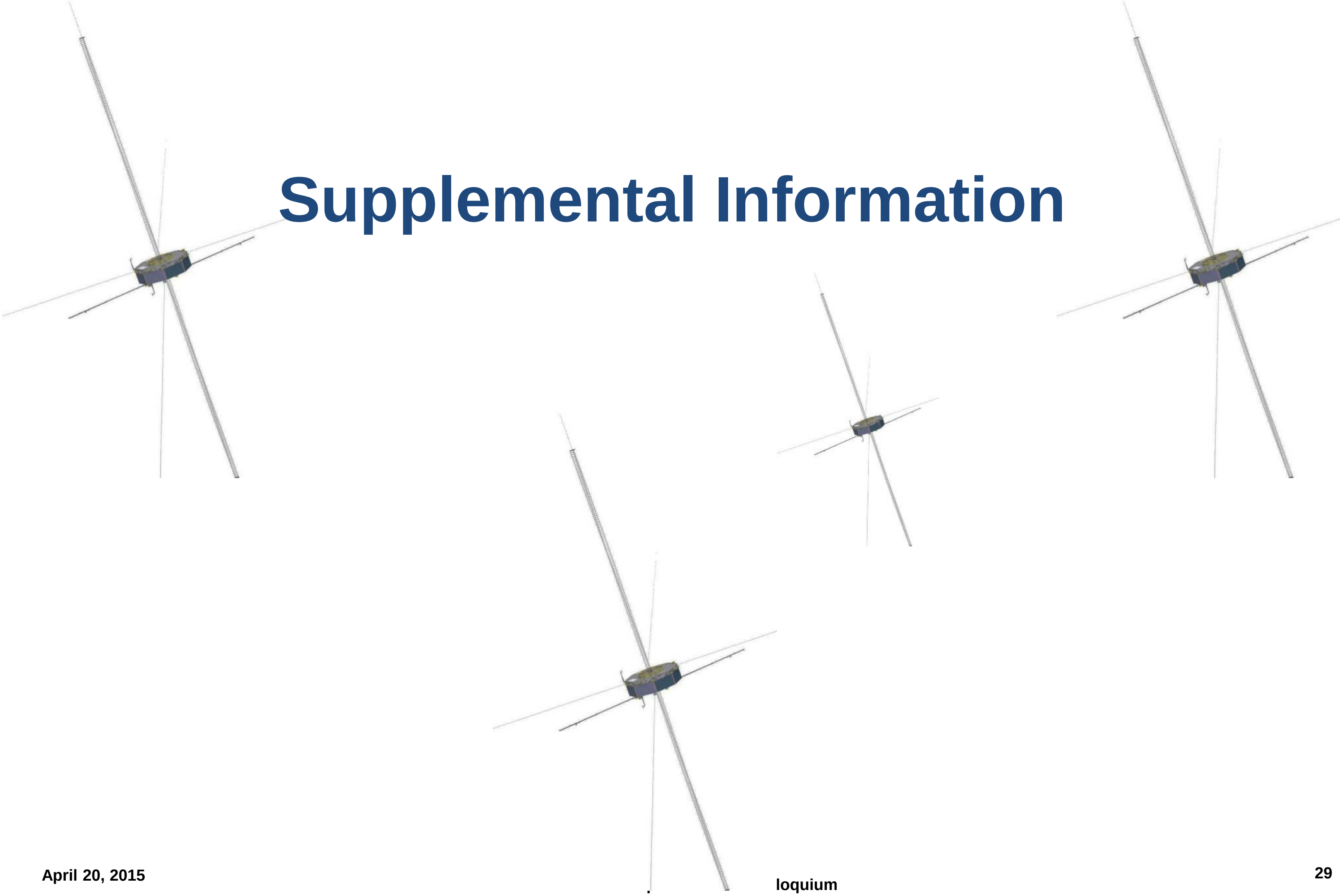
Links for Additional MMS Information & Media Resources

NASA Goddard MMS Website:	http://mms.gsfc.nasa.gov
NASA HQ MMS Website:	http://www.nasa.gov/mission_pages/mms
MMS Facebook:	https://www.facebook.com/MagMultiScale
Southwest Research Institute MMS Website:	http://mms.space.swri.edu
University of New Hampshire MMS Website:	http://mms-fields.unh.edu
Magnetic Reconnection Physics Forum:	http://heliogeophysics.ning.com/

MMS Resources for Photos, Videos, & Animations

http://mms.gsfc.nasa.gov/images_multimedia.html
http://www.nasa.gov/mission_pages/mms/multimedia/index.html#.VQhRNmNTf5w
https://www.flickr.com/photos/nasakennedy/sets/72157649836241016/with/16616462548/
http://www.ulalaunch.com/file-library.aspx

Supplemental Information



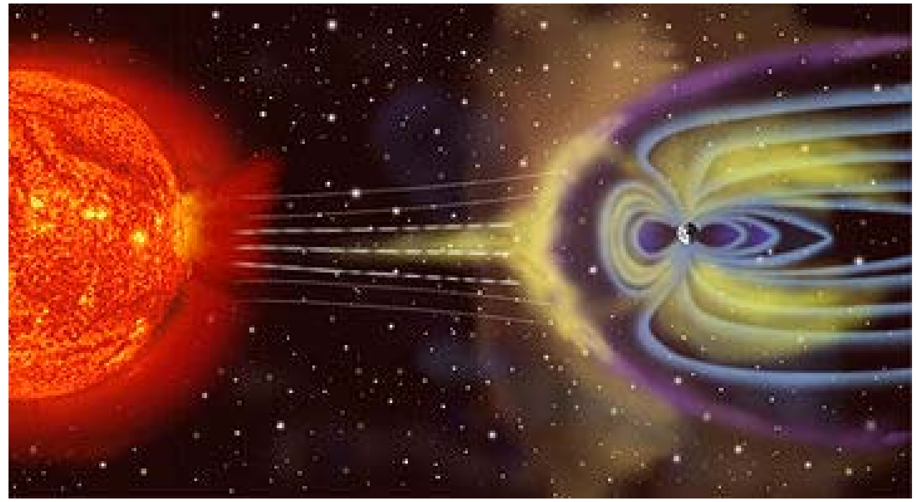
MMS Background - Magnetic Reconnection

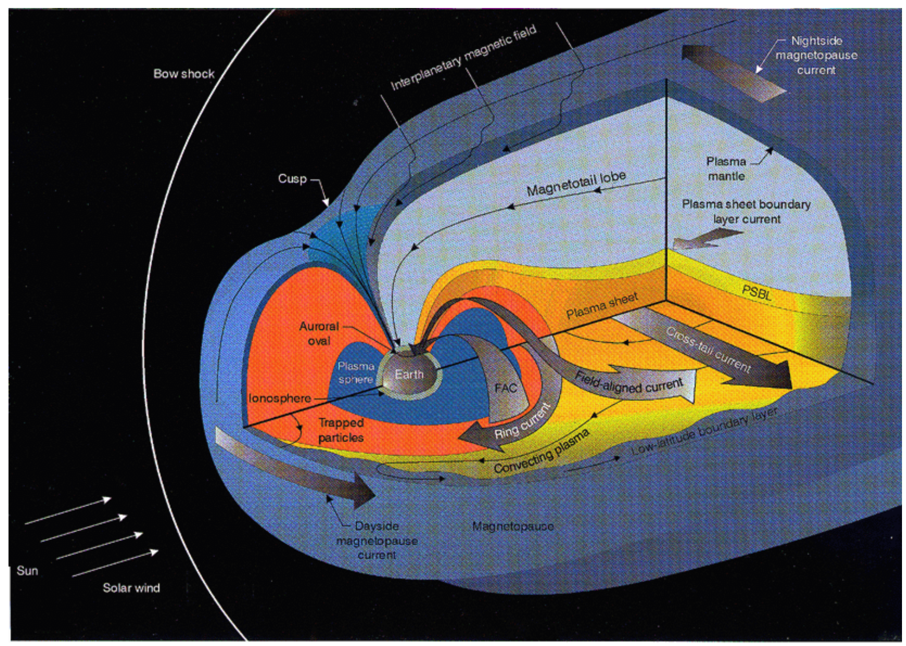
- **Before discussing how NASA is building and flying the MMS mission some explanation of what Magnetic Reconnection is in order.**
- **The MMS mission may be renamed *Maxwell Explorer* or something akin to that in honor of James Clerk Maxwell who is most famous for his equations which unified electricity and magnetism in the 19th century.**

Name	Integral equations	Differential equations
Gauss's law	$\oint\!\!\oint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\, dV$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oint\!\!\oint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot d\boldsymbol{\ell} = -\frac{d}{dt}\iint_\Sigma \mathbf{B}\cdot d\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\oint_{\partial\Sigma} \mathbf{B}\cdot d\boldsymbol{\ell} = \mu_0\iint_\Sigma \left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)\cdot d\mathbf{S}$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

MMS Background- The Magnetosphere

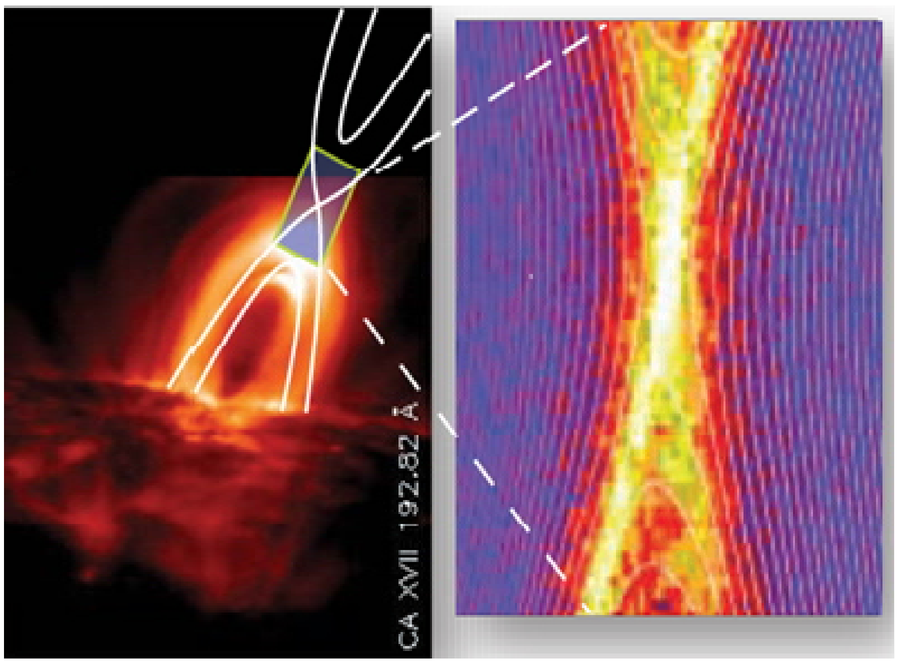
- The **magnetosphere** of Earth is a region in space whose shape is determined by the Earth's internal magnetic field, the solar wind plasma, and the Sun's interplanetary magnetic field. The boundary of the magnetosphere ("magnetopause") is roughly bullet shaped, about 15 Earth Radii (RE) abreast of Earth and on the night side (in the "magnetotail" or "geotail") approaching a cylinder with a radius 20-25 RE. The tail region stretches well past 200 RE. For reference the Moon orbits at about 60 Re.
- Activity in the magnetosphere causes auroras near the Earth's poles
- The interaction of the Earth and Solar activities (Space Weather) and can affect satellites, astronauts, and terrestrial power grids and communication systems.
- Earth's magnetosphere protects the ozone layer from the solar wind. The ozone layer protects the Earth (and life on it) from dangerous ultraviolet radiation





Magnetospheric Multiscale Mission Objective

MMS Objective: ***Finding out how Magnetic Reconnection works***



Solar flare with overlay of magnetic reconnection simulation

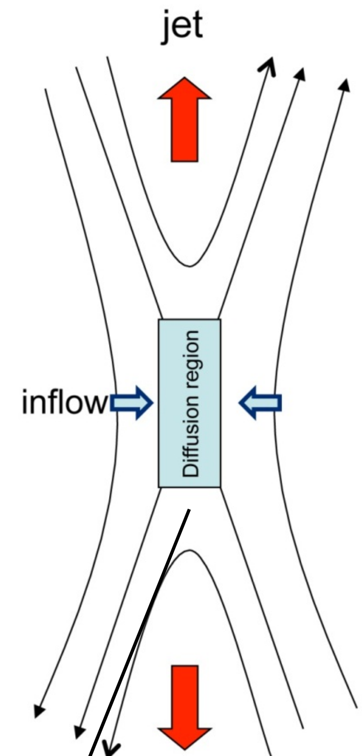
Magnetic Reconnection:

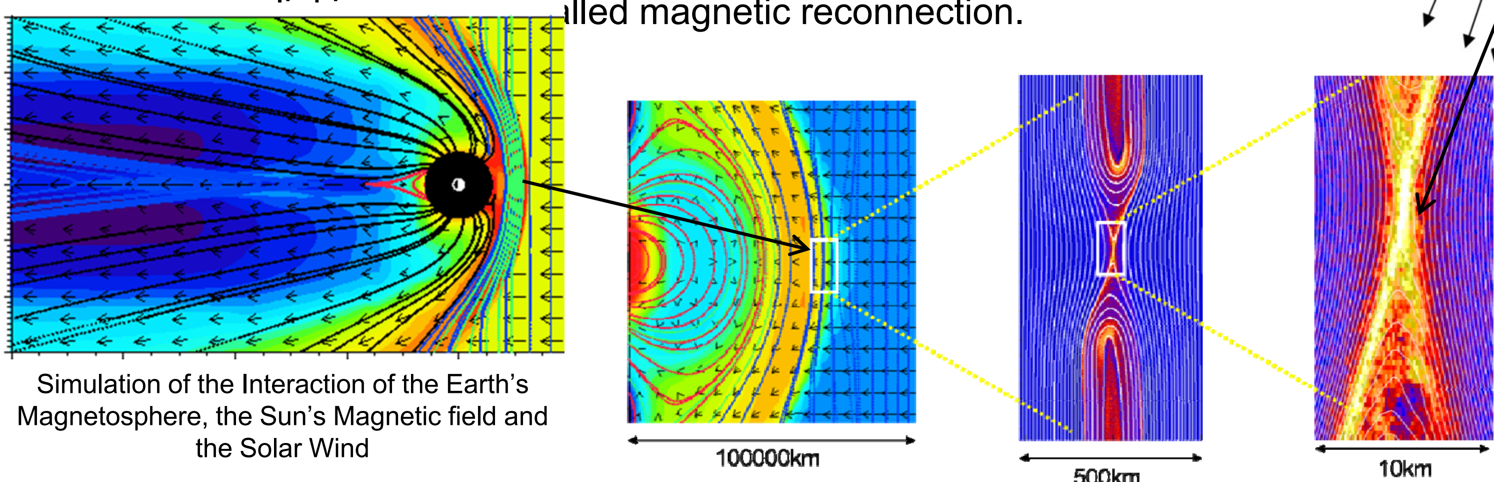
- **connects and disconnects** plasma regions and taps energy stored in their magnetic fields, converting it into flow acceleration and heat, it is the primary mechanism transferring energy from the Sun's magnetic filed into the Earth's magnetosphere
- **unleashes** explosive phenomena ranging from solar flares on the Sun to high-energy cosmic rays to x-ray emissions from neutron star and black hole accretion disks
- **drives** severe "space weather" impacting communications, navigation, power grids, spacecraft and astronaut health and safety
- **reduces** the performance of fusion reactors- an obstacle for achieving fusion power on earth
- **impossible** to create on a significant scale on earth, our magnetosphere is the closest laboratory

Solving magnetic reconnection will unlock understanding of a fundamental and universal energetic plasma process that drives our space weather and affects and limits our use of technologies on Earth

What is Magnetic Reconnection?

- <u>**Magnetic Reconnection is a Fundamental Universal Process**</u>
  - Magnetic Reconnection is an energy transfer mechanism of enormous magnitude that is occurring in our near-space environment as well as throughout the universe. *It's physics are not fully understood.*
    - Magnetic fields pointing in opposite directions in a plasma tend to annihilate each other in a diffusion region, releasing their magnetic energy and heating the charged particles in the surrounding environment.
    - The fast release of magnetic energy requires that oppositely pointing magnetic fields be torn apart and reattached to their neighbors in a … lled magnetic reconnection.





Simulation of the Interaction of the Earth's Magnetosphere, the Sun's Magnetic field and the Solar Wind

Understanding Magnetic Reconnection & what MMS needs to measure

Magnetic Reconnection is a phenomena that occurs as moving electrons and ions (a plasma) interact in the presence of time varying magnetic and electric fields. The expression below[1] termed the "Generalized Ohm's Law" relates the electromagnetic (Maxwell's Eq.s) and the kinetic (Newton/Einstein's laws) behavior of particles and fields in the plasma, written for electrons in this case. In an ideal perfectly conducting plasma the entire right side of the equation equals zero. In a situation involving magnetic reconnection in which the ions and electrons are moving at different speeds (not one fluid) and the magnetic filed lines are not frozen in the plasma but are changing and breaking/reconnecting the right side of the equation represents the departure from the simple ideal case. The terms on the right involve the electrical resistivity, the Hall effect current, and the particle inertia and particle pressure effects. Understanding the conditions that initiate magnetic reconnection and how the energy is both transferred from the magnetic fields to the kinetic energy of the particles as well as how it is dissipated is the fundamental goal of the MMS mission. We understand the equations of reconnections but not, yet, the solutions to them.

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta_s \mathbf{j} + (\mathbf{j} \times \mathbf{B})/ne + m_e/e(\partial \mathbf{v}_e/\partial t + \mathbf{v}_e \cdot \nabla \mathbf{v}_e) - \nabla \cdot \mathbf{P}_e/ne.$$

Thus the suite of instruments on MMS will measure the electric fields (**E**), magnetic fields (**B**), and the abundance, species, and energy levels of the electrons and ions (**j**, **v**, $\mathbf{v}_e$, $\mathbf{P}_e$). It will do this in 3-dimensions on the temporal and spatial scales involved in magnetic reconnection events. The links below are good entry points for anyone desiring to better understand magnetic connection

http://ulysses.phys.wvu.edu/~pcassak/parkerlecture2008.pdf
http://en.wikipedia.org/wiki/Magnetic_reconnection
http://www.scholarpedia.org/article/MHD_reconnection
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=36447

1) M. Yamada, *Understanding the Dynamics of Magnetic Reconnection Layer*, Space Sci Rev (2011) 160:25-43

Mission Success Criteria
Baseline Science

4.1.1 Baseline Science Requirements

- For the Baseline Mission, the following requirements must be met:
  - STP-MMS-M10 through STP-MMS-M80 [Section 4.1.3]
  - STP-MMS-I10 through STP-MMS-I90 [Section 4.1.4]
  - STP-MMS-P10 through STP-MMS-P150 [Section 4.2]
- Achieve four (4) functional satellites in specified orbits
  - Conduct science measurements in a 12 RE dayside magnetopause orbit (Phase 1)
  - Conduct science measurements in a 25 RE nightside neutral sheet orbit (Phase 2)
- Obtain sixteen (16) quality1 reconnection events at specific magnetic shear orientations and density levels, shown in the Table 2:

Table 2 Magnetic Shear Orientation and Density Level Requirements for Baseline Mission

[3]Shear angle / [2]Density change	Large-shear (150°-180°)	Medium-shear (50°-150°)
Small (<50%)	5	1
Large (≥50%)	5	5

1 Quality events are those for which the science observables S10-S150 can be determined

2 Change in plasma density across the shear boundary

3 Total magnetic field rotation across the current sheet

Baseline – Full Mission Success – Fly 4 Observatories for 29 months meeting Instrument requirements and Instrument failure criterion

Mission Success Criteria
Threshold Science

4.1.2 Threshold Science Requirements

- **For the Threshold Mission, the following requirements must be met:**
  - **STP-MMS-M10R, M20, M30, M40R, M50R, M60R** [Section 4.1.3; 4.5]
  - **STP-MMS-I10 through STP-MMS-I50, I60R, I70, I80R** [Section 4.1.4; 4.5]
  - **STP-MMS-P10R, STP-MMS-P30 through STP-MMS-P70** [Section 4.2; 4.5]
- **Achieve three (3) functional satellites in specified orbits**
  - **Conduct science measurements in a 12 R_E dayside magnetopause orbit (Phase 1)**
- **Obtain six (6) quality[1] reconnection events at specific magnetic shear orientations and density levels, shown in the Table 3 below:**

Table 3 Magnetic Shear Orientation and Density Level Requirements for Threshold Mission

[3]Shear angle / [2]Density change	Large-shear (150°-180°)	Medium-shear (50°-150°)
Small (<50%)	2	0
Large (≥50%)	2	2

1 Quality events are those for which the science observables S10-S150 can be determined

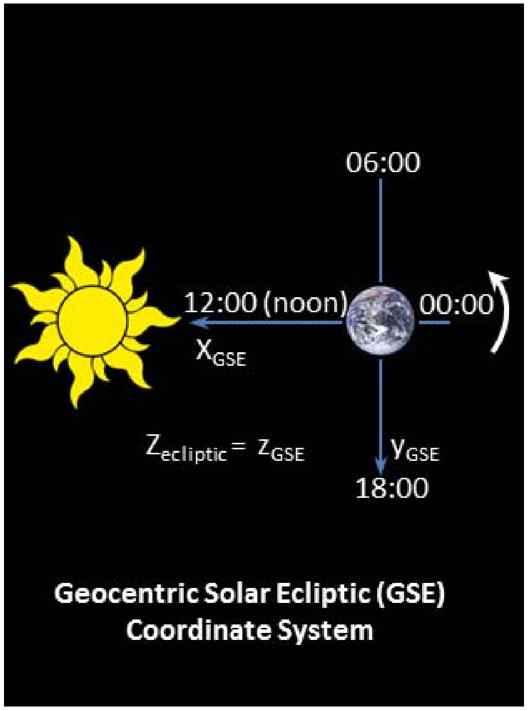
2 Change in plasma density across the shear boundary

3 Total magnetic field rotation across the current sheet

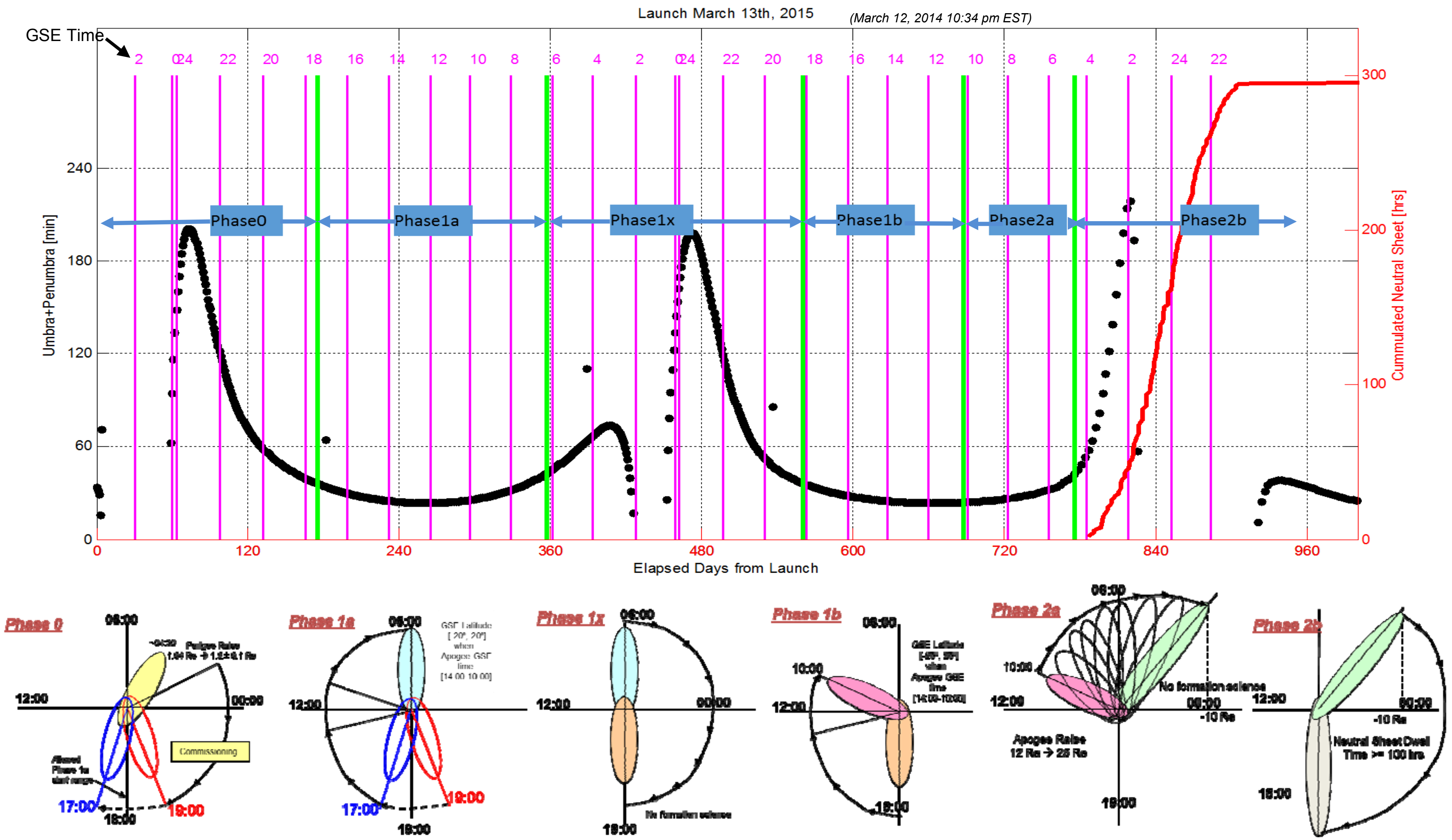
Threshold – Minimum Mission Success – Fly 3 Observatories for ~11 months meeting Instrument requirements and Instrument failure criterion

MMS Mission Phase Timeline Summary

MMS Mission Phase Summary				
Event	**GSE/LT**	**GSE deg**	**Date**	**Elapsed Time (days)**
Launch	4.6	68.556	3/13/2015	0
Phase 0 midnight	0	0	5/26/2015	75
Phase 1 start	18	270	9/1/2015	173
Phase 1a dayside	12	180	12/8/2015	271
Phase 1a dawn/Phase 1x begin	6	90	3/15/2016	369
Phase 1x midnight	0	0	6/21/2016	467
Phase 1x dusk/Phase 1b start	18	270	9/27/2016	565
Phase 1b dayside	12	180	1/3/2017	663
Phase 1b end/Phase 2a start	9	135	2/21/2017	712
Phase 2a end/Phase 2b start	5	75	4/28/2017	777
Phase 2b midnight	0	0	7/18/2017	859
Phase 2b end	21.5	322.5	8/28/2017	900
		elapsed years		2.47



MMS Flight Overview Summary



MMS Mission Phases (Slide 1 of 3)

Mission Phase	Description
Launch	▪ Spans pre-launch countdown sequence, launch, ascent, and launch vehicle separation through separation plus ~8 hours ▪ Atlas-V 421 launched from KSC with observatories in a 'Stacked' configuration ▪ Observatories released from Centaur in sequence - Brief five-minute contacts through TDRS cover separation - Handover to DSN Goldstone for initial tracking and H/K recorder dumps
Early Orbit (L thru L + 4 days)	▪ Executed per integrated mission timeline. For all observatories . . . - Complete ACS and Navigation system activation - Engineering checkout of propulsion system - Initial Instrument Suite (IS) activation • IS Electronics boxes, some low voltage turn ON and initial checkouts - Start perigee raise operations (1.02 Re to 1.2 Re) • 5 burns per spacecraft over ~ 2-week period
Commissioning (~ 25 weeks)	▪ Executed per integrated mission timeline. For all observatories . . . - Complete perigee raise maneuvers (string of pearls formation) - IS boom deployments (8 per observatory); includes spin-rate management - Instrument engineering and science checkout - Maneuvers to establish initial tetrahedron formation (ready to start science) ▪ Long eclipse passages (3.5 hrs max duration). For all umbras > 2 hours . . . - Observatory thermal preconditioning - Configure Instrument Suite to low-power state - Depending on duration of umbra, power off non-essential S/C systems - Commissioning operations supported on a power available basis

MMS Mission Phases (Slide 2 of 3)

Mission Phase	Description
Science Phase 1a (~26 weeks)	▪ 1st primary science data collection phase (dayside magnetopause) ▪ Orbit: 1.2 x 12 Re; naturally evolving inclination; 23.9 hour period ▪ Fast Survey and Burst science collected for ~ 50 % of the orbit during ROI - ROI: orbit region > 9 Re centered about apogee ▪ 65 minute DSN contact per S/C per orbit for H&S, C&DH & CIDP recorder dumps ▪ 2 TDRS passes per S/C per orbit around perigee for H&S operations, downlink of on-board orbit solution (Nav), and D/L of CIDP Metadata ▪ Tetrahedron resizing and formation maintenance maneuvers ~ every 2 weeks then set formation size to what is determined by the science team ▪ Attitude spin-axis maintenance planned in conjunction with Delta-Vs
Science Phase 1x (~ 24 weeks)	▪ Phase 1 night side; No primary science data collection required ▪ No FPI high voltage operations planned to protect optocouplers ▪ Long eclipse passages (3.5 hrs max duration). Similar to that during commissioning. ▪ Maintain tight (25 km) tetrahedron formation to minimize fuel consumption ▪ Real-time pass profile same as Phase 1a

MMS Mission Phases (Slide 3 of 3)

Mission Phase	Description
Science Phase 1b (~ 18 weeks)	▪ Same operations profile as with Phase 1a with the optimal tetrahedron spacing defined by the Science team (nominal: 25 km) ▪ Orbit: 1.2 x 12 Re; naturally evolving inclination; 23.9 hour period ▪ Perform tetrahedron maintenance maneuvers, as required (~2 weeks)
Science Phase 2a (~11 weeks)	▪ Transitional period to 2^{nd} primary science data collection phase ▪ Sequence of 8 maneuvers per S/C performed to raise apogee from 12 to 25 Re ▪ Apogee raise maneuver coverage through TDRS and/or USN ▪ Reform tetrahedron at end of the apogee raise ▪ 1 DSN pass per day for health and safety, C&DH and CIDP recorder dumps
Science Phase 2b (~24 weeks)	▪ 2^{nd} primary science data collection phase (night side magnetotail) - Orbit: 1.2 x 25 Re; 68 hour orbit period ▪ Fast Survey and Burst science collected for ~ 50 % of the orbit during ROI ▪ Science & Eng data downlinked via DSN, 5 passes per S/C spread out over orbit ▪ Health & Safety: 2 to 3 ~ 15 minute passes per orbit around perigee (SN or USN) for H&S operations, CIDP Burst Buffer management commanding, downlink of Navigation telemetry, and ranging (SN only) ▪ Tetrahedron formation maintenance maneuvers ~ every 2 weeks ▪ Long eclipse passages (3.5 hrs max duration). Similar to that during commissioning except that return to science operations will be required before entry into the neutral sheet.
EOM Disposal	No controlled re-entry; re-entry expected within 25 years

MMS Key Performance Margins

Parameter	Requirement/Guideline/Case	Value/Margin
Mass (per observatory)	1368 kg	OBS#1: 1351 kg measured OBS#2: 1353 kg measured OBS#3: 1353 kg estimated OBS#4: 1338 kg measured Stack Margin: 31.2 kg (includes summed uncertainty)
Power	10% guideline	11.4 % (with >50% SOC)
S-band tlm	2.5 Mbps DSN @ 15.4 Re	3dB, 99.97%
S-band cmd	2 kbps DSN @ 25 Re	6dB, 100%
Navigator Accuracy mean semi-major axis	100 m 99% of the time	8m Phase 1 20m Phase 2B
Timing (obs to obs)	0.5 ms	<.325 ms
CPU utilization, CDH	30% guideline	30.2%
CPU utilization, CIDP	30% guideline	29%
Bus utilization, spacewire	10 Mbps	3 Mbps

MMS Project Organizational Chart