Radiation Belt Mappers

> *For the truth of the conclusions of physical science,*
> *observation is the supreme Court of Appeal . . . .*
>
> ***Sir Arthur Eddington***

RBM Study Chronology

Date	Event	Concept
1/21/00	Kick-Off Meeting With M. Hesse	6 Satellites, 3 Instruments
1/21/00 to 2/16/00	Engineering Team Mission Studies	6 Satellites, 1 Launch
1/24/00	Instrument Revision By M. Hesse	1 Cherenkov Detector Added
2/9/00 to 2/10/00	Measurement Requirements Workshop	6 Satellites, 3 Petal Orbits
2/16/00	R. Hoffman Named As Science Lead	To Be Reviewed
2/24/00	First Meeting With R. Hoffman	Clean Sheet Of Paper
2/24/00 to 3/3/00	Candidate Orbit Studies	Elliptical Orbit Contours
3/9/00	RBM Mission Definition Team Meeting	Science, Measurements, Orbits
3/10/00 to 3/12/00	IMDC Pre-Work	6 Or 7 Satellites, 1 Launch
3/12/00 to 3/16/00	R. Hoffman/B. Giles Prioritize Instruments	6 Or 7 Instruments
3/13/00 to 3/17/00	IMDC Study	7 Satellites Each With An AKM
3/31/00 to 5/5/00	Mission Costing (Full Scope)	7 Satellites, 2 Launches
	Mission Costing (Reduced Scope)	3 Satellites, 1 Launch
5/9/00	IMDC Revisit	7 Satellites/BiProp, 6 Petal Orbits
5/31/00	Program Operating Plan Submittal	3 Satellites, 1 Launch*

** Exceeded NASA/HQ cost target and cost-capped funding profile allocation*

RBM Concept Evolution

The Radiation Belt Mappers (RBM) mission was initially envisioned to be a constellation of well-instrumented, small spacecraft in low inclination petal orbits. The GSFC engineering team worked closely with the science team leader to develop a concept that could be further refined during the scheduled IMDC study. From the outset, the engineering team expressed concern about the affordability of the number of instruments and spacecraft desired. To circumvent this issue, it was decided to proceed with a ***building block concept of identical elements*** that could meet science requirements and could be replicated as many times as the budget allocation allowed.

During the initial IMDC conceptualization, apogee kick motors (AKM) were employed to achieve the low inclination orbits desired. This approach severely limited payload mass to orbit and caused mechanical complexities associated with stacking of the satellites on the launch vehicle.

RBM Concept Evolution

It was also judged that the AKM would have to be jettisoned because of the potential deleterious effects on instrument measurements, further complicating the design and operation of the satellite system. After some additional flight dynamics analyses, it was decided to change the launch scenario. An abbreviated IMDC session was scheduled to change the concept to use on-board propulsion in place of the AKM. Some reductions in instrument mass, power, and real-time data requirements were also made at this time.

The charts that follow reflect these changes but, nevertheless, describe a space and ground system concept that seeks to accommodate the full complement of satellites and instruments desired by the science team. Although some preliminary conclusions have been drawn, further trade studies will be required to determine the maximum number of satellites that can be handled by a single launch.

RBM Mission Profile

Description: A small constellation of satellites in low inclination orbits that provide a large scale, time-dependent mapping of particles and fields in the Earth's inner magnetosphere and radiation belt environments

Instruments: Six in-situ instruments on six high flying spacecraft including flux-gate and search coil magnetometers, electric field probes, and low-, mid-, and high-energy particle detectors with a seventh instrument, a high-energy proton detector, added to a single low flying spacecraft

Spacecraft: Seven identical spacecraft, spin-stabilized at 6 to 10 rpm, in highly elliptical, low inclination orbits each with a propulsion system for orbit transfer, station-keeping, and disposal with six spacecraft in 500 km x 6.5 R_E petal orbits and one spacecraft in a 500 km x 2.5 R_E orbit

Launch Date: April, 2008

Mission Life: 2 years with an optional 3-year extension of mission operations as resources permit

Orbits: Six 500 km x 6.5 R_E low inclination (0 to 12 degrees) petal orbits and one 500 km x 2.5 R_E orbit

Space Access: Constrained by cost to one launch on a Medium Class ELV from ETR; secondary launch opportunities to be explored

Key Technologies: Smaller instruments tolerant of a high radiation environment and enhancing technologies at the subsystem or component level

RBM Mission Time Line

The following time spans are assumed for mission planning with July 1, 2000 as the initial reference date:

- 2 years for mission unique technology development
- 2 years for studies, project formulation, and mission definitization
- 4 years from approval to launch readiness
- April 2008 launch
- 2 years for baseline mission operations
- 3 year mission extension (option for evaluation)

RBM Mission Objectives

The RBM mission employs seven spin-stabilized satellites in low inclination, elliptical orbits with a complement of in-situ instruments to make simultaneous, spatially separated measurements of the Earth’s inner magnetosphere and radiation belts.

Specific mission objectives are as follows:

- Create time-dependent maps of the inner magnetosphere, radiation belts, and plasmasphere
- Fully specify and understand the space environment to increase spacecraft reliability and astronaut safety
- Discover the origin and dynamics of high-energy particle populations
- Trace the development and evolution of penetrating radiation during magnetic storms

RBM Instrument Complement

This baseline set of RBM instruments is fully accommodated in the concept presented here. A priority ordering is given below to provide guidance for future trade studies.

(1) High-Energy Particle Detector
(2) High-Energy Proton Detector (Low Flying Spacecraft Only)
(3) Mid-Energy Particle Detector
(4) Flux-Gate Magnetometer
(5) Electric Field Probes
(6) Low-Energy Particle Detector
(7) Search Coil Magnetometer

Instrument system parameters, given in the table that follows, are based on direct heritage from the POLAR, FAST, DS-1, IMEX, STORMS, and DE-1 missions.

The inclusion of a low-energy Thermal Plasma instrument on all seven spacecraft was originally considered, but this instrument was dropped due to mass constraints.

RBM Baseline Instrument Complement

Type/Classification	**Size** LWH or DH (cm)	**Mass** (kg)	**Power** Avg/Peak (W)	**Data Rate** Avg/Peak (kbps)
High Flying Instrument Set				
High-Energy Particle Detector	3@9x25x30	10	8	5
Mid-Energy Particle Detector	15x10x10	5	4	5
Flux-Gate Magnetometer	2m Boom	2	3	3
Electric Field Probes*	15x15x15	15	8	20
Low-Energy Particle Detector	15x15x15	4	3	14
Search Coil Magnetometer	2m Boom	0.75	0.2	12
Total		**36.75**	**26.2**	**59**
Low Flying Instrument Set				
Same As Above		36.75	26.2	59
High-Energy Proton Detector	9x25x30	6	7	3
Total		**42.75**	**33.2**	**62**
* Two sets of orthogonal wire antennas 40-50 m long				

RBM System Synopsis

- Mission objectives require the deployment of multiple satellites into low inclination orbits while minimizing launch costs and spacecraft propulsion.

- The programmatic constraint to launch from the continental U.S. imposes significant restrictions on mission mass for such orbits.

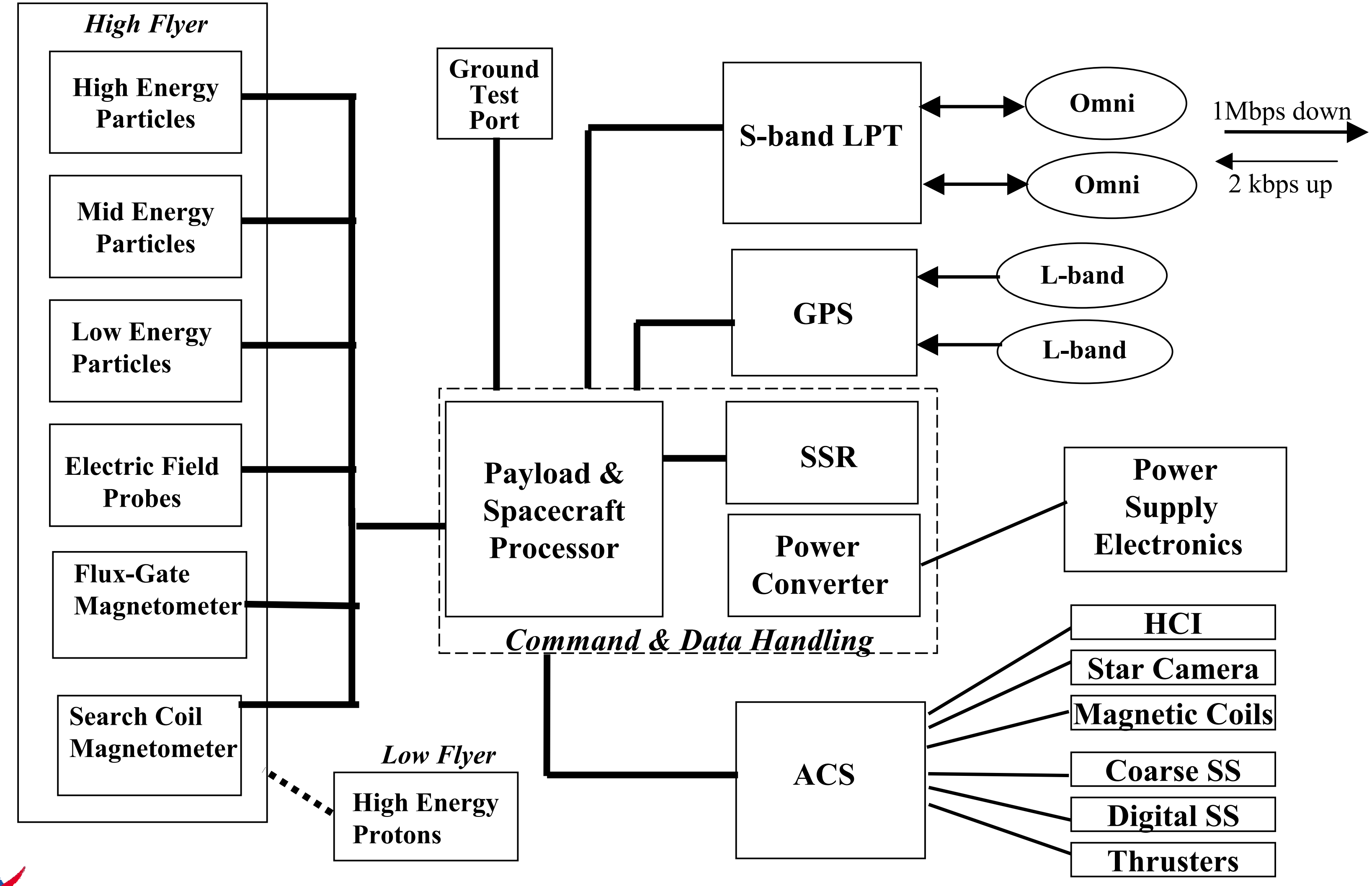
- Three ground stations are required to downlink data from the proposed group of satellites.

- Although a single-string spacecraft design approach was adopted to minimize cost and mass to orbit, some redundancy is inherently achieved by employing a constellation of identical satellites.

- Exposure to high radiation environments and electrostatic cleanliness requirements place additional demands on satellite design.

- Innovative approaches to the design, fabrication, assembly, integration, and testing of multiple satellites and their components are needed to make the most efficient use of available resources.

RBM System Block Diagram


High Flyer

High Energy Particles

Mid Energy Particles

Low Energy Particles

Electric Field Probes

Flux-Gate Magnetometer

Search Coil Magnetometer

Low Flyer

High Energy Protons

Ground Test Port

S-band LPT

Omni

Omni

1Mbps down

2 kbps up

GPS

L-band

L-band

Payload & Spacecraft Processor

SSR

Power Converter

Command & Data Handling

Power Supply Electronics

ACS

HCI

Star Camera

Magnetic Coils

Coarse SS

Digital SS

Thrusters

RBM Mass Summary

Element			High Fly Mass (kg)	Low Fly Mass (kg)
Instruments*			48	54
Spacecraft Bus			199	199
	Mechanical	74		
	Power	17		
	Thermal	12		
	Attitude Control	13		
	Propulsion	40		
	C&DH	5		
	Communications	9		
	Harness	9		
	Balance Mass	7		
	Separation System	13		
Dry Mass Per Satellite			**247**	**253**
Propellant			174	106
Total Mass Per Satellite			**421**	**359**

* Includes 11 kg for booms, antennas, attachments, and harness

Values are best estimates and do not include contingency.

RBM Launch Margin Summary

Category	High Fly Mass (kg)	Low Fly Mass (kg)	Mass (kg)
Mass Per Satellite	421	359	
Number Of Satellites	6	1	
Mass To Orbit	2526	359	
Total Launch Mass			**2885**
Delta II 7920-10 Lift Capability*			**2500**
Delta II 7920H-10 Lift Capability*			**2825**
Launch Mass Margin			**(-)**
Descope Options			
Number Of Satellites/Mass	6	0	2526
	5	1	2464
	5	0	2105
	4	1	2043
	4	0	1684
	3	1	1622
	3	0	1263
* For a 500 x 8391 km orbit at 28° inclination			

See Launch Vehicle Evaluation For Viable Options.

RBM Launch Vehicle Evaluation

During the first IMDC mission concept study, it was assumed that the plane change required to achieve the desired low inclination orbit from ETR would be performed by the launch vehicle. This scenario imposed a significant constraint on launch mass and showed that not even 4 satellites could be accommodated with adequate lift margin by a medium class launch vehicle.

A revised scenario was adopted at the time of the IMDC revisit by which the launch vehicle delivered the satellites to a low apogee, 28° inclination orbit. The spacecraft propulsion systems were then sized to achieve the final orbit. This approach allowed 5 satellites to be accommodated on one launch with adequate margin if the Delta 7920H-10 launch vehicle was chosen.

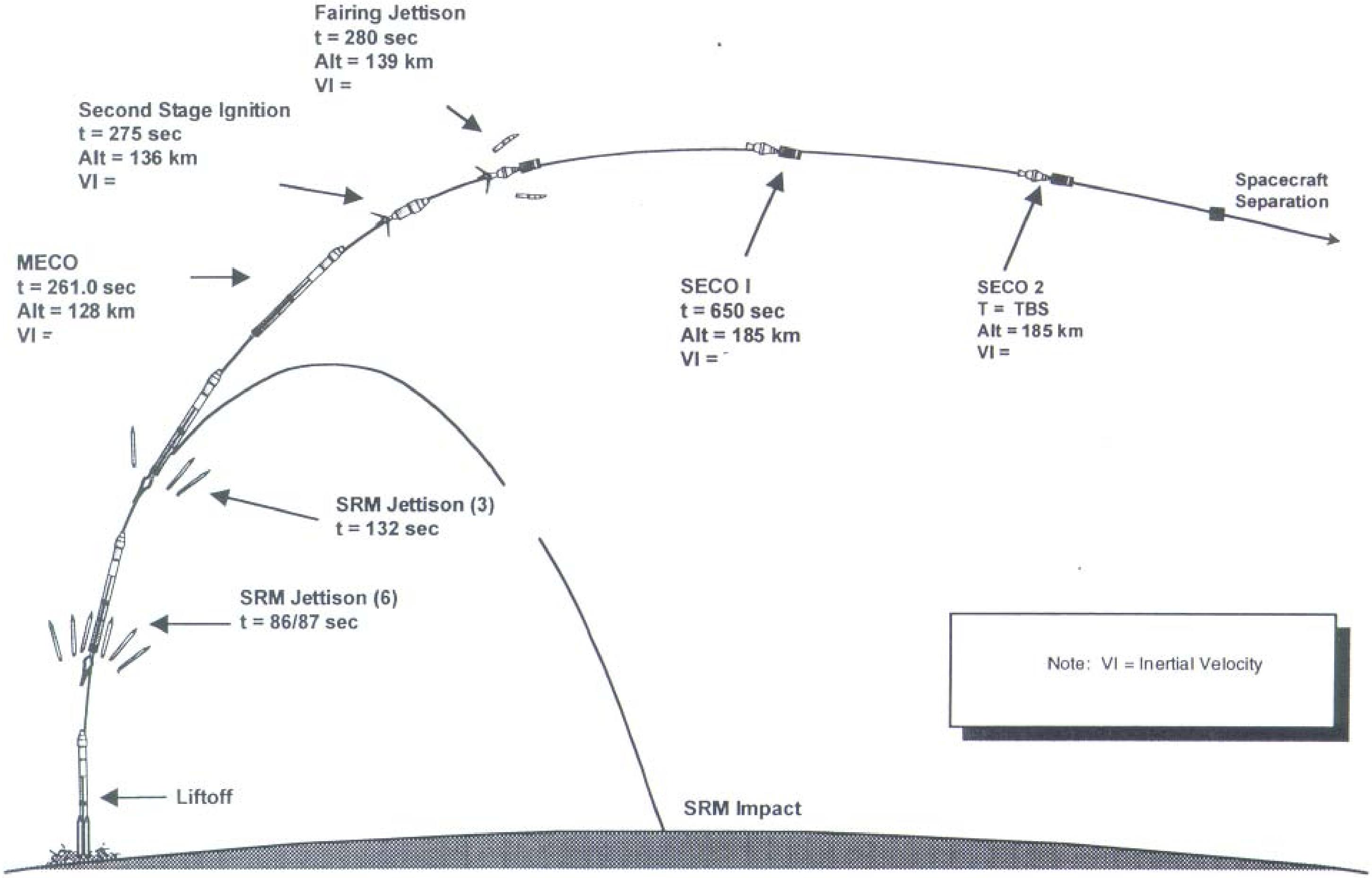
Although the full complement of satellites, described here, can be placed into their desired orbits by a larger class launch vehicle, a trade-off among cost, number of satellites, and inclination angle must be performed to resolve this issue.

RBM Power Summary

Element				**High Fly Power** (W)	**Low Fly Power** (W)
Instruments				26	33
Spacecraft Bus				65	65
	Power		13		
	Thermal		0		
	Attitude Control		10		
	Propulsion		10		
	C&DH		20		
	Communications		9		
	Harness		3		
Total Per Satellite				**91**	**98**
Solar Array Capability (BOL)				165	165
Power Margin (BOL)				**81%**	**68%**
Solar Array Capability (EOL)				145	145
Power Margin (EOL)				**59%**	**48%**

Values are best estimates and do not include contingency.

Typical Delta II 7920-10 Launch Profile



Fairing Jettison
t = 280 sec
Alt = 139 km
VI =

Second Stage Ignition
t = 275 sec
Alt = 136 km
VI =

MECO
t = 261.0 sec
Alt = 128 km
VI =

SECO I
t = 650 sec
Alt = 185 km
VI =

SECO 2
T = TBS
Alt = 185 km
VI =

Spacecraft
Separation

SRM Jettison (3)
t = 132 sec

SRM Jettison (6)
t = 86/87 sec

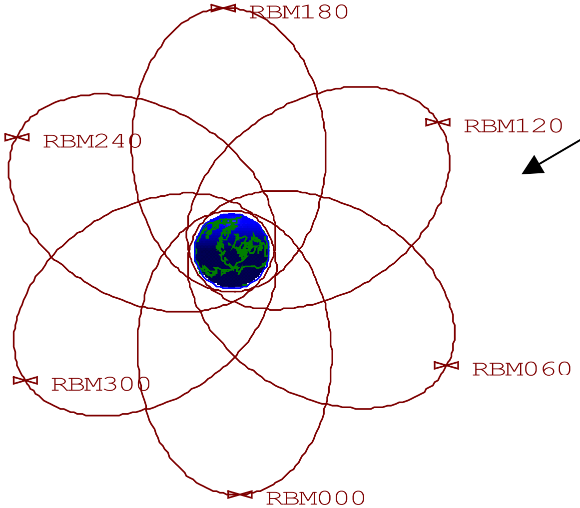
Liftoff

SRM Impact

Note: VI = Inertial Velocity

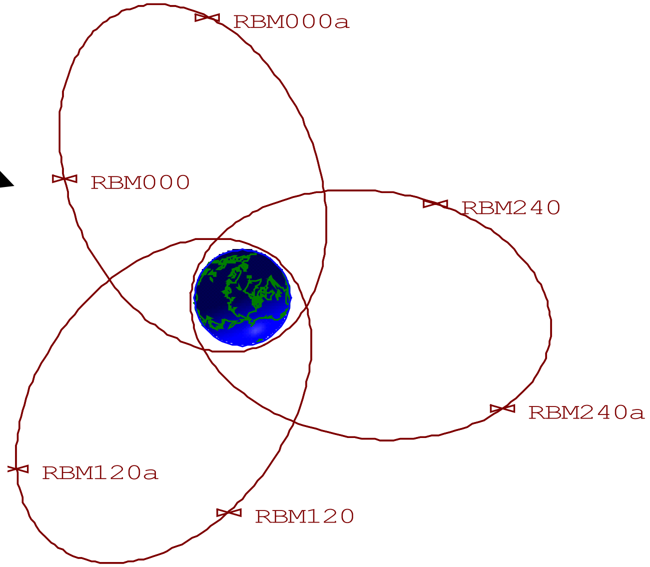
RBM Candidate Orbits

Low apogee orbit
not shown



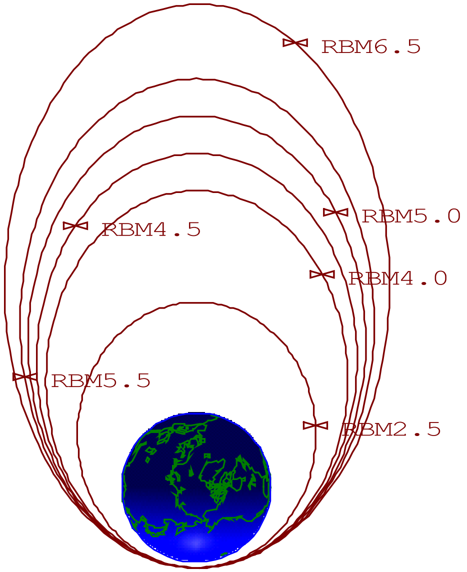
Six Petal Profile

Concept Baseline



Three Petal Profile

Second Choice



Nested Orbit Profile

Third Choice

Orbit Ranking As
Established By
Science Team

RBM Orbit Parameters

The parameters for the concept baseline orbit configuration are given below:

- **Six High Apogee Petal Orbits**
  - 60° separation between coplanar orbits
  - 500 km perigee x 6.5 R_E apogee
  - 12° inclination
  - 10.4 hour period

- **One Low Apogee Orbit**
  - 500 km perigee x 2.5 R_E apogee
  - 12° inclination
  - 3.4 hour period

RBM Orbit Insertion Scenario

- The launch vehicle places all satellites in a 500 km x 8391 km orbit at an inclination of 28°.

- The low apogee and first high apogee satellites are then boosted to their respective apogee heights and their inclination is changed to 12°.

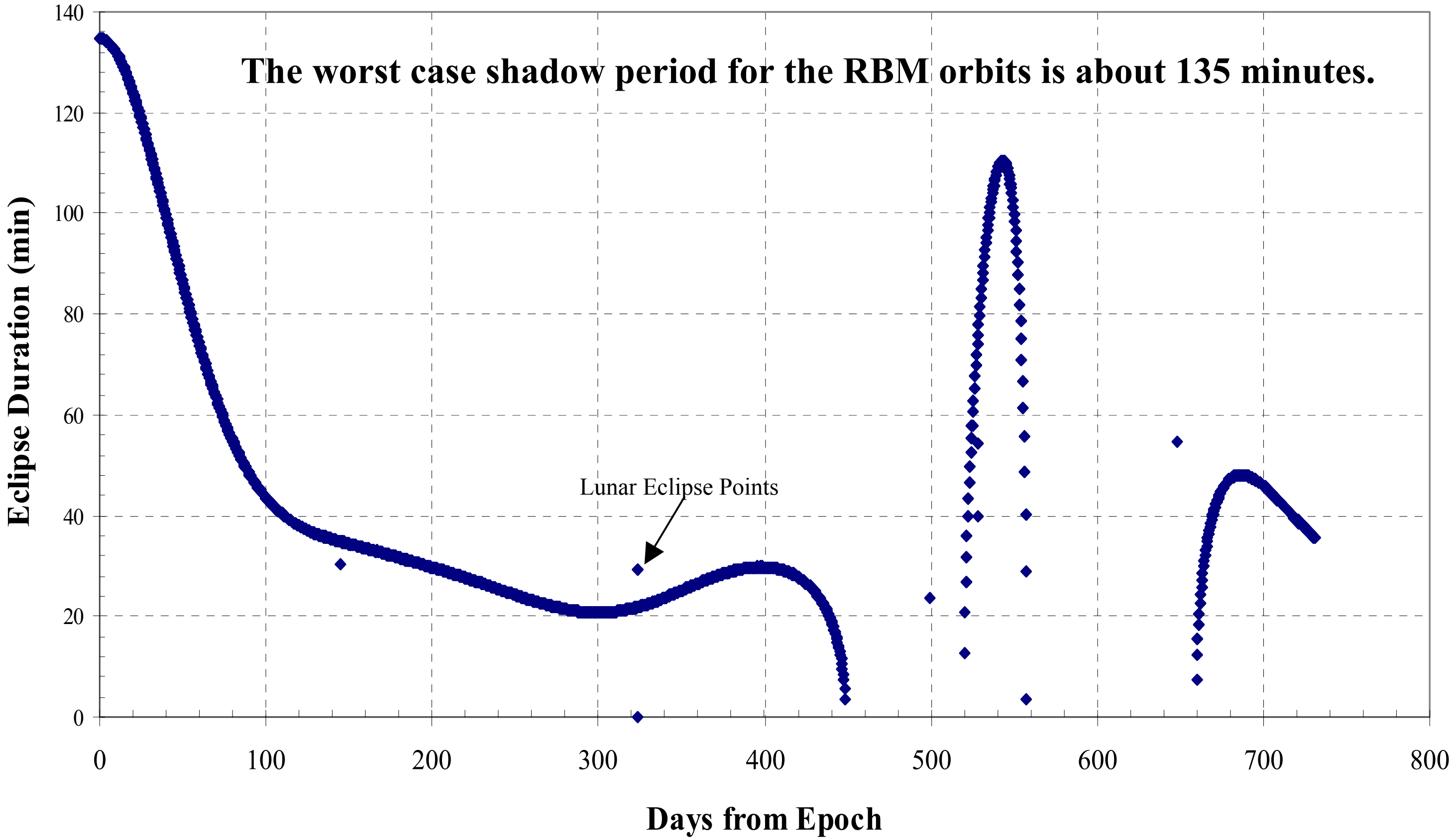
- Orbital precession moves the local time of apogee for the remaining satellites with respect to the above.

- As each satellite moves to the correct local time, it is boosted to the final apogee and its inclination is changed to 12°.

- Establishment of the desired orbit configuration will take about 180 days.

RBM Eclipse Profile

Radiation Belt Mapper
500 km x 6.5 Re, Epoch : March 21, 2007, noon perigee, 12 deg inclination
Combined Umbra and Penumbra Eclipse Times



The worst case shadow period for the RBM orbits is about 135 minutes.

RBM Spacecraft Features

RBM spacecraft features include:

- An identical, mission-unique, spin-stabilized bus design for each satellite
- High radiation tolerant subsystems and components
- Commonality with other LWS multi-spacecraft bus designs, wherever possible, to achieve economies of scale
- Spacecraft spin axis pointed to within +/-15 degrees of the sun during nominal mission operations
- Large bi-propellant system for satellite orbit adjust and inclination change
- Deployable instrument booms and wire antennas
- Body-mounted solar arrays to accommodate instrument fields-of-view and spinning mode
- A payload processor and a burst memory for instruments as part of the C&DH subsystem

RBM Mechanical Subsystem

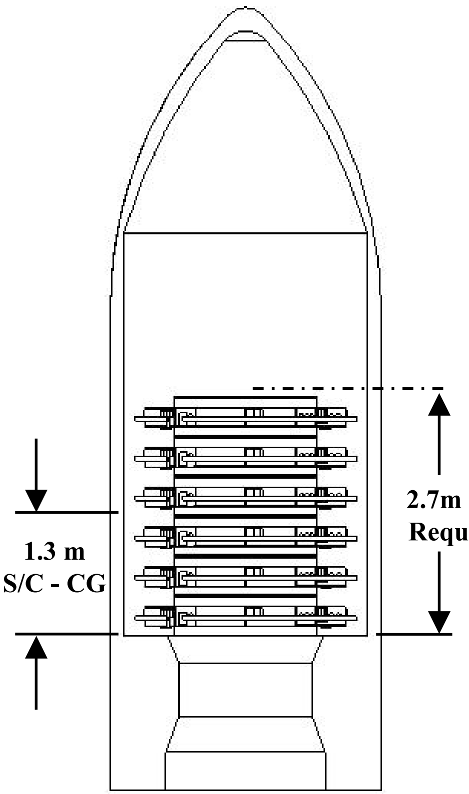
- The RBM Mechanical Subsystem utilizes standard aerospace design practices and fabrication techniques. Aluminum and composite structures are employed to accommodate spacecraft and instrument mass, thermal, and electrical constraints as applicable.

- Spacecraft are stacked for launch and are outfitted with clamp bands and separation springs for deployment from the launch vehicle.

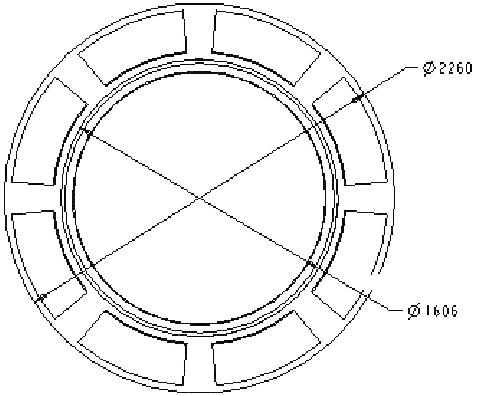
- Highly reliable mechanisms are used to deploy wire antennas for the electric field probes and booms for the flux-gate and search coil magnetometers.

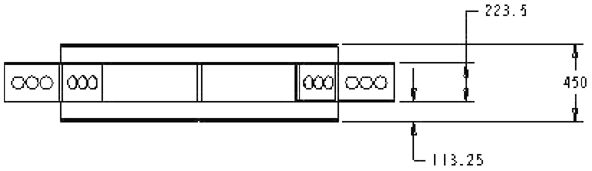
RBM Launch Configuration

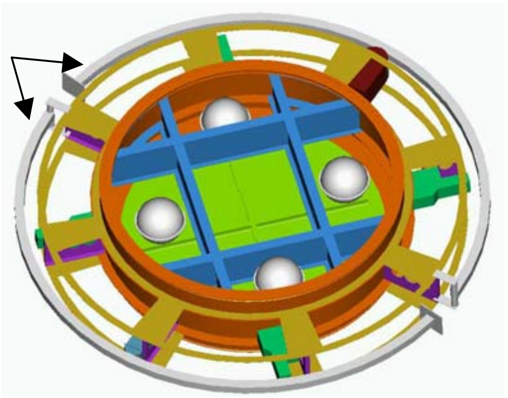
Spacecraft Stacked For Launch In Delta 7920H-10 Fairing

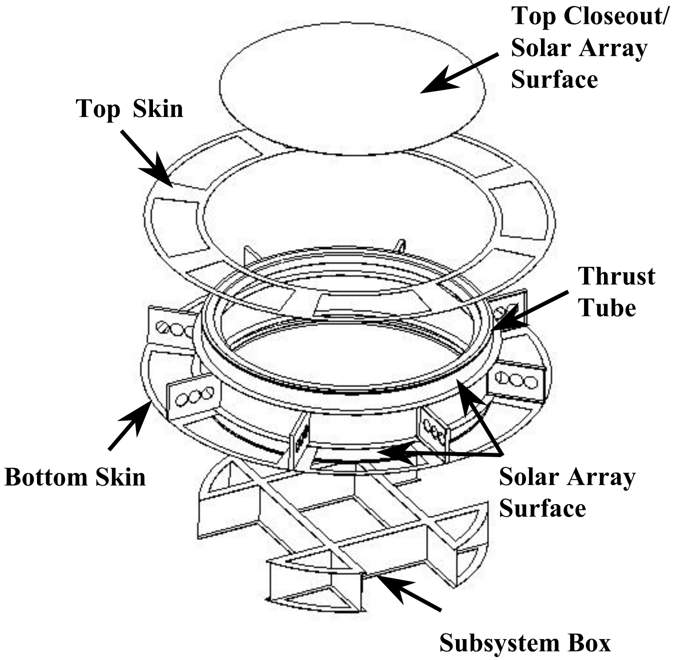


2.7m PAF CG Requirement

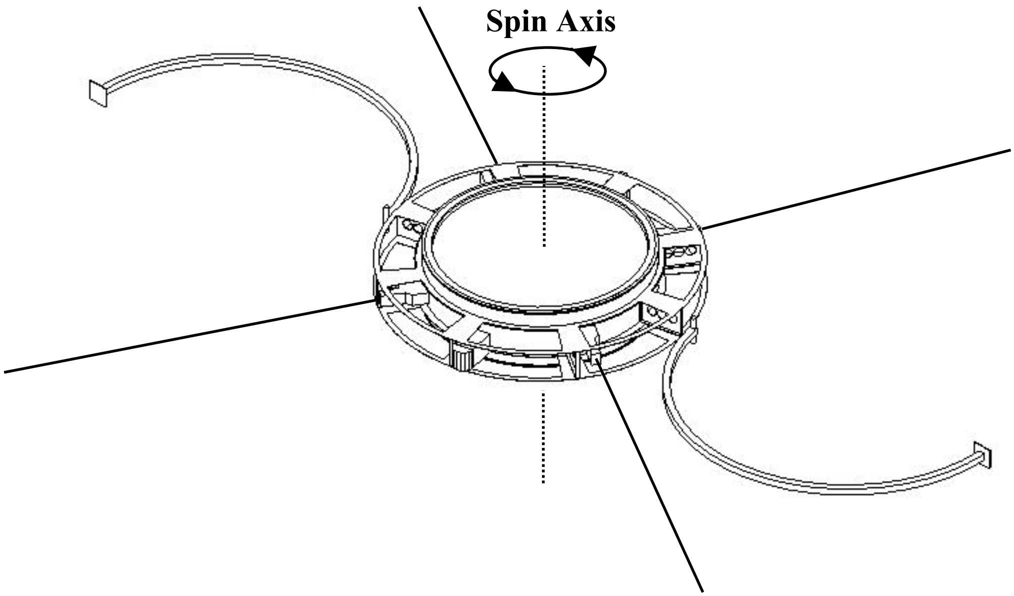




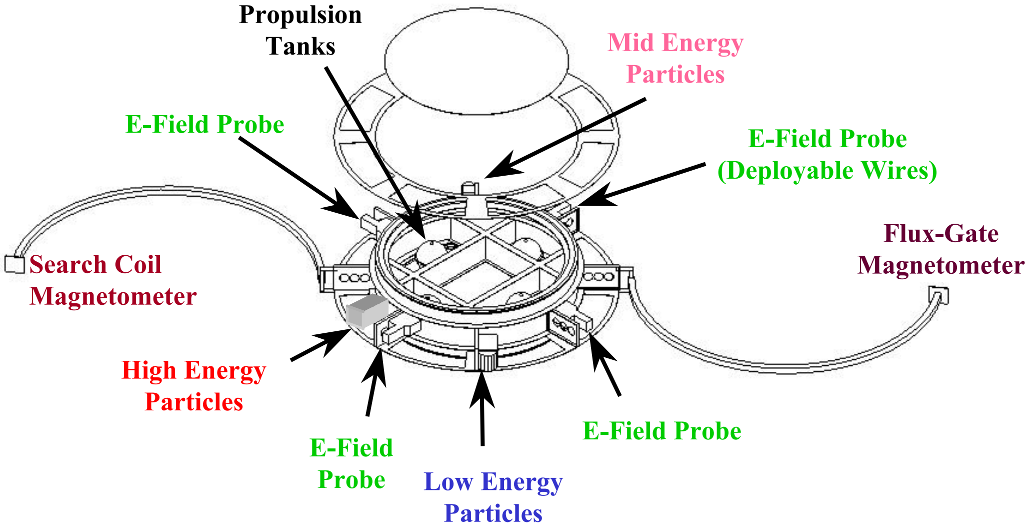




RBM Orbit Configuration



High-Energy Proton Detector On Low Flying Satellite Not Shown



RBM Power Subsystem

The RBM Power Subsystem is a 28-volt direct energy transfer system that can support a load of 98 watts at the end of the nominal mission life. It consists of the following elements:

- Three different body-mounted solar array surface orientations with a total triple junction GaAs cell area of 1.47 m^2 to ensure that power is available for satellite deployment, orbit transfer, normal operations, and safe hold
- Thick coverglass (60 mils) over solar cells on prime power generating areas
- A single 20 ampere hour Li-ion battery sized to handle transfer orbit conditions, the worst-case shadow period, and peak power demands
- Power supply electronics

Solar array degradation over the life of the mission due to UV exposure, ionizing radiation, thermal cycling, and system losses has been taken into account in the array sizing.

RBM Thermal Subsystem

A passive thermal design approach has been adopted that maintains instrument and spacecraft components in the range from 0° to 30° C with margin. Some special features include:

- Instrument and subsystem components mounted to spacecraft box structure
- Insulation blankets, coatings, and materials chosen to maintain the required level of electromagnetic cleanliness
- Doublers added to solar array substrate to minimize temperature gradients
- Conductive heat transfer paths from body-mounted solar arrays to thrust tube to maintain cells below 90° C
- Thrust tube thermally isolated from spacecraft box structure
- Batteries maintained between 5° and 15° C for long life
- Heater power for thermal control during eclipse periods and for propellant freeze protection

RBM Attitude Control Subsystem

The Attitude Control Subsystem (ACS) concept proposed for the RBM satellites can accommodate the instrument spin rate, pointing accuracy, and knowledge requirements as specified below:

- Maintain a stable spin rate between 6 and 10 RPM
- Keep the spin axis of each satellite aligned to within 15^{o} of the sun line
- Provide attitude knowledge of 0.3^{o} (1 sigma)

RBM Attitude Control Subsystem (continued)

The following complement of hardware is used in conjunction with propulsion subsystem thrusters to provide the functions required for attitude control of the satellites during orbit deployment, sun acquisition, science operations, and safehold:

- Coarse sun sensors for sun acquisition
- Digital sun sensor for sun pointing
- Magnetic coils for precession and spin rate control
- Horizon crossing indicator and star camera for attitude knowledge

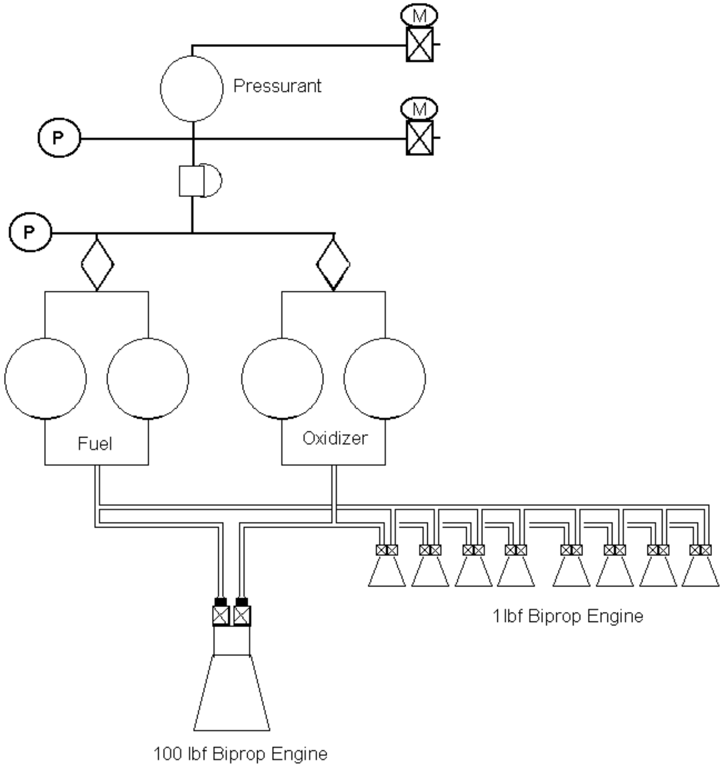
RBM Propulsion Subsystem

The Propulsion Subsystem consists of a single bi-propellant system for apogee raise and inclination change after initial orbit insertion, orbit maintenance during the nominal 2 year mission, and disposal.

The total DV requirements are 1.52 km/s for the high flying satellites and 1.0 km/s for the low flying satellite. The specific impulse used for the bi-propellant (MMH/N_2O_4) is 290 s.

A schematic representation of the proposed Propulsion Subsystem is given in the following chart.

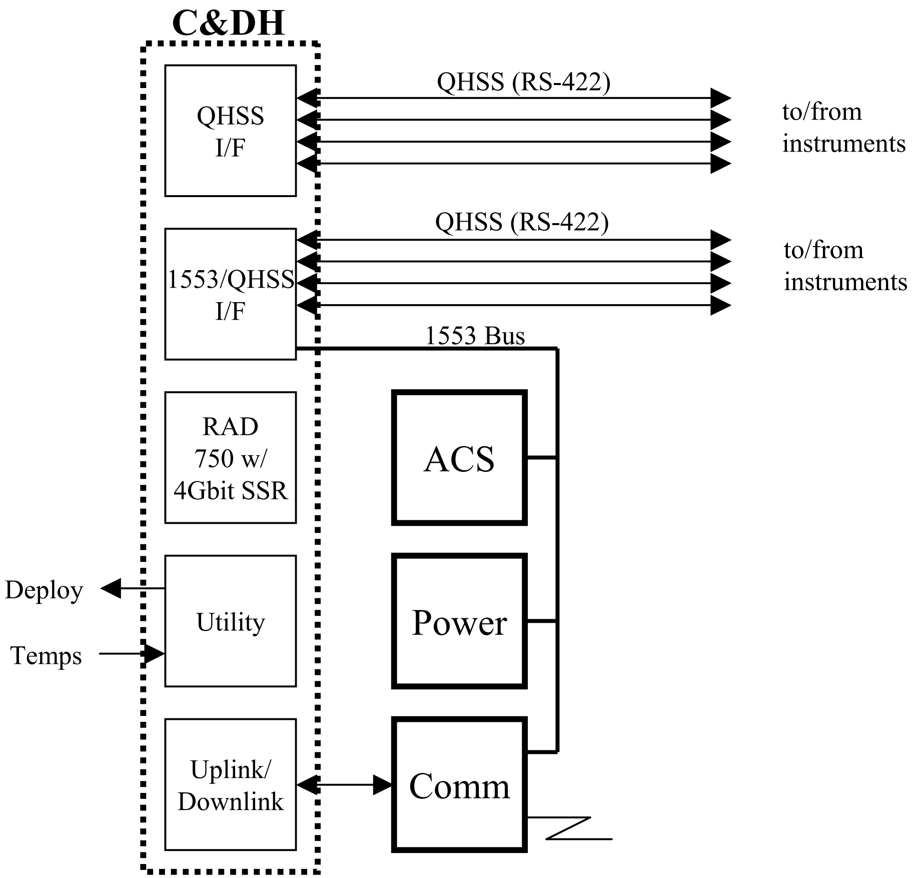
Propulsion Subsystem Schematic



RBM Command and Data Handling Subsystem

The RBM C&DH Subsystem provides the following functions:

- Processing of commands/telemetry
- Master timing
- Sequencing/deployments
- CCSDS formatting
- Programmable data compression
- Data encoding/decoding
- Data recording
- Attitude control
- Watchdog resets

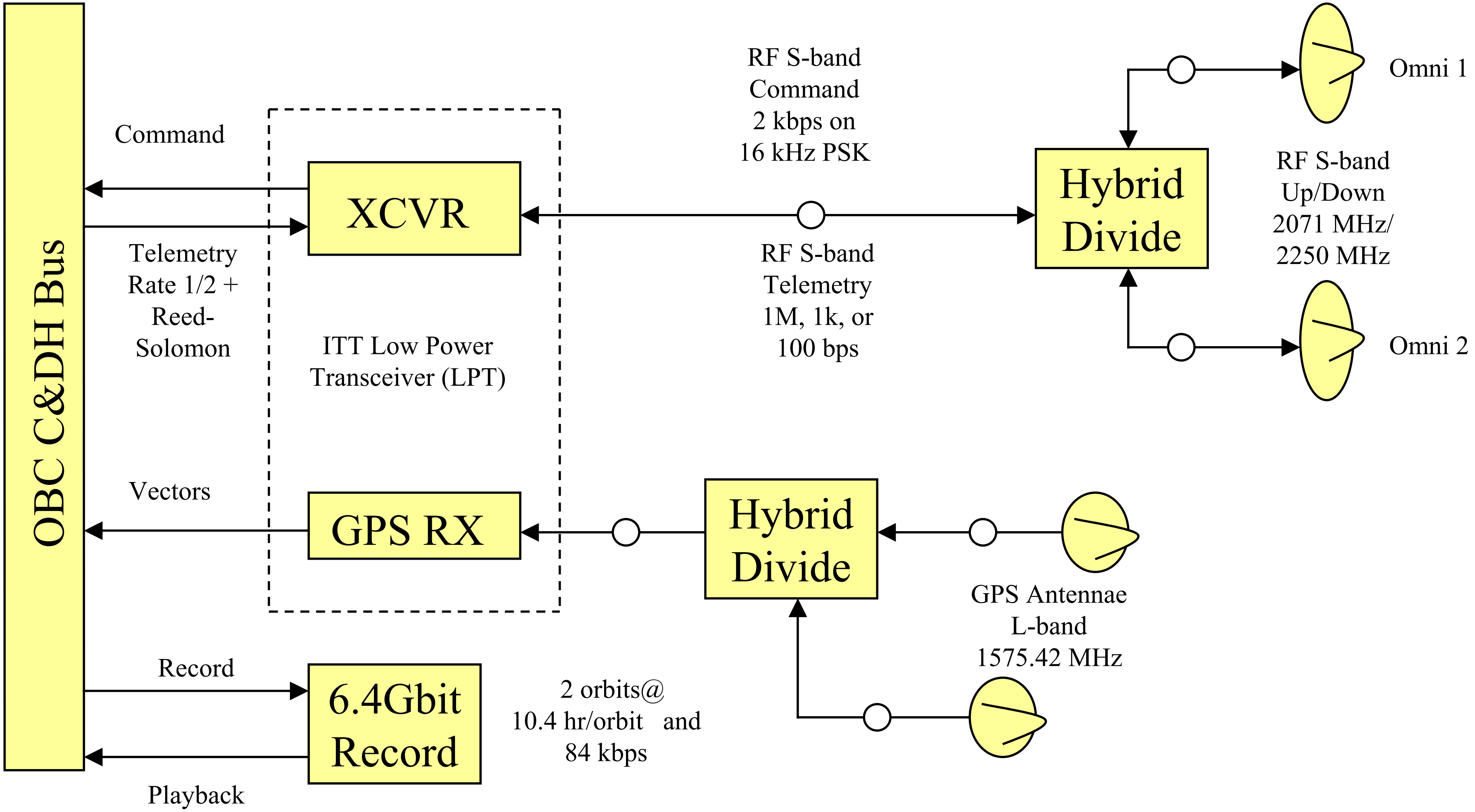


RBM Communications Subsystem

The RBM Communications Subsystem, shown in the schematic that follows, includes the following provisions:

- S-band uplink/downlink with all satellites at the same frequency
- Real-time broadcast mode for limited data set
- Omni-directional antennas for all communications and commanding
- Low power transceiver with GPS for orbit determination
- Rate ½ plus Reed-Solomon encoding

RBM Communications Schematic

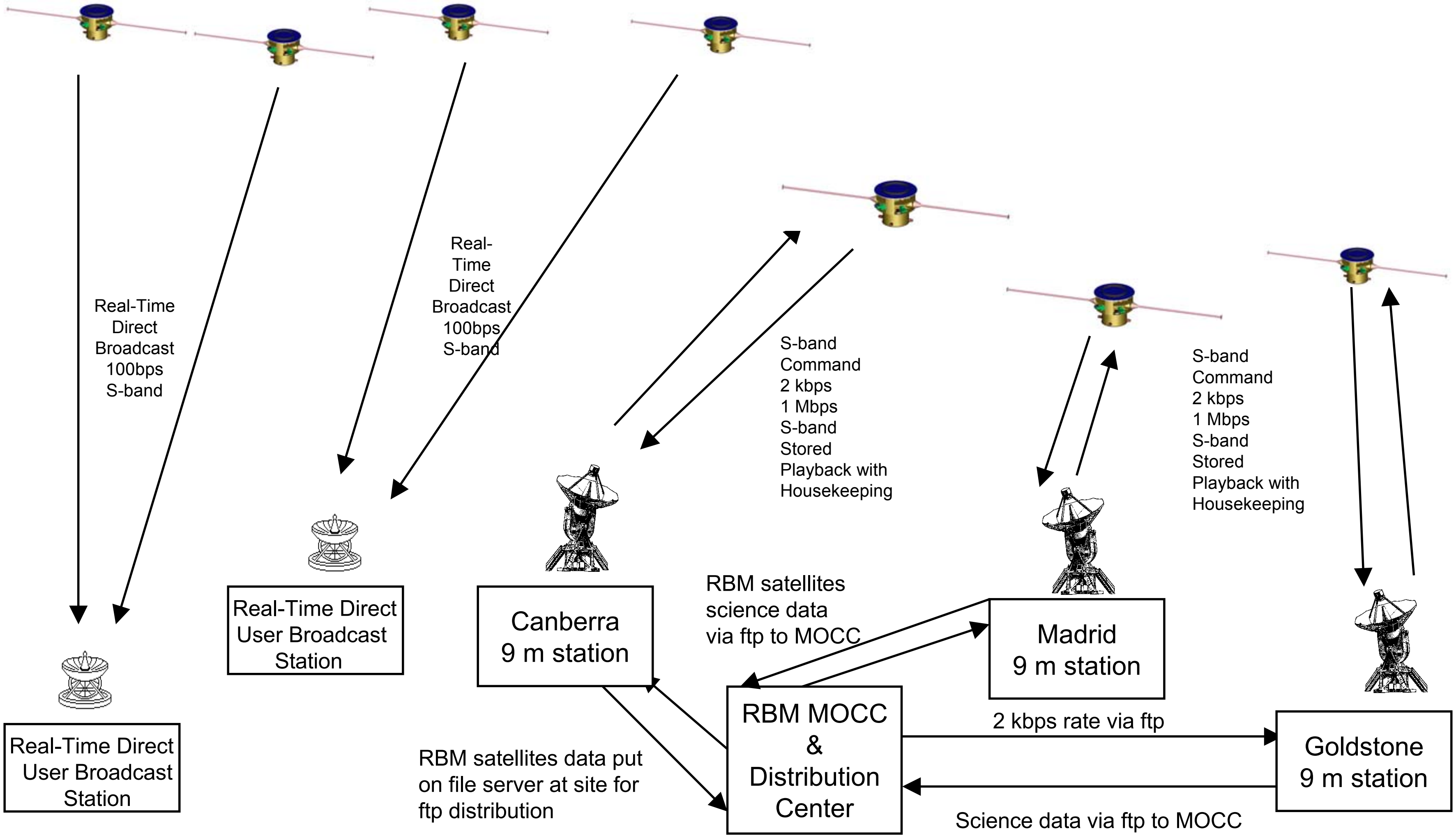


RBM Ground System

The proposed Ground System accommodations take advantage of existing infrastructure and include the following features:

- Three equally spaced 9 m antennas on ground for science data transmissions (Canberra, Madrid, and Goldstone assumed for this study)
- Limited real-time data via a continuous broadcast mode to small (0.5 m) user-provided terminals at remote sites
- Data delivered via ftp from 9 m ground stations to RBM MOCC for processing
- Data Latency
  - 48 hours for science research community
  - Real-time for select users

RBM Ground System Concept



Real-Time Direct Broadcast 100bps S-band

Real-Time Direct Broadcast 100bps S-band

S-band Command 2 kbps 1 Mbps S-band Stored Playback with Housekeeping

S-band Command 2 kbps 1 Mbps S-band Stored Playback with Housekeeping

Real-Time Direct User Broadcast Station

Real-Time Direct User Broadcast Station

Canberra 9 m station

Madrid 9 m station

Goldstone 9 m station

RBM MOCC & Distribution Center

RBM satellites science data via ftp to MOCC

RBM satellites data put on file server at site for ftp distribution

2 kbps rate via ftp

Science data via ftp to MOCC

RBM Mission Operations

A Mission Operations concept has been adopted that encourages automation and makes use of commercial-off-the-shelf (COTS) products. Features include the following:

- Combined Mission and Science Operations Center (MSOC) to support a fleet of up to seven RBM satellites
- COTS command and control system augmented with a minimal amount of mission unique software
- Science data dumps nominally once per orbit
- Science data processed to Level Zero and short-term archival at MSOC
- Lights out operations after an orbital routine is established

RBM Science Data Distribution

The RBM Science Data Distribution provisions include the following:

- Recovery of 95% of all data
- Level Zero data products to science teams within 24 hours of receipt from satellites
- Local 30 day archive at MSOC
- Data pushed to science data centers or put on server for retrieval

RBM Mission Specific Technology

The RBM mission concept incorporates new technologies that are expected to be available in the near term. Such items include:

- Large, radiation resistant, solid-state memory for data storage
- High-efficiency, triple-junction, GaAs solar cells
- Li-ion battery
- Star camera
- Room temperature, super-conducting magnetic coils
- Low power GPS transceiver

RBM Preliminary Risk Assessment

During the course of the RBM concept study, a number of risk areas were identified and are listed below. Further study will be required to fully assess these risks, their potential impact, and mitigation strategies.

- The availability of radiation-hardened electronic devices and materials is critical to successful mission implementation.
- Fairing access to allow on-stand off-loading of propellant from the stack of satellites in the event of an emergency will require special provisions.
- The launch of multiple satellites and reliance on several ground stations complicates the operational scenario during the initial phase of the mission.
- There is the potential for RF interference between the low flying satellite and the high flyers.
- Although conservative assumptions have been made, availability of anticipated technology enhancements must be assessed at regular intervals.

RBM Study Recommendations

- Perform a trade-off study with number of satellites, launch vehicle, and inclination angle as parameters to determine the best way to place multiple satellites into the desired orbits for reasonable cost.
- Consider a staged mission implementation approach in which one satellite is launched first to verify proper operation before launching the remaining complement of satellites.
- Characterize the radiation environment for the RBM instruments and spacecraft for 2 and 5 year lifetimes.
- Develop a detailed mission operations concept for establishing and tracking the constellation of satellites.
- Pursue commonality of RBM/IM instrument and spacecraft designs.
- Identify technology investments that will reduce instrument system resource requirements.
- Identify process developments that simplify the building and testing of multiple research grade instruments and spacecraft.

Acronyms

ACS	Attitude Control Subsystem
AKM	Apogee Kick Motor
BOL	Beginning Of Life
C&DH	Command and Data Handling
CCSDS	Consultative Committee for Space Data Standards
CG	Center of Gravity
COTS	Commercial-Off-The-Shelf
DE	Dynamics Explorer
DS	Deep Space
ELV	Expendable Launch Vehicle
EOL	End Of Life
ETR	Eastern Test Range
FAST	Fast Auroral Snapshot Explorer

Acronyms

GaAs	Gallium Arsenide
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HQ	Headquarters
I/F	Interface
IM	Ionospheric Mappers
IMDC	Integrated Mission Design Center
IMEX	Inner Magnetospheric Explorer
Li	Lithium
LPT	Low Power Transceiver
LWS	Living With a Star
MECO	Main Engine Cut-Off
MMH	Mono-Methyl Hydrazine

Acronyms

MOCC	Mission Operations Control Center
MSOC	Mission and Science Operations Center
NASA	National Aeronautics and Space Administration
OBC	On-Board Computer
PAF	Payload Attach Fitting
RBM	Radiation Belt Mappers
R_E	Earth Radii
RF	Radio Frequency
RPM	Revolutions Per Minute
SECO	Secondary Engine Cut-Off
SRM	Solid Rocket Motor
SSR	Solid State Recorder
UV	Ultraviolet