Propulsion Hardware Selection:
Tanks and Thrusters

FAME Technical Interchange Meeting (TIM)

March 20-21, 2001

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Agenda

- Propulsion System and Mission Overview
- Critical Assumptions
- Mission Analysis
- Propulsion Analysis
- Propellant Budget
- Margin Analysis
- Tank Selection
- Tank Procurement
- Thruster Selection and Procurement
- Issues
Overview: Propulsion Mission Requirements

• Provide Thrust for Spacecraft Orbit Raising, Attitude Control, and Stationkeeping

• Provide Single Fault Tolerant Design
  - Thruster Failure
  - Valve Leakage

• 5 Year Mission Life
  - Design For Delivery by August 15, 2003
    - Derived From Integrated Master Schedule
  - Design, Qualify, and Test for FAME Mission and Launch Environments
    - NCST-TP-FM001, FAME Test Plan
    - New or Re-Designed Systems Will Have Protoflight Testing

• Meet Launch Base Safety Requirements and Verification Process
  - EWR-127-1 TBD Version, Tailored for FAME

• Support Science Mission Requirements
  - Minimize CG Migration, Plume Contamination, and Minimum Impulse Bit

• Minimize Cost and Schedule Risk
  - Provide Most Flexible Design With Given Schedule and Budget
Overview: FAME Propulsion Schematic

- Gas Service Valve
- Hydrazine Tank With PMD
- Dual Solenoid Valves
- (8) 1 or 5 N Thrusters
- (4) 22 N Thrusters (Open Trade Study)

Additional components:
- Pressure Transducer
- Filter
- Latch Valve
Overview: Mission Sequence

• Launch Delta 2925 into FAME Super-Synchronous Transfer Orbit
  - 185 by GEO Alt + 320 Km
  - Apogee Selected for AKM Disposal Orbit
  - 10.6 Hour Period
  - Activate S/C and Wait 2.5 Days for Phasing and Orbit Determination
    - S/C Pointing, Slew Maneuvers, Spin-up, Spin Axis Precession, Nutation Control

• Fire On-Board STAR 37XFP Solid Rocket Motor to Circularize into a Circular Super-Synchronous Orbit
  - 1 Minute SRM Burn
  - Orbit Nominally Circular at GEO + 320 km
  - Dispose of the STAR 37XFP Transfer Stage
  - Orbit Drifts for Approximately 1 Month to Mission Longitude
    - Deploy Sunshield
    - Perform Payload Check Out

• Correct Launch Vehicle Errors and Transfer to the Mission Orbit With On-board Hydrazine System
  - 3 Axis Inertial Pointing With ACS Limit Cycle Motion
Critical Assumptions (1 of 2)

• No Major Changes to the Current Mission Design
  - Delta 2925-10 Launch Vehicle
  - Thiokol STAR 37XFP or Equivalent Solid Upper Stage
  - No Significant Changes in Mission Orbit (i.e. Inclination, Stationkeeping Requirements)

• No Major Component Failures
  - Nominal 3 Sigma Performance for the Launch Vehicle and Upper Stage

• Fuel Cg Knowledge and Propellant Slosh Are Not ADCS Control Issues for Science Collection
  - Assumption of 2 mm Cg Knowledge

• Pointing Accuracy of ±2° for Upper Stages
  - Three Sigma Error For Delta LV is Equivalent to ±1.5°
• 3rd Design Iteration Worst Case Mass Properties Dated 3/07/01 Are Representative of the Final Payload
  - Mass and Inertia Properties
• Debris Mitigation Plans Per NASA NPD 8710.3 and Assessment Per NSS 1740.14 are Approved
  - Normal Review Cycle Includes Submittals at Program PDR and CDR
• No Thruster ACS During Science Collection
  - Solar Precession, Nutation Control, or Fine Spin Control
  - Long Duration Limit Cycle Motion is Fuel Intensive
Mission Analysis Methodology

• Define Disposal Orbits for Debris Mitigation
  - Determine AKM Transfer Stage and Final FAME Disposal Orbits
    - Based on NASA Guidelines
• Evaluate Launch Vehicle Performance to FAME Insertion Orbit
  - Penalize Delta 2425 for Performance to Higher FAME GTO Orbit
    - Mass Penalty is About 10 kg
• Perform AKM Sizing
  - Performance, Loads, Propellant Requirements Including Offload, Determine Mass Allocations and Staging Efficiencies
• Perform Stage Error Analysis
  - Pointing and Total Impulse Error Evaluation and Correction
• Evaluate Orbit Design
  - Calculate Delta Velocity Requirements For Maneuvers
    - Investigate Sub-Synchronous Transfer Option
• Calculate On-Board Hydrazine Requirements
  - Size the Hydrazine Tank
Propulsion Analysis

• Solid
  - Staging Performance for the Delta and STAR 37XFP
  - System Sizing and Motor Selection
  - Calculate Propellant Offloads and Offload Capabilities
  - Perform Total Impulse and Pointing Error Analysis
• Mass Properties Investigated at the Component Level
  - Provided Solid and Liquid System Mass Input Into Mechanical Mass Properties
• Liquid Hydrazine System Fuel Sizing
  - Blowdown Pressurization Pressurization Budget
• Thruster Performance
  - Thrust, Isp, Minimum Impulse
  - Inputs Supplied to Orbit and ACS Analyst
• Final Tank Sizing
  - Hardware Selection and Availability
  - Mechanical and Geometric Constraints
ACS Analysis

• Evaluate Mission Thruster Maneuvers
  - Inertial Pointing
  - Slew Maneuvers
  - Spin Maneuvers
  - Active Nutation Control (ANC)
  - Spin Axis Precession (SAP)
  - ACS During Delta V Maneuvers

• Assumptions Throughout Analysis
  - Worst Case Mass Properties Mass and Inertia
  - Nominal Thrust Performance
  - Conservative Isp
  - Nominal Thruster Moment Arms
  - Nominal Nutation Time Constant
  - Worst Case Thruster Alignment ±1°
  - No ANC During Solid Rocket Motor Firing
## Propellant Budget

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**72.6 Kg (160 lb) Propellant Load**
Margin Analysis (1 of 3)

• Worst Case Margin is 12.8% of Total Propellant Budgeted
  - Nominal Mission Case Margin is 24.7% of Total Propellant Budgeted
    - Nominal Mass, Thruster Performance, Error Correction
• Additional Margin is Built-in to Worst Case Margin Via Conservative Analysis Assumptions
  - Worst Case Launch Vehicle Throw Weight
  - Worst Case Mass Properties
  - Worst Case Launch Vehicle Insertion Error
  - Worst Case (Sum) STAR 37XFP Upper Stage Error
    - Can RMS, RSS, or Perform Monte Carlo Analysis
  - Worst Case Mission Plan
    - Longest Dwell at Energy Dissipating States
      - ANC, Limit Cycle Motion for Inertial Pointing
    - Highest Disposal Orbits for Debris Mitigation
Margin Analysis (2 of 3)

• Additional Propulsion Margin is Possible
  - Can Fill Propellant Tank with 203 lb of Hydrazine (31% Propellant Margin) and Implement a Secondary Pressurization System
    - Requires 2 or 4 Pressurization Tanks to Maintain Spacecraft CG
    - Tank Volume of 1045 cu. In. Required for 3:1 Blowdown
      - Four 20.3 cm (8 in) Diameter Pressurization Tanks
    - Can Move to Higher Blowdown Ratio (Currently 4.78:1)
      - Higher Beginning of Life Thrust and Lower End of Life Thrust
      - Re-Evaluate Tank Maximum Pressure of 350 psia
        - Current Safety Margin is 2:1, Can Move to 1.5:1
  
• Additional Delta V Margin
  - Above GEO Disposal Orbit is CSR Baseline but Below GEO Disposal Has Staging Efficiency That Reduces Overall System Mass
    - Increases Effective Launch Vehicle Throw Weight
  - Conservative Isp of 220 vs. 230 sec

• Additional AKM Propellant Option
  - Overfill the AKM to Guarantee No Orbit Undershoot with Solid
    - Solid Has Higher Isp Performance and Extra Propellant Capability
Margin Analysis (3 of 3)

• Orbit Analysis Performed for LV and Transfer Stage Errors
  – Worst Case Delta V’s Generated (Poor Man’s Monte Carlos)
    - Lowest LV GTO Orbit, Lowest STAR 37XFP Performance
    - Error Correction Would Occur at More Efficient Orbital Positions
      - Apogee Error Corrected in GTO
      - Delta V Equivalent of 39.1 m/s (Propellant Budget Carries 49 m/s)
  – Additional ACS Margin
    - Increase Thruster Moment Arms with Booms
    - Reduce 1 Hour Pre AKM Spin Time (Nutation Control Propellant)
    - Lower Intermediate Spin Rate Prior to High Spin at AKM Firing
    - Eliminate or Relax Inertial Pointing Requirements for Limit Cycle Motion Allowing a Possible Flat Spin Attitude
      - Requires Power and ACS Sensor Analysis
    - Can Boost Conservative Isp of 160 to 180 sec for Thruster Pulse Mode Operations
    - Implement Pure Off-Pulse ACS for Delta V Maneuvers
Tank Selection (1 of 2)

- Tank Selection Issues Requires Additional Analysis
  - Requires Quantification of Propellant and Pressurization
  - Single Blowdown Tank vs. Augmented Pressurization Tank
- Tank Geometry
  - Oblate Spheroid Desired but Has Limited Availability
    - Reduces Spacecraft Overall Height Allowing Preferred Sun Angle Between the Sun Shield and Payload
  - Mounting Options Include Boss and Girth (Tabs or Skirt)
- PMD Selection Limits Availability
  - Passive PMD Is Not Possible (Accelerations, Spin, and CG Control)
  - Trade Elastomeric Tank Bladder vs. Metal Diaphragm
    - Metal Diaphragm Has Higher $\Delta P$ From Gas to Liquid
    - Metal Diaphragm Has Better Cg Control During Accelerations
    - Metal Diaphragm Is Single Use Only
    - Metal Diaphragm Eliminates Gross Mass Motion Slosh
    - Elastomeric Diaphragm is Less Expensive
Tank Selection (1 of 2)

• Cost and Delivery Schedule
  - Heritage Design Is Desirable
  - New Design and Qualification Possible (Lengthy Delivery and Costly)
  - New Tank Design and Qualification Requires 24 Months ARO
    - Program Schedule Supports New Tank Procurement
    - Multiple Designs and Vendors Available
      - PSI, Atlantic Research, Arde, Keystone
• Implication of Oversizing the Hydrazine Tank
  - Lowers the System Blowdown Ratio
    - Smaller BOL to EOL Thrust Variation
      - Effects on Nutation Control (Requires High Thrust)
      - Effects on Minimum Impulse (Requires Low Thrust)
    - Can Overfill to Correct Blowdown Ratio
      - Mass Penalty for Unused Propellant
  - An Oversized Tank is an Excellent Reservoir for Mass Margin
    - Allows for Contingency Operations, Science Mission ACS, or Extended Mission
Tank Baseline: PSI P/N 80388

- Maximum Expected Operating Pressure (MEOP) 350 psia
- Proof Pressure 527 psia, Minimum Burst 700 psia
- Qualified Propellant Load of 72.56 kg (160 lb)
- Geometry
  - 57.15 cm (22.5 in) Outside Diameter
  - Spherical with Offset Polar Outlet Tube
  - Volume 91.1 Liters (5555 cu in)
  - Tank Weight 7.03 kg (15.5 lb)
  - Four Girth Mounted Tabs With Slots
  - AF-E-332 Elastomeric Bladder
- Designed and Previously Flown for KoreaSat, CENTAUR, TOMS-EP, ROCSAT, KOMPSAT, INMARSAT 3, GGS
- Full Mil-Std-1522 Design, Analysis, and Qualification Testing
  - One Known Safety Waiver Required for Last Girth Weld Stress Relief
Tank Procurement Status

- Component Specification Under Development
  - Document Number TBD
- Detailed Discussion With Potential Vendors Ongoing
  - PSI, Arde, Atlantic Research, Keystone
- Baseline PSI Tank is Off-the-Shelf With 18 Month Delivery
- Procurement Package Compiled and Submitted by 13 April 01
  - Initiated Dialog with Contracts Personnel
    - Purchasing Agent TBD
- Auxiliary Pressurization Tanks Are Still Under Investigation
  - Lead Time is Shorter Since Tank Does Not Have PMD
    - 14 Month Delivery Allows a PDR Decision
  - Multiple Vendors Possible
    - Kaiser Compositek
    - Lincoln Composites
    - Structural Composites Industries (SCI)
Propellant Slosh

- Fuel Sloshing in the Propellant Tank Has Not Been Analyzed
- Gross Mass Sloshing is Well Understood
  - CG Control During Expulsion and Accelerations
    - Controlled With Tank Specifications
    - Verified With Qualification or Acceptance Testing
      - Non-Destructive Testing is Possible With Elastomeric Diaphragm Tank but Not Metallic Diaphragm
- Fine Motion of Propellant and Damping Characteristic is Not Well Understood
  - Interaction Between Excitation Sources and Damping Propellant Motion
    - Evaluate All Excitation Sources: Thrusters, Motors, Torque Rods, Thermal Variations, Eclipse Effects
    - Model Propellant Viscous Motion and Damping Effects
      - Mathematical Models Will Take Several Months to Generate
      - Model Verification Through Testing is Not Possible
      - 1g Environment Swamps Subtle Slosh Effects
Thruster Procurements

- Component Specification Under Development
  - Document Number TBD
- Detailed Discussion With Potential Vendors Ongoing
  - General Dynamics, Atlantic Research, ValveTech Consortium
- Procurement Package Compiled and Submitted by 13 April 01
  - Initiated Dialog with Contracts Personnel
    - Thrusters Delivery Is 20 Months
    - Purchasing Agent TBD
- Minimum Impulse Bit Under Investigation
- Multiple Vendors Available
- Multiple Thruster Procurements On-Going For Other Customers
  - Manufacturing and Cost Efficiency
Hydrazine Thrusters (1 of 2)

- **Thruster Quantity and Force Selection**
  - 8 1N or 5N (from CSR) Thrusters
  - Spin Control and 3-Axis ACS
  - Zero, Two, or Four 22 N Thrusters
  - SAP, ANC, and Vehicle Delta V Thrusters
  - Minimum Impulse Bit and Maximum Thrust Are Design Drivers
  - Conflicting Requirements for a Single Thruster Size

- **Multiple Designs and Vendors Including**
  - Hamilton Standard 22N (5 lbf)
    - In Stock at NRL From Previous Programs
    - Single Seat Valve Originally Included was Replaced with Dual Seat Valve For Clementine
    - Documentation Status Unknown
  - Atlantic Research 22 N Thruster
  - MR-106E 22 N (5.0 lbf)
  - MR-50S,T 22 N (5.0 lbf) GOES, Viking, GPS, Voyager
  - MR-111C 4N (1.0 lbf) Flown on Clementine
Hydrazine Thrusters (2 of 2)

- MR-111E 2N (0.5 lbf)
  - Possible Compromise Between the Conflicting Small Impulse and High Thrust Requirements

- MR-103C 1N (0.2 lbf)
  - Small Impulse Bit, but Being Discontinued by Manufacturer
  - Ibitmin= .0044 N-sec @15ms and 100 psia

- MR-103D 1N (0.2lbf) Long Life Thruster Variant
  - More Costly Than Warranted by FAME Mission Requirements

- MR-103G 1N (0.2 lbf) IRIDIUM Design
  - Ibitmin= .0133 N-sec @15ms and 100 psia

- MR-103H 1N (0.2 lbf) Smallest Impulse Bit
  - Single Fast Acting Solenoid Valve Rather Than Dual Valves
  - High Cost ~$80K
  - Ibitmin= .0022 N-sec @15ms and 100 psia

- ValveTech Consortium 0.2 lbf Low Cost Thruster
  - Recently Flight Demonstrated
  - Qualification and Delivery Status TBD
Propulsion Issues

• Validity of Critical Assumption Used to Select Tank
• Tight Schedule to Meet Government Procurement Deadlines
  - Expedited Procurement Process Required If Procurement is Delayed
• Undefined Tank Slosh Requirements
• Major Procurements Are Well Before CDR (Sept 01)
  - Analysis Accuracy Due to Vehicle and Mission Design Uncertainty
• Minimize Different Thruster Designs for Cost Efficiency (Specifications, Procurements, Integration, and Test Simplification)
• Thruster Solar Precession Back-Up Requirement
  - Small Impulse Bit Control System Would Be Required
  - Requirement Evaluation and Definition Are Necessary
    - Long Lead Items Are Required
    - 18 Months for the Tank
    - TBD Months for Pulsed Plasma Thruster
• Thruster and Tank Analysis Are Still Under Investigation
  - We Have the 90% Answer - Good Enough