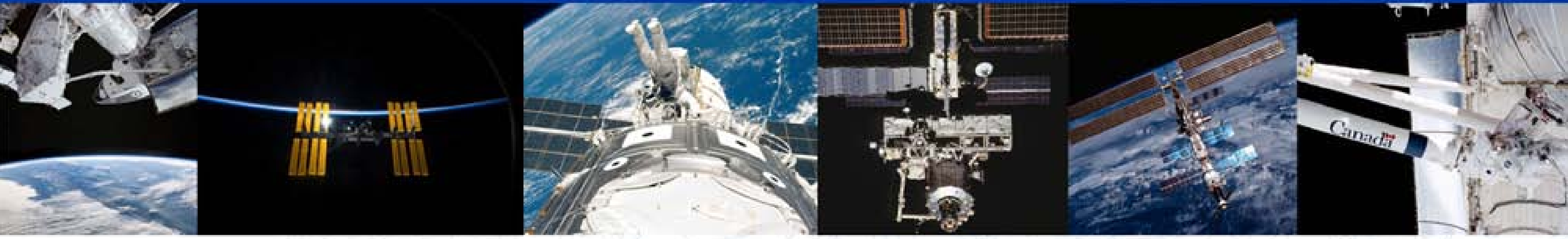
On-Orbit Propulsion and Methods of Momentum Management for the International Space Station



Samuel P. Russell, Victor Spencer and Kevin Metrocavage

NASA Johnson Space Center, Houston TX 77058

Robert A. Swanson, Mark Krajchovich, Matthew Beisner and Ulhas P. Kamath

The Boeing Company, Houston TX 77059

Overview

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Background

- Since the first documented design of a space station in 1929, it has been a dream of many to sustain a permanent presence in space.
- Russia and the US spent several decades competing for a sustained human presence in low Earth orbit.
- In the 1980's, Russia and the US began to openly collaborate to achieve this goal. This collaboration lead to the current design of the ISS.

ISS Propulsion Design Concepts

- **Must perform momentum management and debris avoidance.**
- **Minimize propellant consumption.**
- **Ensure the ISS is flown within the design limits and capabilities of the on-orbit hardware.**

Architectural Overview

- Based on heritage designs from both Russia and the US
- Lessons learned from previous space stations.
- A Torque Equilibrium Attitude (TEA) approach was selected.
  - TEA is a specific ISS Yaw, Pitch, Roll sequence selected so that the cumulative effect of all torques experienced by the vehicle during an orbit is approximately zero.
  - This lead to the need for an active momentum management system.

Architectural Overview

- Designed to allow temporary service vehicles to provide the bulk of the propulsive support while also providing the capability of resupplying propellant.
- Control Moment Gyroscopes (CMGs) are integrated to maintain attitude control between propulsive events.
- Russian hardware provides the bulk of propulsive elements.
- US hardware provides non-propulsive momentum management.

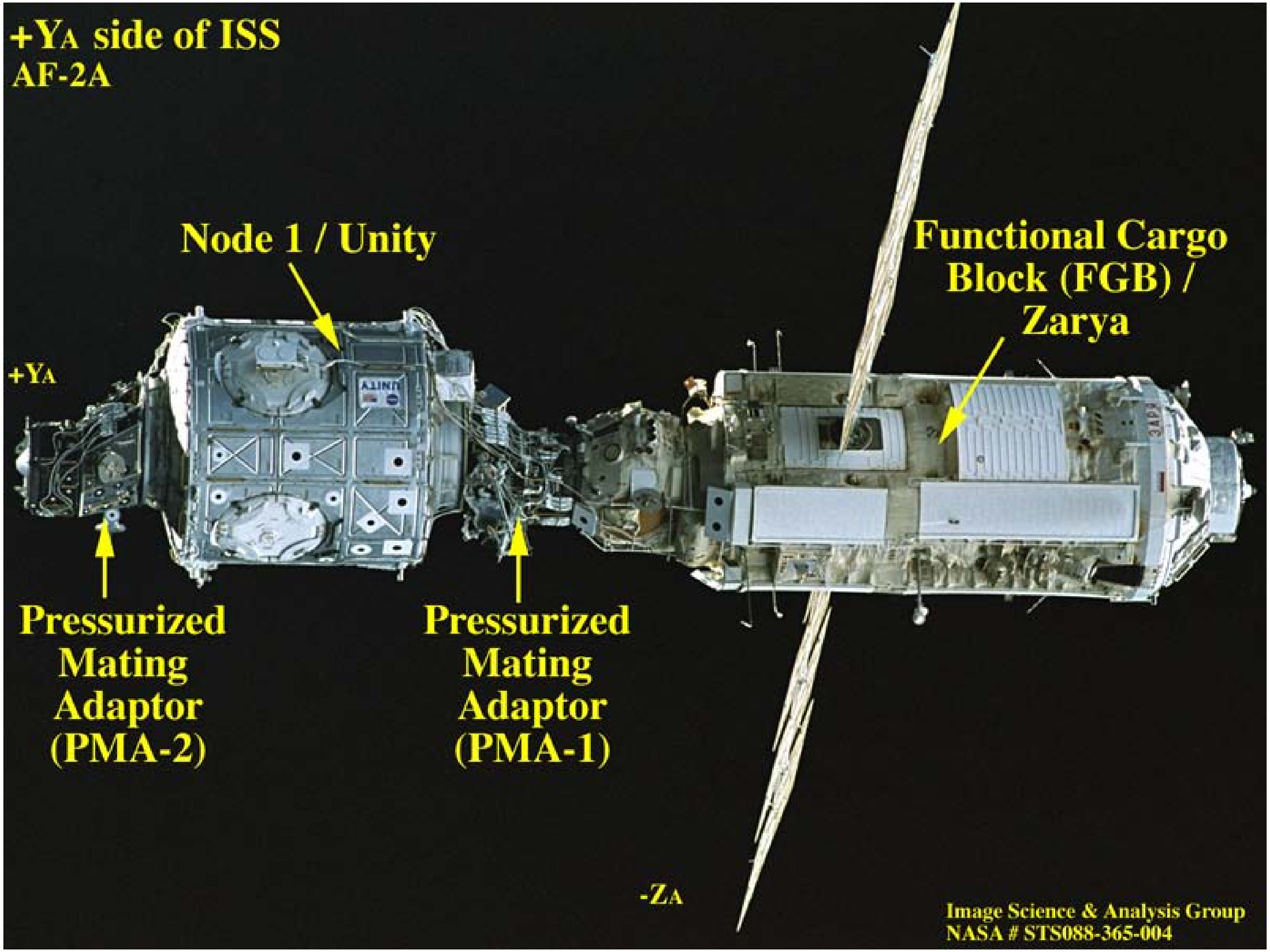
Architectural Overview

- **Combination of permanently attached modules and transient vehicles.**
- **Propulsive Segment**
  - Permanently attached modules:
    - Functional Cargo Block (FGB, Zarya or “Sunrise”)
    - Service Module (SM, Zvezda or “Star”)
    - Docking Compartment (DC1)
    - Mini Research Module 2 (MRM2)
    - Multipurpose Logistics Module (MLM) – not yet in orbit
    - Mini Research Module (MRM1) – not yet in orbit
  - Transient vehicles:
    - Progress
    - European Automated Transfer Vehicle (ATV)
    - Soyuz
    - US Space Shuttle
- **Non-Propulsive Segment**
  - 4 US Control Moment Gyroscopes (CMGs)

Architectual Overview –
Permanently Attached Modules

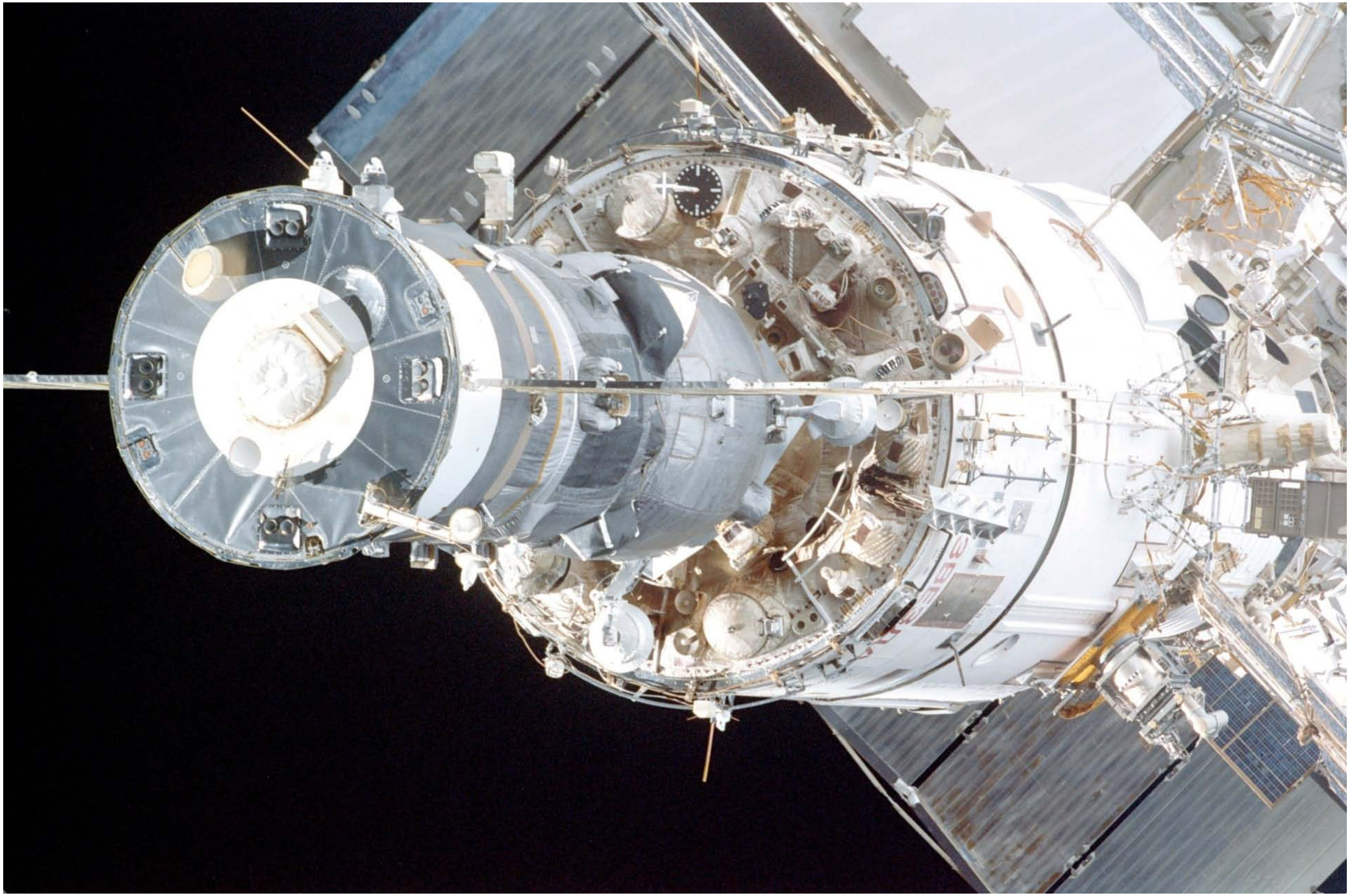
- **FGB**
  - First module of the ISS
  - Main propellant storage facility
  - Thrusters permanently disabled once SM arrived
- **SM**
  - Located at the FGB-aft port
  - Command and control hub using three internally mounted computers
  - Also holds a smaller amount of propellant
  - Provides ISS attitude and altitude control
- **DC1**
  - Currently located at the SM-nadir port
  - An adapter for visiting vehicles to dock to the ISS
  - Provides no propulsion control, but supports propellant resupply operations

FGB & Node 1


+YA side of ISS
AF-2A
Node 1 / Unity
Functional Cargo Block (FGB) / Zarya
+YA
Pressurized Mating Adaptor (PMA-2)
Pressurized Mating Adaptor (PMA-1)
-ZA
Image Science & Analysis Group
NASA # STS088-365-004

DC-1

SM with a Progress vehicle docked to the Aft port



Architectural Overview – Permanently Attached Modules

- **MLM**
  - Not yet in orbit, will replace the DC1
  - Permanent vehicle for ISS roll control
  - More propellant storage space
  - ISS roll control thruster pack
  - Visiting vehicles will be able to dock to the MLM.
- **MRM1**
  - Not yet in orbit, will be berthed to the FGB-nadir port.
  - Will not provide attitude control, but it will support propellant resupply operations.
- **MRM2**
  - Docked to SM Zenith on November 12, 2009.
  - An adapter for visiting vehicles to dock to the ISS
  - Provides no propulsion control, but supports propellant resupply operations

Architectural Overview – Transient Vehicles

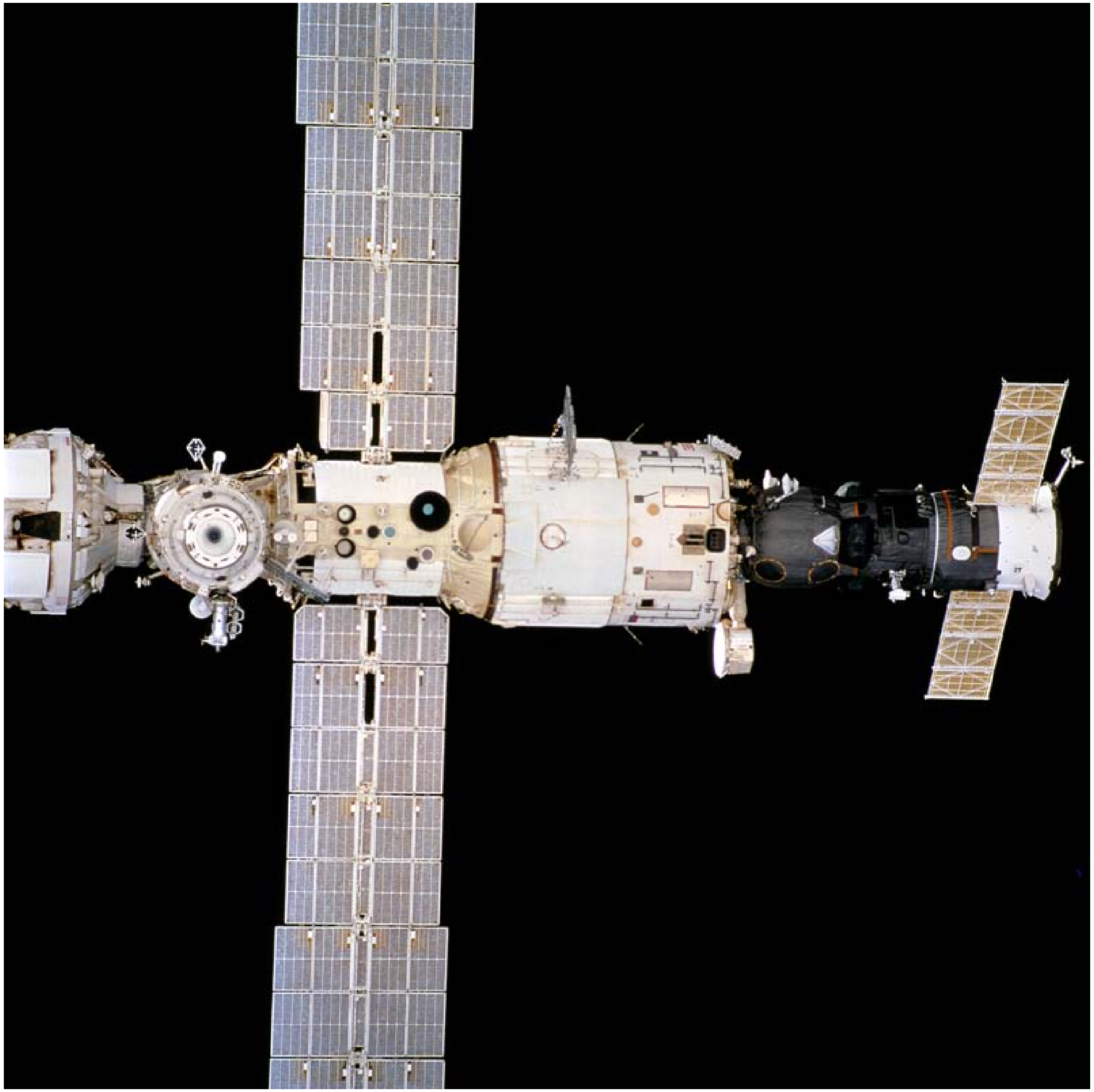
- **Russian Progress and European ATV**
  - Commanded by the SM
  - Can control attitude and altitude
  - Resupply on-orbit propellant storage tanks
- **Russian Soyuz**
  - Provides crew supply and return
  - Technically capable of providing propulsive support, but carries no consumable margin for integrated attitude control
- **US Space Shuttle**
  - Independent from Russian segment
  - Can control ISS attitude and altitude during its docked missions
  - Has no ISS propellant resupply capability

Soyuz docked to the DC-1 Nadir Port

Soyuz in free-flight departing from ISS

ISS011E14111

Progress docked to the SM Aft Port



ATV docked to the SM Aft Port

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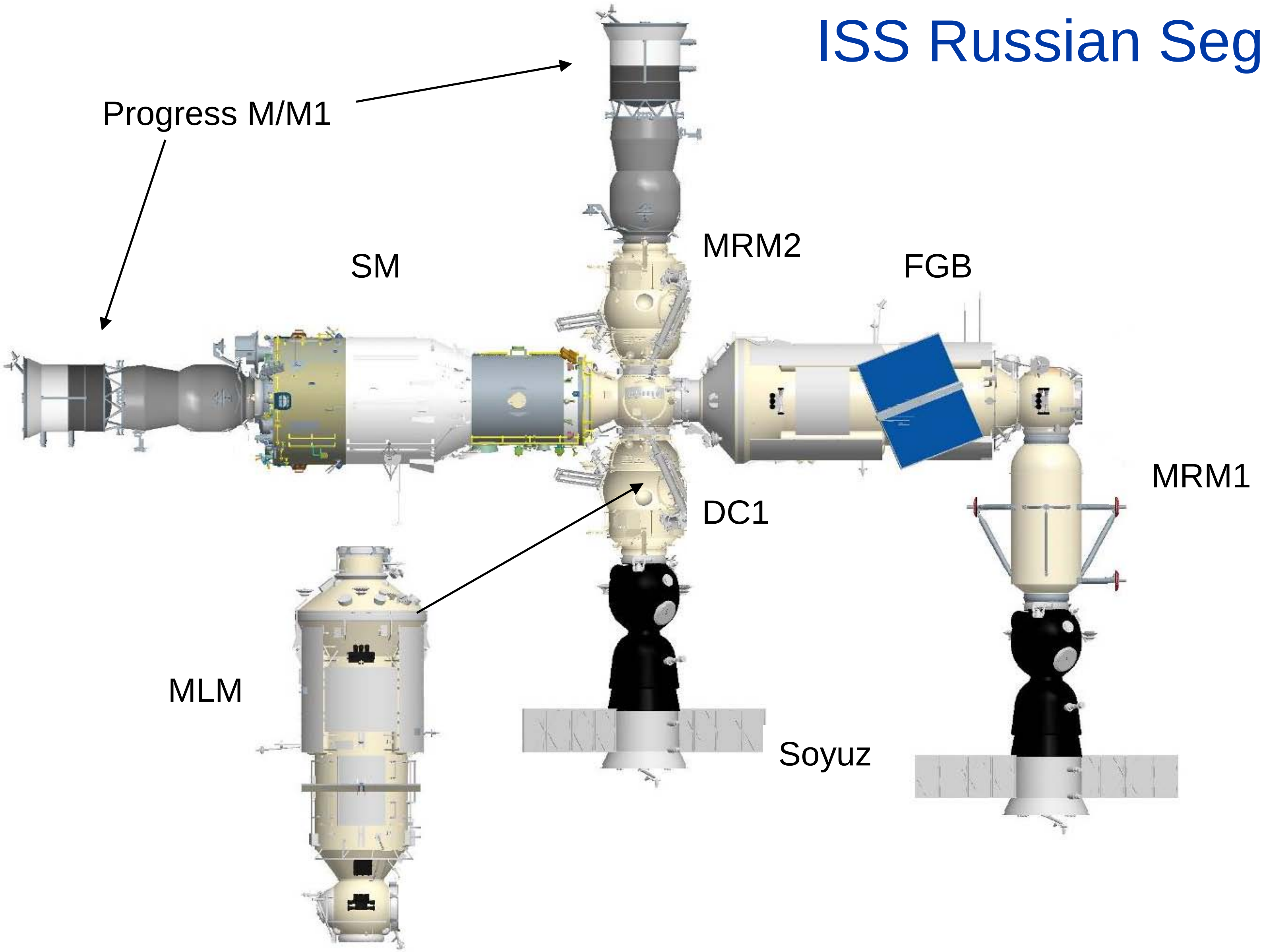
ISS Russian Segment



Propulsion System – Attitude and Altitude Control

- **ISS Attitude Control (yaw, pitch and roll)**
  - Pitch and yaw are provided by a Progress or ATV docked to the SM-aft port.
  - Roll control is provided by a Progress docked to the DC1-nadir port or an ATV docked to the SM-aft port. The MLM attitude control thrusters will primarily control roll once it is docked to the SM-nadir port.
  - SM thrusters can control attitude If vehicles are not available.
- **ISS Altitude Control (debris avoidance and phasing maneuvers)**
  - Performed by either the aft vehicle or SM orbit control thrusters.
  - A Progress docked to the DC1-nadir port can also provide orbit reboosts.
- **Both ISS attitude and altitude can be controlled by the US Space Shuttle Vernier Reaction Control System (VRCS) thrusters.**

Propulsion System – ISS Propellant Resupply

- **Critical for long term support of the ISS.**
- **Serviced by the Progress and ATV vehicles.**
  - Propellant levels can also be managed between the permanent modules.
- **Bellows and diaphragm tanks allow multiple refills and prevent vapor entrainment in the pressurization systems.**
- **Compressors are used to reduce the FGB and SM tank pressures to allow propellant transfers.**

Momentum Management

- **Uses a combination of Control Moment Gyroscopes (CMGs) and Russian Segment (RS) Thrusters**
- **Quiescent Operations**
  - Momentum Management (MM) Controller uses 4 CMGs to maintain a specific momentum vector
  - ISS attitude allowed to deviate slightly (3-4 degrees)
- **Dynamic Operations**
  - Requires RS thruster propulsive control if CMGs cannot maintain desired momentum vector or a tighter attitude threshold is required (<1 degree).
  - Many handovers between the Russian propulsion system and the US MM Controller.
- **Cooperation and innovative operational strategies have helped minimize propellant consumption and keep ISS operation efficient.**

Momentum Management – CMG Saturation

- **Saturation occurs when the CMGs lose control of the momentum vector due to external torques because they can only absorb a certain magnitude of momentum.**
  - CMGs saturate when all angular momentum vectors are parallel and ISS momentum vector still exceeds their combined magnitude
  - ISS will either go into “free drift” or RS thrusters will assume control of the station
  - CMG desaturation is utilized when angular momentum vector reaches its threshold. Uses RS thrusters firings to realign the set of CMG spin axes in opposing directions.

Momentum Management – Torque Compensation Method

- **Previously during extended RS attitude control, the ISS would need to maneuver to a Minimum Propellant Attitude (MPA) to minimize excess propellant consumption.**
- **It was determined that the CMG gimbals could be positioned to create a beneficial torque to compensate for expected external torques. Thus eliminating the maneuvers to and from the MPA.**
- **Propellant Consumption Savings**
  - 50% to 75% savings has been seen for Progress undockings
  - Up to 80% reduction during ISS software uplinks
  - Savings of hundreds of kg per year

Momentum Management – Zero Propellant Maneuver (ZPM)

- **CMG only maneuver**
- **Developed by Draper personnel**
- **First executed in November of 2006**
- **Manually uplink time-tagged commands and attitude updates**
- **Significantly slower than maneuver under RS thruster attitude control**
- **To date, only a few have been executed**
- **Continued success may prompt this method to be standardized**

Momentum Management – New Processes

- **CMG Thruster Assist (CMG TA) mode.**
  - This is currently the primary mode for ISS.
  - CMG TA consists of using the CMGs until momentum gets too high, then the thrusters will pulse to help re-align ISS momentum. Direct handover to thruster control is also an option if large perturbations are observed.
- **Orbiter Deadband Collapse**
  - Involves reducing the associated error in attitude produced by Orbiter VRCS thrusters such that it is within the acceptable controllability range of the CMGs.
  - Allows for direct handover from Orbiter VRCS control to CGM momentum management instead of handing over from VRCS to RS thrusters and then back to CMG control.

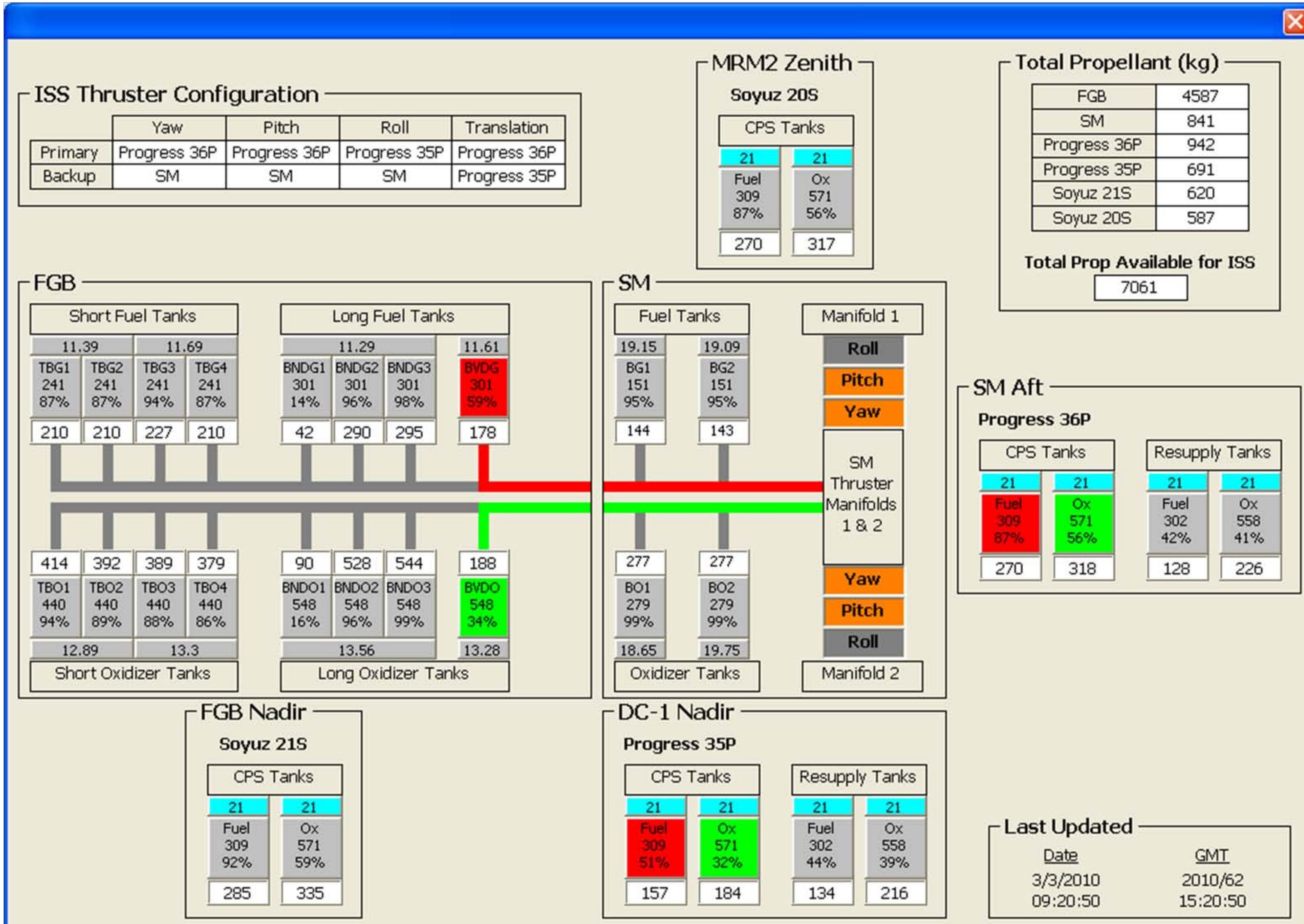
Momentum Management – New Processes

- **110% CMG Controller**
  - When CMGs saturate, angular momentum reaches 100%, indicating the maximum allowable attitude error has been reached.
  - Some torques experienced by the ISS are considered partially conservative, meaning that they will eventually exhibit an opposite torque.
    - Robotic and solar array motions tend to be conservative
    - Changes in mass properties, atmospheric density, surface area and venting are not conservative
  - By relaxing the allowable error on the CMGs beyond 100%, this allows for larger perturbations in ISS attitude before losing control and going into drift.

Propellant Accounting

- **Essential to track and monitor propellant quantity within each individual tank**
- **Measuring devices**
  - Linear Translation Transducers – measures propellant volume
  - Radio Frequency Quantity Gauging – measures propellant volume
  - Flowmeters – measures propellant flow
- **Analytical methods**
  - Burn Time Integration (BTI) – calculate propellant consumed with thruster firing times and flow rates
  - Pressure, Volume, Temperature (PVT) Method
    - Use measured pressures and temperatures
    - Calculate tank ullage volume with ideal gas law: PV=zmTR/M
  - Proven to be most accurate and long term

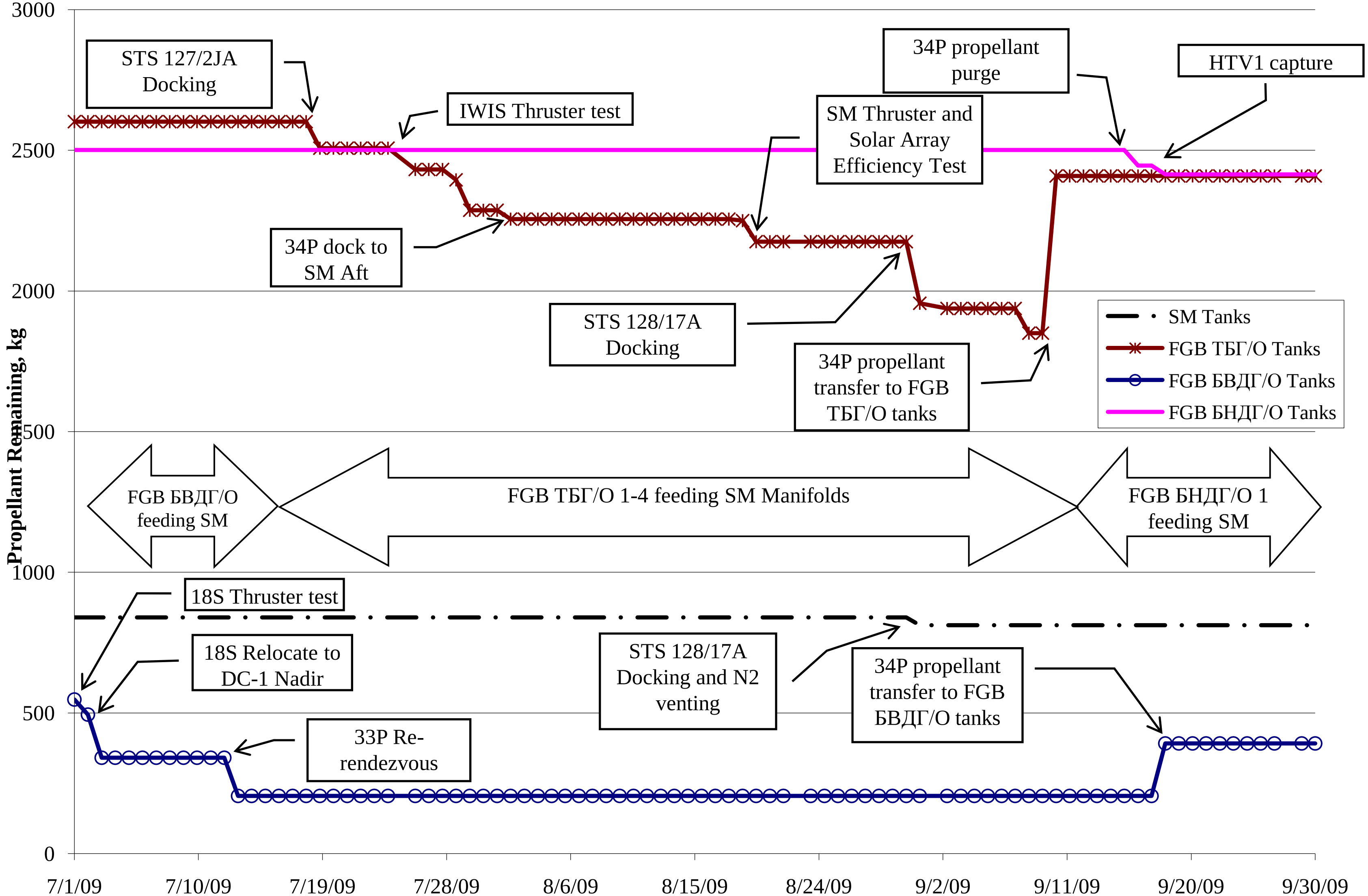
RS Vehicle Configuration Tracking Tool



Propellant Budgeting

- **Difficult to gauge how much propellant consumed for various activities**
- **Recent operations flight rule implemented that defines for propellant management categories**
  - "Category 1" – ISS Program "Reserve"
  - "Category 2" – Nominally planned ISS attitude control activities
  - "Category 3" – Activities not essential for ISS operations
  - "Category 4" – Required for ISS altitude maintenance
- **Categories have been defined, but actual process is still in work.**
- **Once finalized, this will be a reference guide**

Propellant consumption timeline for FGB and SM



Propellant Budgeting – Results

- **Continuous improvement of procedures for controlling the ISS have lead to more efficient propellant management over the years.**
- **Improved efficiency combined with the steady use of cargo vehicles has kept ISS propellant levels well above their defined thresholds in all categories.**
- **The continuing evolution of propellant and momentum management operational strategies demonstrates the capability and flexibility of the ISS propulsion system.**

Conclusion

- **The hard work and cooperation of the international partners and the evolving operational strategies have made the ISS safe and successful.**
- **The ISS's proven success is the foundation for the future of international cooperation for sustaining life in space.**