Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space:
i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

Effect of Attitude Control Jets on the performance of the Space Station Robotic Manipulator System (SSRMS)

A Case Study on Flights 6A and 7A

Harry Iordanou[1] (harry.iordanou@space.gc.ca)
Ken Podwalski[2] (ken.podwalski@space.gc.ca)
József Kövecses[1] (jozsef.kovecses@space.gc.ca)
Gaby Saad[3] (gsaad@mdrobotics.ca)

[1]**MacDonald Dettwiler Space and Advanced Robotics Ltd.**
MSS Operations Analysis, Canadian Space Agency
6767 Route de l'Aeroport, St-Hubert, Quebec, Canada

[2]**Canadian Space Agency**
6767 Route de l'Aeroport, St-Hubert, Quebec, Canada

[3]**MacDonald Dettwiler Space and Advanced Robotics Ltd.**
9445 Airport Road, Brampton, Ontario, Canada

Keywords Attitude Control, International Space Station / Space Shuttle Jets, SSRMS, Flights 6A and 7A

Abstract

The effect of Attitude Control System Jets (ACS) jets on the Space Station Robotic Manipulator System (SSRMS, "Canadarm2") while in stationary, unloaded and loaded configurations define the flight rules that would inhibit the use of ACS during critical points of SSRMS operations. The objective of the analysis performed is to identify potential generic issues, using worst-case ACS magnitude and frequency inputs as forcing functions. The primary concern is that disturbances due to ACS may be large enough in magnitude to cause large motor slippage and joint deviation, which would result in large uncommanded Frame of Resolution (FOR) motion of the SSRMS while it is in Position Hold or in Brakes On mode. Furthermore, these ACS disturbances might induce high loads at the base or tip interfaces of the arm as well as at the joints.

The screening identifies incidents where the use of a particular Attitude Control strategy may be potentially incompatible with flight specific arm configurations based on worst-case considerations. This would result in the more detailed review of available/optional attitude control strategies, mission design, and potentially the generation of generic, flight, or increment specific flight rules. Based on worst-case considerations, this screening identifies viable and safe Attitude Control strategy candidates.

Ultimately, identified incompatibilities at issue will be subject to further analyses, using flight specific ACS inputs and the latest mission design, with this report providing insight into available options to pursue the eventual mission design and analysis solutions to those incompatibilities.

Presented are the results from the Flight 6A and Flight 7A ACS analyses, which became the backbone of the Flight specific ACS tables for the SSRMS.

1 Introduction

The effect of mated-vehicle and/or station-only Attitude Control Strategy (ACS) jets on the SSRMS while in stationary, unloaded and loaded configurations is of great interest to the mission planning and operations communities and sets the criteria and ACS constraints for the particular flight.

The analysis aims to identify potential issues using nominal and worst-case ACS magnitude and frequency input as its forcing function. The primary concern is that disturbances due to ACS may be large enough in magnitude to cause large motor slippage and joint deviation, which would result in large uncommanded FOR motion on the SSRMS while in Position Hold or Brakes On. Furthermore, these ACS disturbances might induce high loads at the base or tip interfaces of the arm as well as at the joints.

2 Analysis Setup - Tool Development

A preliminary screening identifies incidents where the use of a particular ACS may be potentially incompatible with flight specific arm configurations based on worst-case considerations. If this is the case, then a more detailed review of available/optional attitude control strategies, mission design, and potentially the generation of generic, flight or increment, specific flight rules are conducted. This screening also identifies, based on worst-case considerations, viable and safe Attitude Control strategy candidates. Ultimately, identified incompatibilities at issue are subject to further analyses, using flight specific ACS inputs and the latest mission design. The analyses performed and documented in this report provided the inputs in the Interface Control Document (ICD) for the On-Orbit Reaction Control System (RCS) Firing Constraints for both Flights 6A and 7A.

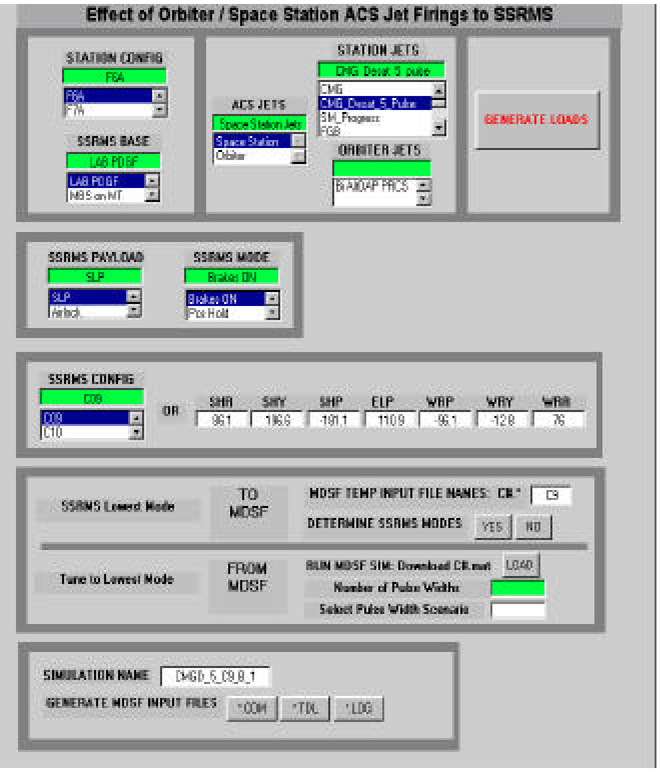
The simulations are performed using the Manipulator Development and Simulation Facility (MDSF) Version 3.3, which hosts the official SSRMS robotic arm model and control software.

The input files to MDSF define the simulation scenarios. The SSRMS can be configured in a desired configuration, with its base attached to the appropriate PDGF, with its tip either unloaded or handling a payload. In addition, a general topology is used which contains bodies such as the Space Station, the Shuttle etc.

A MATLAB tool was developed that autogenerates the necessary input files for MDSF simulations. The files are then transferred to the MDSF server and the simulations are executed.

Figure 1 shows the GUI of the ACS Tool.

Figure 1: ACS Tool GUI



The user can select the following to properly setup the simulations:

Vehicle Selections

- Station configuration; this defines the mass properties for the space station and the space shuttle.

- Base location of the SSRMS; note that the SSRMS can “walk” to different operating bases on the station.
- Space Station Jets; a number of jet families (i.e. Russian Segment Thrusters), as well as correction scenarios (i.e. +Roll correction) are available through subsequent GUIs.
- Space Shuttle Jets; a number of correction scenarios are available through subsequent GUIs.

SSRMS Selections:

- SSRMS Payload; a series of nominal and contingency SSRMS payloads are available.
- SSRMS Mode; available options include Brakes On, Position Hold and Limp Mode.
- SSRMS Configuration; there are two options: either manually enter the 7 joint angles, or select a configuration from a predefined list.

Once the vehicle selections are chosen, the forces and moments that are generated by the selected jets are transformed from their acting location to a point on the station / orbiter that is at a convenient inboard node of a body in the topology of the system. The forces and moments acting at the appropriate node, as well as the SSRMS selections outlined above become the inputs to MDSF.

3 Analysis Procedure

Due to the large range of possible combinations for SSRMS configurations and attached payloads, it was decided to investigate flight specific key configurations for ACS. These key configurations are associated to pause points in the current planned operations, or to critical points at which the operator places the SSRMS in Position Hold or applies brakes so as to change files, etc.

3.1 Flight Specific Inputs

The flight specific key configurations are obtained from the official set of Flight Procedures.

3.1.1 Flight 6A (STS 100)

On Assembly Flight 6A, during which the SSRMS is deployed, and while the shuttle is docked to station, the SSRMS operates from two possible bases; the active Flight Support Equipment Grapple Fixture (aFSEGF) on the Space Lab Pallet (SLP), and the US Lab Power Data Grapple Fixture (Lab PDGF). In the first case, the SSRMS will maneuver to the Lab PDGF while unloaded. Once End B of the SSRMS attaches to the Lab PDGF, the SSRMS changes base from the aFSEGF to the Lab PDGF. With its base at the Lab PDGF, the SSRMS unberths the SLP from the Lab Cradle Assembly (LCA) and positions the SLP for hand off to the awaiting Shuttle Remote Manipulator System (SRMS). The SRMS will then receive the SLP and berth it back in the shuttle bay.

For Flight 6A operations a total of 21 key SSRMS configurations were analyzed. A total of 7 relate to Flight Day 5 of Flight 6A robotic procedures (base: aFSEGF, payload: Unloaded). An additional set of 6 configurations relate to Flight Day 7 of Flight 6A robotic procedures (base: Lab PDGF, payload: SLP). A total of 4 relate to Flight Day 7 and Flight Day 9 of Flight 6A robotic procedures (base: Lab PDGF, payload: Unloaded). An additional couple of SSRMS configurations were included that are not 6A specific but were intended to examine the ACS effects on a worse case arm configuration. Finally, 4 configurations were added to examine the effect of ACS jets during the Airlock Dry Run operations, which are scheduled both during Flight 6A (mated vehicle) as well as and the subsequent 6A Stage (post shuttle undocking).

Figures 2 and 3 present the SSRMS in 2 key configurations while based on the aFSEGF (unloaded) and the Lab PDGF (SLP as payload) respectively.

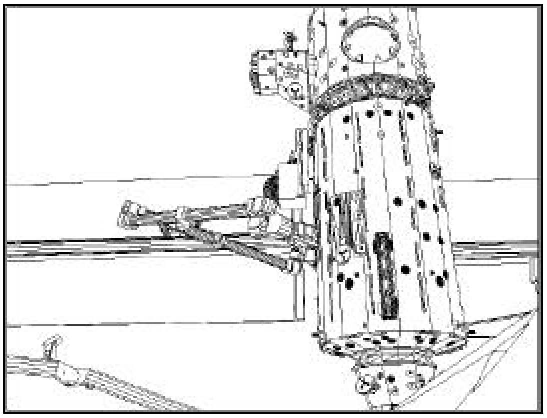


Figure 2: SSRMS based on SLP aFSEGF, tip unloaded above LAB PDGF

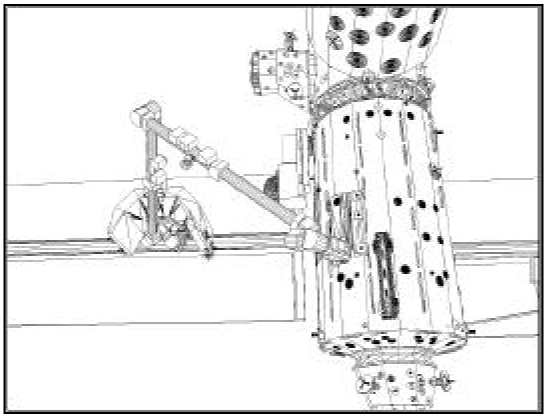


Figure 3: SSRMS based on LAB PDGF, tip loaded with SLP

3.1.2 Flight 7A (STS 104)

On Assembly Flight 7A, and while the shuttle is docked to station, the SSRMS will operate from the Lab PDGF. The main SSRMS tasks during Flight 7A involve unberthing the Airlock from the Shuttle Bay, maneuvering and mating to the Node 1 Starboard. Following this task, the SSRMS will sequentially unberth the 4 Gas Tanks from the shuttle bay, maneuver, and handoff to EVA alongside the Airlock.

For Flight 7A operations an initial set of 21 key SSRMS configurations are analyzed. The first 4 relate to Flight Day 5 of Flight 7A robotic procedures with an unloaded SSRMS. The next 8 relate to Flight Day 4 of Flight 7A robotic procedures with the SSRMS maneuvering the Airlock from the shuttle bay to the mating port on the station. The remaining configurations relate to Flight Days 7 and 9 of Flight 7A robotic procedures with the SSRMS maneuvering the Gas Tanks from the shuttle bay to their respective location on the Airlock.

Figures 4 and 5 present the SSRMS in 2 key configurations while based on the Lab PDGF and handling the Airlock and a Gas Tank respectively.

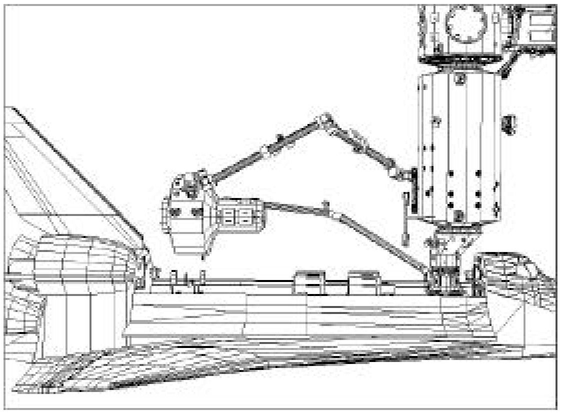


Figure 4: SSRMS based on LAB PDGF, maneuvering the Airlock

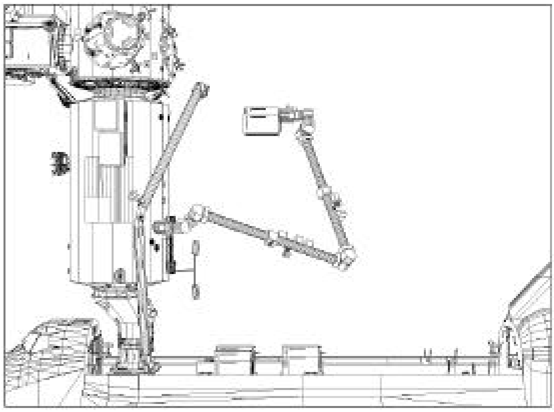


Figure 5: SSRMS based on LAB PDGF, maneuvering the Gas Tank

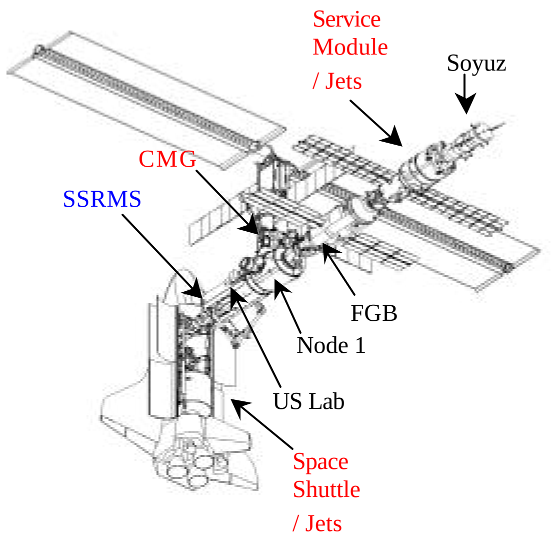
3.2 Attitude Control Strategies

The flight specific ACS options are obtained from the NASA GN&C group. The strategies can be broken into 2 main groups, as shown below:

3.2.1 Space Station Jets

Typically, attitude control is performed by the Control Moment Gyros (CMGs), located at the US Segment of the Station. In the event that the CMGs can no longer provide an adequate correction moment, jets from the Russian Segment can provide assist. The Russian Segment can provide CMG assist as well as a complete ACS with jets located on the Service Module and the Progress Vehicle. For Station Reboost, jets on the Russian segment are initiated that can increase the elevation of the Station. Figure 6 shows the Flight 6A mated vehicle configuration once the SSRMS has been deployed on the Lab PDGF.

Figure 6: Flight 6A Mated Vehicle Config.



3.2.2 Space Shuttle Jets

The shuttle has 2 main categories of Jets, the Primary Reaction Control System (PRCS) Jets and the Vernier Reaction Control System (VRCS) Jets. As the name implies, the PRCS Jets are larger in thrust than the VRCS.

In addition to the available jets options, NASA GN&C has provided CSA with the actual jet profiles (pulse durations and delays) for their implementation as the forcing function in MDSF.

3.3 SSRMS Criteria

Loads at the base of the SSRMS, the drive and cross axes of all joints as well as the tip were recorded and checked against SSRMS specifications and Flight Planning Load Limits (FPLL) for base, joint and tip loads. Log files were generated in the event of any load violation of the FPLL.

Motor position was also recorded and checked for each simulation performed. If high loads act on the base of the SSRMS, then the brakes could slip; this will result in motor slippage and becomes the dominant component of uncommanded and unrecoverable joint angle deviations and FOR errors. Log files were generated in the event of any motor slippage that resulted in considerable joint motion. The value for the motor slippage that is presented in the log files is equal to the total differential range of motor values, i.e. the difference between the maximum and minimum observed motor angle for each of the seven motors for the total duration of the simulation, and thus presents the worst case.

When the SSRMS is disturbed from the ACS jet loads and in the event that the loads are large enough to result in uncommanded FOR motion, the SSRMS Position hold algorithm will command the SSRMS back to its initial position. Joint angle deviation (minimum to maximum) during these transient regions is recorded and a log file is generated in the event that the joint angle deviation exceeds requirements.

Uncommanded FOR motion that results from the ACS jets is recorded. A conservative set of requirements (0.5 Trajectory Tracking and Error Detection (TTED) values) was defined as 6 inches for translation (combined) and 3.75 degrees in rotation (combined).

The log file documents whether soft limit is reached in any of the joints.

3.4 Presentation of Results

Once the simulations are performed, the outputs are collected and a set of MATLAB routines is executed. These routines perform a series of necessary tests and checks that set out to fully describe the overall behavior of the SSRMS at static configurations with or without a payload while all ACS jets are exercised. The results from the performed simulations are archived and further formatted in EXCEL to autogenerate summary tables.

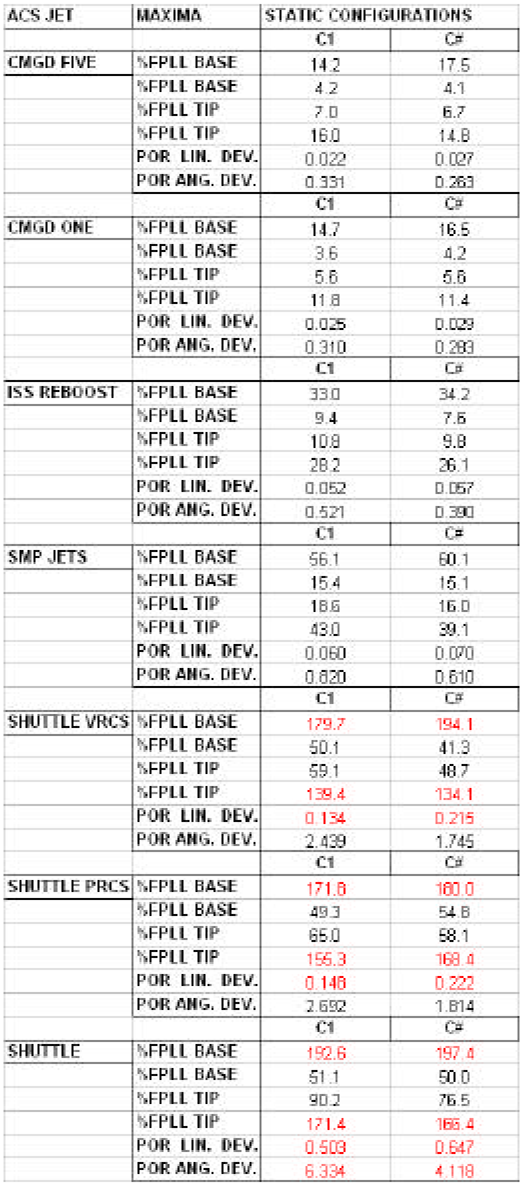
Table 1 shows a sample section from an EXCEL summary table. Note that the shown loads / FOR motions are not representative of actual cases. For each ACS jet family, the table presents the maximum loads (forces and moments) at the base and the tip of the SSRMS for each analyzed configuration as a percentage of FPLL. Furthermore, it tabulates the maximum observed FOR motion (linear and angular) for the aforementioned cases.

The information reflects only static configurations of the SSRMS. Note also that the sequence of the configurations as presented (from left to right) represents the order of SSRMS configurations for Flight Operations. Note that any violations of FPLL or allowable POR motions are presented in RED.

The maximum static loads observed at these static configurations also help to define the constraints for the SSRMS in motion between these static configurations. If the static loads between two consecutive static configurations are below 25% FPLL, then in a worst case safing event where brakes are applied while the SSRMS maneuvers in maximum coarse rates, the expected base, joints and tip loads for the SSRMS should remain within 100 % FPLL. If in the case that one or both of these static configurations exceed the 25% FPLL criterion, then constraints are placed for the ACS Jet strategy for the SSRMS in motion between these static configurations. This approach is similar (but more conservative) to the Shuttle Robotic Manipulator System (SRMS, "Canadarm") in motion constraints criteria.

Table 1 becomes the primary input to tables that appear in the Flight-On-Orbit ICD and influence Generic and Flight Specific Flight Rules.

Table 1: Sample loads / motions summary for SSRMS in key configuration C1 and C2



ACS JET	MAXIMA	STATIC CONFIGURATIONS	
		C1	C#
CMGD FIVE	%FPLL BASE	14.2	17.5
	%FPLL BASE	4.2	4.1
	%FPLL TIP	7.0	6.7
	%FPLL TIP	16.0	14.8
	POR LIN. DEV.	0.022	0.027
	POR ANG. DEV.	0.331	0.263
		C1	C#
CMGD ONE	%FPLL BASE	14.7	16.5
	%FPLL BASE	3.6	4.2
	%FPLL TIP	5.6	5.6
	%FPLL TIP	11.8	11.4
	POR LIN. DEV.	0.025	0.029
	POR ANG. DEV.	0.310	0.283
		C1	C#
ISS REBOOST	%FPLL BASE	33.0	34.2
	%FPLL BASE	9.4	7.6
	%FPLL TIP	10.8	9.8
	%FPLL TIP	28.2	26.1
	POR LIN. DEV.	0.052	0.057
	POR ANG. DEV.	0.521	0.390
		C1	C#
SMP JETS	%FPLL BASE	56.1	60.1
	%FPLL BASE	15.4	15.1
	%FPLL TIP	18.6	16.0
	%FPLL TIP	43.0	39.1
	POR LIN. DEV.	0.060	0.070
	POR ANG. DEV.	0.820	0.610
		C1	C#
SHUTTLE VRCS	%FPLL BASE	179.7	194.1
	%FPLL BASE	50.1	41.3
	%FPLL TIP	59.1	48.7
	%FPLL TIP	139.4	134.1
	POR LIN. DEV.	0.134	0.215
	POR ANG. DEV.	2.439	1.745
		C1	C#
SHUTTLE PRCS	%FPLL BASE	171.8	180.0
	%FPLL BASE	49.3	54.8
	%FPLL TIP	65.0	58.1
	%FPLL TIP	155.3	168.4
	POR LIN. DEV.	0.148	0.222
	POR ANG. DEV.	2.692	1.814
		C1	C#
SHUTTLE	%FPLL BASE	192.6	197.4
	%FPLL BASE	51.1	50.0
	%FPLL TIP	90.2	76.5
	%FPLL TIP	171.4	166.4
	POR LIN. DEV.	0.503	0.647
	POR ANG. DEV.	6.334	4.118

4 Conclusions

The performance of the SSRMS during Station or Shuttle ACS is of great interest and concern for the planning and execution of the International Space Station assembly missions.

Proper analysis defines the constraints that should be placed to ensure safe and viable operations with the SSRMS as it maneuvers payloads from the shuttle bay to their mating locations on the station.

In order to properly analyze the multiple combinations of SSRMS base locations, configurations, modes, payloads, ACS jet profiles, a tool was generated which prepared all necessary input files for the simulator. Once the simulations were performed, the analysis of the simulation outputs was also automated, as well as the generation of the tables that summarized the results.

The table of results is a direct input to each Flight On-Orbit ICD and also helps define the Flight Rules for the safe operation of the SSRMS during ACS events.

References

[1] MOA-TN-006, "ACS Analysis Tool User Manual", Harry Iordanou, Jozsef Kovecses, Gaby Saad, Mission Operations, Canadian Space Agency, May 11th, 2001

[2] MOA-TN-007 , "ACS Assessement Plan and Process", Harry Iordanou, Ken Podwalski, Mission Operations, Canadian Space Agency, May 11th, 2001

[3] MOA-F6A-045-Rev A, "Effect of Shuttle and Space Station Jet Firings on SSRMS Performance: Assembly Flight 6A", Harry Iordanou, Jozsef Kovecses, Mission Operations, Canadian Space Agency, March 1st, 2001

[4] MOA-F6A-055-Rev A, "Hybrid Shuttle Reboost for Overnight Configuration and New Handoff Configuration", Harry Iordanou, Mission Operations, Canadian Space Agency, April 26th, 2001

[5] MOA-F6A-062, "Worst Case Arm Configuration for SLP Maneuvering to Expedited Handoff Configuration and MPLM Stowage Configuration", Harry Iordanou, Jozsef Kovecses, Mission Operations, Canadian Space Agency, April 28th, 2001

[6] MOA-F7A-033-Rev B, "Effect of Shuttle and Space Station Jet Firings on SSRMS Performance: Assembly Flight 7A", Harry Iordanou, Jozsef Kovecses, Gaby Saad, Mission Operations, Canadian Space Agency, May 9th, 2001

[7] MOA-F7A-034, "Effect of Contingency Reboosts during Flight 7A on loaded SSRMS", Harry Iordanou, Mission Operations, Canadian Space Agency, May 7th, 2001