Welcome…

Neil Dennehy
NASA Technical Fellow for Guidance Navigation & Control
cornelius.j.dennehy@nasa.gov

STS/ISS On-Orbit Flight Control: A Historical Perspective

Presented by: **Robert A. Hall**

Mclaurin Aerospace

STS/ISS On-Orbit Flight Control: A Historical Perspective, *or*

Some Funny Things Happened While Assembling the Space Station

Robert A. Hall
McLaurin Aerospace
robert.a.hall@nasa.gov

MCLAURIN

Alternate Title Shamelessly taken from:

Some Funny Things Happened on the Way to the Moon

by Richard H. Battin

Apollo 11 Splashdown Party
MIT Faculty Club
July 24, 1969

STANDING FROM RIGHT TO LEFT: Fred Martin, Eldon Hall, Gerry Levine, Dick Battin, Tom Fitzgibbon, and George Schmidt.

Stealing title justified because:

Reference [1]

Alternate Title Shamelessly taken from:

Some Funny Things Happened on the Way to the Moon

by Richard H. Battin

Apollo 11 Splashdown Party
MIT Faculty Club
July 24, 1969

STANDING FROM RIGHT TO LEFT: Fred Martin, Eldon Hall, Gerry Levine, Dick Battin, Tom Fitzgibbon, and George Schmidt.

Stealing title justified because:

1. **The work in this presentation was also performed by the Draper Laboratory.**

Reference [1]

Alternate Title Shamelessly taken from:

Some Funny Things Happened on the Way to the Moon

by Richard H. Battin

Apollo 11 Splashdown Party
MIT Faculty Club
July 24, 1969

STANDING FROM RIGHT TO LEFT: Fred Martin, Eldon Hall, Gerry Levine, Dick Battin, Tom Fitzgibbon, and George Schmidt.

Stealing title justified because:

1. **The work in this presentation was also performed by the Draper Laboratory.**

2. **This presentation also includes a picture of our flight control team celebrating.**

Reference [1]

The Media was kind to Space Station Assembly

The greatest 15 Engineering Marvels of All Time:

Ancient World pre-500 AD

1. **Projectile weaponry** *(time immemorial-present day)*

2. **The Catacombs of Kom el Shoqafa** *(2nd century AD)*

2. **The Great Pyramid of Giza** *(2560 BC)*

4. **Stonehenge** *(3000-1500 BC)*

5. **Colosseum** *(70-80 AD)*

Middle Ages 500-1500 AD

1. **Taj Mahal** *(1648)*

2. **Hagia Sophia** *(500AD)*

3. **Leaning Tower of Pisa** (1399)

4. **The Great Wall of China** *(7th century BCE-1644)*

5. **Machu Pichu** *(1450)*

Modern Age 1500-present

1. **International Space Station *(1998-present day)***

2. **Sustained powered flight** *(c. 1903)*

3. **The internet *(1991)***

4. **Electrification *(1850-present day)***

5. **The Channel Tunnel** *(1990)*

- **Engineer's Journal,** C. Madden, 23 January 2018

"It's one of the greatest engineering achievements in the history of the world. It ranks with the pyramids."

- Howard McCurdy, American University, author of "The Space Station Decision" as quoted by the Washington Post.

10 Most Amazing Engineering Achievements

1. **The International Space Station (ISS)**
2. **The Large Hadron Collider (LHC)**
3. **The Panama Canal**
4. **The Great Pyramid of Giza**
5. **The Channel Tunnel (The Chunnel)**
6. **The Great Wall Of China**
7. **Hoover Dam**
8. **Burj Khalifa Building**
9. **The Millau Viaduct**
10. **Delta Works flood barrier and the Oosterscheldekering**

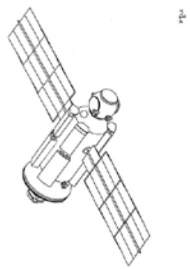
- **10 Most Today, January 19, 2015**

25 amazing feats of engineering around the world:

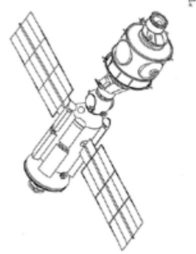
1. **The Palm, Dubai, UAE**
2. **Aqueduct of Segovia, Segovia, Spain**
3. **Great Wall of China, China**
4. **Taj Mahal, Agra, India**
5. **Trans-Siberian Railway, Russia**
6. **Burj Khalifa, Dubai, UAE**
7. **Akashi Kaikyō Bridge, Akashi Strait, Japan**
8. **White Pass and Yukon Route Railroad, Canada**
9. **Tokyo Sky Tree, Tokyo**
10. **International Space Station**
11. **Teotihuacan, Mexico**
12. **Panama Canal, Panama**
13. **Taipei 101, Taipei, Taiwan**
14. **Grand Canyon Skywalk, Arizona**
15. **Shanghai World Financial Center, Shanghai**
16. **Millau Viaduct, Millau, France**
17. **London Underground, London**
18. **Kansai Airport, Osaka, Japan**
19. **Hoover Dam, Arizona/Nevada**
20. **Great Pyramid of Giza, Egypt**
21. **Golden Gate Bridge, San Francisco**
22. **Eiffel Tower, Paris**
23. **Confederation Bridge, Prince Edward Island, Canada**
24. **Colosseum, Rome**
25. **CN Tower, Toronto, Canada**

- **CNN Travel**, T.Hinson, December 2013

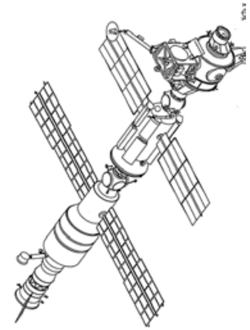
Space Station Assembly



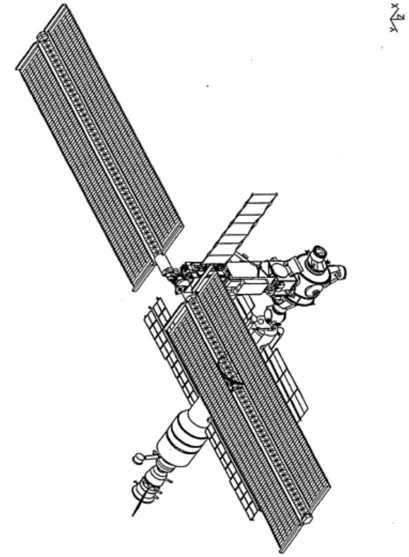
1A/R, ~44,000 lbs



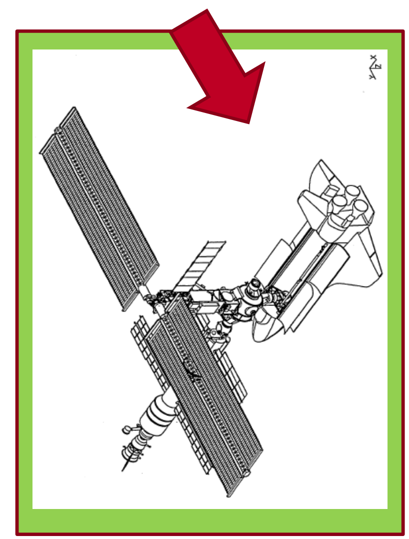
2A, ~68,000 lbs



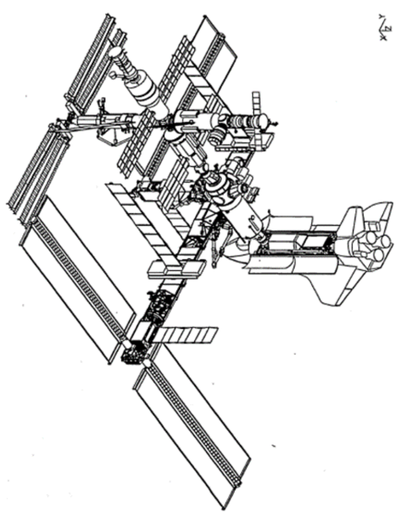
3A, ~155,000 lbs



4A, ~200,000 lbs

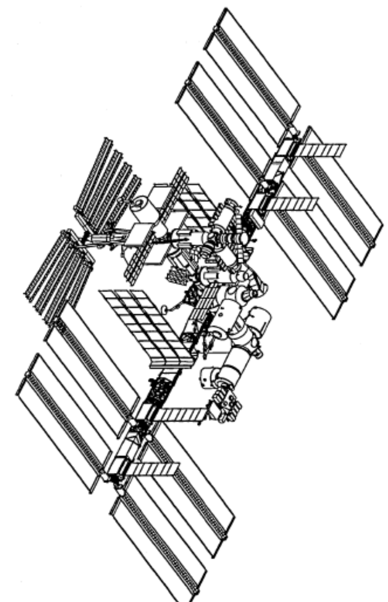


Fast Forward… (including loss of Columbia)



13A, ~558,000 lbs

Fast Forward…



Assembly Complete ~920,000 lbs

Reference [2]

Space Station Assembly: The Space Shuttle Control Rooms

Mission Control actually consists of multiple control rooms. Two keys rooms at Johnson Space Center are:

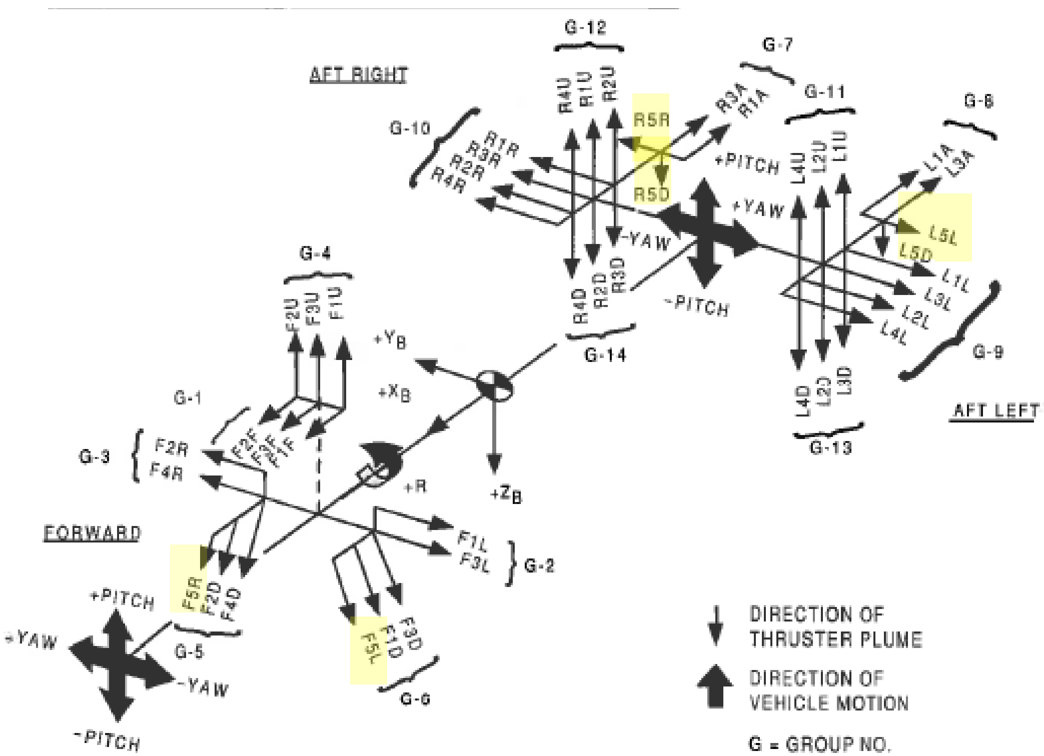
Mission Control Center (MCC), Operations

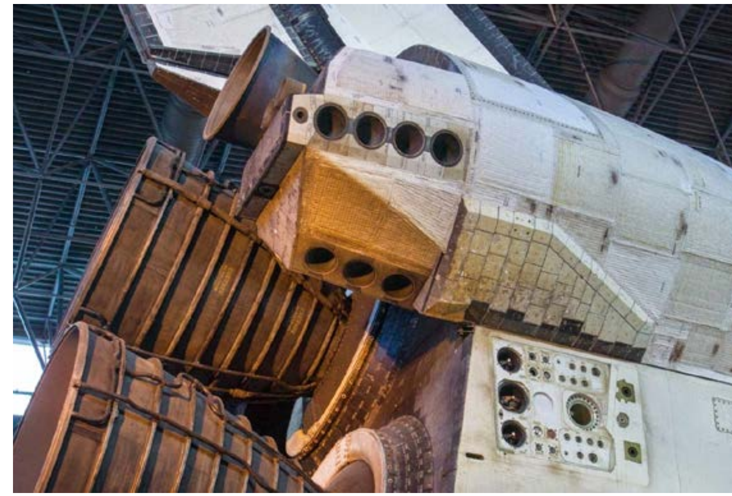
STS-104, ISS 7A, July 12, 2001 (NASA)

Mission Evaluation Room (MER), Engineering

Reference [3]

Orbiter Reaction Control System (RCS) and Orbital Maneuvering System (OMS)





Vernier Thrusters: 24 lbf

Primary thrusters: 870 lbf

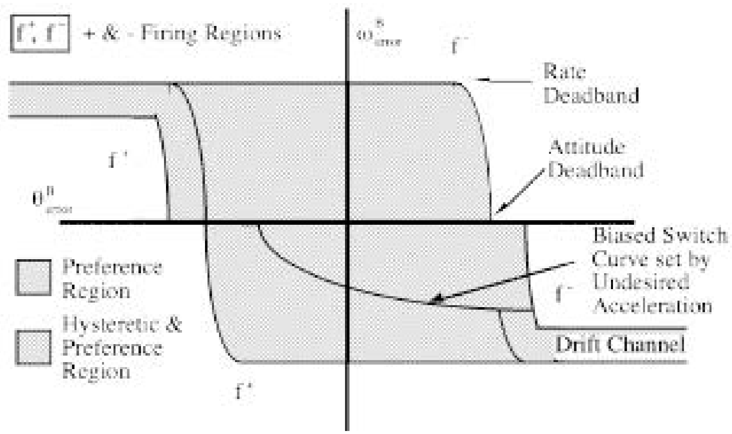
OMS Engines: 6000 lbf

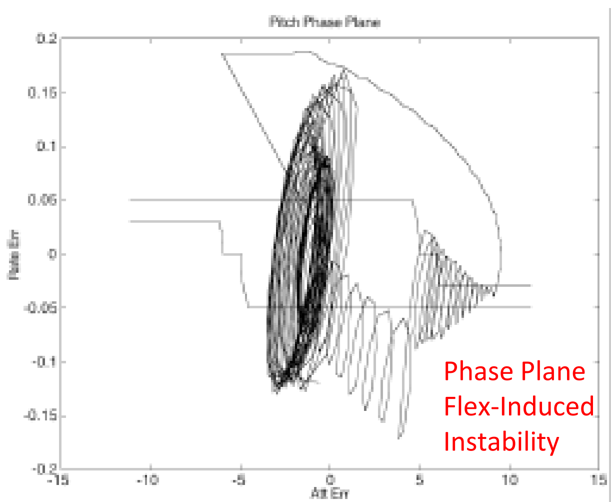
Reference [4]

Image Source: Bruce's Scale Model Domain: http://scalemodelingdomain.blogspot.com/2015/02/part-3-orbiters-aft-main-enginesomsrcs.html

Orbiter RCS Phase Plane and State Estimator (Luenberger Observer)

RCS Phase Plane





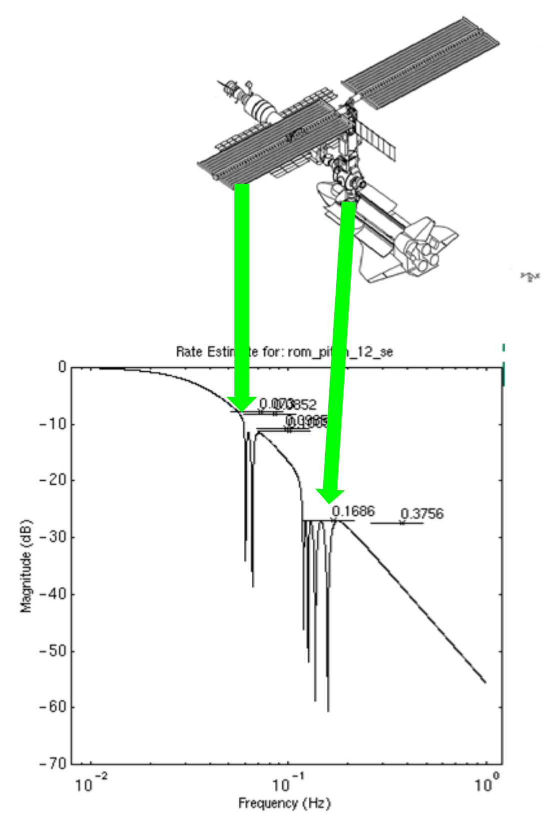
State Estimator

$$\hat{x}(k+1) = A_d\hat{x}(k) + B_d u(k) + L_d(y(k) - \hat{y}(k)),$$

Estimated State	State Transition	Thruster Feed Forward	Error between measured attitude and attitude estimate

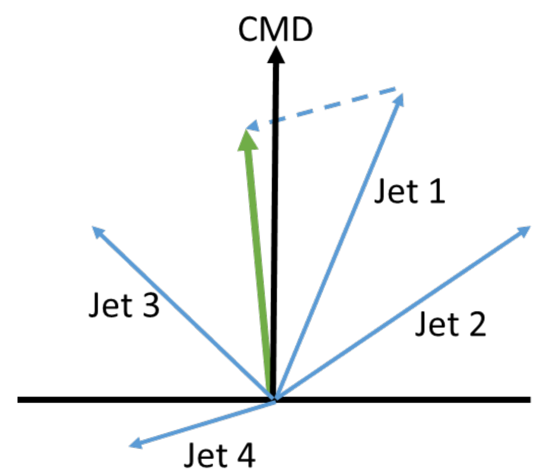
Thruster acceleration “feed-forward” in State Estimator is a great way to minimize sensitivity to latency, but “feed-forward error” was a consideration.

Orbiter Control System Upgrades for Space Station Assembly

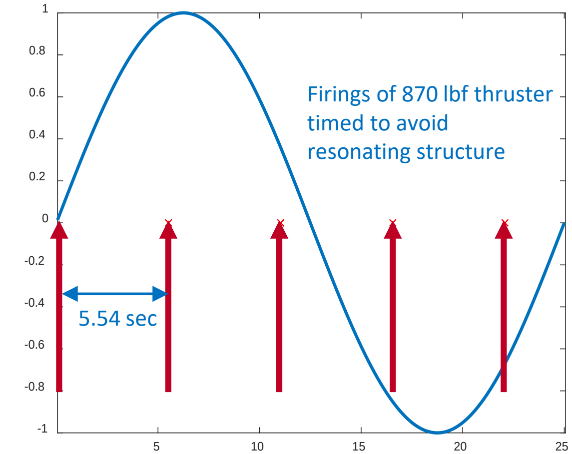


igure 6. Response of Rate Estimator with 4A Final Notch Set

Stability: Notch Filters



Control: Min Angle Jet Select



Loads: Alt PRCS

ALT = Alternate Failed on RCS?

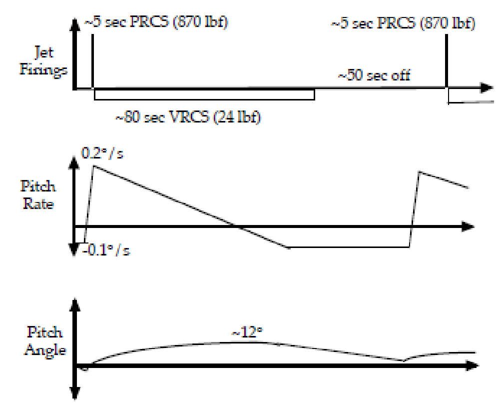


Figure 21: Simplified Reboost Dynamics

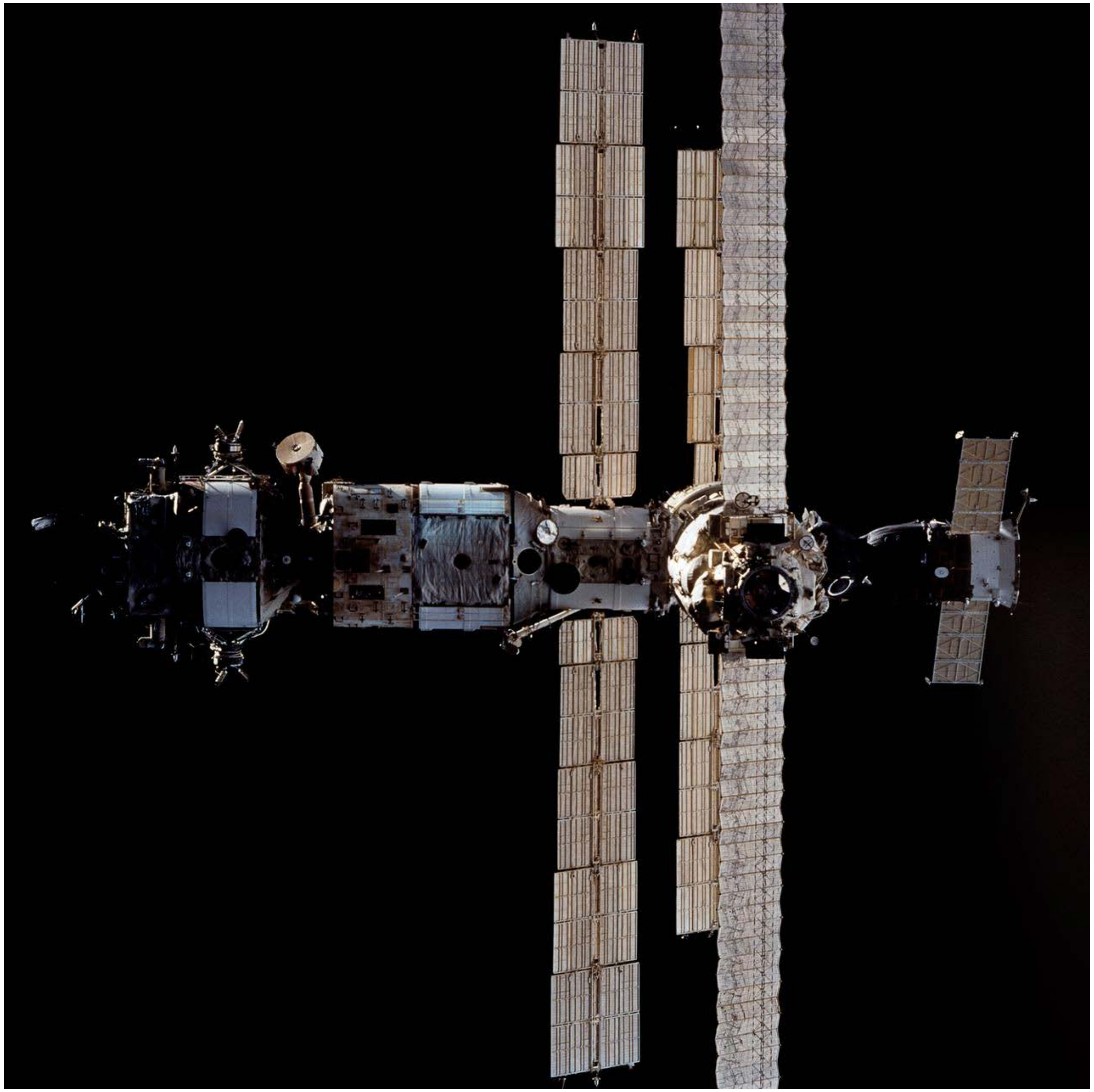
Control: Reboost

Reference [8]

Precursor to Space Station: Docking with the Russian MIR

We shared information:

The Russians had to understand the Shuttle flight control system, and the Americans had to understand the MIR flight control system, to enable docking and control of the mated stack.

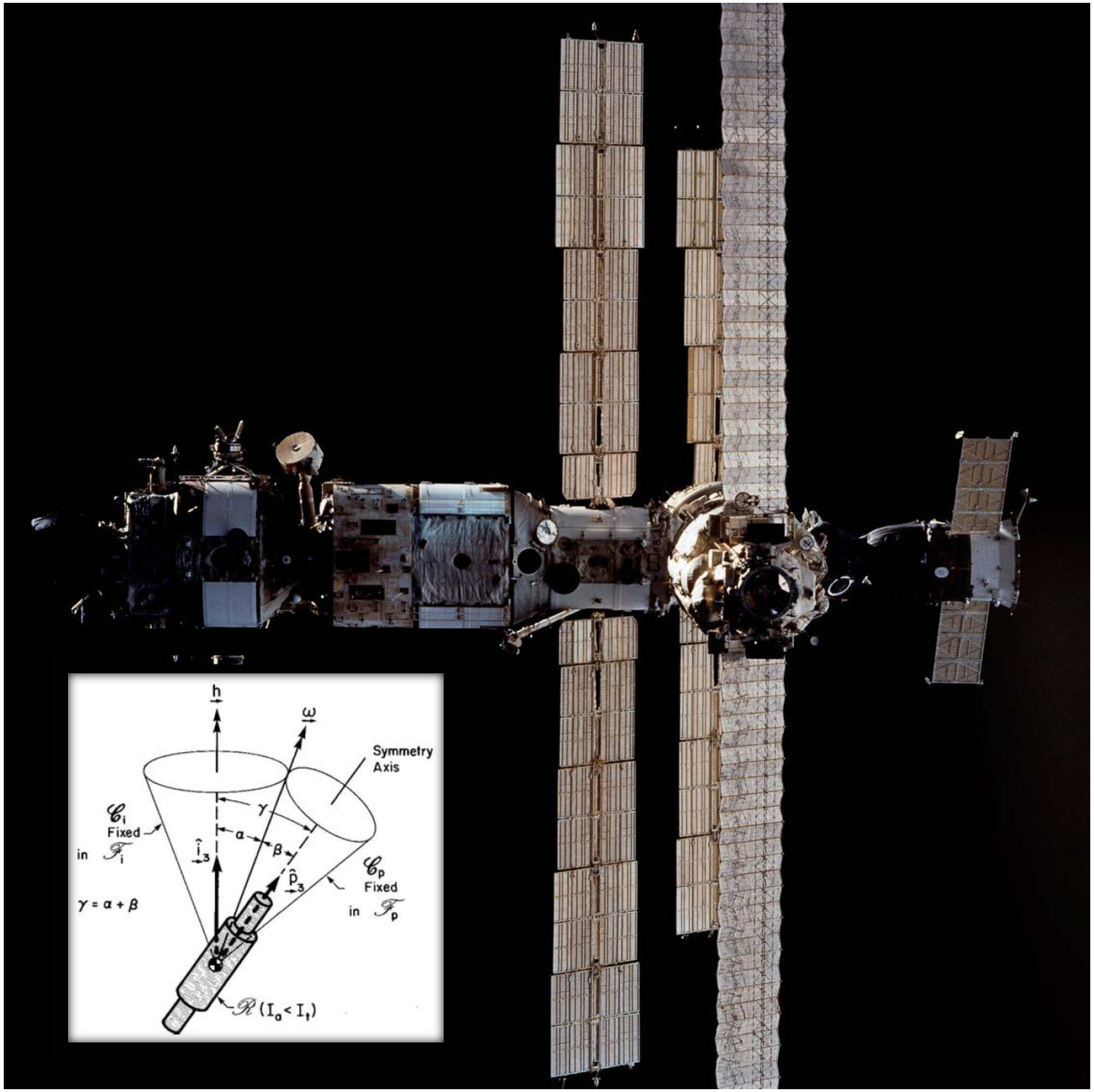


Source: NASA

Two Key Components of MIR Attitude Control system

Pulse Width Modulation in Phase Plane

“Torque Free” Maneuvers



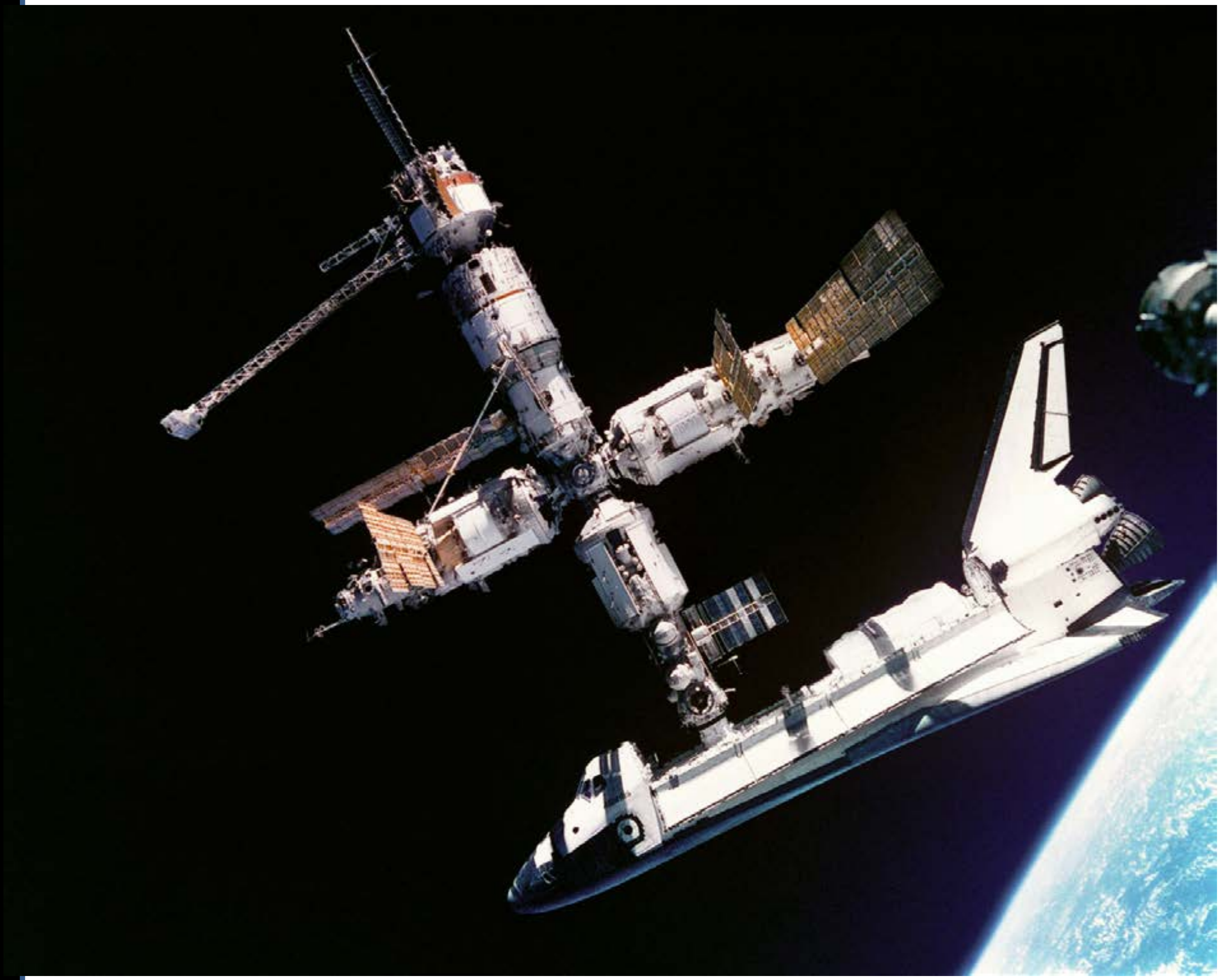
Source: NASA, Hughes [5]

U.S./Russian After Hour Coordination (1994)

Left to Right: Bob Friend (RI/Boeing), Nancy Smith (NASA), Yuri Kasnecheev (Energia), Doug Zimpfer (Draper), Translator, Russian Engineer, Rob Hall (Draper), Vicki Hall

STS-71 (June 1995)

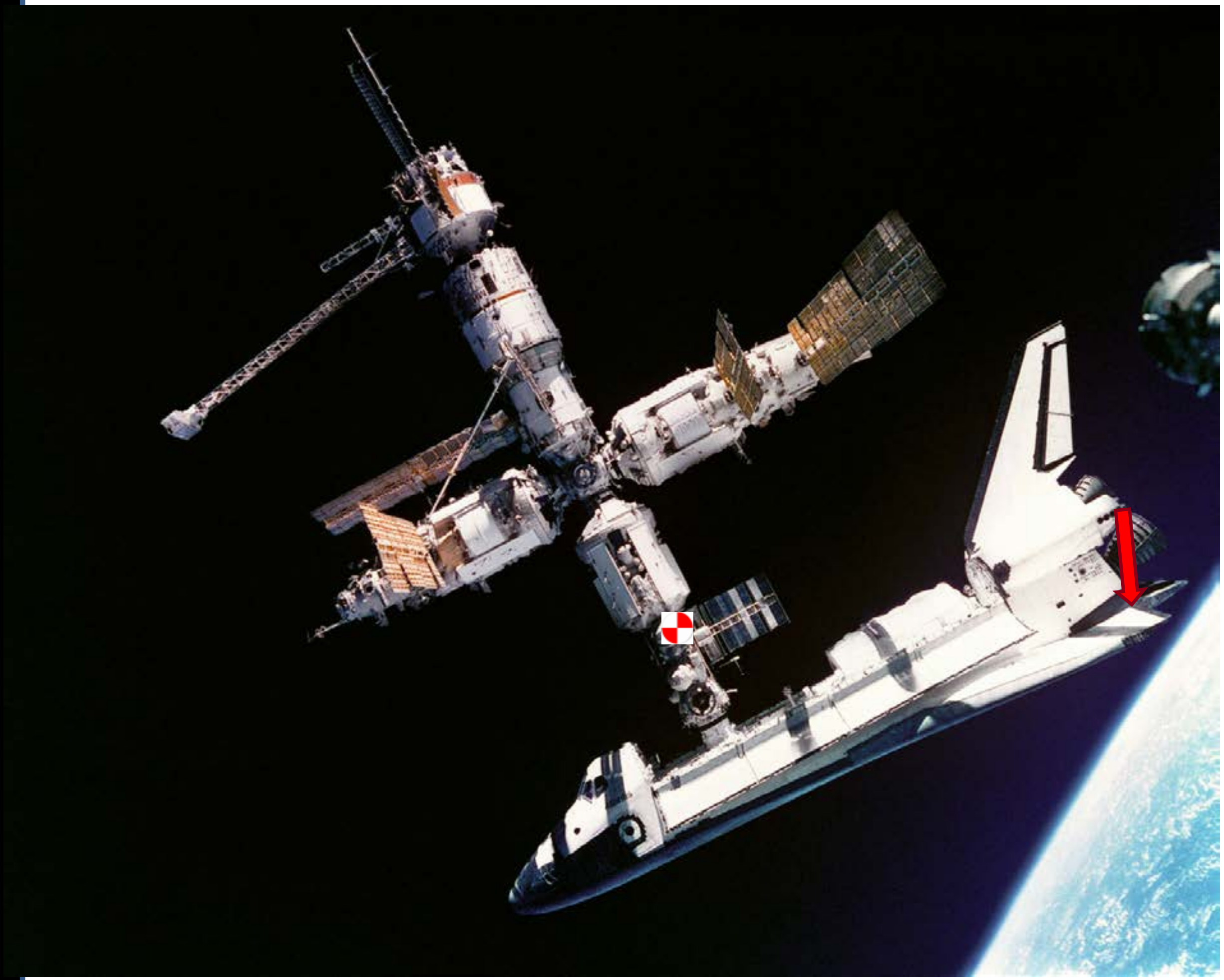
Source: NASA



The Orbiter and MIR took turns controlling the mated stack, demonstrating the capability.

STS-71 (June 1995)

Source: NASA, Mathworks, and Reference [7]



Shuttle RCS Self-impingent on Shuttle Elevons increased propellant usage by ~70%.

- Feed-forward in Orbiter state estimator was incorrect due to self-impingement.

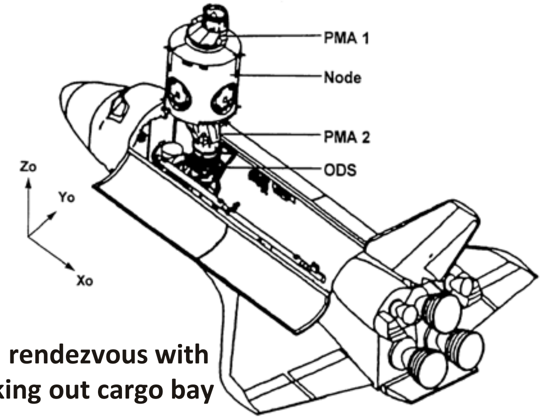
$$\hat{x}(k+1) = A_d\hat{x}(k) + B_d u(k) + L_d(y(k) - \hat{y}(k)),$$

Estimated State | **State Transition** | **Thruster Feed Forward** | **Error between measured attitude and attitude estimate**

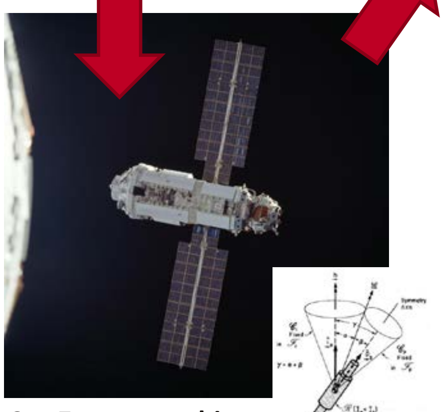
STS-88: First Assembly Flight, December 1998

1. Russians Launch Zarya
20 November 1998

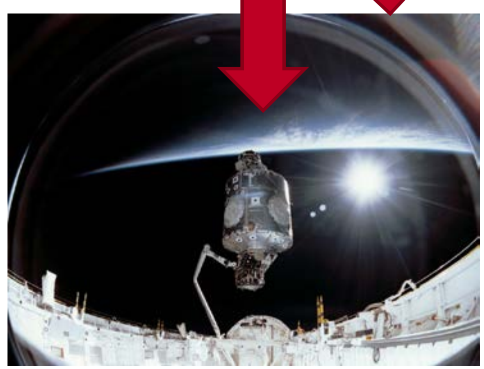
3. Shuttle Launches
16 December 1998



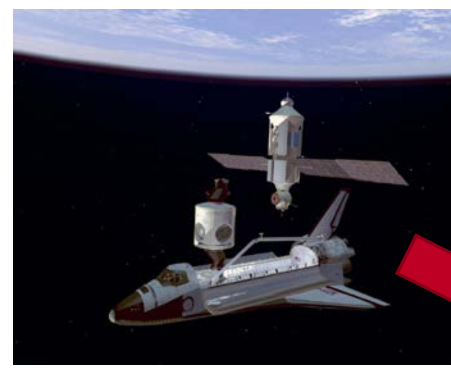
4. Shuttle rendezvous with
Node sticking out cargo bay



2. Zarya on-orbit,
starts spin

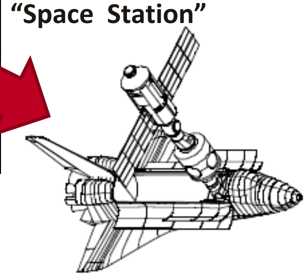


3. Shuttle attaches node
With arm



5. Shuttle grabs Zarya and
'berths' it with arm

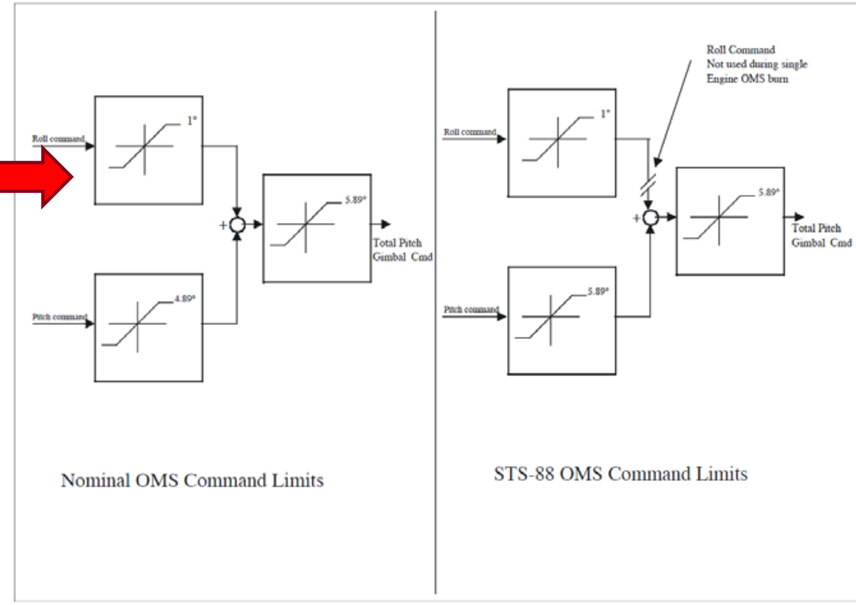
6. Shuttle reboosts new
"Space Station"



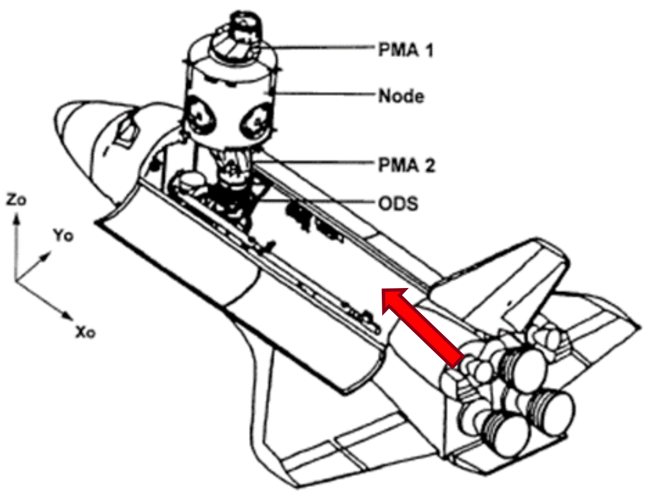
MCLAURIN

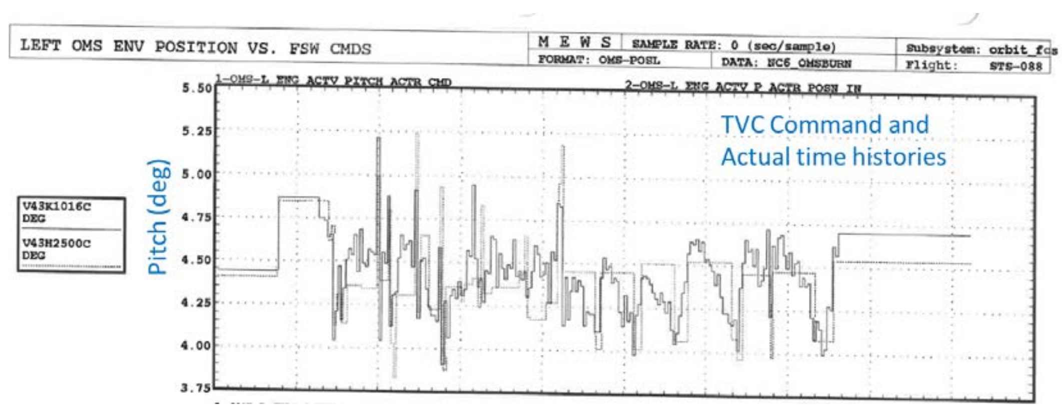
Rendezvous to Zarya with Node Extended From Cargo Bay

- Analysis quickly indicated we couldn't gimbal (trim) through mass center.
  - Shuttle software gimbal limits too small
  - Solution: Single engine burn and use roll gimbal allocation for pitch/yaw control.
- Given uncertainties, it was not clear if OMS system even had adequate hardware gimbal capability
  - Meant the design/loads had to be good for PRCS (870 lbf) thruster pitch/yaw "wrap around" control.



Reference [6]





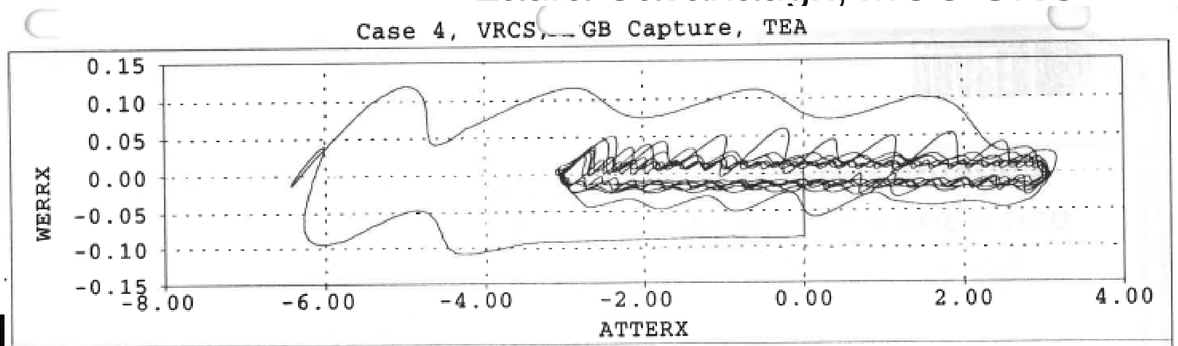
Orbiter Control with the Heaviest Payload Ever on the Shuttle Arm (42,000+ lbs)

Due to loads and stability concerns, two critical control decisions were made, both firsts:

1) Utilize the 870 lbf thrusters instead of the 24 lbf thrusters.

2) Notch out low frequency arm dynamics.

"Looks like the boys from Draper gave us a good DAP."
- Laura Cavanaugh, MCC GNC



VRCS: Phase stable, but Flex dynamics swamped out rigid body motion!

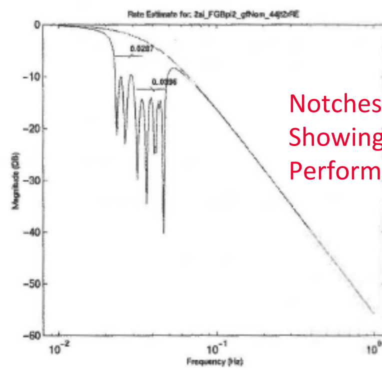
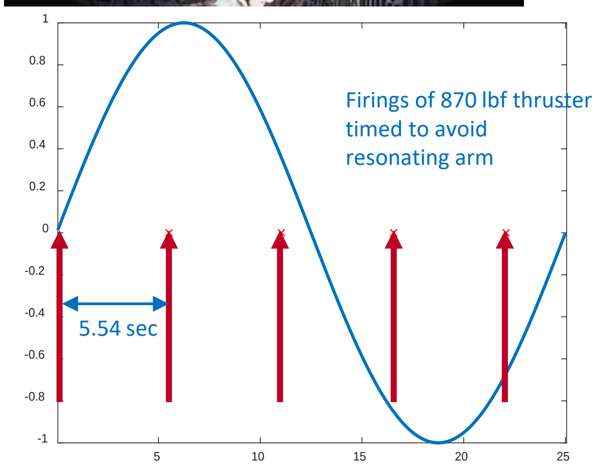


Figure 10: Frequency Response of FGB Pre-Install Filter Design

Notches placed at very low frequency (~0.03 Hz), Showing more concern for stability than Performance.

This is actually not the notch set we intended to fly!



Later flights, with so many structural frequencies, "variable" delays were used to over excitation over a frequency band.

Intrusive notches caused huge lag in measurements/control.

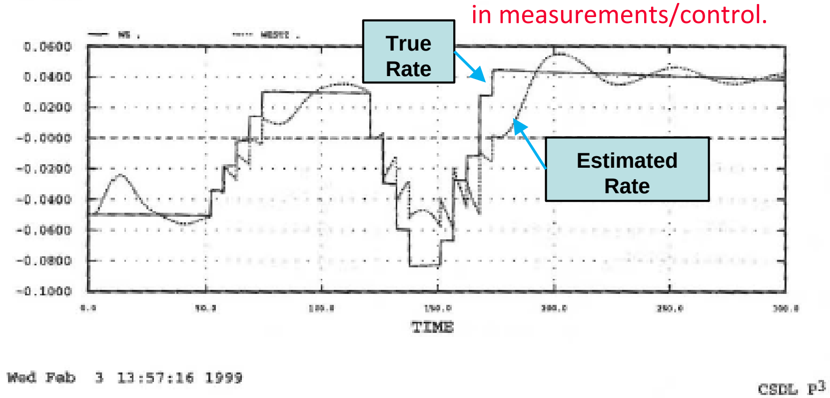
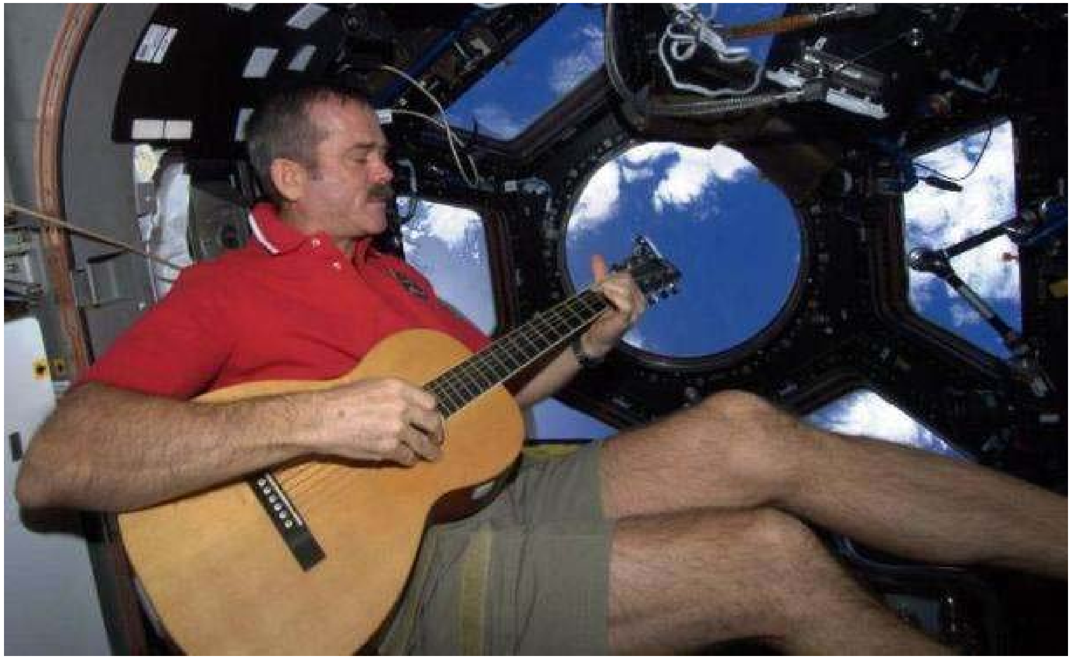
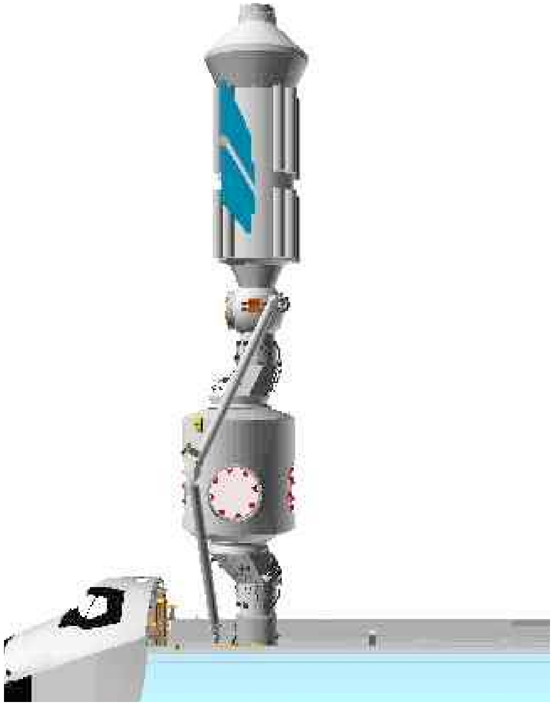


Figure 13: Simulated Rate and Rate Estimate, FGB Pre-Install Position

Problem Hard Mating Zarya to Node

Zayra (FGB) Install Video, STS-88, Chris Hadfield, CapCom, Nancy Currie, RMS Operator





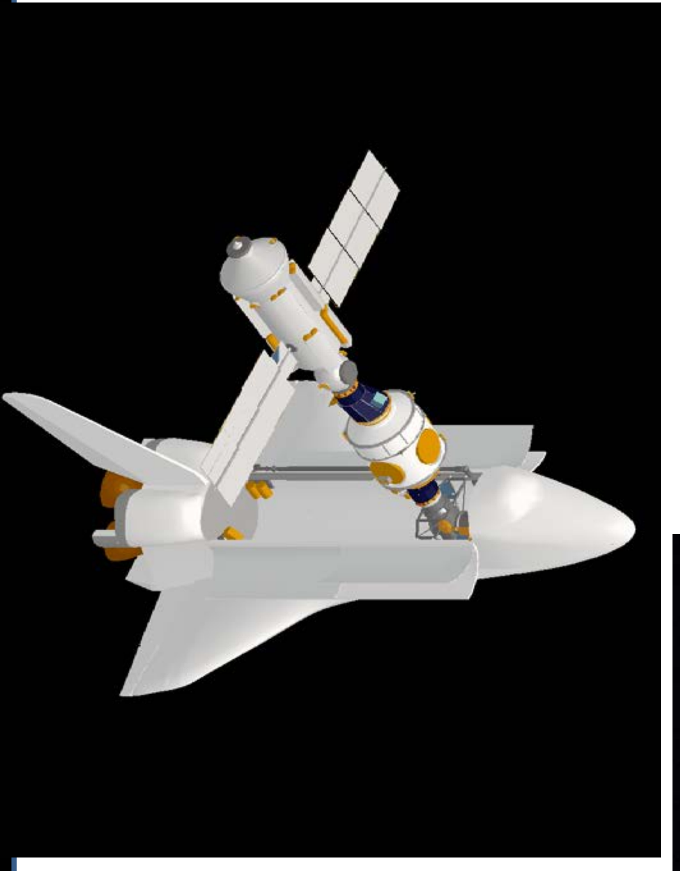
Mission Control animation was not prepared for having to release the arm.

The First "International Space Station" (ISS)

"The Space Station is ready to deploy the Orbiter."

-Anonymous ISS

flight controller.



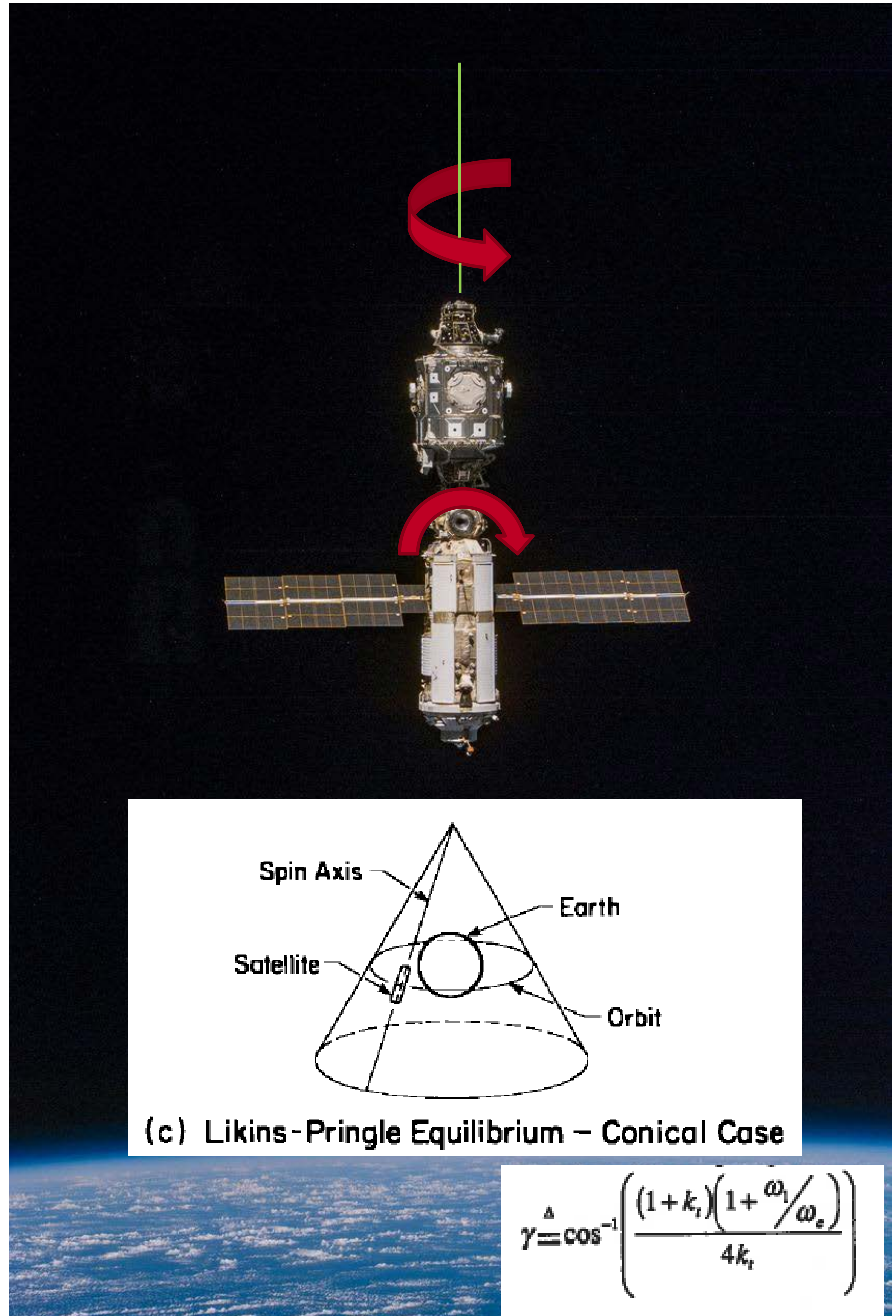
Source: NASA

The First "International Space Station" (ISS)

The Russians recommended the Likins-Pringle Equilibrium for predictable tri-inertial motion, ensuring ISS met power and thermal requirements with minimal propellant usage.

This was necessary because the next Shuttle flight was months away.

NASA called this spin the "X-Nadir Spin".



Source: NASA, Hughes [5]

STS-106 (2A.2b): Running low on propellant

RCS propellant in the forward tanks was generally a concern for early assembly missions.

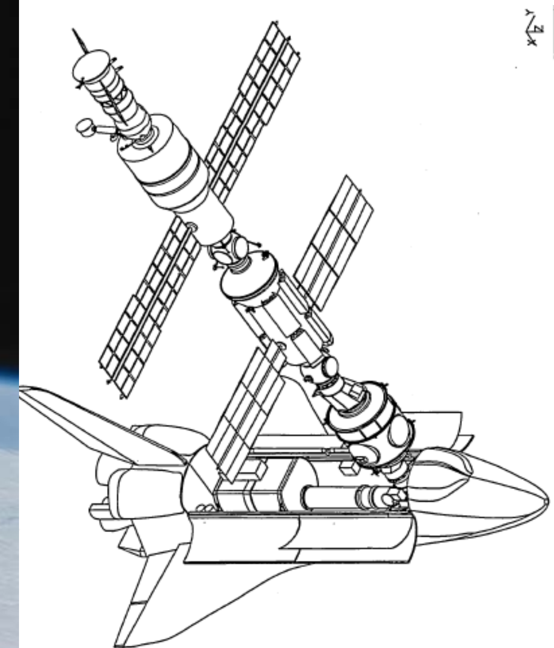
- No way to replenish on-orbit

This mission, in particular, was running red in forward prop usage.

Mated vehicle control was essentially lost with no forward RCS propellant.

Flight control scrambled to redesign the control parameters real time to save propellant.

Successfully undocked over last Russian communication opportunity.



Jet Mode	Maneuver		ODS Pressurized				ODS Depressurized			
			Time (s)	Fuel (lbs)			Time (s)	Fuel (lbs)		
				Total	Aft	Fwd		Total	Aft	Fwd
VRCS	30 Deg	Min	425	16.0	1.1	6.4	445	16.4	10.6	5.8
		Mean	518	38.2	20.7	17.5	567	49.3	26.5	22.8
		Max	835	61.4	34.8	26.6	1142	150.8	77.6	73.2
	60 Deg	Min	722	17.4	9.5	7.6	725	18.7	11.2	7.3
		Mean	836	43.7	22.8	20.9	870	54.1	27.8	26.3
		Max	993	63.7	37.4	29.8	1086	81.8	47.4	43.5
	90 Deg	Min	1021	18.9	9.3	0.0	1009	17.8	7.9	0.0
		Mean	1106	50.8	24.8	26.0	1128	60.2	29.0	31.2
		Max	1305	74.3	38.1	38.1	1284	98.5	52.3	49.5
	170 Deg	Min	1810	22.7	8.7	13.2	1821	24.7	11.7	12.8
		Mean	1941	73.1	32.0	41.1	1976	86.3	39.3	47.0
		Max	2189	124.3	48.5	76.9	2326	137.1	64.1	83.6

Prop usage Table Provided to Flight Ops for Timeline Design

Source: NASA

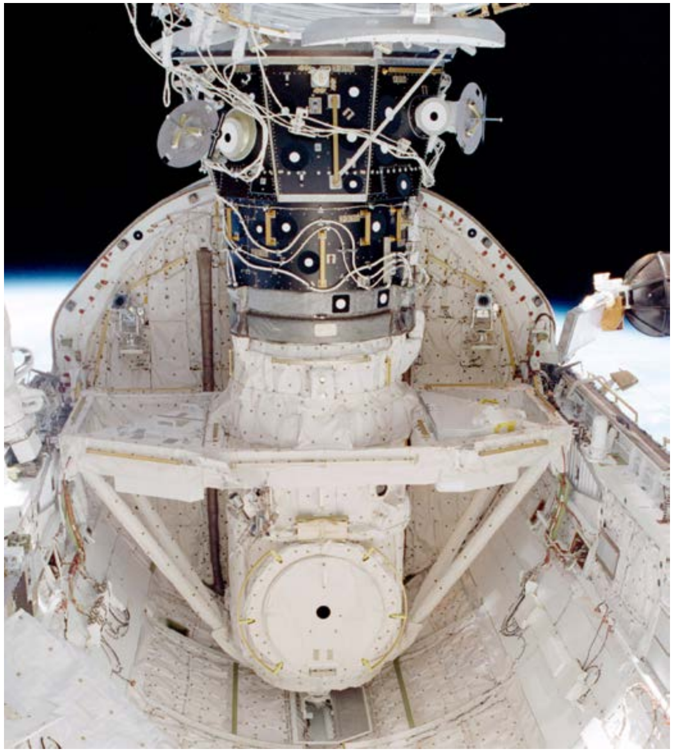
Reboosting the ISS…

Using Russian propellant to reboost the ISS was extremely expensive, so the Shuttle developed the capability.

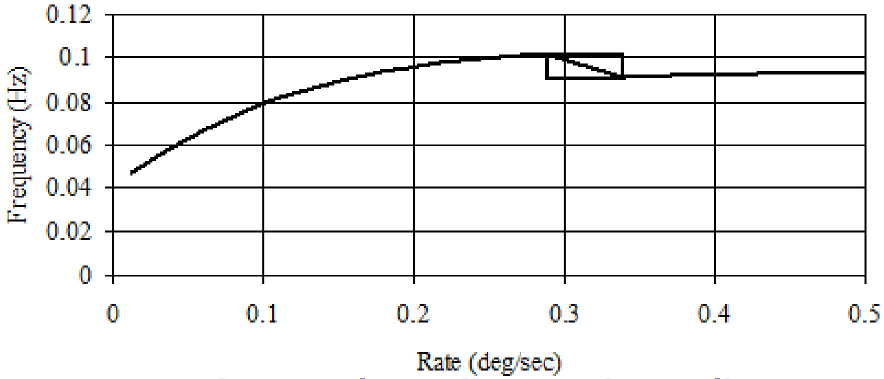
Initial reboost capability was a blend of manual and feedback control, but later became fully automatic with the VRCS thrusters firing for ~ hour duration.

Structural loading was a key consideration.

Stability: Fundamental flex mode transitioned between linear and nonlinear dynamics.



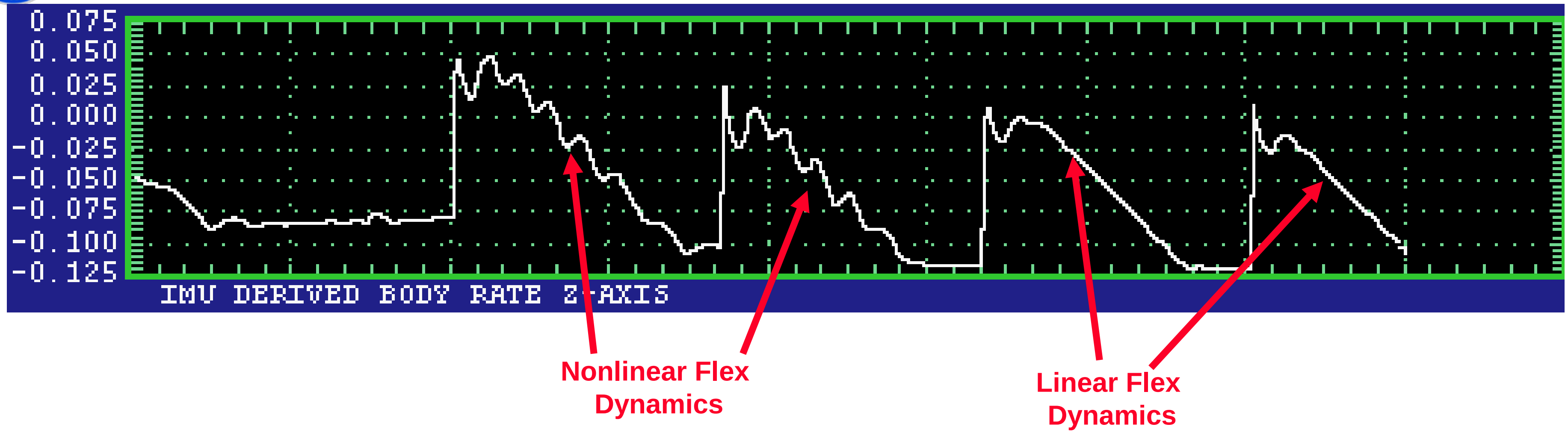
The Orbiter Docking System had freeplay at the trunnions, and the flex dynamics were either linear or nonlinear depending on the pressure differential.

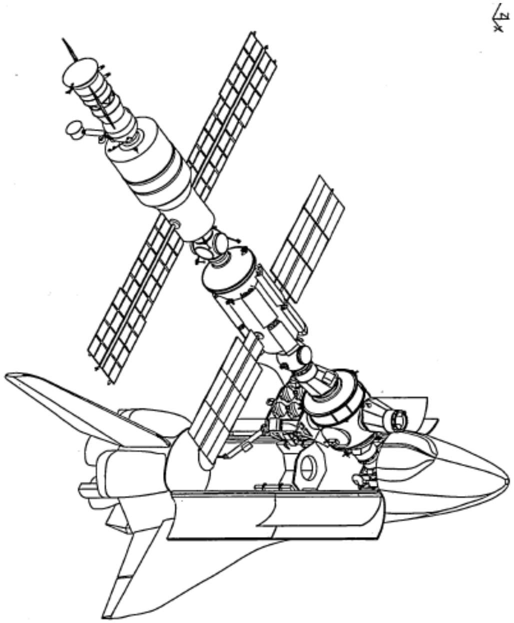


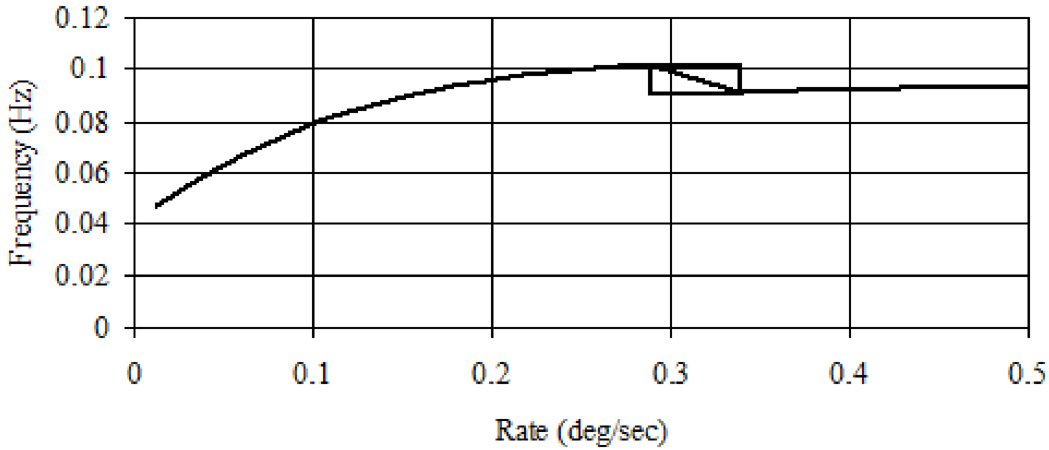
Fundamental Bending Mode nonlinear Relationship With Vehicle Angular Rate

Source: NASA and Ref [12]

STS-92 (3A): Orbiter Pitch Rate (deg/sec) During Reboost

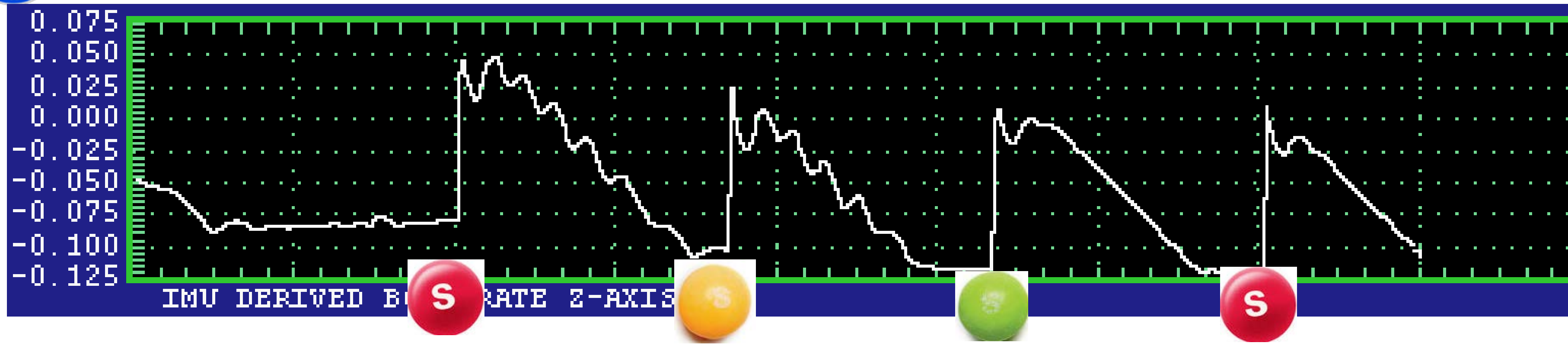




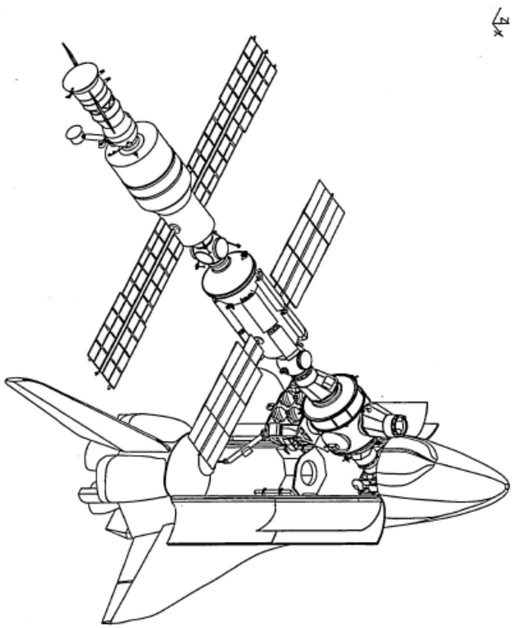


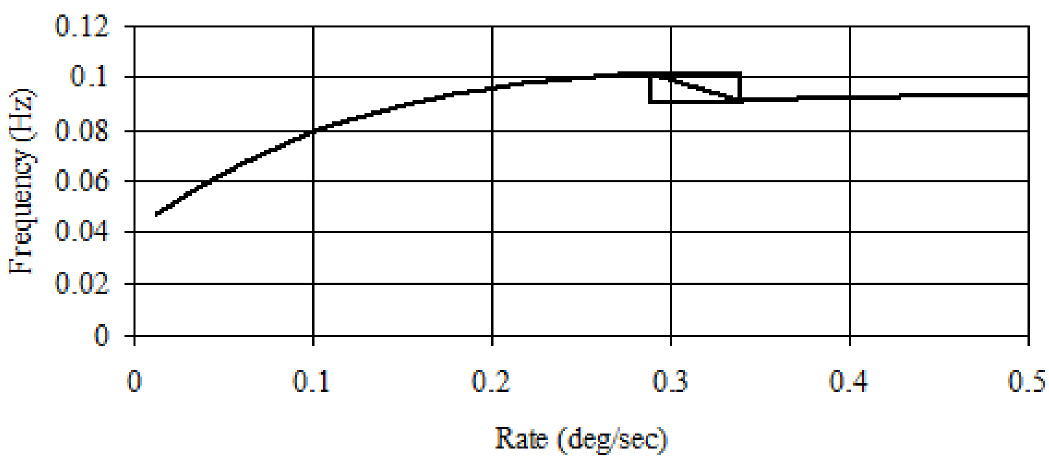
Fundamental Bending Mode nonlinear Relationship With Vehicle Angular Rate

STS-92 (3A): Orbiter Pitch Rate (deg/sec) During Reboost



In the MER, skittles were laid out for the appropriate number of reboost firings





Fundamental Bending Mode nonlinear Relationship With Vehicle Angular Rate

Critical Items at the MER GNC Console Position (STS-96, May1999)

Rob Hall and Mike Martin, Draper Laboratory

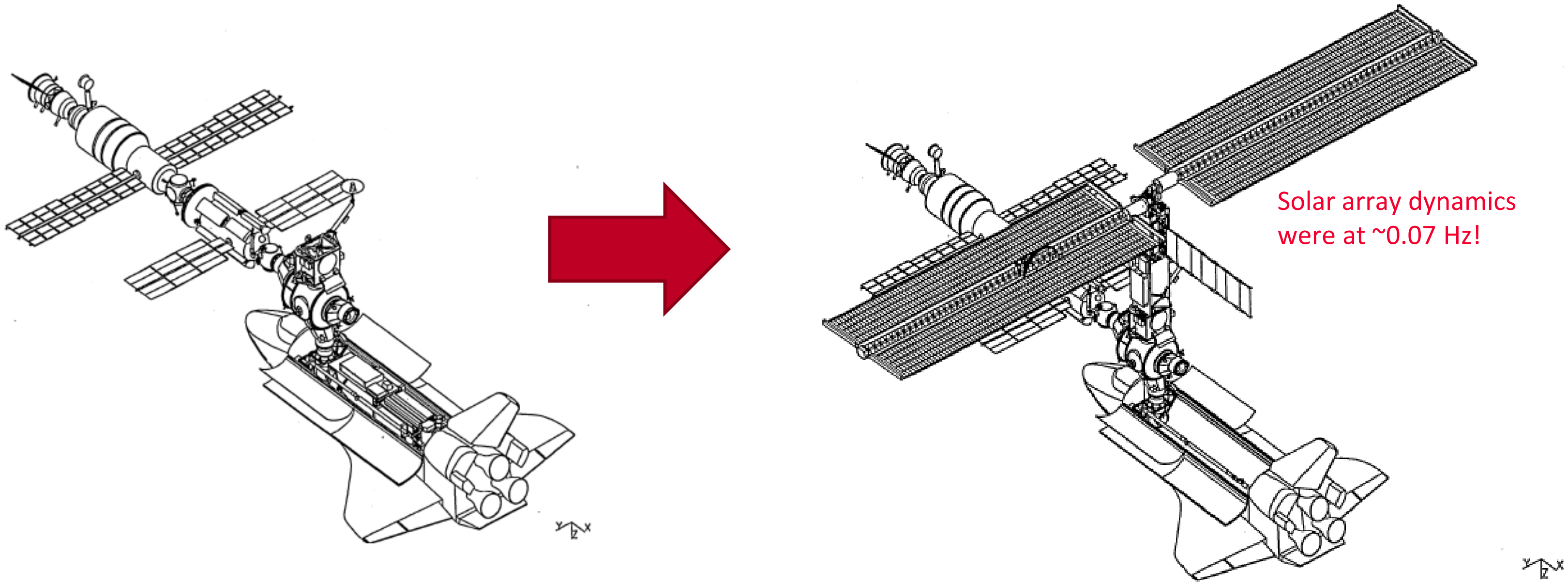
Critical Items at the MER GNC Console Position (STS-96, May1999)

Rob Hall and Mike Martin, Draper Laboratory

STS-97 (4A): Solar Array Fails To Fully Deploy

STS-97 as the first mission to deploy the solar arrays, each ~115 feet in length.

Mass Center was shifted over the Shuttle nose, rendering all forward thrusters unavailable.



Solar array failure-to-deploy was not considered in preflight planning.
- Structural dynamics for a partially-deployed array were completely unknown.
- First array failed to fully deploy.
- Crew performing EVAs for deployment.

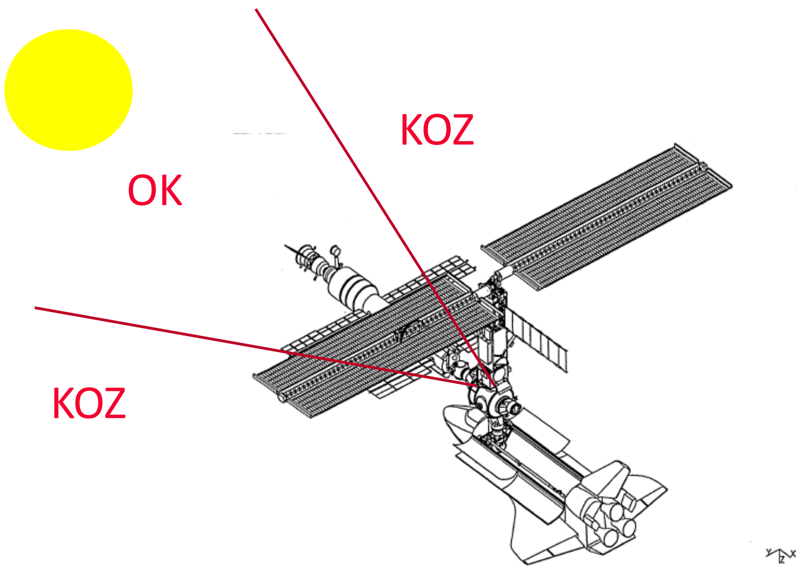
Control was regained by using a robust (but very poor performing) control design
- We had already developed this design, “just in case”.
- Had to verbally call-up the redesign, and crew manually typed in control parameters.

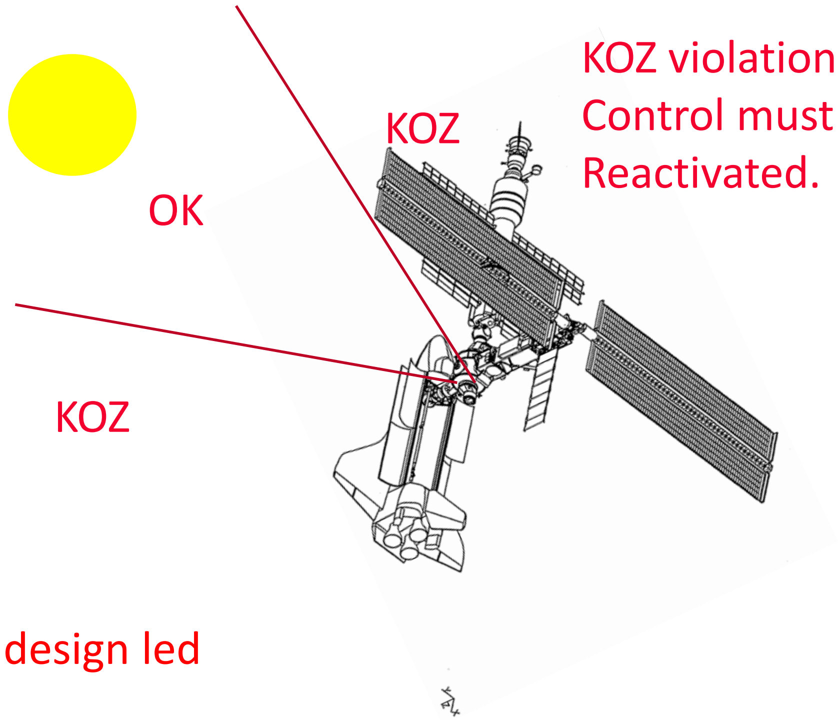
STS-97 (4A): Trying to avoid thermal Keep Out Zones with limited control

After the crew typed in the new control parameters, control was reactived.

Control was allowed only with the arrays tensioned and not deploying.

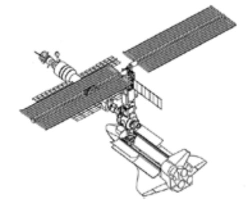
- Most of the time control was turned off ("free drift") while the crew (via EVA) worked on the arrays.
- With no control, thermal and power Keep Out Zones (KOZs) were being violated.





"Robust-but-very-sloppy" back-up control design led to very high rates in KOZ.

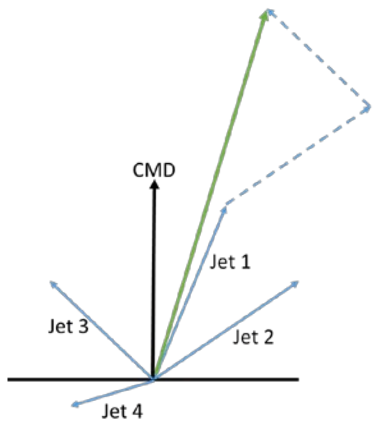
STS-97 (4A): Original Orbiter Jet Select Algorithm Would have Likely Lost Control



To increase controllability for docked operations, decision made early to redesign orbiter jet selection algorithm.

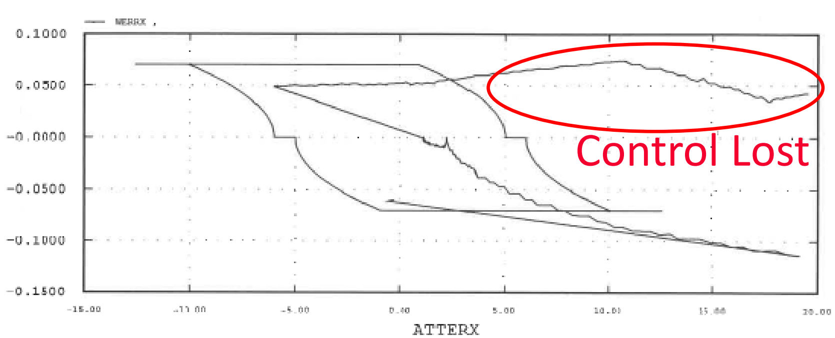
- New design minimized jet cross coupling, at the expense of control acceleration.

Original Jet Select: Dot Product

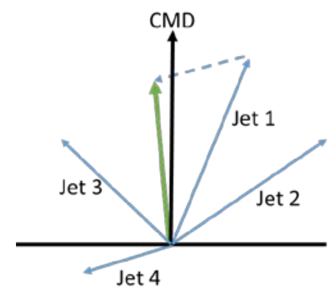


Selects jets 1,2, and 3,
Maximizing acceleration
Projected on CMD

FORMAT: 4A Alt Phase Plane   Run: (+,+,+) eng_cyc dot
DATA: 4a-final-ec/5.0-m0.1-0.07/at2-12.0-0.07/4/dap.dat

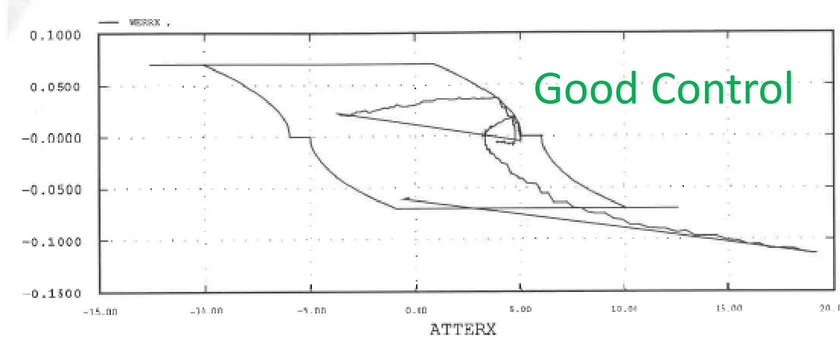


Updated Jet Select: Minimum Angle

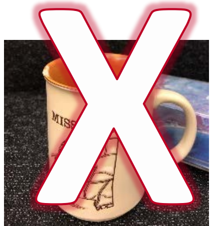


Selects jets 1 and 4,
Minimizing angle
Between CMD and
resulting acceleration,
i.e. minimize cross coupling

ORMAT: 4A Alt Phase Plane   Run: (+,+,+) eng_cyc mina
DATA: 4a-final-ec/5.0-m0.1-0.07/at2-12.0-0.07/4/dap.dat

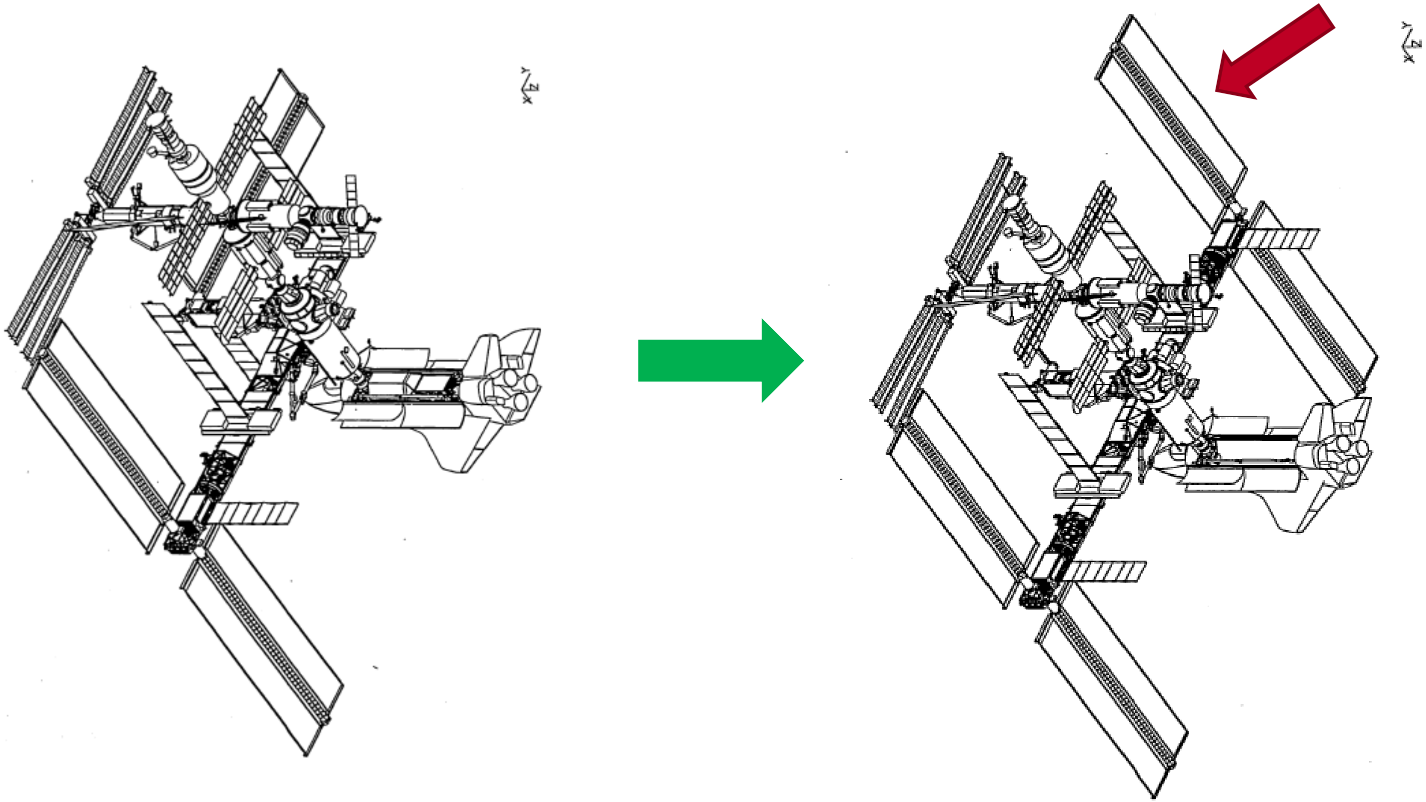


Russian Computers crash on STS-117 (13A), June 2007



Coffee Cup

Installing 2nd Set of Solar Arrays Crashed the Russian Computers



Russian computers were critical to controlling the Space Station after Orbiter left.

- All ISS Reaction Control Thrusters are on Russian Segment.

Russian Computers crash on STS-117 (13A), June 2007

Published online 19 June 2007 | Nature | doi:10.1038/news070618-4

News

Space station computer crash a mystery

As space shuttle returns to Earth, NASA is still puzzling over breakdown.

Geoff Brumfiel

All seems normal on the International Space Station today, as the space shuttle Atlantis prepares to return to Earth, leaving the usual allotment of astronauts behind to mind the station. But engineers are still working hard to understand the cause of a computer glitch that for some 48 hours or so put the station in what was arguably the greatest peril it has ever faced.

In the shade: installing solar panels in the station's shadow could have caused a buildup of static electricity.
NASA

All six Russian navigational computers responsible for maintaining the station's position or 'attitude' in the sky inexplicably crashed on 7 June, around the time that the station's new solar panel was being attached by shuttle astronauts. The computers refused to

Abandon ship

When the computers were down, the station relied on the thrusters of the docked space shuttle to perform emergency adjustments to its orbit. Had the problem persisted past the point when the shuttle had to return home, then astronauts would have been forced to abandon ship and leave the station unmanned for the first time since it was staffed in 2000.

https://www.nature.com/news/2007/070619/full/news070618-4.html

Russian Computers crash on STS-117 (13A), June 2007

Published online 19 June 2007 | Nature | doi:10.1038/news070618-4

News

Space station computer crash a mystery

As space shuttle returns to Earth, NASA is still puzzling over breakdown.

Geoff Brumfiel

All seems normal on the International Space Station today, as the space shuttle Atlantis prepares to return to Earth, leaving the usual allotment of astronauts behind to mind the station. But engineers are still working hard to understand the cause of a computer glitch that for some 48 hours or so put the station in what was arguably the greatest peril it has ever faced.

In the shade: installing solar panels in the station's shadow could have caused a buildup of static electricity. *NASA*

All six Russian navigational computers responsible for maintaining the station's position or 'attitude' in the sky inexplicably crashed on 7 June, around the time that the station's new solar panel was being attached by shuttle astronauts. The computers refused to

Abandon ship

When the computers were down, the station relied on the thrusters of the docked space shuttle to perform emergency adjustments to its orbit. Had the problem persisted past the point when the shuttle had to return home, then astronauts would have been forced to abandon ship and leave the station unmanned for the first time since it was staffed in 2000.

Mystery?

https://www.nature.com/news/2007/070619/full/news070618-4.html

Thanks!

References

1. Battin, Richard H., “Some Funny Things Happened on the Way to the Moon”, Journal of Guidance, Control, and Dynamics, Vol. 25 January-February 2002.
2. “International Space Station on-orbit Assembly, Modeling, and Mass Properties Databook”, Design Analysis Cycle #7 Revision D Assembly Sequence, Lockheed Martin, JSC-26557 Rev I, September 1998.
3. “Mission Control Center/Building 30, Historical Documentation”, NASA, prepared by Archaeological Associated, Sarasota, Florida, October 2010.
4. Hattis, P. D., “A Short History of the Space Shuttle Orbit Flight Control System Development and Application Evolution”, Charles Stark Draper Laboratory, AAS 16-095, 2016.
5. Hughes, Spacecraft Attitude Dynamics, John Wiley & Sons, 1986.
6. Hall, R., Kirchwey, K., Martin, M., Rosch, G., Zimpfer, D., “Flight Control Overview of STS-88, the First Space Station Assembly Flight”, Charles Stark Draper Laboratory memo ESC-94-119, July 22, 1994.
7. Zimpfer, D., Kirchway, C., Hanson, D., Jackson, M., Smith, N., “Shuttle Stability and Control of the STS-71 Shuttle/MIR Mated Configuration”, AAS/AIAA Space Flight Mechanics Meeting, Austin, Texas, February 1996, AAS-96-131.
8. Hall, R. A., Kaznacheyev, Y., V., “Fuel Optimal Rotations of the Space Station MIR”, AIAA Guidance, Navigation, and Control Conference, San Diego, California, July 1996, AIAA 96-3789.
9. Hall, R., Kirchwey, K., Martin, M., Rosch, G., Zimpfer, D., “Flight Control Overview of STS-88, the First Space Station Assembly Flight”, AAS-99-371.
10. “Mission ISS-3A Orbiter/ISS On-Orbit Interface Requirements”, ICD-A-21341-OOR, Boeing North American, Inc., Reusable Space Systems, January 24, 1997.
11. “STS-88 Shuttle/ISS 2A Flight Control Mission Report”. R. Hall, K. Kirchwey, M. Martin, G. Rosch, Charles stark Draper Laboratory CSDL-R-2868, December 10, 1999.
12. Widnall, W. S., “Lunar Module Digital Autopilot”, Journal of Spacecrat, Vol 8, No. 1, page 56, January 1971.

QUESTIONS ???