Image Credit: NASA

STS-74

Space Systems Mission Study

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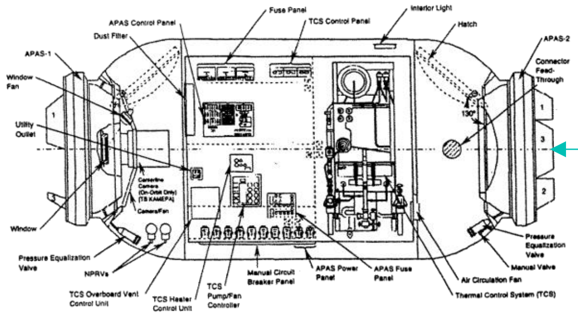
1: Mission

- STS-74 was a **Space Shuttle** Atlantis mission in 1995, carrying the Mir **Docking Module** to the Russian **Mir** space station in **LEO** to facilitate future shuttle-mir **rendezvous**.
- First time astronauts from ESA, Canada, Russia and the U.S. operated in the same orbital complex, a major step in **international space collaboration** and laid the groundwork for the **ISS**
- Atlantis delivered **supplies** (such as water and equipment for ongoing experiments) and **upgrades** to the Mir Station
- Various scientific **experiments** were conducted and returned to Earth
- The docking module was needed to ensure **safe and easy dockings** for future shuttle-Mir mission as the current docking procedure had the shuttle manoeuvring far too close to Mir’s solar arrays

Aim ID	Mission Aim
A1	Docking Module Installation
A2	Facilitate Future Shuttle-Mir Operations
A3	International Cooperation
A4	Resupply Mir Station
A5	Conduct Scientific Experiments

2: Payload

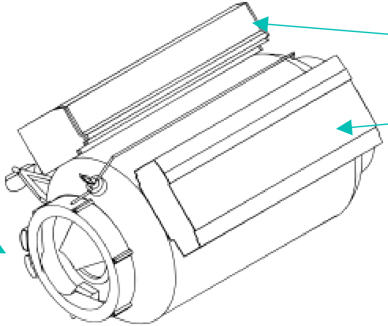
Payload Name	Purpose	Mission Aim	Weight (kg)
Mir docking module	Provide **clearance** between Shuttle and Mir's solar arrays during later dockings	A1,A2,A3	4,100
U.S. Solid Sorbent Air Sampler	Take **air and water samples** to characterize volatile organic compounds on the Mir station to improve systems for the ISS	A2,A5	~0
Cooperative Solar Array	Novel **experimental solar array** development by the US conjunction with Russia, used as proof of concept for future arrays on the ISS and provided power to the module and Mir	A3,A4,A5	2,300
GLO-4	**Broadband spectrograph** studying "glow phenomenon" observed by shuttle astronauts potentially cased by atmospheric gases colliding with the Shuttle	A5	300
Photogrammetric Appendage Structural Dynamics Experiment	Demonstrates a **photogrammetric method** for making structural measurements to aid construction of the ISS	A5	



Docking Module Interior (Starboard)

[28]

Shuttle Side Docking



Solar Arrays

Docking module exterior view

[21]

3: Requirements (student-generated)

ID	Requirement	Rationale
001	An **international** group of astronauts shall fly and operate the shuttle	To support future missions and further reinforce the message of **international collaboration** (A3)
002	The shuttle's cargo bay capacity shall accommodate **10000kg of payload**	To ensure **all** necessary equipment and scientific instruments can be transported to Mir (A5) [4]
003	**NASA-STD-3001 safety standards** for human spaceflight shall be adhered to during shuttle operation and payload installation	To ensure **safety** of both the shuttle and Mir crews during docking module installation (A1) [24]
004	The docking module shall be able to **interface** with both the shuttle and Mir	To ensure it can **dock and communicate** with the shuttle and Mir (A2)
005	The shuttle shall carry **supplies** to support the shuttle crew for the **duration of the mission** and the Mir crew until their next resupply	To ensure crews have enough food and water as well as supplies to maintain their equipment (A4)
006	One member of the crew shall be trained to operate the **Canadarm**	To ensure **effective handling** of the payloads (A1) [30]
007	The shuttle shall **rendezvous** with Mir in orbit	To **dock and install** the module (A1)
008	The payload shall have the capability to meet its **power requirement of 551W**	To ensure it can remain **fully functional** (A1,A2, A5) [25]
009	The payload shall be no more than **4.6 meters in diameter** and **18 meters long**	To **fit inside shuttle** payload bay (A1) [24]
010	The Docking Module shall have a **lifetime of 5 years**	To accommodate **all** planned Shuttle-Mir missions (A2) [11]

4: CONOPS

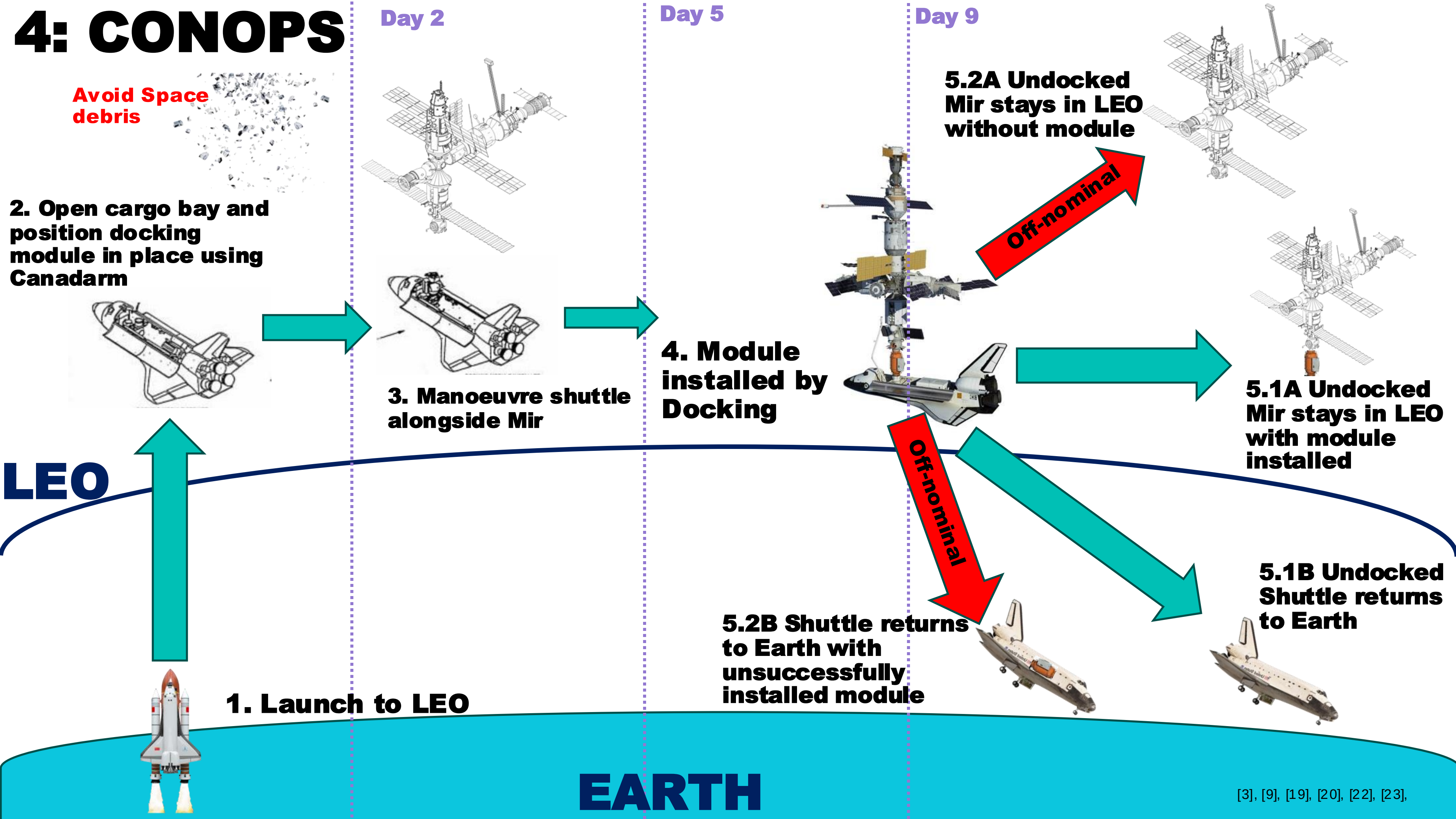

Day 2
Day 5
Day 9
Avoid Space debris
2. Open cargo bay and position docking module in place using Canadarm
3. Manoeuvre shuttle alongside Mir
4. Module installed by Docking
5.2A Undocked Mir stays in LEO without module
Off-nominal
5.1A Undocked Mir stays in LEO with module installed
Off-nominal
5.1B Undocked Shuttle returns to Earth
5.2B Shuttle returns to Earth with unsuccessfully installed module
LEO
1. Launch to LEO
EARTH
[3], [9], [19], [20], [22], [23],

Image Credit: JSC

5: Launcher

- Space Shuttle Atlantis was used and launched from the **Kennedy Space Center**
- The primary specifications of Atlantis are shown below in the table [20]

Max Payload to LEO (kg)	Launcher Height(m)	Shuttle Dry Mass (kg)	Launcher Mass at Ignition (kg)
27,000	56.1	70,500	1,940,000

- The following calculations prove that the shuttle has the capability of **launching** the Mir Docking Module and docking to Mir

5: Launcher

- Space Shuttle Atlantis uses **3 RS-25** Space Shuttle Main Engines (SSME) that burn Liquid Oxygen and Liquid Hydrogen and **2 Solid Rocket Boosters** (SRB) that burned an ammonium perchlorate composite propellant [16][17]

- Launch Sequence
  - **Stage 0**: SRBs and SSMEs fire in parallel with the SSMEs taking fuel from the External Tank (ET)
  - **Stage 1**: SRBs separate and SSMEs continue to fire, ET separates once fuel is depleted

Parameter	SRB (single)	Shuttle +Payload	ET
Diameter/ Wingspan (m)	3.7	23.7	8.4
Length (m)	45	37.2	47
Propellant Mass (kg)	500,000	n/a	698,000
Total Mass (kg)	568,000	79,000	725,000
Thrust (kN)	13,300	5,250	n/a
Isp (sec)	242	455	n/a
Burn Time (sec)	124	512.6	n/a
Separation Time from Launch (sec)	123	n/a	514

5: Launch Calculations

- The following equation was used to determine **delta v** for each stage

$$\Delta v = I_{sp} \ln\left(\frac{m_0}{m_f}\right) \text{ and } I_{sp} = \frac{Thrust}{\dot{m}}$$

Value	Calculation	Result
SRB $\dot{m}$ (kg/s)	$\frac{SRB\ Propellant\ Mass\ \times\ 2}{SRB\ Burn\ Time}$	8000
Shuttle $\dot{m}$ (kg/s)	$\frac{ET\ Propellant\ Mass}{Shuttle\ Burn\ Time}$	1400
Stage 0 Effective I_{sp} (m/s)	$\frac{SRB\ Thrust\ \times\ 2 + Shuttle\ Thrust}{\text{SRB } \dot{m} + \text{Shuttle } \dot{m}}$	3300
Stage 0 m_0 (kg)	$Shuttle\ Wet\ Mass\ + 2 \times SRB\ Wet\ Mass + ET\ wet\ Mass$	1,940,000
Stage 0 m_f (kg)	$m_{0\ stage\ 0} - 2\ \times\ SRB\ propellant\ mass - Shuttle\ \dot{m}\ \times\ SRB\ Burn\ Duration$	766,000
Stage 1 m_0 (kg)	$m_{f\ stage\ 1} - 2\ \times\ SRB\ dry\ mass$	630,000
Stage 1 m_f (kg)	$m_{1\ stage\ 0} - ET\ propellant\ mass + Shuttle\ \dot{m}\ \times\ SRB\ Burn\ Duration$	106,000

5: Launch Calculations

- The following equation was used to determine **delta v** for each stage

$$\Delta v = I_{sp} \ln\left(\frac{m_0}{m_f}\right) \text{ and } I_{sp} = \frac{Thrust}{\dot{m}}$$

Stage	Stage 0	Stage 1	Total
I_{sp} (m/s)	3300	3750	
m_0 (kg)	1,940,000	630,000	
m_f (kg)	766,000	106,000	
Δv (m/s)	3,100	6,700	9,800

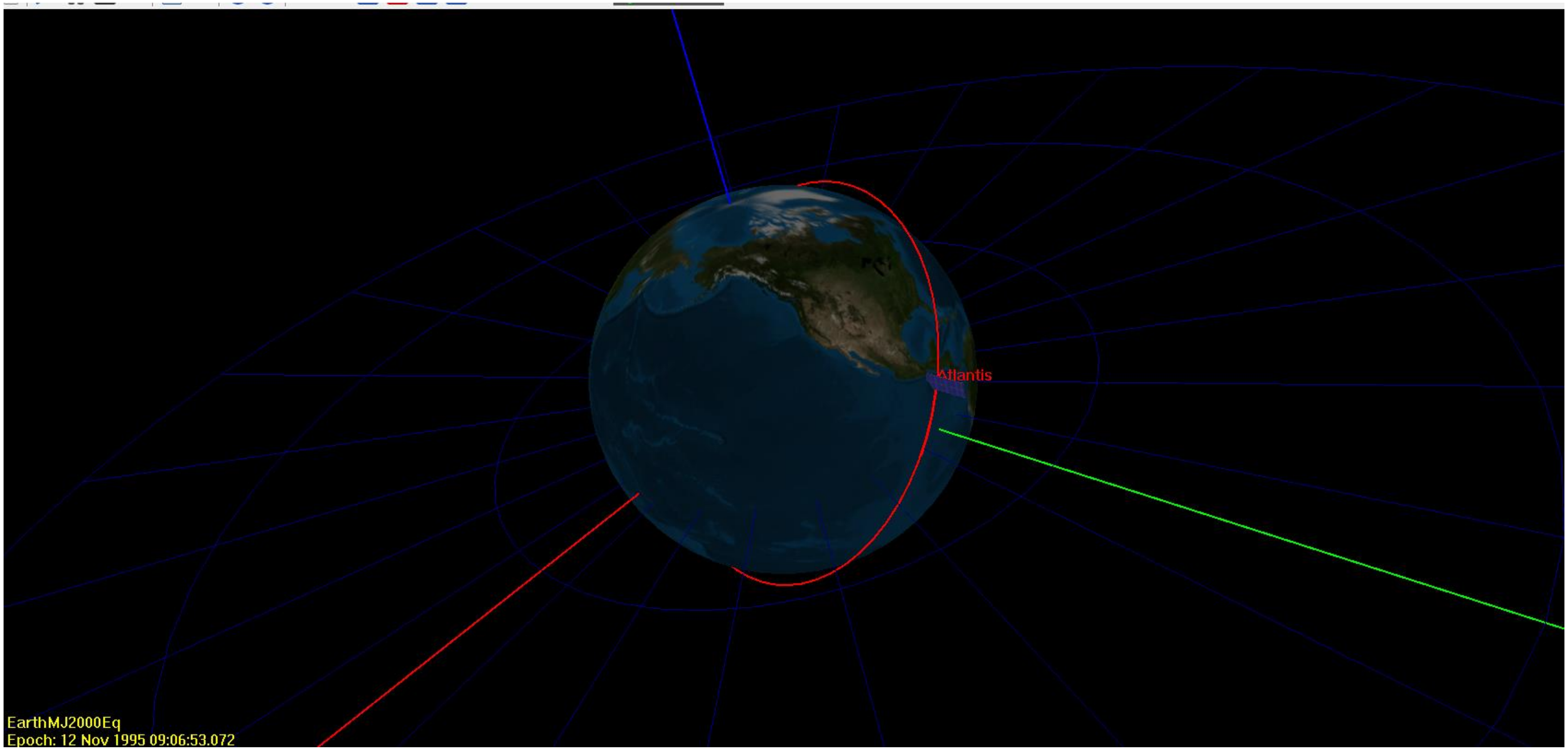
- As shown above, Space Shuttle Atlantis has a **maximum achievable delta V of 9800 m/s** which is **higher** than the **required 9.3 km/s** necessary to achieve the required Low Earth Orbit
- This means that the shuttle **will** be able to launch the payload to its required orbit
- Calculations ignored change in thrust during engine throttle and startup and assumed all SRB fuel used up before instantaneous separation

6: Orbit Selection

- Req-004 dictates orbit needs to be the same as the **Mir Space Station** [10]
- Required orbit is **almost circular** so in later calculations it is assumed to be circular
- In the GMAT script, the **RAAN** was chosen as **80°** since this aligns with the Kennedy Space Center launch site which won't be exact since the Shuttle will manouevre to match Mir's orbit

Element	Value
Orbit Type	LEO
Periapsis Altitude (km)	354
Apoapsis Altitude (km)	374
Orbital Inclination (degrees)	51.6
Orbital Velocity (km/s)	7.69
Eccentricity	0.0015
Semi-Major Axis (km)	364

6: Orbit Selection



7: Delta V

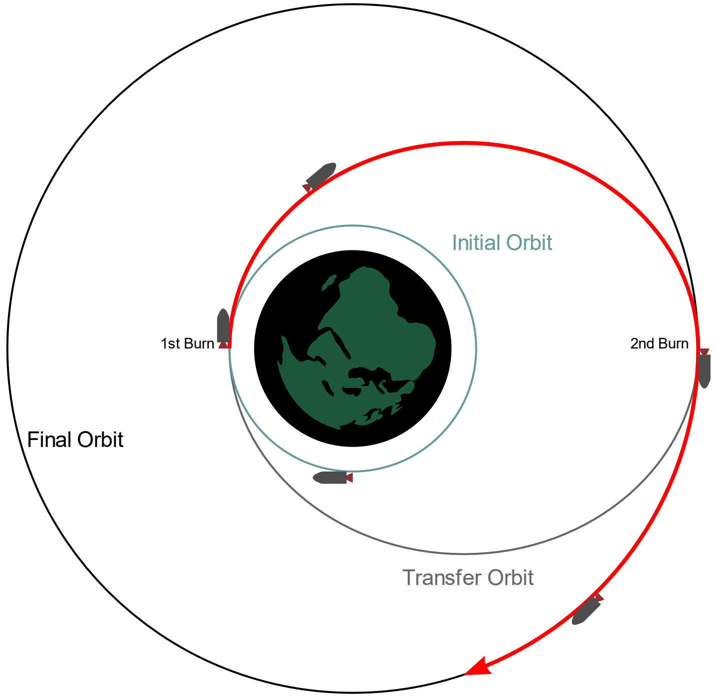
- A **Hohmann transfer** was used to boost from a **circular 200km** orbit to the required orbit
- This required **2 burns** and the delta V needed for the burns was calculated using an expanded version of the **vis-viva equation** seen below:

$$\Delta v = \Delta v_1 + \Delta v_2$$

$$\Delta v = V_1 - V_{c1} + V_{c2} - V_2$$

$$\Delta v = \sqrt{\mu\left(\frac{2}{r_1} - \frac{1}{a_1}\right)} - \sqrt{\frac{\mu}{r_1}} + \sqrt{\frac{\mu}{r_2}} - \sqrt{\mu\left(\frac{2}{r_2} - \frac{1}{a_1}\right)}$$

- The first burn creates an **elliptical orbit** with apogee at the desired altitude and perigee at the initial altitude then the second burn **circularizes** the orbit at desired altitude



[27]

7: Delta V

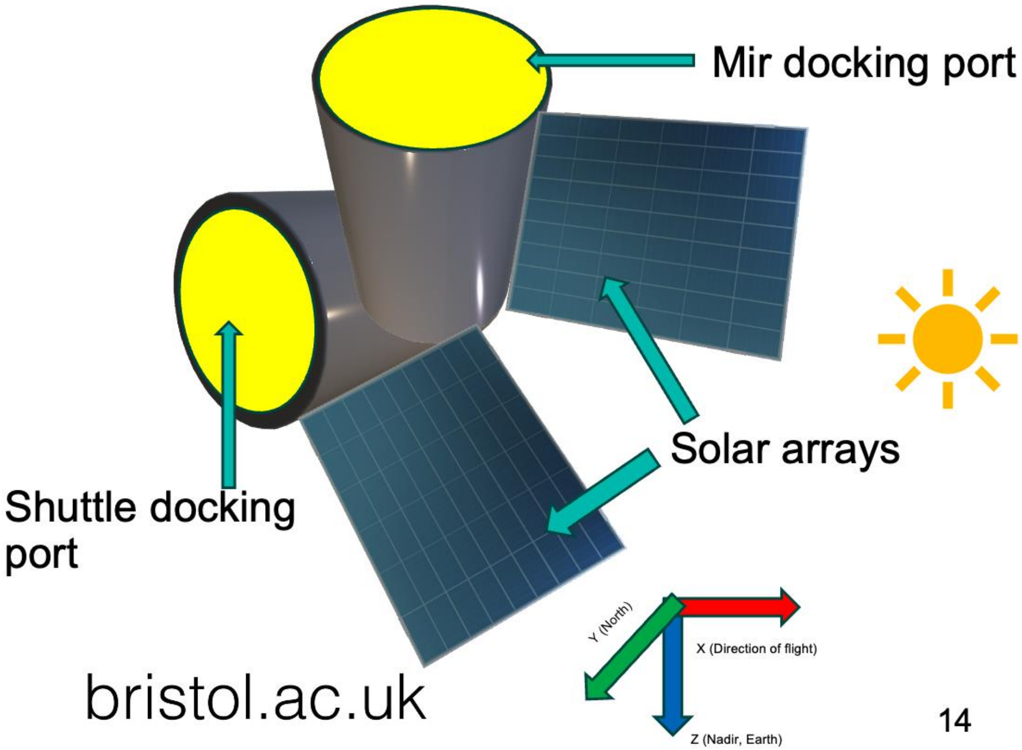
- V_{c1} is the **initial velocity** of the orbit and V_{c2} is the **velocity of the desired orbit**
- V_1 and V_2 are the **velocities of the transfer orbits**
- r is the **radius** of the orbit (altitude + radius of the Earth) and a is the **semi-major axis** of the transfer orbit
- μ is taken to be **3.986E5 km³/s²** and the radius of the Earth is taken as **6371km**

	r (km)	a (km)	Vc (km/s)	V (km/s)	Delta V (km/s)
Burn 1	200 + 6371	6653	7.788	7.836	0.048
Burn 2	354 + 6371	6653	7.699	7.657	0.042

- The first burn brings us to an **elliptical orbit at 354km** and the second burn circularizes the orbit
- The **total delta V** required for the transfer is **0.09km/s**
- The target orbit was assumed to be **circular** because the added delta V for the small eccentricity would be **negligible**

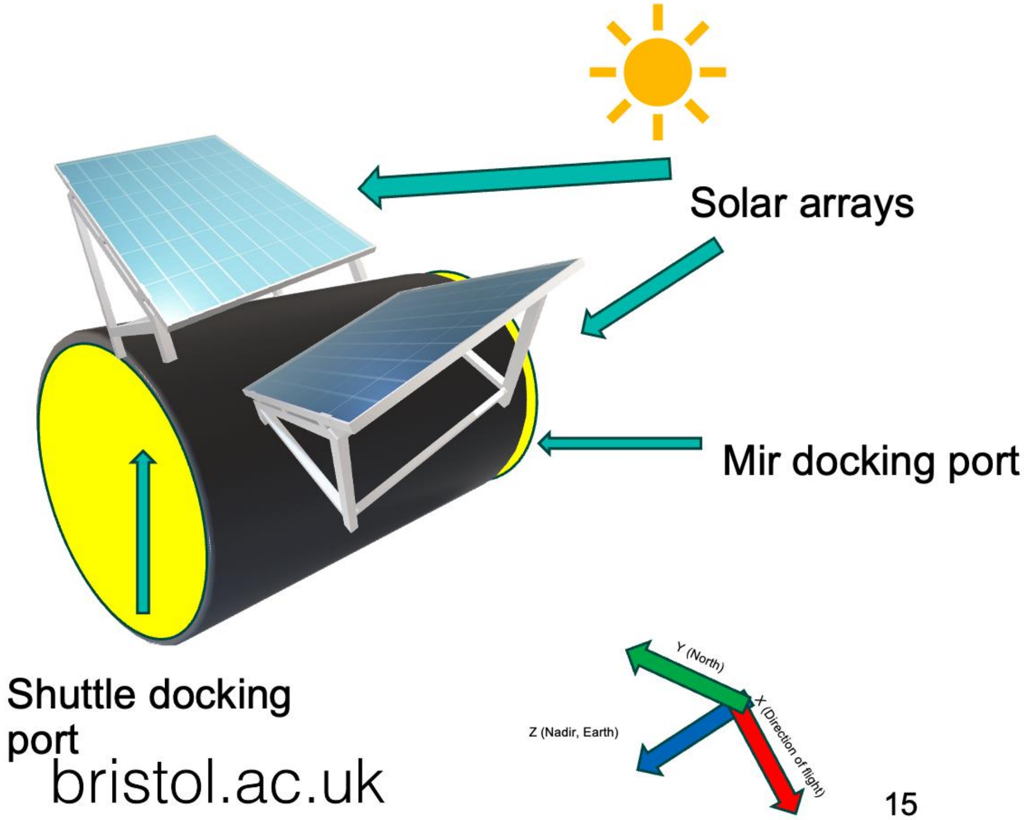
From [9]

8: Configuration (alternative candidate)



- With the Mir and shuttle docking ports **perpendicular** to each other, this arrangement could **complicate docking manoeuvres** for the shuttle
- The **risk of collision** with Mir's solar arrays **increases** due to the angle and **close proximity** of the arrays to the shuttle's approach path
- As Mir orbits Earth, the sun’s position shifts, rotating through the **ZX plane** (Earth-facing and direction of flight axes). This change in the sun’s angle means that the solar arrays may not always be able to **optimally point** toward the **sun** while the docking ports remain aligned for shuttle approach. This can **reduce the effectiveness** of solar energy capture, as the arrays **cannot** always be positioned to **track the sun**.

8: Configuration (selected)



- With the docking ports positioned **directly opposite** each other, the shuttle can **approach more easily** without the risk of colliding with the solar arrays. The **180-degree alignment** creates a clear, unobstructed pathway for docking, simplifying the manoeuvre and **reducing collision risks**.
- In this setup, the solar arrays are placed to capture sunlight more effectively without interfering with the docking approach. The 180-degree docking alignment allows for **flexible orientation** of the solar arrays, as they do not need to be reoriented or folded to accommodate docking maneuvers and they can **more freely capture** sunlight throughout the orbit

9: Power

- **End Of Life power** driven by demands of docking module and other payloads [6][7]

Element	Power (W)
GLO-4	50
Photogrammetric Appendage Structural Dynamics Experiment	100
Androgynous Peripheral Docking System for Docking Module	10
Thermal Control System for Docking Module	50
Interior Centerline Camera for docking alignment in Module	5
Backup Environmental Control and Life Support (ECLS) Systems on the Module	20

From [9]

9: Power

- **Power** is generated by **Solar Arrays** which only work during **daylight time** (no power generated during eclipse when no sunlight reaches array)
- **Eclipse time** and the **power required** for an orbit were calculated using the equation below:

$$T_e = Eclispe\ time = Orbit\ Period\ \times \left(\frac{180 - 2\cos^{-1}\left(\frac{R}{r}\right)}{360}\right)$$

$$T = Orbit\ Period = 2\pi\sqrt{\frac{r^3}{G \times M}}$$

$$Power\ Required = \frac{\frac{P_e T_e}{X_e} + \frac{P_d (T - T_e)}{X_d}}{T - T_e}$$

- This gives an **Orbit Period** of **92 minutes** and an **Eclipse time** of **36 minutes**
- The **total solar array power** requirement for the Payload is **551W**
- Assumed same power during day and eclipse since all payloads need to be active and fully powered throughout the orbit [11]

	Parameter	Value	Source/Calculation
G	Universal Gravitational constant (Nm^2kg^{-2})	6.67E-11	Constant [29]
M	Mass of the Earth (kg)	5.97E24	Constant [20]
R	Radius of the Earth (km)	6371	Constant [29]
AU	Distance between Earth and Sun (km)	1.496E8	Constant [29]
r	Orbit radius (km)	354 + 6371	Orbit Altitude + Earth Radius
X_e	Efficiency of path from array thro' batteries to loads	0.6	Lecture Notes
X_d	Efficiency of path from array directly to loads	0.8	Lecture Notes
P_d	Power required in daylight (W)	235	Total from previous slide

From [9]

9: Power

- The **solar array** and **battery** were sized using the following equation:

$$Array\ Area = \frac{P_d}{Solar\ flux \times \cos(\theta)\, \eta_c \eta_p (1 - D)}$$

$$Solar\ flux = \frac{1370}{\left(1 + \frac{r}{AU}\right)^2}$$

$$Battery\ Capacity = \frac{PT_e}{DoDNn}$$

- This gives a required **Solar flux** of **1369.9W/m^2**, **array area** of **13m^2** and **battery capacity** of **783Whr**
- The **solar arrays** would need to have an area of **13m^2** in order to provide the **551W** of power required
- **One battery** was chosen since **800Whr** batteries are **readily available**
- All the above calculations may not be exact due to the fact that the docking module's power systems were heavily integrated with Mir as explained later in the reflection

	Parameter	Value	Source/Calculation
θ	Solar incidence angle (°)	0	Solar arrays track the sun so incidence is 3.8±3° in June and 1.6±3° in December so can be taken as 0° [13]
η_c	Cell efficiency	0.15	[13]
η_p	Packing efficiency	0.88	[8]
D	Radiation Degradation factor	0.9	[13]
T_e	Eclipse time (mins)	36	Calculated in previous slide
DoD	Depth of Discharge	0.2	Lecture notes
N	Number of batteries	1	Chosen
n	Efficiency of path to battery	0.9	Lecture notes

10. Reflection (400-500 words)

In this assignment, two primary requirements served as the **design drivers** for the docking module: **Requirement 007**, mandating the shuttle rendezvous with the Mir space station, and **Requirement 004**, which required the docking module to interface with both the shuttle and Mir. **Requirement 007** defined the mission's orbit, setting the **inclination at 51.6**° and the **apoapsis at 354 km**, ensuring that the shuttle's orbit matched Mir's [26]. This dictated the required **delta V** needed in the launch vehicle section as well as the orbit selection. **Requirement 004** drove the **configuration and payload design**. This was the main driver in the configuration section as it ensured the module needed accommodate the docking systems of both spacecraft and influenced the placement and orientation of the docking ports.

There were a few differences in the sizing in this presentation compared to literature. The main one being the **solar array sizing** of **13m^2** calculated previously as opposed to the real **48.6m^2** area of the Cooperative solar array. [25] This is largely due to the fact that only the Docking Module and payload power requirements were considered, when in reality it also provided **additional power** to Mir and, since it was a **novel type of array**, NASA wanted a **high degree of redundancy** in order to study the potential failure modes. Quantifying the impact of this discrepancy, had the calculated value of **13m^2** been used in the design, the docking module would likely have been **unable to meet the power demands** if any major issues arose, **compromising mission success** and NASA might not have been able to collect **all the required data** to later implement these style arrays on the **ISS**.

In terms of the launch calculations, there were conflicting values between the **Mission Report** [11], **Press Release** [20] and other literature for the various mass values of the propellants and spacecraft. Ultimately, these inconsistencies tended to be **minor differences** and shouldn't have any consequential effect on the **delta V capabilities** of the shuttle and its ability to **reach the required orbit**. On the other hand, the **RS-25 SSMEs** were quoted in the lecture notes to have an **Isp of 4500m/s in vacuum** while we took it as **3750m/s** in our calculations which is the **sea-level value** [31]. In reality, the value will fall somewhere between the two, since it **increases** as the **atmospheric density decreases**, but with the **non-constant throttle** in combination with the **SRBs**, it would be vastly too complicated to factor this change in Isp in our calculations so the **lower-band value** was taken to get our **9.8km/s of delta V** result and comfortably meet the mission requirements. Had the higher-band been taken, the resulting delta V could have been **upwards of 11km/s**, well beyond the needs for the mission and **requirement 007** but could have provided more **flexibility** in mission design, such as added **redundancy** if an off-nominal launch occurs or the required orbit is missed.

One interesting thing I gained from this assignment is an appreciation for how **requirements can change**. Multiple times while progressing through the assignment, **additional research** or calculations led me to **reevaluate** some of the requirements or replace them with **more important ones** or alter them slightly to be **more clear and precise.** It's clear now that starting off with extremely **well defined** and **achievable requirements** from the beginning would have made the rest of tasks **far easier**.

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