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Study Results

Low Energy Earth Moon Lagrange Point 2 (EM L2) Transfer Project

November 27, 2012

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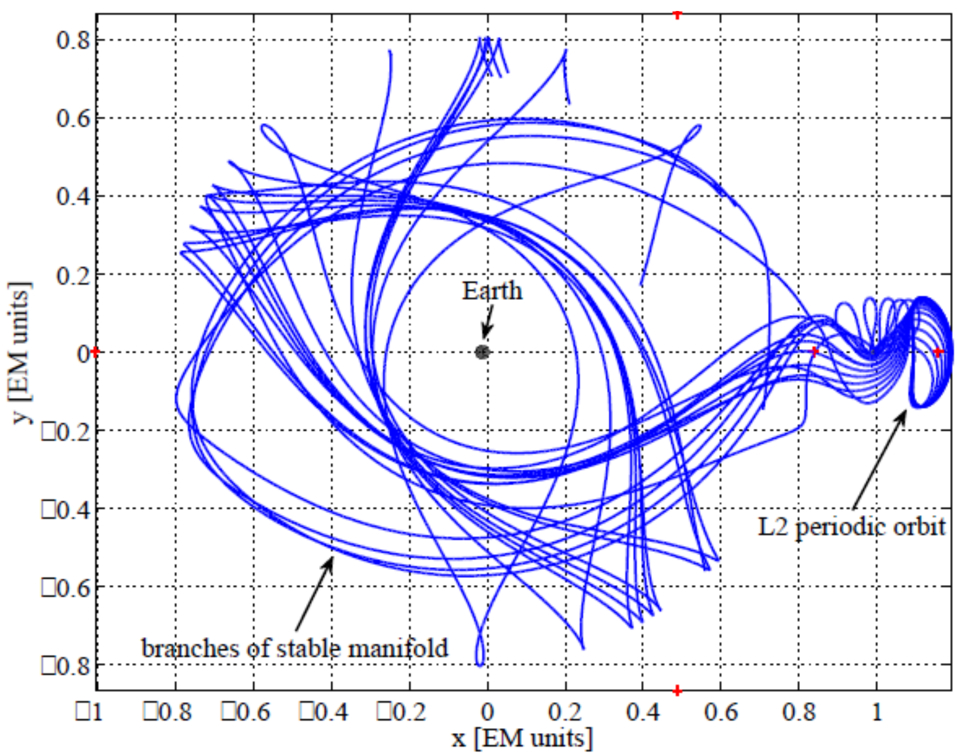
Background and Purpose

- Background
  - Excalibur Almaz (EA) has been working to establish optional locations for our commercial station for several years
    - Low Earth Orbit (LEO)
      - ~200 km circular orbit
    - Locations beyond LEO
      - Earth Moon Lagrange Point 2 (EM L2)
  - In September 2012, EA contracted with Dr. Edward Belbruno, a mathematician and recognized low energy transfer orbital mechanics expert from Princeton college to evaluate low energy transfer options for our station to EM L2
- Purpose
  - This presentation summarizes the results of Dr. Belbruno's efforts in support of EA's evaluation of transfer options for a large commercial spacecraft to EM L2 and return of a crew vehicle

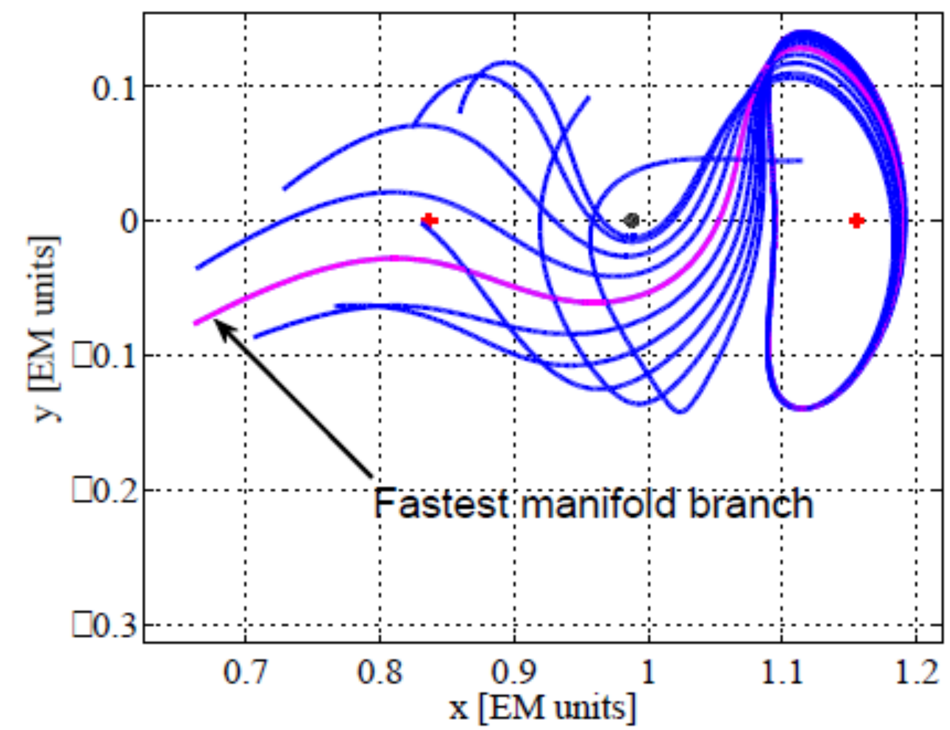
Why Employ Low Energy Transfer?

- Low Energy Transfer Overview
  - Provides a means for interstellar travel which utilizes gravity wells and weak stability boundary conditions present within the solar system to provide a means of transfer assist between interstellar destinations
    - Multiple pathways (also referred to as manifolds) exist based on the specific relationships between gravity wells
    - Technique has been successfully demonstrated in several space programs to date to transfer spacecraft between locations with limited thrust and/or propellant usage
- The major advantages of this transfer technique are:
  - Large masses can be moved utilizing relatively low thrust
  - Propellant requirements are significantly reduced allowing for more usable payload capability for a given spacecraft mass
- The major disadvantages of this transfer technique are:
  - The most direct path (shortest distance) is generally not employed
  - Calculation of transfer manifolds is much more complex than traditional means (e.g., Hohmann transfer)
  - Transfer travel times tend to be significantly longer

General Methodology (EM L2 Example)

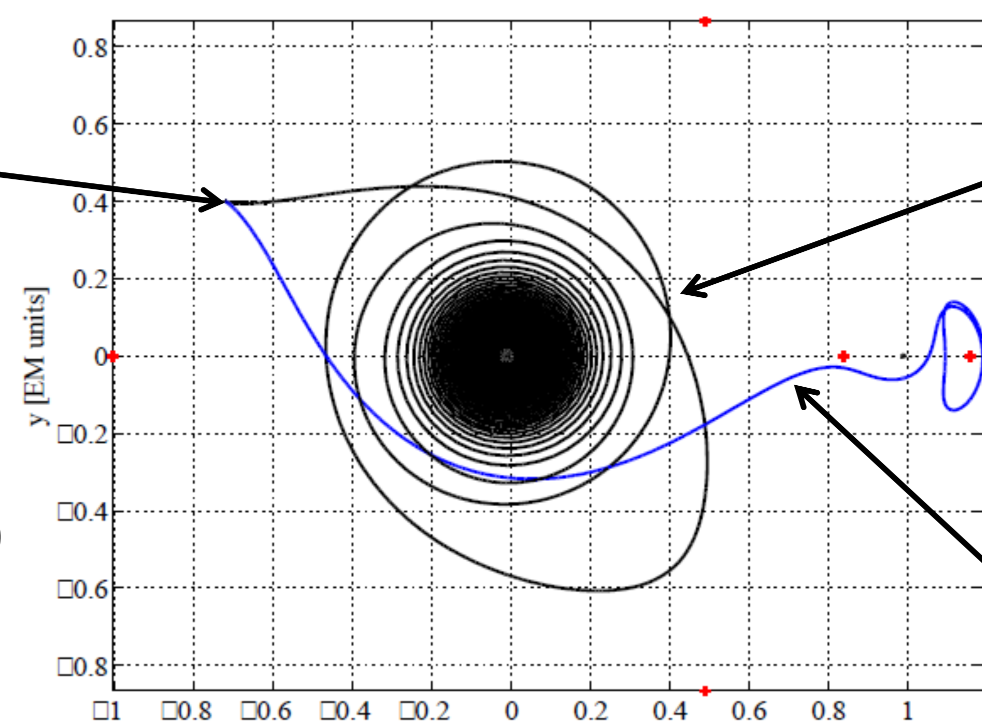


Identify possible stable transfer manifolds



Identify most direct manifold branch(s)

2) Arrive at Intersection Point



1) Spiral to intersection point with most direct manifold branch

Compute total transfer time (Spiral +low energy manifold)

3) Transfer to destination via most direct manifold branch

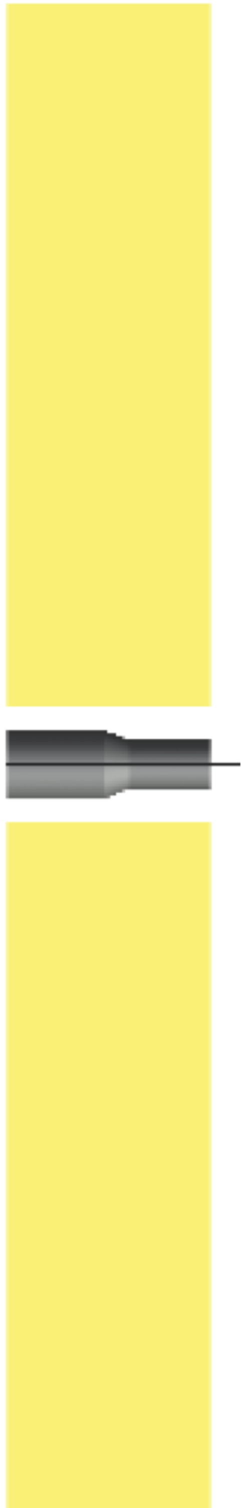
EA's Low Energy EM L2 Transfer Project

- Project Goals
  - Establish the feasibility of placing a large (~21-32 metric tonne) spacecraft in an Earth Moon (EM) Libration Point 2 (L2) halo orbit utilizing a low energy transfer trajectory based on hall effect thrusters and returning a smaller (~11 metric tonne) portion of the spacecraft (crew vehicle) to earth
    - As a result of the feasibility assessment, define:
      - Trajectory approach (internal and/or external transfer)
      - Transit duration (days) for the trip from the earth to EM L2
        - » ~32 metric tonne spacecraft
          - Combination of habitation module and crew return vehicle
        - » ~21 metric tonne spacecraft
          - Habitation module only
      - Transit duration (days) for the return trip from EM L2 to earth for crew return vehicle
        - » Evaluate trajectory options
          - Without or with Lunar fly-by

Mission Scenario 1 (~32 mt Spacecraft)

1) Station launch on Proton from Baikanor to 200 nm circular orbit with 51.6 degree inclination
2) Station checked out on oribit. Once all systems are verified, crew vehicle is launched from Baikanor to 200 nm circular orbit.
3) Crew vehicle checked out on orbit. Once all systems are verified, crew vehicle rendezvous and docks with Station
4) Combined crew and station vehicle then spirals out to **TBD** km to begin low energy transfer to Earth Moon (EM) L2 halo orbit
5) Combined vehicle utilizes internal transfer orbit for voyage to EM L2 destination - Duration **TBD**
6) Combined vehicle remains in orbit for **TBD** days
7) Crew vehicle separates from Station. Station mission life assumed at 15 years
8) Crew vehicle begins return to Earth. (Optional lunar fly by during return) while station remains in EM L2 halo orbit
9) Crew vehicle returns to Earth - transit time (**TBD**)
10) Crew vehicle landing (location **TBD**)
Notes:
1) Future missions of a crew vehicle only may utilize a more traditional approach for transportation to the low energy transition point for transfer to EM L2 location (e.g., chemical propulsion vs. hall thrusters) to reduce transit time and minimize crew associated consumables requirements.
2) Launch mass of crew vehicle in this configuration exceeds lift capability of Soyuz FG due to need for added propellant and habitation/service module for return flight. Test flight of crew vehicle could be done with out crew module on Soyuz FG or Service/Habitation module could be a lower mass inflatable design.
3) Transit time duration for low energy transfer of crew could pose radiation exposure issues
4) Return trip duration (**TBD**) for crew vehicle may dictate need for use of more higher energy transfer technique

Mission Scenario 2 (~21 mt Spacecraft)

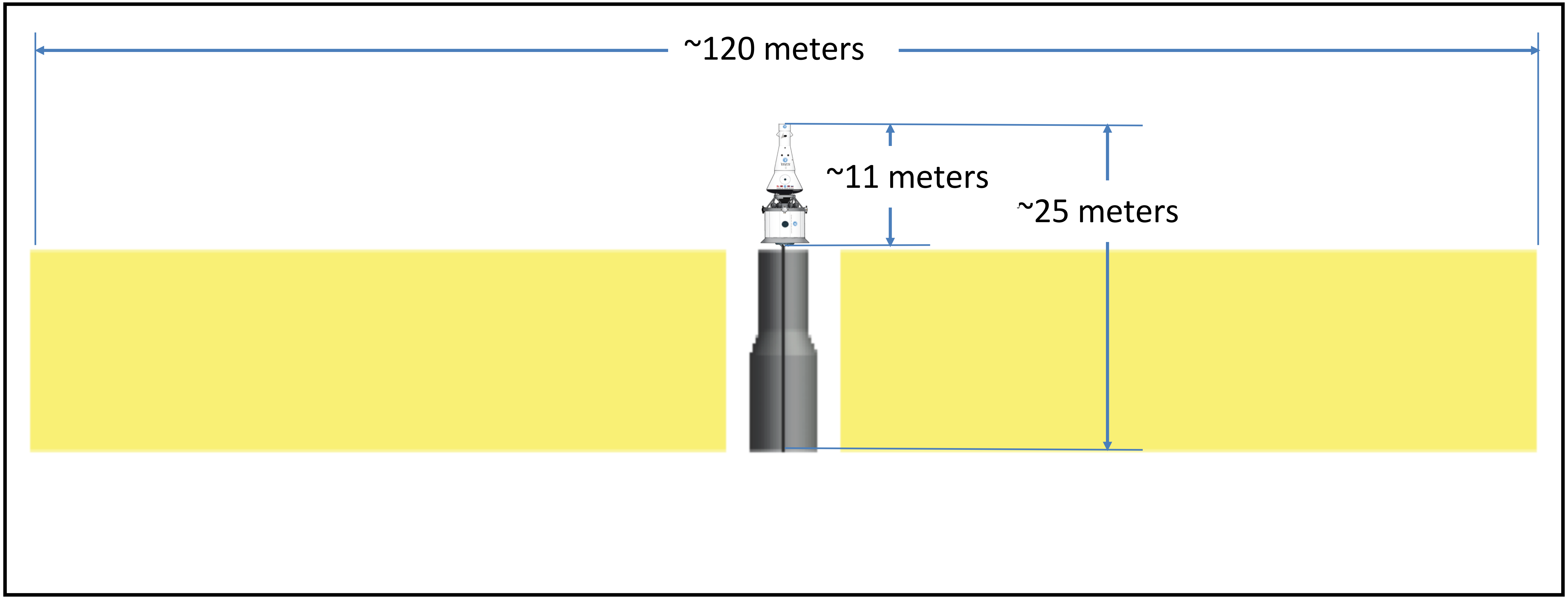


1) Station launch on Proton from Baikanor to 200 nm circular orbit with 51.6 degree inclination
2) Station checked out on oribit.
3) Station vehicle then spirals out to **TBD** km to begin low energy transfer to Earth Moon (EM) L2 halo orbit
4) Station utilizes internal transfer orbit for voyage to EM L2 destination - Duration **TBD**
5) Station vehicle checked out to assure operational status
6) Crew vehicle launched and transfers to EM L2 destination via traditional high energy means
7) Crew vehicle rendezvous and docks with Station
8) Combined vehicle operations occur (**TBD**) days
9) Crew vehicle begins return to Earth. (Optional lunar fly by during return) while station remains in EM L2 halo orbit (Assume Station life requirement of 15 years)
10) Crew vehicle returns to Earth - transit time (**TBD**)
11) Crew vehicle landing (location **TBD**)
Notes:
1) Future missions of a crew vehicle only may utilize a more traditional approach for transportation to the low energy transition point for transfer to EM L2 location to reduce transit time and minimize crew associated consumables requirements.
2) Launch mass of crew vehicle in this configuration exceeds lift capability of Soyuz FG due to need for added propellant and habitation/service module for return flight. Test flight of crew vehicle could be done with out crew module on Soyuz FG or Service/Habitation module could be a lower mass inflatable design.
3) Transit time duration for low energy transfer of crew could pose radiation exposure issues
4) Return trip duration (**TBD**) for crew vehicle may dictate need for use of more higher energy transfer technique

Vehicle Configuration Information

Vehicle Configuration Information	
Combined Vehicle Mass at Leo	
Wet	32 Mt
Dry	27 Mt
Station Vehicle	
Engine Specs for Primary Propulsion (Hall Effect Thruster)	
Number and ISP of engines	4 @ 3000 sec/engine (25 kw of power/engine)
Attitude Control System Propulsion (Bi-Propellant - ~215 N Thrusters)	
Number and ISP of engines	8 thrusters @ 286 sec/thruster
Vehicle Mass at LEO (without launch fairing)	
Wet	21 Mt
Dry	18 Mt
Crew Vehicle	
Engine Specs for Primary Propulsion - (Bi-Propellant - ~215 N Thrusters))	
Number and ISP of engines	8 thrusters @ 286 sec/thruster
Vehicle Mass at LEO (without fairing and emergency escape system)	
Wet	11 Mt
Dry	9 Mt
Notes:	
1) Propellant requirements are very rough estimates	
2)Number of hall effect thrusters are assumed to be 4 in the concept design. The number of engines could be increased or decreased based on trajectory analysis.	

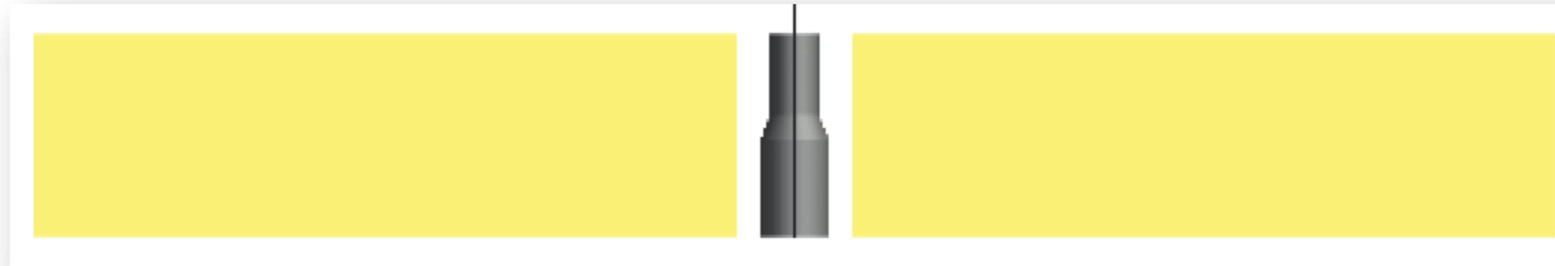
Combined Crew and Station Vehicles

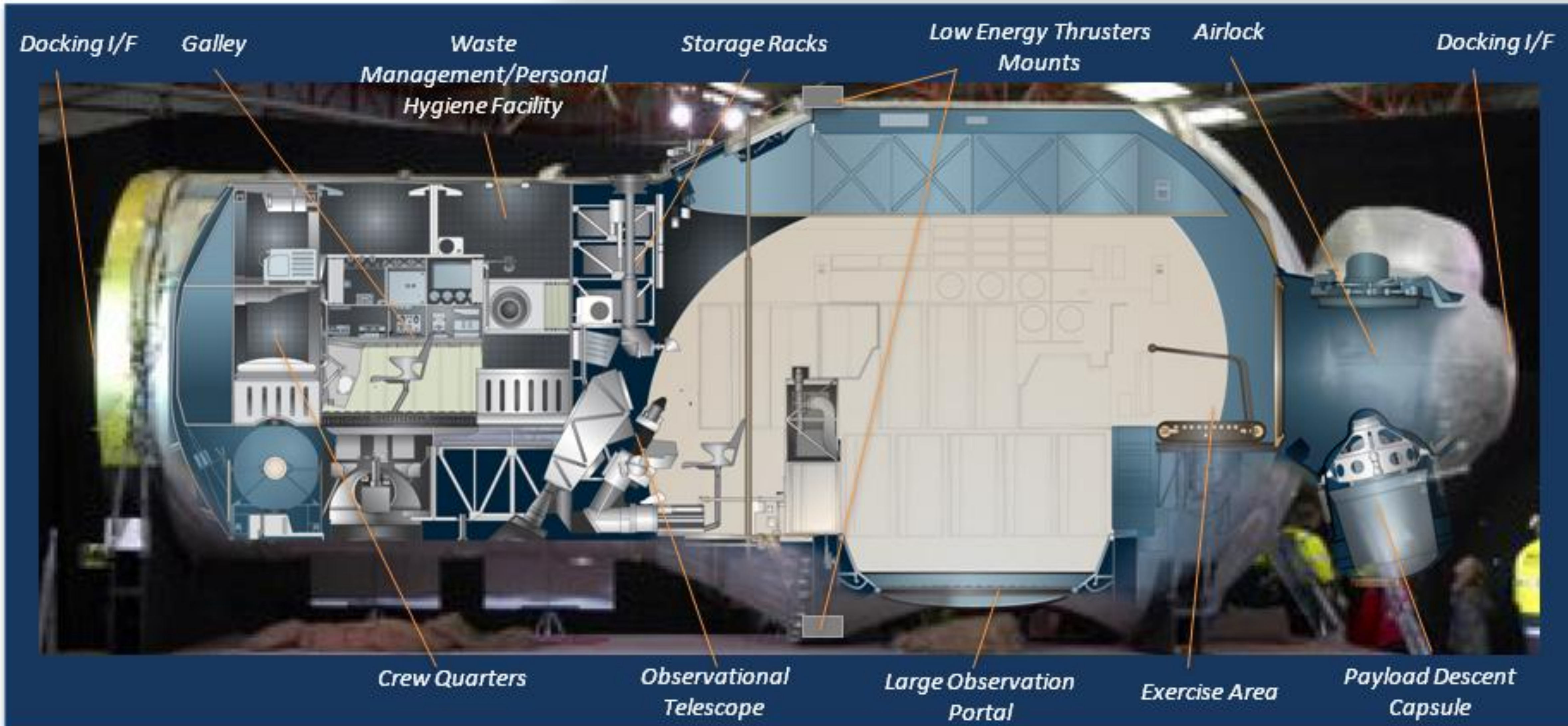


- Russian Salyut class station
- ~ 21 metric tons at launch
- ~ 14 meters long
- ~ 4.2 meters maximum diameter
- ~ 90 cubic meters habitable volume
- ~ 10 to 15 year useful life
- 2 spacecraft are now at EA's facility on the Isle of Man
- Similar space station frames have operated continuously in LEO for many years – e.g. the Salyut, MIR core module and the ISS Zarya module

Zarya module from ISS

Station Vehicle Features





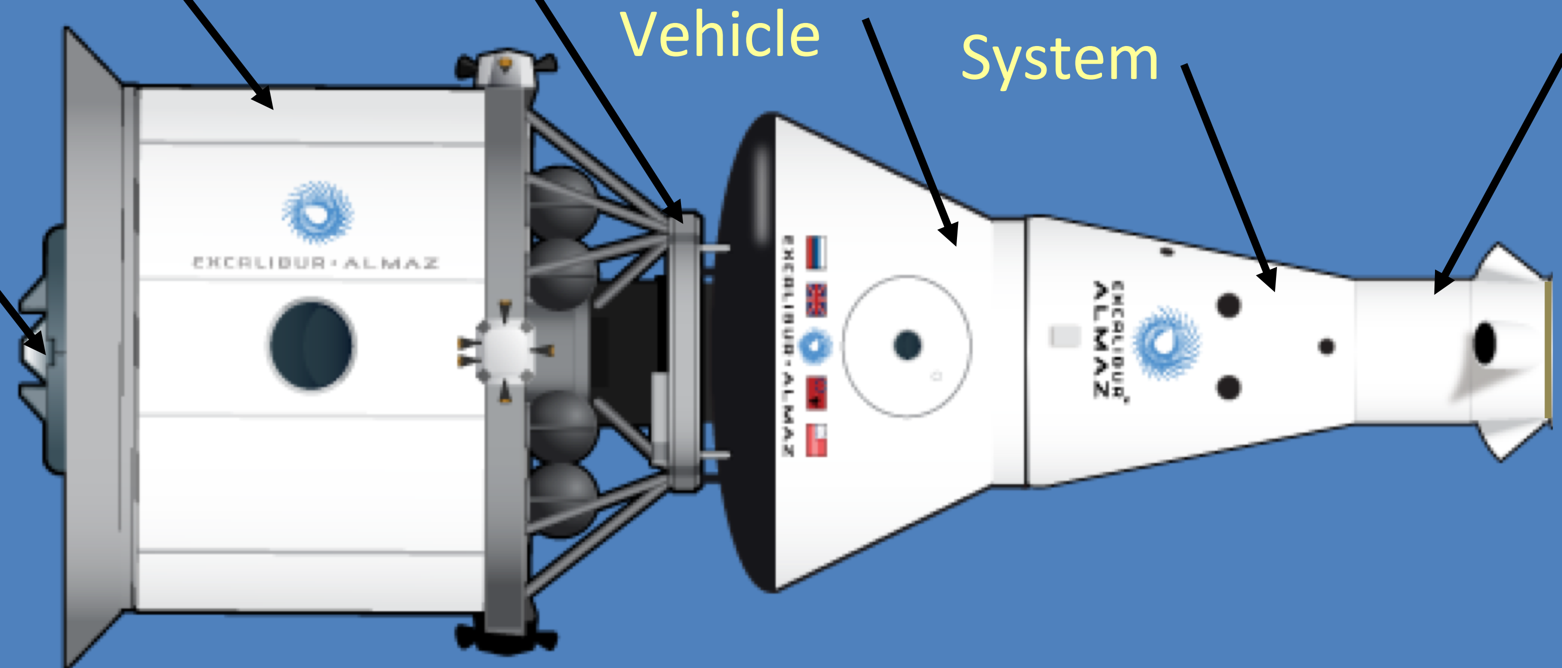
Station Master Equipment List (Initial Draft)

Station Subsystems	Ref.
Communications Equipment	Com
S-Band	Com
Transmitter	Com
Receiver	Com
Antenna	Com
UHF	Com
Transmitter	Com
Receiver	Com
Antenna	Com
Crew restraints	CS
Internal restraints and handholds	CS
External (EVA) restraint and handholds	CS
Exercise Equipment	CS
Sleep stations/restraints	CS
Crew personal effects	CS
Crew clothing	CS
Lighting	CS
Internal	CS
External	CS
Radiation protection	CS
On-orbit Control Complex	DM
Computers	DM
ACS controller	DM
Hall thruster controller	DM
Sensors	DM
Data bus	DM
Instrument/control panels	DM
Caution and warning display panel	DM
Airlock controls	DM
Video provisions	DM
External video cameras and mounts	DM
Internal video cameras and mounts	DM
Air Revitalization System (ARS)	ECLSS
CO2 Removal system	ECLSS
Associated fans and ducting	ECLSS
Pressure Control System (PCS)	ECLSS
Oxygen	ECLSS
Nitrogen	ECLSS
Associated plumbing and tankage	ECLSS
Fire Detection and Suppression System (FDSS)	ECLSS
Fire detection sensors and alarms	ECLSS
Fire extinguishers	ECLSS

Station Subsystems	Ref.
ECLSS Subsystems Continued	
Crew Health Monitoring System (CHMS)	ECLSS
Crew Waste Management System (CWMS)	ECLSS
Crew provisions (toilet, handwash, body cleansing)	ECLSS
Wet trash storage	ECLSS
Dry trash storage	ECLSS
Spacesuits and associated equipment	ECLSS
Spacesuits	ECLSS
Spacesuit storage provisions	ECLSS
Spacesuit interface to ECLSS	ECLSS
Thermal Control System (TCS)	ECLSS
External Thermal Control Panels/Radiators	ECLSS
Associated plumbing, accumulators, etc.	ECLSS
Multi-Layer Insulation (MLI)	ECLSS
Heaters	ECLSS
Water and Nutrition Management System (WNMS)	ECLSS
Water	ECLSS
Water storage	ECLSS
Galley Facility (water dispenser, heating element, table)	ECLSS
Food	ECLSS
Food storage	ECLSS
Power System	EP
Solar Panel(s)	EP
Batteries	EP
Power switching and distribution system	EP
Rendezvous and Docking Equipment	G
Rendezvous antenna(s)	G
Optical sighting system	G
Range-rate lidar/equivalent	G
Targets	G
Station GN&C System	G
Inertial guidance system	G
Star tracker	G
CMGs/equivalent	G
Back-up manual star tracker	G
Payloads (internal)	Pa
Payloads (external)	Pa
Attitude Control System (ACS)	Pr
Engines and associated plumbing	Pr
Fuel	Pr
Fuel Storage tankage	Pr
Main propulsion system	Pr

Station Subsystems	Ref.
Main Propulsion System Continued	
Hall effect thrusters and associated support equipment	Pr
Fuel	Pr
Fuel Storage	Pr
Primary structure (Station module)	S/M
Secondary structure	S/M
Crew systems provisioning	S/M
ECLSS provisioning	S/M
Data Management system provisioning	S/M
Payload provisioning	S/M
Power system provisioning	S/M
Propulsion systems provisioning	S/M
Payload provisioning	S/M
Micro meteor protection	S/M
Internal storage provisions	S/M
Internal payloads	S/M
Avionics	S/M
Crew equipment	S/M
ECLSS	S/M
Internal spare parts	S/M
External storage/experiment provisions	S/M
External payloads	S/M
External spare parts	S/M
Galley/wardroom provisioning	S/M
Refuse ejection airlock	S/M
Forward hatch	S/M
Aft hatch	S/M
Docking structure and mechanisms	S/M
Forward docking system	S/M
Docking interface	S/M
Docking targets	S/M
Aft docking system	S/M
Docking interface	S/M
Docking targets	S/M
Crew Airlock	S/M
Airlock structure	S/M
Airlock hatches	S/M
Airlock purge and vent system	S/M
Airlock gas recovery system	S/M
Window(s) and Utility Pass Throughs	S/M
Window(s)	S/M
Utility Pass Throughs	S/M

Crew Vehicle (On-orbit Configuration)



Note: Emergency Escape System and EES Adapter Not Shown

EA station design does not preclude use of other properly outfitted vehicles for crew transfer (Mission Scenario 2) including: Space X Dragon, Boeing CTS 100 and Orion

Crew Vehicle Master Equipment List

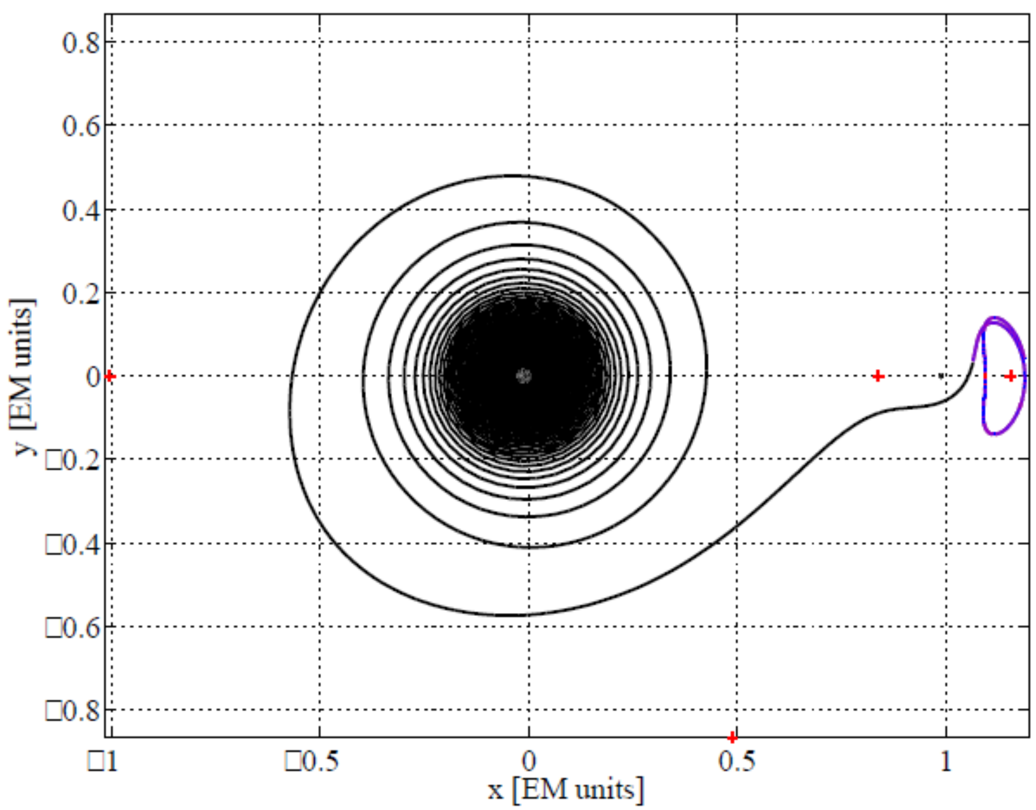
CREW VEHICLE Major Equipment List (MEL)	
EMERGENCY ESCAPE SYSTEM (EES) AND EES ADAPTER	**REUSABLE REENTRY VEHICLE (RRV) (Continued)**
RETRO ROCKET	Pyro devices
NOSE COMPARTMENT	Electrical power generation system
Structure and thermal protection	Onboard cable system
Stability guidance jet engine	Orientation, observation and collimation equipment
Powder rocket engine (PRE) for nose compartment separation	Survival kit
Electrical equipment	Working tools of the crewmembers
Thermal shield	Stability augmentation system
Pyro devices	Balance weights
Search and communications radio equipment	**JETTISONABLE UNITS OF RRV**
AFU (antenna feeder unit)	OCS (orbital coordinate system) fairing
Telemetry equipment	OCS bracket
Depressurization and drain system	Wire tunnel
JET PARACHUTE AND LANDING SYSTEM (JPLS)	Bracket with "Alpha-1", IRV (infra-red vertical)
Parachute system	**INTERMEDIATE STAGE (Tunnel part of H/SM)**
SLE (soft landing engine)	Structure and equipment mounting blocks
JPLS frame with parachute release unit	LPRPP (liquid-propellant rocket power plant)
REUSABLE REENTRY VEHICLE (RRV)	LSS and temperature-control system components
Structure and thermal protection	**HABITATION/SERVICE MODULE (H/SM)**
Equipment and cargo mounts	Tunnel
Crew in spacesuits (3 persons)	Pressurized Segment
Shock-absorbing seats	Non Pressurized Segment
LSS and temperature-control system, thermal shield	Docking Mechanism
Spacesuit ventilation and temperature control system	Docking Electronics - assume can be returned in RRV
OCC (onboard control complex)	Batteries
Pilot control panels	Radiator
Manual controls	LSS/Thermal Control
Radio complex	Misc. secondary structure

Project Organized into 3 Tasks

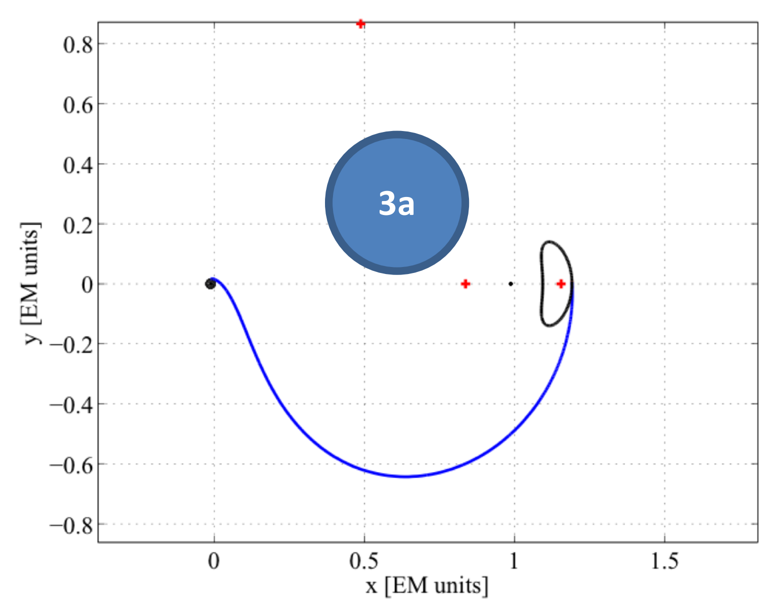
- Task 1
  - Evaluate low energy transfer of combined crew and station vehicles (~32 metric tonnes) to EM L2 Halo orbit to establish mission duration and propellant mass requirements
- Task 2
  - Evaluate low energy transfer of station vehicle (~21 metric tonnes) to EM L2 Halo orbit to establish mission duration and propellant mass requirements
- Task 3
  - Evaluate crew vehicle (~10 metric tonnes) return options (direct return/Lunar fly-by) to establish mission duration and propellant mass requirements

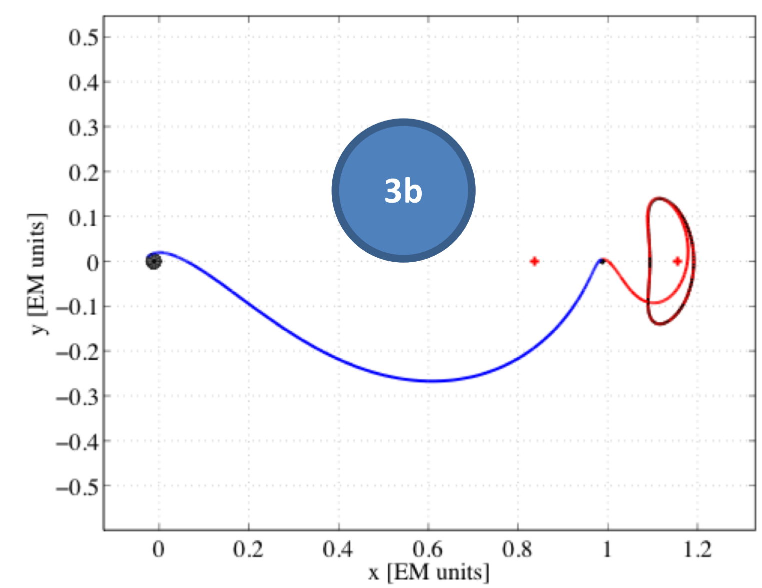
Project Results

Task	Transfer time Earth to Manifold Transition (MT) Point (Days)	Final Transfer Time MT Point to EM L2 (Days)	Transfer time EM L2 to MT Point (Days)	Final Transfer Time MT Point to Earth (Days)	Total Transfer Time (Days)	Propellant Budget (Kg)	Propellant Required (Kg)	Propellant Difference (Kg)
1 Combined Spacecraft	543	26	n/a	n/a	569	3000	6590	(3590)
2 Station Only	365	21	n/a	n/a	386	3000	4320	(1320)
3a Crew Vehicle Direct Return	7	n/a	n/a	n/a	7	2000	2957	(957)
3B Crew Vehicle Return with Lunar Fly-by	n/a	n/a	22.6	3.7	22.6	2000	699	1301



Travel to EM L2





Return from EM L2

Results Interpretations/Conclusions

- General
  - Application of low energy transfer is best suited for “slow transfer” applications and appears feasible for large masses utilizing low thrust levels
  - Project assumed initial starting altitude of 200 km with a circular orbit
    - Injection into a higher altitude initial orbit would reduce spacecraft propellant requirements and shorten the time associated with spiraling out to a given stable manifold location
      - Shifts responsibility to launch vehicle/upper stage
  - Preliminary design includes 4 hall effect thrusters (1 Newton of thrust each)
    - Addition of more engines/higher thrust capability could reduce transfer time
      - Would most likely increase overall propellant requirements
  - If longer transfer time is acceptable, reductions of number of engines and/or engine thrust levels are possible
    - Lower thrust hall effect thrusters would reduce power generation requirements (e.g., solar array size)

Results Interpretations/Conclusions

- Task 1 – Combined Station and Crew Vehicle transfer
  - ~569 days required for transit from 200 km LEO to insertion in EM L2 halo orbit
  - 3590 kg of added propellant required over initial 3000 kg budget
    - Reduces overall payload capacity by ~20%
  - Mission duration could be reduced through any of the following:
    - Added engines
    - More powerful engines
    - Higher initial insertion altitude prior to initiating spiral
  - Conclusions
    - Demonstrates ability to transfer a large mass (~32 mt)
      - Flight without crew could be undertaken with crew vehicle's purpose to provide the assured crew return capability for subsequent missions
    - Having a crew on-board during the 569 day transition would:
      - Provide limited commercial value
      - Add significant programmatic and technical risk
      - Require significant consumables to support a crew of 3 or more

Results Interpretations/Conclusions

- Task 2 – Station only transfer
  - ~365 days required for transit from 200 km LEO to insertion in EM L2 halo orbit
  - ~1320 kg of added propellant required over initial 3000 kg budget
    - Reduces overall payload capability by ~7%
  - Mission duration could be reduced through any of the following:
    - Added engines
    - More powerful engines
    - Higher initial insertion altitude prior to initiating spiral
  - Conclusions
    - Demonstrates the possibility to transport and pre-position a large mass (~21 metric tonnes) asset at EM L2 within a 1 year time period
    - Eliminates risks associated with
      - Facility check-out prior to crew occupation at the final destination
      - Long duration (>1 year) crew transit times

Results Interpretations/Conclusions

- Task 3 – Crew Vehicle Return
  - Task 3a – Direct earth return
    - Use of low thrust chemical engines and low energy direct trajectory results in an ~7 day return time
    - ~957 kg of additional propellant required over initial budget of 2000 kg
  - Task 3a - Conclusions
    - Requires ~ 1/3 more time then the Apollo direct return (~4 days average)
    - Added propellant mass would reduce overall payload capability by ~10%
  - Task 3b – Low energy earth return with Lunar fly-by
    - Use of low thrust engines and low energy direct trajectory results in an ~23 day return time
    - Only ~700 kg of propellant required resulting in a net savings of ~1300 kg from the initial budget of 2000 kg
  - Task 3b - Conclusions
    - Provides commercial benefit of Lunar fly-by
    - Provides ability for ~1300 kg of added payload (>10% increase)
    - Advantages of propellant savings would be offset by added consumable requirements and other added risks associated with the longer mission duration

Back-up Information

Project Milestones

- Milestone 1: Final agreement on mission scenario and project tasks
  - Completion: **Sept. 7, 2012 (Complete)**
- Milestone 2: Transfer method(s) options evaluated and simulation approach defined
  - Completion: **Sept. 14, 2012 (Complete)**
- Milestone 3:
  - Task 1 – Combined spacecraft from 200km circular orbit to Earth Moon L2 Halo Orbit
  - Completion: **Sept. 28, 2012 (Complete)**
    - Model prepared, tested and debugged
    - Simulations complete
    - Results compiled and provided to EA
- Milestone 4:
  - Task 2 - Evaluate space station spacecraft only for Task 1 mission
  - Completion: **October 19, 2012 (Complete)**
    - Model prepared, tested and debugged
    - Simulations complete
    - Results compiled and provided to EA

Project Milestones (Continued)

- Milestone 5:
  - Task 3a – Capsule Return from Earth Moon L2 Halo Orbit, Station remains in EM L2 halo orbit
  - Completion: **November 2, 2012 (Complete)**
    - Model prepared, tested and debugged
    - Simulations complete
    - Results compiled and provided to EA
- Milestone 6:
  - Task 3b– Capsule Return from Earth Moon L2 Halo Orbit with Lunar Fly-by, Station remains in EM L2 halo orbit
  - Completion: **November 16, 2012 (Complete)**
    - Model prepared, tested and debugged
    - Simulations complete
    - Results compiled and provided to EA