Assembly and Servicing of a Large Telescope at the International Space Station

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Abstract—This paper explores the major issues, concerns, limiting conditions and requirements that must be satisfied if a large (10's of meters diameter) infrared telescope astronomy mission is to be successfully assembled and boosted to its operational obit around the Sun-Earth Lagrange 2 (L2) point. Techniques for returning the satellite to the International Space Station (ISS) for servicing are also presented.

The trade-off between astronaut alone, robot alone and an astronaut supervised robot assembly is discussed. The conclusion is that the ISS robots would do the actual assembly work with the supervision of an astronaut during critical phases of the assembly. The robot would use a preprogrammed sequence that had been thoroughly checked out in a neutral buoyancy water tank on the ground. The astronauts would closely monitor the assembly from inside the ISS, as it progressed. They would be aided in this with television systems and independent collision avoidance software that would stop the robot's motion before a collision could occur. The primary benefit of using astronauts in this way is that they can respond to and correct any unanticipated actions. This increases the probability of a successful assembly and checkout to a near certainty.

Following assembly, options for the low-thrust propulsion that is needed to boost the completed satellite into the L2 orbit are presented. Options for returning the satellite to the ISS for servicing are also discussed.

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1. INTRODUCTION

This paper examines several options for assembling large scientific missions at the ISS. A 20-meter diameter infrared telescope mission was selected as a surrogate for any of the smaller astronomy missions envisioned in NASA's Origins Theme Program[1]. For convenience, let's call this 20-meter mission the Next, Next Generation Space Telescope (NNGST) since the mission requirements are similar to the Next Generation Space Telescope, only the telescope is much larger. Also, since some Origins missions are much larger than 20 meters, whatever technology might be developed for a 20-meter mission should be extensible to these larger missions. The earliest that such a large telescope would be launched would probably be 2019 or about 10 years after the planned launch of the Next Generation Space Telescope.

It is presently impossible to launch a one-piece mirror of this diameter, so it must be assembled from a number of smaller mirror segments. The high cost for one of these large telescopes make it imperative that the process used to construct the telescope be very reliable. One way to assure a successful initial assembly is to do that work at the ISS using either astronauts or the ISS robots or a combination of the two for construction. Later in the mission, the NNGST could return to the ISS for servicing thereby extending its useful life.

Another construction method, automatic deployment using self-contained mechanisms, will not be covered in this paper. See reference [1] for a discussion of the relative performance and cost of an automatic deployment verses robotic assembly. The conclusions in that report is that for missions with telescopes 20 meters in diameter and larger, the probability of a successful automatic deployment will be better and less expensive for robot or astronaut assembly than for automatic deployment.

2. PACKAGING THE NNGST FOR LAUNCH

This report assumes that the NNGST would be brought to the ISS in a Shuttle, assembled at the ISS by robots and/or astronauts and then boosted to the L2 operational orbit. Figure 1 shows the NNGST packaged for launch in the Shuttle cargo bay.

[1]For more information on the NASA's Origins Theme see: http://origins.jpl.nasa.gov/missions/tpf.html

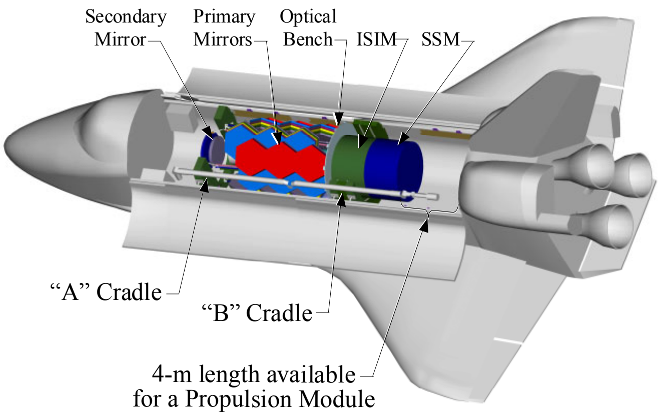


Figure 1 -- 20-Meter NNGST in Shuttle Cargo Bay

NNGST Components—The Telescope

The telescope consists of a 20-m diameter Primary Mirror (PM) and a 2-m secondary mirror with its 4-legged support structure. In the center of the PM is a baffle. Behind the PM is an Optical Bench (OB) to which all optical elements are attached and referenced. Behind the OB is a Science Instrument Module (SIM) that carries the back optics of the telescope and the science instruments. The OB is also the reference for NNGST's attitude control system. Figure 2 shows a front view of the completed telescope.

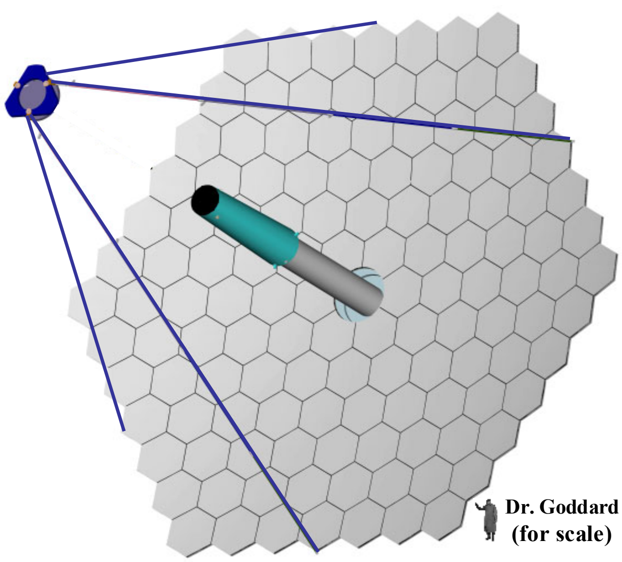
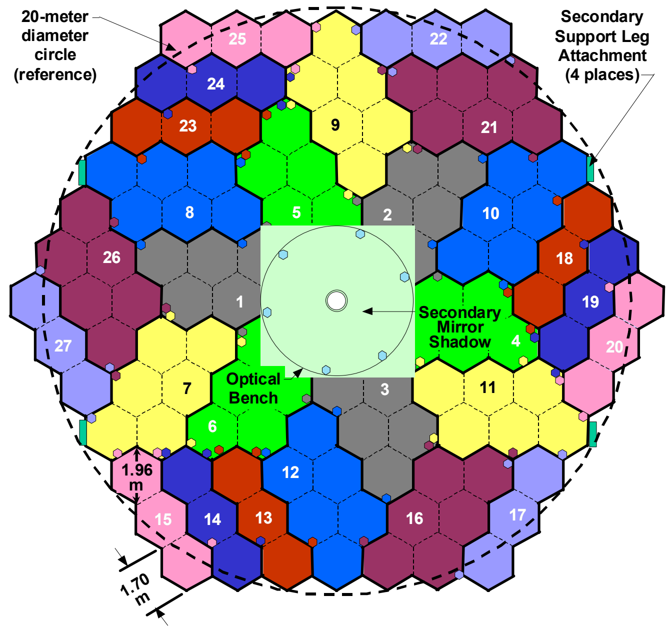


Figure 2 -- Finished 20-Meter NNGST Telescope

The PM is composed of 126 hexagonal, lightweight mirrors about 1.96 meters across their longest dimension. (For reference, the Hubble PM was a single mirror 2.4 m in diameter.) Typically, each hexagonal mirror is a thin, somewhat semi-flexible surface that is mounted to a Segment of the Primary Mirror Support Structure (PMSS) by a number of adjustment mechanisms. The PMSS segments are in two sizes: a Large Segment (LS) carries 6 hexagonal mirrors and a Small Segment (SS) carries 3 hexagonal mirrors. The PM assembly process consists of bolting 6 LSs to a central Optical Bench (OB) and then bolting another 9 LSs and 12 SSs to the first 6 LSs and to each other to form the PM. Figure 3 is a rear view of the PM showing one layout of the LSs and SSs. The different colors define the parts of the PM that are made up of 6-mirror LSs and 3-mirror SSs. In actual practice, the back of the LSs and SSs will probably be flat black. The numbering gives the order in which they would be assembled.



Legend: ⬢ = Grapple Fitting

Notes: 1. Optical Bench shown translucent to show how LSs 1-6 attach to its front side using Grapples that are accessed from the mirror side. All other grapples are accessed from the back side.

2. The dashed lines show the location of the 126 hexagonal mirrors on the front side

Figure 3 -- Rear View of Primary Mirror

The adjustment mechanisms that mount the mirrors to the LSs and SSs are necessary because the final figure of the PM will have to be achieved in the operational orbit at the 50K operational temperature. They will have sufficient adjustment range of motion actuators to accommodate small imperfections in the assembly of the PMSS.

Other NNGST Components

Directly behind the SIM is the Spacecraft Support Module (SSM). A Thermal Isolation Truss and Sunshield completes the NNGST components. For proper infrared operation, the telescope and the SIM must be passively cooled to less than 50K. To achieve this, they must be physically isolated from the warm satellite components by the Thermal Isolation Truss. A multilayer Sunshield that is somewhat larger than the 20-meter PM shadows the telescope and SIM from the Sun, Earth and Moon. It is mounted to the thermal isolation truss between the ISIM and the SSM. The Thermal Isolation Truss and the Sunshield would also be assembled at the ISS.

The NNGST Propulsion Module

The propulsion system to provide the required 3200 m/sec perigee velocity increase would normally be brought to the ISS as a separate module by the same Shuttle and assembled to the NNGST using the same construction techniques. Several propulsion options are discussed later in this report.

3. Assembly Requirements

Minimize Contamination of NNGST Optical Surfaces

The packaging of the NNGST optical elements during ground handling and launch must provide protection for their optical surfaces from molecular and particulate contamination. To do this, the telescope is prepared for shipping in a clean room at the final manufacturing facility. The LSs and SSs are stacked together like an unopened flower with all mirror surfaces facing inwards. A labyrinth seal would close the gaps between the various optical parts. Then, after leaving the clean room and during all subsequent ground handling, a clean purge gas would continuously flow outward through the labyrinth seal. No contamination can penetrate the labyrinth to contaminate the optics. After liftoff, no purge gas will be needed since the depressurization of the cargo bay will cause the internal atmosphere to flow out through the labyrinth seal. In orbit, any contamination that impinges on the packaged telescope would not be able to penetrate through the zigzag turns of the labyrinth to contaminate the mirrors.

After the Shuttle docks with the ISS, the NNGST would be removed from its cargo bay and temporarily mounted to an ISS stowage attachment point by the Remote Manipulator System (RMS) or by one of the ISS robots. The propulsion module would also be removed from the cargo bay and stowed in a safe location on the ISS. With the NNGST in this stowed configuration, all normal activities by the Shuttle or the ISS that might contaminate the optics are allowed.

Later, once NNGST assembly starts, propulsion activity at the ISS must be held to a minimum. No Shuttle or other launch vehicle would be scheduled to arrive or depart. During assembly, the NNGST should be located in a forward facing location where other contamination from the ISS would tend to be swept away by atmospheric drag. Assembly of all non-optical components of the NNGST would be done first to allow them to outgas. This assembly is estimated to take a few days followed by a period of about two weeks for outgassing. During this phase of assembly, the principal requirement on the ISS is that no propulsive plumes directly impinge on these NNGST parts since some types of molecular contaminants can change the thermal properties of these components preventing them from reaching their design low operating temperature. This is particularly important for the Sunshield. Also the orientation of the Sunshield must be such that the Sun does not illuminate its anti-Sun side for any significant length of time. This side would probably be flat black, and a long exposure to the Sun might cause a temperature rise that would destroy the underlying plastic substrate.

After the two weeks of outgassing, assembly of the 20-m telescope optics would start. Once started, the only propulsion to be allowed in the vicinity of the ISS would be the small burns needed to unload the ISS' control moment gyros. The jets that are used for this must be located as far from the assembly site as possible - preferably at the rear of the ISS. To minimize the number of these firings, the ISS would fly a Torque Equilibrium Attitude. It is estimated that actual telescope assembly would take a few days, but a contingency period of a week or two should be scheduled to provide time to deal with problems.

No Sunlight on the Telescope's Mirrors

This requirement is that all optical surfaces kept out of direct sunlight. One reason is that the sunlight might catalyze a contaminant on the mirror causing it to become a non-reflective spot on the mirror. Another reason is that the mirrors would concentrate the solar light into a small volume ~25 meters in front of the mirror. This is unsafe because the focused energy can be very large. For instance, the six mirrors on just one LS this could concentrate as much as 20 kW of solar energy.

This requirement can be met by constraining the way an LS or SS is oriented while it is carried from its storage location to its assembly location. At the assembly location, the NNGST's Sunshield can be used to shade the telescope as it is being assembled. Also, the partially completed NNGST assembly could be mounted on a second robot arm so that it could be reoriented as necessary.

Minimize Impacts on the ISS Operations

Since the ISS would be doing other tasks while assembly of the NNGST is going on, it is reasonable to expect the ISS to place some requirements on the NNGST construction operations. It is also important to minimize impacts on the ISS operations. Some obvious requirements are listed below.

One requirement would be that the partially completed NNGST PM and its Sunshield present the lowest frontal area to the velocity vector to minimize atmospheric drag on the ISS. When the Sunshield and the PM are edge-on to the velocity direction, their area would be less than 100 square meters. The worst-case orientation of the Sunshield and PM has an area of ~630 square meters. It should be possible to orient the NNGST during assembly so that the frontal area would average less than 300 square meters. This compared to the ISS' solar arrays that are over 3000 square meters.

Another requirement would be that the NNGST should not shadow the ISS' solar arrays. Generally, this means the assembly site should be selected somewhat below the level of the ISS' solar arrays.

4. ASTRONAUT / ROBOT TRADEOFF

Astronaut Assembly

Although astronauts using extravehicular activity (EVA) could assemble the telescope, this construction option was rejected as too difficult and expensive. One would have to guarantee the astronauts' safety while they moved the large components from the storage location to the assembly point. The mirror cleanliness requirement would require the development of a space suit that did not produce particles or gasses that could contaminate the mirrors.

Robot Assembly

Similarly, it would be nearly impossible to program the robots to do the entire assembly and guarantee that it would not collide with the ISS or the partially assembled NNGST. Even given that by 2019 software and hardware will be much more stable than today, it is doubtful that it will be perfect without human oversight. Also, the present ISS robots will likely be the same robots that will be available in 2019. Of course, these robots will have proven themselves in the assembly of the ISS and other tasks, but they will not be the latest state of the robot art.

Astronaut Supervised Robot Assembly

An astronaut using the Robotic Workstation would supervise assembly of the telescope. The assembly routine would be loaded into the Robotic Workstation and executed in the Automatic Trajectory mode. This routine would have been thoroughly checked out on the ground using a neutral buoyancy water tank and components that simulated the NNGST. The astronauts would train during this checkout.

The assembly routine would be segmented into parts that require precision movement and parts that do not. For precision movements, the astronaut would closely monitor and, if necessary, adjust the robot's motion. An example of this would be the robot engaging a grapple fitting. Another example would be fitting the part it was carrying between two already assembled parts and then tightening a bolt to hold it in place. The assembly routine software would note any astronaut adjustments so that as the assembly proceeds, fewer and smaller adjustments would be needed. Motions that do not require precision operations such as moving a part from its stowed location to a location near its final installed location would be done automatically.

Independent Collision Avoidance

This is envisioned as software running on a computer that is separate from the robot assembly computer. It would include a Computer Aided Design (CAD) model of the NNGST components both in their stowed configuration and as a final assembly. It would also include a CAD model of the ISS. During assembly, it would monitor all robot joint positions and velocities and it would know which NNGST piece the robot was carrying at the time. It would then continuously run an interference calculation. When it detected an impending collision, it would command the robot to immediately brake to a full stop. The astronauts, with help from the engineers on the ground, would then diagnose the problem and correct it. If necessary, any program changes could be confirmed by simulation in the neutral buoyancy tank.

EVA as a Last Resort

While EVA would not be baselined for normal assembly, it would be available to successfully work through any situation that could not be handled by the robots. One unusual situation would be that there was a failure of the robot to release a grapple fitting while assembling a NNGST part. The astronaut, using EVA, could manually release the robot from the fitting and then the robot could be repaired and put back into operation.

5. ASSEMBLY ON THE ISS

Assembly Location

There is no single fixed location on the ISS structure that satisfies all of the above requirements. However, if one of the three ISS robots holds the NNGST as it is being assembled, the holding robot can reorient the partially assembled NNGST and thereby satisfy the orientation requirements discussed above. The holding robot would also position the partially completed NNGST so one of the other robots can do the assembly work.

One possibility is illustrated in *Figure* 4. It shows the Japanese Experiment Module Remote Manipulator System (JEMRMS) Main Arm (MA) holding the completed NNGST in a forward location. The NNGST is oriented with the PM pointed toward one side so that it is edge-on to the velocity vector. The sun is nearly overhead, and the JEMRMS MA holds the NNGST oriented so that the PM is in shadow. The JEMRMS MA would also rotate the NNGST so that the Space Station Remote Manipulator System (SSRMS) with its Special Purpose Dexterous Manipulator (SPDM) can position and assemble the next part. The JEMRMS MA controller would be programmed to satisfy the various attitude requirements. The NNGST would incorporate suitable robot grapple fixtures that would allow the JEMRMS MA to hold the NNGST as required during assembly.

Assembly Operations

Each part to be assembled will include at least three grapples that are used by the SPDM's end effector to assemble the part. The size and location of these grapples would be essentially the same as shown in the 20-Meter

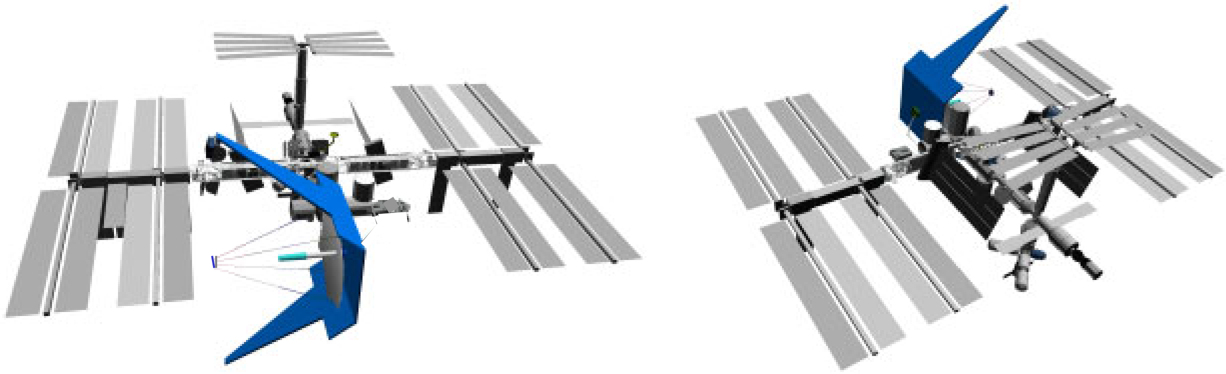


Figure 4 -- Two Views of a 20-m NNGST Attached to the International Space Station

Telescope Study referenced above. Also, the detailed robotic assembly steps would be very similar to the steps described in that study and will not be repeated here.

Each piece to be assembled would be held in the stowed configuration by three or more bolts. Each bolt is captive within a grapple fitting. The SPDM would hold the grapple fitting and unscrew each bolt in turn. While holding the last grapple to be unbolted, it would pick the piece up and move it to a point near its final assembly location. Using television images from the SPDM, the astronaut would verify that the part was correctly positioned and would then authorize the SPDM to slowly mate the new part with the parts that have already been assembled. Alignment guides built into the telescope parts would assure that the final positioning was correct. After tightening the screw within the grapple fitting, the SPDM would release the grapple and move to other grapples, tightening the remaining bolts. The SPDM then repeats the unbolting/positioning/bolting process with the next piece to be assembled. The grapples locally react the torque of the end effector when it loosens or tightens a captive mounting bolt.

Almost all the PM grapples are located on the structural side of the LSs and SSs to maximize the mirror area while minimizing the possibility of damage to the optical surface by accidental contact by the SPDM. The exceptions are one grapple on each of the first six LSs. The bolts in these grapples mate these LSs to the OB. They do not decrease the PM area because the Secondary Mirror shadows them.

6. General Propulsion Requirements

Mass of the NNGST

The 20-m PM will dominate the mass of the completed NNGST. Technology that will minimize mirror mass is vigorously being pursued by the NGST program. The NGST goal is to achieve and areal density of 15 kg/m^2, however, they can launch a mirror that is 22 kg/m^2. It is likely that by 2019, it will be possible to achieve an areal density of only 10 kg/m^2 or less. At 10 kg/m^2 the PM mass would be 3140 kg. The multilayer Sunshield area would be about 500 square meters and, at perhaps 0.2kg/m^2, its mass would be 100 kg. The SM with its supporting tripod structure, the central baffle, the Optical Bench with attached ISIM would probably add another 500 kg. The spacecraft, the thermal isolation truss and other miscellaneous structural items would probably add another 600 kg. The total mass of the NNGST to be placed in orbit about L2 would be 4340 kg.

Propulsion Module Considerations

The above NNGST mass estimates assume that the maximum acceleration will be 0.1 g or less. This minimizes the structural mass of the assembled NNGST, while assuring that the optical shape of the telescope would not change during the propulsion burns. This low thrust rules out large, impulsive rocket engines.

Of course, the unassembled pieces will be built and stowed so as to withstand the launch loads that will be experienced going from Earth to the ISS. One way to do this is to mount the NNGST in cradles that interface the payload with the Shuttle's sill and keel fittings. For this study, it was assumed that the existing Flight Support System (FSS) [2] cradles would be used. The cradles stay mounted in the Shuttle and are returned to Earth for reuse.

The low-thrust propulsion system needed to boost the NNGST from the ISS orbit to L2 orbit could be brought up on the same Shuttle flight. To minimize its the dry mass, the loaded propulsion system would also be carried within a FSS cradle. At the ISS, the propulsion system would be removed from its cradle by a RMS or an ISS robot and stowed in a safe location until it was needed.

Delta-v and Elapsed Time Required for ISS-to-L2 Transfer

The minimum delta-v that is required to boost the NNGST to L2 is 3200 m/sec. The low acceleration of less than 0.1 g means that the NNGST would have to make a series of perigee burns over many orbits until the perigee velocity has increased by 3200 m/sec. If the propulsion burns are not of short duration at perigee, the actual delta-v required would be higher and would require more fuel mass to make up for the "velocity loss" caused by the sub-optimum burns.

For a propulsion option to be acceptable, the time to achieve the delta-v was constrained to be less than 2 months. In that time, the integrated radiation dose taken by the NNGST as it traverses the radiation belts would be less than 2 krads. The damage from this dose is acceptable to the science instrument detectors. For this calculation, it was assumed that the sensitive components are shielded by ~6mm of aluminum provided by the spacecraft structure and normal packaging mass.

7. PROPULSION OPTIONS

Figure 5 illustrates the significant parameters of the propulsion systems discussed below and shows the relative size of the fuel tanks needed for each propulsion system.

Propulsion Option	Sphere Diam. m	Sphere Vol. M^3	Fuel Mass kg
Bi-Prop - MMH+N_2O_4	2.0 (ea.)	3.9 (ea.)	9031
ISUS - N_2H_4	2.3	6.4	6474
ISUS - NH_3	2.4	7.3	5948
Bi-Prop - LH_2+LO_2	3.0 +1.9	14.2+3.5	5023
ISUS - CH_4	2.6	9.2	4277
Arc Jet - N_2H_4	1.8	2.9	2948
ISUS - LH_2	3.8	28.6	2030

Figure 5 -- Propulsion Modules for Various Fuel Combinations

Mono-Methyl Hydrazine (MMH)+Nitrogen Tetroxide (N_2O_2)

The propellant combination MMH + N_2O_2 can achieve an I_{SP} of ~320 seconds. Flight proven engines exist with sufficient thrust so that the assumption of no "velocity loss" is correct. For the NNGST with a NNGST mass of 4340 kg, it is seen that an NNGST with this propulsion system could be launched on one Shuttle flight, but with no mass margin. Today, this would not be acceptable given the fact that a PM of 10 kg/m^2 has yet to be demonstrated. This fuel combination is included for two reasons: 1) By 2019, PMs of even lower areal density may exist and 2) The propulsion module could be brought to the ISS on another Shuttle flight or by some other vehicle.

Liquid Hydrogen (LH_2) + Liquid Oxygen (LO_2)

This propellant combination can achieve an I_{SP} of ~450 seconds. At this I_{SP}, the mass of the fuel just about equals payload mass that would be sent to L2. Small, flight-proven engines exist with sufficient thrust so that the assumption of no "velocity loss" is correct. At present, LH_2 is not allowed in the cargo bay of the Shuttle, but it could be brought to the ISS via an unmanned supply rocket. It is included in this study because by 2019, it may be possible to scavenge residual LH_2 and LO_2 from the Shuttle's external tank.

The Integrated Solar Upper Stage Using LH_2

Boeing is developing the Integrated Solar Upper Stage (ISUS) for the Air Force. It uses a large, lightweight mirror to focus sunlight into an insulated carbon thermal storage block. The carbon absorbs the concentrated solar thermal energy and its temperature rises to ~2400 K. When thrust is desired, the hydrogen propellant is passed through passages in the carbon block so that, when it exits, its temperature is also 2400 K, giving an I_{SP} of 866 seconds and a thrust level of 44 N. At this thrust level, it takes less than 2 months to achieve the L2 trajectory but the multiple thrust durations are longer than the optimum causing a "velocity loss" of about 24% or an additional delta-v of ~770 m/s. Figure 5 includes this additional LH_2 mass and the points plotted for this propulsion option on Figure 6 indicate this penalty. Although hydrogen cannot be carried inside the Shuttle's cargo bay, by 2019 the ISS may have the capability to scavenge hydrogen from the Shuttle's External Tank.

Integrated Solar Upper Stage Using Hydrazine (N_2H_4) or Ammonia (NH_3) or Methane (C_2H_4)

The same carbon block could be used to heat some other propellant. For instance, if N_2H_4 were used, it would achieve an I_{SP} of ~385 seconds and a thrust of ~100 N. If NH_3 were used, it would achieve an ISP of ~405 seconds and a thrust of ~90 N. If C_2H_4 were used, it would achieve an I_{SP} of ~500 seconds and a thrust of ~80 N. The Shuttle can safely carry any of these propellants. These propellants are also much easier to handle than LH_2 since they can be stored as a liquid at normal temperatures and low pressures. Although the fuel mass is higher, the fuel density is about 10 times the density of LH_2, so the tankage would be much smaller and lighter. The higher thrust of these fuels means that there would be very little "velocity loss" over the two-month period needed to achieve a trajectory to L2.

Electrical Propulsion Does Not Meet 2 Month Requirement

The various electric propulsion technologies give very high I_{SP}s, but they all suffer from very low thrust-to-power ratios. Operationally, the NNGST probably will not require more than a 1 kW power system, so addition solar arrays would be needed just to power the propulsion system. The most efficient use of the power system would be to fire the jets continuously, but this results in a spiral orbit with a very large "velocity loss" that typically doubles the required fuel mass. This negates most of the reason to use high I_{SP} electric propulsion in the first place.

NNGST Mass Margin on the Shuttle Columbia

Figure 6 plots NNGST mission mass with a full load of propellant as a function of propulsion I_{SP}. Each of the propulsion options above is marked on the plot. It assumes that the NNGST has a mass of 4340 kg, that the Shuttle Columbia brings it to the ISS and that the propulsion tanks, thrusters, valves and plumbing have a mass equal to 10% of the fuel mass. The capability of Columbia is also plotted along with the mass of the Flight Support System Cradles used to interface the NNGST and the propulsion system to Columbia. The difference between the NNGST mission mass and the Columbia capability after subtracting the mass of the FSS Cradles is the mass margin.

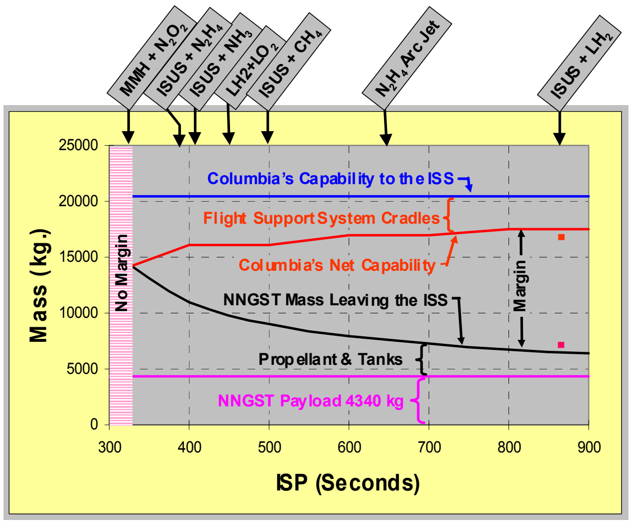


Figure 6 -- NNGST Launch Mass for Various Propulsion Options

Safely Leaving the ISS

After the assembly and test of the NNGST is complete, the ISS robot would mate it with its propulsion module. The robot would then place the entire spacecraft above the ISS and after performing a final self-test, it would properly orient it and then release it. After visually confirming the attitude of the spacecraft, a small burn would be commanded to increase its velocity by 5 m/sec or so.

This places the spacecraft in an orbit with an apogee about 18 km higher than the ISS orbit. Because the period of this orbit is longer than the ISS orbit period, there would be little chance of a collision at the next perigee. However, to guarantee no collisions, after a half orbit the NNGST would make another small burn. This places the NNGST orbit well above the ISS orbit. All perigee burns would be carefully monitored to assure the safety of the ISS and that the NNGST was performing as desired.

8. Returning NNGST to ISS for Servicing

Returning to the ISS from a high orbit such as L2 is not practical if propulsion is used to slow the perigee velocity so that the NNGST matches the ISS orbit. However, if one takes advantage of atmospheric drag, the excess energy can be dissipated as heat.

Using the ISS Sunshield as an Aerobrake

To use the NNGST itself as an aerobrake, one could design the Sunshield to also function as an aerobrake. This would be similar to the aerobraking used to reduce the orbital altitude of both the Mars Global Surveyor Mission [3] and the Mars Odyssey Mission. The mass penalty to the NNGST would probably be 100-200 kg to increase the size of the Sunshield as shown in Figure 7, and to make the hot side capable of higher temperatures.

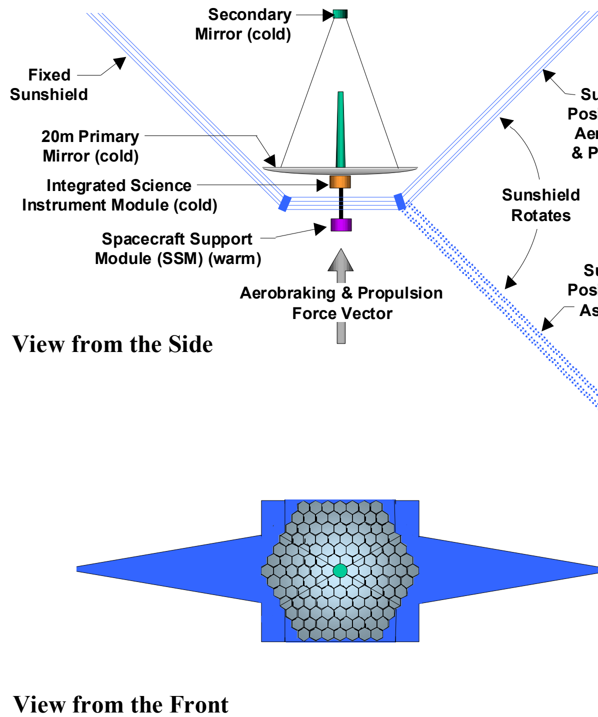


Figure 7 -- Sunshade Converts to an Aerobrake

Using a Deployed Aerobrake

Figure 8 shows a concept of an deployed aerobrake that would consist of a high temperature plastic membrane that has a conical shape with the narrow end attached to the back of the telescope secondary and the wide end held open with a torus. The torus would initially be inflated with a low-pressure gas, but then would become rigid after exposure to Sunlight. The entire aerobrake would be packaged to fit behind the secondary until it was deployed during the three month transfer orbit back from L2. If the diameter of he torus is 60 meters and the cone half-angle is 45 degrees, the entire aerobrake would weigh about 100 kg for a plastic material 0.025 mm thick. It would package into a cylinder the diameter of the secondary mirror and about 3 meters long.

There are several advantages of a deployed aerobrake. One is that the aerobrake would have a larger frontal area and this allows the aerobraking altitude to be higher for the same

Figure 8 -- Deployed 60-m Diameter Aerobrake

delta-v change on each perigee pass. This means that the heating would be spread out over a larger area and this allows temperatures of the Sunshield and aerobrake to be considerably lower. The higher aerobraking altitude will be closer to the altitude of the ISS and this will require less propulsive maneuvering to rendezvous with the ISS. Lastly, active attitude control of the NNGST would not be required during actual aerobraking because the center of pressure would be well behind the center of mass and this will automatically keep the NNGST properly oriented.

The Aerobraking Operation

A small delta-v of less than 25 m/s would cause the NNGST to leave its operational L2 orbit and begin a highly elliptical Earth orbit with a perigee of about 300-400 km and the same 51.6 degree inclination as the ISS. It takes about 90 days to travel from L2 to the first perigee aerobraking pass. The first perigee pass would be designed as a test of the aerobrake to verify its aerodynamic properties. The altitude would be selected on the high side to assure that the heat buildup on the aerobrake and the NNGST would be well within the capabilities of the materials. Based on the performance of the first aerobraking pass, a small burn at the next apogee would lower subsequent perigee passes thereby dissipating more orbital energy per perigee pass while still keeping the aerobrake materials below their maximum design temperature.

Since the energy dissipated by aerobraking during the first pass would be small by design, the time to the next perigee pass would be very long (months). This time can be greatly shortened by making a small delta-v burn shortly after the first (test) aerobraking maneuver is complete. If the total decrease in perigee velocity is 71 m/s, the next apogee would be inside the Moon's orbit and the time to the next aerobraking perigee pass would be only about 10 days. From then on, aerobraking alone on each perigee pass would reduce the next apogee altitude and shorten the orbital period. After each perigee pass, the new orbit would be determined. If too much or little energy was dissipated, a small propulsion maneuver at apogee would adjust the next perigee altitude so that the energy dissipation at the next perigee would be the desired value.

If each aerobraking pass decreases the perigee velocity by 40 m/s, the entire aerobraking period would take about 45 days and 79 orbits after the first aerobraking perigee to lower apogee to the ISS altitude. Then, if a deployed aerobrake were used, it would be released and it would reenter. Propulsion would be used to raise perigee and to adjust the phasing of the NNGST orbit so as to formation fly near the ISS. Later, a Shuttle or a space tug would rendezvous with a safed NNGST, grapple it and transport it to the ISS where the RMS or an ISS robot would stow it on the ISS.

The NNGST could, in principle, maneuver close enough to the ISS so that it could be directly grappled by one of the ISS robots. This option is considered impractical because it would require that the NNGST be built and qualified to safely maneuver that close to the ISS after spending 10 or more years in operation. This would be a prohibitively expensive engineering and reliability challenge. Formation flying at a safe distance from the ISS with subsequent Shuttle or Space Tug transfer to the ISS is a safer and lower cost option.

Servicing and Relaunch to L2

Once the NNGST was stowed on the ISS, the ISS robots would disassemble it as needed, replace any parts that were bad and then reassemble it. A Shuttle would have brought the replacement parts and a new, full propulsion module to the ISS. If a deployed aerobrake were used, a new one would also be brought up and installed. A Shuttle would return the old parts that were removed and the original, empty propulsion module to Earth. After checkout, the refurbished NNGST would be released and relaunched to L2 following the same procedures that were used for its initial launch.

9. SUMMARY

The conclusions of this paper are listed below.

An NNGST (or other large astronomy payload) could be robotically assembled at the ISS with astronaut oversight, checked out and then delivered to an L2. While astronauts using EVA could also do this assembly work at the ISS, a better use of their time would be to supervise the ISS robots from inside the ISS. This would also be somewhat safer, cost less and be less likely to contaminate the NNGST optics.

An independent collision avoidance system would further insure ISS' safety. The ISS robots will have been thoroughly proven during the assembly of the ISS itself. Also, the robot's assembly routine could be thoroughly checked out using a neutral buoyancy facility.

Presently available technology can perform the low thrust propulsion needed to deliver the NNGST from the ISS orbit to the L2 orbit. The propulsion system would be packaged as a separate module and stowed in a safe location on the ISS until needed by the completely assembled NNGST.

Returning the NNGST to the ISS for servicing is technically feasible if aerobraking is used to dissipate the excess orbital energy. Only a few tens of meters per second delta-v is needed to change the operational orbit at L2 into an elliptical Earth orbit with a low perigee and the ISS orbit inclination.

Two options are available for making the aerobrake. One is to design the Sunshield so that it also functions as an aerobrake. A second option is to package a large drogue above the telescope secondary mirror and to deploy it as an aerobrake when needed. The aerobraking operations would be spread out over many perigee passes and would take about two months or less to complete. On every orbit, a small amount of orbital energy would be dissipated to the atmosphere during every perigee pass until apogee is at the ISS altitude. Propulsion would then raise perigee to the ISS altitude.

Once the NNGST achieves the ISS orbit, it would fly in formation with the ISS until the Shuttle or some other vehicle brought it to the ISS

10. References

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11. Biography

Mr. Muller has over 40 years of experience covering all aspects of design, construction, launch and operation of satellites. He has extensive experience in satellite systems engineering and systems management.