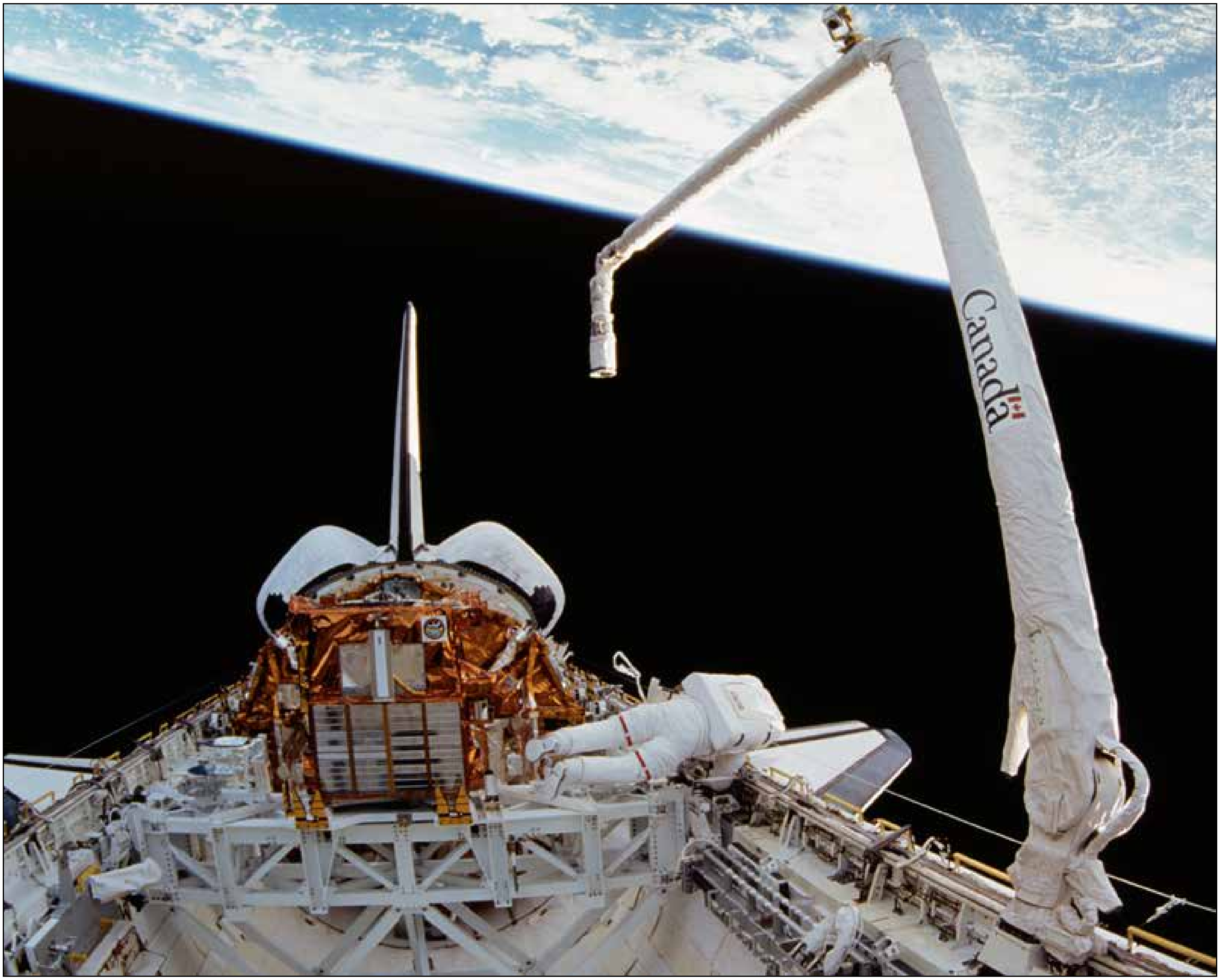
CANADA AVIATION AND SPACE MUSEUM AIRCRAFT

THE CANADIAN DESIGNED AND BUILT SPAR / MDA CANADARMS



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Canada

The Canadian Designed and Built SPAR/MDA *Canadarms*

Canada's Contribution to Space Exploration

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Part 1 - The Shuttle-Based *Canadarm*

Introduction

Early Developments

The Shuttle Remote Manipulator System (SRMS), affectionately known to Canadians as the *Canadarm,*[1] was originally designed and built to deliver and retrieve payloads to and from orbit using the Space Shuttle[2] as the transportation vehicle. As the American space program evolved, with results that proved overwhelmingly successful, it was confirmed that this technology could be used for other space related tasks including repairs to existing orbiting satellites as well as the construction of the International Space Station (ISS).

As a consequence of the decision to employ this technology in the building of the space station, a second version of the Shuttle based *Canadarm* was developed. To those involved in the space program it was known as *Canadarm2.* These two engineering developments were different in the sense that the first manipulator arm was fixed to the Space Shuttle while the second was a mobile version permanently located on the space station. Although the operating principles of both remote manipulator arms were fundamentally the same, their operating conditions and therefore technical requirements were quite different. Both of these Canadian success stories deserve to be told and are reviewed in two parts.

Part I is a summary of the Shuttle based *Canadarm* development and flight history. This version is currently on display at the Canada Aviation and Space Museum (CASM). Part II will focus on *Canadarm2* employed in the building and follow-on maintenance of the space station. Both arms were of Canadian design and manufacture and it is the view of the author that the story of these two engineering triumphs cannot be told separately – they deserve to be told together.

The challenges surrounding the development of both remote manipulator arms have been documented in many scientific and engineering publications. These publications are often technically advanced as well as highly detailed. To fully grasp the many concepts one would almost need a background in several advanced engineering disciplines. This monograph is a Canada Aviation and Space Museum attempt to describe two very complex robotic devices, and how they were employed, in a manner that can be grasped by the non-technical reader. By so doing, it is hoped that more Canadians will become familiar with this highly advanced robotic engineering development work, now recognized as one of Canada's greatest success stories. Before proceeding, a brief summary of the circumstances leading to the development of the two *Canadarms* may be of interest.

[1] To avoid confusion the term "*Canadarm*" will be used to reflect the version used by the five Space Shuttles. "C*anadarm2"* will refer to the single, but more advanced, version permanently mounted on the International Space Station.
[2] The Space Shuttle was also called the "Orbiter". These names are used interchangeably in this monograph.

Historical High Points

Canada was first invited to participate in the American Space Transportation System (Shuttle) program as far back as 1969 but it wasn't until 1974 that Canada decided to formally contribute, determine how to do so, and obtain the required Government funding to enter the project. However, within this overall framework much had already been accomplished. For instance, Canada's engineering community had already made substantial contributions to the American space program noting a cohort of aerospace engineers had been hired following the cancellation of the Avro Arrow project in 1959.

From a purely Canadian perspective Canada had made additional contributions primarily in the development of radio antennae. For several years the National Aeronautics and Space Administration (NASA) had been employing space antennae designed by George Klein of Canada's National Research Council (NRC).[3] This innovative foldable antenna was used on almost all of the *Mercury*, *Gemini* and *Apollo* space exploration programs as well as a large number of unmanned scientific satellites. The major advantages of these antennae were: light weight, small volume for launch, and the ability to autonomously extend and retract them for the duration of the space mission(s).

NASA was most satisfied with this Canadian work and expressed interest in other Canadian engineering applications. Following approval of the Space Shuttle development program by President Nixon in 1971, private sector interest by Canadian companies was emerging, largely because the building of smaller space related components was seen by Canadian entrepreneurs to be financially feasible. In the early stages of the Shuttle development a Canadian engineer, Lloyd Secord, representing his Company, DSMA Atcon Ltd, made a visit to NASA and, in the course of discussions mentioned that his Company had successfully developed a robotic device for the remote fueling of Canadian nuclear reactors. This sparked American interest and, when Secord returned to Canada from his NASA visit, he contacted several companies who he thought might be interested in designing and building a robotic arm for the forthcoming Space Shuttle.

This initiative was to gain support from the National Aeronautical Establishment (NAE), a division of Canada's prestigious NRC. Very soon thereafter it caught the attention of Jeanne Sauvé, the Science Minister, who later became the Governor General of Canada. The project started initially under the overall umbrella of the NRC with Spar Aerospace as lead contractor. Canadian Aviation Electronics Industries Ltd. (CAE) as well as Lloyd Secord's company, DSMA Atcon Ltd., also acted in key roles. In 1999 MacDonald Dettwiler Associates (MDA) took control of all subsequent *Canadarm* development following the business take-over of the SPAR Aerospace Robotics Division. A more complete listing of contractors and their contributions is outlined in the footnote below.[4]

[3] The correct nomenclature was "Storable Tubular Extendable Member (STEM)".

[4] SPAR Aerospace and Dynacon Inc. in Toronto developed the main control algorithms. CAE Electronics Ltd. in Montreal, provided the display and control panel and the hand controllers located in the rear of the Shuttle's mission deck. Other electronic interfaces located on the *Canadarm* were designed and built by SPAR at its Montreal plant. A graphite composite boom provides the structural connection between the shoulder and the elbow joint, and a similar boom connects the elbow to the wrist. The composite booms were manufactured by General Dynamics Ltd. DSMA Atcon and Associates, Ltd. in Toronto were contracted to produce the engineering model End Effector. Rockwell International's Space Transportation Systems Division designed, developed, tested and built the pallet systems used to attach the *Canadarm* to the payload bay of the Space Shuttle. In 1999 the Space Robotics Division of Spar Aerospace Ltd. was acquired by MacDonald Dettwiler and Associates (MDA) Ltd. Neptec Ltd. of Ottawa, Ontario designed and built both the Space Vision System (SVS) used for the construction of the International Space Station as well as the Laser Camera System (LCS) for the Canadarm.

Five Shuttle-based Remote Manipulator Arms were built and subsequently flight qualified although one was lost with all crew during the launch of the Space Shuttle *Challenger* in 1986[5]. These five *Canadarms* flew 91 missions between the delivery of the first arm in April 1981 and the last Shuttle mission to the space station in 2011.

The Working-In-Space Challenge

Early space research missions employing the *Mercury, Gemini* and *Apollo* space craft had proved, beyond doubt, that the ability to maneuver and do work in space was most difficult and was dependent on the installation of supporting hand-holds mounted on the outside of the space craft. The requirement to mount these handholds was a direct consequence of Newton's third law of physics. This law specifies that, to every action, there is an equal and opposite reaction. A device had to be developed which would allow reaction loads to be transferred to a larger body (in physics known as Mass) in order for external work to be done. With the building of the Space Shuttle both NASA and Canadian companies well understood that some form of robotic arm was the only practical solution.

The Shuttle/Orbiter Remote Manipulator System (SRMS) - *Canadarm*

Description and Specifications

The *Canadarm* was designed to be installed in, and operate from, the Space Shuttle's circular payload bay. This cargo bay was 5.0 m (16.5 ft) in diameter, 18.3 m (60 ft) long and could carry a payload of almost 27,000 kg (59,000 lb). The arm was designed to fit into a very narrow space between the closed doors of the Shuttle and the payload itself. After a number of design trade-offs the final Shuttle-based *Canadarm* weighed 410 kg (905 lb) in its stand-alone configuration. When attached and operated as a component of the Shuttle, the total system weight was slightly more at 450 kg (990 lb).

Photo looking rearward from the Shuttle's cabin shows the Canadarm mounted on the port side of the cargo bay. (Credit MDA)

Designed to operate in a microgravity or weightless environment this light physical weight meant that it could not support itself while on earth and, if unsupported, would simply collapse[6]. The maximum length of the arm required for space missions was determined by the size of the space shuttle's cargo bay and was eventually set at 15.2 m (50 ft) with a diameter of 38 cm (15 in).

[5] A *Canadarm* was not carried on board when *Columbia* (STS 107) was lost 1 February 2003.

[6] The *Canadarm* exhibit located at the Canada Aviation and Space Museum is equipped with the support assembly used to simulate motion in space while resident on the ground. This ground-based support assembly prevents the arm from collapsing under its own weight.

Finally, the strength of the arm had to be sufficient to allow it to maneuver the full payload mass into, and out of, the cargo bay.

Canadarm **Operating Modes**

The robotic arm was designed to perform several space related missions. The first was to place payloads in orbit as well as capture/retrieve payloads that were to be returned to earth. When returned, these payloads would undergo maintenance or, if deemed at the end of their economic life, disposed of. Most of these early insertion or capture/retrieval missions were accomplished from inside the Shuttle using a cabin mounted control panel designed to manipulate the arm to which the payload, in turn, was attached. As a significant side benefit, this operating mode allowed the astronauts to work inside the shuttle without the necessity of donning space suits.

The arm was also designed as a support platform permitting astronauts to repair satellites while performing extra-vehicular-activities (EVA's) in their space suits. When work of this nature was anticipated, a platform with foot restraints was installed at the end of the *Canadarm* to prevent the astronaut from floating away while working. Critically important, the arm would permit the work forces created in making repairs, to be transferred through the arm to the larger mass of the Shuttle itself.

Satellite Orbital Delivery

As noted, the initial concept was to allow the Shuttle/Orbiter to deliver or capture/retrieve a payload to, or from, orbit. In the case of satellite delivery, the Shuttle would use the manipulator arm to position the payload about 15 m (50.0 ft) away. Following release it would then employ its maneuvering thrusters to back away from the payload. If the satellite was to be placed in an orbit different from that of the Shuttle, the Johnson Space Center, located in Houston, Texas would use telemetry signals to actuate thrusters mounted on the satellite to place it into its desired orbit.

Satellite Orbital Repairs

When a satellite was to be repaired or retrieved, the shuttle would position itself adjacent to the orbiting satellite. The crew would then use the manipulator arm to capture and lock on to it and, if it was to be repaired, temporarily install it in a pallet fixed in the Shuttle's payload bay. The satellite would be repaired in this location before being re-positioned back in orbit. It would then back away from the satellite employing its internal engines or maneuvering thrusters.

Satellite Orbital Recovery

If the satellite were to be returned to earth the astronauts would employ the arm to securely fasten it in the Shuttle's payload bay. Ensuring secure storage was absolutely essential given the substantial acceleration forces that would occur on the vehicle's re-entry into the atmosphere. Following a return to earth the payload would either undergo follow-on maintenance or be retired.

Engineering Challenges and Solutions

Design Summary

From a design perspective the greatest challenge was to produce a robotic device that was an almost perfect replica of the human arm. For instance, the shoulder of a human arm is said to have two degrees of freedom. This simply means that it can both rotate upwards as well as swing forward and backwards, as in walking. The human elbow can only bend and is said to add a third degree of freedom. In a similar manner, the wrist can also bend and through “flexion” in the forearm can twist. In the human arm this permits a fourth and fifth degree of freedom.

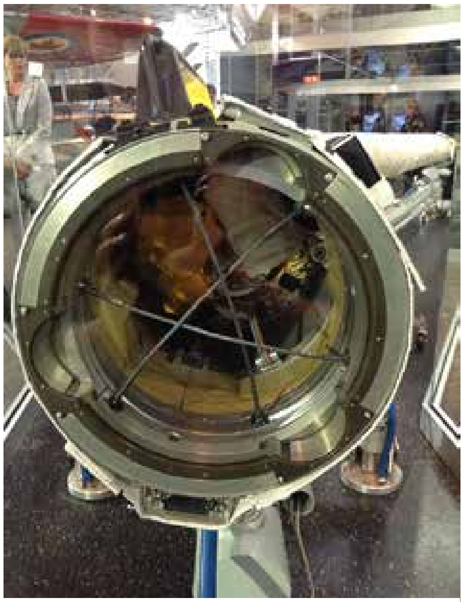
A photograph of the Canadarm used in the final flight of the Space Shuttle Endeavour being accepted in 2012 by Denise Amyot, then President and CEO of the Canada Science and Technology Museum Corporation. (Credit CASM)

The manipulator arm was endowed with six degrees of freedom. These included a shoulder joint, (roll and pitch) an elbow joint, (pitch) and a wrist joint, (pitch, roll and yaw). The decision to design the arm with six degrees of freedom allowed it to precisely position, or recover, payloads into or out of orbit after the space shuttle had been stabilized at something less than 15 m (50 ft) from the target satellite. A summary of the *Canadarm* specifications is attached as Appendix A.

A mechanical hand was attached to the end of the arm. It was capable of grasping and subsequently moving the payload both in and out of the Shuttle’s payload bay. But how was the end of the arm, or mechanical hand, to be configured? The design of the arm required that it first grapple a payload and then lock the *Canadarm* and the payload together with sufficient rigidity so that all three bodies (Shuttle, manipulator arm, and payload) could act as a single unit. The device that would accomplish this was called a Snare Type End Effector - a complex name for a simple device taken from the opening and closing mechanism of a camera’s iris or lens[7].

[7] The concept of using an iris-like design for the *Canadarm* End Effector is attributed to Frank Mee of Canada’s National Research Council.

Using the Snare Type End Effector (Hand)



Snare Type End Effector shown with the three wires that lock on to a knob device mounted on the payload. (Credit Canadian Space Agency)

This Snare Type End Effector, or mechanical “hand” was a cylinder 20.3 cm (8.0 in) diameter and 10 cm (3.9 in) long and was fitted with three cables in the form of a triangle that would act exactly the same as a snare. Actuated from the Shuttle aft mission station this cylinder would first mechanically close the three cables around a knobby pin bolted onto the payload. This was termed the “soft dock”. The three cables would then draw the knobby pin into the cylinder with about 500 kg (1100 lb) of force. This was the “hard dock” and would make the combination Shuttle, *Canadarm* and payload a single semi-rigid structure. As a consequence, the forces generated by movement of the payload in and out of the Shuttle’s cargo bay would be transferred to the entire orbiting body. In short, the problems associated with Newton’s third law of motion were largely resolved. The manipulator arm, by joining the three bodies together, would allow work to be performed in space.

Canadarm Weight

One of the initial engineering challenges had to do with the arm’s weight. The costs of placing weight into low earth orbit using the shuttle as the transportation vehicle had been variously calculated at between 22,000 to 31,000 US dollars/kg (10,000 to 14,000 US dollars/ lb. And, it should be emphasized, this amount did not include the development costs of the Space Shuttle itself. Complicating this was the fact that the Shuttle was designed to lift a pre-determined and fixed payload weight to orbit and the manipulator arm’s weight would reduce this total amount. The minimization of weight therefore, was a major consideration in the overall design. As noted earlier the final *Canadarm* operating weight was 450 kg (990 lb).

Thermal Protection System

Due to the fixed mounting of the arm in the cargo bay of the Shuttle, methods had to be developed to manage the sub-freezing temperature on the shaded side of the arm as well as the extremes of heat on the sunlit side. The solution was to cover the entire length of the arm with a multi-layer insulation thermal blanket, which provided passive thermal control. This material consisted of alternate layers of a DuPont-manufactured product with unique electrical, thermal and chemical properties to reflect the heat and cold. In addition, electric heaters were attached to critical mechanical and electronic components and were sequentially powered on and off to maintain a stable operating temperature.

System Integration and Reliability

Image of the Canadarm wrist joint and forearm covered with insulation to protect components from the heat generated by the sun's radiation. (Credit NASA)

This robotic replica of the human arm included nerves of copper, extensions made of synthetic tubes molded of graphite-fibre, and electric motors acting as muscles. The motors, which are no larger than a modern day smart-phone, are buried in the arm's joints, which service finely machined gears located in housings called gearboxes. Since these gearboxes could be seriously affected by major changes in temperature the metal components had to be built slightly over tolerance and then subjected to both heat and cold treating. They were then machined to the required size. The ratio of these gears was as small as 1800:1 making the machining and subsequent sizing extremely challenging.

The resulting design would allow the Shuttle to perform payload insertion and capture/recovery missions. But only if the engineers successfully developed new and unproven technologies for every one of the thousands of parts that would be required to operate the arm as an overall "system". Managing this number of parts and their inevitable design trade-offs turned out to be one of the most complex tasks associated with the delivery of the final product. To understand this challenge, one must realize that the final *Canadarm* had to be capable of operating from an even more complex machine (the Shuttle/Orbiter) with a stated reliability of 100%. Putting it more simply, it had to work first time and every time! NASA also stipulated that the arm must sustain two major component failures with no threat to the crew. Making it more difficult, this reliability had to be met in the absence of testing in the environment of space in which it was to operate. This testing could only be accomplished through the development of ground-based simulators.

Simulation Requirements

It was determined that two major forms of simulation would be required. The first simulator was conceived to allow engineers to test the device on earth. This was made more difficult in the sense that the lightweight arm, built to operate in the micro-gravity environment of space would, as noted earlier, collapse under its own weight on earth due to the natural force of gravity. The most vulnerable components of the arm were the joints made of finely machined gears discussed earlier. The solution for testing the device was developed by DSMA Atcon Ltd.

This first earthbound simulator took the form of a specially designed steel rig mounted on air-bearings that can be likened to air cushions. This system, located and installed at the Spar Robotics Ormont Drive plant in North York, allowed the rig to seamlessly glide across a perfectly smooth floor thereby simulating a single plane of motion. To test other planes of motion the arm would be turned 90 degrees until all planes had been tested. In this step-by-step manner the *Canadarm* was successfully evaluated and subsequently certified for space operations.

***A Canadarm being tested on the ground for space flight. It is supported by air bearings to simulate operation in the weightlessness of space. On earth, it cannot support its own weight. (Credit DSMA Atcon Ltd**.)*

The second simulator was designed to allow training of the astronauts on the ground so they could become familiar with the arm's response times that would exist in a microgravity or weightless environment[8]. This training device took the form of a retired fuselage taken from a Douglas DC-9 passenger jet with almost identical dimensions as the Space Shuttle cargo bay. Once this simulator was configured and operating, the astronauts were of the opinion that the simulated device on the ground was somewhat harder to operate than the actual arm when used in space. This is a very real compliment to the engineers who designed this training simulator, as good simulator design attempts to produce a simulation that is marginally more difficult than the actual environment in which the device is to be used.

Controlling the *Canadarm*

A control console, located at the Shuttle's aft mission station, was mounted adjacent to two 28 cm (11 in) by 20 cm (8 in) windows that looked onto the Shuttle's large cargo bay allowing the crew to view the *Canadarm* as well as the payload. There were another two windows of the same size mounted overhead. Two Closed Circuit Television Cameras (CCTV's) were installed on each of the elbow and wrist of the arm so the operator could see what the arm was doing in relation to the payload being moved[9]. There were two modes of arm operation. The primary mode employed computers located on board the Shuttle and it was using this mode that most of the payload maneuvering was performed. It could also be operated with reference to the two cameras mounted on the "elbow" and "wrist" of the arm. It was earlier mentioned that the

[8] All machines have a slight response time delay between the initial movement of the controls and the resulting response of the device. In physics these slight delays are known as "time-constants". In the case of both the *Canadarm and Canadarm2,* the astronaut "learns" what these delays are by repeatedly experiencing them in ground-based simulators.
[9] In addition, both the arm and the Orbiter's payload bay were equipped with lights so work could continue when it entered the night component of its orbit.

Canadarm had six degrees of freedom and acted in most respects, like a human arm. Each of these degrees of freedom was represented in two hand controllers. These controllers allowed the *Canadarm* to translate (in and out, side to side and up and down) as well as roll (right and left)

Canadian Mission Specialist Mark Garneau beside the Canadarm control console. The arm's rotational controller is the larger device adjacent to his left hand. The translation controller is above and slightly to the right in the square fitting. (Credit NASA)

pitch (up and down); and yaw (right and left). Each of these motions was programmed into the Orbiter's computer and any combination demanded by the astronaut would cause the arm to respond accordingly. It might be of interest to indicate how computer control of the arm was accomplished.

Since the early days of the manned space program, spacecraft maneuvering thrusters were controlled and operated by a technology referred to as "Fly by Wire" (FBW). A FBW control system is one that places a computer between the operator and the device(s) being moved. For example, there is no physical connection between the two except for digital communication wiring – hence the name! The computer is programmed to understand what the operator (in this case astronaut) is asking the arm to do then almost instantaneously converts these control motions into electrical signals that actuate the small motors in the arm's joints.

The advantage of this technology is that such a control system is relatively light in weight, can be re-programmed to meet different requirements and (more recently) is not as costly as other alternatives. As previously noted there was a back-up mode of operation allowing the *Canadarms* joints to be operated individually. As a matter of interest these FBW control systems are now common in modern aircraft design and are also being introduced in automobiles for acceleration, braking and steering.

The Impact of Losing the Shuttle *Columbia* (STS-107)[10]

Introduction

On 1 February 2003 the Shuttle *Columbia* was lost in a catastrophic accident while re-entering the atmosphere following a successful mission[11]. NASA immediately convened an inquiry. It was determined that the accident was caused by substantial damage to a heat shield tile mounted on the leading edge of the wing. This tile had been struck at high velocity by a large piece of foam insulation that had separated from the orbiter's fuel tank following lift-off. The tile was a critical component of the Thermal Protection System (TPS) used to protect the Shuttle from the searing temperatures on re-entering the earth's atmosphere. On *Columbia's* re-entry, super heated plasma at 1,650 C, (3,000 F) entered the area of the missing tile through a hole about 30 cm (12 in) in size. It severely burned, and therefore weakened, the structural components on the inside of the affected wing causing its failure on re-entering the earth's atmosphere.

As a consequence of this tragic loss NASA made a decision to develop technologies that would enable inspection and repair of the Orbiter's thermal protection system while still on-orbit, and prior to return to earth. The first of these new technologies was an addition to the *Canadarm* enabling it to inspect areas of the Shuttle's heat shield system that could not be reached due to the original length of the Shuttle's *Canadarm*. The second was the development of several potential (on-orbit) tile repair technologies. Both are discussed briefly below.

The Orbiter Boom Sensor System (OBSS)

Since the existing *Canadarm* was too short to inspect the Shuttle's under-wing thermal protection tiles, MacDonald Detwiller Robotics recommended that a boom be developed and attached to the end of the existing *Canadarm*. This boom extension was made up of two 6.1 m (20 ft) long graphite epoxy cylinders that were originally replacement parts for the *Canadarm*. When joined together the resulting extension was called the Orbiter Boom Sensor System (OBSS) and MacDonald Detwiller Robotics was subsequently contracted to build the boom. In its final configuration it had a length of 15.2 m (50 ft) and, when combined with the existing *Canadarm,* provided a reach of 30.4 m (100 ft). This boom extension was included as part of the *Discovery* (STS-114) payload – the first Shuttle mission following the loss of *Columbia*.

Critical to the success of the OBSS was the Canadian Laser Camera System (LCS) developed by Neptec of Ottawa, Ontario. When mounted on the boom extension the combination OBSS/LCS allowed remote inspection of the entire shuttle's heat shield tiles. However, a more sophisticated version was in development. This version could generate a three-dimensional image model at a distance of 10 m (33 ft) of any object - with an accuracy that could be measured in millimeters. Because of the critical importance of this Neptec development work to the construction of the International Space Station it will be described later in this monograph.

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[10] STS is the abbreviated NASA nomenclature for "Space Transportation System". The number following refers to the sequential mission number - hence, STS-107.

[11] *Columbia* was the first Shuttle to be launched into space on an operational mission in April 1981 (STS-1). When the accident occurred, *Columbia* was completing its 28th mission.

A photo of the boom attachments, which extend the length of the Canadarm. The Neptec LCS is mounted on the end of the OBSS and allows the astronauts to inspect the tiles for damage while on-orbit. These critical heat shield tiles are located on the leading edge and underside of the Orbiter's wing. (Credit NASA)

An interesting use of this boom assembly proved highly successful quite unexpectedly during a later mission (STS-120). While installing a space station module, a solar array had become jammed on deployment but the distance was out of reach of the ISS mounted *Canadarm2*. NASA made a decision to attach the Shuttle's boom assembly onto the end of the ISS arm allowing an astronaut to reach the affected array where the necessary repairs were made. This unplanned use of the boom was cause for a subsequent decision to place a modified version of this extension boom permanently on the space station.

The Thermal Protection System Repair Kit (TPRK)

Also included on *Discovery* (STS-114) were several alternative test versions of potential tile repair kit technologies should inspection of the Shuttle's tiles, following lift-off, reveal an unsafe condition. This work turned out to be anything but straight forward and after sixteen months of research NASA determined that it was all but impossible to repair a hole, the size of *Columbia's,* using a repair kit. Initially, NASA held the view that the damage to *Columbia* was caused by faulty foam installation on the external fuel tank[12]. This led to the conclusion that with higher quality control of the fuel tank insulation, along with other measures, this would prevent damage from occurring a second time. But the problem, unfortunately, happened again!

[12] It was later determined that the foam separation was caused by thermal expansion and contraction of the fuel tank when it was being filled with propellant. This weakened the bonding allowing some insulation to separate during lift-off.

A schematic showing how the boom assembly and Neptec Laser Camera System (in red) could be employed to inspect the heat shield tiles located on the underside of the Orbiter's wing. (Credit NASA)

Between two and three seconds after *Discovery's* lift-off a large bird struck the top of the external fuel tank and then slid down the tank without hitting the Shuttle or its heat shield tiles. And, for the second time, there was loss of a piece of foam from the external fuel tank. Although this piece of foam did not strike or damage the Shuttle's tiles, NASA again decided to defer all future flights until this foam separation problem was solved – once and for all.

Schematic showing how the Orbiter exposed its underside to the International Space Station cameras, which were analyzed to confirm no damage had occurred to the tiles on lift-off. (Credit NASA)

However, unrelated to the above incidents, a small fragment of tile about 40 mm (1.5 in) was ejected from an edge tile near one of the Shuttle's landing gear doors sometime before the separation of the booster rockets. While the damage to the orbiter was minimal, NASA had set in motion certain inspection procedures to assure the shuttle's safety. These procedures were employed on this, the STS-114 mission.

For instance, as the Orbiter was closing in on the ISS and about 180 m (600 ft) below the space station it performed a back flip (or pirouette) so the tiles on the bottom of the wing structure were exposed to cameras mounted in the ISS. The period of time the tiles were exposed was only about ninety seconds but this was sufficient for the cameras to fully image the underside of the entire Orbiter's wing. Following a downlink of images to the mission control center in Houston, Texas, and about an hour later, it was confirmed that no significant damage had occurred to the heat tiles in these areas. As for the boom extension, it was carried in the payload bay on all remaining missions.

The *Hubble* Space Telescope (HST), the *Canadarm* and COSTAR (Correction Optics Space Telescope Axial Replacement) - *Endeavour* (STS-61)

Introduction

All C*anadarms* performed superbly until they were retired when *Atlantis* (STS-135) rolled to a stop July 21, 2011 at NASA's Kennedy Space Center in Florida. But of all the missions performed, one Shuttle mission STS-61 (COSTAR) stands out above all the rest. That mission involved the very complex and demanding repair to one of the two mirrors installed on the HST.

By way of background the *Hubble* spacecraft was initially launched into orbit on board the Orbiter *Discovery* (STS-31) in April 1990. It was one of the most heralded and important science initiatives in mankind's attempt to discover more about the formation of the universe. It was designed to make celestial observations, as the universe existed almost fourteen billion light-years in the past.

To accomplish the many scientific objectives set for it, the HST telescope turned out to be both large and heavy. In the shape of a cylinder, at lift-off the spacecraft weighed 11,100 kg (24,500 lb) and was 13.3 m (43.5 ft) in length and was about the size of a tractor-trailer truck. The largest mirror was 2.4 m (7.9 ft) wide.

Assessment and Repair

Sometime after achieving orbit the scientists observed a blurring of certain images that could not be corrected with on-board equipment designed for fine-tuning purposes. Following considerable analysis they determined that the aberration was caused by a production defect in one of the two main reflective mirrors. This defect was subsequently traced to the outer of the two finely machined mirror-like lenses that were instrumental in providing the high-resolution images. Because the HST was to be in orbit for many years it had been designed to accommodate routine maintenance throughout its life - and this maintenance was to be performed by astronauts employing

Image of the Hubble Space Telescope taken from the Shuttle Endeavour at the time repairs were being made to the faulty mirror. (Credit NASA)

space walks. But repairing a primary mirror initially seemed all but impossible. However, after studying the problem the scientists and engineers thought it might be possible to design, manufacture and install a set of “glasses” which could be mounted between the two main mirrors and resolve the aberration in the faulty mirror. This turned out to be feasible and *Endeavour* (STS-61) was subsequently launched with a repair package (COSTAR) that included the “glasses” to be mounted between the two mirrors.

To repair the HST it was temporarily stowed in a pallet at the rear of the orbiter. Note astronaut being moved by the Canadarm to effect repairs. The HST has a high orbit hence the earth’s curvature is seen more clearly. (Credit NASA)

After lift-off, the Orbiter maneuvered into the same orbit as the HST and *Endeavour* was positioned 15 m (50 ft) from the satellite. The *Canadarm* was used to reach out, lock-on and hold the spacecraft firmly. Once stabilized in an end-on vertical position it was slowly maneuvered, and temporarily fixed, to a platform pallet located in the rear of the shuttle’s cargo bay. For the next five days the arm was used to provide the necessary support base for the astronauts. The repairs took thirty hours of EVA before the installation of the COSTAR components were completed.

Following the repairs, the reverse of the HST capture procedure was used to return the satellite to its original orbit. On completion of the COSTAR mission the scientific ground controllers slowly brought the HST systems back to life and proclaimed that the repairs had been successful. The *Canadarm* was central to this success!

Hubble **Space Telescope Follow-On Missions**

There were additional Shuttle missions to the HST but these missions were used for previously planned maintenance or technology upgrades that had been developed since it was originally placed in service[13]. From the first launch into orbit in April 1990 until the last scientific support mission in May of 2009 HST missions spanned a period of more than nineteen years. The HST will reach the end of its planned life sometime in 2018, following which it will be shut down and probably de-orbited. It will be replaced by the James Webb Space Telescope (JWST) currently (2014) under development.

[13] Following the placing of *Hubble* in orbit in April 1990 there were five additional missions. They were: STS-61 *Endeavour* December 1993 (COSTAR); STS-82 *Discovery* February 1997; STS-103 *Discovery* December 1999; STS-109 *Columbia* March, 2002; and STS-125 *Atlantis* May 2009.

Missions of the Canada Aviation and Space Museum (CASM) *Canadarm*

Introductory Remarks

In the following section the Shuttle/Orbiter missions are listed on which the first *Canadarm Serial No. 201*, on loan to the Canada Aviation and Space Museum, flew. The descriptions are taken from two sources. The first are the NASA mission summaries available on the Internet under the NASA Shuttle/Orbiter mission nomenclature i.e. STS-1 through STS-135. Secondly, some summaries also include transcripts from actual tapes taken from official television and radio broadcasts used at the time for wider public consumption. When reviewing these mission summaries the reader should be aware that NASA often refers to the *Canadarm* as the "remote manipulator system". Both terms refer to the same Canadian designed and built robotic device. In most cases where large satellites are placed in, repaired or captured from orbit, the *Canadarm* was used[14].

The reader will also note in the earliest missions, that the arm was being tested to determine how it behaved when astronauts were mounted on footholds installed at the end of the device. These tests were preparatory to follow-on satellite repair missions, the most notable of which was that of the Hubble Space Telescope.

Finally, the Shuttle missions listed do not always follow a chronological order. A change in mission sequencing occurs when a decision was made by NASA to delay or adjust a specific mission as a result of payload equipment delays, Orbiter upgrades or other factors.

STS-2 / *Columbia* (1981)
Check out of all Orbiter systems including the Remote Manipulator System (RMS) (*Canadarm*). Astronauts reported that the RMS performed very well; however, the mission was shortened due to a faulty Shuttle fuel cell.

STS-3 / *Columbia* (1982)
Testing of Space Shuttle systems continued in order to qualify them for later operational flights. Testing of the Canadian RMS (*Canadarm*) and measurements of the thermal response of the Orbiter in various attitudes relative to the sun were conducted. On orbit the astronauts observed some damaged tiles on the nose of the spacecraft. The *Canadarm* wrist and elbow cameras were employed to assess the extent of the damage.

For the first time the *Canadarm* was used to guide a payload (a Plasma Diagnostic Package) out of the Orbiter and around the spacecraft. The results confirmed that the arm was very controllable and proved that it could launch and retrieve spacecraft cargo from the Orbiter's payload bay with relative ease.

STS-4 / *Columbia* (1982)
The crew performed medical experiments on themselves for two student projects and took

[14] Several smaller satellites like WESTAR, INSAT, TDRS, PALAPA and the Canadian ANIK were independently ejected employing springs mounted in transportation pallets located in the Orbiter's payload bay.

photos of lightening activity in the Earth's atmosphere. On the third day they operated the remote manipulator arm (*Canadarm)* for five hours to swing the Induced Environmental Contamination Monitor (IECM) around the Orbiter.

STS-7 / *Challenger* (1983)
Ten experiments were mounted on the German-built Shuttle Pallet Satellite (SPAS-01). These experiments performed research in forming metal alloys in microgravity including the use of a remote sensing scanner. The Shuttle's small control rockets were fired while SPAS-01 was held by the remote manipulator arm (*Canadarm)* to test the movement on an extended arm. Later the SPS-01 was both released into orbit and retrieved by the *Canadarm* later in the mission - the first time this had happened.

STS-8 / *Challenger* (1983)
This flight was the second manned space flight to be launched at night and the first to be recovered at night. During orbit the nose of the Orbiter was oriented away from the sun for 14 hours to test the flight deck area in extreme cold. For the Development Flight Instrumentation Pallet (DFI PLT), the crew filmed performance of an experimental heat pipe mounted in the cargo bay. Also, the Shuttle lowered its orbit to 237 km (139 mi) altitude to perform tests on thin atomic oxygen to identify the cause of glow that surrounds parts of the Shuttle at night. The Canadian remote manipulator system was tested to evaluate the response of the joints to higher loads by employing a massive lead ballasted dumbbell shaped device.

STS-41B / *Challenger* (1984)
This mission was the first in which untethered space walks were carried out. The astronauts used the Manned Maneuvering Unit (MMU) to accomplish these walks. The WESTAR-VI and PALAPA-B2 satellites were deployed, but failure of the Payload Assist Module-D (PAM-D) rocket motors left them in low-Earth orbits. The German-built Shuttle Pallet Satellite (SPAS), originally flown on STS-7, became the first satellite refurbished and carried back into space. SPAS remained in the payload bay due to an electrical problem with the *Canadarm*. The *Canadarm* Mobile Foot Restraints were first used to practice procedures performed for the Solar Maximum satellite retrieval and repair that were being planned for the next mission.

STS-27 / *Atlantis* (1988)
Dedicated to the American Department of Defense.

STS-32 / *Columbia* (1990)
Objectives were the deployment of SYNCOM IV-F5 defense communications satellite and retrieval of NASA's Long Duration Exposure Facility (LDEF). SYNCOM IV-F5 (also known as LEASAT 5) was deployed first, and a third stage *Minuteman* auxiliary solid perigee kick motor boosted the satellite to geosynchronous orbit. The LDEF was retrieved on flight day four using the *Canadarm.*

STS-46 / *Atlantis* (1992)
The primary objective was deployment of the European Space Agency's Retrievable Carrier (called EURECA) and operation of the joint NASA/Italian Space Agency Tethered Satellite System (TSS). The mission was extended one day to complete the science objectives. EURECA deployed one day later than scheduled because of a problem with its data handling system. After deployment, the spacecraft's thrusters were fired to boost EURECA to its planned operating altitude of about 500 km (310 mi). TSS deployment was also delayed one day because of

EURECA. During TSS deployment, the satellite reached a maximum distance of only 256 m (840 ft) from the Orbiter instead of the planned 20 km (12 mi) because of a jammed tether line. Over several days numerous attempts were made to free the tether but TSS operations were finally curtailed and the satellite was stowed for return to Earth.

STS-56 / *Discovery* (1993)
On April 11, the crew used the remote manipulator arm *(Canadarm*) to deploy the Shuttle Point Autonomous Research Tool for Astronomy-201 (SPARTAN-201), a free-flying science instrument platform designed to study velocity and acceleration of the solar wind and observe the sun's corona. Collected data was stored on tape for playback after return to Earth. The SPARTAN-201 platform was retrieved on April 13.

STS -51 / *Discovery* (1993)
One of two primary payloads, the Advanced Communications Technology Satellite (ACTS), was deployed on flight day one. About 45 minutes after ACTS deployment the attached Transfer Orbit Stage (TOS) booster - flying on the Shuttle for the first time was fired to propel this pioneering communications technology spacecraft to a geosynchronous orbit.

On flight day two, the crew deployed the second primary payload called the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph-Shuttle Pallet Satellite (OERFEUS-SPAS). It was the first in a series of ASTRO-SPAS astronomical missions. An IMAX camera mounted on the SPAS recorded extensive footage of the Shuttle. The Joint German-U.S. astrophysics payload was controlled via SPAS Payload Operations Control Center (SPOC) at Kennedy Space Center and was the first Shuttle payload to be managed from Florida. After six days of data collection, the ORFEUS-SPAS was retrieved with the remote manipulator arm (*Canadarm*) and returned to the cargo bay.

On Sept. 16, two mission specialists performed extravehicular activities lasting over seven hours. This concluded a series of generic space walks begun earlier in the year. Astronauts also evaluated tools, tethers and a foot restraint platform mounted on the *Canadarm* intended for the upcoming Hubble Space Telescope servicing mission.

STS-60 / *Discovery* (1994)
On flight day three, the crew made a first attempt to deploy Wake Shield Facility-1 (WSF-1) using the C*anadarm*. WSF-1 is a deployable/retrievable experiment platform designed to leave a vacuum wake behind it in low earth orbit that is 10,000 times greater than achievable on Earth. In this ultra-vacuum environment, defect-free thin-film layers of gallium arsenide and other semiconductor materials can be grown. The first deployment attempt was halted due to radio interference and difficulty reading status signs on WSF-1. After a second deployment attempt on flight day four the tests were cancelled due to problems with the WSF-1 attitude control system. Five out of seven planned films were grown with the WSF-1 platform suspended at the end of the *Canadarm.* WSF-1 was berthed in the cargo bay on flight day six.

STS-64 / *Discovery* (1994)
The primary payload was the Lidar In-Space Technology Experiment (LITE) deployed by *Canadarm*. The Lidar component is a type of optical radar using laser pulses instead of radio waves to study Earth's atmosphere. This instrument operated for 53 hours, yielding more than 43

hours of high-rate data. Unprecedented views were obtained of cloud structures, storm systems, dust clouds, pollutants, and forest burning as well as surface reflectance. Sites studied included atmosphere above northern Europe, Indonesia and the South Pacific, Russia and Africa. Sixty-five groups from twenty countries are making validation measurements with ground-based and aircraft instruments to verify LITE data. LITE science program was part of NASA's "Mission to Planet Earth".

STS-63 / *Discovery* (1995)
Also on flight day two, crew used orbiter remote manipulator system *(Canadarm)* arm to lift the SPARTAN-204 from its support structure in the payload bay. SPARTAN remained suspended on the *Canadarm* for observation of shuttle glow phenomenon and thruster jet firings. SPARTAN-204 was later released from the arm to complete about 40 hours of free-flight, during which time its Far Ultraviolet Imaging Spectrograph instrument studied celestial targets in the interstellar medium, the gas and dust which fills the space between the stars and which is the material from which new stars and planets are formed.

SPARTAN-204 was also used for an EVA near the end of the flight. Two astronauts began their EVA's suspended at the end of the *Canadarm.* This was done away from the payload bay in order to test modifications to their spacesuits designed to keep spacewalkers warmer in the extreme cold of space. Two astronauts were then scheduled to practice handling the approximately 1,130 kg (2,500 lb) SPARTAN to test space station assembly techniques, but both astronauts reported they were becoming very cold -- this portion of walk performed during a night pass -- and mass handling was curtailed. This was the 29th Shuttle space-walk; it lasted 4 hours, 38 minutes.

STS-91 / *Discovery* (1998)
This was the ninth and final docking mission to the Russian space station *Mir.* Flying on STS-91 was an experiment by US Nobel laureate Dr. Samuel C. Ting; it was known as the Alpha Magnetic Spectrometer (AMS) experiment. In 1995, Dr. Ting's research proposal for the AMS space experiment was formally selected by the US Department of Energy. The AMS flew for the first time on the STS-91 mission and a second time on the International Space Station.

Discovery also carried the single SPACEHAB module in its payload bay. The module housed experiments to be performed by the astronauts and served as a cargo carrier for items to be transferred to *Mir* and returned to Earth.

STS-95 / *Discovery* (1998)
The primary objectives of STS-95 included conducting a variety of science experiments in the pressurized *Spacehab* module. It also included the deployment and retrieval of the Spartan free-flyer payload, operations with the Hubble Space Telescope Orbiting Systems Test (HOST) and the International Extreme Ultraviolet Hitchhiker payloads being carried in the payload bay. The scientific research mission also returned space pioneer John Glenn to orbit - 36 years, eight months and nine days after he became the first American to orbit the Earth.

Employing the *Canadarm* the crew also released the Spartan free-flying satellite to study the sun and the solar wind. The Hubble Space Telescope Orbital Systems Test (HOST) provided an on-orbit test bed for hardware that was used during the third *Hubble* servicing mission.

STS-113 / *Endeavour* (2002)

Over the course of the 14-day mission, the STS-113 crew and the Expedition Six crew combined to install the new P1 truss to the ISS, perform three spacewalks to outfit and activate the truss, and transfer supplies and equipment between the two spacecraft. *Endeavour* brought more than 1,130 kg (2,500 lb) of material to the station.

Prior to the first spacewalk, one of the crew removed the P1 truss from *Endeavour's* payload bay, using the Shuttle's robotic arm *(Canadarm)* and handed it off to the station's *Canadarm2.* Two other astronauts maneuvered the P1 truss into its designated position.

Working from the *Canadarm2*, the Crew and Equipment Translation Aid (CETA) cart was lifted to the S1 truss where it was attached to the tracks and secured it to its sister CETA, delivered on STS-112. The move cleared the P1 tracks so the *Canadarm2* could move on them via the Mobile Transporter and Mobile Base System.

STS-118 / *Endeavour* (2007)
Space Shuttle *Endeavour's* STS-118 mission was the 22nd Shuttle flight to the International Space Station. It continued space station construction by delivering a third starboard truss segment.

STS-123 / *Endeavour* (2008)
STS-123 delivered the first of three modules of the Japanese Experiment Module (*Kibo*), as well as the Canadian Special Purpose Dexterous Manipulator, (SPDM) (later abbreviated to *Dextre*) robotic system to the station. The mission duration was 16 days and 14 hours and was the first mission to fully utilize the Station-to-Shuttle Power Transfer System (SSPTS), allowing space station power to augment the shuttle power systems. The mission set a record for the Shuttle's longest stay at the ISS.

STS-126 / *Endeavour* (2008)
STS-126 included the Italian *Leonardo* Multi-Purpose Logistics Module (MPLM) on its fifth spaceflight. *Leonardo* held over 6,350 kg (14,000 lb) of supplies and equipment. Among the items packed into the MPLM were two new crew quarters racks, a second galley (kitchen) for the *Destiny* laboratory, a second Waste and Hygiene Compartment (WHC) rack (lavatory), the advanced Resistive Exercise Device (RED), two water reclamation racks, spare hardware, and new experiments. Also included in *Leonardo* was the General Laboratory Active Cryogenic ISS Experiment Refrigerator, or GLACIER, a double locker cryogenic freezer for transporting and preserving science experiments.

STS-127 / *Endeavour* (2009)
The primary purpose of the STS-127 mission was to deliver and install the final two components of the Japanese Experiment Module. When *Endeavour* docked with the ISS on this mission in July 2009, it set a record for the most humans (13) in space at the same time in the same vehicle.

STS-130 / Endeavour (2010)
Endeavour's 13-day flight included three spacewalks and the delivery of a connecting module that will increase the International Space Station's interior space. Node 3, known as *Tranquility*, will provide additional room for crewmembers and many of the space station's life support and environmental control systems. Attached to the node is a cupola, which is a robotic control station with six windows around its sides and another in the center that will provide a panoramic

view of Earth, celestial objects and visiting spacecraft. After the node and cupola are added, the space station will be about 90 percent complete.

STS-134 / *Endeavour* (2011)

STS-134 (ISS assembly mission ULF6) was the penultimate mission of NASA's space shuttle program. The mission marked the 25th and last spaceflight of the Space Shuttle *Endeavour*. This mission delivered the Alpha Magnetic Spectrometer and an Express Logistics Carrier to the International Space Station.

STS-135 / Atlantis

This was the 135th and final mission of the American Space Shuttle program. It used the Orbiter *Atlantis* and hardware originally planned for the STS-335 contingency mission, which was not flown[15]. STS-135 launched on 8 July 2011, and landed on 21 July 2011, following a one-day mission extension. The four-person crew was the smallest of any shuttle mission since STS-6 in April 1983. The mission's primary cargo was the Multi-Purpose Logistics Module (MPLM) *Raffaello* and a Lightweight Multi-Purpose Carrier (LMC), both of which were delivered to the International Space Station (ISS).

Although the mission was eventually authorized, it initially had no financial appropriation in the NASA budget, raising questions concerning whether the mission would actually fly. On 20 January 2011, program managers changed the STS-335 nomenclature to STS-135 on the flight manifest.

[15] STS-335 was a contingency mission in the event that STS-134 became disabled preventing it from returning to earth. The major concern centered on problems associated with the heat shield tiles. If, following on-orbit inspection, the tiles were found to be damaged STS-335 would be launched to the ISS to recover the STS-134 crew. It was a mission that everyone hoped would never be needed and, fortunately, it wasn’t.

The Canadian Designed and Built SPAR/MDA *Canadarms*
Canada's Contribution to Space

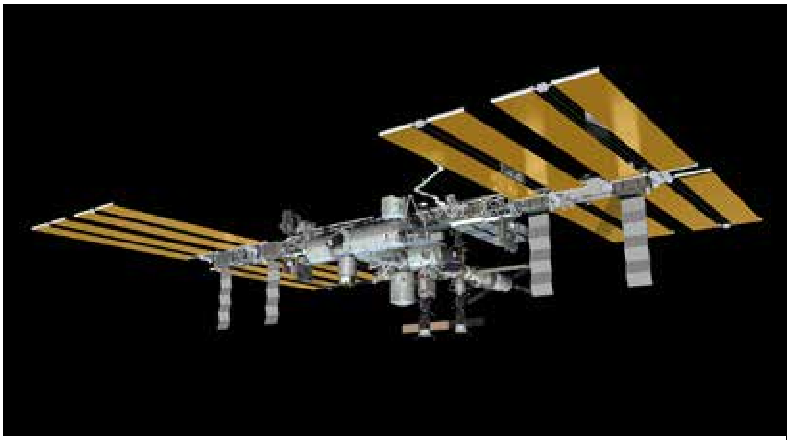
Part II - The International Space Station Based *Canadarm2*

The Truss Structure, Canadarm2, Dextre and the Mobile Base System

Introduction

To construct the International Space Station three major robotic technologies were developed. Two were Canadian and one was American. The two Canadian contributions included the *Canadarm2*, an upgraded version of the Shuttle based *Canadarm* and the second was a robot with a complex name called the Special Purpose Dexterous Manipulator (SPDM). For simplicity purposes this robot's name was shortened to *Dextre.* It was designed to support maintenance operations during and following the building of the station. Complementing these two Canadian technologies was the American Mobile Base System (MBS), a robotic vehicle that allowed the two Canadian robots to move back and forth on a massive truss structure on which this robotic vehicle is mounted. Since this truss structure is the backbone of the ISS, it is discussed first.

The International Space Station Truss Structure



A schematic showing the truss structure which spans the entire space station including the massive solar arrays for powering the ISS. (Credit NASA)

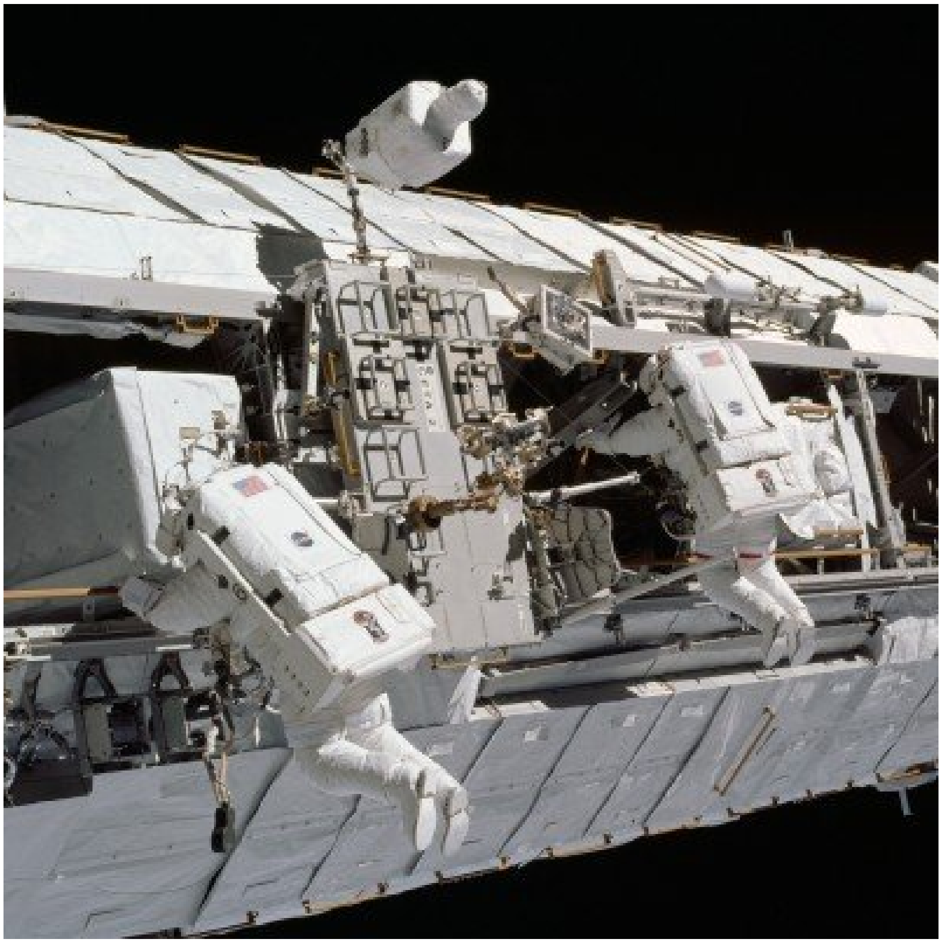
As modules were added and the space station increased in size an enormous truss structure, consisting of ten large sections, were lofted to the ISS where the separate modular sections were attached. In its final configuration this structure spans the entire space station of 109 m (357.5 ft) and acts as the station's backbone and nerve center. For instance, it is equipped with sensors and mini-systems that continuously monitor the health of the station including station laboratories, living quarters and parked payloads. All ISS systems are connected to this truss structure either directly or indirectly.

Mounted on the truss structure is a mini-railway for the American Mobile Base System (MBS) on which both *Canadarm2* and *Dextre* can be mounted. The MBS is simply a sophisticated platform; it was delivered to the ISS in June 2002 (STS-111). This platform rides back and forth on rails attached to the trusses and is equipped with four Grapple Fixtures located on each of the four corners of the platform. They act as holding receptacles for *Canadarm2* and *Dextre*. When attached to one or other of these four receptacles *Canadarm2* can access all critical work sites on the space station. Explained another way the American transporter and platform combined can be likened to a self-propelled go-cart or "doghouse" on wheels. On one or other of the four corners of the "doghouse" the *Canadarm2* can be mounted giving it enormous "reach" and allowing access to all critical components of the station.

Interestingly, the mobile platform moves along the truss at a top speed of only 1.5 m/min. (5.0 ft/min)[16]. In the seventy minutes it takes to move across the space station on the transporter the ISS completes over ¾ of a revolution around the earth.

Finally, this mobile platform was designed to carry equipment and is not normally used by astronauts. While undertaking EVA's, astronauts are supported by a special man powered handcart called the Crew and Equipment Translation Aid (CETA) or more colloquially as the CETA Cart. This device is fitted with receptacles or "pockets" to store tools and equipment such as foot restraints, handrails and safety tether attachment points.

[16] This is quite a space-age contradiction. In this example we have a space station moving over the earth's surface at an orbital speed of about 27,700 km/h (17,200 mph) yet the maximum speed of the mobile platform while traversing the ISS is a paltry 1.5 m/min (5.0 ft/min).



A photograph of the man powered CETA Cart with two astronauts on either side installing components to the truss structure. The CETA Cart, which can move back and forth on the truss structure, acts as an astronaut workstation. (Credit NASA)

Space Station Remote Manipulator System (SSRMS) – *Canadarm2*

Canadarm2 was a second-generation development of the original shuttle-based version and employed the same design principles. It was delivered to the ISS in July 2001 by the Shuttle *Endeavour* (STS-100). Because *Canadarm2* was to remain with the space station only a single arm would be developed and built. It was to have two missions. The first was to assist astronauts in building the space station by moving the modules located in the Orbiter's payload bay and attaching them to the appropriate location on the ISS. The fifteen countries that had earlier elected to participate in the space station construction also supplied modules and technologically sophisticated experiments.[17] The second mission of *Canadarm2* was to enable maintenance to be performed on all station modules and laboratories after the station was built.

Canadarm2 differed from the Shuttle-mounted version in several ways. (See Appendix B for comparisons). First, it was more robust in design. The weight of *Canadarm2* was substantially higher at 1,800 kg (3,970 lb) with an arm length of 17.6 m (57.7 ft). This length would be the maximum "reach" without the extension boom. Unlike the Shuttle-based *Canadarm*, the ISS version is equipped with "force moment sensors" mounted on the End Effector (hand) to provide

[17] Countries participating in the construction of the space station included: USA, Canada, Japan, Russia, Belgium, Denmark, France, Germany, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, and the United Kingdom,

it with a sense of touch. It could manipulate an object in space weighing 116,000 kg (256,000 lb). This was sufficient to capture, move and dock the Space Shuttle. Further, since it was to be mounted as a permanent component of the ISS, it was designed so it could be serviced and upgraded while on-orbit.

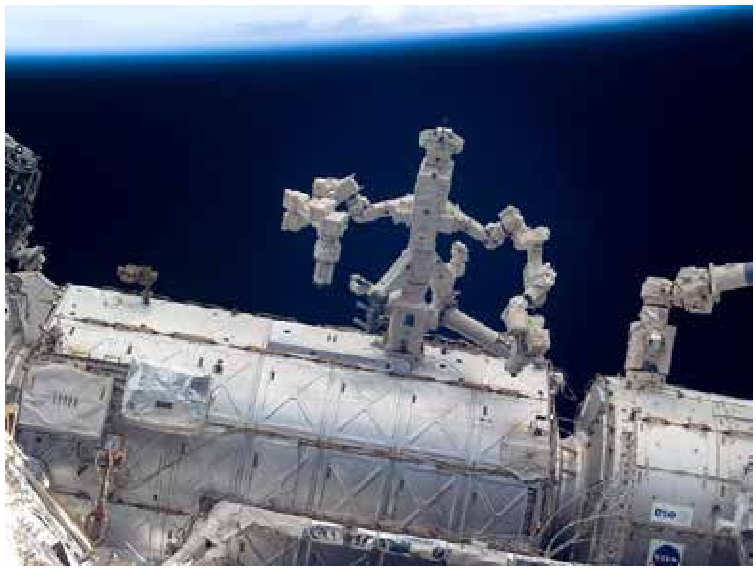
A photograph of Canadarm2 with an astronaut firmly held by foot restraints. Canadarm2 worked in harmony with the Canadian designed Dextre and the American Mobile Base System to attach and service modules to the ISS. (Credit NASA)

Another major difference between the two arms was that *Canadarm2* had seven rather than six degrees of freedom. It will be remembered from the earlier description of the Shuttle based *Canadarm* that the number of degrees of freedom is a complex way of saying that it was hinged in several ways. With *Canadarm2* the shoulder joint could not only move forward and back as well as up and down like human shoulder joints, but could also rotate, which our shoulders cannot do. This last motion was the seventh degree of freedom. In summary *Canadarm2* could move three ways at the shoulder, one at the elbow and three at the wrist – ergo seven degrees of freedom. This extra degree of freedom gave the second-generation arm more flexibility and allowed it to access most of the nooks and crannies of the space station.

When the space station was in the early stages of construction there was no truss structure or mobile platform available to move the *Canadarm2* from place to place. The arm was therefore designed to move around the space station on its own employing an end-over-end movement very much like an inchworm moves over the ground. This movement was under the control of the ISS crew. To accomplish this inch-worm-type movement, modified End Effectors were attached to both ends of the arm. To receive one (or the other) of these End Effectors, the space station was equipped with a number of Power Data Grapple Fixtures (PDGF's) and these fixtures provided power, data and video to the arm allowing it to be controlled from the ISS control station.

While this end-to-end method of movement was adequate while the space station was relatively small in size, as modules were added, and the station became larger, this approach had limitations[18]. For instance, while the *Canadarm2* was in the process of being moved from place to place, this sequential movement required the use of both End Effectors. Only when it arrived at an ISS Grapple Fixture near the intended work location could the other end be used to perform work.

Special Purpose Dexterous Manipulator (SPDM) - *Dextre*



Dextre is seen in this image performing installation work on the payload Destiny. Note Canadarm2 attached to an End Effector to the right. (Credit NASA)

Dextre, designed and built by MacDonald, Detwiller Robotics, is a robot that looks like a human but lacks a head. It was delivered to the space station in March 2008 (STS 123). It measures 3.6 m (12 ft) in height and is 2.3 m (7.7 ft) across the shoulders. *Dextre* weighs 1,662 kg (3,664 lb) and can handle a load of 604 kg (1323 lb). *Dextre* is normally attached to the end of *Canadarm2* but can also ride on the American built mobile transporter previously described. *Dextre* was designed to assist in the ongoing maintenance of the space station and performs tasks such as changing batteries, replacing cameras as well as other routine, but critically important chores. It can be operated directly by the astronauts within the space station or remotely by controllers located on the ground.

In a sense *Dextre* operates like a monkey with one arm hanging from a tree branch while using the other for doing something else. For instance, one of *Dextre's* robotic arms will hold on to certain installed fixtures while the other arm performs the work. This method of operation ensures the robot is held steady in a fixed position so the other arm can precisely locate the items to be serviced and maintained. The Canadian Space Agency is responsible for writing the software required for the robot to perform its work successfully.

In summary, while *Canadarm2* is the core of an integrated technology system, the added robotic additions allow *Canadarm2* to perform many more automated tasks. Taken as an overall system this modular robotic design all but eliminates the need for astronaut EVA's yet permits planned maintenance functions to be performed without the complexity and attendant risks.

[18] This limitation becomes more apparent when one considers the current size of the International Space Station. It spans109.0 m (357.5 ft) - as large as a football field including the overrun ends. It is 51 m (167.3 ft) wide and weighs (on earth) 419,450 kg (924,800 lb). The solar arrays are 72.9 m (239.4 ft) across.

Building The ISS - Employing the *Canadarm2* and Neptec Space Vision System (SVS)

Background and Challenges

The reader may recall a brief description of the Canadian Neptec Laser Camera System (LCS) mounted on the end of the boom assembly and used for the inspection of the orbiter's tiles. In order to artificially "see" the ISS module attach points when these modules were to be installed, an earlier generation was employed. This version was the Neptec Space Vision System (SVS). The necessity for this vision system is interesting and a brief description is outlined in the following paragraphs.

Photograph of the Neptec Laser and Camera System mounted on top of the Orbiter Boom Assembly (in turn mounted on the end of the Canadarm). (Credit NASA)

The environment of space is an incredibly difficult place to perform work. There are several reasons for this but one of the most important is that objects in space appear differently than they do on earth. This is caused by the lack of a background that we subconsciously use on earth to make assessments of another vehicles position and speed. Add to this the many problems of light and dark, along with troublesome shadows that occur as the station orbits the earth sixteen times a day, and it is not hard to imagine some of the difficulties.

In addition to these environmental difficulties there was a more practical problem that had to be overcome. Because of the few viewing ports on the space station (and the Shuttle/Orbiter) most of the assembly and early maintenance of the ISS had to be performed by cameras and range finders mounted on the end of the arm. Unfortunately, ordinary cameras are of limited use as they cannot display objects stereoscopically or, more simply, with the perception of depth. A two-dimension image is not good enough when moving modules of enormous mass that must be mated to the space station docking ports within the very close tolerances required. A three dimension stereoscopic image is, therefore, essential.

Development History

The basic elements of a three dimensional viewing system had been developed and patented by the National Research Council (NRC) in the 1970's - primarily to investigate what happens when cars are crashed into immovable objects such as cement barriers. The motion of the vehicle was tracked against a white and black background using high-speed cameras and computers. After considerable delay required for computers to process the image data, it was possible to calculate a three-dimensional picture that provided scientists information such as the vehicles' position, direction and speed at any given instant. However, this delay in image processing is unacceptable in a space environment – the images had to be displayed in real time to be of any use.

In 1990, the NRC research work was transferred to the Neptec Design Group located in Ottawa, Ontario who adapted it for use in space. This company built and delivered a Space Vision System in only fourteen months, which could provide control cues while operating the Canadarm from inside the Orbiter. It could create a three-dimensional measurement at distances of less than 10 m (33 ft) between objects. The computers could also make the necessary calculations in milliseconds. Neptec also produced a similar vision system called the Artificial Vision Unit that was installed on the ISS. These two systems mounted on two orbiting bodies were critical in guiding large spacecraft as they maneuvered to dock with each other.

Building The ISS – The Two *Canadarms* Working in Harmony

Introduction

The above describes some of the more important engineering technologies developed to facilitate construction of the International Space Station between 1998 and 2011. The station was constructed in a modular building-block manner and in the course of assembly many adjustments were made to the payload sequencing and content. For instance, as habitable modules and research laboratories were installed there was an increasing need for solar power, waste disposal and storage facilities etc. All of this required detailed planning as well as adjustments as unforeseen challenges emerged.

Some of the modules were not transported by the Space Shuttle, particularly the Russian components. These latter additions were lofted into orbit by Russian *Proton* rockets from the Baikonur Cosmodrome located in the desert steppe of Kazakhstan. However, it should be emphasized that most of the heavy lifting was performed by the American Shuttle/Orbiter, including modules and components built by contributing nations.

The now finished space station consists of habitable laboratories designed for research purposes, power supply arrays for electricity, all attached to, and monitored by, the previously mentioned truss structure spanning the length of the station. Each of these modular trusses was delivered in a predetermined sequence and attached employing the robots previously described as well as special tools expressly designed for the purpose.

The First Two International Space Station Modules

By way of background the International Space Station had its start in 1998 when the first two modules were mated – one American and one Russian. The mating of these modules occurred following the launch of the Space Shuttle *Endeavour* (STS-88) in December 1998. In this mission the *Unity* (USA) connecting node[19] was mated with the *Zarya* (Russian) control module that had

[19] The *Unity* was a connecting node enabling the attachment of other space station modules and was the first of three connecting nodes to be launched. The other two were named *Harmony* and *Tranquility*.

been launched from the Baikonur Cosmodrome, about two weeks earlier. This mating first required that the *Unity* node be removed from the payload bay of the Shuttle by the *Canadarm* and then temporarily attached to the Shuttle's payload bay restraint system. Following this procedure the *Canadarm* was then used to capture the *Zarya* control module from orbit and mate it to the *Unity* node. An early version of the Neptec Space Vision System was tested on this mission. Construction of the International Space Station had started!

Transportation Pallets and Pallet Trains

International Space Station payloads were transported to the ISS by attaching them to pallets that were, in turn, mounted in the Orbiter's payload bay. Of robust design they were 4.4 to 5.2 m (14.4 – 17.0 ft) wide and were fitted with multiple attach points. Pallet's weighed between 1130 – 1200 kg (2490 - 2645 lb) and could carry up to 1000 kg (6,720 lb) of payload. They were designed for about 50 orbital trips and could be used individually or in groups of 2-3, known as pallet trains. The Canada Aviation and Space Museum is currently in possession of a pallet carried aboard *Endeavour*. This pallet, which was used by other Shuttle spacecraft as well, spent about 45 days in space over a period of 22 years.

The Two *Canadarms* Working Together

Canadarm2 was delivered to the ISS on board the Shuttle *Endeavour* (STS-100) in April 2001. There would now be two versions operating; one mounted in the Shuttle and the other (to be) permanently installed on the ISS. This meant that *Canadarm2*, was carried as a payload on board the Shuttle. As a consequence it had to be removed from the payload bay and then installed on the station.

The unpacking and transfer of this ISS manipulator arm to the station employed a well-rehearsed and precise set of procedures, as this was a very complex operation. Following the docking of the Shuttle to the ISS[20], the Shuttles robotic arm extracted *Canadarm2's* pallet from the payload bay and maneuvered it toward the *Destiny* Lab module where the transportation pallet was attached to a special cradle. Two astronauts including Canadian Chris Hadfield, while conducting a space walk, unwrapped the *Canadarm2* from its insulating blankets, attached power to the arm and loosened its restraining bolts.

Later in the mission the two space walkers installed a Power Data Grapple Connector or "hand" to the end of the newly delivered arm and then attached this "hand" to the *Destiny* module. To ensure everything was operating correctly, the new *Canadarm2* was tested, by transferring its transportation pallet from the ISS back to the Shuttle's arm. This act of employing the two arms, one mounted in the Shuttle/Orbiter, the second on the space station in order to manipulate a single payload was euphemistically called the *Canadarm* Handshake. This simple explanation, of course, belies the complexity required in moving and docking large orbiting bodies in space.

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[20] After the Shuttle had launched and joined the space station in a coincident orbit, a highly precise procedure would be used to allow docking between the two orbiting bodies. The physical hard docking is done using a combined interface/airlock mounted in the forward part of the Shuttle's cargo bay. Following a series of computer-based checks to ensure all systems were performing correctly the airlock is pressurized and the individual crews are then capable of moving from one vehicle to the other.

An image showing the "Canadarm Handshake". In this photograph the ISS based Canadarm2 is transferring the pallet on which it was transported to the ISS back to the Shuttle's Canadarm for its return journey to earth. (Credit NASA)

Space Station Assembly Sequence

Introduction

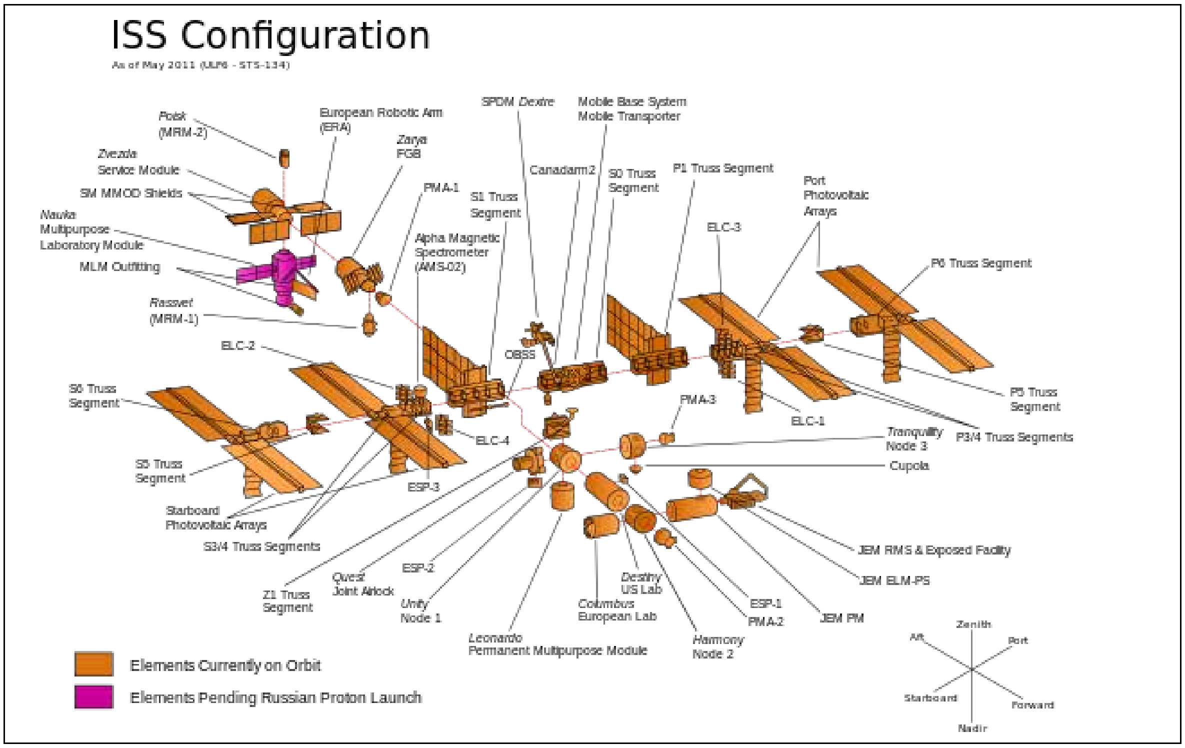
The inherent complexity associated with the overall planning, delivery and installation of the modules that make up the International Space Station, and the unqualified success of the final result, deserve to be acknowledged as one of the greatest engineering feats of mankind. And it was the Canadian designed and built robots that were the main tools that built the station. It was assembled between 1998 and was completed with the last shuttle mission in 2011. The listing below reflects only those missions that directly supported the building of the station. There were several additional missions but these were of a logistic, crew change or resupply nature. A summary of the ISS construction missions is attached at Appendix C.

The following assembly missions are formatted first by the year in which the modules were delivered, the NASA mission designation, the delivery vehicle and a brief description of the components that were lofted into orbit on each mission.

1998 Deliveries

Zarya (Russian Proton Rocket)
This module was the first station module and was launched into orbit by a Russian *Proton* rocket. It was built under contract for NASA and provides power, communications and attitude control. It is now (circa 2014) used for storage and propulsion.

The *Zarya* Module was 12.5 m (41.2 ft) long and 4.0 m (13.5) feet wide at its widest point. Its solar arrays and six nickel-cadmium batteries can provide an average of three kilowatts of electrical power. Its side docking ports accommodate Russian *Soyuz* spacecraft and unpiloted *Progress* resupply spacecraft. Each of the two solar arrays is 10.6 m (35 ft) long and 3.4 m (11.2 ft) wide. The module's 16 fuel tanks combined can hold more than six tons of propellant. The attitude control system for the module includes 24 large steering jets and 12 small steering jets. Before *Zvezda* arrived at the ISS two large engines were available for re-boosting the spacecraft to higher orbits[21].



A schematic of the ISS. The truss structure consists of 10 separate modules and is the backbone of the station. In this schematic it runs from left to right. The habitable modules and research laboratories run 90 degrees to this structure. (Credit NASA)

Node 1 - Unity (STS-88)

This was the first of three US built nodes to arrive at the station. A node is a docking facility permitting the attachment of additional modules. Nodes also provide other functions such as compartments for stowage, sleeping or hygiene. The *Unity* Node contains more than 50,000 mechanical items, 216 lines to carry fluids and gases, and 121 internal and external electrical cables using 10 km (6 mi) of wire. It is 5.5 m (18 ft) long, 4.3 m (14 ft) wide and weighs 11,900 kg (26,230 lb). On 6 Dec 1998, the STS-88 crew captured *Zarya* and mated it with the *Unity* Node on a pallet located inside the Shuttle's payload bay.

[21] The International Space Station loses about 30 m (100 ft) of altitude each day. This is due to friction caused by residual particles from the earth's atmosphere. This friction is aggravated by cyclical solar flares in which the daily loss of altitude is increased. The deterioration of the ISS orbit is solved by periodically using devices such as the *Jules Verne* ATV to accelerate the space station into a higher orbit. The Shuttle, while it was in service, was also used for this purpose.

2000 Deliveries

Zvezda (Russian Proton Rocket)
The first Russian module provides living quarters, an exercise system, a galley and life-support systems.

Z1 Truss (STS-92)
This was the first truss module of the enormous truss assembly to be built, section-by-section, on future missions. The Z1 Truss included solar arrays, radiator panels as well as four gyroscopes to maintain the station in the correct position and attitude while in orbit. The completed truss system is the backbone of the entire space station and all ISS systems are connected to it either directly or indirectly.

P6 Truss (STS-97)
This first solar array was attached to the first truss section. It generates power for the station and its radiator panels help maintain the station's temperature. It was moved to another location on a later mission.

2001 Deliveries

Destiny Laboratory (STS-98)
Destiny is the primary research laboratory on the space station and acts as the command center for all scientific research. It also controls all space station systems. It is 8.4 m (28 ft) long, 4.2 m (14 ft) in diameter and weighs 14,515 kg (32,000 lb).

External Stowage Platform (ESP) (STS-102)
This module holds spare parts and is attached to the *Destiny* Laboratory. The contents are heated by electricity from the station to protect them from the extremes of heat and cold.

Canadarm2 (STS-100)
Canadarm2 is similar to the Space Shuttle version and can reach nearly all points of the space station employing grapple fixtures previously described. With completion of the truss assembly it can also ride back and forth on rails to repair and maintain almost all components of the station

Quest Joint Airlock (STS-104)
This is a pressurized airlock that serves as an exit and entrance area for spacewalks. The astronaut space suits are housed in the airlock.

Pirs - Russian Docking Compartment and Airlock (Soyuz)
The Russian version of the American airlock noted above. It can also be used to dock the Russian *Soyuz* and *Progress* spacecraft.

2002 Deliveries

S0 Truss (STS-110)
This truss is the center section of the major truss structure.
The front of the truss has rails that allow the *Canadarm2* to travel along the structure for construction and maintenance purposes.

Mobile Remote Services Base System (MRSBS) (STS-111).
The working platform for *Canadarm2*.

Starboard1 Truss (STS 112)
An expansion truss that also includes radiator panels to moderate extreme temperature variations. It is mounted on the starboard (right) side of the S1 Truss.

Port1 Truss (STS-113)
The same as the foregoing truss except it's mounted on the port side.

2005 Deliveries

External Stowage Platform (ESP 2) (STS-114)
The second of two external stowage platforms.

2006 Deliveries

Port 3 and Port 4 Trusses (STS-115)
An expansion of the truss system configured with a rotator joint allowing the solar arrays to rotate and face the sun during orbit of the station.

Port 5 Truss (STS-116)
This is a small truss segment that spaces out the distance between the Port 3 and Port 4 solar arrays trusses.

2007 Deliveries

Starboard 3 and Starboard 4 Trusses (STS-117)
These trusses expanded the integrated truss structure on the starboard side. The truss has a rotator joint to allow solar arrays to maintain position relative to the sun.

S5 Truss (STS-118)
A spacer truss to extend the distance between previously mounted trusses and their solar arrays.

Harmony Node (STS 120)
This node is the anchor piece for the attachment of the European and Japanese laboratories.

2008 Deliveries

Columbus Space Lab (STS-122)
This was the first international laboratory. Experiments can be conducted in both the pressurized laboratory or outside the module in zero gravity.

Canadian Dextre (STS123)
The Canadian designed and built robot for ongoing space station maintenance.

Kibo (STS-123, STS-124, and STS-127)

The largest of the labs, it is made up of four major components. Experiments to be conducted include those of space medicine, biology and communications. Attached is a small robotic arm enabling laboratory work to be performed on a large platform located outside the module.

2009 Deliveries

S6 Truss (STS-119)
The last truss component installed. It is capable of generating 110 kilowatts of electricity. The solar panel assemblies work in unison so arrays always face the sun.

Kibo - Exposed Platform (STS-123, STS-124 and STS-127)
A platform for the previously installed *Kibo*.

Poisk (Russian Proton Rocket)
A module for cargo storage; it can also be used as a spacecraft docking port.

Express Logistics Carriers (STS-129)
Externally mounted platforms for handling scientific experiments. They provide for storage, power connections as well as command and data operations for associated experiments.

2010 Deliveries

Tranquility Node (STS-130)
The last of three connecting nodes - it is named after the Apollo 11 lunar landing site in 1969.

Rassvet Mini Research Module-1 (STS-132)
A Russian cargo module used as a docking port for spacecraft; it can also be used for cargo storage.

2011 Deliveries

Raffaello Multi-Purpose Logistics Module (STS-134)
Built by the Italian Space Agency it is a 4,100 kg (9,000 lb) re-supply module used extensively to bring supplies to the space station and return waste products to earth. The last module is permanently attached to the space station.

The Alpha Magnetic Spectrometer (STS-134)
A scientific device designed to look for dark matter and cosmic rays. In addition to *Raffaello* noted above this payload was on the last Shuttle flight to the space station.

Additional Support Vehicles

Three support vehicles were also employed: *Soyuz, Progress* and *Jules Verne.* They are described briefly below.

> *Soyuz:*
> A manned Russian spacecraft used since the mid-1960's. With the retirement of the Space Shuttle, *Soyuz* is the only spacecraft capable of transferring crewmembers from Earth to the ISS and from the ISS back to Earth.

Progress:

An unmanned Russian spacecraft employed since the late 1970's and considered the workhorse of the Russian space program. It is used for resupplying the station with cargo.

Jules Verne:

This spacecraft is a very large 19,400 kg (42,700 lb) French built Automated Transfer Vehicle (ATV). It can move supplies, including water and propellant, to the ISS and can remain for six months. It can also autonomously dock to the space station without assistance of either of the *Canadarms*. The *Jules Verne* can also be used to raise the orbit of the space station. After use it was designed to burn up on re-entry.

Legacy of Canadian Space Engineering

This monograph would be incomplete if it did not acknowledge the significant benefits that accrued to Canadian research, science and engineering by the design and building of the Spar Aerospace *Canadarm, Canadarm2* and DMA developed *Dextre* robots. The export-oriented industrial returns achieved through the development of these systems led to the manufacturing and sale of simulators for Japan and Europe, as well as the sale of robotic systems for the nuclear industry. These success stories established Canada as a world leader in the high-technology fields of advanced robotics.

Also critical to the construction of the International Space Station was the Space Vision System developed by Neptec. This development allowed the Canadarms to mate large space station modules with total precision. Neptec vision systems are currently (2015) used to automate mining operations, to inspect and control sub-sea oil and gas infrastructure and to safely land helicopters in brown out conditions often experienced in desert areas.

Appendix A

The *Canadarm* Technical Specifications

Arm	
Length	15.2 m (50 ft)
Mass	363.0 kg (800 lb)
Maximum Force	6.8 kg (15 lb)
Limits of Motion	
Shoulder Pitch	-145 to +2 degrees
Shoulder Yaw	-180 to +180 degrees
Elbow Pitch	-2 to +160 degrees
Wrist Pitch	-120 to +120 degrees
Wrist Yaw	-120 to +120 degrees
Positioning Accuracy	
Tip Position, Manual Mode	within - 3.8 cm (1.5 in)
Tip Position, Automatic Mode	within - 5.0 cm (2.0 in)
Tip Attitude	within - 5.0 degrees
Maneuvering Speed	
Maximum Load	3 cm/sec (0.1 ft/sec)
Unloaded	60 cm/sec (2.0 ft/sec)
Maximum Payload Size	
Length	18.3 m (60 ft)
Diameter	4.6 m (15 ft)
Mass	29,483 kg (65,000 lb)
Lifetime	
Missions	100
Years	10

Appendix B

Canadarm (Shuttle) and *Canadarm2* (ISS) Comparisons

Technical	***Canadarm*** **(Shuttle Based)**	***Canadarm2*** **(ISS Based)**
Mission Profile:	Returns to Earth.	Permanently on ISS.
Range of Motion:	Reach limited to arm length.	Moves end-over-end in an inch-worm type movement; limited in range only by the number of Power Data Grapple Connectors mounted on the ISS. It can also travel on the Mobile Base System (MBS)
Fixed Joint:	Fixed to Shuttle at one end.	No fixed end.
Degrees of Freedom:	Six	Seven
Joint Rotation:	Elbow limited to 160 degrees.	Full joint rotation, more motion than a human arm.
Senses:	No sense of touch	Full sense of touch Stereoscopic vision Automatic collision avoidance
Length:	15 m (49.2 ft)	17.6 m (57.7 ft)
Weight:	410 kg (905 lb)	1,800 kg (3,970 lb)
Diameter:	33 cm (13 in)	35 cm (13.8 in)
Mass Handling Limit:	29,484 kg (65,000 lb)	116,000 kg (255,700 lb)
Speed of Operation		
Unloaded:	60 cm/sec (1.97 ft/sec)	37 cm/sec (1.21 ft/sec)
Loaded:	60 cm/sec (2.36 in/sec)	0.79 in/sec (0.79 in/sec)
Composition:	16 plies carbon fiber epoxy	19 plies of carbon high strength carbon fiber-thermoplastic.
Repairs:	Repaired on Earth	Repairs in space by Orbital Replacement Units (ORU's)
Control:	Autonomous or by crew	Autonomous or by crew
Cameras:	2 (one each on elbow and wrist)	4 color cameras (one on each side of the elbow, the other two on Latching End Effectors.

Appendix C

Major American and Russian Space Station Sequencing (Larger Modules)

Major Elements	Vehicle	Date	Mass (Kg)
Zarya:	*Proton* K	Nov, 1998	19,323
Unity (Node 1) PMA 1/2:	*Endeavour* (STS-88)	Dec, 1998	11,612
Zvezda Service Module:	*Proton*-K	Jul, 2000	19,051
Z1Truss and PMA-3:	*Discover* (STS-92)	Oct, 2000	8,755 (Z1)
P6 Truss and Solar Arrays:	*Endeavour* (STS-97)	Nov, 2000	15,824
Destiny US Laboratory:	*Atlantis* (STS-98)	Feb, 2001	14,515
External Stowage Platform:	*Discovery* (STS-102)	Mar, 2001	12,700
Canadarm2 (SSRMS):	*Endeavour* (STS-100)	Apr, 2001	4,899
Quest (Joint Airlock/Dock):	*Atlantis* (STS-104)	Jul, 2001	6,064
Pirs (Docking Compt):	*Soyuz*-U	Sep, 2001	3,580
S0 Truss:	*Atlantis* (STS-110)	Apr, 2001	13,970
Mobile Base System:	*Endeavour* (STS 111)	Jun, 2002	1,450
S1 Truss:	*Atlantis* (STS-112)	Oct, 2002	14,120
P1 Truss:	*Endeavour* (STS-113)	Nov, 2002	14,000
ESP-2:	*Discovery* (STS-114)	Jul, 2005	2,676
P3/P4 Truss/Solar Arrays:	*Atlantis* (STS-115)	Sep, 2006	15,900
P5 Truss:	*Discovery* (STS-116)	Dec, 2006	1,818
S3/S4 Truss/Solar Arrays:	*Atlantis* (STS-117)	Jun, 2007	15,900
S5 Truss and ESP-3;	*Endeavour* (STS-118)	Aug, 2007	12,598
Harmony (Node 2):	*Discovery* (STS-120)	Oct, 2007	14,288
Columbus (European Lab):	*Atlantis* (STS-122)	Feb, 2008	12,800
Dextre and ELM-PS:	*Endeavour* (STS-123)	Mar, 2008	4,200 (ELM)
JEM-PM and JEM-RMS	*Discovery* (STS-124)	May, 2008	15,900
S6 Truss/Solar Arrays:	*Discovery* (STS-119)	Mar, 2009	15,900
JEM-EF:	*Endeavour* (STS-127)	Jul, 2009	4,100
Poisk:	*Soyuz*-U (M-M1/M2)	Nov, 2009	3,670
EXP Logistics 1 and 2	*Atlantis* (STS-129)	Nov, 2009	16,027
Cupola and *Tranquility*:	*Endeavour* (STS-130)	Feb, 2010	14,047
Rassvet (MRM-1) :	*Atlantis* (STS-132)	May, 2010	5,075
Leonardo:	*Discovery* (STS-133)	Feb, 2011	9,896
Alpha-Mag-Spec:	*Endeavour* (STS-134)	May, 2011	6,731

ISS Flight Summary

American;	26 Construction flights
	9 Crew change/logistics flights
Russian:	2 *Proton* flights
	25 *Soyuz* Crew flights
	2 *Soyuz* assembly flights
	41 *Progress* resupply flights
European:	2 Automated Transfer Vehicle (ATV) flights
Japanese:	2 H II Transfer Vehicle flights

Space Walks

Shuttle Based:	28 spacewalks
ISS-Based:	127 spacewalks
Total Time:	More than 973 hrs.

Bibliography[22]

The Shuttle Remote Manipulator System (SRMS) – The Canadarm.

1. Dotto, Lydia (1992). "*A Heritage of Excellence: 25 years at Spar Aerospace Limited*" (in English). David Steel. Canada: Spar Aerospace Limited. pp. 41–42. ISBN 0-9696618-0-0. "[Frank] Mee is the inventor of the Canadarm hand, technically known as the "end effector"."
2. Wilks, Brian (2004). "Browsing Science Research at the Federal Level in Canada: History, Research Activities and Publications". University of Toronto Press. p. 117. Retrieved 22 November 2013.
3. Garry Lindberg. "Canadarm and its U of A Connections". *U of A Engineer Magazine* (University of Alberta). Retrieved 7 December 2011.
4. "The Shuttle Remote Manipulator System -- The Canadarm". IEEE Canada. Retrieved 22 November 2013.
5. "Flight History of Canadarm". Canada Space Agency. 28 October 2011. Retrieved 27 October 2012.
6. Justin Ray (5 January 2011). "Vandenberg's space shuttle hangar". *Space Flight Now*. Retrieved 27 October 2012.
7. Chris Gebhardt (17 November 2010). "Discovery's retirement plans provide insight into the fate of the robotic arm". NASA. Retrieved 27 October 2012.
8. Roland Kiehne (27 July 2012). "Letter: Canadarm should be easy to visit". *The Montreal Gazette*. Retrieved 27 October 2012.
9. Andy Johnson (2 May 2013). "Unveiling exhibit, Hadfield sends first Canadarm 'last command' from space". *CTV News*. Retrieved 2 May 2013.
10. Elizabeth Howell (2 May 2013). "Space Shuttle's Robotic Arm Goes on Display at Canadian Museum". *Space.com*. Retrieved 2 May 2013.
11. Canadian Space Agency (2 May 2013). "Minister Moore Unveils Exhibit for Canada's National Space Icon: the Canadarm". *Canadian Space Agency*. Retrieved 1 July 2013.
12. "Canadarm on display: Space shuttle robot arm unveiled at Canadian museum". 2 May 2013.
13. Canadarm – The SRMS Technical Details (http://www.ieee.ca/millenium/canadarm/canadarm_technical.html)

The Inspection Boom (Orbiter Boom Sensor System (OBSS))

1. NASA: Shuttle in Shipshape; Part II (http://www.nasa.gov/returntoflight/system/rtfupgrades_partII.html)
2. CSA: Inspection Boom by MDA: One of critical Canadian tools that serves the return to flight (http://www.space.gc.ca/eng/missions/sts-114mda.asp)
3. "STS-134-Endeavour" (http://plancast.com/p/3zh7/sts-134---endeavour)
4. NASA approve funding to leave OBSS permanently on the ISS" (http://www.nasaspaceflight.com/2009/01/nasa-approve-leave-obss-permanently -on-iss) January 27,2009. Retrieved 2009-02-15.

The Laser Camera System

1. Canadian Space Agency – The Inspection Boom and the Laser Camera System (http://www.asc-csa.gc/eng/canadarm/mdaneptec.asp)

The Hubble Space Telescope

1. The Hubble Program – Servicing Missions- SM1 (http://asd.gsfc.nasa.gov/archive/hubble/missions/sm1.html)

Advanced Space Vision System (ASVS)

1. NRCC (2008) "Space Vision System Helps Astronauts See in Space" (http://www.nrc-cnrc.gc.ca/eng/innovations/discoveries/svs.html. National Research Council of Canada. Retrieved February 13,2008.
2. Neptec (2007). "Neptec's Space Vision System (SVS)" (http://www.neptec.com/Neptec_SVS.html). Neptec
3. CSA (1997) "Advanced Space Vision System (ASVS)" http://www.space.gc.ca/asc/eng/missions/sts-074/asvs.asp). Canadian Space Agency. Retrieved February 13, 2008.
4. Shuttlepresskit.com (1988). Orbiter Space Vision System testing" (http://www.shuttlepresskit.com/sts-95/dto8.htm). NASA – Boeing – United Space Aliance. Retrieved February 13, 2008.

Integrated Truss Structure

1. William Harwood (14 October 2000). "Truss structure to be added to space station today" (http://www.spaceflightnow.com/shuttle/sts092/001014z1truss/) Spaceflight Now. Retrieved 7 Jan, 2014
2. "International Space Station Status Briefing, June 13, 2005" (HTTP://www..nasa.gov/missiom_pages/station/news/iss_status_briefing_061305.html)

[22] With minor exceptions the chronology of the above bibliographical references follows the sequencing of the narrative rather than alphabetically.

3. “International Space Station Status Briefing, June 13,2005 – Commander with packed Z1” (http://www.nasa.gov/images/content/118030maisn_hassman_iss_briefing3_med.jpg).
4. “NASA STS-92 Press Kit” (http://www..jsc.nasa.gov/history/shuttle_pk/pk/Flight_100_STS-092_Press_Kit.pdf) (Press release). 2002-06-02.
5. W illiam Harwood (14 October 2000). "Truss structure to be added to space station today". Spaceflight Now. Retrieved 7 Jan, 2014.
6. "Active and Passive with latches and bolts". "ISS Interface Mechanisms and their Heritage". 2011-01-01. 20110010964.
7. "High-Tech VASIMR Engine Could Power Superfast Journeys to Mars".
8. "Ask The Mission Team - Question and Answer Session". NASA. Retrieved 7 Jan, 2014.
9. "STS-115 Press kit" (PDF). Retrieved September 20, 2006.
10. "Spread Your Wings, It is Time to Fly". NASA. July 26, 2006. Retrieved 7 Jan, 2014.
11. Chris Bergin (November 28, 2007). "STS-122 spacewalkers gain extra protection". NASA SpaceFlight.com. Retrieved 7 Jan, 2014.
12. William Harwood, "New solar array drive motor successfully tested, January 30, 2008, *Spaceflight Now.* Retrieved 7 Jan, 2014.

Canadarm2

1. Canadian Space Agency – Meet Canadarm2 (http://www.asc-csa.gc.ca/eng/iss/canadarm2/nuts_bolts.asp)
2. Canadian Space Agency - An Evolution in Design for Canada’s Robotic Arms (http://www.asc-csa.gc.ca/eng/iss/canadarm2/evolution.asp)
3. Canadian Space Agency – Canadarm and Canadarm2 – Comparitive Table (http://www.asc-csa.gc.ca/eng/iss/canadarm2/cl-c2.asp)
4. Canadian Space Agency – A Legacy of Success (http://www.asc-csa.gc.ca/eng/iss/canadarm2/success.asp)
5. Canadian Space Agency – The First Steps (http://www.asc-csa.gc.ca/emg/iss/canadarm2/first_steps.asp)
6. Canadian Space Agency – Canadarm2’s Cosmic Catches (http://www.asc-csa.gc.ca/eng/iss/canadarm2-grapples.asp)

Mobile Servicing System

1. Mobile Base System Backgrounder (http://www.asc-csa.gc.ca/eng/iss/mobile-base/backgrounder.asp)
2. "The Slowest and Fastest Train in the Universe". (http://www.nasa.gov/missions/shuttle/f_slowtrain.html). NASA.
3. "CSA - STS-111 - Mobile Base System - MBS Design". (http://www.space.gc.ca/eng/missions/sts-111/mobile_design_component.asp) Canadian Space Agency. Retrieved 2008-03-15
4. "CSA - STS-111 - Mobile Base System - Backgrounder". (http://www.space.gc.ca/eng/missions/sts-111/mobile_backgrounder.asp) Canadian Space Agency. Retrieved 2008-03-15.ISS.
5. ISS Assembly:Canadarm2 and the Mobile Servicing System (http://spaceflight.nasa.gov/station/assembly/elements/mss/index.html).
6. Canadian Space Agency information about Canadarm2 (http://www.space.gc.ca/eng/iss/canadarm2/default.asp)

Flight History of Canadarm

1. Canadian Space Agency (http://www.asc-csa.gc.ca/eng/canadarm/flight.asp)
2. Canadarm on Display (http://www.collectspace.com/news/news-050213a.html)

Shuttle Tiles

1. Shuttle Tiles – How Things Work – Air & Space Magazine (http://www.airspacemag.com/how-things-work/shuttle_tiles.html)

Mission and Technology Reporting

1. Additional Shuttle/Orbiter mission information was provided to the author by Mr. William Upton a prominent Canada Aviation and Space Museum researcher. These contributions took the form of personal audiotapes recorded from live telecasts and media news reports broadcast at the time of the event.
2. The author was privileged to interview Mr. Paul Nephin, CEO Neptec at his office located in Ottawa. As earlier noted, Neptec developed both the Space Vision System (SVS) and the Laser Camera System (LCS). These systems were central to the building of the International Space Station as well as allowing on-orbit inspection of the Shuttle/Orbiter’s tiles until it’s retirement in 2011.