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A CONCEPT STUDY INTO A POST ISS ARCHITECTURE

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The study examined a potential architecture to sustain a human presence in low earth orbit after the decommissioning of the International Space Station (ISS). The objective was to provide an initial capability that would be equivalent to the ISS, with lower cost and increased flexibility for expansion in size and location. The architecture selected was multiple small PIA (Post ISS Architecture) stations, each around 50 tonnes in mass and a crew of three or four. Four PIA stations roughly match the ISS capability in terms of rack space, available power and other key parameters. Infrastructure expansion beyond this can either be achieved by building more stations or by adding specialist modules to the free berthing port on the stations already in service. The PIA station would be developed by an international partnership, then each partner would take ownership of one or more of the stations in the overall architecture. A concept design for the PIA station is described to demonstrate the viability of approach. The design highlights the extensive use of the ISS legacy to minimise the impact of transition between the two regimes. The study was also used as a validation exercise for the Universal Space Interface Standard (USIS) requirements. A cost analysis was conducted looking at various partner scenarios. It showed negligible exchange of funds between partners is possible, with each partner getting the advantages of international cooperation in shared development, while also enjoying the benefits of an independent operational capability.

Keywords: ISS, PIA, USIS, space infrastructure, space stations

1. INTRODUCTION

The International Space Station (ISS) is one of mankind's most impressive technical achievements. Building on the extensive Russian experience with the Salyut and Mir stations and the American Space Shuttle; it has been permanently occupied since 2000 and current planning takes its operations to 2024, which would mean a lifetime of over a quarter of a century, and, while it is possible that it will remain operation after that date, it is clear that the development of any successor should be initiated urgently if it is to be ready in time to replace the ISS without any break in capability.

The Post ISS Architecture (PIA) study was a private initiative to explore a potential approach to an in-orbit human infrastructure for beyond 2020. It was intended as a contribution to the debate on how best to replace the ISS by highlighting the advantages of an infrastructure composed of many small stations over an infrastructure composed of a single monolith station like the ISS. It was also undertaken as an exercise to explore the use of the Universal Space Interface Standard (USIS) in a space station architecture as part of the standard's requirement validation and to illustrate its potential [1].

2. PIA REQUIREMENTS

2.1 Political Requirements

The study defined PIA's purpose as being; to provide a public in orbit research capability that at least matches that of the ISS. The extensive utilisation of the ISS shows that there is a need for such a capability in science and engineering research regardless of the ISS other values as a flagship project, an inspiration to humanity and a focus for international cooperation and hence better international relations. A loss of this research capability is likely to be viewed as politically damaging by all of the partners even if a follow on infrastructure does not need to provide the same degree of public inspiration and outreach. However, given that it is envisaged PIA would be publically funded and the past heavy public investment in the ISS that precedes it, it follows that there will be a political need to show considerable legacy value from the ISS and for a smooth (and this now means fast) transition from ISS to PIA. Thus there is a political balancing act between the need to for PIA to maintain the capability and to demonstrate progress, while acknowledging that the lack of outreach and "flags and footprints" prestige factors means this must be achieved with a far more modest programme.

The reduced scale of future US government involvement in any activity after the ISS was suggested in an article in Aviation Week reporting of the fourth ISS R&D conference [2]. It suggested that from the US point of view, even a privately owned station run commercially may be the next step. Whether or not this extreme is practical, or desired, by other ISS partners it does show that the requirement for the PIA will be for a system that is matched to the needs and objectives of a research programme alone.

One of the key political achievements of the ISS has been the creation of a wide ranging international partnership to develop and operate the station leading to a sharing of costs, experience and science results. The study assumed a key political requirement would be to retain this international element of the ISS programme in any successor to maintain both the political and practical advantages already demonstrated. However it should also be recognised that when it comes to operations

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most partners would prefer to have their own sovereign facility, a situation that would also greatly reduce the administrative costs and scheduling problems. Thus there are two apparently contradictory requirements to both have a programme which is an international collaborative effort and to have independent capability solely under national rather than international control.

2.2 Financial Requirements

PIA was assumed to be a publically funded programme like the ISS, rather than a commercial enterprise. This follows from the political requirements, but, as already, highlighted the consequence will be a far reduced budget and any ISS follow on cannot expect anything like the acquisition budget of the ISS.

It was assumed by the study that political and technical requirements must be achieved with an acquisition budgetary impact for each of the partners in line with a large science project such as Cassini-Huygens, Galileo, Hubble or Envisat, that is around €3 billion. At this level of funding the programme can be justified on its science research value alone without the need for any less tangible justifications.

Another key financial requirement was that partner spending in their own economic area should be maximised and if possible there should no exchange of funds between them. This has to a large extent been achieved on the ISS programme, and any successor programme would need to continue this approach.

2.3 Technical Requirements

Given the political requirement is solely for an architecture that can be justified on its science and engineering research, the key technical requirement is to provide facilities that at least match the current ISS and if possible improve upon them.

This went beyond simply supplying a similar a comparable overall mass and volume for payloads. It meant that the detailed customer interfaces such the ISS Standard Payload Racks (ISPR), utility and service supplies would need to match those on the ISS, so that, if required, payloads could be directly interchanged between the old ISS and the new PIA.

The new architecture would also require a greater degree of expandability with the capability to adjust its overall provisions as the demand for its services expanded. It could reasonably be expected to supply the primary crewed orbital research capability for at least two decades, but in that time significant changes could occur in the launch infrastructure, in commercial space operations, or in the focus of research, any of which could generate new demands especially on the size of the infrastructure which PIA should be able to respond to effectively and quickly.

Another new factor that could be expected while the PIA is operational will be a return to human spaceflight beyond Low Earth Orbit (LEO). Studies are already underway with in NASA for a station at the L1 Lagrange point using hardware developed for the ISS [3]. The study considered it a requirement that the PIA infrastructure could be extended beyond LEO.

The factors to be considered when designing a space station for both LEO and environments further away from earth such as geostationary Lagrange points and lunar orbit have been considered elsewhere [4]. This work concluded that the communications and navigation systems design solutions are more constrained in order to meet both applications. Also that the radiation shielding required (enough to create a solar storm shelter for the crew) is more than required for LEO and conversely the impact protection required for LEO is higher than needed for high earth orbit environments. These conclusions were incorporated into the PIA study requirements. So that the architecture could extend the provision of permanent habitation facilities to support the programme expansion of human spaceflight.

3. ARCHITECTURAL APPROACH

3.1 Proposed Architecture and Organisation

The approach explored by the PIA study was the use of several small stations which together provide the overall capability required. The study produced a feasibility design (Fig. 1) which required three launches to produce an operating station centring on a laboratory module with twenty ISPR. Four or five of these fifty tonne stations can provide an experimental provision that is comparable to the ISS.

The three launches could either deliver the module payloads to the ISS for construction while attached to it or to an open space location. In the case of open space assembly once the core module was launched a crew flight would be required before the next module flight as the in orbit assembly required a crew presence to operate the manipulator.

Each of the three launches comprised a Utility Module (which was identical for each launch) and a specialist module starting with a Core Module followed by a module which provided habitation, EVA facilities and external experiment platforms and finally a laboratory module. Thus overall there are four module developments required, and each station comprises three Utility Modules, a Core Module, a Hab. Module and a Lab. Module.

3.2 Small Station Architectures

The general advantages of the approach of using small multiple station in-orbit infrastructures to provide an overall capability have been discussed in References 5 and 6. The approach has been shown to provide a potentially viable low cost route to acquiring in-orbit capability. In general the advantages of the approach can be summarised as:

- the development cost drop because the stations are smaller and less complex,
- the hardware purchase costs drop as the production runs are larger,
- there is a faster acquisition of an initial operational capability,
- growth of the overall infrastructure capability is far easier and cheaper,
- if correctly designed stations can be easily added in high earth and lunar orbits,
- specialist stations can provide better environment for some activities,
- the infrastructure has greater overall resilience.

The main disadvantage of the approach was an increased requirement for support launches during operations. So whether such architectures would be the best overall approach in any particular circumstances depends upon the cost and availability of the operational support launches.

Fig. 1 PIA Station Concept Design.

In the context of a post ISS architecture, a multiple space station architecture can exploit the investment made by the USA in commercial space station support systems. The COTS (Commercial Orbital Transportation Services) and CCDev (Commercial Crew Development) programmes will have led to the development of at least two cargo systems (Dragon and Cygnus) and maybe three crew delivery systems (Dragon 2, CST-100, Dream Chaser). A multiple station architecture creates a market for all these systems some four times that of a single station architecture. Thus the proposed PIA infrastructure would be a way to nurture the nascent human spaceflight support industry the ISS has created.

In addition to the US commercial systems the ISS legacy includes proven support capability from the Russian Soyuz and Progress systems and the Japanese HTV all of which once fitted with the USIS interface could support PIA stations. Indeed the HTV has a unique feature being the only system that can carry the ISPR units which have been used in the PIA concept design.

The increased market a PIA architecture creates and the ISS legacy of support services should keep the support costs viable in the context of annual operations budgets of a few hundred million euros per station per year.

In addition to the general advantages of small multiple station architectures there are some specific advantages to the approach when considered as an ISS replacement.

The first obvious advantage to the PIA approach was that with many stations, ownership and operations do not have to be shared as each partner in the development project could own one of the resulting stations from the production run. This partnership model has been employed on several advanced military aircraft, such as Eurofighter Typhoon, where a multinational consortium developed the aircraft then bought the resulting product for their national air forces.

The nominal organisational arrangement assumed by the study was for four main international partners each to develop one of the modules and then manufacturer sufficient modules for the construction of four stations which have roughly equal value. Then each partner launches and operates one of those four stations independently. Secondary partners who contribute to the programme would be given time and space on one or more of these stations in the similar way as on the ISS programme, but as an arrangement with one of the station owning partners rather than the whole partnership.

This fundamental approach of shared development and independent ownership could work with other arrangements. The study considered a three partners/four stations scenario with one of the partners requiring two stations and a four partners/five stations scenario with the fifth station being a shared international facility, for example maybe in lunar orbit.

3.3 Manned Orbital Facility (MOF)

In many respect the PIA architecture examined here is following the lead of a 1975 study into a Manned Orbital Facility (MOF) run by NASA Marshall Spaceflight Centre supported by McDonnell Douglas (Fig. 2). A publically available User's Guide [7] was produced which detailed its design, features and capabilities. The concept was also reported by Parker [8].

Both the PIA and MOF concepts are small modular stations, around 50 tonnes with power of around 12-14 kW and a crew of four people. Both studies have assumed an architecture of several stations for specialist functions and both also allowed for growth of the core station to larger facilities. As such it makes an interesting point of comparison.

The MOF consisted of a core consisting of a Subsystem Module and a Habitability Module attached to each other and launched together on a single Shuttle flight, which in reality would probably not have been possible given the real payload capability of the Space Shuttle when it entered service. A second launch would deliver a Logistics Module and the Payload

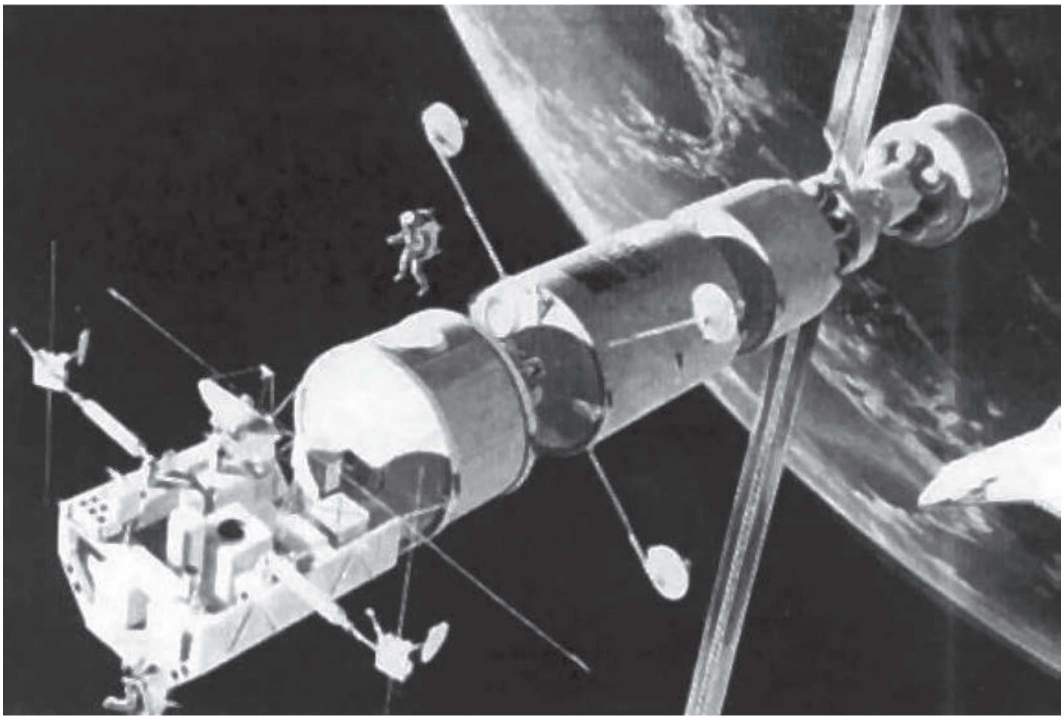


Fig. 2 Manned Orbital Facility NASA.

Module, which would be attached to the either end of the core creating a complete station (Fig. 2). The connection between modules was to be the International Docking Assembly as proven on the Apollo Soyuz Test Project. Although launched two modules at a time they could be split once in orbit and returned to Earth one at a time, reflecting the Space Shuttle's lower return capability.

The MOF study provides independent confirmation of the both the viability and utility of stations of this size and power range. It reinforces the conclusions of the PIA study regarding the viability and capability of space stations in this mass class.

4. THE PIA CONCEPT DESIGN

4.1 Overview

The PIA study produced the concept design in order to demonstrate the feasibility, assess the limitations and produced guide cost estimates for the approach.

The general arrangement of the concept design once assembled is shown in Fig. 3. The Hab. and Lab. Modules were connected to the two side ports on the Core Module creating a configuration that could use gravity gradient stabilisation as the primary means of attitude control, although other configurations would be possible using the reaction wheels. With the Hab. and Lab. modules aligned along the orbit radius vector the Lab. Module's docking port could support R-bar docking approaches, while the Hab. Module's communications antenna had an optimum view of space to support continuous contact with data relay satellites in geostationary orbit.

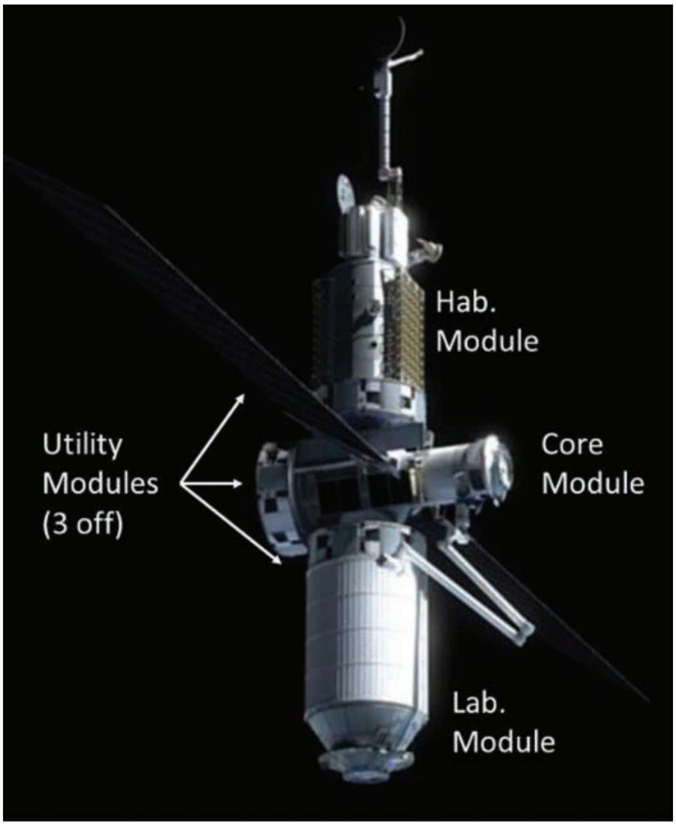


Fig. 3 Module arrangement.

The USIS berthing port on the Core Utility Module was intended as the "hook" for any expansion of the station. The main communications antenna was place on a 7.2 m mast to ensure that any expansion of the station in the +r direction could extend 17 m from the Core Module centreline without interfering with the communications links. In the – r direction (that is alongside the Lab. Module) any expansion was restricted to 10 m to maintain clearance for use of the Lab Module's docking port.

The solar arrays had one degree of rotation to track the sun. For optimum power generation the whole PIA station would rotate about the radius vector to ensure the Sun was full on the arrays.

Orbit make up could use either the Core Module's Utility Module or the other two Utility Modules combined. However it was assumed that operationally most orbit make up would use the crew and logistics supply vehicles while they were attached to the station.

The overall height of the station from Lab. Module's USIS interface plane to the communications antenna mechanism on the Hab. Module was 29.8 m. The width across the deployed arrays was 53.6 m. The length, which was determined by the Core Module, was 9.2 m.

4.2 Utility Module

The Utility Module (Fig. 4) serves two primary functions. First it provides the propulsion, navigation, communication and other functions required to take the module cluster from launch vehicle separation to rendezvous with the station assembly site be it either at the ISS or in open space. Its second function is to provide common services to the module it is mated with, to reduce the amount of duplicated development.

The Utility Module "tug" role centres on a MMH/NTO propulsion system, which can carry up to 1500 kg of propellant in four 900 mm diameter tanks. The propulsion system is pressure fed with a tank pressure of 1.5 MPa which is the nominal supply pressure for the four Leros 2b main engines. The system also has eight thruster clusters each with six thrusters giving full redundant control in roll pitch and yaw and linear control along the module's long axis. The system is pressurised with helium which is stored in four tanks and fed through regulators to the main tanks.

The Utility Module can deliver a 20 tonne module cluster from a 60 km by 400 km altitude to an assembly point in a 400 km circular orbit. In most cases far less than this will be required. Once connected to the Station the main engines and some of the thrusters would be permanently disabled but the remaining propellant can be used for reaction wheel off load and orbit make up though the remaining active thrusters.

The connection to the launch system is by a USIS berthing port which doubles as the module connection point in the construction of the station. The permanent connection to the companion module that it is launched with, is a bolted 1.255 m diameter ring around the modules pressure cylinder.

Power for the delivery flight period was from four lithium ion batteries each of 5 kW hr capacity. Which were supplemented by solar panels on the rear of the module which were designed to slow the discharge rate rather that meet the full supply demands. This would give the module three days from launch to reach the assembly point and be captured and berthed. Once attached the batteries formed the secondary power source during eclipses. In this role the batteries' depth of discharge was below 20%.

During the delivery flight the reaction control would be achieved by the thrusters, but once the station was assembled the gravity gradient stabilisation would be supplemented by four reaction wheels in each of the Utility Modules. Each Utility Module had redundant GPS, and inertia reference units, two star mappers and a compliment of sun sensors to support navigation and attitude control.

The Utility Module also had a redundant pair of flight management computers and the data bus provisions which provided the control functions not only for the Utility Module itself but also the other module it was mated to.

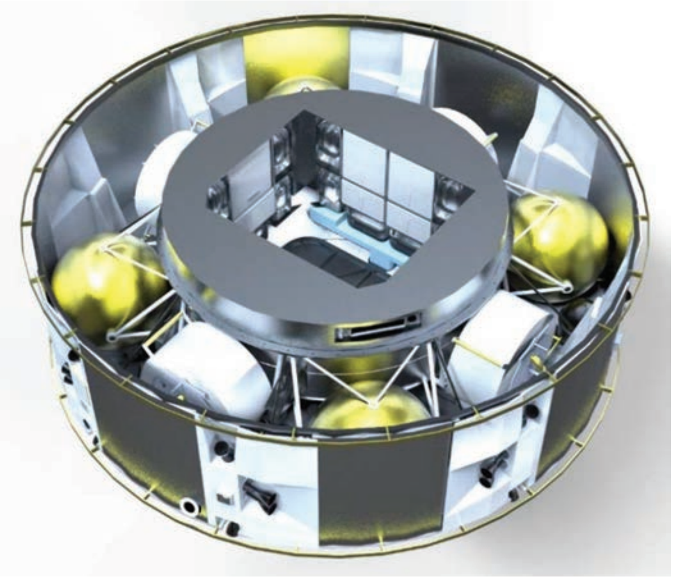


Fig. 4 Utility Module.

Within the pressurised cylinder of the Utility Module were the utility services linking the connections on the USIS berthing port to the permanently attached companion module. This included fans to ensure air circulation and module main electrical distribution and circuit breaker panel. The pressurised area also contained a logistics store with six double CTB (Cargo Transfer Bag) locations, six single CTB locations, and twenty two water carrier locations.

4.3 Core Module

The Core Module as the name implies provided the core services for the space station and it would be the first to be launched. Once launched it could support crew which enabled station construction in open space (which requires operation of the RMS). The module's key functions are:

- node architecture (2 side USIS Ports),
- remote manipulator arm,
- control room/cupola,
- power generation (14 kW average),
- environmental control and life support,
- crew hygiene and exercise.

The primary power generation for the whole station was provided by two deployable solar arrays each with an area of 124 m^2 mounted on a rotating bearing assembly. This power was conditioned by regulators with radiator that were fixed to the side of the Core Module to dump the excess power. The overall power distribution architecture from the regulator to the various modules is shown in Fig. 5.

The Remote Manipulator System (RMS) was assumed to be a remake of the ISS Canadarm with shorter arm sections to enable launch with Core Module in a special launch cradle. The main controls for the manipulator would be located in the Cupola. Like the ISS arm, the RMS would be free to locate on any of several grapples points located throughout the complex.

The two redundant ECLSS units were located at the base

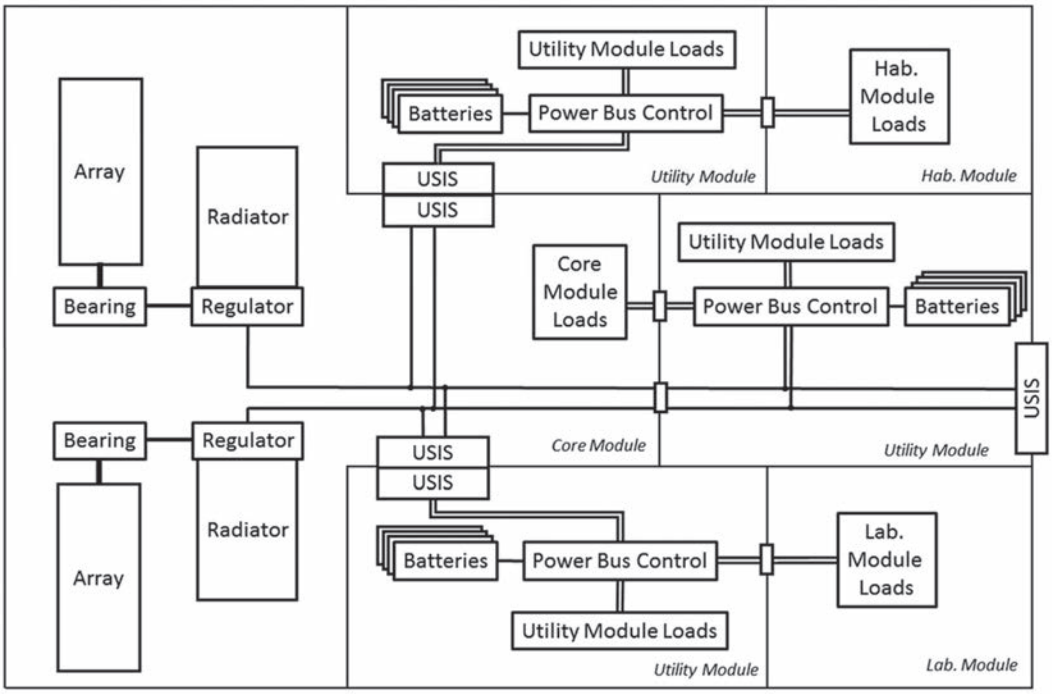


Fig. 5 Power System architecture.

of the pressurised section just above the Utility Module. Each of the systems were housed in an ISPR so that they could be easily replaced in orbit should that be necessary. Also it meant if a minimum mass stripped down launch was required only one ECLSS unit needed to be installed and the second could be installed in orbit. A heat rejection radiator for the ECLSS system was mounted on the outside of the module.

Above the ECLSS bay was corridor running between the two side USIS ports, the main intersection in the stations layout. This area had the hygiene facilities, the main equipment of which was also housed in an ISPR so it could be installed or replaced in orbit. Opposite it was a treadmill for astronaut exercise.

Above this the pressurised hull reduced to 2m diameter. This section housed a logistics store that can house thirty CTB racks and above that a cupola with a series of windows giving a panoramic view of the whole station. The main station control centre and the RMS controller were located here.

At the end of the Core Module was a USIS Docking Port (one of two on the station) that created a docking provision in the h-v plane. This port was normally expected to support v bar approaches.

4.4 Hab Module

The second module cluster to be launched and assembled would be a Utility Module attached to a Habitation Module that provided the:

- the main crew living facilities,
- the main logistics storage areas,
- airlock and other EVA function,
- external payload mounting platforms,
- high data rate communications.

The crew living facilities have two areas contained in the 3m diameter main cylindrical section. The lower half contained four crew cabins and a privacy area for washing and hygiene functions when the main hygiene facility was not available, for example during a solar storm. This area was surrounded by a radiation shield composed of 85 mm thick polythene sheet creating a radiation shelter for use by the crew during Solar Storms. The upper section had the galley and wardroom table making a social area for the crew. It also housed the main logistics store with space for 87 CTBs (another 10 CTB spaces are located inside the storm shelter).

The positioning of the living area and particular the crew rooms above the rest of the station was intended to reduce the impact of secondary radiation when in low earth orbit, as the earth acts as a shield for cosmic rays coming from below the station.

At the top of the module was an airlock to enable Extra-Vehicular Activity (EVA) which had an internal diameter of 1.7m and a length of 2.2m. When depressurised the air would be pumped into a reservoir of two redundant bottles either one of which could pressured the air lock to two atmospheres so that it could serve as a hyperbaric chamber in cases of a decompression emergency. The airlock pressure control system and the store for EVA support tools and other equipment were located on the airlock’s exterior.

The Hab. Module also carried the main communications mast, the main function of which was to position the 2 m diameter antenna clear of the rest of the station. Other antennas and observation cameras were also located at the mast head. The lower section of the mast had six small payload mounting locations

4.5 Lab Module

The Laboratory Module was designed to provide similar payload provisions to the laboratories on the US orbital segment of the ISS. It mostly comprised a 4.24 m internal diameter cylinder, 5.4m long and which can accommodate four rows of five ISPRs (Fig. 6). This compares to four rows of four in the Columbus Laboratory Module and four rows of six in the Destiny Laboratory Module.

The cone end section was primarily intended to move the USIS docking port as far down the station as possible to improve clearance for docking operations. But it had the advantage of creating the biggest free volume for the crew and could also house 12 double CTBs.

The module was assumed to provide active cooling services to the payloads and the heat rejection radiators are flush mounted on the main cylinder body.

Another externally mounted provision was an external platform for ten small payloads (Fig. 7). These payloads were assumed to use a special standard attachment interface, which was not an ISS legacy and which was sized to accommodate payloads carried to the station in single and double CTBs. These would be the same interface as the six placed on the lower communication mast on the Hab. Module. The Lab. Module external platform was also employed to carry a laser range finder and navigation lights.

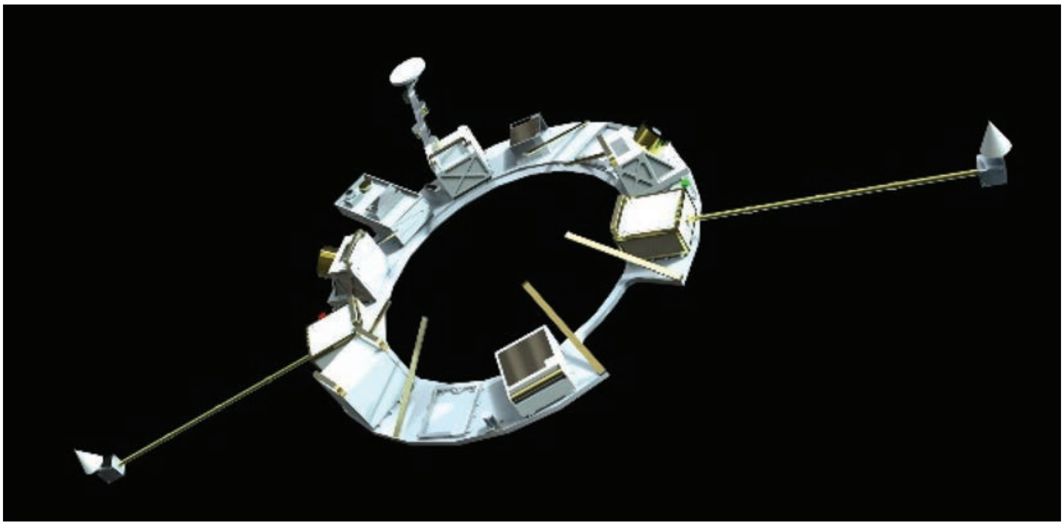
4.6 The Assembled Station

Once all three module clusters were assembled a complete working station would be created. Unlike the slow growth of the ISS where it could be used effectively for applications before its assembly was completed, the PIA has almost no ability to support exploitation until the last flight delivers the Lab. module. This was because the interior architecture (Fig. 8) has greater functional demarcation with a defined living area for sleeping eating and recreation and another defined area for working, whereas on the ISS, particularly in the US segment the habitation and science research functions were mixed up. Given the anticipated speed of assembly of a PIA station waiting for a third launch before it could be used did not seem a great compromise to obtain a better, more ergonomic, layout. For comparison the Destiny laboratory module was launched on the sixth flight ISS construction flight more than two years after assembly had started.

Table 1 gives the key specifications of the assembled PIA station. The key issue with this design was probably the limited logistics and water storage, which at around 4 tonnes was very close to the capability of the typical ISS logistics delivery system. This implies almost a complete exchange of supplies on each logistics visit which was not very practical, so in practice the logistics supply craft would probably make long stays providing additional storage space as well as simple delivery. One conclusion the study drew, having explored means to improve this aspect of the design, was that if addition

Fig. 6 Lab module interior.

Fig. 7 Lab module external platform.



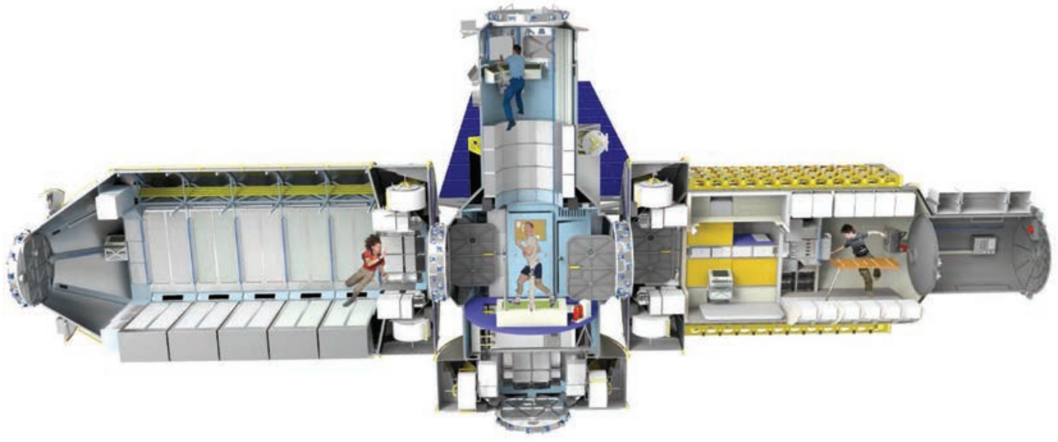


Fig. 8 PIA station interior.

TABLE 1: *PIA Station Specifications*.

Estimated Dry Mass	30.7 tonnes	Includes 20% Margin
Crew	4 max 3 typical	ECLSS sized for 8 in emergency
Power	14 kw	Designed continuous
Pressurised Volume	185 m^3	
Internal Payload	20 ISPRs	Mass typically around 10 tonnes
External Payload	2 main Platforms 16 small locations	Mass typically around 5 tonnes
Logistics Storage	211 Single CTB locations	Mass typically 2.5 tonnes
Water Storage	68 × 20 litre bottles	1.4 tonnes

on board logistics storage was a requirement then the concept would have to move to a four launch station with an additional module.

The complete PIA Infrastructure would comprise 4 or 5 stations and Table 2 shows a comparison of key parameters for the complete infrastructure compared with the ISS. Direct comparison of payload provisions was complicated by the Russian orbital segment not using the ISPRs nor having separate external equipment platforms, so those factors biased the comparison in favour of the PIA. The external platforms on the PIA were slightly bigger than those on the ISS but could only be used effectively on one side. However despite these caveats the 4 PIA infrastructure was broadly comparable to the ISS and the 5 station infrastructure would represent an increase in capability.

The one parameter where the PIA architecture was significantly lower than the ISS was power. Detailed power budgets have not been generated and only rough estimates made. However they confirmed the results of the similar MOF concept which was estimated to be able to provide 8 kW average power to the experimental payload. Like the MOF the PIA specific power (the power per kilogram of complete station) was double the ISS, suggesting PIA should actually be considered power rich. The initial conclusion was that with much smaller and leaner stations to support, a bigger percentage of the generated power could go to the experiments. If later studies concluded that power levels comparable to the ISS were required by the PIA infrastructure that may require a move to a concept requiring four assembly launches

TABLE 2: *Comparison of PIA Infrastructure with ISS*.

Parameter	ISS	4 PIA	5 PIA
ISPR locations	83	80	100
External Platforms	6	8	10
Mass (tonnes)	450	200	250
Crew (3 per PIA)	6	12	15
Power (kW)	130	56	70
Specific Power W/kg	0.14	0.28	0.28
Pressurised Vol. (m^3)	916	740	925

5. LAUNCH

The launch of the modules constituted around 10% of each station's acquisition cost and thus needed to be addressed as part of the early assessment of the approach. There were two possible launch options. Either each partner launches the module they developed both for themselves and the other partners, or each partner launches all the modules for their station including the modules produced by the other partners.

The first approach may seem obvious, it would allow the modules to be tailored and optimised to one launch system. However there are two problems with the partners launching the modules they designed. In the nominal scenario there were four partners and only three launches per station so one partner would not have any launch responsibilities creating a funding imbalance. The second problem was that those partners with launch responsibilities have to provide four launches for the complete programme rather than three and thus had a higher burden on their launch system capability. Therefore the study decided that every module would be designed for launch on all the partner launch systems and accepted the additional constraints this imposed.

The launch systems considered by the study are shown in Table 3 together with the estimated performance. Both the Atlas and Delta offer a range of configuration options hence the performance range of the medium class vehicles is shown. All these launch systems would require a USIS payload interface to be developed to launch the modules.

A composite payload envelope was created (Fig. 9) from all these vehicles with the assumption that a USIS versions would not significantly alter the envelopes defined in the user's guides. The main cylindrical section had a diameter of 4.48 m (driven by Ariane 5) and a height of 6.93 m before the start of the conic section (driven by Proton). The total height was 9.36m with an end diameter of 2.99 m (driven by Skylon). However the removal of any one of these driving launch systems would have very little impact on the composite envelope for as Figure 9 shows for they are all very similar and vary by only a few centimetres. All the modules were design to fit within this payload envelope as shown in Fig. 10.

Table 4 shows the launch masses for each of the launches in three different outfit states. The Module masses were the results of the preliminary mass assessment with a 20% margin added.

The minimum launch outfit would be a Utility Module carrying a minimum fuel load required to rendezvous with the assembly site and the companion module in a "stripped out" configuration where only the capabilities needed for station assembly are incorporated and the module would then have the additional equipment that would be needed for it to become operational delivered separately by a logistics supply craft and installed by the crew in orbit.

The nominal launch outfitting was the Utility Module fully fuelled and the companion module completed fitted out for operation, but with no logistics or experiments.

The maximum launch mass was as the nominal outfit but with every allocated logistics storage space and internal equipment rack filled. The logistics masses were generated by assuming 12 kg in each CTB single space, 20 kg in each water bottle location and 500 kg in each equipment rack location without additional margins.

It can be seen that for a launch on Falcon 9 or Skylon a minimum launch configuration would be necessary. So any

Fig. 9 Composite launch envelope.

TABLE 3: *PIA Launch Systems.*

Launch system	Payload (tonnes)	Orbit (km altitude)	Basis
Ariane 5	19 to 21	400 × 400	Defined in Reference 9
Atlas	7 to 16	60 × 400	Estimated from performance into other low earth orbits defined in Reference 10
Delta	8 to 13	60 × 400	Estimated from performance into other low earth orbits defined in Reference 11
Falcon 9	9.4	400 × 400	Defined in Reference 12
H-IIB	16.5	350 × 460	From Reference 13
Proton	23	180 × 180	Defined in Reference 14
Skylon	10	400 × 400	From Reference 15

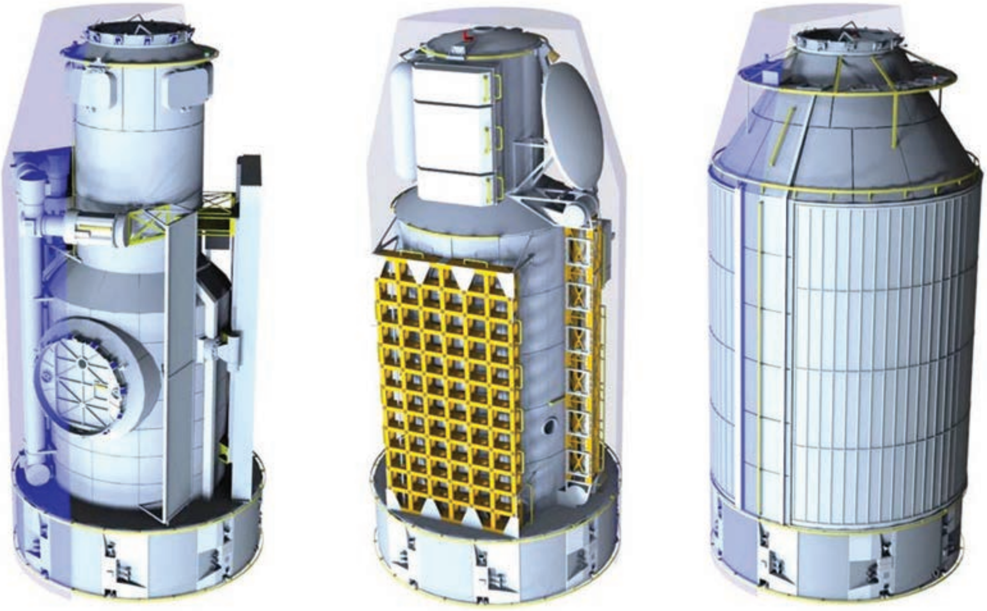


Fig. 10 Modules in launch configuration.

TABLE 4: *PIA Assembly Launches Mass Estimates (kg).*

	Launch 1 - Core	Launch 2 - Hab	Launch 3 - Lab
Minimum Launch			
Utility Module	2650	2650	2650
Module Stripped	6084	4574	6636
Minimum Propellant	200	200	200
Total	**8934**	**7424**	**9486**
Nominal Launch			
Utility Module	2650	2650	2650
Module Operational	8720	7280	6756
Propellant	1500	1500	1500
Total	**12870**	**11430**	**10906**
Maximum Launch			
Utility Module	2650	2650	2650
Utility Logistics	616	616	616
Module operational	8720	7280	6756
Module Logistics	536	1768	10288
Propellant	1500	1500	1500
Total	**14022**	**13814**	**21810**

launch cost advantages these launch system offer must set against the additional logistics flights that would be required for the additional on orbit outfitting. All the other launch systems considered had the capability to launch fully operational module assemblies with some logistics on board. Thus the objective of each partner being able to launch their station using three of their own launch systems was found to be achievable

However the study did find that space limitations within the modules made it difficult to fully exploit the payload capability of the larger systems. In terms of logistics only around two tonnes per module could added to the nominal launch mass. It may be possible to carry more logistics in space normally intended for other roles, but to achieve a significant increase very large intrusions into the habitable volume would be required restricting the crew's ability to operate effectively once the station is assembled.

Refinement of the design may be able to improve this situation a little, but a study conclusion was that having a module configurations that has sufficient variety of launch outfitting options to fully cover the payload mass range offered by all the launch systems would be very difficult and may even not be possible.

6. COST STUDY

The PIA station was parametrically costed using the provisional mass budgets for each module. The overall mass from the budgets were broken down into cost areas of:

- structure & thermal,
- propulsion,
- mechanisms,
- array,
- power storage and distribution,
- ECLSS,
- avionics,
- secondary fittings.

and parametrics applied to them to generate the module cost estimate. The RMS and the radiation shielding were handled as separate items.

The mass model was crude and preliminary and thus the cost results have a higher degree of error than normally expected. Further the model produced cost in 2010 Euros and commercial rather than aerospace inflation factors were applied to get to 2015 Euros. Another caveat is that there was not a good estimate of the software required and so that has not been specifically incorporated in the cost model. However the results were judged sufficiently good to draw the conclusion necessary to establish the PIA concept's financial viability.

Table 5 shows the cost model results for the four separate modules.

The three larger modules were found to be very similar in both development and manufacturing costs, which was not a surprise given their similarity in size and mass. The core module came out a little higher in the cost model, but this was also the location of several items, such as the RMS, that were likely to be supplied by other smaller partner nations so in practice it was thought the disparity would be less for the producer of that module than the numbers in Table 5 suggest.

The Utility Module had a much greater difference both in numbers and in the balance between development and production. This was to be expected as it is smaller than the other modules and the production run were three times as great. Given it represented a key element in the interface between the other modules and the launch systems, and housed the common power, data, and control functions it made it the natural module to be undertaken by the partner that would be taking overall system management of the development and it was proposed that those tasks are combined. This did not completely address the budget imbalance, but it was argued that overall the four partners could adjust the contributions at the next tier to create a reasonably equitable balance of spending in both the development and production phases.

Adding a fifth station added around €1.5 billion ($1.7 billion) to the acquisition cost. If this fifth station were jointly owned (for example it were an international facility in lunar orbit) the spending balance was retained. If the additional station were a requirement for one of the partners, obviously this would introduce an imbalance in production spending, as the partner would effectively have to import over €1.1 billion of equipment from the other partners, so the issue of how to deal with stations beyond the initial production run (which assumes an equal partnership) would need to be addressed in the overall programme arrangements.

When looked at from the point of view of a partner, the acquisition programme costs would look something like those presented in Table 6 making the assumption that each launch cost €90 million ($100 million) each.

TABLE 6: *Typical Partner Acquisition Costs.*

Item	M€	M$
Module Development	1100	1200
Production run for 4 stations	1700	1900
3 launches	270	300
TOTAL	**3070**	**3400**

Thus for a budget of around €3 billion ($3.4 billion) each partner would get their own PIA station delivered in orbit ready for operations. This budget is comparable in real terms to the initial acquisition of the Hubble Space telescope or to the Envisat programme; that is within the scope of space budgets that in the past have been justified on the science return they provide. It should also be noted that the spending for each partner would to a first order be entirely within their own economies. The exchange between partners being primarily bartering modules.

Another scenario investigated was a three partner arrangement where one dominant partner requires two stations and the other two partners require one each. In this case the dominant partner would take the Utility and Core modules and the overall system development and the two smaller partners each take one of the two remaining modules. To the smaller partners the costs and results were the same as the four partner - four station scenario, whereas the dominant partner paid twice as much but of course got two space stations.

There seemed to be a great deal of scope for varying the number of partners and the number of stations per partner while being able to achieve a high degree of equitability between the partner financial contributions.

7. CONCLUSIONS

The study concluded that a three module, fifty tonne, space station design, if multiplied sufficiently, could provide

TABLE 5: *PIA Cost Model Results in €M ($M).*

Module	DDT&E	4 off Production	4 station Total	5 Off Production	5 station Total
Utility	395 (438)	1132 (1256)	1527 (1695)	1375 (1526)	1770 (1965)
Core	1330 (1476)	2077 (2306)	3406 (3781)	2535 (2814)	3864 (4289)
Hab	1031 (1144)	1716 (1904)	2746 (3048)	2093 (2324)	3124 (3468)
Lab	1111 (1233)	1718 (1907)	2829 (3140)	2096 (2326)	3206 (3560)
System	187 (207)	364 (404)	551 (612)	455 (505)	642 (713)
TOTAL	**4053 (4499)**	**7008 (7778)**	**11060 (12277)**	**8555 (9496)**	**12608 (13994)**

equivalent capability to the ISS and thus be a viable approach to its replacement. Two module designs could not provide a sufficiently effective capability regardless of how many were employed. Four module designs would improve the operational station allowing scope to increase power and logistics storage and include other more sophisticated support facilities. However it would require an additional development budget of over a billion Euros and would add over 500 million Euros to the cost of each station. The study concluded this extra cost was not worth the operational gain. However this was not a clear cut, nor quantitatively derived, conclusion.

The four stations created would create an overall infrastructure with a capability comparable to the ISS, and with five stations the capability would exceed the ISS. As the payload interfaces were designed to be the same as the ISS and as the stations would come operational in a sequence of maybe two or three years it was expected that a smooth transition from ISS to PIA could be achieved that would be almost transparent to the user community.

The political objectives set out for PIA were met. The technical and organisation legacy of the ISS programme exploited sufficient to easily argue the long term value of the programme, while it allowed each partner to own an autonomously operated station. From this the study concluded that PIA represented an attractive low risk option for post ISS activity for the public funding sources. And with acquisition costs of around $3.5 billion per partner the investment could be justified on its science return alone. Further the politically driven financial goal of confining each partners spend to their own economics looked possible.

One of the means to achieve a “no exchange of funds” situation was to ensure that each module cluster was capable of being launch on each partners own launch systems. This was shown to be possible in terms of volume and mass constraints assuming that the launchers to be used were fitted with the USIS interface to attach the payload. The as the complete construction of a PIA station required only three launches, it was judged feasible for assembly to be accommodated in one or two years of these launch systems operations despite their limited production runs and long launch campaigns.

The support of the operational stations was another area that was found to be able to advantageously exploit the ISS heritage. The US policy of moving to commercially provided crew and cargo support opened the possibility of commercial selling those services to partners who own stations but do not have complete national support capability. With other nations also having support capabilities to offer the PIA infrastructure would create a larger and hence more diverse market for these services making the businesses more economically viable.

Markets are established by standards; and the standard that enables markets for launch, crew delivery, logistics support and expansion modules is the USIS. Having all four of these interface requirements covered by one universal connection greatly simplified the module design. If they were separated there would need to be two additional external ports and three launch systems interfaces which would be geometrically difficult, given the stations compact design, and have a mass impact between half a tonne and one tonne and a cost impact in excess of $100m.

One of the PIA study’s objectives was to support the validation of the USIS Requirements Specification [16]. It found that a USIS meeting the current specification worked well in the context of both space station construction and operation, with the exception of the strength required to handle the launch loads which were found to exceed the maximum currently defined by up to 50%. It is intended that this result will be incorporated into the formal requirements generation process of the USIS when it is started.

Overall the study concluded that a small station architecture would allow the construction of a replacement infrastructure for the ISS which matches its capability for the cost to each partner comparable to a high end robotic science mission. The resulting infrastructure is flexible and resilience and capable of easy and rapid expansion if the demands on it change. It also opens up the possibility of space stations in high earth and lunar orbits in support of the initiative such as Orion/SLS.

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REFERENCES

1. Mark Hempsell, “Creating a Universal Space Interface Standard”, *JBIS*, **69**, pp.175-182, 2016.
2. Frank Morring, “What Next in LEO”, *Aviation Week and Space Technology*, **177**, 20 July-2 August 2015.
3. Michael Raftery, “ISS Exploration Platform Concept”, http://www.nasa.gov/pdf/604659main_6%20-%20Panel%203_Raftery_Final.pdf. (Last Accessed 14 September 2015)
4. M. Hempsell, “Space Station Element Commonality Between LEO and Lunar Infrastructures”, *JBIS*, **65**, pp.402-409, 2012.
5. M. Hempsell, “The Cost Impact of Space Station Architectural Approaches”, *The Journal of Practical Applications in Space*, **3**, Spring 1992
6. M. Hempsell, “Space Stations Using The Skylon Launch System”, *JBIS*, **65**, pp.392-401, 2012.
7. NASA, “Manned Orbital Facility: A User’s Guide”, 1975.
8. Phillip J. Parker, “Manned Orbital Facility”, *Spaceflight*, **18**, p.426, 1976.
9. “Ariane 5 User’s Manual”, Issue 5, July 2008.
10. “Atlas 5 Launch services User’s Guide”, revision 11, March 2010.
11. “Delta IV Launch services User’s Guide”, June 2013.
12. “Falcon 9 Launch Vehicle Payload User’s Guide”, SCM2008-010 Rev.1, 2009.
13. http://global.jaxa.jp/projects/rockets/h2b/. (Last Accessed 7 September 2015)
14. “Proton Launch System Mission Planners Guide”, revision 7, July 2009.
15. “SKYLON Users’ Manual”, SKY-REL-MA-0001, Rev 1.1 September 2010.
16. “USIS Technical Requirement Specification”, presently unnumbered pending the establishing of a USIS controlling body, Draft F (this can be downloaded from www.hempsellastro.com.

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