

On a Scenario for Sustained Human Space Exploration

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Abstract: The next steps in human space exploration could be three missions: (I) return to the Moon with sustained habitation; (II) first human travel to Mars; (III) possibly a New International Space Station (NISS) with both habitation and spacecraft assembly facilities. The three missions I to III are considered from the points of view of technological challenge, safety of the crew, rescue in case of incident and resources required for implementation. It is argued that the safest sequence, compatible with likely available resources and mature technology, is: (a) first the Mission I of return to the Moon with sustained habitation, which is the focus of ongoing international activities led by the U.S. and China; (b) next an NISS that could support a major large scale expansion of lunar habitation, allowing assembly of a family of spacecraft, including an emergency moon rescue service; (c) the experience gained with sustained lunar habitation combined with the spacecraft assembly capabilities of the NISS, would provide the best background to the more challenging human exploration of Mars, in a sustained and safe manner. An important safety aspect of the Mars mission, due to its long duration, is protection against solar flares and outbursts, for which passive shields may not be sufficient, due to excessive weight and volume; a novel 'active' protection system against high-energy radiation and high-speed particles from solar outbursts is proposed, consisting of a magnetic capsule between the spacecraft and the sun, creating an 'artificial ionosphere' protecting the spacecraft and crew, during the periods of high solar activity.

Keywords: human space exploration, lunar habitation, Mars mission, spacecraft assembly, crew safety, radiation shielding

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1. Introduction

Throughout the history of mankind until recently human activities had no lasting or global effect on the Earth's climate or depletion of natural resources. The more recent and increasing concerns about pollution and scarcity of raw materials show that the limits of the Earth are being approached and, in some cases, exceeded. The only long-term solution to the limited resources available on Earth is the expansion into space.

The exploration of space beyond the limits of Earth starting in the XXth century bears some analogies to the sea travels that in the XVth connected Europe to the rest of the world; the basic issues of transportation, survival and settlement are the same, with very

different technologies at different epochs of human history. Concerning transportation, the sea travels required ships to travel long distances in adverse winds and rough seas and space exploration requires powerful rockets to launch spacecraft into Earth orbit and beyond. Concerning survival, the sailors had to endure long periods without fresh food and with scarce water and the astronauts must adapt to weightlessness or eventually to 'artificial gravity'. Concerning settlements the sea travels lead to permanent remote outposts far away from point of departure and space colonization will require the creation of remote self-sustaining closed environments.

An important difference is that at the age of space travel, in contrast with early sea travels in the Mediterranean sea and Atlantic ocean, and their far reaching expansion to the

whole earth in the XVth-century, mankind has much higher standards of respect for human life, and high risks and excessive casualties are morally and socially unacceptable. When Magellan started the trip around the world he had 156 sailors and 4 ships; after he died from a poisoned arrow in the Philippine archipelago, the remaining crew that returned to the port of departure were 26 sailors barely able to handle 1 ship. As the reactions to the two Space Shuttle accidents show that tolerance to accidents and loss of human life is much lower in our present more civilized society, the lowest possible risk and highest possible safety level are paramount.

The pioneers and leaders in sea travels were those with the most appropriate strategies and technologies to implement them, starting with the Portuguese, Spanish, Dutch and British, and spreading to all European powers. Likewise, the strategy for space exploration should aim at fastest progress with least risk and most effective use of available resources. This introduction (section 1) brings us to the subject of the present paper: which should be the follow-on of current activities in space exploration. The accomplishment of these steps and reaping the technological, economic and social benefits, are aspects that also have analogues.

Space exploration so far may be seen as comprising three epochs: (i) using rocket propulsion to enable the pioneering orbiting of satellites in various orbits, which continues at present with large constellations, besides interplanetary probes; (ii) manned space flight lead to the milestones of the first human landings on the Moon, enabled by remarkably reliable Saturn rockets; (iii) long term space habitation in the International Space Station (ISS), assembled and supported by the first partially reusable launcher, the Space Shuttle (SS), whose role was taken by other launchers after two accidents. The third 'space epoch' of the ISS and SS is very well documented for the general public, for example on the internet with 447 references on ISS [1] and 320 on SS in Wikipedia [2], in dedicated books [3,4] and in the general history of space exploration [5–12], and thus only some general remarks are made. The original aims for the ISS were: (i) demonstrate long-term human space habitation; (ii) in-orbit assembly of spacecraft for missions to the Moon and Mars. The rising costs relative to initial estimations lead to the focus of the ISS being solely (i), as (ii) would stretch beyond available resources. The ISS fully fulfilled its aim of proving long-term space habitation lasting much longer than its original design life. The SS also had two original aims: (i) launch the modules to assemble the ISS in orbit and provide subsequent support; (ii) provide an order of magnitude reduction in satellite launch costs. The second aim was mostly abandoned when the high-cost of refurbishment of the SS after a flight made the 0.5 billion launcher non-competitive with expendable launchers; also risking the lives of a 6-astronaut crew to launch a satellite would be very questionable, as public reaction to the two SS accidents showed. After the second SS accident the support for the ISS was continued by other launchers, as the SS had completed successfully the ISS assembly. In purely statistical terms, the second SS accident on the 135th launch, was a 1.48% failure rate, within the 98% target of minimum reliability for manned launchers.

The next stage or epoch (iv) of human space exploration is currently in progress with the Artemis program [13] envisaging a return to the Moon with permanent habitation of a lunar base as a major step beyond the pioneering sequence of short Apollo missions [14]. Though the main effort is led by NASA with the SLS launcher, Orion capsule [15] and cislunar Gateway, ESA is supplying a service module and commercial space companies like Space X and Blue Origin supply the HLS (human landing system). This ongoing activity in lead by the U.S., and comparable initiatives led by China, of Moon exploration will be referred briefly as space Mission I. The SLS throw weight, as well as that of other heavy launchers in development, such as Starship and New Glenn, returns the historic levels of the pioneering Saturn V [16], and with direct launch replaced by the use of a Gateway in lunar orbit. The future manned exploration of Mars [17], for brevity referred as space Mission II, will need significantly larger spacecraft to support astronauts over longer travel times, that could benefit from some form of in-orbit assembly, for which a New International Space Station (NISS) would be most suitable. The current ISS (International Space Station),

having lasted longer than originally designed for [18] may be retired towards the decade; the building and operation of a follow-on NISS (New ISS) could be a hypothetical space Mission III, providing in-orbit services, that could support both Moon/Mars exploration, simultaneously or not. Thus the 3 choices to be compared are Moon (I) or Mars (II) exploration without NISS, or (III) NISS supporting both Moon and Mars exploration, providing in-orbit services, like refuelling, repair, assembly and manufacture on a larger scale than multiple current efforts in the same direction. The aim of the paper is to compare the three space Missions I to III as impartially as possible, resisting influence from what is currently planned, advocated or being implemented.

The current Artemis program represents the (iv) fourth epoch of space exploration, leveraging the experience of long-term space habitation of the ISS in epoch (iii), to extend pioneering Appollo missions to the Moon in epoch (ii), to a sustained human presence, that is designated for brevity as mission I. For technical and cost reasons, the manned exploration of Mars, which may be designated as mission II, is most likely to come in a fifth space exploration epoch (v), subsequent to sustained Moon presence. Thus while mission I of sustained human presence on the Moon is actually an ongoing activity at early stages, the mission II of manned flight to Mars is a future eventual program. This reminds of the early intentions to use the ISS, then called 'Freedom' SS, to assemble spacecraft for lunar and Mars missions, which could be reconsidered as an mission III for a New International Space Station (NISS). Thus the aim of the paper is to compare three 'missions': (I) sustained human presence on the Moon, which is an on-going program at an early stage, representing the fourth epoch (iv) of space exploration; (II) manned flight to Mars, which is a subject discussed for some time, and could eventually become a fifth epoch (v) of space exploration; (III) a NISS, adding to the habitation capabilities demonstrated by the ISS, the ability to assemble and maintain spacecraft, would be another option for the 5th epoch of space flight, and could both support the continuation of long- term Moon presence (mission I) and a new program of human flight to Mars (mission II). Thus the three missions are partially but not totally overlapping in time and scope: (a) the permanent habitation of the Moon (mission I) is the on-going Artemis program, and could be supported in the future by NISS (mission III); (b) the human flight to Mars (mission II) could be conceived (α) either as an independent program or (β) combined with the NISS (mission III). The three missions will be compared next on their own merits.

All three missions would be a decade long effort. The ISS should be decommissioned in 2030 inevitably leaving a gap until the eventual development of its replacement (Mission III). The Mars travel (mission II) or sustained return to the Moon (mission I) are likely to be sequential as shown by the current focus on the Artemis manned mission to the Moon, relegating Mars exploration to unmanned missions. Available space budgets may struggle to finance one mission only, with two concurrent missions an unlikely prospect and all three in parallel a non-starter. Thus the implementation of these missions could only be sequential and only if the mission I currently being implemented was followed by one of the others, and the third mission taken or not at a later subsequent stage. A possible sequence could be to follow-up the ongoing mission I of Moon exploration with: (i) first the mission III of a NISS supporting a larger scale expansion of Moon exploration; (ii) the experience of Moon exploration then expanded in a much more demanding Mars travel (mission II) for which the NISS would provide support. The much longer duration of the Mars (mission II) relative to Moon (mission I) travel, will require larger spacecraft with longer endurance and higher reliability, for which the NISS could provide the assembly, support, repair and operational base. The present paper starts by outlining the risks and challenges (Section 2) of each mission in isolation, namely: (mission I) sustained Moon presence (Subsection 2.1); (mission II) the Mars travel (Subsection 2.2); (mission III) space station with habitation and assembly facilities (Subsection 2.3) to support (a) the expansion of Moon exploration (mission I) and larger challenge of Mars travel (mission II). Thus missions I and II are sequential, having in between mission III that can support both missions I and II, besides having its own merits.

The three missions are then compared based on 4 criteria: (i) safety of the mission and the ability to respond quickly and effectively to an incident (Subsection 3.1); (ii) cost for a single flight and an extended campaign consisting of many flights (Subsection 3.2); (iii) scalability to adapt to future evolution that may require ever larger spacecraft (Subsection 3.3); (iv) flexibility to adapt to flights with different requirements and timescales (Subsection 3.4). The comparison suggests that although mission III of the NISS may require a larger initial investment, it may be the safest and also the most cost-effective in the long term due to its flexibility and scalability to adapt to a large number of flights.

The flexibility and scalability of the use of the NISS can be considered (Section 4) in three sets of roles: (i) Moon base with fast reaction support from NISS (Subsection 4.1); (ii) launching and retrieving the Mars flight (Subsection 4.2); (iii) NISS uses from Earth services to space science (Subsection 4.3). In addition to this utilization to support the future phases of space exploration, the NISS would retain two fundamental roles (Section 5) for an indefinite future: (i) to serve as near-Earth safer testing facility with more utilization time than any other equipment sent farther into space (Subsection 5.1); (ii) to open the way for free space habitation, not limited to the confines of planets, moons or comets (Subsection 5.2). The NISS can be seen as a step in the evolution of space exploration (Section 6), leveraging current options (Subsection 6.1) with experience from the past (Subsection 6.2) to choose the path to follow in the future (Subsection 6.3).

The conclusion (Section 8) is supported by Tables 1 and 2 comparing options respectively for the Mars mission and Moon base with other missions included in Table 3. The three tables combine well known and possibly innovative elements, with two of the latter illustrated in Figures 1 and 2. The schematic architecture of the NISS (Figure 1) adds an 'industrial' element to the current ISS 'habitation' design; a new idea (Figure 2) is an 'artificial ionosphere' created by an auxiliary unmanned spacecraft to shield the main crewed capsule from solar flares and high energy outbursts. The latter idea may be sufficiently novel and important to justify a more detailed consideration (Section 7) before the conclusion, because it provides a potential solution to an existing problem that could become more serious in the future: a spacecraft outside the radiation belts of the Earth is exposed to high-intensity radiation and high-speed particles from solar flares and outbursts; whereas this risk was accepted in the Apollo missions of a few days to the moon, this will no longer be the case for missions to Mars lasting months or years. Bearing in mind limited effectiveness due to the weight and bulk of 'passive' radiation shielding, a supplement can be 'active' radiation protection of a magnetic capsule creating an artificial ionosphere surrounding the spacecraft.

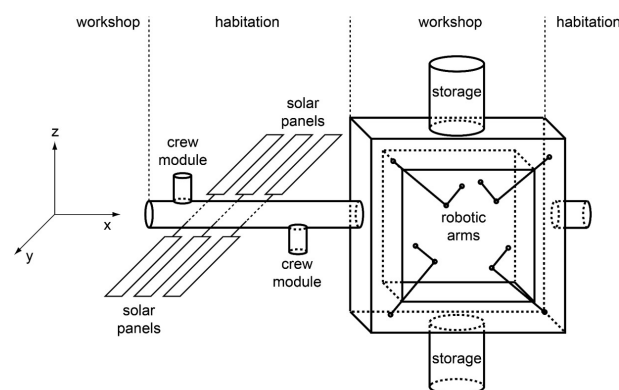


FIGURE 1

Figure 1. Proposed design of the New International Space Station (NISS), featuring habitation modules with solar panels, workshop sections with storage and robotic assembly areas, and expandable modules along a truss structure

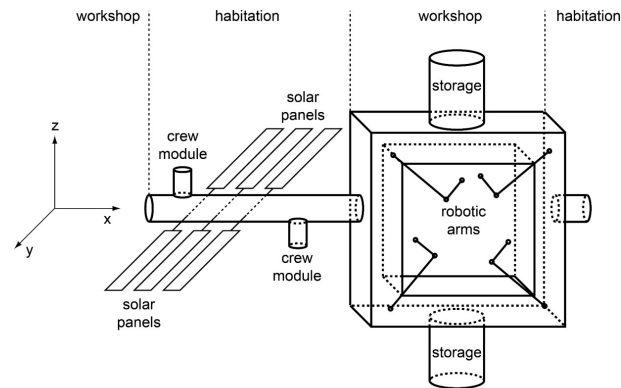


FIGURE 1

Figure 2. Conceptual design of a Mars spacecraft with multiple modules, including a radiation-shielded crew capsule, a magnetic protection module, and auxiliary service modules

Table 1. Comparison of missions for the mars flight

Mission	I + II	III
Approach and consequences	Launch from and return to the Earth's surface	Assembly at the NISS, leaving from and returning to the NISS
Spacecraft configuration	Components launched into orbit to assemble spacecraft in free flight	Modular, extensible configuration with connected or free flying elements and no aerodynamic constraints
Return configuration	Thermal protection needed for re-entry of Earth atmosphere, with no re-use or re-use requiring major refurbishment	Return to the NISS, with re-use following checks and possible replacement of modules or components
Radiation protection- average solar wind	Limited by size and weight of shields	Large and heavy shields can be assembled in orbit
Radiation protection: solar flares	Plasma generation on board causes EMI or needs separate capsule with ejection mechanics	Plasma generator for 'artificial ionosphere' provided by a separate free flying capsule (Figure 2)
Redundancy	Limited by volume, weight and proximity	Redundant crew, payload and other capsules possible
On-board repair	Limited space for spares	Spare and repair modules can be part of the assembled spacecraft
Flight duration	Long: 2-3 years	Reduced to months with auxiliary propulsion/braking module
Risk of failures	High: long duration flight with limited redundancy	Reduced: Shorter flight duration and extensive redundancy
Re-usability	Expendable heavy launcher plus new/service capsule requiring refurbishment	After assembly at the NISS the spacecraft can be reused for multiple missions
Growth potential: Mars orbit, landing, station	Limited by need of larger capsule/fairing and more powerful launchers or more numerous launches of components and more complex assembly	More modules can be added at the NISS to the spacecraft as needed
Cost	High and repetitive: expendable heavy launcher plus capsule replacement/refurbishment	Lower and non-recursive: after first cost of assembly at NISS, mostly checks, replacement and additional modules
Frequency	Low due to high recurring cost of missions and long times for production and refurbishment	High by low cost of re-use and simple repair/addition of modules
Conclusion	A few high-risk, expensive missions, with long time intervals, and limited growth potential: orbital, landing and Mars base difficult to accommodate in the same launcher/capsule	More frequent, lower risk, less expensive flights with growth potential to accommodate orbital, landing and Mars base activities through added modules

Table 2. Comparison of missions for moon base flights

<i>Mission</i>	I	III
Approach and consequences	Launch from and return to the Earth's surface and use of lunar Gateway	Large scale assembly at the NISS followed by flight to the Moon
Size of the modules	Limited to fit a capsule on a rocket with escape velocity to the Moon	Less limited by a larger fairing or smaller rocket to fly at orbital speed to the NISS
Complexity of the modules	Greater need for folding structures and deployment mechanisms	Assembly at the NISS could dispense with some deployment mechanisms
Radiation exposure during assembly	Assembly at the Moon exposed to solar wind and flares	Assembly at the NISS protected by the Earth radiation belts
Transportation to the Moon	Larger number of smaller modules taking more time	Smaller number of larger modules for faster assembly
Learning process	More difficult on the Moon with low gravity, radiation exposure, far from Earth	Doing more tasks at the NISS serves as a safer, easier training for a smaller number of tasks at the Moon
Risk	Higher risk with more operations at the Moon in base build-up phase	Lower risk in building up the Moon base from large elements assembled at the NISS
Rescue service	On the Earth's surface limited by weather windows and launcher countdown	From the NISS: faster response, almost permanent launch window, shorter countdown
Supply service	Supply of stores also limited by launch window and launcher countdown	Fast emergency or reaction supply of critical stores kept at the NISS
Cost	High due to repeated uses of launchers and re-entry capsules for each Moon supply mission	Fewer heavier launches of larger amounts of stores to the NISS
Frequency	Low because each direct flight to the Moon needs a powerful rocket and a payload to justify it	Frequent small or larger packages can be flown to the Moon from the NISS by small thrusters
Conclusion	Higher risk during assembly of Moon base, poor reaction time to emergencies and high cost of sustainment operations	Lower risk with faster assembly of Moon station, and faster reaction emergency/rescue service, less costly provision of regular supplies

Table 3. Multiple uses of the new iss

<i>Mission</i>	<i>Benefits</i>
Mars Mission	Assembly of a spacecraft with redundant modules, enhanced radiation protection, and added elements for orbital, landing and Mars base flights
Moon Base	Assembly of large elements for quick set-up of Moon Base, and provision of fast reaction emergency services and lower cost flexible regular supplies
Earth observation	Assembly of large platforms with multiple and/or high- resolution sensors
Telecommunications	Assembly of large satellite clusters with high data capacity, high-power emissions and extensive on-board capabilities or storage of complete constellations of small satellites to be launched in similar or dissimilar orbits
Space science	Assembly of spacecraft with large antennas and provision of high-power and repair facilities for those that remain attached
Other missions	Enabled by large scale assembly and check-out, large power supply and radiation protected environment close to the Earth
Availability	For large or small mission and experiments, national modules, and advances in human space exploration

2. Critical examination of three current options

A brief analysis is made of the main benefits, risks and challenges of three missions for the future of manned space exploration: (Subsection 2.1) sustained presence at a lunar base (mission I); (Subsection 2.2) manned flight to and from Mars (mission II); (Subsection 2.3) new space station with assembly and workshop capabilities besides habitation and experimentation (mission III).

2.1. Support for sustained human presence on the Moon

The flight to Mars (mission II) and a sustained return to the Moon (mission I) share similar issues with very different travel times and spacecraft sizes favoring a sequential approach. The issues of radiation hazard, risk of failures, cost and flexibility that challenge the Mars mission (Subsection 2.2) also apply to sustained Moon presence on a more manageable or less challenging scale. An important difference between the current Artemis initiative and the historic Apollo program is the existence of a permanent cislunar support station as a waypoint facilitating descent to and ascent from the Moon and various forms of resupply. Something similar could be conceived to support human Mars exploration with more significant design challenges and longer operational time scales.

A permanent or long-term manned station on the Moon would also be exposed to solar radiation and events [19–30]. Unlike the Mars mission that spends part of the time farther from the Sun with somewhat lower radiation levels, the Moon presence stays at a comparable distance. The Moon station could be dug underground offering radiation protection except during the building period and at entry and exit. Hopefully solar events would not occur on those periods. The construction of a deeply buried station on the Moon could be facilitated by using local materials and limiting to the minimum what must be brought from Earth; having astronauts in a “mine” reminds of less fortunate experiences of miners on the Earth, in this case with less accessibility for a “rescue” on the Moon.

Turning to the delicate matter of possible need for “rescue missions”, it is an issue that cannot be ignored for long-term lunar habitation. Astronauts are a strictly selected breed of “super humans” with exceptional health, but not totally invulnerable to illness. Broadening space access to more “ordinary” humans is inevitable if space exploration is to be extended beyond the select few. The risk of a serious health problem requiring attention cannot be dismissed for long term habitation of the Moon. Also, a Moon base could be the site of an

incident or accident, like blocking of the access to an underground inhabited space leaving people inaccessible and requiring external rescue.

Sending a rescue mission from the Earth means waiting for a launch sequence maybe lasting hours or days until there is launch window. If weather is unfavourable the difficult option is either (i) to delay an urgent rescue or (ii) to start a rescue operation in adverse weather that is another risk in itself. Rather than being faced with almost impossible choices in a Moon rescue mission from the surface of the Earth, a similar rescue mission from an Earth (or Moon) orbiting space station can be a much faster and safer assured response.

The risk of random failures in a long-term mission applies both to the Mars spacecraft and Moon base. The difficulties in ensuring redundancy or reconfiguration also apply with one difference that the Moon base could be replenished and upgraded gradually. However, should working on the Moon, such as building up habitation and repair facilities be attempted without first proving it on Earth's orbit? And could repeated flying payloads from the Earth surface to the Moon station be effectively supplemented by supplies pre-stocked in Earth's orbit providing a back-up or a choice of alternatives? And if a large structure is needed on the Moon should it be assembled there exposed to the solar wind? Would it not be better to assemble in Earth orbit protected by the Earth's radiation belts and then fly to the moon? All the arguments on the Mars (Subsection 2.2) and Moon (Subsection 2.1) missions point to another alternative: a space station in Earth orbit with spacecraft assembly capabilities besides human habitation (mission III) is the logical precursor (Subsection 2.3). Thus the three missions are complementary rather than alternatives in a sequence starting with sustained lunar habitation (mission I), whose expansion would be supported by the NISS (mission III) adding to the safest background for the more challenging Mars travel (mission II).

2.2. Manned space mission to Mars in a large spacecraft

The Apollo Program [14,16] still stands several decades later as one of the greatest success of human space flight, and perhaps the biggest human achievement in space due to its combination of advances in every area from technology to physiology. The manned exploration of Mars requires a large spacecraft with long endurance and stretches the Apollo model of launch from the surface of the Earth and re-entry of the Earth's atmosphere on return as this would require a super heavy rocket at the limits or perhaps beyond the scale of SLS/Starship/New Glenn comparable to Saturn V; the Mars travel significantly scales up all the challenges, of which five are mentioned: (i) radiation hazard; (ii) risk of failures; (iii) mission duration; (iv) high cost; (v) lack of flexibility.

The Apollo mission to the Moon left astronauts exposed to solar radiation for about a week whereas the Mars mission would extend the period of vulnerability to up to 1-3 years unless alternative non-chemical propulsion methods (nuclear, solar sails, other) can provide higher speeds. Solar radiation events, like flares and coronal mass ejections [19–25] are not predictable on the scale of weeks let alone years; the only thing that can be predicted for sure is that the longer the mission the greater the risk of major solar event generating more energetic particle streams in the solar wind [26–30]. The weight and volume of physically shielding a spacecraft depends on the desired level of protection against high intensity radiation and particles. This leads to delicate assessment of what level of protection to implement and hence what level of risk to accept bearing in mind the weight and size of passive radiation shielding, suggesting that a complementary approach may be needed (Section 7).

Another issue where flight duration is a critical multiplying factor is the risk of random failures in a complex ensemble of tightly packed systems that a spacecraft must accommodate with minimum volume and mass; the low risks that are acceptable in a short mission lasting a week may be too high in a multi-year mission requiring much higher levels of reliability, or even redundancy. In a tight space capsule: (i) there is limited scope for large scale redundancy, like duplicate crew or support capsules; (ii) the risk of random failures and their spread in some cases is hard to counter for a long lifetime.

The high-cost of a Mars mission is probably inevitable, but might be reduced with spacecraft assembled in-orbit from elements launched from the surface of the Earth, still raising multiple questions: (i) how the cost fits in the budget of any single nation or international collaborative effort? (ii) how to maximize the number and added value of each new mission within a fixed overall budget? (iii) how to avoid that high cost or cost escalation extends the program over time and delays the achievement of its goals? (iv) is adding a new capability, e.g. landing instead of orbiting Mars another expensive (or hardly affordable) decade long development of a larger spacecraft with an even more complex and expensive in-orbit assembly?

The preceding questions raise the issue of flexibility: (i) is the launch from the Earth and in-orbit assembly of spacecraft for Mars exploration going to lead to missions spaced too long with each of them with a budget stretching cost preventing higher frequency? (ii) is there no better way to perform more flights, more frequently, at lower cost and with less risk every time? (iii) must Mars exploration as a significant step beyond Moon habitation lead to the much higher cost in comparison? The comparison of the Mars vs. Moon exploration shows that both share similar problems of radiation exposure, risk of failures, cost and flexibility; these points suggest for long term sustained Mars exploration (Subsection 2.2) and large scale permanent lunar habitation (Subsection 2.1) could both benefit from a NISS as discussed next (Subsection 2.3)

2.3. Space station with workshop facilities orbiting the Earth

The space station(s) orbiting the Earth may not have had the resounding publicity deserved and enjoyed by the Apollo program but might have contributed as much if not more to progress in human space exploration. The gradual evolution to the current international space station (ISS) is as worthy of consideration as any successor to the prestigious Apollo program. The end of life of the ISS towards 2030, could lead to more 'fragmentation': besides the on-going Tiangong Chinese space station, other countries could seek a national space station (SS) like a successor of the Mir SS in the case of Russia or an unprecedented new SS in the case of India. The multiple current activities on 'in-orbit' servicing include refuelling, repair and debris removal, and possibly smaller commercial space stations, that advance technologies beyond the current ISS, although on a more modest scale. If the ISS is to have a worthy successor its development should allow a seamless transition without loss of experience of astronauts and operators or discontinuity in the practice of their highly specialized and very demanding skills. The modules of the current ISS might not be usable in a NISS due to leaks, corrosion or degradation, and even if still in acceptable condition might not have sufficient life left and represent outdated technology made obsolete by more efficient modern design. With or without partial re-use the experience in design and operation of the current ISS together with advances in in-orbit servicing can guide the development of a NISS with scale and capabilities far beyond the ISS, or any of its less capable 'rivals', that put nationalism ahead of innovation or development of more advanced technologies than currently exist.

To represent a significant advance over the ISS and existing or planned national SS, the new ISS (NISS): (i) could as needed have a part, similar or expanded habitation and experimentation capabilities compared with the current ISS; (ii) must add the essential capability to assemble and service spacecraft from major assemblies launched from the Earth. The new capabilities of the NISS might or not include fabrication in space, that could be the next step but should allow: (i) assembling from smaller components a large structure that could not be flown in one-piece from the Earth, as was done on a very large scale with the assemblage of the ISS using the SS; (ii) launching and retrieving a single or multiple spacecraft to the Moon (mission I) or Mars (mission II) or others as an extension of what is already done with ISS crew and supply missions from the Earth. Both capabilities (i) and (ii) are extensions of what has been done on low Earth orbit for decades, and with no more risk than direct flights to Mars or a Moon base from in-orbit assembly of components launched from the surface of the Earth.

The NISS should be a new optimised design benefitting from the experience with elements from the current ISS, depending on the need for compromises to reduce costs or enable multinational participation. The current design of the ISS could be partly redesigned, adapted or reproduced, including (Figure 1) the improvements suggested by current experience, as concerns habitation and experimentation facilities. The new part of the NISS beyond the capabilities of the existing ISS would be the facilities to assemble and service spacecraft, which in fact could use similar technologies with a different geometry, say instead of a truss with habitation modules, a square or rectangular work bay with attached workshops. The workshop section would use robotic arms bigger than those already available and larger storage areas. The additional power requirements would be satisfied by additional set of solar panels inevitably larger than in the current ISS with updated technology as appropriate. The NISS could consist of large modules, such as: (i) modules possibly comparable to those in the current ISS for solar panels and crew modules; (ii) mostly or totally new modules in the NISS for workshops and storage; (iii) the modules (i) and (ii) could be repeated one after the other to expand the habitation and workshop facilities as needed.

Thus the NISS would update and advance ISS experience minimizing risk, development time and cost with flexible extension possibilities together with totally new elements enabled by more recent technologies. It could be developed on a flexible budget and timeline with costs no higher than Mars or Moon base missions. It might require a larger initial investment to complete a NISS with all the habitation and workshop facilities, but also enable the Mars and Moon flights to be accomplished with less risk, lower cost and more flexibility, thus resulting in lower overall cost in the longer term, as more missions are implemented beyond a break-even point. The NISS spacecraft assembly and test facilities would apply to smaller and intermediate missions that would provide valuable in-orbit experience towards assembling the larger Mars and Moon base missions. The large investment in the NISS should not be duplicated, as in the past US-USSR and current US-China Moon races, opening the way to either in collaborative or national contributions, like the European, Japanese and Russian modules today in the ISS and possibly others in the NISS bringing in more or less partners depending on the politics of international cooperation.

3. Four criteria for comparison of 3 missions

The three missions (Section 2) of (I) lunar sustained habitation (Subsection 2.1), (II) in-orbit assembly of spacecraft for Mars (Subsection 2.2) and (III) new ISS (Subsection 2.3) are compared by four criteria of (i) safety (Subsection 3.1), (ii) cost (Subsection 3.2), (iii) scalability (Subsection 3.3) and (iv) flexibility (Subsection 3.4). There are several other important aspects of human space exploration including: (v) recycling and use of in-situ resources; (vi) microbiological approaches versus physicochemical approaches; (vii) use of raw materials to produce substances essential for sustainability; (viii) sustainability rating for space missions. Although the importance of aspects (v) to (viii) is beyond question, they do not provide as strong differentiation between the three missions as the criteria (i) to (iv) addressed next.

3.1. Safety and response to incidents

As space missions increase in scope to a larger number of less physically fit individuals the issues of health and safety become more important; safety may be judged by the total number of casualties or accidents or incidents rather than by their percentage of the total number of flights. If the percentage of mishaps remains constant, the total number rises in proportion to the number of flights or individuals involved, and may become publicly unacceptable. As in aviation, as the number of 'air' or 'space' travellers increases, the safety must improve to compensate, and prevent an increase in fatalities.

A comparable level of safety should be achieved for the three missions, regardless of: (i) distance from the Earth: smallest for NISS (III), intermediate for Moon (II) and largest for Mars (I); (ii) flight duration: shortest for Moon (I), intermediate for Mars (II) and indefinite

for NISS (III). Whereas the three missions might not differ much in absolute safety, more significant differences might apply in the ability to respond quickly and effectively to an incident or emergency.

Examples of emergencies that can occur for long term Moon exploration, be it (i) an Artemis-type mission, (ii) stay at a Gateway orbital outpost or (iii) permanence on a ground base are given at three levels: (a) a serious illness of an individual that cannot be treated locally; (b) a malfunction of an equipment or system critical for collective habitation; (c) a major event such as a 'moonquake' caused by collision with a meteor. In the case (a) evacuation of an ill individual from the Moon base to a Moon orbiting station would be quickest, but if medical care was not available the NISS might have better medical facilities, short of a return to Earth. In the case (b) of malfunction of an essential equipment the orbiting station might have a spare, if not the larger NISS would be more likely to have it, short of being sent from the Earth. In the case (c) of a major mishap the response from the Moon orbiting station or NISS orbiting the Earth could be quicker than launch from the Earth due to: (i) time to ready the launchers and payloads; (ii) having to wait for a launch window; (iii) limited number of launchers, launch pads or launch sites available. Overall, the NISS is the best combination of quick reaction and rescue capacity, comparing with a much smaller and less capable Moon orbiting station and the theoretically unlimited capacity but slow reaction of Earth based launch.

Besides the Moon exploration emergency, another unwelcome scenario to consider would be a mishap on the way to Mars, probably more difficult to resolve than the narrow escape in a well-known Apollo mission. In the case of a mishap on the way to Mars, on the return from there or when orbiting the red planet, the NISS could provide a faster response than launch from the surface of the Earth for the same reasons as before. This assumes that the NISS would have permanently ready a Mars as well as a Moon rescue capsule, sized for very different flight durations. This time difference could be more important the farther the Mars spacecraft was to the Earth. If the Mars spacecraft was far from the Earth a rescue flight launched from the NISS with high specific impulse could provide rescue faster than surface launch with a less powerful four stage booster. In the Mars and in the Moon flight case the NISS would provide the best combination of quick and effective rescue capability, that may be the key element in public acceptance of widespread space travel. Besides the unquestionable priority on safety, the aspects of cost, scalability and flexibility are also considered.

3.2. Cost per mission and campaign

Concerning operational cost per flight, for a small number of flights with similar scope, direct launch from the surface of the Earth has the lowest cost. For longer term exploration of the Moon, an orbiting station or gateway as currently envisaged in the Artemis program would certainly be more cost effective. For a large number of flights to the Moon and Mars, assembly at a NISS would allow re-use of the same spacecraft for several flights instead of spending one spacecraft and one launcher for each flight. The economies of scale of reusable spacecraft over campaigns with many flights could more than compensate for the higher initial cost of setting up a NISS, with assembly, launch, retrieve and repair facilities. The break-even number of flights beyond which the use of the NISS as base for Moon and Mars missions becomes more economical depends on: (i) the initial research, development and manufacturing cost; (ii) the cost saving per flight with reusable spacecraft based on the NISS versus expendable spacecraft launched from the Earth. Whereas (i) could be highest for the NISS and reusable spacecraft, the (ii) savings per flight and avoidance of expendables should predominate in the long term over the large number of flights required by sustained human space exploration. The initial cost of the NISS would be determined not only by research, development and production costs, but also by the number of launches needed to put in low-Earth orbit the components for its assembly; once the number of flights started from NISS is sufficiently high the initial cost would be amortized, and a much larger number of flights could be supported with

much less outlay than launch from the surface of the Earth. The cost advantage of the NISS (mission III) over launch from Earth to Moon or lunar gateway (mission I) or in-orbit assembly of Mars spacecraft (mission II) is increased on account of scalability (Subsection 3.3) and flexibility (Subsection 3.4).

3.3. Scalability over size and time

Launch from the surface of the Earth dictates the size of the rocket from the payload weight and volume. The SLS of NASA, Starship of SpaceX and New Glenn of Blue Origin represent the payload and performance capabilities of new super heavy launchers. Their launch capacity is sufficient for the direct launch to the Moon and in-orbit assembly of Mars spacecraft, possibly supported by intermediate steps like in-orbit refuelling or a gateway. If the colonization of the Moon is envisaged on a large scale, the size and weight allowed in a payload faring will soon become a limitation, not just due to high cost but also the inability to carry larger or heavier items. If the missions to Mars evolve from just a return flight to long term stay or a permanent base, in-orbit assembly may be overly complex with increasing risk of being jeopardised by a single point failure.

Large scale space exploration and habitation will require ever larger and heavier spacecraft that simply cannot be launched in one piece by a rocket from the surface of the Earth or easily be assembled in-orbit as a free space process without supporting infrastructure of an NISS. Space-based assembly of large spacecraft from components launched from the Earth is probably unavoidable and a good way to do so is to use the NISS. The rapid progress in 'in-orbit' servicing, refuelling, debris removal and other missions validates the kind of technologies that could be used on a larger scale in the NISS to assemble complete spacecraft. Thus, space exploration and habitation could reach larger scale through the use of the NISS for assembly and support of interplanetary spacecraft missions. The issue of scalability is closely associated with that of flexibility.

3.4. Flexibility for diverse missions

Large scale space exploration and habitation will require several types of spacecraft for Moon and Mars flights to carry people, equipment and supplies. This need will be best served by a family of modular spacecraft, combining different habitation, life support, propulsion, cargo and equipment modules in various combinations to meet diverse requirements. Launching different combinations of modules from the surface of the Earth would be costly and inefficient and they would have to be assembled in-orbit in any case. A more practical, quicker and economic solution would be to launch once for all the modules to be stored at the NISS, and to use and reuse these modules to assemble different spacecraft suitable for diverse missions. As concerns the four criteria of choice it has been argued that the NISS is (mission III) that which provides faster and more effective rescue capability (Subsection 3.1), leads to a lower long term cost per flight in spite of larger initial investment due to reusability for a large number of flights (Subsection 3.2) and provides benefits in scalability (Subsection 3.3) and flexibility (Subsection 3.4) that are not attainable in the other 2 options. Besides supporting the Moon (mission I) and Mars (mission II) exploration, the NISS (mission III) can have other uses ranging from Earth services to space science.

4. Roles and missions of the new international space station (NISS)

The NISS could thus be used (Section 4) to sustain multiple Mars (Subsection 4.1) and Moon base (Subsection 4.2) flights with lower risk and cost, and higher frequency and in addition concurrently enable smaller intermediate missions by a single nation or a partnership of some of the NISS users (Subsection 4.3).

4.1. Moon base with fast reaction support from the NISS

A Moon base must either use local materials or be assembled from components launched from the Earth, in the latter case with two options: (i) launching directly from

the Earth surface “small components” to the Lunar Gateway or surface and assembling a large number of them in a weak Moon gravity exposed to the solar wind; (ii) assembling large elements at the NISS in Earth orbit protected by the ionosphere and flying them to the Moon for a faster and safer final assembly from radiation protected structures. It is clear that assembly at the NISS is preferable in every respect: (i) better facilities for assembly; (ii) safer environment; (iii) less risk.

The issue of the possible need for rescue mission again points to the advantages of the NISS: (i) it can stock spares and supplies for the Moon base to be delivered at shorter notice than possible from the surface of the Earth; (ii) it can accommodate a permanent “rescue team” able to access the Moon base without waiting for launch windows and launch sequences of a rocket based on the Earth surface; (iii) the “rescue team” can respond faster to medical emergencies at the lunar base with patient return to better facilities at the NISS or to the Earth; (iv) the “rescue team” at the NISS could provide a safety of last resort also for the Mars mission, if all safety layers of the latter had been exhausted, and it was not too far from the Earth; (v) the ability of the rescue team to reach far and fast into space could be enhanced by using the Mars spacecraft propulsion in a rescue vehicle (as is done with submarines in the ocean).

The NISS could support simultaneously the mission II of the Mars mission and mission I of the Moon base because: (i) the cost of each flight would be lower making concurrent new Mars and continued Lunar exploration possible with affordable budgets; (ii) although the “complete” Mars and Moon spacecraft could have distinct “architectures” and modules of different scale due to mission duration, some of the more basic components could be common; (iii) another difference between the Mars and Moon spacecraft could be level of redundancy (two crew capsules instead of one) or size of the supplies; (iv) the smaller scale components (emitters, receivers, actuators, sensors, ...) could form common families for the NISS and Mars, Moon and other spacecraft; (v) these common components would replace the one-of-a-kind design forced by close-packing constraints of capsules launched from the Earth surface; (vi) the common components would reduce development and production costs, increase reliability through more extensive testing and use, and would provide a standardized set of spares and replacements; (vii) the size of the store of spare and replacements would depend on the mission: a large stock at the NISS, a smaller one at the lunar base, and a choice made to measure for long duration Mars-like or short duration Moon-like flights.

The multiple concurrent uses of the NISS not only for Mars and Moon missions but for many others can raise issues like interference, contamination and stabilization. For example, “launch” from the NISS might not use chemical or ionic propulsion, to avoid contamination; instead, a hydraulic ram would separate the Mars or Moon or other spacecraft, whose propulsion system would be activated at a safe distance [35,36]. The reaction motion of the “very large” NISS to the launch of even a “large” spacecraft would be moderate and within the capabilities of the NISS stabilization system. The issues of electromagnetic interference within the ISS/NISS and with attached payloads and spacecraft have been addressed with every space station, and the NISS would evolve in opposite directions of more power (worse for EMI) and more space (better for EMI). A large NISS could have dedicated or moveable “Faraday cages” for assembly in “EMI-free” environment. A price to pay for the flexibility afforded by the use of the NISS would be that some spacecraft assembled or serviced there could need some “de-contamination” or “de-magnetization” capabilities to be used when sufficiently far from the NISS.

4.2. Launching and retrieving the Mars missions from the NISS

The NISS could be used to assemble Mars mission modules into a spacecraft or an ensemble of them with far superior capabilities beyond what can be put together, in free flight in orbit, from components launched from the Earth’s surface, thus addressing much better the issues of (i) radiation hazard, (ii) risk of failures, (iii) mission duration, (iv) cost and (v) flexibility. A larger and heavier shield could be assembled in Earth orbit providing

greater radiation protection for the mission to Mars than what could be packed and lifted in orbit free flying assembly. Also, the Mars mission could include (Figure 2) an auxiliary “plasma generation capsule” ionizing the solar wind and creating a “local ionosphere” to shield [30,31] the main inhabited spacecraft as on the Earth. To be more precise: (i) the manned spacecraft would have a physical shield to protect against the “average” solar wind with a good safety margin; (ii) the additional unmanned capsule flying between the manned spacecraft and the Sun would ionize the solar wind and create an “ionosphere” protecting the manned spacecraft in its wake during periods of high solar activity; (iii) the plasma or “ionosphere” protection would be activated only when a major solar event was detected and would act in advance of the higher intensity particles and radiation reaching the Mars capsule(s); (iv) the ionized shield would be switched-off when no longer needed to avoid interference with electromagnetic waves [32] and disruption of communication with the Earth. This possibly novel idea is reconsidered in more detail subsequently (Section 7).

The Mars spacecraft could be built of several modules besides the plasma protection capsule; the main habitation ensemble could consist of several modules physically linked or flying closer or farther from each other, as may be more appropriate. For example: (i) two manned capsules would be linked, so that astronauts could evacuate from one to the other in the case of failure in one of them; (ii) the two service modules could be separated to minimize the risk of a failure in one affecting the other; (iii) these modules or another could carry essential spares to allow local repair by replacement, to restore redundancy after one failure. In this way the Mars mission would have a level of redundancy, re-configuration and restoration after failure providing much better safety against failures in a long duration mission.

If the Mars flight was “launched” from orbit it could incorporate a propulsion module, chemical, nuclear, ionic or other like solar sail. A flight launched from the Earth to gravity escape speed of 11 km/s would take 2-3 years to Mars and return. Fitting a propulsion module in a “launch” from the NISS would enable acceleration to higher transit speeds and the corresponding deceleration near Mars thus shortening the travel time and the exposure to radiation and reducing the risk of random failures. A good compromise between the choice of propulsion and braking module and the design of crew, service and other modules would minimize risk by combining redundancy and radiation projection over a shorter mission time. The configuration of the Mars spacecraft could change according to mission, e.g. orbital or landing, a separate capsule for communication outside the “local ionosphere”, etc..

Concerning cost, a large proportion in a Mars spacecraft assembled in-orbit with components launched from the surface of the Earth is associated with: (i) accelerating through the atmosphere at launch; (ii) thermal protection [33,34] from an 11 km/s re-entry speed on return; (iii) these “atmospheric” flight phases (i) and (ii) are the most demanding and damaging, make re-usability either very expensive (witness the space shuttle) or not feasible at all. Launching from and returning to the NISS relieves the constraints (i) to (iii) from the Mars mission: (i) the Mars spacecraft or its components do not need to fly through the Earth atmosphere, only the components to assemble it in orbit the first time, with reusability thereafter; (ii) the Mars spacecraft returns to the NISS and is not damaged by re- entry into the Earth atmosphere, only the astronauts need return to Earth in the usual NISS crew module; (iii) the whole Mars spacecraft is re-usable instead of expendable components for return to the Earth; (iv) additional missions, like orbiting or landing, mean adding modules to the Mars spacecraft, not designing and assembly more components in orbit.

The advantages in flexibility in launching the Mars flight from the NISS rather than components assembled in orbit are quite significant: (i) even the first Mars spacecraft assembled in orbit at the NISS may turn out to be more precise and reliable than free flying in-orbit assembly; (ii) the Mars flight from the NISS is better radiation protected, has more redundancy and is shorter in duration, so can be repeated more often; (iii) each Mars flight after the first is cheaper because it uses the “same” Mars spacecraft rather than building

in orbit another spacecraft; (iv) the progress in Mars flights, orbital, landing, etc. is faster because it means adding modules not making ever larger and more complex free flying in-orbit assemblies with higher risks of failure. The launch and service capabilities of the NISS are beneficial not only for the Mars (Subsection 4.1) and Moon (Subsection 4.2) flights but also for many others (Subsection 4.3) ranging from Earth services to space science.

4.3. NISS use from Earth services to space science

Adding to the habitation and experimentation capabilities of the ISS the workshop assembly and service capabilities of the NISS greatly broadens the scope of its potential uses, from mainly human space flight to just about every aspect of space services and exploration, as shown by the following examples of: (i) telecommunications; (ii) Earth observation; (iii) space science. The capabilities of telecommunications satellites have seen an impressive never-remitting growth in power, capacity, frequency coverage, number of channels, type of services. . . This progress has been enabled by advances in electronics and computing, together with increasing size and weight of satellites, driving the development of launchers with bigger payload shrouds and larger mass in orbit capabilities. On the other hand, advances in miniaturisation have enabled constellations of small satellites to provide services comparable or beyond the capabilities of large satellites with greater flexibility, redundancy and freedom in orbits. The NISS could be of use both for large satellites and for mega constellations of small satellites. The feasibility of in-orbit assembly at the NISS of large telecommunications satellites could be a gradual or step change increase in payload capability of launchers; it would virtually remove size and weight constraints, by allowing more components to be joined. The NISS could also store small satellites and launch complete constellations or individual replacements.

Concerning Earth observation and surveillance a permanent limitation is the size of antennas and structures that can be fitted or folded into the payload shrouds and do not exceed the weight-in-orbit capabilities. These may dictate the use of complex deployable space structures and force the design of compact sensor and electronic packages with EMI, cooling and other challenges. The deployment of large space structures folded into smaller payload capsules for launch from the Earth implies: (i) the risk of jamming or failure of the deployment mechanism; (ii) in the case of successful deployment, vibrations may be triggered that are challenging to damp out in the vacuum of space requiring active control systems; (iii) the latter may be needed for accurate pointing and to compensate other causes of vibration like transition from solar shadow to radiation zones. Using nearly self-sufficient modules with simple interconnections that can be performed at the NISS, it would be possible to assemble satellites with enhanced capabilities for a variety of Earth services.

These arguments also apply to space science flights with some qualifications. The objective of most space science missions is (i) to deploy detectors with the greatest possible sensitivity and resolution while avoiding (ii) contaminations and operating interferences that might limit their performance. Assembly at the NISS would allow larger antennas and telescopes to be used than is possible in a single launch provided that the assembly process meets the required tolerances. Also, EMI effects or chemical contaminations might have to be corrected by de-magnetization and decontamination after separation from the NISS. Space science missions not too affected by contamination could remain attached to the NISS benefiting from its ample power supply and service capabilities, that cannot be reproduced in free flight where point failures may be more difficult to overcome. Both in NISS-attached form or free flight, the choice would be whether overcoming EMI and contamination issues would be worth the effort, or to benefit from the size, sensitivity, and resolution of a scientific spacecraft not limited by a single-piece launch from the surface of the Earth.

The NISS would: (i) prolong and broaden the use of the ISS as an habitation and experimentation facility; (ii) enable sustained Moon and Mars exploration concurrently in a safer way, with lower cost and a faster rate-of-progress with more frequent missions; (iii)

enable the assembly of larger satellites or constellations for a wide range of missions ranging from Earth services to space science; (iv) provide an international platform extending the use of existing modules (like the European, Japanese and Russian) to other types of activities involving these or other nations in specific and collaborative efforts, by lowering the current high threshold for effective space investment. The large payload and power capabilities of the NISS could be used to assemble and then launch spacecraft into a variety of orbits and trajectories [37–42] including large sensors for astrophysical missions [43–54]. An example of the use of the NISS as a support for a large array of sensors of different types would be to improve our knowledge of the Earth's atmosphere that is better at lower altitudes below 15 km and space orbits above 200 km than of the intermediate altitude band 15-200 km that is of interest for many reasons including climate change; a space station could be a base point for both remote and in-situ observations. Lowering the access threshold for major space activity could bring more talent and resources to space exploration as an endeavour for the whole of mankind. The use of the NISS could extend beyond the next generation of missions to the Moon and Mars and become an essential base in an even longer term (Section 5).

5. Two long term objectives

Two long term objectives, that apply not only to the next generation of Moon (epoch iv) and Mars (epoch v) missions, but also to whatever follows are: (Subsection 5.1) having a near-Earth laboratory safely below radiation belts to test space exploration and habitation systems before their use in more unprotected outer space; (Subsection 5.2) to free human expansion into space from the constraints and limits of the Moon and Mars, and other existing astronomical bodies, by developing free flying habitats. The NISS is the natural stepping stone to both objectives (subsection 5.3).

5.1. Near-Earth proving ground

Space technology is an extrapolation of aeronautics beyond the Earth's atmosphere and can benefit in many ways from that background. In aviation there is a ground test aircraft with more experimental hours than any flying aircraft has reached to provide advance warning of potential problems or failures. By the same reasoning any equipment or system for long term space exploration and habitation could be dully tested in a near-Earth environment before being sent to outer space. The NISS would provide a suitable testing ground in a space environment protected by the Earth radiation belts before venturing into outer space. The testing at the NISS should exceed in number of hours all similar systems sent to outer space. The tests at the NISS could extend to controlled simulations of failures and incidents that could occur in outer space but cannot be tested there. It should not be expected that testing at a NISS, protected below the Earth radiation belts, would be representative of the harsher conditions in outer space; but it could be a useful intermediate step, requiring a smaller step of extrapolation than ground testing. A major accident in outer space could be explained by testing and simulation on the ground and at the NISS to find a solution. In this way the NISS would become the essential intermediate testing, validation and simulation laboratory between ground testing and outer space missions.

5.2. Free space habitation

The eventual large scale habitation of the Moon, Mars or other celestial bodies, if the harsh conditions prevailing there can be mastered, may be a means to overcome the 'saturation' of the Earth. However, the Moon is much smaller than the Earth and Mars no larger, so their limits can be reached in a shorter or comparable time to the Earth's, besides facing more difficult environments. Other planets are even less hospitable than Mars and a multitude of asteroids less reachable than the Moon. The pre-conception that space habitation has to be 'attached' to an existing astronomical body soon reproduces the limitations of the Earth that was intended to overcome. Would life be conceivable in a self-contained self-supporting free flying space station grown to the size of a city, a nation

or a planet? Building a large habitable community on the Moon or Mars would involve much the same major challenges than making it free flying, apart from the use of some local materials, in addition to those that would have to be sourced and brought from elsewhere. Free space flying might be immune to natural disasters, like earthquakes, floods and storms that all the modern technology still cannot master. The free space flying habitation would be limited only by the raw materials needed to build it and the large-scale assembly of a human friendly environment. The NISS can be viewed in the long term as the human space habitation module, that does not depend on being 'attached' to anything and can be developed safely within easy reach of the Earth. That proximity could be relaxed with growing confidence on the ability to build a safe and habitable free space environment, for which the NISS is the initial precursor. This major extrapolation of the use of NISS as first in a long series of stepping stones into free flying large scale space habitation is admittedly speculative in requiring advances in many areas from technology to physiology, and could occur on a long time scale of more than a century.

5.3. Potential contribution of NISS

It is clear from present commitments to the Artemis mission and its US and Chinese alternatives, that the next step in human space exploration is sustained presence on the Moon. The Mars mission is far more challenging than the moon mission, and mastering the latter is a strongly advisable pre-condition before attempting the former. In the meantime, the current ISS will be decommissioned, but the experience with in-orbit servicing is likely to grow with multiple initiatives on a smaller scale. When space budgets allow, post-Artemis or earlier, there will be a valuable pool of in-orbit servicing experience to enable the design of a NISS. Thus the question might be raised: what follows the Artemis program of human lunar exploration, that is a current and hopefully a stable endeavour (although for convenience labelled here mission I)? Will the sequel be 'direct' human Mars exploration (mission II) or via an NISS (mission III) that also supports exploration of the Moon on a larger scale? The preceding discussion suggests that the mission III of an NISS could support both the continuation of the Moon exploration (mission I) and enable concurrently the Mars exploration (mission II). It has been argued that taking mission III is: (i) a safer, less costly and more sustainable way to implement both mission II (Mars mission) and continue mission I (sustained Moon presence); (ii) it is a relatively low-risk, and an inevitable step in human space exploration. The role of a NISS may be placed in an evolutionary perspective (Section 6) of the progress of space exploration (Subsection 6.1) comparing with the past (Subsection 6.2) and future prospects (Subsection 6.3).

6. Evolutionary perspective

The evolutionary perspective of human space exploration relates the mission prospects available at present (Subsection 6.1) to past experience (Subsection 6.2) and tentative preview of the future (Subsection 6.3).

6.1. Different current options

Defying gravity and accelerating payloads through the atmosphere to reach orbital and escape speeds is one of the major achievements of the XXth century; re-entering the atmosphere at these speeds is also a major challenge for materials, control and other engineering disciplines. Rising through the atmosphere to orbit and re-entering it on return consumes an amount of energy far greater than the useful payload. The need for greater payloads puts a disproportionate demand on launchers to the point where the usual practice of sending all equipment together in a single-shot take-all compact package becomes a costly, lengthy and questionable option. A better alternative is to assemble at the NISS the payloads, that also have to be placed in orbit but not necessarily all together at the same time in a tight capsule. Also in-orbit assembly with the supporting infrastructure of the NISS is more reliable than attempting the same in 'free flight' especially for precise operations that may require human presence and control. Also basing missions on the

NISS avoids the damaging and demanding re-entry into the Earth's atmosphere, making re-usability more feasible.

The in-space assembly of spacecraft is an inevitable step in space exploration, that was proven at scale with SS supported assembly of the ISS and has progressed significantly with new in-orbit servicing capabilities. Space exploration involves carrying out more and more Earth-like tasks in a space environment, and validation in the NISS is the transition between on-Earth simulation and far away implementation of missions to the Moon, Mars or elsewhere. An NISS with workshop and service facilities in addition to habitation and experimentation enhances Earth satellite services, opens new possibilities for space science and will advance human space exploration faster by pursuing a path that is not limited by size of payload shrouds and one-shot lifting capacities of launchers. Having increasing launcher capabilities in terms of payload weight and volume continues to be a major area for progress that is not in question, for multiple reasons including the NISS, since launching a smaller number of larger elements will be of great benefit to minimize the need for space assembly as far as it can be reasonably avoided. The issue is not bigger launchers vs space station assembly but rather most cost-effective and sustainable combination of both, and being able to choose between direct launch and space assembly depending on the merits of the mission. The advances in in-orbit servicing can be applied on a larger scale to the NISS.

The Table 1 summarizes the differences between the Mars flight with launch and return of a spacecraft assembled in-orbit from elements launched from the Earth surface (mission II) and the same mission starting from and ending at NISS (mission III). The Table 2 makes a similar comparison for the Moon Base flight with launch and return to the Earth (mission I) and the same flight starting and ending at the NISS (mission III). In both cases the mission III requires flying modules to the NISS and assembling a large Mars mission spacecraft cluster (mission II) or major Moon Base structures (mission I) as an initial effort. From then on, the continued Mars flights or Moon Base activities require less effort at lower cost enabling higher frequencies than repeated launches and returns to the surface of the Earth. The Table 3 list some additional uses of NISS, beyond supporting the

Mars mission and Moon Base, and including a variety of Earth services and space exploration activities.

6.2. Experience from the past

The analogy between space exploration in the XX – XXIth centuries and sea travels in the XV – XVIth centuries extends beyond the pioneering motivations mentioned in the introduction (section 1) to the materials benefits addressed in the conclusion (Section 8). The early sea travels were financed and supported by the princes and kings that had the vision and the resources to sustain high risk adventures with limited short-term benefit; in contrast the long-term benefit was enormous, opening up trade across all continents and starting the worldwide mobility and exchanges that have grown into the present and will expand further into the future. An important part of that expansion is space exploration, that started in the XXth century as superpower rivalry managed by government space agencies to gain visibility, prestige and technological supremacy. The practical benefits can be seen in the extent to which modern society depends on satellites, for communication, navigation, meteorology, environmental and other surveillance, land planning, and myriad other services. Yet the major benefits of space turned towards the Earth could be exceeded in the future by space turned outward to cosmos.

Overcoming the limitations of the Earth and expanding outwards towards the universe is the major task for the future of mankind, which deserves and can benefit from many contributions besides state-funded governmental space agencies, that were essential precursors to spearhead a much wider take-up by other sectors of society. There are several contributing factors: (i) technological advances, like miniaturization of sensors, advances in computing power, new materials and architectures, more efficient propulsion that enable much smaller satellites and space probes to perform as well or better than much larger platforms in the past; (ii) although large space stations and satellites have advantages

of scale in some respects, they can also benefit from the technologies tested, validated and implemented more efficiently at smaller scales; (iii) the age of large civil and military satellites is rapidly transitioning to constellations that are less vulnerable (no 'space Pearl Harbour'), degrade gradually with plenty of backups (no 'single point failures') and can be replaced and updated more quickly using less resources. The growing capability of smaller spacecraft has bred a vibrant community of new private actors besides the traditional government bodies.

6.3. Trends for the future

The first manned landing of the moon was made possible by a large long-term investment in a government space agency, but the return to the moon already sees a hybrid model with the private sector involved in major items. This is an extension of the trend of orbital services to the Earth that once were the exclusive preserve of a few and have become an open and competitive market. The reach of smaller and new enterprises into space exploration beyond the Earth-moon system is also expanding. The expansion into space and exploration of resources beyond the Earth is the new frontier for mankind, that can only benefit from being driven at all scales from government bodies to commercial activities, from large space agencies to small innovative start-ups, engaging in the process wider sectors of society, that do not fully realize (a) how much they already depend on space in their current daily lives and (b) the transformation that space can bring to the dim prospects of an Earth ultimately limited by environmental effects and limited resources.

The current conditions do not favour the near-term implementation of a NISS: (i) the ISS is long past its original design life and shows inevitable signs of age; (ii) the focus of NASA, supported by ESA and JAXA, is sustained exploration of the moon; (iii) China may have 'missed' the ISS but will certainly pursue its Tiangong SS; (iv) the geopolitical tensions with Russia have increased since the start of collaboration in the ISS, with plans for a national successor to 'Mir', in spite of less than prosperous financial situation; (v) India may follow upon its impressive space progress with a national SS to rival others like China. The rivalry between US and USSR at the beginning of the space age may resume with a US and China race to the Moon. The Artemis mission is being re-considered, with cancellation of SLS/Orion after the third flight, in spite of earlier commitments between NASA, ESA and other national space agencies, to be replaced by unspecified commercial programs, presumably extensions of the HLS of SpaceX and/or Blue Origin, possibly as purely national US programs. The indications of instability and varying programmatic commitments leave little financial scope for a near-term NISS, even without the additional obstacles of geopolitical tensions harbouring nationalism versus international cooperation.

However, time and technology may reverse the situation in the mid-term (Section 8) and safe space exploration may benefit from new ideas (Section 7).

7. Plasma generation capsule to protect spacecraft from solar outbursts

One of the risks of human space travel beyond the protection of ionospheric radiation belts is the exposure to direct solar radiation, in particular high-energy and high-velocity solar radiation and wind streams associated with solar flares and outbursts. The orbit of the ISS below the Van Allen belts was chosen to be protected from high intensity solar radiation and high-speed solar wind, allowing long term habitation with low risk. The Apollo missions to the Moon had a window of risk of a few days in outer space, and fortunately solar flares did not occur over such relatively short periods. The situation is quite different in a manned mission to Mars, lasting several months or 1 or 2 years, since over such a long time span solar outbursts are very likely to occur.

The prediction of solar outburst is a challenge with a long history. It is said that German astronomers persuaded Hitler that they could predict solar flares, and thus ionospheric disruptions of long-range telecommunications, which would be valuable tactical and strategic information to plan military missions and campaigns. Regardless of the accuracy of the account it is a fact that in the Nazi period a string of solar observatories was built in

Germany, several of which still exist today. Solar flares and outbursts are a manifestation of magnetic activity [27,55] along the solar cycle for which dynamo theory [27,56], magnetic reconnection [57,58] and magnetoatmospheric waves [59–61] provide possible explanations, but not yet reliable predictive capability. In spite of the recent focus and progress on ‘space weather’, the average solar radiation and wind conditions are better predicted than the occurrence of explosive high energy events. The ability to predict solar flares would be very useful (i) to plan flights to and from the Moon at safe times, and (ii) to warn astronauts on the Moon to take shelter in advance.

Concerning a manned flight to Mars, the ability to predict solar flares, even if it was reliable, would be of little use to protect the crew of the exposed spacecraft. Radiation shields are less effective against high-energy radiation and particles, and there is a limit to the weight and volume that can be accommodated in a spacecraft limited to ‘passive’ protection. This suggests an ‘active’ spacecraft radiation protection system (Figure 2) using a separate module placed between the spacecraft and the Sun as a plasma [62–65] generation source. If a solar flare occurs, the ‘active’ module generates a strong magnetic field creating an ‘artificial ionosphere’ surrounding the spacecraft, and protecting from high intensity solar radiation and high-energy particles, in the same way as the Earth’s ionosphere has protected the ISS for several decades.

Light takes 8 minutes to travel from the Sun to the Earth, and for a spacecraft travelling beyond the Earth towards the Moon, this is plenty enough time to activate the radiation protection, with no need for unreliable flare prediction. The radiation protection of the spacecraft by the artificial ionosphere generated by the ‘active’ module need be implemented only for a limited period, before the high-intensity radiation and high-speed particles from the flare arrive until the energy of the disturbance decays to a safe level. The artificial ionosphere could disrupt communications of the spacecraft with the Earth during these limited periods; telecommunications could be kept at all times using a separate [32] relay capsule outside the artificial ionosphere. The magnetic capsule, and telecommunications relay capsule, need only be active during flares, thus minimizing energy consumption averaged over time, but possibly with high peaks.

8. Conclusion

History has shown that cost estimation of large-scale programs involving advanced technology may not be accurate at the start and can be significantly exceeded at the end and space programs are no exception. The Appollo program cost 25.8 B \$ at the time, equivalent to 318 B \$ in 2023 when adjusted for inflation. The assembly and operation of the ISS for 10 years cost 100 B \$, just 1/3 by comparison. The current Space Launch System (SLS) was expected to cost 14.7 B \$ at the outset, passed 49.9 B \$ recently and may reach 93 B \$ by current estimates. No attempt has been made to estimate the absolute costs of missions I, II and III, although the ‘evolving’ cost estimates and addition of resources in the Artemis program do correspond to mission I. In comparative terms, the cost of a NISS could be comparable to the cost of the ISS; the cost of manned flight to Mars based on the NISS could be comparable to the Artemis program, and higher without the NISS. The cost of each mission depends on the number of flights. The case for the NISS becomes stronger for a larger number of Moon and Mars flights, not only due to enhanced reusability, but also by the ability to assemble larger space capsules.

There is currently a major expansion and progress in space activities including servicing, refuelling, repair, retrieval. A NISS designed in the near-term might not be a major advance on the ISS, but one or two decades in the future, the progress in orbital operations is likely to lead to a far more capable NISS. In the meantime, the sustained exploration of the Moon may evolve from its current pioneering phase to an almost ‘routine’, if it can ever be, activity, based on reliable experience with moon habitation ‘mastered’. The next challenge will be human exploration of Mars. At that stage the NISS will have all the new technology it needs to (a) support Mars exploration in the most efficient way in parallel with (b) expanded lunar habitation, while providing (c) the stepping stone for further

endeavours directed inward or outward from the Earth. The NISS may not be available at the early stages of sustained Moon exploration (mission I) but will enable its expansion to a much a larger scale. The NISS may be from the outset the best option for Mars exploration as follow-on from Moon exploration. The NISS may support simultaneous Moon and Mars exploration and provide more Earth-bound services as well as being the precursor for free space habitation. The NISS could be important as the precursor for space habitation not attached to existing bodies, which would bring the same limitations on the Earth. The long-term habitation of space may be less dependent on existing celestial bodies (Moon, Mars, Asteroids) as ‘anchors’, than on finding the materials and resources to build large free flying space stations up to the size of a city, country or continent, and the ISS and NISS are early precursors. If space colonisation takes too long, conflicts may emerge on Earth not only about environmental degradation but also for access to limited resources.

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