SPACE EXPLORATION CHALLENGES: ARE THEY SHOWSTOPPERS?

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ABSTRACT

We review the difficulties of manned space exploration most underscored by disbelievers: weightlessness, much studied but curiously without attention to most important aspects; radiations, where taking huge uncertainties margins is definitely not the way to conclude; psychological issues, which require further insight but where we have a lot of background; Mars EDL which requires scaled-up or innovative technologies (including possibly payload fractionation), but nothing unpractical. At the program level, safety and development cost are much put into question. Our long spaceflight experience, as well as smart mission architectural choices, leads to safety evaluations which should be acceptable. As for the cost, the program ambition (e.g. crew size) should be adjusted to the partners' budgetary commitments. All in all, the overstatement of these difficulties appears more driven by skepticism about our capabilities and future than justified by a rational and constructive analysis.

SPACE EXPLORATION CHALLENGED

It is often referred to the Apollo program as the demonstration that our civilization is able to explore celestial bodies. This is certainly true as far as technical means are concerned, because even if getting to Mars is more demanding than going to the Moon, we must remember that we were at that time considerably much less prepared. And we must also take into account the invaluable experience gained in successive spaceflight programs since (with the successful ISS as the top). But the societal and political context has changed, and if technical feasibility critics can be opposed on rather sound basis, there remains touchier programmatic attributes, namely safety and cost, which need to be properly scrutinized. Yet these attributes are largely overlooked in most of the dozens of project studies issued since the space era onset.

Now, if the value of manned space exploration is widely agreed, especially in the space community, there are also opponents to the project, including knowledgeable experts. Among those detractors we find individuals who, while having had the chance to experience the development of space activities, seem not prone to plead for further human space endeavors, raising technical hurdles, risks, safety or cost arguments. That said, those negative arguments are more generally devised by experienced engineers or program managers in the frame of their professional activities, which give them full credibility. Yet, closer scrutiny can reveal that they happen to be driven either by cautiousness (not to put their credibility at risk), or by the fear to see their budgets diverted. In some less straight cases, political objectives (e.g. avoiding expenses) appear to stand behind statements.

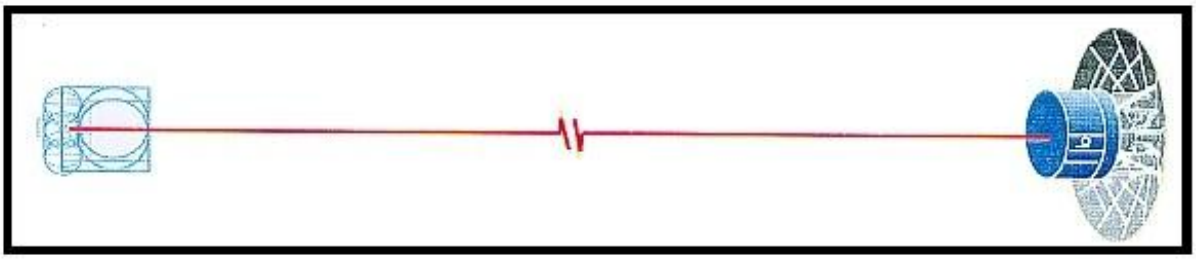
That most of statements, even in science, are not totally devoid of underlying thoughts is a fact; this is also certainly the case of this paper! If ethical of philosophical considerations are at stakes, this adds indeed a human value to what is expressed. But there should be a problem if less noble intents are visible or, even worse, when the reasoning is deliberately distorted.

In light of the consequences of space exploration for our future, for the development of human activities, for innovation and knowledge, as well as for the prospects of peaceful international cooperation and for the sake of youth optimism, it is certainly valuable to discuss the main arguments raised to derail the project. This is done in what follows for the most prominent aspects considered by critics as not manageable in the frame of the project development. Topics still not mastered but which are considered as controllable within a reasonable development effort are examined.

WEIGHTLESSNESS

This subject has been studied till the beginning of human spaceflight. Today it is still topical and one of the main scientific objectives for the ISS, while on the ground guinea pigs continue to perform bed rest tests. Yet, the problem is visibly under control: astronauts are routinely sent to the ISS for 6 months stays, and it has been recently decided to extend this duration to one year for two astronauts in order to test interplanetary flight conditions *(noting that 12 months corresponds to nothing, a transfer to Mars lasting only 6 months)*… This long duration capacity is obtained thanks to counter-measures, mainly through intensive physical exercises aimed at reducing the bones and muscles masses loss. Astronauts endure satisfactorily their 6 months stay, as this will probably be also the case for 12 months. Nevertheless, when they land back, they get a certain number of physiological drawbacks, including balance and orientation deficiencies, as well as cardiovascular misfit. These phenomena are reversible and so considered not significant. So why worry about weightlessness anymore?

A good reason, in the case of the Mars mission, is the question of the crew fitness for the descent and landing phase, as safety dictates that astronauts should be fully fitted at the moment of the final descent, in order to take manual control in case of an anomaly (remember Apollo 11). This is why it has been proposed to create an artificial gravity during the interplanetary transfer, at least for the outbound leg. This can be obtained in a quite straightforward way by linking the inhabited spacecraft to the emptied transfer propulsive stage and having the whole assembly rotating. Several studies, including one sponsored by ESA [1], have shown reasonable dimensioning (e.g. 300 m tether, 3 rpm), compatible with acceptable Coriolis effects, and practical deployment and trajectory correction modes. But, curiously enough, this proposal has been continuously rebutted, with preference given to physiological counter-measures. This is not satisfactory; if this is a means to increase safety (and initial operational phase productivity) then the artificial gravity option should not be ignored but seriously considered.



An artificial gravity concept; the empty transfer stage and the spacecraft, linked by a tether, are put in rotation, creating centrifuge force. Due to the mass ratio of the vehicles, the center of mass is closer to the spacecraft.

(doc. The Mars Society)

Besides this interesting point, there is another even stranger one in the history of spaceflight development. It is widely recognized that the ultimate goal of human spaceflight is to explore accessible celestial bodies (namely the Moon and Mars), with the more distant prospect to develop our presence and activities in the most favorable places. However, almost nothing has been done to understand and verify the physiological effects of a long duration stay in partial gravity! We have been studying zero gravity since 50 years but seem to forget the proper goal of our efforts. Yet, it would be quite simple and not so costly to have an experiment on the ISS, with a small centrifuge (much more reduced in scale than that proposed by the Japanese [2] about ten years ago), inhabited for one month by mice, before returning on Earth for physiological investigations. This is an idea that the European chapters of The Mars Society have proposed to ESA [3], as an answer to its Call for Ideas. When the manned Mars program will be set up, full scale experiments could be made in LEO, aboard of a spacecraft model equipped for the centrifugal device testing.

To sum up, with our wide experience weightlessness is no more a problem, as proven by the recent decisions of a one year long ISS mission. But, strangely, two meaningful points have been overlooked in our decades long effort to master the question, for which affordable ways to begin to fill the gaps nevertheless exist.

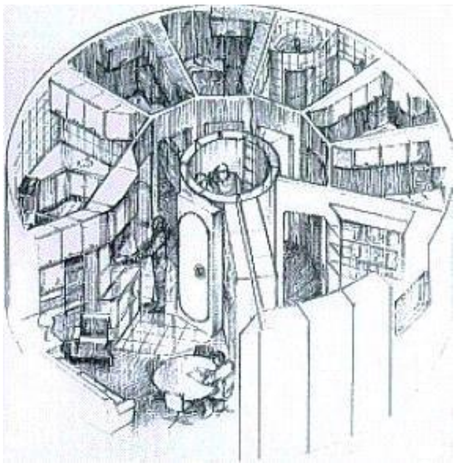
IONIZING RADIATIONS

Much more than the preceding one, this is a concern which needs serious scrutiny [4], for several reasons. The first one is that we still lack a certain number of data about the biological effects of those radiations. The second one is that an interplanetary mission, with long duration in-space transfers, implies an increase of the total incurred dose, when compared to a 6 months ISS stay. And the third one is the fact that the word “radiation” in itself bears such a load of anxiety and irrationality that this question is difficult to discuss, not only in face of the general public, but even between space community members. It is a threatening matter that detractors make use of, even more easily as it is a complex science, touching both physics and biology, where it is rather straightforward to impress people.

The radiations environment in itself is well characterized [5], being for Solar Particles Events (SPE) or for Galactic Cosmic Rays (GCR). And its specific characteristics in the Martian domain, only deduced up to recently through physical models, begin now to be directly measured (Mars Odyssey [6], Curiosity). Those results confirm the predictions, and we can summarize the situation as follows:

-SPE are sporadic infrequent but potentially lethal events, against which it is necessary to shield astronauts; happily, their energy spectrum is sufficiently low that a foot thickness of water, or polyethylene, is suitable. Then, devise a small shielded zone in the habitats where explorers take refuge during the short duration SPE. That’s it.

-Conversely, it is quite difficult to get shielding against the continuous and high energy spectrum of the GCR (even if a 25cm thickness of water - agreed, a quite massive shield for the spacecraft - is dividing the dose by 2).



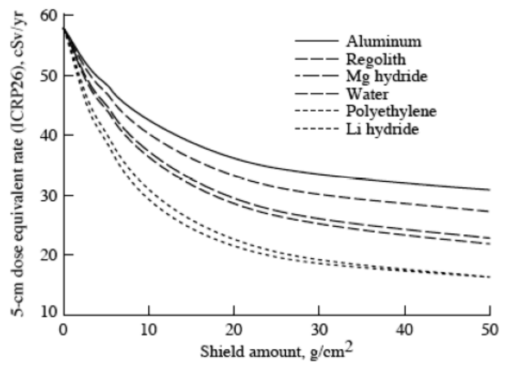


Figure 1. Point estimates of 5-cm depth dose for GCR at Solar Minimum as a function of areal density for various materials (figure1.jpg). (Simonsen et al. 1997)

A small SPE safe haven in the center of the spacecraft, which walls are water tanks and polyethylene. *(doc. Mars Society)*

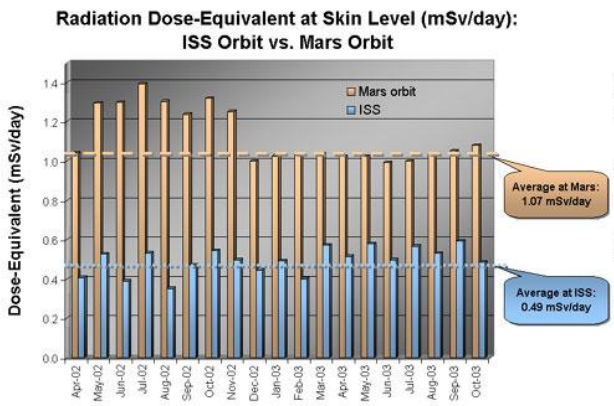
25 cm of water divide by 2 the GCR dose.

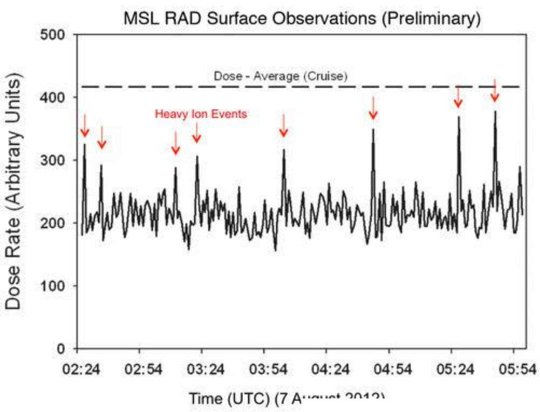
In rough order of magnitude, the doses incurred, compared to LEO (ISS) are the following, as illustrated:

-during interplanetary transfers: ISS * 2

-on the surface of Mars: ISS

being understood that a number of parameters influence the dose: the solar activity, the site altitude…





(doc. NASA/JPL)

-The monthly, yearly and career doses stay within the international regulations limits established for the ISS.

-The main induced risk (increased probability of a late cancer), being statistical and linearly proportional to the dose (no saturation), it is legitimate to consider the risk incurred by the population of astronauts in the course of the program; comparing the permanent 6 crew in the ISS with the 4 crew / 30 months recurrent Mars Direct scheme, we found, over the cyclic 26 months period of the Mars exploration program (ISS_{6m} being the 6 months dose at the ISS):

-ISS: 6 crew * 4.33 times 6 months * ISS_{6m} = 26 ISS_{6m}

-Mars: 4 crew *(4/6* ISS_{6m}* 2 + ISS_{6m}* 2 + ISS_{6m}* 3 + 2/6* ISS_{6m}* 2) = 28 ISS_{6m}

4 last months of preceding mission — *outbound leg* — *planetary stay* — *2 first months of current mission inbound leg*

The total doses are similar; the Mars program is not intrinsically more risky from this point of view. Clearly, other factors (technical and even psychological) dominate the mission risks panel!

But if the physical data uncertainties are being reduced, biological ones still present serious gaps, the most critical being the domain of heavy ions (HZE, e.g. Fe) [7]. Having neglected to investigate this domain is no more understandable than it is for partial gravity. Fortunately, since a few years, NASA has undertaken a dedicated program, creating the NASA Space Radiation Laboratory. Work is also performed in Europe, and within a few years a much better assessment will be possible.

But for the time being, reputed analysts [8] have chosen a quite radical way to deal with the question: considering the uncertainties [9] as given once for all and the statistical nature of the risk, they took as predictive dose the mean evaluation plus 3 standards deviations! Naturally, with such a high figure, regulatory limits are exceeded, to the satisfaction of those prone to play with that fear factor. But, if their process is mathematically justified, it certainly does not permit to conclude to the impracticality of the project, contrary to their assertion; the correct stance would be to say that we presently lack some essential data to guarantee control of the problem, but that there is a good probability to come ultimately to a much less negative conclusion. Furthermore, if the GCR effects during transfers should prove definitely not acceptable, there always remains the possibility to shield the spacecraft, if at the expense of a mass penalty (with 13 T of water, the dose could be divided by 2 within a 4 m diameter sphere).

PSYCHOLOGICAL ISSUES

This domain is generally considered more perplexing than purely technical ones or even, to stay within the realm of human factors, than those of man-machine interfaces or of procedures design.

In the first place, it is recognized that, whatever the sophistication of the selection and training processes, astronauts, as human beings, remain susceptible to develop behavioral or mental problems when submitted to the stressing conditions of spaceflight. Such problems have yet been observed in the long history of LEO spaceflight, as well as in the severe environment of Antarctic stations. Human beings behavior is not totally predictable, and worst cases should be taken into account.

In the case of deep space missions, and more specifically for a Mars expedition, the situation is even more worrying, due to the specific and harsh stressing factors that the crew has to face: long duration, remoteness, radical isolation, confinement (during transfers), promiscuity, limited social interactions, to speak of the most determining. In order to get a truly comprehensive appraisal, it should be nevertheless noted that the 30 months mission to Mars actually is not a 30 months in-space mission; in the middle of this lengthy duration, astronauts will enjoy an undoubtedly exhilarating 18 months exploration phase, visiting scenic landscapes and investigating geologic sites. This modifies the way the mission duration should be considered.

The induced problems include physiological and mental health issues, loss of situation awareness, false judgments and mishaps, group and interpersonal degraded relationship, problems with ground control…

All of those concerns induce, more or less, a risk for crew safety, but also for the mission operational success.
The seriousness of those potential problems, as well as the intrinsic difficulty to fully understand and control the determining factors, demand a special attention. An in-depth study program is required, including an innovative approach [10] where all the project actors are invited, till the design phase onset, to express their concerns and to build a programmatic consensus about what is required, what is acceptable and what is not. Fortunately, such an effort is much less costly when compared to hardware developments, but this is not a reason to consider it as a minor part of the global program. The following parts should be included:

-study of mission specific conditions;
-evaluation of foreseen psychological consequences;
-simulation campaigns in analog sites (on Earth) [11];
-selection process, applied not only to individuals, but also to crew teams as a whole;
-training process;
-habitat design and living environment (including nutrition), a determinant topic, but rather difficult to assess, especially in the case of international crews;
-decision-making procedures, including the balance between ground control authority and crew autonomy;
-human factors related risk analysis.

Provided these psychological issues are taken seriously, we can profit of a lot of (more or less) relevant knowledge, acquired in the course of past spaceflight programs (Apollo, MIR, ISS) but also with the Antarctic outposts and with dedicated efforts, such as the Mars500 simulation ran by Europe and Russia or the Mars Society analog stations in North Canada and in Utah (MDRS). Nuclear submarines experience also is of value.

The Mars500 simulation crew relaxing inside the analog, during its mission. *(doc. ESA)*

The Mars Society Mars Desert Research Station analog, where ESA-commissioned crews trained. *(doc. Heidmann)*

DESCENT ON MARS

NASA did learn to land automatically on Mars payloads of several hundreds of kg, up to 900 kg in the case of MSL. ESA, with its ExoMars program, seeks to gain the same skill. But landing modules (inhabited and not inhabited) the size required by a manned Mars mission presents a new challenge, due to the order of magnitude of the masses to take into consideration: tenths of tons instead of 1 ton. This fact has not been fully appreciated until recent years; for instance, the first issues of the NASA Design Reference Mission (DRM) clearly overlooked the problem. The fact is that, as mass - and size - scale-up, the ballistic coefficient increases, and consequently the atmospheric deceleration decreases, so that at the altitude where parachutes should deploy, the Mach number is still too high to do so. Remembering that the MSL aeroshield diameter was 4.6 m for a total mass of about 2.4 tons, the

practical 10 m limit diameter imposed by future Heavy Lift Vehicles leads to a maximum descent mass of about 10 tons only. Clearly, improved or new technologies are needed.
On this basis, engineers who revealed the problem considered that current technologies (shield, parachutes) were yet at their limits and that new solutions should be applied. Some experts recommended envisioning a very long maturation program (a full generation!) and dictated to include large margins in the vehicles dimensioning [12,13]. As such, in the NASA last reference design (DRA5, 2009), the vehicle thermal protection system mass is taken at 40 tons (without precise justification) and a 15% margin is allocated to the final propulsion propellant load. Those superfluous masses, being positioned very near the top of the masses breakdown, have a considerable influence on the IMLEO and explain the gigantism of this genuine "project killer" (has the lesson from the infamous "90 days study" been forgotten, or was this design study's purpose to postpone space exploration?). Again, as for the margins taken for radiations, proceeding so crudely does not allow drawing a conclusion.
Actually, a lot of avenues for a solution exist. First of all, there is no tangible reason to consider that we have reached the limits of current technologies; still larger and higher-Mach parachutes are conceivable, as well as a cluster of them (as proposed by M.G. Benton) [14]; deployable or inflatable (ballutes) decelerators have been studied; even inflatable large diameter heat shields have been proposed (Babakin Space Center) [15].
Sure, such extrapolations or innovations will need a significant development effort; but the ideas and the means to concretize them are there, and developing such devices is not outside the capabilities of space industry. Anyway, it is not a task for a full generation, and this development duration will easily fit into the overall agenda.
It is also worthwhile to note, should the descent vehicle mass prove definitely unmanageable, that it is conceivable to split the payload between two smaller vehicles, an efficient concept [16], which also presents some drawbacks but which merits to be analyzed. Lastly, some program basic assumptions, such as the crew size, have also a strong influence on the masses (as on the costs) and could be adjusted if necessary.
Yes, descending efficiently (with a high payload ratio) and safely on Mars (on the Moon as well, for different reasons) is a challenge. But it is in no way a showstopper as many ways to face it exist and can be developed in the frame of the program.

SAFETY [17]

For the decision-makers, the crew safety evaluation is a very touchy attribute of any human spaceflight program. It is also very difficult to assess at periods when critical decisions are to be taken (during design, development and initial operations), the domain of human factors being probably the most perplexing. Lastly, safety cannot be measured, and the decision to launch the first operational crew will have to be taken only on the basis of an evaluation, with a certain confidence level. All of this explains why it is not straightforward to speak of and to specify a safety value.
Skeptics' arguments about safety are based on the more stressing characteristics of the mission. The most emphasized of them is the mission duration. Sure, we have demonstrated our capacity to design, produce, assemble and operate equipments at the required reliability level (particularly with the ISS). But maintenance of the spaceships should rely only on the on-board resources and on the crew ingenuity (with consequences on design philosophy), and a rescue mission can be launched only during the next launch window.
In the field of human factors, it is the combination of this duration with the remoteness and the radical isolation that represents the most stressing condition. It is difficult to characterize the magnitude of this category of risks. We can nevertheless rely on our spaceflight experience. Also, a lot is being yet done in simulations.
Another concern is complexity. Compared to ISS ones, Mars (and Moon) missions comprise a much greater number of spacecraft modules and propulsive stages, as well as numerous successive phases

of operation and critical operations. Apart from the mission duration, that in principle can only increase the probability of occurrence of failures or human errors detrimental for safety (nevertheless, the induced mission flexibility also offers a rich spectrum of safety improvement opportunities). The mission architecture options taken in many projects are from this respect quite surprising, as the value to keep it as simple as possible appears largely underestimated. Keep it simple! Go direct.

A lot of alarmist statements have also been made about planetary environment [18], namely dust - lunar or Martian - and possible Martian life form (the topics of weightlessness and ionizing radiations have been yet covered). Martian dust has proved not harmful for equipments, but inhalation of suspended dust in a contaminated habitat could lead to respiratory tract problems or even (not established) toxicity concerns. Anyway, accumulating dust inside the Hab is not acceptable and an efficient means for dust removal should be developed. Keeping back-entry spacesuits outside of the Hab is also very efficient. About the risk of exogenous life contamination, this is actually a concern for humanity safety in the first place. We thus consider that it cannot be a mission safety issue, as the program will not be launched without having answered this fundamental question.

The safety picture can be largely improved by taking advantage of several positive factors.

The most widespread engineering means to dramatically increase safety is to resort to redundancy. This is even more inescapable in the interplanetary cases, due to the difficulty to send spares and to the great number of different equipments involved. The interesting question is: to what extent should it be applied: only to equipments, to whole modules, or even to the overall set of hardware of the expedition?

More globally, safety can be built through smart mission design. Mainly, the choice of a “split” architecture, where the expedition set of hardware is deployed on the occasion of two successive launch windows, procures an almost total redundancy to the expedition without increasing the recurring cost. Also robustness should be built at the highest design level so that as much as possible catastrophic follow-ons of failures could be avoided by back-up phases. From this point of view, the choice to be able to abort to Mars is smart, as the crew will profit from the predeployed infrastructures and, if necessary, from the next mission arriving assets. Last by not least, seek for simplicity! Increasing, even for apparently good reasons, the number of modules and of critical operations (e.g. in-space reconfigurations) is not in favor of safety.

Apart from those desirable mission architecture choices, safety should also be built through the best use of human presence. It is often proclaimed that the mission is unfeasible for the very reason that humans are aboard. But the potential that this presence offers for improving safety is not so often underscored.

Humans on the spot allow performing directly diagnosis operations, dismounting, repairing or exchanging equipments and their components, physically reconfiguring the systems, etc. More specifically, the crew presence increases considerably the probability to fix unforeseen degraded situations, potentially with unforeseen means. The corollary is to design equipments for easy maintenance and reparability, a technical challenge in itself.

We hear general statements such as “mission is too risky” (but how much is too risky?) or “safety is not an option” (but how far it should anyway be compromised with other attributes?). In fact, provided a goal acceptable by astronauts, the challenge is to convince the political deciders about their own risk.

NASA engineers, in the ESAS study of the lunar mission [19], cited a probability of Loss Of Crew of 2%. On the basis of Monte-Carlo evaluations, with reasonable reliability and reparability data, we found that a value of 4% to 5% (Apollo?) looks attainable for the Mars mission. It should be acceptable in regard of the corresponding achievement for humanity.

COSTS

Costs figures are strategic programmatic attributes, which play a central role in the decision processes, both for approbation and for continued support of the program. At the higher decisional level, the projected total development cost and the corresponding budgetary plans for each of the partners may

largely overshadow other attributes, except safety. The recurring operational cost is less sensitive because the missions' frequency will be rather low (every 26 months for Mars, probably no more than every 6 months for the Moon); for those programs, seeking performance and IMLEO reduction at a too big expense of development cost (and development risk) is not so wise.
Giving a reliable quotation for such a complex and long-duration project is not easy task. Reasonably, any figures given outside of a detailed design and of (competitive) industrial requests for quotes should be considered with much reserve; the cost may be actually under evaluated or, as often observed, established without due consideration to it, or on the basis of a more or less unconstrained design (NASA's infamous "90 days study" being probably the most illustrative example).
But most often this is not really the case, and even within the space experts' community, figures span a large spectrum, with several harmful consequences: proclaimed costs cannot be trusted; there is a tendency to add significant margins to them (without more justifications); lastly, the most inflated ones are thankfully used by opponents, who know that this is easy to present, both to the deciders and to the public. A more cautious attitude could be expected.

Development cost, being an essential programmatic attribute for the fate of the project, should be taken more thoroughly by project designers.
First of all, they should keep in mind realistic evaluations of the affordable budgets, and introduce them as entry constraints; after all, it is of no use to issue a technically and operationally smart project if it is deemed to be refuted even before start.
Secondly, they must trim the project's characteristics, mainly its operational performances and the choice of technologies in regard of their TRL, not hesitating in reassessing some most influential factors, usually considered as intangible. Among them: the size of the crew, the planetary mobility (rovers), the scientific equipments complement, the choice of the launcher, the development pace (annual budgets are more decisive than total cost), the inclusion or not of intermediate steps (e.g. purely Moon or Mars orbital flights).
Thirdly, they must be convincing in showing that they have reasonably taken into account developmental hazards, as a function of their probability (TRL) but also of the gravity of their consequences for the program. Exhibiting due provisions in the quotation is the best way to avoid arbitrarily added margins.
Finally, they must take any step to verify that what will be presented indeed demonstrate that they were eager to optimize the project with respect to the different partners' constraints and wishes.
Surpassing the cost challenge requires that many efforts.

CONCLUSION

We surveyed the most prominent aspects which, according to critics, should not be overcome in the frame of an acceptable and affordable project development. Arguments can always be discussed, but at least have we shown that, for each of these challenges, there exists ways to overcome the difficulties, or good reasons to reassess them in a more balanced and positive manner.
Provided political deciders are presented a convincing file, where their own concerns and risks are properly addressed, skills are at hand for success of an affordable program. Those major challenges cannot reasonably be raised as showstoppers, whatever their importance. They appear anyway mostly overplayed and, furthermore, insignificant from a long-term perspective.
This survey points to some possible assessment biases, either linked to risk preconceptions, to incomplete analysis, to constraining space policy orientations, to ethical behavior (e.g. forceful cautiousness) or even to philosophical considerations (e.g. "no future"). This becomes bothersome when the reasoning is deliberately distorted (for instance by taking exaggerated dimensioning margins).

Balking the challenges is refusing to try escaping our planetary confinement, with those issues of resources shortage, energy use limitations, global warming. Not that space exploration and space activities development are guaranteed to preserve a future to humanity, but we have fair hints to believe so.

Our despair facing the saddest world events and our limits as living beings should not lead us to surrender, as this would be to renounce our human condition's dignity. Our species has the unique capacity to escape his trap and spread life. Should we miss this chance?
Are we less gutsy than this cousin of ours, who managed to gnaw through his arm to escape a trap?

André Malraux gave a magnificent rendition of that (in *Les voix du silence*, quoted by J. Arnould):

> *« Il est beau que l'animal, qui sait qu'il doit mourir, arrache à l'ironie des nébuleuses le chant des constellations, et qu'il le lance au hasard des siècles, auxquels il imposera des paroles inconnues. Dans le soir où dessine encore Rembrandt, toutes les Ombres illustres, et celle des dessinateurs des cavernes, suivent du regard la main hésitante qui prépare leur nouvelle survie ou leur nouveau sommeil… Et cette main, dont les millénaires accompagnent le tremblement dans le crépuscule, tremble d'une des formes concrètes, et les plus hautes, de la force et de l'honneur d'être homme. »*

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