REFEREED CORRESPONDENCE

Comments on "Rationale for Flexible Path – A Space Exploration Strategy for the 21st Century" by Schmidt, Landis and Oleson, *JBIS*, 63, pp.42-52, 2010

Dear Editor,

Schmidt *et al.* [1] are to be congratulated for their thoughtful and comprehensive analysis of the so-called 'Flexible Path' approach to future space exploration – one of the alternatives identified by the Augustine Commission's inquiry into the future of US human spaceflight activities [2]. There is little doubt that such an approach would, if steadily and systematically pursued over the coming decades, result in the development of a human spaceflight infrastructure which would facilitate both the scientific exploration, and the economic utilization, of the Solar System later in the 21st century. The authors make a compelling case that Flexible Path is the most realistic route to achieving this desirable objective, and I found myself in agreement with much of what they had to say.

That said, I do have a number of residual concerns about the Flexible Path approach. In the spirit of developing the policy debate, I outline these concerns below and would be interested to know the authors' responses to them.

1. Lack of Clearly Defined Objectives for Exploration

There is perhaps a risk that, by lacking a specific destination and well-defined timescale, the Flexible Path approach may be unable to sustain political and public support. Without such support there must be a risk that budgets initially allocated for developing Flexible Path will be whittled away by on-going deficit reduction measures before there is anything substantive to show for them. Indeed, exactly this view has been reiterated by the recent US House of Representative's Commerce Justice and Science Committee's Report [3] which accompanies the 2012 NASA Appropriations Bill, viz:

> "Exploration destinations. - NASA's stated intention is to pursue a capabilities-based approach to human exploration, which means that the direction of the program will be driven by what technologies are available at a particular time. While this approach may offer some advantages in terms of flexibility, it also lacks the clearly defined goals that have historically driven space exploration achievements. Specific, aggressive goals are necessary both to focus the program and to provide a common vision around which public and political support can be rallied. Consequently, the Committee urges NASA to adopt a destination-based approach to exploration that would designate a specific target location, such as the Moon, to drive development decisions and timelines going forward."

It must be a cause of concern for the Flexible Path approach if, at this early stage, the congressional committee responsible for authorising NASA's funding identifies the lack of specific objectives as a political weakness. Of course, merely identifying a specific target does not guarantee success, and there is the obvious risk that predicating a programme on a single objective may cause everything to grind to a halt if and when that objective is successfully accomplished; the history of the Apollo programme clearly illustrates this danger. Nevertheless, it is perhaps preferable to get some hardware off the ground (both literally and figuratively) in pursuit of a clearly defined objective, than risk getting bogged down in a directionless technology development programme which never actually goes anywhere.

2. Possible Exaggeration of the Efficacy of Tele-robotic Exploration

Although the Flexible Path approach will not enable near-term human landings on the Moon or Mars, it is designed to transport human crews to the vicinity of these planets, in addition to near-Earth objects (NEOs). This raises the possibility that tele-robotic operations on the surfaces of these bodies will be possible, controlled by human operators from orbit. This could be an important contribution to exploration, as tele-robotic operations conducted with a minimal time-delay are likely to be much more efficient and capable than exploration conducted by autonomous robotic vehicles [4]. It also raises the exciting longer-term possibility of tele-robotic operations on (and below) the surfaces of bodies such as Venus and Europa where human exploration may never be possible.

However, I believe the authors exaggerate the capabilities of tele-robotic exploration when they describe it as "human-equivalent" [1; p. 44], and imply [1; Fig. 11] that it will be as efficient and versatile as *in situ* human exploration. This conclusion is at odds with actual field studies (e.g. Snooks et al., [5]) which have found that space-suited astronauts are significantly more efficient in pursuing field geological activities than tele-operated robotic vehicles. Garvin [6] reached the same conclusion, and produced a more detailed comparison of human, robotic, and tele-robotic capabilities, which indicated that humans on site would be expected to out perform tele-operated robots in 18 out of 23 surface tasks considered [6; Fig. 2]. One area where Garvin's analysis indicated that a human presence *in situ* would out perform tele-robotic operations was in establishing drilling operations (e.g. to depths >100m) in planetary crusts, and in handing and analysing the extracted drill cores. This is likely to be an especially important aspect of future geological and biological exploration on both the Moon and Mars, and it very likely will require a human presence on the surface.

An additional point concerns sample return capacity. While tele-presence may enable geologists to interact remotely with a surface planetary environment, much of the scientific benefit of human planetary surface exploration (as demonstrated by Apollo) lies in the quantity and diversity of rock and soil samples which may be returned to Earth for more detailed analysis. Although tele-robots will be useful in examining and caching samples on the surface, transporting them to Earth will require planetary ascent stages, and the sample return capacity is therefore likely to be larger in the context of human surface missions.

The above points do not detract from some of the very exciting possibilities which would be facilitated by tele-robotic operations on planetary surfaces, as enabled by a Flexible Path-like architecture. However, they do indicate that there are important aspects of planetary exploration for which tele-robots alone are unlikely to be sufficient, and where a human presence on the surface will also be desirable.

3. Marginalisation of Lunar Exploration

My final, and most serious, concern about the Flexible Path approach is the extent to which it downplays the status of the Moon (which, interestingly enough, was the only target actually identified by name in the congressional report cited above [3]) as an important destination in Solar System exploration. It is true that the lunar surface is relatively expensive to get to in energy terms, and that a dedicated lunar lander would have to be developed. However, it seems to me that this additional investment would be justified for at least three reasons:

- The provision of a near-term space exploration objective to excite and maintain public and political interest;
- The scientific importance of the Moon itself (which is almost invariably overlooked by Flexible Path advocates); and
- Operational experience gained on the Moon which would help facilitate later human missions to the surfaces of Mars and other planetary bodies.

The first of these bullet points has already been addressed (Section 1); I briefly expand on the remaining two points below.

3.1 Lunar Science

The primary scientific importance of the Moon arises from the fact that it has an extremely ancient surface (mostly older than 3.5 billion years, with some areas extending almost all the way back to the origin of the Moon 4.5 billion years ago). It therefore preserves a record of the early geological evolution of a terrestrial planet, which more complicated planets (such as Earth, Venus and Mars) have long lost. Moreover, the Moon's outer layers also preserve a record of the environment in the inner Solar System (e.g. meteorite flux, interplanetary dust density, solar wind flux and composition, galactic cosmic ray flux) from billions of years ago (see [7] and [8] for a more detailed discussion) . In addition to its astronomical and planetary science importance, the lunar geological record is also of astrobiological significance, as it provides clues to conditions on the early Earth under which life first became established on our planet [9].

Accessing this very rich lunar record will rely mostly on techniques of field geology, including sample identification and return, and deep drilling below the surface, which (as discussed above) are unlikely to be amenable to (tele-) robotic exploration alone. This will be a major *scientific* benefit of a human return to the Moon which stands to be sidelined in the Flexible Path approach.

3.2 Preparing for Mars

For the reasons given above (and in more detail in Reference [9]) the full scientific exploration of Mars will also ultimately require a human presence on the surface. Eventually, therefore, even the Flexible Path architecture will have to evolve to permit planetary surface operations if scientific return is to be maximised. It would clearly make sense to start developing this capability in the context of lunar exploration first, knowing that it will later be required for Mars (and perhaps elsewhere), because this will act as both a near-term focus for exploration activity *and* help address the important lunar science issues discussed above.

Near-term lunar surface exploration will help facilitate Mars surface exploration later in the century as a result of knowledge gained in at least the following areas:

(i) Human physiology in low (but non-zero) gravity environments;

(ii) Radiation protection;

(iii) Dust mitigation;

(iv) Aspects of precision planetary landing capability (but not all aspects, obviously, as the Moon lacks an atmosphere which greatly alters the requirements for a lander compared to what would be required for Mars);

(v) Aspects of In Situ Resource Utilisation (ISRU); and

(vi) Safe and efficient human operations on hostile planetary surfaces.

Note that, in addition to paving the way for future exploration of Mars, the biological aspects of lunar exploration are also of scientific interest in their own right [10, 11], and these cannot be pursued tele-robotically because astronauts actually on the surface will be required as experimental subjects.

4. Conclusion

I have highlighted a number of scientific and technical benefits resulting from human planetary surface exploration which would not occur, or at least which would be postponed indefinitely, in the context of a Flexible Path architecture unable to support human landings on planetary surfaces. This might be a price worth paying if it could be demonstrated that the cost of adding this additional capability would jeopardize the development of a future human spaceflight infrastructure such as described by Schmidt et al. [1]. However, the opposite may be the case – by providing clearly focussed objectives, around which scientists, the public, and politicians can unite, a programme aimed at returning people to the surface of the Moon, and later sending them to Mars and NEOs (the so-called 'Moon First' scenario in [2]) might actually be a better way of building up the kind of 21st Century human spaceflight infrastructure that we all want to see developed.

In fact, it is probably a mistake to see 'Flexible Path' and 'Moon First' as mutually exclusive alternatives. In the early stages both strategies will require the development of essentially identical infrastructural elements, most notably a heavy-lift launch vehicle and some kind of deep space transfer vehicle (e.g. Schmidt et al.'s PTV). Without these human exploration beyond Earth orbit will not be possible on any strategy. I would argue that the additional cost of adding a human planetary landing capability to the mix of infrastructural elements envisaged for Flexible Path (as illustrated in Schmidt et al.'s Fig. 6) would be offset by the scientific and political benefits of an early return to the Moon and a long-term commitment to a human landings on Mars. I would also argue that the cost of these additional investments need not, and should not, fall on the US taxpayer alone, because the development of the various elements of a multi-purpose human spaceflight architecture for the 21st Century naturally lends itself to international cooperation within the context of the recently formulated Global Exploration Strategy [12].

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Response to: Comments on "Rationale for Flexible Path – A Space Exploration Strategy for the 21st Century" by Schmidt, Landis and Oleson, *JBIS*, 63, pp.42-52, 2010

Dear Editor,

We appreciate the thoughtful and insightful comments regarding our article on the Flexible Path exploration strategy. The questions raised are very helpful in refining the arguments for the strategy, and enrich the debate on the future direction of human spaceflight. Before addressing the three main concerns, we should clarify that there have been several interpretations of the term, "Flexible Path," since it was first used by the Augustine Commission [1]. Our version, which we also call "HERRO" (Human Exploration using Real-time Robotic Operations), emphasizes astronauts exploring the surfaces of planetary bodies in deep gravity wells with telerobotics, rather than immediate human presence. The crew controls the telerobots from locations that are energetically much easier to access than going all the way to the surface. Furthermore, these locations are well within the cognitive horizon to enable real-time operation of the telerobots (i.e., distances where the communications latency/delay associated with the speed-of-light limit is indiscernible).

Another key aspect of HERRO is the focus on crew vehicle systems for in-space operations. It is possible to define system architectures that begin with near-term spacecraft elements (e.g., Centaur-based Upper Stages, Orion/Multipurpose Crew Vehicle (MPCV)), and evolve incrementally to extend mission reach and duration through the addition of new propulsion stages and habitation elements. Each increment opens up a new set of mission opportunities and adds to an in-space transportation capability that can ultimately take people to Mars and other planetary bodies. It also enables human missions beyond LEO sooner than waiting for a myriad of new developments prior to the first mission.

1. Lack of Clearly Defined Objectives for Exploration

The cited congressional report stresses the importance of having a single destination as a focus for space exploration, but the reasons stated were more relevant 30 to 40 years ago than they are today. Although the committee that issued the report is responsible for authorizing NASA's funding, the Apollo-type effort it suggests would require support well beyond one congressional committee. It would require backing from the rest of congress, the President and the many influential communities representing diverse scientific and commercial interests outside the government.

These diverse interests have made it very difficult to obtain consensus for a single path forward. In addition, there has been a growing realization over the last 30 years that other destinations, besides the Moon and Mars, could serve as viable targets for human activities in space. One is space servicing, which gained much attention during the Space Shuttle era with repair of the Hubble Space Telescope. There is considerable interest in continuing this type of work on observatories and other high-value assets in the future. Another area is NEOs and small planetary bodies. Not only could these represent an easier initial step for humans beyond Earth orbit, but small planetary bodies could also yield valuable science about evolution and structure of the solar system. Small bodies may also harbor vast amounts of raw material that would help establish a space-based manufacturing economy in the future, and in the case of Phobos and Deimos, could make excellent staging points for future exploration of the Mars surface.

Although these alternative destinations have diminished the chances of obtaining a consensus for a single path forward, some argue that a consensus is not needed, and that the President has the authority to select a focus. However apart from the small number of congressmen with NASA constituents, politicians rarely see civil space as an important issue, and are reluctant to expend political capital to promote a single-destination, Apollo-type initiative. This was the case with President Bush's 2004 Vision for Space Exploration (VSE), where a clear policy was enacted, but the Administration did not follow through with the funding and political support needed to accomplish VSE's goals. In reality, large human spaceflight endeavours are always vulnerable to the vagaries of the political environment, which can change dramatically every few years. Even if a consensus could be reached, it is doubtful that it would survive beyond a few years. These realities make it very difficult to lock onto a single destination goal for any meaningful length of time.

But what about Apollo? It certainly had a single destination focus, and at the time, had most of the country behind it. We contend that there was an oft-forgotten aspect of Apollo that contributed at least as much to the program's solid support as Kennedy's inspirational speech of 1961, Johnson's political opportunism, and the competition of the Cold War. It was the large number of human spaceflight missions that took place before Apollo under the Mercury and Gemini programs. These missions maintained a steady cadence of new accomplishments and demonstrations that excited the public and kept political interest high. Without these missions, one wonders if support for Apollo would have continued beyond just a few years. Kennedy certainly started having doubts soon after his famous speech, and it is likely that others would have too.

In summary, clearly defined objectives are good, but they should not focus on a single destination, especially if the mission requires many years of substantial funding before taking place. A far more sustainable approach is to pursue nearer-term missions, gradually building up to more ambitious endeavours in the future. We feel that HERRO does that with its emphasis on in-space operations and its incremental expansion of capability.

2. Possible Exaggeration of the Efficacy of Telerobotic Exploration

We did not intend to suggest that telerobotic exploration is now equivalent to human in-situ presence. We agree with the Garvin paper, but note that Dr. Garvin's comment about telerobots not being human-equivalent pertains to the current level of technology. We have witnessed a tremendous growth in telerobotics for unmanned aerial vehicles (UAVs), remote mining, surgery, and undersea oil exploration and drilling. It is likely that this technology will continue to advance, and that these systems will become much more sophisticated over the upcoming decades. No one knows when telerobotics will offer a completely seamless interface between human operator and the environment, but most will agree that modern-day telerobotics offer a degree of control at least midway between autonomous robotics and in-situ human presence.

There is also a flip side to this argument. Even with dramatic advancements in Extravehicular Vehicle Activity (EVA) technology, in-situ crew operations will always be very time-consuming. According to Abeles and Schaefer [2], a maximum of 19.5 hours of EVA productive work per astronaut can be achieved in a week without stressing human capabilities in terms of work/rest cycles. A significant portion of the workload is involved in simply putting on suits, checking systems, and operating airlocks. Humans must also operate with many more safety restrictions and procedures, which severely limits the terrain they can investigate and the distance they can travel away from their landing site. A human exploring on the Moon or Mars will have many more encumbrances than a paleontologist looking for fossils in Montana.

In conclusion, telerobotic operation may not fully achieve human-equivalent functions in the near future, at least compared to a scientist doing fieldwork on Earth. But when you seriously consider all the technological, procedural and safety requirements that will be imposed on astronauts working on planetary bodies up to 372 million kilometers from Earth, there may not be much of a difference between the two.

3. Marginalisation of Lunar Exploration

This is a topic that the paper may not have addressed adequately. We actually see the Moon as being a prime candidate for HERRO-type exploration in the early phases of a HERRO architecture. In our paper we reference Lester and Thronson [3], who in addition to developing the concept of cognitive length-scales for effective teleoperations in space, present a near-term concept for a teleoperation center stationed at Earth-Moon L1. This "destination" would provide continuous communication coverage of the Moon's near side, and is well within the cognitive horizon for a wide variety of remotely performed tasks.

For an early HERRO mission, it would be relatively easy to place crews at L1 and even L2 for sustained telerobotic exploration at many points on the lunar surface for a week or more. Eventually, the infrastructure at these points could be built up to allow exploration for longer periods of time. It is also reasonable to consider orbital missions for closer access to assets on the surface, although the coverage would be much more episodic than at L1 or L2.

Finally, there is no reason why a station at L1 couldn't eventually be used as a staging point for crew exploration of the surface. Although the lander and ascent system would not be a part of the HERRO architecture per se, such a system could be deployed separately by a commercial interest, another government agency or even a private venture.

With regards to the Moon, HERRO provides an avenue for performing expanded exploration of the lunar surface, while building up the in-space infrastructure capable of supporting crewed missions to the surface in the future. The main benefit is that one does not have to wait for a number of newly developed systems before initiating exploration from L1, L2 or lunar orbit.

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