Review of Plans Developed by the RLEP 2 Measurement Team

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By the Lunar Exploration Analysis Group
RLEP-2 Measurements Review Specific Action Team

BACKGROUND AND CHARGE TO SPECIFIC ACTION TEAM

At the request of NASA Headquarters (ESMD) and the management team of the second Robotic Lunar Exploration Program mission (RLEP-2), the Lunar Exploration Analysis Group (LEAG) organized a Specific Action Team to rapidly review the findings and recommendations of the RLEP-2 Measurement Team. Specifically, the SAT was asked to review the Measurement Team's conclusions concerning the following, with rapid turn around:

Determine the presence, extent, and purity of water and other volatiles in the lunar south (or north) pole cold traps:

- Number of sites
- Measurement list
- Measurement quality
- Measurement priorities
- Candidate instrument list to accomplish the measurements
- Approximate data volume for a given site (if possible)

Determine the physical environment and lunar regolith geotechnical properties at the crater rim and floor:

- Number of sites at the rim and on the floor
- Measurement list
- Measurement quality
- Measurement priorities
- Candidate instrument list to accomplish the measurements
- Approximate data volume for a given site (if possible)

Characterize the spatial and temporal availability of light at the lunar south (or north) pole:

- Dwell time for sufficient model correlation (i.e., length of operation to verify LRO [LROC and LOLA] data, and includes time of year if less than one year)
- Measurement list and quality
- Candidate instrument list
- Approximate data volume per day (24 hrs) (if possible)

The SAT interpreted its charge to mean that the program wished to have an independent, fresh look at the analysis done by the Measurement Team. We examined the specific issues listed above, but the short turnaround did not allow us to analyze issues in depth. For example, we could not evaluate the specific measurement requirements in detail and suggest detection limits, precision, accuracy, etc. We have, however, identified areas where additional study by the Measurement Team or others will lead to refinements and quantification of the measurement requirements.

The SAT held a 2.5-hour telecon on February 23, 2006. We were first briefed by Dr. Paul Spudis (Measurement Team leader) and then discussed the Measurement Team's plans. We decided that one detailed discussion was sufficient as we reached consensus rapidly about the content of this report. The draft report was circulated among the SAT members for comment, before producing this final report.

SAT MEMBERSHIP

The SAT membership represents a diversity of lunar science and exploration expertise:

G. Jeffrey Taylor (University of Hawai`i), Chair
Bruce Banderdt (JPL)
David Blewett (NovaSol, Inc., Honolulu, Hawai`i)
Dana Crider (Catholic University)
Bradley Jolliff (Washington University in St. Louis)
Robert King (Colorado School of Mines)
Antonio Ricco (Stanford University)
Charles Shearer (University of New Mexico)
Hunter Waite (University of Michigan)

Drs. Jolliff and Shearer were unable to attend the telecon, but sent in comments on the presentation (sent out beforehand by Dr. Spudis) and on the draft of this report. Others attending the telecon were Michael Wargo, George Tahu, and Tom Morgan from NASA Headquarters.

ASSUMPTIONS OF SAT ANALYSIS

The RLEP-2 Measurements Review SAT recognized the following in making its analysis:

1) The RLEP-2 Project has defined the primary goals for the RLEP-2 mission as:

See the Light: Assess the lighting conditions at the poles such that the duration of illumination and eclipse and the extent of partial lighting or shadowing can be determined at spatial scales and timing such that that the information can be used to develop solar power systems for human habitation of the Moon.
Touch the Ice: Determine through direct (i.e., not model-dependent) analyses of subsurface samples the composition, content, form, and distribution of polar volatiles.

Other types of studies may be included in the mission payload, but are not primary goals.

2) The overall architecture for the lunar robotic program has not been developed. This means that neither the SAT nor the Measurement Team could assess how the RLEP-2 mission fits into the overall planning for lunar exploration or what decisions concerning the architecture could be made on the basis of mission observations (e.g., different decisions may be made if there is or is not useful amounts of water at the poles).

3) The SAT recognized that the Measurement Team has focused to date on what the project considers to be key issues that inform mission design and engineering, with more details to be developed later.

4) The Measurement Team has assumed that the mission's primary objective is to collect data that will allow ESMD planners to decide how important a role polar volatiles should play in human exploration of the Moon (decisive information), rather than obtaining enough information to thoroughly characterize polar volatiles for resource utilization and scientific study (definitive information).

Thus, the focus of the SAT analysis was on the measurement issues discussed in the presentation by the Measurement Team, including an assessment of whether any important measurements have not been considered.

SAT FINDINGS

Overall

The measurement team has developed a sound overall measurement plan and their report presents that plan with quantitative details that are most essential for early mission planning. Although no specific priorities are spelled out in their report, the highest priority measurements are clear because they stem from the two main mission objectives (see the light, touch the ice). The Measurement Team's report gives a useful overview of the issues surrounding the somewhat conflicting datasets used to infer that water ice could be present in permanently-shadowed areas in polar regions. The SAT agrees with the emphasis at this stage of mission development on the highest priority data outlined in the report. We look at those more closely below, and discuss other measurements that would be valuable additions to the RLEP-2 payload. It is essential to begin work on defining detailed measurement requirements as soon as possible because those requirements bear not only on choice of instruments and sampling techniques, but on mission design as well.

Number of Measurements

The Measurement Team has addressed the central issue of the number of sampling localities needed to determine satisfactorily (i.e., decisively) if water ice is present or not. The statistical analysis is logical and leads to the reasonable conclusion that on the order of 20 sampling sites would be sufficient to be reasonably (95% probability) certain that a negative result (no detectable water) indicates that there is not abundant water in the region studied. With 20 sites investigated, a positive result will allow good characterization of the spatial distribution and concentration variability of the resource. The number of individual analyses may be greater than the number of sites investigated because some sites would be studied in detail (e.g., several samples from a core, nearby scoop samples, more than one core sample), so the analytical instruments need to be capable of many more than 20 analyses. One unknown in the calculations is the scale of the heterogeneity in the distribution of ice, hence in the distances between sampling sites. The Measurement Team gets around this problem by describing a sound targeting approach using neutron spectrometer and radar data on the LRO mission. This approach addresses a near-worse case where the ice is concentrated in small areas, but is highly valuable because it maximizes the chances of finding H_2O ice, even in the absence of *a priori* knowledge of the distribution of ice.

The plan to use the combination of neutron and radar data to choose likely candidate sites is logical. These are the two LRO instruments whose data bear most directly on prospecting for ice (LEND and the mini-SAR) and one (mini-SAR) on Chandrayaan-1, but the SAT urges the Measurement Team to consider how data from the other LRO instruments (LROC, Diviner, possibly LAMP) can also be used to choose sampling sites. One concern is that the ice might not be in a form that will be detected by orbital radar. It might, for example, be entirely in the form of ice fragments distributed throughout the regolith, the way rock and mineral fragments occur in the regolith. This would make the orbital radar ineffective. At the same time, however, dispersal by impacts of ice from an original surface layer deposited by a comet impact (for example) would also place small amounts (say, 0.1–1%) in most places, and would be detected by appropriate instrumentation. Whether such concentrations would be high enough to be useful in human exploration and development of the Moon requires further study and is beyond the scope of the Measurement Team's responsibilities. A twenty-site set is large enough to allow extrapolation of water contents to larger areas. For example, assume that the studied region is typical of shadowed regions with a given H concentration measured by the neutron spectrometer on LRO. If the distribution of H_2O concentrations is normal with a mean at 2% and a standard deviation of 0.5%, then 5% of the area outside the sampled set will contain >3% (the mean of 1% plus 2 sigma). Conversely, with a mean of 2% and a standard deviation of 0.5%, 95% of the sites will have >1% H_2O (mean minus 2 sigma). Note that in the latter case, only one sample would be needed to detect water at 1% or greater, or if not detected to conclude with 95% probability that there is no occurrences below that level. However, we have no *a priori* knowledge of the mean and standard deviation. Thus, determining the mean and standard deviation of the samples will be necessary to fully characterize the deposits and form a basis for extrapolation to other shadowed areas.

In spite of the uncertainty about the distribution of ice and hence in the ability of the radar measurements to guide RLEP-2 to an optimal study area, the Measurement Team's assessment of the number of sites needed to study is very useful for planning. It is very clear that assessing the total resource potential with a high (95%) confidence level requires about 20 sampling sites, but that hundreds of sampling sites are not needed. It will be useful for the Measurement Team to quantitatively assess the absolute minimum number of sampling sites needed to ensure a reasonable assessment of the presence of useful amounts of ice.

Volatile Measurements

The Measurement Team has not yet made a detailed study of the requirements for measurements of the volatile species that might be present, except for stating that H_2O and other volatiles should be measured to better than 1% accuracy. We understand that such detailed requirements will be determined during the remainder of pre-Phase A and early in Phase A, and give suggestions for that assessment here. Instrument designers will need to know required detection limits, precisions, and accuracies for a series of volatile species. At one extreme the set of volatiles measured could be H_2O only. However, this will not give any information about the other gases present, such as those derived from comets (CO, CH_4, etc.), or H from the solar wind. Measuring H is particularly important to understand the partitioning of H (measured from orbit by neutron spectroscopy) between elemental or molecular H, H_2O, or other species. This is important for broad resource assessment. The measurement of other species such as CO and CH_4 will address the source of the volatiles. Determining isotopic compositions (e.g., D/H ratios) of the species will also shed light on the source of volatiles. This is useful in gaining an overall understanding of the origin and distribution of the resource, and in its characterization: pure H_2O might be more useful than, for example, amorphous ice contaminated with other gases. Measurements will ideally be able to assess the state of the water to completely characterize the resource. For example, H_2O might occur in crystalline and/or amorphous forms, and as slabs, small fragments dispersed in silicate regolith, or thin coatings on regolith grains. There is a gradation from prospecting for ice and the scientific study of the deposit, and it is fundamentally important to decide where to draw the line for the RLEP-2 mission. We suggest that the Measurement Team (or another LEAG SAT or other group, if the mission would prefer) address the issues listed below. Addition to the team of an expert in the measurement of volatiles would be useful.

- Establish a priority of measurements consistent with assessing the resource potential for the sake of informing planning for human exploration.
  - H_2O only, or other species as well?
  - If other species, which ones will be most informative in assessing the overall potential of volatile resources on the Moon?
  - Are isotopic analyses a bonus or essential to characterizing the resource potential?
- For each measurement, it is important to determine the detection limit, precision, and accuracy of the analyses.
- Determine the depth of sampling and vertical sampling interval, consistent with resource evaluation.

The SAT discussed the roles of direct measurements of volatiles (by, for example, GCMS) and indirect measurements by “close sensing” (by, for example, a neutron spectrometer on a rover or hopper). We consider direct measurements to include techniques that directly image samples such as IR or Raman spectroscopy, in addition to measuring evolved gases. Our conclusion is that *direct measurements are essential* to provide unambiguous data about the nature of volatiles in lunar polar regions. This is especially true if it is a high priority to thoroughly characterize the deposits to plan future uses. Indirect techniques will not give the complete characterization needed (e.g., they might determine that H_2O ice could be present, but not other volatiles or the form of the water ice), and the interpretation of the data can be model-dependent. On the other hand, such measurements provide very valuable information about the lateral distribution of water ice when combined with a series of direct measurements. They allow the detailed, direct sample measurements to be placed into a broader context and permit an overall resource assessment. Nevertheless, the SAT places a higher priority on direct measurements than on indirect ones. We note that the direct measurements must be conducted in such a way as to search for volatiles in all three dimensions, i.e. for each of the surface sampling locations, measurement should be made at several different depths (the 20 measurement sites discussed above might thus result in, e.g., 60 measurement points if 3 depths were sampled at each site). The SAT did not discuss the sampling interval with depth; this must be assessed soon.

Geotechnical Measurements

The SAT agrees with the Measurement Team about the importance of measuring geotechnical properties of the regolith. The Measurement Team will investigate measurement requirements before and during Phase A. The SAT offers the following suggestions based on recent NASA-funded studies (for example, at Colorado School of Mines). These studies show that to support excavation and mobility design for future resource extraction in permanently shadowed areas, the following geomechanical properties should be measured. (This list is more specific than the SAT details in other areas because of the thorough nature of recent studies.)

1. Cohesion, C, the shear stress required to cause failure under 0 normal stress. Measured with ASTM D 2850 and D 4767 triaxial or ASTM D 3080 and D2435 direct-shear testing.
2. Angle of Internal Friction, ϕ, the slope of the shear stress versus normal stress failure envelope. Measured with triaxial or direct-shear testing.
3. Density, ρ, mass per unit volume. Measured by weighing a known volume.
4. Soil-tool Friction Angle, δ, the slope of the shear stress vs normal stress slip envelope at the soil-tool interface.
5. Soil-tool Adhesion, Ca, the shear stress required to cause slip at the soil-tool interface under 0 normal stress.
6. Bulk modulus K, the slope of the stress vs volumetric strain curve.
7. Shear modulus G, the slope of the shear stress vs shear strain curve.
8. Young's modulus E, the slope of the uniaxial stress vs uniaxial strain curve. There are secant and tangent modulii for hyperbolic relationships that are equal for linear relationships.
9. Poisson's ratio ν, the ratio of transverse strain/longitudinal strain that is related to the other elastic moduli:

   $\nu = (3K - 2G)/(6K + 2G)$
   $E = 2G(1 + \nu)$

Traditional *in situ* geotechnical instruments aren't capable of measuring this suite of properties very well and the best techniques are to modify and automate standard laboratory equipment or instrument the extraction equipment. Instrumented extraction equipment was used on Apollo and Viking, but it has not been proven to measure the geomechanical properties as well as standard laboratory tests, so additional work is necessary. The probability of success is high and the payoff in reduced mission mass, complexity, and power is considerable. For example, a scoop can measure excavation forces directly, rather than using models based on estimated geomechanical property values. Scoop hardware and experiments can be specially designed for measurement tasks, thereby combining two needed functions: sample acquisition and measurement of geotechnical properties. For example, the front edge of a scoop can gather similar data to a cone penetrometer test, including penetration over a range of angles and forces. All of the terrestrial *in situ* devices rely on Earth gravity and readily available power and mass to create vertical forces. We need to be more innovative in the lunar environment and rely more on horizontal force where reactions can be generated through stabilizers that can be associated with scoop-type tools.

Illumination Conditions

Considering its central importance to the RLEP-2 mission, the "See the Light" measurements do not seem to be as well developed as other aspects of the mission. The Measurement Team has identified the importance of making measurements that will allow accurate assessments of lighting conditions using orbital data (e.g., LROC and LOLA data from LRO), but the details of those surface measurements need to be worked out during the remainder of the pre-Phase A study. It is not clear from the Measurement Team's preliminary analysis as described in the presentation what will be gained by periodic (every two hours) panoramic imaging of the terrain surrounding the lander. If only shadow patterns are to be gathered, this investigation is of limited use. At the low sun angle in polar regions, a broad depression a handful of cm deep could register equally with a shadow cast by a tall boulder, but the former would have no effect on a solar power array (unless placed flat on the ground, an unlikely plan at the pole) while the latter could be important. An alternative approach might be to determine the fine-scale (decimeter) topography of the site, perhaps using stereo cameras or scanning lidar, which would provide quantitative data for geometric modeling to determine the depth of shadows as well as their horizontal extent. This data set would better provide a link to the scale of illumination determined from orbit, especially for the purposes of planning for solar power systems.

A second related investigation of high value to exploration goals would be to study lighting conditions as they relate to operability. The poles represent a unique and unusual illumination environment that may cause operational difficulties for robots or humans. Thought should be given to acquiring data to investigate such issues as extensive high-contrast shadows, recognition of surface textures under dominantly high phase angle lighting, and the extreme change in site appearance (lighting inversion) over the course of a lunar day. How long a period will be needed for imaging needs to be determined. One lunar day? One season? A full year? This will affect plans for the data rate and data volume needed for the mission. Parameters such as camera dynamic range, filters, height of viewpoint, and combinations of near and far fields of view should be considered as soon as possible to define the imaging system requirements.

The Measurement Team has drawn attention to the utility of measuring the properties of the finest fraction of lunar regolith, including an assessment of electrostatic levitation and its correlation with lighting conditions. Such measurements relate to human safety and future scientific studies (e.g., astronomy). Details of how this can be measured using the same imaging system as used to quantify the lighting conditions can be determined during the remainder of the pre-Phase A study.

Experiments Related to Human Health and Performance

Any potential RLEP-2 payload focused on biological effects and/or the chemical properties of lunar dust is by definition both opportunistic and secondary to the goals of “touching the ice” and “seeing the light.” Nonetheless, a payload of 3–15 kg can yield significant, valuable information to:

- Decrease future human mission risk from the standpoint of safety and human performance.

- Constitute a first step toward attaining an appropriately detailed understanding of the longer-term biological consequences of lunar and space habitation to enable development of therapeutic countermeasures to improve human health and performance during extended missions. The need for this should be confirmed through the Human Research/Biomedical Research Program Office.

Given this potential for high return at minimal cost in mass and power, the LEAG-SAT suggests that the Measurement Team define the best possible set of measurements of biological effects and lunar dust reactivity for possible inclusion on the mission. For this reason, and in light of the acknowledgement of the RLEP-2 Measurement Team leader that the requirement to "conduct experiments on the biological effects of lunar dust" (Slide 7) is presently the most poorly defined of all requirements, the LEAG-SAT suggests:

1. Membership of the RLEP-2 Measurement Team should be augmented by addition of at least one expert in the science of the biological effects of space travel/habitation, one member with expertise in the chemical reactivity and toxicological effects of mineral dust, and one member with expertise in microanalytical measurement systems. The SAT recognizes that the Measurement Team is working with another group on biological measurements, but believes that inclusion of appropriate experts would help develop more detailed plans.
2. Dust experiments and biological-response-to-environment experiments (Slide 23) should be reformulated, with the participation and guidance of the experts identified in 1, for optimal information output from experiment(s) within mass/volume limitations consistent with RLEP-2 bounds for this opportunistic payload. Specifically, the use of electron paramagnetic resonance spectroscopy to determine lunar dust chemical reactivity is not likely to make optimal use of limited mass and power budgets, and likely in any case to yield ambiguous or incomplete results for this measurement goal.
3. The RLEP-2 Measurement Team should act as a point of coordination to assimilate, analyze, and respond, via its payload definition, to inputs from JSC's Constellation Program and Biomedical Research Program, from Headquarters' PA&E activities, and from the RLEP Program Office at Ames with regard to biological effects, lunar dust, and human health, performance, and safety issues. The RLEP-2 Measurement Team should incorporate the expertise necessary to make well-informed recommendations in these measurement areas, as opposed to delegating to others the decision regarding choice of measurement.
4. Mention of human health and safety (Slide 31) should refer to human ***performance***, health, and safety (in recognition of the fact that future biological countermeasures could be developed to bring human performance on long-duration missions closer to terrestrial norms by helping to cope with impaired immunity, slowed wound healing, diminished cognitive skills, and other documented effects of long-term space flight).
5. Findings and examples from the LEAG-SAT report of March, 2005 should be considered as useful input regarding the types of measurements that could be made, given an opportunistic payload of 3–15 kg (the 2 relevant slides from the LEAG-SAT/05 findings are attached as an appendix).

In summary, the SAT notes that appropriate experiments on the biological effects of lunar dust would be a valid addition to the RLEP-2 payload, and recognizes that more detailed study of biological and human health and performance issues will be done. The notes that appropriate measurements could reduce risk and improve performance for long-duration human missions by:

a. measuring the compounded effects on biological organisms of radiation, low gravity, and dust;
b. facilitating design and development of countermeasures;
c. providing data to optimize radiation shielding parameters;
d. validating models of radiation effects and confirming terrestrial accelerator experiments in the actual space radiation environment

General Considerations

The work done so far by the Measurement Team has focused correctly on important issues for mission design, such as the number and spatial distribution of sampling sites. As no doubt planned by the Team, future work needs to go into more detail about instrument masses and power requirements, given the types of instruments that the detailed measurement requirements define. Total data volume and degree of instrument and sampling autonomy also must be defined quantitatively.

Minimum Set of Measurements

It will be essential to decide on the minimum set of measurements that need to be done to inform ESMD about the potential for polar volatile resources. As noted above, we suggest that the Measurement Team quantify the minimum number of sampling sites (each of these probed at multiple depths). The number is at least as many as the minimum number (12) suggested by the Measurement Team. In turn, this suggests that the mission floor include mobility: one sampling site will not be enough to determine unambiguously that there is (or is not) a significant water deposit at the poles or to assay the total amount of volatile resource available.

Sample acquisition equipment can be designed to include measurement of geomechanical properties of ultra-cold regolith. Considering the importance of extracting volatiles, such measurements are very important and can be added at modest cost, mass, power, and data rate.

The minimum illumination measurements also need to be established. As discussed above, the shortest time needed to ground truth modeling based on orbital data needs to be established.

If cost constraints become so severe that RLEP-2 can either see the light or touch the ice, but not do both, the SAT suggests that touching the ice is more important in terms of informing future planning for human exploration. Illumination conditions at least can be modeled from orbital data. Water concentration and distribution cannot. We stress that both seeing the light and touching the ice are very important to future human exploration of the Moon.

Future Review of Measurement Team's Studies

This LEAG SAT would be pleased to review additional studies by the RLEP-2 Measurement Team if asked to do so by ESMD, the RLEP program office, and the RLEP-2 project office. Because mission planning is in a critical early stage it would be useful to have an independent review of progress by a group already familiar with the mission goals and plans.

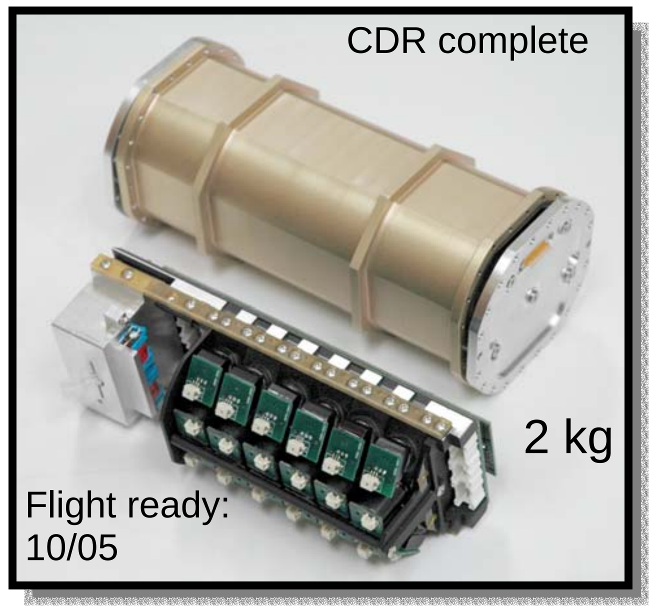
Appendix

Lunar Environment - Impact on Human Performance & Safety

Pertinent slides from LEAG SAT March, 2005 report

Lunar Environment - Impact on Human Performance & Safety

- **Measurement Objectives:**
  - Design measurement systems to quantify integrated effects of extended exposure to lunar environment on living systems. Utilize model and human-reference organisms; human cells, genes, and/or human tissue constructs. System will support normal biological function and autonomous measurements during extended exposure to the spaceflight/Lunar environments.
- **Techniques** and *Biological Relevance***:**
  - DNA damage: SS, DS breaks; chromosomal aberrations and copy changes; point mutations; DNA adducts. *Relevance: slower* ***wound healing****, increased cancer probability*
  - Membrane damage: lipid peroxidation (markers: 4HNE, MDA). *Relevance: compromised immune function, adverse effects on the* ***central nervous system***
  - General oxidation: Superoxide dismutase, total antioxidant capacity. *Relevance :* ***compromised host defense to environmental hazards & pathogens****, shortened lifespan*
  - Protein damage: protein markers & protein aggregates. *Relevance:* ***impaired bone & muscle function****, neural degeneration (Alzheimer's, Parkinson's)*
- **TRL and Cost:**
  - Medium TRL (3 - 6); Cost ~$1.5 M/kg
- **Spacecraft Resources:**
  - Lifetime: 1 month acceptable; 6 months - 1 year optimal
  - 3 - 10 kg; 3 - 10 W
- **Architecture:**
  - LRPM #2: Lunar surface measurements
  - 2011-2015: Development & optimization
  - Spiral 2: Scale & fill gaps
  - Spiral 3: Implement shielding/countermeasures
  - Spiral 4: Validated recommendations available



Lunar Environment - Impact on Human Performance & Safety

- **Summary**:
  - Reduced risk and improved performance for human missions, particularly long-duration Moon and Mars missions.
    - Optimize shielding thickness: impact on engineering, human performance (cognitive; immune function; healing), and risk mitigation
    - Countermeasure design: improve human performance and mitigate risk
    - Compounded effects of unique environment on - humans: radiation, low gravity; and on microbes/pathogens: radiation, low gravity, dust
    - Confirmatory measurements of terrestrial experiments / model validation
- **Implications of not doing:**
  - Greater human risk, poorer human performance (hence greater mission risk)
  - No linkage of biological effects into Spirals 3, 4, and beyond. There is no alternative pathway to achieve comparable reduction of both uncertainty and risk related to human performance and safety for Mars missions
  - Space measurements have not, and terrestrial measurements cannot, address the compounded effects of the Moon/Mars environments

~ 5 kg

ISS Flight Prototype