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Planning for a Mars in situ sample preparation and distribution (SPAD) system

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Abstract

For Mars in situ landed missions, it has become increasingly apparent that significant value may be provided by a shared system that we call a Sample Preparation and Distribution (SPAD) System. A study was conducted to identify the issues and feasibility of such a system for these missions that would provide common functions for: receiving a variety of sample types from multiple sample acquisition systems; conducting preliminary characterization of these samples with non-destructive science instruments and making decisions about what should happen to the samples; performing a variety of sample preparation functions; and, finally, directing the prepared samples to additional science instruments for further analysis. Scientific constraints on the functionality of the system were identified, such as triage, contamination management, and various sample preparation steps, e.g., comminution, splitting, rock surfacing, and sieving. Some simplifying strategies were recommended and an overall science flow was developed. Engineering functional requirements were also investigated and example architectures developed. Preliminary conclusions are that shared SPAD facility systems could indeed add value to future Mars in situ landed missions if they are designed to respond to the particular requirements and constraints of those missions, that such a system appears feasible for consideration, and that certain standards should be developed for key SPAD interfaces.

Keywords: In situ measurement; Sampling; Sample preparation; Comminution; Sample collection; Primary analysis; Advanced analysis; Sample distribution; Sieving; Subsampling; Sample splits

1. Introduction

When a lander or rover operates on the Martian surface, scientific instruments included in the payload need to interact with natural samples (e.g., rocks, ice, regolith) to make their intended measurements. The results of these measurements increase our understanding of Mars. Three strategies for this interaction have been employed to date:

- Optical interrogation, which is effective at a distance.
- Bringing short-range, non-destructive instruments into the proximity of the sample (these are referred to as "contact instruments").
- Sample collection and delivery to analytic instruments for destructive analysis. Many such laboratory instruments

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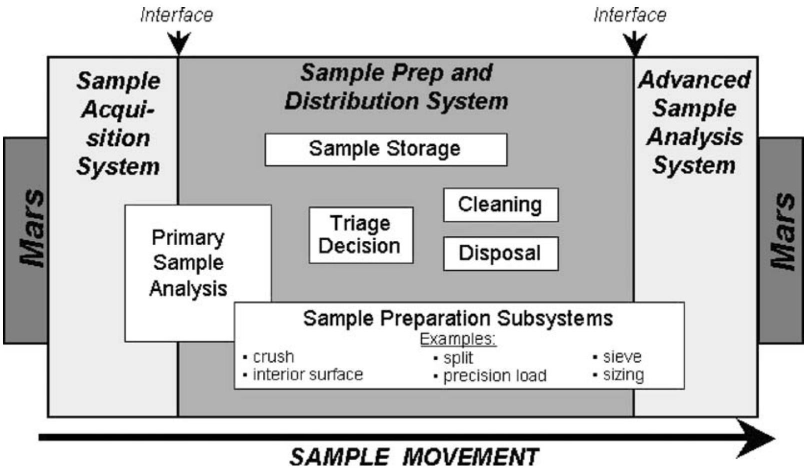


Fig. 1. General SPAD system relationships. Samples are acquired from Mars and are eventually returned to Mars, in one form or another. Note that functions of the Primary Sample Analysis System may appear on the Sample Acquisition System or entirely within the SPAD System. Various sample preparation functions might be located at any of the Primary Analysis System, the SPAD system, or the Advanced Sample Analysis System.

require advance sample preparation and, to date, sample preparation has been limited to sieving.

Implementations of these strategies have been demonstrated on Viking (Soffen, 1977) and Mars Pathfinder (Golombek, 1977; Golombek et al., 1999), as well as in the designs of Mars Polar Lander (Bonitz, et al., 2001), Beagle 2 (Gibson et al., 2003; Sims, et al., 1999) and Mars Exploration Rovers (Erickson et al., 2002; Crisp et al., 2003).

The first two categories of investigation are relatively simple since they do not involve managing samples. However, it has become increasingly apparent that as the scientific questions we are attempting to answer become more refined, we will need to make measurements of increasing sophistication. Our future exploration of Mars will involve a mixture of orbiters, landers, and sample return missions. For the landers and sample return missions, it has been argued that one of the most important factors limiting the relative effectiveness of in situ investigations (compared to returning samples to Earth) is the level of capability for in situ sample preparation. This will be particularly important for the astrobiology missions that will be at the heart of our search for life on Mars. We are going to need significant improvements in our ability to select and acquire a variety of Martian samples, make a broad range of measurements on those samples, and complete certain basic sample preparation procedures. When we are able to carry out the first sample return mission, of course, the full range of sample preparation procedures on Earth is available to us. If some reasonable fraction of that capability can be incorporated into the in situ program, it will make a huge difference to our strategic planning for the exploration of the planet.

In general, advances in our study of Mars will be accomplished by looking at new places, and/or with new instruments, and/or from different vantage points. Although, we do not know the specific objectives of future landed missions, we do know that in general a fundamental capability is the ability to interrogate both rock and regolith samples in order to be able to read the geologic record. If a suite of instruments requires one or more common preparation steps, it may be possible to optimize the engineering by setting up a shared facility. In order to better define possible sample preparation science needs, requirements, and systems engineering, we recently completed a multi-disciplinary study that was intended to develop consensus conclusions and recommendations. A summary of these results is presented in this paper.

1.1. General systems relationships, terminology

The essential systems relationships are shown in Fig. 1, which also serves as a roadmap for our terminology. At the highest level, there are three major systems: the sample acquisition system (which can consist of one or more types of devices, which may be able to acquire different kinds of samples), the sample preparation and distribution system (SPAD), and an advanced analysis system (which consists of a set of instruments that accept samples and make measurements on them). Measurement capability also may be present in what we refer to as the primary analysis system, and the necessary instruments for this may be integrated into either the sample acquisition system, the SPAD system, or both. The various subsystems shown in Fig. 1 as possible ways to configure a SPAD system are discussed in detail in this paper.

For this study, the sample acquisition devices considered included scoop, rake, grabber, mini-corer, subsurface drill, and water/ice acquisition devices. Types of samples delivered by these various devices were assumed to be individual small surface rocks, loosely consolidated surface

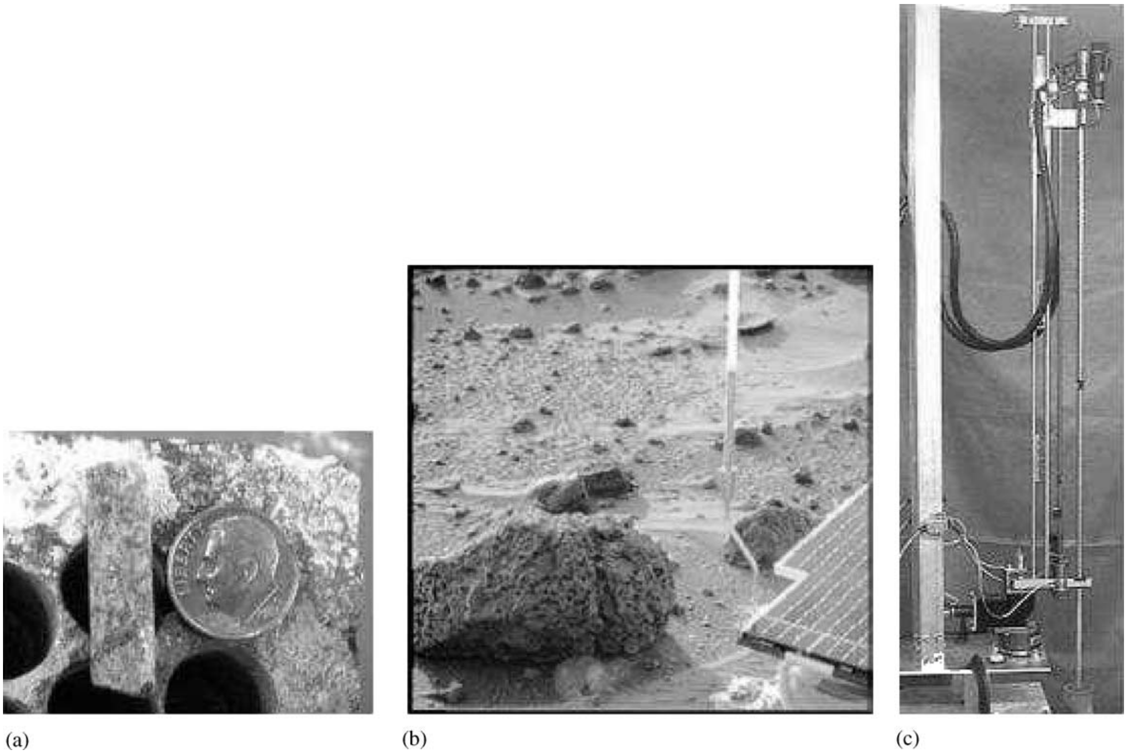


Fig. 2. Science payloads of future Mars in situ landed missions may require analyses of a variety of sample types. The different kinds of samples will be associated with different kinds of sample preparation issues and all will need to be managed by a SPAD system. (a) Mini-cores of rocks are small in size and mass and have regular shapes. (b) Loose material, shown in this image from Mars Pathfinder, is suitable for scooping. Rocks are irregular in size and shape and typically have oxidized rims. (c) Drills, such as this prototype planetary drill from Honeybee Robotics, raise subsurface cores to the surface. Some such devices yield large quantities of both rock samples and cuttings, potentially at a relatively high rate.

material (possibly combined with small surface rocks), small rock cores, subsurface rock (core or chunks), drill cuttings, subsurface ice (core or chunks), rock/ice combinations, and water. Some sample types are illustrated in Fig. 2. Surface rocks are irregular in shape and have a variety of sizes. Small rocks may be suitable to be collected by tongs or other grabbing tools, rakes, or scoops. Rocks typically have oxidized rims, and some science instruments will need access to the interiors. Loose material on the surface is probably best sampled with a scoop, and small admixed rocks may be present. Subsurface rock cores and mini-cores of rock are collected by drills. Cores are regular in shape, although significantly different in size from each other. Longitudinal zoning may be an issue for cores. Also, subsurface cores may be a mixture of both rock and regolith. Some drill designs yield large quantities of cores and cuttings at a relatively high rate (i.e., faster than they can be processed on the surface). Issues associated with ice samples include controlling sublimation and melting as well as possible admixed rocks. With water samples, controlling evaporation and freezing and the potential need for filtration need to be considered. Issues associated with ice and water samples were only minimally addressed in the study and will need considerable attention by other study teams.

2. Scientific rationale for a SPAD system

2.1. *Scientific rationale for sample preparation and distribution, and doing so with a shared system*

Given the above kinds of samples, and the circumstances under which we would be analyzing them, we have identified seven principal strategies for increasing the scientific return from a Martian in situ laboratory. Each of these is dependent on a sample preparation and distribution system.

Strategy #1. Improve accuracy, precision, detection limits: Sample preparation improves accuracy, precision, and detection limits for many kinds of analyses.

Discussion: Many classes of investigations will benefit from sample preparation, including studies of petrology, astrobiology, isotope geochemistry, geochronology, and others. Some examples include crushing of rocks, sieving of regolith, filtration of water, addition of reagents, and exposing fresh surfaces.

Strategy #2. Achieve synergy between instruments: A critical strategy in sample science is to analyze the same sample by more than one instrument. This requires the capability to split a sample into representative sub samples, which can be directed to multiple instruments.

Discussion: Science return from a geological sample increases with the number and type of investigations applied. The greater the diversity of data available, the better a sample can be interpreted.

Strategy #3. Optimize sample size and condition: Many instruments require sample quantity, grain size, and/or other characteristics within certain limits.

Discussion: In particular, delivering too much or too little sample to an instrument can have serious (perhaps even fatal) consequences.

Strategy #4. Increase sample throughput: It will be possible to increase total sample throughput for long-lived missions by using cleanable and reusable preparation and analysis systems.

Discussion: For many types of measurements, a certain amount of cross-contamination can be accepted, and it is possible to dramatically increase the number of samples that can be analyzed by adding the ability to clean dirty surfaces. This is particularly an issue for long-lived missions with nuclear power.

Strategy #5. Analyze the right samples for the right things: On Mars, our analytic instruments will be constrained in time, power, and data rate, and we can optimize science return by managing the resources that are invested in each sample.

Discussion: It is very important to make good decisions about which samples are collected, and beyond that, which samples are analyzed. Some investigations may yield useful results only on samples with certain characteristics. It is typical in Earth laboratories to conduct low-cost “screening” analyses to determine which samples are put through high-cost instruments. As applied to Mars, we need to collect certain general information about all samples in order to decide which instruments receive different samples. For samples coming into any laboratory, there is a decision, which we refer to as “SAMPLE TRIAGE”, with three possible outcomes: analyze immediately, hold for analysis later, or discard.

Strategy #6. Sample analysis sequence: We can optimize science return by analyzing a population of samples in a selected, rather than random, order.

Discussion: If the sample population is heterogeneous, data quality can be increased by analyzing similar samples in order before switching to the analysis of dissimilar samples. In order to implement this strategy, a capability for temporary sample storage, along with decision-making capability, would need to be made available.

Strategy #7. Enable new instruments: If sample preparation is provided, it will promote the development of instruments that can make complex measurements contingent on sample preparation. Many instrument teams are expert in their field of instrument engineering, but not in the field of processing rock samples.

2.2. Rationale AGAINST a shared sample preparation and distribution system

There are several disadvantages to a shared sample preparation system on a Mars lander or rover:

1. A facility SPAD system would require the use of spacecraft resources (mass, volume, energy) and project funds that might otherwise be allocated to the science instrument suite.
2. In some respects, a shared SPAD system adds complexity and risk. Having samples move directly from the sample acquisition devices to the instruments simplifies the critical path. This may also simplify potential accommodation and integration issues. However, making separate sample deliveries to all of the instruments will increase the dependency on the sample acquisition system.
3. The sample preparation function of a SPAD system may slow down some sample analyses.

However, we must look further and address some key questions:

1. Would Principal Investigators (PIs) for the instruments want to include all the sample preparation functions they require within their experiment (and within the resource constraints that they would likely be able to negotiate with the project)? For example, if an instrument intended to analyze material from a rock requires a small particle size, it would need to be able to accept a pebble or a rock core from the sample acquisition system and crush or otherwise reduce it down to the particle size needed. Do PIs want to focus their attention and resources on rock crushers and other similar functions in addition to their analytic instruments?
2. Would two or more instruments require the same or similar enough preparation functions that a savings in the overall resources through sharing these functions makes sense? Rock crushers, for example, are rather massive. If one is needed to reduce the particle size of rocks, should one crusher provide that function for multiple instruments?
3. How useful is it to have a screening function so that, for example, one or more remote sensing instruments can provide information on a sample just acquired to help decide how that sample is to be further analyzed (or not)?
4. How useful is it to have a storage system so that a portion of a sample can be saved for later analysis either by the same instrument (e.g., for confirmation) or by a different instrument that may be limited in the number of samples it can analyze in its lifetime?

These questions need to be evaluated for their cost-benefit characteristics in order to make a final decision on the right answers for a particular project. The next section describes possible SPAD functionalities to help in this evaluation.

3. Science constraints on a SPAD system

3.1. Evaluation of possible SPAD functionalities

3.1.1. Primary sample analysis

This consists of a non-destructive analysis, which precedes destructive sample preparation. The resulting data constitute the informational basis for decision making regarding how a given sample will be managed. For example, recognition that a Martian sample is limestone or shale might call for a very different preparation and analysis plan than for a basalt sample. Note that primary data may be collected either at the site of sample acquisition, at the front end of the SPAD, or both.

3.1.2. Sample movement

Sample movement is required within the SPAD system, from the point at which the sample is delivered by the sample acquisition system through both the primary and advanced analysis systems.

3.1.3. Splitting and subsampling

To allow for analysis of multiple subsamples, either concurrently or sequentially, the ability to split a given sample into one or more subsamples is required. In addition, for some investigations, it is useful to be able to target a specific portion of a given sample for physical separation and subsequent analysis. A variation on this is what is referred to as "precision loading", which involves providing a sample to the instrument in a desired or known orientation. Two areas where the capability for spatial resolution may have its greatest benefit include drill core examination and biological investigations.

3.1.4. Sample holding and storage

There are three main reasons for having the ability to hold and/or store samples. (1) Samples are delivered faster than they can be processed and analyzed. For example, a fetch rover or drill system may deliver samples faster than the analytical facility can process them, and a storage system will keep the rover or drill system fully operational. (2) As discussed above in Strategy #6, rather than running samples in random order, we may wish to hold certain samples to run with other similar samples. (3) To have the ability to store split samples to facilitate multiple analytical procedures on a single sample. Even though sample storage is a desirable capability, it is certainly possible to operate on the Martian surface without it.

3.1.5. Rock surfacing

Several potential investigations either require or are enhanced by rock surfaces modified from their raw form. The required extent of rock surfacing varies widely among different advanced analysis techniques, ranging from broken clean surfaces, to sawn flat surfaces, to polished flat surfaces, and even to polished thin sections. For instance, alpha–proton–X-ray analysis of a flat surfaces is more definitive than on rough surfaces, because of the uniformity of particle path lengths inside and outside the sample.

3.1.6. Comminution

For many types of geochemical analysis it is necessary to crush rock samples so as to obtain powdered or fine-grained material, a process known as comminution. Comminution is valuable for the following reasons: (1) The particle size must be reduced below that of the heterogeneity of the sample in order to obtain a statistically representative split. (2) For organic detection techniques, powdering a rock increases the surface area available for the release of volatiles. The sensitivity of analysis can be increased by many orders of magnitude simply by reducing the grain size and increasing surface area. (3) Some techniques, such as powder X-ray diffraction, require a random powder sample to perform proper analysis. (4) Samples must be made small enough to fit into the volume of the analysis chamber of the instrument.

3.1.7. Sieving

Some kinds of analytic studies can make use of only a specific size fraction of the sample. This is especially true, for example, of the regolith, for which different size fractions will have different scientific meaning, and we may want to subject them to different kinds of measurements. It should be noted that sieving on Mars may be difficult, particularly in reduced gravity with very fine materials.

3.1.8. Contamination control

Sample contamination is a serious issue for sample-related science investigations. For the purpose of this discussion, one must consider environmental contamination (from Martian environment to sample), cross contamination (from sample to sample), and forward contamination (from spacecraft to sample).

3.1.9. Ice-bearing samples

There are special considerations regarding ice samples, and the kind of sample preparation called for will be dependent on the scientific objectives. However, in general, the sample should be investigated by optical interrogation, vaporization (for isotopes), and analysis of meltwater (for chemistry).

3.1.10. Sample disposal

Numerous instruments take in a sample, analyze it, and then need a system for getting rid of the remainder. Either the sample preparation or analysis system needs to account for this functionality.

3.2. Some simplifying strategies

After extensive debate, we have reached consensus on the following four simplifying strategies, each of which would have significant implications for simplifying the engineering of a SPAD system. Note that this is not a representation of the *BEST* way to evaluate a sample, but is proposed as an *ACCEPTABLY SIMPLE* way to process and analyze samples, given the constraints of operating on Mars.

1. *Provide shared sample processing only for instruments that have common sample processing requirements*: Instruments with special preparation needs should be expected to take care of these needs separately. There is no need to design a facility system to take care of all preparation needs for all instruments.
2. *Do not save samples after they have been analyzed*: When samples are sent through the preparation and analysis systems, they should flow through the instruments to disposal. In Earth labs, all possible paths for routing samples can be achieved, but in a robotic system, we need to keep the engineering as simple as possible.
3. *Allow only one sample to be active in the SPAD and advanced analysis system at a given time*: Once a sample enters the preparation and analysis part of the system, all of the required steps on that sample should be completed, and the entire system be cleaned, before the next sample is introduced.
4. *Each instrument specifies a single point in the sample processing flow from which it draws its sample split*: We can greatly simplify the engineering if each instrument can be limited to receiving its sample from a single, pre-determined point in the sample flow. Multiple connections add unnecessary complexity. The single point of sample access could be the outlet of another instrument.

3.3. Science SPAD recommendations

3.3.1. Primary analysis

In order to provide first-order information on a sample and to optimize the use of, and to select among, more sophisticated analytical procedures, some level of non-destructive sample assessment is required prior to any destructive analysis. This “primary analysis” may take place either at the site of sample acquisition, or at the site of the in situ laboratory (or both). We need to have some knowledge of sample characteristics for the following reasons:

- We risk not being able to interpret the data without context information.
- We may damage the instruments if they are exposed to a sample that is either in the wrong condition (e.g., consolidated when thought to be unconsolidated) or is of the wrong type.
- We risk destroying unique, valuable samples prior to understanding their significance.

1. *Basic primary analysis functionalities*: The following information should be collected during the primary analysis stage:
    - *Primary sample characterization*: Instrument Principal Investigators need to know the physical nature of the sample, i.e., whether the incoming sample is regolith, ice, dust, sedimentary rock, or igneous rock.
    - *Sample size*: It will be important to measure the size of the sample—this may affect subsequent sample routing decisions.
    - *Recognition of unusual samples*: The primary analysis system needs to have the capability of recognizing unusual samples that will need either special care in processing, or special care in cleaning the system before and after (e.g., a carbonate sample that will be analyzed in a series of basalt samples).
2. *Case 1* (*Samples arrive at the SPAD system with some information known*): In this case, most of the primary analysis of a sample is assumed to take place during sample collection (e.g., a robotic arm collecting a mini-core from a boulder). This makes the front end of the SPAD system much simpler and tends to pace the rate of samples arriving at the SPAD system. In this case, primary analysis at the SPAD will probably consist of:
    - Confirming that incoming samples are within an acceptable size range.
    - Completing any required analysis not conducted at the site of sample collection (and this could be quite variable, depending on the design of the mission).
    - If needed, breaking or cutting rock samples to expose an interior surface and collecting data from that surface.
    - If called for by the scientific objectives of the mission, locating the best regions of a sample for follow-up specialized analysis.

    A preliminary conclusion was reached, in this case, that the sample storage functionality could be eliminated.
3. *Case 2* (*Samples arrive with little or nothing known about them*): In this case, primary analysis has not taken place during sample collection, and a much higher level of primary analysis must be designed into the SPAD system. In addition, it could be that the rate of samples coming in will be much higher than the rate at which they can be analyzed (e.g., subsurface cores and cuttings systematically coming up from a drilling system). In this case, we strongly recommend including a triage process and sample storage in the SPAD design. In this scenario, time will be of the essence in deciding what should be done with the samples.

3.3.2. Sample decision-making

Sample decision-making is different in the two logical cases defined above.

Case 1: The decision-making for this case can be distilled down to two decisions: (1) Do we analyze the incoming sample? and (2) What happens to the remaining split of a sample that has just gone through the analysis system? For each question, the two possible outcomes are the same: analyze or discard the sample/split. For most kinds of surface sampling activities (e.g. roving, taking a mini-core, scooping, raking, and grabbing with tongs) the decision to acquire the sample is nominally sufficient to retain the sample. The only reason we have identified the option of rejecting a sample in Case 1 is if its mass falls below the minimum needed for processing and analysis.

Case 2: The decision-making for this case is more complicated. We need to know the sample storage capacity of the system, which is critical for the management of samples that are awaiting analysis.

- For high sample input rates, once the storage capacity is filled, we will be faced with a decision of whether to reject a fresh incoming sample, to discard a sample that is currently occupying space in the storage area, or to put the sample acquisition system on hold until the new sample can be accommodated.
- Given a decision not to discard a sample, we will then be faced with the decision of whether to store the sample for future consideration or to analyze it immediately.
- When we are ready to analyze a particular sample, we must decide whether or not to split the sample, and to send half into storage.

A key aspect of the engineering is operation of the sample storage system. The decision-making gets especially interesting when the storage system is full, and the next sample will require either discarding a stored sample, discarding the new sample, or routing it directly to the preparation and analysis system. If mass and volume were not an issue, a storage capacity as large as possible would provide the most flexibility. In discussions on this topic, storage for as much as 20 samples received some support by the science community, but clearly a mission's scientific objectives could be met with less than that.

In the case of drill samples, for which the rate of arrival of sample mass can be very large, there is a fundamental strategic decision: Should we have an instrument look at ALL of the material coming out of the hole, or should the drill be designed to deliver quantized samples from pre-selected down hole positions?

3.4. An illustrative example

Consider a hypothetical mission to Mars for which the science objectives have resulted in the selection of science instruments as shown in Table 1 (additional instruments that do not require samples may also have been selected). Table 1 also specifies the maximum grain size usable by each instrument, where applicable. Further assume that the spacecraft is a fixed lander (no mobility) with a scoop on a robotic arm and a subsurface drill capable of retrieving rock and regolith cores from up to 10 m in depth. The scoop can pick up loose regolith and pebbles. The subsurface cores are 10 cm long by 1.5 cm in diameter.

Table 1
Sample-related science instruments for illustrative example

Instr. ID	Instrument	Sample analysis type	Grain size
A	Microscopic Imager	Non-destructive	N/A
B	Raman Spectrometer	Non-destructive	N/A
C	Mossbauer Spectrometer	Non-destructive	N/A
D	Gas Chromatograph/ Mass Spec.	Destructive	< 1 mm
E	Mass Spec. Magnetic Sector	Destructive	< 2 mm
F	Organic Detector	Destructive	< 1 mm
G	Oxidant Detector	Destructive	< 100 μm

For this example, assume a SPAD system is to be included in the payload as shown in Figs. 3 and 4. Both sample acquisition devices, the scoop and the drill, deposit their samples into a Primary Analysis System that includes a coarse crusher and Instruments A and B. The coarse crusher serves to expose internal rock surfaces as well as to reduce the grain size of any coherent rocks. The SPAD front end also includes a sample splitter and, for the purposes of this example, a bank of several storage containers. Fig. 4 shows that Instruments C–G are included in the Advanced Analysis System, which also contains a sieve. Assume that the grain size of the material output from the coarse crusher is sufficient to satisfy Instruments D–F, i.e., 1 mm. The sieve is used to further process material to satisfy Instrument G. According to the first simplifying strategy (Section 3.2), the sieve would not be part of the shared SPAD system but would be the responsibility of the PI for that instrument.

In this example, the following advantages can be realized:

1. A single coarse crusher, a relatively massive item, serves 4 instruments, thus saving mass and volume (vs. needing 4 copies).
2. Instruments A and B in the Primary Analysis System provide data on which to make decisions, such as which sample to analyze next, which to store, which to discard, thus optimizing the science processing.
3. The splitter provides the benefits described in Section 3.1.3.
4. The storage system provides flexibility, as described earlier.

Key disadvantages of including this SPAD system in the payload, as compared to a payload without the SPAD system

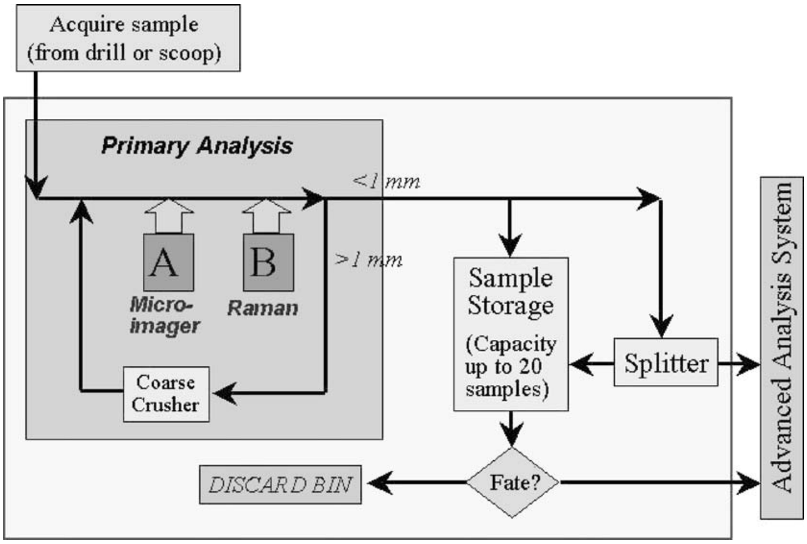


Fig. 3. A simplified functional depiction of the front end of an illustrative example SPAD system. The functions continue with the Advanced Analysis System of Fig. 4.

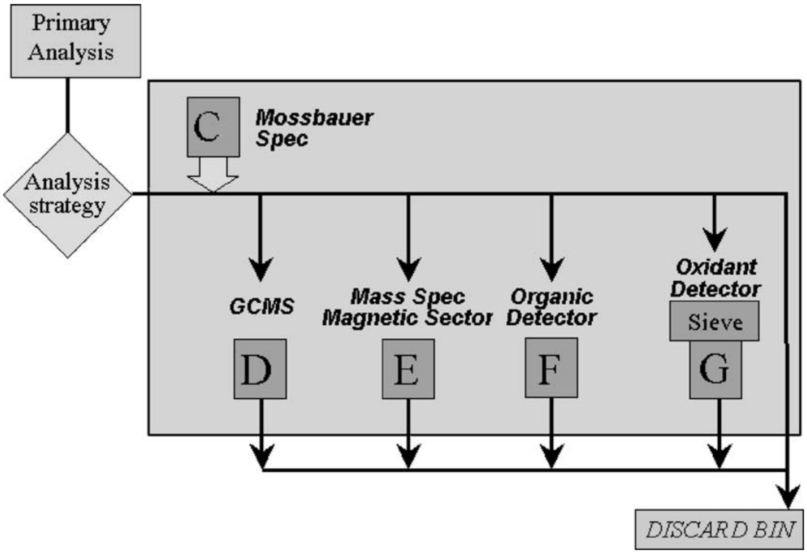


Fig. 4. A functional depiction of the Advanced Analysis System of an illustrative example SPAD system. The "Primary Analysis" and "Analysis strategy" boxes on the left are more fully described by Fig. 3. Instrument C observes the sample non-destructively while Instruments D–G perform destructive analysis.

but with the same preparation functions, are:

1. Some failures in the SPAD system could affect all of the science instruments that rely on it, as opposed to the same failures in just one instrument. However, see Section 4.2 for ways to mitigate this risk.
2. Instruments serviced by the SPAD system need to be integrated with it, which may cause some accommodation issues and more complex interfaces and testing.
3. The distribution function of the SPAD system requires additional mass and volume. This would need to be compared to the mass savings described in Advantage #1 above for an evaluation of the net gain or loss.

4. Systems engineering

4.1. Functional requirements of a SPAD system

Based on the science constraints just described, several of the key engineering functionalities of a SPAD system are: sample receiving, sample movement, sample preparation, contamination management, and autonomy. Sample storage and retrieval is a highly desirable functionality, but it is not considered mandatory in the simplest implementations. Each of these functions could translate to a subsystem. These functions, along with potential functional elements, are briefly described in this section.

Sample receiving: This function provides the interface between SPAD and the sample acquisition system. It consists primarily of one or more containers of one or more types. More than one type of container may be needed depending on the types of samples the SPAD system must be designed to receive for a particular mission application. Examples of potential containers are: bins, ports, hoppers, and cartridge cylinders (e.g., for unconsolidated drill cuttings). Pressure chambers may be required if controlling volatiles is important, such as for ice or water samples. To avoid cross-contamination, samples would not be mixed in a single container and the containers would either need to be limited to a single use or be cleaned between uses. The latter is more likely to be practical for missions gathering enough samples to make the inclusion of a SPAD system in the payload a necessity.

Sample storage and retrieval: As described in Section 3, storage of samples may be required. The main variables parameterizing the design trade space of this subsystem are the use of: (1) a single or many containers, (2) open, closed, or sealed containers, and (3) disposable vs. reusable containers (the cross-contamination issue described for sample receiving containers would also apply to sample storage containers).

Sample movement: A SPAD system requires movement of a sample from the receiving containers through the various steps of primary analysis and preparation and eventually to the analytical instruments. The alternative, of moving these instruments to the sample, is likely to be impractical for designs complex enough to justify a separate SPAD system. More than one movement implementation may be required for different functions within the SPAD system. Several candidates for the primary means of transfer are: carousel, pick-and-place robotic feeder, conveyor, and wheel and gun barrel. Other potential means include: plunger, gravity-feed agitator, micro-fluids pressure jet, etc. Particular attention needs to be paid to the insertion of the sample into the scientific instrument for advanced analysis. The final movement of any sample will be its discard, and there is the potential need for a number of discard points in any SPAD system.

A non-Mars example of a carousel system for distributing samples of cometary material to analytical instruments is found in the drill system on the lander that is planned to be carried by ESAs Rosetta mission (Magnani et al., 1998; Pozzi and Mugnuolo, 1998). Each small sample acquired by the drill is dropped into one of several containers, some of which are ovens, arranged on the carousel. By turning the carousel, the sample could be made available to three instruments sequentially. The system also contains volume checking and oven cleaning functions. Rosetta was ready to be launched in January 2003, but its fate is now uncertain due to an earlier launch vehicle failure.

Sample preparation: As a sample is received and transferred to each processing station, the sample is either interrogated in its initial state (e.g., as a bulk rock) or it is altered to expose unweathered surfaces or to prepare the sample for injection into an instrument for advanced analysis. There are several different mechanical operations that can be employed for sample preparation. Key options include grinding or abrading, tumbling, crushing, sieving, and splitting; others are polishing, adding a reagent, and chemically tagging. Each has purposes for which it is best suited and is accompanied by pros and cons.

As an example, crushing can be done as part of the primary sample analysis process to expose internal surfaces of a rock or as part of the advanced analysis in preparation for injecting a sample into the processing chamber of a science instrument (e.g., an oven). Several configurations are used in terrestrial applications and at least one flight prototype crushing system has been designed and built (NASA's Rockhound mini-crusher).

Contamination management: During this study, a theoretical approach was taken to evaluate the extent of the cross contamination problem for rocky samples during sample preparation and distribution (Rohatgi and Shakkottai, 2003). Additional analyses need to be carried out to evaluate cross contamination risks and solutions for water and ice samples. For rocky samples, the approach consisted of (1) theoretically predicting mass distribution in the particle size ranges of less than 10 μm, 10–100 μm, and larger than 100 μm particles when a Martian rock is crushed using a jaw crusher set with at 1mm gap; and (2) theoretically demonstrating the feasibility of particle removal techniques that will limit the cross contamination of samples.

Preliminary conclusions of the study are:

1. Aerodynamic forces are large enough to remove 10–100 μm diameter particles from grounded, conductive surfaces by using compressed carbon dioxide (hence, potentially, compressed Martian atmosphere).
2. For non-conducting surfaces, ultrasonic vibration produces large enough forces to dislodge particles higher than 8 μm in size.
3. Antistatic coating will help reduce contamination caused by the insulated surfaces.

While further analyses are needed, the preliminary study showed that it may be possible to control cross contamination to less than 0.1% by mass by using a combination of techniques (e.g., brush, compressed Martian atmosphere, and ultrasonic vibration). However, many scientific objectives can be met with less pure samples (e.g., cross contamination of 0.5% by mass). Airborne contamination can be minimized by proper hardware design and good operating procedures.

Autonomy: SPAD operation is interdependent with other systems within the overall spacecraft, especially the sample acquisition system and the sample analysis instruments (both primary and advanced). For example, power is shared within and outside of SPAD. Therefore, the SPAD autonomy function must be implemented as a part of the spacecraft control system and cannot be localized within the SPAD system. However, care should be taken in the design of both to limit the interdependencies.

One example that will be described here has to do with the primary analysis, where one or more non-destructive science instruments are used to determine the appropriate subsequent preparation and routing to other instruments for further analysis. If this determination can be done without consulting scientists on Earth, significant interdependencies are reduced. One approach would be to have a set of pre-determined sample classification profiles on board the spacecraft. Results from on-board data analysis are compared with this set to classify the sample. Also on board would be a set of possible sample flow paths, each associated with a sample classification. In a straightforward manner, samples could be successively analyzed, prepared, and routed for further analysis. One of the allowable sample classifications would be "uncertain"—indicating a need for direction from scientists on the Earth before taking further action.

4.2. Complexity and risk

Does introducing a SPAD system to the payload add complexity and risk? The inherent need in a SPAD system for a distribution function does add an aspect of complexity over a system where the sample acquisition devices deliver the samples directly to the instruments. However, with respect to the sample preparation functionalities, the answer is not so simple and depends on characteristics of the system to which a comparison is being made. If the latter contains the same sample preparation functionalities, but they are embedded in the instruments as needed, the system interfaces would be less complex, but the instruments would be more complex and some functions likely would be duplicated. A project may be tempted to add more functionality to a SPAD system than it would to the instruments in the absence of a SPAD system because those functions may offer a higher benefit for multiple instruments. However, whether a SPAD system is included as part of the payload or not, only those functions should be considered for inclusion for which the additional complexity and risk are justified by the science value.

One difference between including a function, such as reducing grain size, in a SPAD system vs. in the experiments themselves is the implication of failure. If the function fails in one experiment, only that instrument would be affected. However, if it fails in a SPAD system, all the instruments that count on it to perform that function would be affected. A thorough test program would help mitigate this risk. In addition, a common practice in spacecraft design is to have a single point failure policy and one has been suggested for SPAD systems: No single fault in any system or subsystem will preclude the continuing distribution of material to more than one science instrument. Responses to this policy could be to include redundant elements, e.g., two rock crushers, and/or to design for graceful degradation of system performance.

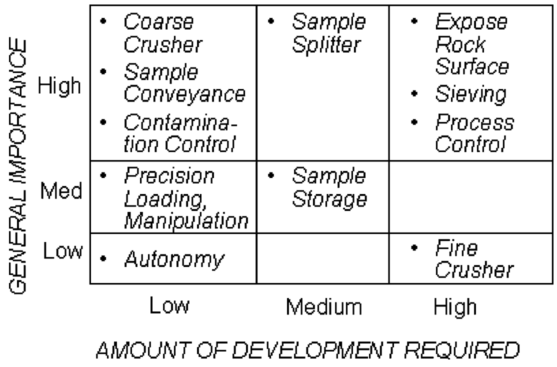
4.3. SPAD architecture feasibility

After the science requirements for a particular application have been identified, and a decision is made as to which of the two cases described in Section 3.3.1 applies, some key issues that need to be investigated for developing a SPAD architecture or selecting among architectures for a particular mission are:

1. What containers are appropriate for receiving, storing and moving the required sample type(s)?
2. Which sample processing elements best satisfy the science requirements?
3. What configuration is mechanically the simplest and requires minimal recalibration? Which has the cleanest fault tolerant design? Which has the lowest operational risk?
4. What configuration has the smallest footprint on the deck of the lander? Which has the lowest stack height? Which has the lowest mass? Which requires the least power?
5. Which configuration is the easiest to be integrated with those science instruments that need access to samples?
6. Which configuration is the simplest with respect to contamination management?
7. What are the technology needs and can the required technologies be ready in time for the mission in question?
8. What design elements need to be included and what are the implications on the testing program to sufficiently mitigate the additional complexity of adding a SPAD system between the sample acquisition systems and the sample analysis instruments?
9. Which configuration leads to the lowest development cost for the project as a whole?

During our study these issues were investigated, along with options for various functional elements as described in Section 4.1, and two candidate architectures were developed: one based on a carousel structure and one based on a pick-and-place design (with a robotic arm). Advantages and disadvantages of each were identified. For example, the carousel structure requires a smaller footprint on the lander deck but a bigger stack height. The mass of a SPAD system for a given project will be highly dependent on the functionalities chosen to be included, as well as on the architecture chosen. Based on our preliminary analysis of a carousel architecture, a SPAD system that includes a modest set of functions might be 25–30 kg. Energy requirements are expected to be less than 25 W. Specifying a volume estimate at this time is premature.

Key technology needs were identified and prioritized, as shown in Fig. 5. The functional need for all but process control was described earlier, in Sections 3.1 and 4.1. Process control is comprised of the sensors,



GENERAL IMPORTANCE	Low	Medium	High
High	• Coarse Crusher • Sample Conveyance • Contamination Control	• Sample Splitter	• Expose Rock Surface • Sieving • Process Control
Med	• Precision Loading, Manipulation	• Sample Storage	
Low	• Autonomy		• Fine Crusher

Fig. 5. Technology development needs for early SPAD systems are shown as a function of importance and difficulty.

algorithms, software, and electronics to make the entire system, including the interfaces, work together efficiently to accomplish the desired tasks. The items on the top row of Fig. 5 would likely be needed for any SPAD system, hence they are given the highest importance rating. Precision loading and manipulation and fine crushing, on the other hand, were required by very few instruments in the survey we conducted. In the near term, such instruments, if proposed and selected, would need to include these functions within their designs. Autonomy needs to wait until the functions for a particular mission are defined and, we felt, could be developed by each project to the level it requires. The technology items were then rated for the amount of development required. For example, at least one prototype rock crusher exists, as mentioned earlier, so it appears in the left column. Process control, however, appears in the right column because SPAD systems are new and require new control designs.

We concluded from these analyses that realistic designs that meet certain sets of science constraints appear to be feasible for SPAD systems, starting for Mars missions launching in 2009.

4.4. Standards for SPAD interfaces

In the process of developing representative SPAD architectures, it was noted how important it would be for some standards to be adopted for key SPAD interfaces. Two examples refer to the interface with the sample acquisition system. Preliminary recommendations are that: (1) samples be delivered with a mass of at least 5 g (to allow sufficient material to be usefully divided among several important instruments) and (2) rock cores be delivered in segments with dimensions no larger than 10 cm long × 1.5 cm in diameter. If adopted, such standards could increase compatibility with subsystems that have long-lead development times.

5. SPAD design appropriate to needs

Any given project that decides to include a SPAD system in the design of its landed platform will, of course, respond to the particular science requirements of that project, as well as to the state of technology readiness and overall spacecraft and other project constraints. For NASA's Mars Science Laboratory 2009 mission, for example, science needs considerably simplified over the more complete set described in Section 3 are being considered, a decision that would greatly simplify the SPAD design over that required to respond to the fuller set. This simplification would result in fewer requirements for technology developments, as well as a system with lower mass, cost, etc.

6. Conclusions

High-level conclusions from the SPAD study are:

(1) For some Mars in situ landed missions, particularly those with several sample analysis instruments and several types of samples to be analyzed, including rock, it may be desirable to include a shared SPAD system in the payload. Such a system appears feasible for consideration if certain technologies are developed. The highest priority technologies to be developed are those capable of providing the following functionalities: Expose interior rock surfaces, Sieving, Process control, Sample splitting, Coarse crushing (which may also be sufficient for exposing interior rock surfaces), Conveyance, and Contamination control.
(2) The design of the SPAD system for a given mission should respond to the science needs and other constraints of the project. Early versions can be relatively simple with more capability evolving for more advanced missions.
(3) Standards should be developed for certain interfaces between SPAD systems and both sample acquisition systems and science instruments.

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