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Inukshuk Landed Robotic Canadian Mission to Mars using a Miniature Sample Analysis Lab for Planetary Mineralogy and Microbiology

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ABSTRACT

This paper discusses the Inukshuk landed rover mission to Mars that is currently undergoing the Phase 0 mission study for the Canadian Space Agency. The Inukshuk landed rover mission addresses key science themes for planetary exploration; focusing on the search for hydrated mineralogy and subsurface water sites that can provide evidence of past or present life. New exploration and science will be accomplished using an innovative tethered combination of a small rover and a self-elevating sky-cam aerostat. The elevating visible (VIS) imager, at about 10 m altitude, will provide an informative high-resolution 2-D view of the rover below and surrounding terrain to greatly assist the semi-autonomous navigation of the rover around obstacles and selection of sites for detailed subsurface exploration.

The solar-powered rover will employ MDA expertise in robotics and drilling with MPB's expertise in miniature infrared (IR) spectrometers and fiber-optic sensors to provide subsurface analysis of mineralogy and temperature distributions at depths to about 1 m. Mission cost effectiveness is achieved through a synergistic instrument suite based on advanced but mature miniaturization technologies that enable high IR spectral measurement performance with minimal mass and power. Insitu systematic sample analysis at depths to about 1 m will be performed using a monolithic fiber-optic coupled probe integrated directly with the tethered mole driller.

For space-based systems, the important drivers are reliability, power consumption, mass and simplicity of operation. MPB has advanced its patented IOSPEC technology for miniature integrated IR spectrometers to provide high performance comparable to large laboratory spectrometers but in a very compact and ruggedized footprint weighing under 2.0 kg. Inukshuk sample analysis will employ the data synergy provided by a miniature suite of high-performance instruments, including IR reflection between 0.8 and 4.5 microns at about 4 nm resolution, microscopic VIS colour imaging to 1 µm spatial resolution, and complementary IR Raman spectroscopy between 500 and 3500 cm^{-1} for direct C-C biological detection. The combined data can, for the first time, directly and unambiguously detect H_2O and determine its state (ice/liquid/structural), distinguish key mineral species (including those associated with favorable habitats for microbial activity) and determine their hydration states, as well as detect and differentiate various C-H and C-C molecular structures for astrobiological investigations.

INTRODUCTION

Mankind's past history has been about the exploration of our own world through voyages of discovery and opportunity. The next natural step is Mars, our closest planetary neighbour and the subject of much speculation regarding the possibilities of life beyond Earth. The differences and similarities in the planetary evolution of Mars relative to Earth can provide fundamental insight into the evolution of planets capable of sustaining life. The weathered surface of Mars may be hiding clues about the past existence of liquid water and life on Mars and evidence of any current microorganisms. Equally important is a survey of the available resources for assessment of potential future habitability.

The current Martian surface conditions are relatively inhospitable to carbon-based organic life with average diurnal temperature ranges from approximately 170 K to 268 K, a relatively low-pressure (7.4 to 10 mbar, as measured by NASA's Viking 1) atmosphere consisting of about 95% CO_2 that largely transmits the incident UV portion of the Solar radiation. The resulting intense incident Solar UV radiation effectively sterilizes the surface. The combination of low air pressure and intense UV will make any unbound surface liquid water unstable.

There is increasing evidence to support the notion that the near subsurface of Mars may differ dramatically from the uppermost surface. Fig. 1 is an image from the MER Spirit rover at Columbia Hills. Its wheel tracks inadvertently revealed the presence of what are presumed to be sulfate-rich soils (the light coloured materials exposed in the wheel tracks). It is unknown at this point whether such materials would remain stable under current Mars surface conditions; the best approach to analyzing materials that may destabilize if removed from the local environment is to examine them in situ.

Fig. 1: Image of bright presumably sulfate-rich soils exposed in the wheel tracks of the Spirit rover at Columbia Hills [image Sol721A_P2538_L257F-A721R1_br.jpg, 1].

Further evidence for the scientific benefits that can be derived from subsurface analysis comes from the Opportunity rover at the edge of Victoria crater. The image in Fig. 2 shows clear evidence of stratigraphic variations in rocks exposed at the edge of this crater. Craters are a useful probe of subsurface lithology and stratigraphy. However, any unstable materials that may have existed and are exposed by the cratering event would undergo decomposition upon exposure.

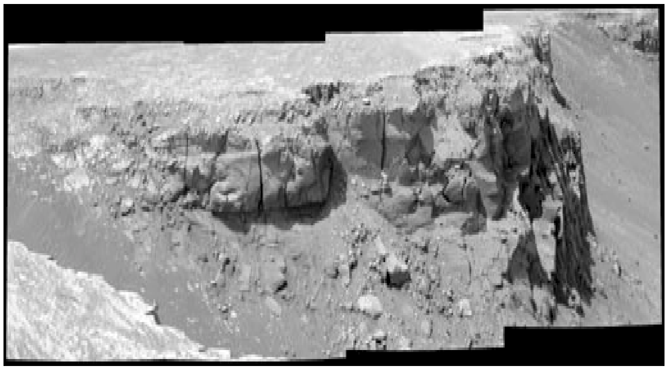

Fig. 2: MER Opportunity rover view of a promontory exposed on the edge of Victoria crater [image Sol952B_P2389_L257atc2g_br.jpg., 1].

The most compelling evidence for the benefits of in situ analysis of the near subsurface comes from the images in Fig. 3 from the Mars Global Surveyor. These images are the best evidence yet that the near subsurface may harbour liquid water or brines, that periodically erupt into the surface of the planet. The composition of such brines and associated materials can only be analyzed in situ, as once they erupt to the surface, the composition of the brine and any entrained materials would be dramatically altered by exposure to Mars surface conditions. While the nature of the process that caused these changes in surface appearance has not yet been fully resolved, the evidence suggests that the changes in the imagery are associated with the eruption of near surface water.

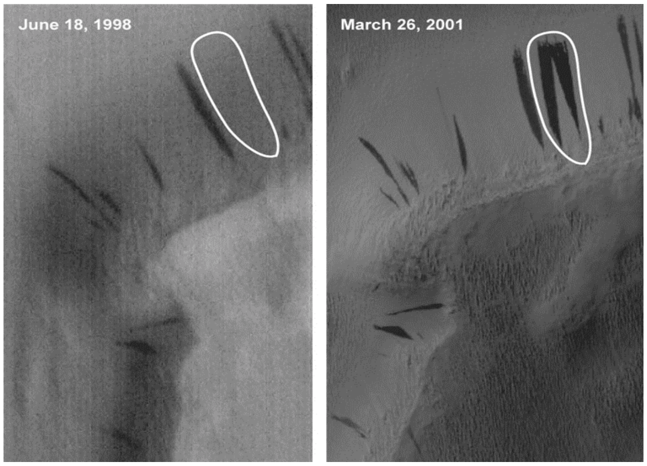

Fig. 3: Mars Global Surveyor MOC images ("before" and "after") of the walls of a crater that is the best evidence yet for the eruption of near surface brines on Mars at the present time [2].

Table 1 summarizes the previous successful landed missions to Mars and their instrumentation. Most of the previous planetary missions have employed relatively indirect or low-sensitivity measurements in the search for water and biosignatures. Mineralogy is an important tool in planetary exploration for the investigation of conditions that may be, or previously have been, conducive to the support of life. The interpretation of these conditions is based on, but not limited to, experience gained from studies of the diverse terrestrial ecosystems, particularly those found within particularly harsh environments. In terms of the classical carbon-based lifeforms, potential indicators include the presence of water, suitable nutrients and simple hydrocarbon structures and proteins. In this respect, infrared spectroscopy can provide detailed information regarding planetary mineralogy and the presence of any biomarkers. Unambiguous interpretation of data, based on experience gained from previous Mars missions (Mars Mariner, Global Surveyor, Omega on Mars Express) and laboratory studies [6], requires broad-band spectral measurements from 0.9 to about 4.3 µm with a signal-to-noise ratio (SNR) exceeding >1000.

Table 1: Summary of previous landed missions to Mars.

Mission	Instrumentation	Mars Landing Site (see Fig. 4)
Viking 1 and 2 Landers [3]. **(576 kg, powered using radioisotope thermoelectric generators)**	**• Gas chromatograph /mass spectrometer,** **• X-ray fluorescence,** **• seismometer,** **• stereo color cameras.**	**Viking 1 lander descended on the western slope of Chryse Planitia, while the Viking 2 lander settled down at Utopia Planitia.**
Mars Pathfinder Rover [4]. **(10.6 kg, Solar-powered)**	**• Alpha Proton X-ray Spectrometer,** **• stereoscopic camera with filters.**	**Ares Vallis in Northern Hemisphere, believed to be a flood plain.**
NASA Spirit and Opportunity Rovers [5]. **(Solar-powered)**	**• Panoramic camera (753-nm, 535 nm and 432 nm filters),** **• miniature thermal emission spectrometer (mini-TES),** **• Mössbauer spectrometer,** **• alpha particle X-ray spectrometer,** **• a microscopic VIS imager from JPL,** **• rock abrasion tool.**	**Spirit landed in Gusev Crater, a basin that may have once held a lake, based on the shapes of the landscape. Opportunity landed in the broad plain Meridiani Planum based on mineral-mapping by Mars Global Surveyor that identified an exposure of gray hematite, a mineral that forms in the presence of liquid water.**

This paper provides an overview of the Inukshuk landed mission to Mars that is currently undergoing a Phase 0 study for the Canadian Space Agency, and discusses the proposed rover payload, miniature instrumentation, and associated extendible mole driller.

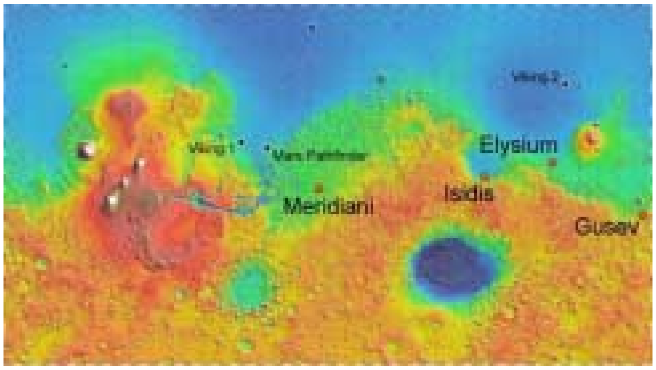

Fig. 4: Mapping of previous landing sites on Mars (NASA/JPL).

INUKSHUK MISSION

Inukshuk is a landed rover mission (see Fig. 5) that addresses key science themes for planetary exploration; focusing on the search for hydrated mineralogy and subsurface water sites that can provide evidence of past or present life using an innovative landed rover. New exploration and science will be accomplished using an innovative tethered combination of a small rover and a self-elevating Skycam VIS imager.

The mission will be achieved cost-effectively on a small, solar-powered rover platform with a net mass of about 81 kg using a miniature suite of synergistic diagnostic instruments and additional fiber-optic sensors operating in collaboration with an extendible tethered mole drill. An integral bore-hole probe will provide systematic *in-situ* subsurface exploration of planetary stratigraphy, mineralogy and microbiology.

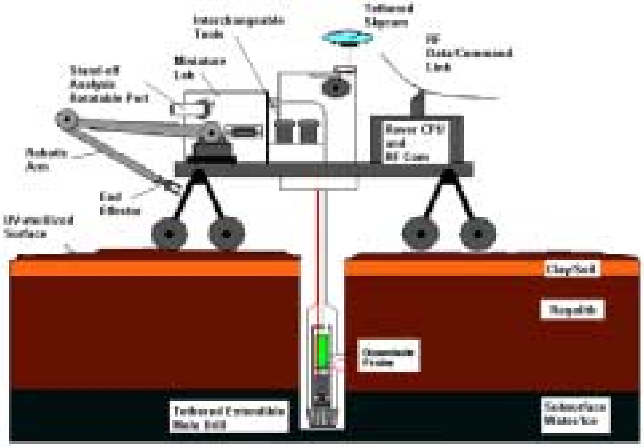

Fig. 5: Schematic of preliminary Inukshuk Rover Concept.

The landing site selection is based on the science requirements for evidence of prior extended surface aqueous activities based on data provided by the Omega NIR spectral imager on Mars Express and other previous and planned missions to Mars. The presence of a residual boundary-layer water cycle may also be evidence of some remaining near-surface activity. The landed mission also requires a terrain suitable for the landing and rover operations.

The mission features an elevated Skycam aerostat [7], as shown schematically in Fig. 6, with a tethered harness to the rover. It will provide stereographic 2-D VIS surface mappings of the rover and its surroundings to improve the rover maneuverability around obstacles and allow greater rover operations autonomy, as well as to provide a broad-area geological context for the detailed subsurface investigations. The super-pressure aerostat will employ a He reservoir on the rover to maintain the He pressure via a stainless steel (s.s.) microtube tether. The aerostat will also facilitate additional rover/Skycam near-surface boundary-layer science (air temperature distributions, wind speeds at rover and Skycam altitude, CH_4 and water vapour studies) and assist with the selection of sites for detailed subsurface investigation.

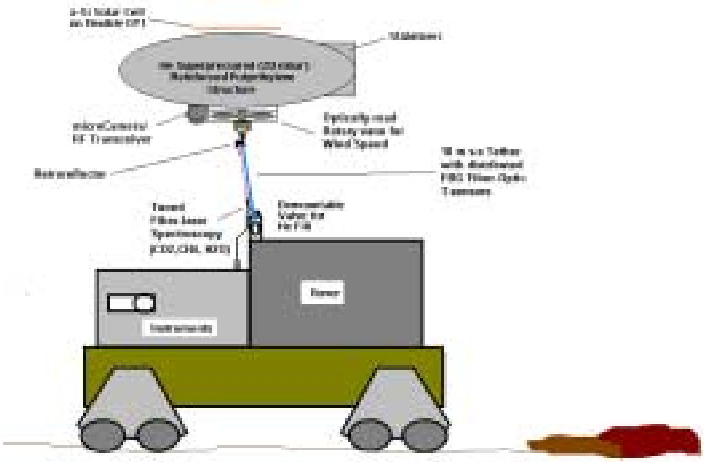

Fig. 6: Schematic of preliminary Inukshuk Skycam aerostat concept.

The main requirements for the Mars planetary landed exploration include:

1. **Unambiguous, direct detection of H_2O and its state (ice, liquid),**
2. **Differentiation of various sulphates, clays and carbonates and their hydration states,**
3. **Mineral crystallinity,**
4. **Detection of C-C bond structures for microbiology,**
5. **Subsurface stratigraphy and corresponding mineral layer structure,**
6. **Detection of clues that can infer information related to previous or current microbiological activities.**

Infrared spectroscopy probes the characteristic vibrational and rotational modes of chemical bonds in molecules to provide information about both the chemical composition and the bonding configuration of a sample. This provides high specificity for the identification of a wide range of unknown substances in vapor, liquid or solid form. Based on a review of the spectral characteristics of the various relevant samples [6], this information is best provided using IR reflection measurements between 0.9 to about 4.3 µm with a suitable controlled miniature MIR light source.

For example, IR reflection spectroscopy provides direct information on the presence of H_2O or OH, either as free H_2O or bonded within hydrated minerals through the measurement of the fundamental H-O-H vibrational stretching modes near 3 µm, as well as overtone modes such as the O-H (hydroxyl) stretch near 1.4 µm and the combination H-O-H bend/stretch mode near 1.9 µm [8].

The usefulness of the IR data for Mars is evidenced by the large scientific return of the OMEGA NIR imager aboard Mars Express [9]. The main instrument requirements are a spectral resolution below 10 nm and a SNR exceeding 1000 within the operating spectral band. A supplementary VIS micro-imager is also highly desirable to provide information on the sample morphology and grain size.

Inukshuk will employ a deployable tethered robotic driller to allow protected *in-situ* subsurface probing systematically to depths of about 1 m. Sample analysis will employ an “insitu” bore-hole probe integrated into the driller with fiber-optic coupling to the IR spectrometer aboard the rover.

INSTRUMENT SUITE

Inukshuk sample analysis will employ the data synergy provided by a miniature suite of high-performance instruments, including IR reflection between 0.85 and 4.5 microns at about 4 nm resolution, microscopic imaging to 1 µm spatial resolution, and complementary IR Raman spectroscopy for direct C-C bond biological detection. The combined data can, for the first time, directly and unambiguously detect H_2O and determine its state (ice/liquid/structural), distinguish key mineral species (including those associated with favourable habitats for microbial activity) and determine their hydration states, as well as detect and differentiate various C-H and C-C molecular structures for astrobiological investigations.

The measurement geometry requirements for the Inukshuk sample analysis include:

1. **Stand-off IR reflection and VIS imaging measurements to select sites for detailed subsurface analysis,**
2. **Detailed “in situ” sample analysis and temperature distributions down drilled bore holes at intervals of 1-2 mm to a depth of about 1 m.**

In situ bore hole analysis has an advantage for detecting biomarkers for astrobiology on Mars in that the alteration of the sample by surface radiation [10] can be minimized. The Rover body and drill deployment unit will be used to shield the bore hole against degradation by the incident UV.

The core IR processor will be a next-generation version of MPB's patented IOSPEC technology [11] for miniature **I**ntegrated-**O**ptic IR **Spec**trometers to provide high performance comparable to large bench-top laboratory spectrometer systems but in a very compact and ruggedized footprint [12]. IOSPEC employs a broadband IR slab-waveguide structure to integrate an input IR fiber or slit, a concave reflection grating, and a linear detector array at the optical output plane in a compact, monolithic structure. Light is coupled into the spectrometer either directly through a miniature slit, or through a suitable IR fiber array. This precisely defines the position of the diffracted signal at the output focal plane, providing robust long-term optical alignment. The optical signal is guided within the slab waveguide onto a master blazed grating that also serves as a concave reflector. The precision master grating, formed using microfabrication techniques, provides diffraction efficiencies approaching theoretical limits (> 85% peak diffraction efficiency) with low background signal scattering (<0.05%). Additional integrated optics assist to linearize the output focal plane, as wide as 25 mm. Relatively high spectral resolution (4 to 8 nm) in first-order diffraction (m=1) is attainable over a broad spectral range of about 4000 nm in a single unit.

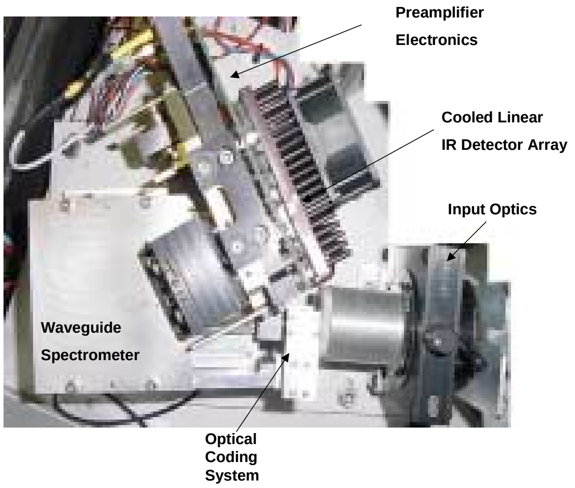

Fig. 7: Photograph of current IOSPEC module weighing under 2 kg including input optics and TE-cooled IR detector array.

For space-based systems, the important drivers are reliability, power consumption, mass and simplicity of operation. The current 1.2 to 5 μm IOSPEC integrated optical spectrometer has been packaged by MPB in a compact module, as shown in Fig. 7, that is approximately 20 x 20 x 15 cm in size and under 2 kg in mass. Further mass reduction is feasible.

An innovative monolithically-integrated miniature instrument suite (see Fig. 8) is being developed for the Canadian Space Agency to provide relatively comprehensive analysis capabilities for planetary mineralogy, water/ice and bioindicator detection that approaches laboratory capabilities. The main photonic analysis techniques include:

1. **MIR reflection – primary molecular chemical structure data using a controlled miniature MIR source,**
2. **VIS microscopic imaging – supplementary information on sample morphology,**
3. **IR Raman spectroscopy for complimentary data on IR inactive bond vibrational modes and C-C.**
4. **Tunable fiber laser with FBG temperature sensors and high-resolution (0.01 nm) spectroscopy of boundary-layer CO_2 and CH_4.**

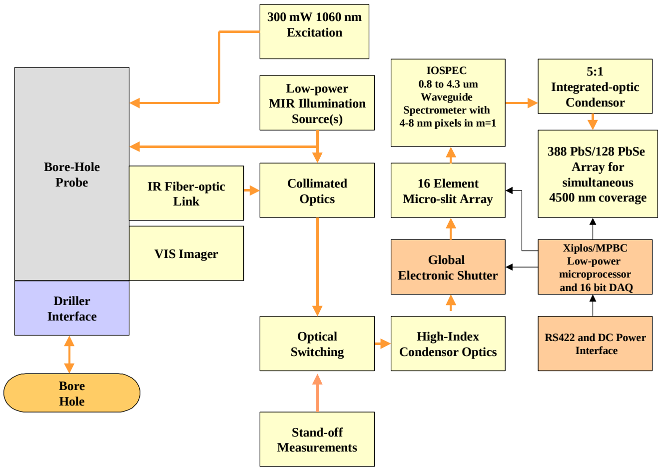

Fig. 8: Schematic of instrument suite with selectable stand-off and in situ bore-hole modes of sample analysis via configurable mirrors.

The fiber-optic tray with the IR Raman excitation source (1060 nm fiber laser) and 1550 nm tunable fiber laser for the Fiber Bragg Grating (FBG) sensors and CO_2/CH_4 absorption spectroscopy will be mounted within the instrument enclosure in the space underneath the IR spectrometer to provide a compact overall structure and maximize the radiation shielding for the fiber-optics. The overall instrument payload packaged with electronics is only 17 x15x31 cm in size and under 5 kg in mass, as summarized in Table 2.

Fig. 9: Photograph of low-power 16 bit spacegrade analog processing and data acquisition PCB.

The instrument control and processing features a low-power microprocessor control PCB (as developed with Xiphos Technologies for ESA's Proba-2 spacecraft) with space-grade FPGA, redundant SRAM and RS422 communications interface. The multichannel analog signal processing PCB (see Fig. 9) uses a 16 bit A/D converter from Maxwell with 24 multiplexed analog signal lines and filtered preamplifiers for various sensors, including a Radfet for received radiation total dose monitoring. The PCB will provide 4 Gbytes of low-power flash memory with fault-tolerant memory management for the VIS imager data. The electronics have undergone 3-axis random vibration to 16.2 grms and TVAC operation from -40 to +60°C.

Table 2: Summary of Inukshuk instrumentation.

Instrument	Capabilities	Mass	Pwr
		kg	W
IOSPEC waveguide spectrometer	**900 nm to 4300 nm with 4 nm/pixel from 900 to 3200 nm (PbS array) and 8 nm/pixel from 3200 to 4300 nm (PbSe array).** **2 mm input aperture at NA=0.25.** **5 to 1 output integrated-optic condensor for high SNR.** **Integral order sorting filters**	**< 2**	**< 1.5**
VIS Imager	**1024 x 1024 pixels, zoom magnification.**	**<0.3**	**<0.6**
MIR Light Source (x2)	**Miniature sealed Tungsten lamp with sapphire window.**	**0.2**	**< 3**
Fiber laser tray with IR Raman output (1060 nm) and 1550nm tuneable output for fiber sensors.	**Complimentary IR Raman spectra of molecular structures in m=2 at 2 nm/pixel.** **Supplementary FBG sensors (temperature, wind speed).** **0.01 nm resolution CO_2/CH_4 spectroscopy near 1550 nm.**	**< 0.7**	**< 3**
Spacegrade Micro PCB	**Redundant RS 422 communications interface,** **Spacegrade FPGA, 1536 kbytes of SRAM**	**0.3**	**< 1.5**
MPBC spacegrade 16 bit Data Acquisition PCB.	**16 bit analog signal processing.** **24 analog MUX channels.** **4 GB of flash memory with fault-tolerant management.**	**0.3**	**< 1**
Monolithic Optical Train with reference standards	**Switchable between stand-off and bore-hole measurements.** **Fiber-optic Interface with robotic driller.** **Wavelength and IR reflectance reference standards.**	**<1.0**	**<0.5**
Bore-hole Probe	**Integral microimager.** **Fiber-optic links for IR Raman and IR reflectance measurements.**	**0.15**	
Total:	**Use the 1060 nm laser or MIR source alternately.**	**< 5.0 kg**	**< 8 W**

IR REFLECTANCE SPECTROSCOPY

As part of the development of the miniature chemical analysis instrument suite, a laboratory test set up has been prepared as shown in Fig. 10. This section discusses some of the preliminary experimental test results that focused on the IR reflection measurements using a selected low power (3 W) MIR light source that could be employed for the flight instrumentation with some redundancy. The set-up employed a 60° illumination incidence angle and a 0° emission angle. The waveguide spectrometer was equipped with a 50 µm input slit. The output spectra were detected using 256 element PbSe or Pbs detector arrays that provided about 8 nm/pixel and can be selectively positioned within a selected 2100 nm band at the 1.2 to 5 µm output focal plane of the waveguide spectrometer.

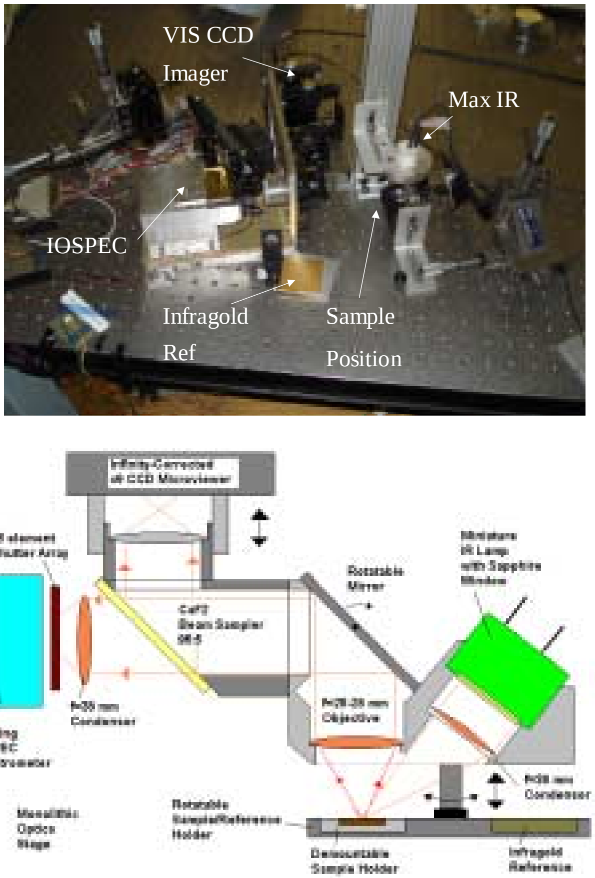

Fig. 10: IR reflection/VIS imaging test set-up with IOSPEC unit using a PbSe or PbS detector array at 265 K and single 50 µm input slit.

A lightweight Al stage to monolithically integrate the various optical elements and optical sources to the IR spectrometer and VIS imager has been designed and is currently being prototyped.

IOSPEC employs a parallel-processing detector array that can provide spectral scan rates exceeding several hundred scans per second to facilitate a relatively high sample throughput and averaging. The elimination of moving components and integration of the optical system provides more reliable long-term performance in non-ideal environments. However, even with active cooling and nominal temperature stabilization, infrared detector arrays such as PbSe can exhibit some unwanted signal drift and instability that can be comparable in magnitude to weaker optical signals. Moreover, the attainable detectivity of an infrared detector array can be significantly less than that indicated by the theoretical NEP rating of individual pixels due to the multiplexing nonidealities.

Proprietary iterative smart optical signal processing algorithms have been developed that facilitate a significant increase in the attainable SNR for multiplexed linear detector arrays. Using the traditional signal averaging techniques, the ultimate signal detectivity achievable rapidly saturates due to the increasing contribution of systematic variations in the detector signal, significantly limiting the attainable SNR. However, with the patented active smart averaging, as shown in Fig. 11 for a 256 pixel PbS array, no such saturation in noise reduction was observed even for extended measurement times, allowing the peak-to-peak noise to be reduced to about 10 µV relative to 10 V full scale. This provides the potential of two to three orders of magnitude improvement in the attainable SNR relative to traditional signal processing techniques.

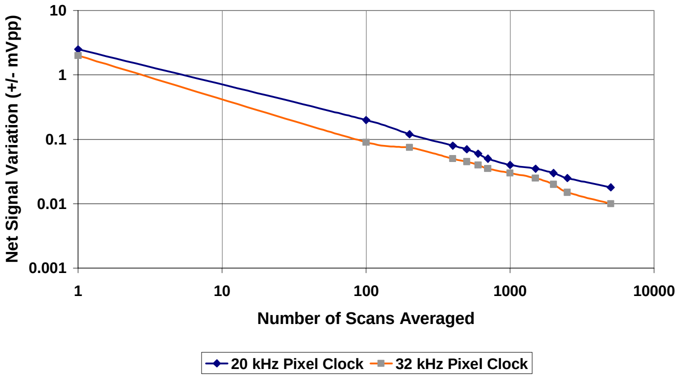

Fig. 11: Variation of the typical net noise for 256 pixel multiplexed PbS linear array at 260K with the number of scans in active smart average with a full scale of 10V.

For the lab measurement predevelopment, a miniature MIR Max-IR light source was selected that features a sapphire window for IR illumination to beyond 4.3 µm. The source power requirements are under 3 W peak and the mass is under 100 g, allowing two redundant signal sources to be considered for the flight instrument.

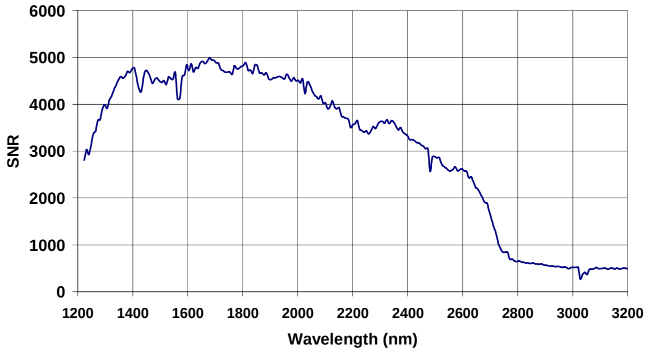

Fig. 12: Achieved spectral measurement SNR for Infragold Diffuse Reflectance Target with current IOSPEC using PbS array at RT and miniature MIR light source at 3 W for f=28 mm collector and 60s total measurement time.

Fig. 12 summarizes the attained spectral SNR for a 60 sec. measurement time with a PbS array at room temperature. The SNR was defined using

$$SNR(\lambda) = V(R100\%)/Vnoise\text{-}avg(R0\%),$$

as achieved with the current IOSPEC miniature IR spectrometer using a 50 µm input slit and miniature MIR ceramic light source at 3 W. The R100% was obtained for an Infragold target at the sample position. The optical signal above 2.7 µm was attenuated by the f=28 mm quartz condensor that was used to collect the diffuse reflected signal from the illuminated Infragold target. This needs to be replaced by a suitable AR-coated sapphire or ZnSe lens to extend the high SNR measurement range to longer wavelengths.

Reference samples were prepared at the U. of Winnipeg by dry sieving to a size of 45 microns. The reference samples were characterized using X-ray diffraction for sample crystallography. The reference mineral samples were previously identified and characterized using a combination of X-ray fluorescence for elemental composition, X-ray diffraction for structure and IR reflectance spectroscopy.

Preliminary spectra of alunite, kieserite, gypsum and copiate were measured, as shown in Fig. 13, with the 8 nm m=1 pixel spacing of the current waveguide spectrometer using the low-power MIR light source. These trial spectra show similar features to the reference spectra as provided using large bulk-optic spectrometers.

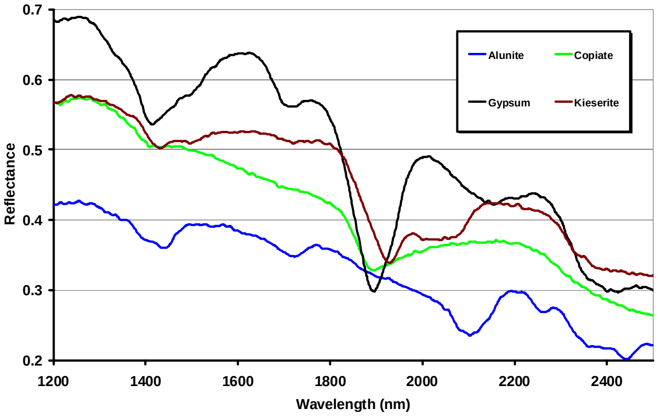

Fig. 13: IR Reflectance spectra of several representative minerals as measured using miniature IOSPEC IR spectrometer and low-power MIR light source with 50 µm input slits and PbSe detector array, relative to an Infragold reference for R=100%.

Fig. 14 shows the expanded view of the alunite O-H band as measured by the IOSPEC system equipped with a 50 µm input slit. This provided relatively good resolution of the OH fine structure near 1430 nm and 1480 nm. The measured spectral features can be further sharpened using additional post-accumulation processing (alunite-filtered) that employs the measured output focal spot at the detector focal plane. Sufficient SNR could be obtained using MPBC's patented smart signal processing even with the low-sensitivity PbSe detector array.

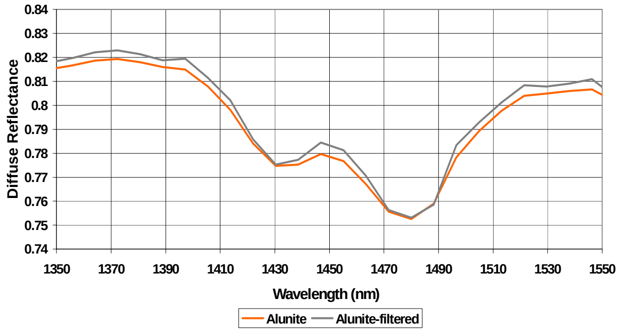

Fig.14: Expanded view of the measured alunite reflection in vicinity of the OH band.

The absorption peaks comprising the O-H band fine structure are only about 10 to 15 nm wide. Therefore, a somewhat finer sampling than the current 8 nm per pixel is desirable. For the next-generation version of the waveguide spectrometer, it is planned to increase the output dispersion of the guided-wave spectrometer to about 0.075 nm/µm from the current 0.15 nm/µm to provide a nominal 4 nm bandwidth per 50 µm wide detector pixel, similar to the laboratory reference spectra.

IR RAMAN Accessory

With supplementary IR Raman spectroscopy, one can detect various IR inactive vibrational modes [13]. While IR Raman spectra do not offer the wealth of information on OH and H_2O as is provided by IR reflection measurements, they can provide additional collaborative information. IR Raman spectroscopy is especially useful to provide spectral information on C-C and C-O structures for biochemical analysis. Whereas IR reflectance provides a continuum spectrum, the IR Raman provides relatively sharp peaks that are less sensitive to the sample physical characteristics. By combining information from both IR reflection spectroscopy and the corresponding IR Raman spectra, less ambiguous identification of the composition and structure of a sample is feasible.

The Stokes-shifted Raman signal is typically less than 10^{-6} of the IR diffuse reflectance signal and can have a significant background fluorescence signal for excitation at shorter wavelengths (see Fig. 15). The background fluorescence can be reduced by selecting a longer-wavelength excitation; however, the resulting Raman signal intensity is reduced by a factor of $1/\lambda^4$.

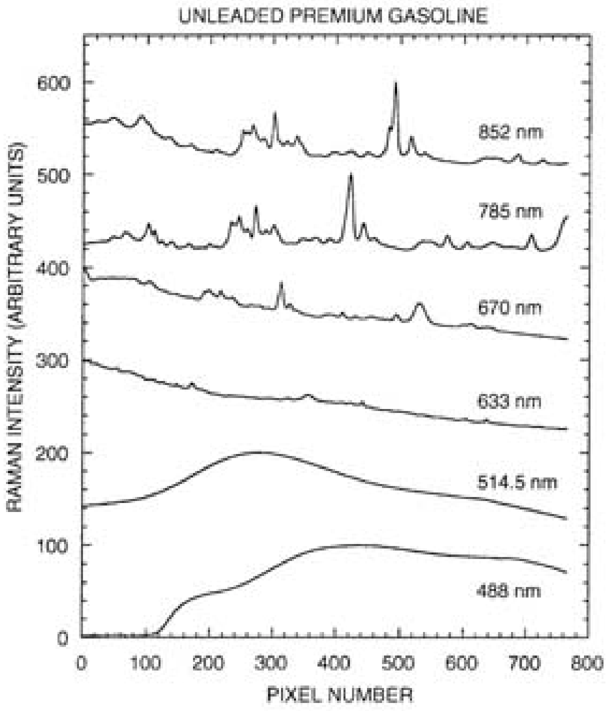

Fig. 15: Effect of the excitation wavelength, λo, on the measured spectral characteristics of a gasoline sample. The pixel number corresponds to the relative wavelength for a Stokes-shifted response (after Process Instruments Inc, www.process-instruments-inc.com).

Table 3 summarizes the preliminary trade-offs for the selection of the excitation wavelength for the Inukshuk IR Raman accessory. Overall, except for the decrease in the available Raman signal, using the 1060 nm fiber laser signal is more advantageous; offering greater redundancy through multiple pumps and more robust, all-fiber optics alignment.

Table 3: IR Raman Trade-offs.

Parameter	785 nm Diode Laser	Rating x/10	1060 nm Fiber Laser	Rating x/10
Background Fluorescence	Low	8	Lowest	10
Relative Signal	1	10	0.3	3
Notch Filter	Yes	10	Use c-Si edge filter.	10
Spectral Measurement Range (500 to 3500 cm^{-1})	800 to 1100 nm	8	1100 to 1700 nm. Spectrum more spread out.	10
Waveguide	ZnSe	10	ZnSe or c-Si	10
Required Spectral Resolution	1.3 nm with 512 pixels in m=3.	8	2 nm with 512 pixels in m=2.	10
Laser Power	300 – 500 mW	8	0.5 to 1 W available	10
Laser alignment	External cavity used	8	Laser in fiber, no mis-allignment.	10
TEC Cooling	Needed	8	Not required	10
Redundancy	No	8	Multiple diode pumps	10
Laser linewidth	0 2 nm	8	0.05 nm (MPBC)	10
Net Rating:		**94/110**		**103/110**

A minimum spectral resolution of 30 cm^{-1} or better is generally specified on the various Raman websites and papers for usable IR Raman spectroscopy. Diffractive spectrometers such as the IOSPEC have a relatively constant spectral resolution with wavelength over their operating spectral range. Based on simulations, as summarized in Fig. 16, a pixel bandwidth of about 4 nm will exceed the minimum resolution requirements for wavenumbers above 750 cm^{-1}. This is compatible with the proposed m=1 spectral resolution for the IR reflection measurements.

For the 1060 nm excitation, as suggested by the trade-off study in Table 3, the required spectral measurement range for the Stokes-shifted Raman signal is about 1100 to 1700 nm. Therefore, it is feasible to accomplish the IR Raman measurements in m=2 (2200 to 3400 nm focal plane output) to reduce the effective pixel bandwidth to about 2 nm. This then could be accomplished using the same spectrometer as proposed for the IR reflectance, with suitable selection of the grating blaze wavelength. This will require switching in additional notch/edge filtering to reduce the 1060 nm excitation signal.

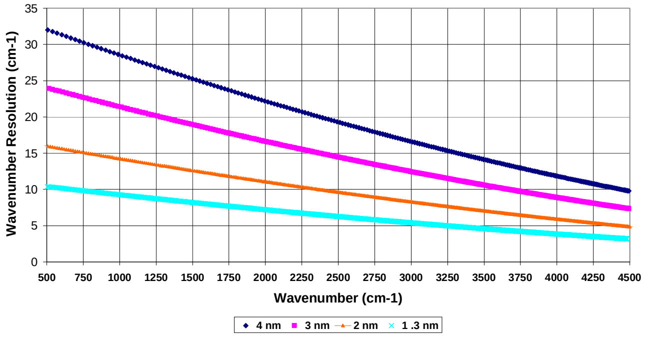

Fig. 16: IR Raman spectral resolution for different pixel bandwidths.

In order to minimize the added mass for the IR Raman measurements, it is planned to share resources, where feasible, including the optical train, PbS/PbSe detector array and electronics, with the IR spectrometer.

A next-generation IOSPEC waveguide spectrometer with extended spectral dispersion for about 1.2 nm/pixel in the 1100 to 1700 nm range in m=6 is currently being integrated for the IR Raman breadboard. This will employ an MPBC 1060 nm fiber laser for the Raman excitation. The results will be described in a future paper.

The IR Raman and IR reflectance measurements will employ different illumination sources and intensities and be performed sequentially, not simultaneously. For the IR Raman, a laser excitation power on the order of 300 to 500 mW is anticipated to provide a SNR of about 200-300 using PbS as the detector material, coupled with the actively-coded smart signal processing.

MDA ROBOTIC DRILLER

A number of drill systems have been or are currently under development for planetary exploration missions. Two have already flown; the PLUTO drill provided by DLR to Beagle and the SD2 drill provided by Technospazio to the Rosetta comet mission. Unfortunately, PLUTO was lost during the Beagle landing failure. The Rosetta drill will not be deployed until 2014 when the spacecraft rendezvous with Comet Churyumov-Gerasimenko. A third drill system currently under flight development is the MSL Drill being developed by JPL. If launched as part of the MSL payload in 2009, the MSL Drill could well be the first drill system since the manually operated drills used by the Apollo lunar missions to be used extra terrestrially.

Single drill string systems are inherently simpler through the elimination of the additional complexity required to add new rods onto the down-hole drill string. The main draw back to this approach is that depth is limited to the package length.

Extendable drill string systems are capable of achieving greater depth using a smaller drill package, but have the added complexity of a drill rod carousel for drill rod storage and retrieval, a head and foot clamp for drill rod integration, and a drill rod transfer mechanism. Tether-deployed drill systems, as shown schematically in Fig. 17, offer the potential of less system complexity, power from the rover and achieving greater depth for a given drill system mass, as the mass of the tether is significantly less than that of an added drill rod.

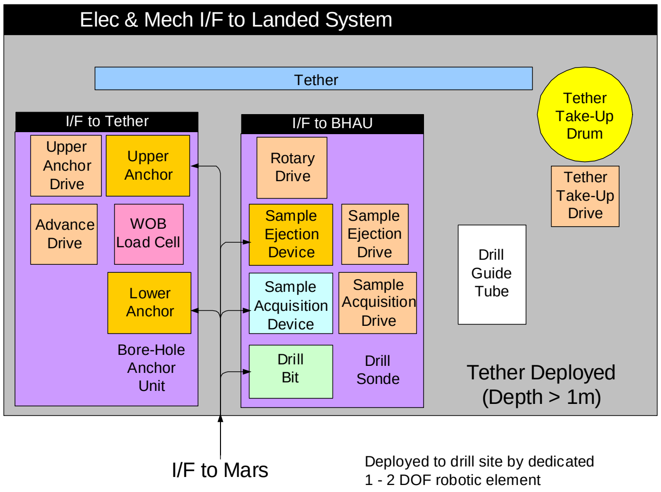

Fig. 17: Generic Architecture for Medium-Depth tethered Drill System.

Table 4: Resource Summary for Inukshuk Concept Drill System (MDA).

Component	Unit Mass with 23% contingency
Deployment Assembly (DA)	**1960 g**
Down Hole Assembly (DHA):	**2100 g**
• *Bore Hole Anchor Unit (DHA-BHAU)*	**1130 g**
• *Drill Sonde (DHA DS)*	**980 g**
Total Mass	**< 4100 g**

The main consideration with the tethered drill approach is pretesting of the selected drill site to check for sufficient layer cohesiveness to minimize the risk that the bore hole may collapse on the drill. The drill is initially mechanically supported by the drill deployment tube. During the drilling, the telemetry includes the motor current, drill depth and drill bit temperature. The rate of penetration data will be used to provide information on the rock strength and regolith cohesion. If there is some uncertainty, the drill will be retracted and the hole examined visually prior to full deployment of the drill.

For Inukshuk, it is proposed to use a tethered drill system with reinforced tether that employs an innovative mole crawler that can crawl up or down the bore hole. This minimizes the risk that the drill will get stuck in the event of a collapse of the bore hole, using a reinforced tether and bore hole anchor system that allows the mole driller to push its way upwards to escape from a collapsed bore-hole. This can be further augumented by using an extendible telescopic shield to protect the bore hole against collapse.

The estimated power consumption of the Inukshuk concept drill system is shown in Table 5. The power estimates include the DHA actuators and DHA specific sensors (load cell, thermistors).

Table 5: Power Summary for Concept Drill System (MDA).

Peak Power	Average Power	Energy to 1 m Depth
39.3 W	**14.3 W**	**102 W-hr**

BORE HOLE PROBE

Table 6 compares the attributes and challenges of sample analysis based on *in-situ* bore hole measurements or sample extraction from the bore hole with subsequent measurement within the miniature lab.

Table 6: Trade-offs for instrument interfacing to the target sample.

Parameter	Bore hole Probe	Extracted Sample Analysis
Sample protection	**Need to shield bore hole. Closest to “as is” sample status.**	**Need to protect sample against UV and low surface pressure.**
Sample Stratigraphy	**Can be preserved for relatively cohesive strata.**	**Use core sample to preserve layers.**
Complexity of Robotics	**Drill design can accommodate Probe.**	**Need additional robotic arm and protected sample stage.**
Autonomy of Robotics	**No sample handling required.**	**More complex sample handling with greater number of operations.**
Instrument Performance	**IR limited by light-pipe coupling.**	**Best SNR**
MIR Light Source	**Miniature lamp integrated in probe.**	**Provide redundancy.**
On Site Calibration	**Build accessible targets into inside of driller.**	**Rotate into view of Probe.**
Measurement Modes	**Switch between stand off and bore-hole.**	**Switch between stand off and close-up extracted-sample analysis.**
IR Raman	**Feasible due to standard fiber coupling.**	**Can achieve higher SNR due to more direct optical signal coupling.**

The bore hole sample extraction requires a more complex and bulkier drill assembly, while the insitu measurements result in additional optical signal losses due to the fiber-optic signal coupling to the rover-based IR spectral instruments. However, based on the science requirements, insitu bore hole measurements are the preferred approach to facilitate investigation of the most pristine samples.

Fig. 18 shows a very preliminary schematic of the bore-hole probe. The probe will be integrated within the mole driller. The drill concept provides about 20 mm I.D. for the integration of the sample probe directly within the driller. It is proposed to directly incorporate a VIS micro-imager and LED illumination into the probe. The Raman excitation signal can be coupled efficiently into the probe using standard optical fiber. For coupling the resulting spectral signal back into the spectrometer, there is the choice of hollow-core IR fiber with broad spectral transmission characteristics, relatively fragile fluoride IR fiber with attenuation of about 0.5 dB/m, and sapphire fiber with an insertion loss of about 1 dB/m.

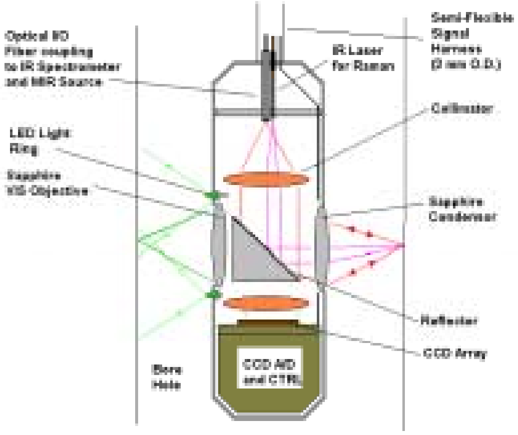

Fig. 18: Preliminary schematic of bore hole probe.

DISCUSSION

Previous landed missions to Mars (Viking, Pathfinder, Spirit and Opportunity) have mainly examined the UV radiated, FeO dust laden surface layer of Mars that is relatively devoid of organic molecules.

The NIR Omega spectral imager aboard ESA's Mars Express orbiter has provided ample evidence of hydrated sulphates and clays clustered in certain areas of Mars with exposed outcroppings, such as Marwth Vallis, that suggest previous surface aqueous activities over an extended timeframe [9]. There is also mounting evidence that the near surface of Mars is significantly different from the weathered and UV sterilized surface that has been observed to date. There is also some hint, as provided by the Planetary Fourier Spectrometer (PFS), of some active near surface processes resulting in excess atmospheric H_2O and CH_4 [14] in some locations on Mars.

Inukshuk seeks to unravel and clarify some of these questions by combining near-surface and subsurface investigations using a unique combination of a small rover with drilling capabilities to a depth of 1 m and an elevated Skycam aerostat. Inukshuk will employ an advanced version of the relatively mature miniature high-performance IOSPEC IR spectrometer coupled with complimentary IR Raman and VIS microimaging to provide unambiguous detection of H_2O and its state, either free or hydrated in minerals, as well as seek clues suggestive of any prior or current biological activities.

Experimental work at the U. of Winnipeg using a Mars Simulation chamber indicates that the current Martian near-surface conditions of low atmospheric pressure and intense UV solar radiation can result in an alteration of samples once they are exposed [10]. To minimize the alteration of the samples, Inukshuk will integrate a fiber-optic coupled probe with the MDA tethered mole driller to facilitate insitu measurements of relatively pristine samples. This will employ a wear-resistant sapphire window for its optical interface to the bore-hole. During the drilling, a mechanical s.s. shutter will be rotated into position to protect the probe optical aperture.

The main challenge is the contamination of the probe window with dust and particulates. This is currently being addressed. The rover will feature a cleaning facility for the mole driller and probe to minimize accumulation of dust and measurement cross-contamination. In the drill extracted position, a mechanically actuated brush will be used to provide cleaning for the drill and the integral bore hole probe optical aperture. Additionally, excess compressed He relative to the Skycam requirements is being considered to provide a pressurized airflow to assist the brush cleaning and direct dislodged dust and particles away from the drill and probe aperture.

Cleaning the bore hole probe aperture during the mole driller bore-hole deployment is also being considered. There are a number of options. The probe design features a dual shutter/wiper system. The s.s. shutter mechanically protects the probe optical aperture during the drilling. The internal protected wiper is actuated as the shutter is opened to wipe the sapphire window surface prior to each bore hole measurement.

The basic Inukshuk experimental procedure consists of a number of steps that combine the stand-off near-surface and insitu bore hole analysis capabilities:

1. **Select target sites for drilling and subsurface investigation:**

- Determine the surface geology in the vicinity of the rover using the Skycam imaging and rover

IR reflection/VIS imaging stand-off measurements.

- Check for any near–surface excess CH_4 or H_2O vapour as indicators of residual active subsurface processes.

2. **Partially deploy the mole driller and test for the site cohesiveness for drilling using engineering telemetry and visual inspection.**
3. **Alternate between bore hole drilling and layer analysis with depth in steps of a few mm to a depth of about 1 m for the bore-hole probe. The probe is protected during drilling using a dual shutter/wiper system.**

- Perform a primary IR spectral reflectance scan (about 1-2 minutes duration).
- Record the subsurface temperature using integral FBG temperature sensors.
- Perform IR Raman measurement scans at coarser depth intervals or if certain peaks in the reflectance spectrum are observed.
- Record a VIS image of the bore-hole surface at coarser depth intervals using the integral VIS illumination.

4. **Extract the mole driller and clean the driller and bore hole probe aperture.**

The mole driller itself will need to penetrate to a depth of about 1.2 m to provide the measurement capability to 1 m depth. The entire iterative drilling and sample analysis at a selected drill site will require about 3 Martian solar days.

Prof. E. Cloutis and his group at the U. of Winnipeg is currently assembling a library of relevant IR reflectance spectra taken under simulated Martian atmospheric conditions (UV radiation, atmospheric pressure and composition) using a Mars Simulation Chamber to assist the IR data validation and analysis. This work is being currently performed to help interpret the OMEGA NIR spectra being provided by ESA's Mars Express.

The prize is a detailed mapping of the Martian subsurface geology and mineralogy with correlation to the residual near-surface processes. This will be performed at multiple strategic points near the selected landing site to greatly assist the understanding of the evolution of Mars, the changes that it underwent, and its current state.

The detailed mineralogical depth profiles and search for subsurface H_2O will provide new knowledge on the resource capabilities of Mars to assist in the planning of future manned missions to Mars.

CONCLUSIONS

The Inukshuk landed rover mission to Mars seeks to advance our understanding of the prior evolution and current status of Mars through an innovative systematic investigation of the Mars subsurface mineralogy, stratigraphy, biochemistry and potentially the detection of H_2O. IR spectral measurement techniques (reflectance and Raman) can provide unambiguous detection of H_2O and its state, as well as differentiation of a wide range of minerals and relevant molecular structures as clues to prior or current Martian biochemistry.

With the added small Skycam aerostat, Inukshuk will also provide boundary layer investigations of residual processes with very high 0.01 nm spectral resolution for CO_2 and CH_4 to correlate with the subsurface findings.

The Inukshuk Mission cost effectiveness is achieved through a synergistic instrument suite based on advanced, but mature, patented MPBC IOSPEC miniaturization technologies that enable high IR spectral measurement performance with minimal mass and power. The net payload, consisting of the instrument suite and tethered mole driller, is under 12 kg and 40 W peak power, allowing accommodation on a small solar-powered Marshokhod-like rover in the 80 to 90 kg range.

The IOSPEC technology, using proprietary active signal processing, has extended the state-of-the-art for high accuracy infrared transmittance measurements by miniature spectrometers. The IOSPEC IR spectrometer performance is being further improved through the use of binary multi-slit optical coding at the spectrometer input using a linear array of programmable input slits and through the introduction of an integrated optical condenser at the waveguide spectrometer output face to minimize the detector pixel height [12]. The multislit input binary optical coding methodology reduces some of the limitations inherent in diffractive spectrometers by increasing the effective input aperture, for a given spectral resolution, by a factor of $N_s/2$, where N_s is the number of programmable input slits in the linear array. The multislit input coding will also enable compositional multi-spectral mapping to assist in the differentiation of trace materials from the nominal background.

The innovative miniature IR spectrometer technology can enable a level of science on smaller space platforms such as microsat and planetary rover missions that approaches that of a terrestrial laboratory. The high resulting measurement sensitivity with a suitable, controlled illumination source can enable direct detection of trace impurities in a matrix down to the 10 ppm level without sample concentration. This is further assisted by the compositional mapping enabled through the use of the programmable multiple input slits to provide spectral line imaging.

By adding a 1060 nm laser source for sample excitation, the same miniature IR spectrometer can also be used to provide complementary IR Raman spectra. Lab breadboard testing of this concept is currently being set-up at MPBC using MPB's fiber laser expertise.

The benefits of this approach include:

- IR spectrometer mass under 2 kg with broad-band infrared spectral measurements from 900 to 4300 nm at 4 to 8 nm per pixel bandwidth,
- Mechanical simplicity with no moving parts for better optical alignment and long term reliability,
- Large IR spectrometer input aperture of about 2x2 mm using 16 programmable input microslits,
- Binary-coded wavelength multiplexing for Felgett's SNR advantage and data redundancy with exact, simple binary inverse transform for high transmittance accuracy,
- Nondestructive analysis for potential sample archiving,
- Data synergy of complimentary IR Raman spectra and VIS microimaging,
- High resolution spectra in selected narrow bands using tuneable fiber laser technology as initially developed and qualified for the FSD payload on Proba-2,
- Compact, low-power microprocessor and 16 bit DAQ system that already has passed ground qualifications (EMI/EMC, 16.2 grms random vibration, TVAC operation from –40 to +60^{o}C).

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ACRYNOMS AND NOMENCLATURE

SYMBOL	DESCRIPTION
Ai	**Input aperture size**
DMA	**Digital micro-mirror array**
FBG	**Fiber Bragg Grating**
FT-IR	**Fourier Transform Infrared**
fs	**Spectral scan rate**
FWHM	**Full Width Half Maximum**
HT	**Hadamard Transform**
hw	**Slab waveguide height**
IOSPEC	**MPB Integrated Optical SPECtrometer**

IR	Infrared
MIR	Mid-Infrared
NEP	Photodetector Noise Equivalent optical Power for SNR=1
Ns	Number of programmable slits
PbSe	Lead Selenide detector material (primarily for 1 to 5 µm spectral range).
SNR	Signal to noise ratio
Vmeas	Measured voltage at output of detector preamplifier
VIS	Visible spectral range
w	Slit width

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