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#### Infrared Spectrometer for ExoMars

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### INFRARED SPECTROMETER FOR EXOMARS (ISEM), A MAST-MOUNTED INSTRUMENT FOR THE ROVER

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# INFRARED SPECTROMETER FOR EXOMARS (ISEM), A MAST MOUNTED INSTRUMENT FOR THE ROVER 3

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## 3132 Abstract

- 33 ISEM (Infrared Spectrometer for ExoMars) is a pencil-beam infrared
- 34 spectrometer that will measure reflected solar radiation in the near infrared range
- 35 for context assessment of the surface mineralogy in the vicinity of the ExoMars
- 36 rover. The instrument will be accommodated on the mast of the rover, and will be

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operated together with the PanCam High-Resolution Camera (HRC). ISEM will study the mineralogical and petrographic composition of the martian surface in the vicinity of the rover, and in combination with the other remote sensing instruments, aid the selection of potential targets for close-up investigations and drilling sites. Of particular scientific interest are water-bearing minerals, such as phyllosilicates, sulfates, carbonates, and minerals indicative of astrobiological potential, such as borates, nitrates, and ammonium-bearing minerals. The instrument has a  $\sim 1^{\circ}$  field of view and covers the spectral range between 1.15– 3.30 µm with a spectral resolution varying from 3.3 nm at 1.15 µm to 28 nm at  $3.30 \,\mu\text{m}$ . ISEM's optical head is mounted on the mast, and its electronics box is located inside the rover's body. The spectrometer employs an acousto-optic tunable filter (AOTF), and a Peltier-cooled InAs detector. The mass of ISEM is 1.74 kg, including the electronics and harness. The science objectives of the experiment, the instrument design, and operational scenarios are described. 

#### 53 1 Introduction

The ExoMars rover is a mobile laboratory equipped with a drill to sample the surface of Mars to a maximum depth of 2 m, and a suite of instruments to analyze the samples. The drilling device is the only means to access near subsurface materials and introduce them to the internal analytical laboratory. As the number of samples obtained with the drill will be limited, the selection of high value sites for drilling will be crucial. The rover's mast is therefore equipped with a set of remote sensing instruments to assist the selection process by characterizing the geological and compositional properties of the surrounding terrains. It includes several cameras – a pair of navigation cameras (NavCam), and a panoramic camera (PanCam). PanCam consists of stereo multispectral wide-angle camera pair (the WACs) and a high-resolution color camera (HRC) (Coates et al, this issue) and will provide the context images used to plan travelling and sampling. To complement and enhance the capabilities of the remote sensing suit, an infrared spectrometer able to unambiguously distinguish many rocks and minerals from their spectral reflectance, will allow remote characterization and selection of potential astrobiological targets. This mast-mounted IR spectrometer was proposed during an early discussion of the new ESA-Roscosmos ExoMars configuration as a useful addition to the rover science and to help operations by characterizing from afar the mineralogical interest of targets that the rover could

visit.

- ISEM is a derivative of the Lunar Infrared Spectrometer (LIS) (Korablev et al, 2015) being developed at the Space Research Institute (IKI) in Moscow for the Luna-25 and Luna-27 Russian landers planned for flight in 2019 and 2021, respectively (Zelenvi et al. 2014). Both the ISEM and LIS instruments have been conceived with similar spectral capabilities. The ISEM design is improved with respect to that of LIS, and modifications were also necessary to comply with the more stringent environmental conditions on the ExoMars rover. A fully operational model of ISEM is not ready at the moment of the paper submission, and the assessment of its measurement performance has been made with the available LIS prototype. ISEM is one of two Roscosmos-provided instruments for the ExoMars Rover. It is being predominantly developed at IKI, but includes contributions from the National Research Institute for Physicotechnical and Radio Engineering Measurements (VNIIFTRI) in Russia, Moscow State University, also in Russia, and the Main Astrophysical Observatory, National Academy of Sciences in Ukraine. A calibration target to be used jointly by PanCam and ISEM is being contributed by Aberystwyth University, United Kingdom. Key components, such as the AOTF and the detector, are purchased from NII Micropribor (Russia) and Teledyne (USA). The science team includes researchers from Russia (IKI and Vernadsky Institute), France, Italy, Sweden, Germany, UK, and Canada. The team shares science team members with the PanCam and MicrOmega rover instrument teams. A full list of the ISEM Science and Technical teams is given at the end of the paper. After a brief summary of the major objectives of the ExoMars mission, we describe the scientific goals of the ISEM instrument. The technical design is then detailed. Measured performances of LIS prototype and and expected performances of ISEM are presented subsequently. We conclude the paper by addressing the operational scenarios and related environmental constraints.
  - **Science Objectives**
- 2.1 Contribution to overall rover mission science
- The scientific objectives of the ExoMars Program are defined as (Vago et al, this

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109	issue):
110	1. To search for signs of past and present life on Mars;
111	2. To investigate the water/geochemical environment as a function of depth
112	in the shallow subsurface;
113	3. To study martian atmospheric trace gases and their sources;
114	4. To characterize the surface environment
115	
116	The first two objectives are the most relevant to the ExoMars rover. The ISEM
117	experiment will contribute to achieving each of these objectives in the following
118	ways:
119	1. Many of the minerals and rocks detectable by ISEM are good indicators of
120	past habitable conditions, and of biological processes (e.g, carbonates,
121	oxalates, borates, nitrates, NH <sub>4</sub> -bearing minerals (Applin et al, 2015; Berg
122	et al, 2016; Cloutis et al, 2016)) and may even contain biomolecules in
123	detectable concentrations. These include a class of biogenic minerals
124	which are further known to provide a substrate for, and catalyze pre-biotic
125	reactions. Organic compounds, including Polycyclic Aromatic
126	Hydrocarbons (PAHs) and those containing aliphatic C-H molecules, can
127	also be distinguished by ISEM (e.g, Clark et al, 2009; Izawa et al, 2014).
128	2. The ISEM instrument is capable of recognizing minerals and rocks, which
129	are indicative of the presence of water as well as geochemical
130	environmental indicators. ISEM can also be used to analyze the drill
131	cuttings excavated by the ExoMars drill system. The operating drill
132	obscures ISEM's view, and observing the cuttings is only possible after
133	the rover moves off and revisits the drilling site.
134	3. If present, ISEM could detect organic-bearing materials, possibly evolving
135	trace gases, such as hydrocarbons.
136	4. ISEM can carry out atmosphere observations, providing information on
137	dust and clouds, and contributing to characterization of the atmospheric
138	humidity. ISEM is capable of identifying and monitoring surface frost, and
139	may assess the diversity and stability of various minerals on the martian
140	surface, e.g, by monitoring changes in the spectral properties of drill
141	cuttings over time.
142	
143	In terms of where the rover will land, ESA has issued the following scientific
144	criteria for landing site selection (Vago et al, 2015):

145	
146	For the ExoMars Rover to achieve results regarding the possible existence of
147	biosignatures, the mission has to land in a scientifically appropriate setting:
148	1. The site must be <b>ancient</b> (older than 3.6 Ga) — from Mars' early, more
149	life-friendly period: the Noachian to the Noachian/Hesperian boundary;
150	2. The site must show abundant morphological and mineral evidence for
151	long-term, or frequently reoccurring, aqueous activity;
152	3. The site must include numerous sedimentary outcrops;
153	4. The outcrops must be <b>distributed</b> over the landing ellipse to ensure the
154	rover can get to some of them (typical rover traverse range is a few km);
155	5. The site must have little dust coverage.
156	
157	ISEM addresses these criteria in the following ways:
158	1. The suite of samples that we have used to characterize ISEM in laboratory
159	tests includes materials similar to those found in Noachian terrains (e.g.
160	phyllosilicates, carbonates, etc.)
161	2. ISEM will be able to identify minerals that are indicative of aqueous
162	activity, such as phyllosilicates and hydrated sulfates.
163	3. Rocks and minerals presumed to have formed in sedimentary
164	environments are the main focus of our investigation and ISEM is
165	particularly well suited to detect and characterize them.
166	4. ISEM as a remote instrument is well adapted to characterize the
167	stratification at the outcrop scale.
168	5. Our investigation will assess the obscuring effects of dust, first of all on
169	the target areas, but also observing dust accumulation on the calibration
170	target, excavated drill cuttings (e.g, Rice et al, 2011).
171	
172	2.2. Synergies with other instruments
173	The main goal of ISEM is to establish the mineral composition of Mars' surface
174	materials remotely. ISEM, together with PanCam (Fig. 1) offer high potential for
175	the remote identification and characterization of any scientifically high-value
176	targets in the vicinity of the rover, including proximal and distant rocks, outcrops,
177	and other geological formations. ISEM will help to establish the geological
178	context of each site along the rover traverse, discriminating between various
179	classes of minerals and rocks. ISEM will also be important in order to select
180	promising sites for subsurface sampling.
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181	
182	Infrared reflectance spectroscopy allows the study of the composition in the
183	uppermost few millimeters of a rock's surface. It allows discriminating between
184	various classes of silicates, (hydr-)oxides, hydrated/hydroxilated salts and
185	carbonates. As shown in Fig. 2, the 1.3° Field of View (FOV) of ISEM lies within
186	the 5° FOV of the color PanCam high-resolution camera (HRC), and they both
187	are within a much wider FOV (38.6°) of the Wide Angle Cameras (WACs) with
188	multispectral capabilities (Coates et al, this issue). The multispectral data are
189	produced using a filter wheel with 11 filter positions for each of the two WACs.
190	Out of the 22 filters, six are devoted to red, green, and blue broadband color,
191	duplicated in the both cameras, 12 are optimized for mineralogy in the 400-1000
192	nm range, and four "solar" filters are dedicated to atmospheric studies. By
193	extending the wavelength range beyond PanCam, ISEM will enable many more
194	spectral features diagnostic of specific mineralogy to be detected. Together
195	PanCam and ISEM provide spectrally resolved information from 0.4 to 3.3 $\mu$ m.
196	
197	The identification and mapping of the distribution of aqueous alteration products
198	in the upper surface layer, combined with subsurface data from the neutron
199	detector ADRON and the ground-penetrating radar WISDOM, will help to
200	understand the subsurface structure and the exobiology potential at each
201	prospective drilling site.
202	
203	The collected drill samples will be analyzed in the rover's Analytical Laboratory
204	Drawer (ALD) by several instruments. The first is an infrared hyperspectral
205	microscope MicrOmega (Bibring et al, this issue). The principle of MicrOmega is
206	very similar to that of ISEM. The reflectance spectroscopy is performed in the
207	near-IR, but the analysis is done at the microscopic scale and the sample is
208	illuminated by monochromatic light source. In contrast to MicrOmega, ISEM has
209	a much wider field of view and range of detection. The distance to a target is not
210	really limited, and practically may reach hundreds of meters. Thus, ISEM is better
211	suited for accommodation on the rover mast, where it can be employed for target
212	identification of far away objects, but also for investigating outcrop, rock, and soil
213	mineralogy at close range.
214	
215	There is no specific instrument dedicated to environmental characterization on the
216	rover. Although hampered by the limited number of observation cycles, ISEM,
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jointly with PanCam, will deliver information regarding atmospheric aerosol opacity and the atmospheric gaseous composition. The data on water vapor content and aerosol will be retrieved as a by-product of reflectance spectra, from in-flight calibration, from the direct Sun imaging by PanCam, and from sky observations by PanCam and ISEM.

## 



Figure 1. Schematic view of the ExoMars Rover mast instruments: PanCam,

- navigation cameras, and ISEM.



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Figure 2. Schematic representation of possible ISEM and PanCam joint
observation scenario showing a sequence of ISEM measurements acquired
together with WAC and HRC PanCam frames.

## **2.3 The method**

Near-IR spectroscopic observations of the Mars surface have not been performed from any surface platform to date. Spectroscopy was employed on the Mars Exploration Rovers (MER) in the thermal IR range (the radiation emitted by the surface, 5-29 µm) with the Mini-TES instrument (Christensen et al, 2003, 2004a,b). These remote observations proved very useful for selecting targets for in situ analyses by the Alpha Proton X-Ray Spectrometer (APXS) and Mossbauer instruments on Spirit and Opportunity (e.g., Squyres et al, 2004). They also allowed the identification of carbonates in Gusev Crater (Morris et al. 2010), and undertook a number of atmospheric investigations (Smith et al, 2006). 

Conversely, the near-IR spectral range (i.e. the infrared solar reflected radiation) is being widely used in orbital observations, as it allows for significantly better characterization of aqueous minerals than does the thermal infrared. To illustrate this point, the TES instrument on Mars Global Surveyor (MGS) in the wavelength range from 6 to 50 µm has mapped the distribution of both mafic and anhydrous high-silica minerals (Bandfield et al, 2000; Christensen et al, 2001), but could not unambiguously detect clay/clay-like minerals and salts, including carbonates. In the near-IR, the OMEGA hyperspectral instrument on Mars Express (MEx) measured the martian surface reflectance from 0.5 to 5.2  $\mu$ m, and was able to recognize a number of different phyllosilicates and sulfates (Bibring et al, 2006). Building on OMEGA's success, the higher spatial resolution of the CRISM instrument on Mars Reconnaissance Orbiter (MRO), which measures reflectance from 0.362 to 3.92  $\mu$ m, permitted the first detections of carbonates and serpentine (Ehlmann et al, 2008, 2010). One shortcoming of the orbital observations is the limited surface resolution (300-500 m per pixel for OMEGA/MEx and  $\sim$ 20 m for CRISM/MRO), hindering the detection of small-scale exposures. In addition, such instruments suffer from limited detection sensitivity owing to the combination of the subtle nature of aqueous mineral spectroscopic features and to the short dwell time of orbiting spacecraft. The wide variety of minerals on Mars detected by the higher spatial resolution CRISM instrument compared to the lower resolution

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5		
6	264	OMEGA instrument demonstrates the greater mineralogical diversity that can be
7 8	265	identified as spatial resolution improves. Therefore the close-up near-IR
9	266	capability of ISEM on the ExoMars rover offers a very high diagnostic potential.
10 11	267	
12	268	The small size and low mass of the ISEM instrument allows it to be
13 14	269	accommodated more easily on a rover platform. A similar AOTF-based near IR
14	270	spectrometer has been selected to enhance the capabilities of the successor to the
16	271	ChemCam instrument on the Curiosity Rover (Fouchet et al, 2015). The new
17 18	272	SuperCam instrument planned for the NASA 2020 rover utilizes a combination of
19	273	the Laser-Induced Breakdown Spectrometer (LIBS), Raman, and near-IR
20	274	reflectance spectroscopy, offering complementary elemental and mineralogical
21 22	275	analysis techniques.
23	276	
24 25	277	Spectral range: An optimal spectral range for a near-IR mineralogical
26	278	characterization is 0.9-4.0 µm to encompass a broad absorption centered in the
27	279	0.95-1.1 µm region characteristic for pyroxene or olivine, and 3.4-3.9 µm for
28 29	280	carbonate overtones. The spectral range of the prototype LIS spectrometer is a
30	281	compromise of science requirements and technical limitations. Its longwave
31 32	282	bound of 3.3 $\mu$ m allows for detection of hydration features in the 3 $\mu$ m region
33	283	that can be used to discriminate different types of phyllosilicates and other
34	284	water/hydroxyl-bearing materials (e.g, Clark et al, 1990). The broad absorption in
35 36	285	the 3 $\mu$ m region has contributions from the long wavelength wing of a hydroxyl
37	286	(OH) fundamental stretch usually centered near 2.7-2.8 $\mu$ m, H <sub>2</sub> O fundamental
38 20	287	stretches, and the first overtone of the $H_2O$ bending fundamental (Clark et al,
39 40	288	1990). On Mars, hydration is strong enough that it can be detected at shorter
41	289	discriminated from evertenes and combinations observation features at 1.4 um
42 43	290	1.0 um and 2.2.2.3 um. Detection of corbonates by ISEM will be possible using
44	291	~1.9 µm, and 2.2-2.5 µm. Detection of carbonates by ISEM will be possible using correlated 2.3 and 2.5 µm region bands, similar to CRISM/MRO (Ehlmann et al.
45 46	292	2008) Beyond 3 3-3.4 um the signal is complicated by the thermal radiation of
40 47	293	the surface (and from the instrument itself, detectors with longer-wavelength
48	295	bound are much less sensitive because of thermal background). On the short
49 50	296	wavelength bound the sensitivity of detectors optimized for 3-um range falls
51	297	abruptly below 1 µm hampering mafic silicate identification and characterization
52 53	298	However mafic silicates can be recognized and discriminated by the shape of the
53 54	299	long wavelength wing of the 1-um ferrous iron absorption band and the
55		
56 57		
58		
59 60		
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300	wavelength position of the 2-µm ferrous iron absorption (see the following
301	section for the details).
302	
303	Taking into account the advantages of the heritage design, we choose using the
304	same 1.15-3.3 µm range for ISEM on ExoMars as for the lunar instrument.
305	
306	Spectral resolution. The spectral features of Mars surface materials will generally
307	include a mixture of several minerals, and are usually broad (>20 nm full width at
308	half maximum), so that there is no stringent requirement on the spectral resolution
309	for orbital instruments (see Table 1). With increasing spatial resolution, individual
310	minerals may become more apparent, with deeper characteristic absorption
311	features. Pure minerals can likely be observed only at the scale of individual
312	grains, e.g, with the microscope-spectrometer MicrOmega. Given that the ISEM
313	FOV will typically encompass an area of few cm <sup>2</sup> , a mixture of minerals will
314	likely be present, therefore a spectral resolution requirement of 25 cm <sup>-1</sup> was
315	chosen that corresponds to 3.3 nm at 1.15 $\mu$ m, 16 nm at 2.5 $\mu$ m, and 28 nm at 3.3
316	μm.
317	
318	In mineralogical studies, the best approach is the acquisition of the full available
319	spectral range. Nyquist sampling (two measured points per spectral resolution) of
320	the full 1.15-3.30 $\mu$ m (3030-8696 cm <sup>-1</sup> ) range with a spectral resolution of 25 cm <sup>-1</sup>
321	results in 453 (512 with margin) spectral points. With a one-second exposure for
322	each spectral point, a complete spectrum is therefore measured in 8.5 minutes.
323	Customable or random wavelength access by the AOTF (see below) allows
324	oversampling, selecting different portions of the spectrum, and focusing on the
325	most interesting or diagnostic spectral intervals.
326	
327	The color and IR reflectance of the Mars surface are what one would expect of
328	iron-bearing mineral species that are either primary or formed by hydrous or
329	anhydrous chemical weathering. The infrared reflectance varies from 5% to 35%,
330	with typical values being 15-20% for low albedo regions and 25-30% for high-
331	albedo regions (Erard 2001). A characteristic feature of Mars spectra is a deep
332	absorption feature starting beyond the 2.7- $\mu$ m CO <sub>2</sub> saturated atmospheric band.
333	Its depth reflects the degree of hydration of the martian surface. An increase in
334	measured reflectance toward longer wavelengths signifies an increasing
335	contribution from emitted thermal radiation. Observations from the ExoMars
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rover mast will be carried out using a broad range of phase angles, preferably athigh Sun. There is no Sun avoidance requirement for ISEM.

Table 1. Near-IR spectrometers used and planned to study Mars surface

Instrument	Spectral	Spectral	Surface	Ref.
	range, µm	resolution, nm	resolution	
ISM/Phobos 2	0.8 -3.1	50	20x30 km	Bibring et al,
				1990
OMEGA/MEx	0.35-1	7	0.3-5 km	Bibring et al,
	1-2.5	14		2004
	2.5-5.1	20		
CRISM/MRO	0.362-3.92	6.6/pix	18 m	Murchie et al,
				2007
ISEM/ExoMars	1.1-3.3	3.3 at 1.15 μm	3-10 cm	This study
		16 at 2.5 µm		
		28 at 3.3 µm		
MicrOmega/	0.5-3.65	2 at 1.0 µm	20 µm	Bibring et al,
ExoMars		25 at 3.6 µm		this issue
SuperCam/	1.3-2.6	5 at 1.3 μm,	1.3-7 mm	Fouchet et al,
2020 Rover		20 at 2.6 µm		2015

## **2.4 Potentially detectable mineral groups**

The greatest share of what we know about martian mineralogy has been gleaned from orbital near- and thermal-infrared spectroscopy measurements. The infrared instruments have been successful in identifying igneous minerals, while the near-IR instruments were more important for detecting ancient hydrated minerals, such as phyllosilicates, as well as carbonates and sulfates, which could be used to develop a timeline of changing environmental conditions on Mars and evidence of previous more clement epochs on Mars. The capabilities of ISEM can be gauged against these detections to assess its expected science return, as well as expectations for detecting other mineral species of high scientific value, all in the context of the proposed ExoMars landing sites. 1. Phyllosilicates: The identification of hydrated phyllosilicates on the martian

355 surface is one of the discoveries driving *in situ* exploration of Mars.

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6 7	356	Phyllosilicates are commonly detected in ancient, Noachian-aged martian terrains
8	357	(Poulet et al, 2005). Various types of phyllosilicates have been observed,
9	358	including Fe/Mg and Al-rich smectites micas vermiculites kaolinite chlorite
10	359	and serpentine (Ehlmann et al. 2009: Murchie et al. 2009: Carter et al. 2013). The
11	360	presence of these minerals likely indicates that conditions in the past were
13	261	for the program of liquid water of or poor the surface. They are
14	301	avolable for the presence of inquid water at of hear the surface. They are
15	362	considered good reaction templates for organic molecules and excellent for
16 17	363	biosignature preservation (Bishop et al, 2013, and references therein).
18	364	Phyllosilicates have been detected from orbit within the ellipse of two out of the
19	365	three candidate landing sites for the ExoMars rover, Oxia Planum and Mawrth
20	366	Vallis (Vago et al, this issue). They have not been detected in Aram Dorsum yet;
21	367	even if they are there, it may be difficult to see them from orbit. ISEM will have
23	368	the capabilities to detect sharp features between 1.35 and 2.6 µm in phyllosilicate
24	369	reflectance spectra, which are related to combinations and overtones of OH-M
25	370	stretching and bending bound to various cations (M) as well as the H-O-H stretch
20 27	371	and bend from water bound in interlayer regions or adsorbed on mineral surfaces
28	372	(Clark et al. 1990) (Figures 3a, h, and c)
29	372	(Churk et ul, 1990) (1 igures 5u, 0, und 0).
30 21	274	2. Carbonatos have been discovered on Mars at a number of locations from orbit
32	275	<u>2. Carbonates</u> have been discovered on wars at a number of locations from orbit (Ehlmann et al. 2008, Wray et al. 2016), by surface rovers (Marris et al. 2010)
33	373	(Eminann et al, 2008, wray et al, 2010), by surface rovers (Morris et al, 2010),
34	3/6	and in martian meteorites (e.g., McKay et al, 1996). The precise species are not
35 36	377	always known, but various Mg-Fe-Ca carbonates provide the best match for
37	378	observed spectral features. Carbonates are important minerals for identification as
38	379	they often indicate the presence of habitable (circum-neutral) environments. They
39	380	are also widely implicated in explaining the loss of a substantial fraction of the
40 41	381	presumed early Mars dense carbon dioxide atmosphere. Carbonate detection and
42	382	characterization is possible in a number of wavelength regions. The 2.2-2.6 $\mu$ m
43	383	region is one of the best because it is not affected by thermal emission, and
44 45	384	absorption bands in this region vary in their positions for different carbonate
46	385	species (Figure 3d). ISEM may also be able to identify Fe-bearing from Fe-free
47	386	carbonates on the basis of the presence or absence of a ferrous iron absorption
48	387	band near 1.2 um
49 50	388	
51	200	2. Sulfator: A number of sulfate minerals have been absorved on Mars both from
52	202	<u>5. Surfaces.</u> A number of surface numerals have been observed on whats, both from
53	390	orbit and in situ, including poorly ( $\leq 2 H_2O$ ) hydrated species (gypsum, kieserite,
04 55	391	bassanite), and polyhydrated varieties (Squyres et al, 2004; Gendrin et al, 2005;
56		
57		
58		

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	13	
3	92 Wang et al. 2006; Flahaut et al. 2014; Nachon et al. 2014) as well as hydroxylated	
3	93 species (copiapite, jarosite, alunite and the dehydrated form of amarantite	
3	94 (FeSO <sub>4</sub> (OH)). These sulfates are all water/hydroxyl-bearing and several are also	
3	95 indicative of circum-neutral, perhaps habitable environments. Sulfates also have	
3	96 the potential to preserve microfossils (e.g, Allwood et al, 2013) and concentrate	
3	97 organic compounds (Noe Dobrea et al, 2016). Specific sulfates can be powerful	
3	98 indicators of environmental conditions on Mars, past and present (e.g, Leftwich et	
3	al, 2013). Sulfate discrimination is possible using a number of wavelength	
4	intervals in the ISEM range. For example, gypsum is characterized by a uniquely-	
4	of shaped absorption band in the 1.4- $\mu$ m region, jarosite and alunite by absorption	
4	bands in the 1.8- $\mu$ m region, and other suffaces by S-O associated absorption bands in the 2.0.25 $\mu$ m region (Clautia et al. 2006) (Eigungs 25 and 6)	
4	In the 2.0-2.5 $\mu$ m region (Clouds et al, 2006) (Figures 5e and 1).	
н 4	05 4 Silica: Silica in a variety of forms is present in a number of terrains on Mars	
4	06 (Bandfield et al. 2004: Smith and Bandfield. 2012: Smith et al. 2013. Carter et al.	
4	07 2013). Differences in reflectance spectra can be used to distinguish different	
4	forms of silica, some of which are associated with habitability (Rice et al. 2013).	
4	09 The region most useful for distinguishing different forms of silica is located near	
4	10 2.2 µm and is due to Si-OH overtones. The nature and abundance of these bonds	
4	varies among different types of silica (Rice et al, 2013). This diagnostic feature	
4	12 can be clearly seen in the reflectance spectra of two different grain sizes of quartz	
4	13 (Figure 3g).	
4	14	
4	15 <u>5. Igneous minerals.</u> Petrologic investigations of martian rocks have been	
4	accomplished by mineralogical, geochemical, and textural analyses by remote	
4	sensing observations, in situ investigations, and laboratory analyses of martian	
4	meteorites. Igneous rocks are found in numerous settings; NIR spectroscopy from	
4	orbiting spacecraft has been an effective mineralogic tool to identify and to map	
4	at a global scale various fock-forming minerals such as offvines, pyroxenes and iron bearing plagicaleses (Poulet et al. 2000; Ody et al. 2012; Carter and Poulet	
4	21 Inon-bearing plaglociases (Poulet et al. 2009, Ody et al. 2015, Calter and Poulet 22 2013) (Figure 3h and i)	
4	22 2015). (Figure 5it and 1).	
4	24 6 Ferrous oxides/hydroxides. These minerals are the widespread weathering	
4	25 products of primary iron-bearing materials (Ody et al. 2012). In the ISEM spectral	
4	26 range, they manifest themselves mainly in the shape of the continuum.	
4	27 Hydroxides exhibit shallow absorption features, including near 1.41 and 1.93 μm,	
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and several species have been reported from NIR orbital investigations. Some iron-bearing species, such as goethite, exhibit Fe-OH absorption bands longward of the same band in Fe-free minerals (Beck et al, 2011) (Figure 3j). Several other potential candidates that are amenable to detection and analysis by ISEM, and are of high scientific value, are described below. Organic ompounds –PAHs. Infrared spectroscopy is potentially sensitive to the presence of organic compounds, which have already been identified *in situ*, though in trace quantities, within Mars samples (Freissinet et al, 2015). PAHs are generally a stable form of organic molecules, and if organic compounds are or were present on the surface of Mars, they have likely transformed to PAHs (Anders et al, 1996). PAHs are also the dominant form of organic material in Archaean terrestrial rocks (Marshall et al, 2007; and references therein). Their reflectance spectra exhibit absorption features that are largely associated with a number of functional groups that may be present, particularly aliphatic C-H molecules (Izawa et al, 2014). They can exhibit absorption bands near 1.69 µm due to CH overtones, 1.50 µm due to N-H stretching overtones, and numerous other overtone and combination bands beyond 2.1 µm. A shoulder of the fundamental 3.2-3.35 µm aromatic band could be also detectable in the spectra, though complicated by a deep 3-µm absorption, characteristic for Mars reflectance in general, see below. Perchlorates and chlorides. Perchlorates are strongly suspected to be present on Mars on the basis of analytical results from the Phoenix lander in the polar region (Hecht et al, 2009; Cull et al, 2010) and from the MSL Curiosity rover in the near-equatorial region (Farley et al, 2016). Perchlorates have been linked both to the destruction of organic compounds, and to liquid water. They can absorb atmospheric water and allow for the existence of stable liquid water brines (Martin-Torres et al, 2015). Their spectral properties have been the focus of multiple studies (Bishop et al. 2014; Hanley et al. 2015) since the presence of perchlorates could have strong implications for the (non) preservation of biosignatures. Reflectance spectra are characterized by possible Cl-O-H<sub>2</sub>O-associated absorption bands near 1.35, 1.75, and 2.15 µm. The 3-micron signature of water is present in IR spectra of perchlorate samples in the form of hydrate, ice or liquid brine (Zorzano et al, 2009). Spectral features in a more suitable NIR 

464	range have possibly been detected from orbit (Ojha et al, 2015), the efforts to
465	confirm this are under way. While anhydrous chloride salts are mostly featureless
466	in the wavelength range of ISEM, chlorinated species have been detected in
467	abundance at Mars (Osterloo et al, 2010), and their hydrated forms would be
468	detectable in the NIR (Hanley et al, 2011).
469	
470	Oxalates. Oxalates are carbon-bearing minerals that new evidence suggests may
471	be present on Mars in addition to, or instead of, carbonates (Applin et al, 2015).
472	Terrestrial oxalates are typically formed in biological processes (Applin et al,
473	2016, and references therein). Their presence on Mars would suggest past
474	habitability and possibly biological processes. Oxalates have some similarities
475	with carbonates in terms of multiple C-O associated absorption bands, but their
476	wavelength positions and shapes differ from carbonates and can be used to
477	discriminate different oxalate species. Major oxalate absorption bands are present
478	in the 2.2-2.5 and 3.2-3.3 µm regions.
479	
480	Water ice. The presence of water ice at the landing site during daytime
481	observations is unlikely, but cannot be excluded (Carrozzo et al, 2009). Seasonal
482	frost, if present at the landing site, will be readily identifiable by ISEM, allowing
483	study of its season deposition cycle and dependence on local conditions.
484	Unambiguous signatures of water ice are present in the ISEM wavelength range
485	with diagnostic absorption bands at 1.25, 1.5, 2.0 and 3.0 $\mu$ m.
486	
487	Nitrates. Nitrates may have been detected in situ on Mars (Navarro-Gonzalez et al,
488	2013). They are important minerals because they may indicate the operation of
489	biological processes and/or can serve as a bioavailable source of nitrogen. Their
490	spectral reflectance properties have recently been studied (Cloutis et al, 2016).
491	The NO <sub>3</sub> molecule gives rise to multiple absorption bands that can be detected
492	down to as low as 1.8 μm.
493	
494	Phosphates. Phosphates are important as a potential indicator of biological
495	processes. They are a likely possibility to explain phosphorus, which has been
496	detected on Mars (Blake et al, 2013), but its form is not yet determined. Their
497	spectral properties are only partially known (Lane et al, 2011). They share some
498	similarities with some other mineral groups, including ferrous iron-associated
499	absorption bands in the 1- $\mu$ m region and weak P-O absorption bands in the 2-2.5
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500	um region. Robust phosphate detection by ISEM may not be feasible.
501	
502	Borates. Borates are another important mineral group that can be associated with
503	habitability and biological processes (Stephenson et al. 2013). Boron cannot be
504	detected with an APXS instrument (Cloutis et al, 2016), but it has been detected
505	and quantified in clays from martian meteorite MIL090030 (Stephenson et al.
506	2013). Borate deposits on Earth are often associated with enclosed evaporitic
507	deposits and might be present in association with martian chlorides and sulfate
508	salts. Borates exhibit B-O associated absorption bands in the 1.55, and 2.15-2.25
509	$\mu$ m regions, enabling their detection using multiple wavelength intervals and
510	absorption features measurable by ISEM. Absorption band positions and shapes
511	vary between different borates.
512	
513	Ammonium-bearing minerals. The presence of the ammonium (NH <sub>4</sub> ) molecule in
514	various minerals leads to strong absorption bands in the 1.6, 2.0-2.2 and 3.1 $\mu$ m
515	regions. Band shapes and positions can be used to discriminate different
516	ammonium-bearing minerals (Berg et al, 2016). Ammonium-bearing minerals are
517	of astrobiological importance for a number of reasons. Ammonium is often of
518	biological origin, has high thermal stability, and can withstand some level of
519	metamorphism (Boyd, 2001). Ammonium-bearing minerals on Mars have
520	possibly been detected from spectroscopic observations made from orbit (Sefton-
521	Nash et al, 2012), and a nitrogen cycle on Mars has been suggested to operate
522	(Manning et al, 2008). Low concentrations of ammonium in soil have been
523	reported for the Phoenix landing site (Quinn et al, 2011).
524	
525	One of the limitations of spectrally characterizing Mars-relevant minerals with
526	ISEM under ambient terrestrial conditions is that these mineral spectra display a
527	nearly ubiquitous broad and frequently deep absorption feature in the 3-µm region.
528	This is normally attributable to water that may be present in various forms,
529	including adsorbed, fluid inclusions, impurities or accessory phases, or due to
530	incipient alteration. This feature is normally seen even in nominally anhydrous
531	minerals, such as olivine and pyroxene (see Figure 3h and i; more examples of
532	Mars background material spectra are presented in Figure 3 j, k, and l). When
533	such minerals are exposed to Mars-like surface conditions, the 3-µm feature
534	commonly shows a reduction in both depth and width, but rarely disappears
535	completely (Cloutis et al, 2007; Cloutis et al, 2008). It may be possible to use
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<ul> <li>characteristics of the 3-µm absorption feature to constrain or det</li> <li>content (Milliken and Mustard, 2005), but in multicomponent ta</li> <li>determinations will be more difficult. Small amounts of water in</li> <li>subsurface and on the surface of Mars also seems to be ubiquitor</li> <li>seasonal variations (Milliken et al, 2007). Collectively these resu</li> <li>the 3-µm region may not be best suited for mineralogical determines</li> <li>ISEM. However, as discussed above, other wavelength regions a</li> <li>ISEM have significant diagnostic potential for a wide range of n</li> <li>demonstrated effusively from terrestrial and Mars orbital studies</li> </ul>	ermine water rgets, such the near us, displaying ults suggest that ninations using accessible to ninerals, as
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553 spectra of minerals the most significant for habitability, while the spectra shown

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554 in the lower half (g-i) are more relevant to background minerals and dust. The 555 spectral resolution of CRISM is close to that of ISEM in the center of the range; 556 ISEM resolution is better at shorter wavelengths, and coarser at 3  $\mu$ m (see Table 557 1).

#### **2.5** Atmospheric studies (aerosol, gaseous content)

There is no dedicated instrument, such as e.g. meteorological station on the ExoMars rover to characterize the environmental conditions. Therefore any information available by other means is of particular value. Spectrally resolved data in the visible-NIR and in the thermal IR ranges have been used to assess the atmospheric state from Mars Pathfinder and Mars Exploration Rovers. In the spectral range of ISEM there are absorption bands of atmospheric  $CO_2$  (at 1.43, 1.6, 2.0, and 2.7  $\mu$ m) and H<sub>2</sub>O (at 1.38 and 2.56  $\mu$ m), and it is well suited, in particular its short-wave sub-range to characterize the main mode of the martian dust (Fedorova et al, 2014). The condensation clouds in the equatorial region consist predominantly of water ice (Vincendon et al, 2011), with multiple absorption bands within the ISEM spectral range (see section 2.4). Carbon dioxide clouds if present at high altitudes may be detected by distinct features of solid CO<sub>2</sub> near 1.2, 1.4, 1.5, 2.0, 2.7, and 3.0 µm. 

The gaseous absorptions will be measured by ISEM as a by-product of every surface measurement. Depth of the CO<sub>2</sub> absorptions can be used to determine the surface pressure, and the H<sub>2</sub>O absorptions quantify the total column water contents in the atmosphere above the site. To disentangle the possible overlapping atmospheric and mineral features in the reflected surface spectra, preferentially the observations of the *in situ* calibration target will be interpreted. The estimate of accuracy to retrieve the atmospheric pressure by ISEM is given by OMEGA study of the 2- $\mu$ m CO<sub>2</sub> absorption from the orbit: 7-10 Pa (~1%) 1-sigma. (Forget et al, 2007). With the optical path being half of the OMEGA case, our retrieval accuracy will be comparable.

585 More precise measurements of surface pressure, minor gases, and better 586 characterization of the atmospheric dust and cloud situation by ISEM will be 587 possible using dedicated atmospheric observations. They will be coordinated with 588 those by PanCam. The PanCam atmospheric study (Coates et al, this issue) will 589 include direct solar observations just prior to sunset (to take advantage of the

2		
3		
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6 7	590	maximal atmospheric path lengths) and cross sky brightness measurements. Such
8	591	observations, e.g. performed with Mars Pathfinder camera (Titov et al, 1999;
9	592	Markiewicz et al. 1999) or MERs (Lemmon et al. 2004 <sup>.</sup> Smith et al. 2006) can be
10	593	significantly strengthened by extending the spectral range to the near-IR
11	598	significantly strongthened by exteriantly the speedal range to the near fit.
12	574	Direct color charmations by ISEM are not so for in the baseline. Their
14	595	Direct solar observations by ISEW are not so far in the baseline. Then
15	596	implementation would allow for high-accuracy pressure and water retrievals,
16 17	597	better optical characterization of dust, direct and localized detection of $H_2O$ ice
17	598	and, if present, the $CO_2$ ice clouds. Observing the Sun at different zenith angles
19	599	helps putting constraints on the vertical distribution of water vapor. However
20	600	ISEM is optimized for weak reflected light, and measuring the direct Sun signal
21	601	may not be feasible. We successfully tested this possibility with the lunar
22 23	602	prototype, but the ISEM aperture is larger, and a solar-blind filter within the
24	603	foreoptics might become necessary. Such a filter would cause a several percent
25	604	signal loss for the baseline ISEM observations. A final assessment of the direct
26 27	605	Sun mode will be done during the characterization of the flight model
27 28	606	Sui mode win be done during the characterization of the fight model.
29	606	
30	607	The cross-sky brightness measurements by ISEM are the best suited for
31	608	characterizing the aerosol component of the Mars atmosphere. Because of quasi-
32 33	609	permanent aerosol loading, the brightness of the martian sky at low zenith angles
34	610	is not significantly lower than that from light scattered from the surface.
35	611	Measurements at a range of phase angles will allow to extract the size distribution,
36	612	optical properties, and even to assess the shape of aerosols suspended in the
37 38	613	atmosphere. Water vapor absorption at 2.56 µm is much stronger than that at 0.94
39	614	um to be observed by WAC in solar filters, and the ISEM data might put
40	615	additional constraints on the vertical distribution of water in the boundary layer of
41 42	616	atmosphere
42 43	617	autiosphere.
44	(10	The variety of strategies and are any one onto by ISEM calibrated using on in site
45	618	The variety of atmospheric measurements by ISEM calibrated using an <i>in situ</i>
46	619	calibration target will allow the refinement of atmospheric scattering models and
47 48	620	therefore refinement of the calibration of orbital spectral measurements of the
49	621	martian surface.
50	622	
51	623	3 Instrument Description
5∠ 53	624	3.1 Instrument concept
54	625	The measurement principle of ISEM is based on the use of an AOTF The core
55	020	
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57 58		
59		
60		

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		21	
	626	element of an AOTF is a birefringent crystal (typically of paratellurite, TeO <sub>2</sub> , due	
	627	to the combination of acoustic and optical properties) with a welded	
h	628	piezotransducer. The radio frequency (RF) applied to the transducer generates an	
,	629	acoustic field in the crystal, implementing acousto-optic interactions in Bragg's	
2	630	regime. The spectral selectivity of the acousto-optic diffraction allows the	
5	631	filtering of light. The diffraction occurs for a single wavelength, and there are no	
5	632	diffraction orders. The applied RF controls the tuning of the AOTF. AOTFs are	
) ,	633	technologically mature and widely used for spectral analysis. The robust design,	
3	634	small dimensions and mass, coupled to the absence of moving parts in an AOTF-	
)	635	based spectrometer, makes them popular for space applications. So far AOTF-	
)	636	based spectrometers have been used in space science: (1) to study the atmospheric	
2	637	composition of Mars and Venus (Korablev et al, 2006, 2012); (11) on the Moon	
8	638	within the Chang'e-3 VNIS spectrometer (0.45-2.4 $\mu$ m) mounted on the Yutu	
r 5	639	rover (He et al, 2014); (iii) for isolation of echelle-spectrometer diffraction orders	
5	040 641	Nasfa et al. 2015); and (iv) to illuminate the sample of an ID microscope with	
8	041 642	monochrometic light (Pilorget and Pibring 2012)	
)	642 643	monochromatic right (Pholget and Blotting 2015).	
)	644	Wider application of the AOTEs in remote sensing is hampered by the inherent	
2	645	requirement to sequentially scan the spectrum. On an orbital mission with a short	
3	646	dwell time, this scanning interferes with the spacecraft or line of sight motion	
+ - 	647	complicating the analysis. Even for a pencil-beam device, different parts of the	
5	648	acquired spectrum would correspond to different observed areas. Conversely,	
, }	649	observations from a static point, such as a planetary lander, or a rover, which	
)	650	remains immobile during the measurement, are well suited for AOTF-based	
)	651	instruments.	
2	652		
3	653	As described in the Introduction, ISEM is a close equivalent of LIS being	
5	654	developed for two Russian lunar landers. The LIS development is more advanced	
6	655	with respect to that of ISEM — by about two years. LIS benefited from the	
2	656	experience gained from the pencil-beam spectrometer design of the Mars Express	
)	657	and Venus Express instruments, and from the early developments of MicrOmega.	
)	658	SPICAM-IR AOTF spectrometer with the spectral range 0.9-1.7 µm (Korablev et	
2	659	al, 2006) has been operating in Mars orbit since 2004. A similar SPICAV-IR	
3	660	instrument employing a double-range AOTF operated in Venus orbit from 2006	
ŀ	661	to 2014 (Korablev et al, 2012). A double-range AOTF for the spectral range of	
, )			
•			
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)			
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0.7-4.1 µm serving as a prototype to the LIS and ISEM's AOTFs was developed for the Phobos Grunt mission (Leroi et al, 2009). 

In order to reduce the influence of the extreme temperature conditions at the

rover's mast on the electronics, the instrument is implemented as two separate 

boxes, a mast-mounted Optical Box (OB) and the Electronics Box (EB) (Fig. 4).

The thermally stabilized EB is mounted within the rover's body.



Figure 4. The ISEM instrument, the photographs of the optical and electronics

- box structural and thermal models.

Table 1. ISEM main characteristics and resources

Parameter	Value		
Spectral range	1.15-3.3 μm		
Spectral resolution	better than 25 cm <sup>-1</sup>		
	3.3 nm at 1.15 μm, 16 nm at 2.5 μm, 28 nm at 3.3		
	μm		
FOV	1.3°		
Temperature range, operational	-45°C+30°C (Optical box, OB)		
	-40°C+50°C (Electronics box, EB)		
Temperature range, non-operational	-60°+60°C (OB and EB)		
	-130°+60°C for OB pending final confirmation		
AOTF			
Material	TeO <sub>2</sub>		
Spectral range	1.15-3.39 μm		
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Parameter	Value
Effectiveness	>50 % (in polarized light)
Aperture	Ø 5 mm, 5°×5°;
Mean RF power	5 W
RF frequency range	23-82 MHz
Detector	InAs photodiode, Ø1 mm, 1-3.45 µm
	Teledyne Judson Technologies J12TE3-66D
	R01M, 3-stage Peltier cooler
ADC	16-bit
Number of points per spectral range	variable, by default 1024 for one observation
Data volume	variable, by default 20 Kbit for one observat
Data/command interface	RS-422
Powers supply voltage	28 V
Power consumption, W	
Peak	14
Average	11.5
Standby	9
Dimensions	160×80×96 mm OB
	116×84×55 mm EB
Mass, overall	1.740 kg
OB	0.690 kg
EB	0.560 kg
Calibration target (ISEM part)	0.014 kg
Harness	0.476 kg including 20% margin (TAS-I data
577	
578	
579	
580 <b>3.1 The Optical Box</b>	
581 Though most of the electronics a	re in the EB, some electronics such as the
682 detector's preamplifier and the F	RF conditioning electronics remain in the OB
583 Neither the weak photodiode cur	rent nor the power RF can be transmitted via th
684 5 m harnass. The block diagram	of ISEM is presented in Fig. 5
COF	or iselve is presented in Fig. 5.
The OB contains all the optical of	elements, the AOTF with associated electronics
587 (ultrasound frequency synthesize	r and amplifier boards), the photo detector and
the photo detector board (Fig. 6).	



691 Figure 5. The block diagram of the ISEM control electronics.



Figure 6. The 3D model open view of the ISEM Optical Box. The main elements

- are visible: 1- baffle, 2- entry optics; 3, 7- AOTF collimating optics; 4, 6-
- 696 polarizers; 5- AOTF crystal; 8- detector; 9- detector's preamplifier; 10- AOTF RF

697 proximity electronics.

The spectrometer is built following a standard layout for an AOTF spectrometer, with the AOTF in the path of a quasi-parallel beam. The optical scheme is based on a Galileo system with remote pupil built using  $CaF_2$  and ZnSe lenses and it is presented in Fig. 7. The image is transferred through the optical system, and the field-of-view (FOV) of 1.3° is formed on the detector sensitive area. The achromatic lens entry telescope (1) has the aperture of 25 mm. The AOTF crystal (5) is placed in a quasi-parallel beam between collimating lenses (3, 7), and a pair

of polarizers (4, 6); the output collimating lens (8) serves also as a focusing optic

- for the detector (8).



- Figure 7. ISEM optical scheme. The numbering is the same as in Fig. 6. 2-
- foreoptics; 3, 7- AOTF collimating optics; 4, 6- polarizers; 5- AOTF crystal; 8sensitive area of the detector.

- A wide-angle AOTF from NII Micropribor in Zelenograd, Russia is manufactured
- on the base of a tellurium dioxide crystal. The ultrasound frequency range of 23-
- 716 82 MHz provides a spectral range from 1.15  $\mu$ m to 3.3  $\mu$ m with two
- 717 piezotransducers. The transducers operate in the sub-bands of 23-42 MHz and 42-
- 718 82 MHz. The crystal cut-off angle is 12.5° in the (110) crystallographic plane.
- 719 The anisotropic Bragg diffraction regime is used. The incident optical radiation
- has ordinary polarization and the diffracted optical beam has the extraordinary
- 721 polarization. The angle between the passed and diffracted optical beams is 6° at
- the output of the AO crystal. A pair of polarizers with crossed polarizing planes is
- visual real to filter out the non-desired zero diffraction order.

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724	
725	The AOTE and its electronics are assembled in a single functional unit which
726	includes the acousto-ontic cell the polarizers a proximity RF matching board an
727	RF synthesizer the driver of the AO crystal (the RF power amplifier) and a
728	dedicated internal microcontroller which communicates with the Main Controller
729	(MC) in the EB and controls all the functions of the acousto-optic module
730	(AOM). Commands define magnitude and frequency of the RF signal applied, as
731	well as the RF driver ON/OFF states. Within the RF range of 23-82 MHz, the
732	minimum step of frequency sweeping is 10 kHz (5900 frequency points). The RF
733	amplitude is may be set at one of 16 even levels. The AOM transmits back to the
734	MC a few housekeeping parameters, such as measured RF voltage, AO crystal
735	temperature, etc. The MC and the AOM are connected via an RS-485 interface
736	running at a speed of 115.2 Kbit/s.
737	
738	During the measurement, the RF level is being alternated between ON and OFF
739	states, with the cadence being defined by integration time. The measured signal is
740	then processed as the AC allowing to remove offsets caused by the detector's dark
741	current and stray light, and improving the dynamic range of the instrument.
742	
743	The detector is a single-pixel InAs thermo-electrically cooled photodiode. A
744	detector module J12TE3-66D-R01M from Teledyne Judson Technologies is used.
745	The built-in three-stage thermo-electric Peltier cooler maintains a detector
746	temperature about 90°C below that of the hot side. For the ISEM OB operating in
747	the range from $-10^{\circ}$ to $+30^{\circ}$ C, it results in the detector's temperature ranging
748	between $-100^{\circ}$ and $-60^{\circ}$ C, the corresponding detector's shunt resistance is
749	therefore 60-400 kOhms. The temperature of the sensitive area is monitored by a
750	built-in thermistor.
751	
752	The detector's photocurrent is amplified with a two-stage circuit. The first stage is
753	a trans-impedance amplifier, AC-coupled (1 s time constant) to the second stage.
754	The second stage has a gain of 83 and a time constant of 80 $\mu$ s and is based on an
755	ADA4610 (Analog Devices) operational amplifier characterized by low current
/56	and voltage noise (50 tA Hz <sup></sup> , /.5 nV Hz <sup></sup> ). Its output signal is transmitted via
/5/	the narness to the Electronic Box.
/58	
759	<b>3.2 The Electronics Box</b>



		Astrobiology	Page 28 of 53
		27	
	760	The EB is mounted inside the rover at the rear balcony, and it is thermally	
	761	stabilized. It includes the ADC, the main and auxiliary controllers, power	
,	762	conditioning (power supply unit, PSU), and the interface and bridge boards,	
)	763	which support RS-422 communication between the ISEM and the Rover data and	
2	764	command system.	
\$ L	765		
r 5	766	The two ISEM blocks are connected via a 5-m harness running from the inside of	
5	767	the Rover to the mast. It is fabricated by Thales Alenia Space-Italy (TAS-I). The	
3	768	cable includes the analog signals from the detector and the thermal sensor, the	
)	769	power supply lines and a digital RS-485 connection to control the AOFT RF	
)	770	synthesizer and the power amplifier.	
2	771		
3	772	The Main Controller (MC) located in the EB commands the operation of all	
+ 	773	modules of the instrument. It uses a MSP430FR5739 Texas Instruments circuit	
5	774	running at 19.68 MHz. The controller is equipped with 1 Kbyte of RAM and 16	
, )	775	Kbyte of ferroelectric memory (FRAM) used for program and data storage.	
)	776	Compared to commonly used FLASH memory, the FRAM has better radiation	
)	777	immunity. A 10-bit internal ADC of the Main controller is used to digitize the	
)	778	signal from the detector's thermistor.	
- 3	779		
ļ	780	The main ADC serves to digitize the signal from the detector, amplified in the OB.	
) ;	781	A 16-bit ADC (ADS8320, Texas Instruments) is used. The full-scale range of the	
•	/82	ADC is 2.9 V and the peak-to-peak noise is 3 LSB (22 $\mu$ V RMS). The Main	
3	783	Controller receives the ADC output data via a serial interface operating at 2	
, )	784 705	signal note that the Jahragen noise of the detector controls the limit of signal	
	705	detector controls the Johnson horse of the detector controls the limit of signal	
<u> </u>	700	detection.	
ŀ	788	The Auxiliary controller, based on C8051E121 Silicon Laboratories circuit	
5	789	operating at 12.25 MHz incorporates a 12-bit ADC and serves to monitor power	
,	790	supply voltages and to dispatch the operation of different memory devices. In all	
3	791	ISEM employs two built-in FLASH memories within the microcontroller and	
) )	792	two external chips of ferroelectric (FRAM) and magneto-resistive (MRAM)	
	793	memory	
<u>)</u> - 2	794	inclucity.	
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The two microcontrollers hold four identical copies of their firmware in program memories. At the start of operation, the controllers check the copies, repair
damaged ones and run a validation program. In order to increase its reliability,
ISEM contains two redundant main controller units. After turning on, first the
MC1 is powered. Its sequence, if performed correctly, commands the PSU to keep
power at MC1. If not commanded in 5 seconds, the PSU automatically powers on
the MC2, and so on.

The rover Onboard Computer (OBC) controls ISEM operations via RS-422
interface. There are two (nominal and redundant) RS-422 links. Communication
via only one of the links is available at a given time. The baud rate is 112.179
±1% Kbit/s.

#### 808 3.3 The Calibration Target

In order to determine the incident solar illumination spectrum for deriving I/F data, and to verify the in-flight performance and stability of the instrument, ISEM will observe the radiometric calibration target prior to each measurement. The target is used for the in-flight radiometric calibration of both PanCam and ISEM, and will be located on the front deck of the rover as shown in Fig. 8. At this location it will be interrogated by ISEM from a distance of 1.1 m at an emittance angle of 24°. The calibration target occupies an area of 67×76 mm<sup>2</sup> and has a mass of 40 g.

816

807

817 The target includes 8 stained glass diffuse reflectance calibration patches with 818 different spectral reflectance properties. Two of these calibration patches will be 819 used by ISEM - the "white" which has a reflectance near 100% in the 0.4-3.0 µm 820 spectral range, and the multiband patch, which has distinct spectral features. The 821 white patch is manufactured from Pyroceram provided by the Vavilov State 822 Optical Institute in St. Petersburg and the multiband patch is manufactured from 823 WCT-2065 — a rare earth doped glass manufactured by Schott and supplied by 824 Avian Technologies in the USA. The calibration patches will be calibrated for 825 absolute total hemispherical reflectance and Bidirectional Reflectance 826 Distribution Function (BRDF) and all measurement will be traceable to 827 photometric standards.

828

829 Dust deposition on the radiometric calibration target during the ExoMars mission

830 will be accounted for in the data processing by developing a model of the

calibration target and dust system, building on the results of previous missions,

- measurements of settling rates on the rover panels, solar arrays, etc. (Kinch et al.
- 2007, 2015), and from PanCam calibration results.



- Figure 8. PanCam and ISEM calibration target and its location on the rover.
- Larger circles (Ø30 mm) are for both ISEM and PanCam. The smaller circles
- (Ø18 mm) and the shadow posts will be used by PanCam only.

#### **4 Measurement Scenario**

- 4.1 The Experiment Cycle
- The Experiment Cycle (EC) consists of one spectrum measurement by ISEM. It is
- explained in Figure 9.

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In order to eliminate the dark signal of the detector and any possible stray light
signal, the instrument measures photocurrents when the AOTF RF is OFF (the
dark signal) and when it is ON (the full signal). A subtraction of the two values
gives the true signal corresponding to the spectrally filtered radiation on the
detector.

During both the ON and OFF states, the main ADC continuously samples signals at a 20 kHz rate. The MC stacks all the measured values and makes the ON-OFF subtraction. This elementary measurement can be repeated up to 256 times ("accumulation factor" parameter), effectively increasing the integration time. All resulting values are stacked as well. Each elementary measurement includes a dead time of  $\sim 0.6$  ms needed to turn the AOTF ON or OFF. These overheads are mostly the result of remote commanding of the acousto-optic module in the OB, but also include two 0.12-ms transients in the AOTF. An additional dead time of 0.45 ms is needed to change the RF. The integration time, variable between 1 and 256 ms and defining the ON/OFF timing, and the number of repeated ON/OFF cycles for a given RF value (the accumulation factor) are set by a command. As discussed above, the measurement time is a critical factor. To achieve flexibility in spectral sampling, up to 8 "windows" can be defined for one

measurement of a spectrum. Every window can be placed anywhere in the AOM
frequency range and it has its own number of spectrum points, frequency steps,
and accumulation factors.

During an elementary measurement the 16-bit ADC readings add up to a 24-bit
value, and further accumulation, up to 256 times, results in a 32-bit value for each
spectrum point. Only 16 bits out of it are used, three options being (i) to transfer
merely the 16 LSBs, or (ii) 16 bits starting from a certain bit in order to remove
noise, or (iii) to normalize within one spectrum so that the maximum fits exactly
within 16 bits. In the latter case the risk is that an errant spike distorts the entire
spectrum.

878 The exchange of commands between ISEM and the OBC proceeds as follows.

- 879 The OBC transmits a command (TC) and Rover Elapsed Time (RET). The TC
- defines ISEM operation parameters and triggers the spectrum measurement. The
- 881 RET command synchronizes ISEM's internal time. In the course of operation, the



ISEM sends scientific and housekeeping packets to the OBC and these data arestored into the OBC memory.



Figure 9. A diagram showing timing and breakdown of one spectrum

888 measurement.

## 

892 ISEM operations over the course of the Reference Surface Mission (RSM) are

intimately connected those of the mast and PanCam. All operations are to be

894 guided by the mast's pointing. Three basic operating regimes have been

895 identified:

896897 1) Operations to support 1

897 1) Operations to support sampling.

4.2 Operations on the surface

- 898 ISEM will work in parallel with PanCam, as shown in Fig. 2. First the WAC
- observes an area panoramically, and then the HRC is pointed to the most
- 900 interesting spots. The spot must be illuminated by direct sunlight. At least one

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901	ISEM spectrum is planned be acquired together with every HRC image and
902	ISEM measurements may be also conducted separately. The ISEM data will be
903	used to characterize the mineral composition. Sometimes ISEM will be used
904	together with the WAC "geology" filters however full analysis with the PanCam
905	WAC geological filters is slower and produces much more data so this capability
906	cannot be used regularly.
907	
908	2) Operations to assess the geology value of targets
909	A number of geologically interesting scenes may be distant from the planned
910	rover track or inaccessible for rover sampling, such as crater rims, outcrops, etc.
911	Remote characterization is the only possibility in this case. ISEM will be operated
912	in the same manner as in the first case. There is no theoretical limit on the
913	sounding range provided the illumination conditions (including the phase angle)
914	are acceptable. For instance, illuminated hill slopes may be observed from dozens
915	of km. A practical limit is determined by the ISEM's FOV, a ~1-meter spot is
916	observed from 44-meter distance. This mode could be used for rover-orbiters
917	coordinated measurements and validations. For a favorable scene ISEM may
918	provide cross-validation over the area covering multiple CRISM pixels.
919	
920	3) Dedicated environmental operations
921	ISEM data may be used to characterize atmospheric humidity and aerosol loading.
922	Some information will be obtained as a by-product of geological measurements
923	intermitted with observations of the calibration target. The information about the
924	gaseous atmospheric absorption will be assured by dense spectral sampling of the
925	appropriate spectral intervals. Aerosols are best characterized by cross sky
926	observations. PanCam WAC plans direct Sun observations and cross sky viewing
927	atmospheric campaigns. As discussed in Section 2.5, the ISEM capability to
928	observe the direct Sun is not confirmed. At the same time, following preliminary
929	laboratory characterization we do not expect any operational constraints placed by
930	ISEM on PanCam solar imaging.
931	
932	In the case of cross sky imaging the ISEM line of sight will be oriented above the
933	horizon, and a special ISEM data acquisition sequence will be implemented. The
934	HRC measurements are not needed, and ISEM will observe in parallel with WAC.
935	The elevation and phase angle for these measurements needs to be carefully
936	planned, targeting as much as possible range of phase angles for WAC and
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detectable scattered signal in the IR for ISEM. **4.2 Resources required** ISEM's data volume is relatively small. One spectrum is only two kilobytes in size (see Table 1 and Section 3). The factor most affecting the rover operations is the measurement time. Fixed surface platforms are better suited for lengthy operations, generally allowing significant accumulation of measurements. However, sequential acquisition of spectra effectively increases the recording time, and, as a result, required measurement times become an important factor for the rover operation cycle. The allocated duration of measurements is from 2.5 min (minimum case) to 8.0 minutes (optimal case) for a single target. During the whole sequence, ISEM will consume  $\sim 12W$ , requiring an energy of 0.5-4.4 Watts per hour. As described in section 3.3 the length of the spectrum, or the number of points in the spectrum, can be selected. For a "geology" target we will always measure across the full spectral range of ISEM, which may be divided into 1-8 intervals with different sampling. The total number of points in one spectrum will vary between 256 and 1024. Within the spectral range, some portions of the spectrum will be measured more accurately, where e.g. a narrow mineral absorption feature or important atmospheric absorption are expected, while other portions of smooth continuous character can be undersampled. 4.3 Measurement performance, examples, comparison with state of the art As the full working prototype of ISEM has not been built yet, the performance of the instrument was verified using the closest prototype, the qualification model (QM) of LIS for the Luna 25 lander. The ISEM hardware involves some improvements with respect to LIS, including better optical throughput (and more sensitive detector featuring the three-stage Peltier cooler. The spectral properties of the AOTF remain the same. Spectral range and spectral resolution. The bounds of the spectral range were verified using He-Ne 1.152 µm and 3.39 µm laser lines. The theoretical shape of an AOTF spectral instrument function is close to  $sinc^2 x$ . Side lobes of this function modify the measured spectrum, but this could be readily accounted for once the bandpass is properly characterized. More dangerous are distant side

lobes, which manifest themselves as a sort of stray light and may reduce the apparent depth of spectral features. More discussion on this aspect of AOTF characterization may be found in Korablev et al. (2013). The measured band pass transmission function of the ISEM prototype is shown in Fig. 10a. The evolution of the resolving power  $\lambda/\Delta\lambda$  through the spectral range measured at multiple wavelengths using light sources with sharp emission features (different He-Ne laser, single-mode laser diodes, low-pressure gas-filled lamps) is shown in Fig. 10b. Normalized diffraction efficiency 0.8 0.6 0.4 0.2 -60 -40 Ó  $\Delta \upsilon, \mathbf{Cm}^{-1}$ Experiment Linear fit Resolving power 5000 6000 Wavelength, cm<sup>-1</sup> 

Figure 10. (a) Normalized transmission function of the instrument measured at  $1.523 \mu m$  laser line. The FWHM is 19 cm<sup>-1</sup> (2.7 nm). (b) The resolving power measures through the full spectral range.

A simulation measurement of a mineral spectrum of a Mars analogue by LIS prototype is presented in Fig. 11. Crystalline gypsum was manually ground and sieved to obtain  $\sim$ 1-mm grains, and the resulting sample was illuminated with a 150-W halogen lamp from a distance of 18 cm. The full time to measure this spectrum was 30 min, and the effective exposure to measure one spectral point was 1 s in the long-wave AOTF sub-range, and 0.6 s in the short-wave sub-range. The spectrum shown is normalized by a spectrum of a Lambertian screen (metal surface covered by special reflective coating). The differences between the library and measured spectra might be attributed to different origin of the samples; the difference between the FTS and ISEM spectra are likely due to different observation geometry.



Figure 11. A reflectance spectrum of crystalline gypsum measured by the closest
equivalent of ISEM: LIS qualification prototype, and a laboratory Fourierspectrometer (Bruker), compared to a CRISM library spectrum (LASF41A).

<u>Signal-to-noise ratio estimation.</u> The signal-to-noise ratio (S/N) of ISEM and its
 LIS prototype is limited by the detector background noise (see section 3.1), so we

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3 4		
5		
6	1007	may estimate the S/N for ISEM based on LIS prototype testing. With 3 ms
7 8	1008	integration time repeated 6 times per point LIS provides the $S/N \sim 10$ in the center
9	1009	of the spectral range and 3-5 on the edges. This estimation using the reflected
10	1010	sunlight and laboratory light sources involves many uncertainties including
11	1010	transparency of the terrestrial atmosphere, scaling to the Sun intensity at Mars
12	1011	distance and autropolation. In turn there remains a margin on the duration of the
14	1012	distance, and extrapolation. In turn there remains a margin on the duration of the
15	1013	measurement. The real time to measure one spectral point is not 18 ms, but $(2-2) = 0.05 \pm 0.05$ and $(2-2) = 0.05 \pm 0.05$
10	1014	$(3 \cdot 2 + 0.6) \cdot 6 + 0.45 = 40.05$ ms, because the light measurement is alternated with
18	1015	dark measurement, and there are some extra delays in the system (see section 4.1.)
19	1016	With 3 ms integration time the full spectrum is measured in 41 s, while the
20 21	1017	measurements at the surface of Mars may last 2.5-8 min (see section 4.2) that
22	1018	translates in sensitivity gain of 2-3.
23	1019	
24 25	1020	The improvements in ISEM with respect to LIS are i) the deeply cooled detector
26	1021	with a peak sensitivity attaining a factor of 10 better, and ii) the larger throughput
27	1022	of the entry optics and the AOTF: The LIS f-number is F:6; the improved ISEM
28	1023	throughput is ~F:1.7, but vignetting in the AOTF results in effective throughput of
29 30	1024	~F:2. The resulting gain factor is therefore ~90. The detector's peak sensitivity is
31	1025	at 3.3 µm in both cases but the curve for the LIS detector is somewhat more flat.
32	1026	The AOTF characteristics may vary as well. Using more conservative factor of 30
33 34	1027	the resulting S/N of ISEM can be estimated as $\sim$ 300 in the center of the range, and
35	1028	100-150 at the edges.
36	1029	Ŭ O
37 38	1030	Estimation of detection capabilities. Starting from the S/N estimation above we
39	1031	may estimate minimum detectable abundance for minerals discussed in section
40	1032	2.4 (see Fig. 1) Precaution factors in the measurement time (2-3) and in
41 42	1032	sensitivity ( $\sim$ 3) allow sufficient margin to account for $e^{-g}$ unfavorable phase
43	1034	angle or other factors. We used spectra of different minerals of interest (Fig. 1 a-
44	1034	f) on the background spectra of "bright" and "dark" regions of Mars (Frard
45 46	1035	1007) to simulate the reflectance of an admixture to the bulk spectrum of the
40 47	1030	martian surface. The proliminary consistivity estimates to detect the fraction of the
48	1037	salacted minoral are presented in Table 2. Civen relatively high ISEM S/N ratio
49 50	1030	selected mineral are presented in Table 5. Given relatively night ISENI S/N ratio
50 51	1039	deduced above, these estimates based on the relative depth of individual spectral
52	1040	teatures are very conservative. A better sensitivity analysis is planned in the
53	1041	tuture, involving analysis of martian mineral analogues, and multicomponent
54 55	1042	analysis.
56		
57		

1044 Table. 3. Preliminary estimation of the ISEM sensitivity to detect different

1045 minerals and mineral groups from CRISM spectral library (Fig. 1) on the

1046 background of bright and dark region Mars spectra (Erard, 1997). Mineral

1047 features used to estimate the sensitivity are listed in the last column.

Mineral or mineral group	Bright region	Dark region	Comment
Kaolinite (Fig. 1a)	<5%	5-10%	1.4, 2.2, 2.4 μm
Montmorillonite (Fig. 1b)	5-10%	10-15%	1.4, 1.9, 2.2-2.3 μm
Serpentine (Fig. 1c)	5-10%	5-10%	1.4, 2, 2.35 μm
Carbonates (Fig. 1d)	5-10%	~10%	2.3, 2.5, 3.4 μm
Gypsum (Fig. 1e)	~5%	5-10%	1.4-1.6, 1.8, 2.2 μm
Kieserite (Fig. 1e)	<5%	~10%	Broad structure 1.4-
			2.4 μm
Jarosite (Fig. 1f)	<5%	5-10%	1.48, 1.75, 2.25 etc.
			μm

## 

The issue of detection capabilities can be divided into two broad categories: (1) characterization of a target in the presence of windblown dust; and (2) detection of a phase or phases of interest in a multicomponent assemblages. There are a number of studies that have examined detection limits for various components that are relevant to this issue, and these are supplemented by ongoing studies by our team that are designed to specifically address this issue. The results of these studies are summarized in Table 4 below. Some selected examples are shown in Figures 12-14.

1058 Detection limits depend on a wide variety of factors, beside end member

abundances. These include factors such as relative grain size, the availability ofdiagnostic absorption bands, the relative intensity of diagnostic absorption bands,

and physical properties such as whether phases of interest are physically mixed,

1062 or whether an obscuring phase, such as dust cover ir present.

We have found that, at least for the variety of mixtures examined, detection limits
are on the order of 10-25 wt.%. For some phases, such as certain organic

1066 compounds, detection limits are much lower (e.g. 1 wt.% adenine is detectable in

1067 the presence of 99 wt.% nontronite (an iron-bearing clay) or hematite (an iron

1068 oxide) (Figures 13 and 14)). Further extensive tests of mineral mixtures and

5 6

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- detection limits are ongoing and planned.
- Table 4. Summary of some studies concerning detection limits and discrimination
- of different phases relevant to the capabilities of ISEM

	Detection limit	Characteristic	Source
		spectral features	
Orthopyroxene +	~15% of either	2 μm region	Cloutis and Gaffey
clinopyroxene	phase		(1991)
Olivine +	~20% olivine,	2 μm region	Cloutis et al. (1986)
orthopyroxene	5% pyroxene		
Orthopyroxene +	~15% of either	2 μm region	Cloutis and Gaffey
clinopyroxene	phase		(1991)
Pyroxene + palagonitic	~10% pyroxene	2 μm region	Cloutis and Bell (2004)
dust (spectral	17		
equivalent of Mars			
dust) or hematite			
Carbonate + basalt	~20% carbonate	2.3-2.6 µm	Palomba et al. (2009) and
		region	this study
Carbonate + palagonitic	~15% carbonate	2.3-2.6 µm	Palomba et al. (2009) and
dust (Fig. 12)		region	this study
Palagonitic dust on	<~500 um thick	2.3. 2.5 um	This study
carbonate (Fig. 12)	nalagonite	regions	5
euroonate (11 <u>5</u> . 12)	conting required	regions	
Palagonitic dust on	$\sim 250 \mu\text{m}$ thick		I his study
basalt	palagonite		
	coating required		
Kaolinite + illite	~20% of either	2.2-2.5 μm	This study
	phase	region	
Gypsum + basalt	~5% gypsum	1.4, 1.9 μm	This study
		regions	
Gypsum + palagonitic	~5% gypsum	1.4, 1.9 μm	This study
dust		regions	
Durrama   vialannia	~15% pyroxene	2 μm region	This study
Pyroxelle + voicallic			
glass			
glass Palagonitic dust +	~20% carbonate	2.3, 2.5 μm	This study
glass Palagonitic dust + carbonate	~20% carbonate	2.3, 2.5 μm regions	This study
Pyroxene + vorcanic glass Palagonitic dust + carbonate Nontronite + adenine	~20% carbonate ~1% adenine	2.3, 2.5 μm regions 1.65, 2.2 μm	This study This study
Pyroxene + vorcanic glass Palagonitic dust + carbonate Nontronite + adenine (Fig. 13)	~20% carbonate ~1% adenine	2.3, 2.5 μm regions 1.65, 2.2 μm regions	This study This study





Figure 13. Reflectance spectra of intimate mixtures of nontronite (an Fe-rich

clay) and adenine (a component of DNA). The brown arrows indicate spectral

L. ITOW. Itable wh. regions where adenine absorption bands are still detectable when only 1 wt.% of

adenine is present in the mixtures.



#### 

Figure 14. Reflectance spectra of intimate mixtures of hematite (an Fe-oxide) and
adenine (a component of DNA). The brown arrows indicate spectral regions
where adenine absorption bands are still detectable when only 1.3 wt.% of
adenine is present in the mixtures.

## 1097 4.4. Environmental requirements and characterization

The placement of the ISEM optical head on the Rover mast with no possibility of thermal control imposes stringent requirements on survival temperature. The AOTF is a critical device involving bonding of highly anisotropic materials, such as TeO<sub>2</sub> and LiNbO<sub>3</sub>. Anisotropic thermal expansion makes the AOTF devices vulnerable to large temperature excursion, in particular at low temperatures. AOTF technology has demonstrated survival and even operation down to  $-130^{\circ}$ C and below (Leroi et al, 2009; Mantsevich et al, 2015). Several non-operational thermal cycles attaining -130°C lower bound were also performed on two dedicated ISEM acousto-optic components; more testing to fully validate the technology is to be completed. 

An important aspect of the AOTF spectrometer characterization is the thermal

relatively wide temperature range. Some results of thermal characterization of the

acousto-optic module are described in Mantsevich et al. (2015). The operation of

the AO filters was tested in the range of  $-50^{\circ}$  to  $+40^{\circ}$ C. The temperature affects

The variation of the  $TeO_2$  refraction coefficient as a function of temperature is

noticeable shift of the dispersion curve, comparable with the AO filter pass band

in the operating temperature range. The characterization of the flight instrument

will therefore include calibration of the dispersion curve within the operational

Sampling from beneath the martian surface to reach and to analyze material

perhaps the strongest advantage of the ExoMars rover. The selection of the

unaltered or minimally affected by cosmic radiation is a significant feature and

sampling sites and, in more general terms, the remote reconnaissance and studies

of the landing site area, are a major part of the Rover's mission. ISEM offers a

method of mineralogical characterization using IR reflectance spectroscopy, a

technique well proven in orbital studies, and expected to be even more valuable

In the coming year we aim to deliver field-compatible hardware and to participate

in tests at terrestrial analogue sites and in other joint validations of instrument

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negligible. In turn, the change of the slow acoustic wave velocity causes a

the elastic properties of TeO<sub>2</sub>, changing the ultrasound velocity and birefringence.

calibration, because the optical heads are intended for operations across a

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temperature range.

and precise at the local scale.

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5. Conclusions

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