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THE SUPERCAM INSTRUMENT ON THE NASA MARS 2020 MISSION – OPTICAL DESIGN AND PERFORMANCE

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I. INTRODUCTION TO THE MARS2020 MISSION:

NASA is developing the MARS2020 mission, which includes a rover that will land and operate on the surface of Mars. MARS2020, scheduled for launch in July, 2020, is designed to conduct an assessment of Mars' past habitability, search for potential biosignatures, demonstrate progress toward the future return of samples to Earth, and contribute to NASA's Human Exploration and Space Technology Programs.

The mission will focus on a roving, long-duration science laboratory that will provide a quantitative improvement in surface measurements and pave the way for future Martian surface and sample return missions. The habitability assessment is to be made through multidisciplinary measurements related to biology, climatology, mineralogy, geology and geochemistry in terrain, which may include sedimentary, hydrothermal and ancient deposits. The SuperCam instrument will provide powerful remote sensing capabilities, to help the M2020 rover to reach those scientific goals [1].

II. THE SUPERCAM INSTRUMENT (OVERVIEW):

The SuperCam instrument represents an advancement from the design of ChemCam on MSL-Curiosity [2]. This new package is capable of four different remote-sensing techniques. In addition to the existing LIBS (Laser Induced Breakdown Spectroscopy) elemental analysis capabilities, a new Raman and time-resolved fluorescence spectroscopic analysis is implemented [3], as well as an Infra-Red passive Spectrometer (IRS) [4]. Both of these techniques add mineralogical capabilities as well as potential organic detection. For context imaging, an improvement of the Remote Micro Imager (RMI) is provided by a new color detector [5]. And recently, a microphone (SCM) has been added to record LIBS impacts, wind and rover sounds on the Martian surface.

SuperCam consists of three separate major units: Body Unit, Mast Unit and Calibration Targets (Fig. 1).

The Mast Unit (SCMU), provided by IRAP, France and funded by CNES, consists of a telescope with a focusing stage, a "red" or "green" pulsed laser and its associated electronics, an infrared spectrometer, a color CMOS micro-imager, and the microphone.

The Body Unit (SCBU), provided by LANL, USA, consists of three spectrometers covering the UV, violet, and visible and near-infrared (VNIR) ranges needed for LIBS. The UV and violet spectrometers are Czerny-Turner units identical to ChemCam. The VNIR spectrometer uses a transmission grating and an intensifier so that it can be used for Raman spectroscopy as well as LIBS and passive reflectance spectroscopy. The intensifier allows rapid time gating needed to remove the background light so that the weak Raman emission signals can be easily observed, and enables time-resolved florescence studies.

A fiber optic cable, and signal and power cables, provided by JPL, connects SCBU and SCMU.

A set of calibration targets (SCCT), provided by UVa, Spain, will enable periodic calibration of the instrument.

The three units are independent mechanically, simplifying interface controls as well as development overseas, under the leadership of LANL.

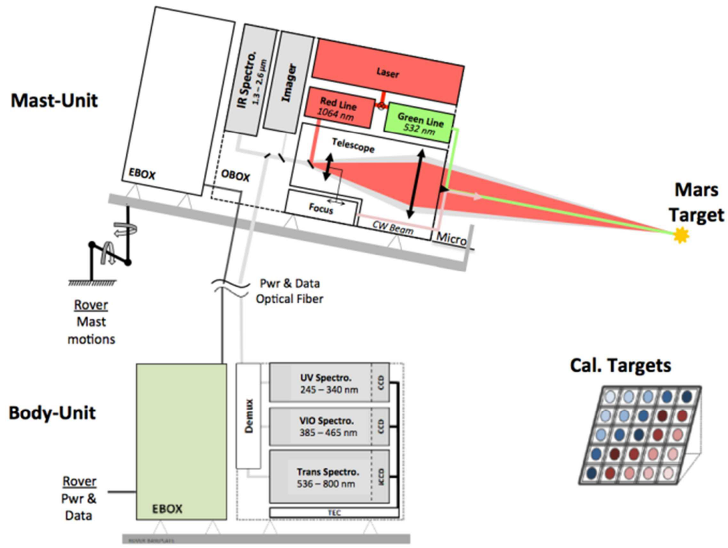

Figure 1: The SuperCam Instrument block diagram

III. THE SUPERCAM SCIENCE OBJECTIVES:

The SuperCam suite of techniques supports all Mission Science objectives with the following instrument science goals: 1- rock identification, 2- sediment stratigraphy, 3- organics biosignatures, 4- volatiles, 5- morphology, 6- coatings and varnishes, 7- regolith characterization, 8- atmospheric characterization.

Synergy between the four techniques is key. Because they are co-boresighted, multiple types of measurements can be made rapidly on the same sample, providing a multi-dimensional analysis.

A. The LIBS spectroscopy

The LIBS benefits from four years of ChemCam operation on the Martian surface. This technique uses powerful laser pulses [6], focused on a small spot on target rock and soil samples within 7 m of the rover to ablate atoms and ions in electronically excited states, from which they decay, producing illuminated plasma. The plasma light is collected by a telescope, and focused onto the end of an optical fiber. The fiber carries the light to a demultiplexer and three spectrographs that record the spectrum over a range from 240 – 850 nm (fig. 3). The spectra yield emission lines of elements present in the samples. Typical rock and soil analyses yield detectable quantities of Na, Mg, Al, Si, Ca, K, Ti, Mn, Fe, H, C, O, Li, Sr and Ba. Other elements that may be observed in soils and rocks include F, Cl, S, N, P, B, Ni, Zn, Cu and Rb.

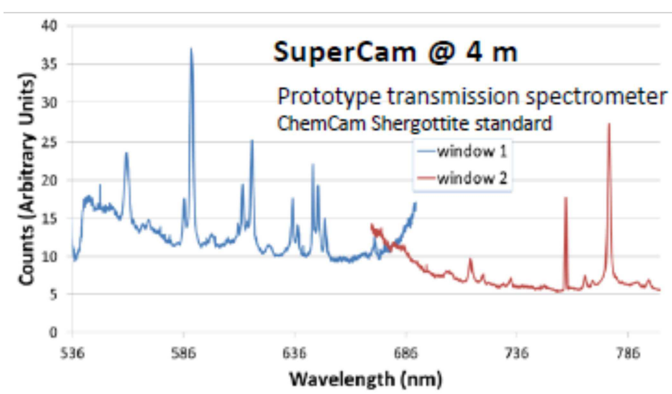

Figure 3: LIBS spectrum (example – only a portion of the spectra is shown)

B. The Raman and fluorescence spectroscopy

Stand-off Raman spectroscopy provides point detection of many minerals and potential detection of different organic compounds if they exist on Mars. To perform Raman spectroscopy, the laser beam is frequency doubled and is directed towards the target in a 532 nm pulsed beam of low dispersion. The target is thus illuminated at lower power density than LIBS, such that the molecules at the surface are vibrationally excited, resulting in scattered light that is modulated by the vibrational frequency of the material. This “Raman” scattered light can be detected if the much stronger Rayleigh-scattered light at the laser wavelength is blocked. Like LIBS, the telescope collects the Raman signal; it is transferred via a fiber cable to a transmission spectrometer in the rover body. The signal is intensified and recorded. The intensifier allows the exposure to be gated to a very short duration, removing background ambient light. Time-resolved fluorescence can also be recorded. Organic and biological molecules produce fluorescence both with UV and visible laser excitation with very short lifetimes (< 1 ns to 200 ns). SuperCam will be able to distinguish short-lived organic fluorescence from that of longer-lived (µs-ms) minerals and rocks on Mars, thus identifying targets that have biological molecules embedded in them (fig. 4). In the absence of biological materials, SuperCam Raman will not have interference from short-lived fluorescence backgrounds.

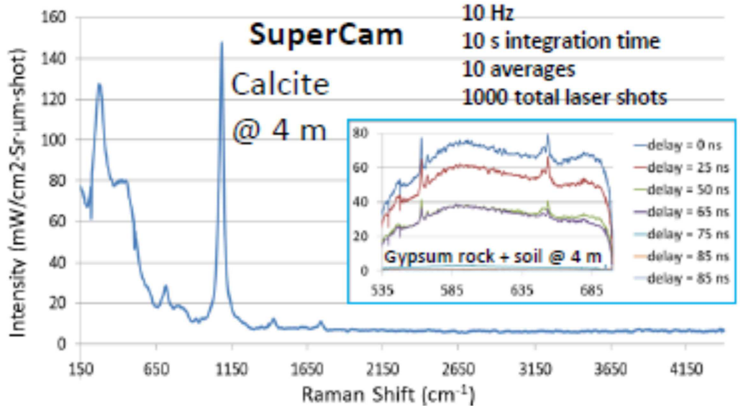

Figure 4: Raman and time-resolved fluorescence spectrum (low resolution example)

C. The visible and infra-red spectroscopy

VISIR passive spectroscopy has demonstrated its powerful capability in the detection and identification of mineral phases through characteristic absorption features related to vibrational stretching and/or bending of characteristic molecular bounds. The SuperCam wavelength range (0.4–0.85 µm, 1.3–2.6 µm) provides easy identification of most minerals to be found in the Mars geological record (fig. 5):

- Oxides and hydroxides;
- Ortho- and chain silicates;
- Sheet silicates (phyllosilicates, smectite);
- Sulfates (mono- and polyhydrated);
- Carbonates.

It might provide a tool to identify complex organic compounds from absorptions at 1.7 and 2.3-2.5 µm.

For atmospheric measurements, SuperCam records CO_2, CO, H_2O, O_2 (IR and 700-850 nm) and O_3 (UV). The full spectral range is used to measure scattered light diagnostic of aerosol size distribution, composition, and opacity.

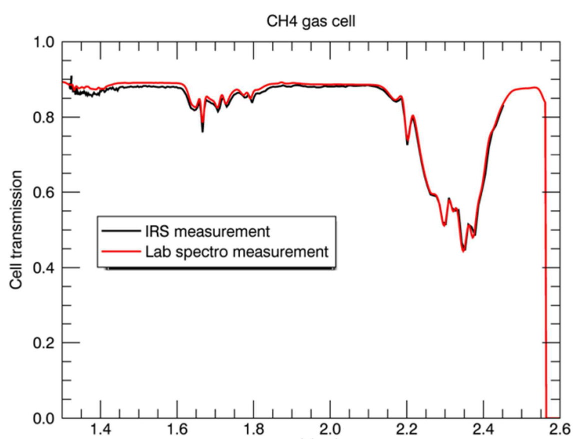

Figure 5: VISIR spectrum (example – IR part only)

D. The context imaging

The Remote Micro-Imager [7] places the chemical and mineralogical analyses in their geomorphological context, as well as independently remotely imaging small details without needing to drive up to the samples. The RMI will help determine which samples within the vicinity of the rover are of sufficient interest to use the contact and in-situ instruments for further characterization. It will also provide primary science in and of itself, in providing analyses of samples that are inaccessible to contact and in-situ instruments, such as vertical outcrops in canyon or crater walls that might display strata of geological interest. Analysis of these strata may provide information on the climate history of Mars. Fig. 6 simulates a SuperCam RMI color image, by merging a high-resolution ChemCam image and a color MastCam image.

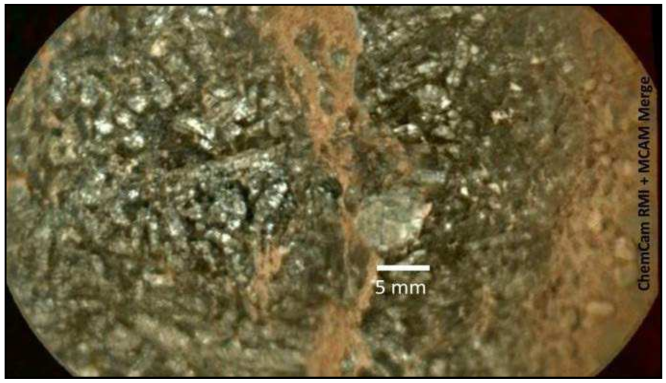

Figure 6: Color context image (example - simulation)

E. The Microphone:

The SCM Primary science objective is to support the LIBS investigation to obtain unique properties of Mars rocks and soils through their coupling with the LIBS laser.

In addition, other opportunistic science objectives are to monitor various artificial sounds (rover sounds), and to contribute to basic atmospheric science: wind, convective vortices, dust devils at close distance, or saltation (wind-blown sand).

F. On-board Calibration:

In addition, a set of calibration targets mounted nominally 1.56 m from the Mast Unit will enable periodic calibration of the instrument. Our experience on ChemCam showed that these calibration targets are invaluable for LIBS, and we will fly more targets on this mission. The SCCT will include targets for Raman, VISIR spectroscopy, and RMI, as well.

IV. THE INSTRUMENT DESIGN, PERFORMANCE AND VERIFICATION:

The MU combines several functions: it focuses the telescope, generates the laser beam to produce the LIBS plasma and Raman scattering; it collects LIBS/Raman/VIS light which is redirected to the BU spectrometers; it analyses the IR signal, reads RMI images and records sound. The BU performs the LIBS and Raman spectroscopies, and has the overall control of the instrument.

A. The Laser beam emission

The laser is the heart of the LIBS and Raman experiments [6]. It is similar to the ChemCam laser, but differs in three important ways: (1) the "exotic" Nd:KGW crystal is replaced by an "ordinary" Nd:YAG crystal. It can sustain higher heat flux, which enables a sustained burst of 1000 pulses at 10 Hz. Simultaneously, the beam quality is improved (specified M2 < 2 vs. 3 on ChemCam) for better focus. (2) The three 700 W pumping diodes are replaced by one Quantel 1200 W multi-color diode. Its emission wavelength (795-805 nm) covers a wide range to cope with the narrower spectral acceptance of the YAG crystal and its variations over temperature. (3) A doubling crystal (KTP) is added to convert the 1064 nm line in 532 nm. The commutation is performed using a qualified Pockels cell (the same as for the Q-switch).

The 1064 nm laser beam is expanded from 3 mm to 1 cm by a compact Galilean telescope and injected into the main Schmidt-Cassegrain telescope, with an output diameter of 110 mm, then focused on the target at distances from 1.5m to 7m, with a minimal energy of 12 mJ, and a minimal irradiance of 10 MW/mm², (computed in a circle of 75% of the energy), over a 40°C range of temperature. The telescope's transmission for LIBS is above 50% (with the principal attenuation due to the central obstruction of the baffled secondary mirror).

The 532 nm beam follows a different optical path. The beam is also expanded to 1 cm by another compact Galilean telescope, but it remains collimated and is co-aligned with the primary telescope axis by a 2-mirrors periscopic system (fig. 7), illuminating the target with an energy > 11 mJ, and a 30 KW/mm² irradiance up to 12

m. The telescope's transmission for Raman is above 86%. For Raman, a shutter is activated to block the 1064 nm residual beam, at the entrance of the Red Galilean expander.

The focus capability relies on fine displacements of the secondary mirror. Two autofocus modes are carried over from ChemCam: one illuminates the target with a 10 KHz-modulated, 50 mW laser diode and used a photodiode to find the secondary mirror position that maximizes the signal ; the second analyzes a series of RMI images taken at different focus positions.

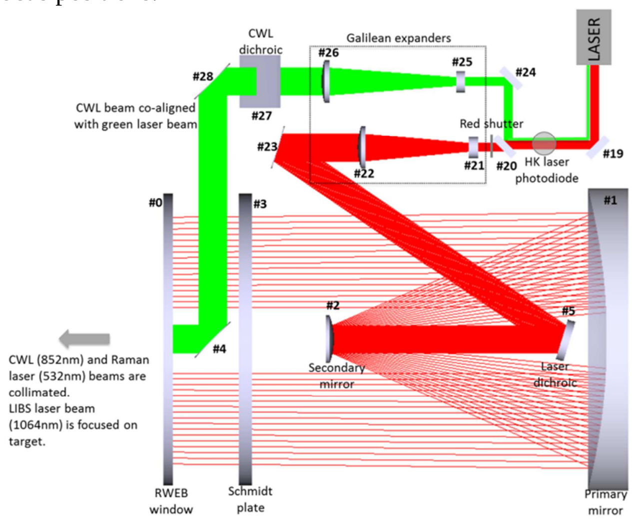

Figure 7: The laser beams (LIBS in red, Raman in green)

B. The optical collection

The same Schmidt-Cassegrain telescope collects light from the target, with a primary mirror diameter of 110 mm. The telescope is diffraction-limited on the optical axis for LIBS. Photons cross the laser dichroic (transparent in the 240-2600 nm range, except for the 1064 nm beam), and focused by a 3-lens objective. A beamsplitter directs the photons to the different sub-assemblies for analysis. Light below 950 nm is fed into a 300 µm-core fiber for LIBS/Raman/VIS reflectance analysis, after being notched to remove the 532 nm. A fraction of the visible light from a 20 mrad cone around the analysis spot goes to the camera. Longer wavelengths [1.3 – 2.6 µm] are diverted to the IR spectrometer through a periscopic assembly (fig. 8). The telescope transmission budget up to the BU fiber entrance is computed using all the optical elements' performance curves, above 15% in 245-300 nm range, and above 25% in the visible range.

The different beams (red, green pulsed beams; autofocus CW diode laser beam) and spectral (LIBS, Raman, VISIR) fields of view are aligned with an accuracy better than 0.35 mrad over the operational temperature range, which requires a thermo-mechanical design minimizing the thermal deformations.

Tolerancing is key for this alignment. For each optical element, the centering (µm) and the tilt (arcmin) are specified and controlled with respect to the local reference attached to the optical element.

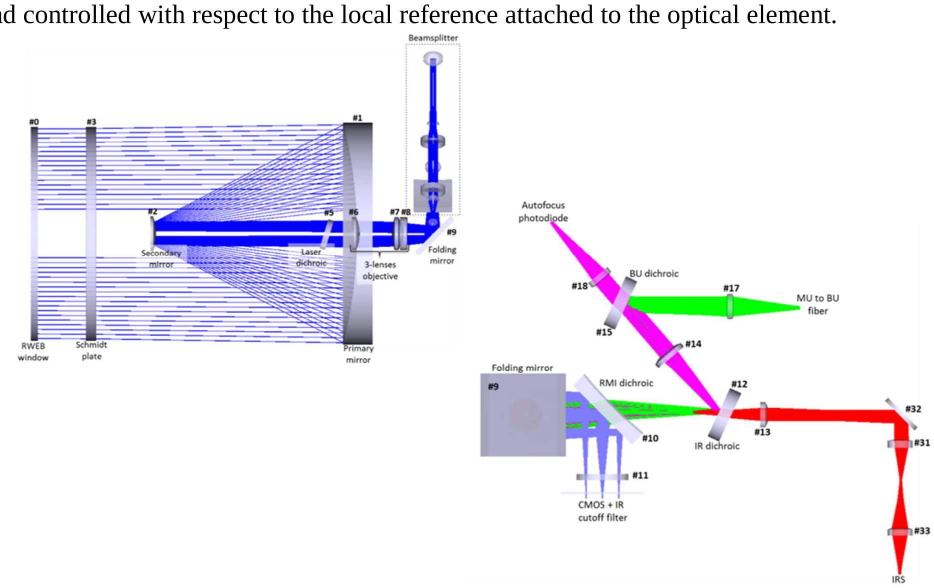

Figure 8: VIS – The collect path (left: telescope and right: beamsplitter)

C. The Body Unit Spectrometers (LIBS, Raman, VIS spectroscopy)

Light is transported from the telescope on the rover's mast to the rover body via a 6 meter optical fiber which bypasses the azimuth and elevation gimbals using twist caps. The fiber is nominally wound three times at each twist cap, with the ability to loosen and tighten as each gimbal rotates. The fiber transmits the light into an optical demultiplexer in SuperCam's body unit. The demultiplexer, of ChemCam heritage, contains two dichroic mirrors and one aluminized mirror to split the light into three wavelength bands for the appropriate spectrometers. From the mirrors the light is routed to three spectrometers via optical fiber bundles. Each bundle consists of 19 fibers with 50 µm cores. The fibers are arranged in a closest-packed circular configuration at the demultiplexer and in a linear configuration at the spectrometers. The spectrometers' aperture slits (20-30 µm x 1 mm) are epoxied directly onto the ends of the ferrules.

Characteristics of the body-unit spectrometers are presented in Table 1. All three spectrometers are used for LIBS, covering a similar spectral range to ChemCam. The two reflection spectrometers have strong ChemCam heritage [8]. They are crossed Czerny-Turner designs using 25 mm diameter spherical-curvature dielectric mirrors for collimation and focusing. The primary changes are the spectrometers' construction out of titanium instead of beryllium and improved heat conductance from the CCDs.

	UV Reflection	Violet Reflection	Transmission
Function	LIBS	LIBS, VIS passive	LIBS, VIS, Raman
Range	240-340 nm	385-465 mm	535-855 nm (150-7000 cm^{-1})
Resolution (FWHM)	0.20 nm	0.20 nm	0.25-0.4 nm; < 10 cm^{-1}
# Channels	2048	2048	6144
Nominal exposure	3 ms	3 ms or longer	100 ns or longer

Table 1: Body unit spectrometer characteristics

The transmission spectrometer facilitates the collection of remote Raman spectra while maintaining and enhancing the LIBS and passive VIS spectroscopy. The spectrometer design is shown in Fig. 9. The weak Raman signal is only produced within picoseconds of the laser interrogation (5 ns pulse duration), and so it is necessary to suppress ambient light and amplify the Raman signal by using a time-gated intensifier. The light from the fiber bundle is collimated and passed through a dichroic splitter that forms separate beams for the longer and shorter wavelength light. The shorter wavelength light encounters a compound grating that disperses the light into two traces (535-615 and 600-725 nm) on the intensifier surface. The longer-wavelength light (710-855 nm) encounters a separate grating, dispersing light onto a third trace (the spectrum in Fig. 3 only has two traces). The intensifier outputs monochromatic (phosphor green) light, which is relayed to the CCD with a f/2.6 lens system. The CCD is an off-the-shelf e2v 42-10 scientific-grade detector, identical to those used on ChemCam. The three spectral traces are transferred into the serial register sequentially. The CCDs are cooled to < 0°C by thermo-electric coolers to minimize dark noise.

The intensifier, built by Harris for night-vision goggles, has an 18 mm diameter field of view and provides adjustable gain up to 40,000. Raman analyses use the maximum gain, while LIBS and VIS passive analyses use lower gain. The gain is adjusted by changing the voltage on all intensifier elements together rather than adjusting only the multi-channel plate as normally done in the laboratory. Tests have shown no significant degradation in resolution over the range of gain needed by SuperCam. A custom high-voltage power supply is built by Los Alamos to operate the intensifier in the Mars environment (~1 kPa pressure).

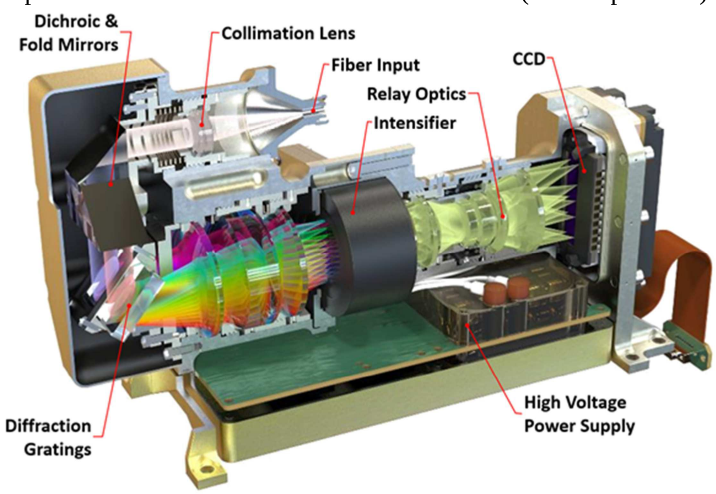

Figure 9: Transmission spectrometer design

D. The IR spectrometer

The infrared spectrometer concept is inherited from SPICAM and SPICAV instruments flying on MarsExpress and VenusExpress respectively and operates by scanning of an AOTF (Acousto-Optic Tunable Filter).

The IRS acquires the spectra of the reflected sun on the Mars surface in the bandpass [1.3-2.6] µm with a 30 cm^{-1} resolution. Its mass is only 430 g and is located in the collection path of the MU telescope. At the output of the Schmidt-Cassegrain telescope, a set of dichroics split the collected bandpass. The light is guided to the IRS with a periscope and a set of lenses that inject the image in a 400µm diameter pinhole with a 0.18NA and relay the entrance pupil in the spectrometer near the entrance of the AOTF.

An AOTF relies on interferences between acoustic and electromagnetic waves, creating non-periodic diffraction patterns. The phase matching principle does not generate order overlapping like in a classical diffraction grating. Applying a RF signal on a transducer mounted directly on the AOTF crystal generates the acoustic waves. For specific crystal and transducer geometry, there is a unique so-called tuning relation between the RF signal frequency and the output wavelength.

When a RF signal at a given frequency is generated, the AOTF will diffract a zero order, one e-ray order and one o-ray order. The e-ray and the o-ray orders are diffracted at the same wavelength defined by the tuning relation. The zero-order contains all the entrance energy except the energy diffracted in the e-ray and the o-ray orders.

In the IRS concept the zero-order is trapped in a light trap. The e-ray and o-ray orders are projected on two different photodiodes using two lenses.

The optical path inside the IRS (fig. 10) consists of an entrance hole lighted by the MU-telescope, a folding mirror and a ZnSe collimator lens, the AOTF, a ZnSe objective that images the 3-AOTF outputs, two photodiodes including one ZnSe relay lens that images the entrance hole on the sensitive part of the photodiode.

The detection is done by MCT photodiodes by Judson mounted with a front-end electronic package. In order to limit the dark current, the photodiodes are cooled using a 3-stage TEC.

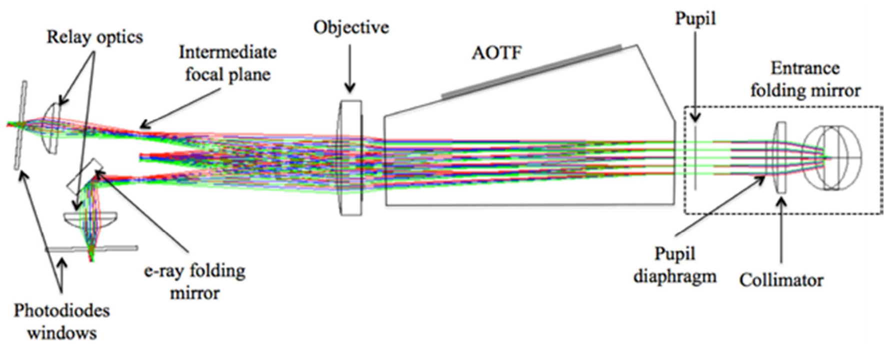

Figure 10: IRS overview

Performance:

SNR has been modelled taking into account observation modes, all the source of noise and the typical environment conditions on Mars in terms of solar irradiance on the target and spectrometer temperatures. Computation shows the compliancy with the requirement to get a SNR higher than 60 with the spectrometer colder than -5 °C in a maximum 80 s integration time for the acquisition of 86 spectels [8].

E. The RMI imager

A context image showing the spectroscopic analysis spots is captured at the rear of the telescope. The optical path to the camera is unchanged from ChemCam. The panchromatic CCD is replaced by a color CMOS. The CMV4000 device with a Bayer filter from CMOSIS was selected. Its optical area (width 11.26 mm) is comparable to ChemCam CCD (14.34 mm), allowing the implementation of the former with minor changes of the objective in front of the sensor. The CMOS pixels are 5.5 µm (2k x 2k pixels). The telescope resolution covers a 15-µm area at the focal plane. As in a typical Bayer filter, several pixels of different colors are illuminated, providing color images with the same resolution (that is given by the telescope) as ChemCam (MTF > 0.2 (horizontal) for the 20 cycles/mm frequency). The CMV4000 device is integrated in a Microcamera 3D cube [7], with its own front-end electronics and FPGA (fig. 11).

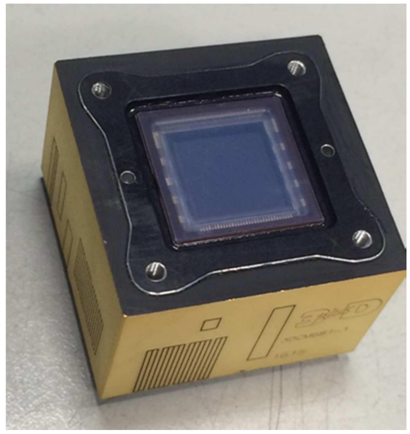

Figure 11: The RMI prototype model

For a correct white balance, a 650 nm cut-off filter is implemented in front of the RMI. The telescope and objective transmission budget is in the [7 – 15%] range from 400 to 650 nm, as most of the light goes to the spectrometers.

SuperCam will benefit from a High Dynamic Range (HDR) mode, to reach a minimum SNR of 200.

Even if the optical system is not optimized for RMI (but for LIBS and Raman), flat field, ghost and stray light analyses and characterizations are performed to improve the quality of the context images on the Martian surface.

V. CONCLUSION:

With additional capabilities versus the ChemCam instrument on MSL, and with a good synergy between all its different techniques, SuperCam will offer to the MARS2020 mission multi-dimensional analysis in chemistry, mineralogy, atmospheric characterization, and potential organics biosignatures. Covering a much larger wavelength range, and requiring co-alignment of the different techniques over a large temperature range, the optical design is more challenging than on ChemCam. Modelling of the signal-to-noise ratios for the various techniques, along with first results of tests, show that the desired performance will be obtained.

REFERENCES

[1] Maurice S. et al., “Science Objectives of the SuperCam Instrument for the Mars2020 Rover”, *46th Lunar and Planetary Science Conference*. LPI Contribution No. 1832, p.2818

[2] Wiens R.C. et al., “The ChemCam Instruments on the Mars Science Laboratory (MSL) Rover: Body Unit and Combined System Performance”, Spa. Sci. Rev. 170, 167-227, doi 10.1007/S11214-012-9902-4

[3] Clegg S. et al., “Remote Geochemical and Mineralogical Analysis with SuperCam for the Mars 2020 Rover”, *46th Lunar and Planetary Science Conference*. LPI Contribution No. 1832, p.2781

[4] Fouchet T. et al., “The Infrared Investigation on the SuperCam Instrument for the Mars2020 Rover”, *46th Lunar and Planetary Science Conference*. LPI Contribution No. 1832, p.1736

[5] Gasnault O. et al., “SuperCam Remote Micro-Imager on Mars 2020”, *46th Lunar and Planetary Science Conference*. LPI Contribution No. 1832, p.2990

[6] Durand E. et al., “Conduction cooled compact laser for the SuperCam LIBS-RAMAN instrument”, *ICSO 2016, this conference*

[7] C. Sellier, D. Gambart, N. Perrot, E. Garcia-Sanchez, C. Virmontois, A. Bardoux “CMOS Microcamera for Space Applications”, *ICSO 2016, this conference*

[8] Reess J.-M. et al., “The SuperCam Infra-Red instrument for the Mars2020 mission : optical design and performance”, *ICSO 2016, this conference*