The ISM infra-red imaging spectrometer of the Soviet Phobos mission

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ABSTRACT. The infra-red imaging spectrometer ISM has been flown on board the Soviet Phobos spacecraft. Its major scientific goals and technical characteristics are summarized and the concept of the sub-systems described. Optical calibration and alignment procedures are then presented and the first results indicated.

1 INTRODUCTION

ISM instrument is an infra-red imaging spectrometer developed by French CNRS laboratories with the support of CNES, the French space agency. It was mechanically and functionally interfaced with the Soviet KRFM spectro-photometer on the Phobos 2 probe. Partly complementary to KRFM goals, its major scientific objectives were to provide a mineralogic mapping of the low latitude zone of Mars for a better understanding of the history of the planet and to return significant data on the time and space variability of the atmosphere. For Phobos it was supposed to give information about the mineralogical composition of the surface with high spatial resolution for assessing the mean composition and the level of heterogeneity of this small body.

2 INSTRUMENT CHARACTERISTICS

The main characteristics of the instrument can be summarized as follows:

Telescope	f/4;100 mm focal length;25 mm aperture
Field of view	± 20° (by a 2400 steps scanner)
Imaging Method	Whiskbroom (full aperture, object-space scanner)
Spectrometer	spectrograph: f/4;grating disperser;magnification=1

	room optics: 1/2.5 magnification factor
Detectors	two 64 element PbS pseudo-linear arrays - 70 to -40°C (200 to 230 K) operating temperature temperature regulation ≤ 0.1 K 0.125 to 1 second integration time 100 x 100 µm pixel size (160 µm pitch, 180 µm offset)
Spectral Ranges	0.76 µm to 1.54 µm in the second order of the grating 1.65 µm to 3.14 µm in the first order
Spectral Sampling	64 elements per channel giving a resolution per pixel of: 0.025 µm in the first order 0.0125 µm in the second order
Spatial Sampling	3.6 mrad (0.2°)
Beam Etendue (SΩ)	$2.68\ 10^{-5}$ cm^{2}.steradian
Internal Calibration	Filament lamp
Cooling system	Passive
Electronics	128 signal amplifiers, programmable gain ; programmable gain, AD signal conversion microprocessor based with spatial summing, spatial and spectral capability autonomous and programmable operation 2 to 18 Kbps output data bit rate
Power	≈14 W (including scanner) during the working sessions ≈1 W during stand-by
Size	≈274 x 271 x 212 mm for ISM1 (optics and processing electronics) ≈184 x 180 x 108 mm for ISM2 (electronics)
Weight	≈4 kg for ISM1 ≈2.1 kg for ISM2

3 INSTRUMENT DESCRIPTION

3.1. General concept

Based upon a grating spectrograph, the ISM imaging spectrometer uses a whiskbroom concept with a one axis internal scanning mechanism in the crosstrack direction and the movement of the spacecraft for downtrack to make the cartography of Mars and Phobos.

Due to internal specifications and external accommodation constraints, the instrument is divided into two parts, one mainly optical (ISM1) and one purely electrical (ISM2), interconnected by an electrical cable. They are both directly mounted on the structure of the Soviet instrument KRFM which is providing ISM with supply voltages and commands.

The optical block is made of three parts, the fore-optics being installed within the first one, the telescope and spectrometer inside the second and the acquisition module being the third one.

The periscopic shape of the entrance unit was imposed by the necessity to transfer the optical axis out of spacecraft reservoirs. A 1 arc-minute step rotating mirror makes this transfer and is used for scanning purpose over a ± 20° angle in a plane which is inclined by 112.5° referring to the spacecraft velocity vector.

Inside the second part, a 25 mm diameter Ritchey-Chretien telescope defines a 40 minutes field of view. An Ebert-Fastie type spectrograph scatters the light. After optical filtering, two 64 pixels linear PbS arrays receive respectively the first and second order wavelength ranges of the spectrum. Each one is organized in two staggered rows of 32 elements the size of each defining the spatial resolution within the direction parallel to the slit (12 arc-minutes) and the spectral width in the other. The "odd" and "even" pixels corresponding to the two rows are looking east and west with a 23 arc-minutes angular distance. The detectors are mounted on a mechanical support which is thermally isolated from the structure and cooled down 200K by means of a thermal conduction to a passive radiator.

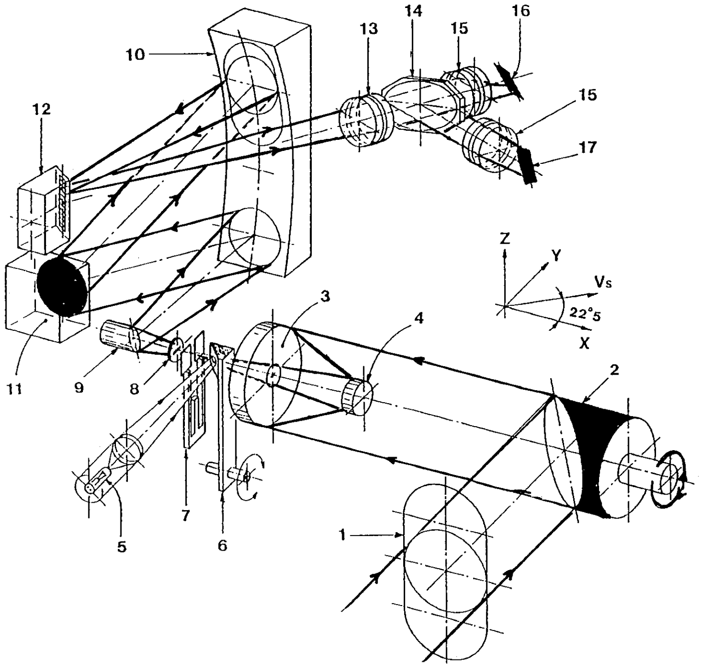
Mechanically associated to the optical block, a processing electronic amplifies the 128 analog signals and insures their demodulation.

The electronic module ISM2 samples, amplifies and digitizes the information issued from the processing electronics. A central processing system integrates those scientific data over one among four integration times (1/8,1/4,1/2 and 1s) and then formats them after adding housekeeping information before the stream is transferred to the spacecraft telemetry line.

3.2. Optical sub-system

The optical system presented in the figure 1 is integrated inside the ISM1 block. Two autonomous mechanical housings contain the scanning mirror for one and the rest of it (spectrograph and detection block) for the other. The basic principles applied were first the mounting of pre-adjusted parts leading for minimum post integration corrections and second an easy access to each sub-system, the quick exchange of the detection block being for instance possible with the only need for alignment verification.

The scanning mirror located in the fore part is a flat elliptical (36.7 x 28 mm) one inclined by 45° on the entrance beam. It scans over ±20° up and down the equator direction by 1 arc-minute increments at a maximum speed of approximately 6°.s^{-1}. Due to the mechanical integration on the spacecraft, the angle between the scanning and the S/C speed vector directions is 112.5°. In front of the mirror, an entrance baffle made of epoxy limits the input of parasitic light in the instrument.



1 - Entrance Baffle
2 - Scanning Mirror
3 - Primary Mirror
4 - Secondary Mirror
5 - Calibration Source
6 - Tilting Mirror
7 - Modulator
8 - Entrance Slit
9 - Folding Mirror
10 - Parabolic Mirror
11 - Grating
12 - Field Mirror
13 - Entrance lenses
14 - Beamsplitter
15 - Imaging lenses
16 - 1.6 to 3.2 µm detector
17 - 0.8 to 1.6 µm detector

Figure 1: Optical Configuration

In the second block, the optical flux issued from the scanning mirror is collected by a Ritchey-Chretien type telescope which has a 25 mm opening aperture and a 100 mm focal length. Associated to an electroformed, nickel slit 1.2 x 0.350 mm in size, it defines a 40 arc-minutes field of view. Made by the French company SESO, it uses the molecular adherence principle to fix the mirrors on a cylindrical support of the same glass material. Between the telescope and the slit is located a mechanism working as a shutter and equipped with a 45° folding mirror which reflects, in the close condition, the beam emitted by a calibration source towards the entrance slit of the spectrograph; close to it, a tuning fork type chopper with a 0.7 mm wide aperture at rest, modulates the planet or the calibration beam at a frequency of 256 Hz.

Behind the slit, a flat mirror adjustable around one axis reflects the beam towards the spectrograph. This Ebert-Fastie type spectrograph, working with a magnification factor of 1, is made of a parabolic mirror (manufactured by the French company Stigma Optique) and a 112.5 grooves per mm flat grating (machined by the French Instruments SA) which form the first and second order spectra via a spherical field mirror on the entrance of the detection block. A 1/2.5 magnification factor, Petzval type, correcting optical system mounted on the detection block adjusts the image of the slit to the dimension of the detector. After optical filtering, the 64 pixels PbS arrays receive the first order spectrum transmitted through a beam splitter and the second order reflected spectrum respectively.

All mirrors are made in PK50 glass and are covered by a chromium film and a gold coating. The lenses and beam splitter were made in ZnSe by Stigma Optique and coated by Matra.

Two sets of 64 elements pseudo linear PbS photoconductors arrays constitute the detectors. Each of them is constituted of two 32 pixels staggered rows, with a pixel size 100 x 100 μm^2 pixel size, a pitch of 160 µm, and a spatial offset of 180 µm between the two rows. Their detectivity is better than 10^{11}cm.Hz$^{1/2}$.W^{-1} at 2 µm and 200 K and are developed by the French SAT company.

3.2. Mechanical sub-system

The instrument is made of two units, one, ISM1 mainly optical and the other, ISM2 electrical. ISM1, L shaped, is constituted of three blocks. A magnesium structure contains the scanning mechanism; a titanium housing the telescope, the spectrograph and the detection block; the electronic module of the third one is made in magnesium . It is mechanically integrated on the top of KRFM instrument thanks to three low thermal conductance foot-pads. ISM2 is a magnesium module mounted on the side wall of KRFM.

Three electro-mechanisms are used, one scanner, one chopper and one shutter.

The scanning mechanism moves the entrance mirror over a ±20° range by steps of one arc-minute, at a maximum speed of 341 steps per second. This driving is done by a variable reluctance type stepper motor working with 24 steps per turn. Associated to a 1/900 reduction factor gear box, it is coupled to the moving mirror by a polyamid pulley. A home made capacitive rotating sensor monitors the absolute position of the mirror. The motoreductor component is developed by SFMI. The chopper described before, manufactured by FCP (American company), is tightly mounted on a rigid support in order to reduce the parasitic vibration coupling. The shutter and calibration mechanism developed by IAS is made of a slight rotating lever equipped with a reflecting mirror and actuated by a linear one shot IMC solenoid. Moving by 15°, it stops the optical beam and reflects the calibration one towards the spectrograph in the activated mode. A spiral spring brings it back automatically when deactivated. It can work at 16 Hz to perform the optical modulation in case of chopper failure.

Most of the optical components are separately mounted directly on titanium supports, on the main structure. Due to its 66 x 20 mm rather large size, the aspherical mirror of the spectrograph uses a special mounting principle. It is sticked on one end to three titanium, sheet form, flexible brackets, the other end being used for mechanical fixation.

The detection block gathers inside the same unit the imaging optical system, the beamsplitter and the detectors. The main block and detectors supports are made of OFHC copper to obtain a good thermal conduction and to limit the fluctuations. The use of ceramic substrate for detectors, ZnSe for the optical components and iron-nickel (N42) or titanium for the intermediate mounting plates minimizes differential thermal stresses. This block is mounted on the structure through an epoxy made tube.

3.3. Thermal sub-system

Three levels of temperatures were required on the instrument: 200 to 230 K for the detectors, 240 K minimum value for the spectrograph and standard for the other elements. The cooling was obtained by using passive radiation and conductive transfer means.

ISM1 is conductively isolated from KRFM instrument by three epoxy foot-pads and titanium bolts. The detection block is also isolated from the structure by an epoxy tube but is connected to a 1.5 dm^2 radiator oriented to space. The processing module decoupled from the optical part is equipped with a radiative 0.5 dm^2 surface. ISM1 is externally fully protected by a multilayer insulation blanket.

ISM2 is conductively connected to the KRFM electronics part by two lugs and isolated from the KRFM optical part by two more epoxy foot-pads, fixed by titanium bolts. A 0.64 dm^2 surface on the external side of the module is opened in the overall thermal shielding to radiate towards space the 5 watts of internal heat load.

In order to protect these classical thermal protections against the severe heat spike just following the cap opening, a special blanket was added over part of the instrument.

Heaters are used to keep sub-systems as the detectors, the scanning motor and some electrical parts above a minimum temperature when the instrument is off.

3.4. Electrical sub-system

The electronic sub-systems necessary for ISM instrument as they are presented in the block-diagram of the figure 2 are distributed into three boxes. The processing module is integrated in ISM1. The acquisition and timing electronics, the command and control function, the process and data handling one are gathered in ISM2. The power converters, the power distribution unit and the digital command management unit are located in the KRFM electronics module or its simulation.

The processing electronics handles 128 channels shared onto 16 x 8 hybrid units. Each unit has programmable amplifiers with two (1 or 3) possible factors, a synchronous detection stage which performs the filtering with a 40 ms integration time of the signals modulated at 256 Hz. A common multiplexer is in charge of transferring the output information to ISM2 module.

Inside ISM2 all the components are of dual in line type and are mounted on standard cards. The acquisition and timing electronics generates the basic clocks, performs the information multiplexing and the analog to digital conversion in a 12 bit ADC which gives the possibility to double the scientific data range thanks to a programmable gain stage. The command and control system is in charge of driving the scanning mirror at 341 Hz and the shutter and calibration mechanism at the nominal very low rate (twice per operation sequence) or at 16 Hz (chopper failure situation), of powering the calibration lamp at four different levels, of controlling the optical chopper and of regulating at a precision better than 0.1 K the temperature of the detectors with the capability of heating them up to 40°C for "depollution" purpose. The process and data handling system is based on

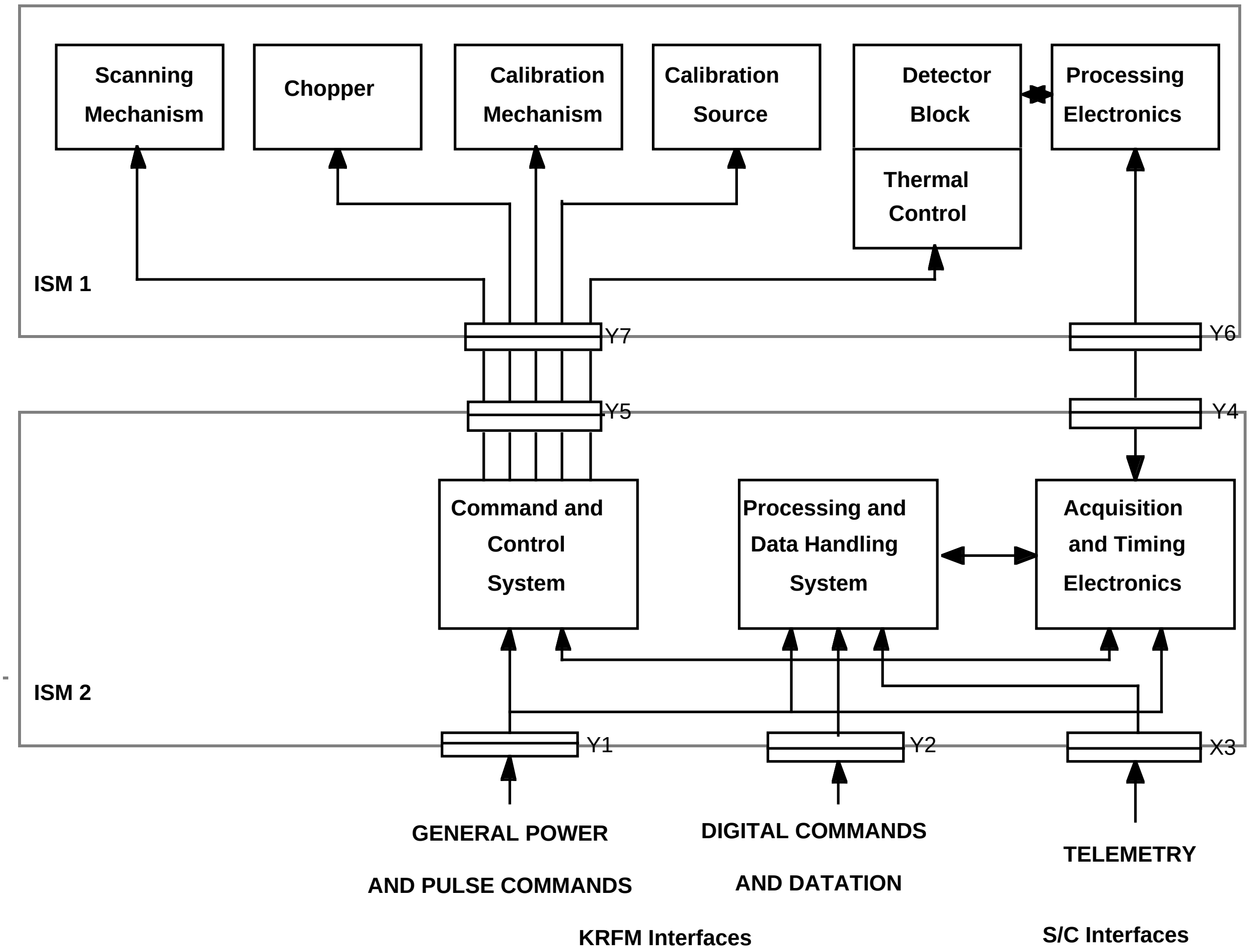


Figure 2: Electronic Bloc-diagram

one single Harris 80C86 microprocessor. It performs the management, coordination, digital data processing and formatting functions for both ISM and KRFM experiments. Switching on in a default mode configuration with no command received, it manages several types of observations that are adapted to orbital characteristics and to the scene to be analyzed and suppose the reception of ground commands. It controls the integration time and the different sub-systems of the instrument. Fully written in assembly language, the program is stored in 12 Kbytes bi-polar ROM memories. This technology for memories was imposed by radiation constraints. To save power, they are powered by a pulsating supply. The total capacity of the associated RAM is 32 Kbytes among which 30 Kbytes are used for telemetry storage pool.

3.5. Optical calibration

The calibration of the instrument was done in the French IAS facility located in Meudon. It was mainly made of a vacuum chamber equipped with an imaging foreoptics and a collimating device. The instrument was fixed on a cold plate simulating the temperature of the spacecraft and mounted on a two axis rotating platform. A device possibly cooled down to 80 K was placed in front of the experiment and a plate cooled with liquid nitrogen was facing the main ISM1 radiator. The sources for calibration were: a 300-400 K black-body, within the chamber; an IR spectrometer, purged with dry nitrogen, operating between 0.7 and 3.5 µm, with a spectral resolution of 200 and using a Globar source heated at 1300-1500 K; a Xe lamp calibrated by the French Bureau of Standards.

The first calibration step was to determine the wavelength of each spectral element by using the monochromator and making the data reduction by means of a centroid approach. The second one consisted in determining the transfer function in the first order, above 1.8 µm with the black-body source and over the whole range from a scattering screen lit by the xenon source. The results we got are matching very well in the 1.8-2.4 µm range. In the second order, the determination of the transfer function was less easy. The high flux Globar source gave good results above 1 µm but the strong and narrow lines emitted by the scattering screen and the Xe source generated some difficulties . Nevertheless, the relative contribution of the first and second orders on this channel was measured. In that case, the final transfer function resulted from a combination with theoretical expectations, an improvement of the data with self consistency tests made during flight observations, a comparison of these data with ground based observations of the planet and with spectra of materials expected to be analogous to Phobos one. Finally, the absolute accuracies obtained over the first and second orders are 5 and 10% respectively and the relative accuracy is better than 2%. The estimation of the precise direction of the optical axis was done with the Globar source.

Apart from these spectral, relative and absolute calibrations, we performed spatial calibrations to monitor the response within the field of view of the instrument. Finally, we obtained spectra of a variety of terrestrial samples, selected to match the constituent of the Martian soil.

3.6. Alignment process

The internal adjustment of the main pointing direction of the instrument was made in reference to a mirror that was mounted on the ISM1 structure by the side of the entrance baffle. It consisted in the adjustment of the scanning mirror in the so called equatorial plane so that the image of the entrance slit of the spectrograph was imaged in the direction defined by the perpendicular of the reference mirror and then in the reset of the electrical information of the pointing sensor.

After integration on the spacecraft, the angle between the ISM control mirror and the camera/spacecraft one was measured to infer the looking angle of the instrument as compared to that of the camera and to the spacecraft reference frame.

3.7. First results

On both spacecraft, the behavior of the instrument was fully satisfactory. Due to well known mission problems, only the Phobos 2 probe was able to return scientific data.

On Mars, two observation tracks were done from a low altitude below 2000 km on Tharsis Montes and Pavonis Mons for one and through Biblis and Ullyses Patera for the other. Nine more observations from circular orbits at 6300 km altitude permitted to map seven regions in the western hemisphere covering 25% of the Tharsis Montes and Valles Marineris (figure 3) area and two regions in the eastern hemisphere. The total number of spectra obtained on Mars is close to 40,000 (6,000 at high resolution and 30,000 at lower resolution, with a 3-axis stabilization, 4,000 during the spinning mode).

On Phobos, two observations were possible, from a distance of 200km, leading to one track 1x200 pixels long, close to the equator, and one 20x20 km2 map (figure 4), corresponding approximately to one third of the lighted hemisphere. The Phobos albedo was concluded to be one fourth of that of the Tharsis plateau on Mars and the hydration level of the soil much weaker than the Martian one. The number of acquired spectra on Phobos was about 600.

4. CONCLUSION

In spite of the difficult conditions for the development of such a new instrument integrated on a new probe within a very reduced time, and whatever the deception to see such a fruitful mission ended before its main step, the Phobos fly-by, this program can really be considered as a success within the domain of infra-red analysis of Mars and Phobos. It has, for the first time, provided the infrared mapping of a planet and a small body of the Solar System. It opens a new era in the IR in-situ analysis of planets. What has been learned to improve the concept of such a system is of great interest. The advantage of using homogeneous and very well known detectors, of developing a concept minimizing the mechanical adjustments, optimizing the SNR and performing very careful optical and physical calibrations was clearly pointed out. Furthermore, it has underlined the necessity of taking into account the operational specificities of an imaging system placed on a moving platform both for the on-ground constraints and for the on-board programming flexibility.

We would thank all the participants which have been involved in the development of this program both on the French and Soviet sides. Each of them may consider that this success is his personal one and that he has opened a new way for future cooperation for scientific space programs.