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Interplanetary missions instruments for infrared survey of planets and moons

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The role, objectives and applications of operating and future space missions for infrared remote sensing of planets and moons are discussed. The review of on-board instruments for infrared survey of planets and moons is presented. The main development trends of on-board instruments for infrared remote sensing of planets and moons were analyzed.

АПАРАТУРА МІЖПЛАНЕТНИХ МІСІЙ ДЛЯ ІНФРАЧЕРВОНОЇ ЗЙОМКИ ПЛАНЕТ І СУПУТНИКІВ, Станкевич С.А. — Обговорюються роль, цілі і задачі діючих і майбутніх космічних місій для інфрачервоного дистанційного зондування планет і супутників. Представлено огляд бортової апаратури для інфрачервоної зйомки планет і супутників. Проаналізовано основні напрями розвитку бортових систем інфрачервоного дистанційного зондування планет і супутників.

АППАРАТУРА МЕЖПЛАНЕТНЫХ МИССИЙ ДЛЯ ИНФРАКРАСНОЙ СЪЁМКИ ПЛАНЕТ И СПУТНИКОВ, Станкевич С.А. — Обсуждаются роль, цели и задачи действующих и будущих космических миссий для инфракрасного дистанционного зондирования планет и спутников. Представлен обзор бортовой аппаратуры для инфракрасной съёмки планет и спутников. Проанализированы основные направления развития бортовых систем инфракрасного дистанционного зондирования планет и спутников.

Ключевые слова: межпланетная миссия; инфракрасное дистанционное зондирование; съёмочная аппаратура; картирование температуры поверхности.

Key words: interplanetary mission; infrared remote sensing; imaging instrument; surface temperature mapping.

Remote sensing in infrared spectral range ($0,8 \mu\text{m} - 1 \text{ mm}$) is quite important for studies of planets and moons in solar system. Especially important is the high resolution extra-atmospheric infrared imaging, which is performed from interplanetary spacecraft and orbital probes. That is why all modern interplanetary research missions must include instruments for infrared imaging.

Infrared remote sensing is very important for understanding the evolution of planets and moons, for development and verification of geological and physical models, for minerals mapping, for surface temperature distribution analysis, for the study of atmosphere composition and planetary climate, for anomaly objects detection and recognition.

All of these tasks are accomplished using the on-board instruments for infrared measurements. These devices have gone a long way of improvements, and now ones are, as a rule, precision imaging spectrometers based on different types of photodetectors for infrared radiation. Continuous progress in semiconductor manufacturing technologies and microelectronics makes it possible to create new infrared instruments with enhanced performance, reduced weight and power consumption.

The main specifications of infrared survey instruments are the number and location of working bands in infrared spectrum, provided spatial resolution, selected type of infrared photodetector and design features. Table 1 below summarizes main specifications of advanced infrared instruments for current and future interplanetary research missions in solar system. Table lists the infrared instruments of 20 missions to planets and moons in solar system. Following these missions are discussed a bit more detail.

The MESSENGER mission (NASA, 2004–2015) is intended for a comprehensive study of Mercury. In particular, MESSENGER carries high-resolution visible-infrared spectrograph VIRS for measuring the composition and structure of Mercury surface reflectance [14]. In 2015 MESSENGER orbiter ended its mission near Mercury and crashed into the planet.

The ESA mission BepiColombo, to be launched in 2017 will explore the planet from a short distance. The spacecraft houses a state of the art mid-infrared spectrometer. MERTIS is the first thermal imaging dispersive spectrometer for planetary deep space missions and the first thermal infrared imaging spectrometry for a mission to Mercury. The scientific goal of MERTIS is to provide detailed information about the mineralogical composition of Mercury's surface layer by measuring the spectral emittance of different locations in the

Table 1. On-board instruments for infrared survey of planets and moons

Target	Mission	Instrument	Spectral range, μm	Bands number	Angular resolution, mrad	Design
Mercury	MESSENGER (Mercury Surface, Space Environment, Geochemistry, and Ranging)	VIRS (Visible-Infrared Spectrograph)	0,3 – 1,45	288	0,4	fused-silica fiber-optic bundle, concave holographic diffraction grating, dichroic beam splitter, 256 elements line array InGaAs detector
	BepiColombo	MERTIS (Mercury Radiometer and Thermal Infrared Spectrometer)	7 – 14	78	0,7	pushbroom imager, three mirror anastigmatic optics, Offner convex grating spectrometer, 160×120 elements uncooled microbolometer array, on-board blackbody calibration target
Venus	Venus Express	VIRTIS (Visible and Infrared Thermal Imaging Spectrometer)	0,28 – 5,13	380	0,25	Shafer telescope, Offner grating spectrometer, torque scanning mirror, actively cooled 270×438 elements array HgCdTe detector
		PFS (Planetary Fourier Spectrometer)	0,9 – 45	7252	35	pointing device, CaF_2 dichroic mirror beam splitter, two double pendulum type interferometers, SWIR photoinductor PbSe/PbS sandwich photodetector, LWIR pyroelectric LiTaO ₃ photodetector, reference black body
	Akatsuki (Venus Climate Orbiter)	IR2 (2- μm Infrared Camera)	1,5 – 2,3	5	0,2	simple triplet (ZnS and quartz) foreoptics, PtSi-CSD/CCD 1040×1040 elements Stirling-cooled detector
		LIR (Longwave Infrared Camera)	8 – 12	1	0,87	three germanium lenses foreoptics, mechanical shutter as blackbody for calibration, 328×248 elements uncooled microbolometer array, Peltier temperature control system, sequential image acquisition, averaging and offset subtraction
Moon	SMART-1 (Small Mission for Advanced Research in Technology)	SIR (SMART-1 Infrared Spectrometer)	0,94 – 2,4	256	1,11	off-axis mirror system, concave grating spectrometer, 256 elements InGaAs photodiode sensor array with Peltier cooling
	Chandrayaan-1	M ³ (Moon Mineral Mapper)	0,43 – 3,0	261	0,7	pushbroom imaging spectrometer, unobscured TMA telescope, e-beam curved grating, 640 elements cross-track HgCdTe detector array
Mars	LRO (Lunar Reconnaissance Orbiter)	DLRE (Diviner Lunar Radiometer Experiment)	0,35 – 400	9	3,4	nadir push-broom imager, two identical three-mirror off-axis telescopes, 21 thermopile detectors cross-track for each of nine spectral bands
	MGS (Mars Global Surveyor)	TES (Thermal Emission Spectrometer)	0,3 – 2,9 5,8 – 50	286	8,3	reflecting afocal telescope, Michelson interferometer, uncooled six-element array infrared bolometer
	Mars Odyssey	THEMIS (Thermal Emission Imaging System)	0,425 – 14,88	14	0,25	three-mirror anastigmatic telescope, infrared and visible multispectral imagers, 320×240 elements uncooled microbolometer array, 10-strip filter pushbroom spectrometer
	Mars Express	OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité)	0,35 – 5,2	338	1,2	Telescope with a scanner, entrance slit, concave holographic grating mirror, CCD focal plane array, VINR pushbroom mode, SWIR whiskbroom mode

Target	Mission	Instrument	Spectral range, μm	Bands number	Angular resolution, mrad	Design
	MRO (Mars Reconnaissance Orbiter)	CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)	0,362 – 3,92	545	0,0615	gimbaled sensor system, pushbroom imager, heat pipes cooler assembly
	MOM (Mars Orbiter Mission)	TIS (Thermal Infrared Imaging Spectrometer)	7 – 14	12	0,69	split collimator, infrared dispersive grating, 120×160 elements uncooled bolometer array detector
Ceres, Vesta	Dawn	VIR (Visible and Infrared Spectrometer)	0,25 – 5,03	432	0,25	Shafer telescope, Offner grating spectrometer, 270×435 elements HgCdTe infrared detector, Stirling cooler
67P Churyumov-Gerasimenko comet	Rosetta	VIRTIS (Visible and Infrared Thermal Imaging Spectrometer)	0,28 – 5,13	380	0,25	Shafer telescope, Offner grating spectrometer, torque scanning mirror, HgCdTe infrared focal plane array, Stirling cycle cooler
Jupiter, Jovian satellites	Galileo	NIMS (Near Infrared Mapping Spectrometer)	0,7 – 5,2	408	0,5	Ritchey-Chretien telescope, Dall-Kirkham collimator, plane grating, InSb and Si photodetectors
Jupiter	Juno (Jupiter Polar Orbiter)	JIRAM (Jovian Infrared Auroral Mapper)	2 – 5	256	0,237	two dioptric doublets telescope, aperture de-spin mirror, beam splitter, 256×432 elements HgCdTe CMOS detector
Ganymede, Europa	JUICE (Jupiter Icy Moon Explorer)	MAJIS (Moons and Jupiter Imaging Spectrometer)	0,4 – 5,7	1720	0,125	TMA telescope, two Czerny-Turner imaging spectrometers, two 640×480 elements HgCdTe passively cooled detectors, internal calibration unit
Europa	Europa Clipper	ThI (Thermal Imager)	8 – 35 35 – 100	2	2,5	pushbroom imager, scan mirror switcher, 40 elements thermopile array detector operating at room temperature, internal blackbody
		SWIRS (Short-wave Infrared Spectrometer)	0,85 – 5,0	420	0,15	single optic single grating spectrometer, scan mirror TMC, HgCdTe passive detector, passive spectrometer cooling
Saturn, Titan	Cassini-Huygens	CIRS (Composite Infrared Spectrometer)	7,16 – 16,67	40	0,273	Shafer telescope, far infrared interferometer, mid infrared interferometer, moving scan mechanism
		VIMS (Visible and Infrared Mapping Spectrometer)	0,35 – 5,1	352	0,125	Cassegrain telescope, diffraction grating, InSb linear array focal plane assembly, whiskbroom scanning imager
Saturn, Uranus, Neptune	Voyager-2	IRIS (Infrared Radiometer Interferometer and Spectrometer)	0,33 – 2 2,5 – 55	540	4	Cassegrain telescope, sapphire window, dichroic mirror beams splitter, Michelson interferometer, 128×128 elements HgCdTe Schwartz-type thermopile infrared detector

spectral range from 7–14 μm . Knowledge of mineralogical composition is crucial for choosing the best of several competing theories, and thus for selecting the valid model for origin and evolution of the planet [3].

The Venus Express mission (ESA, 2005–2014) was aimed to perform a global investigation of the Venusian atmosphere, including infrared sounding using planetary Fourier spectrometer PFS and visible/near-infrared mapping spectrometer VIRTIS. The VIRTIS allows the systematic mapping of the surface and of the near-surface atmosphere of Venus in the near infrared bands. The main topics for VIRTIS science observations are study of the lower atmosphere composition, study of the cloud structure and scattering properties, measurements of the temperature field [24]. Also, the VIRTIS instrument provided an emissivity hotspots detection and mapping, which may be occurrence of recent volcanism on Venus [25].

Akatsuki, which is the first Japanese Venus orbiter, aims at understanding the atmospheric dynamics and cloud physics of Venus. Akatsuki maps clouds, minor constituents successively and thermal emission using among them three infrared cameras — near, mid, and long-wave ones [13].

SMART-1 (Sweden-ESA, 2003–2006) is the first European mission to visit the Moon. During orbiting around the Moon it makes lunar science. One of the scientific tasks is spectroscopic measurements of rocks to provide minerals identification. The SIR instrument, near-infrared grating spectrometer, performs mineral absorption bands registration between 0,7 and 3,0 micron [20].

Chandrayaan-1, the polar Lunar orbiter mission of Indian Space Research Organization, successfully carried out study of Moon's environment and surface processes for a period of about nine months during 2008–2009. The on-board infrared hyperspectral sensor M³ with capability of spectral measurements from 0,4 to 3 μm , could detect various constituents present at the lunar surface and intended for mineral mapping [14].

DLRE on NASA's Lunar Reconnaissance Orbiter (in operation from 2009) is a nine-band pushbroom infrared radiometer designed for characterizing the Moon's thermal environment, mapping lunar surface properties and investigating polar cold traps [22].

The Thermal Emission Spectrometer (TES) investigation on Mars Global Surveyor (NASA, 1996–2006) is aimed at determining the composition of surface minerals, rocks, and ices; the temperature and dynamics of the atmosphere; the properties of the atmospheric aerosols and clouds; the nature of the polar regions; and the thermophysical properties of the surface materials [9].

The THEMIS instrument on Mars Odyssey probe (NASA, 2001, in operation) intended for investigation the surface mineralogy and physical properties of Mars using multispectral thermal-infrared imagery in nine spectral bands centered from 6,8 to 14,9 μm , and visible/near-infrared imagery in five spectral bands centered from 0,42 to 0,86 μm . THEMIS will map the entire planet in both day and night by multi-spectral infrared images at 100 m per pixel resolution [10].

The OMEGA IR Mineralogical Mapping Spectrometer on Mars Express probe (ESA mission, 2003, in operation) determines the mineral content of the Martian surface and the molecular composition of the atmosphere by analyzing sunlight reflected from the surface and diffused through the atmosphere. It also performs similar analyses on heat radiation emitted from the surface. Information from OMEGA will contribute to our understanding of the structure of the Martian landscape and the role played by water over timescales ranging from seasons to billions of years [6].

The MRO (NASA, 2005 in operation) mission's primary objectives are to characterize seasonal variations in dust and ice aerosols and water content of surface materials, to search for evidence of aqueous and/or hydrothermal activity, and to map and characterize the composition, geology, and stratigraphy of surface deposits. The MRO's CRISM conducts hyperspectral imaging investigations to characterize Martian geology, climate, and environments of present or past life [21].

The Mars Orbiter Mission (MOM) is the first interplanetary mission of India (ISRO, 2013, in operation). The scientific objectives include exploration of Mars surface features, morphology, mineralogy and Martian atmosphere by TIR Imaging Spectrometer (TIS) instrument [5].

Rosetta, the Solar System cornerstone mission of ESA (2004, in operation), consists of an orbiter and a lander for the comet 67P/Churyumov–Gerasimenko exploration. VIRTIS is part of the scientific payload of the Rosetta Orbiter intended to detect and characterize the evolution of specific signatures — such as the typical spectral bands of minerals and molecules. The identification of spectral features is a primary goal of the Rosetta mission [11].

Dawn is the NASA interplanetary mission that orbit two massive main belt asteroids Vesta and Ceres. The Dawn mapping spectrometer (VIR) is a modification of the VIRTIS mapping spectrometer on board the ESA Rosetta mission. VIR is intended to map the compositions of Vesta and Ceres with a spatial resolution of a few tens of meters for determination of the mineral composition and spatial distribution of the various surface materials [12].

The Near-Infrared Mapping Spectrometer (NIMS) experiment on the Galileo orbiter spacecraft (NASA, 1989–2003) represents a combination of imaging and spectroscopic methods for asteroids, Jupiter atmosphere, and Jovian satellites surface materials identification and mapping [8]. The NIMS instrument aboard Galileo

Fig. 1. Color-composite mosaic of Mercury surface (MESSENGER/VIRS, March 17, 2011)

Fig. 2. Infrared mapping data of the Venus southern hemisphere (Venus Express/VIRTIS, July 14, 2009)

Fig. 3. High-emissivity anomaly at Idunn Mons region of Venus (Venus Express/VIRTIS, averaged over 1,5 Earth years)

detected hot spots on the Jovian moon Io surface, which were not previously known to be volcanically active areas [19].

The Jovian Infrared Auroral Mapper (JIRAM) has been included in the New Frontiers mission Juno (NASA, 2011, in operation). JIRAM will explore the dynamics and the chemistry of Jupiter's auroral regions by high-contrast imaging and spectroscopy. It will also analyze Jovian hot spots to determine their vertical structure and infer possible mechanisms for their formation [1].

The MAJIS instrument is an imaging spectrometer on board the JUICE mission (ESA, 2022 planned) and it is perfectly suitable to obtain a comprehensive data about the Jupiter system including the Jupiter's atmosphere as well as the surfaces of Galilean satellites [18].

The Europa Clipper mission (NASA, 2021 planned) could meet the science requirements and engineering challenges to fly to Jupiter system and its moon Europa observing by short-wave infrared spectrometer

Fig. 4. Earth infrared image at 250 000 km distance (Aka-tsuki/LIR, May 21, 2010)

Fig. 5. Mineralogy map of Lacus Excellentiae on the Moon (SMART-1/SIR, August 17, 2006)

Fig. 6. Water-rich materials encircle the lunar crater on the away side of the Moon (Chandrayaan-1/M3, September 24, 2009)

Fig. 7. Surface temperature map of the south polar region of the Moon (LRO/DLRE, October 21, 2010)

Fig. 8. Mars surface infrared albedo (MGS/TES, mosaic 2001)

Fig. 9. Hematite abundance of Aram Chaos impact crater on Mars (Mars Odyssey/THEMIS, mosaic 2005)

SWIRS. The main science goal for the proposed mission is to explore Europa to investigate its habitability [23].

The Composite Infrared Spectrometer (CIRS) is a major science instrument aboard NASA-ESA Cassini-Huygens mission (1997, in operation) to Saturn. It measures the thermal infrared radiation from Saturn, its rings and its moons, especially Titan, in order to study their thermal structure and composition [16]. The Visual and Infrared Mapping Spectrometer (VIMS) is a state-of-the-art, imaging spectrometer that spans the 0,3–5,1 μm wavelength range. The addition of data of relatively high-spatial resolution, but of modest spectral resolution, to a data set of high spectral resolution and modest spatial resolution results in synergistic scientific advances well beyond those which could be accomplished using either data set separately [7]. The

Fig. 10. Mars hydrated minerals map (Mars Express/OMEGA, mosaic 2005)

Fig. 11. Nili Fossae region of Mars (MRO/CHRISM, October 4, 2006)

Fig. 12. Temperature distribution over 67P/Churyumov-Gerasimenko comet surface (Rosetta/VIRTIS, July–August 2014)

Fig. 13. Hydrogen abundance distribution over Vesta dwarf planet surface (Dawn/VIR, July 18, 2011)

Fig. 14. Jupiter's moon Europa coverage (Galileo/NIMS, April 1997)

overall objectives of CIRS and VIMS are to investigate Saturn and Titan ongoing chemical and dynamical processes in a diverse range of planetary and satellite atmospheres, and determine constraints on planetary formation processes and evolutionary histories.

Voyager-2 and Voyager-1 missions (NASA, 1977–2011, in hibernation until 2017) were launched forty years ago. They continue to return information from distances more than 120 AU. During their first dozen years of flight, the Voyagers made detailed explorations of Jupiter, Saturn, and their moons, and conducted the first explorations of Uranus and Neptune. The main imaging instruments of Voyager are the narrow/wide angle camera as well as ultraviolet UVS and infrared IRIS spectrometers [15].

Thus, the available instruments for orbital infrared imaging of planets and moons allow to conduct detailed studies of the surface mineralogy, to contribute a better understanding of planetary genesis, to provide global, high-resolution, infrared spectral and temperature data about bodies surface and atmosphere.

Fig. 15. Lower atmosphere of the Saturn's largest moon, Titan (Cassini/CIRS, October 25, 2004)

Fig. 16. Kraken Mare, south of Titan's largest sea (Cassini/VIMS, August 21, 2014)

Fig. 17. Uranus planet (Voyager-2/IRIS, 1986)

Fig. 18. Neptune planet (Voyager-2/IRIS, 1989)

At moment the main development trends of on-board instruments for infrared remote sensing of planets and moons are: gradual transition to uncooled microbolometer detectors of infrared radiation; the capability to control the field of view depending on the current challenges; the spectral range extension in the long-wave infrared region from 14–16 μm up to 50–100 μm ; the substantial resolution enhancement, both spatial and spectral; the reducing in size, mass, and power consumption; the higher level of integration; the robust and reliable thermo-mechanical/thermo-electrical properties to survive strong vibrations, thermal stress, and extreme solar radiation fluxes; qualified onboard software solutions in accordance with different observation modes and onboard calibration procedures [2, 17].

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