

Spectral imaging for the outer solar system: Missions, instruments and current challenges

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Key Points:

- Missions to the outer solar system have been divided into three phases: reconnaissance, detailed characterization, and habitability assessment.
- We also discuss the technology development and performance characteristics of imaging spectrometers.
- The current challenges of spectral imaging for the outer solar system have been presented, followed by a brief discussion of solutions and future prospects.

Abstract:

Spectral imaging is a key technique for investigating the surface composition and geological properties of objects in the outer solar system. Over the past few decades, missions to explore these objects have been conducted. According to different types and scientific objectives, these missions can be broadly categorized into three phases: reconnaissance, detailed characterization, and habitability assessment. The technology development and performance characteristics of imaging spectrometers onboard these spacecraft are systematically reviewed. As the performance of spectral imaging payloads approaches its limits and deep-space missions venture ever closer to the edge of the Solar System, three key technical challenges have emerged: photon-limited conditions, constrained data downlink capability, and communication delays. To address these issues, solutions are discussed across three levels: data acquisition, data management, and mission execution. This framework provides valuable guidance for designing imaging spectrometers for future outer solar system missions.

Keyword:

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spectral imaging; the outer solar system; imaging spectrometer

1. Introduction

The outer solar system generally refers to the region beyond Jupiter's orbit (approximately 5 AU) (Encrenaz, 2009). This region contains a diverse range of objects, including planets, dwarf planets, and small bodies (Ksanfomality, 2007), and therefore provides an important natural laboratory for investigating the origin and evolution of planetary systems, planetary habitability, and the formation history of the Solar System. These research directions are closely related to the three priority science themes identified for the next decade by the National Academies of Sciences, Engineering, and Medicine, namely Origins, Worlds and Processes, and Life and Habitability (NASEM, 2023).

The outer solar system includes the four giant planets and their associated systems, including rings and moons. Jupiter and Saturn are gas giants, while Uranus and Neptune are ice giants. Studying these planets not only reveals the origins and evolutionary processes of the giant planets but also highlights their dominant role in shaping the formation, evolution, and migration patterns of the solar system, as they constitute the most massive class of planets within it. More importantly, many icy moons exhibit active geologic process and possess ice crusts of varying thicknesses. Research on these objects will provide crucial clues for addressing questions regarding the existence of extraterrestrial life and planetary habitability. Beyond the giant planets, the outer solar system also includes dwarf planets such as Pluto, as well as small bodies like comets and asteroids. Because these bodies have long been in a low-temperature, low-disturbance environment, they often preserve the historical environments of the early solar system. Studying these bodies will provide invaluable insights into the origin of the outer solar system and the properties of the primordial solar nebula.

Over the past few decades, a series of planetary missions have been conducted, such as Cassini-Huygens (Matson et al., 2002), Europa Clipper (Howell et al., 2020), and New Horizons (Stern, 2008). These missions generally carry high-performance spectral imaging instruments which combines techniques of imaging and spectroscopy to enable both topographic interpretation and composition analysis. For the giant planets and their systems, the Cassini Visual and Infrared Mapping Spectrometer (VIMS) operates in the wavelength from 0.3 to 5.1 μm . It obtains observations of targets in the Saturnian system include the surfaces and the atmospheres of Saturn, Titan, the icy moons and the rings (Brown et al., 2004); Regarding the habitability of icy moons, the Mapping Imaging Spectrometer for Europa (MISE) on board the Europa Clipper spacecraft will focus on distinguishing the composition of organics, salts, acid hydrates, water ice phases, altered silicates, radiolytic compounds, and warm thermal anomalies across different landforms on

Europa, thereby assessing its habitability (Blaney et al., 2024; Vance et al., 2023); In the exploration of dwarf planets and small bodies, the Ralph instrument on board the New Horizons has achieved a detailed characterization of the surface composition, temperature and spatial distribution on Pluto/Charon system and the Kuiper Belt objects (Reuter et al., 2008). Consequently, spectral imaging technology, by integrating both spatial and spectral information, has become a core technique for studying surface geology and composition of objects in the outer solar system.

The first part of this paper describes the definition of the outer solar system and the objects within it. The second part of this paper describe the evolution of outer solar system observation and advances of spectral imaging instruments. The current challenges and corresponding solutions of spectral imaging technique for outer solar system exploration are discussed in the third part. Finally, conclusions have been presented in the end.

The intent for this paper is to highlight the technical progress of spectral imaging in the outer solar system and to identify the challenges that occurred in the outer solar system observation and how to resolve these issues in the future.

2. Evolution of outer solar system Missions and Advances in Spectral Imaging Instruments

2.1 Evolution of outer solar system Missions

To make the content and structure clear, missions that only conducted gravity-assist flybys, as well as those whose targets lie within 5 AU of the Sun are not included in this review. Since the Pioneer 10/11 and Voyager 1/2 missions first ventured deep into the outer solar system (Hall, 1975; Smith et al., 1979a, 1979b), countries around the world have never ceased their exploration of this region. To date, a total of thirteen scientific missions have targeted outer Solar System bodies. Eleven of these missions have already been launched and carried out their scientific investigations, while the remaining two are currently under development. Based on the types and science objectives of different missions, the evolution of outer solar system missions can be divided into three phases: reconnaissance, detailed characterization, and habitability assessment.

The reconnaissance phase was marked by the U.S. missions Pioneer 10/11, Voyager 1/2, New Horizons, and Lucy. Pioneer 10/11 were the first spacecraft to fly past Jupiter and Saturn, while Voyager 1/2 further explored these planets and, in the case of Voyager 2, provided the first close-up data on Uranus and Neptune, obtaining the first remote sensing data on these giant planets and their moons (Hall, 1975; Smith et al., 1979a, 1979b). New Horizons, meanwhile, conducted the first exploration to Pluto and the Kuiper Belt object Arrokoth up close, establishing a comprehensive understanding of dwarf planets and Kuiper Belt objects (Stern, 2008). Lucy is

currently enroute to Jupiter's Trojan asteroids and is expected to conduct flybys of three main-belt asteroids and eight Trojan asteroids (Olkin et al., 2024). The primary objective of this phase is to establish a basic understanding of the targets' morphology, composition, and geology. This phase is characterized by broad coverage and multiple flybys, but the short dwell time at each target makes it difficult to support sustained, in-depth research.

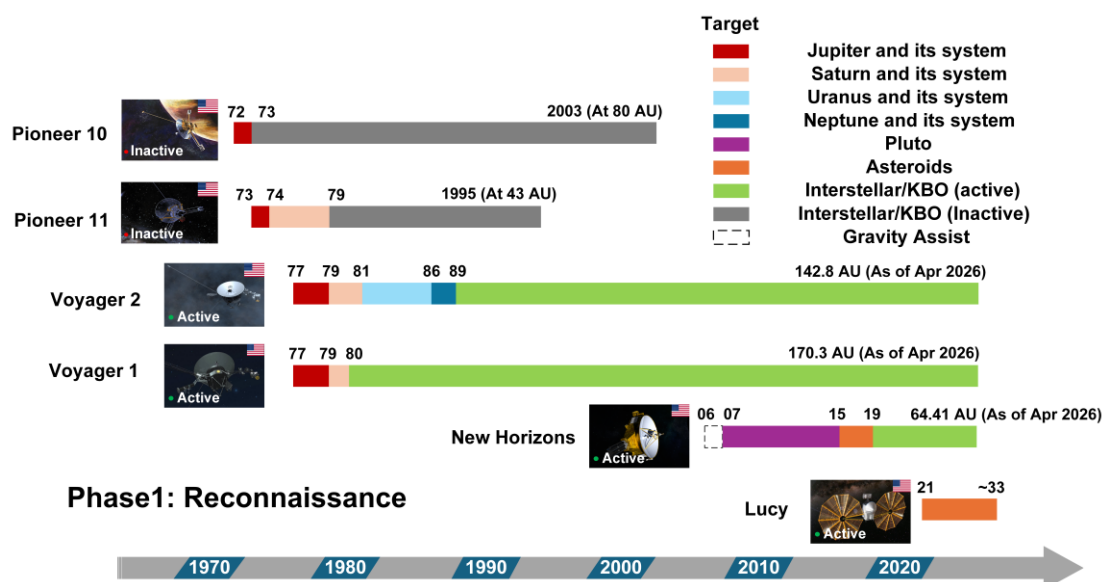


Figure 1. Missions to the outer solar system (Phase1: Reconnaissance)

Consequently, a second phase of exploration—the detailed characterization phase—was launched, comprising three major scientific missions: Galileo (Johnson et al., 1992), Cassini-Huygens, and Juno (Bolton et al., 2017). This phase shifted from flybys of multiple planets and asteroids to orbital and in-situ measurements of a planet. Galileo was the first spacecraft to achieve orbital and in-situ observations of Jupiter. By combining these two types of methods together, it collected detailed scientific data on Jupiter's atmosphere, magnetic field, and moons, thereby conducting a comprehensive survey of Jupiter and its moons (Johnson et al., 1992). Cassini-Huygens was the first spacecraft to achieve both orbital observations of Saturn and in-situ measurements of Titan. Similar to Galileo, this mission consists of the Cassini Saturn Orbiter and the Huygens Titan Probe: Cassini performed orbital measurements of Saturn, while Huygens entered the atmosphere of Titan and finally makes a soft landing on it. The mission studies Saturn's magnetic field, atmosphere, rings, Titan, and icy moons, achieving a comprehensive survey of Saturn and its system (Matson et al., 2002). Juno, designed to investigate Jupiter's origin and evolution, employed an elliptical polar orbit to obtain the first-ever images of cyclonic structures at its poles (Bolton et al., 2017; Adriani et al., 2018). Exploration during the detailed characterization phase focuses on a specific planet or comet. Characterized

by high specificity and the integration of multiple exploration methods, this phase enables a comprehensive study of the composition, morphology, origin and evolutionary processes of planets.

With the discovery of water vapor plumes and subsurface oceans on icy moons (Carr et al., 1988; McCord et al., 2001; Khurana et al., 1998; Coustenis et al., 1998; Hansen et al., 2006), exploration has shifted from general astrophysical and chemical characterization to focused investigations of planetary habitability and the potential for life. This period is summarized as the habitability assessment phase, exemplified by missions like JUICE (Fletcher et al., 2023), Europa Clipper (Pappalardo et al., 2024), Dragonfly, and Tianwen-4. Both JUICE and Europa Clipper have already been launched and are scheduled to arrive at Jupiter around 2030, with the aim of studying the habitability and potential for life on the two icy moons, Ganymede and Europa. Dragonfly is scheduled to launch in 2028 and reach Saturn's moon Titan in late 2036 to investigate the moon's habitability (Lorenz et al., 2018). Tianwen-4 is scheduled for launch in 2030 and will conduct orbital and in-situ exploration of Callisto, with the goal of studying the geological structure and evolutionary history of this ancient moon (Wei et al., 2018).

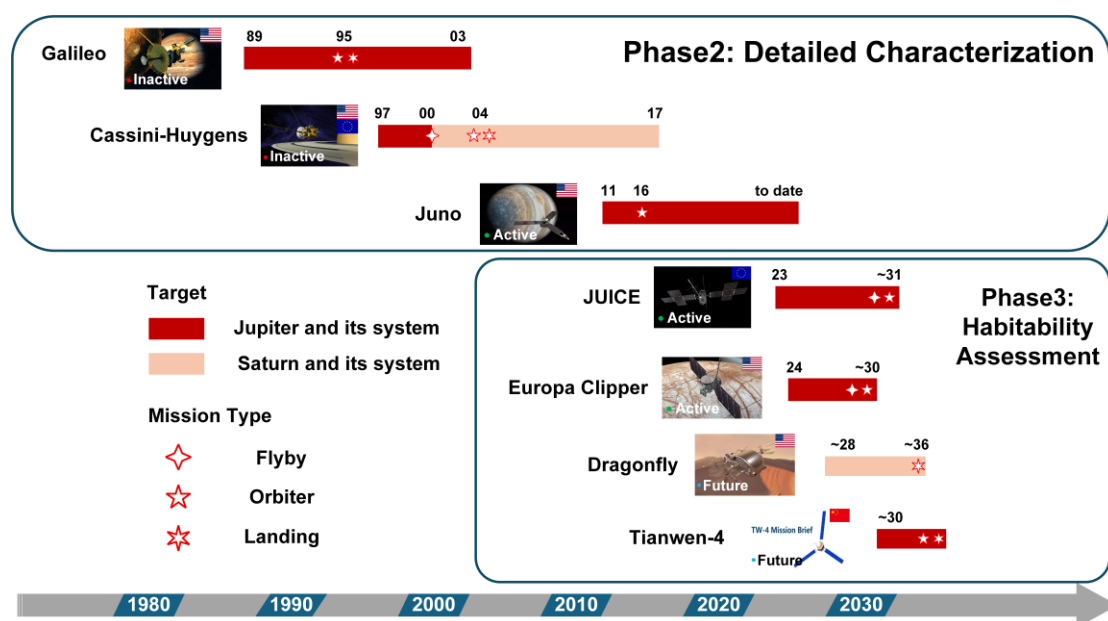


Figure 2. Missions to the outer solar system (Phase2: Detailed Characterization; Phase3: Habitability Assessment)

According to the three phases of outer solar system missions, several key trends can be summarized. First, approaches to observe the outer solar system have evolved from multi-target flybys toward more sustained and focused investigations centered on a single target, including orbital investigation, in situ measurements. Second, outer solar system exploration was initially dominated by the United States, but has since

expanded to include more different countries. Europe collaborated with the United States on missions such as Cassini–Huygens, and led missions such as JUICE, while China is planning Tianwen-4 around 2030. Finally, exploration has shifted from general survey to detailed characterization, and is now moving toward assessing planetary habitability.

2.2 Advances in Spectral Imaging Instruments

Imaging spectrometers have been a key remote sensing payload across planetary space missions. Among the eleven outer solar system missions conducted to date, excluding the early Pioneer 10/11 and Voyager 1/2 missions, seven missions carried imaging spectrometers as part of their scientific payloads. To investigate the development trends and technical characteristics of imaging instruments, seven representative instruments are considered: Near-infrared mapping spectrometer (NIMS) (Carlson et al., 1992), VIMS (Brown et al., 2004), Jovian InfraRed Auroral Mapper (JIRAM) (Adriani et al., 2017), Moons and Jupiter Imaging Spectrometer (MAJIS) (Carlier et al., 2024), MISE (Blaney et al., 2024), Ralph (Reuter et al., 2008) and L'Ralph (Reuter et al., 2023). These instruments are perfectly suitable for the analysis of composition and interpretation of topography. This section reviews the development of seven representative imaging spectrometers, examining how the instrument techniques, architectures and performance characteristics have evolved over time. Building on this analysis, it also discusses the performance limits and technical constraints in current studies.

2.2.1 Techniques and Architectures

Dispersion elements are the most important part of the imaging spectrometer, which can disperse light into different wavelengths. Based on different types of dispersive methods, spectral imaging instruments can be separated into two main groups: one consists of spectrometers based on filter-based spectroscopy, and the other consists of spectrometers based on traditional dispersive spectroscopy. These two methods have their own advantages and disadvantages. Dispersive Spectrometers which use prisms or gratings for light dispersion have more complex optical designs, enabling higher spectral resolution and covering a broader spectral range. Spectral filters which use Linear Variable Filter (LVF) for light dispersion have simpler optical designs, more compact and lower mass. However, since they are bandpass filters, they have lower light throughput and the spectral range is often constrained by physical dimensions.

Instruments from the reconnaissance phase employ a variety of dispersing methods, among which filter-based approaches are represented by Ralph and L'Ralph. In the detailed characterization phase, instruments such as NIMS and VIMS adopted grating-based dispersive method. Building on this heritage, successive instruments achieved substantial improvements in detector formats, operating modes, and imaging methods, enabling more comprehensive observations of planetary bodies. For the habitability assessment phase, instruments including MAJIS and MISE largely retain

grating-based dispersive approach but introduce significant enhancements, particularly in spectral and spatial resolution as well as radiation tolerance. These instruments place greater emphasis on distinguishing water-bearing materials and organic compounds, and on linking composition and physical properties with geological context, in support of assessing planetary habitability and the potential for life (Bender et al., 2019; Piccioni et al., 2019).

During the reconnaissance phase, the Ralph instrument on New Horizons and the L'Ralph instrument on Lucy employed a filter-based imaging approach. Both payloads are characterized by low mass, power efficient, few moving parts, and high degree of redundancy, making them suitable for long-duration, multi-target flyby missions. L'Ralph is the successor to Ralph and features a similar imaging system, both consisting of a Multi-spectral Visible Imaging Camera (MVIC) and a Linear Etalon Imaging Spectral Array (LEISA). The MVIC employs multiple CCD arrays and operates in time delay integration (TDI) mode to accumulate charges line by line along the scan direction, thereby improving the signal-to-noise ratio of the instruments. The LEISA, on the other hand, uses a Linear Variable Filter (LVF), forming a spectral image by scanning the FOV across the surface in a pushbroom mode; its detector is a two-dimensional HgCdTe array. Compared to Ralph, L'Ralph has a boarder spectral wavelength and uses a scanning mirror to replace the movement of the spacecraft (Reuter et al., 2008; Reuter et al., 2023).

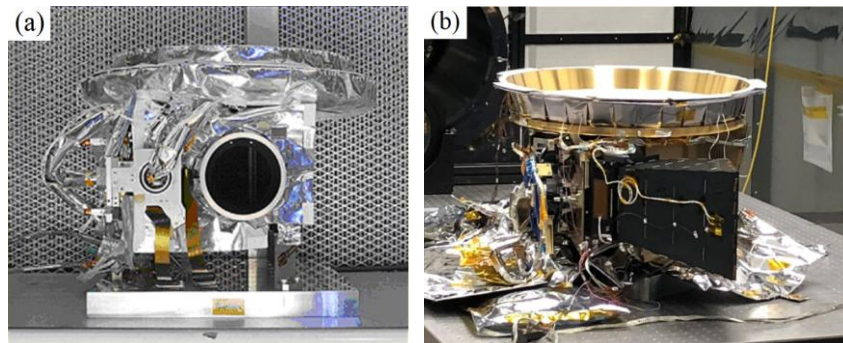
During the detailed characterization phase, NIMS, VIMS, and JIRAM employ traditional grating-based dispersive technique. These payloads have all been enhanced and optimized based on their previous generations to meet the specific requirements of different missions, demonstrating a clear path of technological evolution. The NIMS instrument aboard Galileo is a typical whiskbroom imaging spectrometer. The instrument achieves a line-of-sight field of view of approximately 10×0.5 mrad through continuous scanning of the telescope's secondary mirror. The other dimension of spatial scanning is achieved by the spacecraft movements in the cone direction. It employs a grating step-scanning method to sequentially disperse light across different wavelength bands, projecting the signals from each band onto 17 individual detectors, thereby achieving full-spectrum coverage from the visible to the infrared (Carlson et al., 1992). Since both the spatial and spectral imaging of NIMS rely on mechanical scanning, this type of payload requires frequent control during imaging, resulting in low observational efficiency, high demand for system coordination and high accuracy for system control.

The VIMS instrument aboard Cassini is an international payload developed through a collaboration between the United States and Europe. The visible and near-infrared channel (VIMS-VIS) was designed by Europe, while the infrared channel (VIMS-IR) was designed by the United States. The two channels are independent of each other in

terms of their optical systems and spectrometer architectures. VIMS-IR inherits the opto-mechanical design of NIMS and images in whiskbroom mode. The detector has evolved from individual detectors to a 256-element InSb linear array detector. The entire spectral range can be covered through a single dispersion process, significantly improving imaging efficiency. The movable, two-blaze NIMS grating is replaced by a fixed, three-blaze grating to optimize the acquired spectral signals and reduce mechanical displacement of optical components. The secondary mirror has also been changed from one-dimensional scanning to two-dimensional scanning, thereby eliminating the need for the movement of the spacecraft. (Brown et al., 2004; Miller et al., 1996) On the other hand, VIMS-VIS uses a two-dimensional Charge-Coupled Device (CCD) area array detector and acquires image cubes in pushbroom mode. Compared to whiskbroom imaging spectrometers, it does not require mechanical scanning along the track direction, thereby improving the system's observational efficiency and stability.

The JIRAM instrument aboard Juno builds on the design of VIMS-VIS and adopts a two-dimensional HgCdTe detector for pushbroom imaging. However, since Juno is a rotating spacecraft, a scanning mirror assembly was incorporated into JIRAM's front-end optics to compensate for the platform's rotation and maintain a stable field of view. To meet the scientific objectives, JIRAM divides the 2–5 μm infrared band into imaging and spectral channels, both of which share the same front-end optical system, thereby maximizing scientific return within limited resources.

In the new generation of Jovian missions, to study the habitability of icy moons, the MAJIS on board the JUICE spacecraft and the MISE instrument on board Europa Clipper follow the traditional grating-based dispersive approach, employing a pushbroom imaging mode and HgCdTe area-array detectors. However, their resolution specifications, operating modes, and on-board data processing have all been optimized. Specifically, MAJIS has divided the entire spectral range into two segments—0.5–2.35 μm and 2.27–5.55 μm —based on science goals and radiation characteristics (Carlier et al., 2024). Meanwhile, MISE employs a Dyson spectrometer in place of the traditional Offner design, thereby achieving a more compact layout and higher throughput (Blaney et al., 2024).



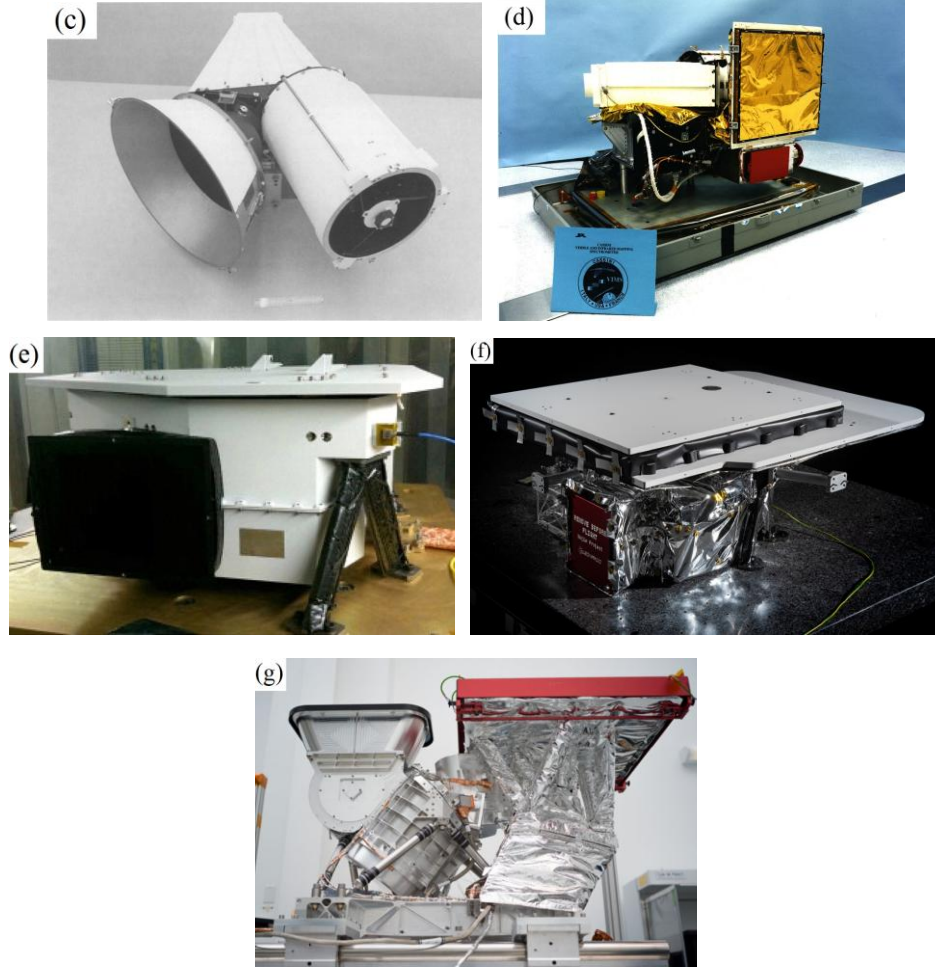


Figure 2. Typical spectral imaging payloads (a) Ralph (Reuter et al., 2008) (b) L’Ralph (Reuter et al., 2023) (c) NIMS (Carlson et al., 1992) (d) VIMS (Brown et al., 2004) (e) JIRAM (Adriani et al., 2017) (f) MAJIS (Carlier et al., 2024) (g) MISE (Blaney et al., 2024)

By placing these payloads in the same evolutionary sequence based on detection phase and dispersion method, a trend of technology evolution for imaging spectrometers can be summarized in four aspects. First, detector technologies have undergone significant evolution. Silicon-based CCDs have remained the primary choice for visible-wavelength imaging, while infrared detector materials have progressed from InSb to HgCdTe, enabling broader and more flexibly tailored spectral coverage. Meanwhile, focal-plane array formats have evolved from discrete detector elements to linear arrays and, more recently, to large-format two-dimensional area arrays. This evolution significantly increased the spatial information acquired in a single observation, thereby improving imaging efficiency and spatial coverage, while also supporting the development of more advanced spectral imaging systems. Second, the traditional dispersion method has evolved from mechanically scanned grating dispersion to single-pass dispersive spectroscopy and multi-region grating designs. Meanwhile, filter-based spectral imaging method has emerged, offering simpler

optical architectures and greater structural flexibility. Third, the imaging method has gradually shifted from whiskbroom to pushbroom, further dividing into two implementation paths: spatial-dimension push-broom and spectral-dimension push-broom. Fourth, instrument capability has expanded from single-mode spectral imaging to integrated systems combining high-resolution imaging, high-resolution spectroscopy, and multi-mode observations.

Table 1. Technology evolution for the imaging spectrometers based on dispersion method

Dispersive method	Instrument	Imaging method	Operating mode	Detector format	References
Filter-Based Method (LVF)	Ralph (MVIC)	Pushbroom	Multispectral Imaging (TDI)	CCD Area Array Detector	(Reuter et al., 2008)
	Ralph (LEISA)	Pushbroom	Hyperspectral Imaging	HgCdTe Area Array Detector	(Reuter et al., 2008)
	L'Ralph (MVIC)	Pushbroom	Multispectral Imaging (TDI)	CCD Area Array Detector	(Reuter et al., 2023)
	Ralph (LEISA)	Pushbroom	Hyperspectral Imaging	HgCdTe Area Array Detector	(Reuter et al., 2023)
Grating, Method	NIMS	Whiskbroom	Hyperspectral Imaging	InSb, Si Individual Detector	(Carlson et al., 1992)
	VIMS	Whiskbroom, Pushbroom	Hyperspectral Imaging (Point, Line Mode)	InSb Linear detector, Si Area Array Detector	(Brown et al., 2004)
	JIRAM (imager)	Pushbroom	Multispectral imaging,	HgCdTe Area Array Detector	(Adriani et al., 2017)
	JIRAM (spectrometer)	Pushbroom	Hyperspectral imaging	HgCdTe Area Array Detector	(Adriani et al., 2017)
	MAJIS	Pushbroom	Hyperspectral imaging	HgCdTe Area Array Detector	(Carlier et al., 2024)
	MISE	Pushbroom	Hyperspectral imaging	HgCdTe Area Array Detector	(Blaney et al., 2024)

2.2.2 Performance Characteristics

The performance characteristics of a spectral imaging instrument directly reflect its imaging capabilities and are typically configured to address different scientific objectives. Therefore, differences in mission and scientific goals lead to variations in performance parameters. The main parameters of a spectral imaging system generally include spectral resolution, spatial resolution, spectral range, signal-to-noise ratio, power, mass, etc. Some performance characteristics of representative imaging spectrometers have been listed in Table 2.

Spectral resolution refers to the ability to distinguish the smallest difference between two adjacent spectral features (such as wavelength or frequency). There are many factors that can affect the spectral resolution design such as slit width, dispersion components, and detector formats. As investigations of the outer solar system shift from broad compositional detection to precise material discrimination, higher spectral resolution is increasingly needed for the discrimination between different compounds with similar spectral characteristics. For example, on the ice moons, both hydrates and water ice exhibit similar spectral features. Water ice has absorption features at 1.04, 1.25, 1.5, 2.0, and 3 μm (McCord et al., 1998), whereas hydrates such as Na/Mg hydrated sulfates and Na/Mg hydrated chlorides exhibit absorption feature near 1.0, 1.2, 1.45, 1.8, 1.95, 2.5, and 2.8 μm . To distinguish between these two components, the spectral resolution should be better than 10 nm (Carlier et al., 2024). Compared to the early spectral imaging payloads such as NIMS and VIMS, the spectral resolution of the new generation imaging spectrometer has reached better than 10 nm. For those filter-based spectral imaging systems, the spectral resolution varies across the whole spectral range. For example, in the 1.25–2.5 μm wavelength range, the average spectral resolving power of the Ralph LEISA channel is 240. This means that the spectral resolution varies from 5.2 to 10.4 nm across the near-infrared spectrum.

The spatial resolution of a payload determines its ability to identify surface features and morphological characteristics of the target. Typically, the payload's instantaneous field of view (IFOV) is fixed, so spatial resolution mainly depends on orbital altitude. As the altitude decreases, each pixel covers a smaller ground area, resulting in higher spatial resolution. For Ralph and L'Ralph, which operate in flyby missions, the IFOV is deliberately kept small to meet high spatial resolution requirements at relatively large observation distances. The closest distance at which Ralph observed Pluto was 10,000 km. To achieve a spatial resolution of 1 km/line pair, the MVIC channel's IFOV must be at least 50 μrad . Since this represents the lowest orbital altitude and a certain engineering margin has been factored in, the MVIC channel was designed with an IFOV of 20 μrad (Reuter et al., 2008). For NIMS and VIMS, which operate in orbital missions, the relatively low spacecraft altitude allows high spatial resolution to be achieved without requiring a very small IFOV. However, as mission objectives have evolved, increasing demands for spatial resolution have generally led to a reduction in the instantaneous field of view of payloads. For payloads in the habitability assessment phase, such as MAJIS and MISE, the instantaneous field of

view is generally 250 μrad or less, resulting in approximately twice the angular sampling of the earlier NIMS.

The spectral range refers to the range of wavelengths that an imaging system can measure. This parameter is typically driven by the scientific objectives: the spectral range needs to encompass the wavelength band containing the target's main diagnostic features. For example, the 2–5 μm spectral range of JIRAM was selected to simultaneously support Jupiter's auroral observations, atmospheric sounding, and compositional analysis. The extension toward 2 μm enables the detection of NH_3 ice, NH_4SH , water clouds at different atmospheric pressure levels, while the coverage beyond 3 μm provides additional diagnostics of Jupiter's upper and deep atmosphere. In particular, the 3.2–4 μm region supports H_3^+ auroral observations, whereas the relatively cloud-free 4–5 μm Jovian hot spots allow thermal sounding of deeper atmospheric layers (Adriani et al., 2017). MAJIS's spectral range extend to 5.5 μm , beyond the 5.0 μm upper limit of JIRAM, enables improved coverage of gaseous H_2O and NH_3 absorption bands. In addition to Jovian atmospheric investigations, MAJIS is also designed to observe the icy Galilean satellites and characterize both water ice and non-ice materials on their surfaces in the 0.5–3 μm spectral range (Piccioni et al., 2019).

Signal-to-noise ratio (SNR) is defined as the ratio between the effective spectral signal and the system noise level, which directly determines the capability of an instrument to detect weak targets and subtle spectral absorption features. The SNR is influenced by various factors, including the radiative environment of the target body and the parameters of the imaging spectrometer. During the reconnaissance and detailed characterization phases, early imaging spectrometers, such as Galileo/NIMS, were constrained by the detector technology and various noise sources, which limited their SNR performance and the capability for fine discrimination of material compositions. As outer solar system exploration has evolved toward habitability assessment, payloads are required to achieve more precise discrimination and characterization of material compositions, which has imposed higher SNR requirements. For example, the MAJIS onboard ESA's JUICE mission requires an average SNR greater than 100 for observations of Ganymede and Callisto, and an SNR greater than 30 in the 3.2–3.6 μm organic-sensitive spectral region for Europa observations (Carlier et al., 2024).

Finally, the performance characteristics are also subject to engineering trade-offs and constraints, such as power consumption, mass, data rates, and thermal architecture. Therefore, instrument parameters are not simply optimized to achieve maximum performance, but rather balanced between scientific requirements and engineering constraints. For example, higher resolution typically implies larger data volumes and higher signal-to-noise ratio requirements, which in turn place greater demands on cooling capacity, power consumption, and data transmission. Ultimately, spectral imaging payloads for different missions, while building upon the technical framework

of previous generations, will develop their own technical characteristics based on mission objectives and resource constraints, achieving a compromise between scientific requirements and system resources.

Table 2. Representative spectral imaging systems.

Instrument	Mission	Spectral range (μm)	Spectral resolution (nm)	Field of view (cross $\times$ along) (mrad)	IFOV (μrad)	SNR ^a	Power (W)	Mass (kg)	Reference
Ralph	New Horizons	0.4-0.97, 1.25-2.5	5.2-10.4 (1.25-2.5 μm), 3.75-4 (2.1-2.25 μm)	98.85 $\times$ 0.63 (0.4-0.97 μm for TDI array), 98.85 $\times$ 2.53 (0.4-0.97 μm for framing camera), 15.57 $\times$ 15.57 (1.25-2.5 μm)	19.77 (0.4-0.97 μm), 60.83 (1.25-2.5 μm)	50 (0.4-0.97 μm), 15 (0.86-0.91 μm), 32 (1.25 μm), 27 (2 μm), 18 (2.15 μm)	7.1	10.5	(Reuter et al., 2008)
L'Ralph	Lucy	0.35-3.95	<10 (1-3.8 μm)	144 $\times$ 1.84 (0.35-0.95 μm), 40.96 $\times$ 58.88 (0.95-3.95 μm)	28.8 (0.35-0.95 μm), 40 (0.95-3.95 μm)	>25	24.5	32.3	(Reuter et al., 2023)
NIMS	Galileo	0.7-5.2	12.5 (0.7-1 μm), 25 (1-5.2 μm)	0.5 $\times$ 0.5	500	10 (for Io), 30 (for Europa), 100 (for Ganymede)	12	18	(Carlson et al., 1992)
VIMS	Cassini	0.3-5.1	1.46 (0.3-1.05 μm), 7.3 (0.3-1.05 μm ; 5 pixel	0.5 $\times$ 0.5 (0.3-1.05 μm), 32 $\times$ 0.5 (0.85-5.1 μm)	170 (0.3-1.05 μm), 500 (0.3-1.05 μm ; 3 $\times$ 3 sum), 250 $\times$	- ^b	23.9	- ^b	(Brown et al., 2004)

Table 2. (continued) Representative spectral imaging systems.

Instrument	Mission	Spectral range (μm)	Spectral resolution (nm)	Field of view (cross $\times$ along) (mrad)	IFOV (μrad)	SNR ^a	Power (W)	Mass (kg)	Reference
			summing), 16.6 (0.85-5.1 μm)		500 (0.85-5.1 μm), 500 (0.85-5.1 μm ; 1 $\times$ 2 sum)				
JIRAM	Juno	2.0-5.0	10	64 $\times$ 0.25 (2-5 μm), 108 $\times$ 32 (3.3-3.6 μm ; 4.5-5 μm)	250	- ^b	16.4	12.9	(Adriani et al., 2017)
MAJIS	JUICE	0.50-5.55	3.5-3.8 (0.5-2.35 μm), 5.9-6.9 (2.27-5.55 μm)	60 $\times$ 0.15	150	>100 (for $\lambda < 2.8 \mu\text{m}$), >30 (3.2-3.6 μm), >20 (for $\lambda > 3.6 \mu\text{m}$)	25-26	50.84	(Carlier et al., 2024)
MISE	Europa Clipper	0.8-5.0	10	75 $\times$ 0.25	250	- ^b	60	65	(Blaney et al., 2024)

^a Ralph's SNR: 50 (33 AU, 0.35 I/F, 0.4-0.97 μm); 15 (33 AU, 0.35 I/F, 0.86-0.91 μm); 32 (1.25 μm ; Pluto); 27 (2.00 μm ; Pluto); 18 (2.15 μm ; Pluto); L'Ralph's SNR: >25 (5.7 AU, 0.0014 I/F; 5.2 AU, 0.005 I/F; 1.2 s Maximum integration time, 0.35-0.95 μm); >25 (5.7 AU, 0.0019 I/F; 5.2 AU, 0.0068 I/F; 1.5 s Maximum integration time, 1.0-3.4 μm); MAJIS's SNR: >100 (0.5-2.8 μm , except for the 0.6-0.7 μm range that may be impacted by a spectrally structured straylight component; icy satellites); >30 (3.2-3.6 μm ; icy satellites); >20 (3.6-5.55 μm ; icy satellites); >100 (0.50-5.55 μm , methane absorption excluded; Jupiter); >10 (Jupiter' aurora)

^b“-”: indicates that no corresponding value was found in the available literature.

Overall, the development of spectrometers' performance follows an evolutionary pattern in which scientific demands drive performance improvements, while engineering constraints determine the implementation methods. This has led to payloads for different missions gradually forming distinct development paths in terms of spectral range, resolution, swath width.

However, as payload performance, particularly in terms of spatial and spectral resolution, continues to approach its limits, a series of technical challenges arise. First, given a finite number of photons, improvements in spectral and spatial resolution will inevitably lead to a significant reduction in the number of photons captured per wavelength or per pixel, thereby affecting the SNR of the acquired data; second, when the number of spatial samples in both dimensions and the number of spectral samples are each doubled, the resulting data volume increases eightfold, whereas the deep-space downlink rate cannot grow at the same rate. The contradiction between massive data volumes and low data transmission efficiency, which became apparent during the Galileo mission, is even more pronounced in next-generation spectral imaging missions.

3. Challenges, Solutions and Future Prospect in Spectral Imaging Technology for the Outer Solar System

3.1 Challenges

The technical constraints resulting from improvements in spectral and spatial resolution are further magnified in the extreme deep-space environment of the outer solar system, giving rise to numerous technical challenges.

First, outer solar system objects are located at heliocentric distances exceeding 5 AU, where the available solar irradiance drops to less than 4% of that at 1 AU and decreases further for more distant targets. Consequently, spectral imaging in the outer solar system is inherently photon-limited because of the extremely weak solar irradiance at large heliocentric distances. Increasing spatial and spectral resolution further decreases the photon count received by each detector element, resulting in a significant reduction in the signal received by the detector. At the same time, under low-light conditions, noise has a particularly severe impact on the signal-to-noise ratio of the spectral data.

Second, spectral imaging data are typically organized as three-dimensional image cubes. Improvements in spatial and spectral resolution lead to a substantial increase in data volume and data generation rate. Moreover, the extremely long transmission distances in outer solar system missions significantly reduce data return capability and limit achievable downlink rates. As a result, a growing mismatch emerges between data collection rate and downlink capability, making it difficult to transmit large

amounts of spectral data in real time.

Finally, the substantial communication latency in outer solar system missions, typically exceeding 30 minutes one-way, greatly limits the capability for real-time ground intervention and payload operation. As a result, spacecraft are unable to rapidly adjust observation strategies in response to transient or unexpected phenomena, posing significant challenges for time-sensitive scientific events.

3.2 Solutions and Future Prospect

To address the challenges posed by photon-limited observation conditions, constrained data downlink capability, and long communication latency, spectral imaging systems are evolving along three complementary directions: enhanced low-light data acquisition, adaptive onboard data management, and autonomous observation. At the data acquisition level, techniques such as motion compensation and cryogenic optics are employed to ensure the acquisition of high-quality raw data even under extremely weak illumination conditions. At the onboard data management level, multi-resolution imaging and prioritized transmission strategies are introduced to mitigate the growing imbalance between data acquisition rate and downlink capability, thereby reducing transmission burden while preserving high-value scientific information. At the mission execution level, autonomous observation and decision-making capabilities are increasingly integrated into spacecraft and payload systems, enabling rapid identification and observation of scientifically valuable targets with reduced reliance on real-time ground control.

To achieve high-sensitivity observations under photon-limited conditions, motion compensation techniques (Murchie et al., 2007; Carlier et al., 2024) are employed to extend the integral time, thereby increasing the collected photon signal and improving the SNR of the instrument. This approach mitigates image degradation caused by extremely weak illumination in outer solar system observations. However, under long-integration operating mode, dark current and thermal background radiation from the optical system and detector can become comparable to or even exceed the target signal, severely constraining detection performance. To suppress dark current and background noise and enable high-sensitivity observations, spectral imaging payloads widely incorporate cryogenic optical systems to cool both the opto-mechanical assembly and the focal plane detector (Carlier et al., 2024; Blaney et al., 2024). These cooling systems significantly reduce thermal background emission and detector dark current, making long-integration, low-noise spectral imaging feasible in extremely low-illumination environments. In addition, low-noise infrared detectors, advanced readout architectures (Zhong et al., 2026; Liu et al., 2026), and techniques such as pixel binning and multi-frame integration can effectively enhance the signal-to-noise ratio and improve data quality under low-light conditions.

To mitigate the growing imbalance between data acquisition rate and limited downlink capability, multi-resolution imaging (He et al., 2021; Gui et al., 2022; Brown et al., 2004), data compression method (Hernández-Cabronero et al., 2021; Ghasemi et al., 2025), and prioritized transmission strategies are employed. On the one hand, through multi-resolution adaptive sampling strategies (such as pixel binning), spatial and spectral resolutions are dynamically adjusted according to observational requirements. Spectral imaging data is generated on demand, thereby avoiding data redundancy in full-resolution mode. On the other hand, once spectral imaging data are acquired, data compression algorithms can be applied to further reduce data redundancy and thereby decrease the volume of data to be transmitted. Intelligent data analysis algorithms are also introduced to evaluate the scientific value of acquired datasets, extract key spectral features, and generate preliminary scientific products. The MAJIS team uses browse data to assess the scientific value of the acquired data and determine which datasets should be downlinked first (Carlier et al., 2024). These capabilities enable prioritized transmission of scientifically valuable data under constrained downlink conditions.

Long communication latency in outer solar system missions severely limits the effectiveness of real-time ground-directed observations. By the time telecommands transmitted from earth reach the spacecraft, observation conditions may already have changed, making it difficult to capture transient phenomena. To address this limitation, an autonomous observation system (Chien et al., 2005; Bowkett et al., 2025; Rijlaarsdam et al., 2024) has been proposed at the mission level. Through the integration of onboard scientific event detection (Wagstaff et al., 2019), autonomous mission planning and scheduling, and observation execution, spacecraft are capable of forming an autonomous observation workflow. This enables spacecraft and payloads to independently identify, prioritize, and observe scientifically valuable targets with minimal reliance on real-time ground intervention. Such autonomous observation capabilities significantly reduce operational dependence on long-latency deep-space communication links and improve the responsiveness of spacecraft to dynamic scientific events in the outer solar system.

These three levels of solutions are deeply interdependent, collectively forming an integrated architecture that not only addresses current mission constraints but also charts a coherent path toward the next generation of spectral imaging for the outer solar system. First, technologies such as motion compensation and cryogenic optics improve photon collection efficiency and image quality under extremely weak illumination conditions, providing reliable input for subsequent onboard analysis and interpretation. Higher-quality observational data preserve more scientifically meaningful spectral information, thereby improving the accuracy and robustness of onboard data processing algorithms. At the same time, autonomous observation and mission replanning capabilities rely heavily on onboard data analysis results. Through

the integration of data acquisition, onboard data processing, and autonomous observation, future spectral imaging systems are expected to form an intelligent observation framework capable of adapting to the severe environmental and operational constraints of outer solar system exploration. This new framework will transform the next generation of outer solar system spectral imaging from passive data recorders into adaptive, self-directed scientific observatories.

4. Conclusions

In this review, we have categorized outer solar system missions into three evolutionary phases: reconnaissance, detailed characterization, and habitability assessment. Three trends expected to shape future mission development are also identified and discussed. The imaging spectrometers onboard these spacecraft are systematically reviewed, with comparative analysis of their spectral dispersion mechanisms, imaging methods, operating modes, and detector formats, followed by a comprehensive evaluation of their key performance parameters. A technological evolution path driven by progressive hardware advancements has been proposed. As instrument performance continues to approach its physical limits, several technical challenges have emerged under the extreme deep-space environment: photon-limited conditions, constrained data downlink capability, and long communication latency. To address these issues, three sets of solutions have been proposed, collectively constituting a unified framework for next-generation spectral imaging in outer solar system exploration.

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