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Review of Spaceborne Optical Payloads

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1.1 Introduction

The objectives of a space mission are accomplished by the hardware (i.e., instruments) and software, which are referred to as payloads, onboard the platform of a spacecraft. Payloads sense or interact with the subject, are typically unique to each mission, and are the fundamental reason that the spacecraft is flown. The purpose of the rest of the subsystems is to keep the payloads healthy, happy, and pointed in the right direction. The payloads largely determine the mission's cost, complexity, and effectiveness. A critical part of a mission analysis and design is to understand what drives a particular set of payloads so that these demands can become part of the overall system trade process designed to meet mission objectives at minimum cost and risk.

Payloads of space missions can be roughly classified into two categories in terms of the wavelength of their operating: optical and microwave. Optical payloads, or sensors, measure reflective light in wavelength range from ultraviolet, visible, to infrared (including near infrared, intermediate infrared, thermal infrared), while microwave sensors measure microwaves whose wavelength is longer than visible light and infrared (IR) rays. Microwaves are radio waves with wavelengths ranging from as long as 1 m to as short as 1 mm, or equivalently, with frequencies between 300 MHz (0.3 GHz) and 300 GHz. The observation of microwave sensors is not affected by day, night, or weather. Radar sensors and synthetic aperture radar (SAR) sensors are the typical microwave sensors.

There are two types of observation methods for both optical and microwave payloads: passive and active. Passive payloads detect and measure natural radiation that is emitted or reflected by the objects or surrounding area being observed. Reflected sunlight is the most common source of radiation measured by passive sensors. Active sensors, on the other hand, emit energy in order to scan the area of objects and then detect and measure the radiation that is reflected or backscattered from the objects. Radar and lidar sensors are active sensors, where the time delay between emission and return is measured, establishing the location, height, speed, and direction of an object.

The focus of this book is optical payloads for space missions. Radar payloads are beyond the scope of this book.

Optical payloads can be roughly classified into following six types based on their functions:

1. Panchromatic sensors
2. Multispectral sensors

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3. Imaging spectroscopy sensors
4. Fourier transform spectroscopy sensors
5. Light detection and ranging (lidar) sensors
6. Spectrometers and radiometers

This book consists of eight parts (Part One – Part Eight) and covers all these six types of optical payloads. Part One (Chapter 1) is the overview of spaceborne optical sensors. Parts Two through Six each describe one type of optical sensors except for the panchromatic sensors, which are included in Part Two or Part Three together with their hyperspectral or multispectral sensors onboard the same platform. Part Seven describes spaceborne optical sensors other than these six types. Part Eight describes optical sensors onboard microsatellites and nanosatellites.

1.1.1 Panchromatic Sensors

Panchromatic refers to black and white imagery exposed by all visible light. However, a spaceborne panchromatic sensor often acquires visible light within a wavelength range typically between 0.50 and 0.80 μm using a minus blue filter to reduce the scattering that occurs in the blue wavelengths. A panchromatic sensor produces images with a much finer ground footprint size (or spatial resolution) than those produced by the multispectral sensor or hyperspectral sensor onboard the same satellite. For example, the QuickBird satellite produces panchromatic imagery having a ground footprint size of 0.6 m × 0.6 m, while the multispectral pixels represent an area of 2.4 m × 2.4 m.

1.1.2 Multispectral Sensors

Unlike a panchromatic sensor that records the total intensity of radiation falling on each pixel and generates only a panchromatic image, a multispectral sensor acquires multiple images of the scene simultaneously at specific spectral bands, or wavelength ranges. Multispectral images acquired by multispectral sensors are the main type of remote sensing images. Usually, a multispectral sensor has three or more spectral imagers (Landsat 7 has seven). Each one is a scene image in a band of visible spectra, ranging from 0.4 μm to 0.7 μm, called red (635–700 nm), green (490–560 nm), and blue (450–490 nm) (RGB) region, and going to IR wavelengths of 0.8 μm to 10 μm or longer, classified as near infrared (NIR), middle infrared (MIR), and far infrared (FIR or thermal). In the case of Landsat 7, the acquired images comprise seven-band multispectral images. A list of spaceborne multispectral sensors together with their satellite platforms and detailed technical information can be found in Table 1.1 of Reference 1.

1.1.3 Imaging Spectroscopy Sensors

An imaging spectroscopy sensor, also known as hyperspectral sensor, collects images of a scene simultaneously in hundreds of contiguous narrow spectral bands and inherently registered over wavelengths that range from the near ultraviolet through the shortwave infrared. The image data are capable of providing direct identification of surface materials and are used in a wide variety of remote sensing applications including geology, oceans, soils, vegetation, atmosphere, snow/ice, and so forth. The collected image data is a 3-dimensional (3D) cube comprising two spatial dimensions and one spectral dimension. Each ground sample cell (i.e., pixel) in the scene has its unique characteristics across the electromagnetic spectrum (also called “fingerprints”). These fingerprints are known as spectral signatures and enable identification of the materials. For example, a spectral signature of gold helps mineralogists find new gold fields. The primary advantage to hyperspectral sensors compared to the multispectral sensors is that, because an entire spectrum of a ground sample is acquired, a user can identify the materials in the scene by analyzing the spectra. Information processing allows all available information from the data cube to be exploited. Hyperspectral imaging can also take advantage of the spatial relationships among the different spectra of ground samples in a neighborhood, allowing more elaborate spectral-spatial models for a more accurate identification, segmentation, and classification of the image.

1.1.4 Fourier Transform Spectroscopy Sensors

Fourier transform spectroscopy (FTS) is a measurement technique whereby spectra are collected based on measurements of the coherence of a radiative source using time-domain or space-domain measurements of the electromagnetic radiation or other type of radiation. The measurement principle of a Fourier transform spectrometer is different from a conventional spectrometer. Rather than allowing only one wavelength at a time to pass through to the detector in a conventional spectrometer, a Fourier transform spectrometer lets through a beam containing many different wavelengths of light at once, and measures the total beam intensity. Between the light source and the detector, there is a certain modulation configuration of mirrors that allows some wavelengths to pass through but blocks others due to wave interference by moving one of the mirrors. A Fourier transform is required to turn the measured raw data, called an "interferogram," into the actual spectrum.

There are two types of Fourier transform spectrometers based on the modulation of the interferometer being used: spectral modulation and spatial modulation. Most of the Fourier transform spectrometers are the spectrally modulated ones. A FTS sensor with a single detector element or a few detector elements is referred to as a FTS sounder. A FTS sensor with a 2D detector array is referred to as an imaging FTS. The main difference between an imaging FTS and a FTS sounder is that a FTS sounder provides spectral information (e.g., vertical profile of the atmosphere) of a single footprint or a few of coarse resolution footprints within the field-of-view (FOV) of the instrument. No spatial image for each spectral band is available in a FTS sounder.

1.1.5 Lidar Sensors

Lidar sensors can measure the distance to the target or other properties of a target by illuminating, using pulses from a laser. Passive sensors have a lot of difficulty with vertically resolving and uniquely determining tropospheric species in Earth observation. The innate characteristics of lidar sensors would provide a small footprint on the ground, that is, high horizontal spatial resolution, very high vertical resolution, a high sensitivity for atmosphere to measure aerosols and clouds, and an excellent discrimination against noise because of laser spectral purity. Perhaps most importantly, these characteristics allow lidar sensors to probe between clouds and penetrate through optically thin clouds and, therefore, profile the troposphere. Lidar sensors have applications in many areas such as archaeology, atmospheric physics, geography, geology, geomatics, geomorphology, seismology, forestry, and remote sensing, as well as in airborne laser altimetry, laser swath mapping, and lidar contour mapping.

A lidar sensor uses a light source at wavelength from ultraviolet (250 nm), visible, to IR (10 μm) to image objects. The targets include non-metallic objects, rocks, rain, chemical compounds, aerosols, and clouds. A narrow laser beam can be used to map physical features with very high resolution. Typically light is reflected via backscattering. Different types of scattering are used for different lidar applications; most common are Rayleigh scattering, Mie scattering, Raman scattering, and fluorescence. Based on different kinds of backscattering, a lidar sensor can be accordingly called Rayleigh lidar, Mie lidar, Raman lidar, and Na/Fe/K fluorescence lidar sensor.

1.1.6 Spectrometers and Radiometers

Spectrometers, sometimes also referred to as spectrographs, spectroscopes, or spectrophotometers, are instruments used to measure properties of light source over a specific portion of the electromagnetic spectrum, typically used in spectroscopic analysis to identify materials. They have been deployed as payloads in space missions for many years. Spectrometers are used in spectroscopy for producing spectral lines and measuring their wavelengths and intensities. The variable measured is most often the light's intensities of the objects at specific wavelengths but could also, for instance, be the polarization state. The independent variable is usually the wavelength of the light or a unit directly proportional to the photon energy, such as electrons or volts. Spectrometers operate over a very wide range of wavelengths, from gamma rays and X-rays into the FIR. If an instrument is designed to measure the spectrum in absolute units rather than relative units, then it is typically referred to as a spectrophotometer. The majority of spectrophotometers are used in spectral regions near the visible spectrum.

A radiometer is a device for measuring the radiant flux power or the intensity of radiant energy of electromagnetic radiation of objects typically in ultraviolet and IR. In order to measure radiation emitted from a specific spectrum or to incorporate the radiometer within a certain spectral response, an optical filter is normally used. Such optical filtering offers a simpler and more cost-effective solution. A radiometer measures either radiance or irradiance when the radiation emission source is in an ultraviolet region. A radiometer measures IR radiance to determine the temperature of objects, as all material emits IR radiation according to its thermal energies.

1.2 Imaging Spectroscopy Sensors

As a diagnostic monitoring technology, imaging spectroscopy sensors play a decisive role in obtaining accurate information for better understanding of the observing targets, their identification information, risks, and consequences of the changes. During the last few decades, this technology has become a cornerstone science for recording, quantifying, and modeling surface processes and analyzing coverage of our Earth and planets. The increasing availability of global high quality hyperspectral imaging in the near future will significantly contribute to improving knowledge of the complex processes and feedback mechanisms, interconnecting Earth's various spheres, like the atmosphere, biosphere, pedosphere, lithosphere, and hydrosphere.

This book dedicates 11 chapters to describing a variety of imaging spectroscopy sensors that flew, are flying, or are to be flown in orbits or in situ of Earth, Moon, and Mars (Chapters 2–12). These imaging spectrometers are briefly reviewed below.

1.2.1 Hyperspectral Imager for the Coastal Ocean

The Hyperspectral Imager for the Coastal Ocean (HICO®) is the first spaceborne imaging spectrometer designed to sample the coastal ocean with high spatial (approximately 100 m) and spectral (5.7 nm) sampling, continuous visible and near infrared (VNIR) spectral coverage (380–960 nm), and a very high signal-to-noise ratio (SNR) for low albedo water scenes (maximum SNR 470 : 1 at 480 nm, SNR > 200 : 1 in 400–600 nm). HICO was designed and developed by the Naval Research Laboratory (NRL), built on the legacy of the NRL's Ocean Portable Hyperspectral Imager for Low-Light Spectroscopy (Ocean PHILLS) airborne imagers. It was funded as an Innovative Naval Prototype by the Office of Naval Research. HICO has operated nearly continuously aboard the International Space Station since its launch in September 2009, collecting over 9000 images by mid-2014 and greatly exceeding the design lifetime. The data have enabled ocean color scientists and managers to assess data quality and apply the imagery to a variety of scientific and societal problems, including shallow water bathymetric mapping, detecting and identifying benthic features, monitoring water quality, and assessing impacts from extreme events. The modest development and construction cost of HICO combined with the high quality of the data suggests a path forward toward more capable systems for assessing the health of coastal ecosystems and responses to important stressors related to climate change and population growth, even in times of increasing fiscal constraint.

1.2.2 Moderate-Resolution Imaging Spectroradiometer

The Moderate-resolution Imaging Spectroradiometer (MODIS) is a scientific payload launched into Earth orbit by NASA in 1999 onboard the Terra satellite (Earth observing system morning equator crossing time), and in 2002 onboard the Aqua satellite (Earth observing system afternoon equator crossing time). The Terra mission emphasis would be on land processes and the Aqua mission would focus on the hydrological cycle and other related Earth-atmosphere parameters. The initial mission lifetime specification for these two satellites was five years each; however, there has been well over a decade of successful operation for both missions. The MODIS instruments acquire image data in 36 spectral bands ranging in wavelength from 0.4 μm to 14.4 μm and at varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m, and 29 bands at 1 km). Together the instruments image the entire Earth every 1–2 days. They are designed to provide measurements in large-scale global dynamics including changes in Earth's cloud cover, radiation budget, and processes occurring in the oceans, on land, and in the lower atmosphere.

Extensive pre-launch and on-orbit calibration and characterization efforts have been made to ensure both sensors meet a wide variety of radiometric, spectral, and spatial performance requirements. The on-orbit performance shows using onboard calibrators, lunar observations, and well-known vicarious Earth targets that the MODIS instruments have achieved or exceeded specifications of 5% in radiance and 2% in reflectance for the reflected solar bands, and 1% for most thermal emissive bands. In addition, both sensors' spectral and spatial performance has been very stable.

1.2.3 Medium Resolution Imaging Spectrometer

Medium Resolution Imaging Spectrometer (MERIS) is one of the main instruments on board the European Space Agency (ESA)'s ENVISAT platform launched on 1 March 2002, for observing the ocean color, both in the open ocean and in coastal zones, to study the oceanic component of the global carbon cycle and the productivity of these regions, amongst other applications. ENVISAT is the ESA's most complex Earth observation satellite ever placed into orbit. The mission has provided long-term continuous data sets that are crucial for addressing environmental and climatological issues. With 10 instruments onboard ENVISAT is particularly adapted to monitor environmentally crucial processes as diverse as changes in ocean circulation, the ice caps, land use, and atmospheric pollution.

MERIS is the first spaceborne wide-field imaging spectrometer operated in a push-broom mode. It is composed of five imaging spectrometers disposed side by side for covering a swath width of 1150 km. The spatial sampling varies in the across track direction, between 300 m at nadir and 390 m at swath extremities. The MERIS covers the global of the Earth in three days. By design each of the five imaging spectrometers could record 390 wavebands within the spectral range from 412.5 nm to 900 nm when the spectral interval is set to 1.25 nm. However, the MERIS is restricted by its downlink capability and transmits only 15 bands. These spectral bands are programmable in position, width, and gain. This allows a large set of applications, making the instrument concept also attractive for future Earth observation missions.

1.2.4 Visible and Near-Infrared Imaging Spectrometer

The Visible and Near-infrared Imaging Spectrometer (VNIS) is one of the main scientific payloads of China's lunar rover Yutu ("Jade Rabbit" in Chinese) of the Chang'E 3 mission. The objective of VNIS is to make in situ measurements of the composition and resources of the lunar surface via imaging and spectrometry in the VNIR wavelengths. VNIS consists of a VNIR imaging spectrometer (0.45–0.95 μm) and a SWIR spectrometer (0.9–2.4 μm). Acousto-optic tunable filters are used as the dispersive components of the two spectrometers. VNIS equips with an anti-dust accumulation and in-orbit calibration functions. It features a miniaturized design with low mass and high performance. The VNIS is mounted on the rover Yutu in the front, to detect the lunar surface objects with a 45° view angle and acquire spectral and geometric data. To meet the scientific objective of mineral detection, VNIS not only can collect images and spectral data from the lunar surface to distinguish the materials but also can identify geometric features of the observed target.

The VNIS has carried out several in-orbit calibrations and lunar surface measurements since it was first successfully operated on the Moon on 23 December 2013, which was the first in situ spectral imaging detection on the lunar surface. The high resolution and effective spectral imaging data obtained by VNIS has provided valuable hyperspectral data for lunar scientific applications.

1.2.5 IMS-1 Hyperspectral Imager

A compact hyperspectral imager (HySI) was designed and developed for the Indian Chandrayaan-1 mission. Considering the opportunity available, an instrument similar to the characteristics of Chandrayaan-1 HySI was first flown on Indian Mini Satellite-1 (IMS-1) in 2008. There are minor differences between the two versions of HySI, as the interfaces varied. The IMS-1 satellite was originally called the Third World Satellite (TWSAT). It carried a miniature multispectral camera (IMS1-MX) in addition to IMS1-HySI. The main goals of this project were to design, build, and operate a three-axis stabilized remote sensing satellite providing easy access of data to students and scientists of developing countries.

The HySI is an optical linear variable filter (wedge filter) based imaging spectrometer with 64 band of spectral sampling interval about 9 nm within spectral range of 400–950 nm, spatial resolution of about 500 m, and a swath of about 130 km. It consists of fore-optics, an area array detector with wedge filter near its focal plane, and highly miniaturized mechanical structure and the associated front-end electronics. IMS1-HySI was aimed at validating the design of the compact instrument and providing hands-on experience to the scientists on the usage of data acquired by a wedge filter based imaging spectrometer before they use Moon data from Chandrayaan-1. This experience was also used in designing a highly sensitive 512-band hyperspectral imager for measuring airglow spectrum onboard Youthsat.

1.2.6 Environmental Mapping and Analysis Program

Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral Earth observation satellite under the aegis of the Space Administration of the German Aerospace Center (DLR), with the launch scheduled for 2018. Its spectral measurements will be used to obtain a diagnostic characterization of the Earth's surface and to derive quantitative surface parameters on the status of terrestrial and aquatic ecosystems and the changes they undergo. EnMAP data will supply a basis for quantifying and modeling crucial ecosystem processes, thereby making a major contribution toward understanding the complexities of the Earth system.

EnMAP is a push-broom type imaging spectrometer with 30 km swath width at a ground sampling distance of 30 m, covering the full range of strong solar irradiation from 420 nm to 2450 nm with two spectrometers, one each for the VNIR and SWIR range. The spectrometer is a novel design that uses the imaging heritage of an Offner design and combines it with a curved prism disperser. It will be operated for five years on a Sun-synchronous orbit with a local time descending node (LTDN) at 11:00. At near nadir orientation (±5°) the repeat rate of EnMAP is 27 days. Using the across track platform pointing capability of ±30° enables frequent access to any global site within four days, allowing short-term evolutions of ecosystems to be studied with high precision. Data takes can be acquired with an accumulated length of 5000 km along track per day, with individual segments ranging from 30 km to 1000 km. Image data are downlinked via the Neustrelitz ground station using an X-band link at 320 MBit/s.

1.2.7 PRISMA

The PRecursore IperSpettrale della Missione Applicativa (PRISMA) is an Italian Space Agency (Agenzia Spaziale Italiana) pre-operational and technology demonstrator hyperspectral mission for Earth observation based on a mono-payload single satellite. It is currently under development by an Italian consortium and scheduled for launch in 2017. Selex ES in Campi Bisenzio is in charge of the design and building of the payload.

The PRISMA payload consists of a reflective common telescope in three-mirror anastigmat (TMA) configuration, a single slit aperture, a panchromatic (PAN) camera (700–900 nm), and an imaging spectrometer with two channels covering VNIR and SWIR regions, each channel using a suitable prism configuration and spectrally separated by a beam splitter. The hyperspectral images will have 30 m ground sampling distance (GSD), 30 km swath width, and spectral bands at an interval better than 12 nm. The PAN images will have higher spatial resolution (5 m), co-registered to the hyperspectral ones, so as to allow images fusion techniques. To provide the required data quality for the entire mission lifetime (five years), an accurate and stable calibration unit (radiometric and spectral) is integrated for the in-flight instrument calibration.

1.2.8 Hyperspectral Imager Suite

Hyperspectral Imager Suite (HISUI) consists of a hyperspectral imager and a multispectral imager. It is a spaceborne Earth imaging system under development by the Japanese Ministry of Economy, Trade, and Industry (METI). The current target launch year is 2018 or later. The primary objectives of the mission are to promote (1) global energy and resource related applications including observations for environmental assessments that are indispensable to resource developments; (2) other applications such as environmental monitoring, agriculture, and forestry; and (3) domestic space and space utilization industries through wider applications of HISUI data.

The hyperspectral imager will produce 185 narrow bands in the 0.4–2.5 μm spectral region with 30 m spatial resolution and 30 km swath, while the multispectral imager will produce four broad bands in the 0.4–1.0 μm spectral region with 5 m spatial resolution and 90 km swath. The designed SNR is 450:1 and 300:1 for hyperspectral VNIR and SWIR channels, respectively. To satisfy the high SNR requirements, the diameter of the telescope of the hyperspectral imager is designed to around 30 cm for the GSD of 30 m and the F-number of 2.2. One of main characteristics of the hyperspectral imager is its onboard data processing functionality for radiometric correction, binning, spectral correction, and lossless data compression.

1.2.9 Ocean and Land Color Imaging Spectrometer

The Ocean and Land Color Imager (OLCI) is a VNIR push-broom imaging spectrometer. It is one of the main payloads selected for ESA's Sentinel-3 mission as a part of the Copernicus program formerly referred to as Global Monitoring for Environment and Security (GMES). The Sentinel-3 mission plans to launch various satellites starting with satellite A in 2015, and subsequent satellites B–D for a 20-year observation to provide continuity to ENVISAT capability to meet the European users' needs. Sentinel-3 carries a companion optical payload: a dual-view Sea and Land Surface Temperature Radiometer (SLSTR) for delivering accurate surface observation of ocean, land, and ice temperature. Sentinel-3 also has an altimetry topography instrument package including four payloads: a dual-frequency Synthetic Aperture Radar Altimeter (SRAL) supported by a dual-frequency passive Microwave Radiometer (MWR) for wet-tropospheric correction, a Laser Retro-Reflector (LRR), and a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) instrument.

The primary goal of the OLCI onboard the Sentinel-3 satellites is to provide global and regional measurements of ocean and land surface at high accuracy useful for environment climate and meteorology. The OLCI instrument is based on the opto-mechanical and imaging spectrometer design of its predecessor MERIS onboard ENVISAT. Its design is improved compared to MERIS, resulting in a 300 m spatial resolution across its 1270 km swath over land and ocean, 21 spectral bands instead of 15, daily revisit time (with two satellites constellation), and improved SNR. The FOV of OLCI is arranged in a way to avoid Sun-glint contamination of ocean scene and to allow full overlap with the SLSTR.

1.2.10 Spaceborne Hyperspectral Applicative Land and Ocean Mission

Spaceborne Hyperspectral Applicative Land and Ocean Mission (SHALOM) is co-funded and managed by the Israeli Space Agency (ISA) and the Italian Space Agency (ASI) to launch a next-generation hyperspectral imaging satellite in orbit. The mission aims at pushing the hyperspectral imaging from the space sector further into a commercial sector by providing higher spatial resolution, larger area coverage, short revisit times, precise geo-location, and distribution of value-added products to end users. The uniqueness of SHALOM will be to provide high quality hyperspectral data and deliver high-level data products to end users according to their demand. This mission is still in early phase. Chapter 11 summarizes the Phase A study and provides some important statements about the foreseen commercial operation of hyperspectral technology on orbit.

The Space segment will use the heritage of ASI's agile spacecraft bus OPTSAT-3000. The payload will use Israel's heritage from the Jupiter program and Italian Selex-ES heritage in the PRISMA mission. The SHALOM sensor will have 10 m spatial resolution for hyperspectral images with a 2.5 m panchromatic sharp channel, 240 spectral bands across the visible, NIR, and SWIR spectral regions with 10 nm spectral resolution, and revisit time of less than four days.

1.2.11 Hyperspectral and Luminescence Observer for Mars

The Canadian Space Agency (CSA) has funded the Canadian industry and science community to carry out studies on Mars exploration under its Exploration Core Program. One of the projects was Hyperspectral and Luminescence Observer (HALO) in the context of the Mars Sample Return Network (MSR-NET) for possible inclusion in the ESA-NASA-led MSR-NET mission. This study examined the utility of an agile and intelligent orbital hyperspectral imager for addressing fundamental questions about Mars with an in situ luminescence instrument on a rover for providing ground truth to support the imager classification of spectral characteristics.

The focus of the HALO study is to design, build, and integrate a prototype imaging spectrometer and luminescence spectrometer with high optical throughput and low distortion. The HALO hyperspectral imager has been developed based on heritage from the Canadian Hyperspectral Environment and Resource Observer (HERO) mission and builds on the significant expertise developed in Canada for luminescence and optical spectroscopic studies of geological materials. Chapter 12 describes an early phase study that examined the combination of an orbital hyperspectral imager and rover-borne optically stimulated luminescence instrument for a Mars sample return network. Coupling orbital and surface observations of Mars provides a powerful means for "calibrating" orbital observations with actual ground conditions and a number of complementary and synergistic elements. This enables more comprehensive characterization of the Martian surface to be conducted than by one instrument operating alone.

1.3 Multispectral Sensors

Multispectral images are the main type of images in Earth observation and remote sensing applications. The Landsat satellites and SPOT (Système Pour l'Observation de la Terre) satellites are the two main multispectral satellite series. The Landsat series of satellites provides the longest continuous record of multispectral images of the Earth. As such, Landsat is an invaluable resource for monitoring global change and is a primary source of medium spatial resolution Earth observations used in decision-making. Multispectral sensors aboard SPOT satellites have contributed to improve the knowledge and management of the Earth by exploring the Earth's resources, detecting and forecasting phenomena involving climatology and oceanography, and monitoring human activities and natural phenomena. These pioneer multispectral sensors have been reported extensively in literature and described in earlier published books. This book discusses five more recent multispectral sensors aboard different satellites (Chapters 13–17).

1.3.1 Infrared Scanner onboard Chinese Environmental and Disaster Monitoring Satellites

The Infrared Scanner (IRS) is a multispectral imager. It is one of the main payloads onboard the constellation satellite B of the Chinese Small Satellite Constellation for Environment and Disaster Monitoring and Forecasting mission. The satellite B is the second satellite of the constellation launched in September 2008 in a Sun-synchronous orbit. The main objective of the mission is the monitoring, prediction, and evaluation of natural disasters and environment pollution. The IRS has four multispectral bands including NIR, SWIR, MWIR, and LWIR with a ground swath of 720 km and spatial resolution of 150 m for NIR, SWIR, and MWIR bands and 300 m for LWIR band. The IRS has shown successful applications in monitoring and evaluation natural disasters such as fires, droughts, snowstorms, floods, plant diseases, insect invasions, water pollution, sandstorms, and so forth.

1.3.2 MUX Multispectral Camera for the CBERS 3&4 Satellites

The China-Brazil Earth Resources Satellites (CBERS) 3&4 is the second generation of the CBERS 1&2. There are four sensors onboard the CBERS 3&4 satellite series for the observation of forest areas, agricultural fields, water-continent borders, use of land, urban sprawling, and cartographic analysis: (1) Wide Field Imager camera (WFICAM), (2) Multispectral Camera (MUXCAM), (3) Infrared Medium Resolution Scanner (IRSCAM), and (4) PanMux Camera (PANMUX). The MUX is a new design based on an upgraded specification of the CCD camera onboard CBERS 1, 2, and 2B. Like its predecessor, MUXCAM has four multispectral bands: 0.45–0.52 μm, 0.5–0.59 μm, 0.63–0.69 μm, and 0.77–0.89 μm. Its GSD is 20 m with a swath of 120 km and revisit time of 26 days. The MUXCAM is equipped with focus optical adjustment and in-orbit calibration capabilities. The MUXCAM imager is the first high technology satellite payload completely developed and assembled in Brazil; therefore it constitutes remarkable progress in Brazilian capability and skills in optical payloads for spaceborne remote sensing applications.

1.3.3 Multispectral Camera onboard IMS-1

Multispectral camera (MX) onboard IMS-1 was designed and developed to provide access to data to students and scientists of third world countries, thus it was also called Third World Satellite (TWSAT). MX is a push-broom camera with four multispectral bands selected to cater to natural resources and disaster related monitoring. Each band has separate optics, linear detector array and the associated front-end electronics. It has a spatial resolution of 36 m and a swath of 151 km. The main design goal of the MX multispectral camera was to achieve the required performance with minimum resources of mass, power, data rate, and size. This was achieved by maximally using indigenous components and commercial off-the-shelf (COTS) components. The performance and functional goals were achieved within two years. Chapter 15 describes the MX instrument and subsystems, developmental highlights, and test results. It also gives a brief account of data products and post-launch performance of the MX.

1.3.4 Wide Field Imager for the CBERS 3&4 Satellite Series

The Wide Field Imager (WFI) camera is one of the four sensors installed in the payload module of the CBERS 3&4 satellite. It has the widest swath of 866 km and the shortest revisit time of five days of the four sensors in the payload module aboard the CBERS 3&4 satellites. It is designed for imaging large territorial extensions and observing phenomena in macro-regional or state scale thanks to its large swath width. WFI camera has the same four multispectral bandwidths as the MUX camera covering a spectral range 450–890 nm from blue to NIR. The GSD of the WFI is 64 m, which is larger than that of the MUX camera.

1.3.5 Optical Payload aboard FORMOSAT-2

The FORMOSAT-2 (also known as ROCSAT-2) is a Taiwanese satellite. It carries two optical payloads: (1) a remote sensing instrument (RSI) for supporting aftermath relief, and (2) a scientific instrument called imager of sprites and upper atmospheric lightning (ISUAL) for observing transient luminous events. The RSI contains a panchromatic imager with 2 m GSD and a four broadband multispectral imager with 8 m GSD covering a swath of width of 24 km. The spacecraft bus and the RSI were built by Astrium in France in cooperation with the National Space Organization (NSPO) of Taiwan, and the ISUAL was built by the University of California at Berkeley (UCB) in cooperation with Nation Cheng Kung University (NCKU) in Taiwan. With a higher orbital altitude of 888 km and a larger field of regard of 45°, FORMOSAT-2 can take images in the world with daily repeat to monitor urgent disaster events to support relief and management efforts. FORMOSAT-2 has been the first, in many cases, to take images through continuously monitoring over the world after many large events.

1.4 Fourier Transform Spectrometers

Earth's upper atmosphere contains atomic and molecular species in metastable states, resulting from chemical reactions driven by photons and energetic particles from the Sun and the magnetosphere interacting with the atmospheric species. These states emit narrow spectral lines in the form of airglow and aurora, allowing species concentrations to be measured from their emission rates, temperatures from their linewidths, and winds from their Doppler shifts. Fourier transform spectrometers on space platforms can acquire these narrow spectral lines globally and thus help human beings better understand Earth's atmospheres, their composition, thermal structure, and dynamics. Atmospheric sounding has been one of the main motivations of the meteorological satellite program.

The earliest spaceborne FTS instrument is the Infrared Radiation Interferometer Spectrometer (IRIS), a Michelson interferometer sounder launched in the 1960s by NASA. It measured the spectrum of IR radiation emitted to space by the Earth and atmosphere with 5 cm^{-1} spectral resolution within the 5–25 μm wavelength regions. However, the impact of the early atmosphere sounders suffered from their lack of vertical resolution. The so-called second-generation sounders based on ultra-spectral resolution (0.5 cm^{-1}) concept could provide 1–2 km vertical resolution from polar and geostationary satellites. They can measure a large portion of the IR spectrum of Earth-atmospheric radiance to space in order to obtain a very large number of spectral channels of atmospheric radiance, each having a different altitude sensitivity, for inferring atmospheric profiles of temperature, water vapor, and trace gases. The high spectral resolution and large number of spectral channels both serve to optimize the vertical resolving power of the measurements.

This book includes five spaceborne second-generation Fourier transform spectrometers for atmospheric missions (Chapters 18–22).

1.4.1 Wind Imaging Interferometer on Upper Atmosphere Research Satellite

The WIND Imaging Interferometer (WINDII) is a FTS instrument onboard NASA's Upper Atmosphere Research Satellite (UARS) launched on 12 September 1991. It was a Canadian contribution to the mission funded by the CSA. The planned mission life was 18 months with an optional extension to 30 months. The WINDII instrument operated perfectly until 2003 when it was turned off, while the spacecraft continued to operate until 2005. WINDII observed temperature and winds in the atmosphere and the lower thermosphere by measuring Doppler widths and shifts of isolated spectral lines by airglow and aurora. It viewed the atmospheric limb through a field-widened Michelson interferometer in two directions, 45° and 135° from the velocity vector. It simultaneously measured temperature and wind profiles over altitude range 70–310 km with a vertical resolution of 2 km and horizontal resolution of 20–100 km.

Chapter 18 describes the instrument design, fabrication, characterization, operations, and in-flight calibration as well as scientific results.

1.4.2 Atmospheric Chemistry Experiment – Fourier Transform Spectrometer on Canadian Science Satellite SCISAT

The Atmospheric Chemistry Experiment – Fourier Transform Spectrometer (ACE-FTS) is the primary instrument onboard the Canadian science satellite SCISAT launched on 12 August 2003. It is composed of an IR Fourier transform spectrometer operating over a broad spectral range from 2.2 to 13.3 μm (750–4400 cm^{-1}) with a high spectral resolution of 0.02 cm^{-1} as well as two imaging channels. The ACE-FTS is an adapted version of the classical Michelson interferometer using a folded and double pass optical layout that permits high spectral resolution with a compact size. ABB Inc. in Quebec City, Canada (formerly Bomem Inc.) was the prime contractor for the design and manufacture of the ACE-FTS instrument.

The primary scientific goal of ACE is to measure the chemical and dynamical processes that affect the distribution of ozone in the upper troposphere and stratosphere with particular emphasis on ozone in the Arctic region. The principle of ACE is the solar occultation technique, which permits measuring the solar radiance outside and through the atmosphere at satellite sunrises and sunsets for altitudes varying between 5 and 150 km above the tangent horizon of the Earth. A high inclination (74°) and low Earth orbit (650 km) are required in order to provide the FTS coverage of tropical, mid-latitude, and polar regions. As the solar radiation passes through the atmosphere it is partially attenuated by the chemical components present in the atmosphere. The spectra measured in the limb viewing geometry with different slant paths and tangent heights are inverted to obtain vertical profiles of temperature, pressure, and volume mixing ratios for dozens of trace gases with a vertical resolution of 3–4 km from the cloud tops up to about 120 km. The ACE-FTS was designed for a two-year mission. After 11 years in orbit, it is still functioning well and continues to provide data to the scientific society. It is a success story of a Canadian science mission.

1.4.3 Cross-Track Infrared Sounder on NOAA/NASA Joint Polar Satellite

The Cross-track Infrared Sounder (CrIS) is one of the mission-critical sensors onboard the Suomi National Polar-orbiting Partnership satellite launched into low Earth orbit on 28 October 2011. CrIS collects upwelling atmospheric radiance at 2205 IR channels covering wavelength ranges LWIR (9.14–15.38 μm), MWIR (5.71– 8.26 μm), and SWIR (3.92–4.64 μm) with excellent radiometric precision. A companion microwave sounder on the same platform, called the Advanced Technology Microwave Sounder (ATMS), provides a "first guess" as a starting point for the CrIS retrievals. Collectively, the CrIS and ATMS are referred to as the Cross-track Infrared and Microwave

Sounding Suite. The data acquired by the two sounders are merged to construct vertical profiles of atmospheric temperature, moisture, and pressure on a global basis. CrIS data is a critical input to worldwide three- to five-day weather forecasts and is substantially improving the accuracy of these forecasts.

CrIS utilizes plane mirror interferometer technology. It performs a pattern of step-stare Earth-scene views consisting of 30 stares at Earth locations, which creates a wide swath of 2200 km across the Earth, one stare at deep space (the cold calibration point), and one stare at the Internal Calibration Target location (the warm calibration point). At each stare location, CrIS observes with a FOV of 3 × 3 grid, each of which has a 14 km spatial resolution at nadir.

1.4.4 Fourier Transform Spectrometer Onboard Japanese Greenhouse Gases Observing Satellite

The Greenhouse Gases Observing Satellite (GOSAT) is a Japanese mission to monitor carbon dioxide (CO_2) and methane (CH_4) from space. It was launched into a Sun-synchronous orbit on 23 January 2009. Its mission objective is to collect the measurements needed to quantify the column-averaged dry air mole fraction of CO_2 with a relative accuracy at three-month intervals of 1% (4 ppmv, with a goal of 1 ppmv) on subcontinental spatial scales of the Kyoto Protocol. GOSAT carries two optical payloads: the Thermal And Near infrared Sensor for carbon Observation Fourier Transform Spectrometer (TANSO-FTS) and the Cloud and Aerosol Imager (TANSO-CAI). TANSO-CAI is an ultraviolet, visible, NIR, and SWIR radiometer and will be briefly reviewed in Section 1.6.6.

TANSO-FTS has four spectral bands with 0.2 cm^{-1} spectral interval to measure the SWIR radiance reflected from the Earth's surface and thermal infrared (TIR) radiated by the ground and the atmosphere. SWIR bands (Bands 1, 2, and 3) covering the wavelength ranges of 0.758–0.775, 1.56–1.72, 1.92–2.08 μm, respectively, record spectra of the sunlight reflected from the Earth's surface on the dayside with two linear polarized lights. The TIR band (Band 4) covers the 5.56–14.3 μm wavelength range and records IR radiation from the atmosphere and the Earth's surface in the dayside and the nightside. The spectral resolution, defined as the full width at half maximum (FWHM) of instrument line shape (ILS), is < 0.6 cm^{-1} in Band 1 and < 0.27 cm^{-1} in Bands 2, 3, and 4. The TANSO-FTS measures reflected radiances in the 0.76 μm oxygen band and in the weak and strong CO_2 bands at 1.6 μm and 2.0 μm, respectively.

1.4.5 Geostationary Imaging Fourier Transform Spectrometer

The Geostationary Imaging Fourier Transform Spectrometer (GIFTS) was selected from a competitive proposal process in 1999 for the NASA New Millennium Program (NMP) Earth Observing-3 (EO-3) mission to produce and validate in space the technology and measurement concept needed to revolutionize severe storm and extended range weather prediction. Due to the cancellation of the NMP EO-3 mission, NASA completed the GIFTS instrument as an Engineering Development Unit (EDU) to mitigate imaging spectrometer risk on future research and operational satellites in geostationary orbit in 2005.

The GIFTS is intended for geosynchronous orbit while AIRS, IASI, and CrIS were designed for polar orbit. A geostationary orbiting satellite is suitable for observing atmospheric dynamics (e.g., water vapor flux and winds), while a polar orbiting satellite provides global coverage. The spectral characteristics of GIFTS are similar to the polar orbiting ultra-spectral sounders. The main difference between the GIFTS and the polar orbiting ultra-spectral sounders is the footprint size and spatial sampling density. The GIFTS is an imaging FTS sensor, which has two IR 128 × 128 pixel detector arrays to provide instantaneous large area coverage with high horizontal resolution. This imaging FTS enables atmospheric radiance spectra to be observed simultaneously for all spatial spots in the scene, thereby providing high vertical resolution temperature and moisture sounding information. Each spatial spot corresponds to an instantaneous FOV of 4 km × 4 km, giving the GIFTS instrument a square 512 km FOV at nadir. Since each detector pixel images a different spot on the Earth, the instrument collects 16 384 separate interferograms (actually 32 768 when both detectors are considered) in that period. With its rapid repeat capability, the GIFTS can provide a 4D image of the atmosphere, the fourth dimension, time, being provided by the geosynchronous satellite platform, which enables near continuous imaging of the atmosphere's 3D structure.

1.5 Lidar and Active Sensors

Lidar and active optical sensors are increasingly being utilized for range finding and orbital element calculation of relative velocity in proximity operations and station keeping of spacecraft. Using short pulses of laser light beamed from a spacecraft, lidar can accurately determine the location, distribution, and nature of the particles. Lidar is a new tool for studying constituents in the atmosphere, from cloud droplets to industrial pollutants that are difficult to detect by other means. Since the first spaceborne lidar sensor Lidar In-space Technology Experiment (LITE) flew on space shuttle Discovery in September 1994, a number of lidar sensors have flown in space. Following are some examples. Shuttle Laser Altimeter (SLA) was designed to evaluate engineering and algorithm techniques for obtaining high resolution, orbital laser altimeter observations of terrestrial surfaces. The SLA-I was the first flight of the sensor aboard the space shuttle Endeavour on the STS-72 mission in January 1996. The SLA-II was the second flight of the sensor onboard the space shuttle Discovery in August 1997 during the STS-85 mission. The Mars Orbiter Laser Altimeter (MOLA) on board the Mars Global Surveyor (MGS) spacecraft flew in Mars orbit from September 1997 to November 2006. Geoscience Laser Altimeter System (GLAS), the sole payload on board the Ice, Cloud, and land Elevation Satellite (ICESat) launched in January 2003, flew the Earth in a lower near-circular and near-polar orbit to quantify ice sheet mass balance and understand how changes in the Earth's atmosphere and climate affect polar ice masses and global sea level. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) flew onboard the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) launched in April 2006 with a two-wavelength polarization-sensitive lidar to measure high-resolution vertical profiles of aerosols and clouds. The Lunar Orbiter Laser Altimeter (LOLA) flew on Lunar Reconnaissance Orbiter (LRO) launched in June 2009 to provide a precise global lunar topographic map for assisting in the selection of landing sites on the Moon for future robotic and human exploration missions, and attempts to detect the presence of water ice on or near the surface. The Mercury Laser Altimeter (MLA), derived from the MOLA but at about 1/5 the size and weight and two to four times the ranging capability, flew Mercury orbit in March 2011 to measure the topography or surface relief of the northern hemisphere of Mercury and create topographic maps.

This book discusses five lidar or active optical sensors flying or to be flown in Mars, lunar, and Earth orbits (Chapters 23–27).

1.5.1 Canadian Mars Phoenix Lidar

The Phoenix mission landed in the north polar region of Mars on 25 May 2008, and operated for five months until there was insufficient solar energy to continue. The meteorological station built by the CSA recorded the daily weather of the Martian northern plains using temperature and pressure sensors as well as a lidar to advance our knowledge of the climate on Mars by combining lidar remote sensing of atmospheric dust and clouds with measurements of solar radiation and in situ sampling of temperature, pressure, wind, and water vapor. The lidar signal was used to derive the optical extinction coefficient that is a measure of the absorption and/or scattering of atmospheric constituents. Understanding this extinction is critical for understanding the weather and climate, as it is a measure of where the Sun's energy is deposited. In particular, the absorption and scattering of solar radiation by dust has a first-order effect on heating of the atmosphere and surface. The derived optical extinction coefficient can also be related to the amount of scattering material.

The Phoenix lidar used both 532 nm and 1064 nm laser transmitters to measure the height profile of backscattered laser light from airborne dust and clouds at heights of up to 20 km. The most significant result from the Phoenix lidar observations was the observation that water ice crystals grow large enough to precipitate significant distances through the atmosphere of Mars.

1.5.2 Laser Altimeter onboard Chinese Chang'E 1 Orbiter

Chang'E 1 laser altimeter is one of the main scientific instruments aboard the Chang'E 1 orbiter, the first Chinese spacecraft to the Moon launched in 2007. The primary objective of the laser altimeter is to produce an accurate global topographic model of the Moon. By acquiring the flight time of its laser pulses, the laser altimeter can measure the distance between the orbiter and the lunar surface. The topographic height of the lunar surface at the laser footprint is then determined through the geometry of the Moon radius, the spacecraft orbit altitude, and the pointing angle of the instrument. The laser altimeter has one beam and operates at 1 Hz, with a nominal accuracy of 5 m. It operated successfully on lunar orbit and acquired over 9 million data points about the lunar altitude.

1.5.3 Canadian ASTRO-H Metrology System

The Canadian Astro-H Metrology System (CAMS) is the Canadian contribution to an international astrophysical X-ray observatory mission called Astro-H X-ray led by the Japan Aerospace Exploration Agency (JAXA) for addressing high-energy astrophysics that encompasses a broad range of astrophysical science missions. The Astro-H observatory will provide the scientific community with tremendous improvement in high energy spectral resolution and broad energy band pass and with imaging capabilities at E> 10 keV. The Astro-H mission includes five scientific instruments: two hard X-ray imagers, a soft X-ray spectrometer, a soft X-ray imager, and a soft gamma-ray detector.

The CAMS is a laser metrology system. It is designed to measure lateral displacement of the detectors of hard X-ray imagers relative to their telescope axes caused by spacecraft maneuvers and thermal changes in the 14 m spaceborne deployable optical bench. The CAMS measurements can be used to reconstruct images of stellar objects of interest for high-energy astrophysics, such as black holes, supernova remnants, galaxies, and clusters of galaxies. The CAMS system is composed of an active part containing the laser and an imaging sensor and a passive part containing a retroreflector. The active part is installed near the X-ray telescope and the passive is located 12 m away on the extendable optical bench near the hard X-ray imager. The principle of CAMS measurement is based on determination of centroid location of the retroreflected laser beam. The key driving requirement of the design is the stability in the accuracy of the CAMS measurement. The CAMS development and qualification activities demonstrate the feasibility of a microradian-level metrology instrument in a compact package. The principle and the technology developed for CAMS will find its way into various future applications and space missions.

1.5.4 Atmospheric Lidar onboard EarthCARE Satellite

The Earth Cloud Aerosol and Radiation Explorer (EarthCARE) is a joint venture mission between ESA and JAXA to address the interaction and impact of clouds and aerosols on the Earth’s radiative budget. It carries a suite of four complementary instruments to make simultaneous observations of the same cloud/aerosol scene. ESA is in charge of the development of three optical instruments, the ATmospheric LIDar (ATLID), Multi-Spectral Imager (MSI), and Broad-Band Radiometer (BBR). The Japanese team is in charge of the development of Cloud Profiling Radar (CPR). The EarthCARE satellite is aimed at being launched in 2018 by ESA.

ATLID is an atmospheric backscatter lidar. It will determine vertical profiles of cloud and aerosol physical parameters, including altitude, optical depth, backscatter ratio, and depolarization ratio, in synergy with the other three instruments. Operating in the ultraviolet range at 355 nm, ATLID provides atmospheric echoes with a vertical resolution up to 100 m from ground to an altitude of 40 km. Thanks to a high spectral resolution filtering, it is able to separate the relative contribution of aerosol and molecular scattering, which gives access to aerosol optical depth. Co-polarized and cross-polarized components of the Mie scattering contribution are also separated and measured on dedicated channels. The combination of a powerful laser transmitter delivering short pulses at 51 Hz and low noise detection chains based on memory CCD provide capability to measure even faint backscatter from subvisible cirrus. ATLID radiometric stability is ensured by a continuous active realignment system maintaining the accurate co-alignment of emission and reception paths, and by a highly stable injection of the single-mode laser transmitter.

1.5.5 Small Optical Transponder for Small Satellite Data Transmission

The use of miniaturized satellites (typically 50 kg; satellites with this level of mass are often referred to as micro-satellites) is an interesting idea in space activities. Their relatively short-term development is helpful to adopt recent technologies such as high-resolution imaging and wideband measurements. However, due to the limitation of resources, such as the volume, mass, and electric power, their data transmission rate could be constrained. Recently laser communication technologies show potential of large capacity optical data transmission with lower volume and mass compared to those in radio frequency communications.

The development of an optical communication terminal named the Small Optical TrAnsponder (SOTA) is reported on in this book. It is designed to exceed the data transmission rate of 1 Mbps and be able to be installed in a microsatellite of about 50 kg mass in a low Earth orbit. Research and development activities are carried out to measure the atmospheric influence on propagating light and to evaluate the acquisition, tracking, and pointing performances of the optical terminal. The SOTA has been built and demonstrated. During the demonstration, the data rates of 1 Mbps and 10 Mbps have been achieved. The SOTA has been used in a Japanese microsatellite and will be installed in the Space Optical Communications Research Advanced Technology Satellite (SOCRATES).

1.6 Spectrometers and Radiometers

Spaceborne spectrometers and radiometers are being used in Earth observation, solar study, and planetary exploration missions. In Earth observation these instruments measure atmospheric trace gases associated with greenhouse gases, such as CO_2 and CH_4 and various trace-gas pollutants, as well as the underlying ground coverage using their characteristic spectral signatures. Solar study missions address three essential objectives: solar, climate, and atmospheric physics. The Earth's atmosphere properties, including temperature, composition, and dynamics, result from the Sun's input as a function of wavelength. It is essential to understand how the solar activities affect our Earth. These instruments in planetary science missions are designed to investigate surface characteristics of a region of Mars or the Moon that has never been explored in orbit observation or in situ to address fundamental geologic and planetary resources issues.

This book has six chapters on spaceborne spectrometers or radiometers flown, in flight, or to be flown in Earth observation, solar study, and planetary exploration missions (Chapters 28–33).

1.6.1 UV-Visible-NIR Spectrophotometer on Canadian Science Satellite SCISAT

The SCISAT is Canada's first scientific satellite for examining the composition of the Earth's atmosphere from space, with special emphasis on the middle atmosphere ozone distribution and related trace gases in the Arctic. The Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO) instrument is the second payload accompanying the FTS instrument described in Chapter 19. Both the FTS and MAESTRO make measurements in the solar occultation mode and share a common Sun tracker and optical boresight. Therefore, they examine almost the same slant column of air, albeit with different FOVs.

The MAESTRO is a dual, diode-array spectrometer measuring in the ultraviolet-visible-near-infrared (UV-VIS-NIR) spectral regions with a nominal wavelength range between 285 and 1015 nm (400 and 1010 nm for its primary measurement mode of solar occultation). The VIS imager array operates at 527.1 nm with a FWHM filter bandwidth of 13.3 nm, and the NIR imager operates at 1020.6 nm with a bandwidth of 19.4 nm. The primary scientific goal of MAESTRO is the determination of the altitude dependence of wavelength-dependent extinction from atmospheric aerosol. The extinction due to aerosol is measured by accounting for gas absorption using a spectral fitting algorithm and determining the residual extinction due to aerosol.

1.6.2 MOPITT aboard Terra Satellite

The Measurements Of Pollution In The Troposphere (MOPITT) instrument was designed to measure carbon monoxide from space. It is a Canadian instrument funded by the CSA as one of five instruments on NASA's Earth Observing System flagship mission – the Terra spacecraft launched on 18 December 1999. MOPITT is a nadir sounding (vertically downward pointing) instrument that measures upwelling IR radiation at 4.7 μm and 2.2–2.4 μm. It was a novel design that utilized gas correlation spectroscopy, which is a technique of gas detection by which the spectral features of the gas of interest are compared to the same features in a gas sample cell in the instrument. By modulating the gas amount in the cell by changing its length or pressure, the specific emission of the gas of interest can be identified and the gaseous composition quantified. The major advantages of the correlation technique are the high spectral resolution and the higher SNR. The MOPITT instrument contains eight optical channels, with each channel comprised of a calibration source, lenses, mirrors, mechanisms, and a detector. The mechanisms include a scan mirror assembly, a full beam chopper, and a gas modulator, either a length modulated cell or a pressure modulated cell depending on the cell gas pressure.

In 3–4 days the MOPITT instrument can produce a complete map of the cloud-free areas of the Earth with a resolution of about ¼° × ¼° (22 km × 22 km pixel at nadir). It has taken nearly four billion measurements of CO over the whole Earth and is able to distinguish some features of the vertical variations as well as the total column amount over any one point. The design life of the instrument was five years on orbit. As of December 2014, the MOPITT instrument has been operating for 15 years.

1.6.3 SOLSPEC Spectrometers and SolACES Spectrometer onboard International Space Station

Three optical instruments for measuring the solar total spectral irradiance from 16 nm to 2900 nm were selected under an ESA-funded mission for study of solar, atmospheric, and climate physics. These three instruments are referred to as the SOLAR payload, which is placed as an external platform for the COLUMBUS laboratory launched on 7 February 2008, onboard the International Space Station. The first instrument, called Solar Auto-Calibrating Extreme Ultraviolet and Ultraviolet Spectrometers (SolACES), covers the wavelength range from 16 nm to 150 nm. The second instrument, called Solar Spectral irradiance measurements (SOLSPEC) covers the wavelength range from 170 nm to 2900 nm. The third instrument, called Solar Variability Irradiance Monitor (SOVIM), is made up of two absolute radiometers and filter-radiometers. The primary objective of this mission is the measurement of the solar total spectral irradiance and its variability using these three instruments.

Chapter 30 describes both the SolACES and SOLSPEC instruments and their performance, as well as their most recent results and future plans. The SolACES is a new design of extreme ultraviolet spectrometer for overcoming the problem of aging in space by repeated recalibration of the instruments. It consists of four grazing incidence planar grating spectrometers plus two three-current ionization chambers with 42 narrowband filters to determine the absolute fluxes. The SOLSPEC instrument consists of three spectrometers, one each dedicated to the measurement of the ultraviolet, visible, and IR solar irradiance. Each spectrometer is made up of a double monochromator using holographic gratings. The SOLSPEC also includes a set of lamps to monitor the instrument aging, the wavelength scale, and spectrometer slit function.

1.6.4 Optical Spectrograph and Infrared Imager for Measurements of Atmospheric Composition and Emissions aboard Odin Satellite

The Optical Spectrograph and InfraRed Imager System (OSIRIS) is a Canadian payload onboard the Odin satellite launched in February 2001. Odin is a joint Swedish, Canadian, Finnish, and French mission originally designed to make both astronomy and atmospheric measurements using OSIRIS and the Swedish-led Sub-millimetre and Millimetre Radiometer (SMR). OSIRIS was designed to measure both atmospheric emissions and spectrally dispersed limb scattered sunlight to detect aerosol layers and abundances of species such as O_3, NO_2, OClO, and BrO. This instrument was designed and built by Routes Astro Engineering Ltd. in Ottawa with funding from the CSA and was still in operation in late 2014 when Chapter 31 was written. It makes world-class radiance measurements from which climate quality data records are derived. These data have proved extremely valuable for the study of ozone and the chemistry associated with its depletion due to chlorofluorocarbons and its subsequent increases, as a result of the Montreal Protocol.

OSIRIS is a UV-VIS-IR limb sounder. It consists of two instrument modules: (1) a UV-VIS spectrograph, and (2) an IR imager, both of them in a common optical housing and supported by common electronics. The UV-VIS spectrograph uses compact reflective optics and an aspherical ruled grating along with UV-enhanced CCD arrays.

The IR imager has three IR telescopes co-aligned single-lens imagers operating at 1263, 1273, and 1530 nm. A CCD detector of size 1353 × 286 array is operated in a frame transfer multi-pin-phase mode with only 32 rows of the imaging section of the array illuminated by the slit image.

1.6.5 Sea and Land Surface Temperature Radiometer on Sentinel-3

The Sea and Land Surface Temperature Radiometer is one of the main instruments selected for the Sentinel-3 mission. SLSTR is a high accuracy radiometer to provide sea-surface temperature data continuity with respect to the previous Advanced Along-Track Scanning Radiometer (AATSR) onboard ENVISAT and Along-Track Scanning Radiometer (ATSR) onboard ERS for climatology and new data for meteorology.

SLSTR has an improved design compared to AATSR and ATSR with a large near nadir and oblique view swaths (1400 and 740 km) for sea and land surface temperature global coverage at 1 km spatial resolution with a daily revisit time (with two satellites), appropriate for climate and meteorology. Additional to the classical IR channels, the visible and SWIR channels have a higher spatial resolution (500 m). Further, there are two additional channels included to monitor high temperature events, such as forest fires. The two swaths are obtained with two conical scans and telescopes combined optically at a common focus, representing the input of a cooled focal plane assembly, where 11 channels are separated with dichroic and focalized on detectors with appropriate optical relays.

1.6.6 Cloud and Aerosol Imager onboard Japanese Greenhouse Gases Observing Satellite

Thermal And Near infrared Sensor for carbon Observation – Cloud and Aerosol Imager (TANSO-CAI) is a radiometer for retrieving cloud and aerosol characteristics with more accurate data than those of the TANSO-FTS. It has four spectral bands, 0.380 μm, 0.674 μm, 0.870 μm, and 1.60 μm, to identify clear soundings and to provide image data for retrieval of cloud and aerosol optical properties. TANSO-CAI has a continuous spatial coverage, larger FOV, and higher spatial resolution than TANSO-FTS. Due to wide distribution of aerosol a wide swath is required. TANSO-CAI has a swath of ±36.1°, which is much wider than that of the TANSO-FTS. There is no gap between 44 orbits in three days recurrence of the GOSAT. The details of TANSO-CAI are described in Chapter 21 together with TANSO-FTS.

1.6.7 Miniaturized Spectrometers for Low-Cost Space Platforms

The high access cost to space has spurred the development of lower cost orbital platforms such as nanosatellites and microsatellites and microrovers for landed planetary exploration. While these platforms have limited payload capacities, it is still desirable to be able to perform significant Earth and planetary observations. These low-cost space platforms require suitable miniaturized payloads with sufficient performance to provide meaningful measurements and new science capabilities. In this respect, optical spectroscopy has been widely used in space missions to provide valuable information on the molecular composition and bonding in gases, solids, and liquids for atmospheric studies, land cover mapping, planetary mineralogy, and astrobiology.

This book includes a chapter on miniaturized spectrometers for low-cost space platforms (Chapter 33). It describes three technologies for miniaturized spectrometers to enhance the capabilities of microsatellites and microrover platforms; high performance integrated guided-wave spectrometers, monolithic Fabry–Perot imaging spectrometers, and Dyson hyperspectral imagers.

1.7 Other Types of Optical Sensors

There are also other kinds of spaceborne optical payloads, equipment, or components other than the six types described above. In order to attain a comprehensive coverage of all kinds of spaceborne optical payloads, this book covers these optical sensors or components in five chapters (Chapters 34–38). These sensors range from payloads for military surveillance satellites and next-generation space telescopes to a focal plane array that is the key component of an optical sensor.

1.7.1 Optical Payload of Canadian SAPPHIRE Space Surveillance Mission

SAPPHIRE is Canada's first military satellite, launched on 25 February 2013. It is a microsatellite with a mass of 148 kg designed to monitor space debris within an orbit 6000–40,000 km above Earth, as a Canadian contribution to the U.S. Space Surveillance Network for enhancing the ability of the both countries to detect and avoid the collision of critical space platforms with orbital debris. The SAPPHIRE satellite has been providing data to the U.S. Space Surveillance Network since January 2014.

The optical payload of SAPPHIRE is a visible-band electro-optical imager. It incorporates a small three mirror anastigmat telescope, which is similar in design to the Space Based Visible (SBV) sensor on the U.S. Midcourse Space Experiment satellite (MSX), two redundant high sensitivity back-illuminated frame-transfer CCDs and a data handling and control subsystem.

1.7.2 JWST Fine Guidance Sensor and Near-Infrared Imager and Slitless Spectrograph

The James Webb Space Telescope (JWST), a successor to the Hubble Space Telescope, is an international collaboration among NASA, ESA, and CSA. It is an infrared (0.6–27 μm) space telescope with a large primary mirror diameter of 6.5 m for observing the first galaxies of the early universe, the birth of stars, and proto-planetary systems as well as exoplanets, scheduled to be launched to orbit the Sun–Earth Lagrange 2 point 1.5 million km away in 2018. The Canadian contributions to the mission are the Fine Guidance Sensor (FGS) and the Near-Infrared Imager and Slitless Spectrograph (NIRISS). These two instruments share a lot of design, fabrication alignment, integration, and test features. For this reason they are described together in the same chapter.

The FGS is a precision optical guide sensor. It will produce a stream of guide star centroids that drive the Fine Steering Mirror (FSM) of the telescope. The movement of the FSM, located at the pupil of the telescope, will provide the line of sight pointing and stabilization for the telescope.

The NIRISS is a multimode optical instrument that can be configured to function as a broadband NIR imager, multiobject low-resolution slitless spectrometer, high-contrast interferometric imager, and cross-dispersed spectrometer optimized for exoplanet transit study. Thus, it provides four observing modes: (1) broadband NIR imaging; (2) wide-field slitless spectroscopy at a resolving power of ~150 between 1 and 2.5 μm; (3) single-object cross-dispersed slitless spectroscopy enabling simultaneous wavelength coverage between 0.7 and 2.5 μm at a resolving power of ~660, a mode optimized for transit spectroscopy of relatively bright ($J > 7$) stars, and (4) sparse aperture interferometric imaging between 3.8 and 4.8 μm, enabling high contrast ($\sim 10^{-4}$) imaging of $M < 8$ point sources at angular separations between 70 and 500 milli-arcsec. Chapter 35 presents an overview of the FGS/NIRISS design with a focus on the scientific capabilities and performance.

1.7.3 Spaceborne Optical Equipment Using Commercial Off-the-Shelf Devices

An important issue in considering the utilization of optical equipment in space missions is the cost of the space system. In the near future, more satellites are expected to be deployed to orbit the Earth to form a constellation in order to increase spatiotemporal resolution available to scientists. The high cost of Earth observation satellites can be a major barrier to such developments. In general, spaceborne equipment has a large size compared to ground-based ones with the same function in order to achieve high reliability and sustain the harsh space environment and thus are more expensive. Use of commercial off-the-shelf (COTS) devices for spaceborne equipment has been proposed as a cost-reduction approach thanks to their low cost, small size, ease of use, and reasonably high-quality performance. This book includes a chapter on this subject (Chapter 36). It describes the possibility and some examples of the utilization of COTS devices as optical equipment for low cost space missions, such as nanosatellites.

1.7.4 Focal Plane Arrays for Optical Payloads

Space missions rely heavily on electro-optical sensors to achieve their science objectives and operational goals. The focal plane array (FPA) is the key of an optical payload, as it dominates the sensitivity, resolution, and data quality of the payload. Next-generation optical space missions require very sensitive detectors and large arrays. Modern innovative sensor technologies offer optical system designers a broad range of choices of FPAs. In many optical systems the detector is the performance-limiting component. The optical design, cryogenics, and signal processing must satisfy the conditions of the FPA in order to achieve the performance.

In selecting the detector technologies for each unique application, the performance requirements must flow down from the mission level to the instrument, from the instrument to the system, from the system to its subsystems, and from subsystems to components. The challenges associated with the applications of state-of-the-art detectors include optimization of array format, device architecture, operating temperature, quantum efficiency (QE), read noise, and dark current for each technology. In addition, space applications require highly reliable, radiation-tolerant devices incorporated into unique space-qualified flight packages.

This book includes a chapter on FPAs for optical payloads (Chapter 37). It reviews the focal plane array technologies that have been developed for applications in space missions. The focus is the considerations and constraints on detectors in the development of optical payloads. Applications of FPAs in scientific optical payloads for atmospheric science, Earth observation, and space astronomy are described.

1.7.5 Lunar Imaging Sensors

Under the Chinese Lunar Exploration Program, China has launched two lunar orbiters, Chang'E 1 and Chang'E 2, in 2007 and 2010, respectively. Chang'E 3, which contains a lunar lander and rover, was launched on 1 December 2013, and successfully soft-landed on the Moon on 14 December 2013. It will be followed by a sample return mission, Chang'E 5, scheduled for launch in 2017. The lunar imaging sensor is one of the important components in China's lunar exploration program.

An ultraviolet lunar sensor (UVLS) was developed and deployed on the Chang'E 1 spacecraft. The UVLS output two-axis attitude angles, including pitch angle and roll angle, through processing lunar images. A variety of new features have emerged in determining the attitude using the ultraviolet lunar sensor. This book includes a chapter describing the UVLS (Chapter 38). An infrared binocular camera was built and equipped on the Chang'E 3. Due to a very large diagonal FOV (170°) of the binocular camera that introduces a significantly large distortion on images and makes the calibration algorithms for conventional cameras dysfunctional, a new photogrammetric calibration method for the type of fish-eye optic was investigated and developed. This chapter also describes the development for this method and presents the flight results.

1.8 Optical Sensors for Nanosatellites and Microsatellites

Although widely used, satellites are expensive to build and launch. Miniaturized satellites, such as microsatellites and nanosatellites, are developed in order to significantly reduce the cost and development period. A microsatellite usually has a wet mass between 10 and 100 kg, while a nanosatellite typically has a wet mass between 1 and 10 kg. Cube satellites are classified as nanosatellites, as their mass falls in this range. A cube satellite with a volume of exactly 1 liter (10 cm × 10 cm × 10 cm) and a mass of no more than 1.3 kg is referred to as "one unit" (1U). Cube satellites such as a "2U" (20 cm × 10 cm × 10 cm) and a "3U" (30 cm × 10 cm × 10 cm) version have been built and launched. Miniaturized satellites typically use COTS components for reducing the cost and shortening the development period, and they benefit from the constant improvements in price and performance being achieved by the consumer-electronics industry.

Space launches usually comprise one or more primary payloads and require ballast to balance the rocket. Microsatellites or nanosatellites could take the place of some of this ballast or be launched as secondary payloads to significantly reduce the launch cost. These miniaturized satellites are ideal for cost-effective missions focusing on technological research, low cost science, and commercial proof-of-concept missions.

On 19 November 2013, Orbital Sciences, an American company, launched a rocket that carried 29 nanosatellites aloft and released them into low Earth orbit, a record for a single mission. Thirty hours later, Kosmotras, a Russian joint venture, carried 32 nanosatellites into a similar orbit. Then, in January 2014, Orbital Sciences carried 33 nanosatellites up to the International Space Station, where they were cast off a month later. In the next five years or so some 1000 nanosatellites are expected to be launched.

With continued advances in the miniaturization and capability of electronic technology and the use of satellite constellations, nanosatellites are increasingly capable of performing commercial missions that previously required small or microsatellites. For example, a 6U cube satellite has been proposed to enable a constellation of 35 Earth-imaging satellites (8 kg each) to replace a constellation of five RapidEye Earth-imaging satellites (156 kg each) at the same mission cost with a significantly shorter revisit time. Every area of the globe can be imaged every 3.5 hours rather than once per 24 hours as with the RapidEye constellation. More rapid revisit time is a significant improvement for nations during disaster response, which was the purpose of the RapidEye constellation.

This book includes four chapters on miniaturized satellites. Three chapters (Chapters 39–41) describe nanosatellites and microsatellites for astronomy and atmosphere and Earth observation. One chapter (Chapter 42) describes five microsatellites for various uses in scientific research and applications.

1.8.1 BRITE-Constellation of Nanosatellites for Astronomy

A constellation of six nanosatellites is formed to observe the “BRITE” stars in the Earth’s sky ($V < 4$) that have been poorly studied relative to their fainter counterparts. These six nanosatellites are doing precision two-color photometry of bright stars, three with blue (390–460 nm) bandpass filters and the other three with red (550–700 nm) bandpass filters. At the time Chapter 39 was written the BRITE satellites were in their second year of operation. It is believed the BRITE-Constellations are the first nanosatellites dedicated to astronomy.

Each BRITE satellite carries a single CCD blue or red band photometry refractive telescope. Though the designs for the red and blue telescope are slightly different in optical prescription, they are similar enough. Each BRITE telescope is composed of three modules, the header electronics tray, the optical cell, and the baffle. The optical cell houses five spherically ground lenses and the spacers that position and align the lenses with respect to each other. The electronics tray contains the CCD header board, which includes the CCD and thermal control electronics.

1.8.2 Nanosatellite for Monitoring Earth Aerosol

The Nanosatellite for Earth Monitoring and Observation – Aerosol Monitor (NEMO-AM) is a high performance nanosatellite in the final stages of development at the time Chapter 40 was written at the University of Toronto (UoT). The mission is funded by the Indian Space Research Organization (ISRO) for the purpose of detecting atmospheric aerosols in multiple bands over particular geographical areas with subdegree accuracy. The satellite design leverages the lessons learned on previous UoT missions and is developed around the Generic Nanosatellite Bus (GNB) concept, where a multipurpose and adaptable GNB is designed to work with a wide range of payloads with little or no modification. Consequently, many of the hardware components on NEMO-AM are inherited from the GNB and likewise boast flight heritage. The satellite also employs new technologies facilitated by COTS hardware. This enables shorter design cycles but allows those periods to be focused more on mission-specific goals.

The bus envelopes a volume of 20 cm × 20 cm × 40 cm (16U) and has a mass of 16.1 kg, 9 kg of which is dedicated to the payload. A large solar array of 62 cm × 58 cm is attached on the +X face for power generation of 80 W. NEMO-AM consists of a standard suite of attitude and orbit control subsystem components, a GPS receiver, communication antennas (S-band for uplink and downlink), onboard computers for task management, a power distribution network including batteries and solar cells, and a multispectral imager to capture aerosol concentration measurements.

1.8.3 Nanosatellite for High Definition Earth Imaging and Video

The Nanosatellite for Earth Monitoring and Observation – High Definition (NEMO-HD) is a multispectral Earth-observation microsatellite built by the UoT for the Slovenian Centre of Excellence for Space Sciences and Technologies (SPACE-SI). It is planned for launch in 2015. The mass of the spacecraft is 65 kg. NEMO-HD performs a multitude of roles, from acting as an experimental test bed for the development of novel control and image processing algorithms, to providing a commercial service offering rapid response for monitoring crops and the effects of environmental disasters. Data acquired by NEMO-HD is also used to augment terrestrial mapping services.

NEMO-HD has a panchromatic channel with a GSD of 2.8 m and four multispectral bands including red, blue, green, and NIR with a GSD of 5.8 m. In addition, NEMO-HD carries two high definition video channels, each providing real-time video at 25 frames per second. The primary channel has a swath 5 km with a GSD of 2.8 m, while the secondary channel has a swath 75 km with a GSD of 40 m. The video channels are co-registered with the multispectral imagery bands. This allows for a unique real-time imaging mode, in which an operator can view the real-time video feed and command the spacecraft to image a target of interest.

1.8.4 Microsatellites Hodoyoshi and UNIFORM Series

Hodoyoshi ("reasonably reliable" in Japanese) is a microsatellite project funded by the Japanese government under the FIRST program (Funding Program for World-Leading Innovative R&D on Science and Technology). The University International Formation Flight (UNIFORM) is another Japanese government funded microsatellite project. The objectives of the Hodoyoshi project are to study (1) "reasonably reliable" systems engineering, (2) innovation of nanosatellite equipment to solve the "size problems," (3) nanosatellite architecture standardization and modularity, and (4) an all-Japanese nanosatellite consortium establishment to combine Japanese universities and small business competencies. The objectives of the UNIFORM project are to develop a wildfire monitoring system with micro-satellite constellation and to provide capacity building. The UNIFORM project is the follow-up of the Micro STAR program of the JAXA. In 2014, four microsatellites, UNIFORM-1, Hodoyoshi-3, Hodoyoshi-4, and Hodoyoshi-1, were successfully launched in May, June, June, and November, respectively. UNIFORM-1 has almost the same spacecraft bus as Hodoyoshi-3.

Hodoyoshi-1 has a mass of 60 kg, of which 13.3 kg is payload mass. It carries a push-broom four-band multispectral sensor with 6.75 m GSD and 27.8 km swath. Hodoyoshi-2 has a mass of 55 kg. It is also called the Rapid International Scientific Experiment Satellite (RISESAT). Its launch was postponed due to the delay of the launcher. Hodoyoshi-3 and -4 have a mass of 60 kg and 66 kg, respectively. Hodoyoshi-3 carries two cameras: (1) a medium-resolution camera (MCAM) of mass 250 g having three bands with a GSD of 40.3 m at 630 km altitude, and (2) a low-resolution camera (LCAM) of mass 190 g having RGB bands with a GSD of 252 m. Hodoyoshi-4 carries a high-resolution camera (HCAM) of mass 5.9 kg. It is a push-broom scanning type four-band multispectral imager with a GSD of 6.3 m and swath of 25.7 km at 630 km altitude. UNIFORM-1 has a mass of 50 kg and carries two optical sensors: an infrared camera (an uncooled microbolometer, 0.8 kg) and a visible camera (0.58 kg). The visible camera is for finding locations of wildfires and has a GSD of 86 m and a FOV of 110.2 km × 88.2 km.

1.9 Summary

Consisting of 42 chapters, this book describes over 50 optical payloads that have flown, are flying, and are to be flown in various space missions, including Earth observation, communications, weather, science satellites, and deep space exploration. These optical payloads cover all the six types of optical payloads defined at the beginning of this chapter. In addition, some optical payloads that do not fall in these six types are also included for a more comprehensive coverage. Furthermore, this book also includes chapters for optical payloads developed for microsatellites and nanosatellites.

The payload descriptions in this book are all written by the rocket scientists at the nation's space agencies and the world's primary space industry companies and principal investigators of the missions with first-hand experience

Table 1.1 Summary of Optical payloads collected in the book

No.	Ch.	Payload Type	Payload name	Acronym name	Platform or Mission	Launch year	Active? (in Dec. 2014)	Country
1	2	Imaging Spectroscopy Sensor	Hyperspectral Imager for the Coastal Ocean	HICO	International Space Station	2009	until Sept. 2014	DoD, USA
2	3		Moderate Resolution Imaging Spectroradiometer	MODIS	Terra, Aqua	1999, 2002	Yes	NASA, USA
3	4		Medium Resolution Imaging Spectrometer for Ocean Color	MERIS	ENVISAT	2002	Until 2012	ESA
4	5		Visible and Near-infrared Imaging Spectrometer	VNIS	Chang'E 3	2013	Yes	China
5	6		Hyperspectral Imager HySI	HySI	IMS-1	2008	Yes	India
6	7		Environmental Mapping and Analysis Program	EnMap	EnMap	2018	–	Germany
7	8		PRecursore IperSpettrale della Missione Applicativa	PRISMA	PRISMA	2017	–	Italy
8	9		Hyperspectral Imager Suite	HISUI	HISUI	2018	–	Japan
9	10		Ocean and Land Color Imager	OLCI	Sentinel–3	2015	–	ESA
10	11		Spaceborne Hyperspectral Applicative Land and Ocean Mission	SHALOM	SHALOM	2020	–	Israel
11	12		Hyperspectral and Luminescence Observer	HALO	Mars Rover	–	–	Canada
12	13	Multispectral Sensor	Infrared Scanner	IRS	HJ-1-B	2008	Yes	China
13	14		MUX Multispectral Camera	MUXCAM	CBERS 4	2014	Yes	Brazil
14	15		Multispectral camera MX	MX	IMS-1	2008	Yes	India
15	16		WFI Wide Field Imager	WFICAM	CBERS 4	2014	Yes	Brazil
16	17		Remote Sensing Instrument	RSI	FORMOSAT-2	2004	Yes	ROC (Taiwan)
17	18	Fourier Transform Spectrometer	WIND Imaging Interferometer	WINDII	NASA UARS	1991	Until 2003	Canada
18	19		Atmospheric Chemistry Experiment - Fourier Transform Spectrometer	ACE-FTS	SCISAT	2003	Yes	Canada
19	20		Cross-track Infrared Sounder	CrIS	Suomi NPP/JPSS	2011	Yes	NOAA, USA
20	21		Thermal And Near infrared Sensor for carbon Observation Fourier Transform Spectrometer	TANSO-FTS	GOSAT	2009	Yes	Japan
21	22		Geostationary Imaging Fourier Transform Spectrometer	GIFTS	for EO-3	2005 (EDU)	–	NASA, USA
22	23	Lidar and Active Sensor	Mars Phoenix Lidar	–	Phoenix lander	2008	No	Canada
23	24		Laser Altimeter	–	Chang'E 1	2007	No	China
24	25		Canadian Astro-H Metrology System	CAMS	Astro-H	2016	–	Canada
25	26		Atmospheric Lidar	ATLID	EarthCARE	2018	–	ESA
26	27		Small Optical Transponder	SOTA	Hodoyoshi-2	2015	–	Japan

(*Continued overleaf*)

Table 1.1 (*Continued*)

No.	Ch.	Payload Type	Payload name	Acronym name	Platform or Mission	Launch year	Active? (in Dec. 2014)	Country
27	28	Spectrometer and Radiometer	UV-Visible-NIR Spectrophotometer	MAESTRO	SCISAT	2003	Yes	Canada
28	29		Measurements Of Pollution In The Troposphere	MOPITT	Terra	1999	Yes	Canada
29	30		Solar Auto-Calibrating Extreme Ultraviolet and Ultraviolet Spectrometers	SolACES	International Space Station	2008	Yes	Germany
30	30		Solar Spectral irradiance measurements	SOLSPEC	International Space Station	2008	Yes	France
31	31		UV/VIS Spectrograph	OSIRIS	Odin	2001	Yes	Canada
32	31		Infrared imager	OSIRIS	Odin	2001	Yes	Canada
33	32		Sea and Land Surface Temperature Radiometer	SLSTR	Sentinel-3	2015	–	ESA
34	21		Thermal And Near infrared Sensor for carbon Observation - Cloud and Aerosol Imager	TANSO-CAI	GOSAT	2009	Yes	Japan
35	33		Miniaturized Spectrometers for Low-cost Space Platforms	–	Low-cost Platforms	–	–	Canada
36	34	Other Types Optical Sensor	Canadian Sapphire Space Surveillance Satellite	Sapphire	Sapphire	2013	Yes	Canada
37	35		Fine Guidance Sensor	FGS	JWST	2018	–	Canada
38	35		Near-Infrared Imager and Slitless Spectrograph	NIRISS	JWST	2018	–	Canada
39	36		Spaceborne Optical Equipment Using Commercial Off-the-Shelf Devices	COTS	–	–	–	Japan
40	37		Focal Plane Arrays for Optical Payloads	FPA	–	–	–	Canada
41	38		Ultraviolet lunar sensor	UVLS	Chang'E 1	2007	–	China
42	38		Infrared Binocular Camera	IBC	Chang'E 3	2013	–	China
43	39	Optical Sensors for Nanosatellites and Microsatellites	CCD blue or red band photometry refractive telescope	–	BRITE Constellation	2013	Yes	Canada Austria Poland
44	40		NEMO Aerosol Monitor	AM	NEMO-AM	TBD	–	Canada
45	41		4-band Multispectral Camera + Pan channel	–	NEMO-HD	2015	–	Canada
46	41		2 HD Video Cameras	–	NEMO-HD	2015	–	Canada
47	42		4-Band Multispectral Sensor	–	Hodoyoshi-1	2014	Yes	Japan
48	42		High-Precision Telescope	HPT	Hodoyoshi-2	2015	–	Japan
49	42		Low-Resolution Camera	LCAM	Hodoyoshi-3	2014	Yes	Japan
50	42		Medium-Resolution Camera	MCAM	Hodoyoshi-3	2014	Yes	Japan
51	42		High-Resolution Camera	HCAM	Hodoyoshi-4	2014	Yes	Japan
52	42		Thermal Infrared Camera	–	UNIFORM-1	2014	Yes	Japan
53	42		Visible Camera	–	UNIFORM-1	2014	Yes	Japan

and knowledge. The descriptions of each of the optical payloads provided in the book are deemed to be information rich, helpful, and practical since the authors are the persons involved in the development phases from mission initiation, payload design and building, assembly, integration and test, to operations.

Table 1.1 summarizes the optical payloads described in this book in the order of their chapter number and payload type. The table also lists information such as the platform or mission of the payloads deployed, their launch year, current status, and the country to help readers gain an overall picture of all the payloads included in this book.

Reference

[1] Qian, S.-E., Optical Satellite Signal Processing and Enhancement. Bellingham, WA: SPIE Press, 2013.