KiboCUBE Academy

Lecture 24

Optical Earth Observation with Microsatellites

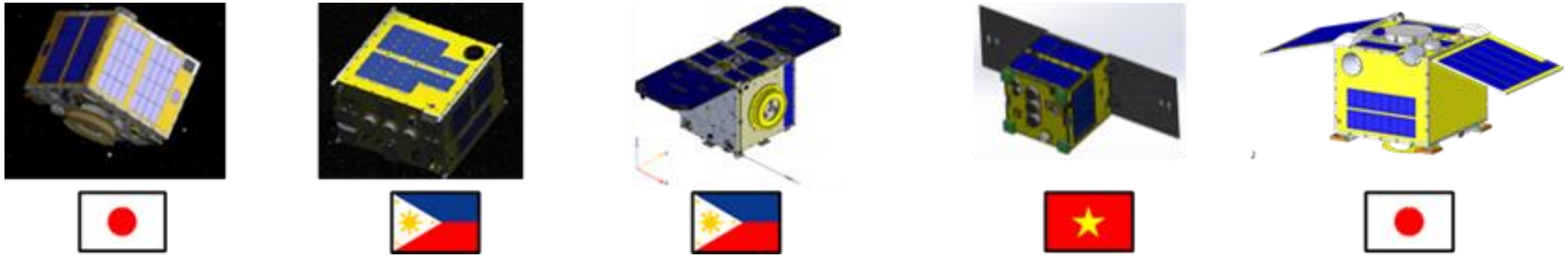
Hokkaido Information University

Space Information Center

Associate Professor Dr. Junichi Kurihara

This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
The specific information and requirements for applying to KiboCUBE can be found at:
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

Lecturer Introduction



RISING-2 (2014), DIWATA-1 (2016), DIWATA-2 (2018), MicroDragon (2019), RISESAT (2019), etc.

Junichi Kurihara, Ph.D.

Position:

2004 - Project Researcher, Japan Aerospace Exploration Agency
2007 - JSPS Postdoctoral Researcher, Nagoya University
2010 - Postdoctoral Researcher (2010 - 2011), Assistant Professor (2011 - 2013), Associate Professor (2013 - 2022), Hokkaido University
2022 - Associate Professor, Hokkaido Information University

Research Topics:

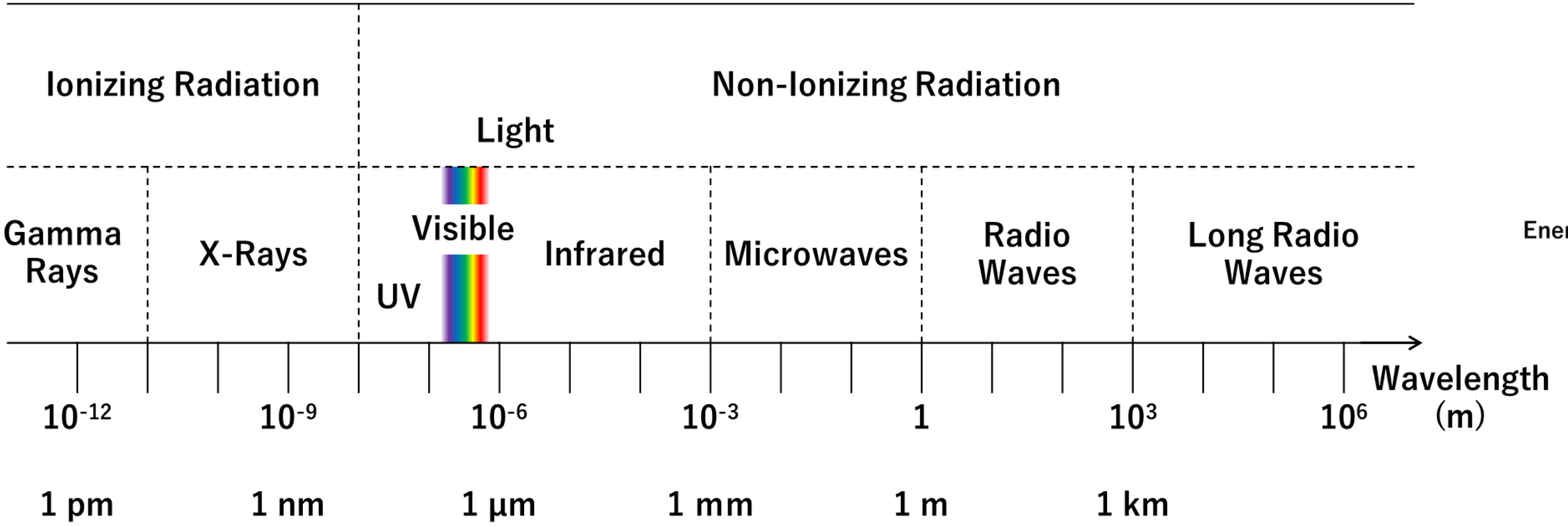
Remote Sensing, Hyperspectral Imaging, Earth Observation

Contents

1. Introduction to Optical Sensors

1.1. Wavelength of Light and its Detectors

- Light is electromagnetic waves with wavelengths from 10 nm to 1 mm



Planck constant (6.6×10^-34 J·s) Speed of light (3×10^8 m/s)

Energy of photon (J)

$$E = \frac{h \cdot c}{\lambda}$$

Wavelength (m)

- Light has both particle and wave properties → wave–particle duality

1.1. Wavelength of Light and its Detectors

- Light is detected by different types of detectors, depending on its wavelength

Violet Blue Cyan Green Yellow Orange Red

Thermal infrared（TIR）

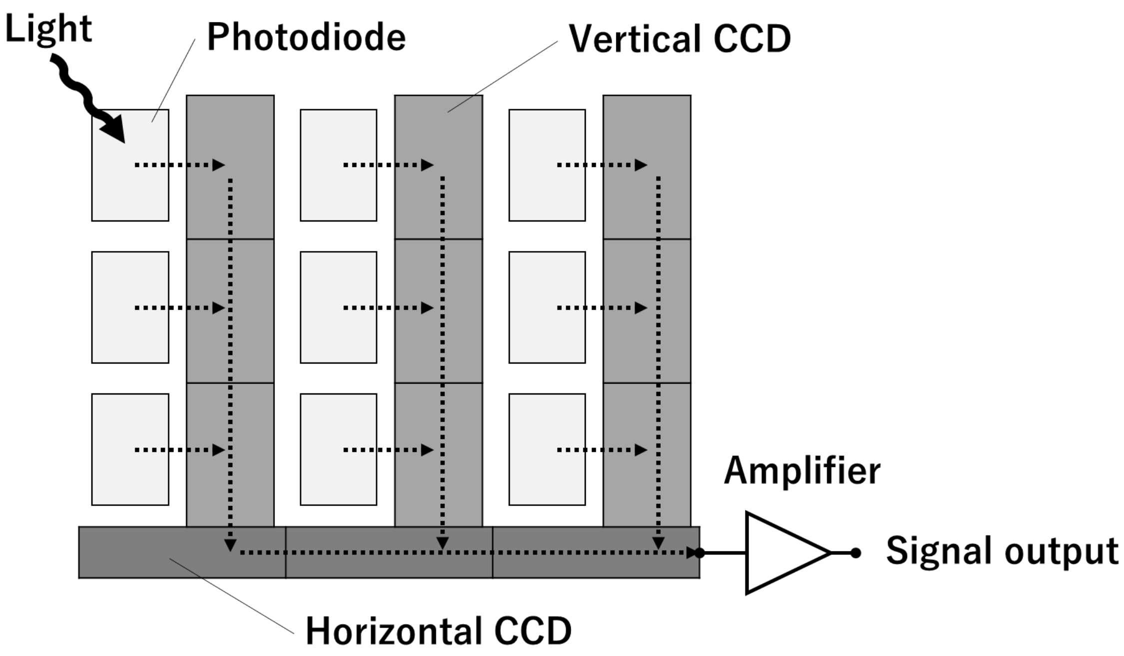
Ultra violet (UV)	Visible (VIS)	Near-infrared (NIR)	Short-wavelength infrared (SWIR)	Mid-wavelength infrared (MWIR)	Long-wavelength infrared (LWIR)	Far infrared (FIR)

Wavelength 0.4 0.7 1.4 3 8 15 µm

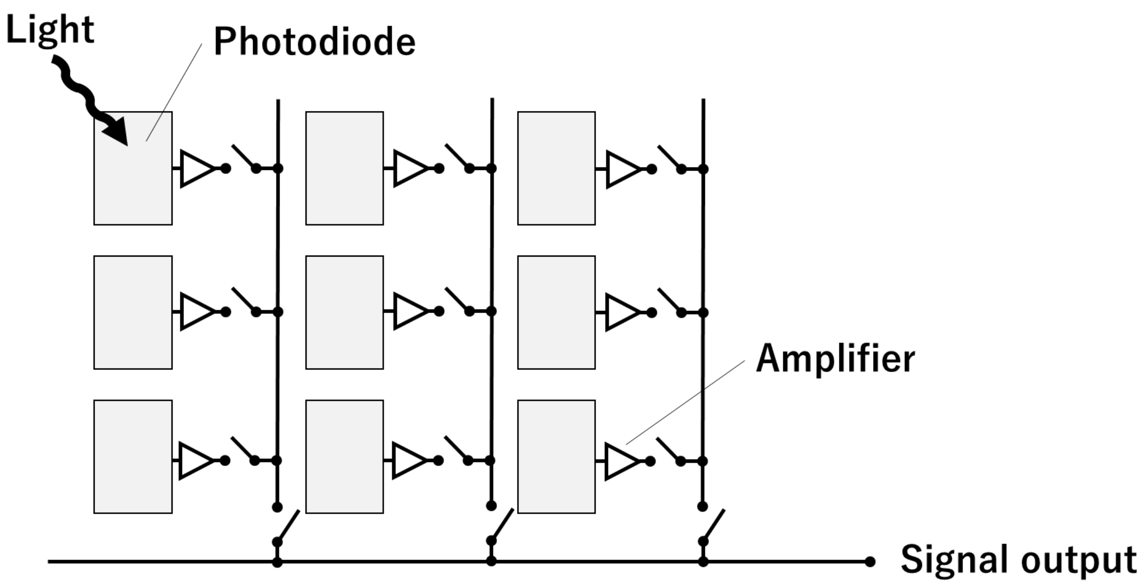
Photomultiplier tube（PMT）	0.3—0.9 µm
Silicon photodiodes：CCD, CMOS	0.4—1.0 µm
Indium gallium arsenide（InGaAs）photodiodes	0.9—1.7 µm
Cooled: Indium antimonide (InSb), Mercury cadmium telluride（MCT）	1.5—5.4 µm
Uncooled: Microbolometer	8—14 µm

1.1. Wavelength of Light and its Detectors

- CCD image sensor vs. CMOS image sensor



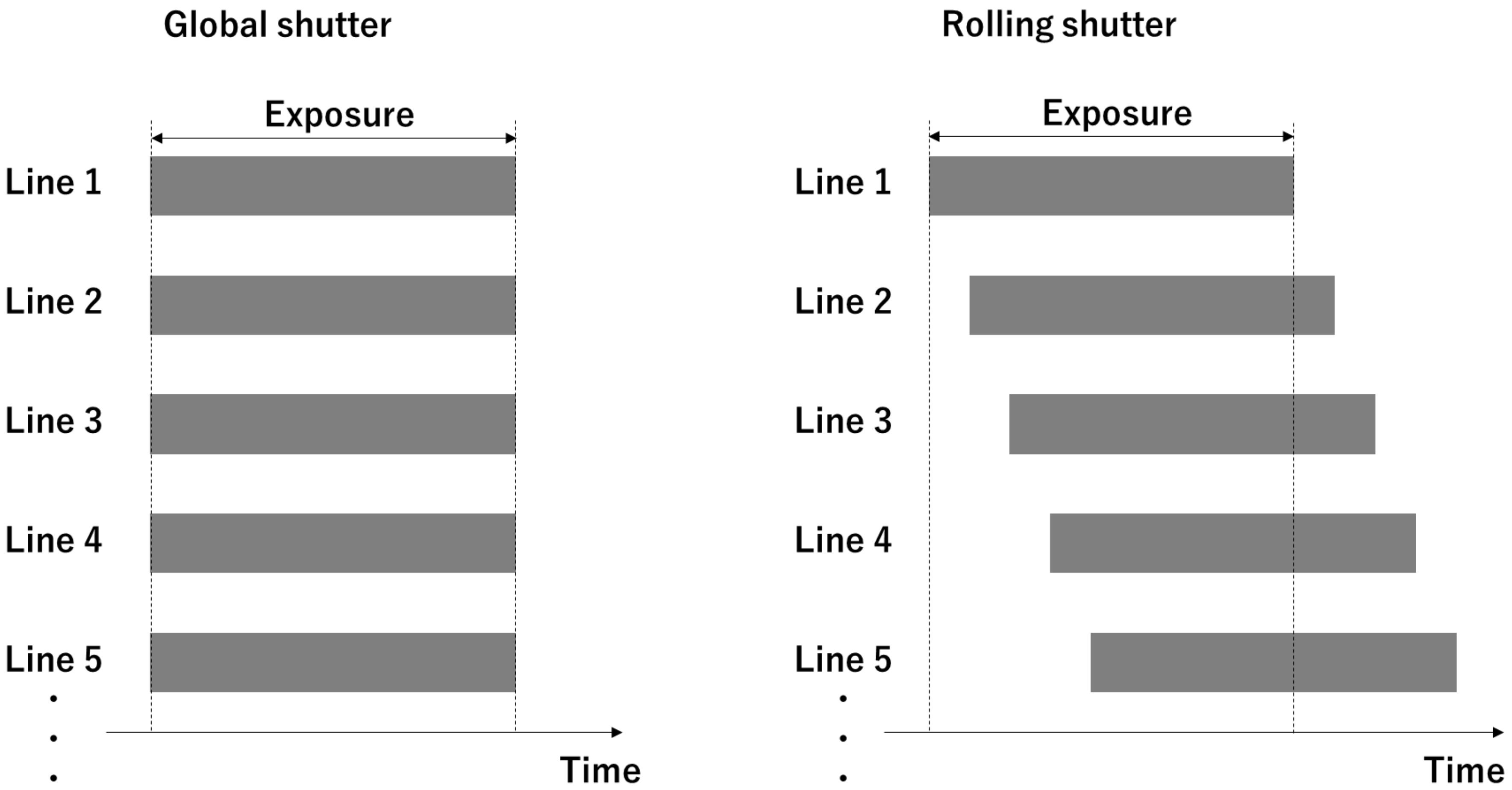
CCD (Charge Coupled Device)



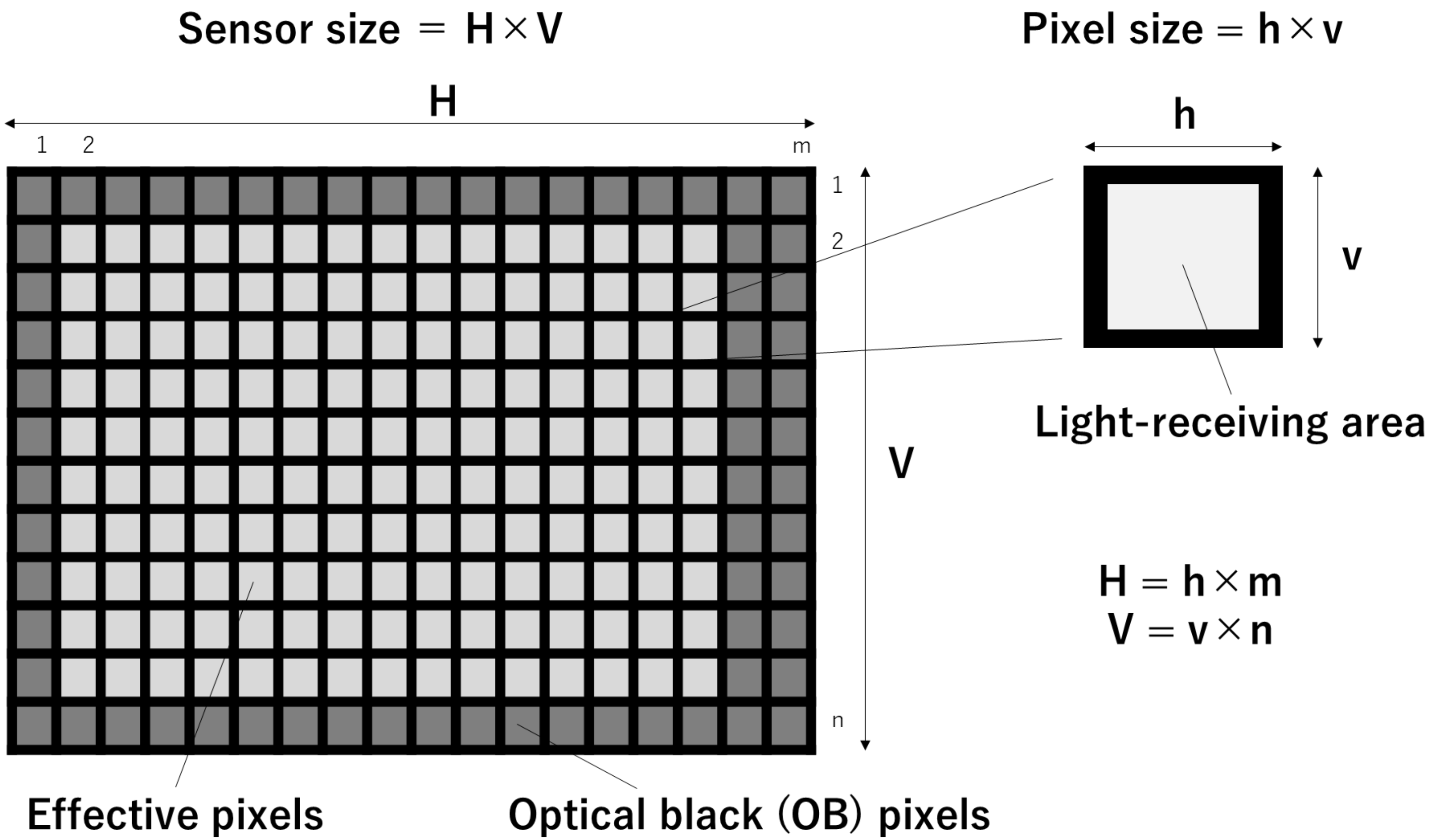
CMOS (Complementary Metal Oxide Semiconductor)

1.1. Wavelength of Light and its Detectors

- Global shutter vs. Rolling shutter

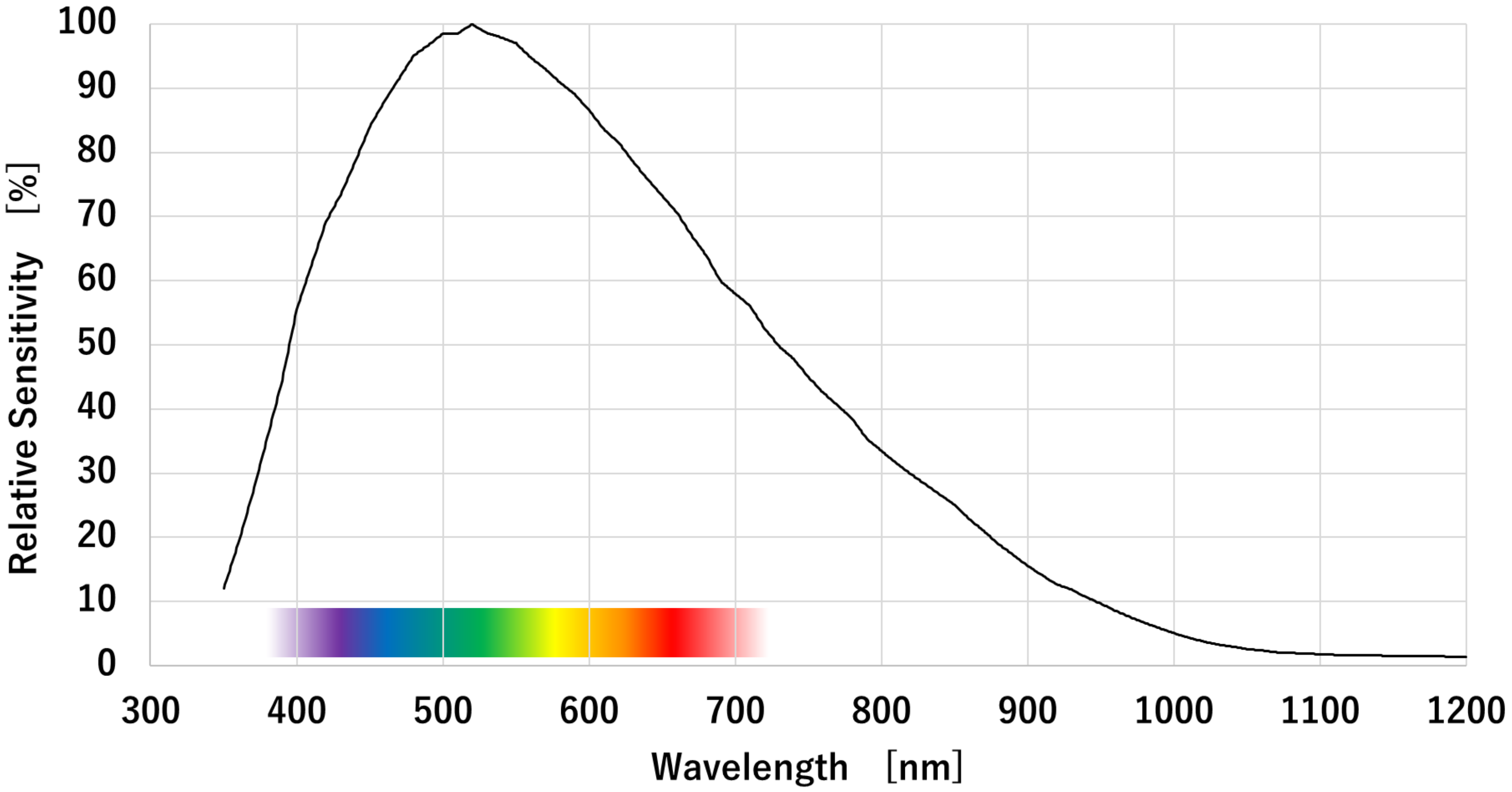


- Format of Image sensor



1.1. Wavelength of Light and its Detectors

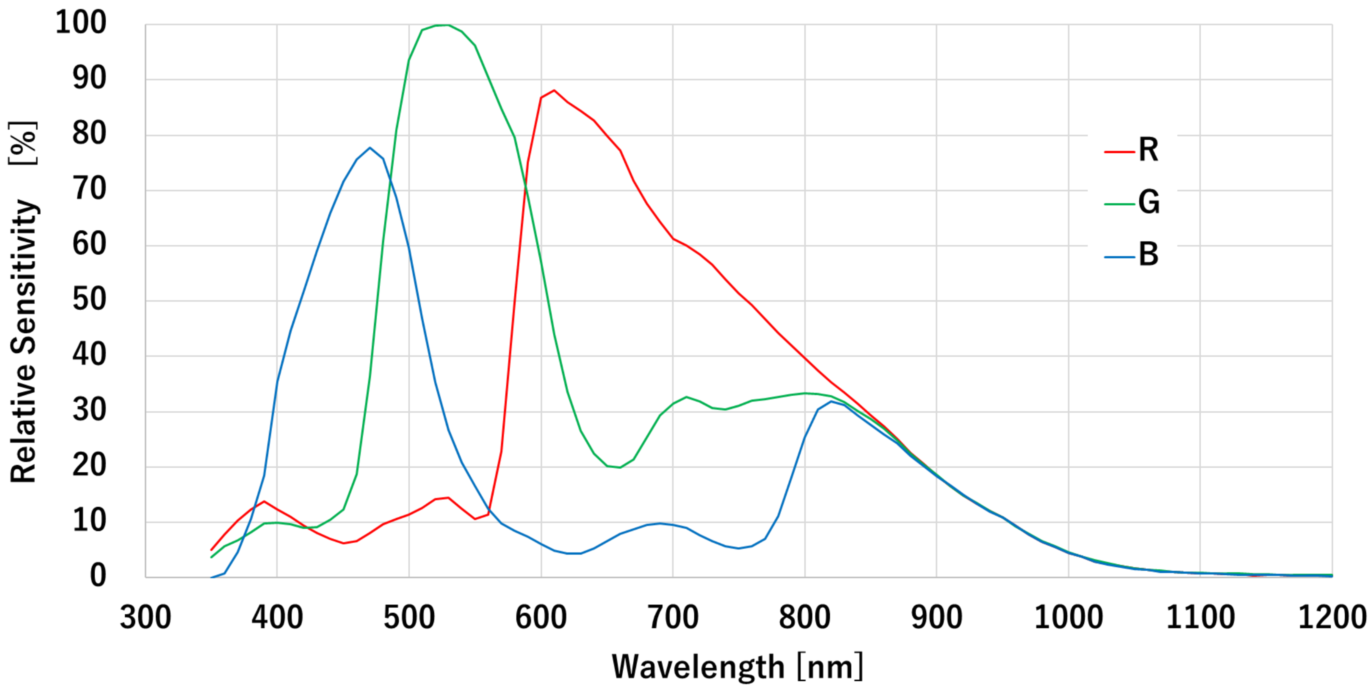
- Spectral sensitivity of image sensor



1. Introduction to Optical Sensors

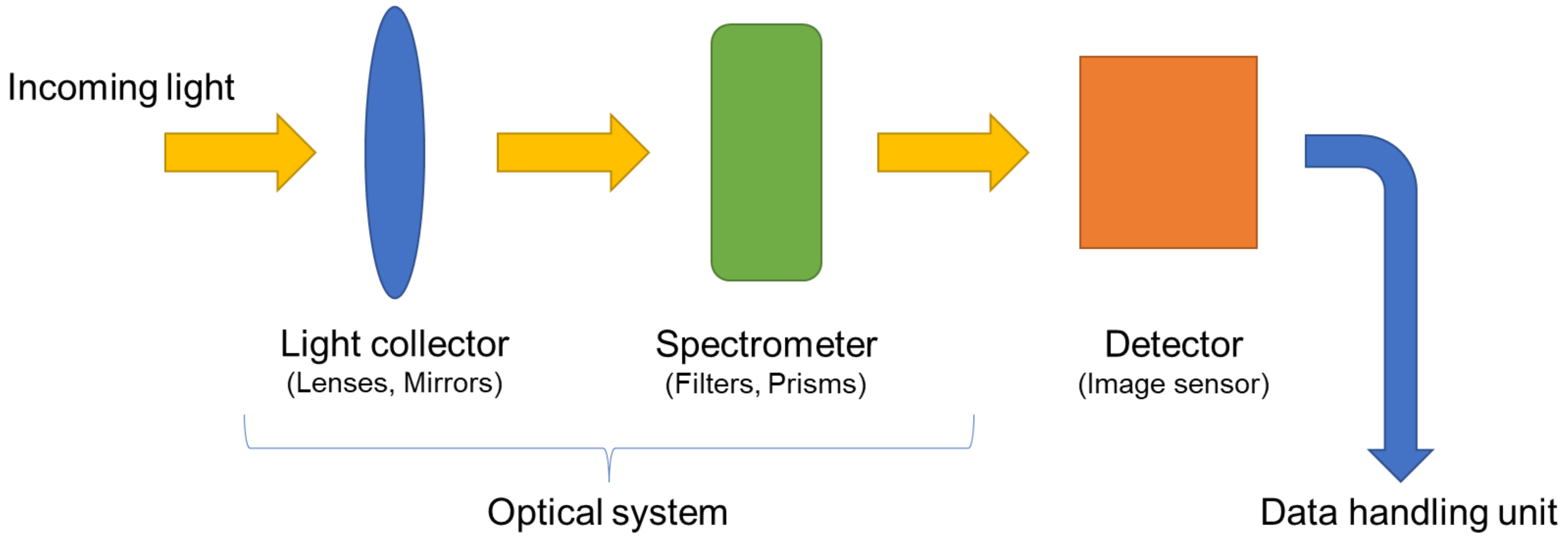
1.1. Wavelength of Light and its Detectors

- Bayer filter for RGB color sensor



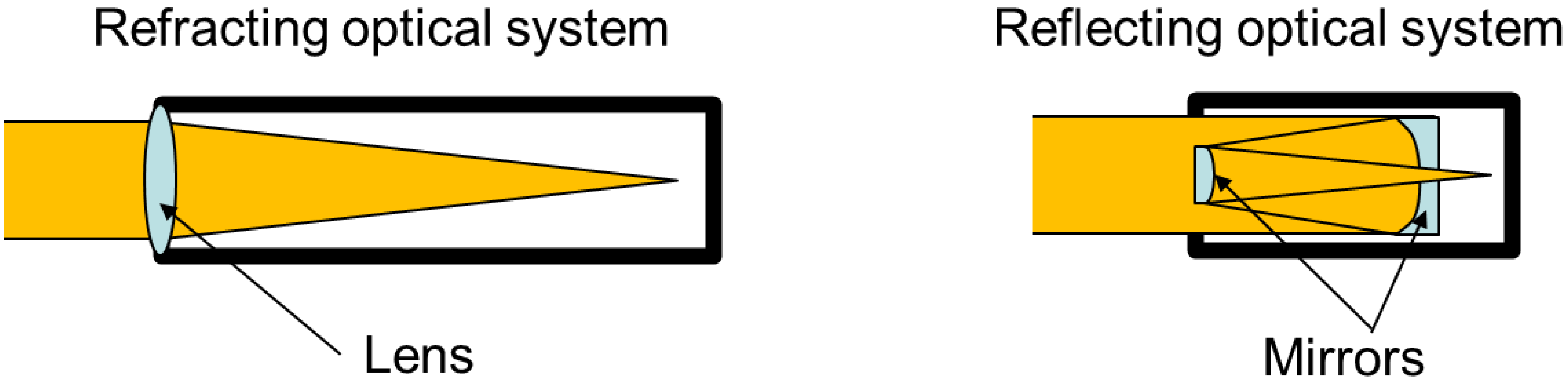
1.2. Types and Characteristics of Optical Sensors

- Basic components of optical sensor

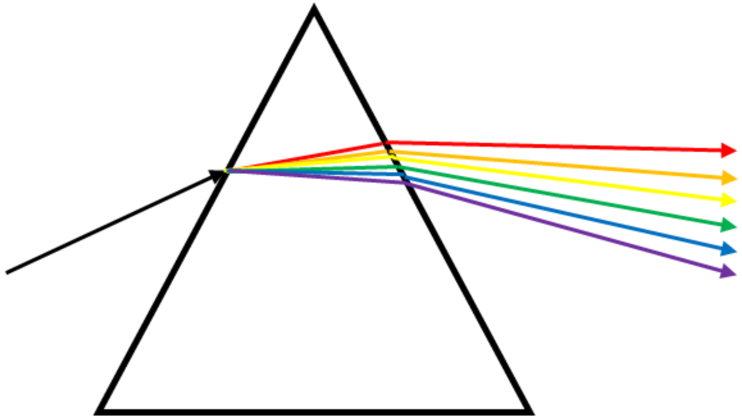


1.2. Types and Characteristics of Optical Sensors

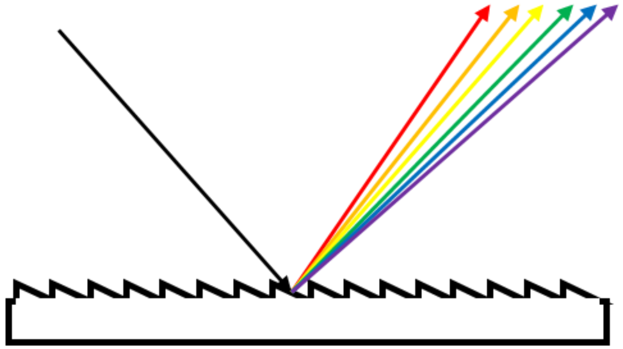
- Basic optical systems of light collector



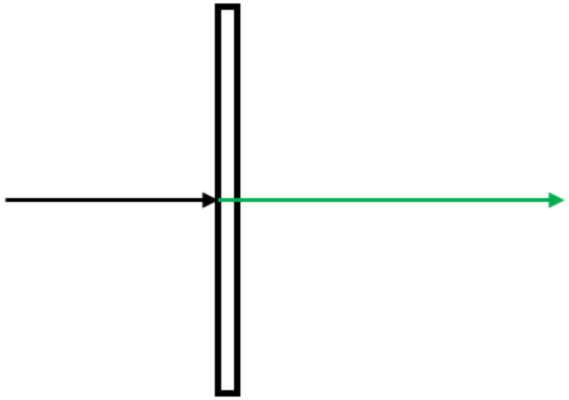
- Optical elements of spectrometer



Prism



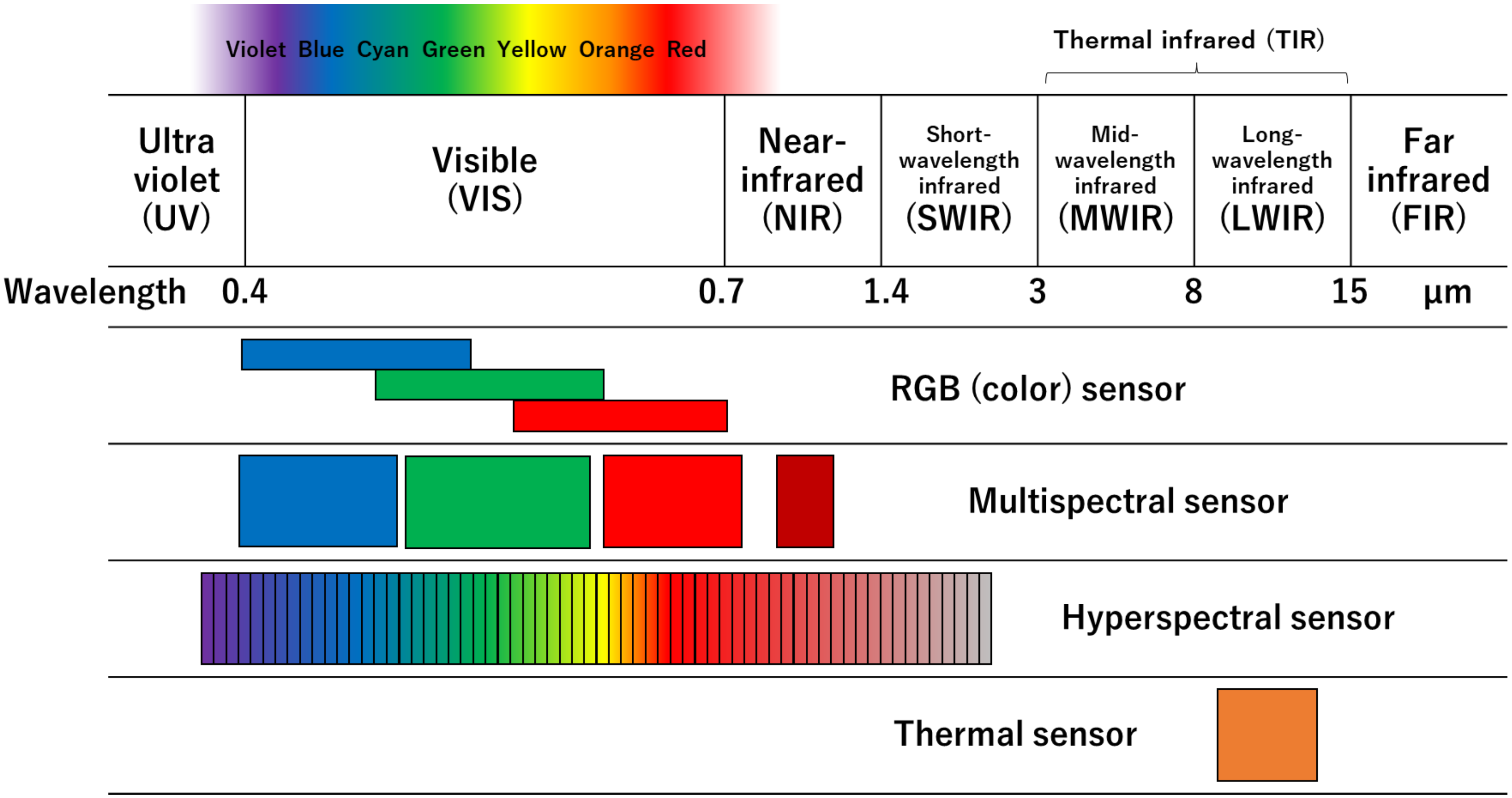
Diffraction grating



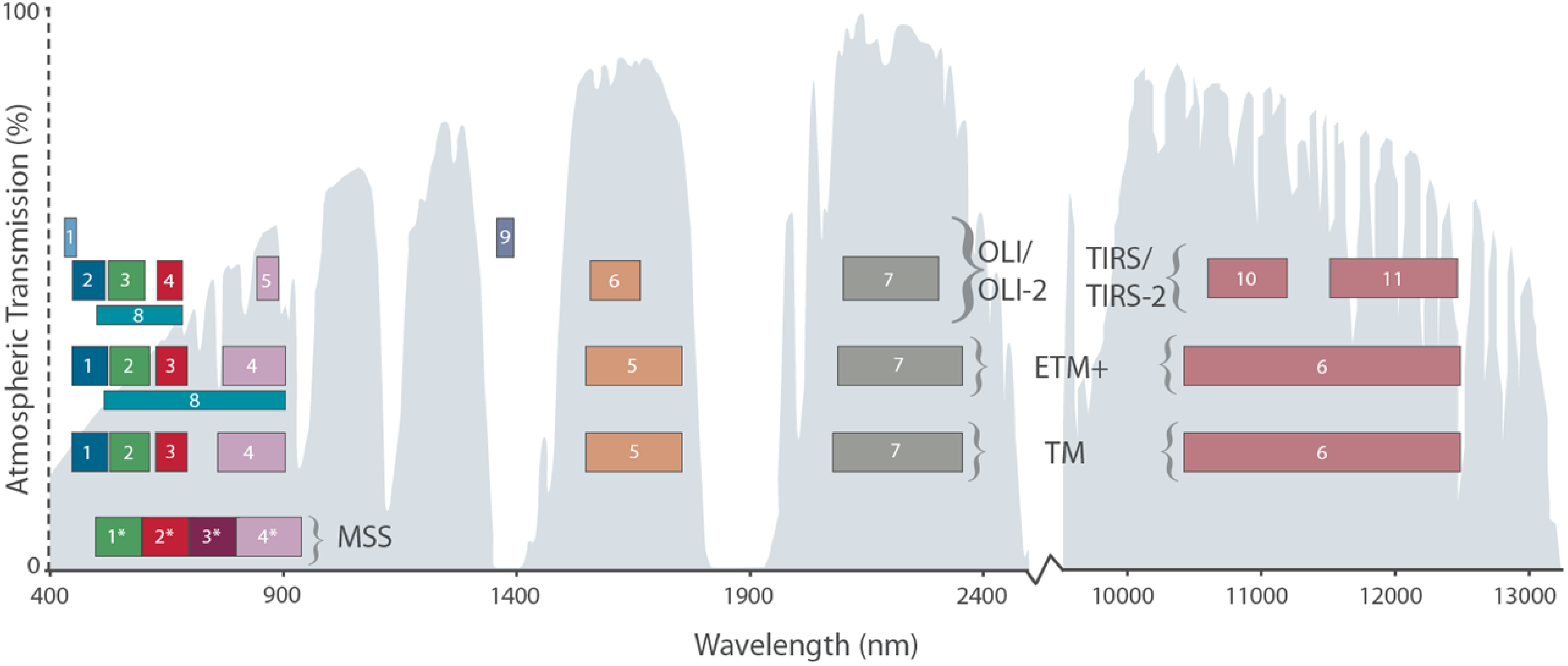
Filter

1.2. Types and Characteristics of Optical Sensors

- Spectral range and spectral resolution of optical sensors



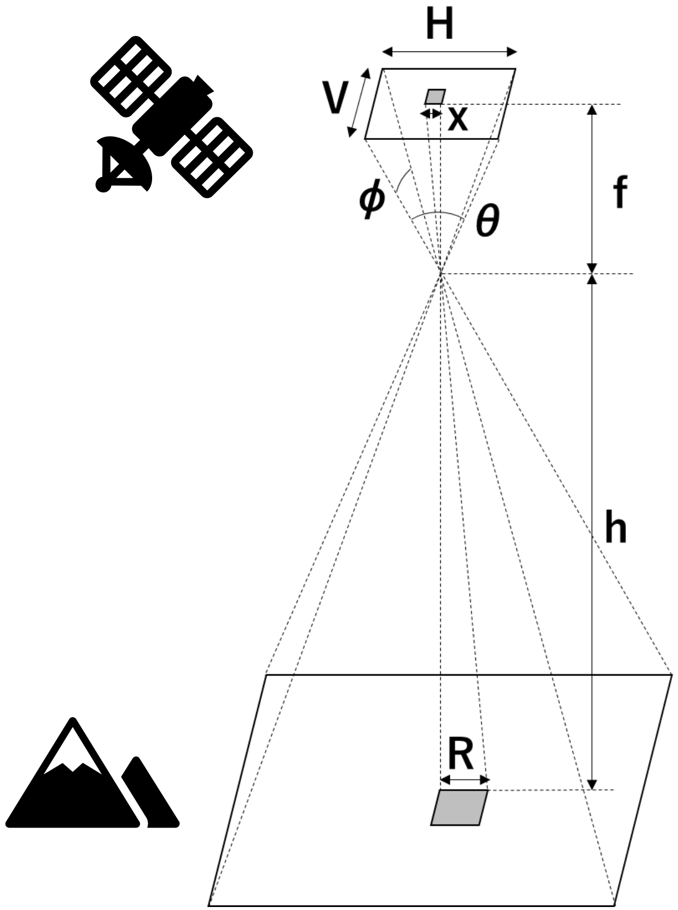
- Landsat 1—9 satellites' spectral bands



Credit: NASA

1.2. Types and Characteristics of Optical Sensors

- Field of view (FOV) and spatial resolution of optical sensor



Credit: J. Kurihara, Hokkaido Information University

Altitude h: 600 km

Focal length f: 1 m

Sensor size H×V: 4.8 mm × 3.6 mm

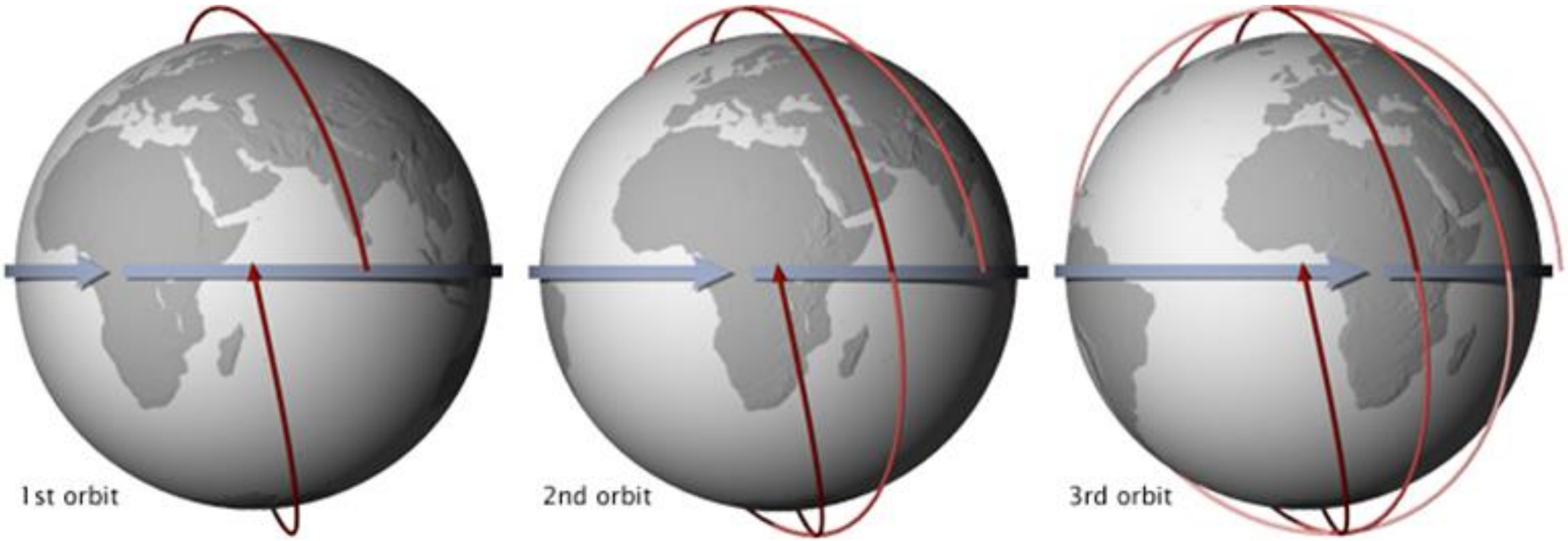
Pixel size x: 7.4 μm × 7.4 μm

FOV: $\theta = \tan^{-1}(H / f) = 0.28°$
$\Phi = \tan^{-1}(V / f) = 0.21°$

Ground sample distance (GSD) :
$R = h / f \times x = 4.5$ m

- Orbit and Time of observation

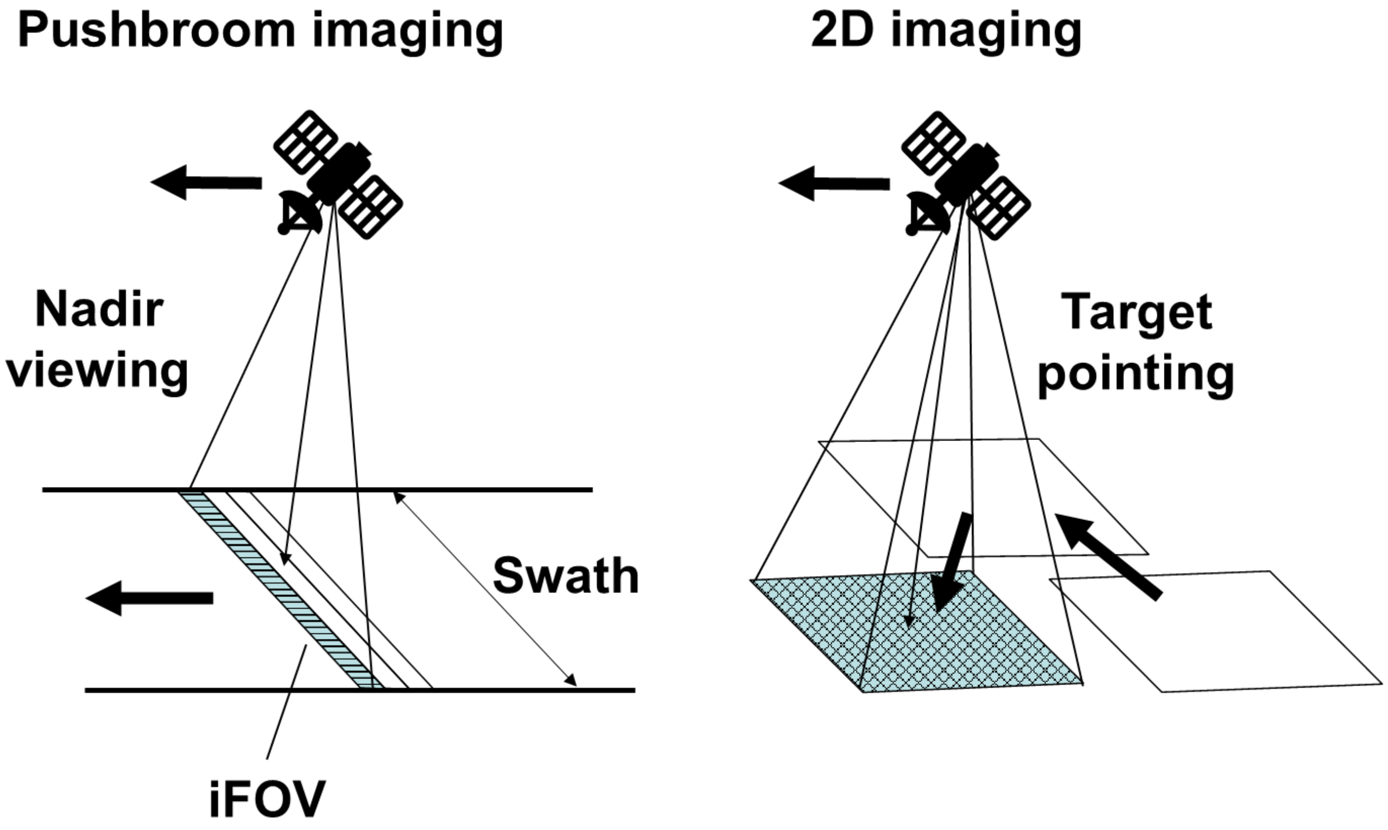
Sun-Synchronous Orbit (SSO)



Credit: NASA

1.2. Types and Characteristics of Optical Sensors

- Imaging methods



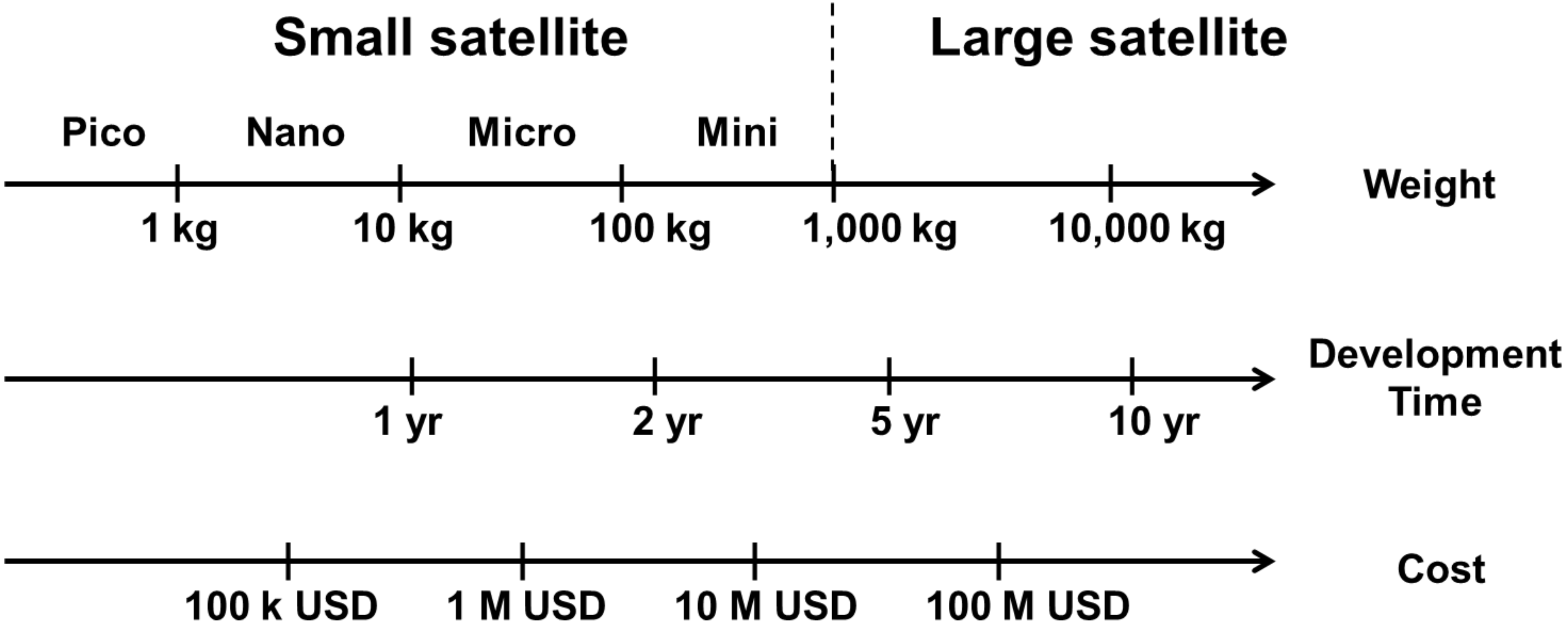
Credit: J. Kurihara, Hokkaido Information University

2. History and Trends in Earth Observation

2. History and Trends in Earth Observation

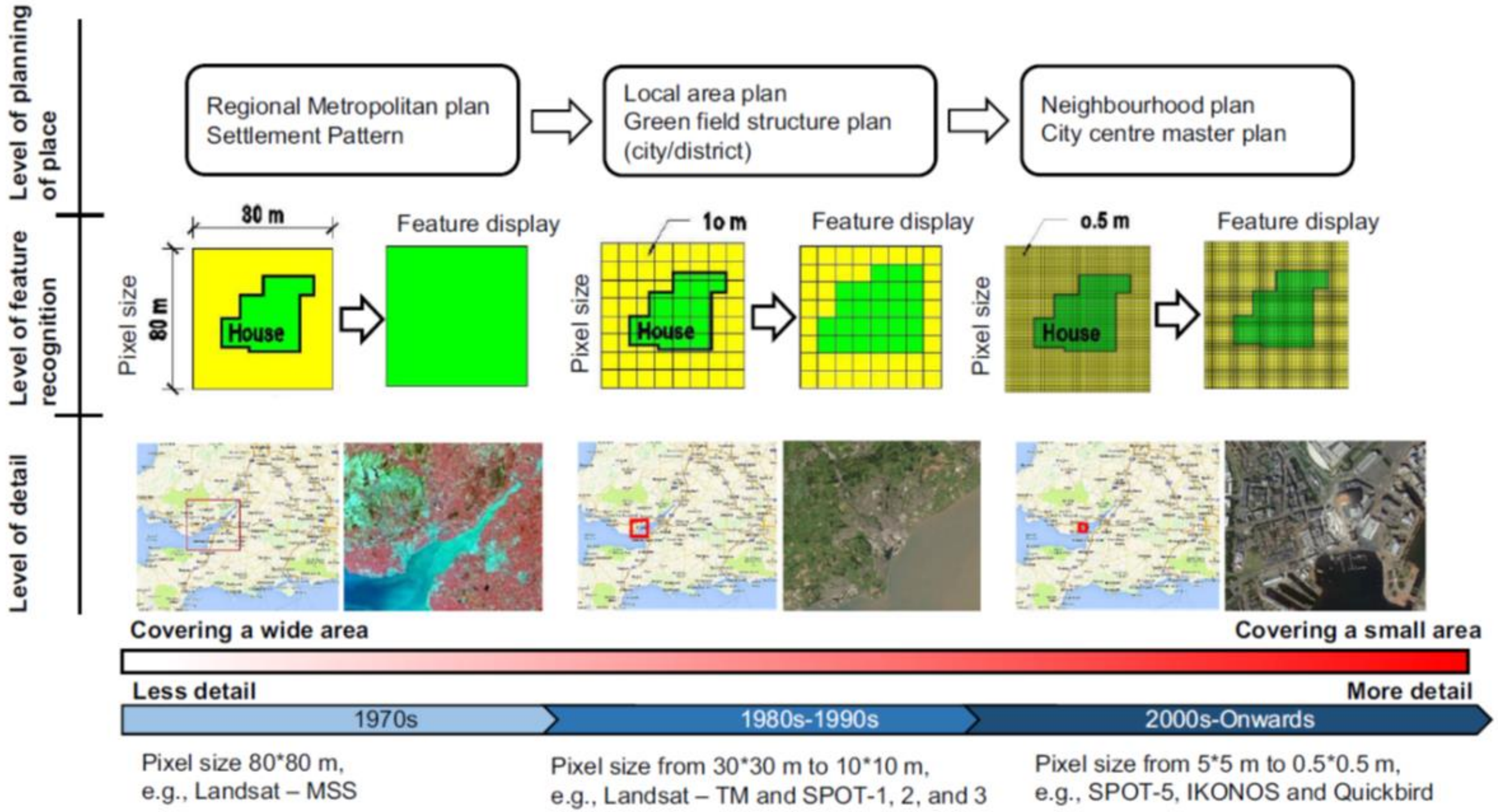
2.1. Development and Limitations of Large Satellites

- Satellite sizes and development



2.1. Development and Limitations of Large Satellites

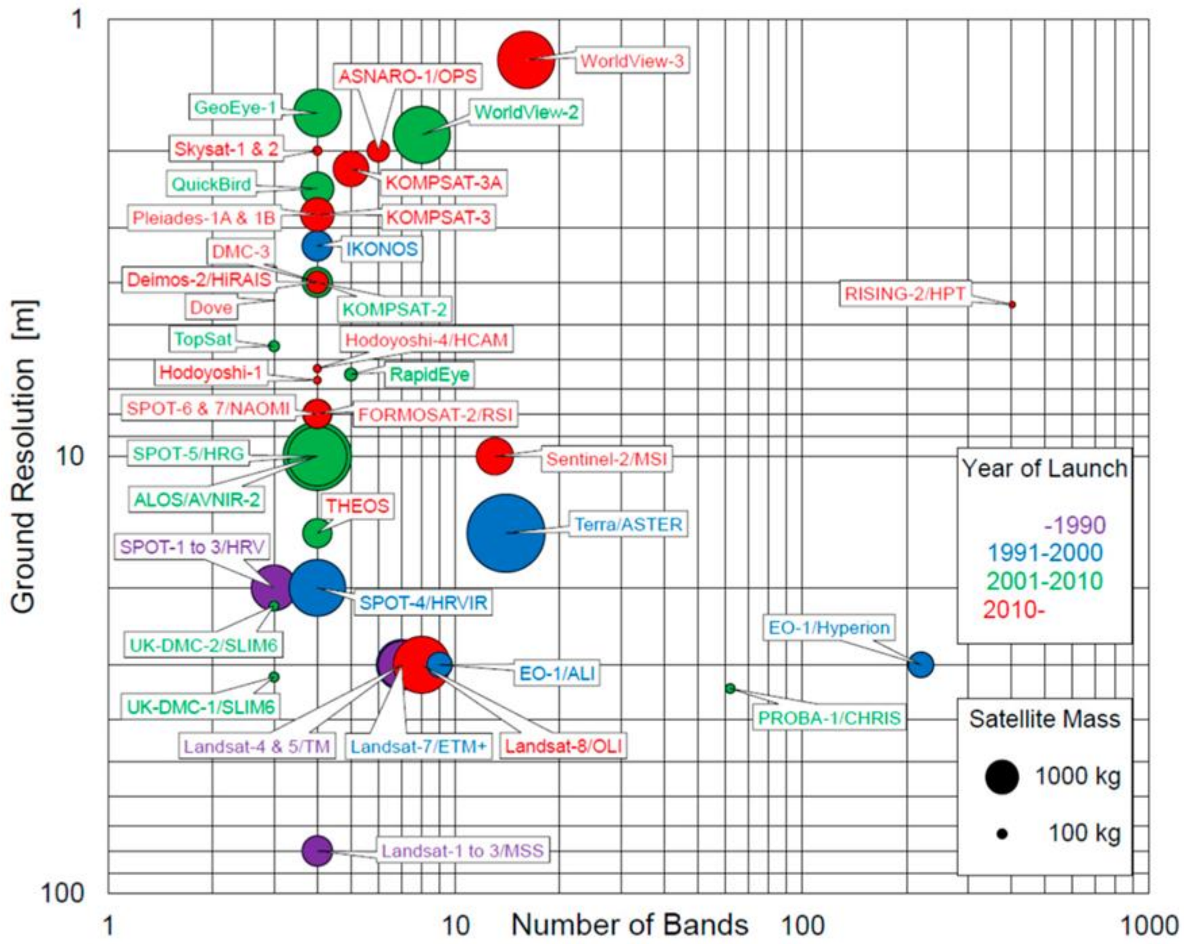
- Improvement of spatial resolution



(Kadhim et al., 2016)

2.1. Development and Limitations of Large Satellites

- Spatial resolution vs. spectral bands

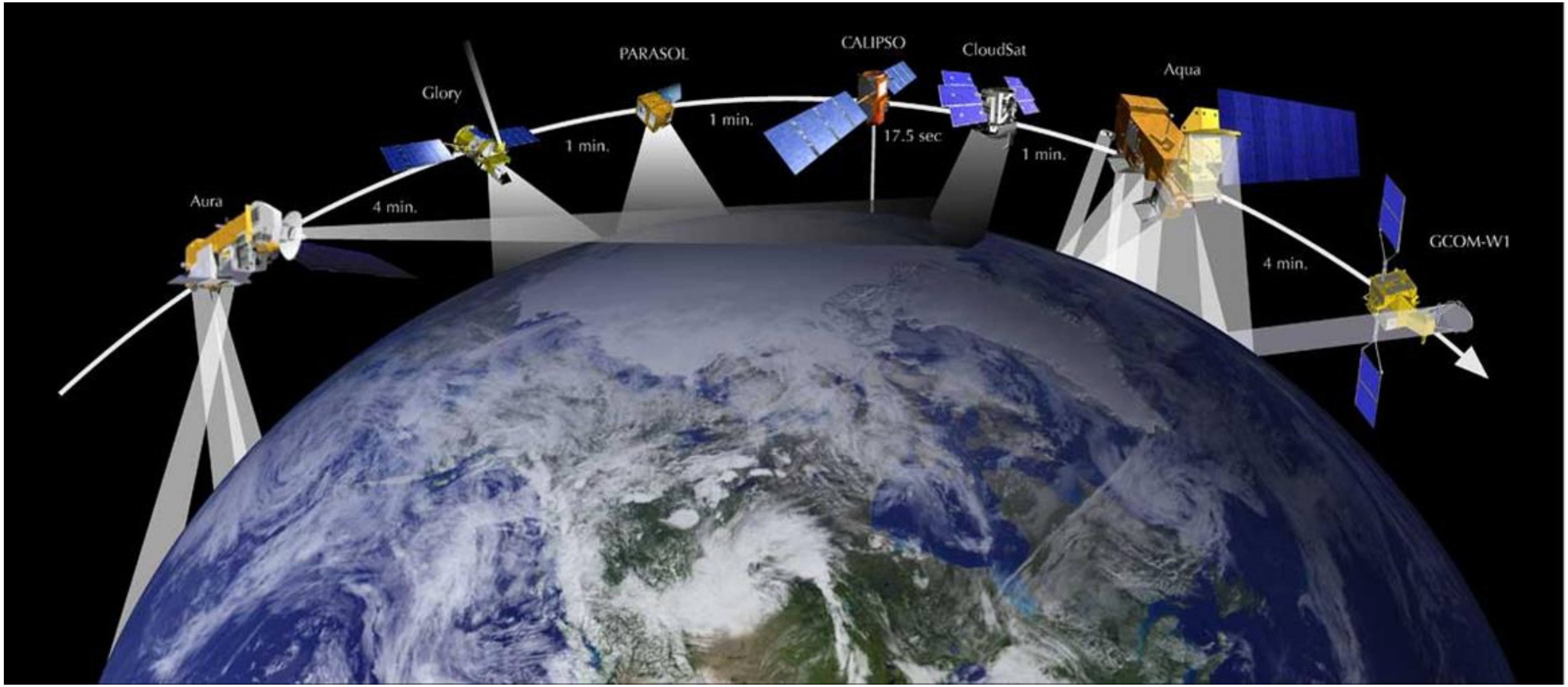


(Kurihara et al., 2018)

2. History and Trends in Earth Observation

2.1. Development and Limitations of Large Satellites

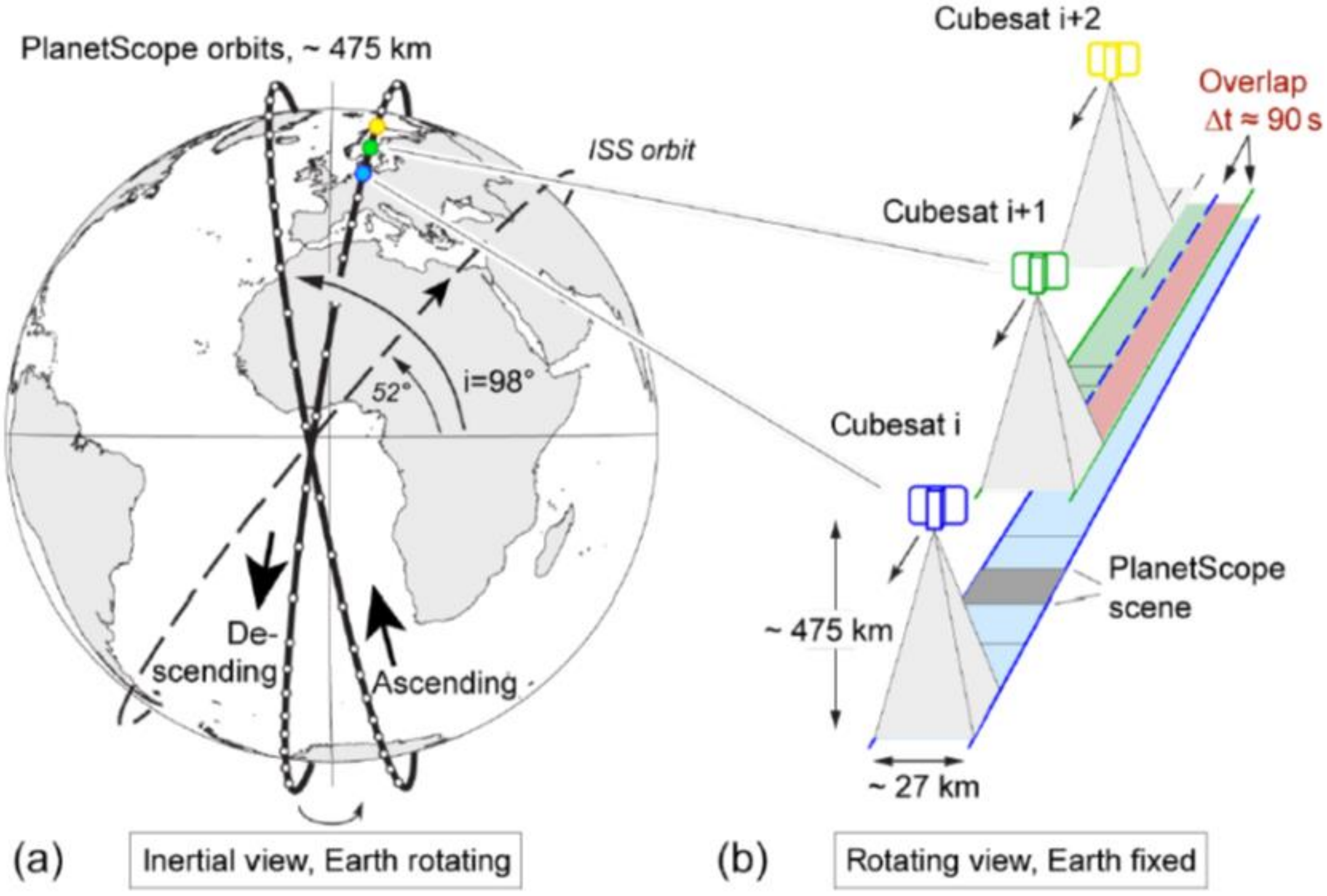
- A-train constellation



(Credit: NASA)

2.2. Emergence and Evolution of Microsatellites

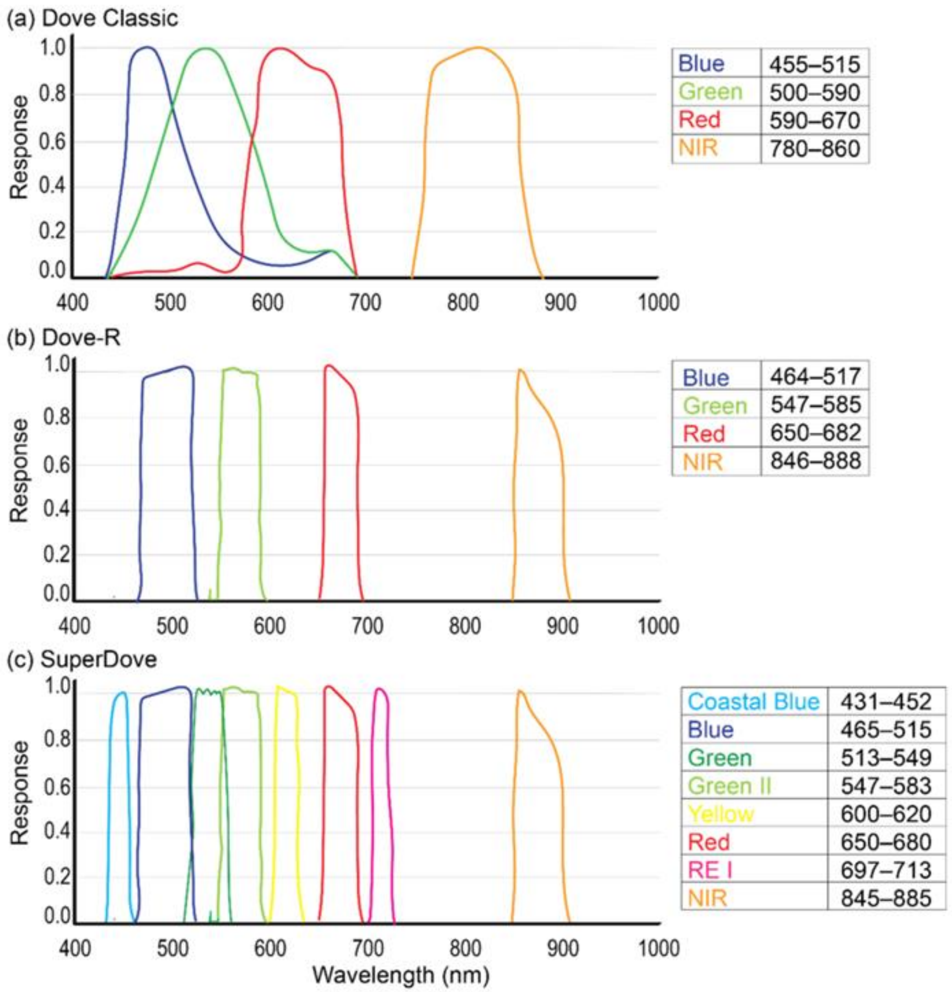
- Planet's 3U cubesat "Dove" constellation



(Kääb et al., 2019)

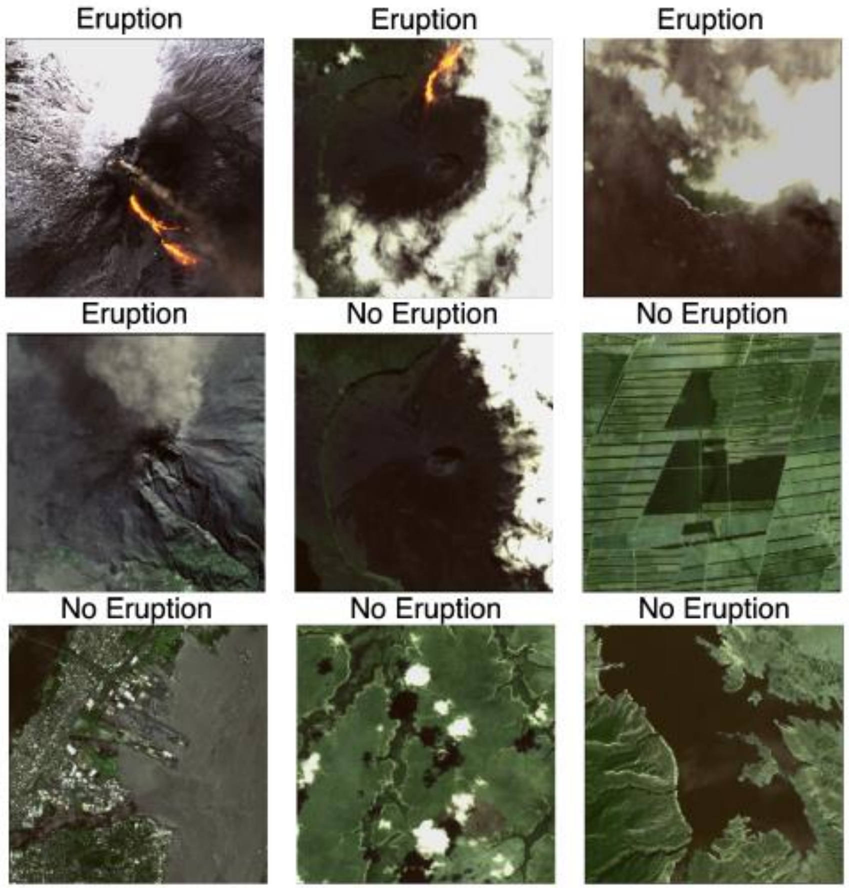
2.2. Emergence and Evolution of Microsatellites

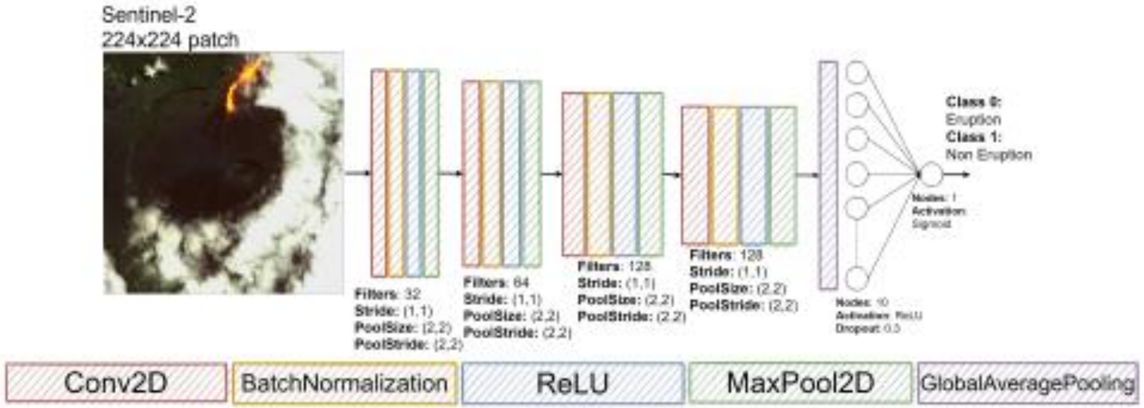
- Evolution of Dove cubesats

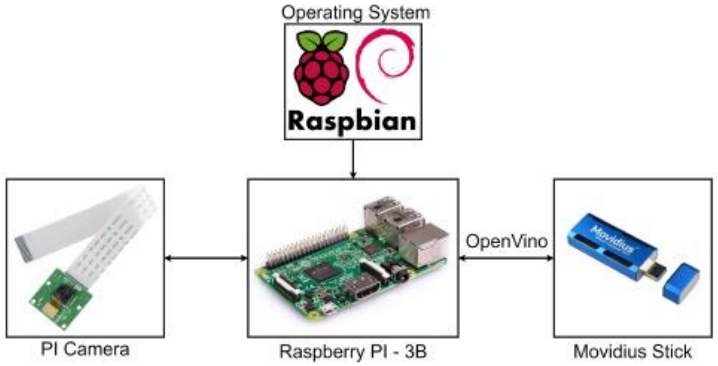


(Frazier and Hemingway, 2021)

- ESA’s 6U cubesat “Phy-Sat (ϕ-sat)”







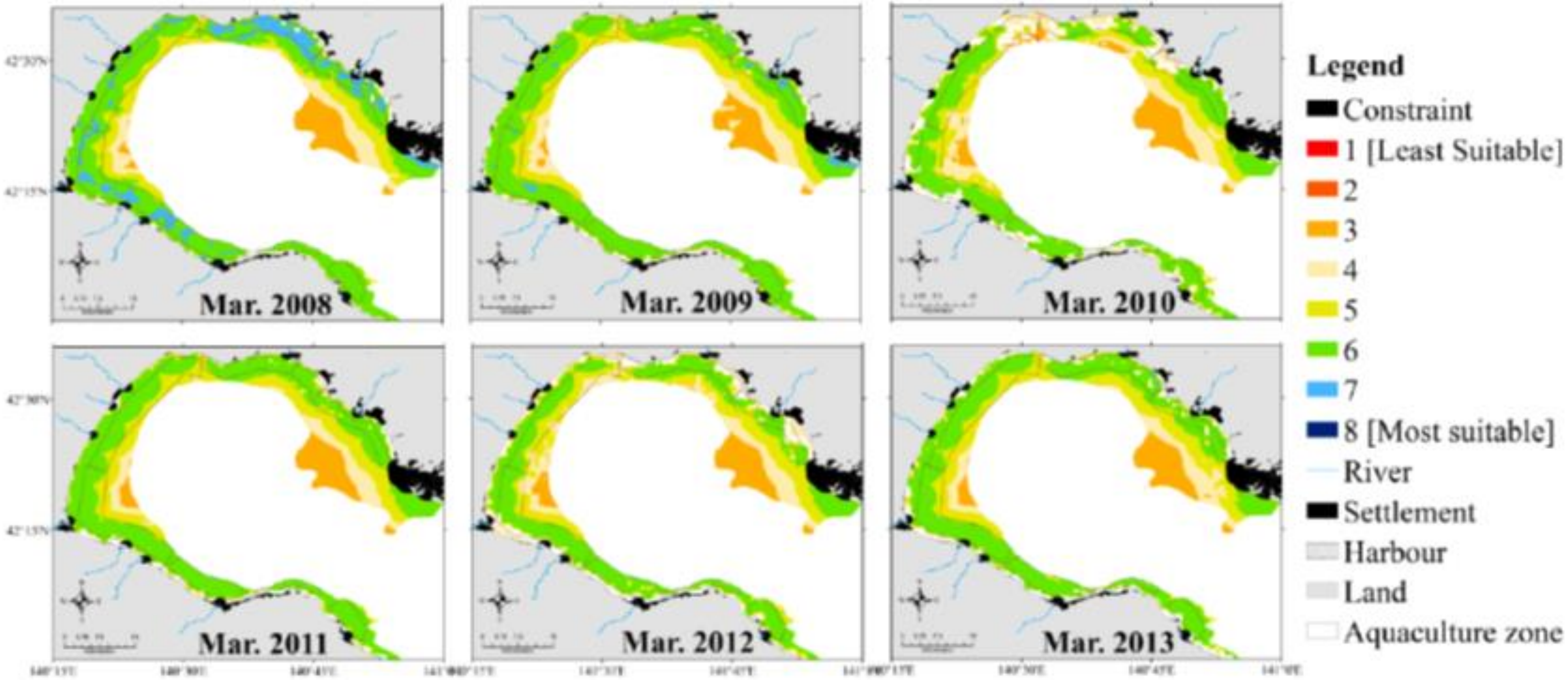
(Del Rosso et al., 2020)

3. Design and Manufacture of Optical Sensors

3.1. Mission Definition and Observation Requirements

- Mission example: Ocean color remote sensing

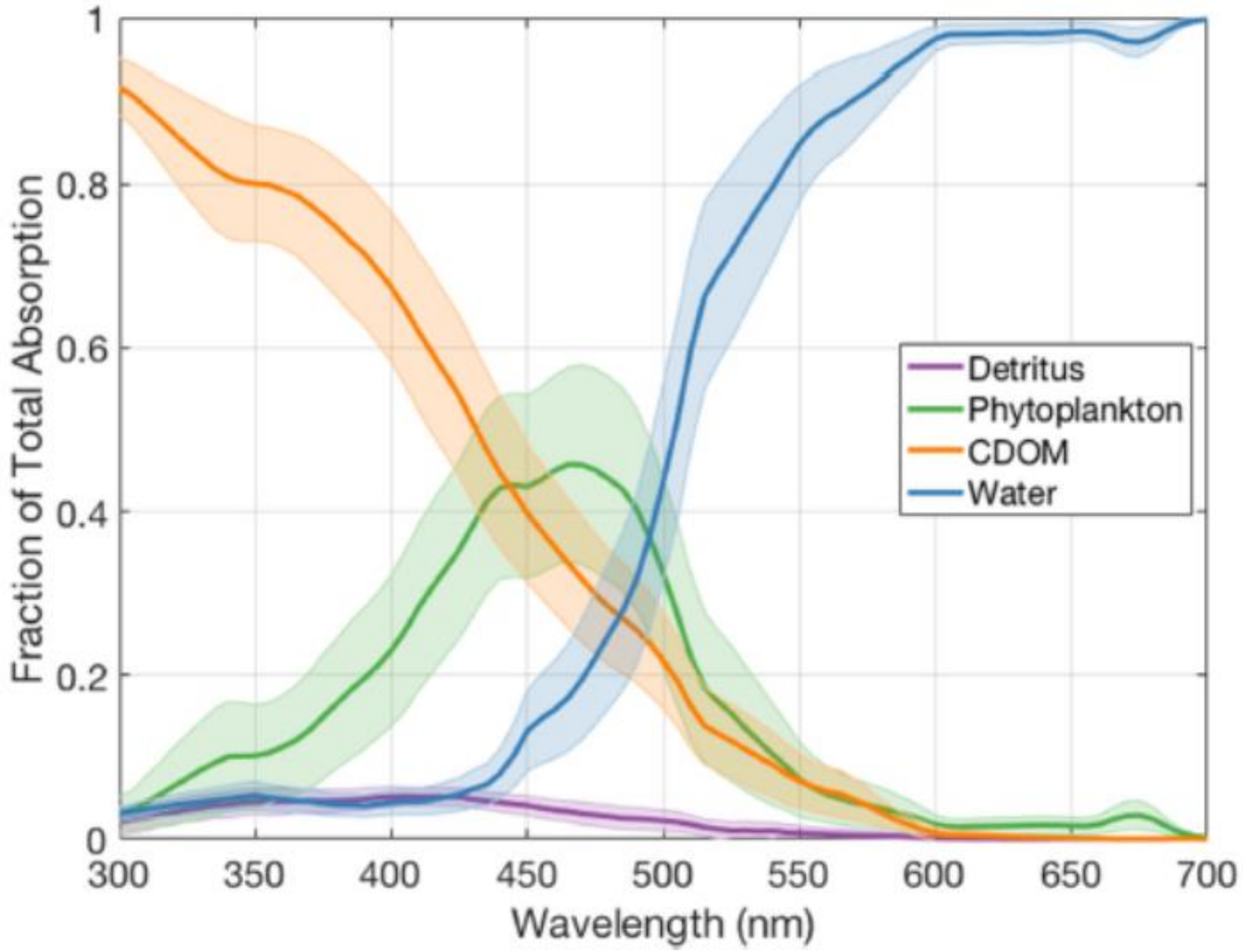
Suitable sites for Japanese scallop aquaculture



(Liu et al., 2015)

3.1. Mission Definition and Observation Requirements

- Observation target: Colored Dissolved Organic Matter (CDOM)



(Allen et al., 2020)

3. Design and Manufacture of Optical Sensors

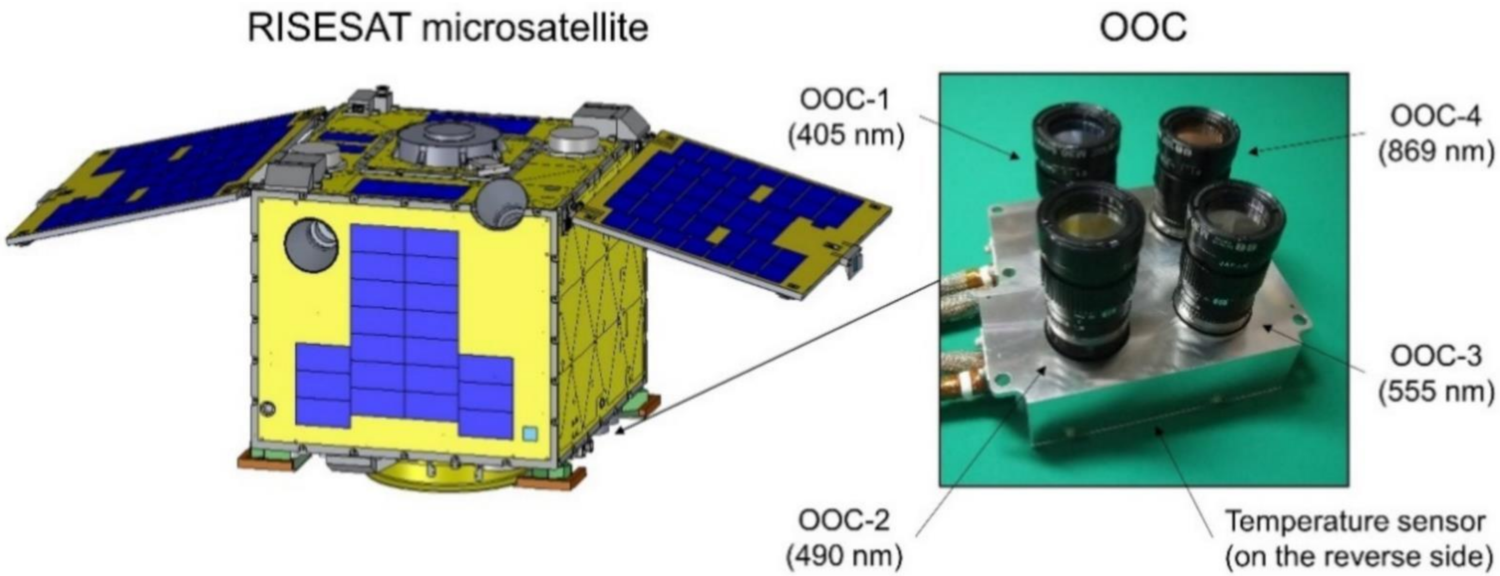
3.1. Mission Definition and Observation Requirements

- Observation requirements

Item	Requirement
Spectral range	Visible-NIR bands including 400—430 nm
Spectral resolution	10—30 nm
FOV	30—50 km
Spatial resolution	<100 m
Observation time	10 AM

3.2. Design and Manufacturing Concept

- Ocean observation camera (OOC) on RISESAT microsatellite



Size	388 × 161 × 124 mm
Weight	0.8 kg
GSD	74 m (at 500 km alt.)
FOV	5.6° × 4.2° (48 × 36 km at 500 km alt.)

Spectral Bands	OOC-1: 405 nm OOC-2: 490 nm OOC-3: 555 nm OOC-4: 869 nm
Image Size	659 × 494 pixels
Data Quantization	10 bit

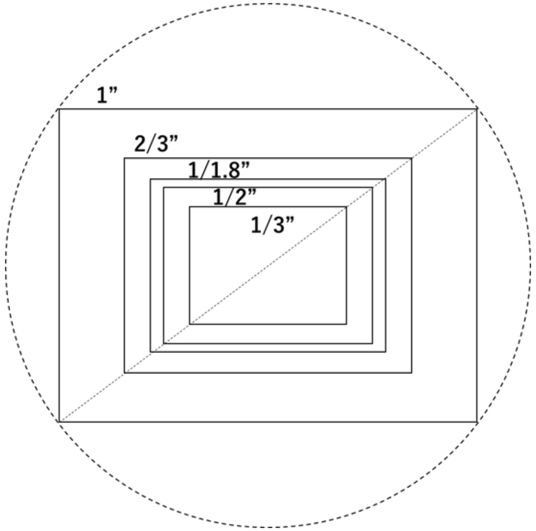
(Imai et al., 2021)

3. Design and Manufacture of Optical Sensors

3.2. Design and Manufacturing Concept

- How to select a detector
  - CCD vs. CMOS
  - Sensor size
  - Image size
  - Space proven

WATEC T065



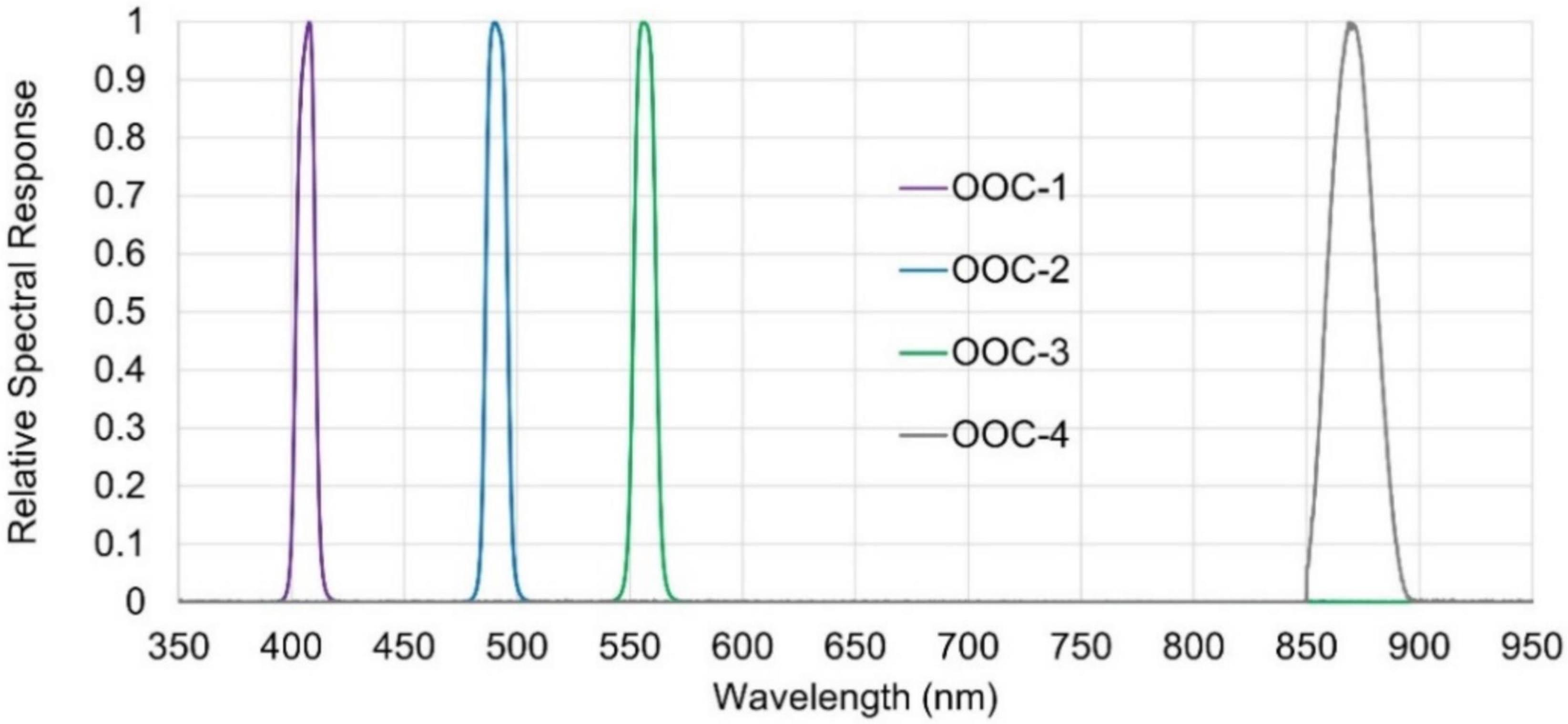
- How to select a lens
  - Focal length
  - FOV
  - Spatial resolution
  - Spectral range
  - Customization

MORITEX ML-5018

Format	Sensor size	Diagonal length
1”	12.8 × 9.6 mm	16 mm
2/3”	8.8 × 6.6 mm	11 mm
1/1.8”	7.2 × 5.3 mm	9 mm
1/2”	6.4 × 4.8 mm	8 mm
1/3”	4.8 × 3.6 mm	6 mm

3.2. Design and Manufacturing Concept

- How to select a bandpass filter
  - Center wavelength
  - Band width
  - Peak transmittance
  - Blocking
  - Optical density

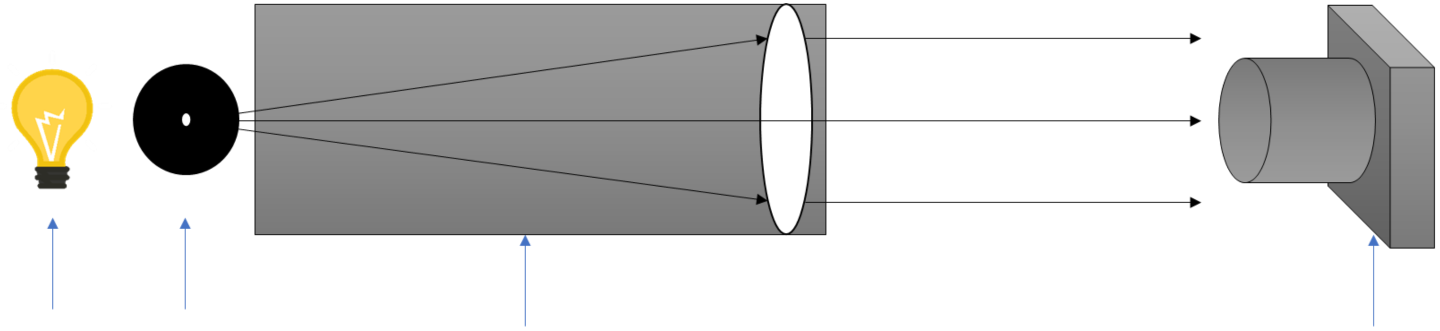


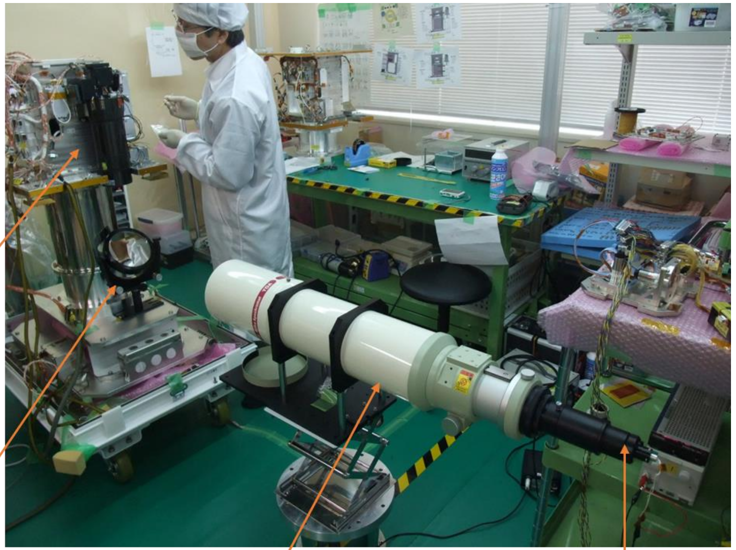
(Imai et al., 2021)

4. Testing and Control of Optical Sensors

4.1. Objectives and Methods of Tests

- Focus adjustment



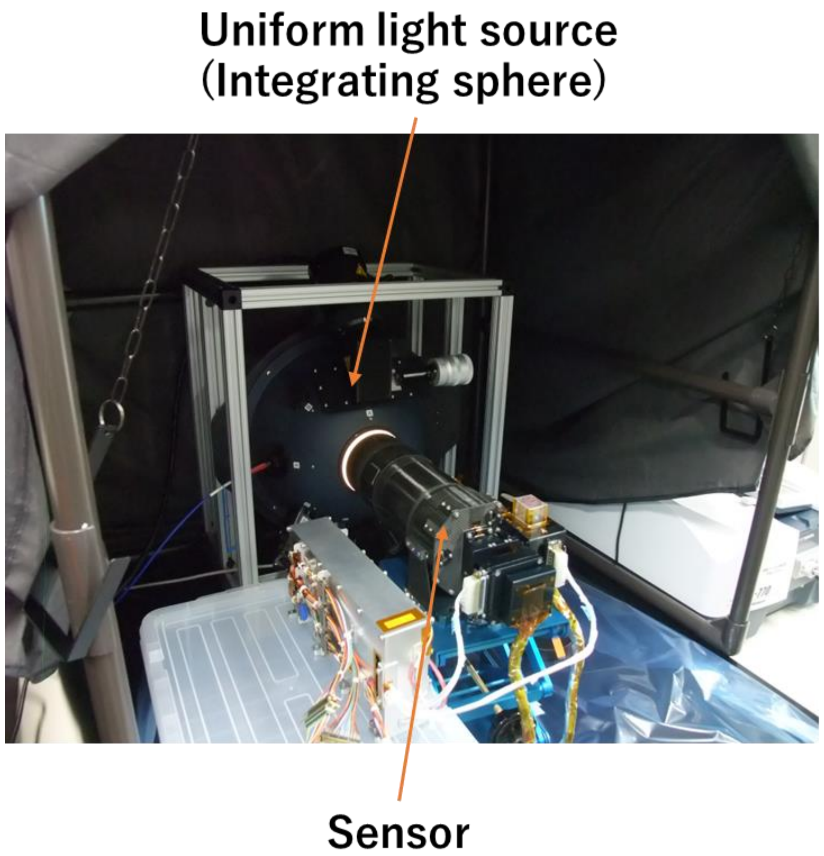


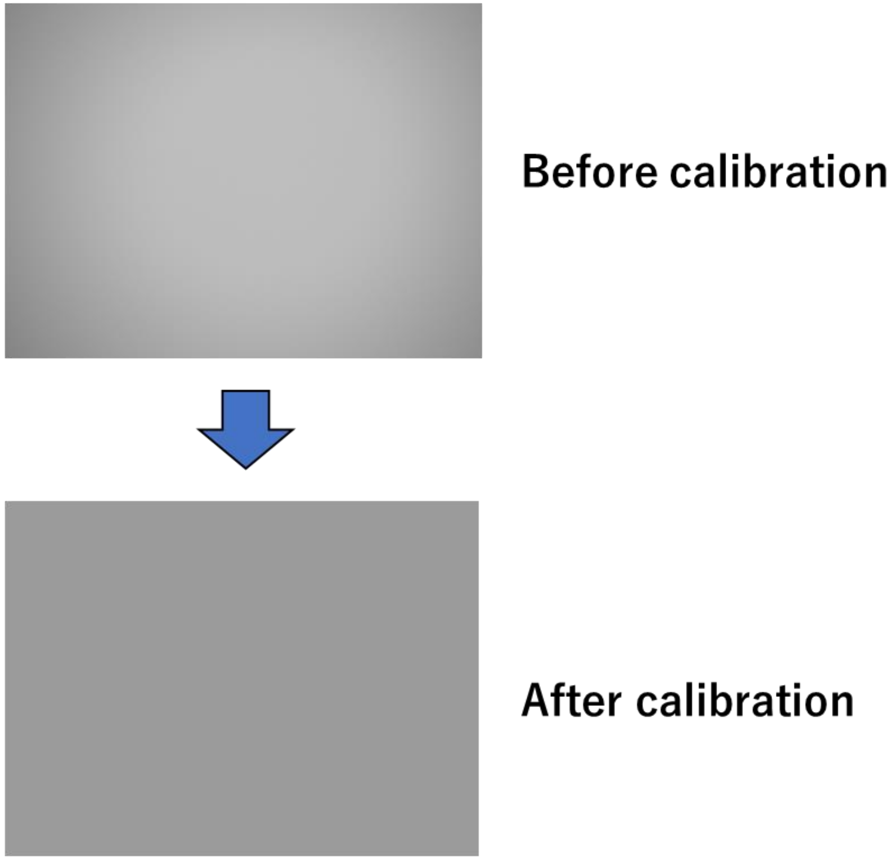
Credit: J. Kurihara, Hokkaido Information University

4. Testing and Control of Optical Sensors

4.1. Objectives and Methods of Tests

- Radiometric calibration (Laboratory)

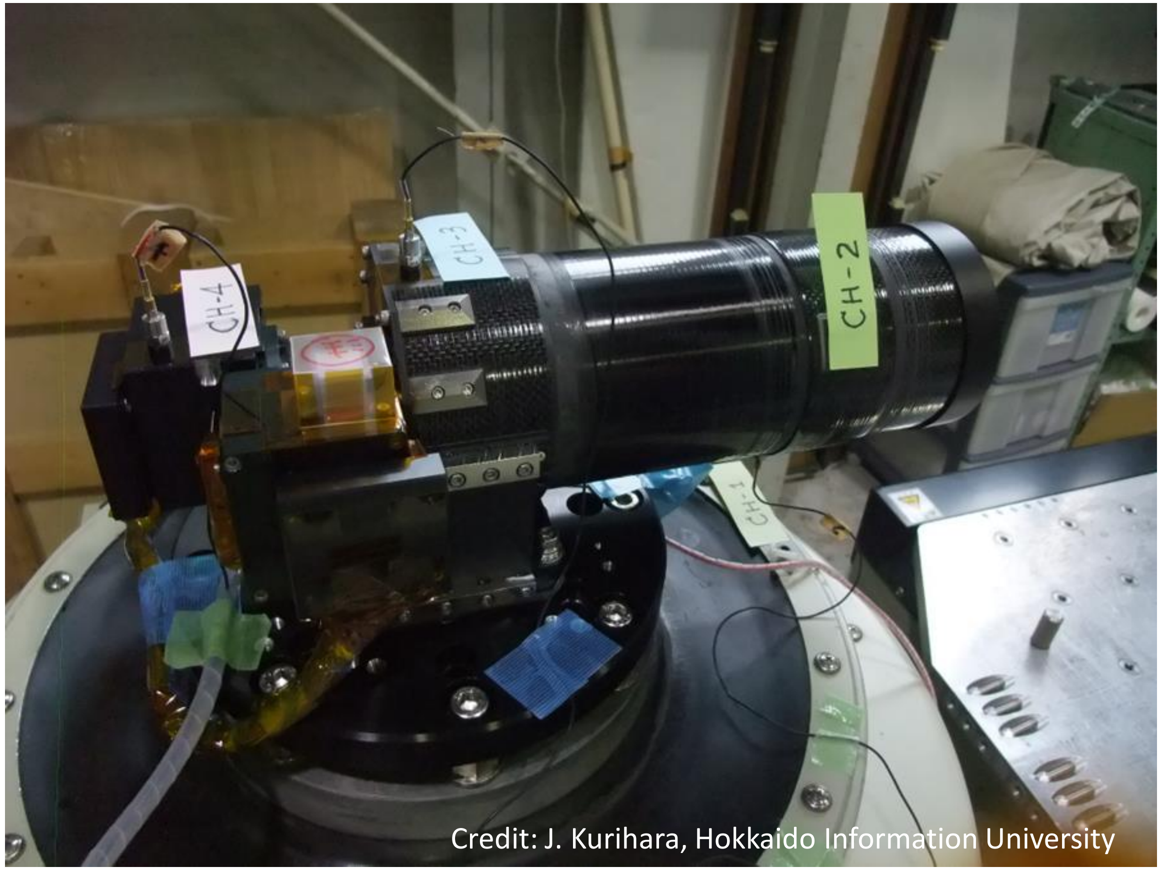




Credit: J. Kurihara, Hokkaido Information University

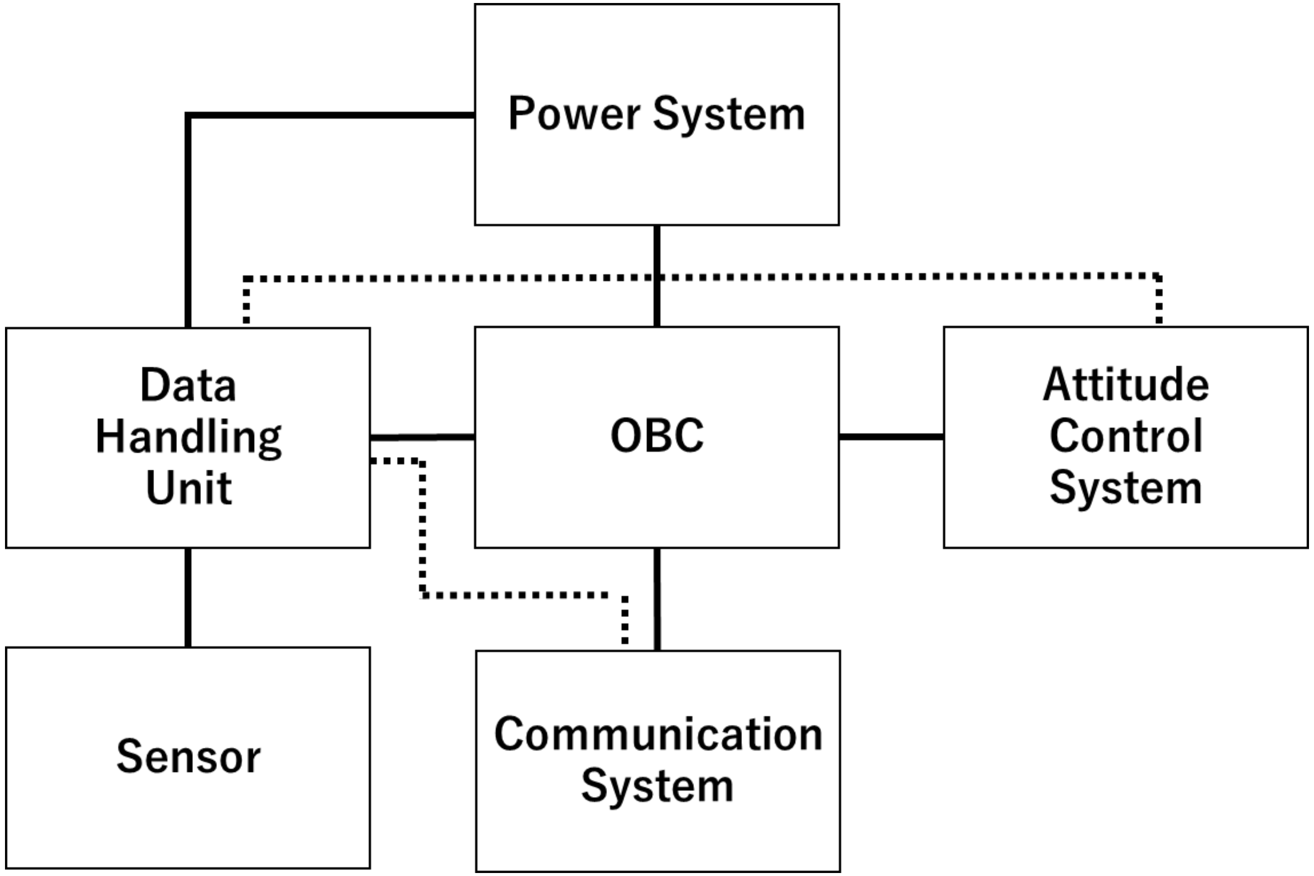
4.1. Objectives and Methods of Tests

- Other environment tests
  - Vibration and shock tests
  - Thermal and vacuum tests
  - Radiation tests



Credit: J. Kurihara, Hokkaido Information University

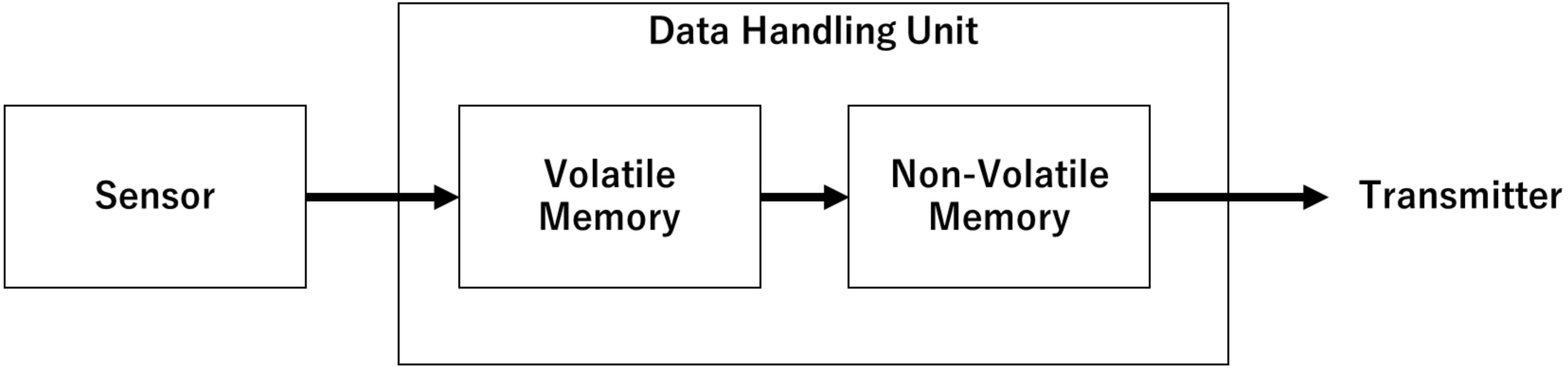
- What is Data Handling Unit (DHU)?



4. Testing and Control of Optical Sensors

4.2. Data Processing and Communication Devices

- Volatile and non-volatile memories



5. Satellite Operation and Data Processing

5.1. From Commissioning Phase to Nominal Operation Phase

- After completion of a satellite …
  1. Completion of a satellite
  2. Handover
  3. Launch
  4. Commissioning phase
  5. Nominal Operation

- Re-plan operations during the period between completion and launch of the satellite

5. Satellite Operation and Data Processing

5.1. From Commissioning Phase to Nominal Operation Phase

- Notes on initial operation
  - Confirmation of satellite bus system (power, communication, etc.) operation is the top priority
  - Operation of an optical sensor is checked after establishment of coarse attitude control
  - Check each of the important functions one by one, starting with the most important ones
    1. Power ON/OFF
    2. House Keeping (HK) status such as voltage, current, and temperature
    3. Image capture
    4. Exposure time and gain change
    5. Memory storage
    6. Downlink communication
  - Use the same procedures and commands as before launch

5. Satellite Operation and Data Processing

5.1. From Commissioning Phase to Nominal Operation Phase

- If problems occur during commissioning phase …
  - Carefully check for differences from pre-launch (commands, status, procedures…)
  - Need to question pre-launch data/records
  - Reproduce experiments using remaining EM equipment on the ground
  - Consider the possibility that transportation and launch may have caused the problem
  - Share with the community as valuable lessons learned

- Difference between commissioning phase and nominal operation phase
  - Commissioning phase
    - Short-term (a few days to a few months)
    - Concentration of human resources
    - Information sharing with the same members
  - Nominal operation phase
    - Long-term (cannot see the future)
    - Need to streamline human resources
    - Succession occurs due to change of members

- Documentation and automation of operational procedures in the commissioning phase is important

5. Satellite Operation and Data Processing

5.2. Data Processing Levels

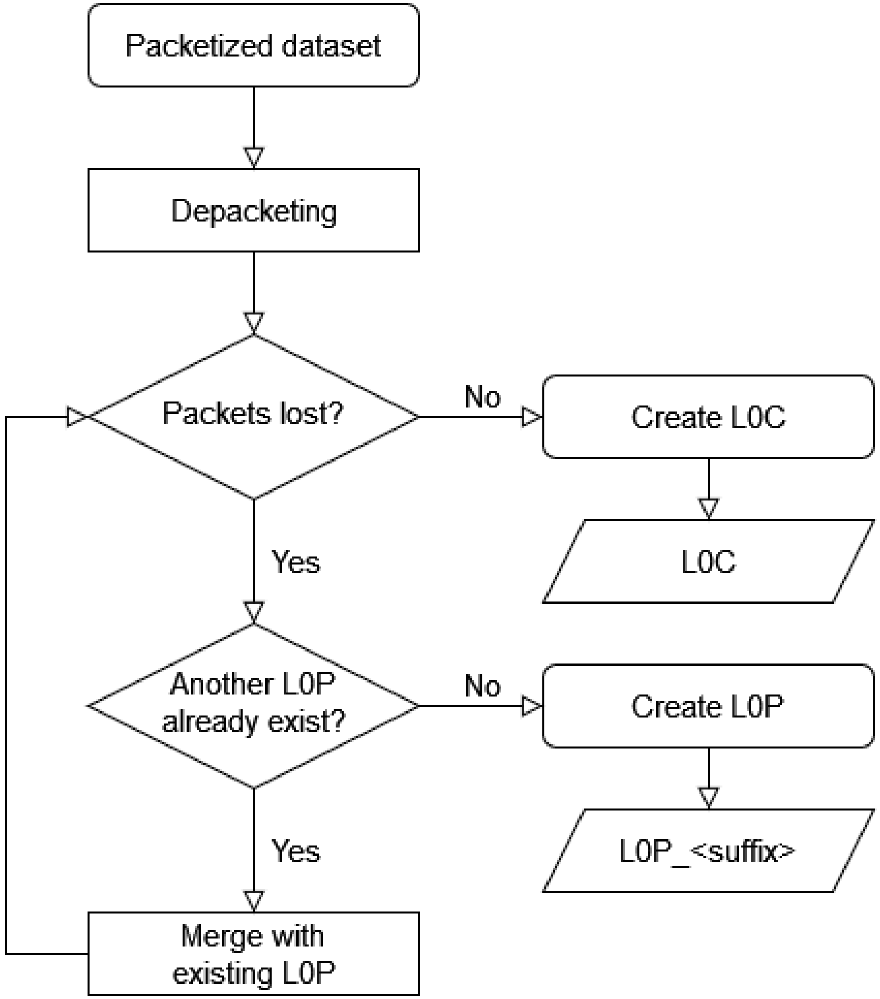
- Definition of data processing levels

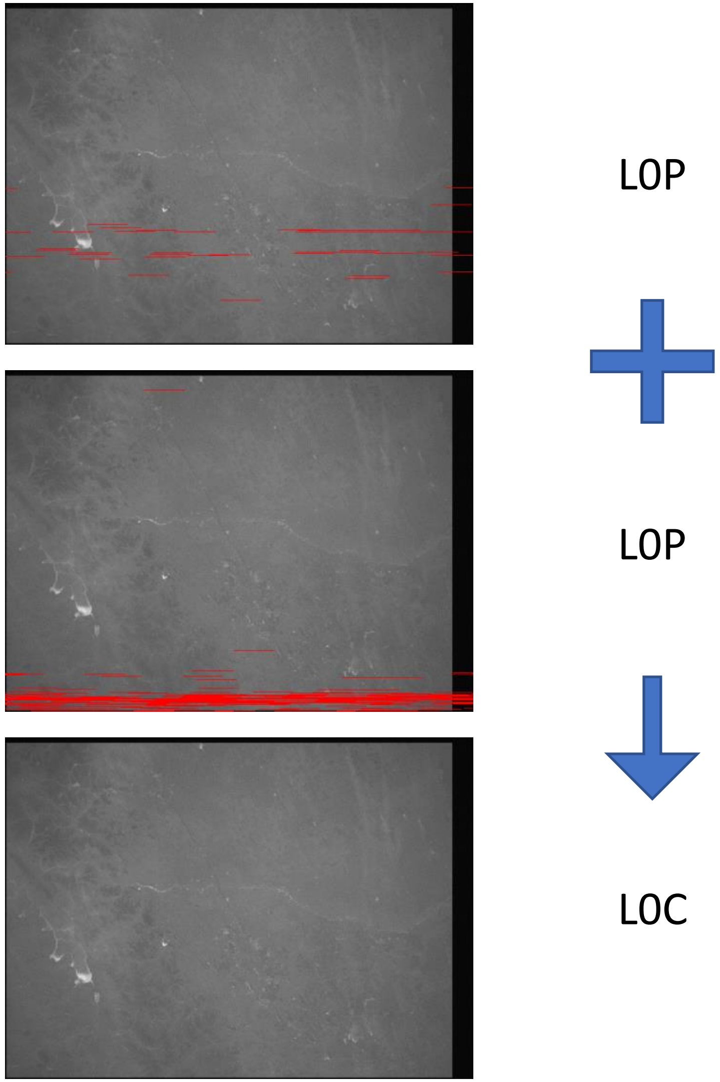
Data Levels	Definitions
Level 0	Unprocessed raw data
Level 1A	Unprocessed data with ancillary data
Level 1B	Radiometrically and geometrically corrected data
Level 2	Atmospherically corrected data

5. Satellite Operation and Data Processing

5.2. Data Processing Levels

- L0 data processing



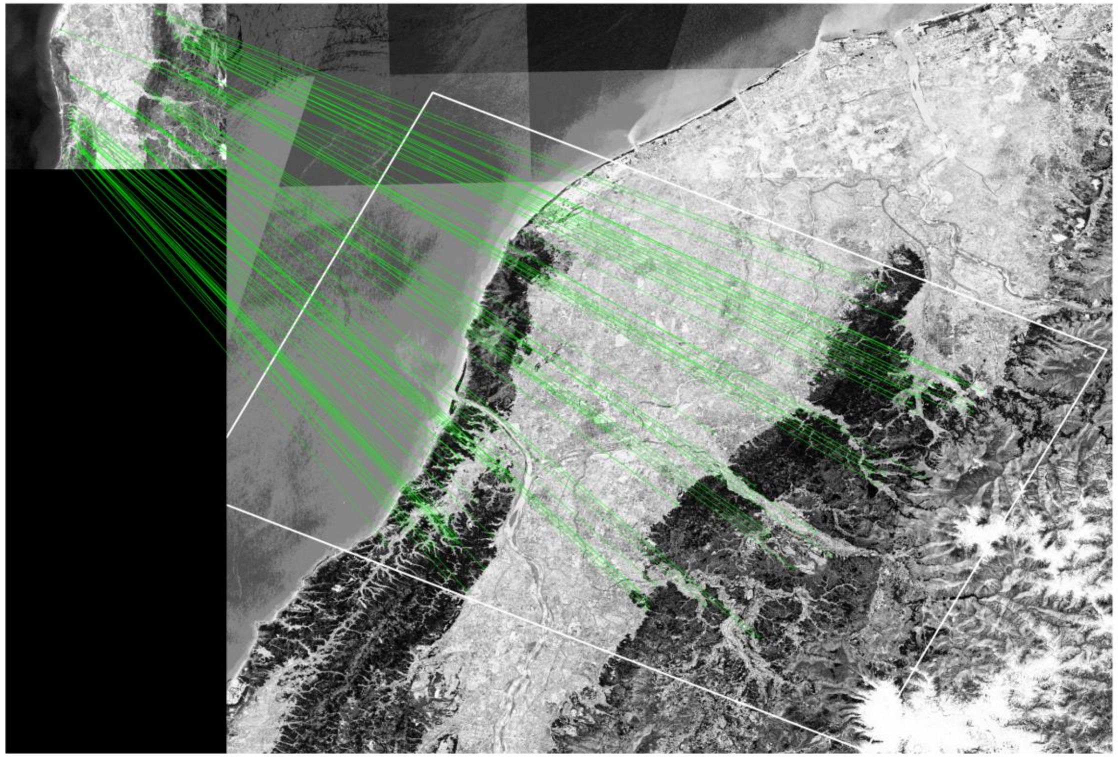


(Kurihara et al., 2023)

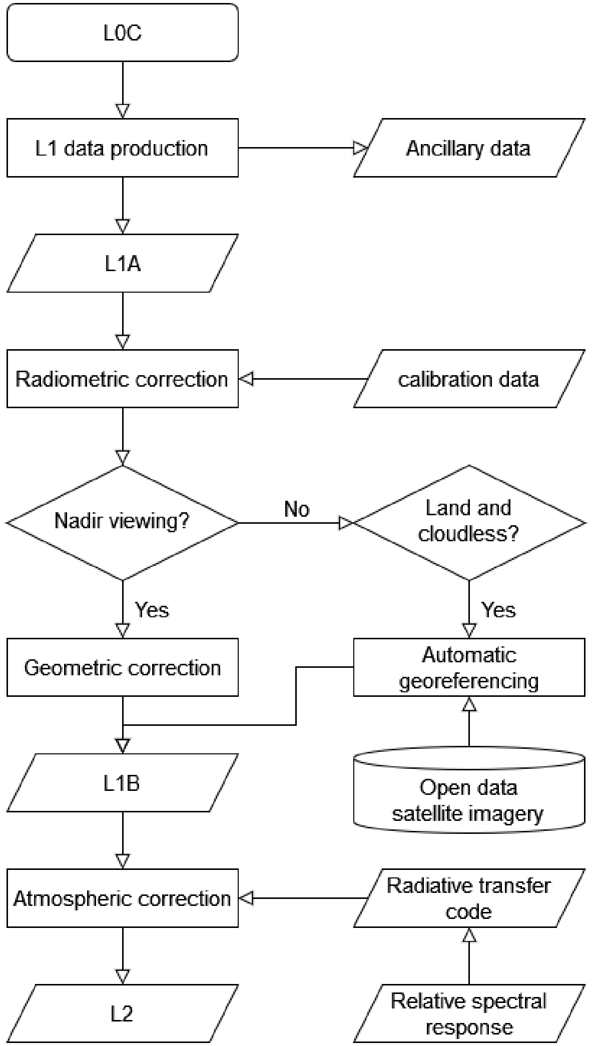
5. Satellite Operation and Data Processing

5.2. Data Processing Levels

- L1 and higher-level data processing



(Kurihara et al., 2023)



6. On-orbit Calibration and Data Management

6. On-orbit Calibration and Data Management

6.1. Examples of On-orbit Calibration

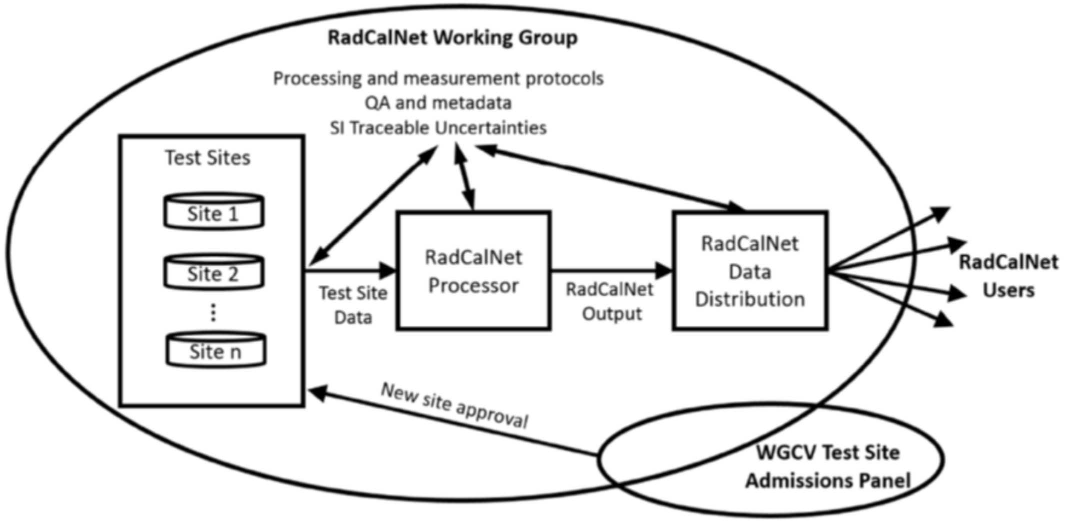
- On-orbit calibration methods
  - Onboard calibration
    - Calibration equipment (lamps and solar diffusers) to be mounted on the satellite
    - Calibration equipment itself may also deteriorate due to launch and aging
    - Difficult to mount on small satellites
  - Vicarious calibration
    - Observation of ground targets with known radiative properties (e.g. deserts)
    - Simultaneous ground observation data required
    - Uncertainty in atmospheric correction
  - Lunar calibration
    - Lunar observations are free from atmospheric effects, and changes in lunar reflectance over time are negligible
    - Observation opportunities around twice a month, before and after the full moon
    - Accuracy depends on lunar reflectance model used
    - Large satellites cannot observe the Moon at high frequency

6. On-orbit Calibration and Data Management

6.1. Examples of On-orbit Calibration

- Suitable target site for vicarious calibration
  - High reflectance, isotropically diffuse, and spatially homogeneous ground surface
  - High frequency of clear-skies and dry atmosphere

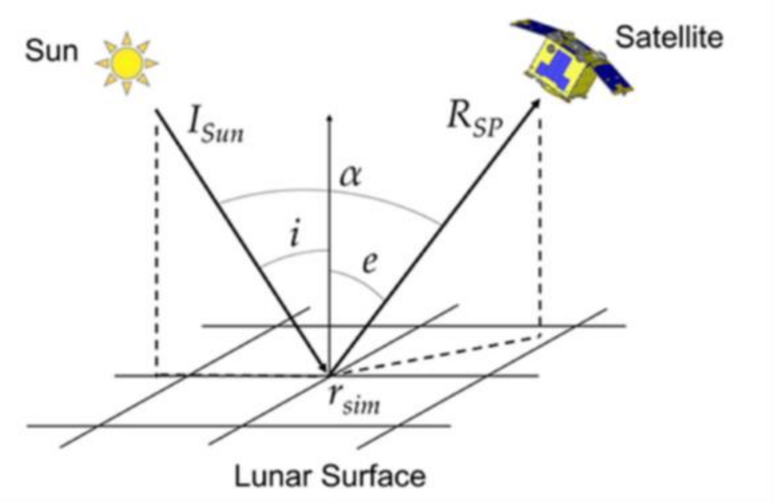
- RadCalNet (Radiometric Calibration Network)
  - A network of vicarious calibration sites operated under the Committee on Earth Observation Satellites (CEOS)
  - Data from each site is collected, processed, and published on the Internet

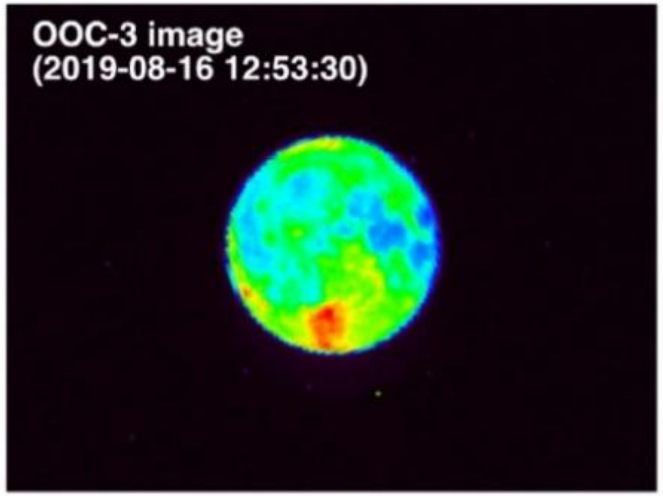


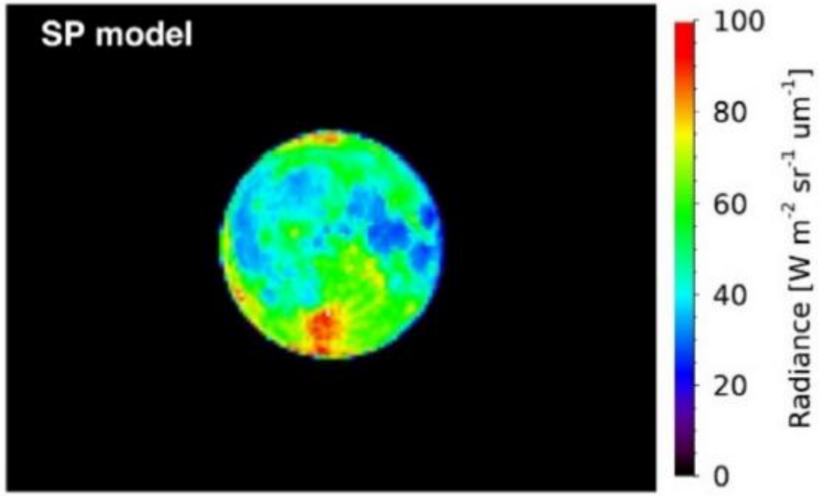
(Bouvet et al., 2021)

6.1. Examples of On-orbit Calibration

- Lunar calibration requirements
  - Before or after full moon, phase angle α is more than 7°
  - Moon is completely in the field of view → ROLO model
  - Moon is only partially in the field of view → SP model







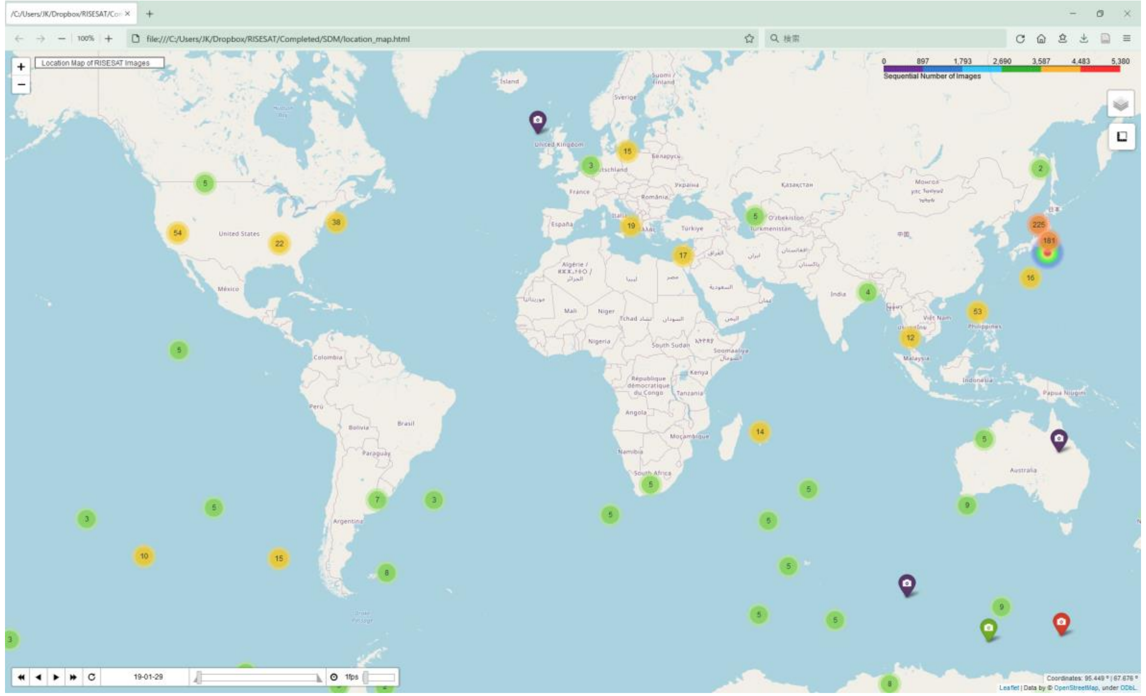
(Imai et al., 2021)

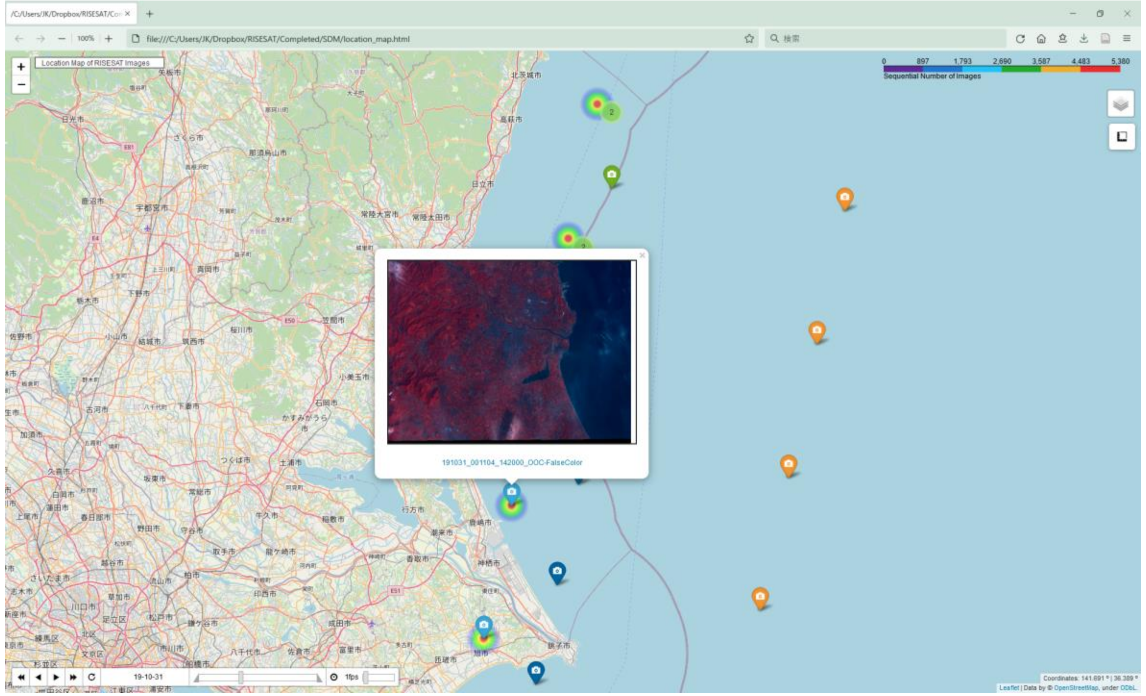
6.2. Management of Observation Data

- Problems related to observation data
  - Security
    - Satellite remote sensing law
  - Reliability
    - Various data processing and processing levels (Chapter 5.2)
    - On-orbit calibration (Chapter 6.1)
  - Availability
    - Automation and efficiency of data processing (Chapters 5.1 and 5.2)
    - Management of observation data (this section)

6.2. Management of Observation Data

- Satellite Data Manager (SDM)





(Kurihara et al., 2023)

7. Conclusion

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- When designing an optical sensor, it is necessary to carefully examine the optical characteristics of the observation target and select the optics and detector suitable for the observation

- When installing an optical sensor on a small satellite or cubesat, it is necessary to conduct tests to confirm its optical performance in addition to environmental tests

- Even for small satellites or cubesats, observation data from optical sensors are large, so it is advisable to plan data processing and management well in advance of launch.

Thank you very much.

[Disclaimer]
The views and opinions expressed in this presentation are those of the authors and do not necessarily reflect those of the United Nations.