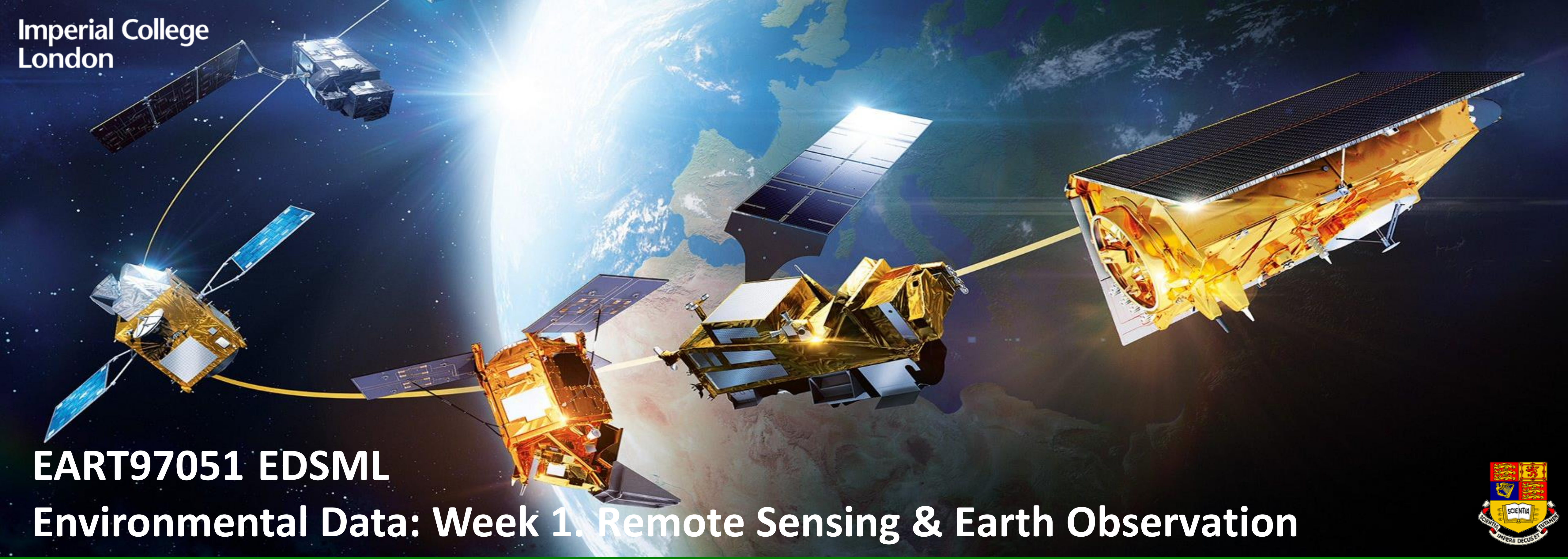

Imperial College London

EART97051 EDSML

Environmental Data: Week 1. Remote Sensing & Earth Observation

1a Physical principles, orbits, sensors & resolution

Dr Philippa J. Mason

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Department of Earth Science & Engineering, Imperial College London, SW7 2AZ, UK
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Environmental Data Module

Summary: This course is about understanding complex datasets – what the data contain and what they mean, how they are collected, and what we can do with them

Course Outline:

Week 1: Remote Sensing and Earth Observation - 8th -12th Jan 2024 (Philippa Mason)

Week 2: Seismic imaging - 15th -19th Jan 2024 (Becky Bell)

Week 3: Climate data and analysis - 22nd - 26th Jan 2024 (Yves Plancherel)

Assessment:

Multiple choice exam on the last day of the module, 26th January (containing an even split of questions drawing from each of the 3 elements of the module)

1. Remote Sensing & Earth Observation - Course structure

Summary: Remote sensing principles, sensors, data types & essential image processing tools (mainly optical data and an introduction to SAR data and its uses)

Assessment: Multiple-choice on 26th Jan 2024

Course Outline: Lectures and related practical exercises (and approximate timings)

Mon	Tues	Wed	Thurs	Fri
10.00 – 11.00 L1a 11.15 – 12.00 L1b	09.00 – 10.00 L3 10.15 – 12.00 P3	09.00 – 10.00 L5 10.15 – 12.00 P5	Independent Group Project work (with support from GTAs between 10.00 and 12.00 and 13.00 and 15.00)	Project presentations Starting at 09.00 with a one-hour lunchbreak at 12.00
13.00 – 13.45 L2 14.00 – 16.00 P2	13.00 – 14.00 L4 14.15 – 16.00 P4	Free time		

1. Mon: am – (L1) Physics, sensor tech., resolution; (L2) pm - digital raster image data, point ops & algebraic operations
2. Tues: (L3) am - Colour coordinate transformations & PCA; (L4) pm – radar remote sensing
3. Wed: (L5) am - terrain analysis and project examples; pm – free time, sports etc
4. Thurs: Group project work – Nagasaki environmental assessment
5. Fri: Group project presentations

Module Learning Objectives

In this course, the emphasis is on **EO data and numerical tools for processing them, to extract and understand their information**, rather than on coding. However, there will be time for you to experiment with coding (especially in the GEE sessions with Shuaib) and the assessment will offer an opportunity to write some code to process image data yourself.

Liu & Mason, Image Processing and GIS for Remote Sensing: Techniques and Applications, Second Edition, 2016, Wiley, Online ISBN:9781118724194

Plus there are tons of resources (and ready code) available for EO applications. Check out:

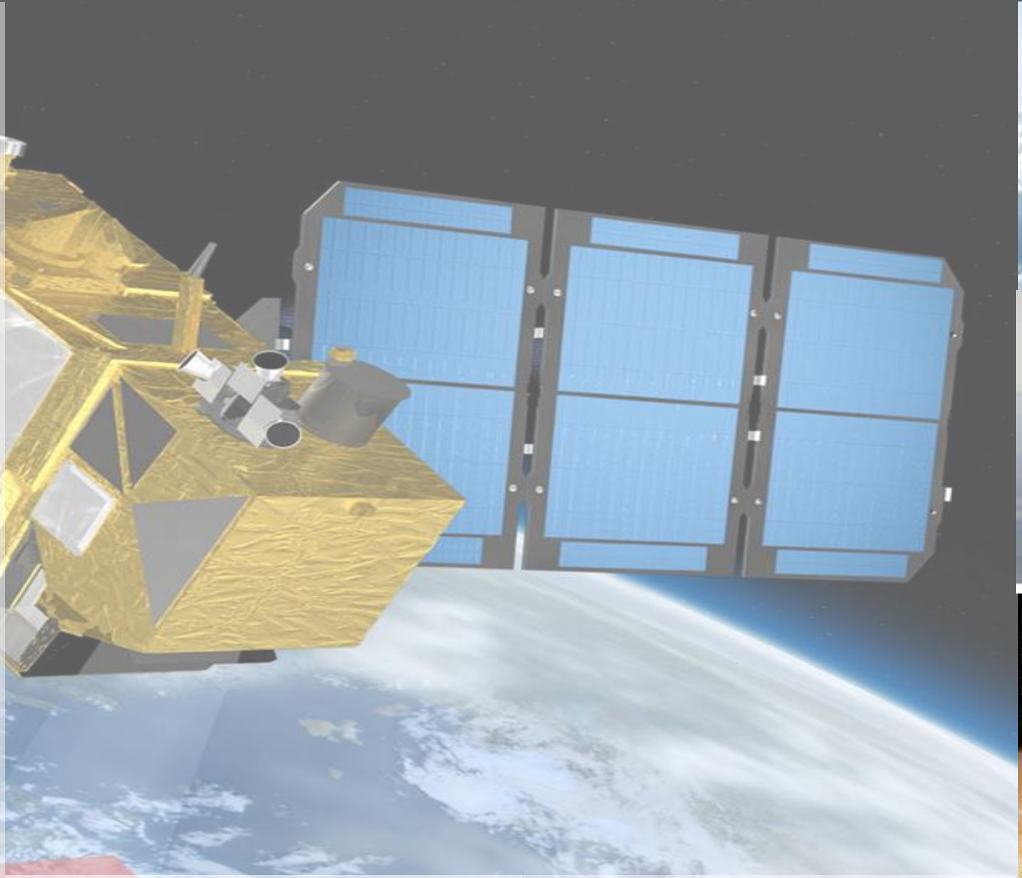
1. eo-learn https://pypi.org/project/eo-learn
2. GitHub.com/arcgeospatial/awesome-earthobservation-code
3. GitHub.com/sentinel-hub/eo-learn-workshop
4. GitHub.com/earthlab/earth-analytics-python-env
5. **ESE Jupyter notebooks (by Raul Adraeinsen)**
6. Earthdatascience.org/courses/earth-analytics-python
7. Raster data format descriptors and drivers **GDAL.org**

Remote sensing is …
the acquisition of information about an object without making physical contact with that object. In plain English this refers to …

the taking of images from spacecraft and aircraft, and the use of those images to extract information about the Earth's surface (land, oceans or atmosphere). Techniques pioneered by aerial photography (first practiced over Paris, in 1858).

The term ***Remote Sensing*** first used after the first Earth Resources Satellite, Landsat-1, was successfully launched in 1972. Today there are 1000s of such satellites in operation around Earth.

Now popularly known as **Earth Observation**

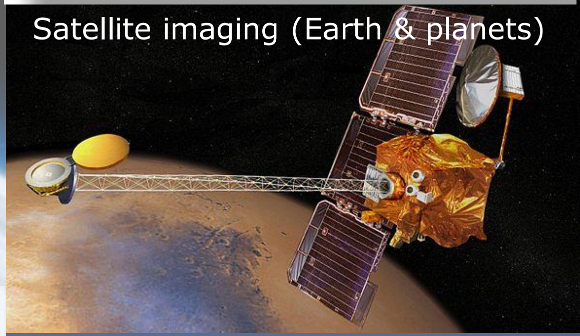


GEOSPHERE
BIOSPHERE
CRYOSPHERE

HYDROSPHERE
Ocean colour
SST & circulation

ATMOSPHERE
Circulation
Weather
Pollution

ANTHROPOSPHERE
Hazards
Urban applications
Shipping



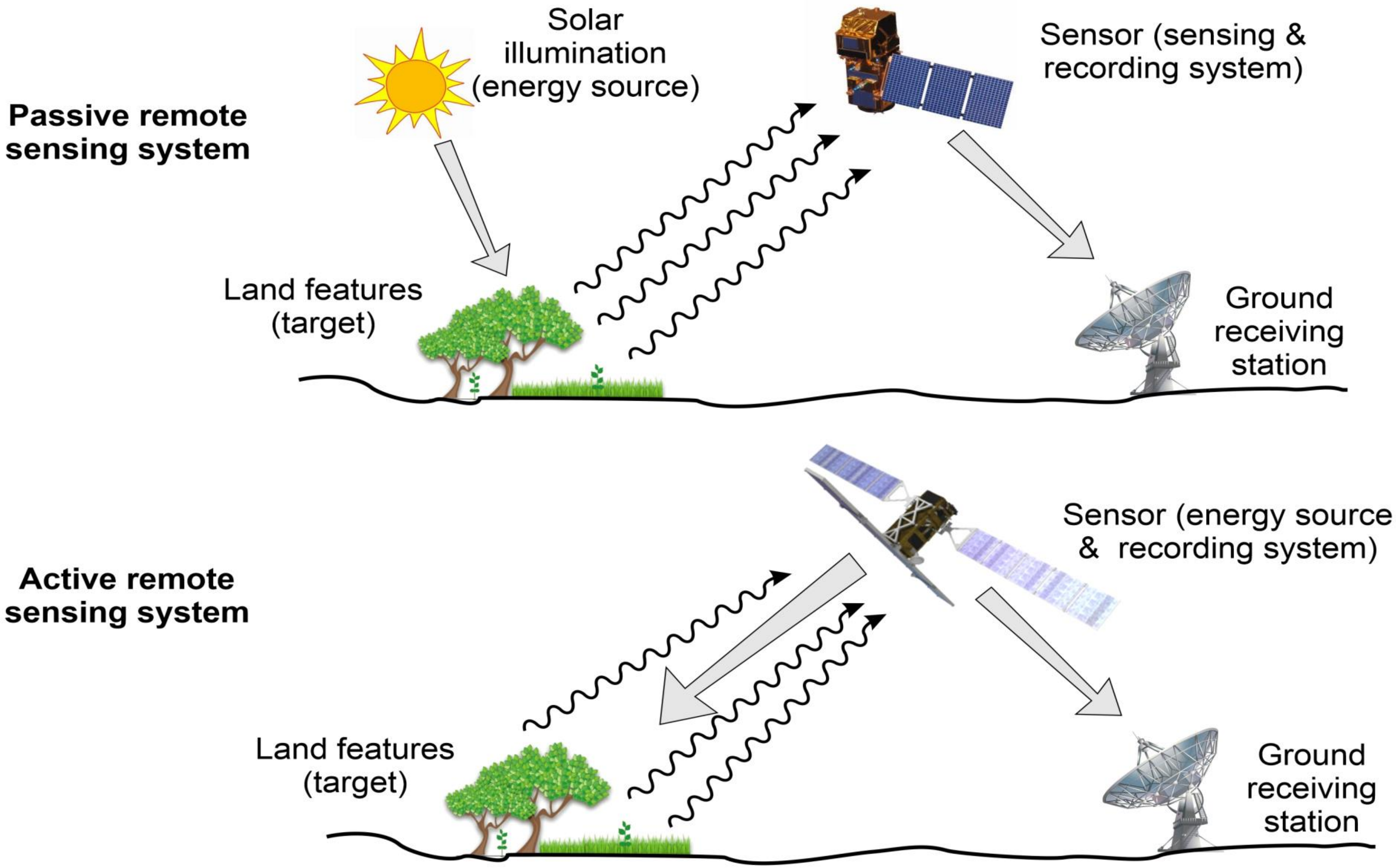
Three major aspects of remote sensing/earth observation to consider:

1) **Physical principles:** energy, waves, photons, interactions, atmosphere
2) **Technology:** sensors & platforms (satellites, aircraft etc.)
3) **Applications**: environmental challenges that have key characteristics:-

   large/global extent, spatial and temporal variation, affected by complex interactions/processes that are difficult to visualise, contain subtle/complex internal patterns and trends that are difficult to visualise

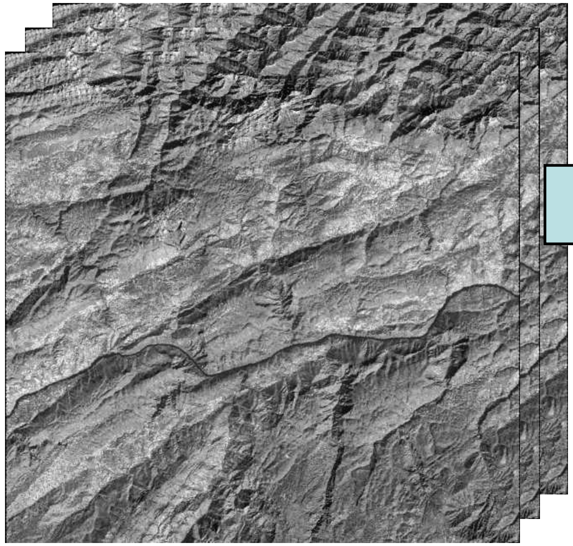
How can we process EO data to effectively extract information?

Types of remote sensing

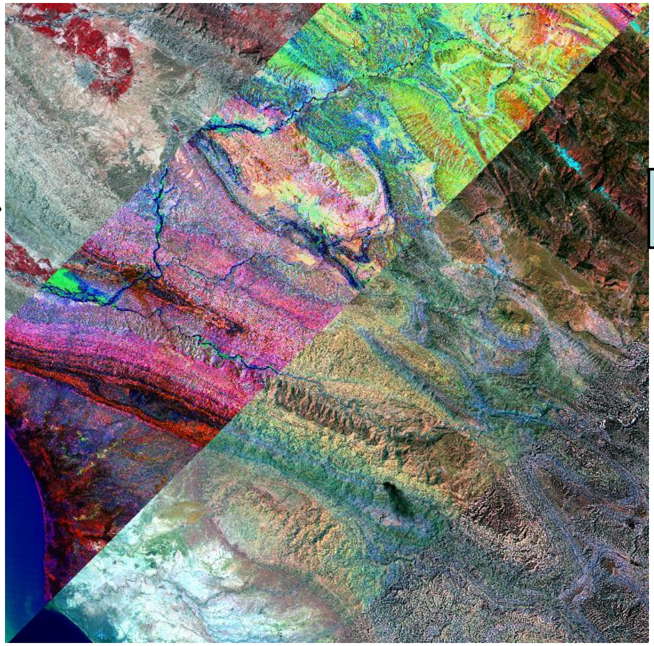


Conventional workflow <2000

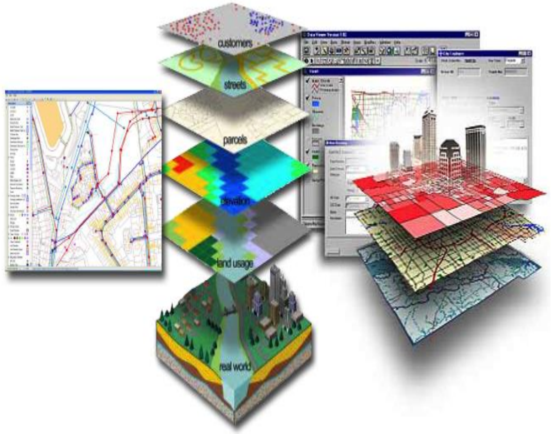
Remotely Sensed (EO) data collection (level-0 raw data)



Search & order/pay for raw data delivery (uncorrected level-1 binary .bil), manual geocoding & pre-processing



Process and produce GIS-ready images (level-1A, 1B, 1G & 1C products)



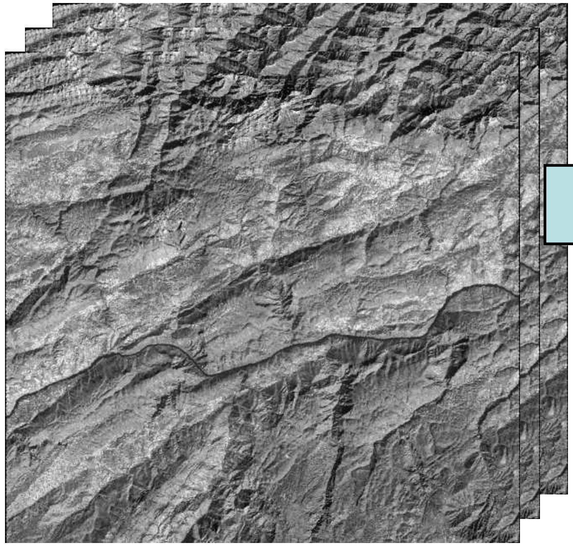
Interpret locally and distribute hardcopy prints and digital information (level 2 and 3 products)

National & corporate archives (Server)

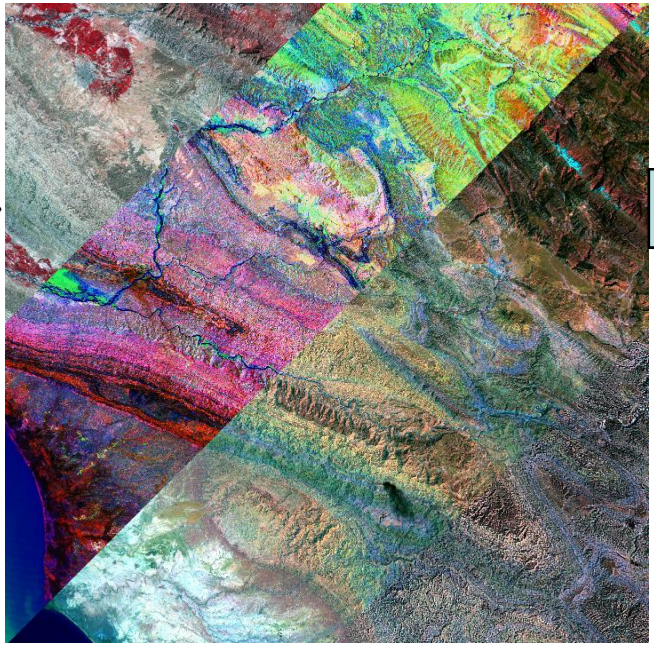
Local storage

Workflow 2000 - 2015

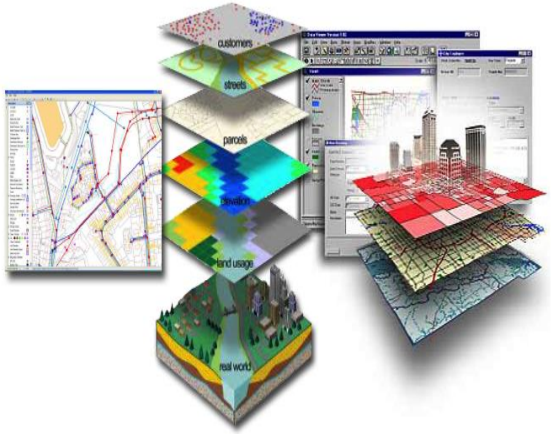
Remotely Sensed (EO) data collection (level-0 raw data)



Basic data pre-processing online. Search, download geo-coded data (level-1A, 1B & 1G geotiffs, .hdf etc)



Local processing, analysis and production of GIS-ready image images (level-1B, 1G, 1T 1C & 2 products)



Interpret locally and distribute hardcopy and increasingly digital products & information via web. Early web-mapping, mobile mapping etc (level 2 products)

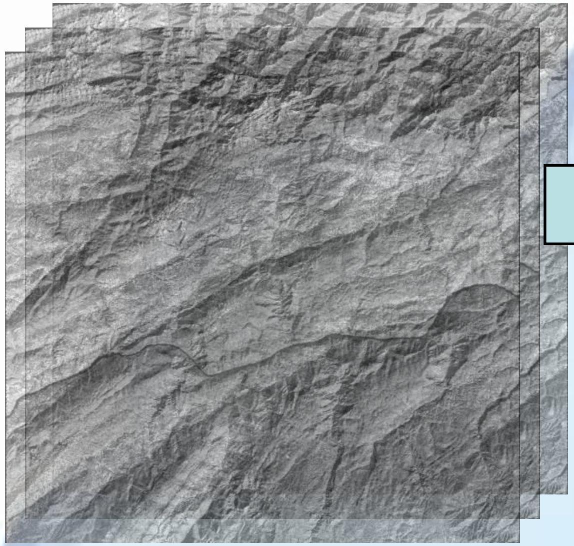
National & corporate archives (Server)

Local storage

Current and future workflow

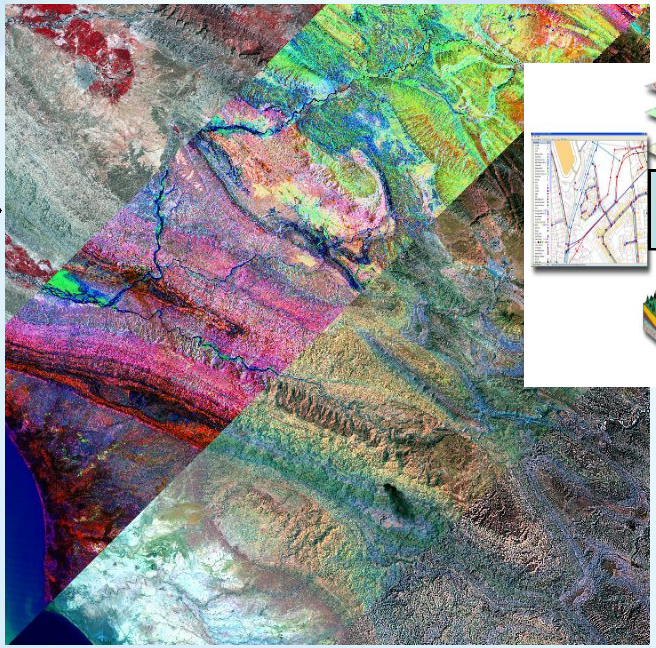
… and your new job market!

Remotely Sensed (EO) data collection (level-0 raw data)

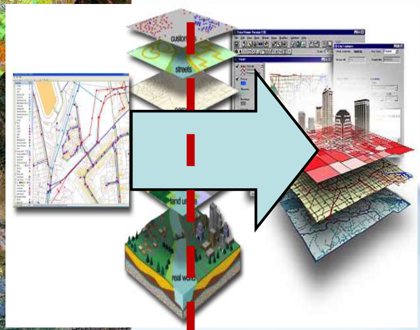


Geo-coded multitemporal multisource data archive (level-1B, 1G, 1T, 1C & 2 products)

Level 1A products no longer available in some cases



Direct processing on cloud - to extract information, analyse & make GIS ready products & stats (Level 2 & 3 products)

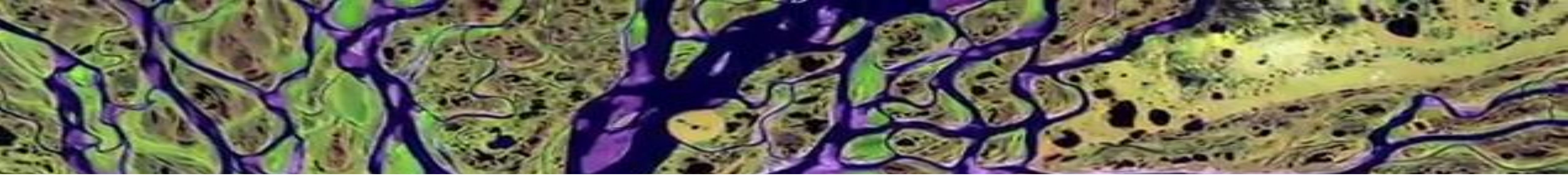


Data analytics

*Web-based & mobile apps, fast, dynamic, **response & predictive**, interactive, direct feed to other systems, and increasingly ML/DL & AI development)*

National & corporate archives (Server) & global open archives e.g. GEE (Server)

'Local' storage

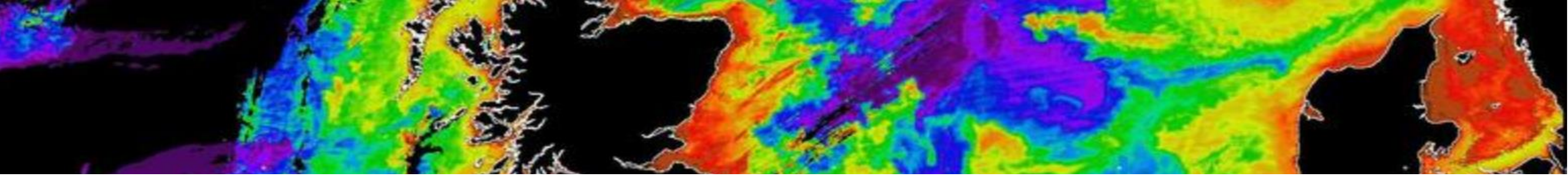


Major land applications

- **Geological mapping**: structure and lithology – enhancement of visualisation and image interpretation - multi-spectral imaging (lithological & mineral-group discrimination)
- **Mineral exploration**: mineral mapping with hyperspectral image data
- **Hydrosphere & cryosphere**: monitoring surface water bodies (rivers, lakes, ice, snow, etc.), drainage systems and coast zones, glaciers and their dynamics
- **Environmental mapping & monitoring** of dynamic geosphere, biosphere & anthroposphere: soil erosion, desertification, land instability, interaction between man and environment, i.e. understanding effects of urbanization, infrastructure, mining, on our environment etc.
- **Geohazards:** Quantitative measurement of deformation from rapid (earthquakes) and slow (subsidence or heave), landslides, landscape and environmental change
- **Vegetation and landcover:** backbone of remote sensing for the last ~50 years
- **Planetary science**: understanding other solid bodies in the solar system

Climate related

Optical & Radar (microwave)



Major oceanographic and atmospheric applications

Climate related

OCEAN

- **Sea surface temperature** for climate and weather forecasting
- **Total suspended solids** for hydrodynamic modelling
- **Ocean colour & chlorophyll content** for plankton and algae concentration
- **Sea surface height, pattern & circulation** for navigation & ocean mixture modelling

ATMOSPHERE

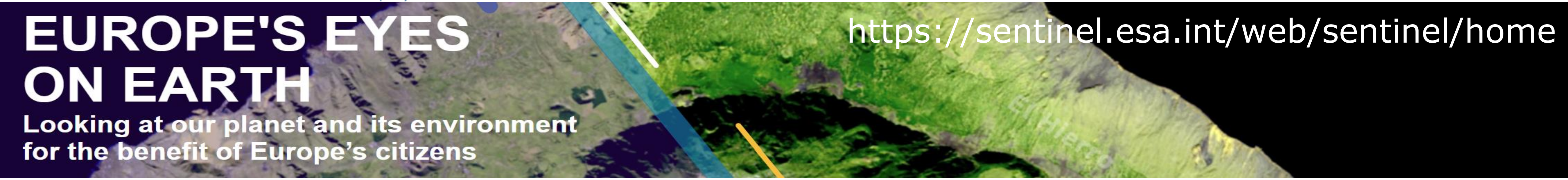
- Solar & terrestrial **radiation budget**
- **Air quality** (aerosols, trace gases, haze) time-series & forecasting
- Cloud properties & **ozone** observations for air quality
- **Hydrological cycle & meterological** observations for forecasting
- Monitoring & quantifying gas **emissions** (anthropogenic and natural)
- **Pollution** monitoring (anthropogenic)

Optical & Radar (microwave)

PROGRAMME OF THE EUROPEAN UNION

opernicus
Europe's eyes on Earth

About Copernicus   Copernicus Services   Opportunities   Access to Data



The Sentinels:

- Sentinel-1A & 1B - all-weather, day-and-night Synthetic Aperture Radar (SAR) imaging for land and ocean. Launched 2014 & 2016
  - 1B damaged (lost) and will be replaced by 1C imminently
- Sentinel-2A & 2B - multispectral VHR imaging for land monitoring (and for emergency services). Launched 2015 & 2017
- Sentinel-3A & 3B - multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean colour and land colour. Launched 2016 & 2018.
- Sentinel-4 onboard a Meteosat 3rd Generation-Sounder (MTG-S) satellite in geostationary orbit. Dedicated to atmospheric monitoring. Planned for launch 2019 & 2027
- Sentinel-5 - MetOp Second Generation satellite for atmospheric monitoring with UV, VIS & SWIR spectrometers. Launched 2020.
- Sentinel-5P - Atmospheric monitoring. Carries TROPOMI. Launched 2017
- Sentinel-6 - POSEIDON-4 radar altimeter for sea-surface height measurement. Launched 2020

Many new international collaborative developments – dedicated satellite systems ..

SPACE4CLIMATE

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NEODAAS

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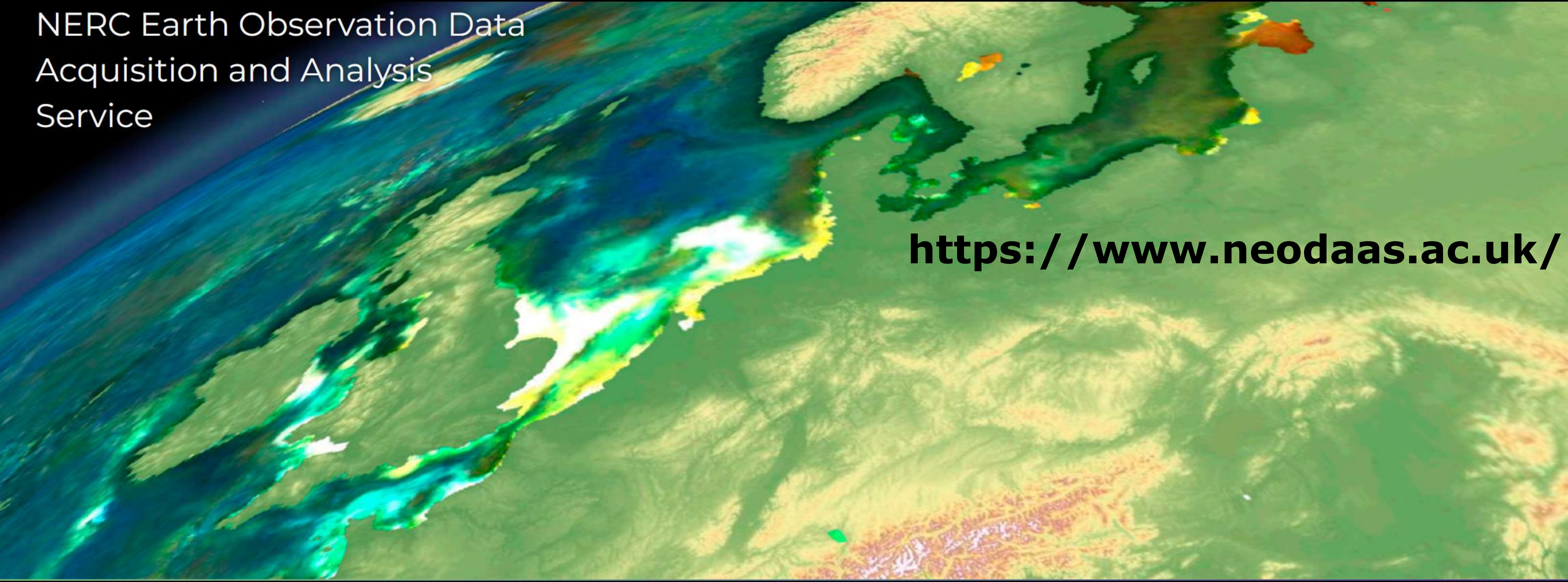
NERC Earth Observation Data Acquisition and Analysis Service



https://www.neodaas.ac.uk/

NEODAAS is hosted at Plymouth Marine Laboratory (PML), overseen by the National Centre for Earth Observation (NCEO) and funded by the Natural Environment Research Council (NERC).

PML | Plymouth Marine Laboratory

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

UKRI Natural Environment Research Council https://www.nceo.ac.uk/

Science

Earth Observation

Earth observation satellites have a unique vantage point on the world enabling us to identify, review and track regional and global trends consistently, and to trace their influence across the planet.

At NCEO we harness data from satellites as well as aircraft and ground-based instruments to study the Earth System and its continually changing nature, ranging from variations in atmospheric composition to the carbon content of forests.

Read about NCEO research

Research Highlights 2016

Selected NCEO research 2016

→ Download

NCEO Impact Brochure 2017

Read about the impact of NCEO research on society across a range of applications.

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MicroCarb

First European satellite dedicated to measuring atmospheric CO_2

CNES PROJECTS LIBRARY

MICROCARB

MicroCarb is expected to launch in 2025

Measuring global CO2 distribution

AT A GLANCE

HOME

IN DEPTH

EVENTS ARCHIVE

MISSION

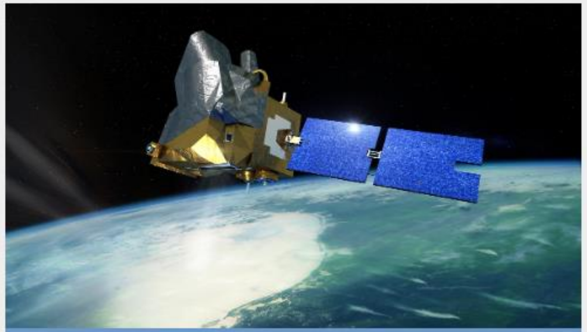
SYSTEM

SATELLITE

April 19, 2023

MICROCARB

MicroCarb is designed to map sources and sinks of carbon dioxide (CO2)—the most important greenhouse gas—on a global scale. The mission is currently in ... microsatellite



Mission Measure global CO_2 distribution

https://microcarb.cnes.fr/en/MICROCARB/index.htm

https://www.gov.uk/government/case-studies/microcarb

GHGSAT

PULSE GHGSAT

https://www.ghgsat.com/en/

BE THE FIRST TO KNOW

GLOBAL EMISSIONS MONITORING

Biomass is expected to launch in 2024

1st	666 km	1250 kg	12 m
P-band radar in space	altitude	mass	diameter antenna

APPLICATIONS

biomass

ESA's forest mission

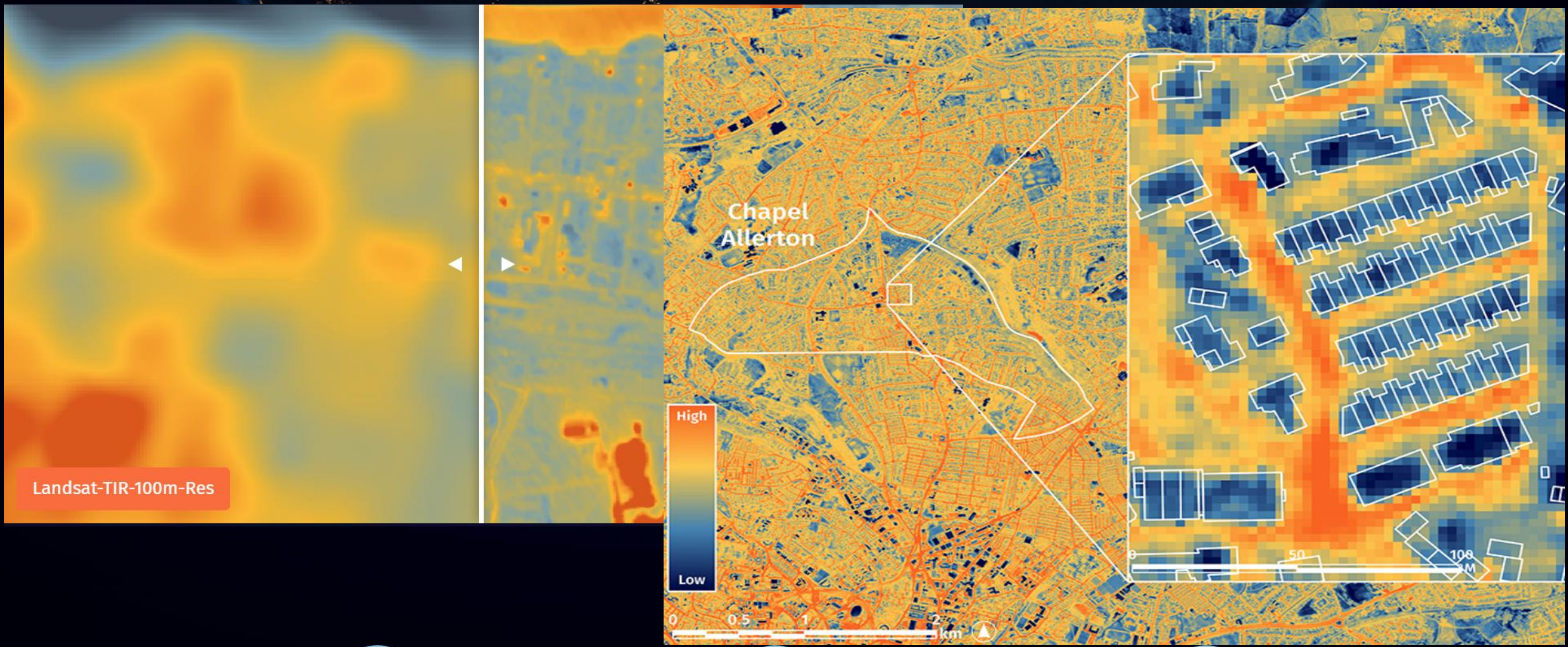
Built by Airbus UK

https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Biomass

Home Product Sectors Case Studies About

SatVu

Platform Login



Unparalleled resolution

Globally scalable with uniform coverage

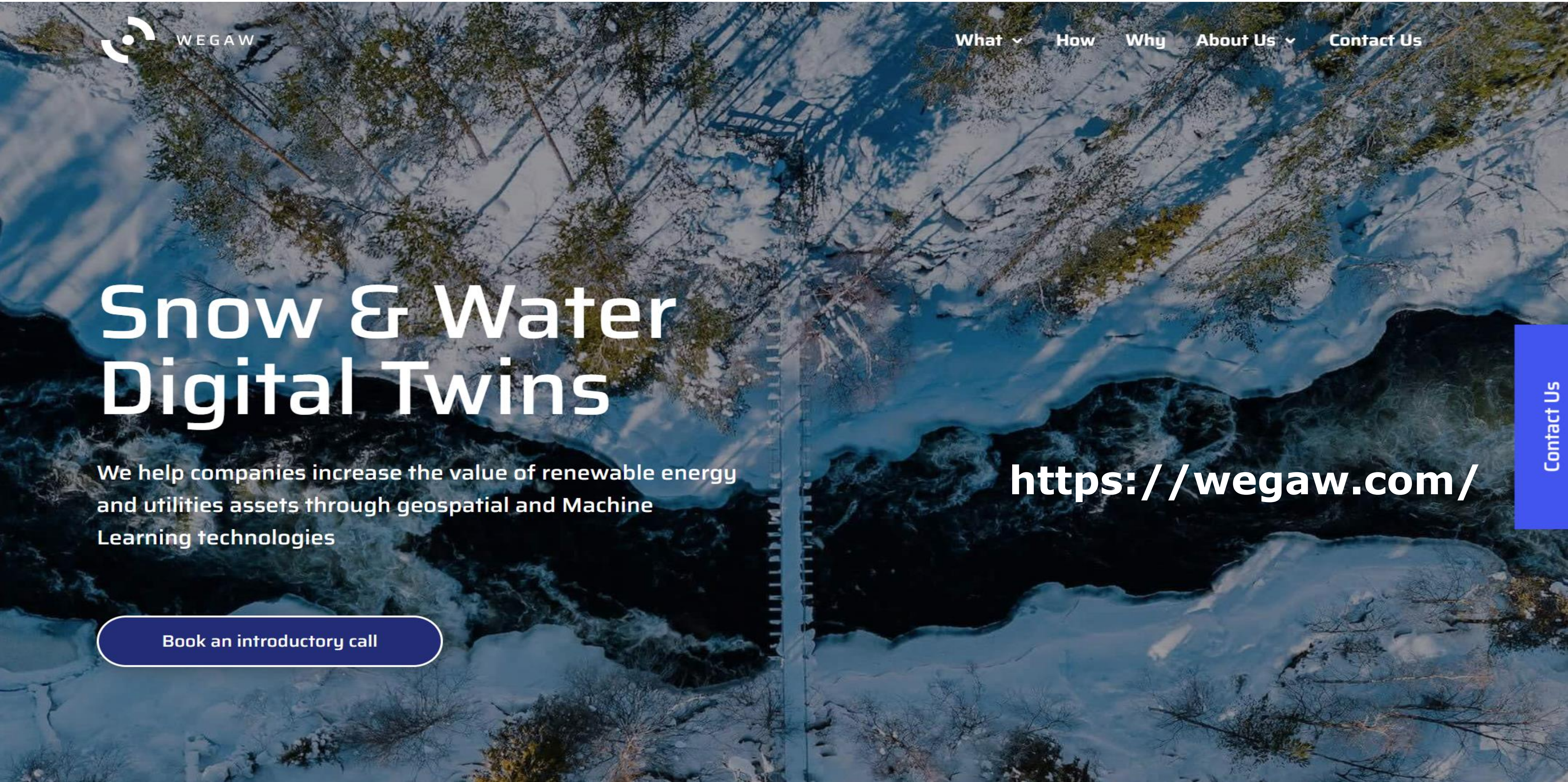
Monitor at night

https://www.satellitevu.com/

MANY start-ups in EO data analytics, e.g.:

https://www.terrabotics.co.uk

MANY start-ups in EO data analytics, e.g.:

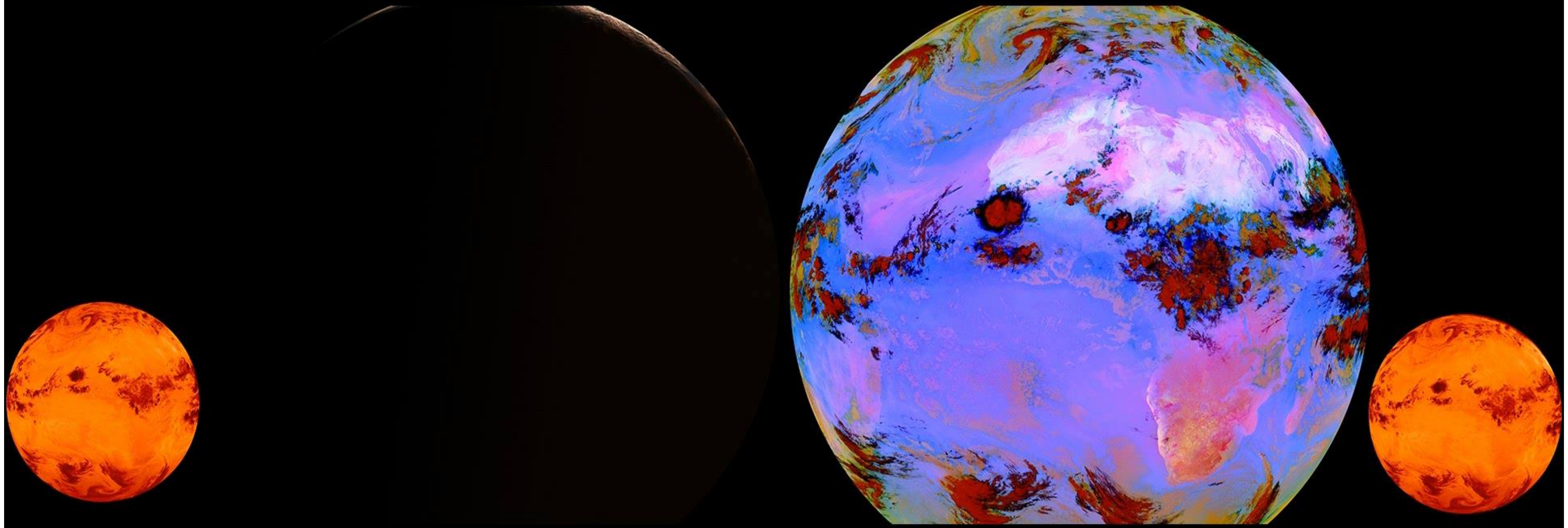


LOTS going on in Research here @ ICL

e.g. Global, high temporal resolution observations to reveal Earth’s heat budget

Dept of Physics ICL
Leading unique climate science missions & research

Central large disks: visible and infrared imagery from SEVIRI



Corresponding energy budget from GERB shown in the smaller disks. **Left:** reflected solar and emitted thermal energy; **Right:** net incoming and net outgoing energy. Combining the data allows the physical mechanisms causing variations to be identified and tracked, and their energetic effect quantified

Contacts:
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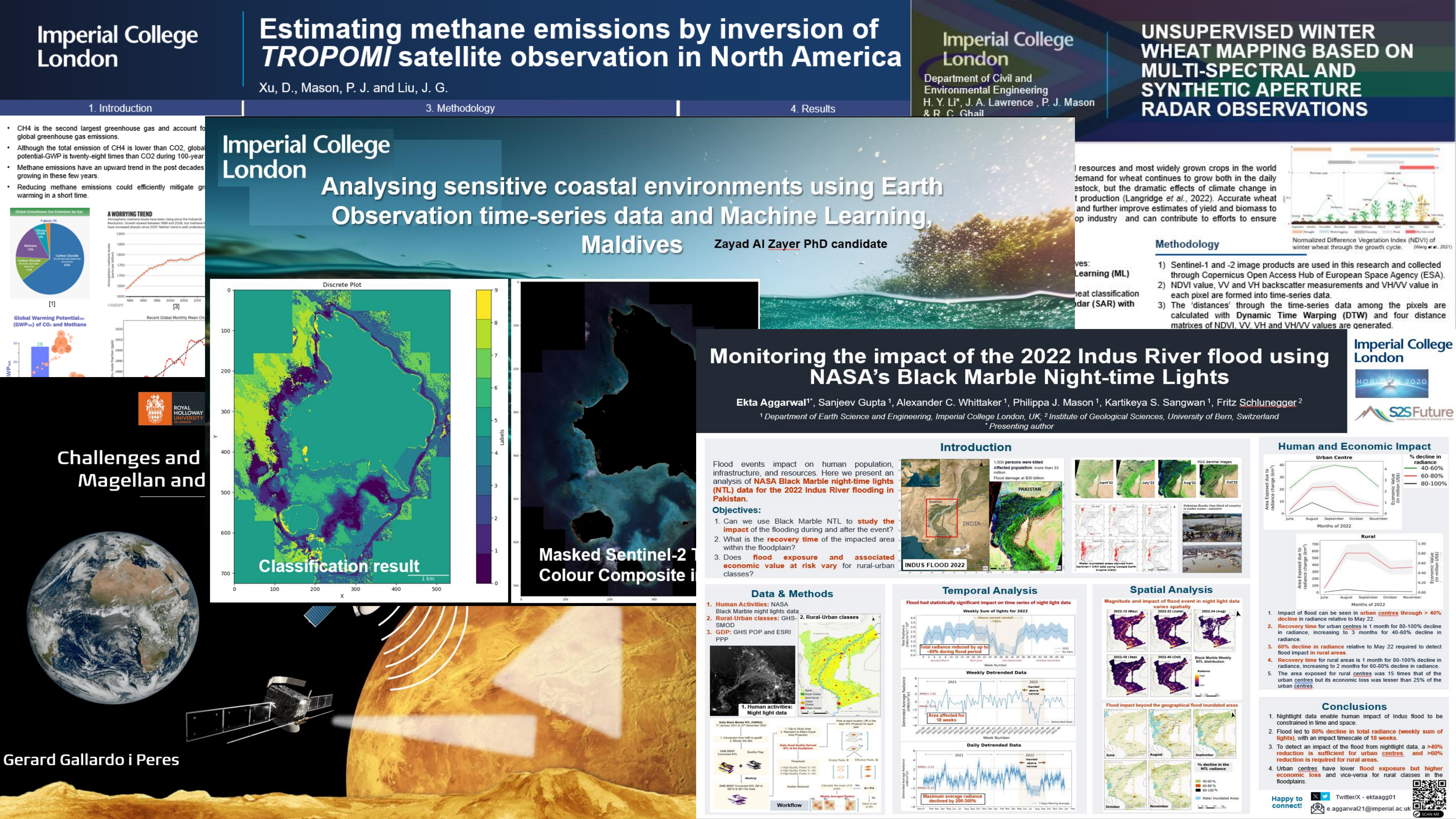
j.russell@imperial.ac.uk



Imperial College London
Estimating methane emissions by inversion of TROPOMI satellite observation in North America
Xu, D., Mason, P. J. and Liu, J. G.
1. Introduction
3. Methodology
4. Results
CH4 is the second largest greenhouse gas and account fo global greenhouse gas emissions.
Methane emissions have an upward trend in the post decades growing in these few years.
Reducing methane emissions could efficiently mitigate gr warming in a short time.
A WORRYING TREND
Global Warming Potential (GWP) of CO2 and Methane
Imperial College London
Department of Civil and Environmental Engineering
H. Y. Li*, J. A. Lawrence , P. J. Mason & R. C. Ghail
UNSUPERVISED WINTER WHEAT MAPPING BASED ON MULTI-SPECTRAL AND SYNTHETIC APERTURE RADAR OBSERVATIONS
Methodology
1) Sentinel-1 and -2 image products are used in this research and collected through Copernicus Open Access Hub of European Space Agency (ESA).
2) NDVI value, VV and VH backscatter measurements and VH/VV value in each pixel are formed into time-series data.
3) The 'distances' through the time-series data among the pixels are calculated with Dynamic Time Warping (DTW) and four distance matrixes of NDVI, VV, VH and VH/VV values are generated.
Normalized Difference Vegetation Index (NDVI) of winter wheat through the growth cycle.
Imperial College London
Analysing sensitive coastal environments using Earth Observation time-series data and Machine Learning, Maldives
Zayad Al Zayer PhD candidate
Discrete Plot
Classification result
Masked Sentinel-2 T Colour Composite i
ROYAL HOLLOWAY UNIVERSITY OF LONDON
Challenges and Magellan and
Gerard Gallardo i Peres
Monitoring the impact of the 2022 Indus River flood using NASA's Black Marble Night-time Lights
Imperial College London
HORIZON 2020
S2S Future
Ekta Aggarwal1*, Sanjeev Gupta 1, Alexander C. Whittaker 1, Philippa J. Mason 1, Kartikeya S. Sangwan 1, Fritz Schlunegger 2
1 Department of Earth Science and Engineering, Imperial College London, UK; 2 Institute of Geological Sciences, University of Bern, Switzerland
* Presenting author
Introduction
Flood events impact on human population, infrastructure, and resources. Here we present an analysis of NASA Black Marble night-time lights (NTL) data for the 2022 Indus River flooding in Pakistan.
Objectives:
1. Can we use Black Marble NTL to study the impact of the flooding during and after the event?
2. What is the recovery time of the impacted area within the floodplain?
3. Does flood exposure and associated economic value at risk vary for rural-urban classes?
INDUS FLOOD 2022
PAKISTAN
INDIA
Data & Methods
1. Human Activities: NASA Black Marble night lights data
2. Rural-Urban classes: GHS-SMOD
3. GDP: GHS POP and ESRI PPP
Workflow
Temporal Analysis
Flood had statistically significant impact on time series of night light data
Weekly Sum of lights for 2022
Weekly Detrended Data
Daily Detrended Data
Spatial Analysis
Magnitude and impact of flood event in night light data varies spatially
Flood impact beyond the geographical flood inundated areas
Human and Economic Impact
Urban Centre
Rural
1. Impact of flood can be seen in urban centres through > 40% decline in radiance relative to May 22.
2. Recovery time for urban centres is 1 month for 80-100% decline in radiance, increasing to 3 months for 40-60% decline in radiance.
3. 60% decline in radiance relative to May 22 required to detect flood impact in rural areas.
4. Recovery time for rural areas is 1 month for 80-100% decline in radiance, increasing to 2 months for 60-80% decline in radiance.
5. The area exposed for rural centres was 15 times that of the urban centres but its economic loss was lesser than 25% of the urban centres.
Conclusions
1. Nightlight data enable human impact of Indus flood to be constrained in time and space.
2. Flood led to 80% decline in total radiance (weekly sum of lights), with an impact timescale of 18 weeks.
3. To detect an impact of the flood from nightlight data, a >40% reduction is sufficient for urban centres and >60% reduction is required for rural areas.
4. Urban centres have lower flood exposure but higher economic loss and vice-versa for rural classes in the floodplains.
Happy to connect!
Twitter/X - ektaagg01
e.aggarwal21@imperial.ac.uk

1 Physical principles

i.e. how does remote sensing work?

… bit of revision is needed

1.1 Electro-Magnetic Radiation (EMR)

Electromagnetic radiation or EMR is an energy wave propagated through space between electric and magnetic fields

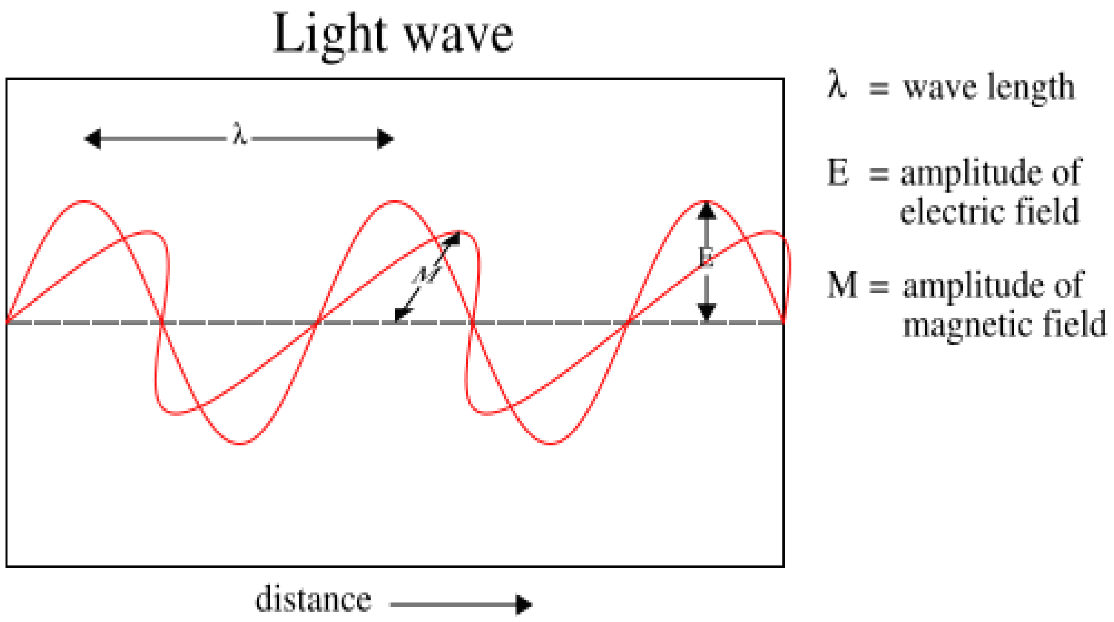
$$c = \nu\lambda \qquad (1.1)$$

where $c = 3\times10^8 \ m/\sec$ is the light speed that is essentially a constant, ν frequency and λ wavelength.

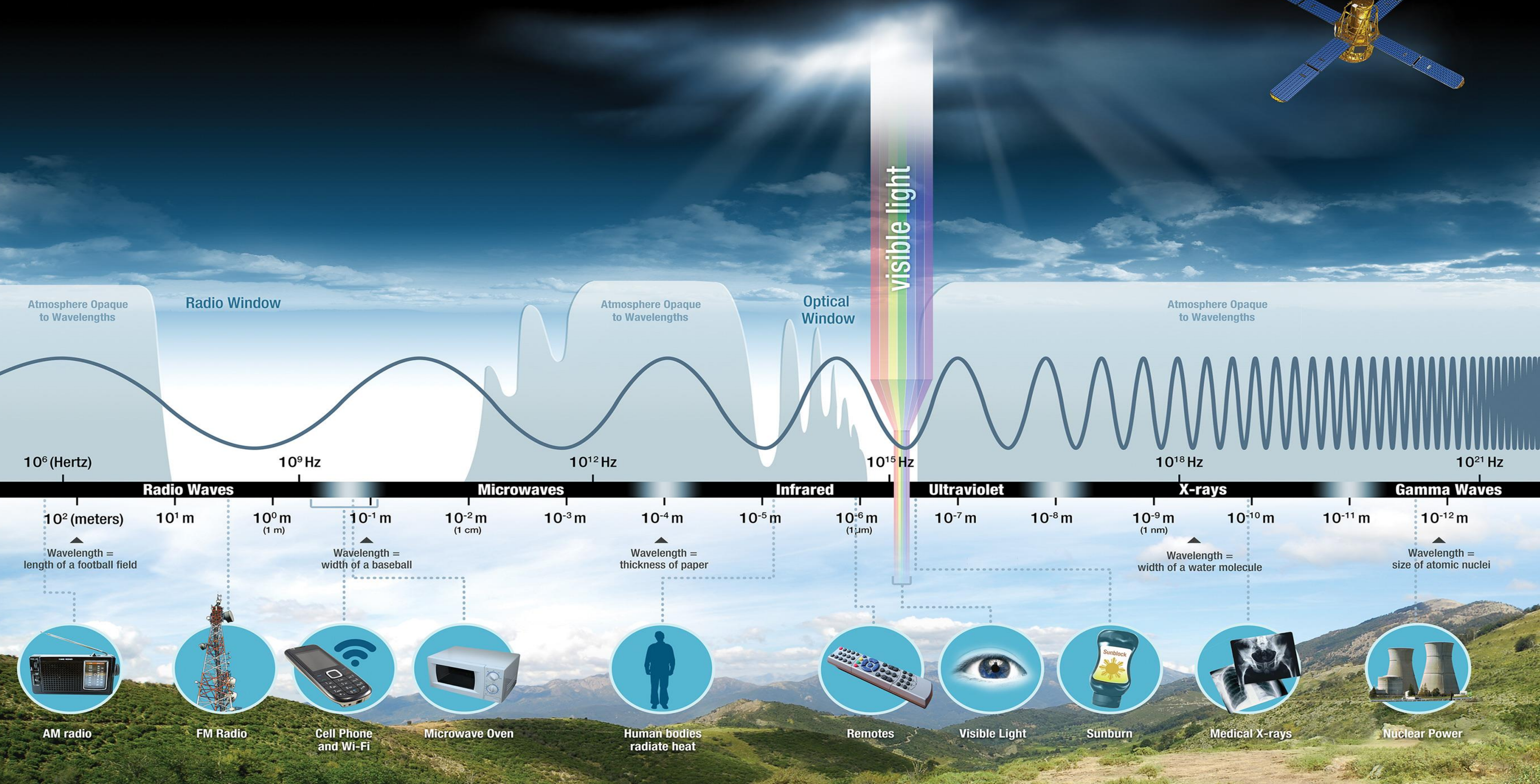
High frequency EMR has short wavelength.

The magnetic field is related to the electric field in such a way that magnetic fields move perpendicular the electric field

We can receive EMR directly or reflected by another body



Electromagnetic radiation (EMR) spectrum

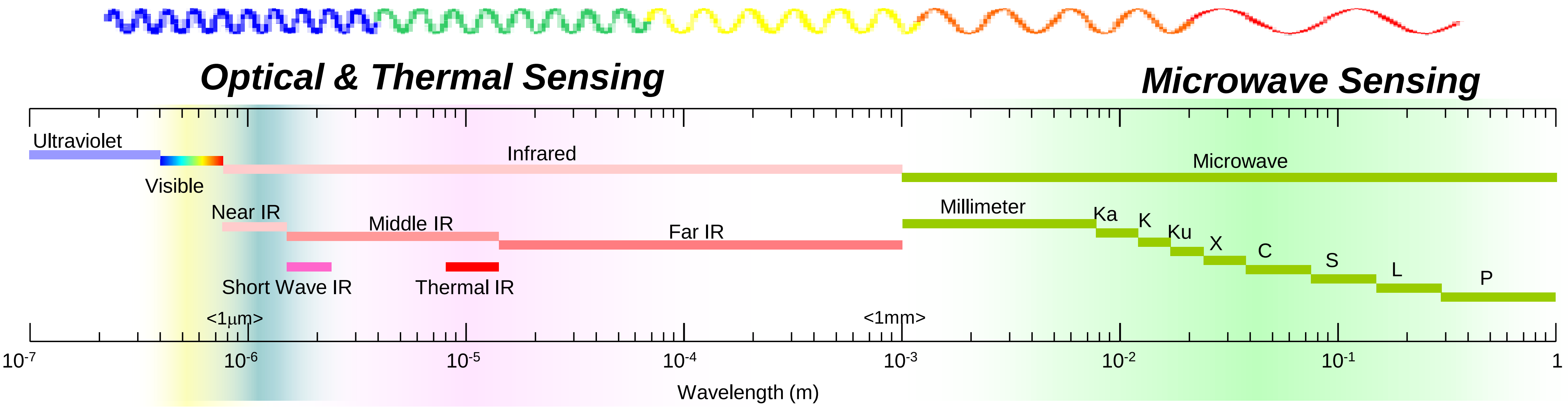


Major spectral regions that can be used

REFLECTED SOLAR	Visible light	0.38 - 0.75 μm (for most humans)	
	Blue	0.45 - 0.52 μm	
	Green	0.52 - 0.60 μm	
	Red	0.60 - 0.75 μm	
	(Photographic VIS-IR film	0.40 – 0.9 μm)	
	Reflective Infrared (IR)	0.75 - 3.0 μm	
	Near Infrared (NIR)	0.75 - 1.3 μm	
	Short Wave Infrared (SWIR)	1.30 - 3.0 μm	
THERMALLY EMITTED	Thermal infrared	3.0 - 5.0 μm & 8.0 - 14.0 μm	
ACTIVE SENSING	Microwave & radio	0.1 (1 mm) to 100 *cm*	CAN BE USED PASSIVELY

R071101a

Types of Remote Sensing expanded



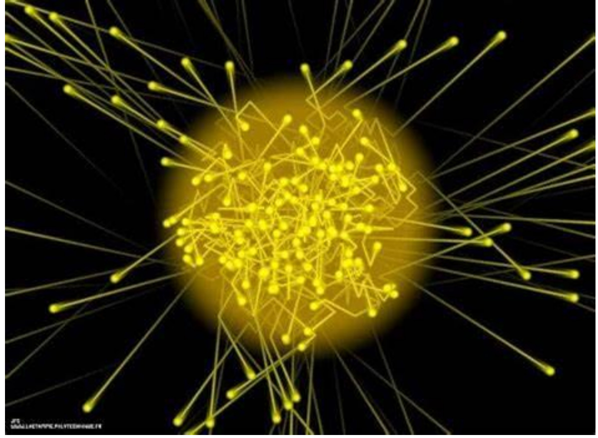
Based on electromagnetic spectrum, remote sensing is generally categorized as:

1. Passive Optical (**reflected** light) Sensing : Visible to Short Wave Infrared
Thermal (**emitted** energy) Sensing: Thermal Infrared

2. Active Microwave Sensing: imaging RADAR
Light Detection And Ranging: LiDAR (at variable wavelengths)

(Different sensor technology required for each)

1.2 Photons and EMR energy



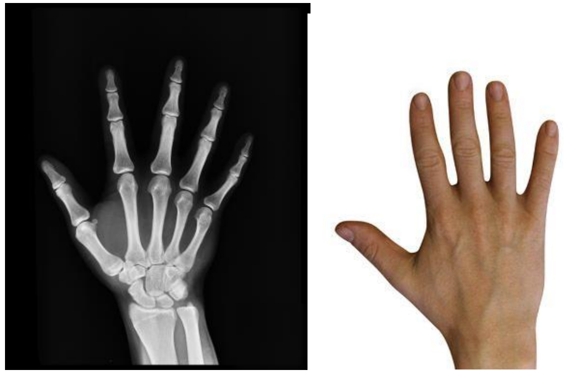
EMR can be described by wave theory but actually EMR is composed of many discrete units of matter called photons (or quanta) according to the particle theory of quantum physics.

$$Q = h\nu$$

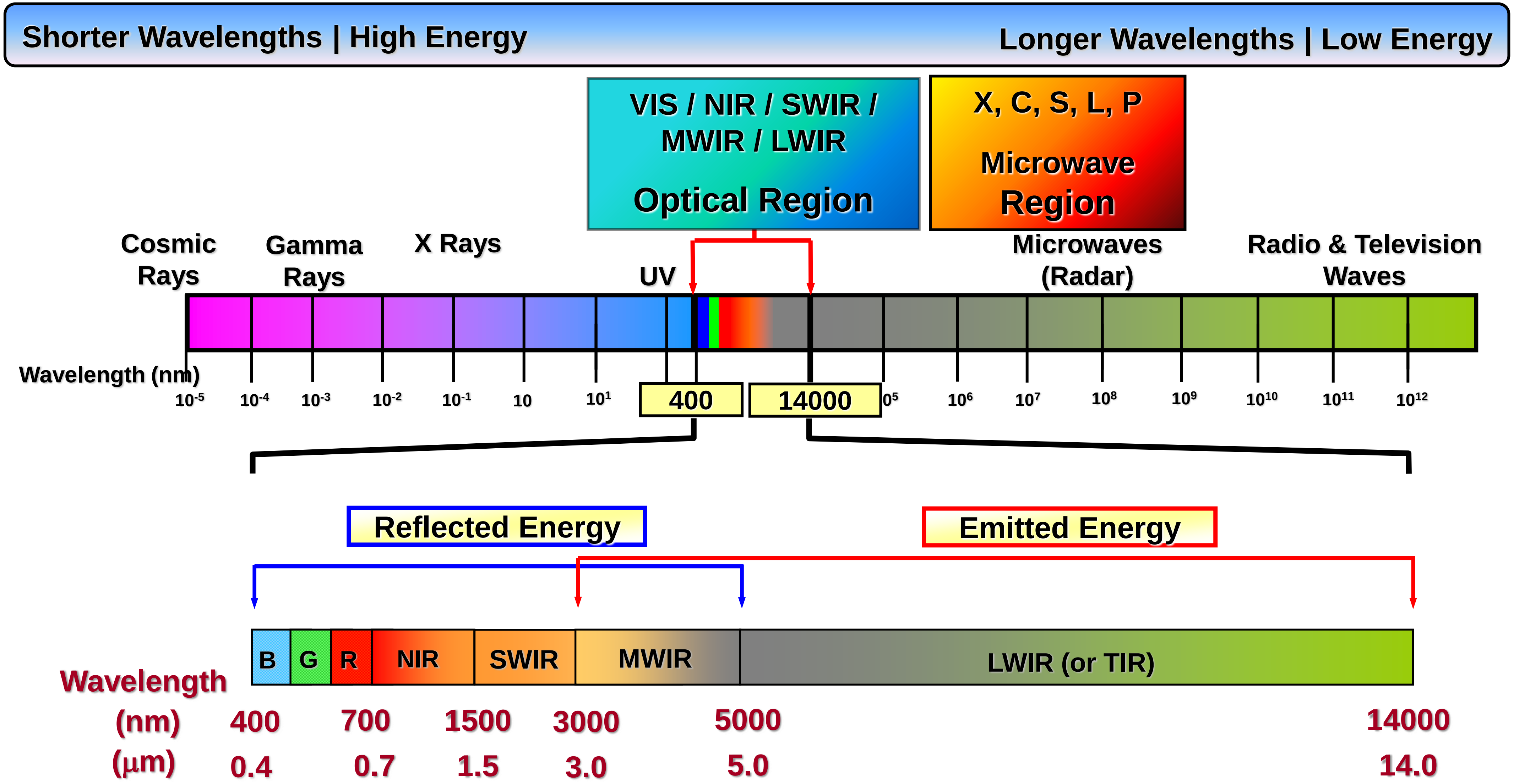
Q = energy of a photon, joules (J)
h = Planck's constant, $6.626\times10^{-34}\,Js$
ν = frequency (1.2)

Relate the wave and photon definitions of EMR by solving (1.1) for ν in (1.2), we then have:

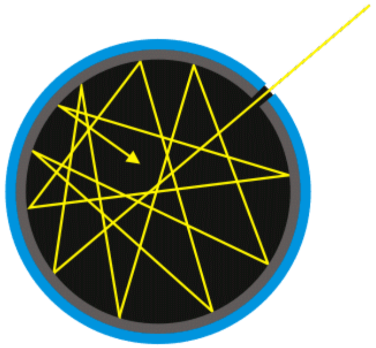
$$Q = \frac{hc}{\lambda} \qquad (1.3)$$



Electromagnetic Spectrum and its Energy



1.3 Stefan-Boltzmann law



Conceptual Black Body

Regarding black-body radiant emittance. All matter at temperature greater than absolute zero (0° K, or -273° C) emits EMR.

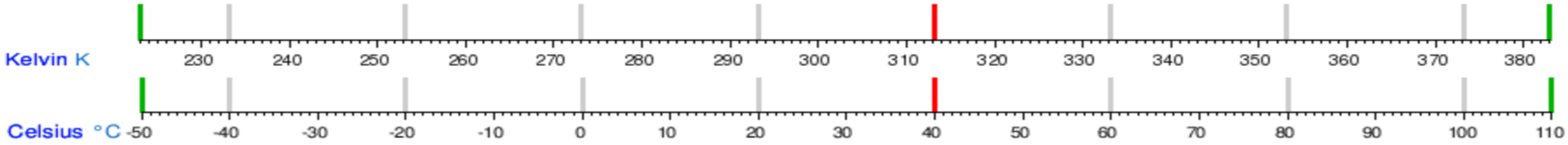
How much energy an object radiates is a function of the surface temperature of the object as expressed by *Stefan-Boltzmann law:*

$$M = \sigma T^4 \qquad (1.4)$$

M = total energy flux density radiated from the surface of a material, Wm^{-2}

σ = *Stefan-Boltzmann constant* $5.6697 \times 10^{-8} Wm^{-2} K^{-4}$

T = absolute temperature (K) of the emitting material



1.4 Wien's displacement law

Now we try to link the temperature of an object radiating energy to the EMR wavelength at its radiation peak (the wavelength at which blackbody radiation reaches the maximum).

This is *Wien's displacement law:*

$$\lambda_m = \frac{A}{T} \tag{1.5}$$

λ_m = wavelength of maximum spectral radiation, μm

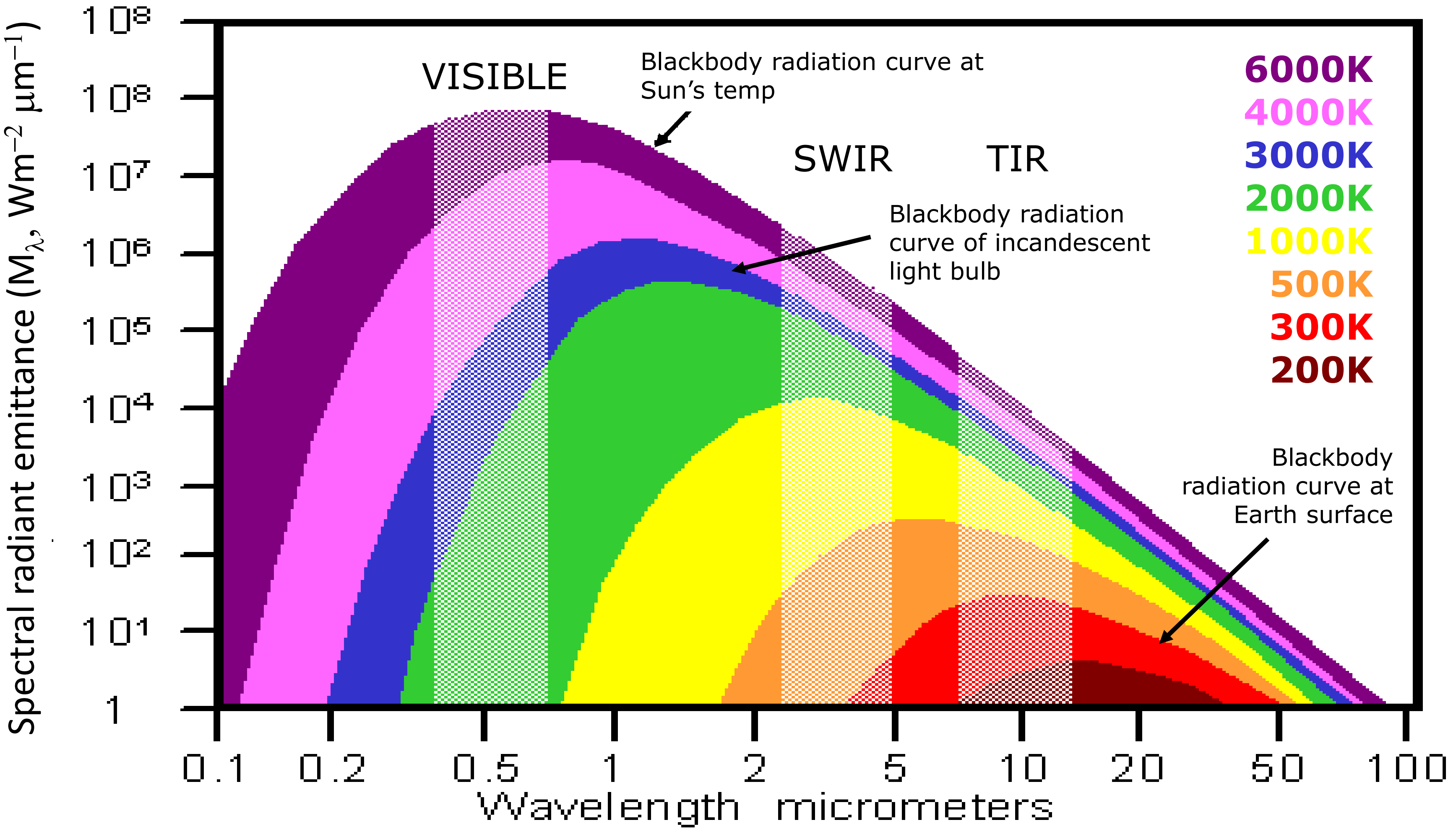
A = 2898 μmK (Wein's constant of proportionality)

T = temperature, K

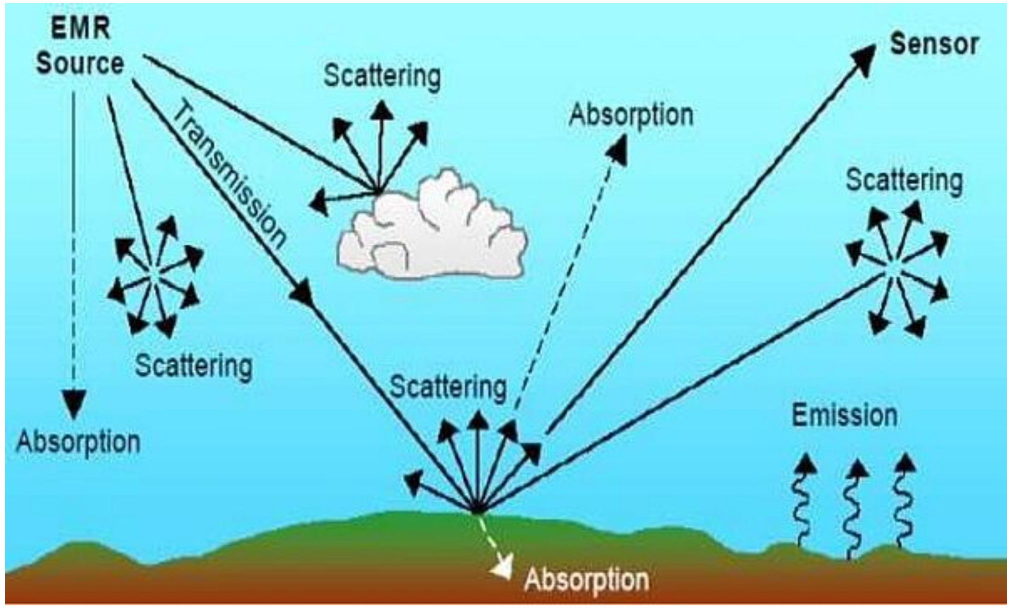
So given the temperature of an object we can calculate the wavelength of its peak radiation

e.g. think of a freshly erupted lava flow whose surface temp may be 1400 deg C …

Spectral distribution of radiation and the radiation peaks of blackbodies at various temperatures



1.5 Interaction between EMR and atmosphere

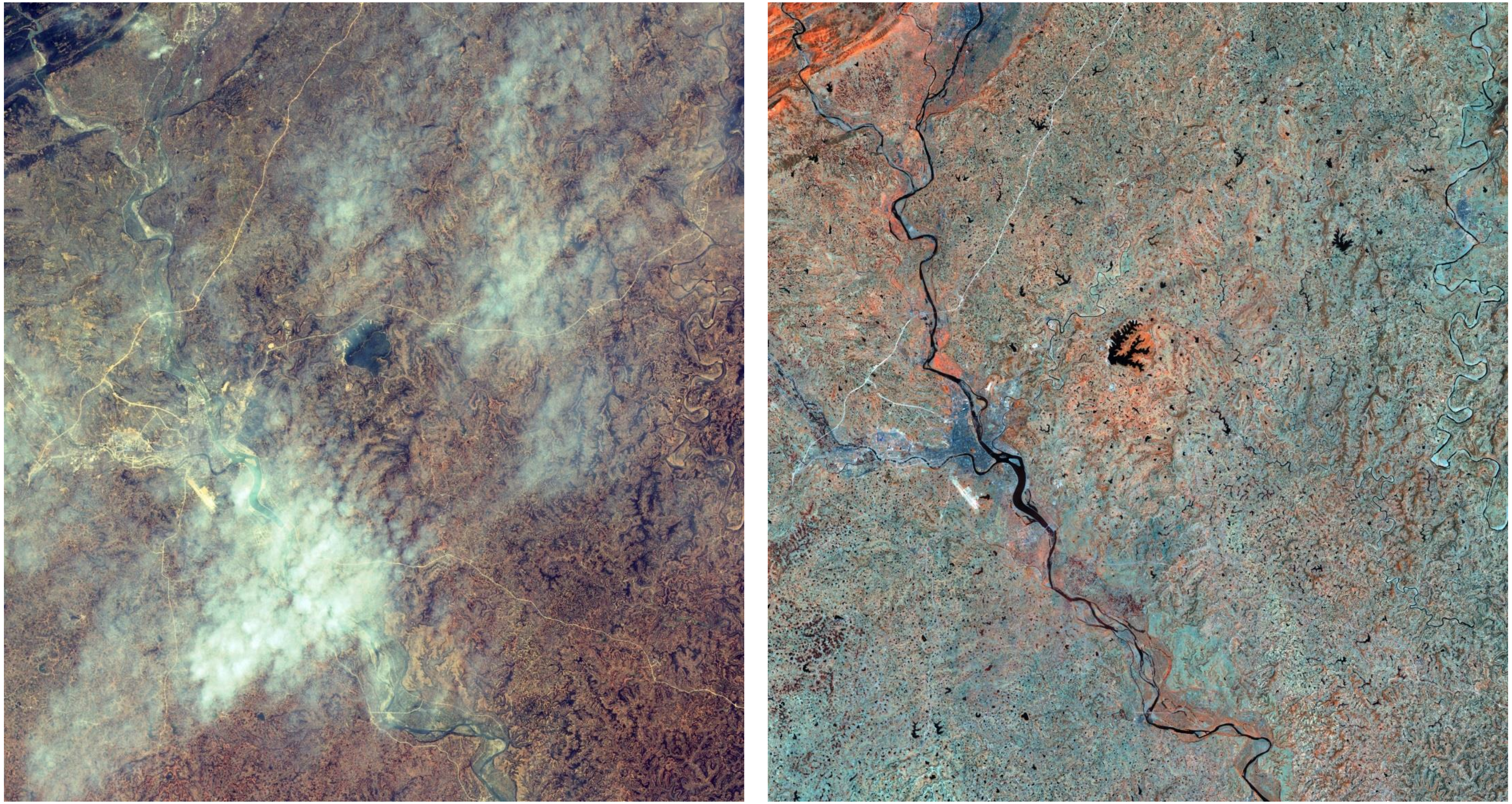


a) Scattering: Atmospheric scattering is the unpredictable diffusion of radiation by particles in the atmosphere. There are 3 types:

- ***Rayleigh*** *scattering* is common when radiation interacts with atmospheric gas molecules and other tiny particles which are **much smaller in diameter than the wavelength** of the interacting radiation. The effect of Rayleigh scattering in the atmosphere is inversely **proportional to the 4th power of wavelength**. Hence, the effects mainly occur at short wavelengths...

- ***Mie*** *scattering* exists when atmospheric **particle diameter essentially equals the wavelength** of EMR been sensed. Water vapour and dust are the major causes of this type of scattering, and they tends to influence longer wavelengths of light.
- ***Non-selective*** *scattering* is caused by particles **much larger than the wavelength** of EMR. The effect simply blocks all the EMR with wavelengths much shorter than the dimension of the particle non-selectively. Aerosols and water droplets can cause this type of scattering.

EMR in the SWIR region can penetrate thin clouds and smoke

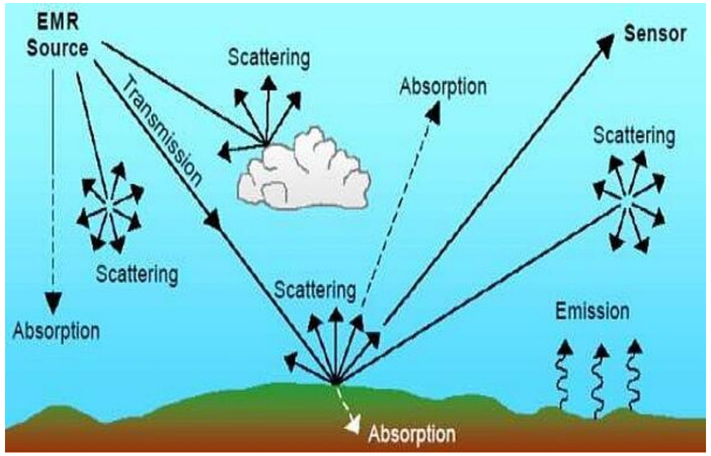


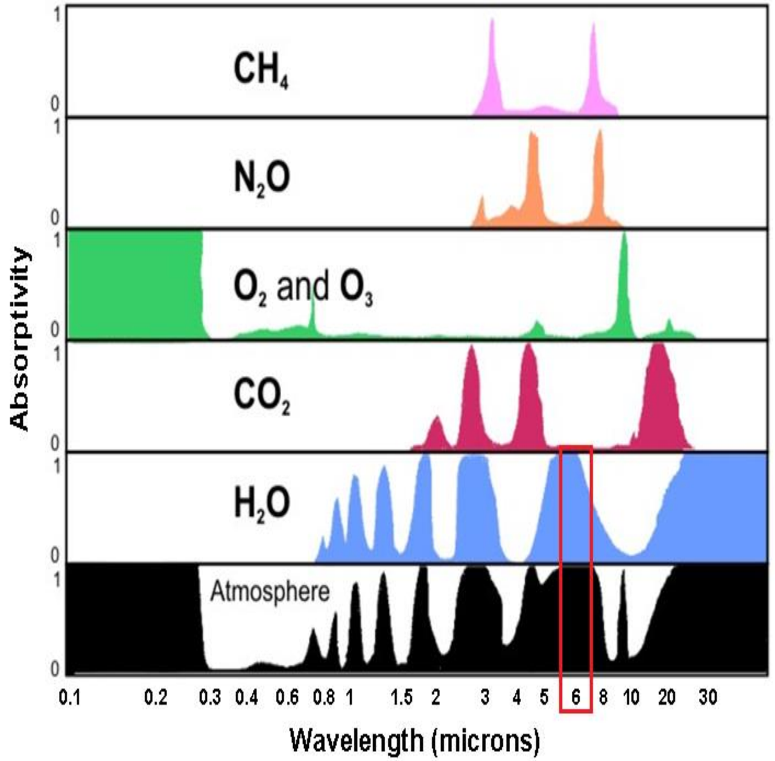
Landsat-5 TM images over Chengdu region, China.
Left: true colour composite image of blue, green and red bands (TM321RGB).
Right: false colour composite of NIR band in R, SWIR-1 in G and SWIR-2 in B (TM457RGB).

1.5 Interaction between EMR and atmosphere cont'd

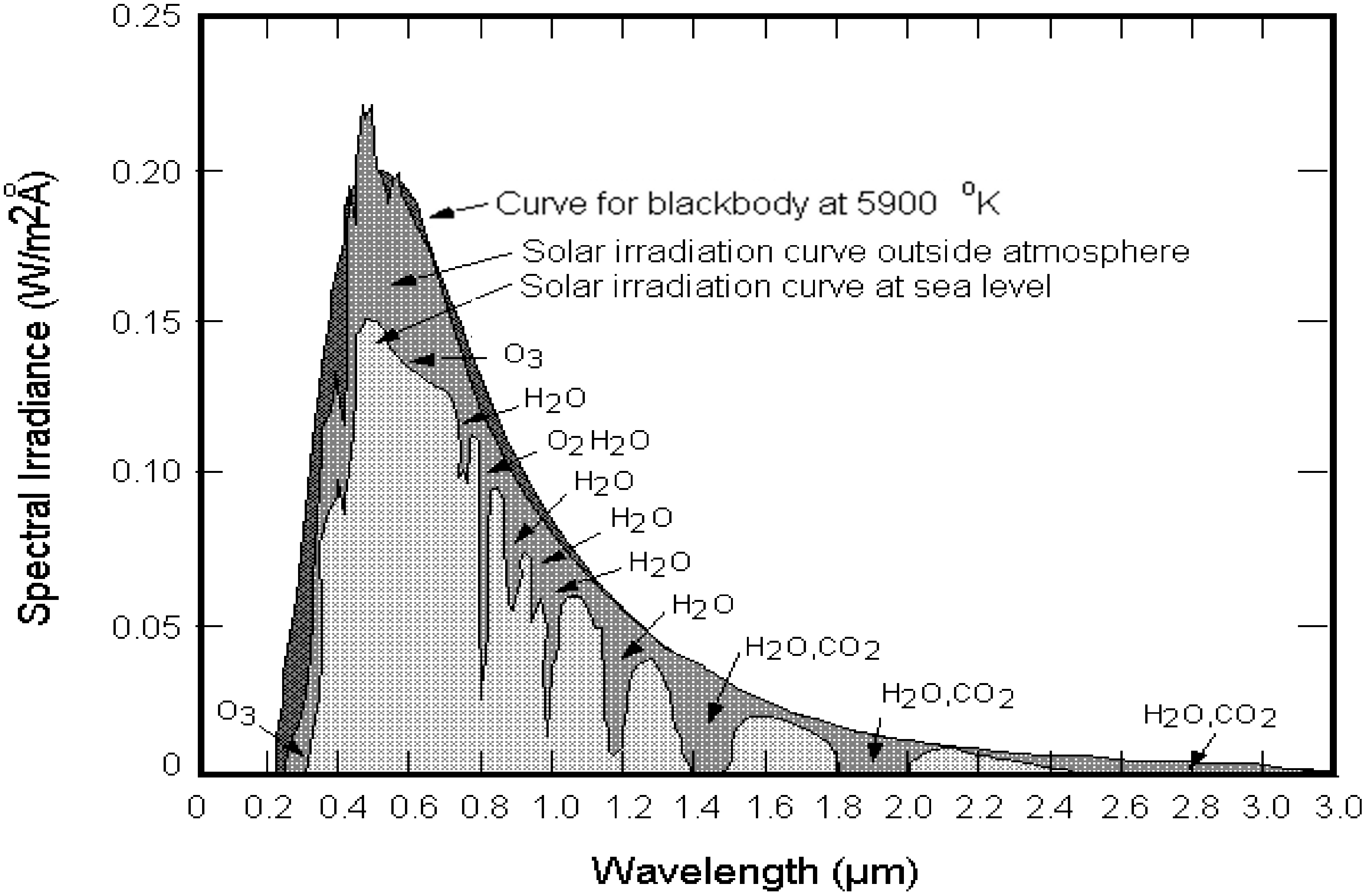
b) Absorption: Atmospheric absorption results in the effective loss of EMR energy to atmospheric constituents. This absorption normally occurs at particular wavelengths.

- The most efficient absorbers of solar radiation in this regard are water vapour, carbon dioxide and ozone.
- One result of this is that the atmosphere is opaque within the spectral ranges where solar radiation is largely absorbed, and these spectral ranges therefore **cannot be used for remote sensing**.
- The atmosphere is largely transparent to sensors in spectral ranges where little absorption occurs. These spectral ranges are suitable for remote sensing and called ***atmospheric windows***.

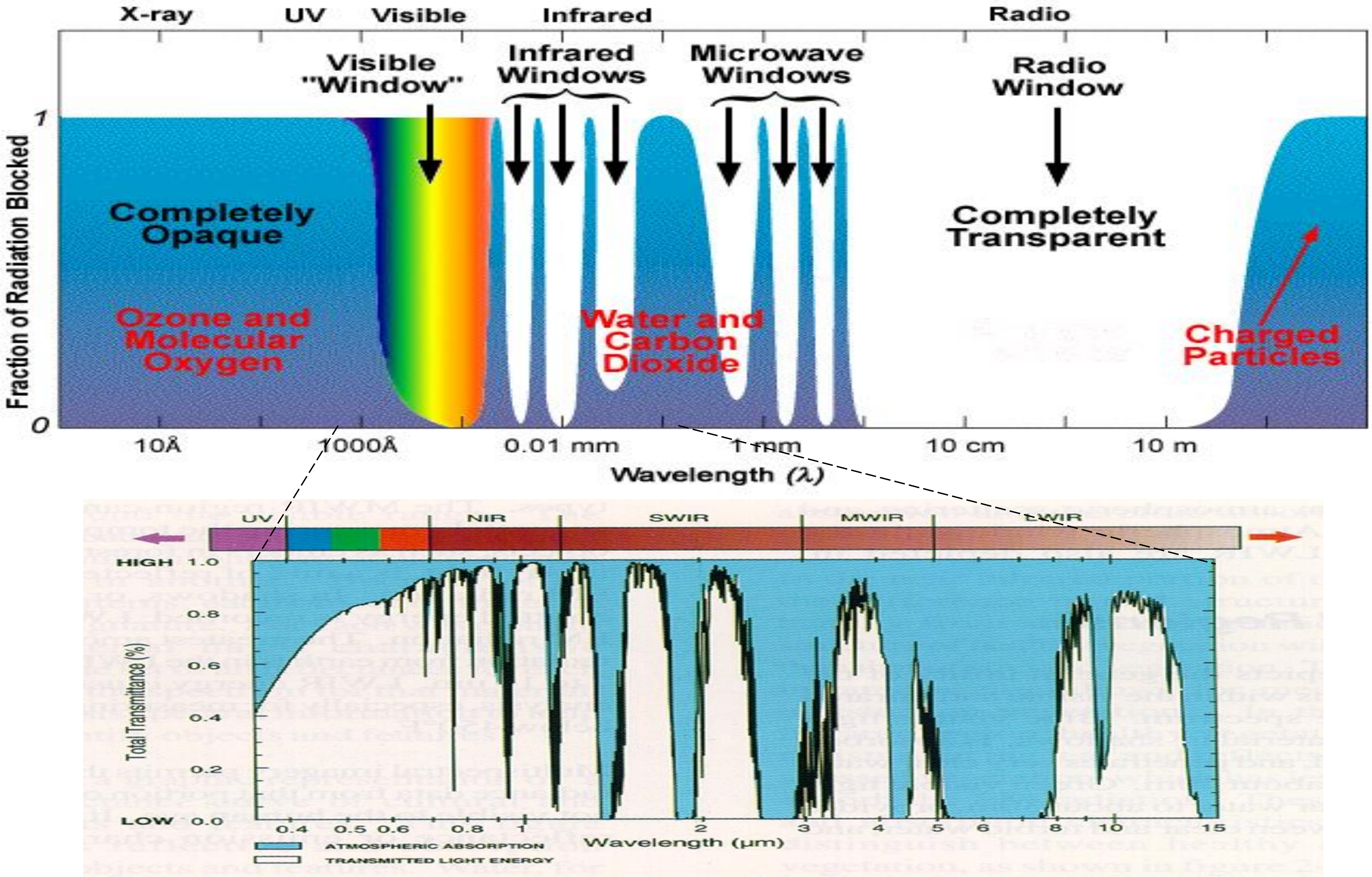




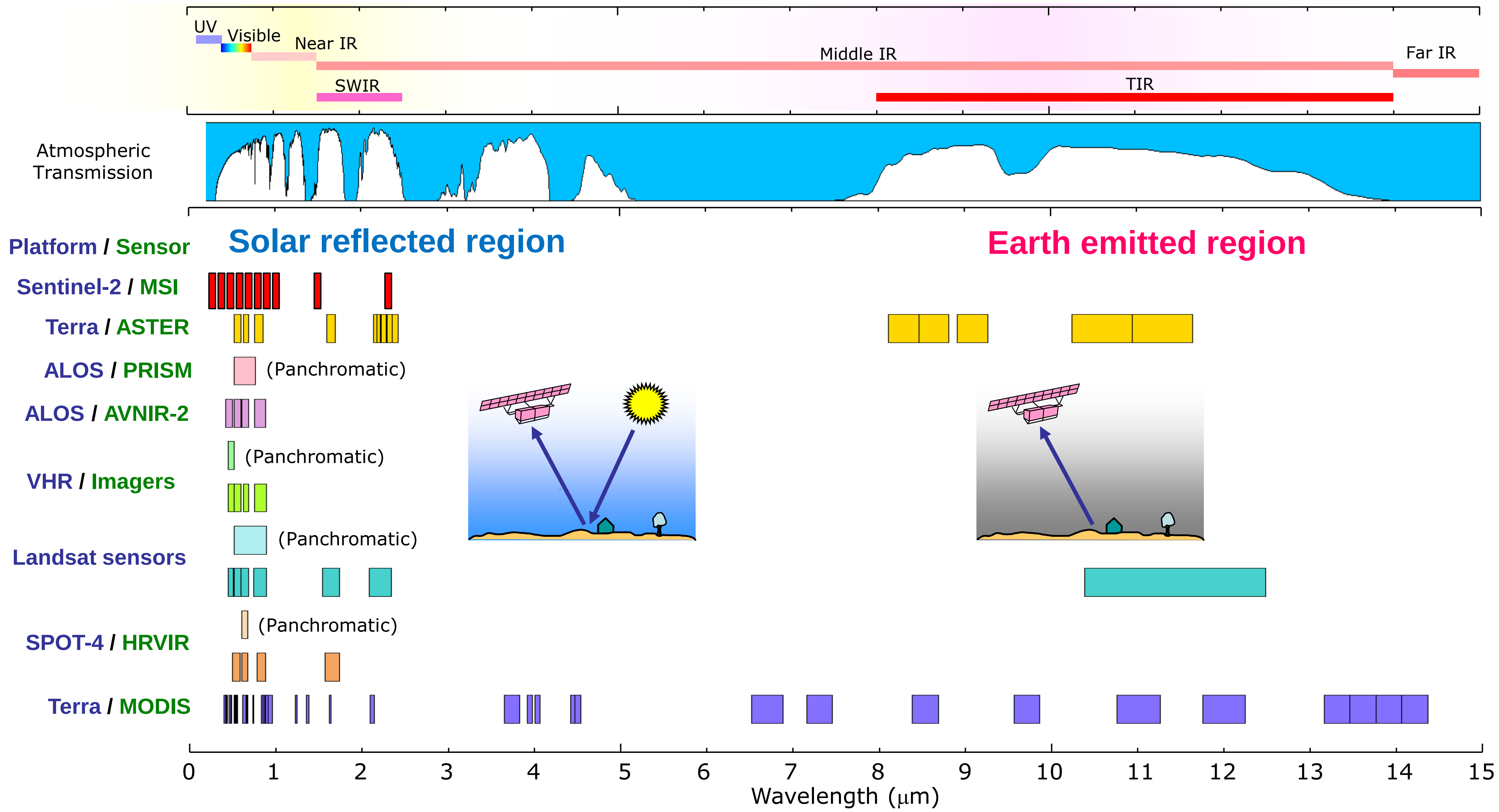
Solar radiation and atmospheric absorption regions



Atmospheric windows and absorption zones



Spectral coverage of optical & thermal sensors



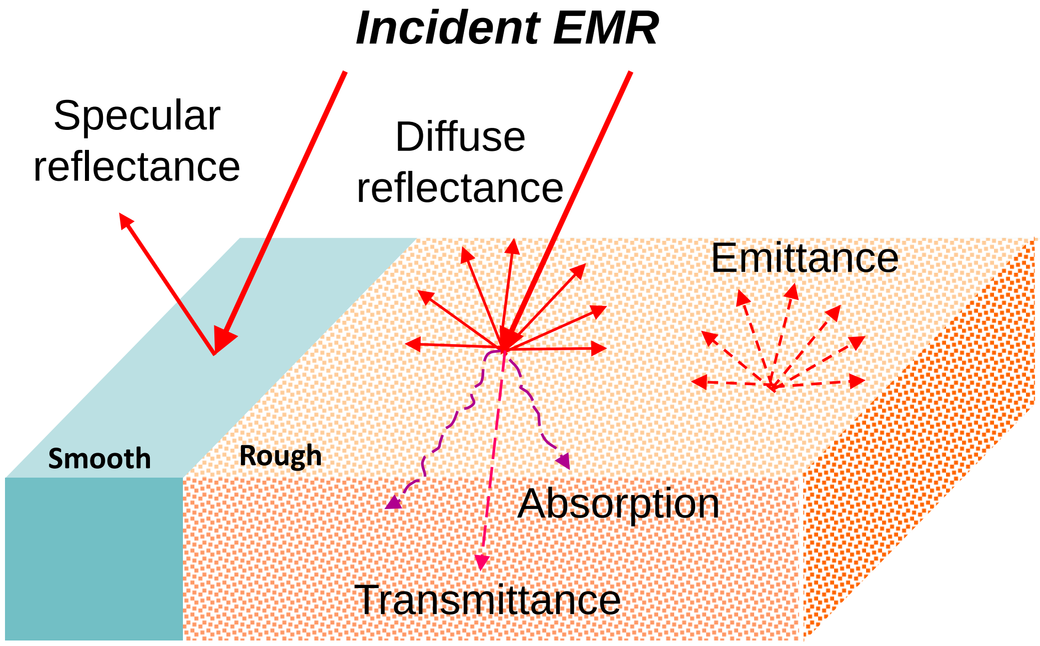
.. Why?

1.6 Interaction between EMR with the earth's surface

When solar EMR impinges on the Earth's surface, it will be partially **reflected, absorbed** and **transmitted** depending on the spectral properties of the surface materials:

$$E_I(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda) \quad (1.6)$$

Where, E denotes energy, subscripts I, R, A, T indicate Incident, Reflected, Absorbed and Transmitted, λ is the wavelength of EMR.



The absorbed and transmitted solar EMR energy will increase the earth temperature and eventually (later) be emitted from the earth's surface according to ***Stefan-Boltzmann law***.

Reflectance behavior depends on several things, including **surface roughness** …

… Why can we see each other?

Effect of surface roughness

- There are two general types of reflecting surfaces that interact with EMR:
  - ***specular*** (smooth)
  - ***diffuse*** (rough)
- These terms are defined geometrically and relatively, not physically. A surface may appear smooth in a physical sense, i.e. it appears and feels smooth, but at a scale on the order of wavelengths of light, many irregularities may occur throughout that surface.
- Radiation impinging on a diffuse (rough) surface tends to be reflected in many directions (Lambertian or diffuse scattering).
- The ***Rayleigh*** criterion can be used to determine surface roughness with respect to radiation. A surface is smooth if the following condition is true, otherwise it is rough:

$$h < \frac{\lambda}{8 \sin \theta}$$

where h is the surface irregularity height, or surface roughness, λ the wavelength and θ the angle between incident EMR and the surface.

Effect of key spectral properties

- ***Spectral reflectance*** is the reflectivity of a material to EMR at a particular wavelength.

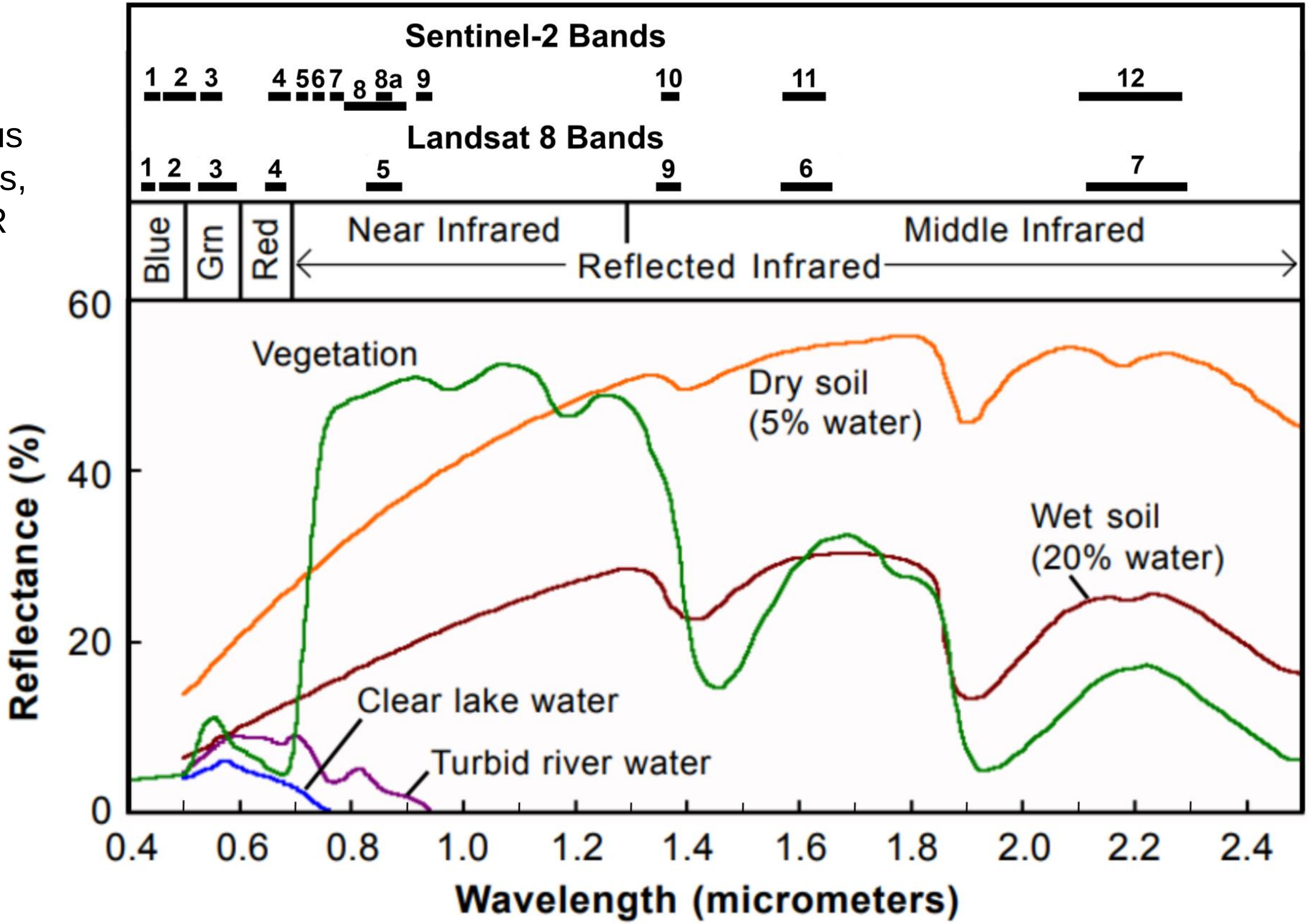
$$\rho(\lambda) = \frac{E_R(\lambda)}{E_I(\lambda)} \qquad (1.7)$$

- ***Albedo,*** or the total radiant reflectance, is the integral of reflected spectral radiation, weighted by irradiance, over all spectral range. Useful **general measure of an object's reflective properties**

$$\rho = \frac{\int_0^\infty \rho(\lambda) E(\lambda) d\lambda}{E} \qquad (1.8)$$

What is left after all that absorption and scattering?

Reflected energy profiles (reflectance spectra) or spectral signatures, of various Earth materials, plant species, and water, in VIS-NIR-SWIR spectral ranges

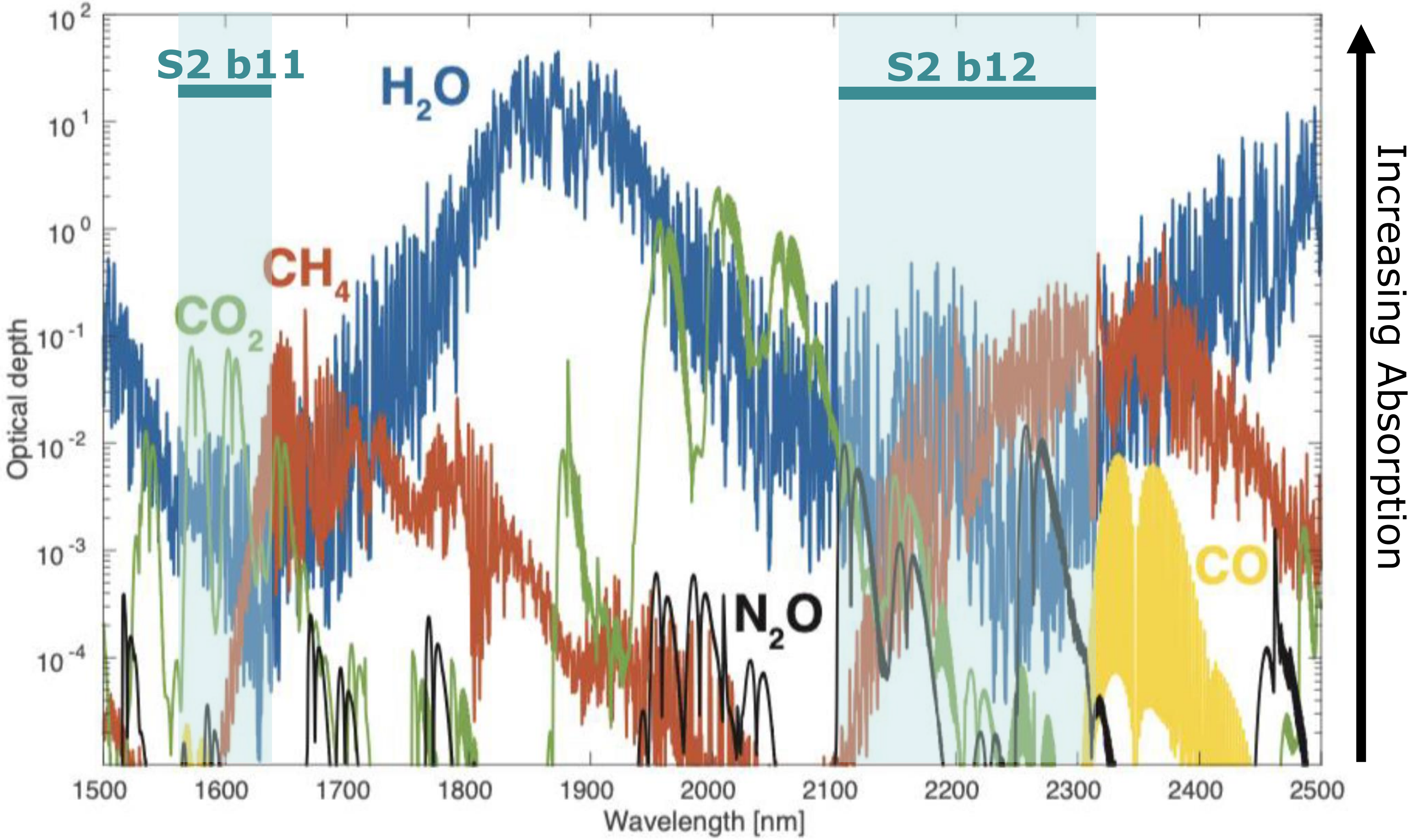


Atmospheric absorption also has uses!

Identify composition & retrieve concentrations in Earth & other planetary atmospheres

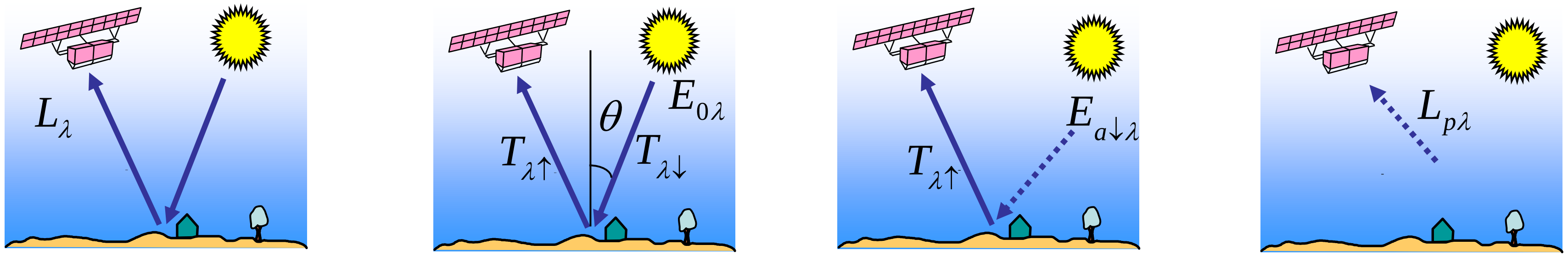
EO instruments operating in SWIR, at 1.65 µm and 2.3 µm can be used to retrieve greenhouse gas concentrations by measuring solar radiation reflected & absorbed by Earth's atmosphere across these wavelengths, e.g., AVIRIS-NG, SCIAMACHY, GOSAT, TROPOMI and GHGSat

CH_4, CO_2, N_2O, CO and H_2O gases optical depth in the 1.5-2.5 µm spatial range based on the US Standard Atmosphere:



(FORCE, AIR. 1986. AFGL atmospheric constituent profiles (0-120 gm))

A reminder about radiance, reflectance and atmosphere



ρ_λ ρ_λ

Observed radiance | Surface reflection (direct component) | Surface reflection (diffuse component) | Path radiance

$$L_\lambda = \frac{E_{0\lambda}T_{\lambda\downarrow}\cos\theta}{\pi}\rho_\lambda T_{\uparrow\lambda} + \frac{E_{a\downarrow\lambda}}{\pi}\rho_\lambda T_{\uparrow\lambda} + L_{p\lambda}$$

$T_{\lambda\uparrow}, T_{\lambda\downarrow}$**: Upward/Downward atmospheric transmittance**

ρ_λ **: Surface reflectance**

$E_{0\lambda}$ **: Solar irradiance**

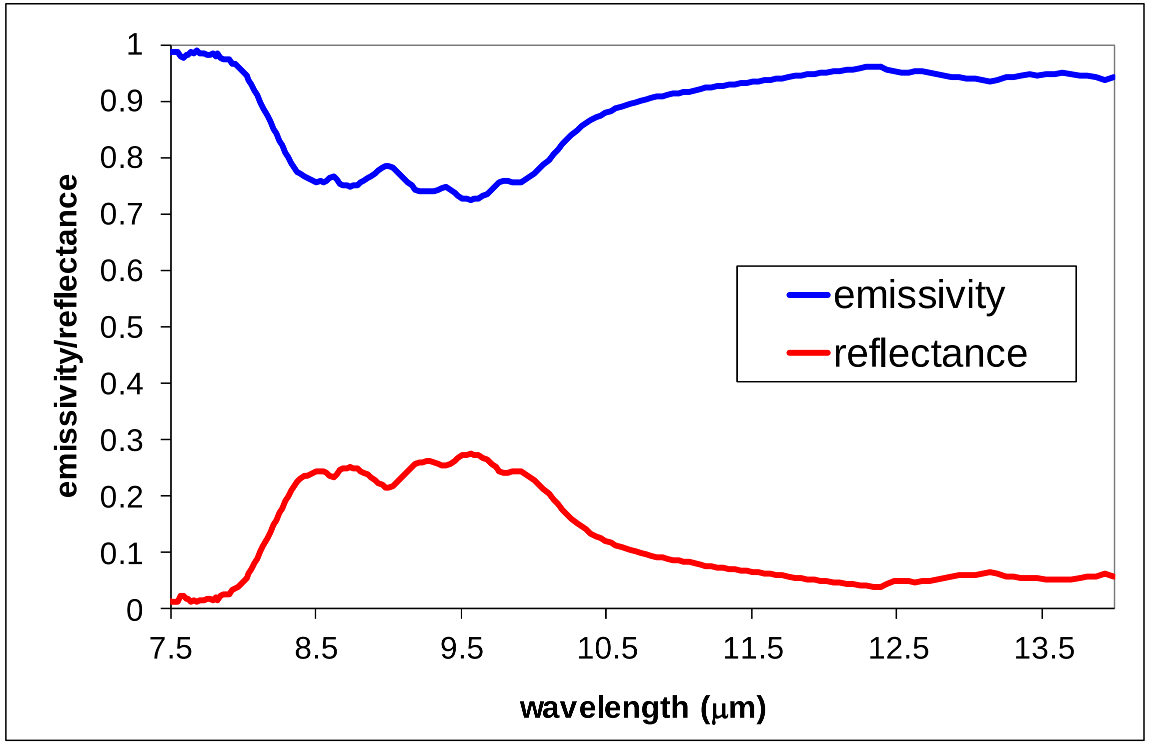
$L_{p\lambda}$ **: Path radiance**

$E_{a\downarrow\lambda}$ **: Diffuse solar irradiance**

θ **: Solar zenith angle**

- Spectral reflectance is a property of ground features we would like to measure
- Thus raw hyperspectral data need correction for atmospheric scattering and path radiance effects and thus to get closer to true spectral reflectance values, a measure we call '**apparent reflectance'** (a 'level 2' product)

Emissivity & Reflectance



Most natural materials are grey bodies

$$E_I(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda)$$

$\rho + \alpha = 1$ $\qquad \alpha = \varepsilon = \tau$ and $\qquad \varepsilon = 1 - \rho$

according to Kirchoff's law, where τ =transmittance,
a = absorptance, ε = emittance and ρ = reflectivity (albedo)

Reflectance and emissivity of an object are influenced by:

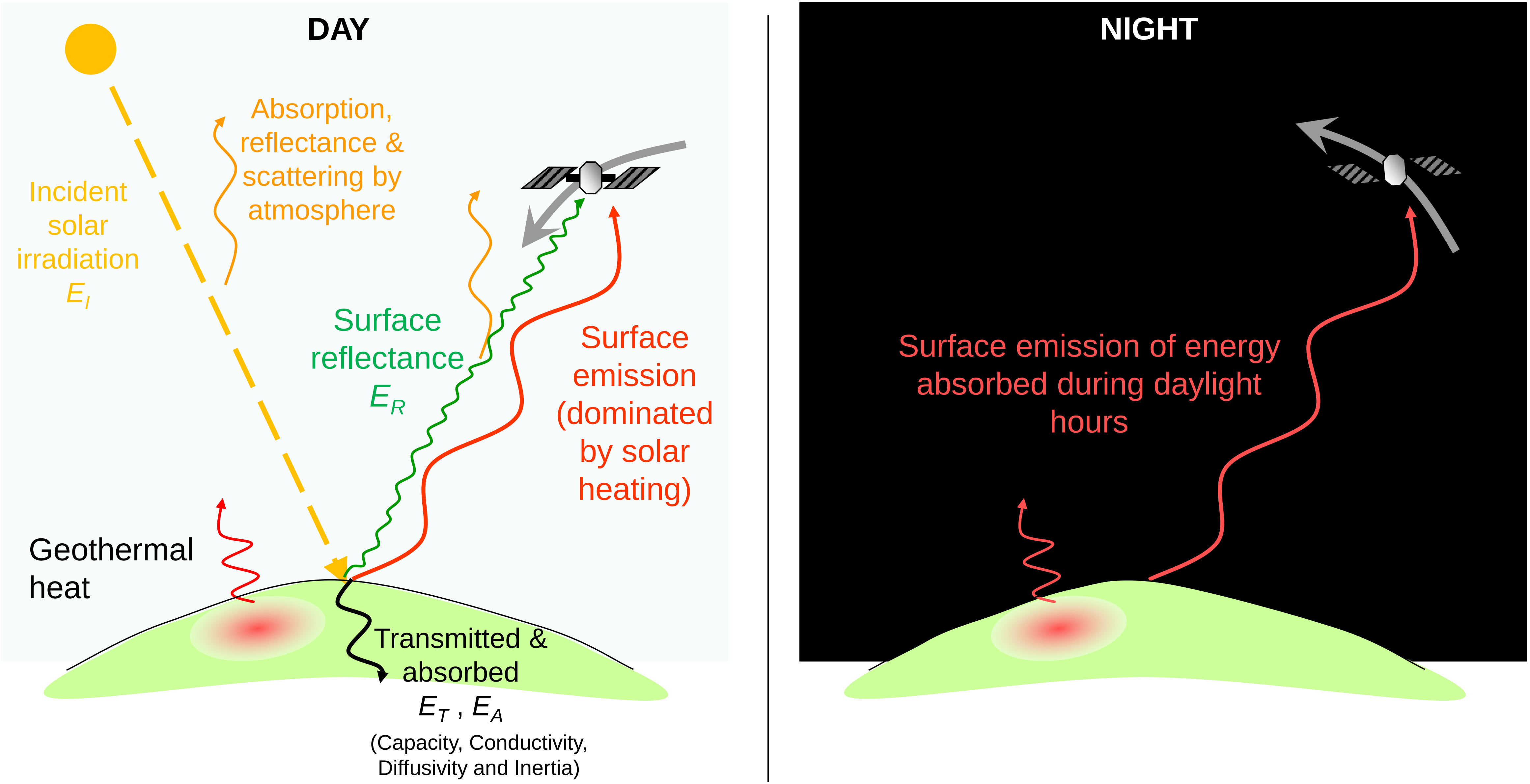
- Colour & Composition
- Surface roughness, moisture content & compaction

(all wavelength-dependent)

Thermal Properties: Water, rocks, soil, vegetation, atmosphere, and human tissue can all **conduct** heat directly through them (**thermal conductivity**) onto another surface and to store heat (**thermal capacity**).

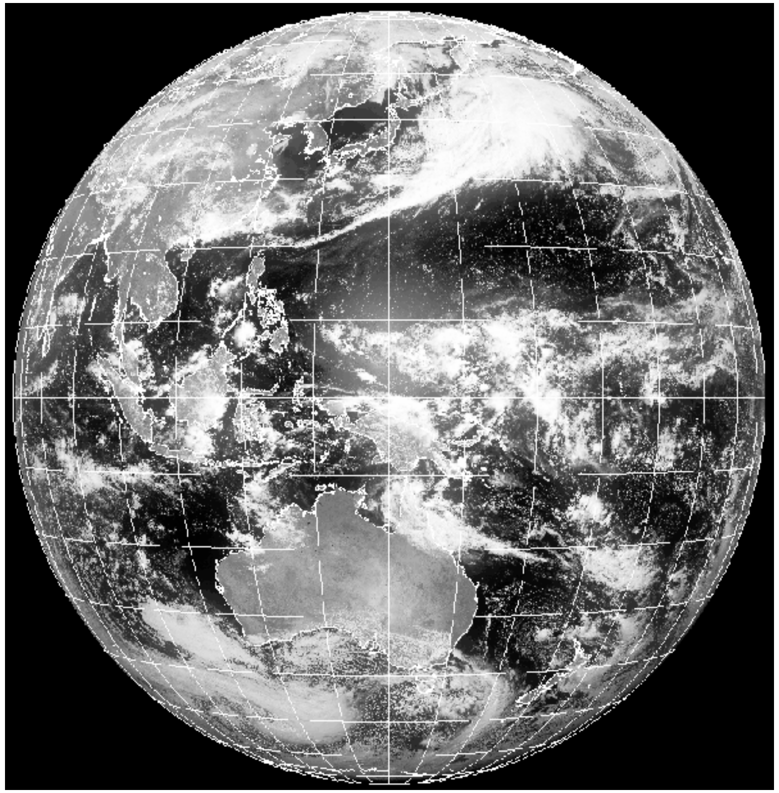
<u>Some materials respond to changes in temperature more rapidly or slowly than others (**thermal inertia**).</u>

Understanding day-time (optical) & night-time (thermal) images

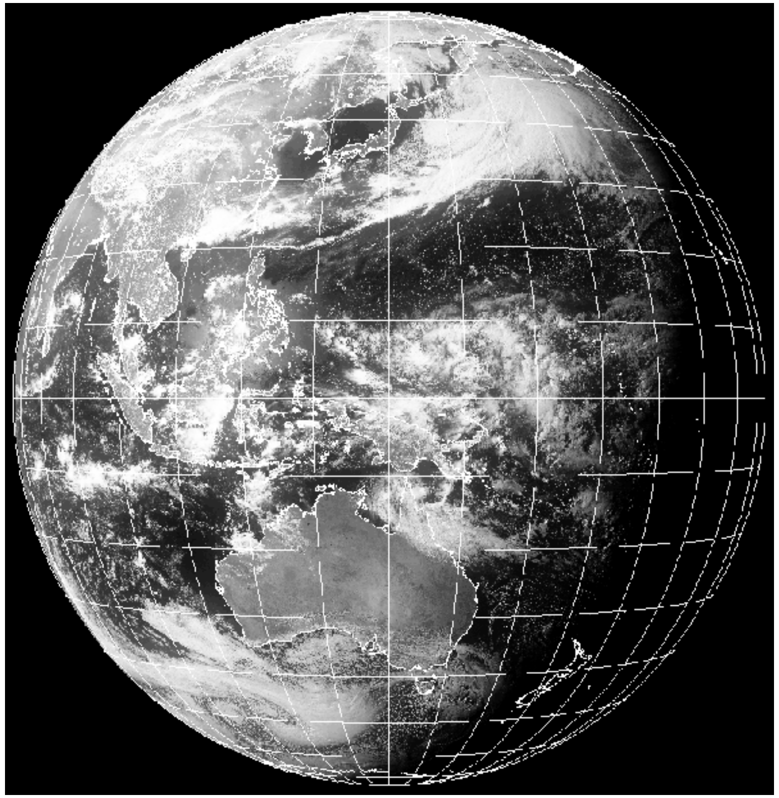


VISIBLE images from the Japanese Meteorological Satellite on May 3, 2006

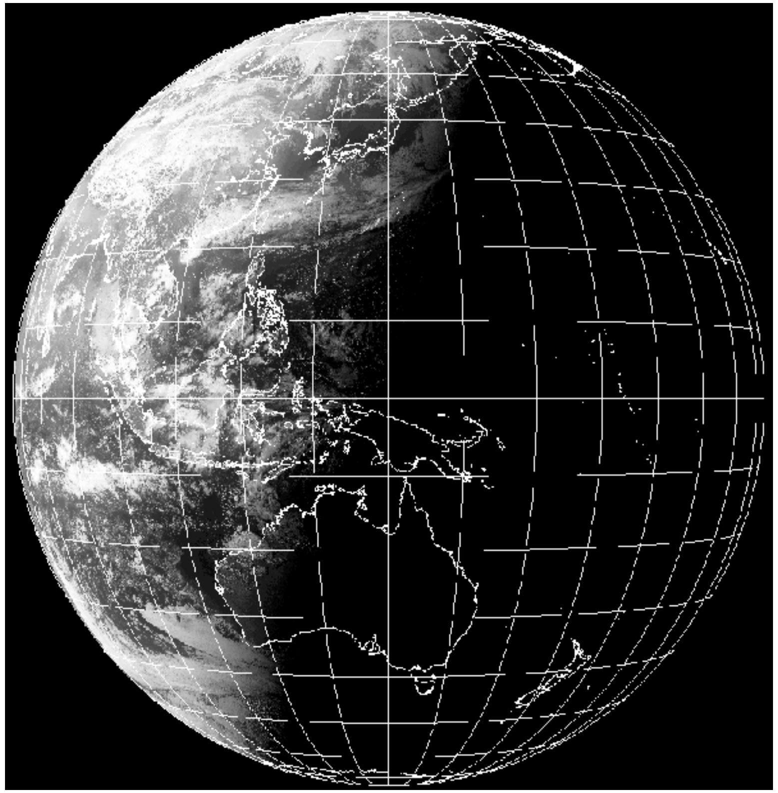
DAY 12:00 JST



DAY 15:00 JST



DAY/NIGHT 18:00 JST

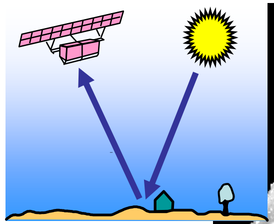


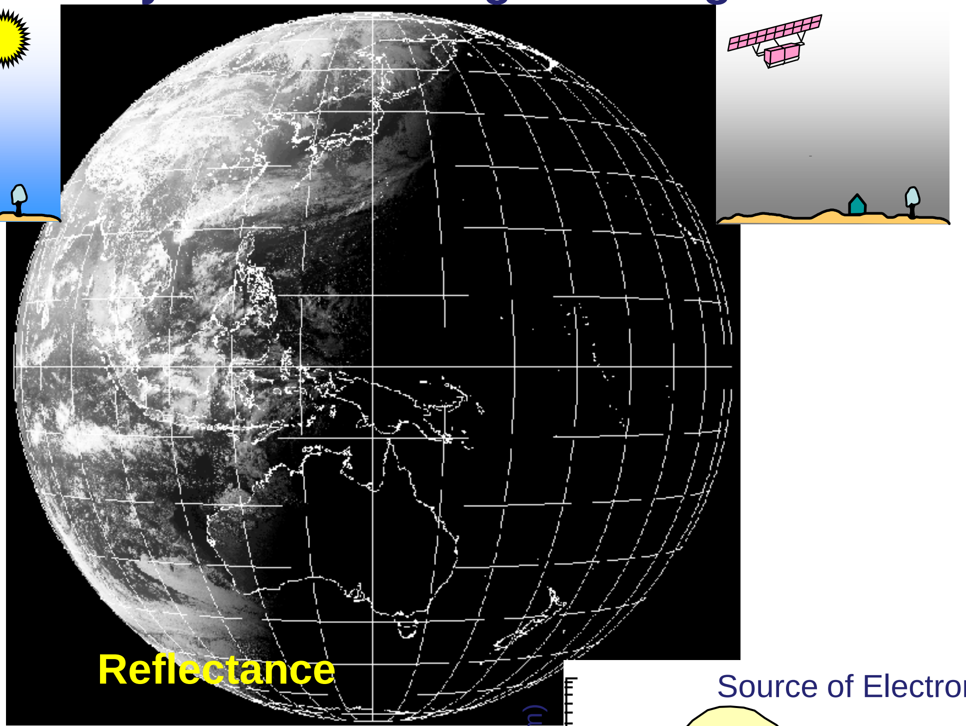
Daytime Reflectance in VIS

Japanese weather satellite Himawari 8 (ひまわり8号)

VIS & TIR Images – what do we see if we also image at night?

Day Evening Night



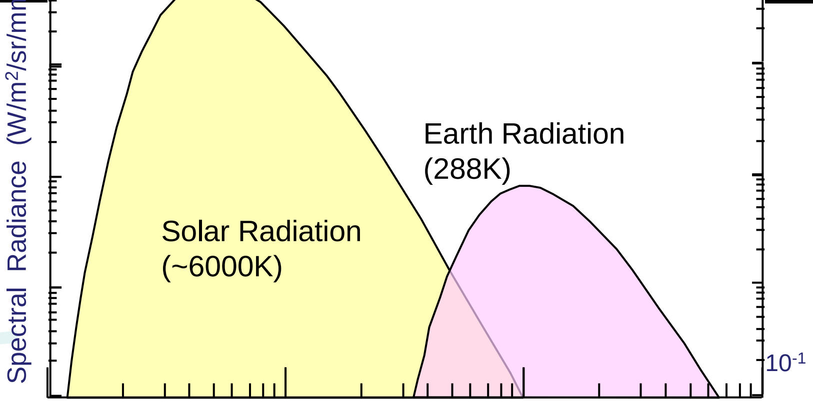


High intensity
High reflectance
= Appears Bright

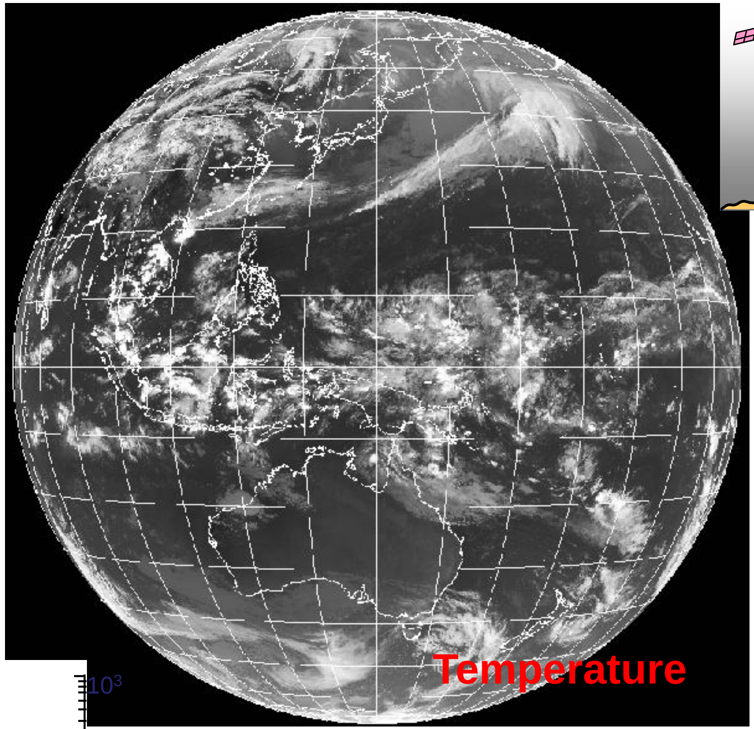
Low intensity
Low reflectance
= Appears Dark

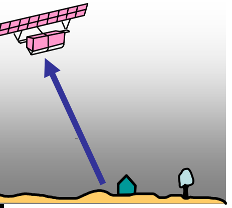
Reflectance
in the Visible

Japanese weather satellite
Himawari 8 (ひまわり8号)



Night TIR





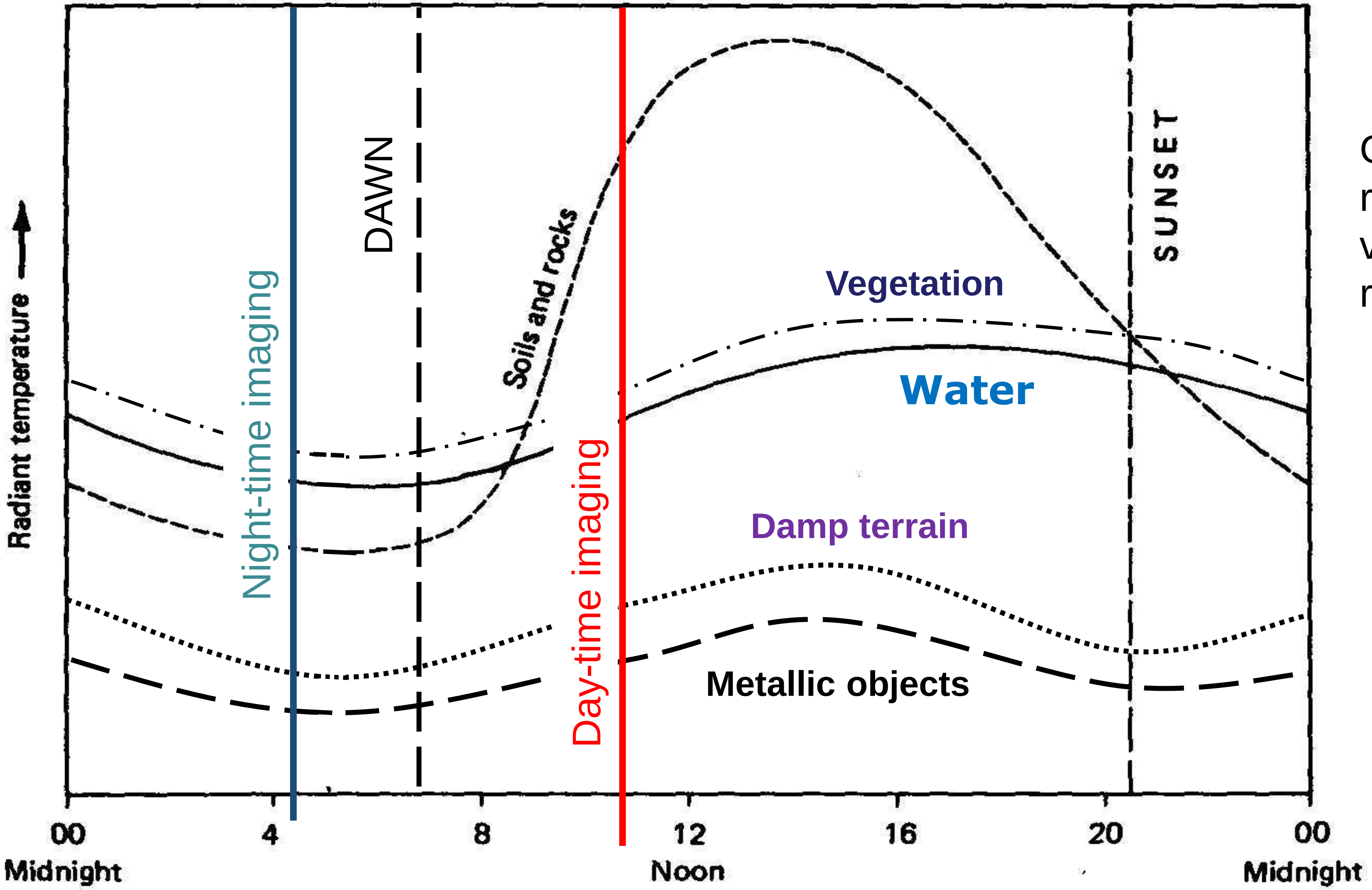
High intensity
High emission
= Warm

Low intensity
Low emission
= Cold

Emission
in the TIR

NB Colour scale in
TIR images from
<u>weather satellites</u>
is reversed

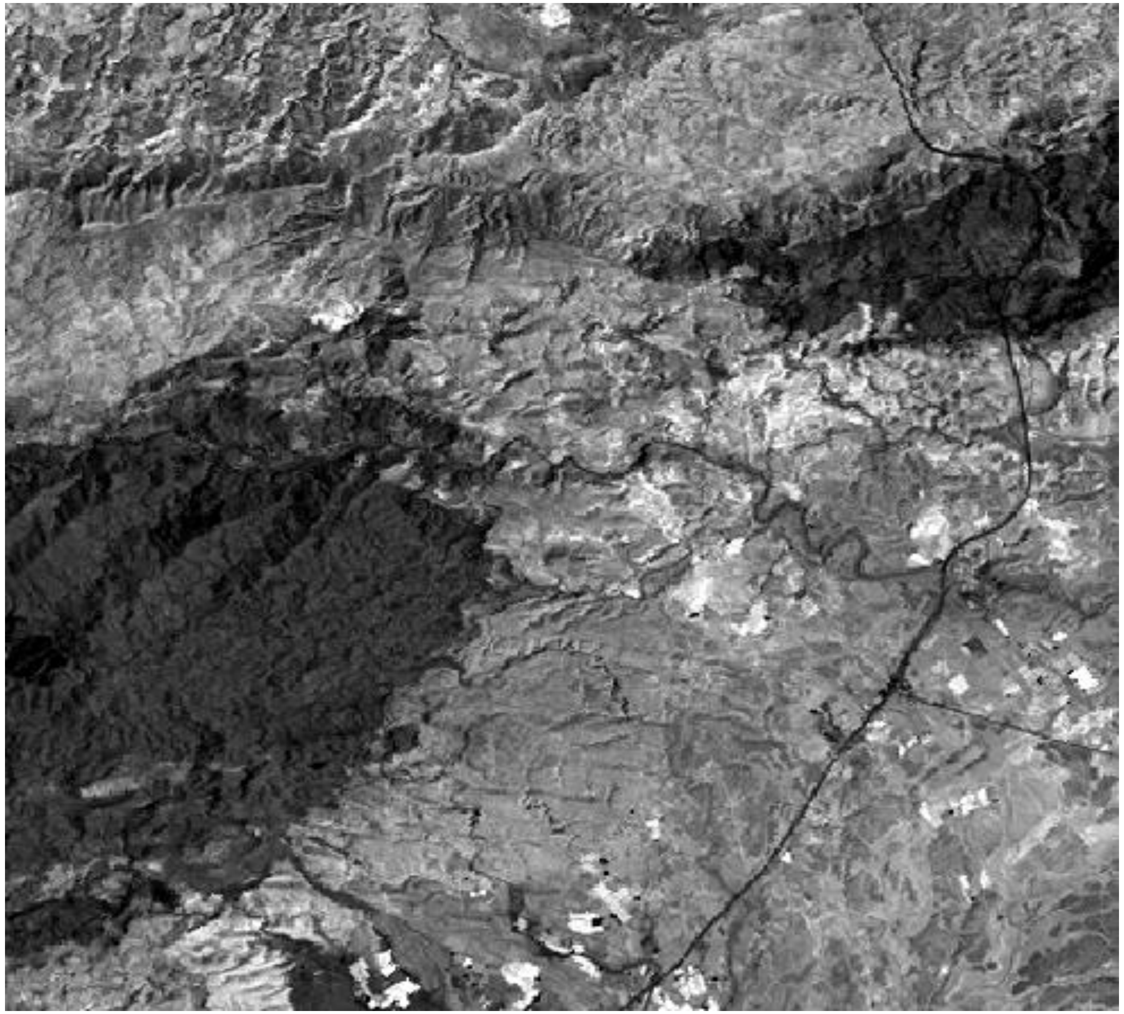
Diurnal variation in thermal radiation from the land surface



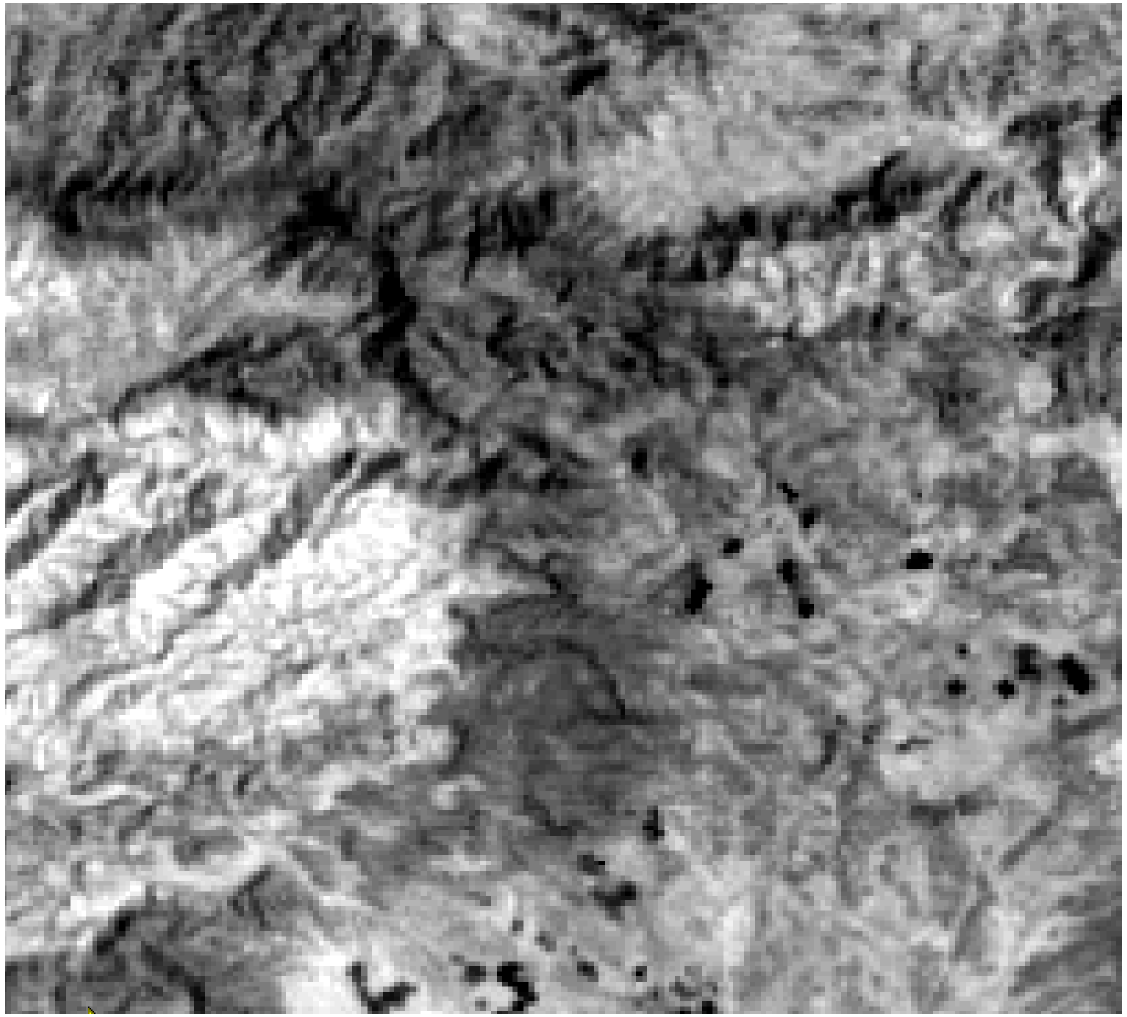
Generalised diurnal radiant temperature variation for soils & rocks versus water.

Thermal properties of Rocks & Soils (day time)

TM Band 1 Reflected VIS Blue



TM Band 6 – Daytime TIR



NB Colour scale is normal in daytime TIR image
(i.e. bright = warm, dark = cool)

e.g. Mica-schists, graphite-schists, basalts – all dark in VIS & bright in day-time TIR

Image tone and reflective & thermal properties – Simple principles for interpretation

- Materials which appear **bright** @ VISIBLE wavelengths (λ)
- Have **High** reflectance (high albedo)
  - Low absorption
- Reflect sunlight and remain cool to the touch
- Have low emissivity & appear **dark** in TIR
- E.g. Pale coloured rocks e.g. Siltstones, sandstones & some limestones, desert sands

- Materials which appear **dark** @ VISIBLE wavelengths (λ)
- Have **Low** reflectance (low albedo)
  - High absorption VIS & NIR
- Absorb sunlight and are warm to the touch
- Have high emissivity & appear **bright** in TIR
- E.g. Dark coloured rocks e.g. mica and graphitic schists, basic (mafic) volcanics, wet & clay-rich soils

2 Introduction to Satellite Remote Sensing and Sensor Technology

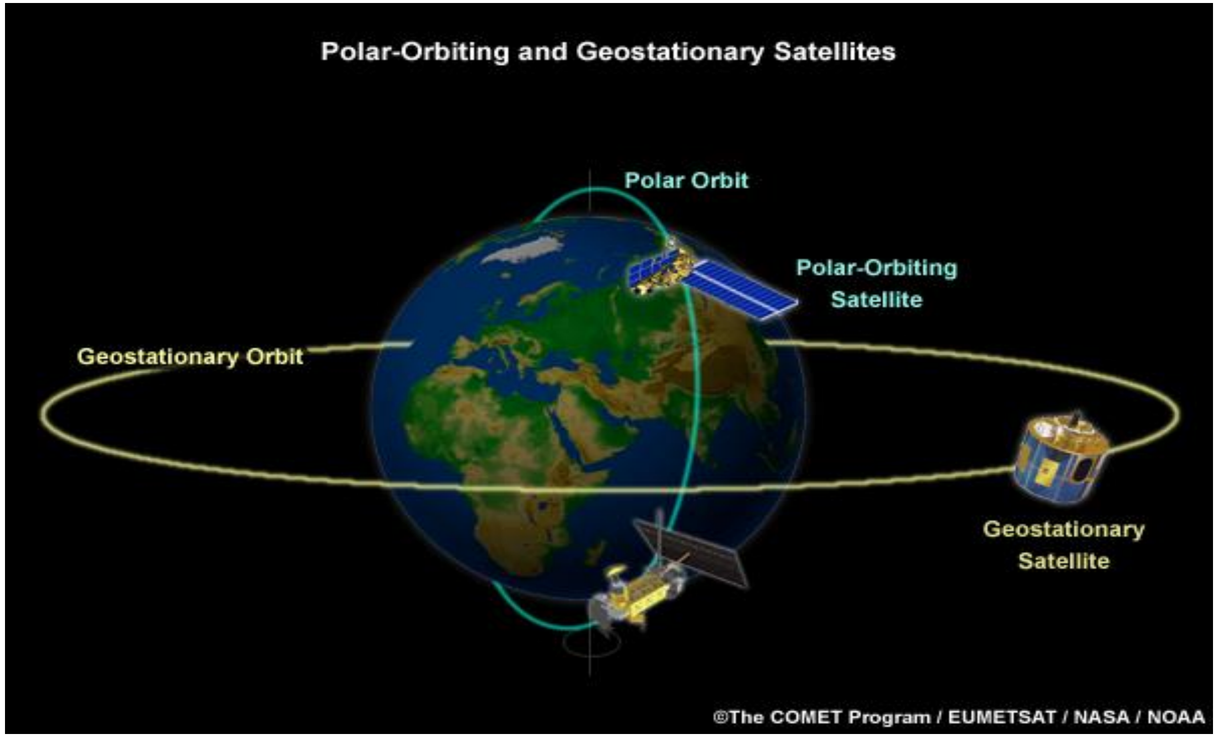
i.e. how remotely sensed image data are acquired ….

2.1 Platform

- **Ground:** portable spectrometer for field ground truth data collection
- **Airborne:** target orientated investigation
- **Spaceborne:** regional information and regular monitoring

Each has advantages and disadvantages

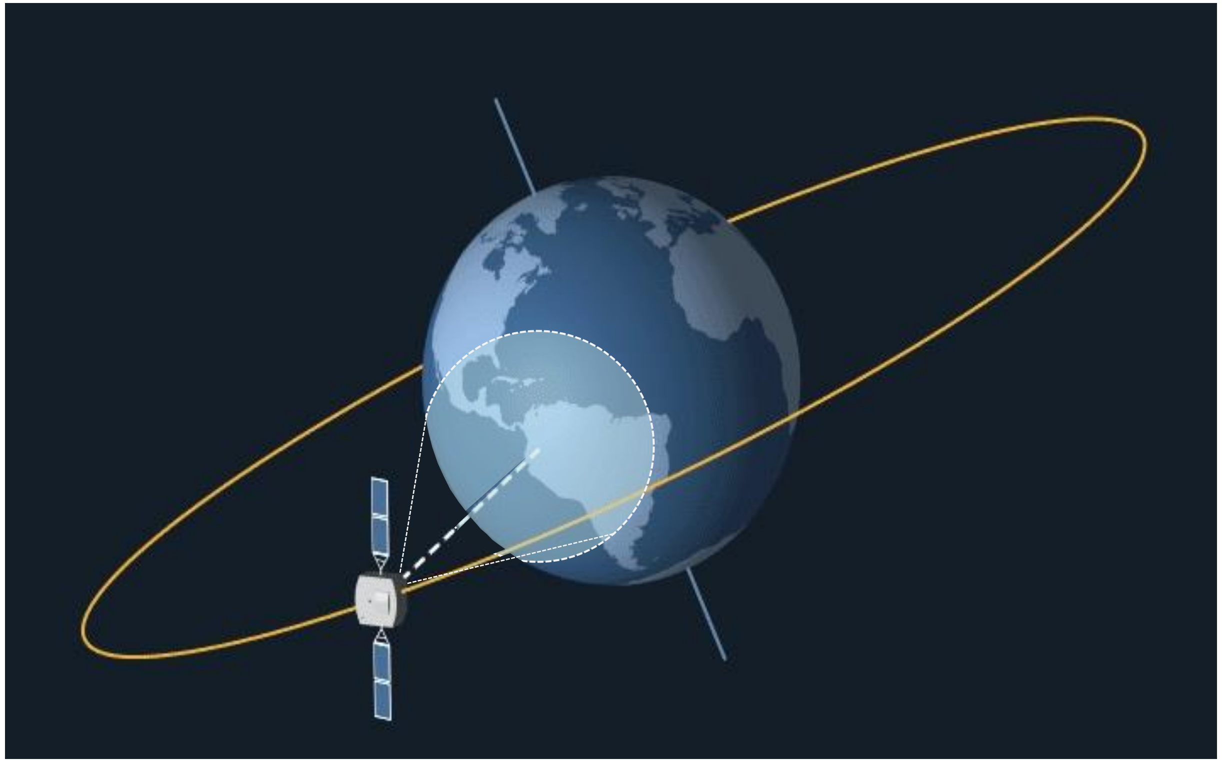
2.2 Orbits



Geostationary orbit:

At altitude of ~36000 km, synchronous with the rotation of the Earth.

Used by most meteorological satellites, e.g. GOES, and communication satellites.



Produces images of low spatial resolution (~1 km) but allows continuous monitoring of up to a third of the earth surface, with very frequent repeat (~30 or 60 mins).

Recent sensor development has achieved 50 m resolution on this orbit!!

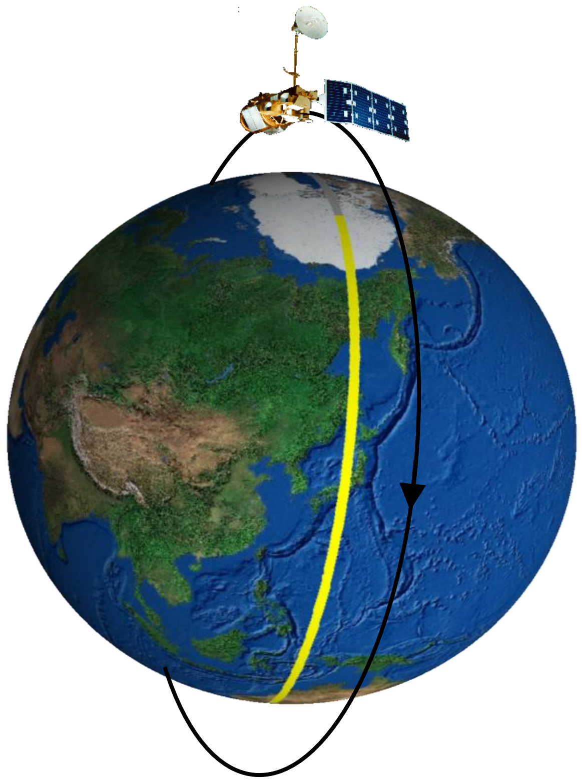
2.2 Orbits cont'd

Circular, near-polar, sun-synchronous:

Altitude 400-900 km, and so covering most of the earth (except the near polar areas), at nearly the same local time imaging (hence sun-synchronous), at the same scale of intermediate to high spatial resolution, revisit the same scene in a fixed period (e.g. 18 days for Landsat 4 & 5).

Most Earth Observation satellites:

e.g. Landsat, all Sentinels, SPOT, ERS, ENVISAT, Terra, JERS, ALOS, Radarsat, NOAA, IKONOS, QuickBird, OrbitView, etc.



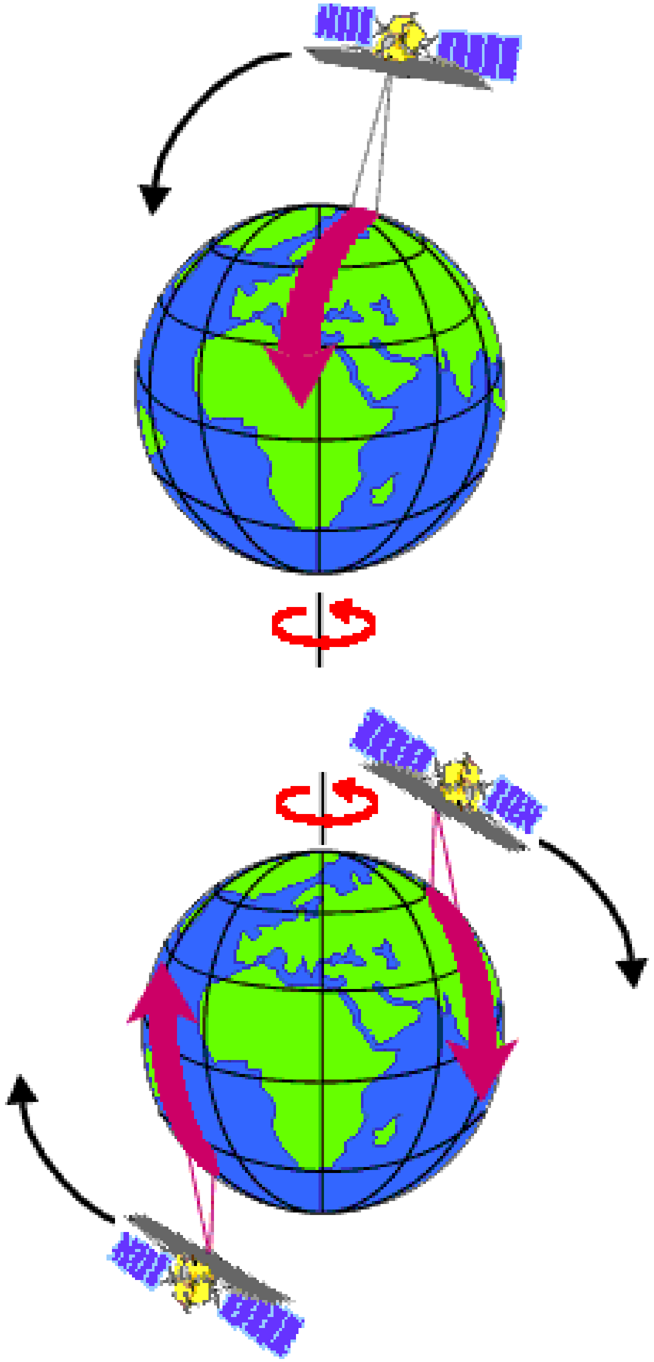
2.2 Orbits cont'd

Ascending and descending passes:

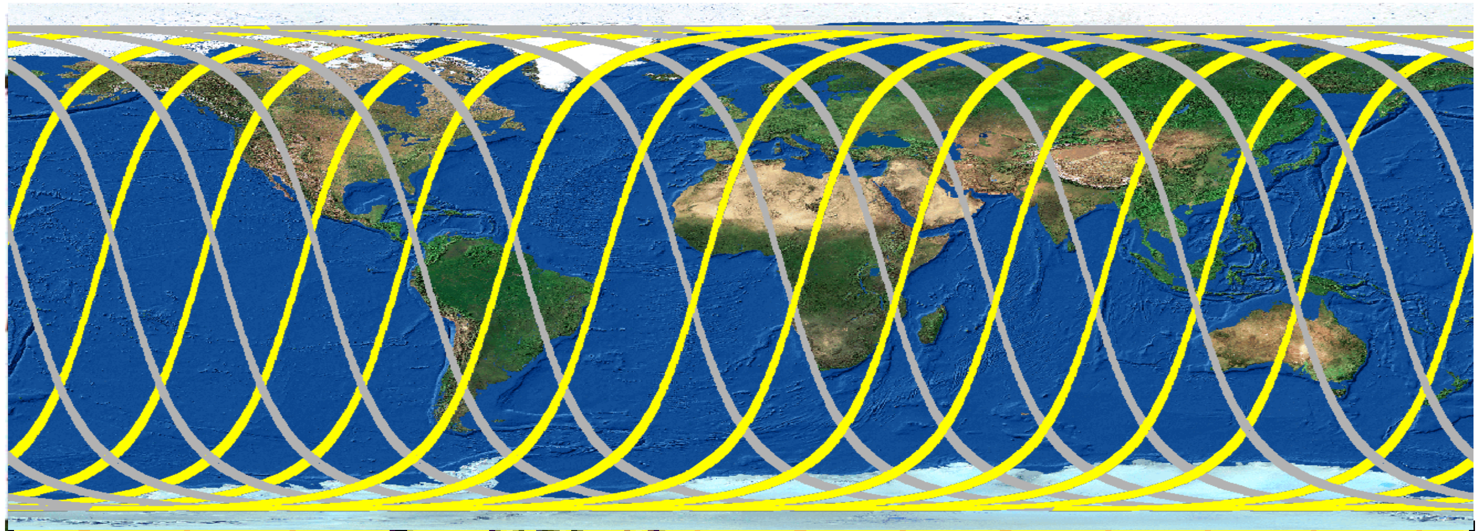
This type of obits must have inclination angle of ~98^o rather than going exactly through the north and south poles.

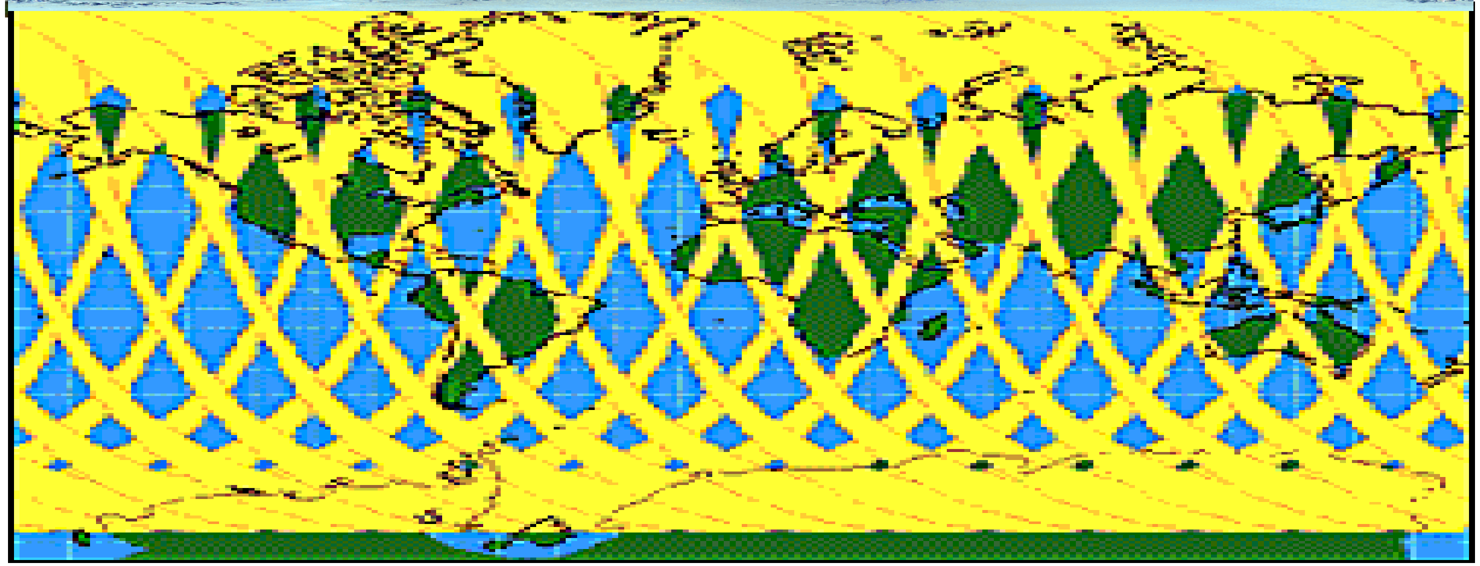
The satellite travels towards North pole of the Earth and then toward the South pole on the second half of its orbit. These are called **ascending and descending passes**.

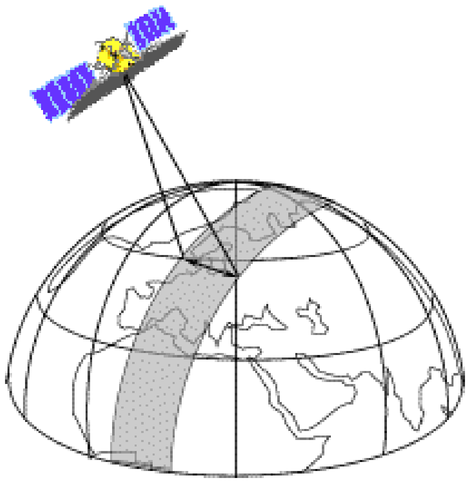
The inclination angle is configured such that the **descending pass is always on the sunlit side (day)**. Sensors recording only reflected solar energy image the Earth only on the descending pass, when solar illumination is available (**thermal and active sensors may operate on the night side**)

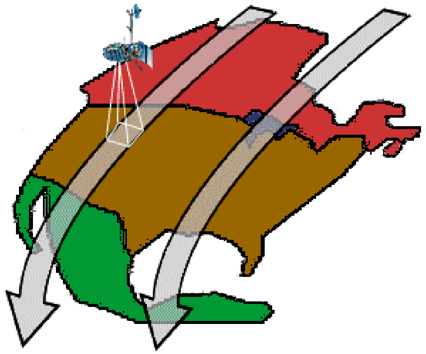


Orbital paths Swath, revisit period and overlap







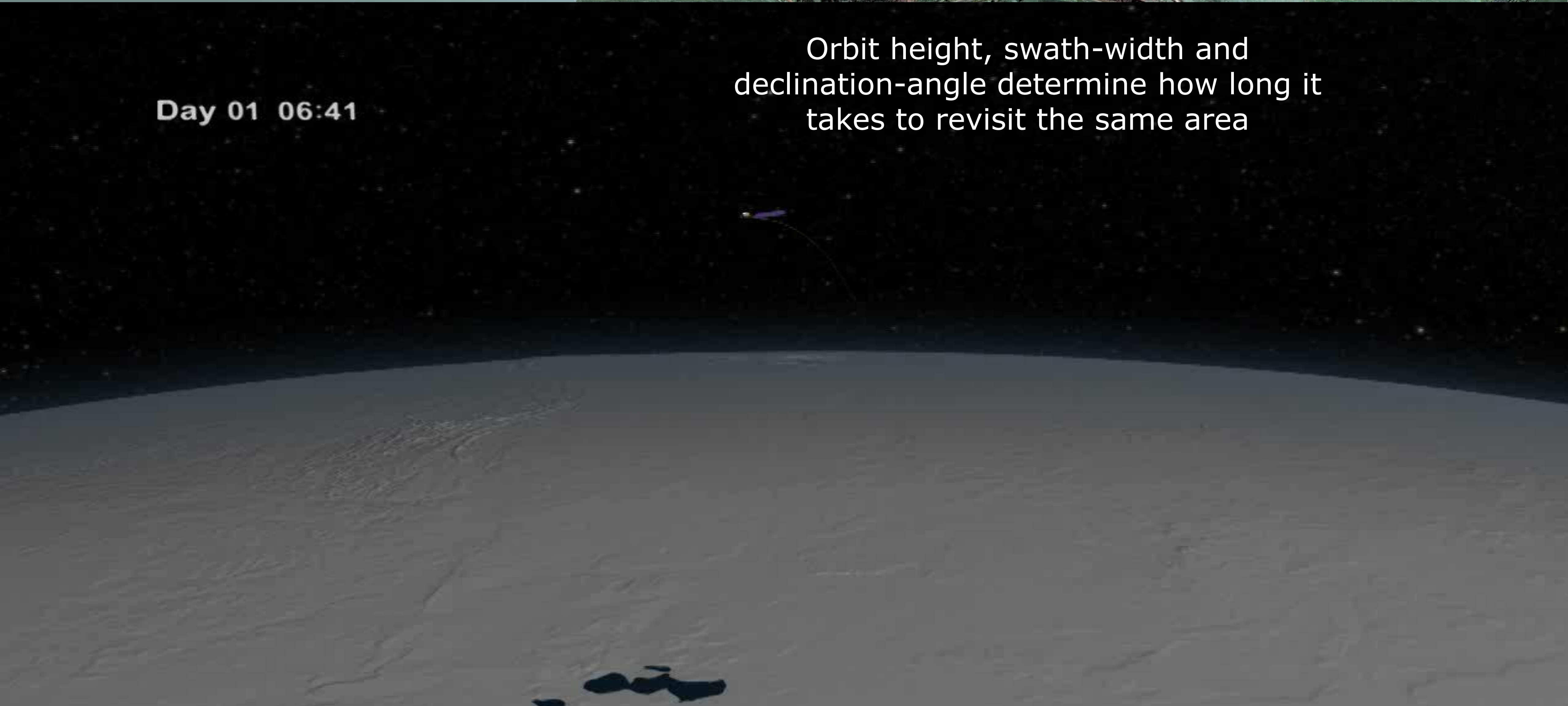


Revisit period >= Reimaging period!

Because of inclination angle, the obit cannot cover the polar area.

How does that work?

Orbit height, swath-width and declination-angle determine how long it takes to revisit the same area



2.3 Passive Sensors

Broad band multi-spectral and panchromatic optical sensor systems

- Large format and metric cameras, Multi-Spectral Scanner (MSS), Return Beam Vidicon (RBV)
- Scanners: Thematic Mapper (TM), ETM+, High Resolution Visible (HRV), AVHRR, ASTER, ASTR

Main imaging mechanisms:

- Photography (frame), one-way scanning, two-way scanning, **push-broom** scanning.

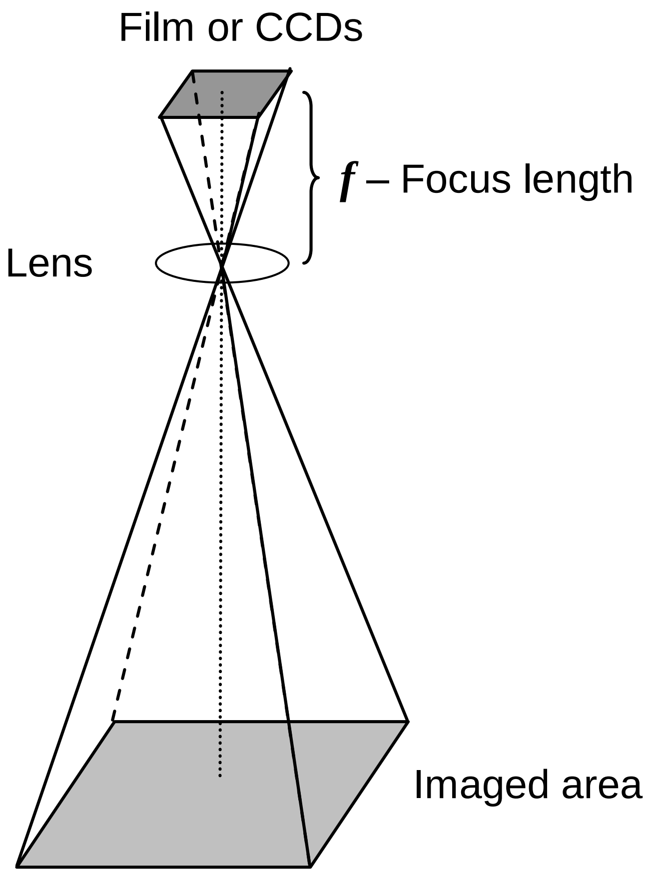
Imaging geometry:

- **Nadir**
- **Along track off-nadir (simultaneous stereo)**
- **Across track off-nadir (multi-temporal stereo and short revisit time)**

?

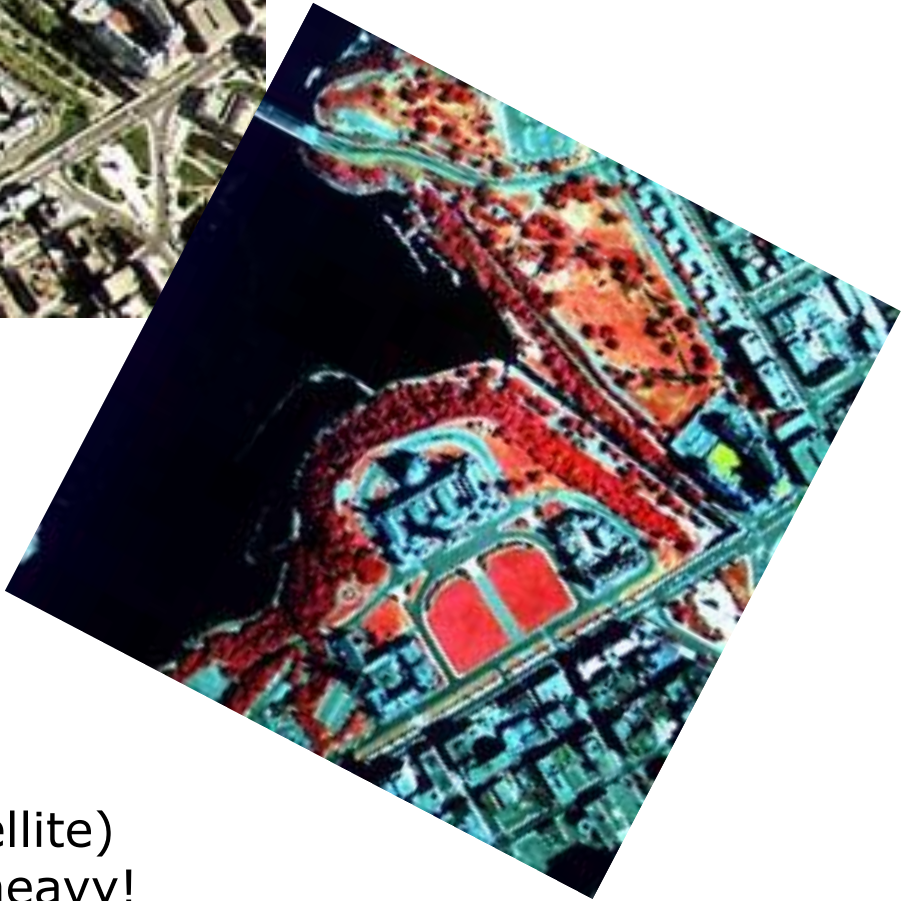
2.3 Sensors cont'd

Cameras and Aerial Photography



Optical concept of a frame camera system.

True colour

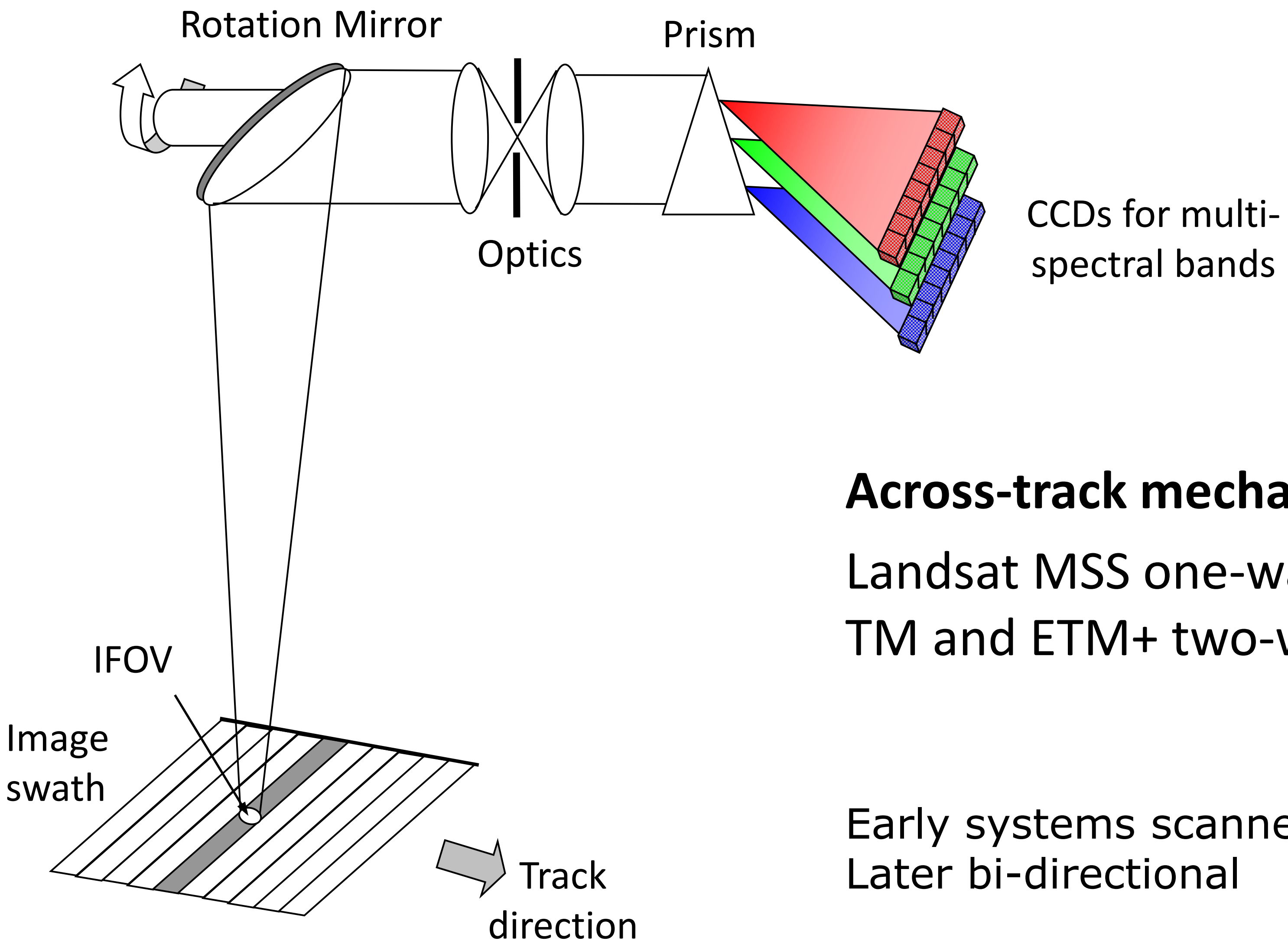


False Colour

Early (spy satellite) cameras were heavy!

2.3 Sensors cont'd

Multi-Spectral Scanner



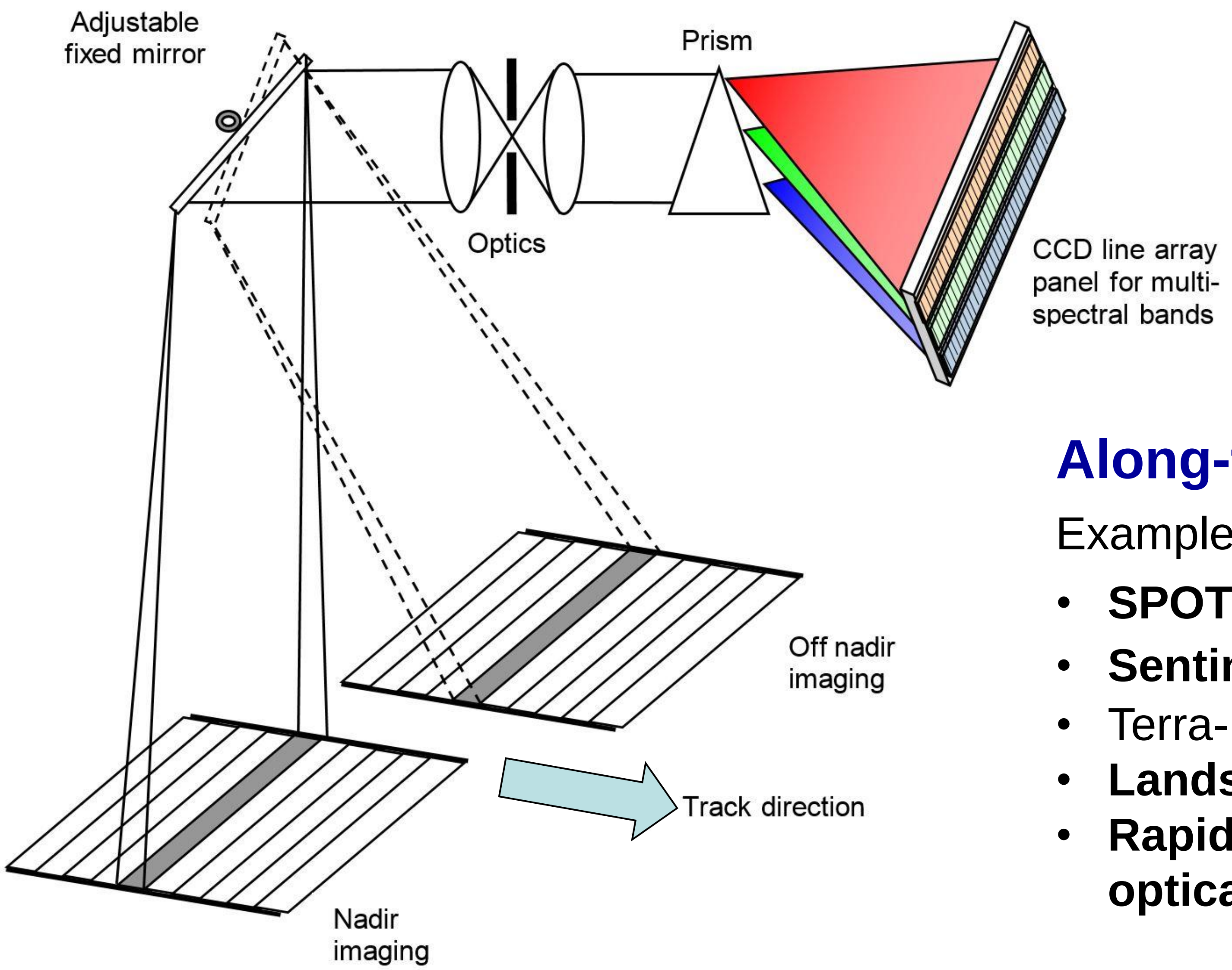
Across-track mechanical ('whisk-broom') scanner

Landsat MSS one-way scan;
TM and ETM+ two-way scan

Early systems scanned in one-direction
Later bi-directional

2.3 Sensors cont'd

Multi-spectral line scanner



Along-track '<u>push broom' </u>scanner

Examples include:

- **SPOT (the 1st one)**
- **Sentinel-2 Multispectral Instrument (MSI)**
- Terra-1 ASTER
- **Landsat 8 & 9 OLI & TIRS**
- **RapidEye, Earth I, WorldView (most VHR optical sensors, including cubesats)**

‘Whisk broom’ (across track, one way scan) configuration.

A mirror scans across the satellite’s path, reflecting light into a single detector which collects data one pixel at a time.

The moving parts make this type of sensor expensive and more prone to wearing out and image-internal distortions.

e.g L 1-5 MSS (two-way scan L5 & L7 TM & ETM+)

‘Push broom’ (along track) configuration.

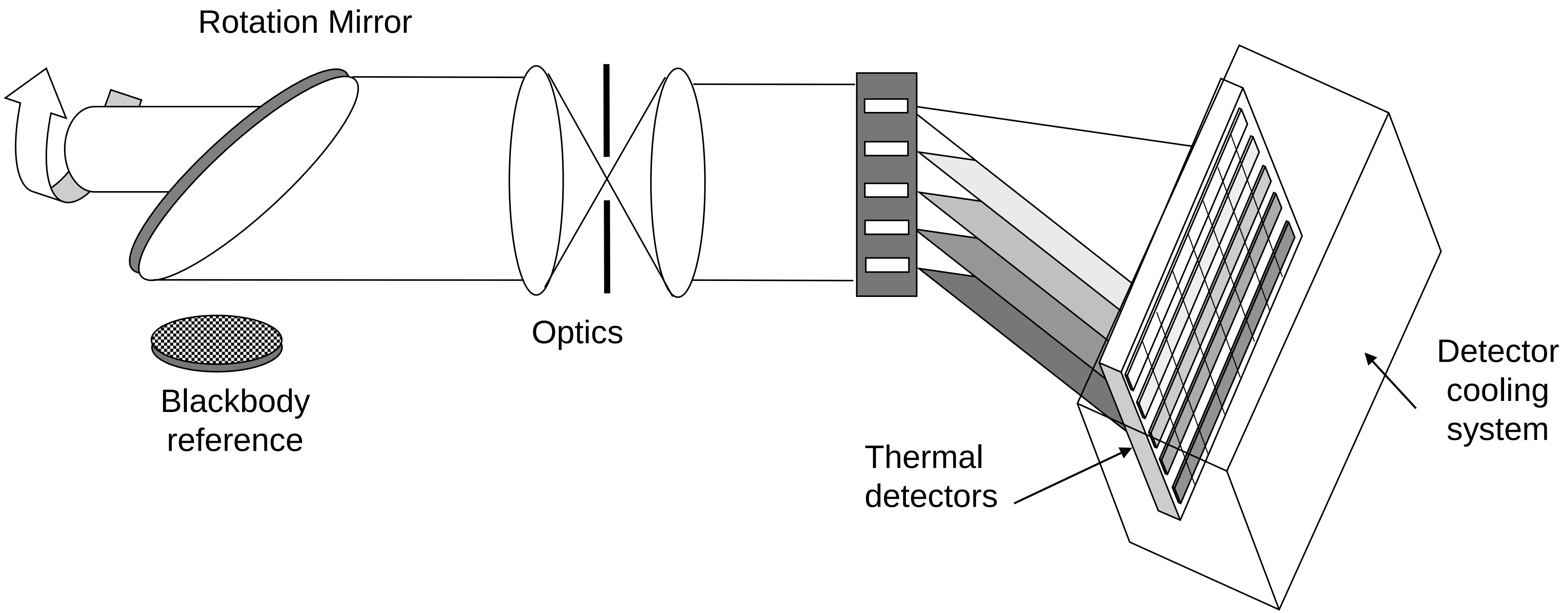
Consists of a line of sensors arranged perpendicular to the flight direction of the spacecraft. Different areas of the surface are imaged as the spacecraft flies forward.

Generally lighter and less expensive than whisk broom, and can gather more light because they look at a particular area for a longer time, like a long exposure on a camera.

e.g. L8, STL-2, most VHR sensors

2.3 Sensors cont'd

Multi-spectral thermal scanner



Examples:

Airborne: TMS

Spaceborne: ASTER, TM, ETM+, TIRS

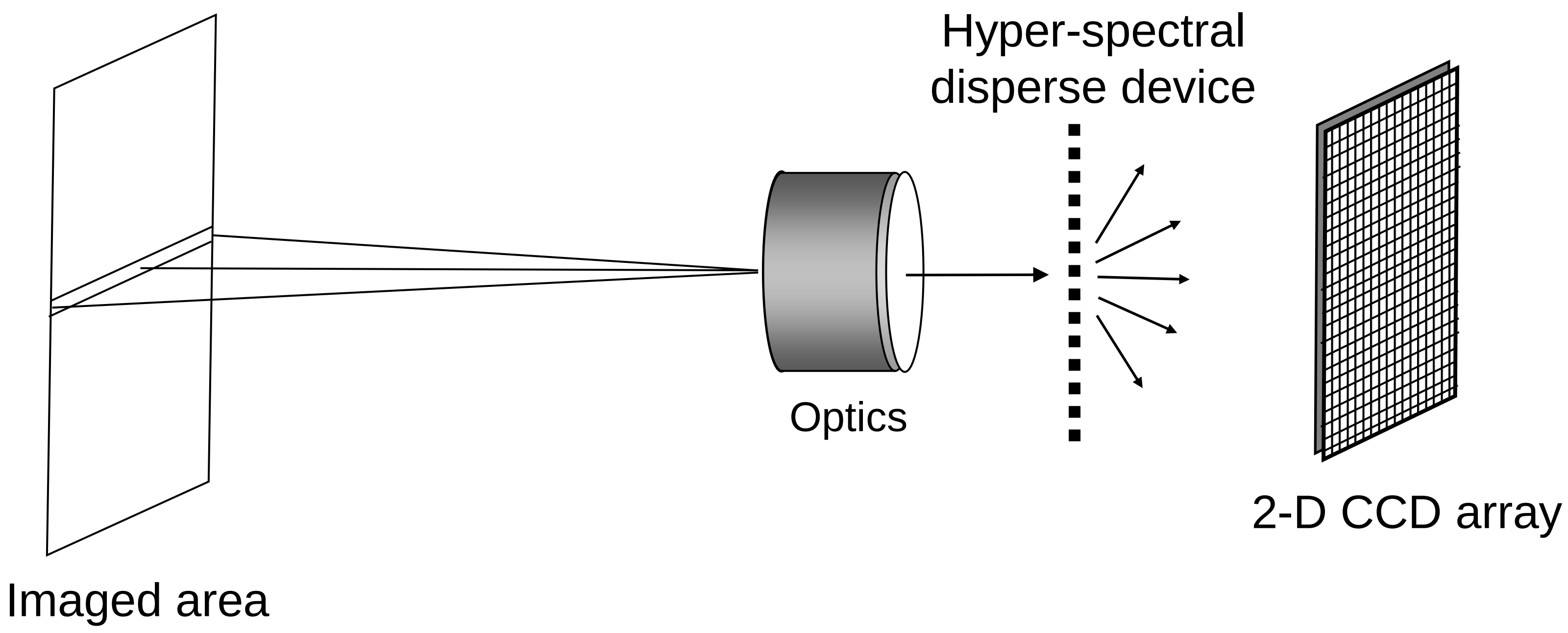
Modern TIR scanners are now Push broom

2.3 Sensors cont'd

Hyperspectral sensor system

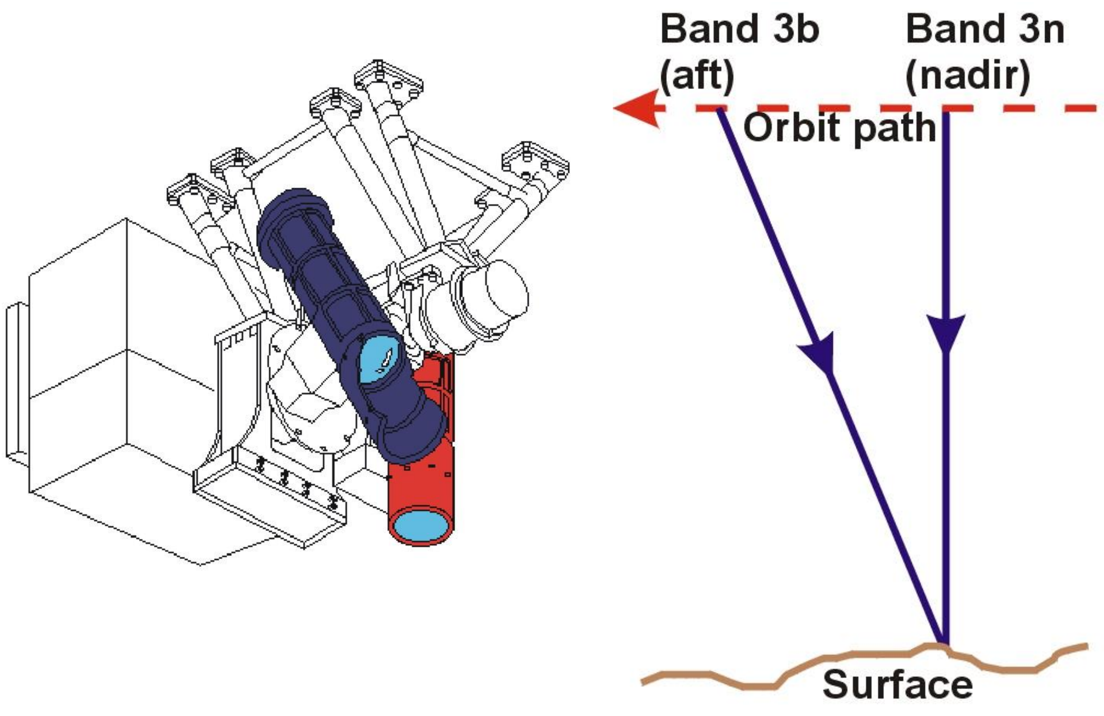
These have 10s to 100s of spectral bands. Mainly airborne so far. Examples:

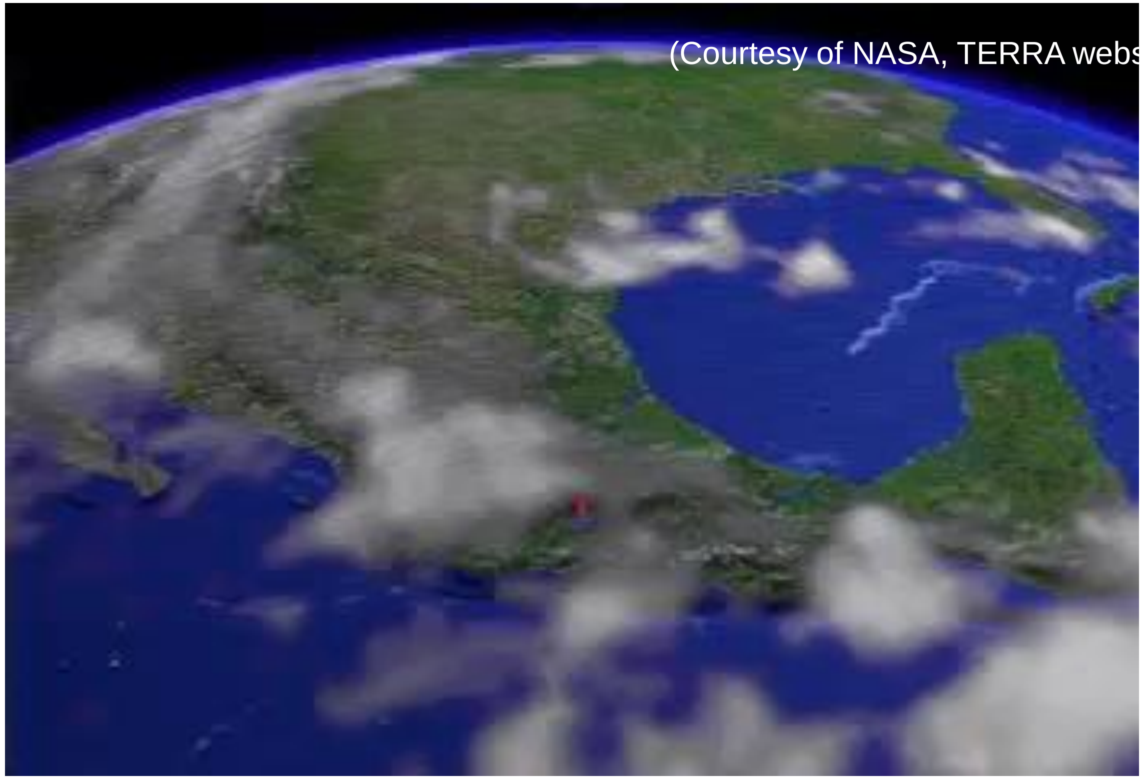
- Airborne Visible-Infrared Imaging Spectrometer (AVIRIS 224 bands),
- Compact Airborne Spectrographic Imager (CASI 288 bands),
- Geophysical and Environmental Research Imaging Airborne Spectrometer (GERAIS 63 bands).
- HyMap – first commercial system (airborne), VIS - SWIR, ~10 nm bandwidth, variable resolution
- EO-1 Hyperion – 1st satellite borne sensor, NASA & USGS (220 bands VIS-SWIR, 30 m resolution)



2.3 Sensors cont'd

Stereo Imaging





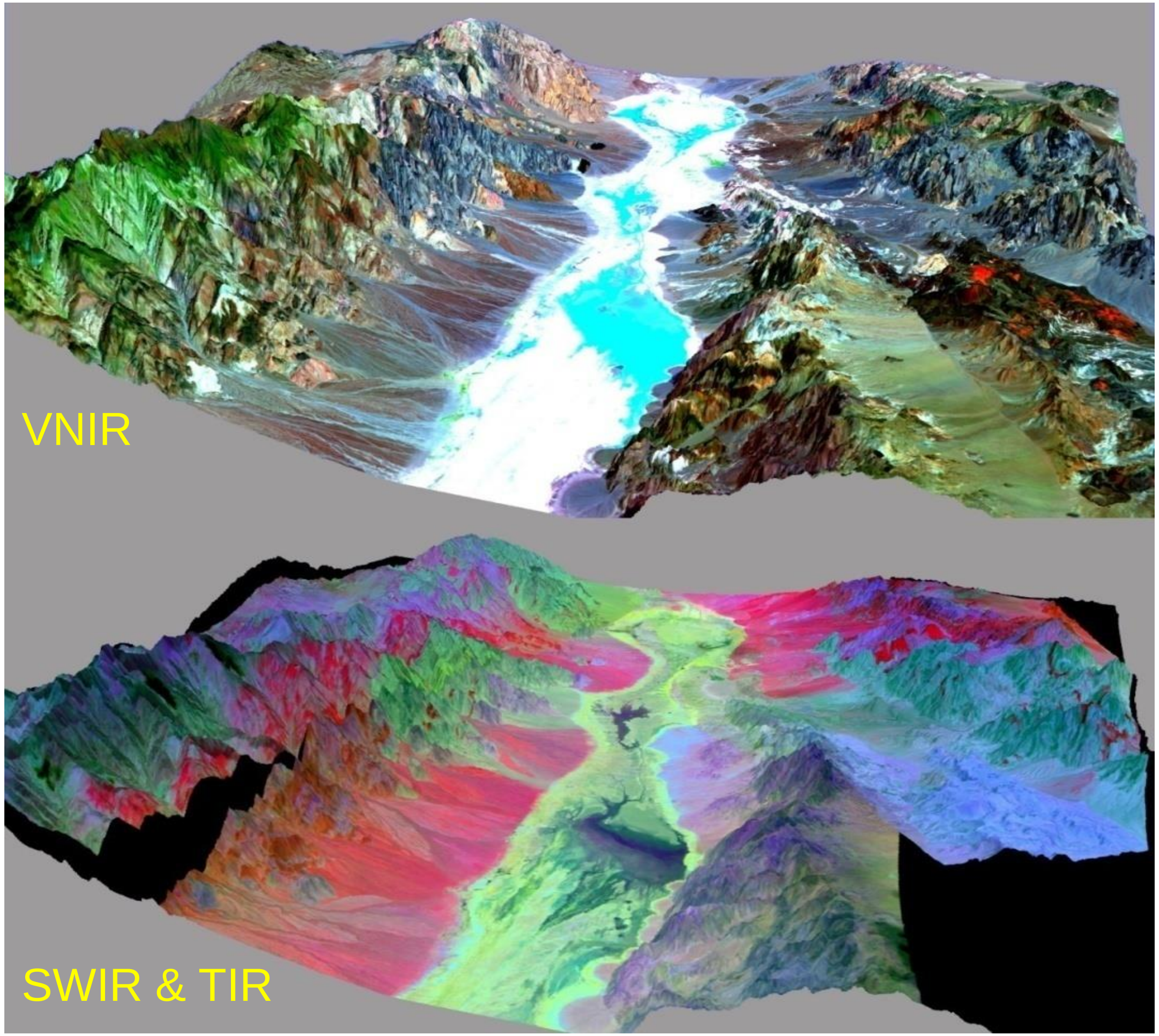
Enabling generation of Digital Elevation Models (DEMs) for terrain analysis and 3D visualisation

ASTER & SPOT were first to use along-track stereo imagery (nadir and back looking along track stereo)

Used to generate Digital Elevation Models (DEMs) i.e. topography

Now High Res and Very High Res satellites are fully pointable, enabling stereo from multiple angles (along- and across-track)

ASTER – colour composites & DEM

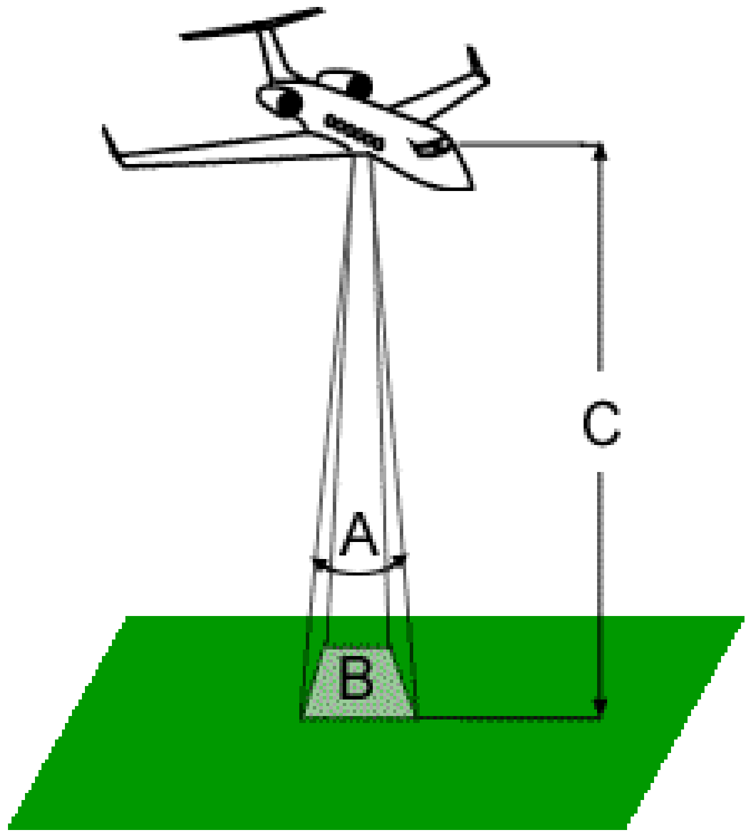


2.4 Image Resolution

Spatial resolution

The detail discernible in an image depends on the **spatial resolution** of the sensor, which is the size of the smallest separation between two objects that can be resolved by a sensor

The spatial resolution of a passive sensor depends primarily on its *Instantaneous Field of View* (**IFOV**) which is decided by spatial sample density of an optical sensor system. The IFOV determines the size of the area seen from a given altitude (B).

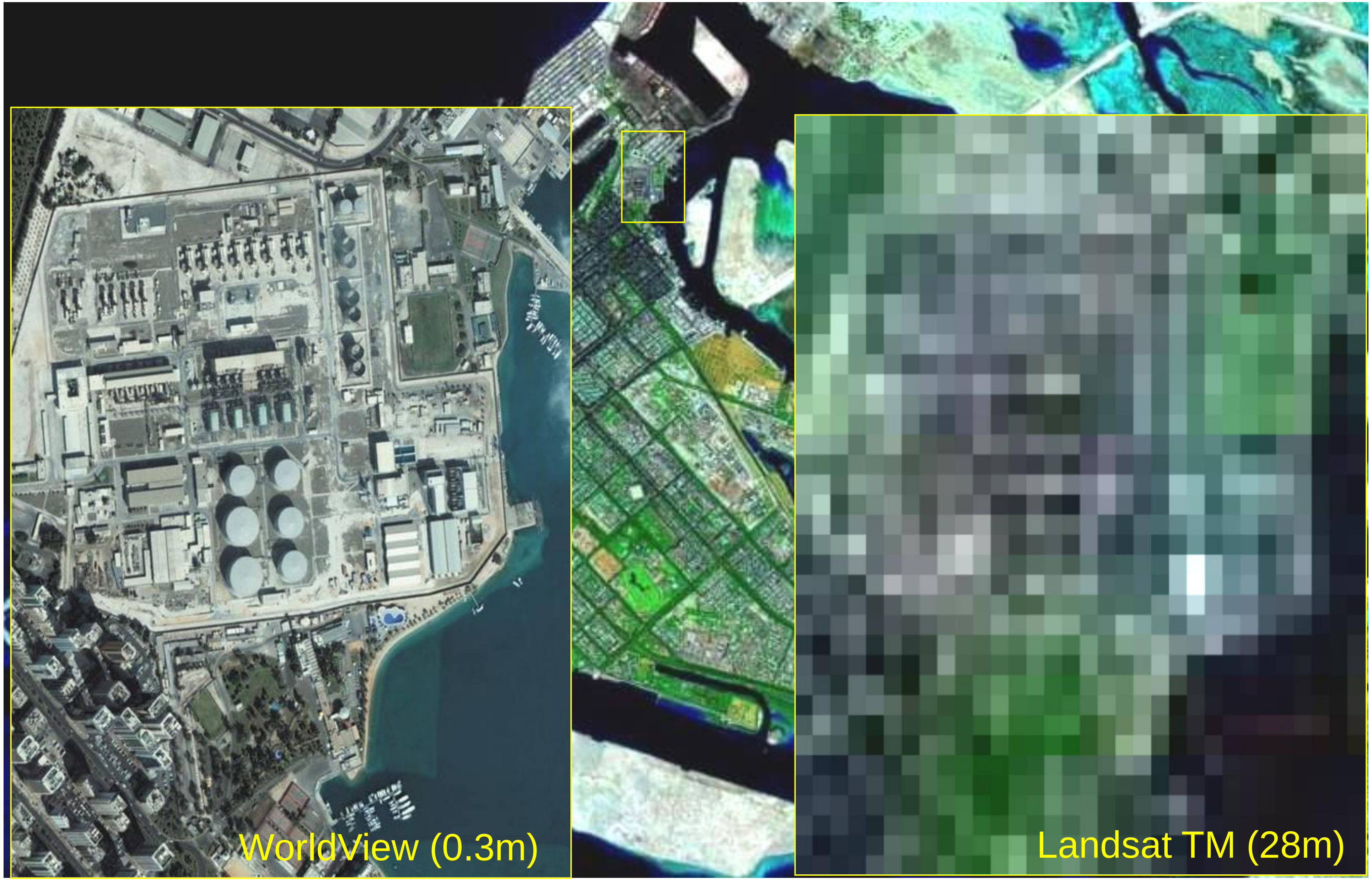


As shown in the Figure, IFOV is the angular cone (A) of visibility to a detector (i.e. CCD), which records the EMR reflected from area (B), over a distance or altitude (C), at a particular moment in time, as a digital number (DN) in one image pixel.

So the area viewed (**B**) **= IFOV × C**

The area (B) on the ground is called the **ground resolution cell** and primarily determines the image spatial resolution.

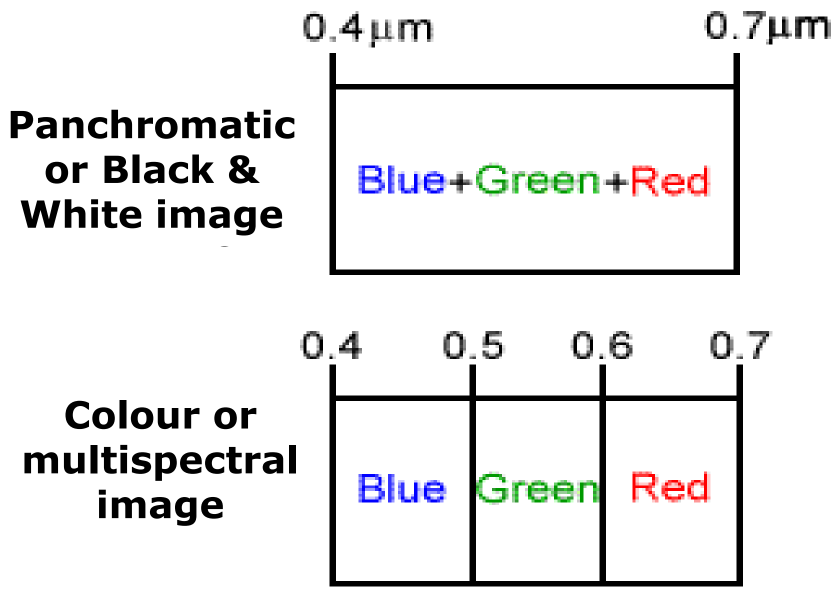
EO Satellites – Comparison of Spatial resolution

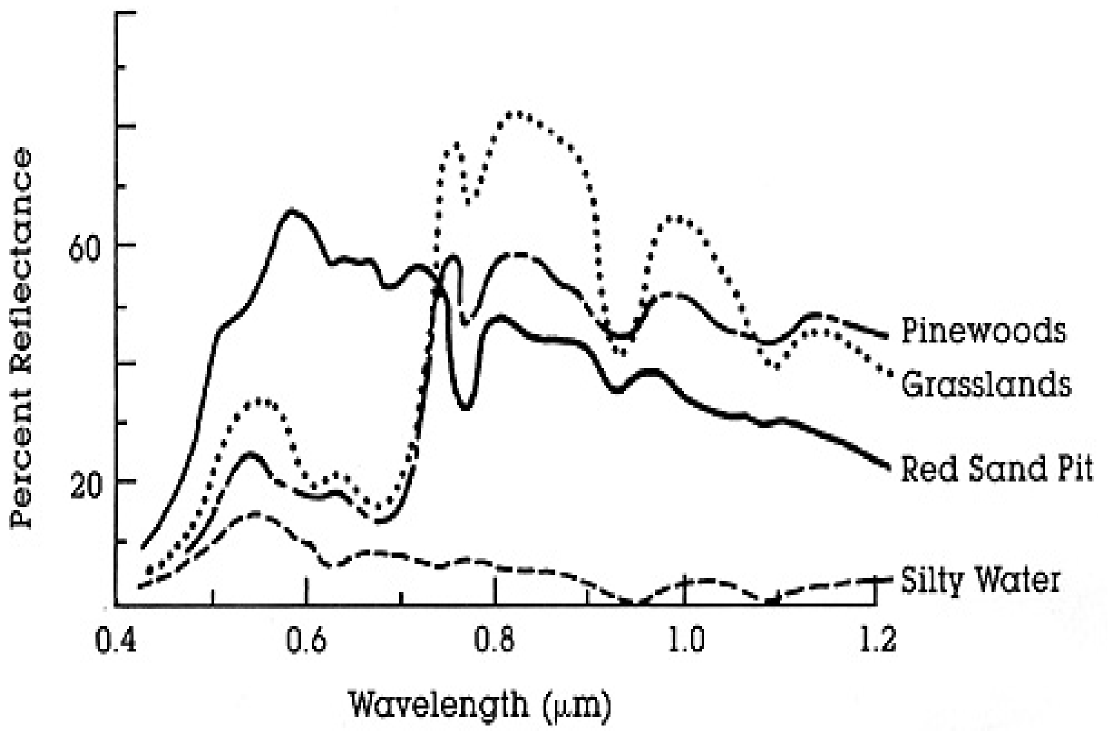


2.4 Image Resolution cont'd

Spectral resolution

Spectral resolution describes the ability of a sensor to **define fine intervals of wavelength**.



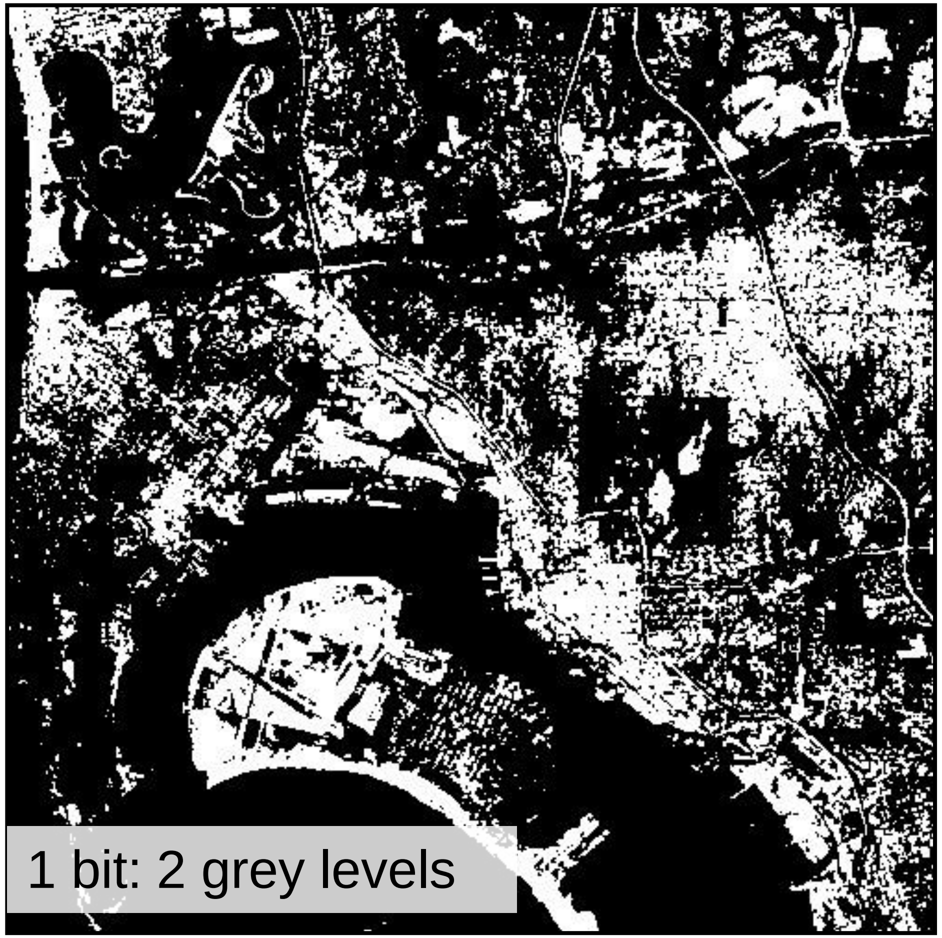


Higher spectral resolution means more spectral bands with narrower spectral intervals covering a spectral range.

A hyperspectral sensor has 100s of narrow bands across the VIS-NIR-SWIR range (0.4 – 2.5 microns)

2.4 Image Resolution cont'd

Radiometric resolution

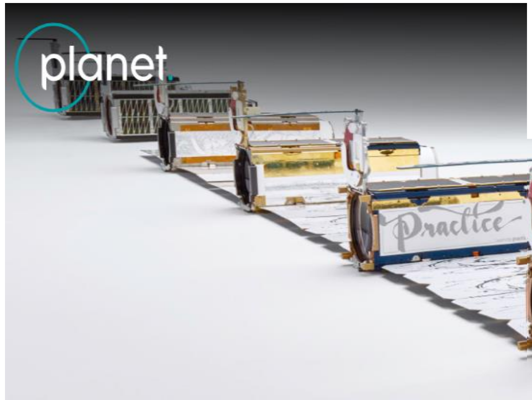


- The sensitivity of a sensor to the magnitude of the electromagnetic energy determines its **radiometric resolution**.
- The radiometric resolution therefore describes its ability to discriminate very slight differences in sensor received energy levels (brightness), and is quantitatively characterised as a number of bits (per pixel).

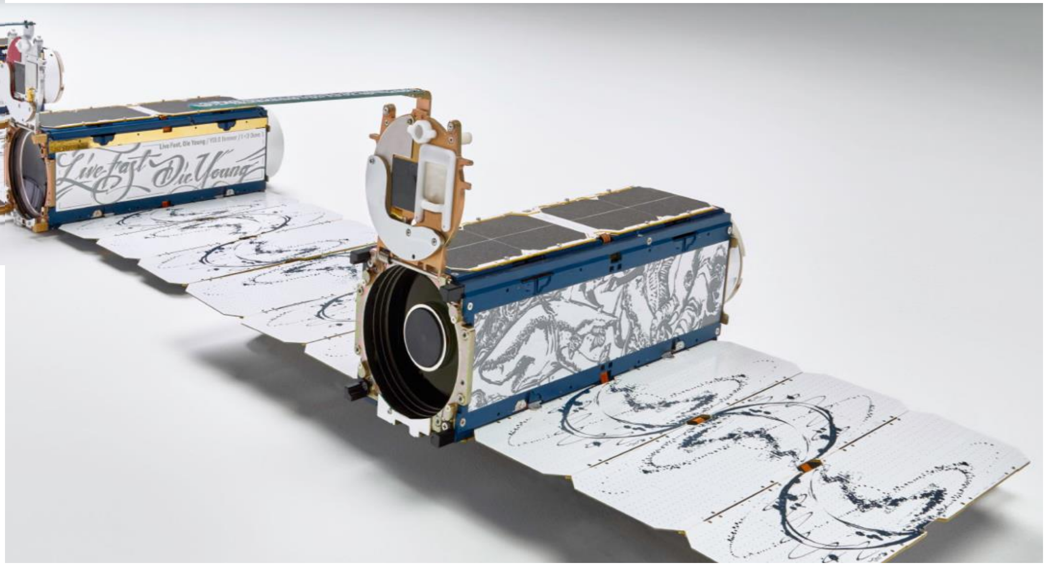
2.4 Image Resolution cont'd

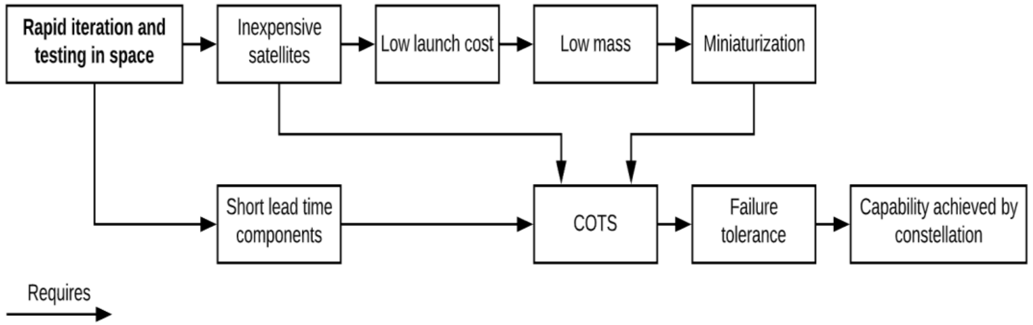
<u>Temporal resolution</u>

- Temporal resolution describes the re-imaging period or repeat time.
- Absolute temporal resolution (to image the same area at same view angle, a second time) is the **revisit/repeat period**.
- Some systems **angle/point** their sensors to image between passes, separated by one to many days within the revisiting period
- Sensors in **constellations can image much more frequently** = 'Agile Aerospace'
  - ➢ **Daily VHR acquisitions** from: Planet's Doves, Earth-i, Vivid-i, SuperView, DMC, Kompsat, TripleSat
- So re-imaging period <= revisit period for any sensor
- Actual temporal resolution depends on several factors, including the satellite/sensor capabilities, the swath overlap, and latitude.

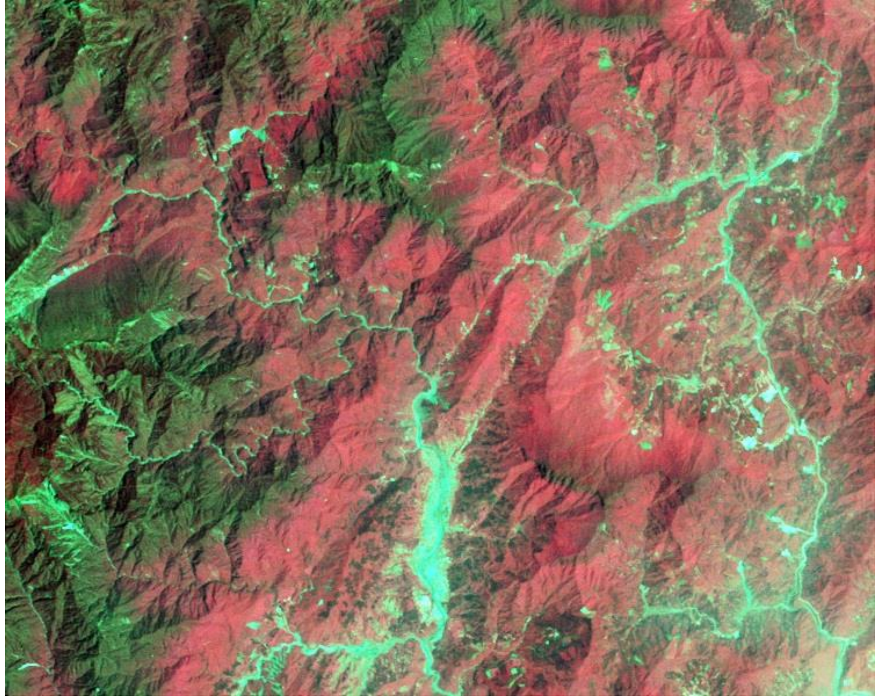


Planet's Doves, in operation since 2012





2007

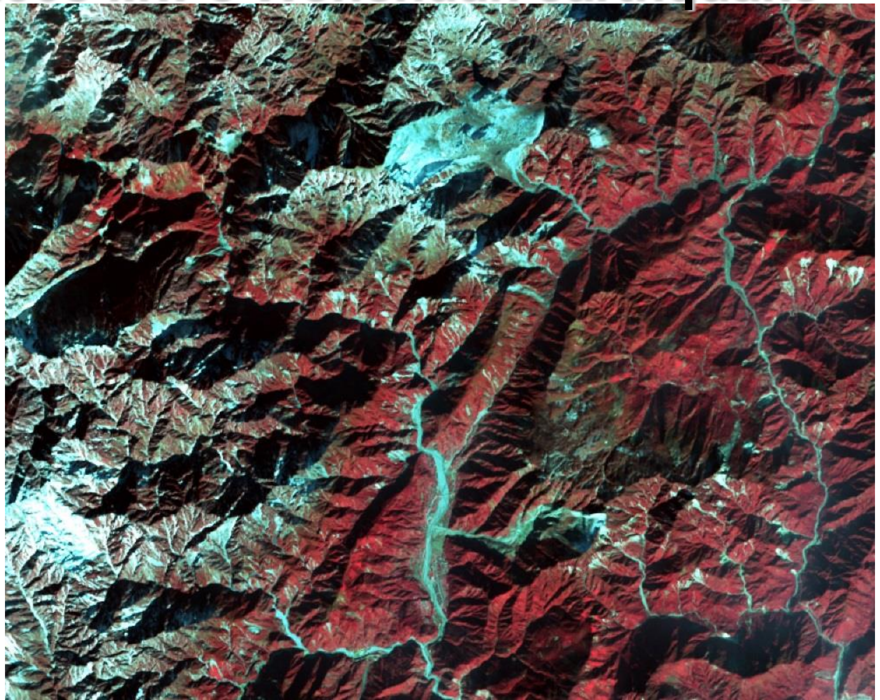


2009

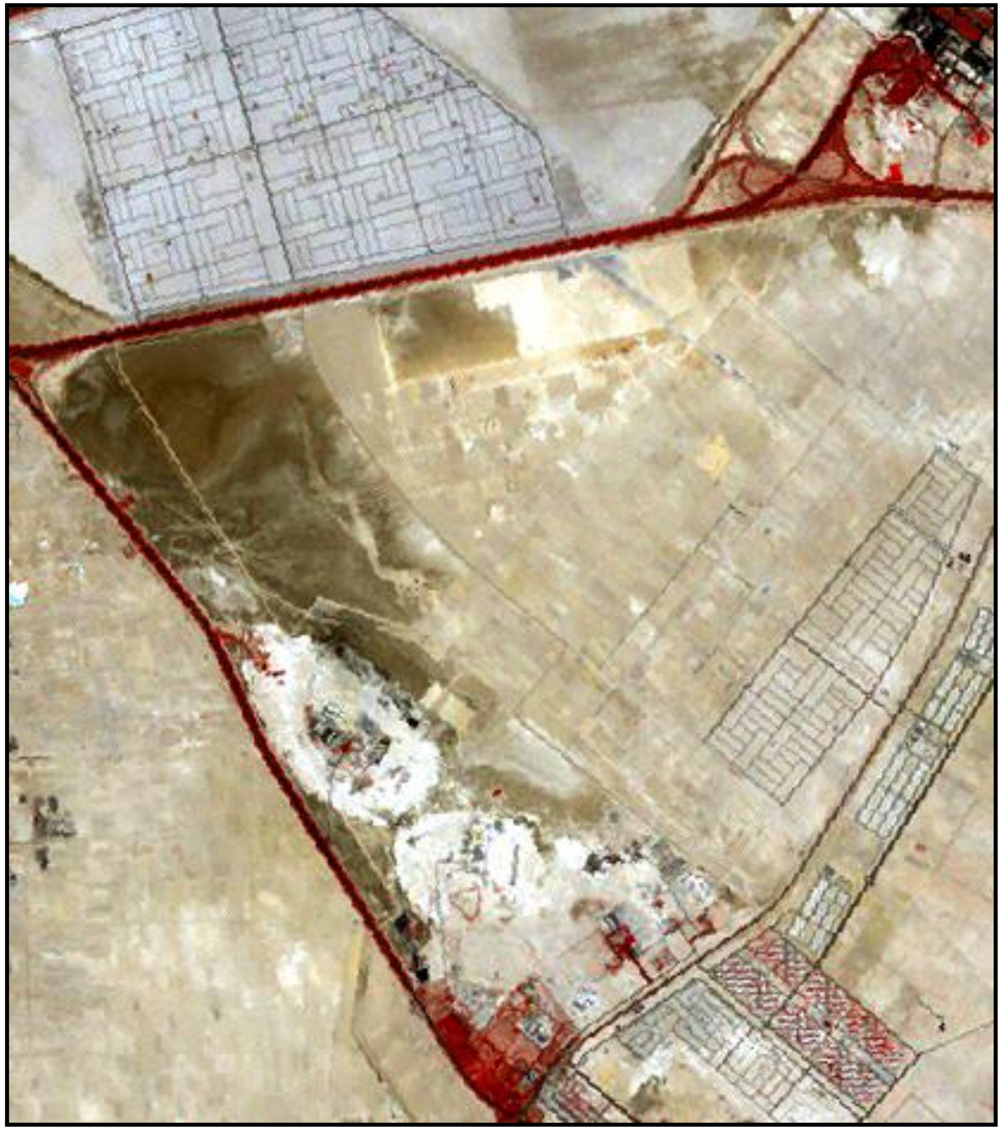
Landsat images before & after 2008 Mw 8 Wenchuan earthquake

2011

2013



Change detection in Abu Dhabi City (UAE)



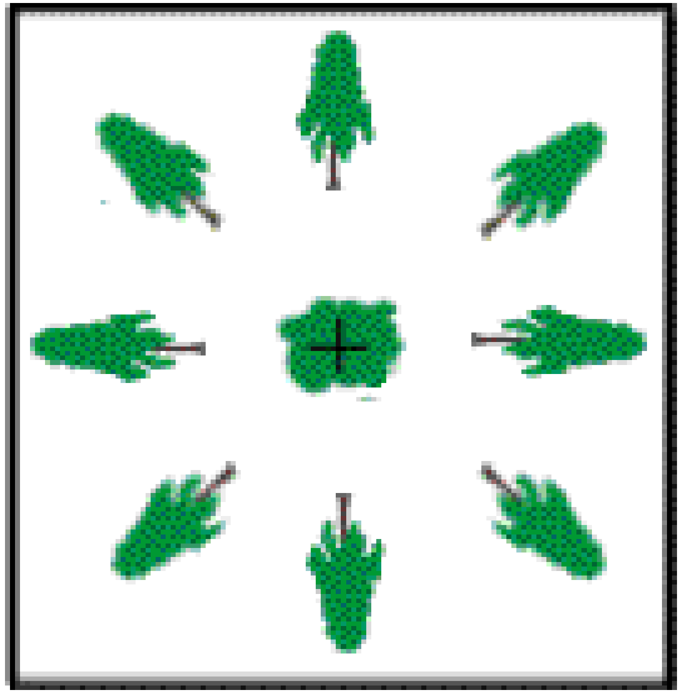
Landsat ETM+ - Aug 2000

Terra/ASTER – May 2006

2.5 Geometric distortion

All remote sensing images are subject to some form of geometric distortions, caused by one or more of the following:

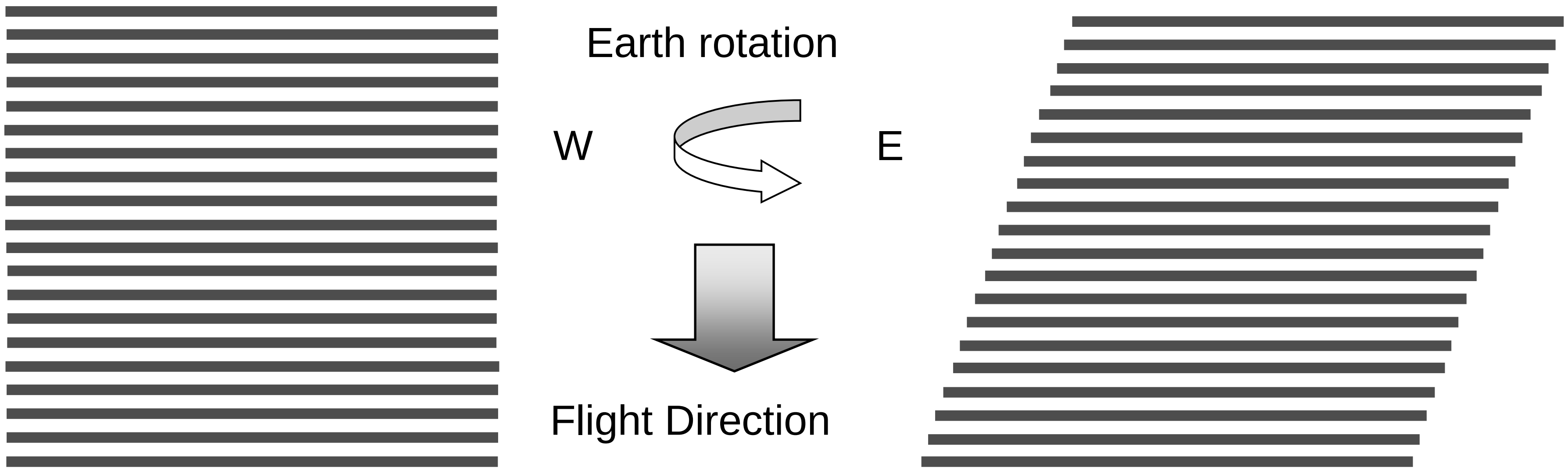
- **Perspective of the sensor optics,**
- **Motion of the scanning system,**
- **3D stability of the platform,**
- **Platform altitude, attitude, and velocity,**
- **Terrain relief, and**
- **Curvature and rotation of the Earth.**



Relief displacement of camera is shown in the figure. This is the primary geometric distortion in vertical aerial photography and VHR satellite imagery.

The distortion geometry of along-track push-broom scanner imagery is similar to that of an aerial photograph but for each individual scan line.

Skew distortion of satellite scanner images



- An EO satellite on a circular, near-polar, sun synchronous orbit travels nearly perpendicular to Earth rotation direction, to image nearly every part of Earth's surface at about the same local time.
- For an imaging scanner on-board the satellite, the image is build line-by-line in a time sequence, with the satellite flying above a rotating Earth.
- The Earth's rotation produces a skew effect in the image: the image is recorded as on the left, but actually covers an area of Earth's surface as on the right of the above diagram.
- This effect is typical for a push-broom scanner. For an across-track two way scanner (*e.g.* Thematic Mapper), the distortion pattern is even more complex as every pixel along a swath is imaged at a slightly different time and the actual scanning speed on the earth surface changes not only from nadir to the edge of a swath but also between swathes for and against earth rotation.

2.6 Summary remarks (revision)

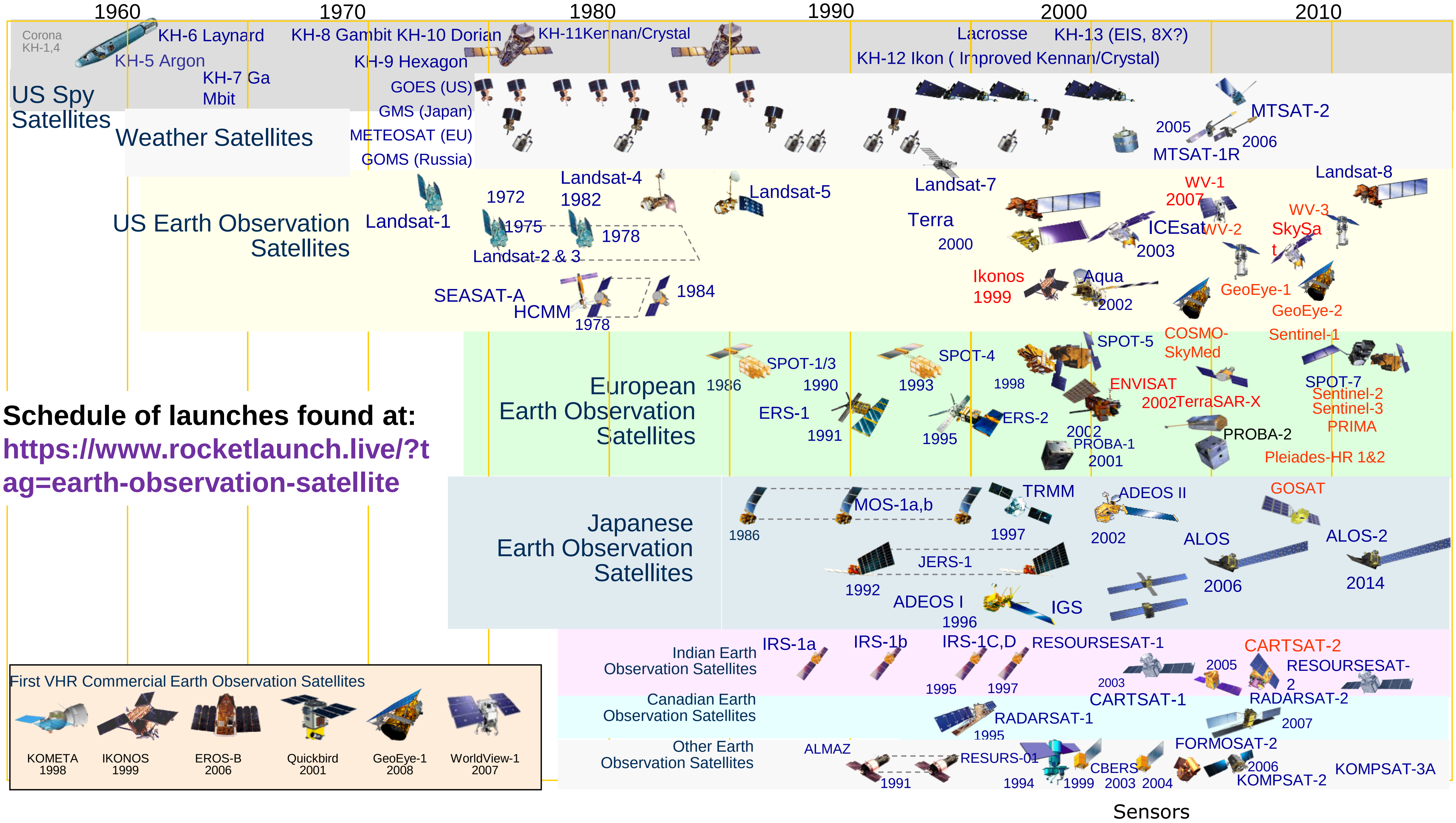
- This part falls under this LO: *Understand common data format and database structures specific to representative fields of environmental science*
- Major spectral regions are Visible (VIS, 0.3 - 0.75 mm) Near Infra-Red (NIR, 0.75 - 1.3 mm), Short-wave InfraRed (SWIR, 1.3 - 3.0 mm), Mid or Thermal Infra-Red (MIR or TIR, 3 - 5 & 8 - 14 mm) and microwave (0.1 - 100 cm) – all of which are important for remote sensing
- EMR is composed of photons - relate Planck's constant to wave theory: $Q=hv/\lambda$
- An object radiates energy as a function of temperature $M=\sigma T^4$
- Wavelength at which a blackbody radiation peaks $\lambda_{max}=A/T$
- Incident energy is affected by 3 types of scattering in the atmosphere (**Mie, Rayleigh & non-selective**, according to the size of particle w.r.t. wavelength)
- Solar radiation is absorbed by **water vapour, carbon dioxide** and **ozone**. Regions of spectrum where absorption does not occur called **atmospheric transmission windows** (they are VIS, NIR, SWIR, TIR & microwave)
- EMR impinges on the Earth's surface, and is partially **reflected, absorbed** and **transmitted** depending on the spectral properties of the surface materials
- Cont'd……..

2.6 Summary Remarks (revision cont'd)

- There are 2 types of reflecting surfaces that interact with EMR: ***specular*** (smooth) and ***diffuse*** (rough). Rayleigh criterion is used to calculate the surface variations to predict rough or smooth
- ***Spectral reflectance*** is the reflectivity of a material to EMR at a particular wavelength. ***Albedo*** or the total radiant reflectance is the integral of reflected spectral radiation, weighted by irradiance, over all spectral range
- Most optical sensors now operate as **along-track push broom scanner**
- Ultimately, the image resolution is decided by the sensor resolution.
- For a given sensor system, within its optical resolution limit, the spatial resolution is dictated by the minimal energy level of EMR that can make a signal distinguishable from the electronic background noise, i.e. the dark current, of the instrument.
- This minimal energy of EMR is proportional to the product of **radiation intensity** over a spectral range, **IFOV** (Instant Field Of View) and **dwell time**.
- So in general, for most sensors:
    - Lower spatial resolution >> higher spectral/radiometric resolution.
    - Lower spectral resolution >> higher spatial/radiometric resolution.
    - Longer dwell time >> higher spatial/spectral/radiometric resolution.
    - Higher sensitivity of sensor >> higher radiometric resolution.

Some reference information about EO sensors and their development history and some information on key datasets for you ..

Post-Cold War development of EO history



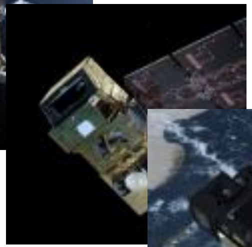
Schedule of launches found at:
https://www.rocketlaunch.live/?tag=earth-observation-satellite

After 2015… there are far too many to list!!!!

Important EO satellites for global environmental analysis

(medium resolution, routinely acquiring, available free to user)

- Landsat program (multispectral & panchromatic)
  - L5 TM & L7 ETM
  - L8 OLI & TIRS
  - L9 launched Monday, Sept. 27, 2021
- Copernicus Sentinel programme
  - S1 SAR
  - S2 MultiSpectral Imager (MSI)
  - S3 OLCI, SLSTR, SRAL & DORIS
  - S4 (trace gases & aerosols)
  - S5 (air quality & climate)
  - S5P TROPOMI



a) Medium Resolution Sensors

The Landsat Program!

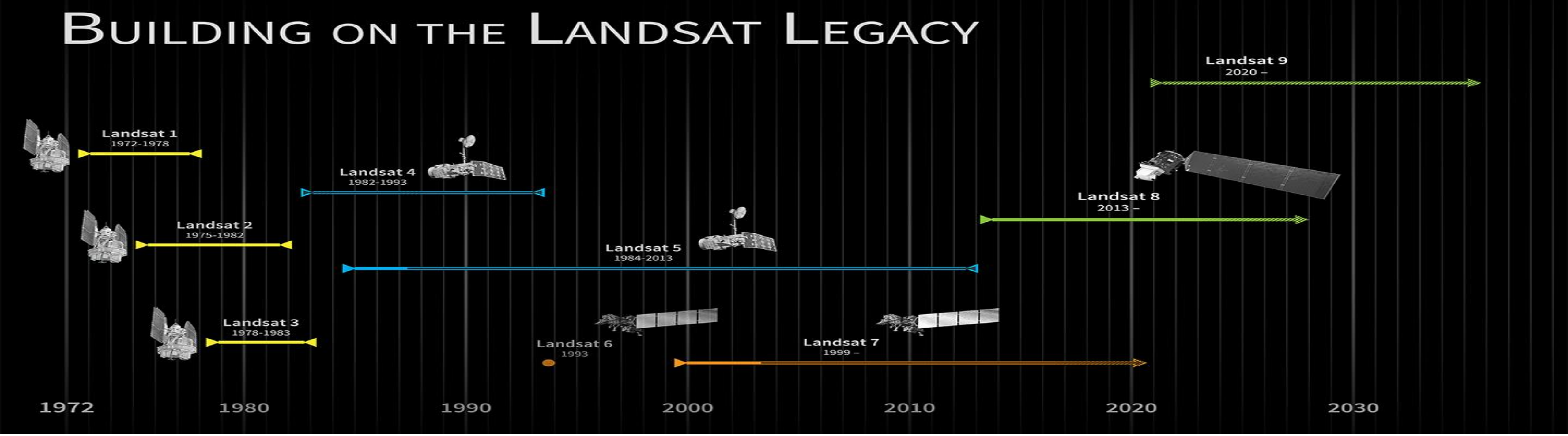
Landsat 7 Enhanced Thematic Mapper (ETM+) and L8 & L9 Operational Land Imager/Thermal Infra-Red Sensor (OLI/TIRS) compared

L7 ETM+ (1999-2003)

Band	Range	Resolution
1 BLUE	0.45 - 0.52	30 m
2 GREEN	0.53 - 0.61	30 m
3 RED	0.63 - 0.69	30 m
4 NIR	0.75 - 0.90	30 m
5 SWIR	1.55 - 1.75	30 m
7 SWIR	2.09 - 2.35	30 m
6 TIR	10.4 - 12.5	60 m
8 Pan	0.52 - 0.90	15 m

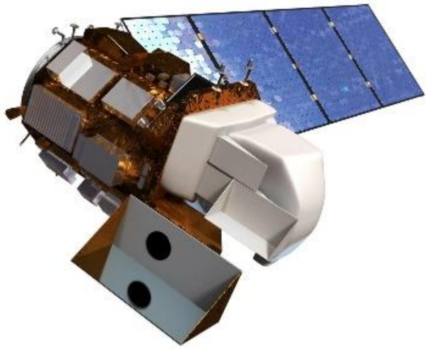
L8 & L9 OLI/TIRS (2013+)

Band	Spectral Range	Resolution	
1 Coast	0.433 - 0.453	30 m	New band
2 BLUE	0.45 - 0.53	30 m	
3 GREEN	0.52 - 0.60	30 m	
4 RED	0.63 - 0.69	30 m	
5 NIR	0.76 - 0.90	30 m	
6 SWIR1	1.56 - 1.66	30 m	
7 SWIR2	2.10 - 2.30	30 m	
9 Cirrus	1.36 - 1.39	30 m	New band
10 TIR1	10.6 - 11.2	100 m	New band
11 TIR2	11.5 - 12.5	100 m	
8 Pan	0.50 - 0.68	15 m	



Landsat 4-7 Orbit

Altitude:	705km
Inclination:	98.2deg
Orbit:	Near-polar, sun-sync
Equator cross time:	10:30am (7) 9:30am (4-5)
Revolution:	99 minutes
Repeat cover:	16 days
Swath:	185 km



Satellite	Year	Sensor(s)	Status
Landsat 1	1972	RBV, MSS	Exp 1-6-78
Landsat 2	1975	RBV, MSS	Exp 2-5-82
Landsat 3	1978	RBV, MSS	Exp 3-31-83
Landsat 4	1982	MSS, TM	Exp 1993
Landsat 5	1985	MSS, TM	Decommissioned 2014
Landsat 6	1993	MSS, ETM	Lost
Landsat 7	1999	ETM+	2003+ Partial-operational
Landsat 8	**2013**	**OLI & TIRS**	**Operational**
Landsat 9	2021	**OLI & TIRS**	In testing

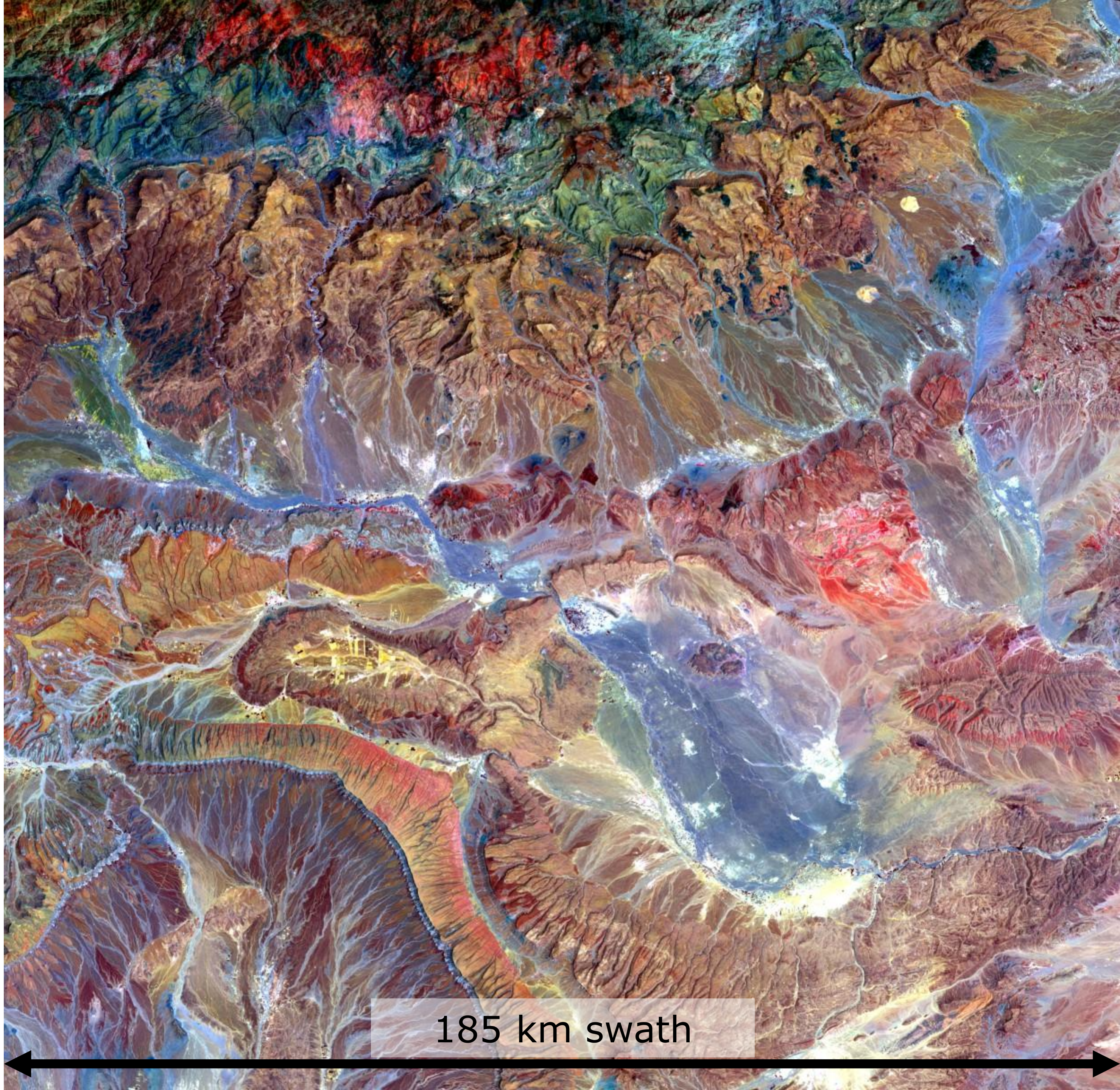
Landsat-9 OLI

bands 642 (RGB)

Morocco

This spectacular false colour composite is designed to reveal spectral variations in rocks and soils.

Such images are most effective in semi-arid areas where there is little vegetative cover, and there is little atmospheric haze (or cloud)



Landsat program naming convention & path/row system

e.g. LC80390222013076EDC00

Path number

Ground Station Identifier

LXS PPPRRR YYYYDDD GSIVV

Landsat

Sensor

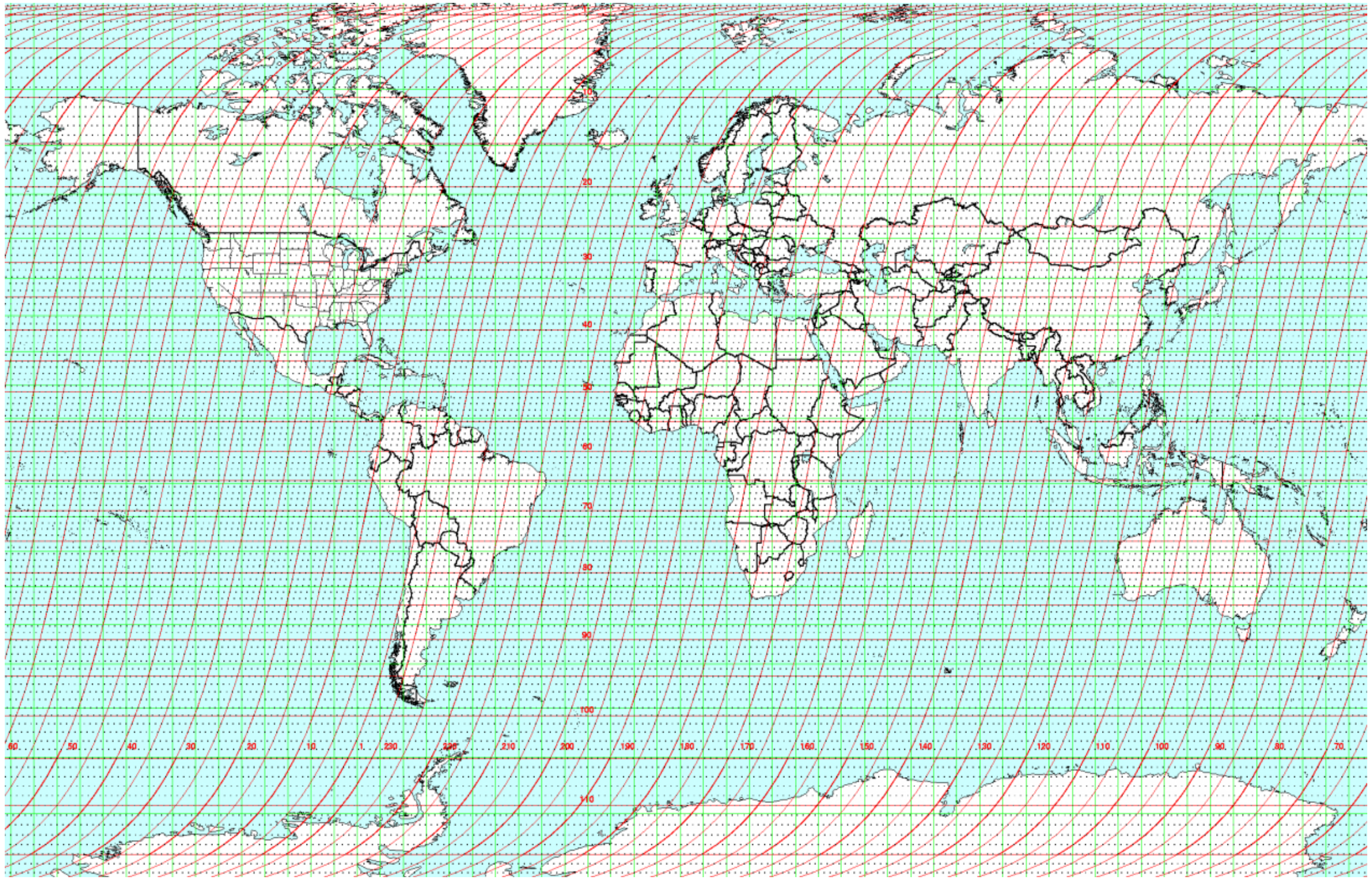
Satellite

Year & Julian Date

Archive Version

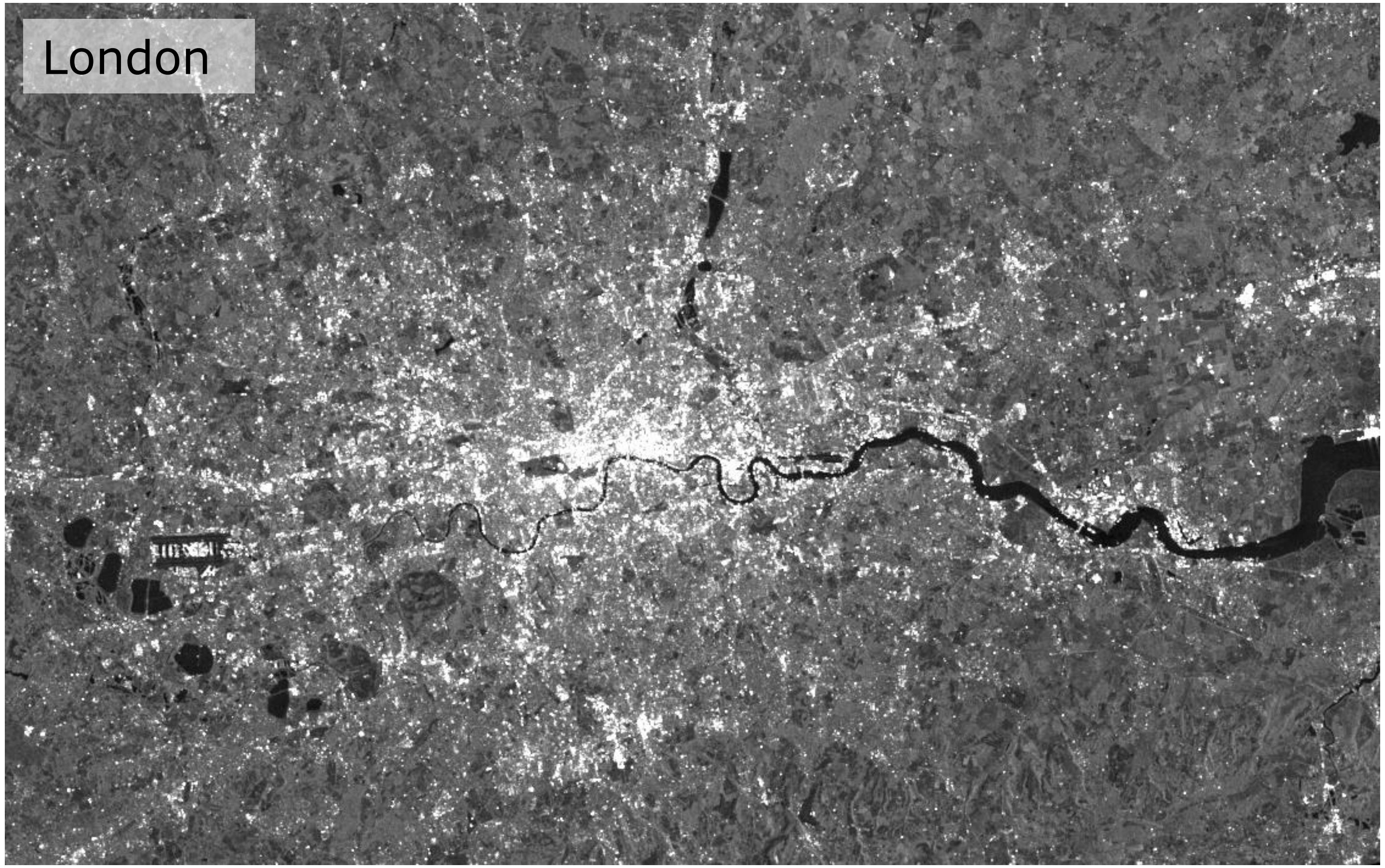
Rows 1-117

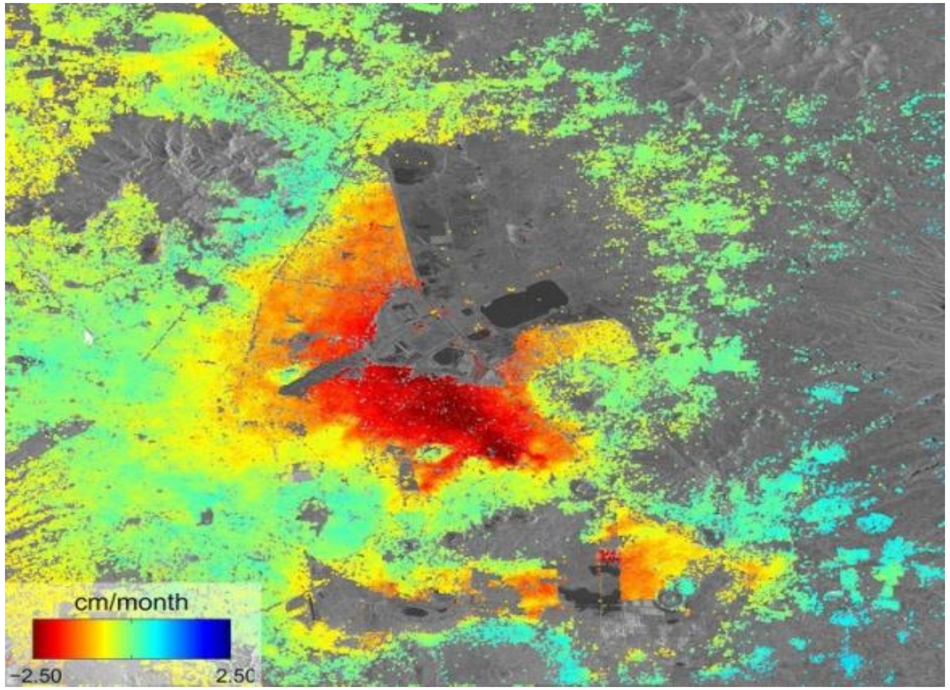
Paths 1-230



Sentinel-1 Synthetic Aperture Radar (SAR)

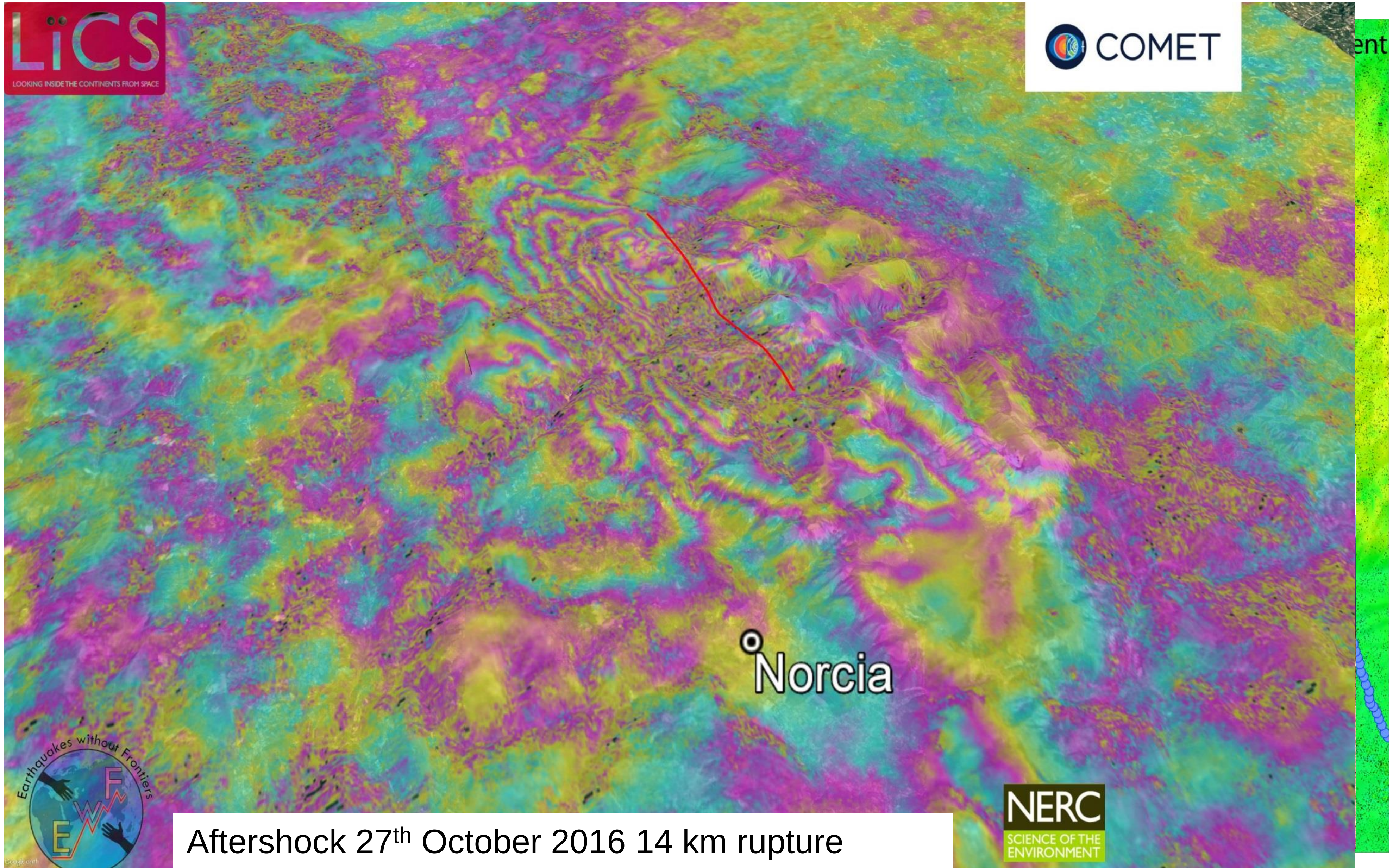
Sentinel-1A Launched 2014 & -1B launched 2016
C band Synthetic Aperture Radar (SAR (5.6 cm)
1-A and 1-B – each revisits every 12 days but six days apart



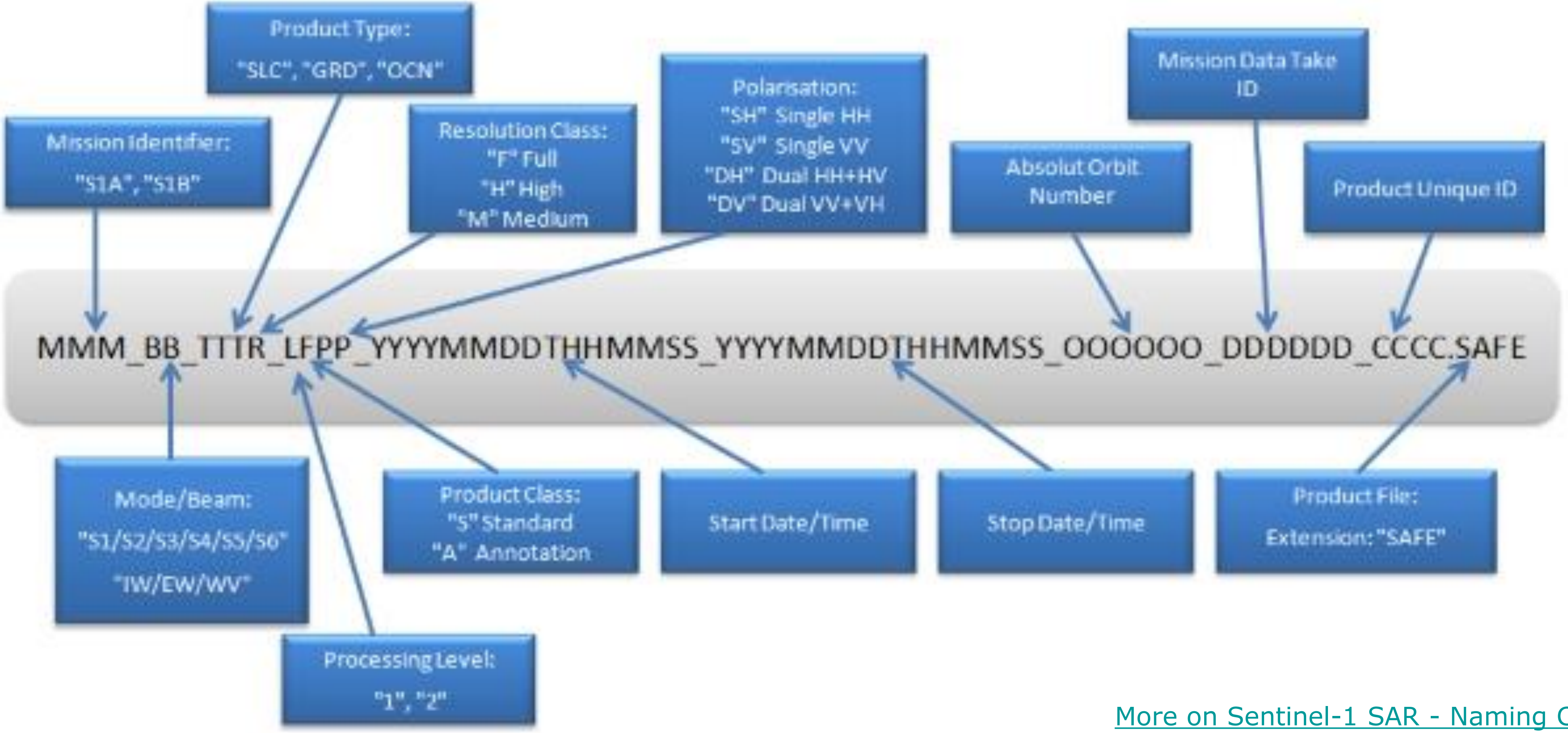


Subsidence in Mexico city – time-series of Sentinel-1A SAR scenes (3 Oct and 2 Dec 2014) – used to measure small-scale ground deformation - caused by ground water extraction.
Some areas subsiding at up to 2.5 cm/month (red).

Sentinel-1 workhorse for global earthquake & volcano monitoring



EO data products & file naming conventions: Sentinel-1

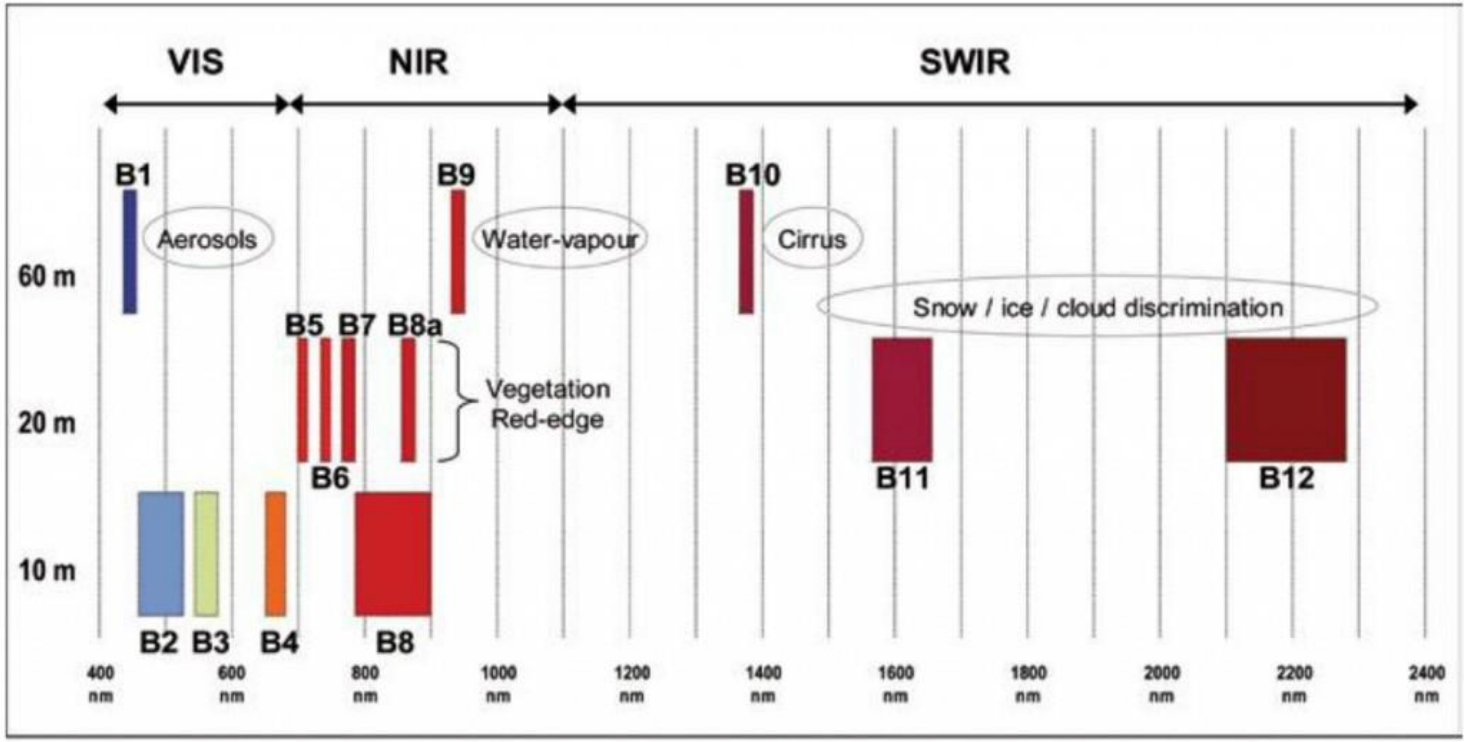


[More on Sentinel-1 SAR - Naming Conventions]

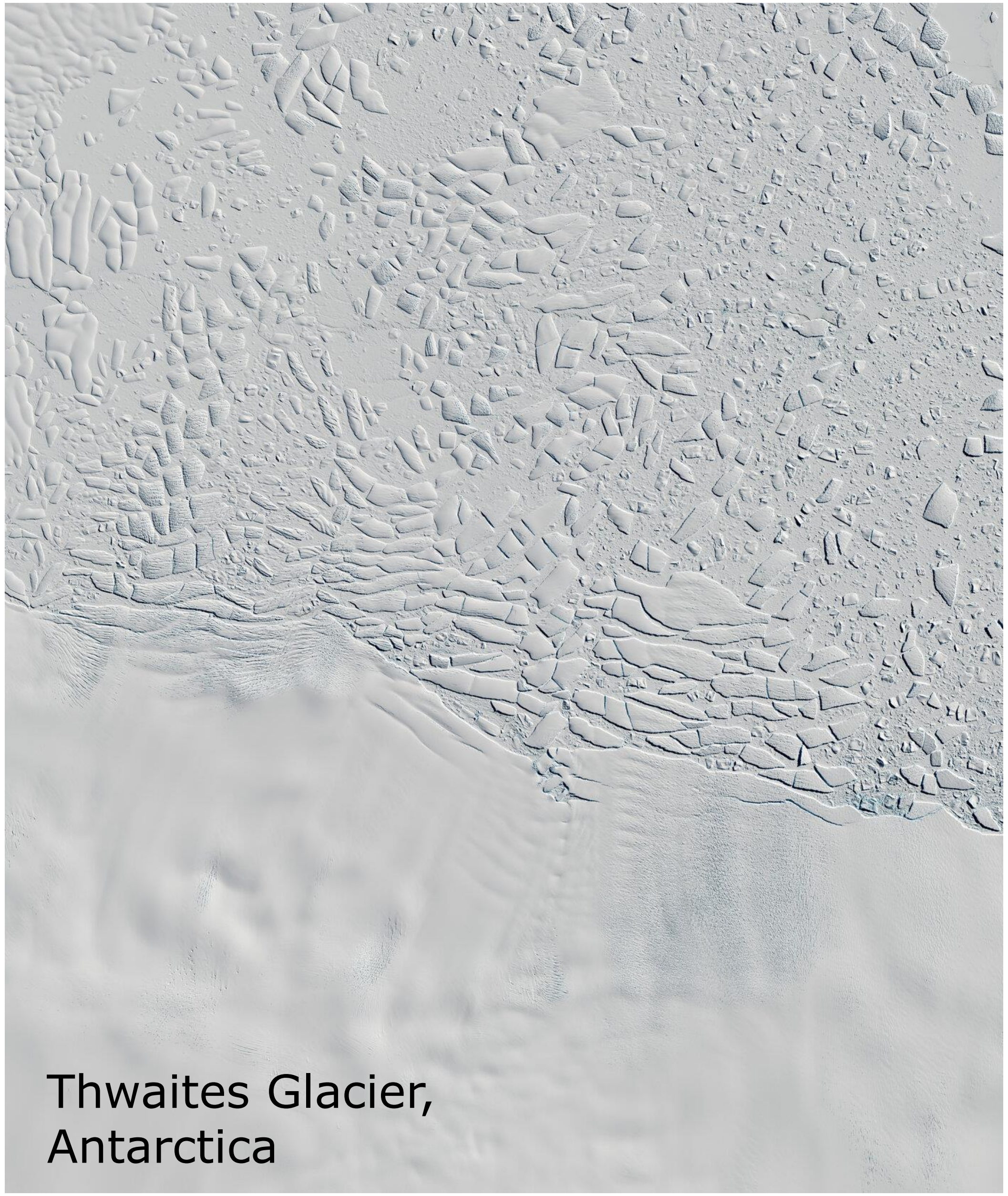
S1 User guide: [User Guide - Sentinel-1 SAR data]

Sentinel-2 MultiSpectral Imager (MSI)

Launched 2015/2017

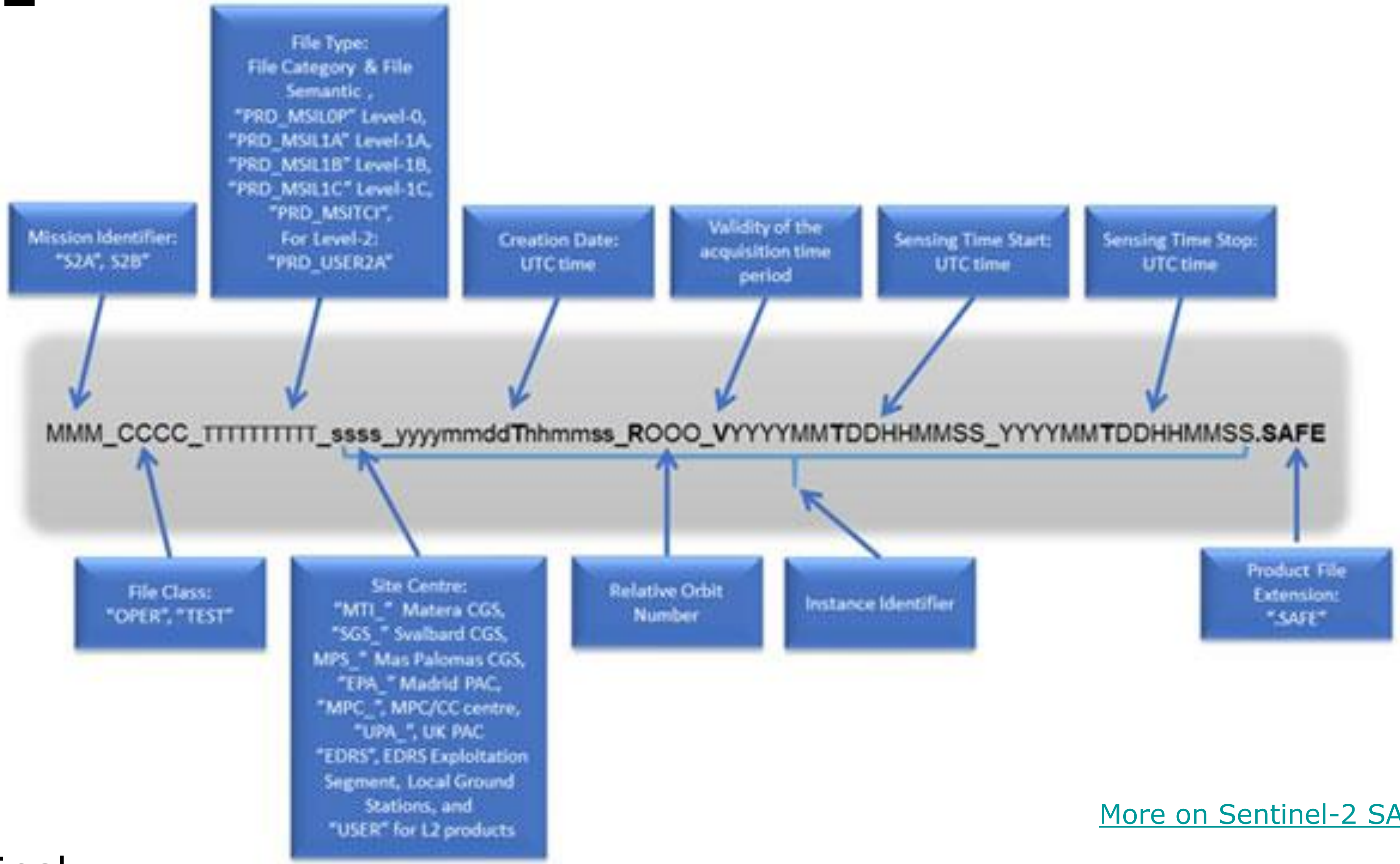


False colour composite
French Riviera



Thwaites Glacier,
Antarctica

EO data products & file naming conventions: Sentinel-2



More on Sentinel-2 SAR - Naming Conventions

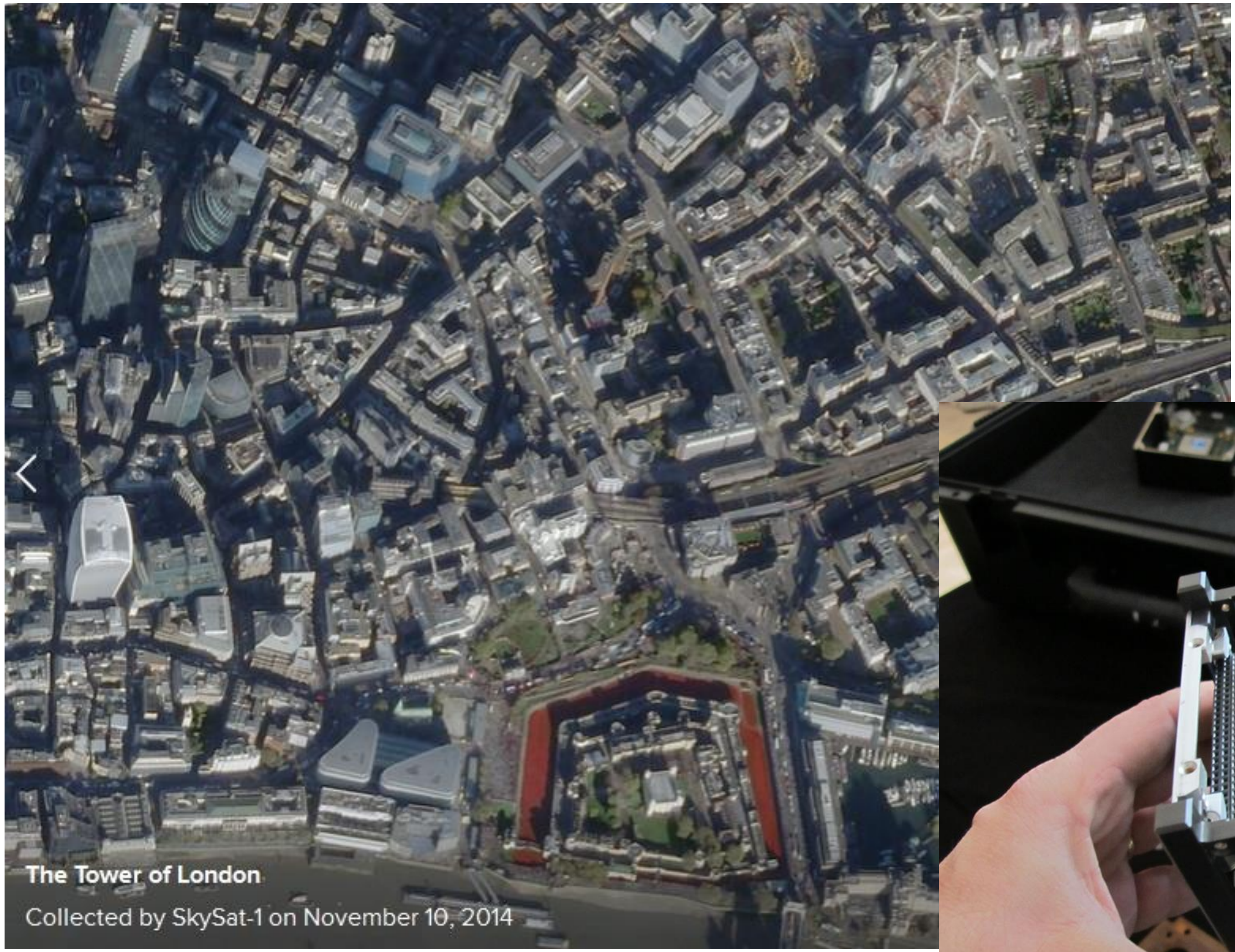
Other Sentinel datasets follow similar convention

S1 User guide: User Guide - Sentinel-2 SAR data

HD video from space - SkySat-1 & -2

- Small, high-performance, low cost satellites
- Cubesats
- Image spatial resolution : 1 m (Pan) & 2 m (MS)

Blue	0.450 - 0.515
Green	0.515 - 0.595
Red	0.605 - 0.695
NIR	0.740 - 0.900



https://www.youtube.com/watch?v=BsW6IGc4tt0

VHR sensors compared: GeoEye, Worldview, Earth i & Planet

	GeoEye-1 (2008)	WV-2 (2009)	WV-3 (2014)	Earth i (x3) (2015)	Planet Doves (2021)
Spatial Resolution:	0.41 m (Pan) 1.65 x 1.65 m (MS)	0.5 m (Pan) 2.0 or 2.4 m (MS)	0.31 (Pan) 1.24 m(VNIR)& 3.7 m(SWIR)	<1.00 m (Pan) <4.0 m (MS)	3 m (MS)
Spectral Range:	450–800 nm (Pan) 450–510 nm (B) 510–580 nm (G) 655–690 nm (R) 780–920 nm (NIR)	450–900 nm (Pan) 400-450 nm (coastal B) 450–510 nm (B) 510–580 nm (G) 585-625 nm (Y) 630–690 nm (R) 705-745 nm (R edge) 770–895 nm (NIR 1) 860-1040 nm (NIR 2)	450–800 nm (Pan) 400-450 nm (coastal B) 450–510 nm (B) 510–580 nm (G) 585-625 nm (Y) 630–690 nm (R) 705-745 nm (R edge) 770–895 nm (NIR 1) 860-1040 nm (NIR 2) 1195-1225 (SWIR1) 1550-1590 (SWIR2) 1640-1680 (SWIR3) 1710-1750 (SWIR4) 2145-2185 (SWIR5) 2185-2225 (SWIR6) 2235-2285 (SWIR7) 2295-2365 (SWIR8)	450–800 nm (Pan) 450–510 nm (B) 510–580 nm (G) 655–690 nm (R) 780–920 nm (NIR)	431-452 nm (B) 547-585 nm (G) 650-682 nm (R) 846-888 nm (NIR)
Swath Width	15.2 km	16.4 to 17.7 km		23 km	24 x 16 km
Off-Nadir Imaging	+/- 60 deg	+/- 60 deg		+/- 45 deg	+/- 60 deg
Dynamic Range	11 bits per pixel	8 or 16 bits per pixel		10 bits	8 bit
Mission Life	> 10 years	> 10 years		>10 years	Indefinitely – 180 in operation at a time
Revisit Time	< 3 days	< 3 days	< 1 day	<1 day	Daily
Orbital Altitude	681 km	770 km	620 km	651 km	

Common image formats & processing levels

- Most commonly used EO image formats
  - Geotiff .tif [GeoTIFF - Wikipedia]
  - Hierarchical Data Format .hdf https://www.hdfgroup.org/
  - ‘Flat’ binary raster .bil, .bip, .bsq, .flt, .img, .dat, .ers
  - .jp2 & .ecw - lossless wavelet compression formats
  - Consult **GDAL** for all raster (& vector) format definitions & drivers https://gdal.org/

- Processing levels*
  - Level 0 Raw system corrected data
  - Level 1A Radiometrically corrected (top-of-atmosphere radiance)
  - Level 1C Corrected to apparent reflectance
  - Level 1G Geometrically corrected
  - Level 1T Ortho-corrected (terrain distortions corrected)
  - Level 2 Generally value-added products e.g. spectral indices

* Level numbers are different between NASA and ESA product standards

Global Earth Observation data archive sources

Copernicus Sentinel Data Hub https://scihub.copernicus.eu/ ALL archived data FREE!

USGS EarthExplorer https://earthexplorer.usgs.gov ALL FREE!

Planet https://www.planet.com/products/planet-imagery NOT free BUT FREE through ESE agreement for 15TB (~ 30 million sq km) of free 3m data for education and research project usage e.g. your summer projects

Maxar https://discover.digitalglobe.com/ NOT free but we can apply for free data for research purposes

Google Earth Engine – entire Landsat & Sentinel archives accessible via java script interface FREE!

- https://developers.google.com/earth-engine/guides/image_visualization#colab-python

Amazon cloud – entire Landsat & Sentinel archives Not FREE!

Copernicus Data and Information Access Service (DIAS) cloud: Some services free (https://scihub.copernicus.eu/ Data Hub and API), some not (https://www.sentinel-hub.com/)

Important proprietary EO VHR satellite datasets & data costs

(≤5 m = Very High Resolution, routinely acquiring & tasking, commercial data are not free!)

- Planet Scope (3 m and daily repeat)
  - Multispectral from ‘Doves’ constellation (VNIR) €€ (free access account in ESE)
  - SkySAT (High Def. VIS video & stills) €€
- Earth i constellation
  - Earth i, Rapid-Eye & others (VNIR) €€
- Maxar’s WorldView (0.31 cm to 4 m, and repeat every 3-4 days)
  - WV-3 panchromatic & multispectral - VIS-NIR-SWIR €€€
  - WV-1 & 2 panchromatic & multispectral – VNIR only €
- SpaceImaging’s Ikonos (1m pan & 2.5m MS) 1999+ €
- X-band high-resolution SAR (~3 m and repeat ~3 days)
  - TerraSAR-X €€
  - Tandem-X €€
  - IceEye €€
  - Capella X-SAR constellation €€