Training on Applications of
GEMS and Remote Sensing Data for Air Pollution Monitoring

19 - 30 Jun 2023

ESCAP 75
MOVING FORWARD TOGETHER

DhaHyun Ahn
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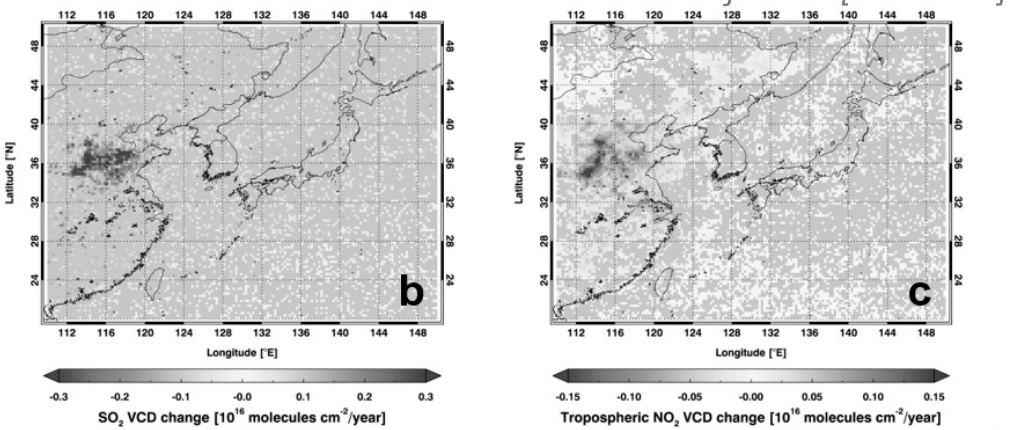
Instructor: DhaHyun Ahn

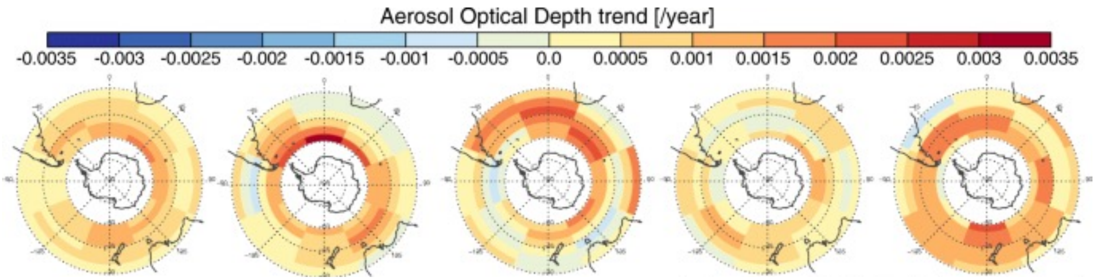
- April 2023 – current: Consultant, United Nations Economic and Social Commission for Asia and the Pacific
- February 2022: Ph.D candidate, Atmospheric Sciences, Yonsei University
- August 2017: B.S., Atmospheric Sciences, Yonsei University

Research Interest

- Developing nitrous acid (HONO) retrieval algorithm from GEMS
- Air quality analysis using satellite data – trend analysis over East Asia and Southern hemisphere using OMI, MODIS, IASI, MOPITT and GOCI
- Ozone variation over Antarctica (Satellite and Brewer spectrophotometer)

Under review for RSE [Ahn et al.]





[Ahn et al., 2019]

Goals

- Provide an opportunity for building capacity of applying remote sensing data for air pollution monitoring
    - Processing and visualizing GEMS and remote sensing data for air pollution monitoring
- Build up to the in-person training being organized in July 2023

Expected outcomes

- Improve understanding of air quality analysis, combining with using relevant earth observation data to properly identify, measure, and analyze air quality events of your choosing

Training Schedule

Lecture

- 09:30-11:00 (UTC+7) on every MON, WED, and FRI

Coaching (Q&A)

- 13:30-16:00 (UTC+7) on every FRI
- Recommended on individually or country basis group

    *If you have a question and plan to join a coaching session, it's more efficient if you notify me (dhahyun.ahn@un.org) the problem in advance (at least until **Thursday noon_UTC+7**)!*

Curriculum

#1	19 Jun (Mon)	Basic concept of satellite data: from L0 to L4 • Download GEMS data
#2	21 Jun (Wed)	Utilizing satellite data: how to read and visualize • Apply quality filter from ATBD on GEMS data using Python
#3	23 Jun (Fri)	Processing satellite data: regridding • Produce Level 3 (daily and monthly) data from GEMS Level 2 data
#4	26 Jun (Mon)	Space-borne instrument: LEO and GEO • Download observation data from other satellite
#5	28 Jun (Wed)	Ground-based observation: remote-sensing and in-situ • AERONET and Pandonia Global Network (PGN)
#6	30 Jun (Fri)	Intercomparison of data from satellite and ground-based observations: collocation • Compare observations from satellite and ground-based by applying collocation criteria

Basic concept of satellite data: from L0 to L4

19 Jun 2023

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Contents

1. Fundamentals of radiation for atmospheric applications
2. Satellite retrieval for monitoring air quality
3. Guide to GEMS products
   - How to download GEMS data

Fundamentals of radiation for atmospheric applications

Electromagnetic spectrum

Radiation

- One of the process to transfer energy with conduction and convection, but possible in vacuum
- **Electromagnetic wave:** Wave and Streams of photons
- Give the information of medium
  - Absorption, emission of molecules (H_2O, CO_2, O_3, ...)
  - scattering by cloud droplets, aerosol, molecules

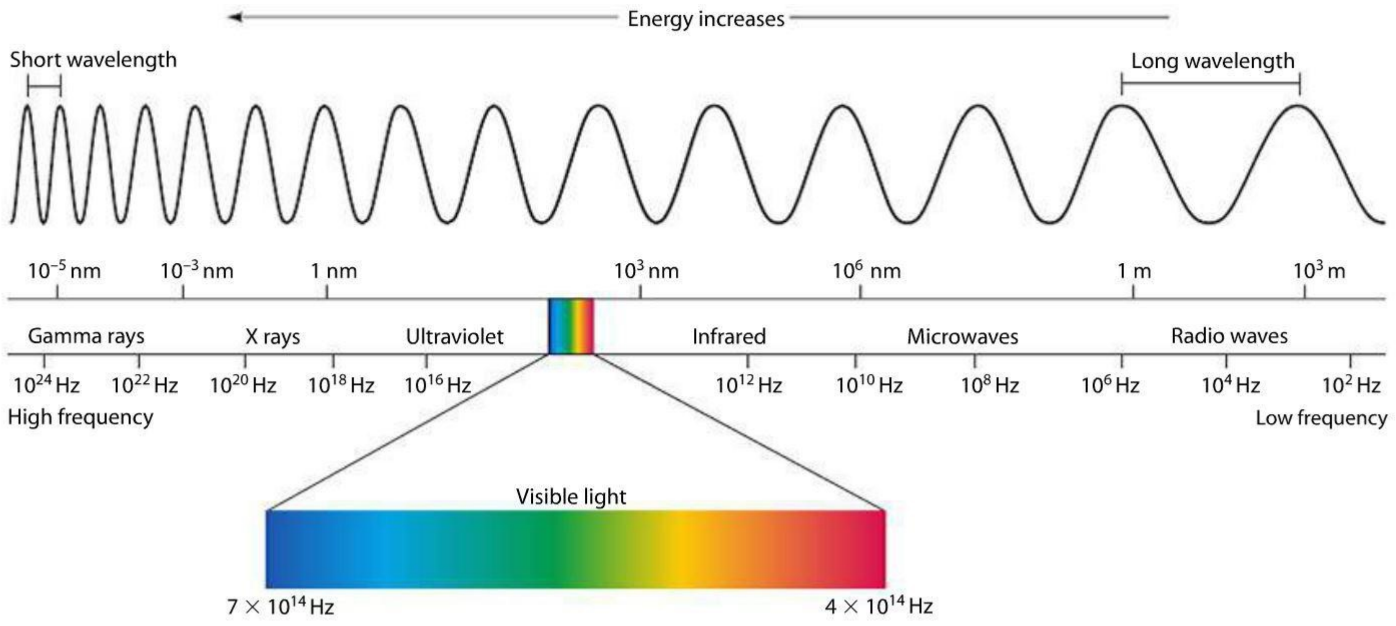
  ⇒ Application to remote sensing

Wavelengths for remote sensing

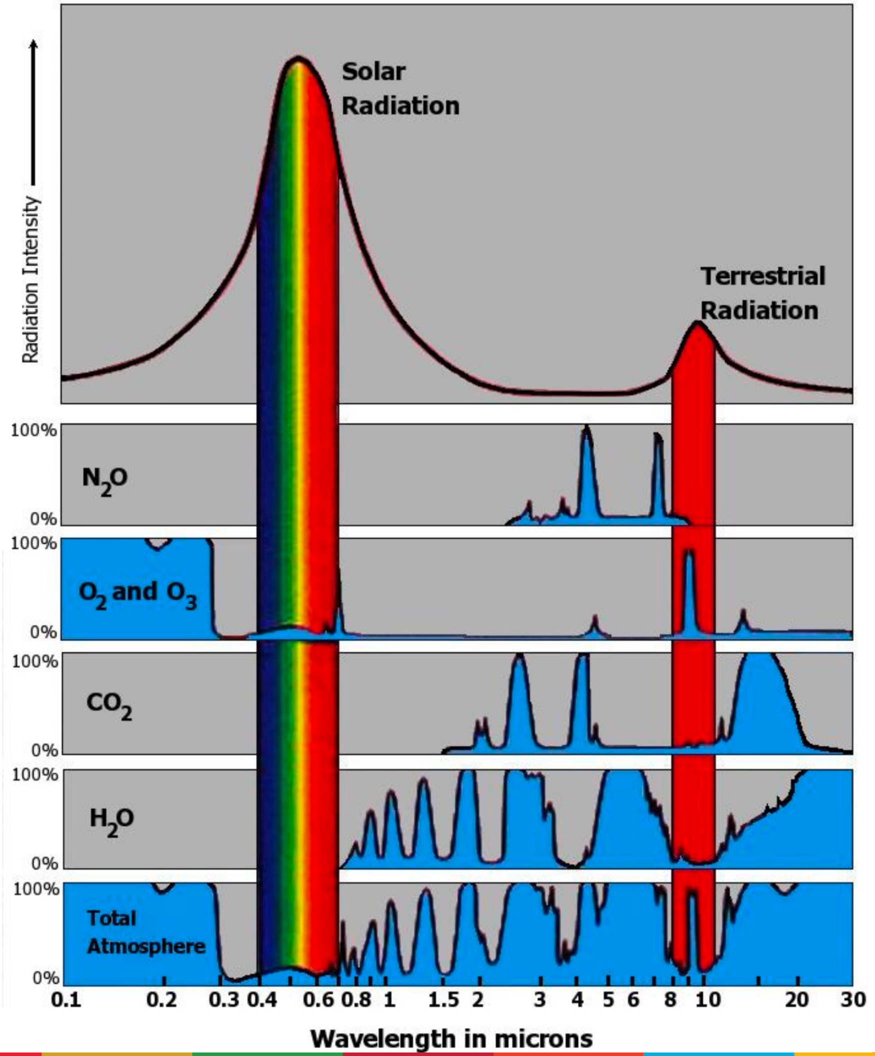
- All electromagnetic radiation is light, but we can only see a small portion of this radiation – visible light
- Light in **Near UV – Visible – Near IR**: sensitive to aerosols*

  *Atmospheric aerosols: particles composed of solid or liquid matter suspended in the atmosphere**

  **PM_{10} and $PM_{2.5}$ are also classified as aerosols
- Light in **UV - VIS**: sensitive to trace gases (O_3, NO_2, SO_2, HCHO, …)



Wavelengths for remote sensing



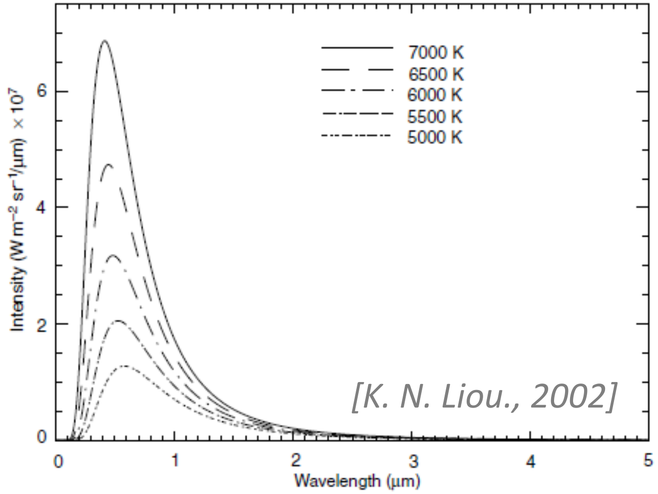
- The Earth absorbs solar radiation (shortwave; SW) and emits terrestrial (longwave; LW) radiation*
- Solar radiation is mostly transmitant by atmopheric gases, but it is efficiently scattered/absorbed by suspended particles (aerosols and clouds)
- Terrestrial radiation is significantly absorbed (thus emitted**) by atmospheric gases such as CO_2, H_2O, CH_4, and etc

* Blackbody, Planck's law, and Wien's law

**Kirchoff's law

Blackbody radiation laws

- Blackbody: an object which absorbs all radiation falling upon it, and does not *reflect* any. All radiation emitted by a blackbody is due to its temperature. A star is a near perfect blackbody
- Planck's law: Light at a particular wavelength has a specific energy
- Wien's law: An object emits radiation at several wavelengths. However the *peak* wavelength emitted depends on the object's temperature. The cooler the object, the longer the wavelength at which most of the radiation is emitted
- Stefan-Boltzmann law: The amount of energy radiated by an object is related to its temperature. The hotter the object, the more energy it releases

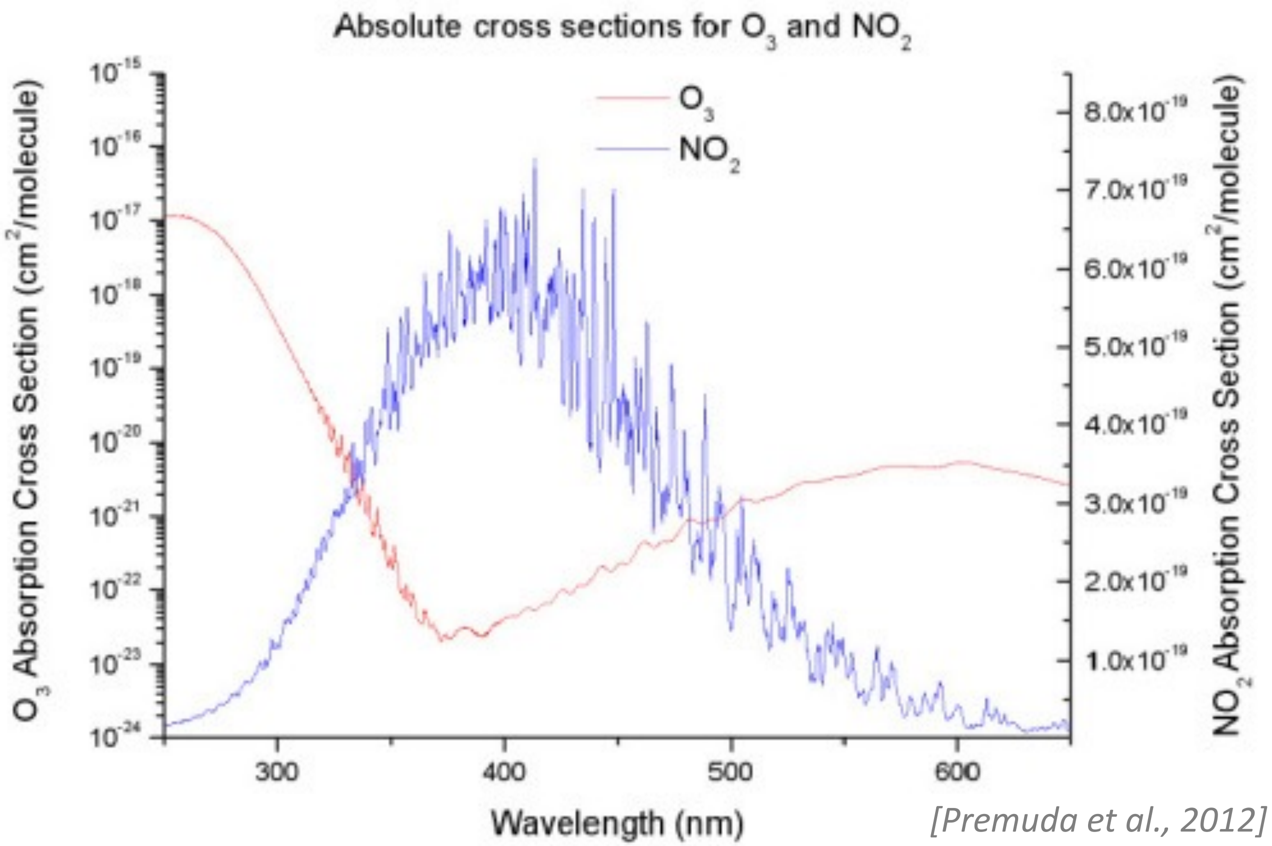


[K. N. Liou., 2002]

Absorption and Scattering

- Absorption: Energy is converted to heat and lost for optical sensing
- Gases have their own absorption spectra
- Cross section denotes the amount of energy removed from the original beam by the particle

- Scattering: Rays bounce off particles. Energy remains in the form of radiation, but does not travel along a straight path



[Premuda et al., 2012]

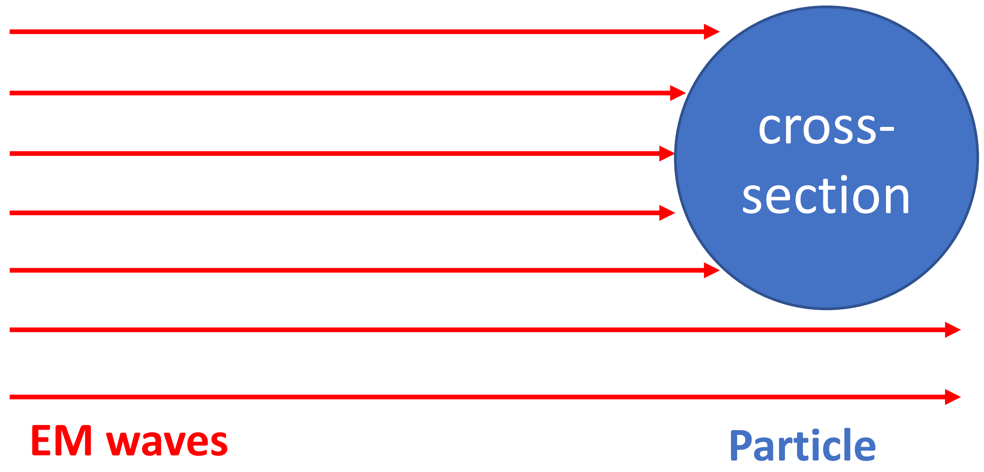
Absorption and Scattering

Extinction = absorption + scattering

- Extinction coefficient [km^{-1}]: Amount of light extinction per unit distance

$$\beta_\mathrm{e} = n\sigma_e$$
$$\beta_\mathrm{s} = n\sigma_s$$
$$\beta_\mathrm{a} = n\sigma_a$$

β: extinction/absorption/scattering coefficient
n: number of particles
σ : extinction/absorption/scattering cross-section



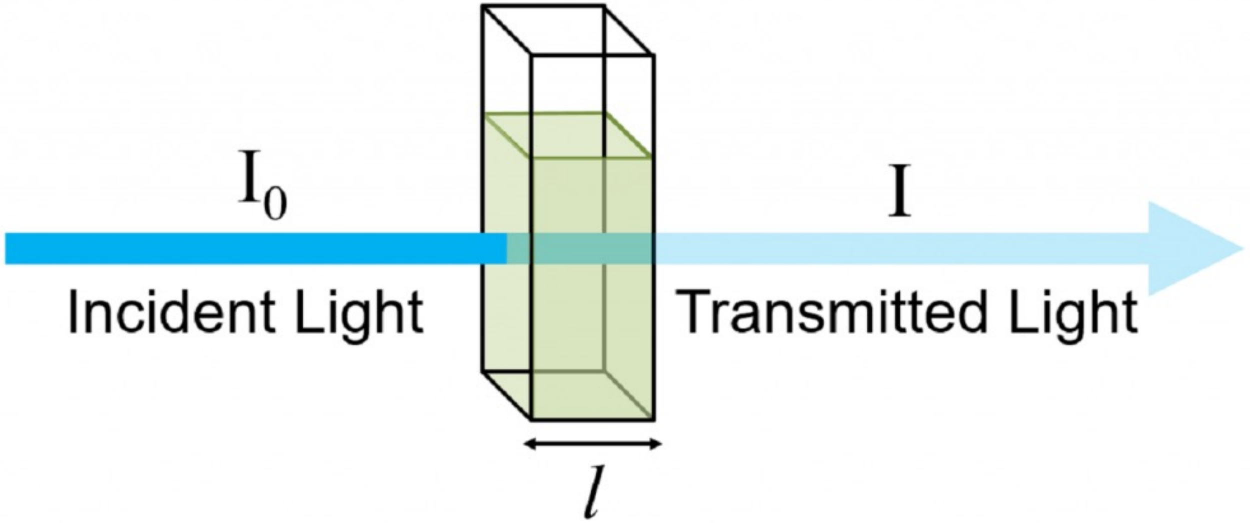
→ **Photons reaching to the particle cross-section are absorbed or scattered**

Courtesy of Ukkyo Jeong

Beer-Lambert law

- The attenuation of incident light is directly proportional to the path length of the medium and the concentration of the attenuation species in the medium.
- Transmittance = $\frac{I}{I_0}$

→ How initial light intensity is reduced after passing through an optically opaque medium



https://www.edinst.com/blog/the-beer-lambert-law/

$$I = I_0 e^{-\int \beta \mathrm{d}l} \quad \text{or} \quad \frac{I}{I_0} = e^{-\int \beta \mathrm{d}l}$$

β : extinction coefficient [length^{-1}]

Courtesy of Ukkyo Jeong

Optical depth

- $\tau \ (= \int \beta \, dl)$ [unitless]: Optical depth (or thickness)

$$\tau_{Atmos} = \tau_{cld} + \tau_{aer} + \tau_{gas} \text{ in Near UV-VIS-NIR}$$

- τ_{Atmos}: Total optical depth of the atmosphere
  - Total column integrated value from surface to top-of-atmosphere
- τ_{cld}: Cloud optical depth → mostly scattering by particles larger than aerosol
- **$\boldsymbol{\tau_{aer}}$: Aerosol optical depth** → dominantly scattering but also absorbing
  - The degree to which aerosols prevent the transmission of light by absorption or scattering
- **$\boldsymbol{\tau_{gas}}$: Gas optical depth** → Rayleigh scattering* + molecular absorption

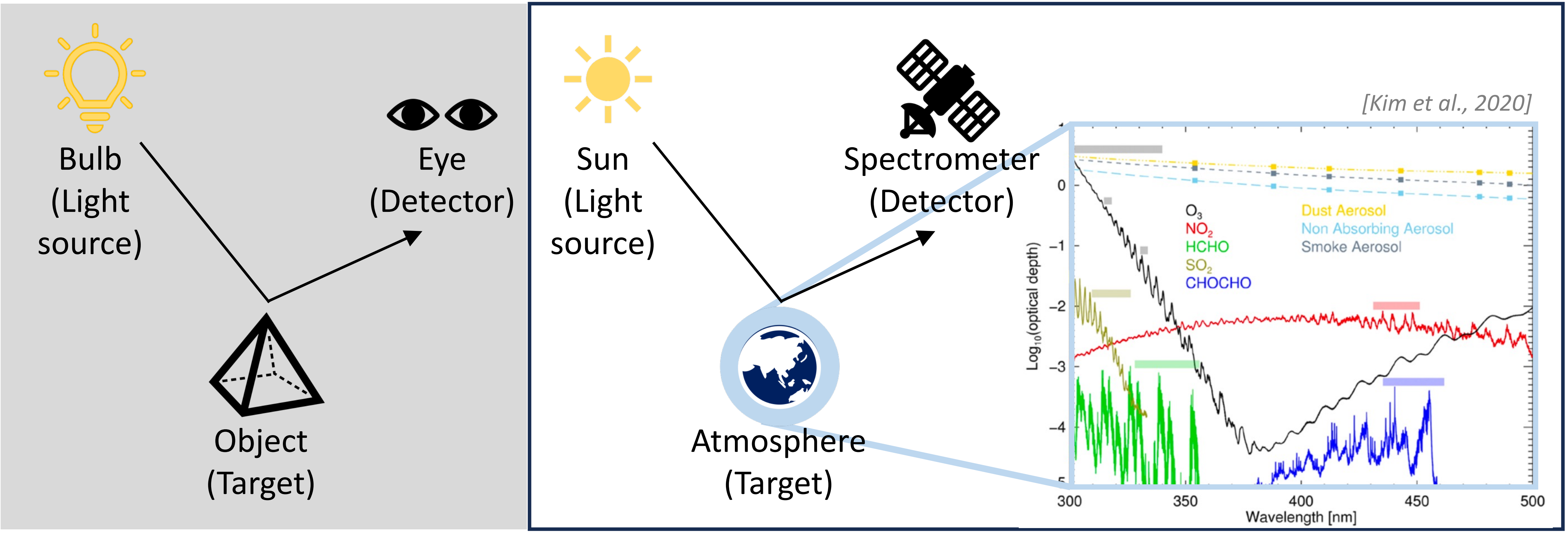
* Scattering from small, spherical particles whose diameter is one-tenth or less of the wavelength of the incident radiation.

Courtesy of Ukkyo Jeong

Satellite retrieval for monitoring air quality

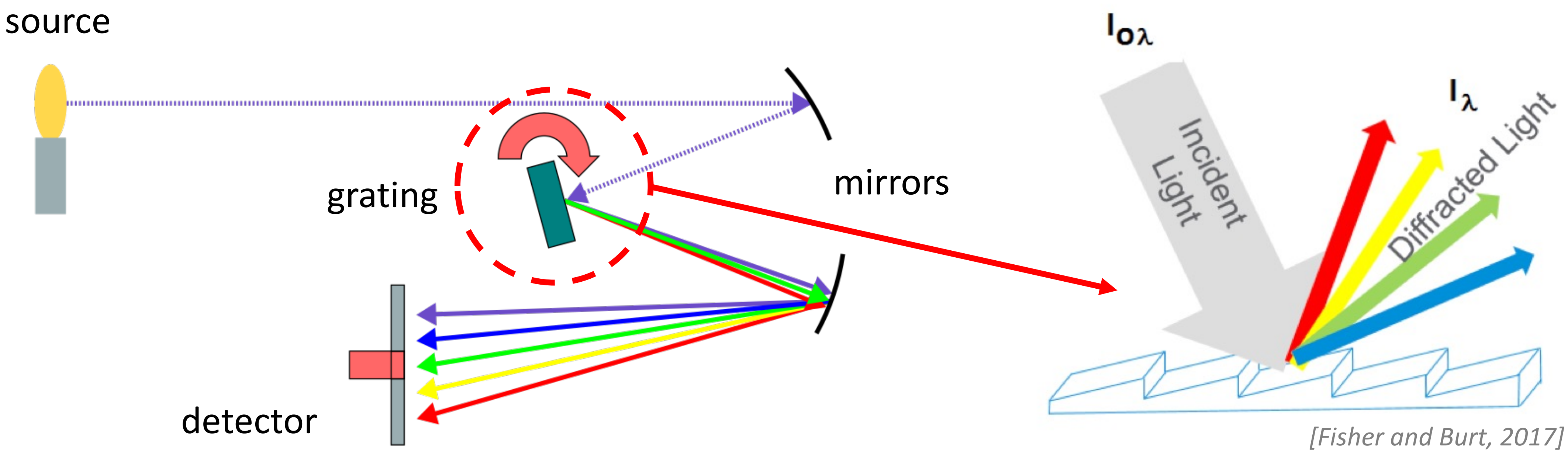
Remote sensing

- Measurement of electromagnetic radiation, measured some distance away
- Visible (VIS) vs. UV-VIS



Spectrometer

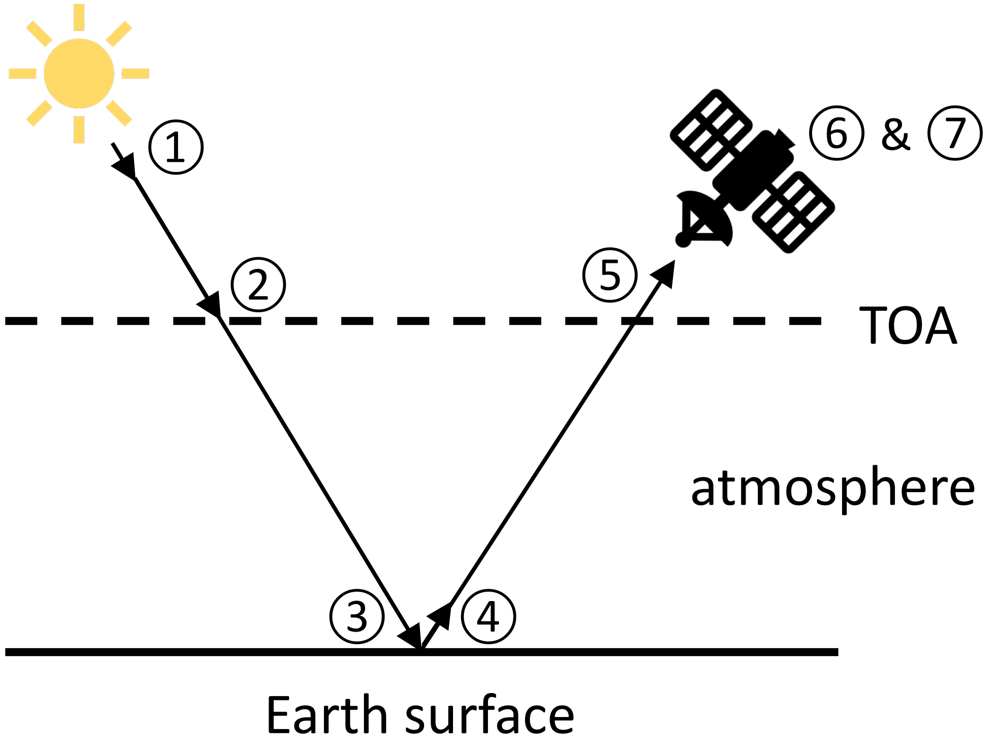
- A sensor that contains a component, such as a prism, that can break radiation extending over a range of the EM spectrum into discrete wavelengths and separate them at different angles to detectors



[Fisher and Burt, 2017]

Satellite remote sensing

- What we usually want: information about the **surface / atmosphere of the earth**



① Radiation emitted by the sun
+ sun-earth distance, solar activity

② Radiation arriving at top of atmosphere
+ incidence angle, atmosphere

③ Radiation arriving at surface
+ surface reflectance

④ Radiation leaving surface
+ atmosphere

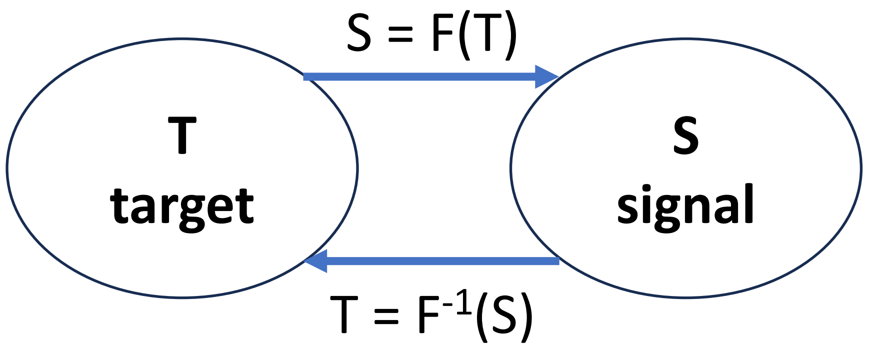
⑤ Radiation arriving at sensor
+ sensor electronics

⑥ Voltage reaching in sensor
+ offset, quantization

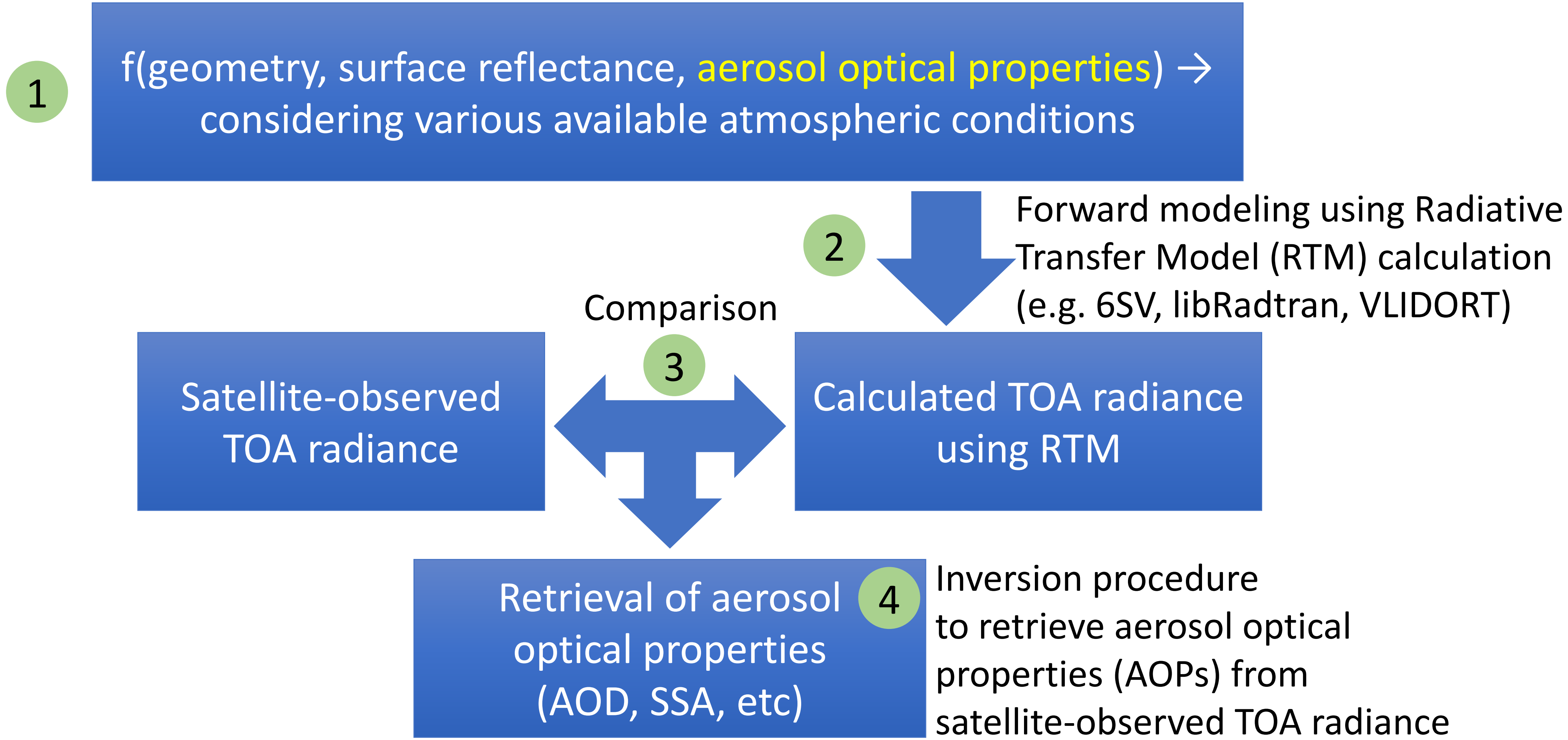
⑦ **Digital number in image file** → What we usually get!

Satellite remote sensing

- Where F denotes a function, not necessarily linear
  - If F is simple → direct inversion
  - If F is complex → not straightforward
- Fundamental obstacle in remote sensing inversion
  → "The uniqueness of the solution"
- Non-uniqueness: the medium is composed of number of unknown parameters
- In general, most of the remote sensing inversion problem ins ill-posed



General concept of aerosol retrieval from satellite



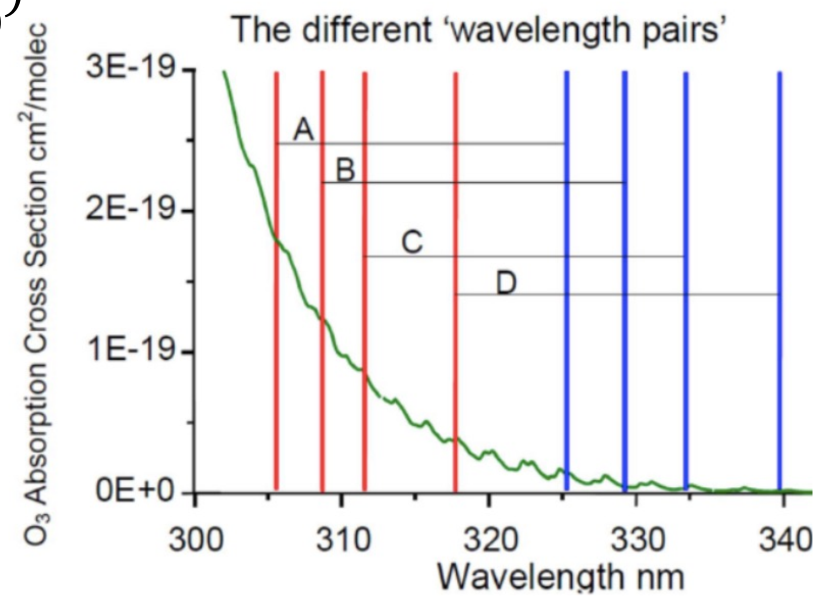
Courtesy of Jhoon Kim and Seoyoung Lee

Total ozone retrieval from remote sensing

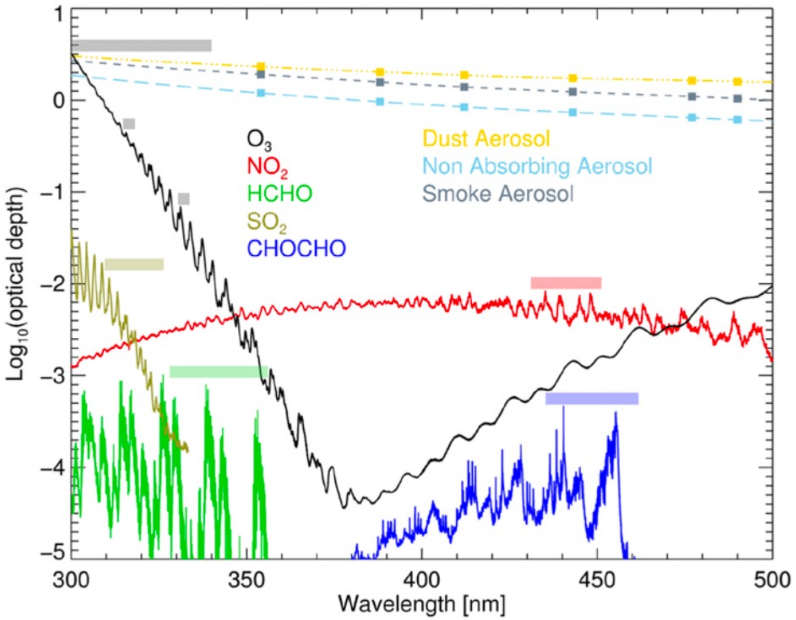
- The ozone column density is calculated from the intensity ratio of radiation at the two wavelengths of one of the ‘wavelength pairs’
- From Beer-Lambert law,

$$ln(\frac{I(\lambda_1)}{I_0(\lambda_1)}) = -(\tau_{O3} + \tau_{aer} + \tau_{Rayleigh})$$

- N-value = $ln\left(\frac{I(\lambda_1)}{I_0(\lambda_1)}\right) - ln(\frac{I(\lambda_2)}{I_0(\lambda_2)})$
- Subtract N-value from two pairs, the difference in aerosol and Rayleigh scattering can be neglected



[Kim et al., 2020]



Trace gas retrieval from satellite

- Direct fitting method

$$F(\lambda) = [I_0(\lambda)\exp\boxed{(-\tau(\lambda))} + R(\lambda)]P_{sc}(\lambda) + P_{bl}(\lambda)$$

Modeled radiance spectrum — Source spectrum — Trace gas optical depth — Reference Ring spectrum — Scaling polynomial — Baseline polynomial

$$\tau(\lambda) = \sum_{i}^{n} \sigma_i(\lambda) \times dSCD_i$$

Absorption cross-section

- Difference with Differential Optical Absorption Spectroscopy (DOAS)

$$\sum_{i=1}(Lc_{i\lambda}\sigma_i) = \ln\left[\frac{I_0(\lambda)}{I(\lambda)}\right] \equiv \tau(\lambda)$$

GEMS radiance/irradiance measurements

↓

Spectral calibration

↓

Spectral fitting based on the direct fitting method

↓

Differential Slant column density (ΔSCD)

↓

Geometric air mass factor calculations

↓

Vertical column density (ΔVCD)

Data processing levels

- The retrieval algorithms mentioned previous aim to **"Probabilistically find a state in which a solution can exist"** → Always be caution to the presence of **"uncertainty"**

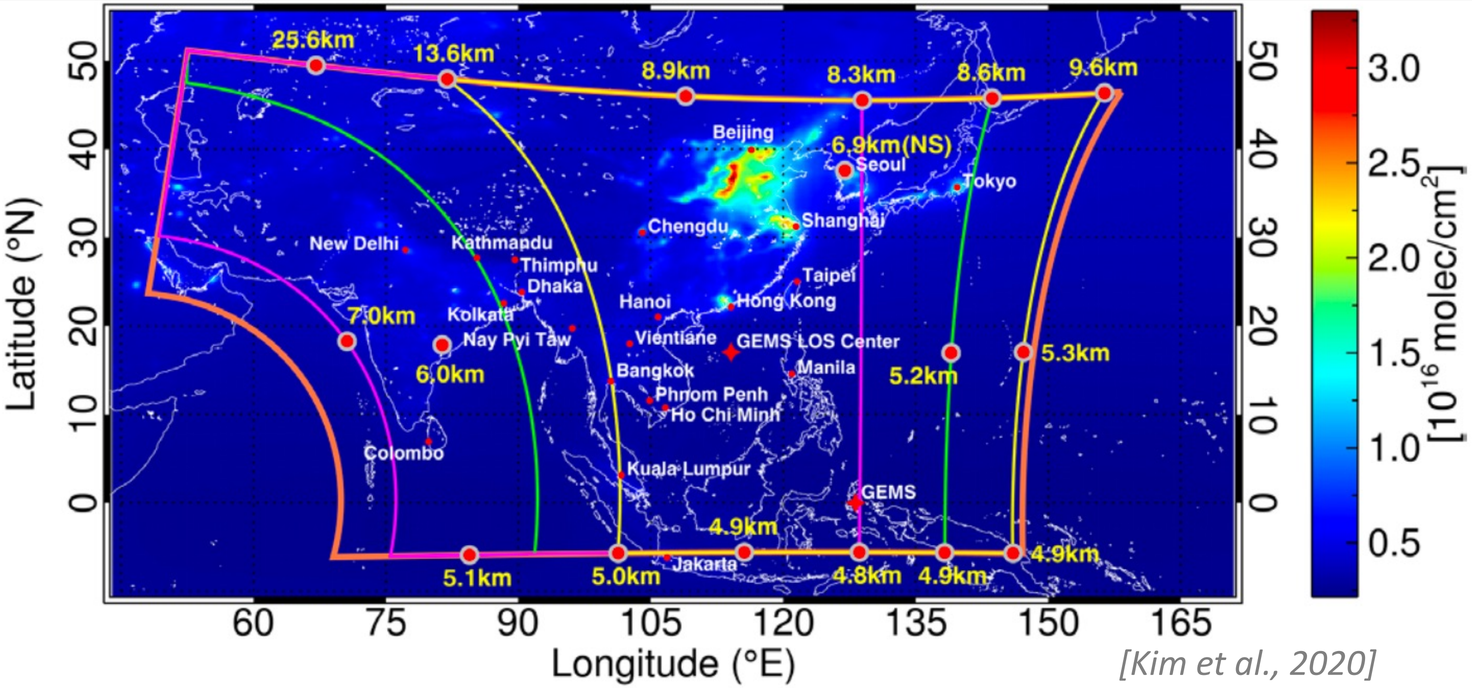
Data Level	Description
Level 0	Detected signal from true light (effect of measurement error, offset)
Level 1	True light information provided with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (not applied to L0 data)
Level 2	Derived geophysical variables at the same resolution and location as L1 source data.
Level 3	Variables mapped on uniform space-time grid scales, usually with some **completeness** and **consistency**
Level 4	Model output or results from analyses of lower-level data (e.g., derived from multiple measurements)

- Depending on the ancillary information included in the product, each level is categorized into sub-levels from A to C

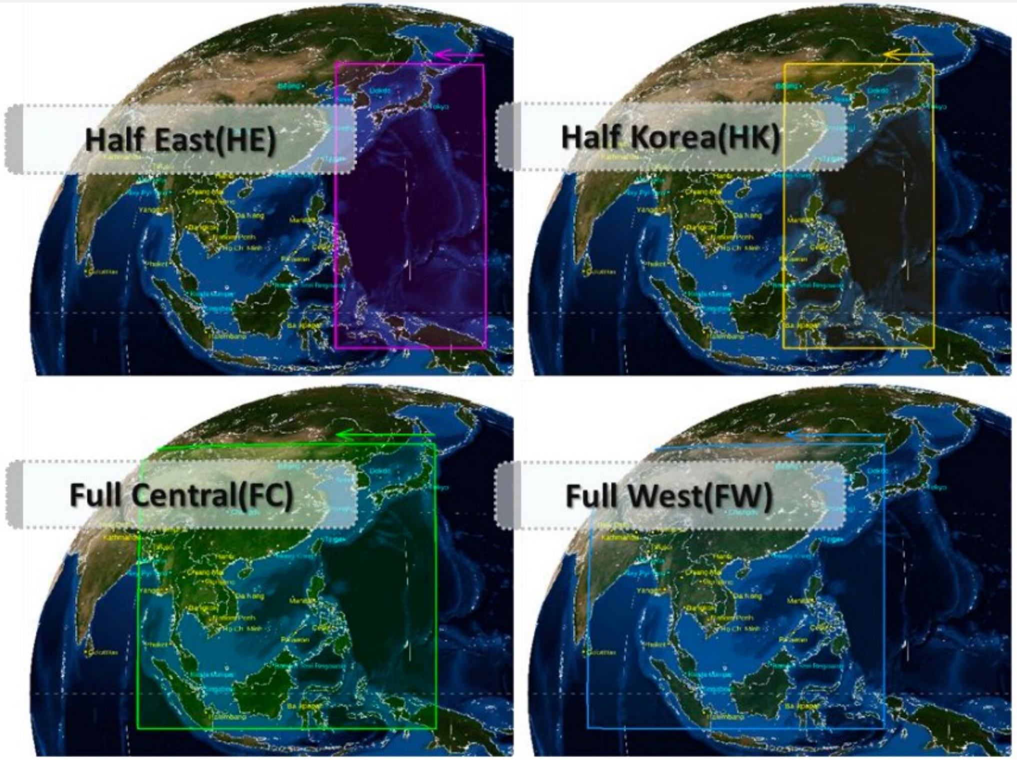
Guide to GEMS products

Geostationary Environment Monitoring Spectrometer

Courtesy of NIER



[Kim et al., 2020]



Wavelength range	300 – 500 nm (UV-VIS)	
FWHM	< 0.6 nm	
Temporal resolution	1 hour	
Spatial sampling @ Seoul [km^2]	3.5 x 8 km^2 (Aerosol)	7 x 8 km^2 (Trace gas)

- GEMS, onboard the GEO-KOMPSAT2B (Geostationary Korea Multi-Purpose Satellite), is a geostationary scanning ultraviolet-visible spectrometer.
- It is designed to monitor trans-boundary pollution events for the Korean peninsula and the Asia-Pacific region.

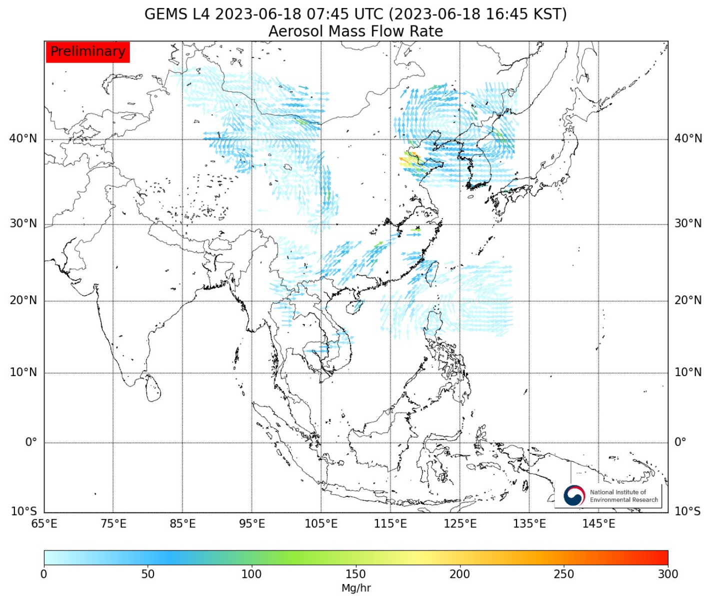
Official product of GEMS

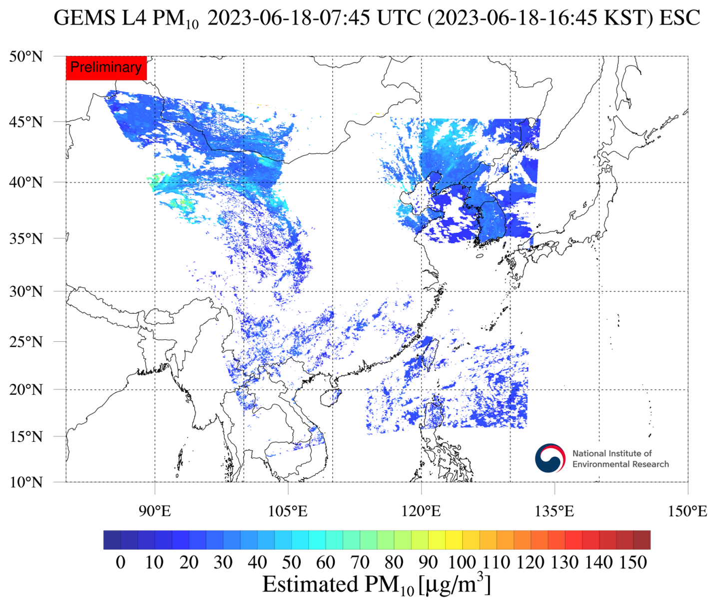
Product Group	Product	Product Group	Product
1. Aerosol	Aerosol Optical Depth @ 443 nm	7. HCHO	Formaldehyde
	Sing Scattering Albedo	8. CHOCHO	Glyoxal
	UV Aerosol Index	9. NO2	Total Nitrogen dioxide **(L3 – monthly, daily)**
	VIS Aerosol Index		Tropospheric Nitrogen dioxide **(L3 – monthly, daily)**
2. AEH	Aerosol Effective Height	10. SO2	Sulfur dioxide
3. Cloud	Effective Cloud Fraction	11. UVI	UV Index
	Effective Cloud Pressure		Plant Response Index
	Cloud Radiance Fraction		DNA Damage Index
4. SFC	Surface Reflectance		VitaminD Synthesis index
5. O3T	Ozone Total		
6. O3P	Tropospheric Ozone Profile		
	Stratospheric Ozone Profile		

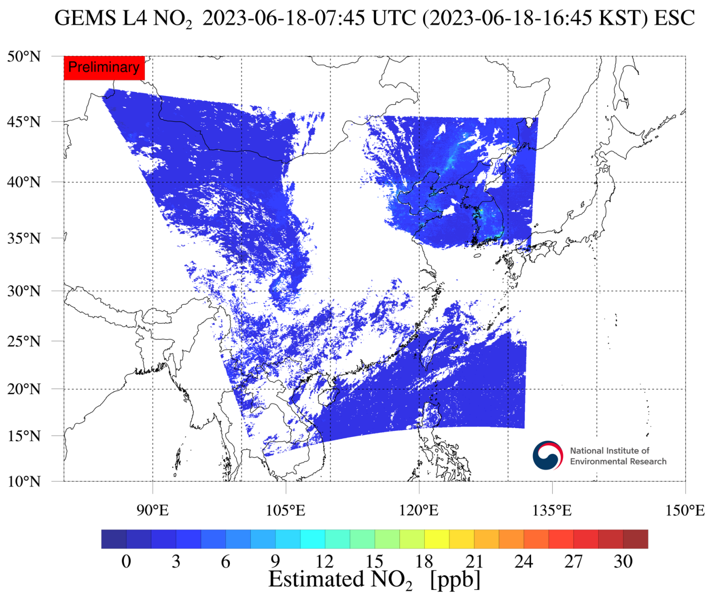
- 25 different L2 products available
- 6 different L3 products available

Official product of GEMS

- 5 different L4 products available only for image
  - Aerosol mass flow rate [Mg/hr]
  - SO_2 mass flow rate [Mg/hr]
  - Estimated surface $PM_{2.5}$ and PM_{10} concentration [μg/m^3]
  - Estimated surface NO_2 concentration [ppb]







How to access GEMS data

1. Download from Environmental satellite center (ESC) website: https://nesc.nier.go.kr/en/html/index.do

- Anyone can download GEMS data without logging in.
- Up to 20 GB and 40 files

2. SFTP service (A written application form required)

- An account is issued for the user's public IP address, which is allowed to pass through the ESC's Web Application Firewall (WAF).
- Log in to the SFTP server using the account and download data.

3. External hard drive (A written application form required)

- GEMS data can be downloaded to an external hard drive (sent to the ESC by the user via mail), which is then mailed back to the user.

Application for GEMS Data

☐ Applicants Information

- **Affiliation(Company/School/Institution):**
- **Name:**
- **Phone Number:**
- **E-Mail Address:**

☐ Purpose of Use:

☐ Details

Duration	○ Date(DD/MM/YY ~ DD/MM/YY): ~ ○ Time(UTC) : 22, 23, 00, 01, 02, 03, 04, 05, 06, 07 *(Example) All, 00~07 UTC, etc.*
Proposed products	☐ Level 1C(L1C) ☐ Level 2(L2)
Proposed date form	☐ Network*(SFTP) ☐ Electronic media (external hard drive, etc.) ☐ Etc. *Network (If you chose Network, please fill in the information below.) ·Name of Account: ·Public IP Address: *※SFTP operation : To allow applicants' public IP address into SFTP of Environmental Satellite Center(ESC)*

/ /

Date Name Signature

To Director of Environmental Satellite Center(ESC)

Utilizing satellite data: How to read and visualize

21 Jun 2023

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Space Applications Section
ICT and Disaster Risk Reduction Division

Contents

1. How to read GEMS data
2. Visualize GEMS data with Python

How to read GEMS data

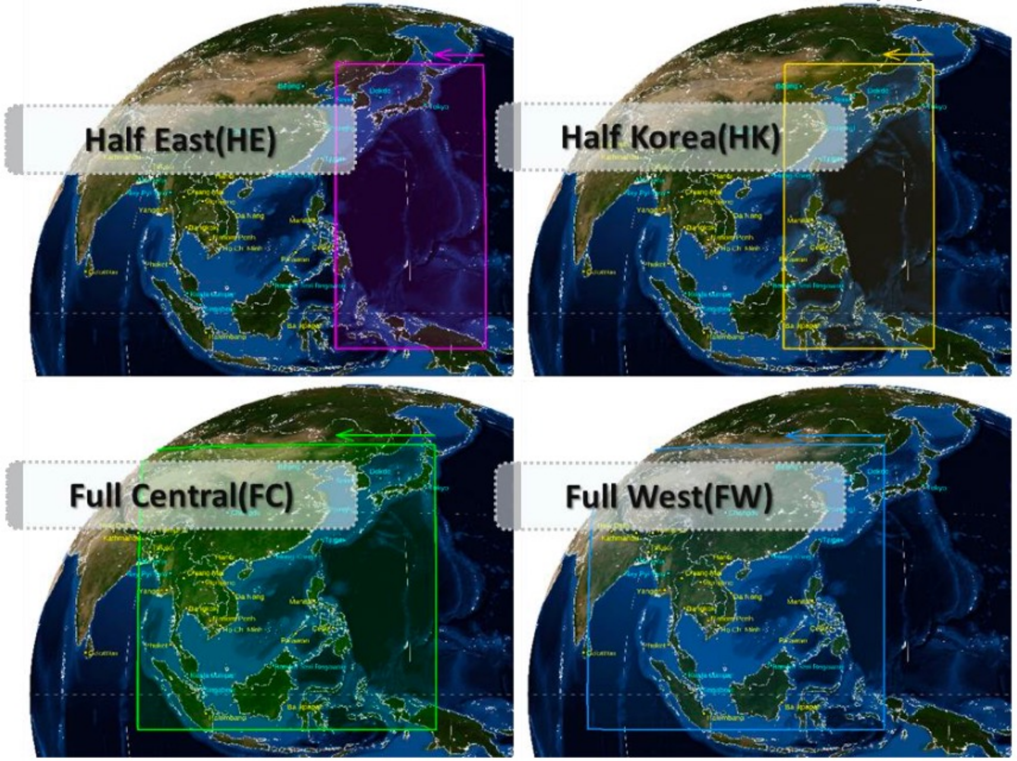
GEMS netCDF file

SAT_Instrument_Level_ Date_Time_ALG_Area_ProcessType_BIN.Extension

i.e., GK2_GEMS_L2_20210705_2245_AERAOD_HE_DPRO_ORI.nc

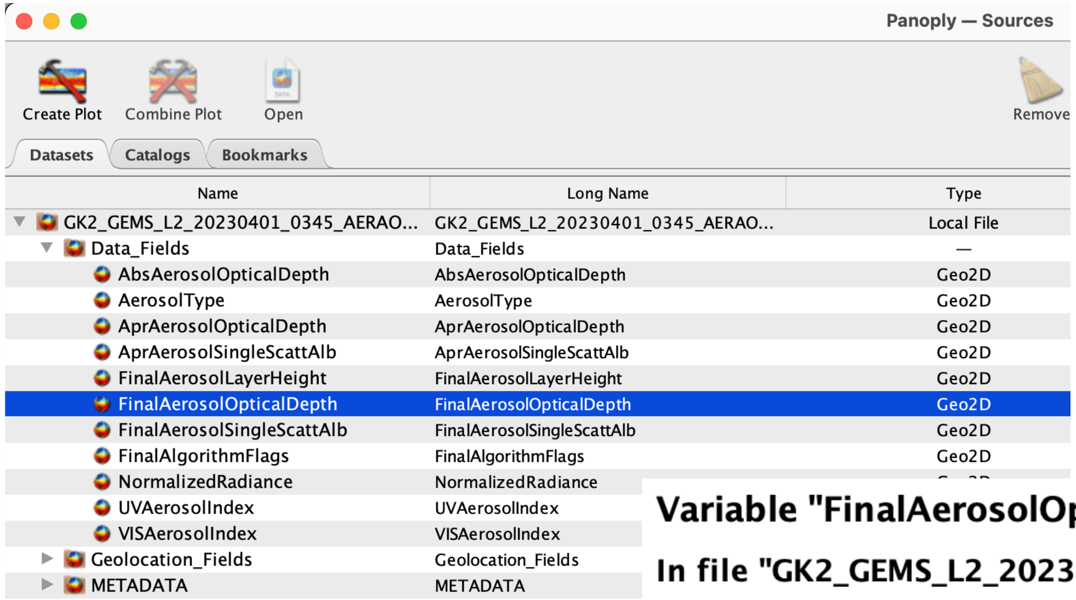
- SAT: Satellite name, GK2B (GEO-KOMPSAT 2B: Geostationary Korea Multi-Purpose Satellite)
- Instrument: Instrument name, GEMS
- Level: Data processing level, L2
- Date: Observation date, 20210705
- Time: Start time of GEMS observation, 2245UTC
- ALG: Algorithm name, AERAOD
- Area: GEMS scan area, HE
- ProcessType: information of data type (DPRO: Daytime RPRO: Re-processing)
- BIN: binning or original (ORI, 2X2, 4X4)
- Extension: File format, NC (NetCDF4 file)

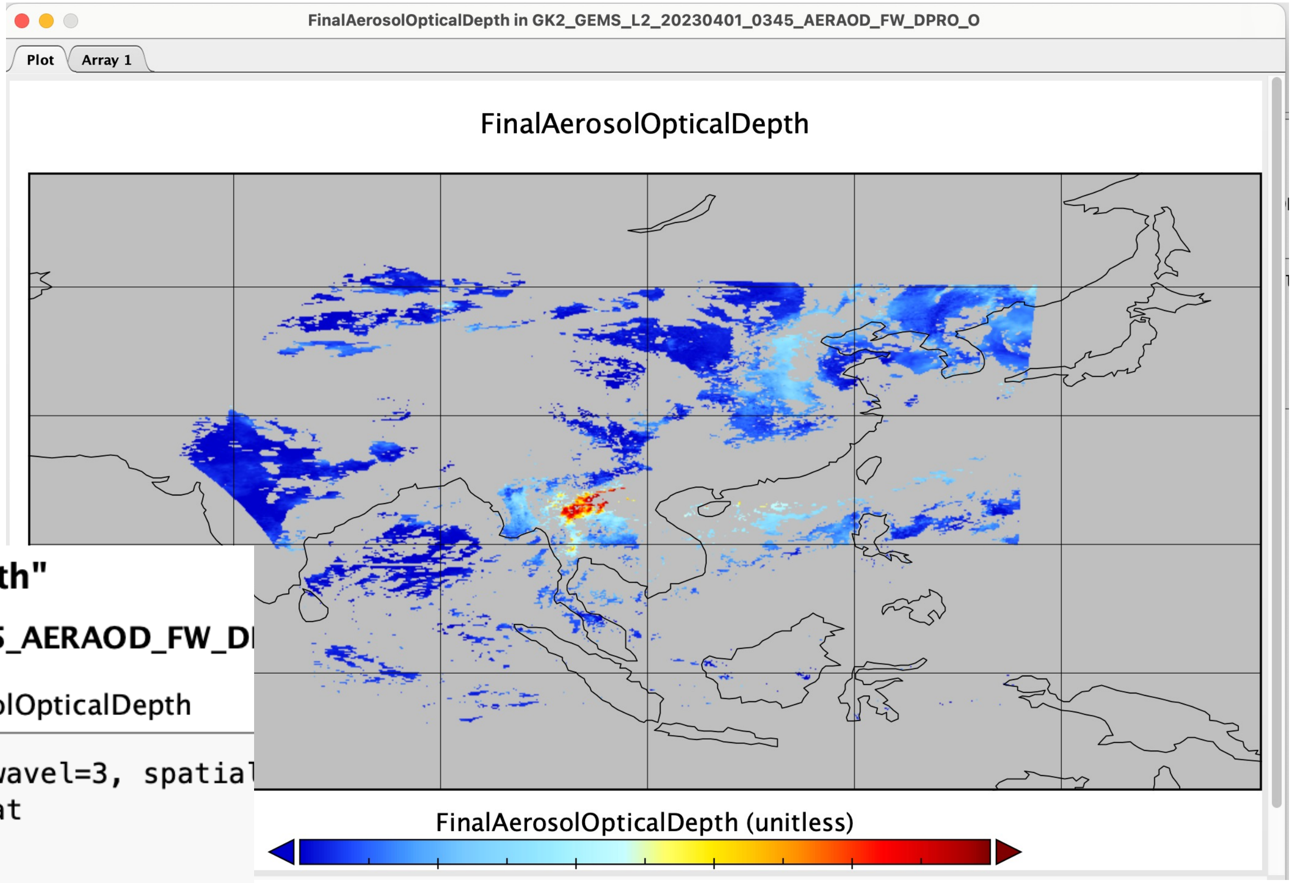
Courtesy of NIER

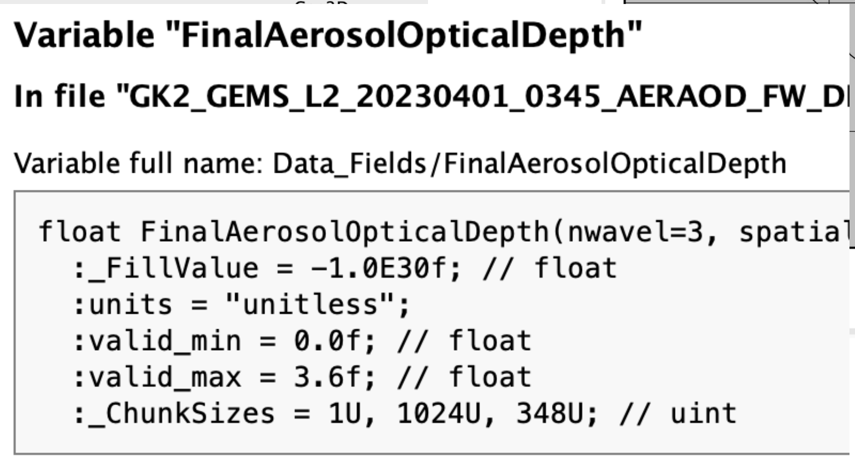


Panoply

- https://www.giss.nasa.gov/tools/panoply/







What is ATBD?

- A document intended to describe the physical and mathematical description of the algorithms to be used in the generation of data products
- Description of algorithm and products, and validation
- https://nesc.nier.go.kr/en/html/satellite/doc/doc.do

Quality flags (QFs)

- Provide the information about the quality of data value
- Use ATBD or user guide officially provided for the public from the representative institute

Quality flags for the GEMS Aerosol L2 file

Bits	Definition	Note	Description
0	Reliable (AOD, SSA, ALH)	Good	(0, Good; 1 : have issue) AOD > 0.2 & ALH AK > 0.2
1	Less reliable (AOD, SSA, ALH)	Suspect	AOD < 0.2 or ALH AK < 0.2
2	Out-of-bounds SSA or AOD at 443 nm.	Bad	AOD < −0.05 or AOD > 3.6 or SSA < 0.82 or SSA > 1.0
3	OE fitting error	Bad	Fitting error during optimal estimation.
4	Normalized radiance above threshold	Bad	High normalized radiance
5	Surface albedo above threshold	Bad	High surface albedo
6	Cloud masking	Cloud	Presence of clouds
7	Solar zenith angle above threshold (69°) or viewing zenith angle above threshold (69°).	Bad	SZA > 69° or VZA > 69°
8	Sun-glint angle below threshold over water	Bad	Sun glint angle < 35°
9	Terrain height high	Suspect	Terrain height > 2 km
10	Previous L2 SFC (-5day) are used	Suspect	Absence of L2 SFC information
11	OMI climatology used for surface albedo	Suspect	Absence of L2 SFC information
12	Previous irradiance used	Suspect	Absence of L1C irradiance
13	AMI cloud-masking used	Cloud	Cloud masking using AMI L2 Cloud product.
14	Less reliable of surface albedo	Suspect	Less accurate AERAOD surface albedo
15	Interpolated radiance used	Suspect	L1C Radiance QF = 2

Courtesy of Jhoon Kim and Seoyoung Lee

Quality flags for the GEMS Aerosol L2 file

- The example of quality flag of 2561

Bits	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1
	$2^0+2^9+2^{11}=1+512+2048=2561$															

- Each number in the bits column represents the exponent of the appropriate term in the equation used to calculate the quality flag.
- For example, a quality flag of 2561 in a given pixel means that there is more than one issue ($2^0 = 1$), high Terrain Height ($2^9 = 512$), and absence of L2 SFC information ($2^{11} = 2048$) (in this case, the aerosol products are retrieved using OMI climatology data), or 1 + 512 + 2048 = 2561.
- If the quality flag is 0, the quality of retrieval is reliable. If bits are 1, 9, 10, 11, 12, 14, or 15, the quality of retrieval is less reliable (= suspect).

Courtesy of Jhoon Kim and Seoyoung Lee

Quality flags for the GEMS SO_2 L2 file

VCD Quality Flags		
Bits	Definition	Note
0	SCD error	Bad
1	Geometric slant O3 column ≥ Threshold (currently set at 1500 DU)	Bad
2	Reflectivity at 317 nm > 15%	Bad
3	Cloud error	Cloud
4	O3 error	Suspect
5	Reflectivity error	Suspect
6	Aerosol error	Suspect
7	Operation error	Bad
8	L1B radiance warning, error, or missing	Bad
9	L1B irradiance warning, error, or missing	Bad
10	LUT error	Bad

Algorithm Quality Flags		
Bits	Definition	Note
0	DOAS Fitting error in GEMS SO_2 algorithm	Bad
1	DOAS Reference spectrum error	Bad
2	Background correction error	Bad
3	Cloud fraction > Threshold (current 0.5)	Cloud
4	PCA Fitting error in GEMS SO_2 algorithm	Bad
5	PCA clean sector pixel number > Threshold (current 100)	Suspect

Lee and Yang, 2020

Quality flags for the GEMS L2 file

GEMS VOC L2

- In ATBD, 'Measurement data quality flag' is provided in the product. But 2 flags in the real product, 'FinalAlgorithmFlags' and 'FitConvergenceFlag' are contained.

Measurement data quality flag		
Value	Description	Note
0	Retrieved vertical columns+2σ > 0, σ is fitting uncertainty	Good
1	Retrieved vertical columns+2σ < 0, but Retrieved vertical columns+3σ > 0	Suspect
2	Retrieved vertical columns+3σ < 0	Bad
-1	Missing	-

Park and Kwon, 2020

GEMS NO_2 L2

- 3 flags in the real product, 'AlgorithmQualityFlags', 'FinalAlgorithmFlags' and 'AMFQualityFlags' are contained.

Ground pixel quality flag (GPQF)

- Ground pixel quality flag in GEMS AOD products, and Pixel quality flag in GEMS NO2 products
- The GPQF provides information on the Earth's surface characteristics within a GEMS ground pixel

Fill value	Description
-999	Deep-space
Bit	**Description**
0	0=Water, 1=Land
1	0=No glint, 1=Glint
2	0=Snow/ice-free, 1=Snow/Ice
3-14	Reserved

Courtesy of Jhoon Kim and Seoyoung Lee

Apply QF

Quality flags (cont'd)

- If you can't find the information in the ATBD or user guide, search the ***appropriate references***
  - Some references can give you more useful information for your purpose
  - e.g., additional criteria using solar zenith angle threshold
    - 'We take GEMS data with a ***solar zenith angle of less than 75 deg.*** to avoid GEMS errors that may occur due to the high solar zenith angle of GEMS data.' (Baek et al., 2022)
  - Some references can give you more useful information for your purpose
- ***Depending on the type of product, the flags and additional filtering method are different***
- Sometimes you can find the description in the file itself (use Panoply)

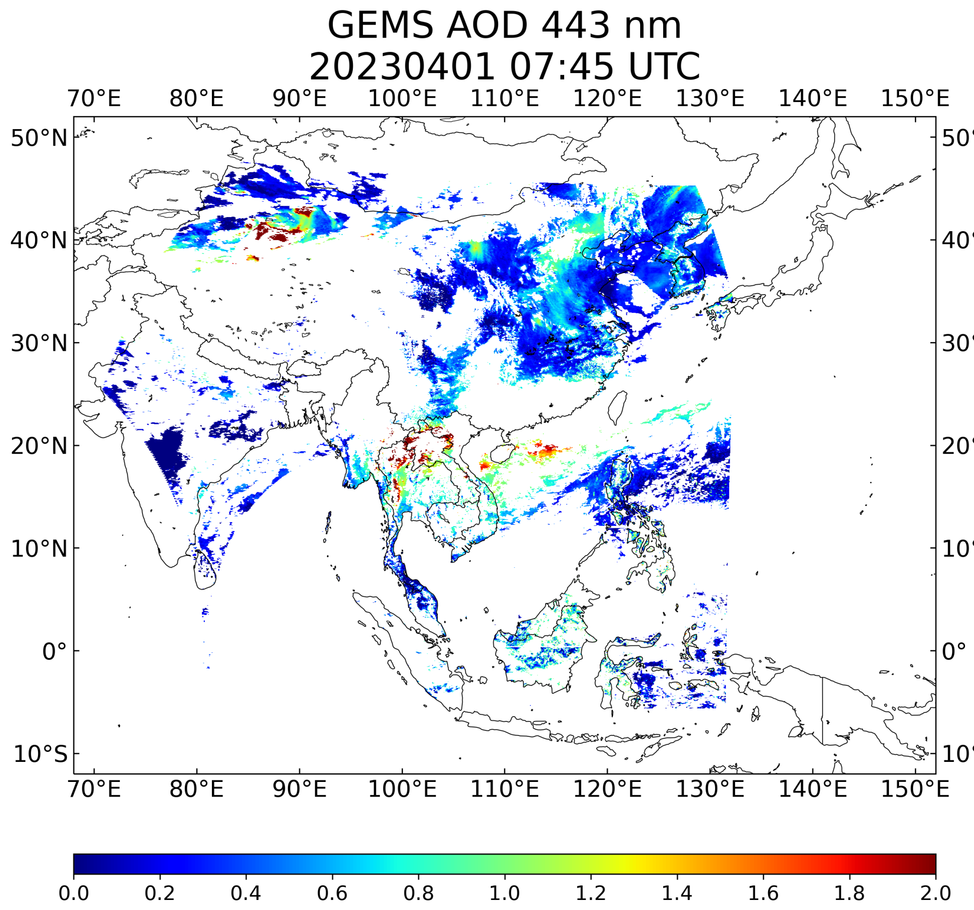
* The user guide of GEMS will be published in this year

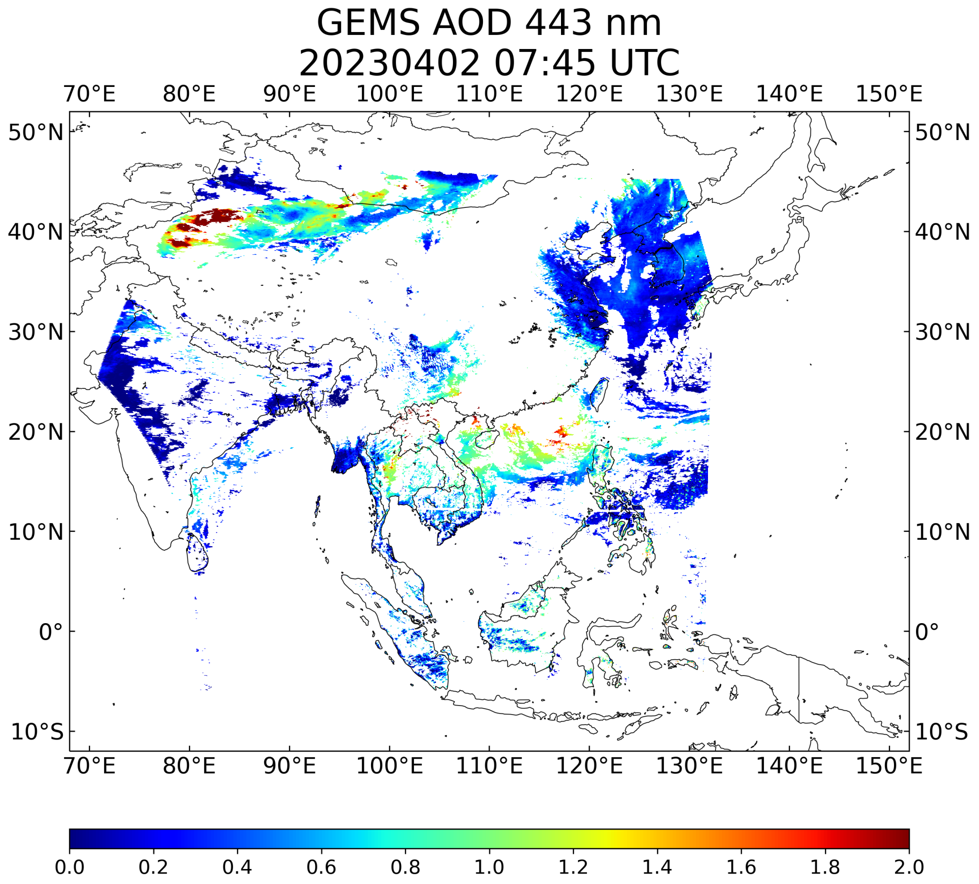
Visualization GEMS data with Python

Library required to visualize GEMS data

1. **numpy**
   - It facilitates processing large, multi-dimensional arrays and matrices, along with a large collection of high-level mathematical functions to operate on these arrays
2. **netCDF4**
   - It allows us to read, edit, and write netCDF4 format (most used format for satellite data)
3. **cartopy**
   - It supports geospatial data processing in order to produce maps and other geospatial data analyses
   - select coordinate reference systems (crs), draw coastlines, and so on
4. **matplotlib**
   - It is a comprehensive library for creating static, animated, and interactive visualizations
   - matplotlib.pyplot: a collection of functions like MATLAB
5. **datetime, glob…**

GEMS Aerosol Optical Depth @ 443 nm





Processing satellite data: Regridding

23 Jun 2023

MOVING FORWARD TOGETHER

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Why do use level 3 data?

Level 3 data

- Variables mapped on uniform space-time grid scales, usually with some completeness and consistency
- L3A: generally periodic summaries (weekly, ten-day, monthly) of L2 products

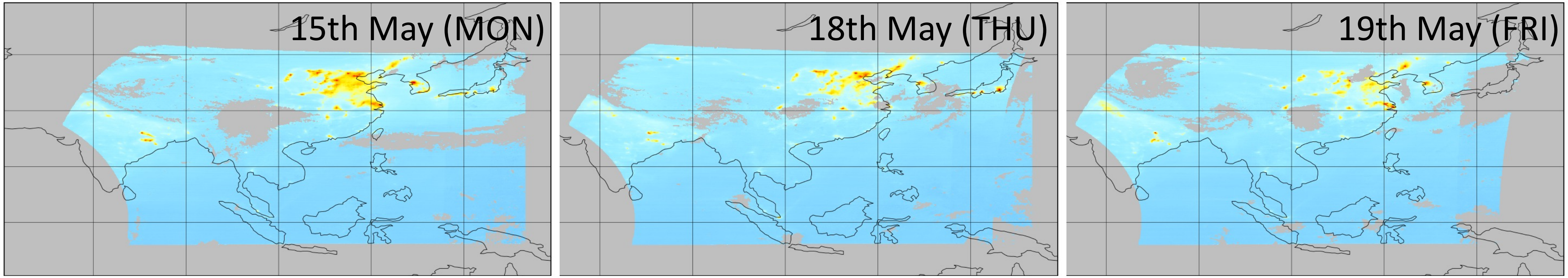
- Increase the number of observation (available data)
- Mean value of reliable data (quality flags applied) as gridded format → more accessible to general users
  - In case of GEMS, the numbers and locations of pixels (max 695 pixels in E-W, and 2048 pixels in N-S) are different by each observations → a little hard to use for general users

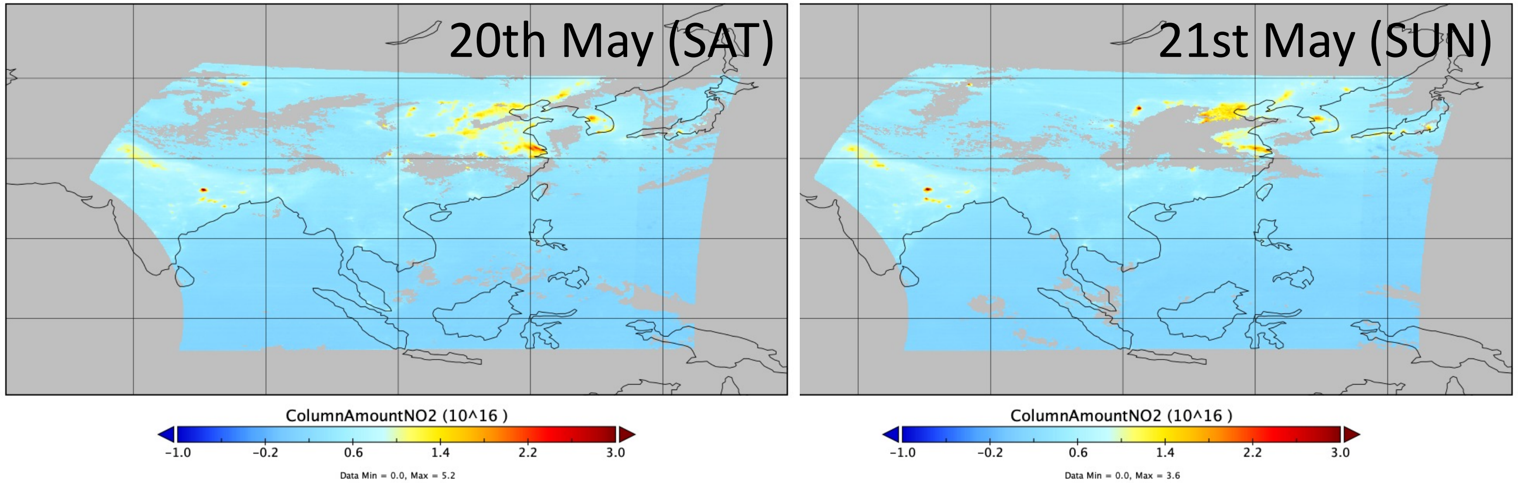
Visualize GEMS level 3 data using Panoply

GEMS gridded mean NO_2 (Level 3)

- Daily and monthly average for both column and troposphere
- Availability: Daily on the following day, monthly on the following day of the end of the month
- Cloud pixels are removed
- Accuracy depending on the effect of cloud pixel removal and the number of observation

Visualize GEMS level 3 data using Panoply





NO_2 total column

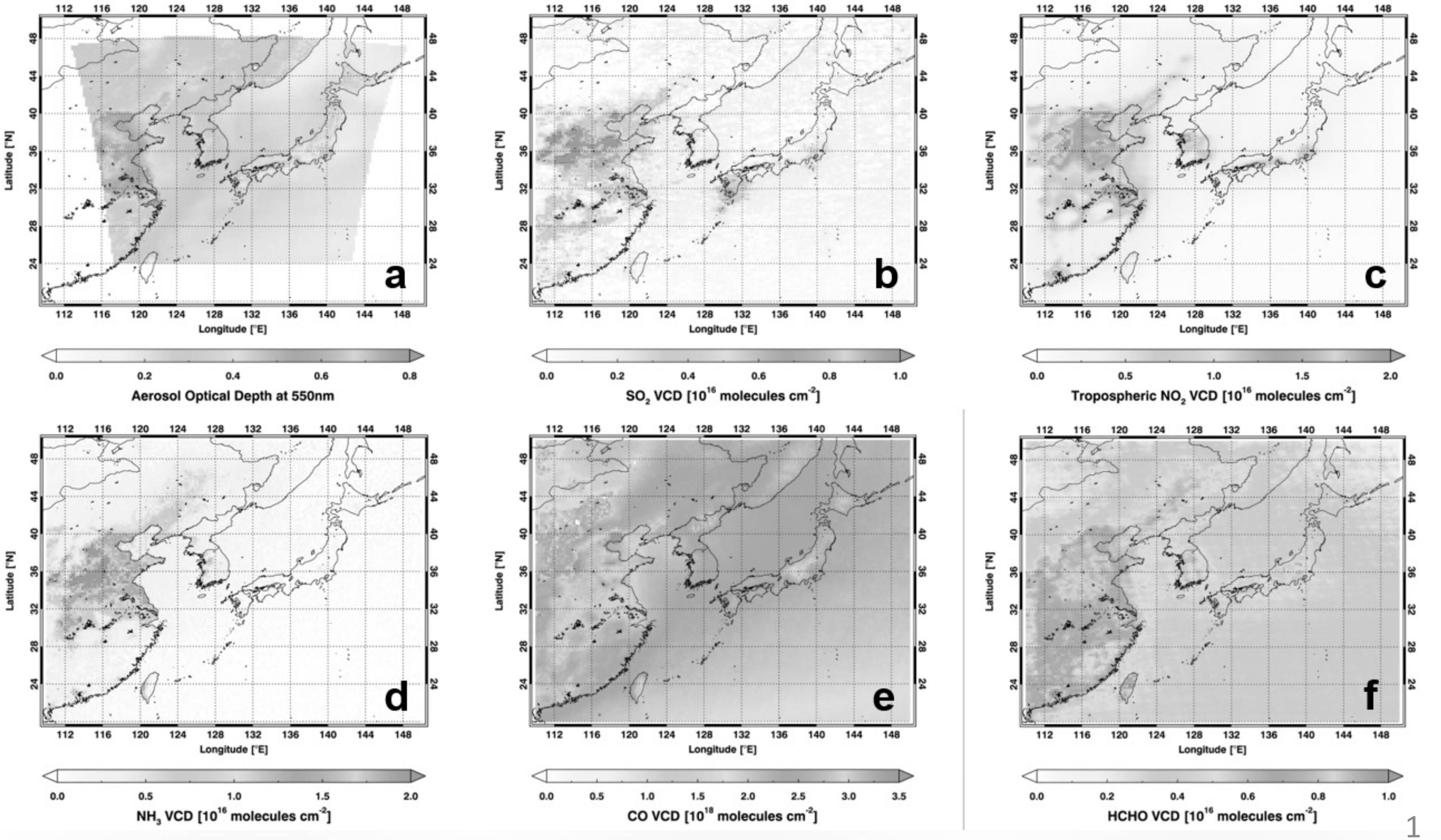
- Major sources: energy consumption, such as vehicles and power plants
- Short lifetime → hotspots are detected around major cities

Example (1) Climatological mean

- GOCI AOD
- OMI SO_2, tropo. NO_2, and HCHO
- IASI NH_3
- MOPITT CO

- Confirm the feature attributed to the source, sink and lifetime of aerosol and trace gases

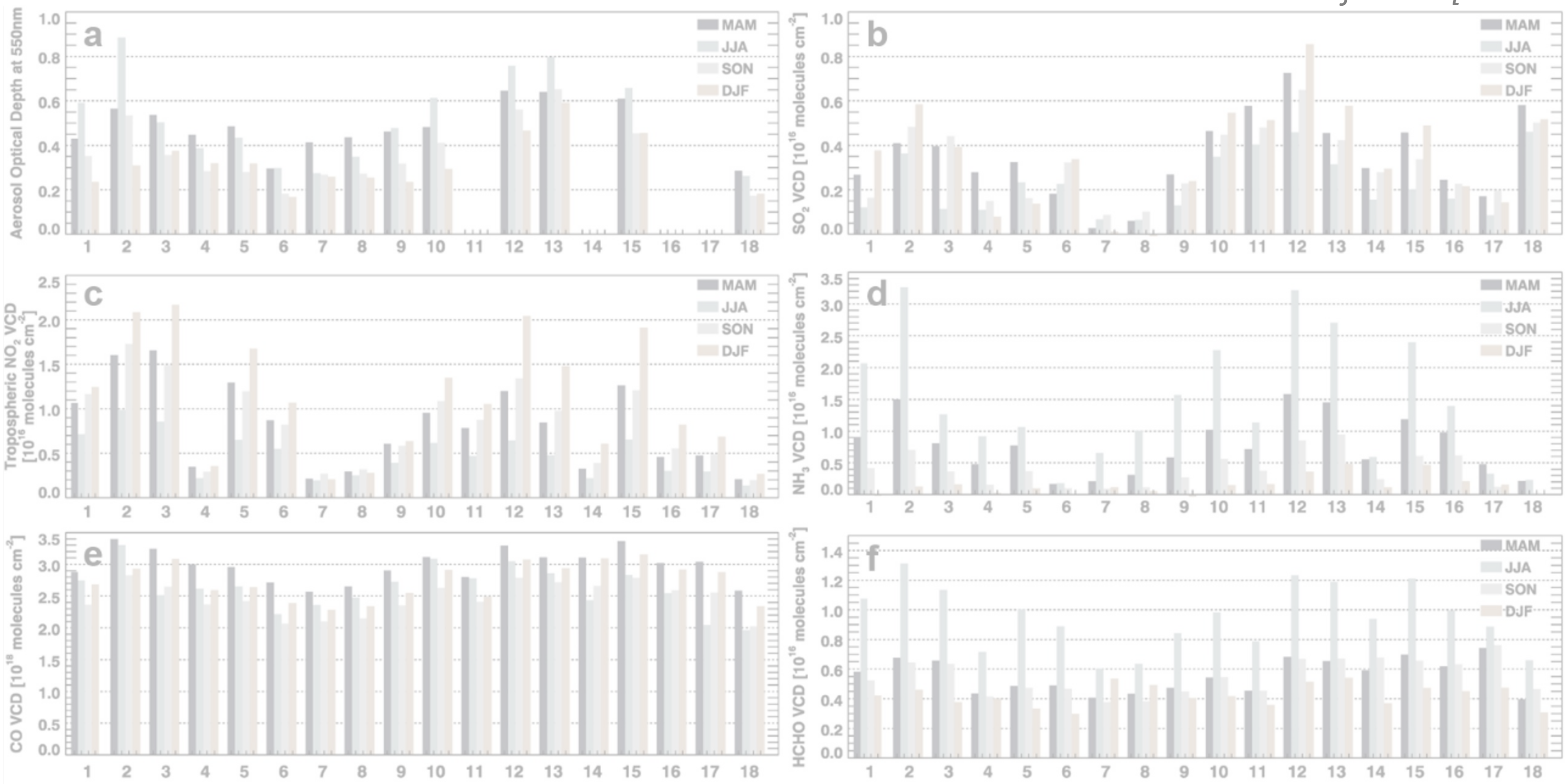
Under review for RSE [Ahn et al.]



Example (2) Seasonal variation

- Seasonal characteristics of air pollutants
- AOD: max. in summer (hygroscopic growth and secondary formation of aerosols) and min. in winter
- oxidation by hydroxyl radical (OH) and fossil fuel combustions
- NH_3: temperature dependency
- HCHO: photochemical oxidation of hydrocarbons, biomass burning

Under review for RSE [Ahn et al.]



1: Beijing	2: Tianjin	3: Shanghai	4: Pyongyang	5: Seoul	6: Tokyo
7: Heilongjiang	8: Jilin	9: Liaoning	10: Hebei	11: Shanxi	12: Shandong
13: Henan	14: Hunan	15: Jiangsu	16: Hubei	17: Guangdong	18: Kyushu

Space-borne instrument: LEO and GEO

26 Jun 2023

ESCAP 75
MOVING FORWARD TOGETHER

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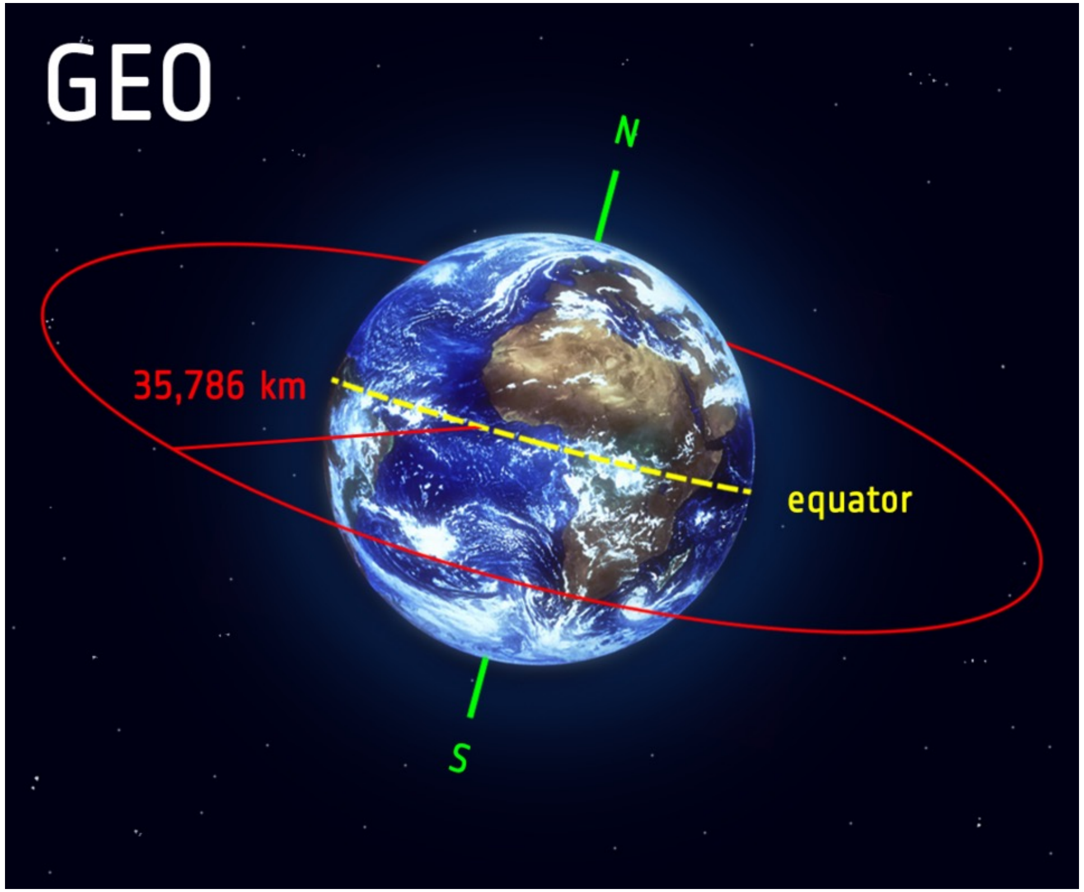
Satellite orbits

Geostationary earth orbit (GEO)

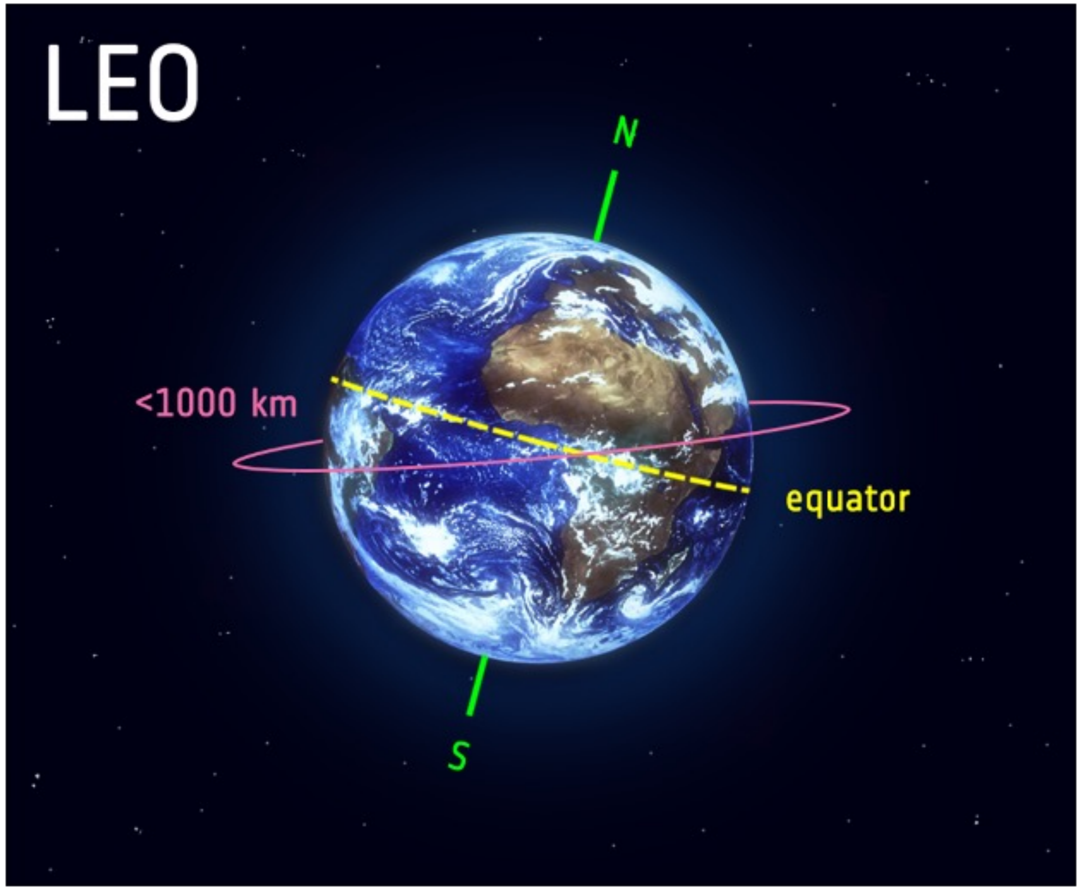
- Circular orbit around the equator with zero inclination
- Orbital period = period of Earth's rotation
- Orbit is stationary with respect to a location on the Earth
- 35,786 km
- Communication, broadcast, earth observation
- Advantages: high temporal resolution, always visible (e.g., weather forecasting, communications); ~5-15 minutes
- Disadvantages: cost, lower spatial resolution than polar orbiting sensors, poor coverage of high latitudes (>55), limited global coverage (~1/3 maximum)



Credit: ESA

Low earth orbit (LEO)

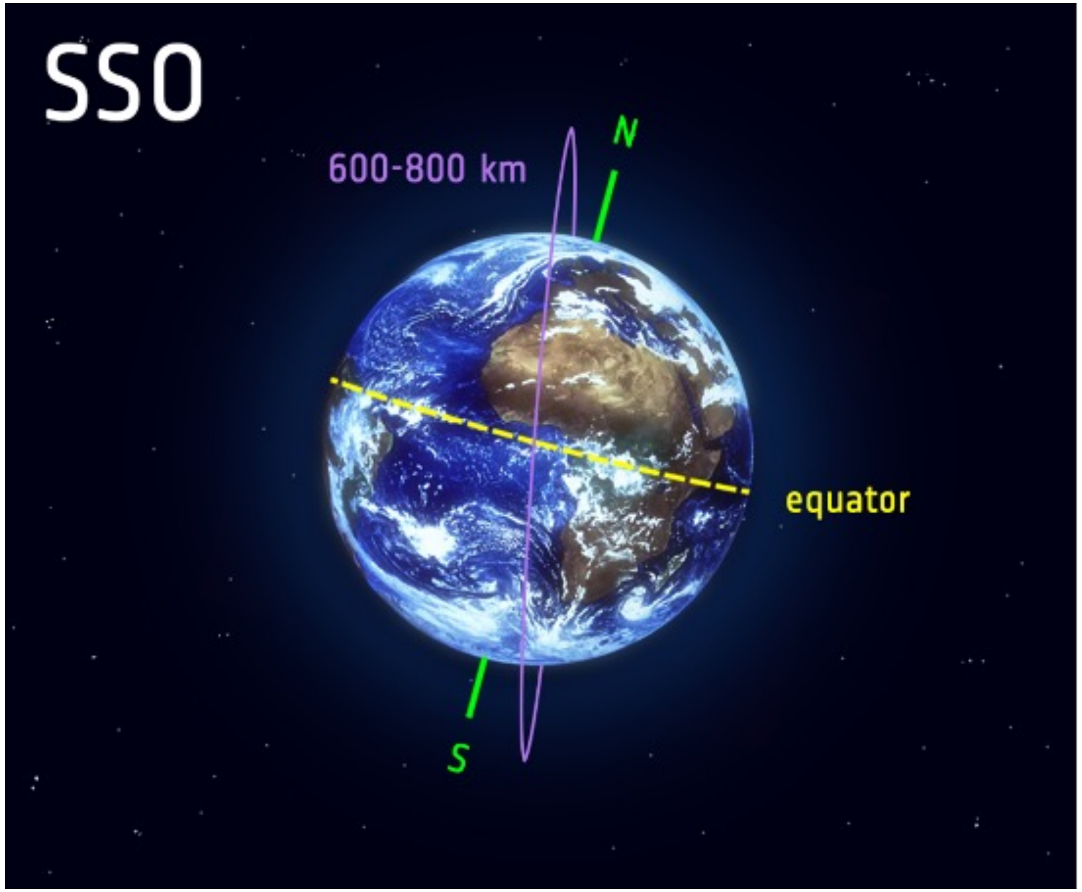
- Orbit that is relatively close to Earth's surface
- 150 – 2,000 km
- The plane LEO satellites rotated can be tilted, so more available routes for satellites in LEO
- Advantages: high spatial resolution, polar coverage
- Disadvantages: low temporal resolution (at low latitudes)



Credit: ESA

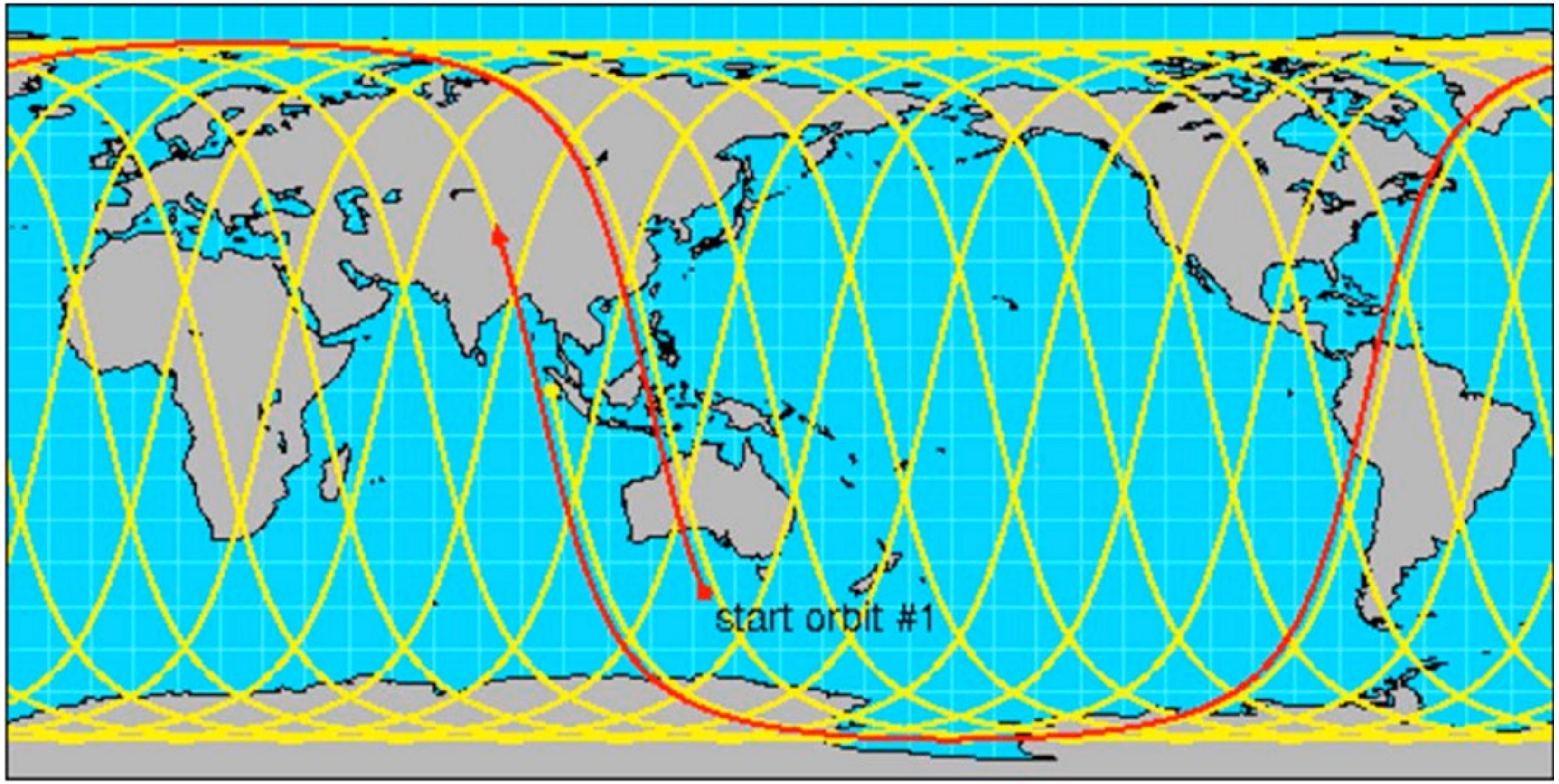
Polar orbit and Sun-synchronous orbit (SSO)

- A type of low Earth orbit
- Sun-synchronous orbits precesses at the same rate that the Earth orbits the Sun
  - Satellite will always observe a point on the Earth at the same local time
  - Altitudes – 700 ~ 800 km, periods of 98-102 minutes
  - 14- 15 orbits per day
  - e.g., NOAA-X satellites (US), MetOp (Europe)



Credit: ESA

LEO repeat cycles



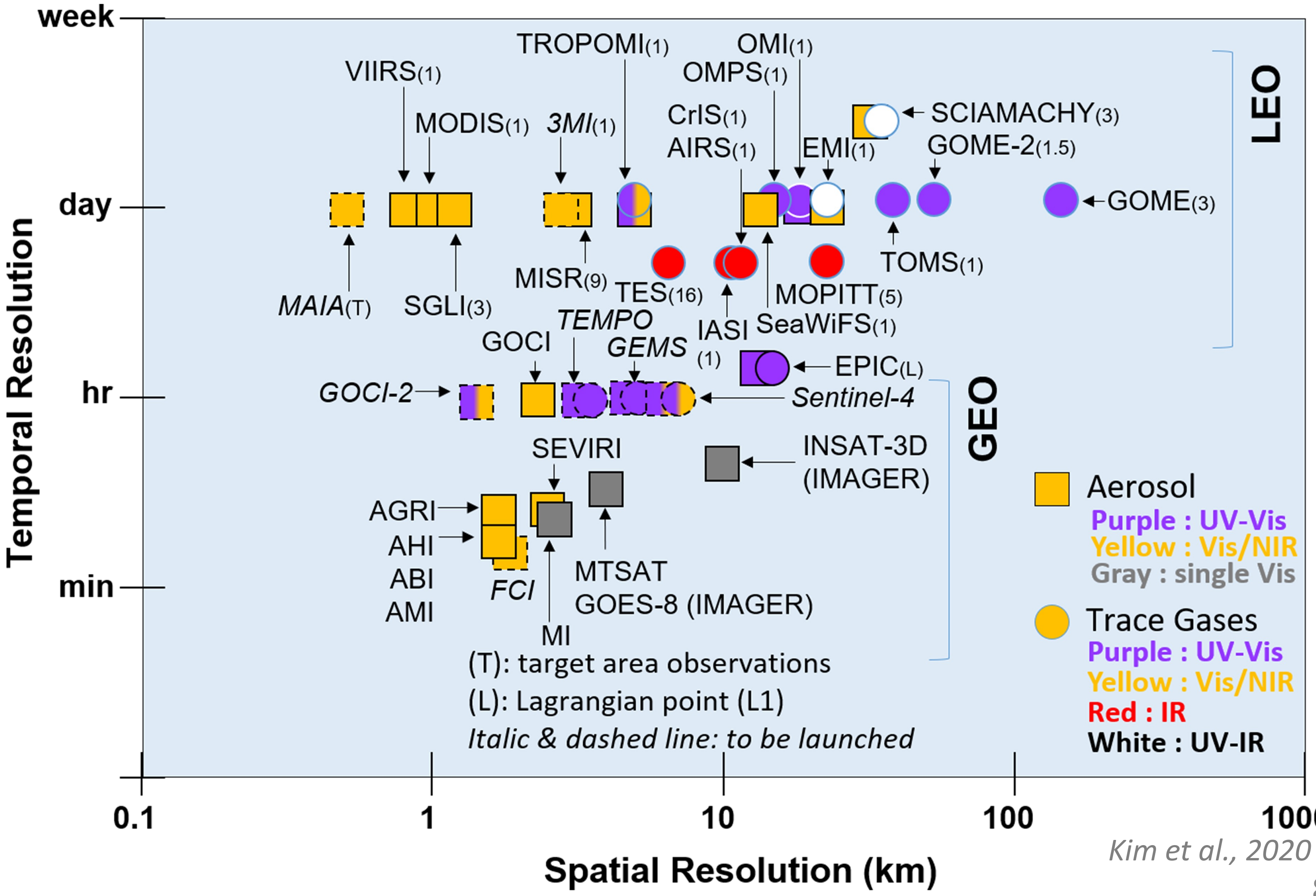
- If earth makes an integral number of rotations in the time taken for the satellite to complete an integral number of orbits, the sub-satellite track repeats exactly.

e.g., NASA Aura satellite (705 km altitude) has a 16-day (233 orbit) repeat cycle

Satellites on LEO and GEO

Satellite instruments for monitoring air quality

- Trace gas concentrations such as O_3, NO_2, SO_2, HCHO, carbon monoxide (CO)
- High temporal and spatial resolution observations of aerosol properties have been available from GEO instruments



Kim et al., 2020

TROPOMI

- Tropospheric Monitoring Instrument
- Measures in the UV and VIS (270-500 nm), near-infrared (675-775 nm) and shortwave infrared (2305-2385 nm) spectral bands
- NO_2, O_3, HCHO, SO_2, CH_4, CO @ 7 x 3.5 km^2

- TROPOMI official website: https://www.tropomi.eu
- Data access: https://s5phub.copernicus.eu/dhus/#/home
- User guide: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-5p-tropomi

OMPS and OMI

Ozone Mapping and Profiler Suite (OMPS)

- Total column O_3, O_3 profile, total column SO_2, and UV aerosol index

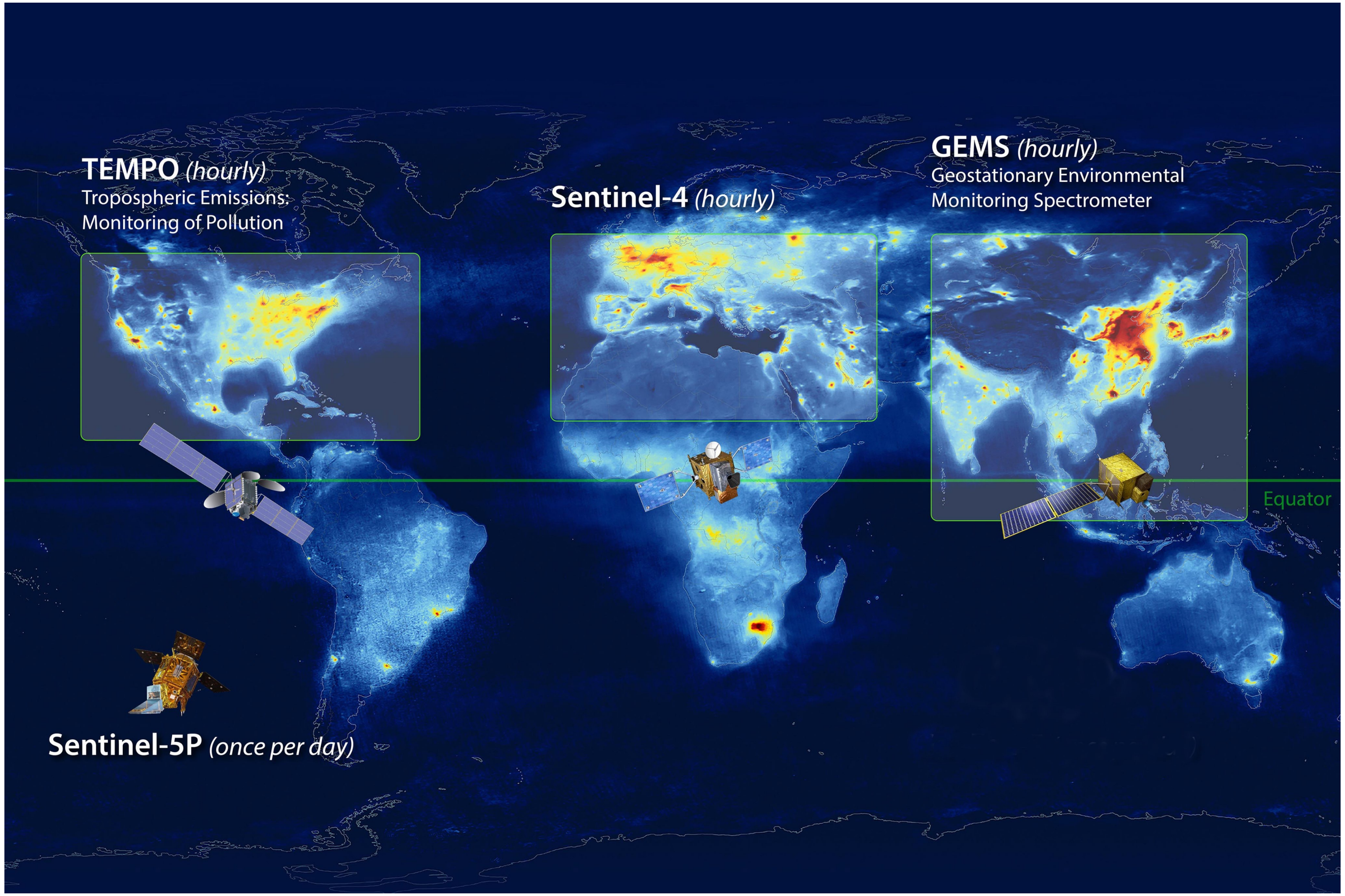
Ozone Monitoring Instrument (OMI)

- Continuous observation archive after TOMS and GOME (GOME-2)
- Ozone Monitoring Instrument (OMI): total column O_3, total column NO_2, SO_2, aerosols, volcanic ashes, O_3 profile, BrO, HCHO, OClO

- Get the information for satellite data: https://urs.earthdata.nasa.gov
- Download data: https://disc.gsfc.nasa.gov
- Visualization using GIOVANNI: https://giovanni.gsfc.nasa.gov/giovanni/

A global constellation of satellites

- 3 environmental satellites on GEO → measuring air quality
- GEMS (https://nesc.nier.go.kr/en/html/index.do) launched in February 2020
- TEMPO (https://tempo.si.edu/index.html) launched in April 2023
- Sentinel-4 (https://sentinel.esa.int/web/sentinel/missions/sentinel-4) will be launched in 2024



Ground-based observation: remote-sensing and in-situ

28 Jun 2023

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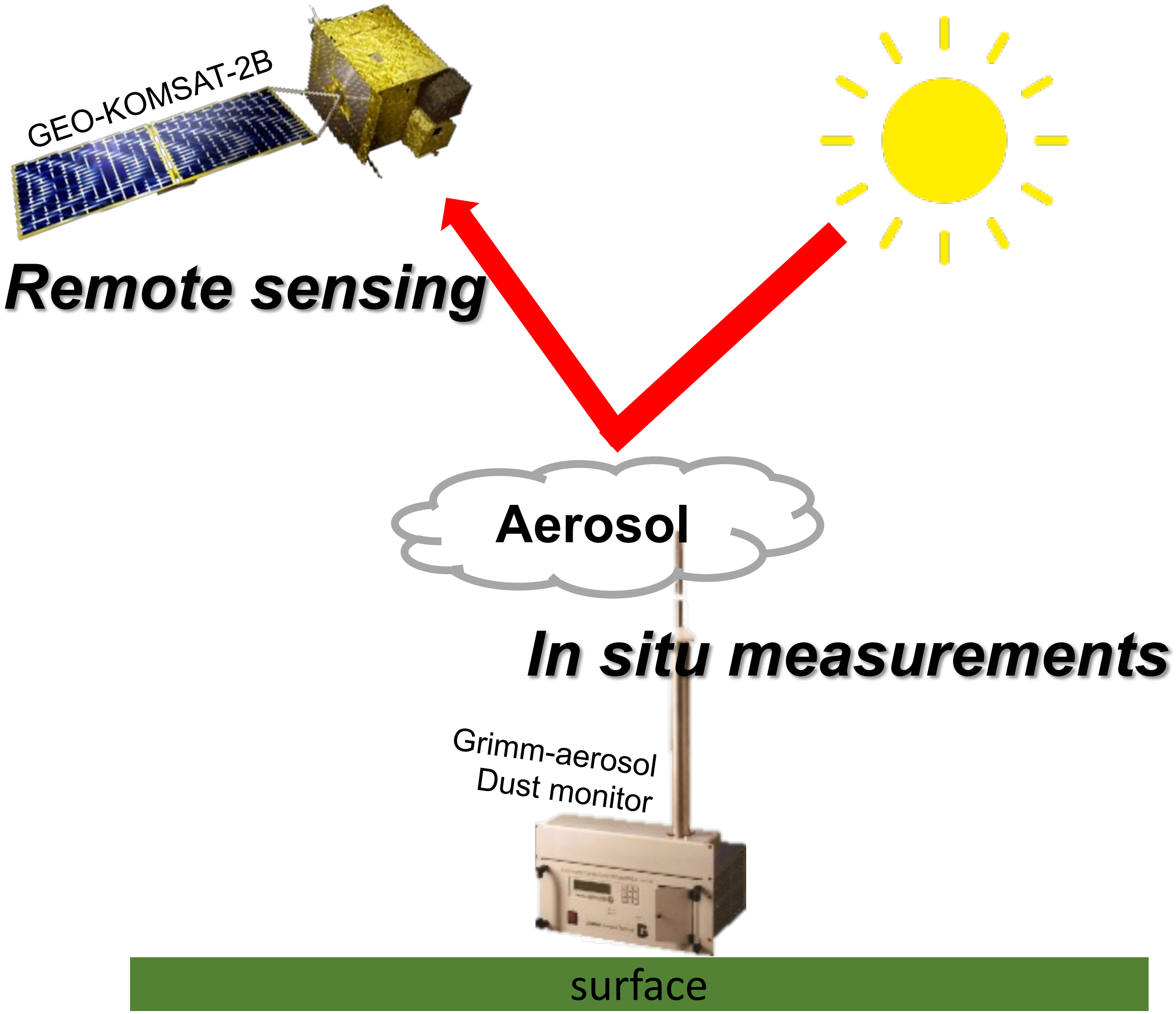
How to get the aerosol and traces gases concentration

In situ measurements

- Observation made within the medium
- E.g., CO2 flask sampling, dust monitor, O3 measurement by balloon

Remote sensing

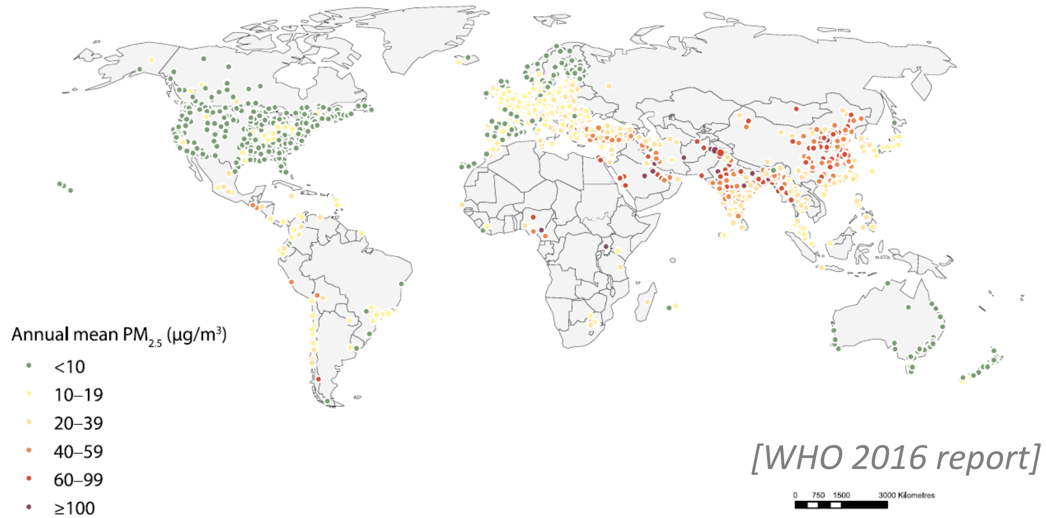
- Measurement of EM radiation measured some distance away
- E.g., spectrometer, lidar, sunphotometer



In situ measurement vs. Remote sensing

In situ measurements

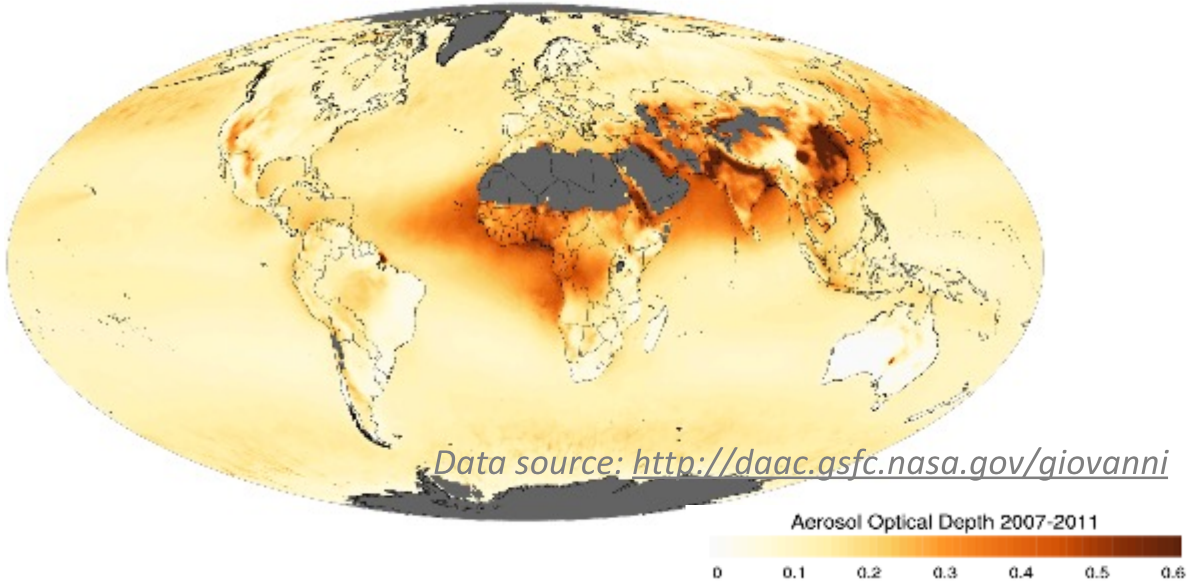
Location of the monitoring stations and $PM_{2.5}$ concentration in nearly 3,000 human settlements, 2008-2015



[WHO 2016 report]

Remote sensing

Modis Terra aerosol optical depth at 550nm averaged from 2007 to 2011



Data source: http://daac.gsfc.nasa.gov/giovanni

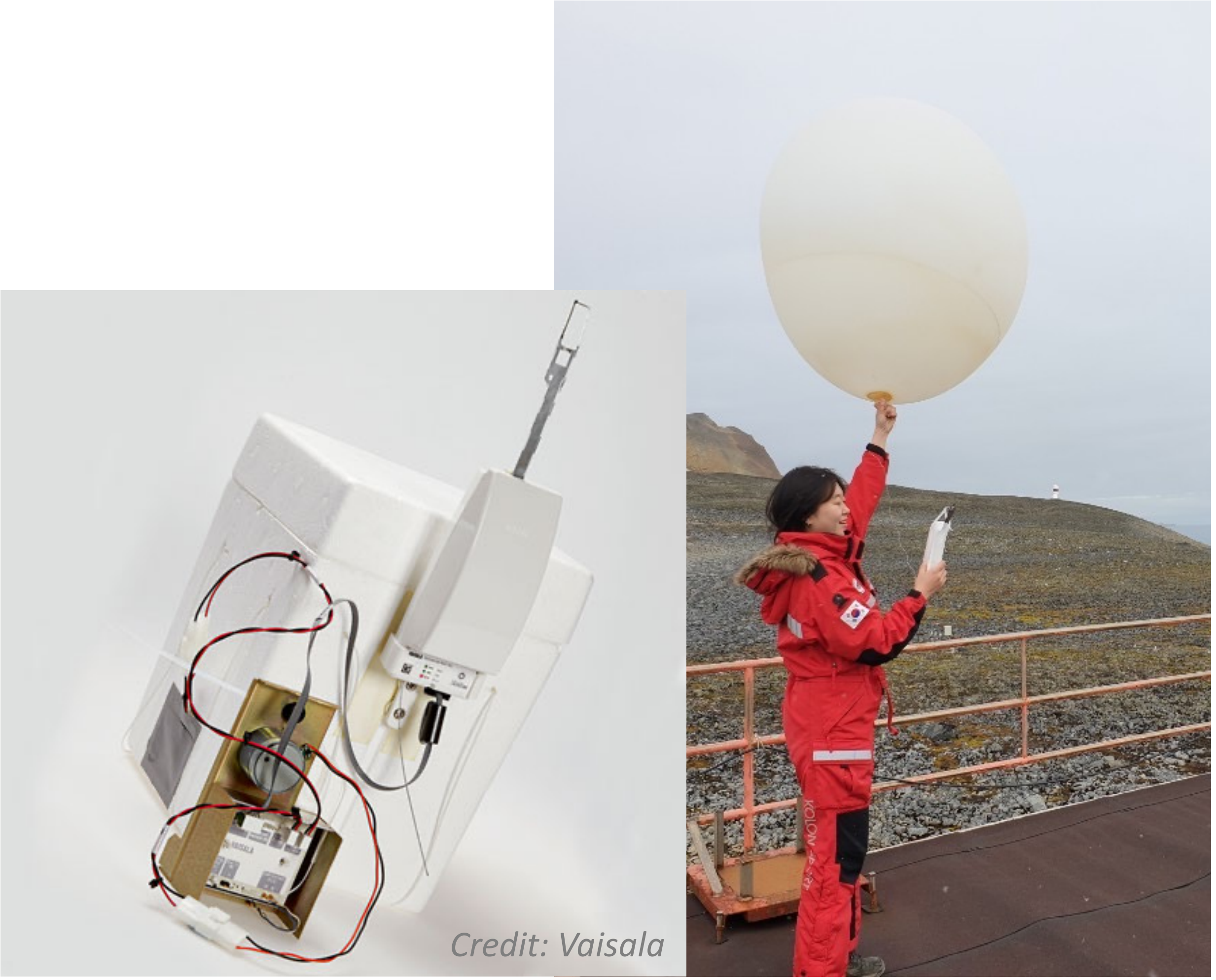
- Ground-based in-situ PM can be measured at only a few sites in global
- Satellite can provide global distribution of aerosol concentration

In situ measurement: Ozone sensor

- balloon-borne instrument launched with radiosonde
- ozone profile up to about 35 km or about 4 hPa

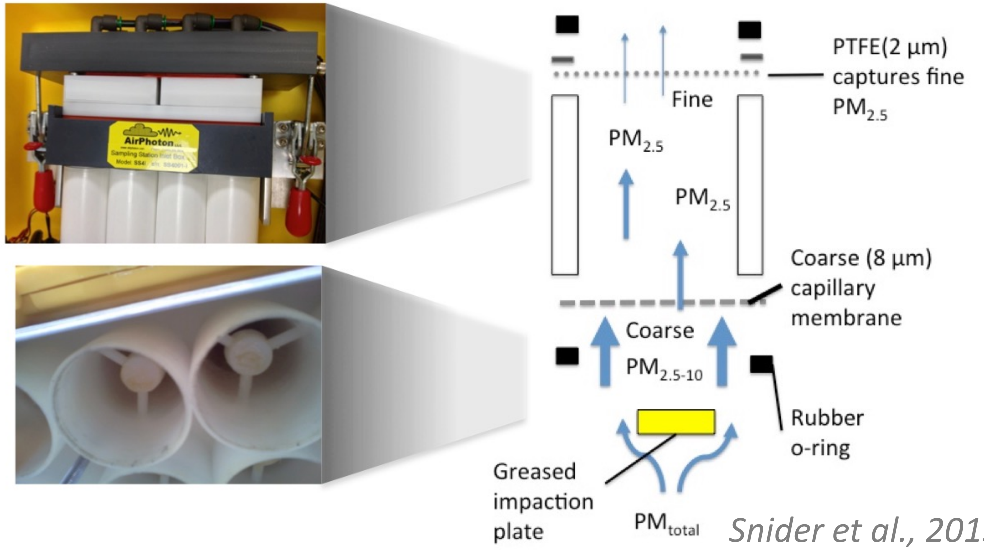
Electrochemical concentration cell (ECC)

- Reaction with a dilute solution of potassium iodide producing a weak electrical current proportional to the ozone concentration of the sampled air

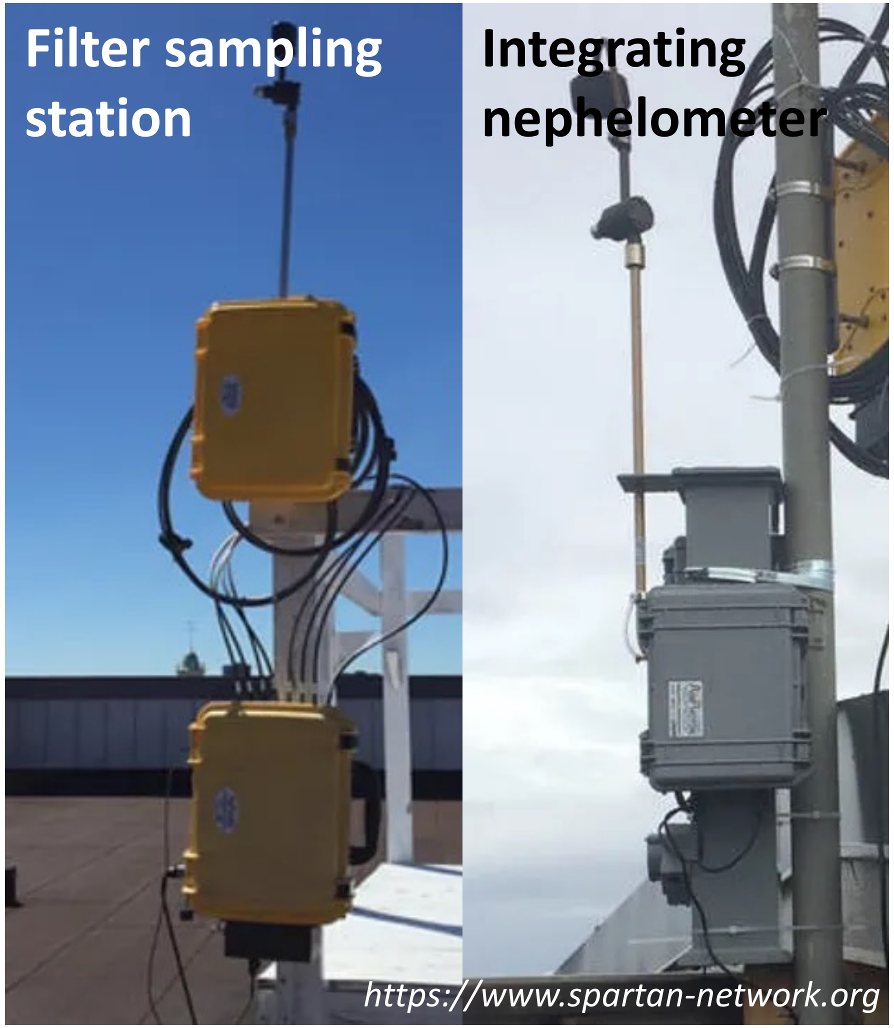


In situ measurement: SPARTAN

- Surface Particulate Matter Network (SPARTAN)
- Filter sampling station and integrating nephelometer
- $PM_{2.5}$ mass, chemical composition (sulfate, nitrate, BC, …), and optical characteristics
- Filter-based, Nephelometer, and Time resolved $PM_{2.5}$
- https://www.spartan-network.org

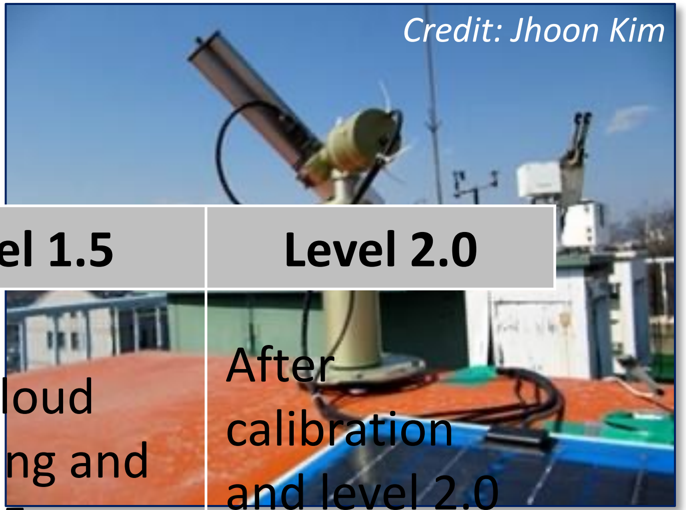


Snider et al., 2015



Remote sensing: AERONET sunphotometer

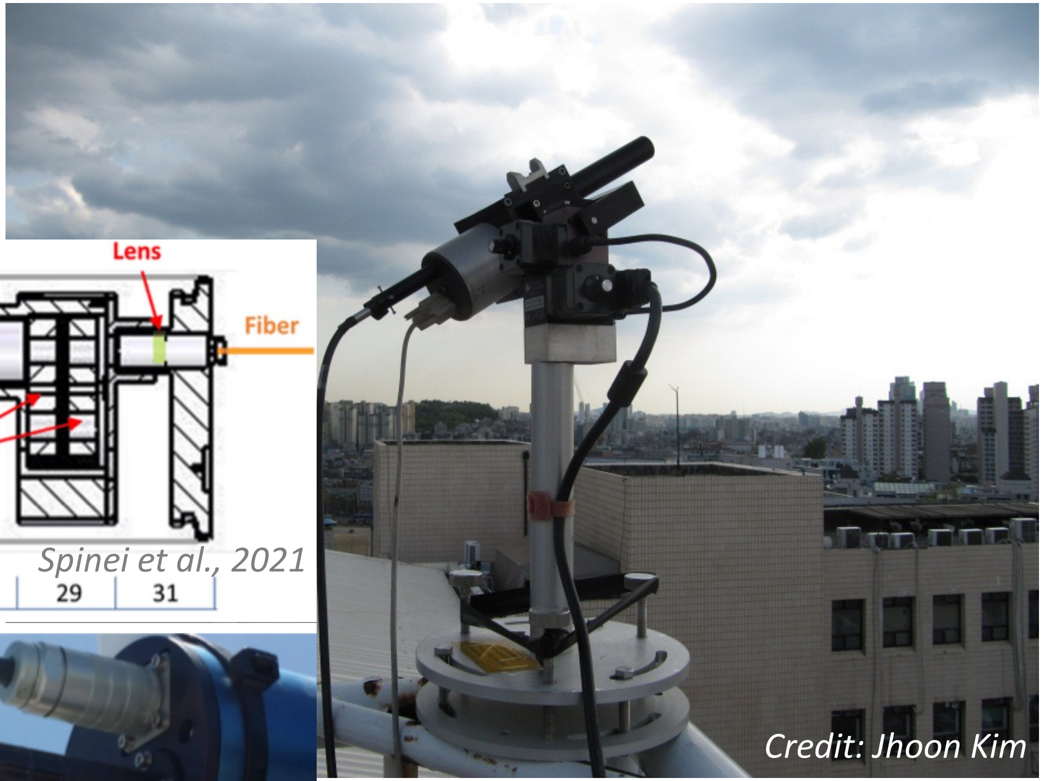
- Aerosol Robotic NETwork (https://aeronet.gsfc.nasa.gov)
- Sunphotometer: measure the amount of sunlight for a narrow range of colors or wavelengths


Credit: Jhoon Kim

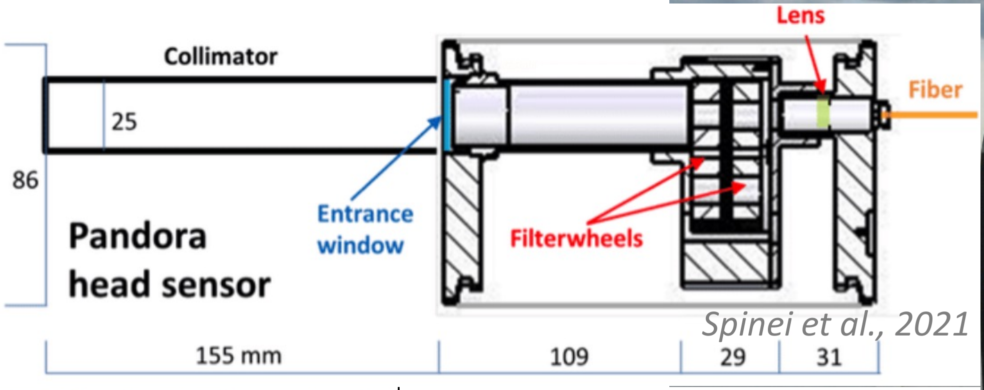
	Data list	Level 1.0	Level 1.5	Level 2.0
AOD data	- spectral AOD (340, 380, 440, 500, 675, 870, 1020, (1640) nm) - Water vapor, 440-870 Angstrom Exponent, Fine/Coarse AOD, Fine-mode Fraction	No cloud screening and quality control (only AOD)	After Cloud screening and level 1.5 quality control	After calibration and level 2.0 quality control
Inversion data	- Size distribution, Phase functions , Refractive Index (Real, Imaginary), Absorption/Extinction Optical Depth, Single scattering albedo, Asymmetry Factor	1 hour (AOD) or 1 day after observations (Inversion) provided from NASA AERONET website		Provided by NASA GSFC after calibration

Remote sensing: Pandora spectrophotometer

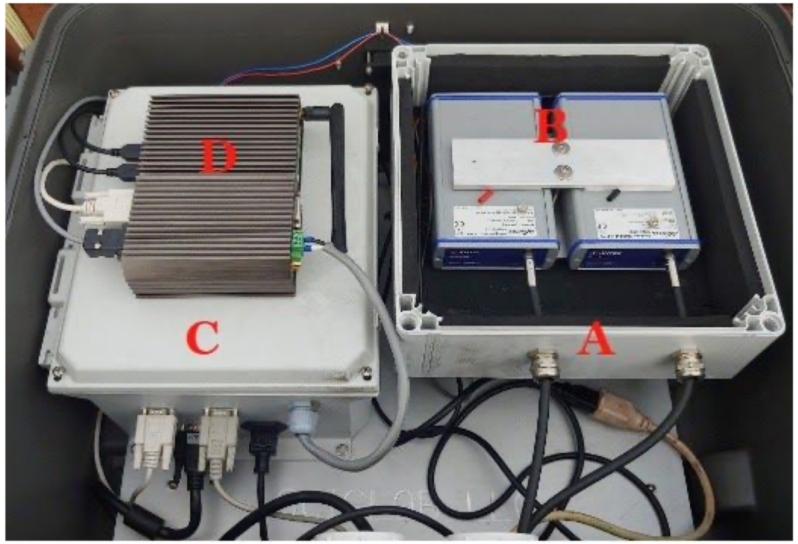
- Spectral range: 270-530 nm
- Resolution: 0.5 nm
- Products: NO_2, O_3, H_2O, SO_2, HCHO, aerosol, and profile of NO_2 and O_3

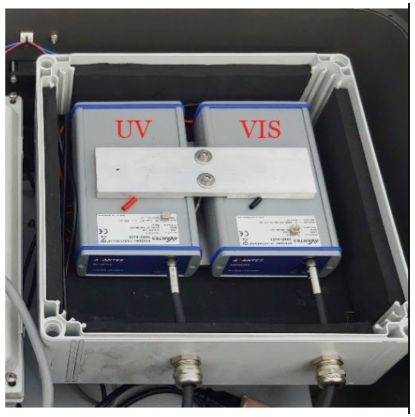


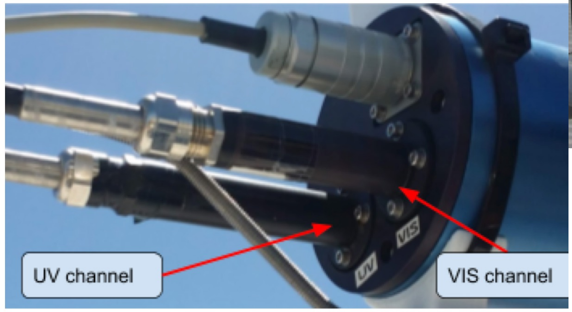
Credit: Jhoon Kim



Spinei et al., 2021



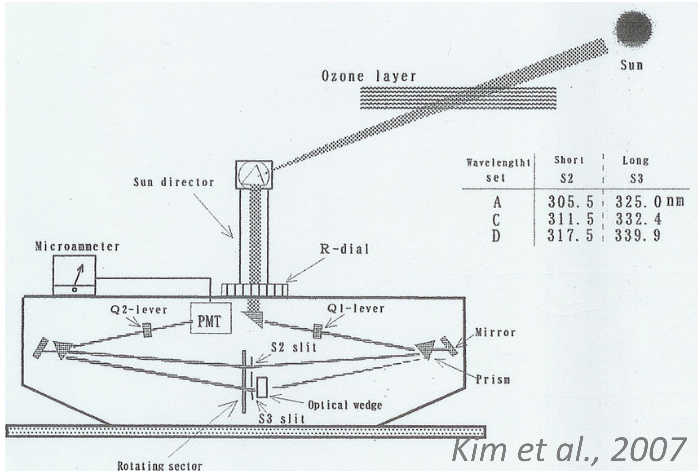




Credit: Sciglob

Remote sensing: Dobson spectrophotometer


Credit: Jhoon Kim



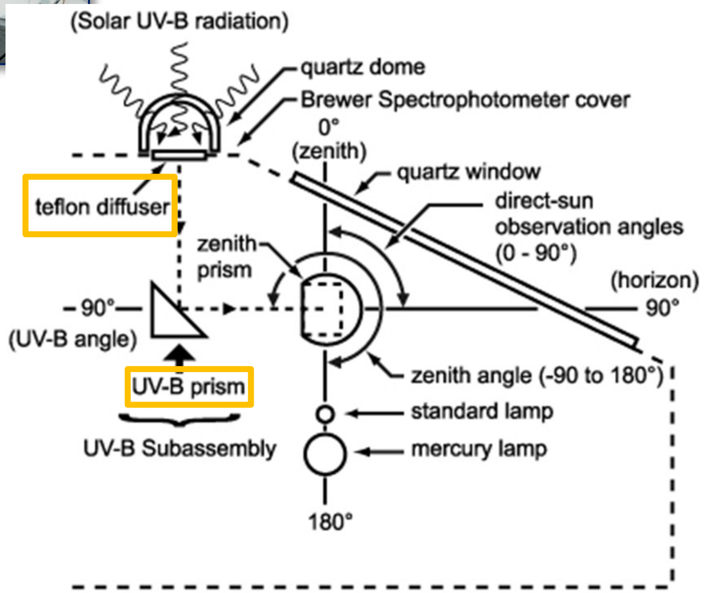
Kim et al., 2007

	Total column ozone	Ozone vertical distribution
Observation	- Wavelength pair (N-value method) - A:305.5/325.0 nm, D:317.5/339.9 nm - Direct Sun and Zenith Sky - 3 times / day (Manually perform observations based on a given solar zenith angle)	- Umkehr method - 2 times / day (sunrise and sunset)

Remote sensing: Brewer spectrophotometer

- Total ozone column, surface solar irradiance, total SO_2 column, Total NO_2 column, Aerosol optical depth (320.1 nm), Ozone vertical distribution (Umkehr)
- Automatic observation based on the schedule

Brewer around the globe



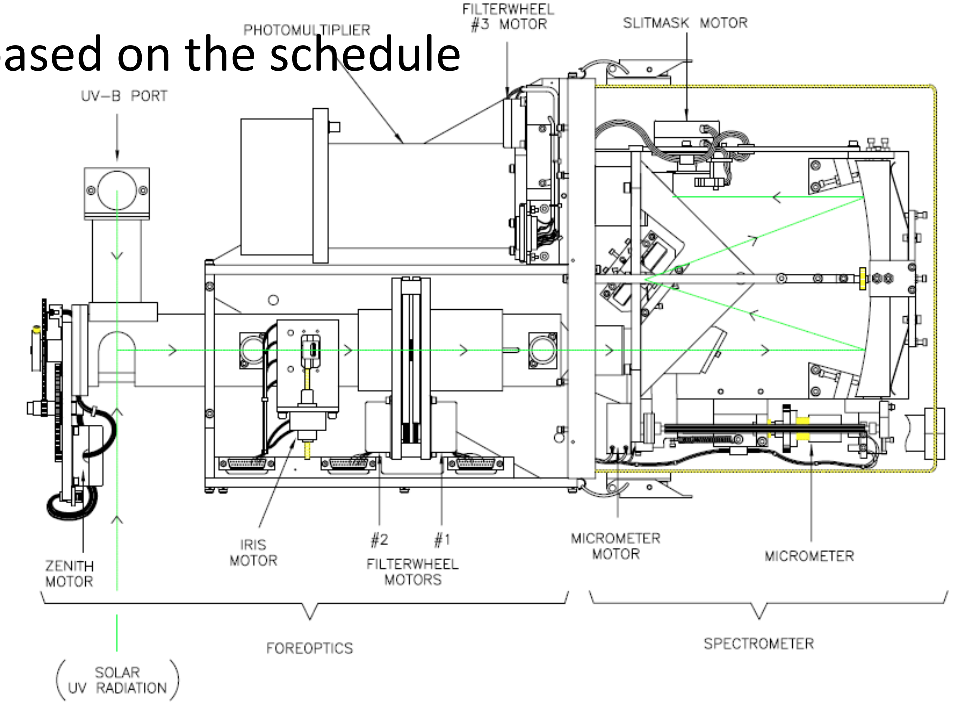
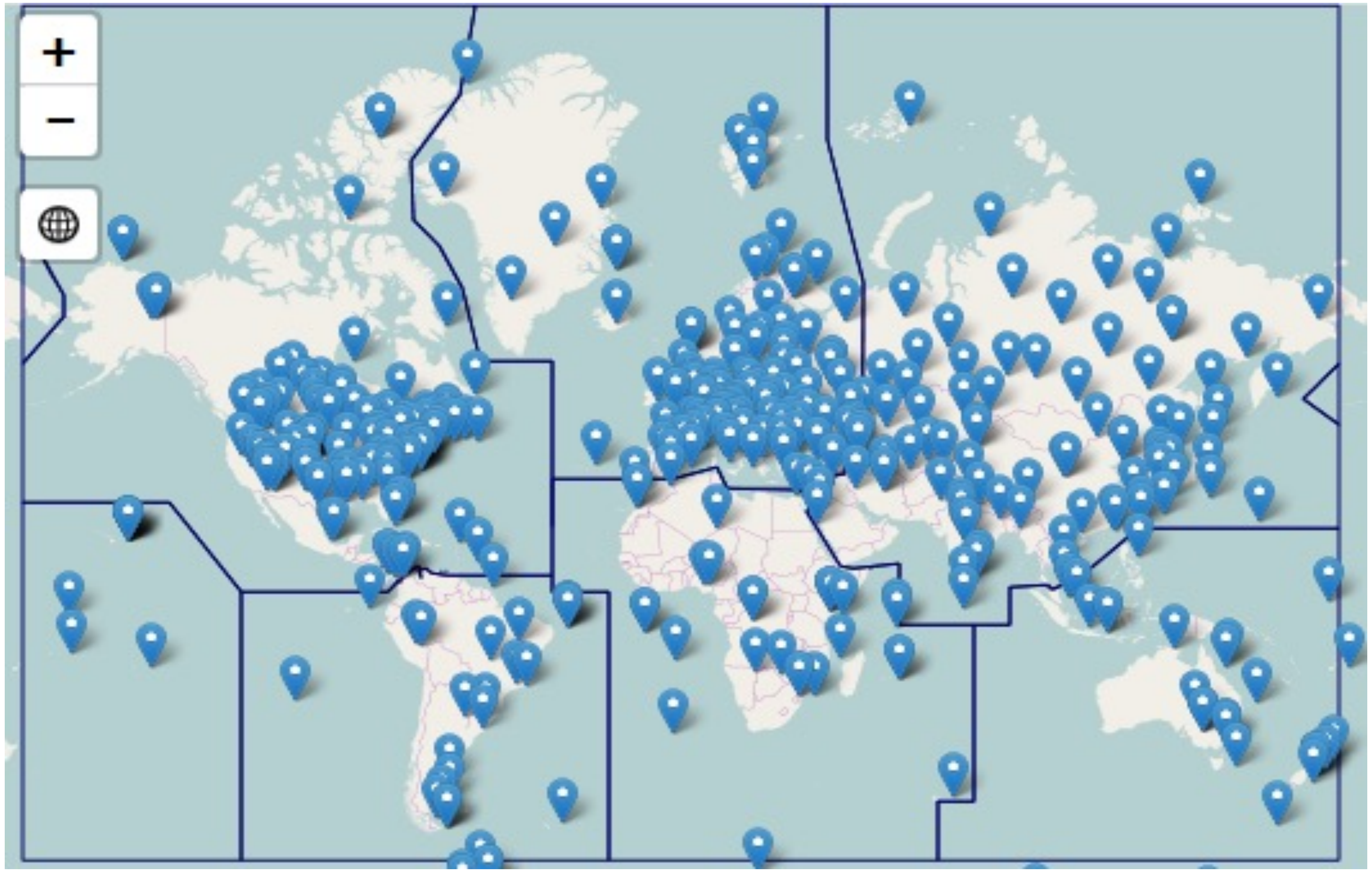


Figure 2-5: Top View of Spectrophotometer

World Ozone and Ultraviolet Radiation Data Centre

- https://woudc.org/home.php



Intercomparison of data from satellite and ground-based observations: colocation

30 Jun 2023

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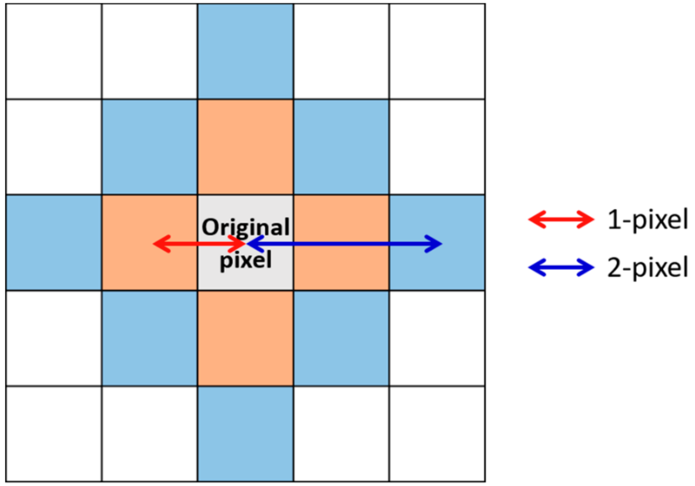
Validation considering spatio-temporal variability

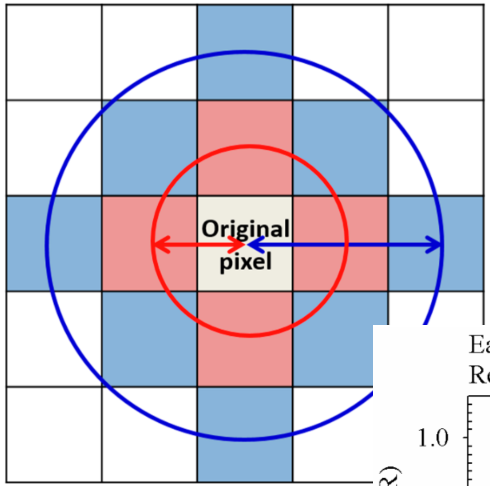
Spatio-Temporal Variability of Aerosol Optical Depth, Total Ozone and NO_2 Over East Asia: Strategy for the Validation to the GEMS Scientific Products (Park et al., 2020)

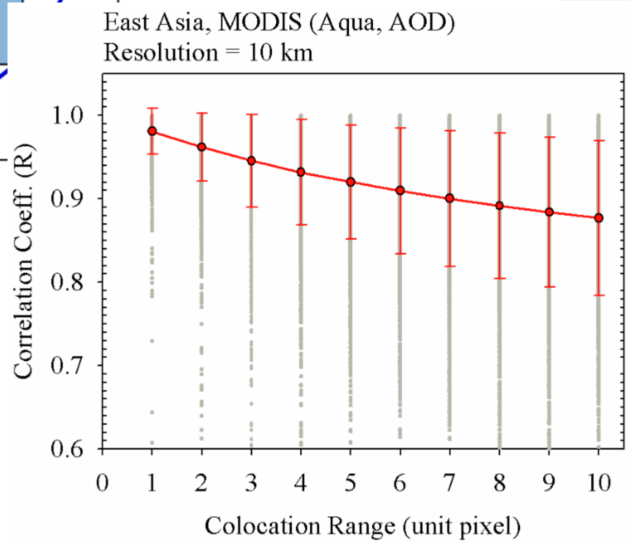
- satellite observation projects need inter-comparison and validation processes
- ground-based measurements with optical instruments used for validation
- Due to the differences in spatial and temporal scales between ground and satellite observations, the spatio-temporal collocation range is essential to assume the mean value calculations of satellite observation datasets
- Closest pixel method, but still problems remains related to the representability of data
- Colocation mismatch uncertainty (CMU) is caused by radiance uncertainty, due to cloud and surface reflectance and differences in viewing geometry
- Averaging method, but…the spatial scale for high concentrations of pollutants is presented on a city-scaled range, which is similar to or smaller than the spatial resolution of the satellite observation

Validation considering spatio-temporal variability

Spatio-Temporal Variability of Aerosol Optical Depth, Total Ozone and NO_2 Over East Asia: Strategy for the Validation to the GEMS Scientific Products (Park et al., 2020)







Time Lag (minute)	R^2	Mean Bias	RMSE
(a) Yonsei University			
10	0.989	−0.00007	0.037
20	0.978	−0.00002	0.054
30	0.968	−0.00005	0.066
40	0.958	−0.00026	0.074
50	0.947	−0.00062	0.083
60	0.936	−0.00068	0.092
(b) Anmyeon			
10	0.988	0.00010	0.032
20	0.977	0.00129	0.044
30	0.966	0.00226	0.054
40	0.952	0.00267	0.063
50	0.940	0.00326	0.073
60	0.929	0.00265	0.080
(c) GIST			
10	0.983	0.00038	0.032
20	0.973	0.00113	0.039
30	0.957	0.00044	0.053
40	0.946	0.00232	0.056
50	0.927	0.00166	0.069
60	0.909	0.00141	0.079