

## TRAINING KIT

# Monitoring tropospheric NO<sub>2</sub> with Sentinel-5P

## Part 1

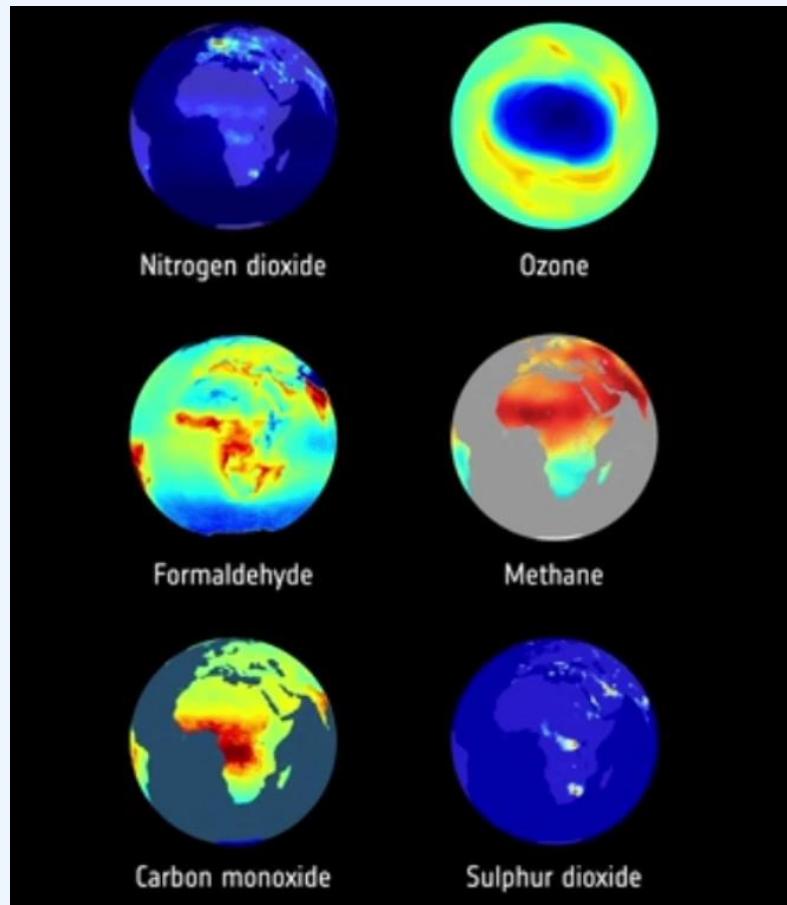
S. BOITARD - NOVELTIS | [simon.boitard@noveltis.fr](mailto:simon.boitard@noveltis.fr)

RUS Online | 22<sup>nd</sup> September 2021

- Sentinel-5P
- The Sentinel 5P products
- Focus on NO<sub>2</sub>
- The Atmospheric Toolbox
- Exercises

- **Sentinel-5P**
- The Sentinel 5P products
- Focus on NO<sub>2</sub>
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- Poor air quality results in 400,000 premature deaths in Europe (EEA) per year
- 1 in 8 deaths in Europe is linked to air pollution
- Mapping atmospheric gases, the Sentinel-5P mission arms decision-makers with the information they need to implement appropriate strategies to reduce air pollution, which in turn will help save lives



## MISSION OBJECTIVE

Provide global information on a multitude of atmospheric trace gases, aerosols and cloud distributions affecting air quality and climate.

Air Quality

Ozone Layer

Climate change

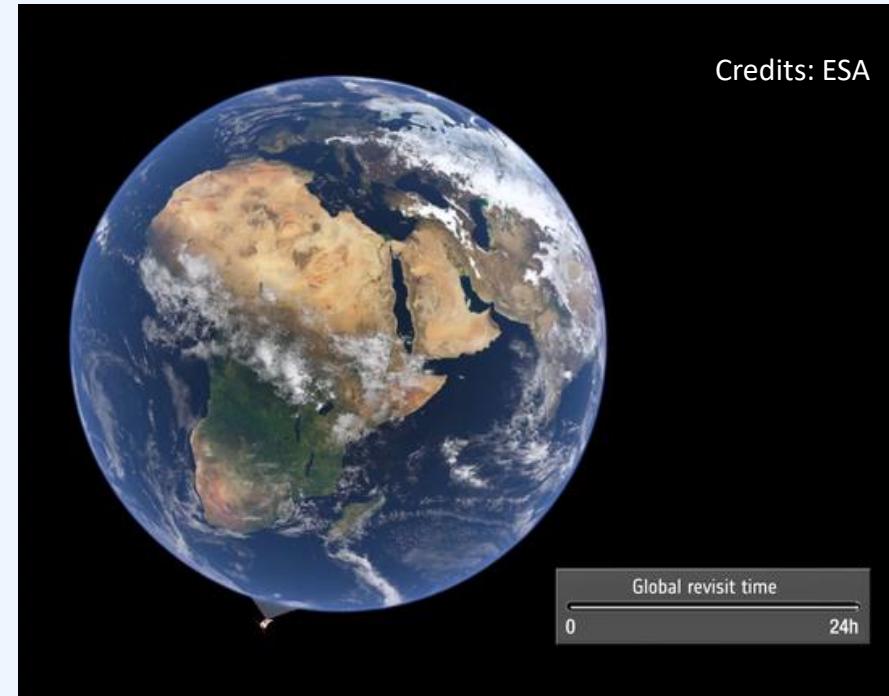
Input data to  
CAMS

Measurement continuity between previous  
(ENVISAT, AURA) and future (S5) missions



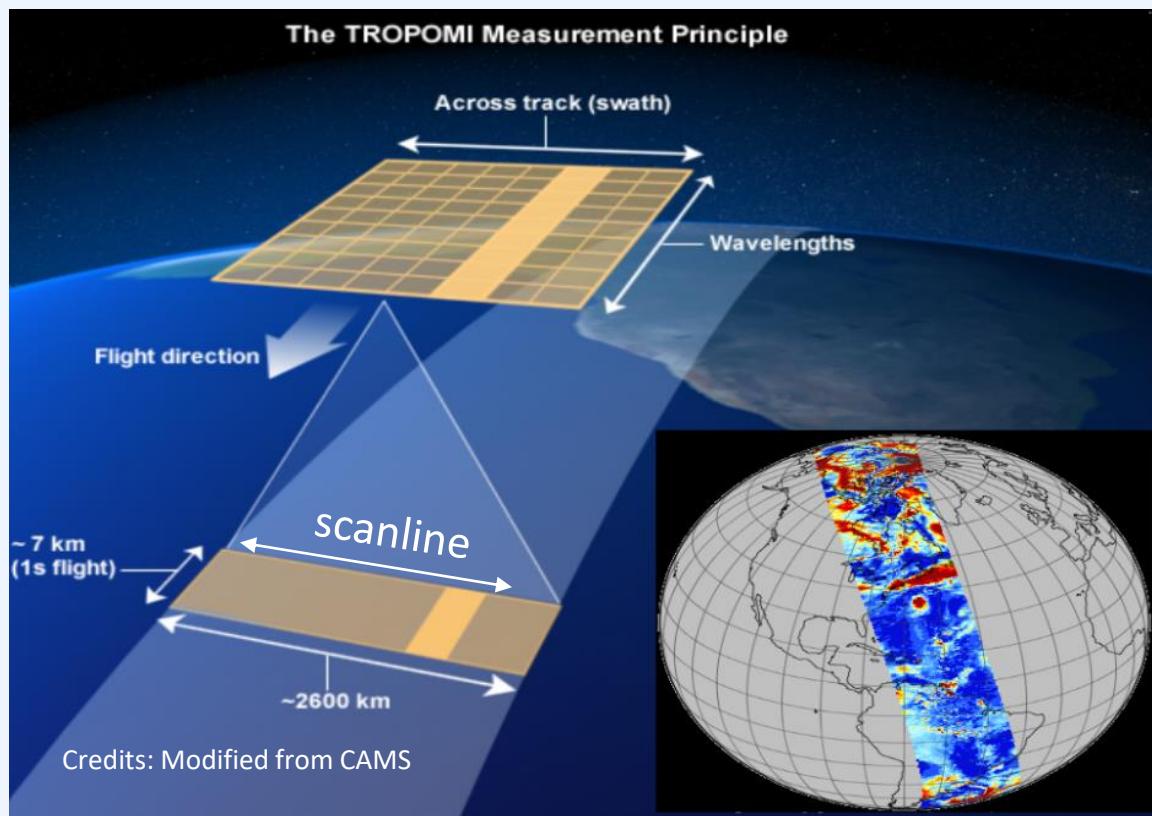
# RUS Sentinel-5P | Characteristics

- European Earth Observation satellite
- Single satellite mission carrying a single payload (TROPOMI)
- Swath: **2600 km**, allowing the whole planet to be mapped every 24 hours.
- Revisit time: **Daily** global coverage
- Spatial resampling: **5.5 km x 3.5 km**
- **Orbit:** Polar, Sun-synchronous at an altitude of 824 km



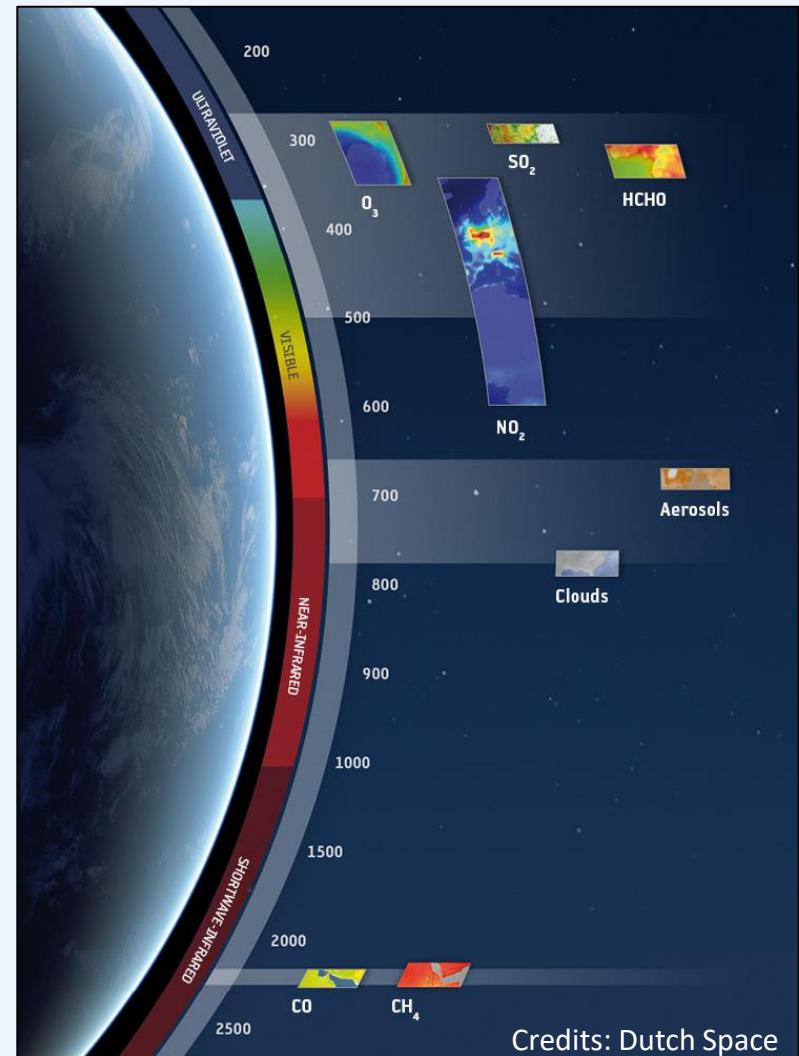
Launch: 2017

Operational phase:  
early 2019



- A 1-second swath is called a scanline
- Each scanline is divided into 450 ground pixels
- We will find these terms as dimensions in native Sentinel-5P Level-2 products

- **Instrument:** Tropospheric Monitoring Instrument (Tropomi)
- Passive sun backscatter imaging spectrometer
- Collects parts of the solar spectrum reflected back by the Earth
- Large spectral range for a large number of trace gas species detection
- 8 different spectral bands
  - 2 in ultraviolet (270 – 320 nm)
  - 2 in visible (320 – 500 nm)
  - 2 in NIR (675 – 775 nm)
  - 2 in SWIR (2305 – 2385 nm)

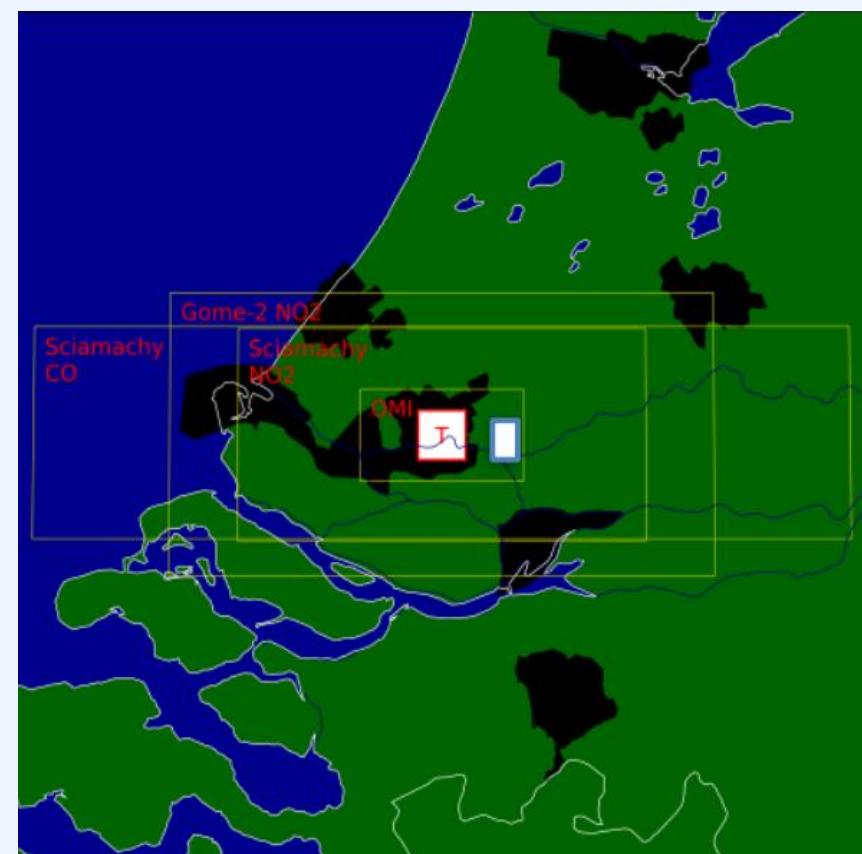


## TROPOspheric Monitoring Instrument

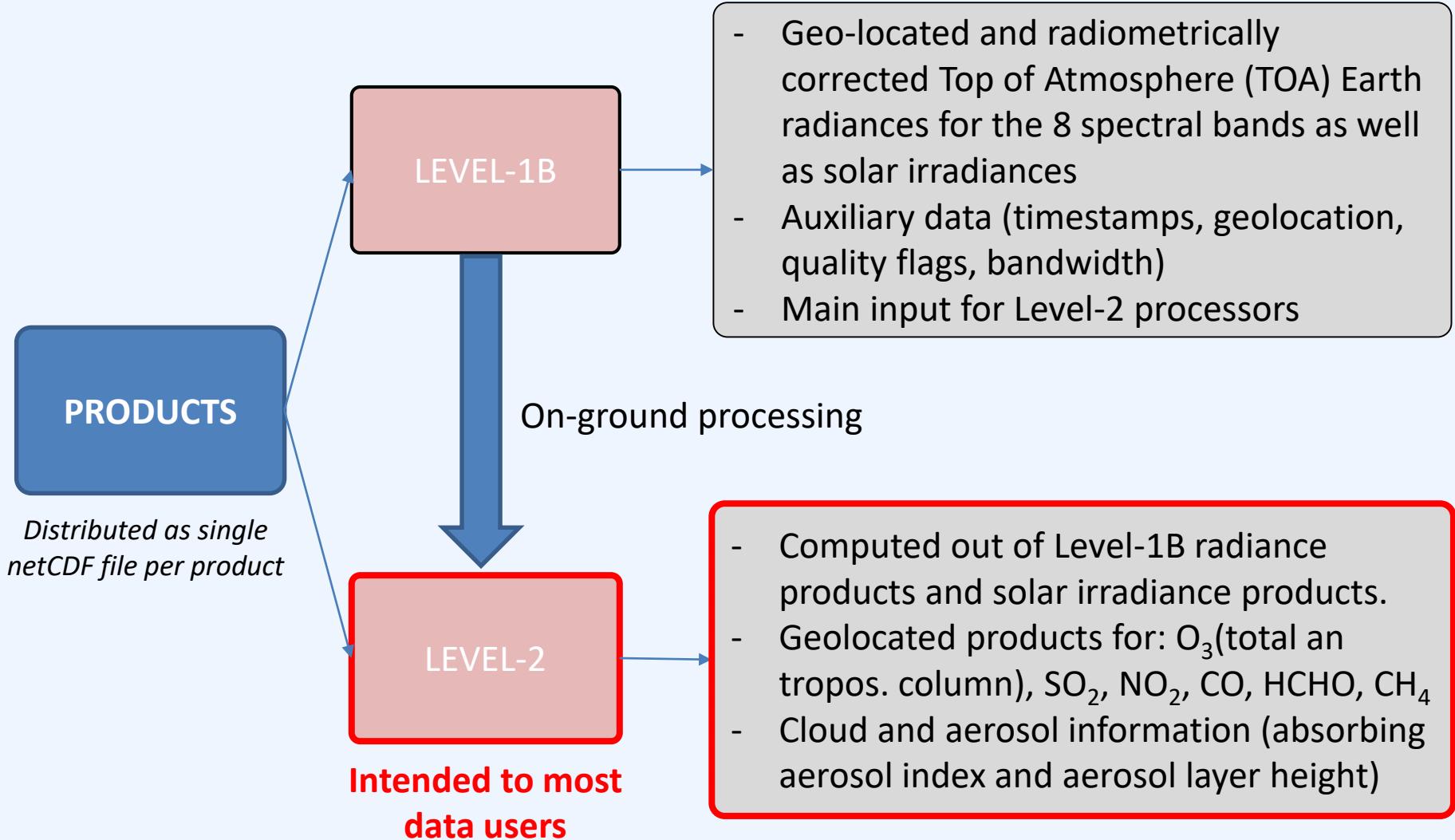
Daily global coverage



High spatial resolution 3.5x5.5 km<sup>2</sup>



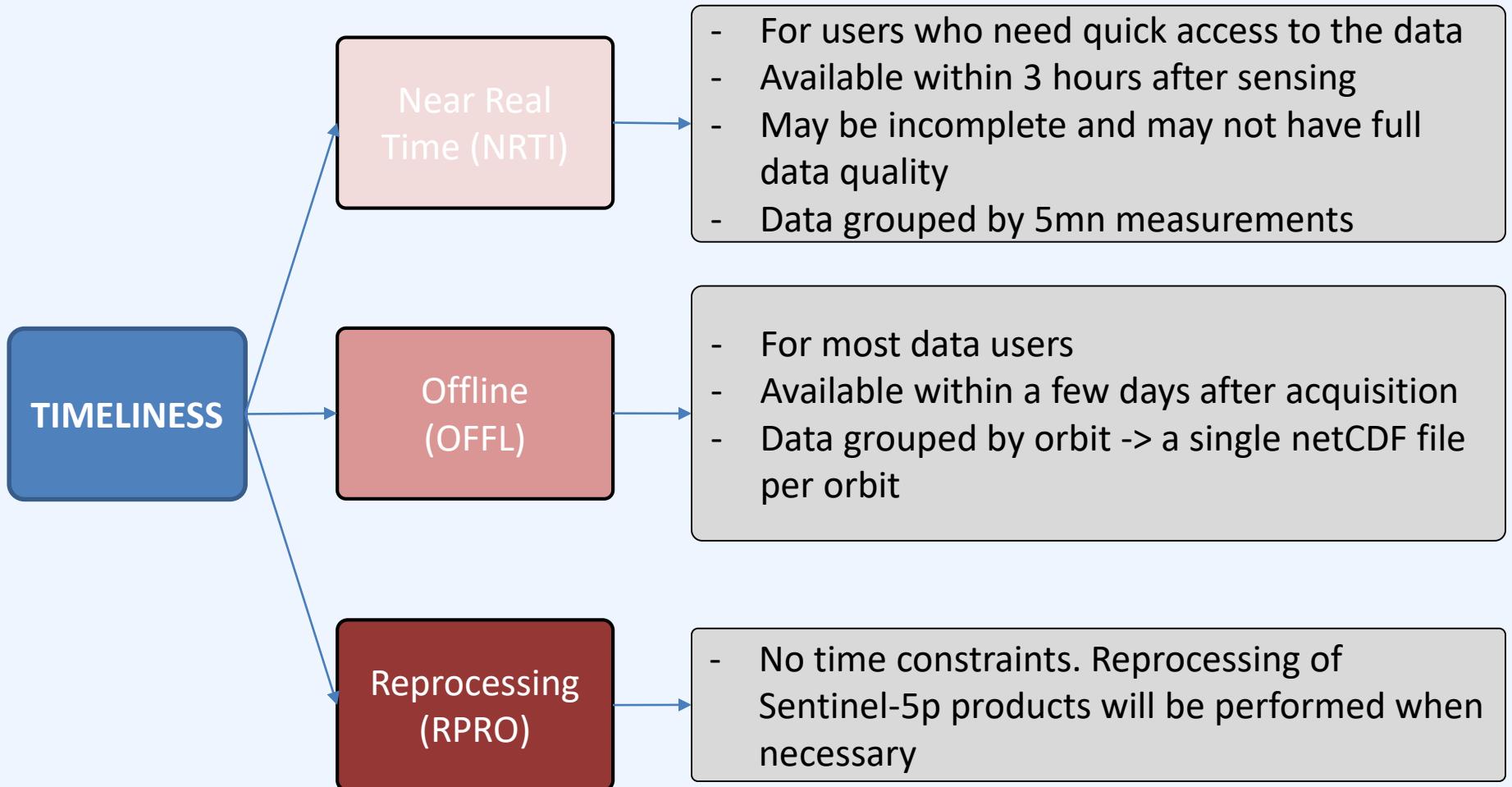
- Sentinel-5P
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File type	Spectrometer	Spectral range [nm]	Comment
L1B_RA_BD1	UV	270 - 300	Radiance product band 1
L1B_RA_BD2		300 - 320	Radiance product band 2
L1B_RA_BD3	UVIS	320 - 405	Radiance product band 3
L1B_RA_BD4		405 - 500	Radiance product band 4
L1B_RA_BD5	NIR	675 - 725	Radiance product band 5
L1B_RA_BD6		725 - 775	Radiance product band 6
L1B_RA_BD7	SWIR	2305-2345	Radiance product band 7
L1B_RA_BD8		2345-2385	Radiance product band 8

*TROPOMI Level 1B radiance products (Credit: S5P technical guide, ESA)*

PRODUCT TYPE	PARAMETER
L2_O3_	Ozone ( $O_3$ ) total column
L2_O3_TCL	$O_3$ tropospheric column
L2_NO2_	Nitrogen Dioxide ( $NO_2$ ) total and tropospheric columns
L2_SO2_	Sulfur Dioxide ( $SO_2$ ) total column
L2_CO_	Carbon monoxide (CO) total column
L2_CH4_	Methane ( $CH_4$ ) total column
L2_HCHO_	Formaldehyde (HCHO) total column
L2_CLOUD_	Cloud fraction, albedo, cloud height (pressure)
L2_AER_AI	UV Aerosol Index
L2_AER_LH	Aerosol Layer Height (mid-level pressure)



**S5P\_OFFL\_L2\_O3\_20200406T120948\_20200406T121448\_12855**

**Mission name, always S5P**

**Processing stream:** Near Real Time (**NRTI**), Offline (**OFFL**), Reprocessing (**RPRO**)

**Processing level:** Level-1B (**L1B**), Level-2 (**L2**)

**Product identifier (Level-2):** Cloud (**CLOUD**), HCHO (**HCHO**), SO<sub>2</sub> (**SO2**), O<sub>3</sub> Total Column (**O3**) O<sub>3</sub> Tropospheric Column (**O3\_TCL**), Aerosol layer height (**AER\_LH**), Ultra violet aerosol index (**AER\_AI**) O<sub>3</sub> Full profile (**O3\_PR**), NO<sub>2</sub> (**NO2**), CO (**CO**), CH<sub>4</sub> (**CH4**), NPP-VIIRS Clouds (**NO\_BDx**)

**Start and end of the granule in UTC (YYYYMMDDTHHMMSS) where T is a fixed character**

**Orbit number**

## netCDF File

Stores multidimensional scientific data (variables) such as temperature, humidity, pressure, wind speed, and direction

### Self-describing

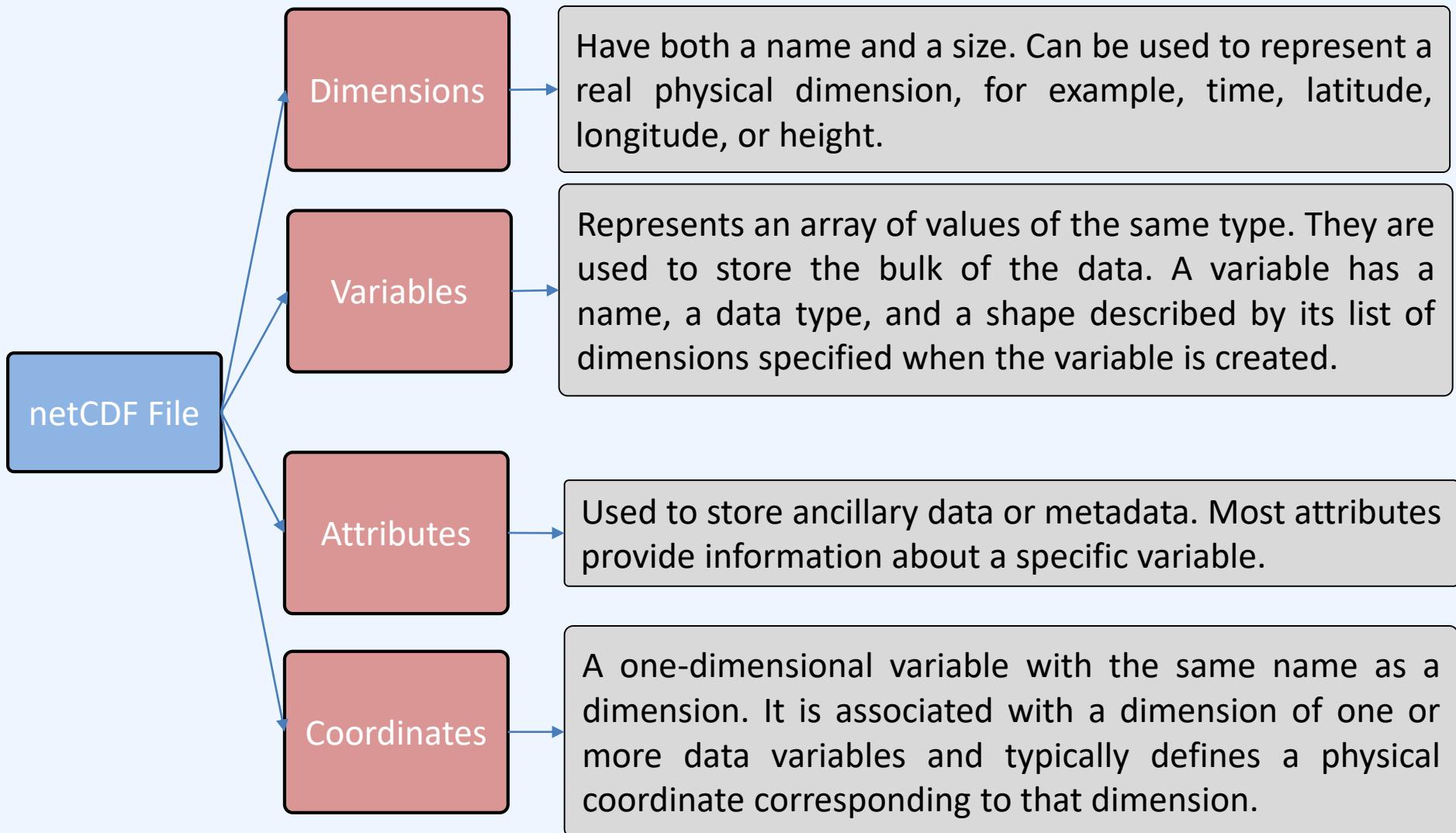
A netCDF file includes information about the data it contains, such as when data elements were captured and what units of measurement were used.

### Portable

A netCDF file created on one type of operating system can often be read by software on another type of operating system.

### Scalable

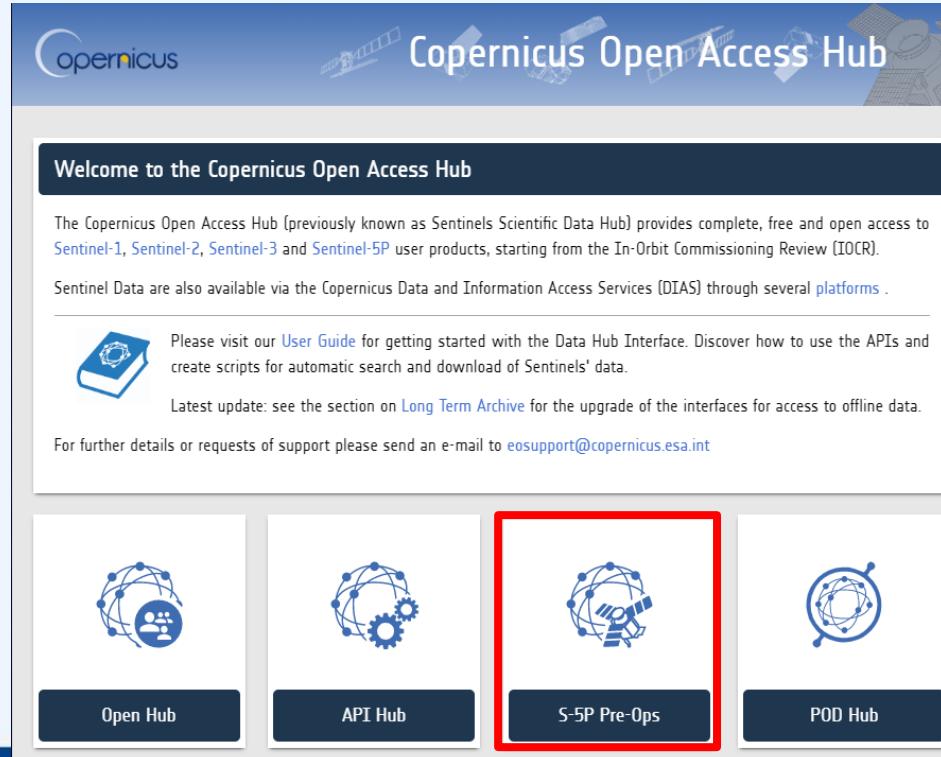
A small subset of a large netCDF file can be accessed efficiently without reading the entire file.



## Where to find Sentinel-5P data ?

- **S5P data products are provided by ESA**
  - Copernicus Open Access Hub: <https://scihub.copernicus.eu/>
- More information on S5P products can be found at:
  - <http://www.tropomi.eu>
  - <https://earth.esa.int/web/sentinel/technical-guides/sentinel-5p/products-algorithms>
  - Contact: [EOSupport@Copernicus.esa.int](mailto:EOSupport@Copernicus.esa.int) for any questions related to S5P data

- S5P products are provided by ESA
  - Copernicus Open Access Hub: <https://scihub.copernicus.eu/>
  - S5P dedicated hub: **S-5P Pre-Obs**



Welcome to the Copernicus Open Access Hub

The Copernicus Open Access Hub (previously known as Sentinels Scientific Data Hub) provides complete, free and open access to Sentinel-1, Sentinel-2, Sentinel-3 and Sentinel-5P user products, starting from the In-Orbit Commissioning Review (IOCR). Sentinel Data are also available via the Copernicus Data and Information Access Services (DIAS) through several platforms .

Please visit our [User Guide](#) for getting started with the Data Hub Interface. Discover how to use the APIs and create scripts for automatic search and download of Sentinels' data.

Latest update: see the section on [Long Term Archive](#) for the upgrade of the interfaces for access to offline data.

For further details or requests of support please send an e-mail to [eosupport@copernicus.esa.int](mailto:eosupport@copernicus.esa.int)

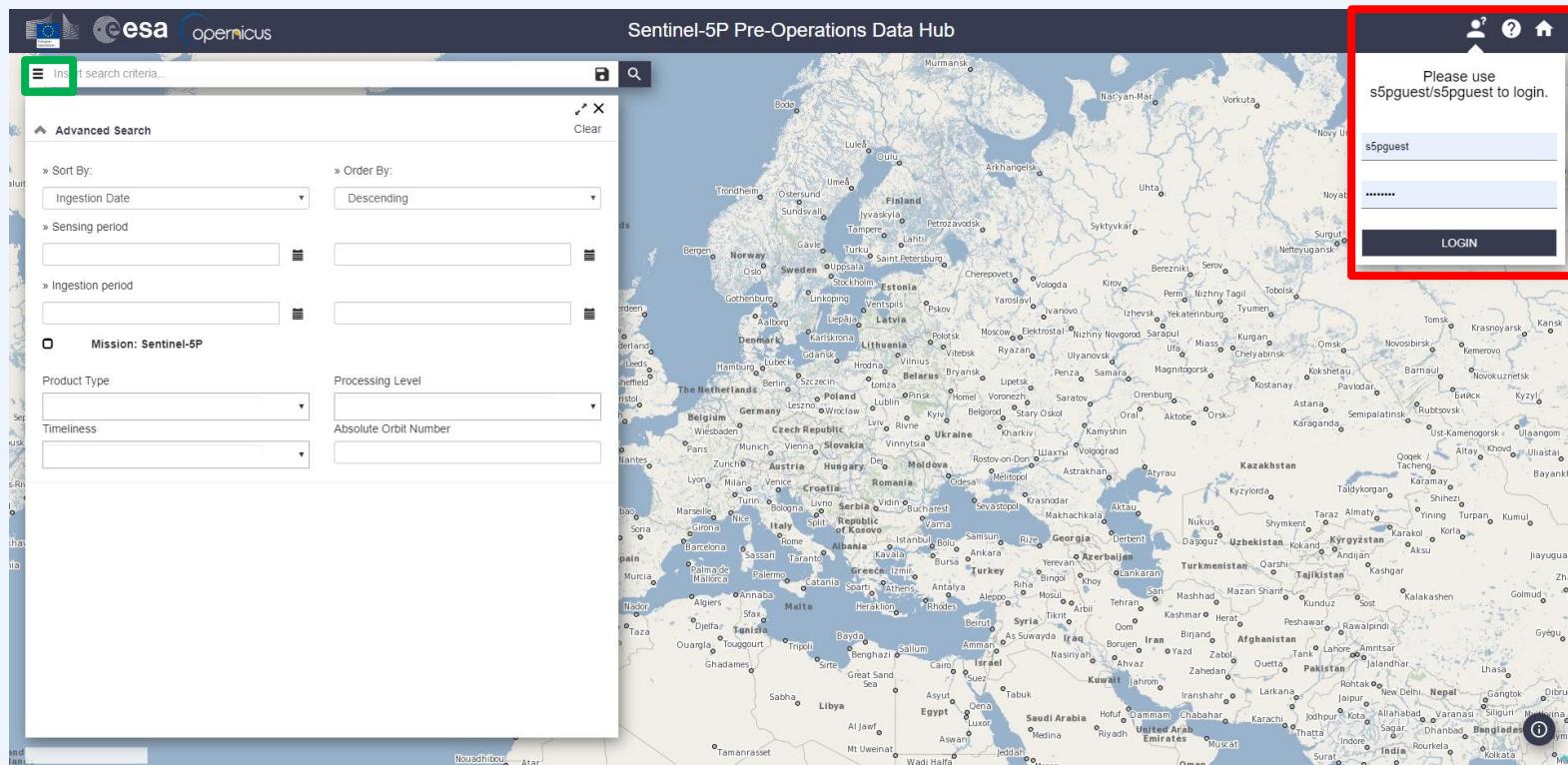
**Open Hub**    **API Hub**    **S-5P Pre-Ops**    **POD Hub**

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# RUS S5P products | Download

- S-5P Pre-Obs Interface
  - Login/Password: s5pguest/s5pguest
  - Open the product searching tool by clicking on the **top-left button**

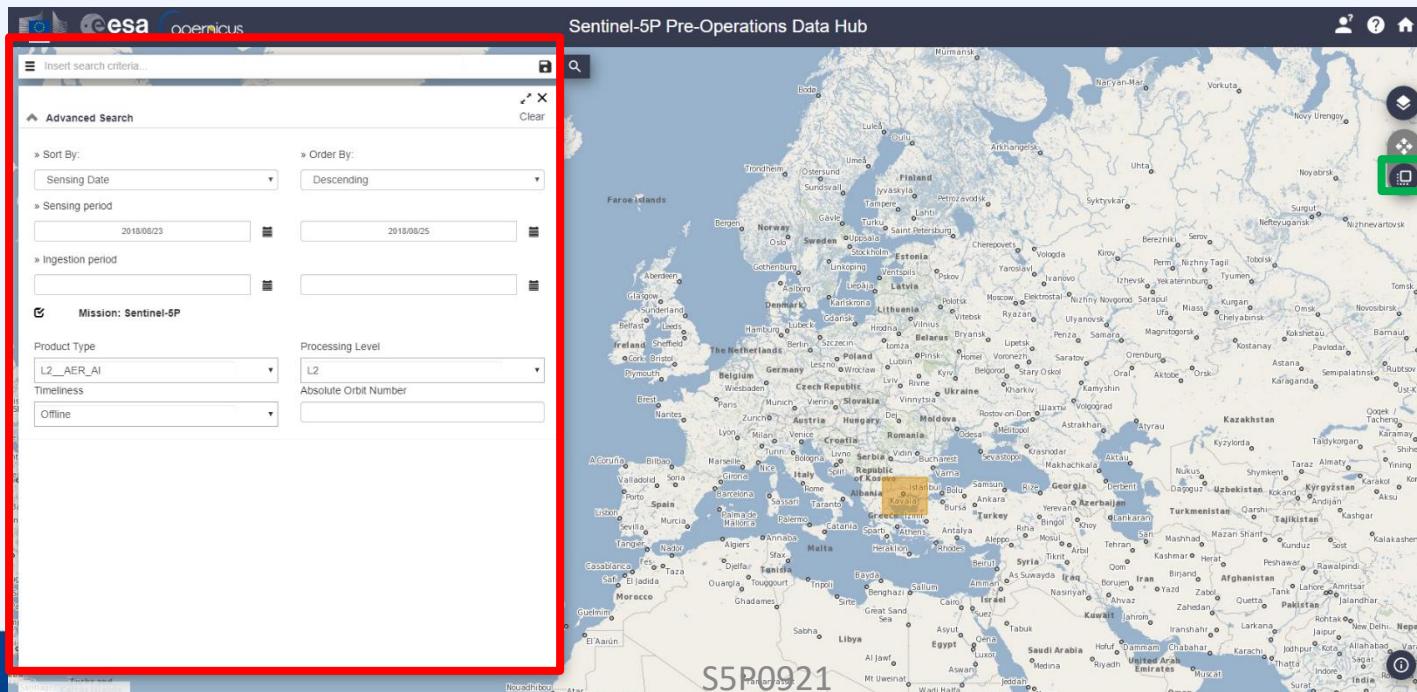


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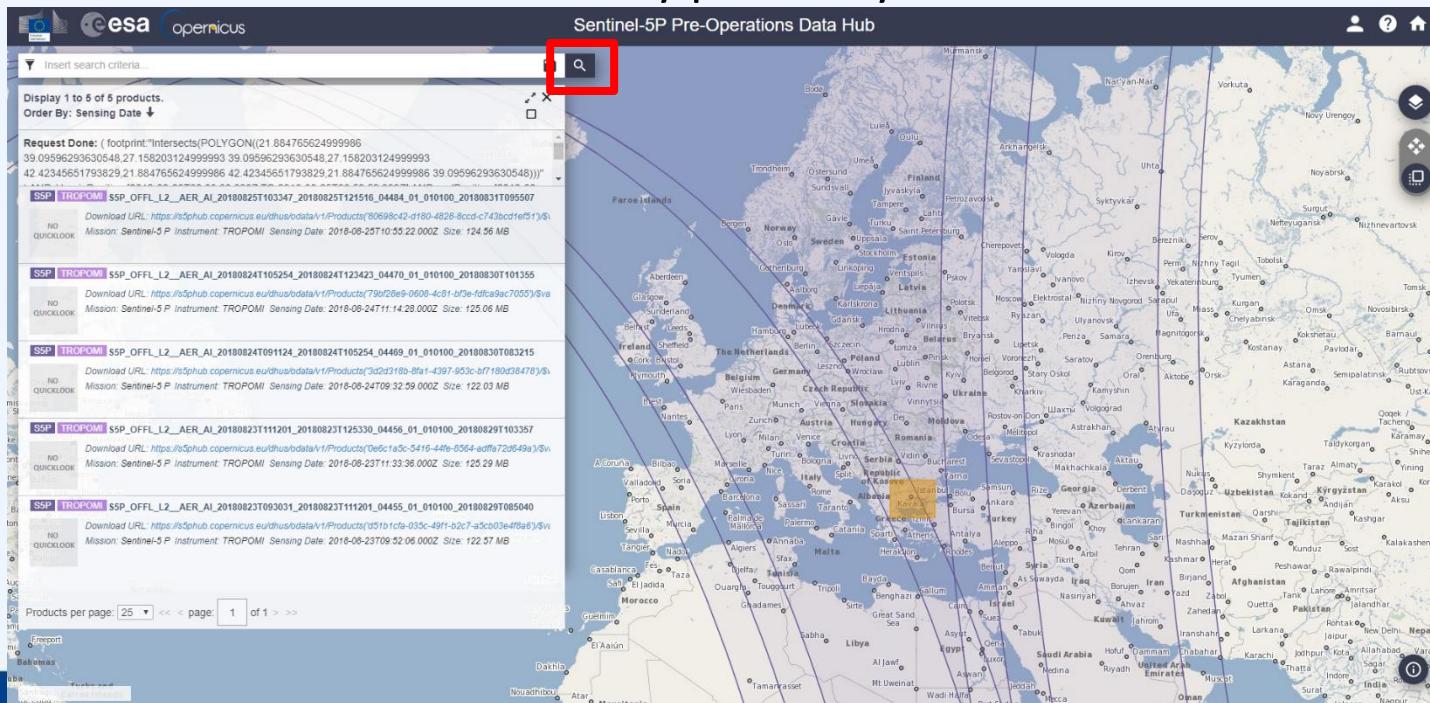
- **S-5P Pre-Obs Interface**

- Use the **left pannel** to define your search criteria (date of interest, product type, Timeliness, processing level)
- Hit the **double square button** on the right, to draw your area of interest



# CORUS S5P products | Download

- S-5P Pre-Obs Interface
  - Hit the **search button!**
  - The purple contours show the geographical hold of each product
  - You can then download any product you want



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- Sentinel-5P
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- **Focus on NO<sub>2</sub>**
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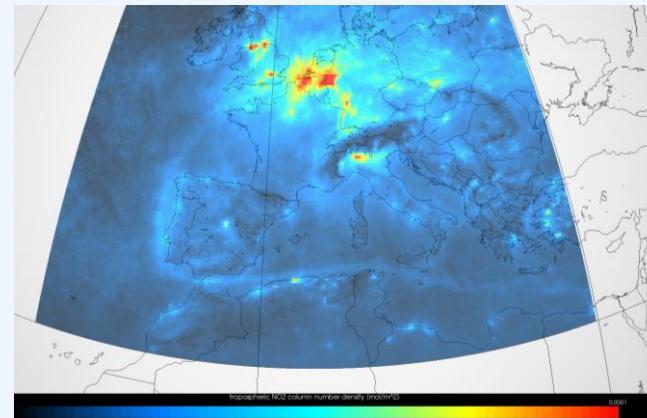
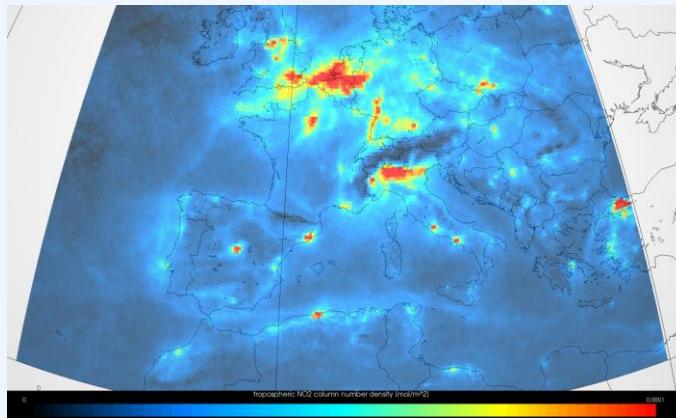
- Nitrogen Dioxide is an important trace gas in the Earth's atmosphere
- Brown gas responsible for the colour of photochemical smog
- Most of the NO<sub>2</sub> is in the troposphere
- Enters the atmosphere as a result of:
  - Anthropogenic activities (traffic, industrial fossil fuel combustion, biomass burning, ships)
  - Natural processes (wildfires, lightning)
- Irritating gaz -> Increases the intensity and frequency of asthma attacks

- NO<sub>2</sub> has a short lifetime in the atmosphere: from a few hours up to a half day
- NO<sub>2</sub> concentrations are indicators on changes in economic slowdowns
- Remains relatively close to its source -> NO<sub>2</sub> sources well detectable from space.
- Measures still need to be completed by ground-based measurements
- NO<sub>2</sub> concentrations in the atmosphere vary widely from day to day (emissions and weather conditions variations)
- To identify longer-term variations, two-week averages are computed

- More information on NO<sub>2</sub> effects and the computation method for TROPOMI can be found [here](#)
- If you are more interested in NO<sub>2</sub> retrieval processes from satellite measurements, visit the [EUMETSAT second Joint school on Atmospheric Composition.](#)
  - [Presentation on NO<sub>2</sub> column computation from S5P measurement](#)
  - [Associated YouTube video](#)
- [S5P L2 NO<sub>2</sub> Product User Manual](#)
- Easily check NO<sub>2</sub> concentrations maps on the [Copernicus S5P Mapping Portal](#)

# CORUS NO<sub>2</sub> | S5P Products

- Available quantities in the product:
  - **Tropospheric** vertical column of NO<sub>2</sub> (mol/m<sup>2</sup> or molec/cm<sup>2</sup>): for a ground pixel, integrated amount of NO<sub>2</sub> in the **troposphere** (lower layer of the atmosphere)
  - **Stratospheric** vertical column of NO<sub>2</sub> (mol/m<sup>2</sup> or molec/cm<sup>2</sup>): for a ground pixel, integrated amount of NO<sub>2</sub> in the **stratosphere** (upper layer of the atmosphere)
  - **Total** vertical column of NO<sub>2</sub> (mol/m<sup>2</sup> or molec/cm<sup>2</sup>) in the **atmosphere**



TROPOMI averaged tropospheric NO<sub>2</sub> column over Europe in March 2019 (left) & March 2020 (right)

- The Sentinel-5P mission
- The Sentinel 5P products
- Focus on NO<sub>2</sub>
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- **Atmospheric Toolbox**

- Open source software for ingesting, processing and analyzing atmospheric remote sensing data
- Developed, designed and maintained under ESA contracts
- Support several instruments: TROPOMI, GOME-2 and IASI, OMI, TES and MLS, MIPAS and SCIAMACHY
- Help can be found at: <https://atmospherictoolbox.org/>  
*Extremely useful forum for questions : <https://forum.atmospherictoolbox.org/>*

- **3 components:**

- **HARP:**

- Toolset for ingesting and processing atmospheric data
    - Set of command line tools, a library of analysis functions and direct import/export interfaces for Python, IDL and MATLAB

- **VISAN:**

- Visualization and analysis application for atmospheric data.
    - Commands provided through Python
    - 2D plots and worldplots

- **CODA:**

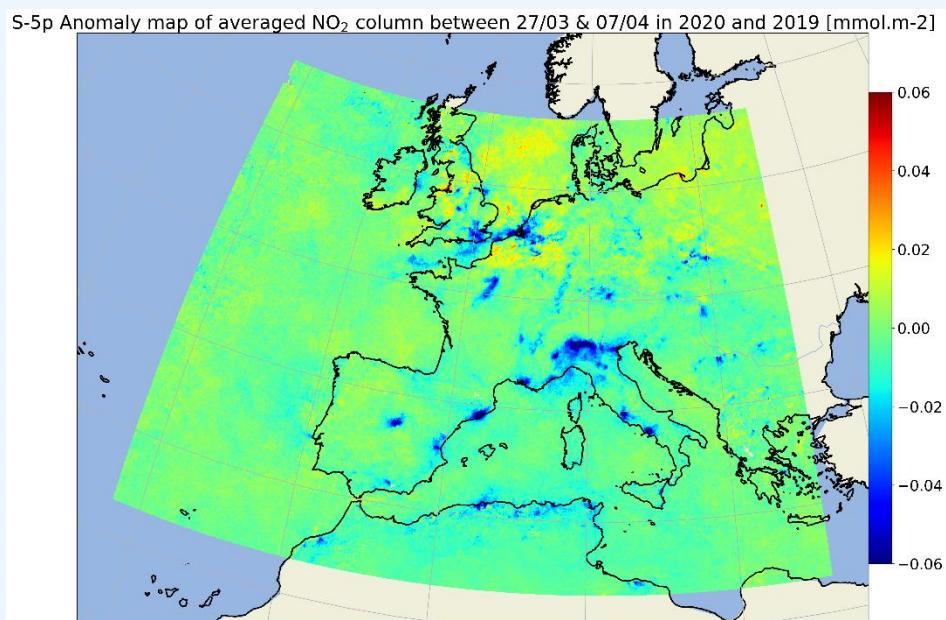
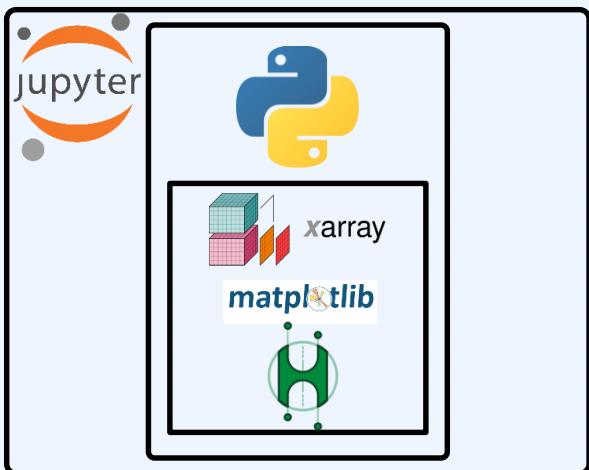
- Direct reading access to product data thanks to a C library
    - Other interfaces are allowed e.g.: Fortran, IDL, MATLAB & Python

- The Sentinel-5P mission
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- **Exercises**
  - **Introduction**
  - Starting with the RUS environment
  - Starting with Panoply
  - Creation of NO<sub>2</sub> gridded product
  - Jupyter Notebook exercises

## OBJECTIVE

Monitor the tropospheric NO<sub>2</sub> in the atmosphere and assess the impact of anthropogenic activities on air quality.

## TOOLS





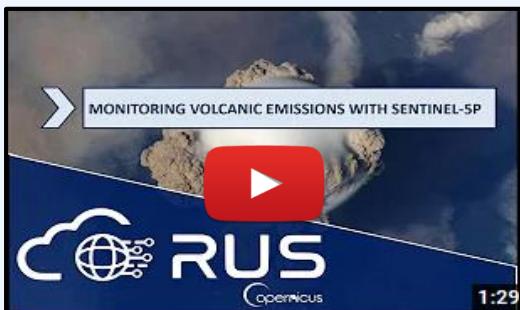
# Exercise | Introduction



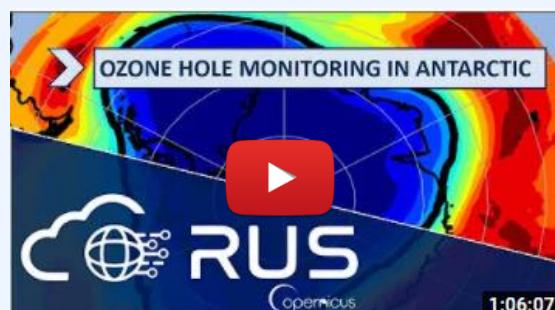
ATMO01 Available in YouTube  
<https://bit.ly/2Vcz7eP>



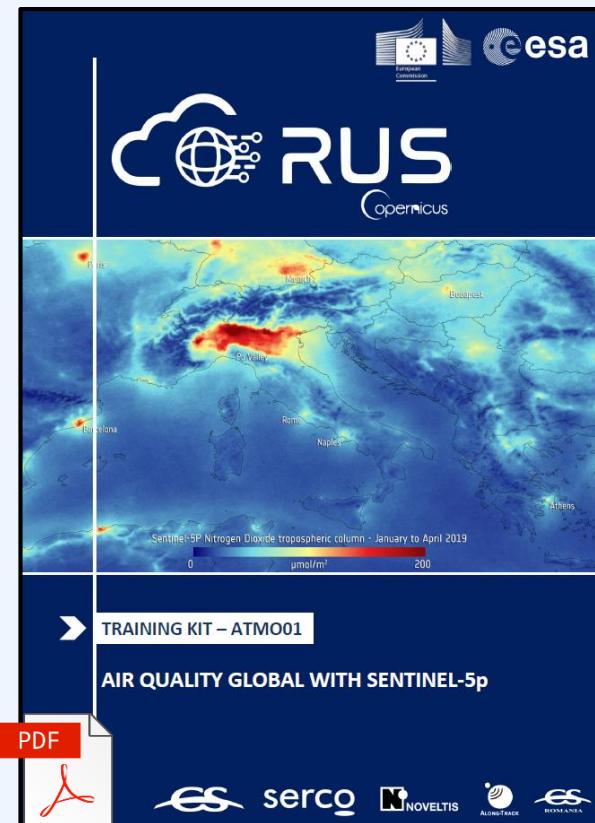
ATMO02 Available in YouTube  
<https://bit.ly/2TgMX37>



ATMO03 Available in YouTube  
<https://bit.ly/3x9p4ZR>



ATMO04 Available in YouTube  
<https://bit.ly/3BSuhHt>



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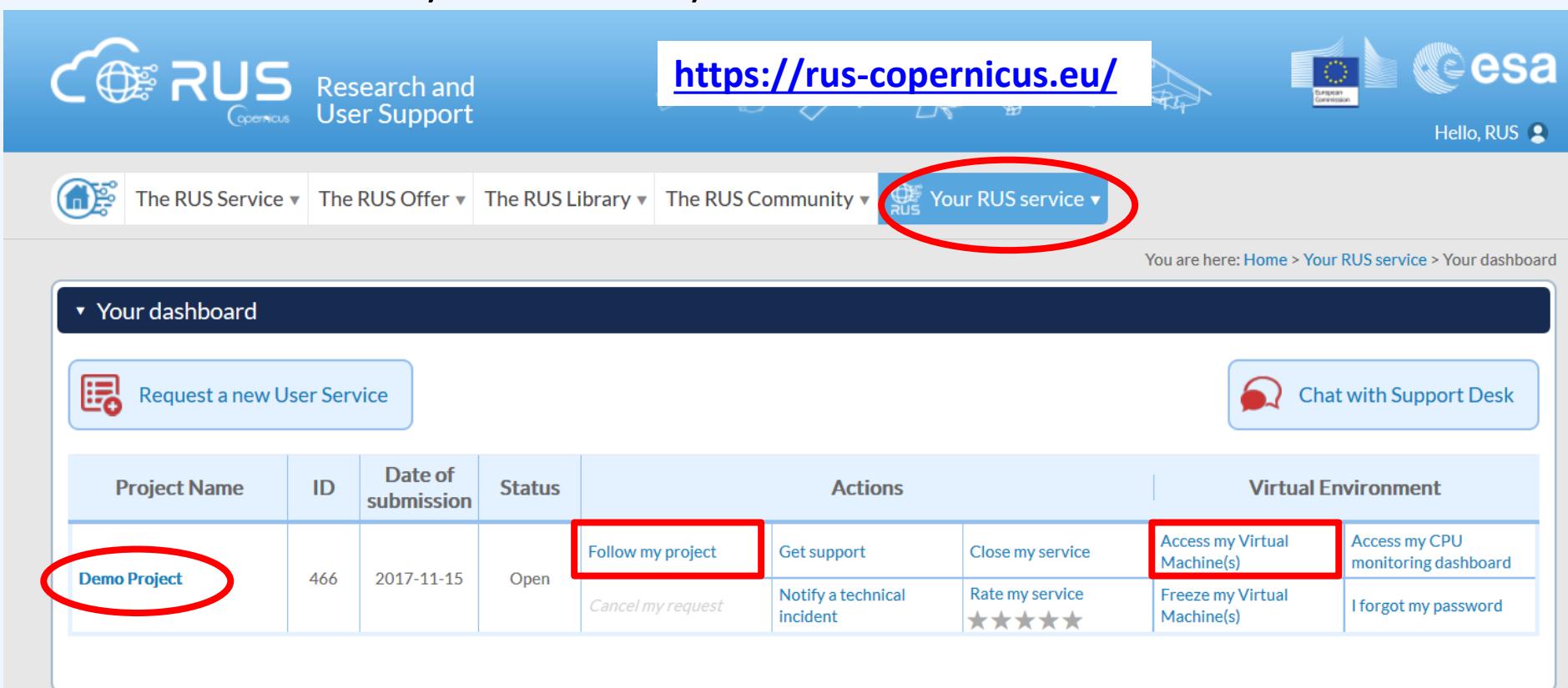
33



- The Sentinel-5P mission
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# RUS The RUS virtual machine

- **How to connect to your RUS virtual machine**
  - Go to your Virtual Machine (VM) from your RUS dashboard or using the direct URL you received by email in a web browser

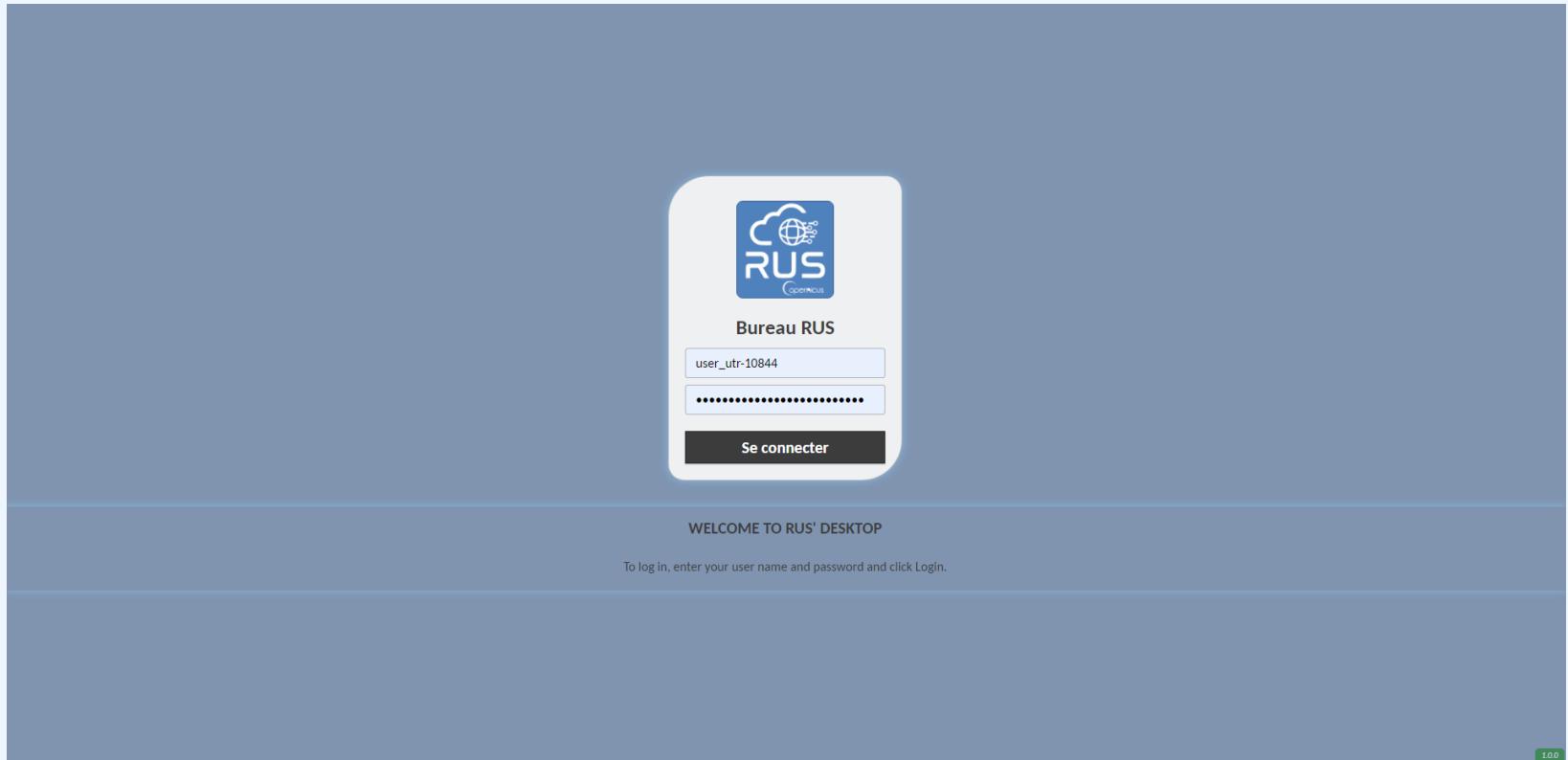


The screenshot shows the RUS (Research and User Support) dashboard. At the top, there's a navigation bar with links: "The RUS Service", "The RUS Offer", "The RUS Library", "The RUS Community", and "Your RUS service". The "Your RUS service" link is highlighted with a red oval. To its right is the URL <https://rus-copernicus.eu/>. On the far right, there are logos for the European Commission and ESA, and a "Hello, RUS" greeting with a user icon.

In the main content area, there's a section titled "Your dashboard" with a "Request a new User Service" button and a "Chat with Support Desk" button. Below this is a table with columns: Project Name, ID, Date of submission, Status, Actions, and Virtual Environment. A row for a "Demo Project" is shown. The "Follow my project" button in the Actions column and the "Access my Virtual Machine(s)" button in the Virtual Environment column are both highlighted with red ovals. The "Demo Project" row also has a red oval around its first column.

Project Name	ID	Date of submission	Status	Actions	Virtual Environment			
Demo Project	466	2017-11-15	Open	<a href="#">Follow my project</a> <a href="#">Cancel my request</a>	<a href="#">Get support</a> <a href="#">Notify a technical incident</a>	<a href="#">Close my service</a> <a href="#">Rate my service</a> ★★★★★	<a href="#">Access my Virtual Machine(s)</a> <a href="#">Freeze my Virtual Machine(s)</a>	<a href="#">Access my CPU monitoring dashboard</a> <a href="#">I forgot my password</a>

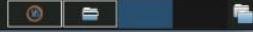
- **How to connect to your RUS virtual machine**
  - Authorize the access certificate
  - Log in with your **RUS VM identifiers** (in the Follow my project tab of your dashboard)





# The RUS virtual machine

- Exploring the desktop of your Virtual Machine



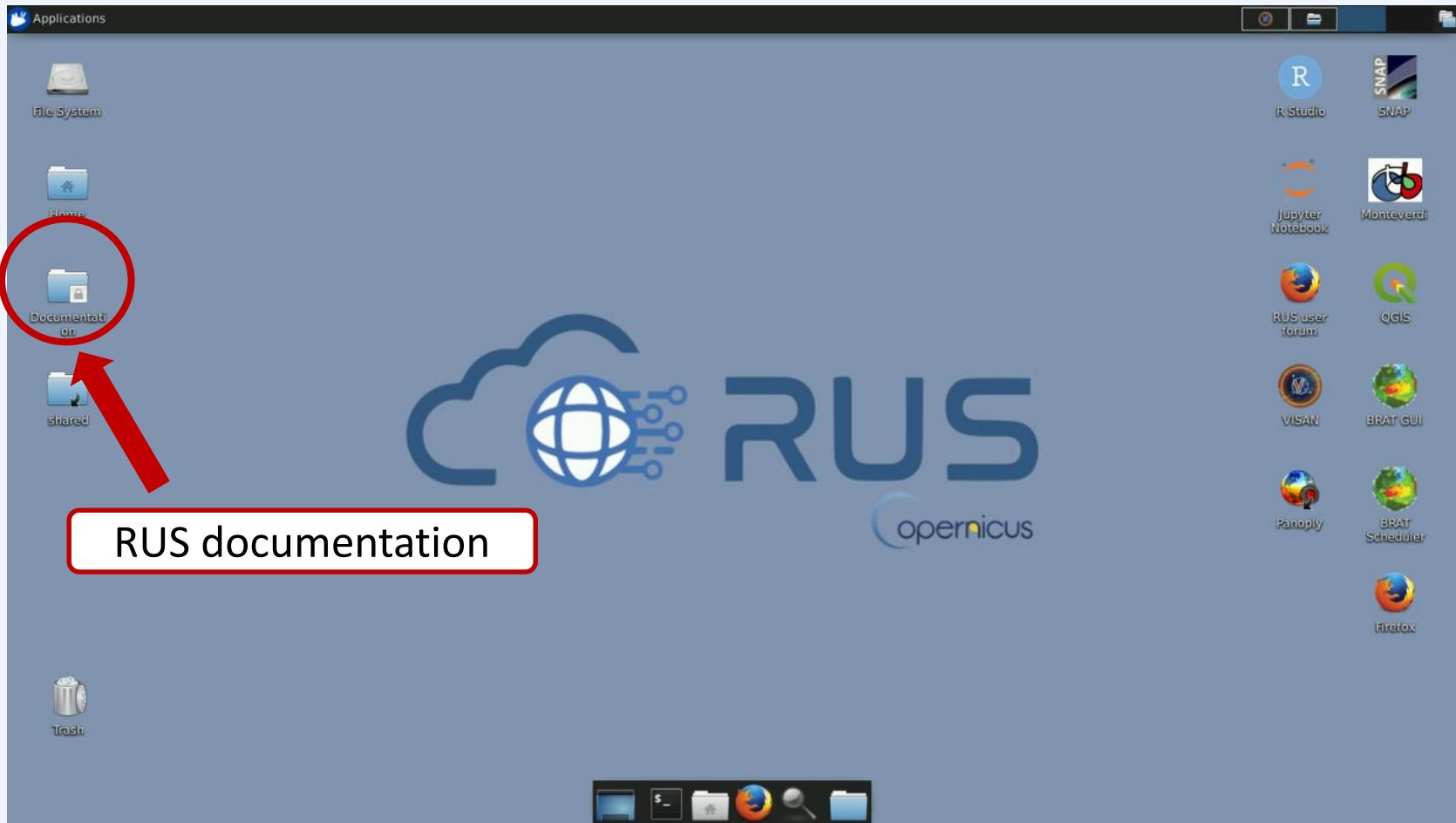
# RUS The RUS virtual machine

- Exploring the desktop of your Virtual Machine



# Corus The RUS virtual machine

- Exploring the desktop of your Virtual Machine



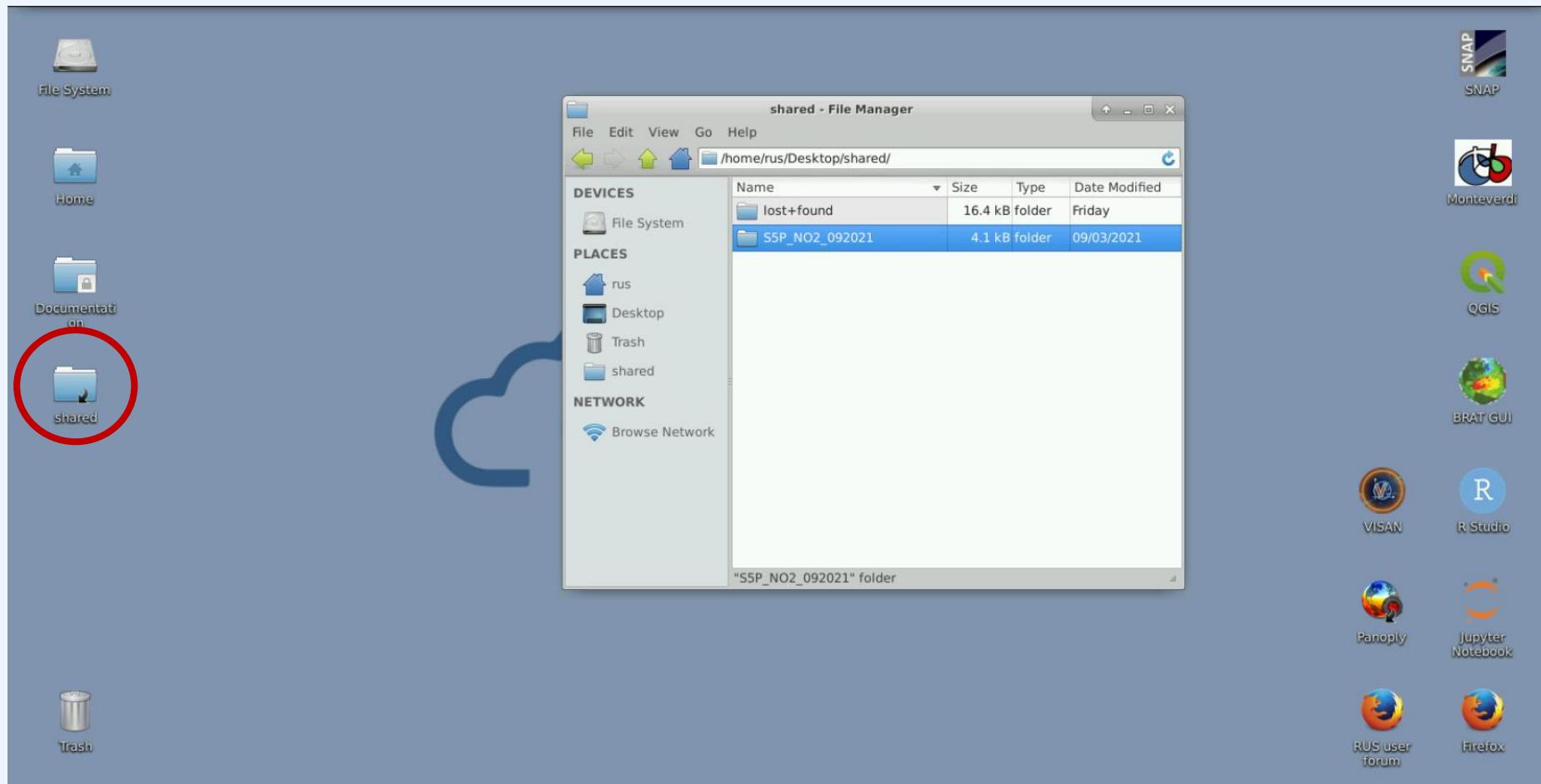
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- Exploring the desktop of your Virtual Machine



- Exploring the desktop of your Virtual Machine



# RUS The RUS virtual machine

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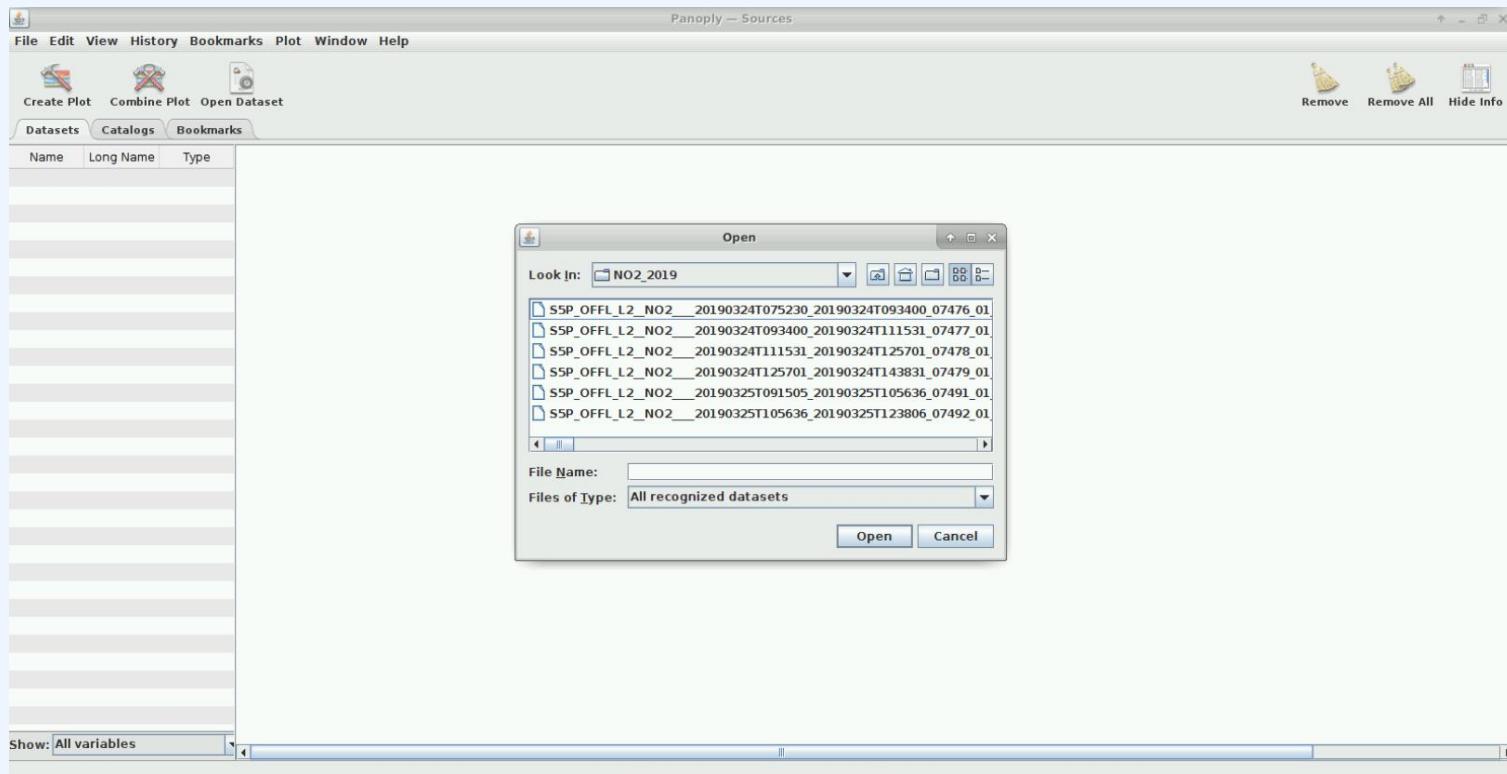
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# About Panoply

- Panoply plots geo-referenced and other arrays from netCDF, HDF, GRIB and other datasets
- It is a cross-platform application that runs on Macintosh, Windows, Linux and other desktop computers.
- Link to panoply website:  
<https://www.giss.nasa.gov/tools/panoply/>
- [Download panoply](#)



- Let's start exploring a S5P L2 product!
- Open a product from  
`/shared/S5P_NO2_092021/training_NO2_22092021/Original/NO2_24032019`



- There are two groups in each Sentinel-5P netCDF file
  - METADATA:** This is a group to collect metadata items (facilitate dataset discovery)
  - PRODUCT:** This group stores the main fields (latitude, longitude, main variables)

Panoply — Sources

File "SSP\_OFFL\_L2\_NO2\_20190324T075230\_20190324T093400\_07476\_01\_010300\_201" File type: Hierarchical Data Format, version 5

```

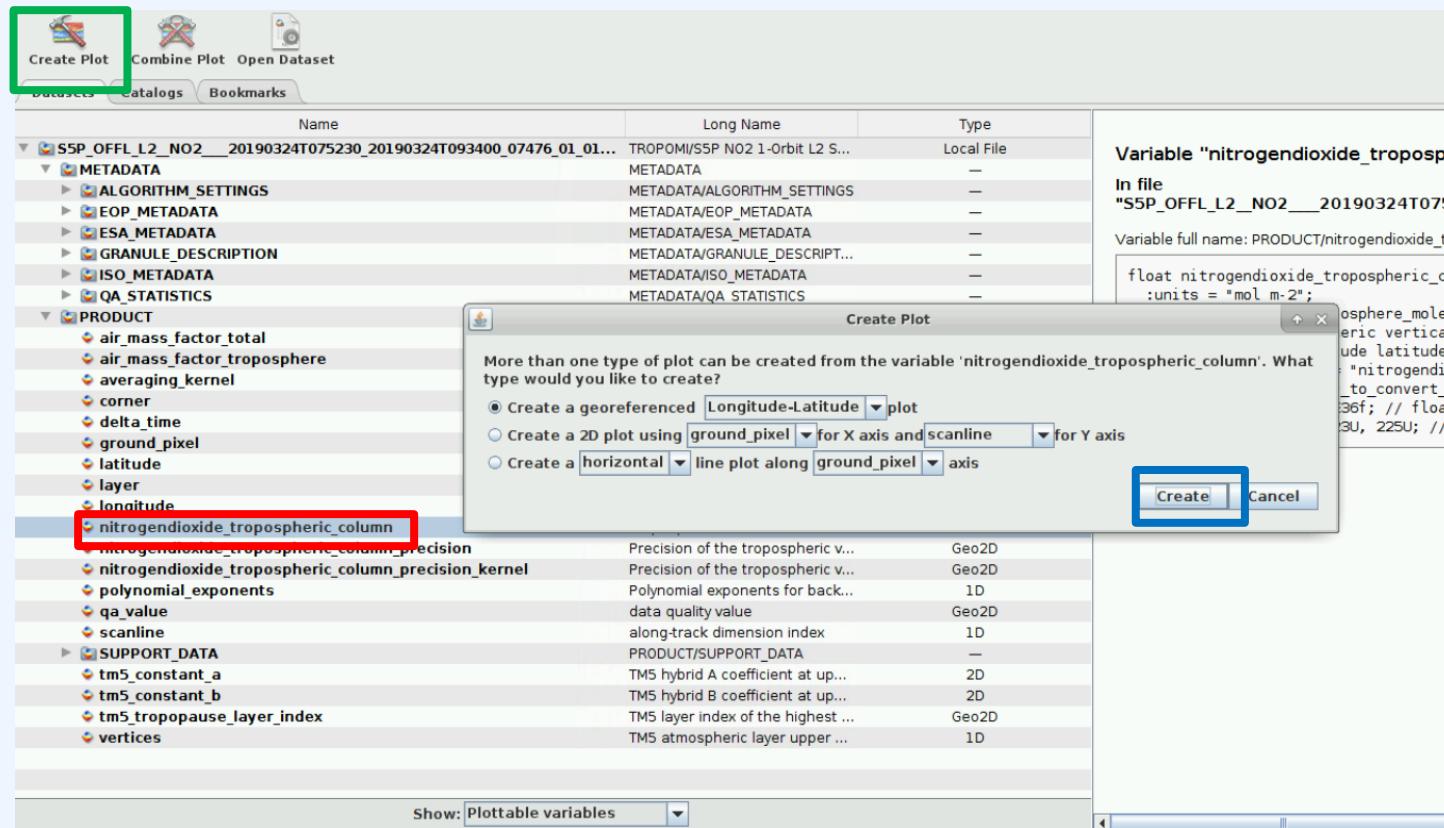
netcdf file:/home/rus/shared/Sentinel5P_0121/data/inputs/N02_2019/SSP_OFFL_L2_NO2_20190324T075230_20190324T093400_07476_01_010300_201 {
  group: METADATA {
    group: QA_STATISTICS {
      dimensions:
        vertices = 2;
      nitrogendioxide_stratospheric_column_histogram_axis = 100;
      nitrogendioxide_stratospheric_column_pdf_axis = 400;
      nitrogendioxide_tropospheric_column_histogram_axis = 100;
      nitrogendioxide_tropospheric_column_pdf_axis = 400;
      nitrogendioxide_total_column_histogram_axis = 100;
      nitrogendioxide_total_column_pdf_axis = 400;
    }
    variables:
      float nitrogendioxide_stratospheric_column_histogram_axis(nitrogendioxide_stratospheric_col
        :units = "mol m^-2";
        :comment = "Histogram of the stratospheric NO2 vertical column";
        :long_name = "Histogram of the stratospheric NO2 vertical column";
        :bounds = "nitrogendioxide_stratospheric_column_histogram_bounds";
        :_FillValue = 9.96921E36f; // float
        :_ChunkSizes = 1000; // uint
      float nitrogendioxide_stratospheric_column_pdf_axis(nitrogendioxide_stratospheric_col
        :units = "mol m^-2";
        :comment = "Probability density function of the stratospheric NO2 vertical column";
        :long_name = "Probability density function of the stratospheric NO2 vertical column";
        :bounds = "aerosol_nitrogendioxide_stratospheric_column_pdf_bounds";
        :_FillValue = 9.96921E36f; // float
        :_ChunkSizes = 4000; // uint
      float nitrogendioxide_stratospheric_column_histogram_bounds(nitrogendioxide_stratosph
        :_FillValue = 9.96921E36f; // float
    }
  }
}
  
```

Datasets Catalogs Bookmarks

Name	Long Name	Type
SSP_OFFL_L2_NO2_20190324T075230_20190324T093400_07476_01_010300_201	TROPOMI/SSP NO2 1-orbit L2 Swath 7x3...	Local File
<b>METADATA</b>	METADATA	—
<b>ALGORITHM_SETTINGS</b>	METADATA/ALGORITHM_SETTINGS	—
<b>EOP_METADATA</b>	METADATA/EOP_METADATA	—
<b>ESA_METADATA</b>	METADATA/ESA_METADATA	—
<b>GRANULE_DESCRIPTION</b>	METADATA/GRANULE_DESCRIPTION	—
<b>ISO_METADATA</b>	METADATA/ISO_METADATA	—
<b>QA_STATISTICS</b>	METADATA/QA_STATISTICS	—
<b>PRODUCT</b>	PRODUCT	—
air_mass_factor_total	Total air mass factor	Geo2D
air_mass_factor_tropos...	Tropospheric air mass factor	Geo2D
averaging_kernel	Averaging kernel	Geo2D
corner	pixel corner index	1D
delta_time	offset of start time of measurement rel...	1D
ground_pixel	across-track dimension index	1D
intensity_offset_poly...	Polynomial exponents for intensity offset	—
latitude	pixel center latitude	Geo2D
layer	TM5 atmospheric layer numbers	1D
longitude	pixel center longitude	Geo2D
nitrogendioxide_tropos...	Tropospheric vertical column of nitroge...	Geo2D
nitrogendioxide_tropos...	Precision of the tropospheric vertical c...	Geo2D
nitrogendioxide_tropos...	Precision of the tropospheric vertical c...	Geo2D
polynomial_exponents	Polynomial exponents for background ...	1D
qa_value	data quality value	Geo2D
scanline	along-track dimension index	1D
<b>SUPPORT_DATA</b>	PRODUCT/SUPPORT_DATA	—
time	reference time for the measurements	—
time_utc	Time of observation as ISO 8601 date...	—
tm5_constant_a	TM5 hybrid A coefficient at upper and l...	2D
tm5_constant_b	TM5 hybrid B coefficient at upper and l...	2D
tm5_tropopause_layer...	TM5 layer index of the highest layer in ...	Geo2D

Show: All variables

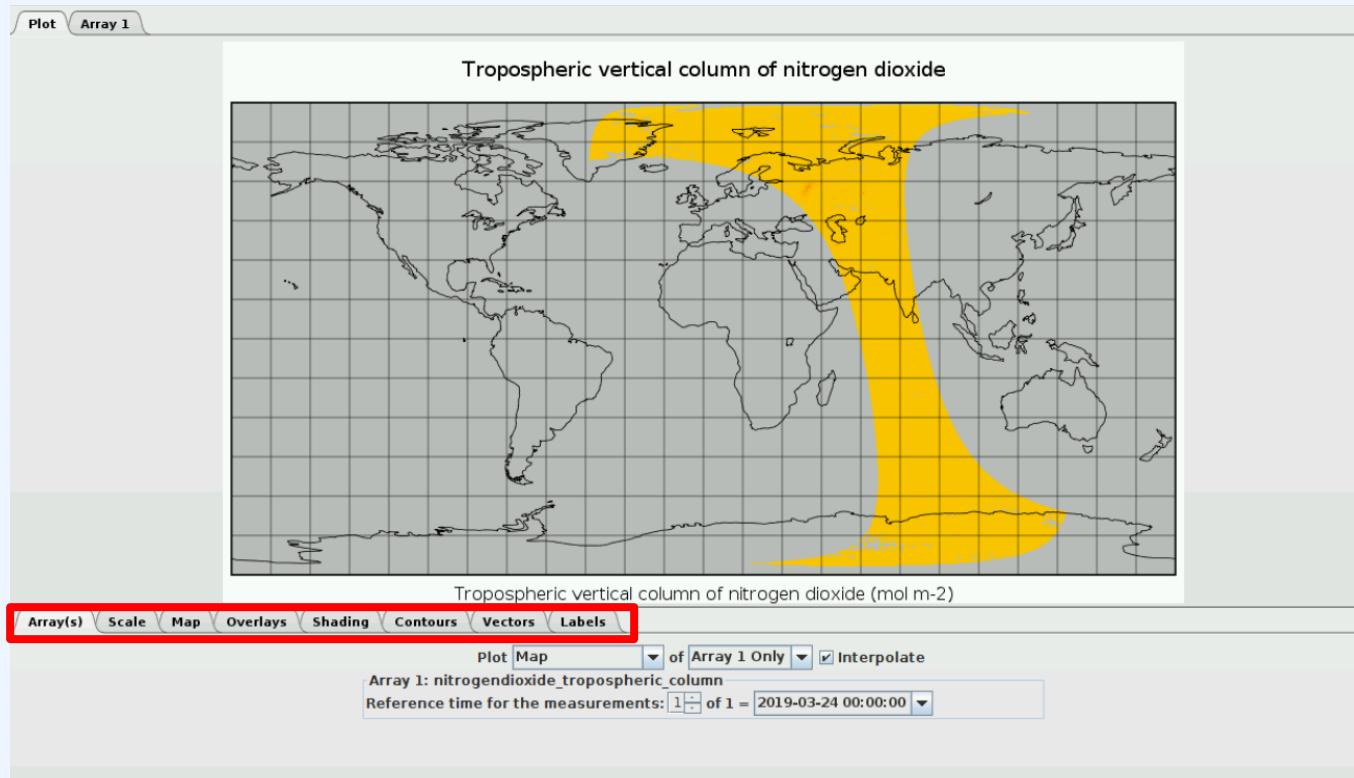
- Plotting an imported product in Panoply
  - Select the **nitrogendioxide\_tropospheric\_column** and hit **Create plot**
  - Finally click on “**Create**”



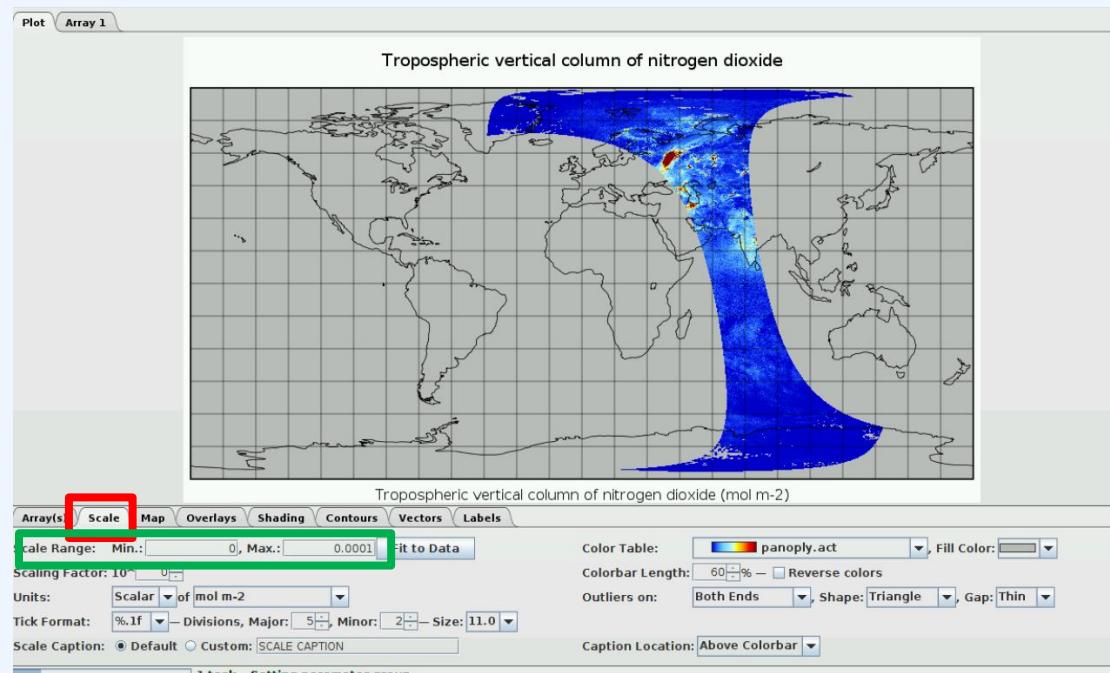
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- The plot of the variable opens
- All the **tabs down the plots** are very useful to set up the plot options



- Plotting an imported product in Panoply
  - Select **Scale** and change the Scale Range :
    - Min : 0,0000 mol.m<sup>-2</sup>**
    - Max : 0.0001 mol.m<sup>-2</sup>**
  - Some NO<sub>2</sub> tropospheric column values are negative
  - This is expected when the NO<sub>2</sub> tropos. Column value is low and the error is high
  - As the error is random, some values end up being below 0.



- The Sentinel-5P mission
- The Sentinel 5P products
- The Atmospheric Toolbox
- **Exercises**
  - Introduction
  - Starting with the RUS environment
  - Starting with Panoply
  - **Creation of NO<sub>2</sub> gridded product**
  - Jupyter Notebook exercises

## Creation of L3 gridded products

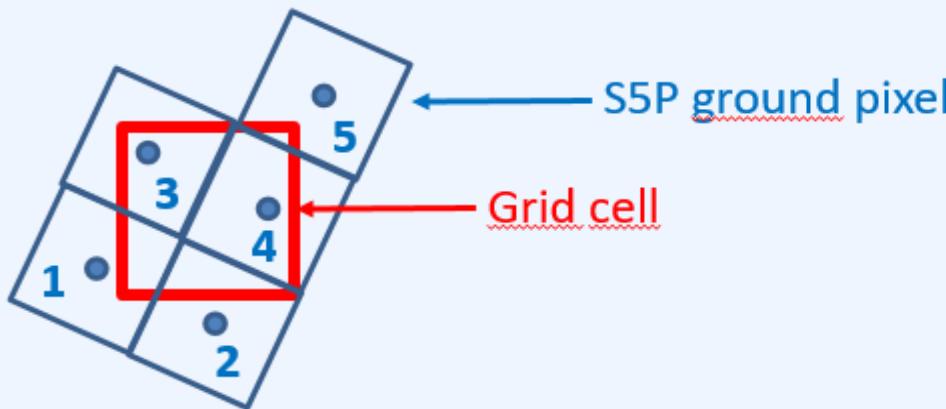
- 1 S5P file per orbit. What if we want to map a whole day over a user defined area?
- Original S5P data is binned by time, not by latitude/longitude
- Before merging several L2 products having different spatial grids, we need to convert them to L3 products and create a common regular grid for all orbits

## The HARP bin\_spatial() operation: practical use

- **bin\_spatial(lat\_edge\_length, lat\_edge\_offset, lat\_edge\_step, lon\_edge\_length, lon\_edge\_offset, lon\_edge\_step)**: for all variables in a product, map all time samples onto a regular spatial lat/lon grid
  - Example: `bin_spatial(120,-90,0.5,720,-180,0.5)` bins all samples into a regular 0.5°\*0.5° lat/lon grid where:
    - Lat min=-90
    - Lat max=-90+120\*0.5=-30
    - Lon min=-180
    - Lon max= -180+720\*0.5=180
  - The choice of the **spatial resolution (lat/ion\_edge\_step)** and the boundaries (**lat/ion\_edge\_offset, lat/ion\_edge\_length**) are up to the user
  - A better resolution and a larger area of interest increase the computing time
  - A 0.5°\*0.5° resolution is sufficient for this example but you can increase it later on to practice.

## How does bin\_spatial() operate?

- If only lat/lon center coordinates of ground pixels in the products: **bin\_spatial()** performs an average of all values whose center point falls in the grid cell: **Case 1**
- S5P products provide with lat/lon\_bounds variables: **bin\_spatial()** proceeds to an area weighted average based on ground pixel areas and grid cell intersection ( $a_i$ ): **Case 2**



$$\text{Value} = \frac{\text{Pixel}_3 + \text{Pixel}_4}{2}$$

$$\text{Value} = \frac{\sum_{i=1}^5 a_i * \text{Pixel}_i}{\sum_{i=1}^5 a_i}$$

## The HARP derive() operation: practical use

- When spatially binning a product with **bin\_spatial()**, only the lat/lon\_bounds of the grid cells will be saved in the output product.
- Most software and GIS tools will expect the lat/lon center coord. of the pixels to plot the NO<sub>2</sub> column.
- To write the lat/lon center coord. of the spatial grid in the output use:
  - Derive(variable {dimension})
  - Example: ‘derive(longitude {longitude});derive(latitude {latitude})’

## The HARP comparison filter operation: practical use

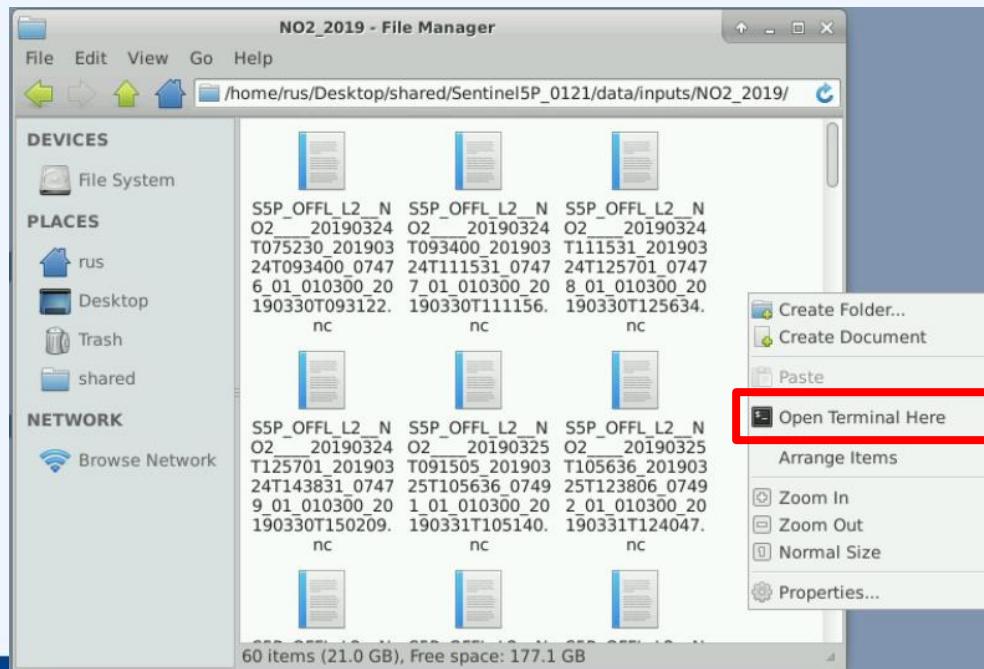
- Filter a dimension for all variables in the product such that items for which the value of the provided variable does not match the expression get excluded
- Example: 'longitude>0 [degree\_east]; '
- To filter by variable, use the keep() operation  
Example keep(latitude,longitude,tropospheric\_NO<sub>2</sub>\_column\_number\_density) if you wish to only keep these three variables
- Restricting the output product to your variable of interest will greatly enhance the computing time.

## HARPCONVERT Command line tool: practical use

- Allows to define a list of operations to apply to each product :  
**-a 'operation\_list()'**
  - Example: -a 'bin\_spatial(...); derive(...)'
- Allows to define ingestion options: **-o 'ingestion\_option'**
- Allows to define the output format: **-f 'format'**
  - The default NETCDF format will be kept during the exercise
  - HDF4 and HDF5 are supported too
- When ingesting products, HARP will rename the product variables.  
The HARP variable mapping for S5P products is available [here](#).

## HARPCONVERT Command line tool: practical use

- In a file browser, from the working directory, go to  
/shared/S5P\_NO2\_092021/training\_NO2\_22092021/Original/NO2\_24032019/
- In this directory, all S5P NO2 products on March 24th have been downloaded ahead of this training session
- Hit the right button of your mouse and **Open Terminal Here**



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## HARPCONVERT Command line tool: practical use

- **harpconvert -a 'operations\_list' -o 'ingestion\_option' input\_file output\_Directory/output\_file**
- Grid cell area is fixed at 0.5\*0.5 to avoid long processing time
- No ingestion option

## HARPCONVERT Command line tool: practical use

- Right click on the NO<sub>2</sub>\_command\_line.sh file in the AuxData/bash/ folder and select Open with -> Open with « Mousepad »
- In Mousepad select View -> Color Scheme -> Classic
- Copy/Paste the following command line in the open terminal and press Enter
- `harpconvert -a 'latitude > -50 [degree_east]; latitude < 50 [degree_east]; bin_spatial(200,-50,0.5,360,0,0.5); derive(latitude {latitude}); derive(longitude {longitude}); keep(latitude,longitude,tropospheric_NO2_column_number_density)' /shared/S5P_NO2_092021/training_NO2_22092021/Original/NO2_24032019/S5P_OFFL_L2_NO2____20190324T075230_20190324T093400_07476_01_010300_20190330T093122.nc /shared/S5P_NO2_092021/training_NO2_22092021/Processing/pre_processed_files/on_e_file/S5PConverted_onefile.nc`

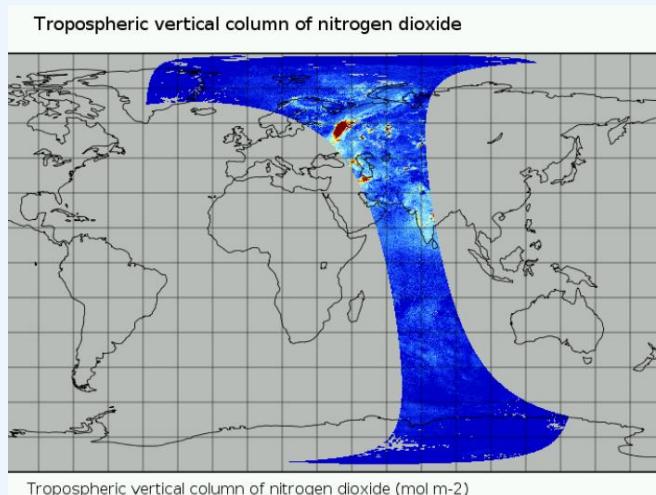
## HARPCONVERT Command line tool: Visualizing the output

- Import the **S5P\_converted\_onefile.nc** product in Panoply (File -> Open...)
- File Path  
**/shared/S5P\_NO2\_092021/training\_NO2\_22092021/Processing/pre\_processed\_files/one\_file/**
- All groups have disappeared, and only the *longitude, latitude and tropospheric\_NO2\_column\_number\_density* variables are present as requested by the *keep()* operation
- Double click on the **tropospheric\_NO2\_column\_number\_density** variable and hit « Create »

## HARPCONVERT Command line tool: Visualizing the output

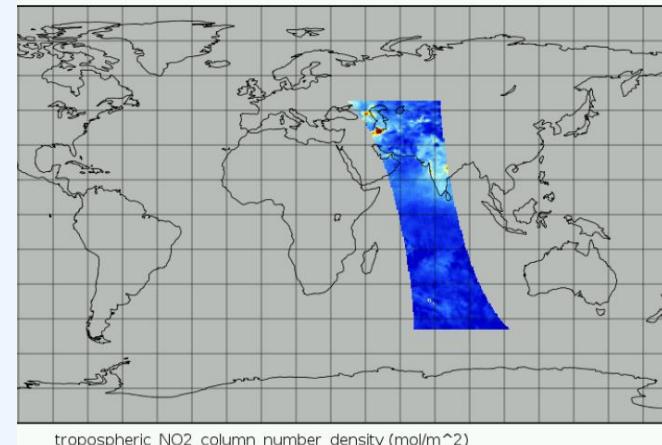
- The product has been regridded into a lower resolution
- Later, you can try to regrid it into a higher resolution!
- Data above 50°N and below 50°S have been discarded thanks to a filter on latitude
- Set the Min/Max of the colorbar to 0.0/0.0001

L2 NO<sub>2</sub>  
product



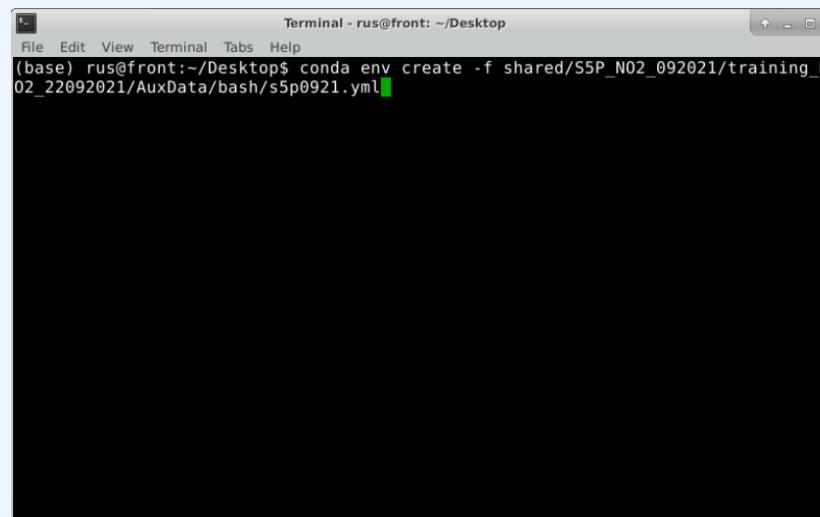
tropospheric\_NO<sub>2</sub>\_column\_number\_density

L3 NO<sub>2</sub>  
product



- The Sentinel-5P mission
- The Sentinel 5P products
- The Atmospheric Toolbox
- **Exercises**
  - Introduction
  - Starting with the RUS environment
  - Starting with VISAN
  - Creation of NO<sub>2</sub> gridded product
  - **Jupyter Notebook exercises**
    - Discovery of Python in the Jupyter Notebook environment
    - Creation of daily averages of tropospheric NO<sub>2</sub> column products out of single orbit files

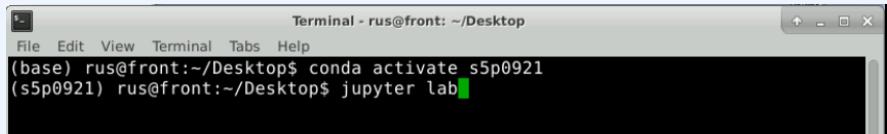
- Second part of the training will be performed using Python code in JupyterLab (Anaconda Distribution)
- We will open JupyterLab by launching it from a specific conda environment (named **s5p0921**) that is provided to you
- Open a Terminal in your RUS virtual machine and copy paste the following line:
- `conda env create -f shared/S5P_NO2_092021/training_NO2_22092021/AuxData/bash/s5p0921.yml`



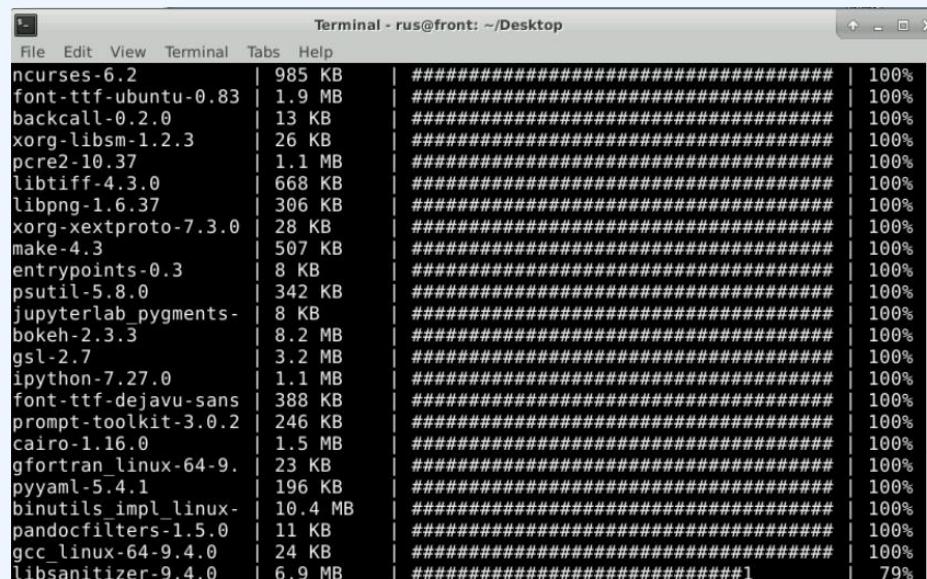
```
Terminal - rus@front: ~/Desktop
File Edit View Terminal Tabs Help
(base) rus@front:~/Desktop$ conda env create -f shared/S5P_NO2_092021/training_N
02_22092021/AuxData/bash/s5p0921.yml
```

- It may take a few minutes to download and install all libraries
- In the meantime... A few words about Anaconda
  - Free & open source distribution of Python & R
  - For scientific computing
  - Simplifies package management (conda) and deployment
  - More info at <https://www.anaconda.com/distribution/>
- And Jupyter
  - Notebooks contain both computer code & rich text elements
- More info at <https://www.jupyter.org>

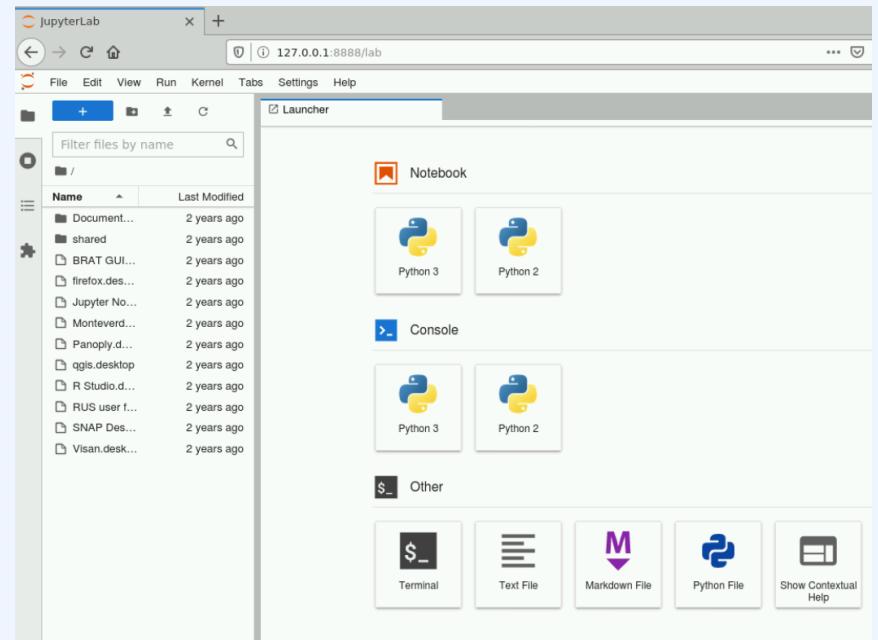
- Once the processing is finished, simply write
  - conda activate s5p0921
  - jupyter lab
- A JupyterLab instance opens



```
Terminal - rus@front: ~/Desktop
File Edit View Terminal Tabs Help
(base) rus@front:~/Desktop$ conda activate s5p0921
(s5p0921) rus@front:~/Desktop$ jupyter lab
```

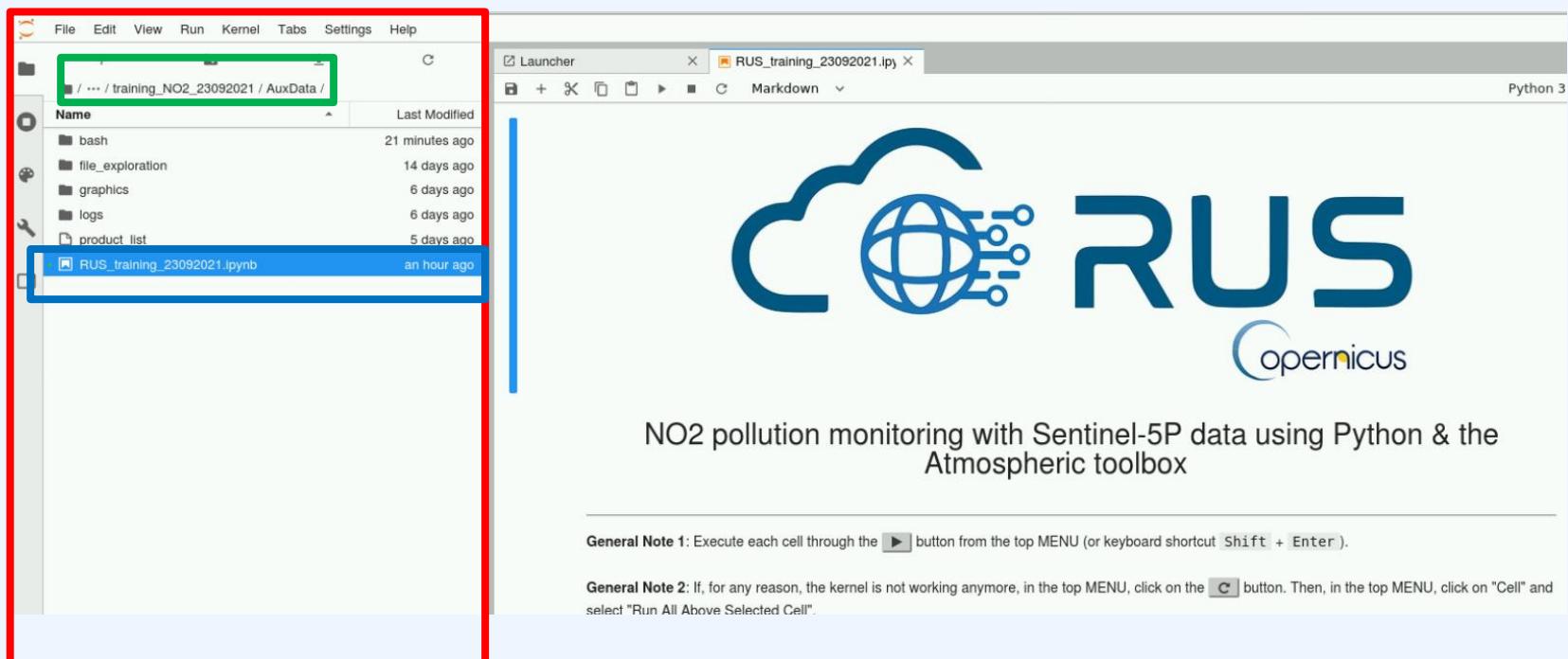


```
Terminal - rus@front: ~/Desktop
File Edit View Terminal Tabs Help
nurses-6.2          985 KB | ######| 100%
font-ttf-ubuntu-0.83 1.9 MB | #####| 100%
backcall-0.2.0       13 KB | #####| 100%
xorg-libsm-1.2.3    26 KB | #####| 100%
pcre2-10.37         1.1 MB | #####| 100%
libtiff-4.3.0        668 KB | #####| 100%
libpng-1.6.37        306 KB | #####| 100%
xorg-xextproto-7.3.0 28 KB | #####| 100%
make-4.3             507 KB | #####| 100%
entrypoints-0.3      8 KB | #####| 100%
psutil-5.8.0          342 KB | #####| 100%
jupyterlab_pygments- 8 KB | #####| 100%
bokeh-2.3.3           8.2 MB | #####| 100%
gsl-2.7               3.2 MB | #####| 100%
ipython-7.27.0         1.1 MB | #####| 100%
font-ttf-dejavu-sans 388 KB | #####| 100%
prompt-toolkit-3.0.2  246 KB | #####| 100%
cairo-1.16.0            1.5 MB | #####| 100%
gfortran_linux-64-9. 23 KB | #####| 100%
pyyaml-5.4.1            196 KB | #####| 100%
binutils_impl_linux- 10.4 MB | #####| 100%
pandocfilters-1.5.0   11 KB | #####| 100%
gcc_linux-64-9.4.0    24 KB | #####| 100%
libsanitizer-9.4.0     6.9 MB | #####| 79%
```



# CORUS Jupyter Notebook

- From the **left panel**, navigate to  
*/shared/S5P\_NO2\_092021/training\_NO2\_22092021/AuxData/*  
Open *RUS\_training\_22092021.ipynb*



From now on, let's follow the exercises on the Notebook!

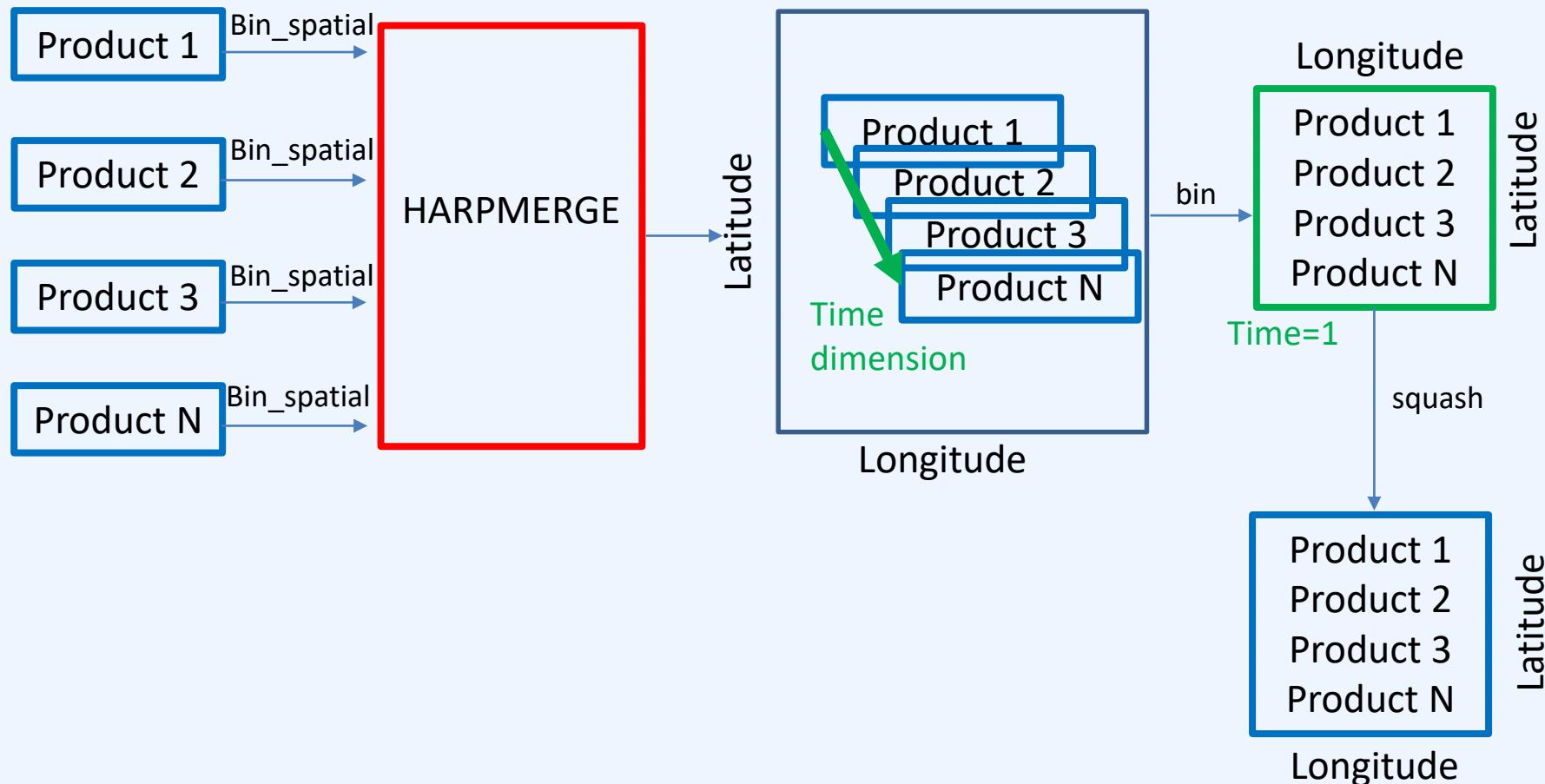
## Combining multiple products: HARPMERGE Command line/function

- Combines multiple products from files or directories by appending them across the time dimension and storing the result into a single output file
- Defines a list of operations to apply to each product before it is appended:  
**-a 'operation1(); operation2(); operationN();'**
  - *Performs the same processing as the HARPCONVERT command line tool*
- Defines a list of operations to apply to the merged product:  
**-ap 'operation1(); operation2(); operationN();'**
  - *Operations to properly concatenate the inputs and export the merged product*
- Define ingestion options: **-o 'ingestion\_option'**
- Define the output format: **-f 'format'**
  - The default NETCDF format will be kept during the exercise
  - HDF4 and HDF5 are supported too

## HARPMERGE Command line tool: practical use

- **Harpmerge –ap ‘operations\_list’ –a ‘operations\_list’ –o ‘ingestion\_option’  
input\_files output\_Directory/output\_file**
- bin\_spatial creates a regular lat/lon grid per product (dimension {lat,lon})
- Merging multiple products with the same lat/lon grid will produce {time,lat,lon} elements (time = number of merged products)
- In the **–ap** argument we will use:
  - **Bin()** operation: **average each of the lat/lon grid cells over time** so that we have {1,lat,lon} elements
  - **squash(time, (latitude,longitude))**: **remove the artificial time=1 dimension** created by the **bin()** operation from lat/lon variables to have proper **Georeferenced products for further use in other softwares** (e.g: QGIS, Panoply...)
  - **Keep(latitude, longitude, tropospheric\_NO2\_column\_number\_density,weight)** : All variables marked for inclusion will be kept in the ingested product, all other variables will be excluded.

## HARPMERGE Command line tool: Merging several products



## HARPMERGE Command line tool:

- “qa\_value” parameter summarizes the processing flags into a continuous value, giving a quality percentage: 100 % is the most optimal value, 0 % is a processing failure
- Pixels can be filtered out by applying a quality filter when executing the HARPMERGE command line tool
  - **tropospheric\_NO2\_column\_number\_density\_validity>75 (0: worst quality and 100: full quality, 75 is the recommended value)**
- From the notebook run the line:

```
#Starting time of the cell
t0= time.time()

#harpmerge in command line
!harpmerge -ap 'bin(); squash(time, (latitude,longitude,tropospheric_NO2_column_number_density))' \
-a 'tropospheric_NO2_column_number_density_validity>75; \
bin_spatial(1800,-90,0.1,3600,-180,0.1); \
derive(longitude {longitude});derive(latitude {latitude}); \
keep(latitude,longitude,tropospheric_NO2_column_number_density,weight)' \
/shared/S5P_N02_092021/training_N02_22092021/Original/N02_24032019/S5P_OFFL_L2_N02___20190*.nc \
/shared/S5P_N02_092021/training_N02_22092021/Processing/merged_files/command_line/converted_N02_command_line.nc

#End time for command line
t1 = time.time()

command_line_time = t1-t0

print("Command line time: {} seconds".format(command_line_time))
```

Thank you !

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