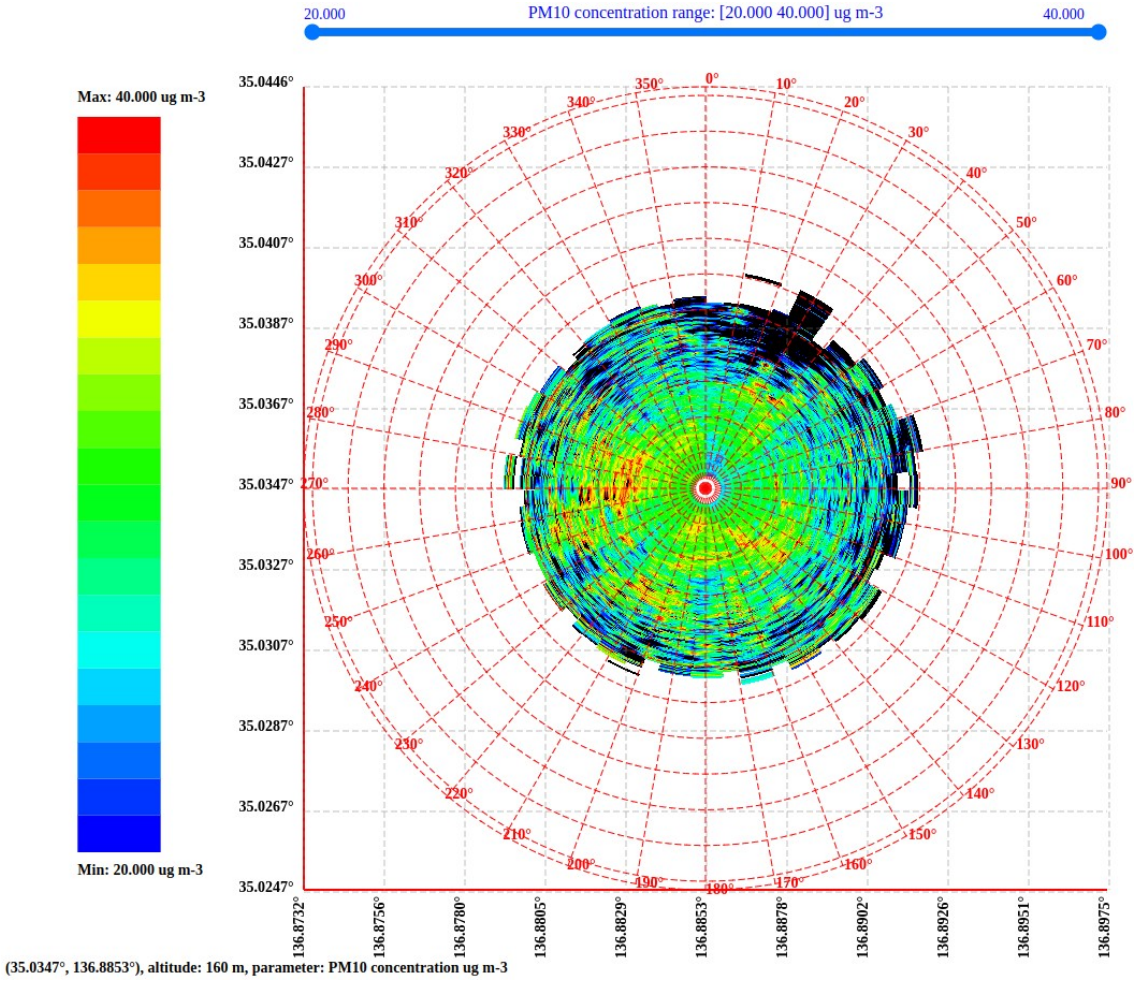
Dali (**D**ynamic **a**nalysis of **li**dar data)



Introduction

"Dali" is an utility designed to visualize and analyze lidar data. It can classify meteorological objects and aerosols, identify storms and hurricanes, and determine zones of turbulence and icing.

The program runs on both Linux and Windows platforms and was written from scratch without any third-party code.

Input data can be in HDF5, GRIB, and netCDF formats.

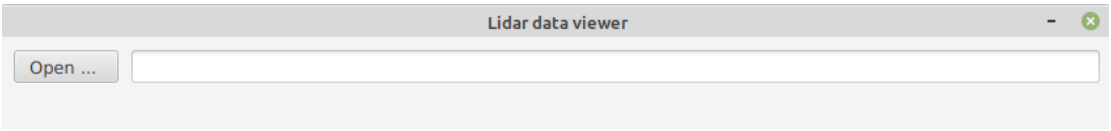
"Cassandra 3D" consists of two modules.

The first module extracts data from lidar scans and defines a color palette to display the data.

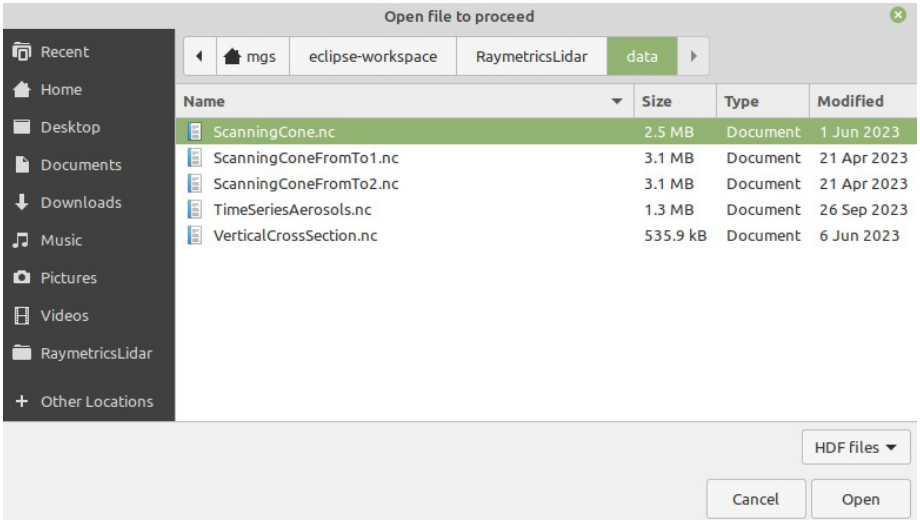
The second module visualizes, compares, filters, and classifies lidar data. It uses a web browser to display the data in 3D and can operate in both online and offline modes.

1. Data preparation module

Launch the “Dali” program and click the **Open** button.



Then, select an HDF5 file that contains one or more lidar parameters from a single scan.



Once you have selected the file, a new window will appear (see Fig. 1.1).

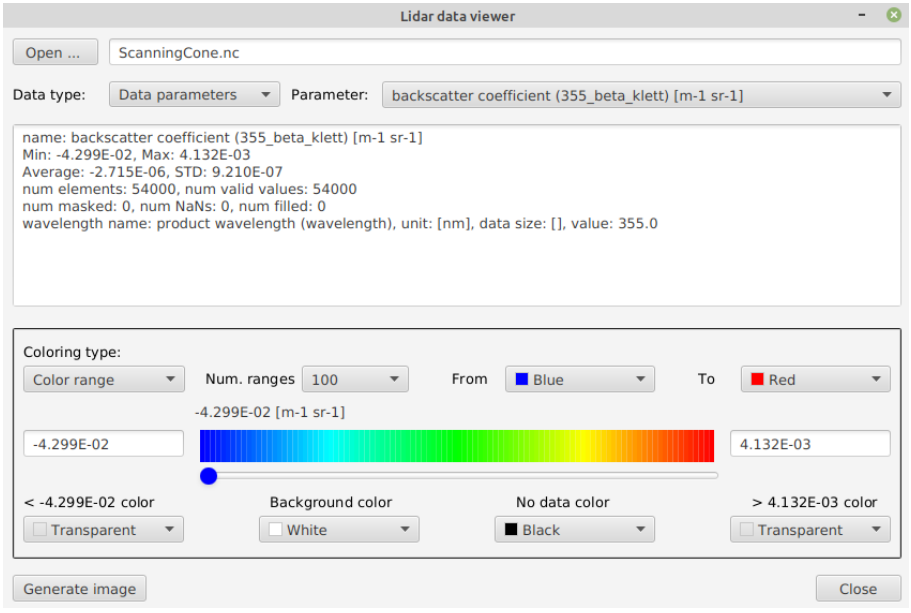


Fig 1.1 Data preparation module.

At the top of the window there is a data section (see Fig. 1.2). This block contains a list of available parameters and auxiliary variables and displays data, weather and storm warnings, and system information. The bottom section of the window holds the controls for color coding the selected data (see Fig. 1.8).

1.1 Data section

At the top of the window, you can find the data section (see Fig. 1.2) which contains **Data type** selector. The **Parameter** list will display content based on the element selected in the **Data type**. The lower part of the section will show the characteristics of the chosen element in the **Parameter** selector.

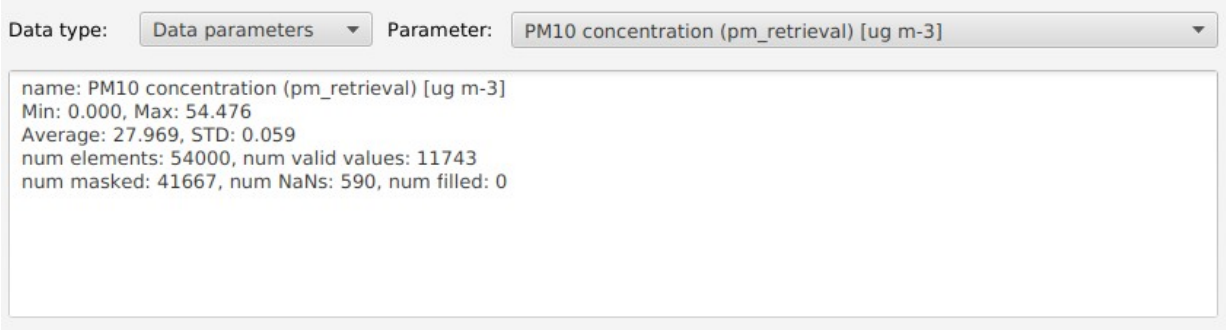


Fig. 1.2 Data section.

The **Data type** selector consists of the following elements (refer to Fig. 1.3):

1) **Data parameters**: All data from this list can be displayed as various types of charts. Data parameters may include the concentration of particles smaller than 10 micrometers (PM10 concentration), backscatter coefficient, etc. (see Fig. 1.4). The complete list of lidar parameters can be found in Appendix 1. Corresponding statistical information will be displayed below the selected parameter (refer to Fig. 1.2).

2) **System variables**: Auxiliary variables used for preparing charts for data visualization (refer to Fig. 1.5). For example, scanning time, range and distance between pulses, latitude, longitude and elevation of the lidar system, atmospheric pressure and ambient temperature, etc. The complete list of supported auxiliary variables is provided in Appendix 2.

3) **System info**: This includes information about the system, scanning time, the geographic coordinates of the lidar and its altitude above sea level (refer to Fig. 1.6).

4) **Alerts**: Contains parameters for weather and storm warnings (refer to Fig. 1.7). The complete list of warning parameters is provided in Appendix 3.

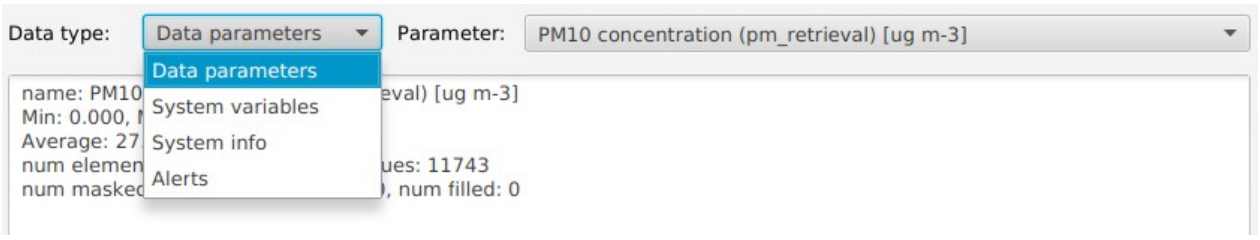


Fig. 1.3 Available data types.

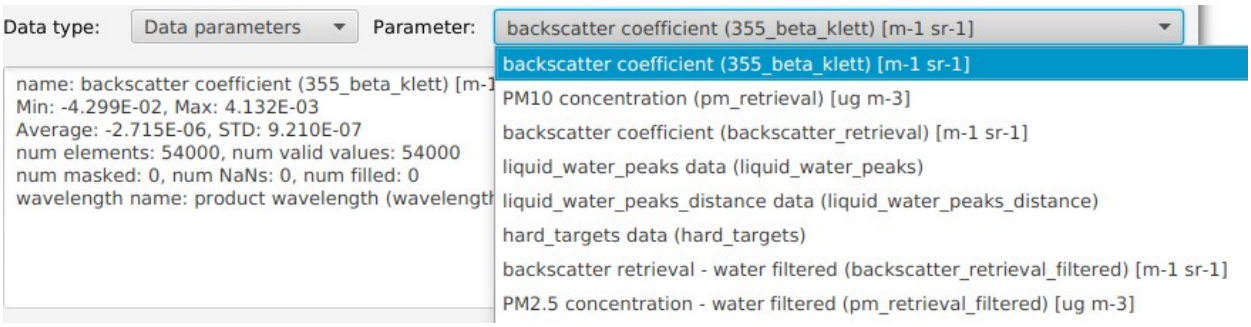


Fig. 1.4 List of lidar data available for visualization.

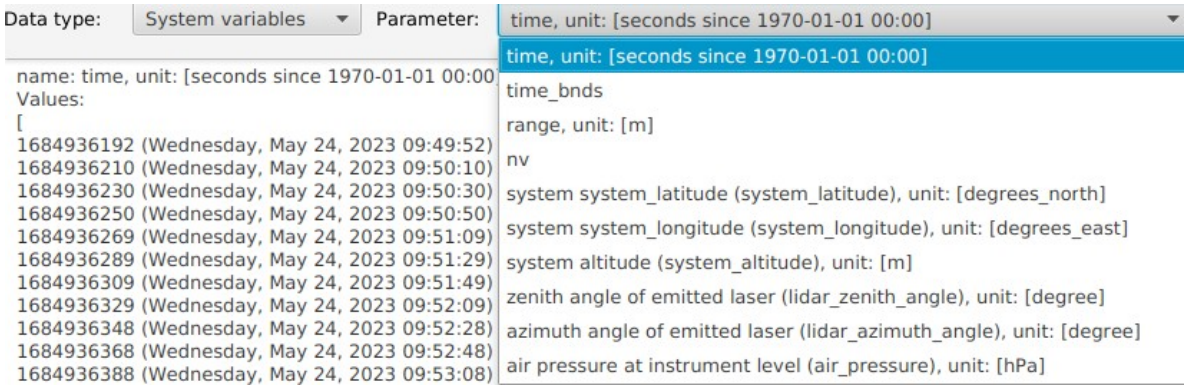


Fig. 1.5 List of auxiliary variables and their values.

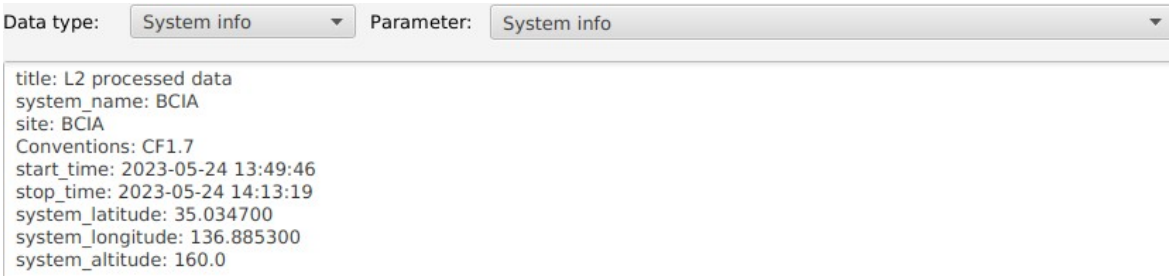


Fig. 1.6 System information.

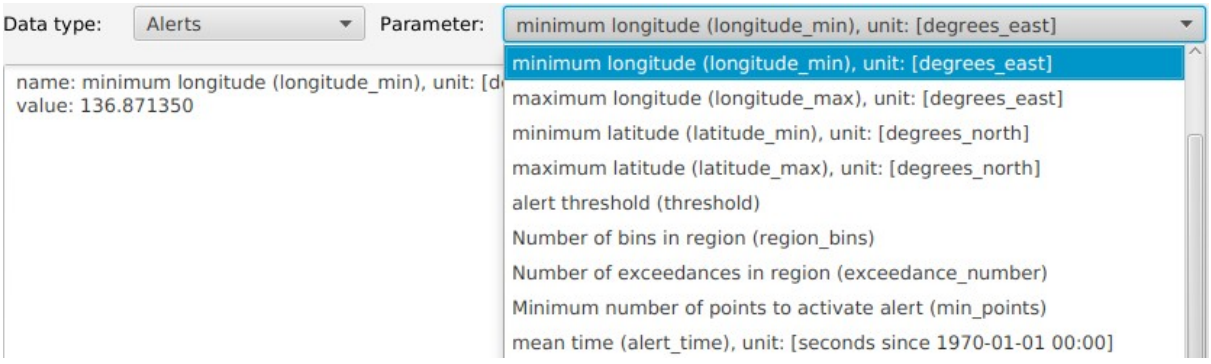


Fig. 1.7 Meteorological and storm warning parameters.

1.2 Color coding section

The coloring section is located at the bottom of the window and is used to match data values and palette colors.

The section consists of the following parts: a **Coloring type** selector, a color palette, and a range of data to display, defined by the minimum and maximum values (see Fig. 1.8). Additionally, you can also select colors for data that falls outside of this range and NaN values.

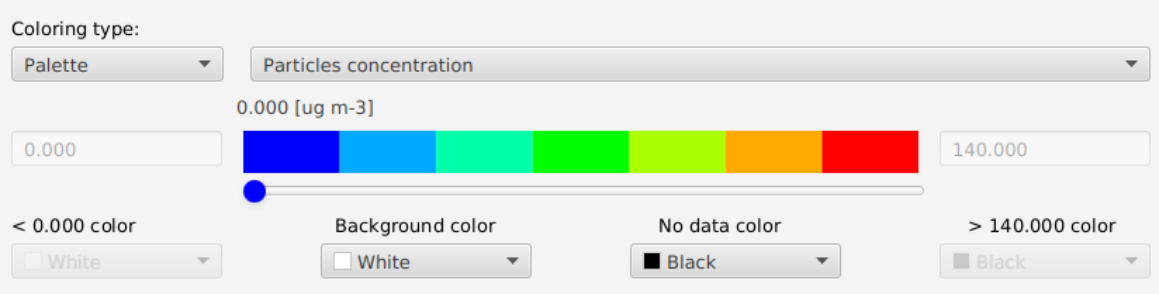


Fig. 1.8 Controls of the color coding section.

In “Dali” the following coloring options are available (see Fig. 1.9):

1) Pre-defined palettes (**Palette**)
2) Palettes defined by starting and ending colors and the number of elements in between (**Color range**)
3) Color sequences generated by **Sinebow** algorithm

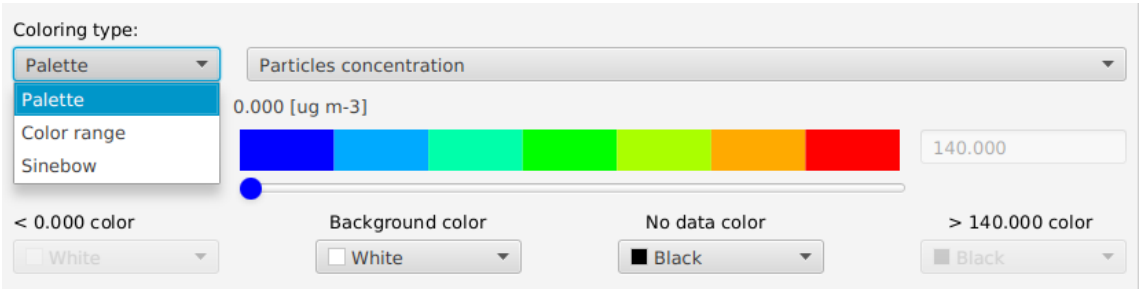


Fig. 1.9 Color coding types.

1.2.1 Pre-defined palettes (Palette)

There are pre-defined standard color palettes available for many lidar parameters. For instance, a pre-defined palette **Particles concentration** of 7 colors corresponds to PM10 concentration for the range from 0 to 140 mg/m^3, with 20 mg/m^3 step (see Fig. 1.8). The standard color palettes, range of values, and units of measurement for each parameter are provided in Appendix 1.

When you choose a parameter that has a standard color palette through the **Parameter** control, the **Palette** mode is automatically selected. This sets up a color range and palette based on the selected data. For instance, when you choose the **355_vldr** parameter (volume linear depolarization ratio), the color mode is set to **Palette**, and the **Particles concentration** palette is automatically selected (refer to Fig. 1.9). The parameter data range lies between 0.03 to 0.2.

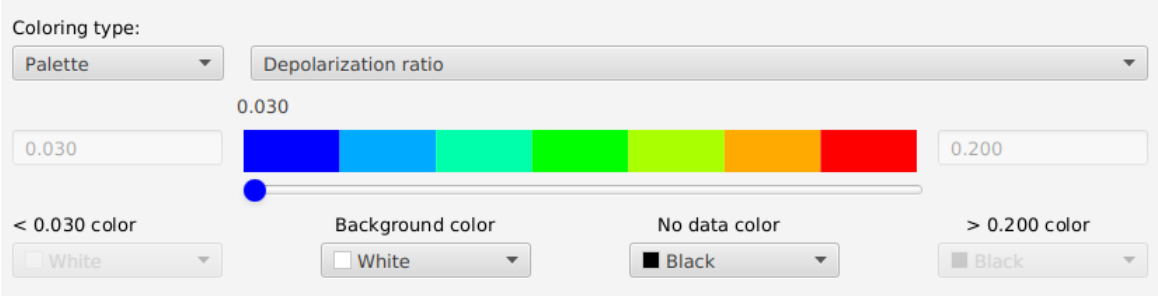


Fig. 1.9 Pre-defined color palette for volume linear depolarization ratio.

To color code data, you may use any of the available palettes by selecting it from the list, as shown in Fig. 1.10. The editable minimum and maximum values of the selected parameter are located to the left and right of the color palette. These values determine the range of data that will be color-coded by the selected color palette. As you move the slider cursor along the color palette, you can see which color corresponds to a specific value or range of values.

For example, in Fig. 1.11 **Temperature** color palette was selected for the **PM 2.5 concentration** parameter, and the minimum value was set to 10 and the maximum to 40 mg/m^3. White color corresponds to concentration values of 10 mg/m^3, 40 mg/m^3 values will be colored black, and data having the value of 20 mg/m^3 will be represented by blue color. Concentration data having values less then 10 or more then 40 mg/m^3 will not be shown.

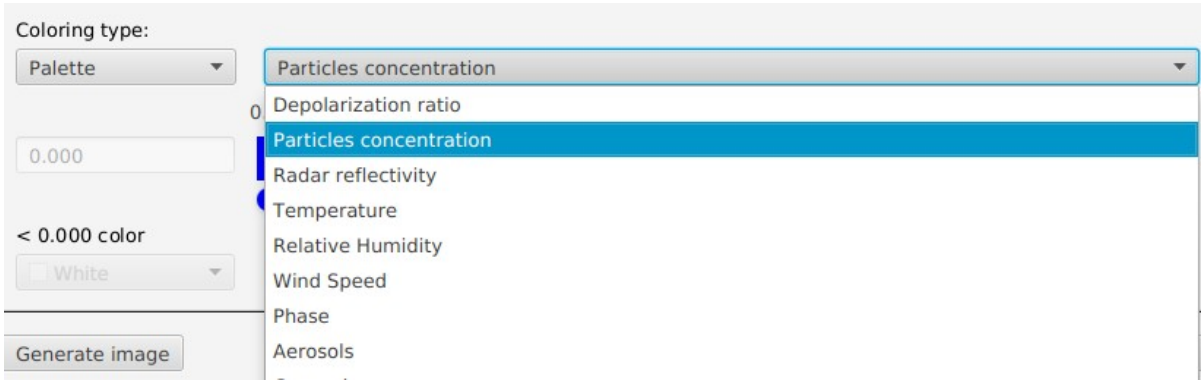


Fig. 1.10 List of available color palettes.

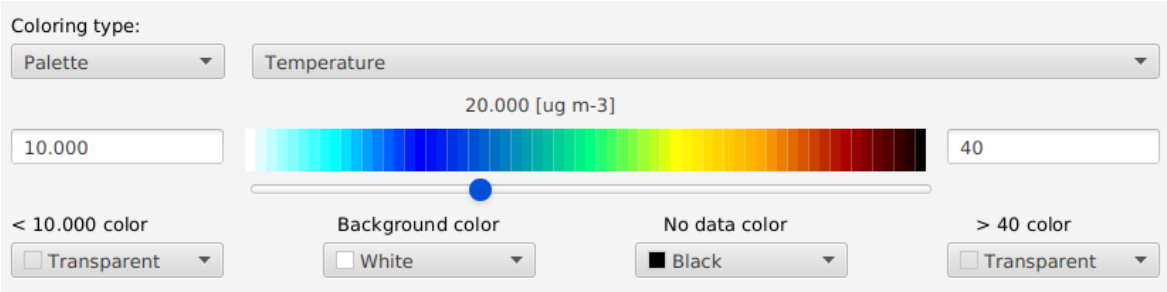


Fig. 1.11 Selecting a palette and setting the data range for color coding.

In some cases, it may be necessary to display data that falls outside of the specified range. To achieve this, colors can be assigned to values that are below the minimum or above the maximum. You can select these colors by using the controls located to the left and right of the color palette, respectively, and below the minimum and maximum values. For instance, in 1.12 gray color was chosen for concentration values that are less then 20 mg/m^3, while values greater than 30 mg/m^3 were represented by the color purple.

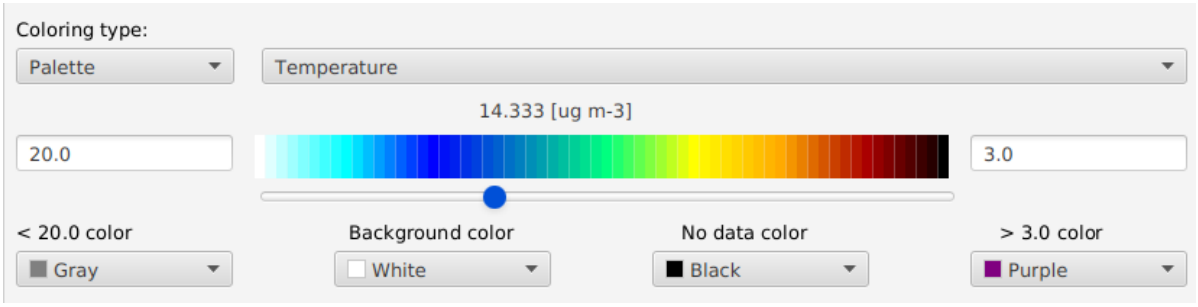


Fig. 1.12 Setting colors to display data outside the selected interval.

To create a new palette, you can use any text editor. Each color value is written in RGB hexadecimal notation, such as 0x00 0xff 0xff. Once you have created the palette, save it in the **palettes** directory, and it will be available for use along with the existing palettes.

1.2.2 Color range

If you select a parameter that doesn't have a corresponding color palette, the **Color range** mode will be automatically chosen. In this mode, the color palette is generated based on the color that corresponds to the minimum value (**From**) to the color that corresponds to the maximum value (**To**) of the selected parameter. You can adjust the number of colors in the palette using the selector labeled **Intervals**.

In the example shown in 1.13, the **backscatter coefficient** was selected. The **Color range** mode was automatically selected, where blue represents a backscatter coefficient of 0, and red represents a value of 5.448E-06 $m^{-1}sr^{-1}$. The color palette consists of 20 elements, and by moving the slider cursor along the palette, you can see which color corresponds to a specific value or range of values of the correlation coefficient.

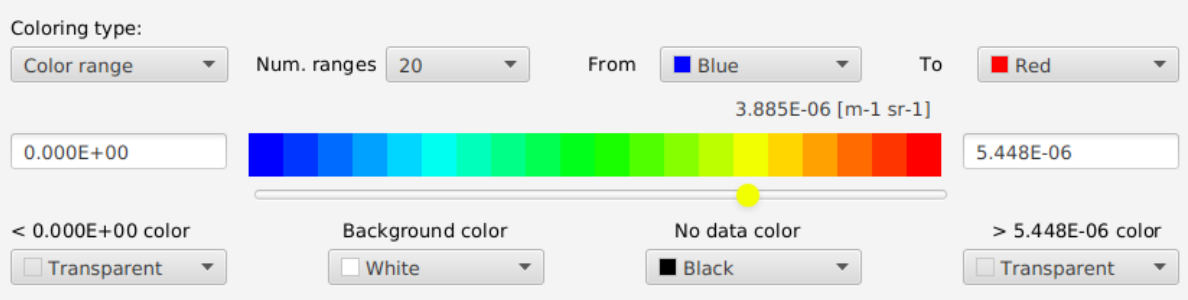


Fig. 1.13 The color palette from blue to red for the backscatter coefficient.

If you need to display data that falls outside the color coding range, there are color pickers available below the minimum and maximum values. For instance, in Fig. 1.14 the color white represents backscatter coefficient values less than 1.5E-06 $m^{-1}sr^{-1}$, whereas black corresponds to values greater than 4.5E-06 $m^{-1}sr^{-1}$.

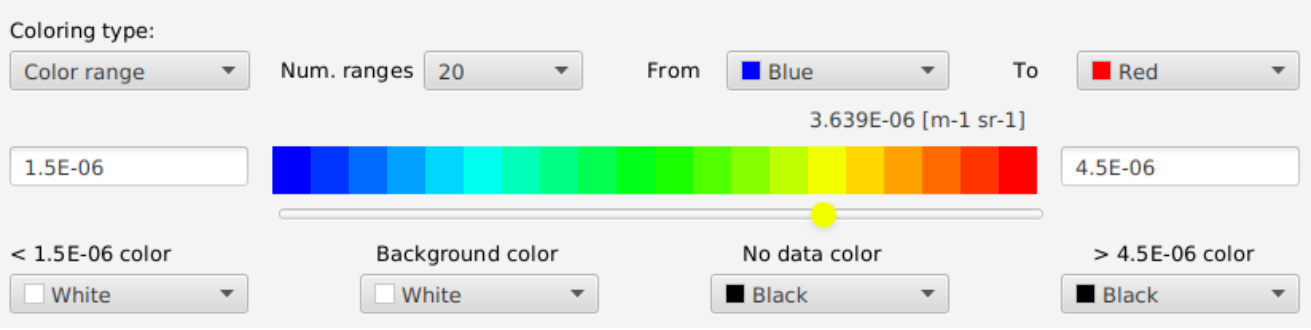


Fig. 1.14 Setting colors to display data outside the selected interval.

1.2.3 Color sequences generated by Sinebow algorithm

Using the well-proven Sinebow algorithm, you can easily generate smooth color ranges by specifying the number of intervals and allowing the color palette to be generated automatically.

In Fig. 1.15, the **particle linear depolarization ratio** was chosen and a color palette with 10 intervals was displayed. By sliding the cursor along the palette, you can easily determine which color corresponds to a specific particle depolarization ratio.

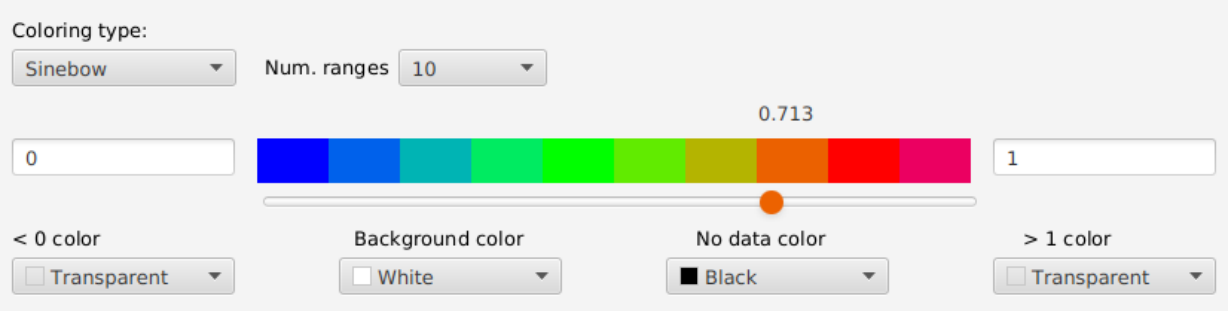


Fig. 1.15 Color palette generated by Sinebow algorithm.

To view data that falls outside the color coding range, you can utilize the color pickers located below the minimum and maximum values. To illustrate, in Fig. 1.16 the color yellow corresponds to particle depolarization ratio values less than 0.5, whereas black is used for values greater than 0.99.

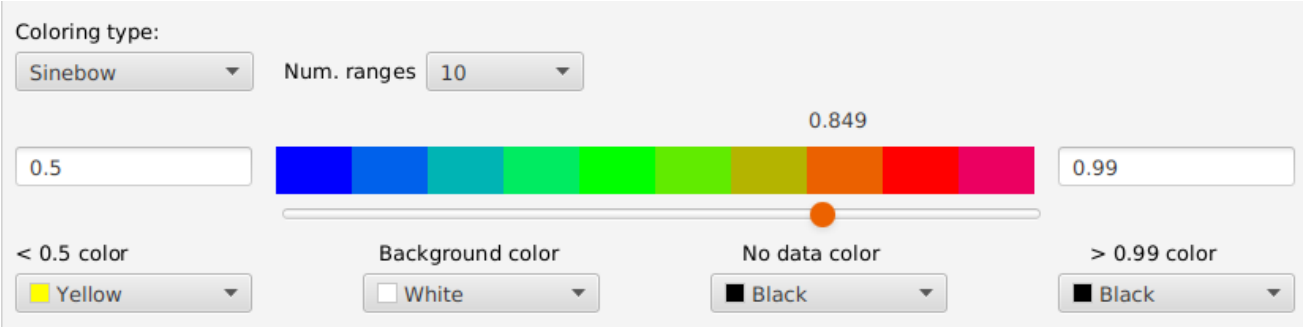


Fig. 1.16 Setting colors to display data outside the selected interval.

Sometimes radar data may contain unreliable values, which are encoded as NaNs or filled values. Use the **No data color** picker to set a color for these values.

Use **Background color** element to set it.

When you click on the "**Build image**" button (as shown in Fig. 1.1), a dynamic chart will be generated using the selected data and color palette.

2. Visualization module

The visualization module visualizes, compares, filters, and classifies lidar data. It uses a web browser to display data in 3D and can operate in both online and offline modes.

Depending on the the type of data, the following visualization charts are available:

1) Cone scan. This mode is used when the original data is obtained by scanning along the azimuth angle at a fixed zenith angle. The lidar scan is projected onto a plane in the form of a sector or circle from the maximum to minimum value of the azimuth angle (see Fig. 2.3 and 2.6).

2) Vertical cross-section. In this mode, the lidar scan is generated from data having different zenith (elevation) angle at a fixed azimuth. The diagram is constructed in the form of a sector of a circle from the maximum to the minimum value of the zenith angle (see Fig. 2.7).

3) Time series chart. This mode is used when the source data is obtained at a fixed zenith angle, close to vertical (0°). The azimuth angle is also fixed, and the data itself is a sequence of reflected signal values for different time intervals (see Fig . 2.10).

4) Classification of aerosols. Represents a time diagram in which data are grouped by aerosol type for different altitude (see Fig. 2.13).

All the above visualization charts contain the following elements:

- Chart to display data
- Color palette
- Data filter
- Information area, the content of which is dynamically determined by the position of the mouse cursor on the diagram
- Grid of geographical coordinates, and radials along azimuth and zenith angles
- Text field containing lidar coordinates and the name of the displayed parameter

2.1 Cone scan

Cone scan data is obtained by scanning along the azimuth angle at a fixed zenith angle of the lidar. As an illustration, in the data section we select the item **System variables** for **Data type** (see Fig. 1.5). Then set the value of **zenith angle of emitted laser** in selector **Parameter**. For instance, in Fig. 2.1 the zenith (elevation) angle is a constant 87.9° (90° – 87.9° = 2.1°) for all 79 observations.

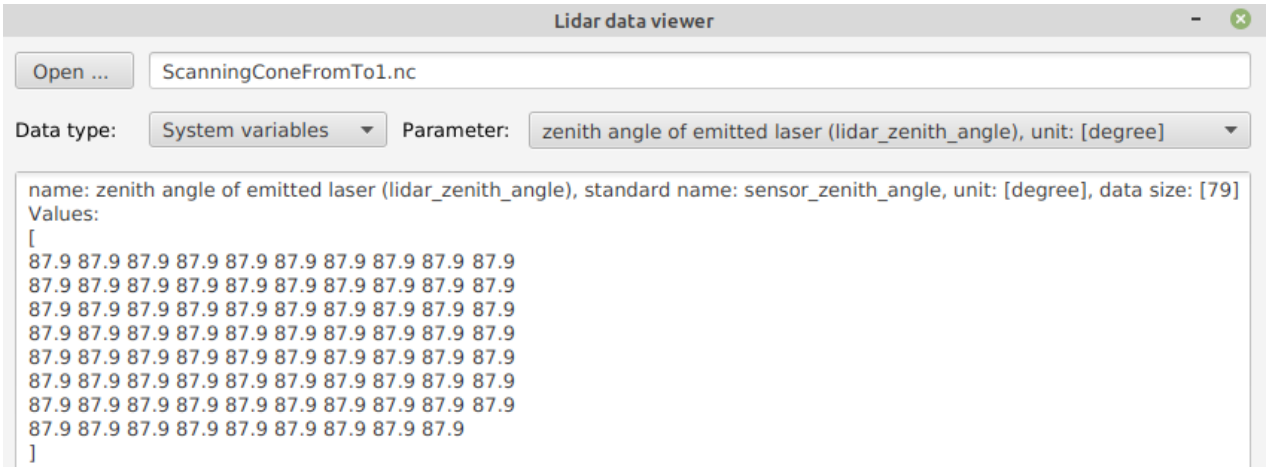


Fig. 2.1 Zenith angle values.

By selecting the **azimuth angle of emitted laser** parameter, we find that the azimuth angle contains 79 values that vary from 202.8° to 37.8° in increments of 2.5° (see Fig. 2.2).

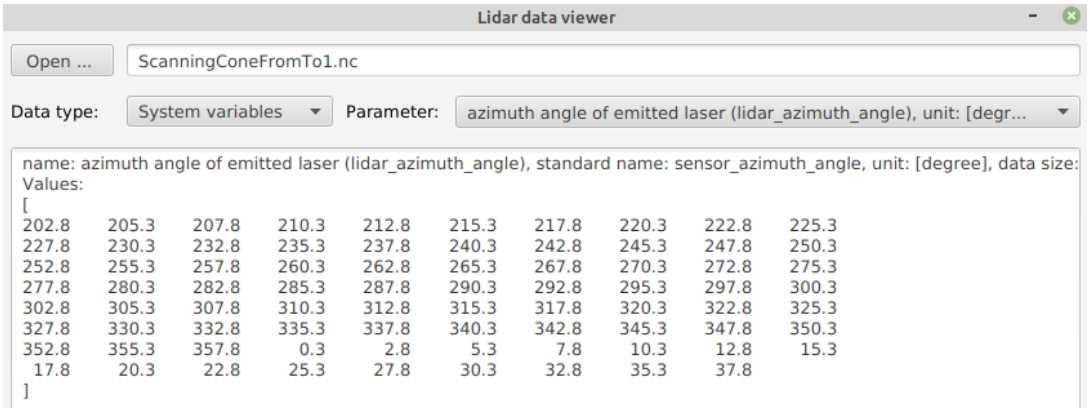


Fig. 2.2 Azimuth angle values.

In Fig. 2.3, the lidar scan for the selected parameter is projected onto the plane as a circle sector from 202.8° to 37.8°.

The diagram shown in Fig. 2.3 contains:

1) A data display area that occupies most of the screen. There is also a geographic coordinate grid with latitude and longitude markers. Polar coordinates are specified in increments of 1 km in distance and 10° in azimuth angle.
2) A data filter located at the top of the screen that allows you to display a selected range of parameter values. For example, in Fig. 2.4 shows only the values of the backscattering coefficient that lie within the limits from 3.5E-6 to 1.0E-5 $m^{-1}sr^{-1}$.
3) The color palette located on the left side of the screen. The palette is identical to that set in the color coding section (see section 1.2). The color representation of the parameter values is carried out according to the palette. When you select an element of the color palette with the mouse cursor, the data of the corresponding range is highlighted on the diagram. For example, in Fig. 2.5 all values of the backscattering coefficient having values from 5.0E-7 to 1.0E-6 $m^{-1}sr^{-1}$ are highlighted in white.
4) Information about the system and the selected option, located in the lower left corner of the screen.

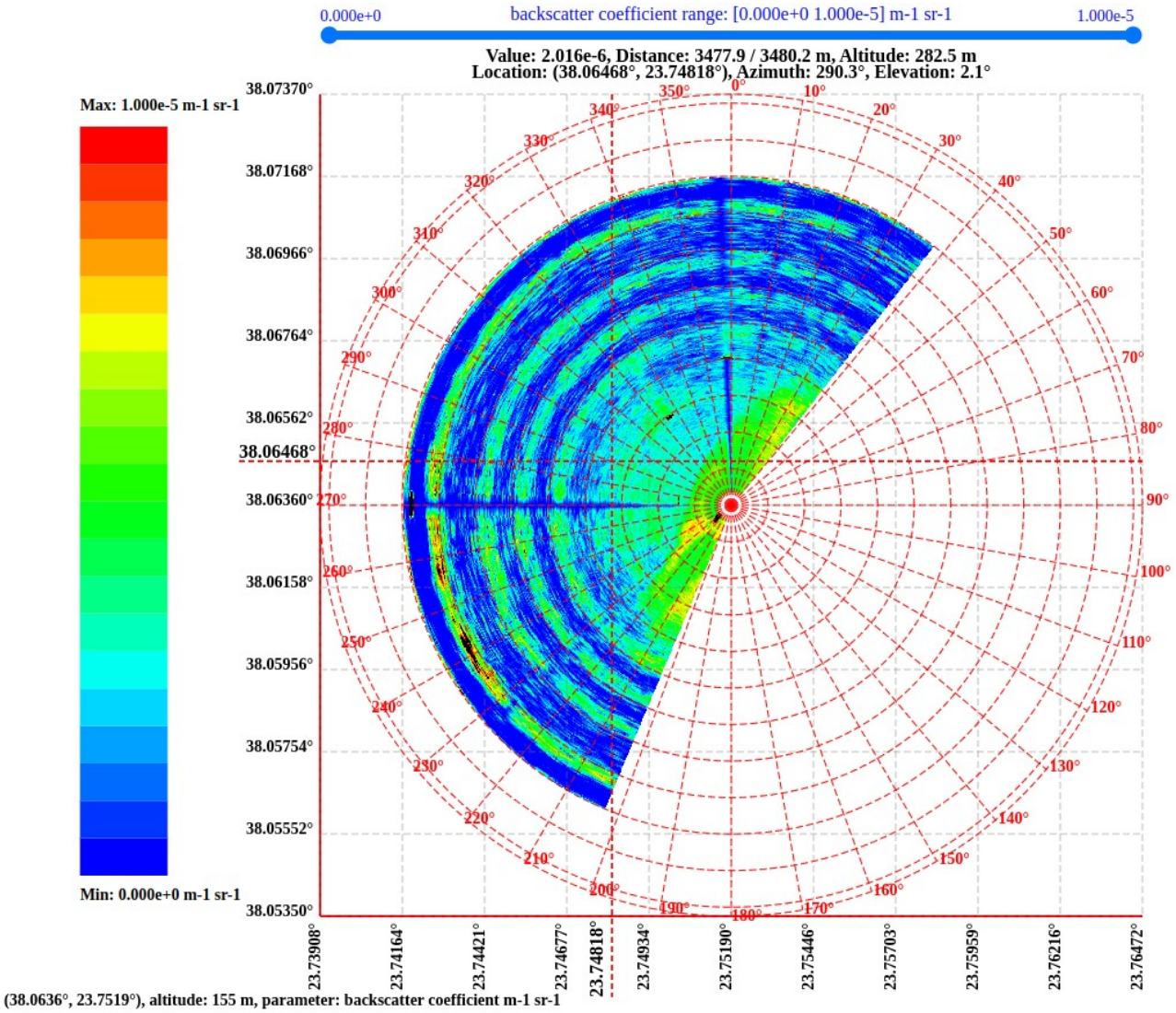


Fig. 2.3 Lidar data chart as a projection of a scanning cone onto a plane.

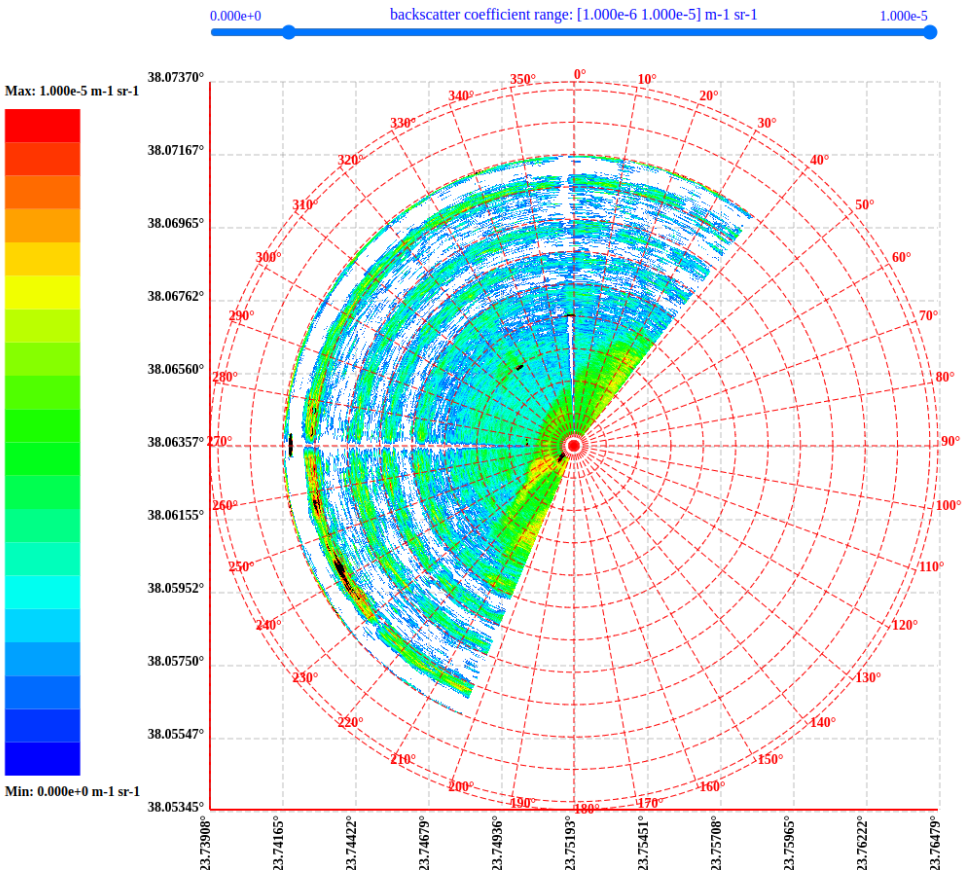


Fig. 2.4 Filtration of backscattering coefficient values.

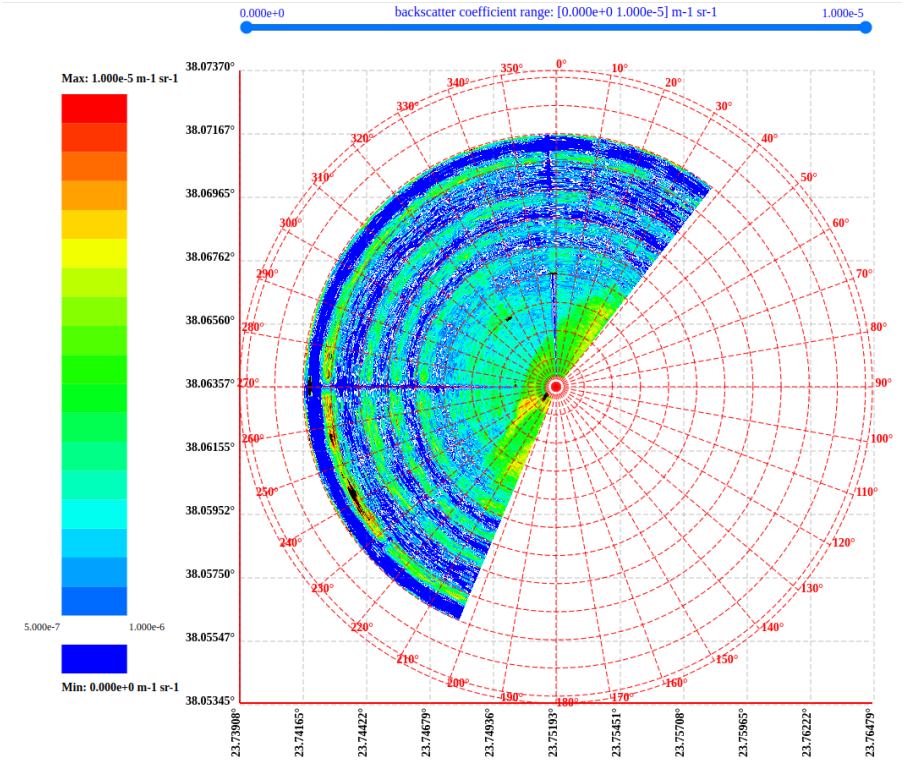


Fig. 2.5 Highlights data range according to the selected color.

As you move the mouse cursor across the diagram, geographic coordinates corresponding to the mouse position are displayed on the left and bottom of the screen. At the top of the screen, below the data filter, the following information is displayed (refer to Fig. 2.3):

- value of the selected parameter at the point (2.016E-6 $m^{-1}sr^{-1}$)
- distance from the lidar to the selected point, excluding and taking into account the elevation (3477.6 / 3480.2 m)
- geographical coordinates and altitude above sea level (38.06468°, 23.74818°), 282.5 m
- elevation and azimuth angles (2.1° and 290.3° respectively)

In Fig. 2.6 shows a circular chart of backscatter coefficient while scanning from 0 to 360° by azimuth with a fixed zenith angle.

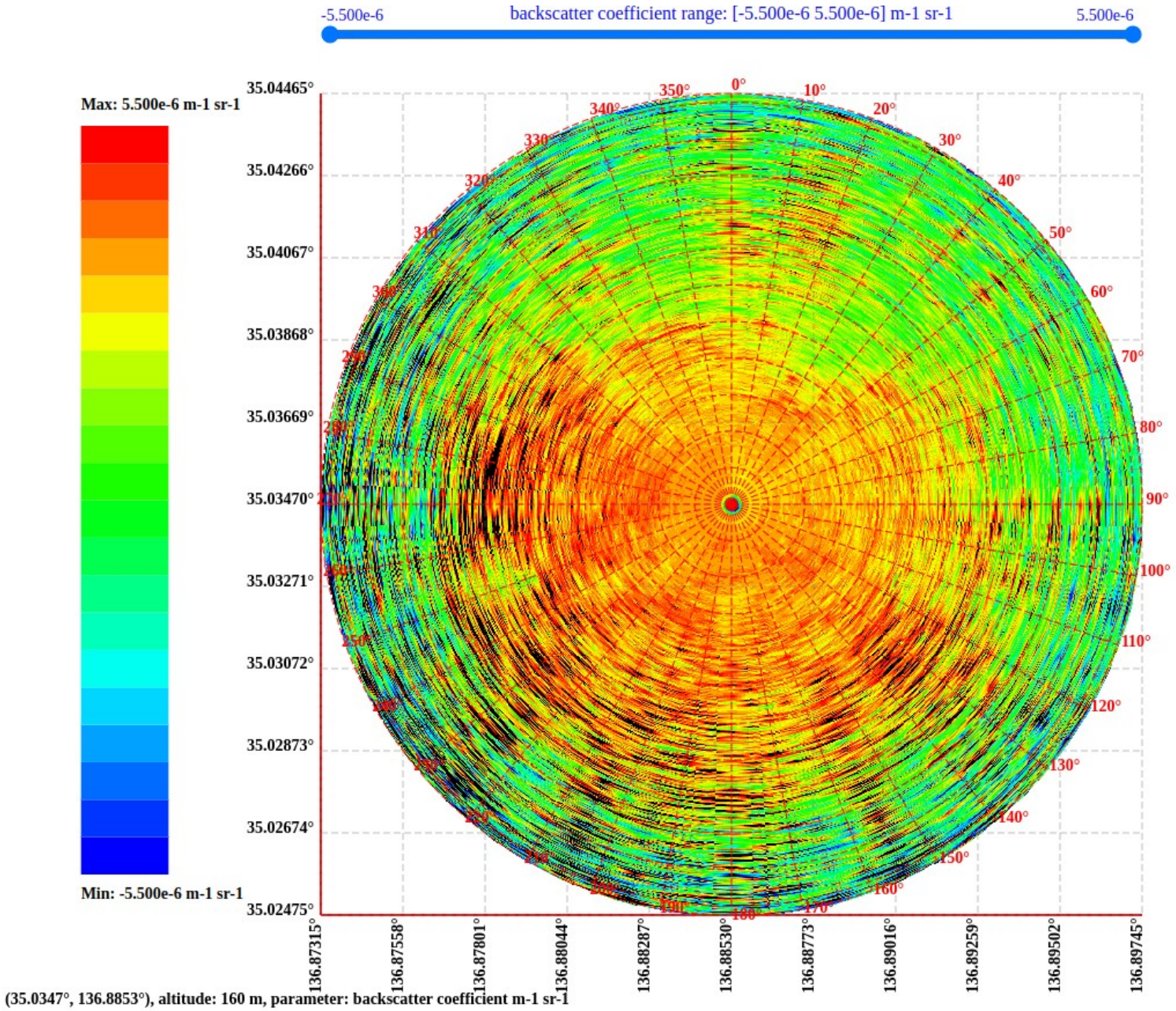


Fig. 2.6 Circular chart while scanning from 0 to 360° by azimuth.

2.2 Vertical cross-section

In this mode, the Lidar scan is produced using data with varying zenith (elevation) angles at a fixed azimuth. The diagram is constructed in the form of a sector of a circle from the maximum to the minimum value of the zenith angle (as seen in Figure 2.7). In the given example, the zenith angle changes from 90° to 0° with a step of 10°, whereas the azimuth angle is constant at 200°.

The diagram in Figure 2.7 contains the following:

1) A data display area that occupies most of the screen. There is also a coordinate grid with marks in height and distance from the lidar, with a step of 1000 m. The polar coordinate grid has a step of 10° in elevation angle.
2) A data filter located at the top of the screen, which allows you to display a selected range of parameter values. For instance, in Fig. 2.8, only the values of the particle volume depolarization ratio in the range from 0.025 to 0.3 are shown.
3) The color palette, located on the left side of the screen, which is identical to that set in the color coding section (refer to section 1.2). The coloring of the parameter values is carried out in accordance with it. When you select an element of the color palette with the mouse cursor, the corresponding range data is highlighted on the diagram. For example, in Fig. 2.9, all values of the particle volume depolarization ratio, having values from 0.007 to 0.043, are highlighted in white.
4) Information about the system and the selected parameter, located in the lower left corner of the screen.

When you move the mouse cursor over the diagram, you will notice vertical and horizontal dotted lines that appear, intersecting at the cursor location. At the intersection of the dotted lines, the value of the chosen parameter (0.016) and the elevation angle (57.7°) are displayed. To the right of the diagram, the altitude above sea level (2069 m) is displayed, and at the bottom, the distance from the lidar (1308 m) to the selected point.

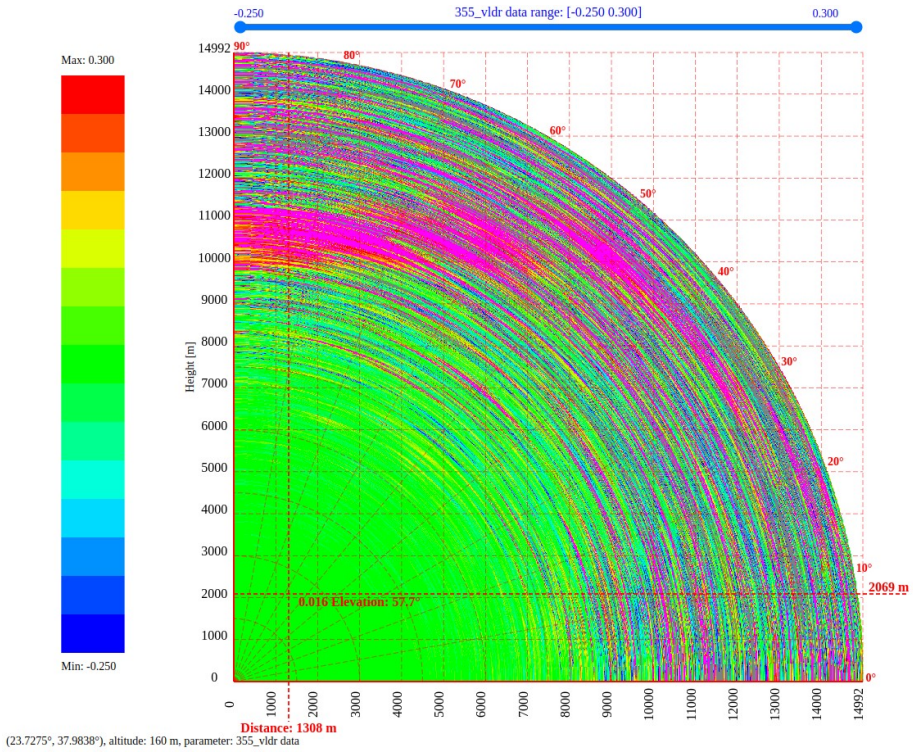


Fig. 2.7 Vertical cross-section.

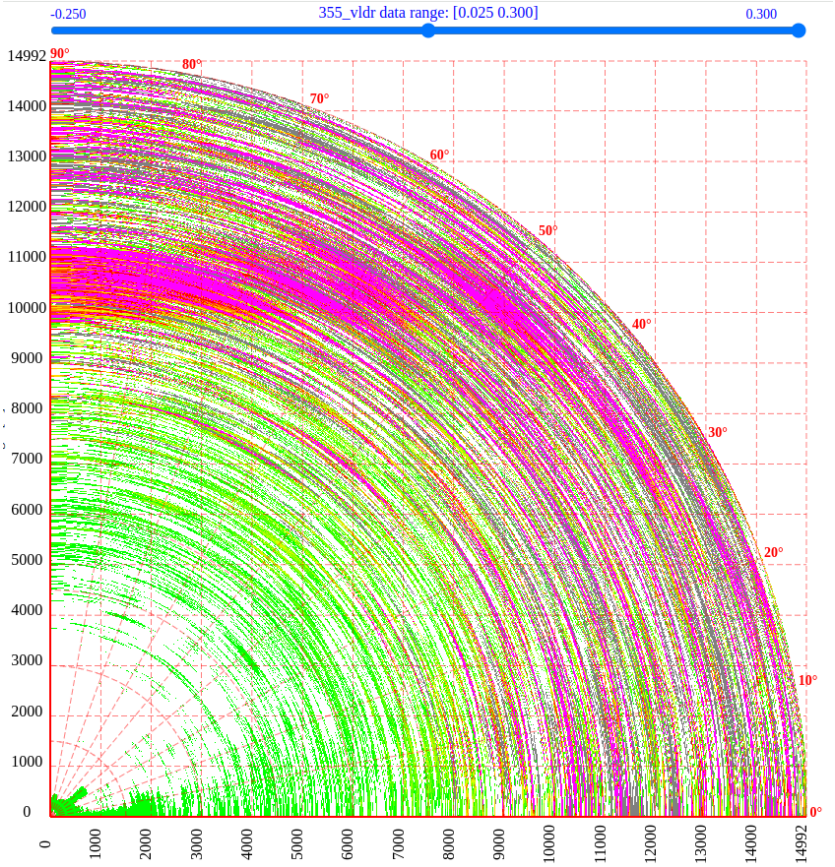


Fig. 2.8 Filtration of particle volume depolarization ratio values.

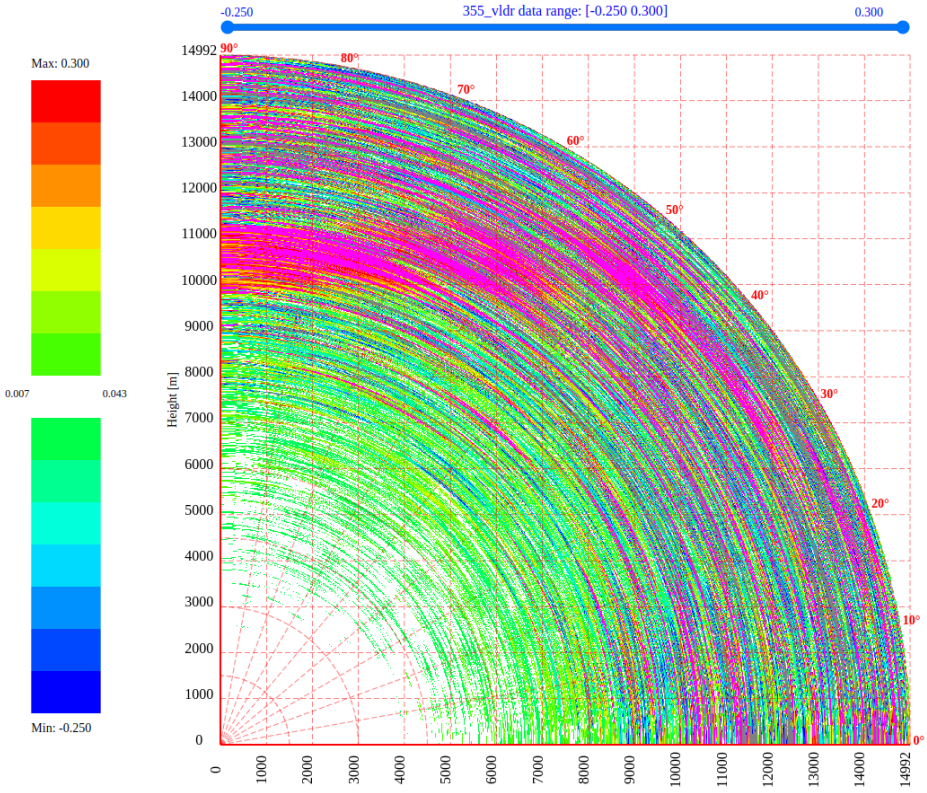


Fig. 2.9 Highlighting data range according to the selected color.

2.3 Time series chart

Data for time diagrams is collected at a fixed zenith angle close to the vertical (0°) for successive time intervals. The azimuth angle is also fixed. The collected data represents the reflected signal values for various observation periods, as shown in Fig. 2.10.

In the example below, the zenith angle is 2° and the azimuth is 0°. The observation period consists of 60 one-minute intervals.

The diagram displayed in Figure 2.10 includes the following components:

1) A data display area that occupies most of the screen. The ordinate axis shows the altitude, with marks every 1000 meters. The abscissa shows the observation time, with marks every 5 minutes.

2) A data filter located at the top of the screen that allows you to display a selected range of parameter values. For example, in Fig. 2.10, only the values of the particle volume depolarization ratio in the range from 0.01 to 0.07 are shown.

3) A color palette located on the left side of the screen, identical to the color scheme selected in the color coding section (see section 1.2). The coloring of the parameter values is carried out in accordance with the palette. When you select an element of the color palette with the mouse cursor, the data of the corresponding data range is highlighted on the diagram. For example, in Fig. 2.11, all values of the particle volume depolarization ratio from 0.007 to 0.043 are highlighted.

4) Information about the system and the selected parameter, located in the lower left corner of the screen.

As you move the mouse cursor over the chart, two histograms will appear on the right and top of the screen. The top histogram displays the distribution of values of the parameter at a fixed height for all time intervals, while the histogram on the right shows how the height data changes at a fixed observation time (see Figure 2.12).

When you move the mouse cursor over the diagram, vertical and horizontal dotted lines appear, intersecting at the cursor location. At the intersection of the dotted lines, the parameter value (0.029) is displayed. To the right of the diagram, the altitude above sea level (832 m) is shown, and at the bottom, the observation time (May 2, 2023, 20:21:28) is displayed, according to the cursor position on the screen (see Fig. 2.12).

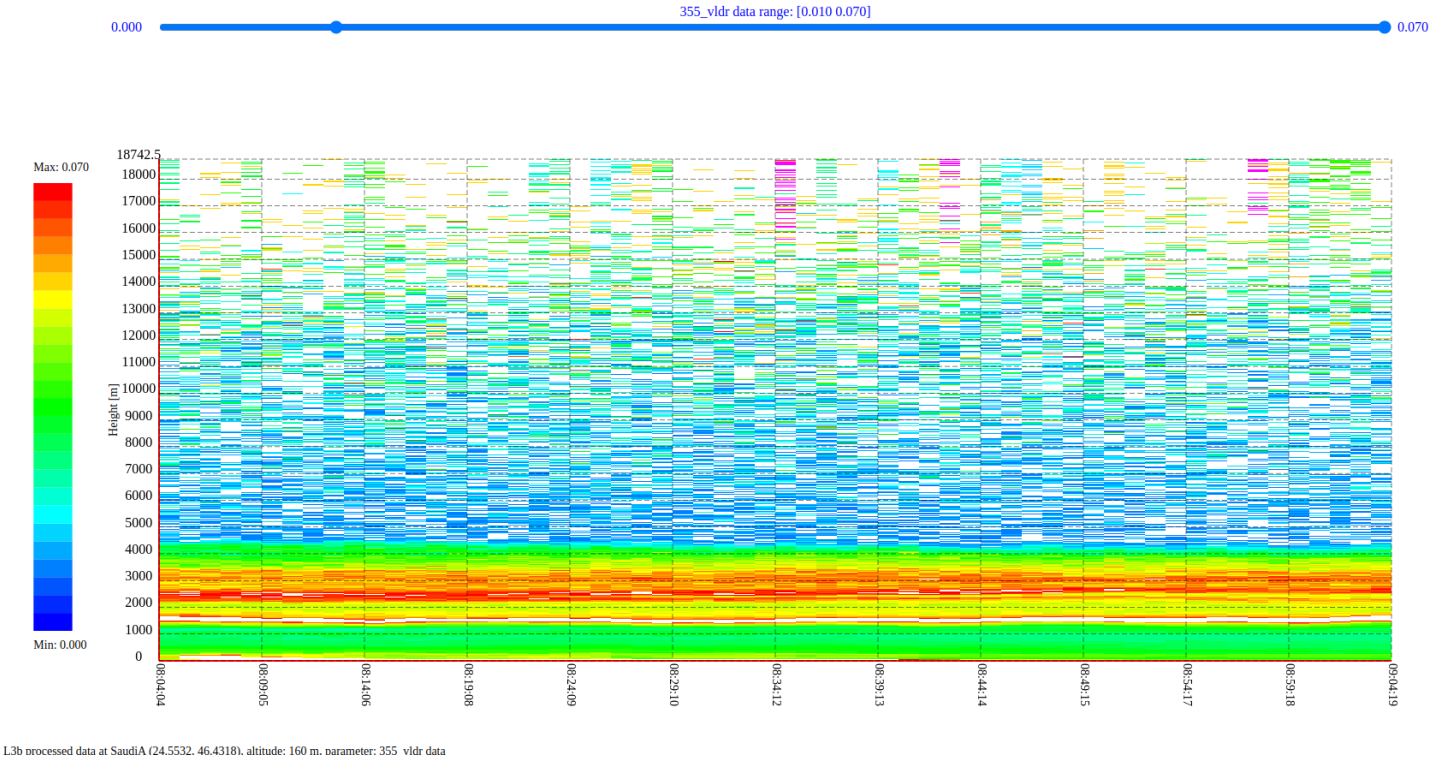


Fig. 2.10 Filtering particles volumetric depolarization ratio on the time series chart.

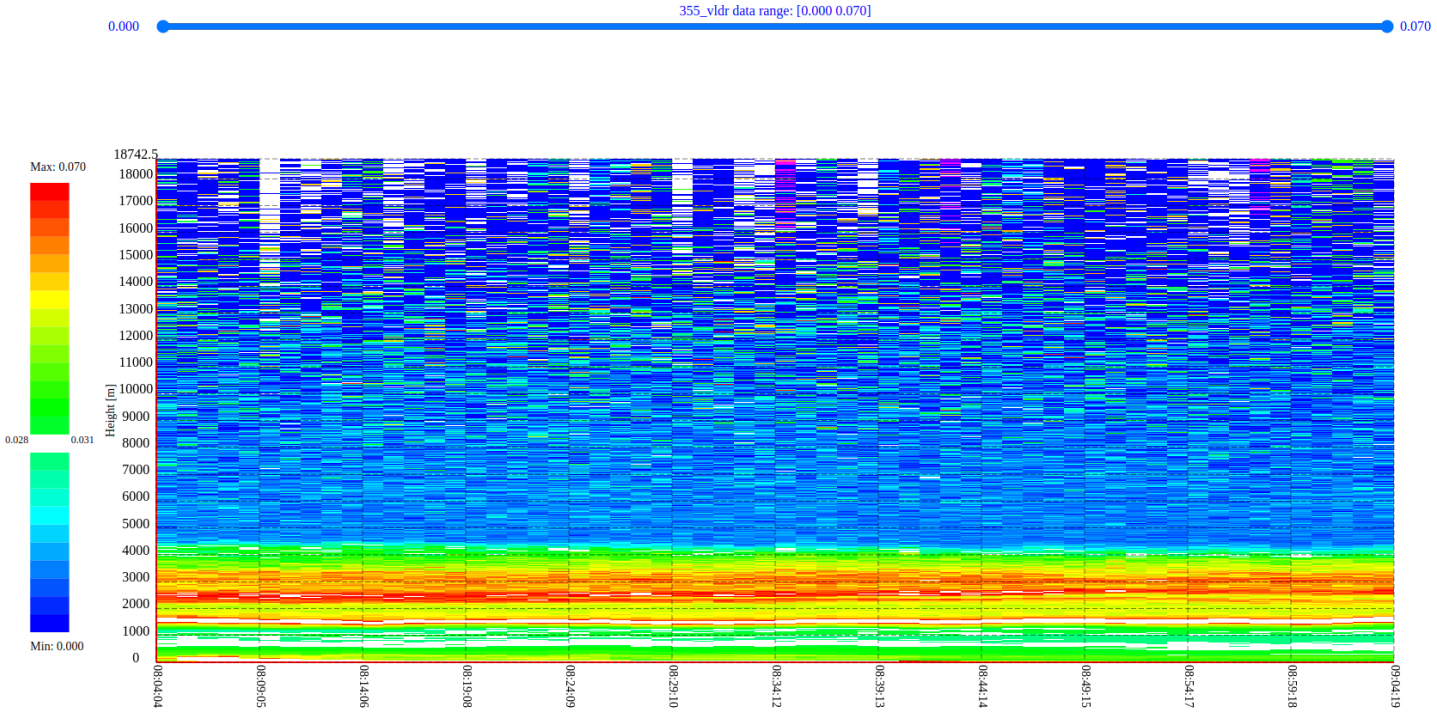


Fig. 2.11 Highlighting data range according to the selected color.

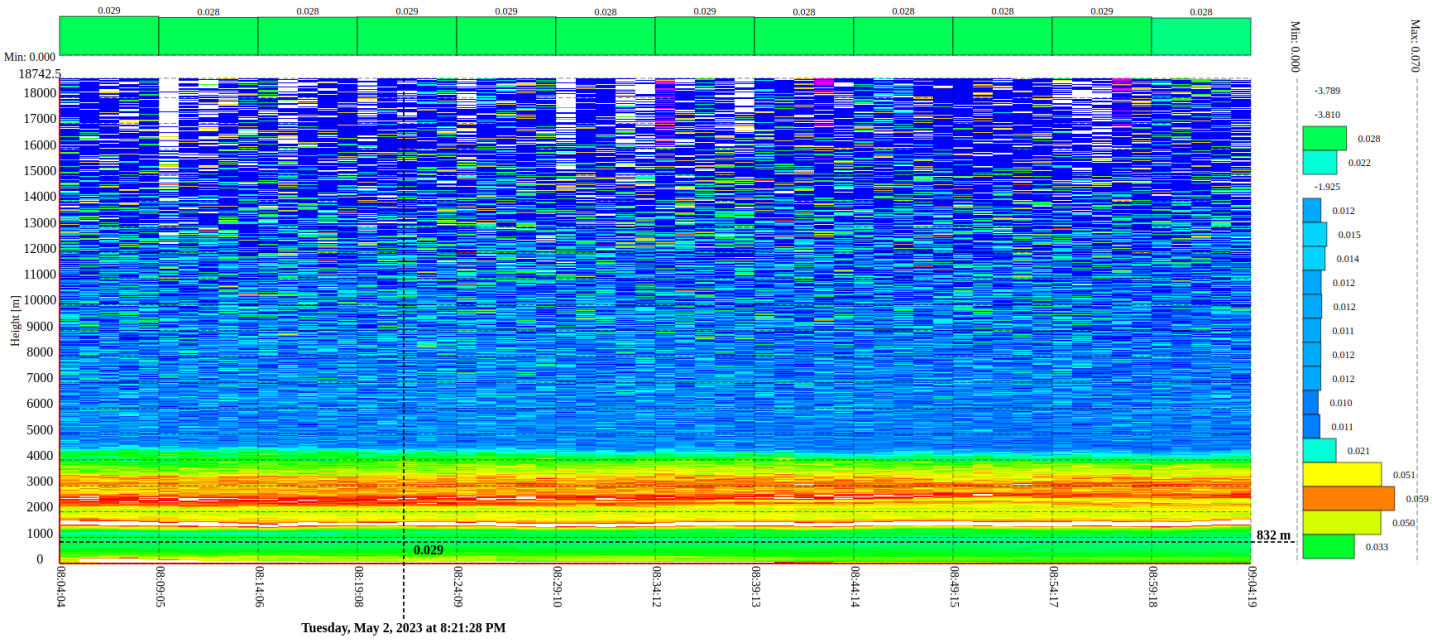


Fig. 2.12 On the top of the screen, a histogram shows the distribution of the parameter over time at a fixed height. On the right, the histogram indicates the distribution of data by height for the selected observation time.

2.4 Classification of aerosols

This diagram is a type of time chart that groups aerosol data by type and altitude.

Currently, aerosols and air pollution are classified into the following types:

- **Unclassified**.
- **Urban/dust/marine**.
- **Mixed aerosol (smoke, dust, urban)**.
- **Dust**.
- **Unclassified aerosol**.
- **Cloud**.
- **Ice cloud**.
- **Unclassified cloud**.

The data for time diagrams is collected at a fixed zenith angle close to the vertical (0°) for successive time intervals, with a fixed azimuth angle. The aerosol categories are then grouped by height for different time intervals.

For example, Fig. 2.13 shows a diagram with a zenith angle of 2° and an azimuth of 0°, with an observation period consisting of 60 one-minute intervals.

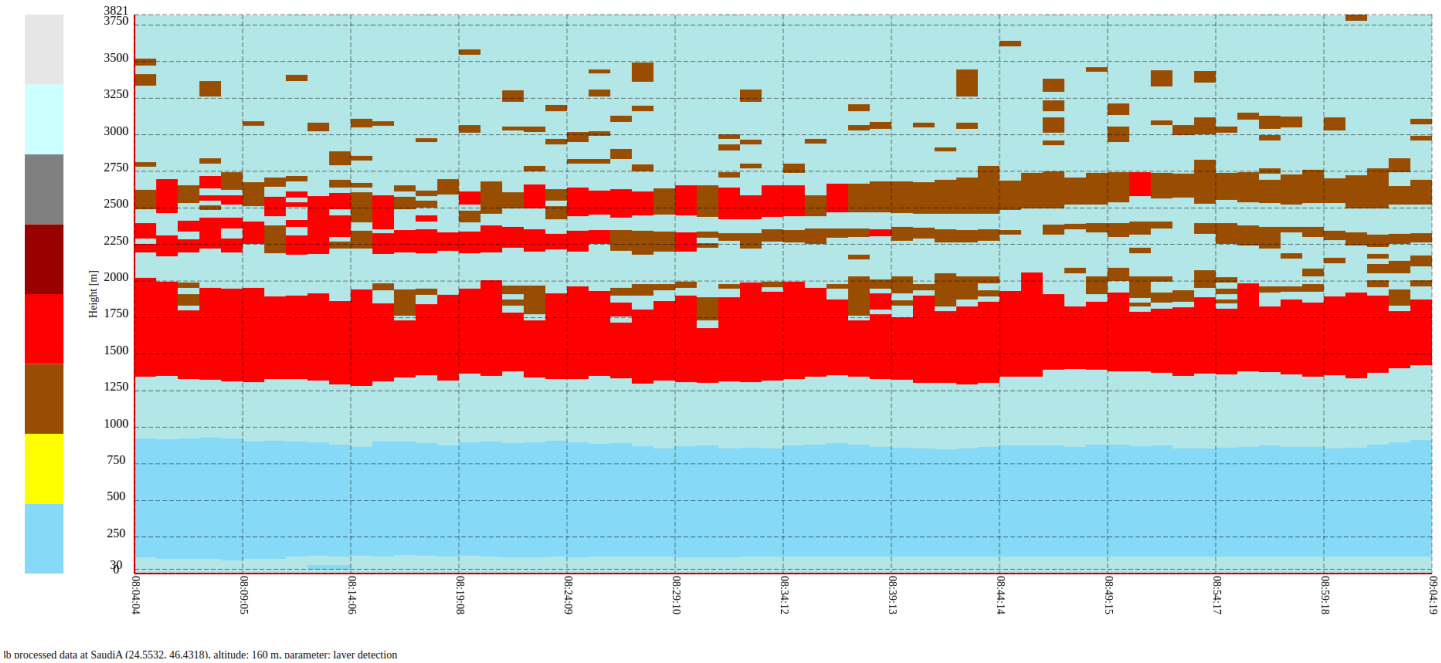
The diagram includes:

1) A data display area, with the ordinate axis showing height with marks every 250 m, and the abscissa showing observation time with marks every 5 minutes.

2) A color palette on the left side of the screen, which is identical to the color scheme selected in the color coding section. The aerosols are colored according to this palette. When you select an element of the color palette with the mouse cursor, the selected type of aerosol will be highlighted on the diagram. For instance, in Fig. 2.14, all aerosols containing dust are highlighted in green.

3) Additional information about the location of the lidar and the selected parameter is located in the lower left corner of the screen.

When you move the mouse cursor over the diagram, vertical and horizontal dotted lines appear at the cursor location, and the aerosol type is displayed where the dotted lines intersect. The altitude above sea level is shown to the right of the diagram (2618 m), and the observation time is displayed at the bottom of the diagram (May 2, 2023, 20:37:53) according to the cursor position on the screen (see Fig. 2.15).



Ib processed data at SaudiA (24.5532, 46.4318), altitude: 160 m, parameter: layer detection

Fig. 2.13 Distribution of aerosols by height and time.

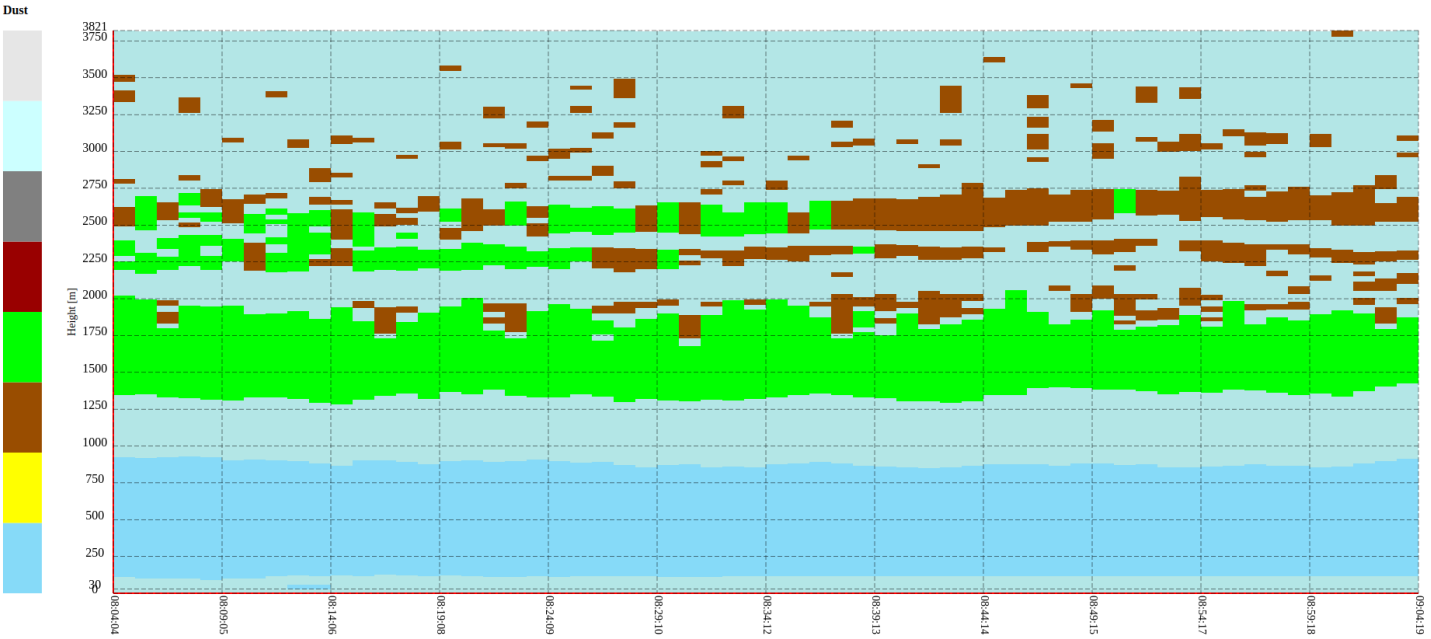


Fig. 2.14 Highlighting aerosols containing dust in green.

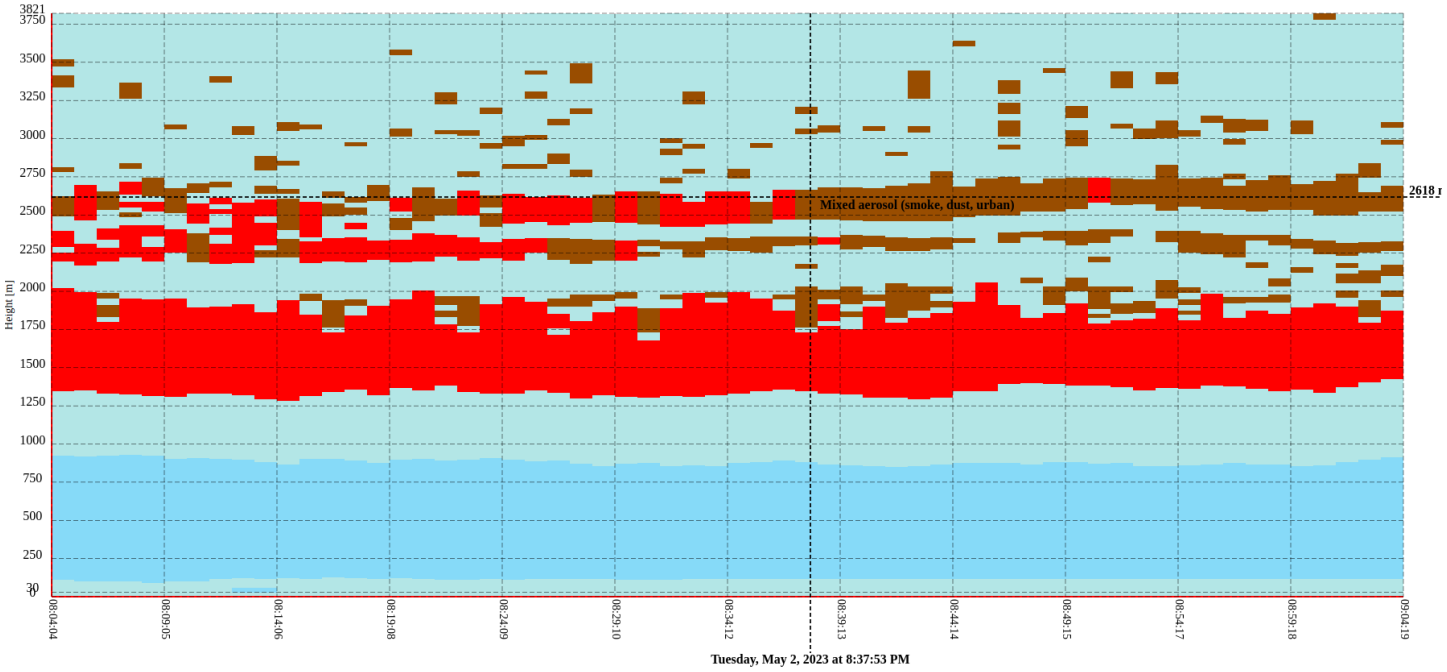


Fig. 2.15 Aerosol properties at the selected point.

Appendix 1. List of supported parameters

Parameter name and abbreviation	Data range	Standard palette
Backscatter retrieval (**355_beta_klett**)	$m^{-1}sr^{-1}$	N/A
Backscatter retrieval **(backscatter_retrieval**)	$m^{-1}sr^{-1}$	N/A
Backscatter retrieval - water filtered (**backscatter_retrieval_filtered**)	$m^{-1}sr^{-1}$	N/A
Liquid water peaks (**liquid_water_peaks**)	$m^{-1}sr^{-1}$	N/A
Liquid water peaks distance (**liquid_water_peaks_distance**)	$m^{-1}sr^{-1}$	N/A
Solid bodies (**hard_targets**)		N/A
PM10 concentration (**pm_retrieval**)	[0, 140] mg/m^3	Particles concentration
PM2.5 concentration - water filtered (**pm_retrieval_filtered**)	[0, 140] mg/m^3	Particles concentration
Interpolation of pm filtered (**interpolation_of_pm_filtered**)	[0, 140] mg/m^3	Particles concentration
Particle linear depolarization ratio (**355_pldr**)	[0.1, 1.0]	Depolarization ratio
Volume linear depolarization ratio (**355_vldr**)	[0.03, 0.2]	Depolarization ratio

Appendix 2. List of auxiliary variables

Variable name	Description	Unit
air_temperature	Ambient temperature	°K / °C
air_pressure	Atmosphere pressure	hPa
azimuth_angle	Azimuth angle	°
zenith_angle	Zenith angle	°
range	Lidar range	m
time	Measurement time	Seconds since January 1-st, 1970
time_bnds	Measurement interval	Seconds since January1-st, 1970

Appendix 3. Weather and storm warning parameters

Warining parameter	Description
region	Name of the region for which the warning is issued
region_id	Region ID for which the warning is issued
longitude_min	Minimum longitude of the region for which the warning is activated
longitude_max	Maximum longitude of the region for which the warning is activated
latitude_min	Minimum latitude of the region for which the warning is activated
latitude_max	Maximum latitude of the region for which the warning is activated
threshold	Threshold level for activating a storm warning
region_bins	Number of storm bins in the region
exceedance_number	Exceedance number of threshold level in the region
min_points	Minimum number of storm bins to activate warning
alert_time	Time of warning announcement
alert_time_bnds	Time interval for which the warning is issued