Comenius University, Bratislava
Faculty of Mathematics, Physics and Informatics

Visualising Data from CloudSat and CALIPSO Satellites

2010

Peter Kuma

Comenius University, Bratislava
Faculty of Mathematics, Physics and Informatics

Visualising Data from CloudSat and CALIPSO Satellites

Bachelor's Thesis

Degree Programme: Physics
Field of Study: 4.1.1 Physics
School: Division of Meteorology and Climatology
Department of Astronomy, Physics of the Earth and Meteorology
Mentor: Mgr. Ivan Bašták Ďurán, PhD.

Bratislava, 2010

Peter Kuma

Univerzita Komenského v Bratislave
Fakulta matematiky, fyziky a informatiky

Zadanie

Meno a priezvisko študenta: Peter Kuma
Študijný program: Fyzika
Študijný odbor: 4.1.1 Fyzika
Typ záverečnej práce: Bakalárska práca
Jazyk záverečnej práce: Anglický
Sekundárny jazyk: Slovenský

Názov: Visualising Data from CloudSat and CALIPSO Satellites
Cieľ práce: Vizuálne spracovanie údajov z meteorologických družíc Cloudsat a CALIPSO.

Vedúci: Mgr. Ivan Bašták Ďurán, PhD.
Školiteľ: Mgr. Ivan Bašták Ďurán, PhD.
Katedra: Katedra astronómie, fyziky Zeme a meteorológie
Vedúci katedry: Prof. RNDr. Peter Moczo, DrSc.
Spôsob sprístupnenia elektronickej verzie práce:

Dátum schválenia:

vedúci katedry

študent

vedúci, resp. školiteľ

vedúci

Vizualizácia dát zo satelitov CloudSat a CALIPSO

Súhrn práce

CloudSat a CALIPSO sú satelity obiehajúce okolo Zeme na polárnej dráhe, slúžiace primárne na meranie oblakov a aerosólov. Prevádzkované sú organizáciami NASA a CNES. Sú súčasťou formácie satelitov nazývanej A-Train (Afternoon Train, čiže poobedný), lebo prelietajú cez rovník približne o 13:30 stredného miestneho času. Vďaka svojej blízkosti (iba asi 15 min) a rozmanitosti meracích prístrojov poskytujú bohaté informácie o atmosfére a povrchu Zeme na danom mieste a v danom čase.

CloudSat nesie na palube radar CPR podobný pozemným zrážkovým rádiolokátorom využívanými meteorologickými službami, pracujúci na frekvencii 94 GHz. Slúži na vytváranie dvojrozmerných rezov atmosférou od povrchu do 30 km, na ktorých sú identifikovateľné hlavne oblaky tvorené z kvapiek.

CALIPSO nesie lidar (laserový radar) CALIOP, pracujúci vo viditeľnom a infračervenom spektre (presnejšie vlnová dĺžka 532 nm, resp. 1064 nm). Jeho hlavné produky sú podobné ako produkty CPR, čiže vertikálne rezy atmosférou. Vďaka kratšej vlnovej dĺžke je citlivý na menšie objekty, hlavne aerosóly a oblaky tvorené z ľadových kryštálov.

Satelity CloudSat a CALIPSO, ale aj ostatné členy zostavy A-Train, sú vďaka širokej plejáde produktov, globálnemu pokrytiu a súbežnosti meraní veľmi užitočným nástrojom pre výskum atmosféry a klimatického systému Zeme. Sú využívané tak v meteorologickom, ako aj klimatologickom výskume.

Keďže dostupné aplikácie na vizualizáciu dát z CPR a CALIOP buď nespĺňajú naše požiadavky na vyextrahovanie maximálnej úrovne detailov a produkčnú kvalitu výstupu, alebo vyžadujú veľmi nákladné platformy ako ITTVIS IDL, bolo potrebné, aby sme vyvinuli vlastný nástroj. To sme si stanovili ako cieľ tejto práce.

Takýto nástroj sme vyvinuli a nazvali sme ho ccplot. Je to unixový program používajúci voľne dostupné knižnice a programovací jazyk Python. Umožnuje vizualizáciu niekoľkých typov produktov nielen z CPR a CALIOP, ale aj spektrorádiometra MODIS na satelite Aqua (tiež člen zostavy A-Train), a tak užívateľom poskytuje pomerne široký prehľad o študovanej situácii. ccplot sme uverejnili prostredníctvom Internetu pod licenciou umožňujúcou bezplatné používanie bez obmedzení, ako aj úpravu zdrojového kódu a redistribúciu.

V tejto práci sa sústredíme na predstavenie jednotlivých produktov, vysvetlenie fyzikálneho princípu ich merania a spracovania, na technické detaily formátu používaného na distribúciu produktov, detailný popis implementácie a algoritmov použitých v programe ccplot, a podanie návodu, ako používať tento program.

Abstrakt

Kuma, P., 2010: Vizualizácia dát zo satelitov CloudSat a CALIPSO. Univerzita Komenského, Bratislava, Fakulta matematiky, fyziky a informatiky, Katedra astronómie, fyziky Zeme a meteorológie. 77pp. Školiteľ: Bašták Ďurán, I.

CloudSat a CALIPSO sú pozemské satelity obiehajúce na polárnej dráhe prevádzkované NASA, resp. NASA a CNES. CloudSat nesie radar vysielajúci na milimetrovej vlnovej dĺžke na pozorovanie oblakov. CALIPSO nesie polarizačný lidar merajúci vo viditeľnom a infračervenom spektre na pozorovanie aerosólov a studených oblakov. Dáta z týchto satelitov sú distribuované vo forme HDF4 a HDF-EOS2 súborov. Predstavujeme softwarový nástroj *ccplot* schopný vizualizovať niekoľko dátových zostáv z produktov *CloudSat 2B-GEOPROF*, *CALIPSO Lidar L1B Profiles Products*, *CALIPSO Lidar L2 Cloud Layer Products* a *Aqua MODIS L1B Products*. *ccplot* je skriptovateľný, unixový nástroj pracujúci cez príkazový riadok. *ccplot* sme uvoľnili na Internete pod open-source kompatibilnou BSD licenciou.

Kľúčové slová: CloudSat, CALIPSO, MODIS, A-Train, HDF4, HDF-EOS2, ccplot, graf, vizualizácia

Abstract

Kuma, P., 2010: Visualising Data from CloudSat and CALIPSO Satellites. Comenius University, Bratislava, Faculty of Mathematics, Physics and Informatics, Department of Astronomy, Physics of the Earth and Meteorology. 77pp. Mentor: Bašták Ďurán, I.

CloudSat and CALIPSO are NASA, resp. joint NASA and CNES polar-orbiting Earth observation satellites. CloudSat carries a millimetre-wave radar for observation of clouds. CALIPSO carries a visible and infrared polarisation-sensitive lidar for observation of aerosols and ice-phase clouds. Data from these satellites are distributed in the form of HDF4 and HDF-EOS2 product files. We introduce a software tool *ccplot* capable of visualising several data sets from the *CloudSat 2B-GEOPROF*, *CALIPSO Lidar L1B Profiles*, *CALIPSO Lidar L2 Cloud Layer* and *Aqua MODIS L1B* products. *ccplot* is a scriptable, unix command-line tool. We released *ccplot* on the Internet under the open-source-compatible BSD license.

Keywords: CloudSat, CALIPSO, MODIS, A-Train, HDF4, HDF-EOS2, ccplot, plot, visualization

Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank the CloudSat, CALIPSO and MODIS missions for giving us access to data products through their web ordering systems, Mgr. Ivan Bašták Ďurán, PhD. and Mgr. Alois Sokol for consultation in preparation of the thesis and testing of ccplot, the developers of PyNIO, matplotlib, numpy, basemap, and Python for providing us with a strong software basis for development of ccplot, and the open-source hosting provider SourceForge for offering a free web hosting service for the ccplot web site and supplementary development tools.

Chapter 1

Introduction

CloudSat and CALIPSO are Earth observation satellites launched and operated by NASA, and NASA and CNES (respectively), developed in order to deepen our understanding of clouds, aerosols, and how they influence the Earth's radiation budget. As of June 2010 they are still in operation, and so far they have generated hundreds of terabytes of data, ranging from raw sensor measurement to highly processed measurements combined with data from other satellites, model outputs and databases. All this information can only be useful to the broader scientific community if they are provided with tools that enable them to visualise it. Although the CloudSat and CALIPSO missions provide such tools, they have a number of shortcomings, which make them unsuitable in some situations. They are either in the form of ITTVIS IDL and MATLAB scripts, which are expensive proprietary platforms, or provided through the web service Giovanni, which does not offer the flexibility of a standalone application. There is also an implementation of a CALIPSO visualisation tool for Google Earth, but it does not provide the level of details of traditional two-dimensional forms of presentation and publication quality output. To accommodate the needs of our research at the *Department of Astronomy, Physics of the Earth and Meteorology* of the *Comenius University*, it was necessary to develop a computer program which would allow us to visualise this data efficiently and in high quality. The aim of this thesis was to develop and document such a tool. We shall call it ccplot.

1.1 Goals

The following features were desired:

- **Products support.** Support several data sets, especially:
  - **CALIPSO:** Total Attenuated Backscatter 532 nm, Attenuated Backscatter 1064 nm, Perpendicular Attenuated Backscatter 532 nm, Integrated Attenuated Backscatter 532 nm, Integrated Attenuated Backscatter 1064 nm
  - **CloudSat:** Radar Reflectivity Factor
  - **MODIS Level 1:** Band 1 RSB, Band 31 TEB
- **Extent selection.** Allow plot extent to be selected vertically by height, and horizontally by rays, time, geographical coordinates, scanlines and samples.
- **Color maps.** Custom color maps for the supported data sets should be constructed.

- **Map projections.** At least Transverse Mercator projection should be supported.
- **Interpolation algorithm.** The interpolation algorithm should preserve as much details as possible.
- **Scriptability.** The program should provide interface which allows it to be used with other programs and scripts.

1.2 CloudSat and CALIPSO Satellites

The CloudSat and CALIPSO missions are build on the legacy of ground-based rainfall radars and airborne lidars, but the extent of their coverage is unmatched by any ground or air operations. CloudSat is a satellite equipped with a millimetre-wavelength radar especially suited for studying the properties of warm and mixed-phase clouds. The primary products coming from CloudSat are two-dimensional vertical cross-sections of the atmosphere extending from the ground to some 30 km of altitude.

CALIPSO is equipped with a visible and near-infrared lidar. Due to its small wavelength, it is capable of detecting ice-phase clouds and aerosols. The primary products are cross-sections of the atmosphere similar to those of CloudSat. Because CloudSat and CALIPSO fly in a formation no more than 15 s apart, their output can be readily matched to make a more comprehensive view of the situation.

Thanks to the global scale and time continuity of the measurements CloudSat and CALIPSO provide a great potential for advancement of our understanding of processes influencing the Earth's climate system. The data can also aid meteorologists in studying the structure and development of clouds and aerosols, although not in weather forecasting, because of the intermittent character of coverage inherent to polar-orbiting satellites.

Data from CloudSat and CALIPSO are well-suited to be combined with measurements from the visible and infrared spectroradiometer MODIS carried on board of the satellite Aqua, thereby providing the user with information about broader circumstances surrounding the situation that is being studied.

CloudSat, CALIPSO and Aqua are members of a larger formation of Earth observation satellites *A-Train*, operated mostly by NASA.

Organisation

- **Chapter 1. Introduction** explains what the CloudSat and CALIPSO satellites are, and what kind of measurements they provide.
- **Chapter 2. A-Train** starts by introducing the A-Train constellation of satellites, and continues by describing their instruments and data products provided by the missions.
- **Chapter 3. The Physical Basis** aims to present the reader with the scientific basis underlying the operation of radars and lidars by first introducing the physical laws governing radiation transfer and scattering in the atmosphere, and secondly by explaining equations used by the missions in converting of raw data originating from detectors into useful physical quantities suitable for visualisation.

- **Chapter 4. HDF4 Data Files** provides information on the technical details of the file standard employed by NASA EOS missions for storage and distribution of their products — the HDF4 and HDF-EOS2 file formats. Particularities of CloudSat, CALIPSO and MODIS such as the file naming conventions and fine data structure are also discussed in this chapter.
- **Chapter 5. Visualising CloudSat** and CALIPSO Data strives to document the design and implementation details of ccplot, including the relationship of various components of ccplot, calculations of plot dimensions, and the interpolation and layer processing algorithms.
- **Chapter 6. ccplot Manual** is a standalone part of the thesis aimed at proving a first-time ccplot user with an easy to follow tutorial, diving into more complex aspects such as plot customisation and description how to make your own color maps.
- **Chapter 7. Conclusion** summarises the outcomes of our work on ccplot, and presents visions we have for the future versions of ccplot.
- **Appendix A. ccplot Manual Page** is a full ccplot reference in the form of a traditional UNIX manual page.
- **Appendix B. Case Studies** contains three case studies serving as a visual presentation of what can be achieved with ccplot.

Chapter 2

A-Train

A-Train, also called the '*Afternoon constellation*', is a formation of five polar-orbiting satellites, one of which was launched by the French space research agency CNES, and the remainder were launched as part of NASA EOS (Earth Observing System) and NASA ESPP (Earth System Science Pathfinder) missions. The primary focus of the constellation is to provide observations of clouds and aerosols which would not be possible from ground-based or airborne applications. Aqua, the first member of the constellation, was launched in 2002, followed by Aura and PARASOL in 2004, and CloudSat and CALIPSO in 2006 (A-Train Factsheet, 2003; King, 2006). The group was to be joined by OCO (Orbiting Carbon Observatory) in 2009; however, the satellite failed to make orbit and disintegrated in the atmosphere (Palmer, 2009). Fig. 2.1 gives a simplistic view of the constellation.

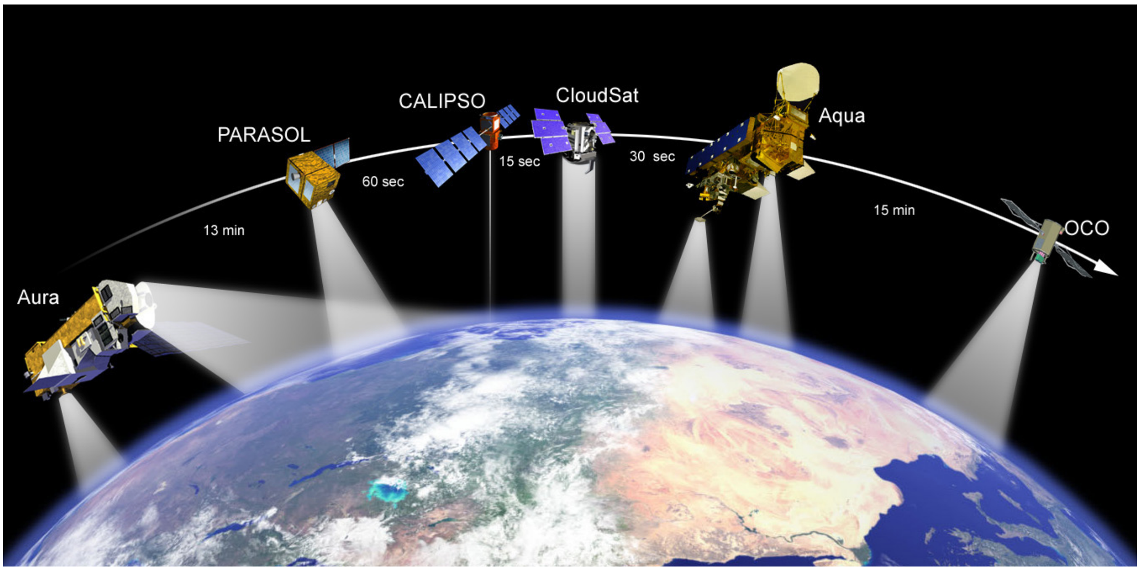


Figure 2.1 | A not-to-scale overview of the A-Train constellation. Listed under the track is the approximate temporal separation. Note that as a result of launch failure, OCO is not in the constellation. [Adapted from http://www.nasa.gov/mission_pages/cloudsat/multimedia/a-train.html.]

The satellites fly on a 705-km sun-synchronous retrograde orbit at an inclination of 98°, and velocity of about 7 km s^{-1}. The leading and trailing members are separated by approx. 15 min. The formation is dubbed '*afternoon*', because it crosses the equator at 1:30 pm local mean time, circulating around the Earth 14.56 times per 24 h (CloudSat Standard

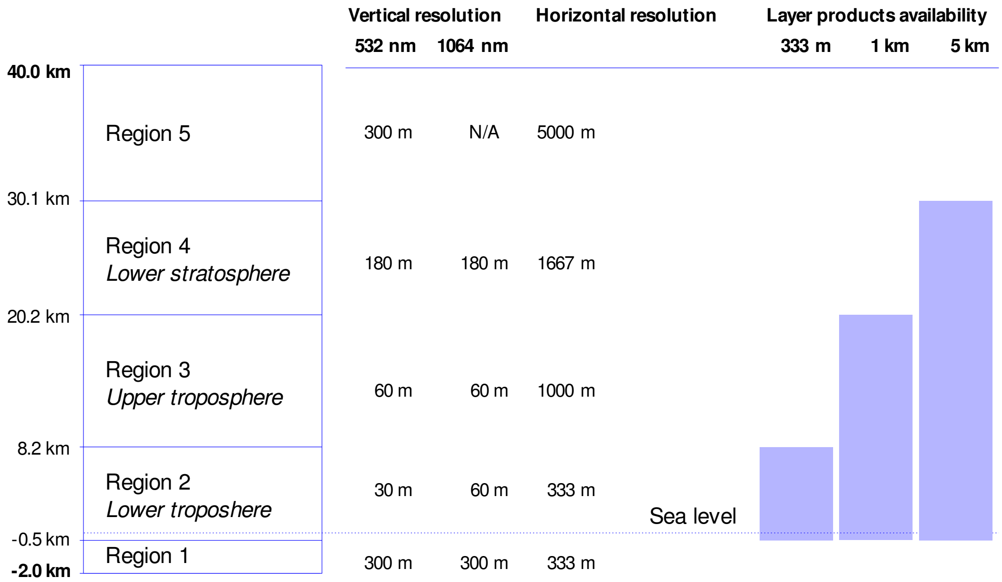


Figure 2.2 | CALIOP regions. Typically, products based on CALIOP measurements cover the lowest 40 km of the atmosphere, separated logically into five regions based on sampling resolution (Winker et al., 2004).

Data Products Handbook, 2008). The A-Train travels northward during the day half-orbit, and southward during the night half-orbit. The leading satellite Aqua repeats its ground track every 16 days. CloudSat is maneuvered to maintain a maximum of 15 s along-track distance from CALIPSO, which itself is configured to lag Aqua by no more than 120 s (Gutro et al., 2005). Such proximity means that data from a diversity of instruments can easily be combined together. The instruments covered here are the CALIOP lidar on CALIPSO, the millimetre-wave radar CPR on CloudSat and the passive spectroradiometer MODIS carried on-board of Aqua.

2.1 CALIPSO

The satellite CALIPSO (Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation) carries three nadir-viewing instruments that can be used to observe properties of aerosols and micrometre-sized cloud particels: CALIOP lidar, IIR imaging infrared radiometer, and a Wide Field Camera (WFC).

2.1.1 CALIOP

CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) is a polarisation-sensitive lidar capable of measuring backscatter intensity at wavelengths of 532 nm and 1064 nm at a repetition rate of 20.16 Hz (CALIPSO Data Products Catalog, 2007). The primary products of this instrument are vertical atmosphere profiles covering 5 vertical regions between −2.0 km and 40.0 km (Fig. 2.2).

As you can see in Fig. 2.3, the instrument's primary components are a receiver and lasers mounted with a boresight mechanism. The Nd:YAG lasers generate 20 nsec pulses of 110 mJ at two wavelengths: 532 nm and 1064 nm. The bandwidth is 30 pm, and polarisation purity

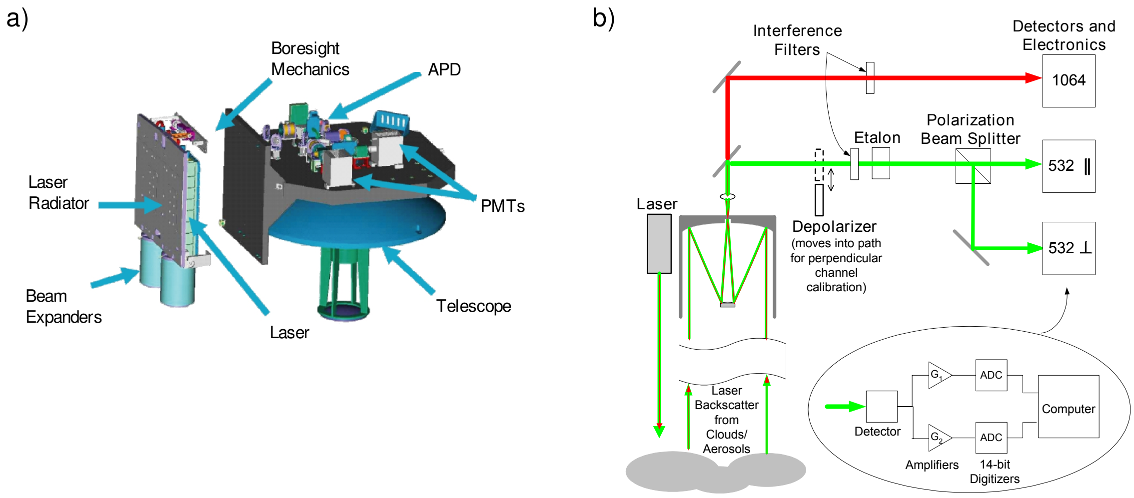


Figure 2.3 | CALIOP. a, CALIOP transmitter and receiver subsystems. **b**, Functional block diagram of CALIOP. [Adapted from PC-SCI-201 (2006).]

is 1000:1. Emitted light is directed through beam expanders, which ensure divergence of 100 μrad, i.e. a beam diameter of 70 m on the ground. The main components of the receiver subsystem are a 1-m-wide telescope and three detectors — one for the 1064 nm channel and two for the parallel and perpendicular polarisation of the 532 nm channel (PC-SCI-202.01, 2006).

2.1.2 Data Products

Data obtained by CALIPSO are processes by NASA LaRC (Langley Research Center) into products and distributed as HDF (Hierarchical Data Format) files to the scientific community. The products come in a set of levels depending on the amount of processing that has been performed as defined by the EOS guidelines (Tab. 2.1). Each level of products originating from a half-orbit (day or night) is stored in a standalone HDF file.

The physical quantities used in the products description below are introduced in Chapter 3. Please read the relevant sections of this chapter first if you are unfamiliar with the notation.

a. Lidar Instrument Level 1 Data Products

Lidar Instrument Level 1 Data Products contain data sets spanning a vertical cross-section of the atmosphere. Values are stored in rasters. Rows are associated with altitude, and columns are associated with time, latitude and longitude (technically, the data sets are stored transposed, but we like to think of columns as the vertical slices) . These products are processed to sensor units and geolocated. As of April 2010, Lidar Instrument Level 1 Data Products are available in the *Validated Stage 1* maturity level (version 3.01), which means that '*uncertainties are estimated from independent measurements at selected locations and times*' (CALIPSO Quality Statements, 2010).

Table 2.1 | EOS processing levels. Products from NASA EOS missions are available in a number of levels depending on the amount of processing that has been performed on raw data. A more detailed description is to be found in King et al. (2004).

Level	Description
Level 0	Reconstructed, unprocessed instrument/payload data at full resolution; any and all communications artifacts, e.g., synchronisation frames, communications headers, duplicate data removed.
Level 1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters, e.g, platform ephemeris, computed and appended but not applied to the Level 0 data.
Level 1B	Level 1A data that have been processed to sensor units (not all instruments have Level 1B data products).
Level 2	Derived geophysical variables at the same resolution and location as the Level 1 source data.
Level 3	Variables mapped on uniform space-time grids, usually with some completeness and consistency.
Level 4	Model output or results from analyses of lower level data, e.g., variables derived from multiple measurements.

Total Attenuated Backscatter 532nm

The *Total Attenuated Backscatter 532nm* is defined by the equation:

$$\beta'_{532} = \beta_{532} T^2_{532} = (\beta_{532,\parallel} + \beta_{532,\perp}) T^2_{532} \tag{2.1}$$

This are essentially the signals from the 532-nm parallel and perpendicular detectors combined, calibrated and normalised to amplifier gain, laser energy and range (Section 3.2.1).

Perpendicular Attenuated Backscatter 532nm

The *Perpendicular Attenuated Backscatter 532nm* is the attenuated perpendicular component of the 532-nm backscatter $\beta'_{532,\perp}$:

$$\beta'_{532,\perp} = \beta_{532,\perp} T^2_{532} \tag{2.2}$$

Attenuated Backscatter 1064nm

The *Attenuated Backscatter 1064nm* is β'_{1064} as described in Chapter 3.

Attenuated Color Ratio

The *Attenuated Color Ratio* is defined by the equation:

$$\chi' = \frac{\beta'_{1064}}{\beta'_{532}} \tag{2.3}$$

This data set is not contained within the Level 1 product files, but is calculated by ccplot (Chapter 5).

Depolarization Ratio

The *Depolarization Ratio* (at 532 nm) is defined by the equation:

$$\delta = \frac{\beta_{532,\perp}}{\beta_{532,\parallel}} = \frac{\beta_{532,\perp} T_{532}^2}{\beta_{532,\parallel} T_{532}^2} = \frac{\beta'_{532,\perp}}{\beta'_{532,\parallel}} \tag{2.4}$$

Note that since attenuation is the same for the perpendicular and parallel component of the 532-nm channel, the depolarization ratio is in fact the same as the *attenuated* depolarization ratio.

b. Lidar Level 2 Cloud and Aerosol Layer Products

Lidar Level 2 Cloud and Aerosol Layer Products are higher-level products that contain scientific values integrated over vertical areas called *layers*, associated with atmospheric features such as clouds and aerosols. Layers are contained in a procession of *columns*. Column properties include the number of features found within the column, and temporal and geospatial location. Layer properties include layer top and base altitude, and physical properties of the feature such as the *Integrated Attenuated Backscatter* or the *Integrated Volume Depolarization Ratio*, some of which are described below. More information can be found in CALIPSO Quality Statements: Lidar Level 2 Cloud and Aerosol Profile Products (2009).

As of April 2010, Lidar Level 2 Cloud and Aerosol Layer Products are only available in the *Provisional* maturity level (version 2.02), which means that '*limited comparisons with independent sources have been made and obvious artifacts fixed*' (CALIPSO Quality Statements, 2010).

Integrated Attenuated Backscatter 532nm & Integrated Attenuated Backscatter 1064nm

The *Integrated Attenuated Backscatter* is computed by integrating the attenuated backscatter coefficient (3.9) due to particulates (with attenuations due to molecules and ozone removed) over a vertical path through the feature (PC-SCI-202.02, 2005, Equation 3.11):

$$\gamma'_\lambda = \int_{top}^{base} \beta_{p,\lambda}(r)\, T_{p,\lambda}^2(r)\, \mathrm{d}r \tag{2.5}$$

where λ is either 532 or 1064 depending on wavelength.

Integrated Attenuated Total Color Ratio 1064nm/532nm

The *Integrated Attenuated Total Color Ratio* is defined by the equation (PC-SCI-202.02, 2005, Equation 6.13):

$$\chi' = \frac{\sum_{k=top}^{base} B_{1064}(z_k)}{\sum_{k=top}^{base} B_{532}(z_k)} \tag{2.6}$$

where B_λ is the value of β'_λ corrected for attenuation by molecules and ozone (but not particles):

$$B_\lambda = \frac{\beta'_\lambda}{T_{m,\lambda}^2\, T_{O_3,\lambda}^2} \tag{2.7}$$

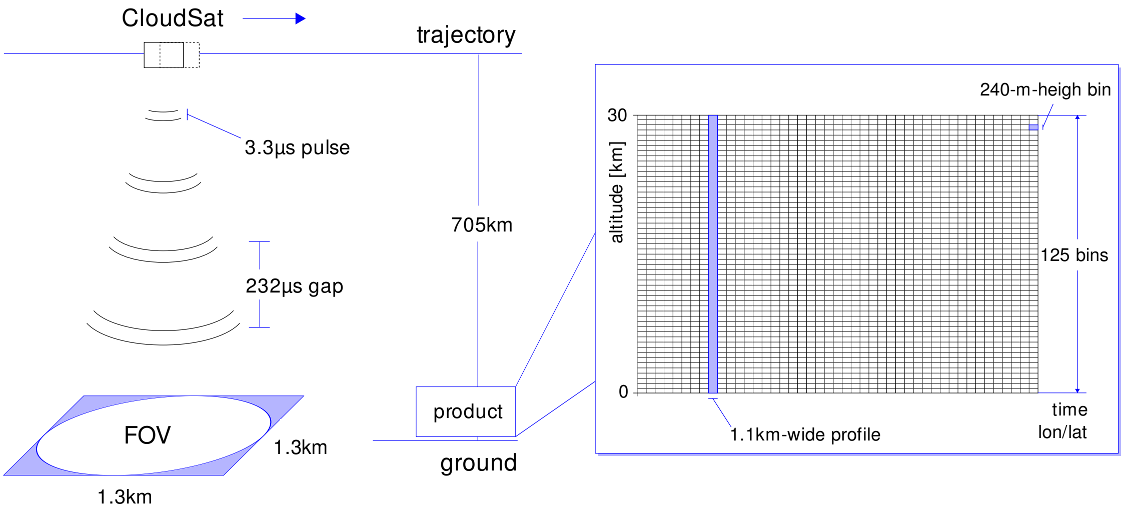


Figure 2.4 | Scheme of CloudSat CPR operation. The radar sends 3.3-µm pulses at a rate of 4300 Hz. Pulses cover 1.3 km × 1.3 km instantaneous footprint on the ground, but the effective FOV is 1.3 km × 1.7 km. Products are generated for the lowest 30 km. Profiles are sampled 1.1 km apart by averaging 688 pulses within 0.16 s. Bins are sampled 240 m apart. Horizontal precision of profiles is 1.7 km, vertical precision of bins is 500 m.

Integrated Volume Depolarization Ratio

The *Integrated Volume Depolarization Ratio* is defined by the equation (PC-SCI-202.02, 2005, Equation 6.10):

$$\delta = \frac{\sum_{k=top}^{base} \beta'_{532,\perp}(z_k)}{\sum_{k=top}^{base} \beta'_{532,\parallel}(z_k)} \tag{2.8}$$

Midlayer Temperature

This is the temperature in the geometric midpoint (vertically) of the layer derived from the GEOS-5 data product.

2.2 CloudSat

CloudSat is a NASA ESSP mission administered by the Colorado State University. CloudSat is a '*burdened*' satellite of the A-Train constellation, which means it adjusts its position to be in a precise position with respect to CALIPSO and Aqua, in order to overlap the footprint of instruments. The satellite carries a single scientific instrument — a nadir-viewing 94-GHz (3.2-mm wavelength) radar called CPR (Cloud Profiling Radar), whose aim is to observe vertical structure of clouds. CPR is similar in design to airborne cloud radars. It operates by sending 3.3-µs pulses and measuring power backscattered by cloud droplets or other hydrometeors as a function of distance. Pulses are generated at PRF (Pulse Repetition Frequency) of 4300 Hz, meaning two consecutive pulses are 232 µs apart. Only pluses backscattered from up to 30 km from the ground are measured. Instantaneous FOV (Field of View) of a pulse on the ground is approx. 1.3 km. However, since a single profile is

Table 2.2 | MODIS bands. Bands are organised in band groupings by their resolution.

Band grouping	Resolution	Bands
EV_250_RefSB	250 m	1, 2
EV_500_RefSB	500 m	3, 4, 5, 6, 7
EV_1KM_RefSB	1 km	8-12, 13lo, 13hi, 14lo, 14hi[a], 15-19, 26[b]
EV_1KM_Emissive	1 km	20-25, 27-36

[a] Bands 13 and 14 are split into two sub-bands: high and low.
[b] Band 26 is exceptional in a sense that it is a Reflective Solar Band in 1-km-resolution, and as such does not appear in night mode granules (as thermal bands do). Consequently, it is stored as a standalone SDS in HDF-EOS2 product files in order to save space.

produced by integrating 688 pulses over a period of 0.16 s, the effective FOV is elongated in the along-track direction to 1.7 km. The primary output of CPR is a vertical profile of the atmosphere (Fig. 2.4).

2.2.1 Data Products

Measurements are down-linked, processed into products, and distributed by the CloudSat Data Processing Centre as HDF-EOS2 files. Number of products are available (CloudSat Standard Data Products Handbook, 2008). Since the lowest-level product 1B-CPR does not contain physical quantities suitable for immediate use by scientific applications, we will focus on a higher-level product 2B-GEOPROF.

a. 2B-GEOPROF

The *2B-GEOPROF* product, also called the *Cloud Geometrical Profile*, contains the primary useful physical quantity which can be calculated from the received echo power — Radar Reflectivity Factor Z. Its value expresses a relative attenuated backscatter strength as described in Section 3.3 of *The Physical Basis* chapter. Radar Reflectivity Factor is comprised of 1.1-km-wide columns called *rays* (or *profiles*), which are further composed of 125 240-m *bins* in the vertical direction. A single scientific value is assigned to each bin. All bins together form a 2-dimensional raster on a 30-km-high irregular grid. This product is available for both day and night granules (1B-CPR_PDICD, 2007; 2B-GEOPROF_PDICD, 2007; Stephens et al., 2002).

2.3 Aqua

The NASA EOS mission satellite Aqua carries instruments predominantly used for water cycle observation, but some of them also aid weather forecasting by measuring temperature and humidity of the atmosphere, or the Earth Radiation Budget. Aqua is one of the key EOS missions, the other being Terra, which complements Aqua in land observations (Parkinson, 2003). There are six instruments installed:

1. AIRS (Atmospheric Infrared Sounder)

2. AMSR-E (Advanced Microwave Scanning Radiometer - EOS)
3. AMSU (Advanced Microwave Sounding Unit)
4. CERES (Clouds and the Earth's Radiant Energy System)
5. HSB (Humidity Sounder for Brazil)
6. MODIS (Moderate-Resolution Imaging Spectroradiometer)

These instruments serve variety of purposes, and provide a very diverse range of products (Gutro et al., 2002). We will confine our discussion to the spectroradiometer MODIS.

2.3.1 MODIS

MODIS is a cross-track scanning radiometer administered by the MODIS Science Team at NASA Goddard Space Flight Centre. Measurements are performed via the means of a rotating scan mirror and an array of detectors. The structure of its viewing swath is explained in Fig. 2.5. The spectroradiometer scans incident radiation at 36 different visible and infrared channels at spatial resolution of 250 m, 500 m and 1 km depending on band (Tab. 2.2). Bands 1–19 and 26 are reflective solar bands (RSB) raging from 0.405 μm to 2.155 μm. Bands 20–25 and 27–36 are thermal emissive bands (TEB) raging from 3.66 μm to 14.385 μm MODIS Specifications (2010). A large number of algorithms is employed to convert measured data into products related to biosphere, oceans, atmosphere, land and cryosphere (Parkinson, 2002). Total global coverage is completed within the course of two days (Xiong and Barnes, 2006).

2.3.2 Level 1B Data Products

MODIS products are categorised according to the EOS levels (Tab. 2.1). Level 1B products are derived from Level 0 products by calibration, geolocation and stripping into 5-minute swath granules. These are then distributed in to form of HDF-EOS2 files through the EOS Data Gateway. Science Level 1B products are: **MYD02QKM** (250-m-resolution bands), **MYD02HKM** (500-m-resolution bands and aggregated 250-m bands), and **MYD021KM** (1-km-resolution bands and aggregated 250-m- and 500-m-resolution bands). Documentation of MODIS products can be found in MODIS Level 1B Product User's Guide (2009).

2.4 Data Ordering

HDF4 and HDF-EOS2 data product files provided by CloudSat, CALIPSO and MODIS missions can be downloaded from the Internet through their respective ordering systems:

- **CloudSat**. CloudSat products can be ordered from the *CloudSat DPC* upon registration. Registration and ordering are free of charge.

  http://www.cloudsat.cira.colostate.edu

- **CALIPSO**. CALIPSO products can be ordered from *Atmospheric Science Data Center* upon registration. Registration and ordering are free of charge.

  http://eosweb.larc.nasa.gov/PRODOCS/calipso/table_calipso.html

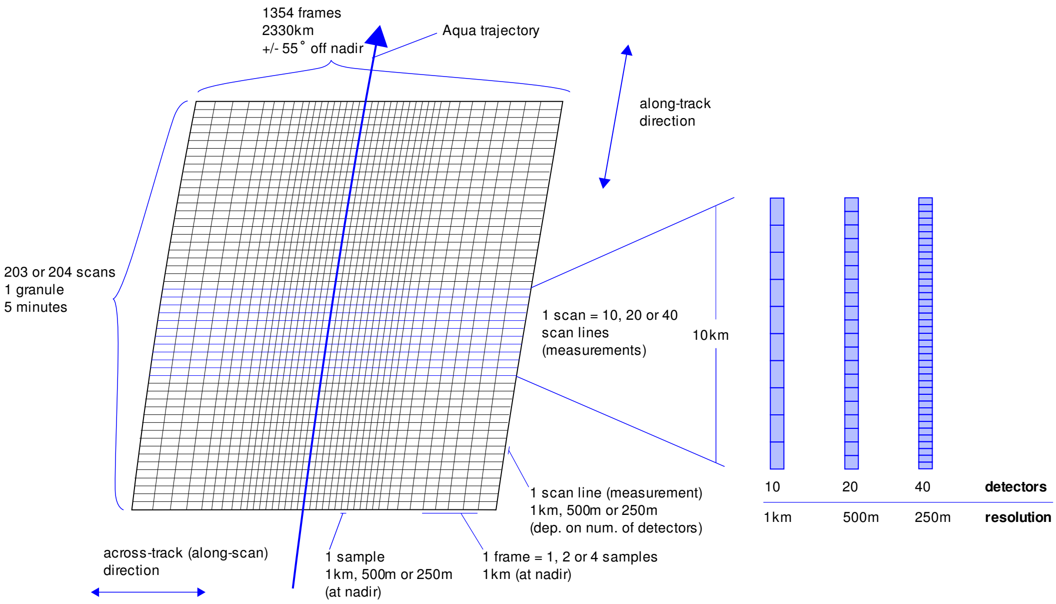


Figure 2.5 | Layout of a MODIS granule. The observational swath is divided into 5-min granules of 203 scans in the along-track direction. Field of view is ±55° relative to nadir. The 250-m resolution bands have 40 detectors, the 500-m resolution bands have 20 detectors and the 1-km-resolution bands have 10 detectors each. As indicated by the line density, resolution decreases with increasing distance from the trajectory. A 10-km *scan* of a mirror comprises 10, 20 or 40 scan lines. Similarly, a 1-km *frame* comprises 1, 2 or 4 *samples*, depending on resolution.

- **MODIS**. MODIS products are available through the *LAADS Web* without registration. http://ladsweb.nascom.nasa.gov

Chapter 3

The Physical Basis

3.1 The Physics of Scattering

3.1.1 Radiance Attenuation

The core physical principle behind observations performed by CPR and CALIOP is scattering of radiation by molecules, aerosols and cloud particles. When an electromagnetic wave passes through a particle, it can either be scattered, absorbed, or pass unperturbed. The difference between scattering and absorption is that in scattering, a new electromagnetic wave is generated immediately, while in absorption, a part of the energy is absorbed, and is re-emitted later. Both processes can be described in terms of *monochromatic radiance* attenuation by the equation:

$$dI_\lambda = -I_\lambda \sigma_\lambda \,\mathrm{d}s \tag{3.1}$$

where I_λ is monochromatic radiance at wavelength λ, σ_λ is the *volume extinction coefficient* due to scattering and absorption in m^{-1}, and $\mathrm{d}s$ is a path length through the medium (air). σ_λ is a function of the medium. Alternatively, the same can be expressed in terms of *extinction efficiency* K_λ (Wallace and Hobbs, 2006):

$$dI_\lambda = -I_\lambda u N K_\lambda \,\mathrm{d}s \tag{3.2}$$

where N is the number of particles per unit volume, and u is the *areal cross section* of particles[1]. By integrating (3.1) from altitude z_0 to $z > z_0$, we get:

$$I_\lambda = I_{\lambda,0} e^{-\int_{z_0}^{z} \sigma_\lambda(z')\,\mathrm{d}z'} \tag{3.3}$$

where I_λ is monochromatic radiance at z, and $I_{\lambda,0}$ is monochromatic radiance at z_0.
We define *transmission* T as a fraction of radiation that passes through a slab of atmosphere:

$$T = e^{-\int_{z_0}^{z} \sigma(z')\,\mathrm{d}z'} \tag{3.4}$$

(3.3) can then be formulated as:

$$I_\lambda = I_{\lambda,0} T \tag{3.5}$$

[1] In Wallace and Hobbs (2006), u is denoted by σ. To avoid confusion with the volume extinction coefficient, we changed the symbol to u.

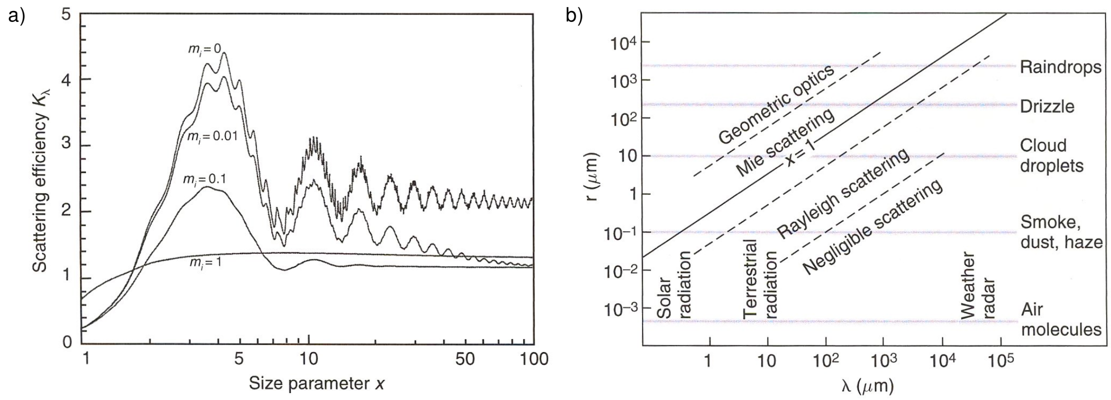


Figure 3.1 | Scattering by a spherical particle. **a**, Scattering efficiency K_λ as a function of the dimensionless size parameter x for four different indices of refraction with m_r = 1.5. **b**, Size parameter x as a function of wavelength λ of the incident radiation and particle radius r. [Adapted from Wallace and Hobbs (2006).]

3.1.2 Elastic and Inelastic Scattering

Scattering can either be *elastic* or *inelastic*. Elastic scattering occurs when there is no change in frequency of the generated wave relative to the original wave, i.e. the particle is excited to a higher energy state, but instantaneously returns to the original energy state. Examples of elastic scattering are *Rayleigh scattering* and *Mie scattering*. Inelastic scattering, also called *Raman scattering*, the frequency of the scattered light is either lower (*Stokes scattering*) or higher (*anti-Stokes scattering*). Molecular Raman scattering can be due to excitation of *rotational* or *vibrational* modes. Elastic scattering of monochromatic light produces a so-called *Cabannes line* (She, 2001).

3.1.3 Scattering by an Idealised Spherical Particle

It is interesting to consider the case of an ideal spherical particle of homogeneous material with a complex index of refraction $m = m_r + im_i$. It turns out that the extinction efficiency K_λ can be expressed as a function of a dimensionless parameter x (Wallace and Hobbs, 2006):

$$x = 2\pi \frac{r}{\lambda} \tag{3.6}$$

where r is the radius of the particle, and λ is the wavelength of the incoming monochromatic plane wave.

As you can see in Fig. 3.1a, for x approaching 1 (and in fact, for $x \leq 1$ as well), the scattering efficiency is very low, and is proportional to λ^{-4}. This is called the *Rayleigh scattering regime*. For $0.1 \leq x \lesssim 50$, K_λ exhibits an oscillatory behaviour, and is referred to as the *Mie scattering regime*. For $x \gtrsim 50$, K_λ approaches 2. This is the *geometric optics regime*.

The parameter x can give us a an impression of how strongly radiation from CALIOP and CPR is scattered from various components of the atmosphere. For 512-nm waves, we can expect Rayleigh scattering from air molecules, Mie scattering from aerosol particles of size 10 nm to 4 μm, and geometric reflection from water droplets and ice crystals. For 1064-nm waves, Rayleigh scattering from molecules should be about 16 times weaker compared to 512-nm waves (by the λ^{-4} equation), Mie scattering can be expected from particles of size 17 nm to 8.5 μm, and geometric reflection can be expected from cloud particles. The situation is very different in the case of the much longer wavelength radiation from the CPR radar. 3.2-mm waves are likely to be weakly scattered by molecules and aerosols in the Rayleigh regime, but much more strongly scattered from particles larger than 50 μm, such as cloud droplets, rain drops, hail, and large ice crystals (Fig. 3.1).

3.2 Physics Behind CALIOP

3.2.1 The Fundamental Equation

After a pulse of light is generated by the CALIOP laser, the receiver measures light backscattered from molecules, aerosols and cloud particles in the atmosphere. Altitude which the received signal relates to is inferred from delay between sending the pulse and receiving the signal. Absorption-emission and multiple scattering are therefore not accounted for. Moreover, the receiver subsystem contains a narrowband filter, which only allows the Cabannes line to pass, therefore the inelastically scattered light at different wavelengths is filtered out. The fundamental lidar equation that relates measured signal strength P to *volume backscatter coefficient* β at range r from the satellite is (PC-SCI-201, 2006):

$$P(r) = EG_A C \frac{1}{r^2} \beta(r) T^2(r) \tag{3.7}$$

where G_A is the *amplifier gain*, C is the *calibration constant*, E is the laser energy. The r^{-2} term results from geometry of spreading out of the beam, and the coefficient T^2 expresses *two-way attenuation* of radiation by (3.4) on its way from the satellie at altitude z_{sat} to and from the slab of air at range r:

$$T^2(r) = e^{-2 \int_{z_{sat}-r}^{z_{sat}} \sigma(z)\, \mathrm{d}z} \tag{3.8}$$

The Level 1 products are expressed in terms of *attenuated backscatter coefficient*:

$$\beta'(r) = \beta(r) T^2(r) \tag{3.9}$$

Elimination of attenuation and multiple-scattering correction is the done for the Level 2 products by the SIBYL and HERA algorithms (Vaughana et al., 2004).

There are several types of backscatter coefficients. Two for the parallel and perpendicular components of the 532-nm channel ($\beta_{532,\parallel}$ and $\beta_{532,\perp}$), one for the 1064-nm channel (β_{1064}), and the *total backscatter coefficient* at 532 nm:

$$\beta_{532} = \beta_{532,\parallel} + \beta_{532,\perp} \tag{3.10}$$

All of them can be broken up into scattering due to molecules and scattering due to particulates:

$$\beta = \beta_m + \beta_p \tag{3.11}$$

Attenuation is typically split into attenuation due to molecules, particulates and ozone:

$$T^2 = T_m^2 T_p^2 T_{O_3}^2 \tag{3.12}$$

In addition to the coefficients described above, backscatter coefficients can be combined to produce other useful physical quantities (PC-SCI-202.02, 2005). *Total color ratio* χ is defined by the equation:

$$\chi = \frac{\beta_{1064}}{\beta_{532}} \tag{3.13}$$

Volume depolarization ratio δ is defined as the ratio of the perpendicular to the parallel component of the 532-nm channel:

$$\delta = \frac{\beta_{532,\perp}}{\beta_{532,\parallel}} \tag{3.14}$$

3.3 Physics behind CPR

CPR operates by sending pulses at a wavelength of 3.2 mm. Power received by the antenna P_r is related to the radiated power P_t by the equation (1B-CPR_PDICD, 2007):

$$P_r(r) = P_t \frac{1}{r^2} \frac{1}{C} \eta(r) \tag{3.15}$$

where r is the *range* from the radar, C is the *calibration constant*, and η is the *attenuated volume backscatter coefficient*. The attenuated volume backscatter coefficient can be converted to the *radar reflectivity factor* Z by:

$$\tilde{Z}^*(r) = \frac{\lambda^4 \eta(r)}{\pi^5 |K|^2} \tag{3.16}$$

$$\tilde{Z}_0 = 1\,\mathrm{mm}^6\mathrm{m}^{-3} \tag{3.17}$$

$$Z(r) = 10 \log_{10} \frac{\tilde{Z}^*}{\tilde{Z}_0}\ \mathrm{dBZ} \tag{3.18}$$

where K is is a function of the dielectric constant (about 0.75). The 2B-GEOPROF product contains backscatter information expressed in terms of Z. Techniques of elimination of attenuation from η, and therefore retrieving true backscatter properties at a particular range are discussed in Li et al. (2001).

3.4 Brightness Temperature

By treating the monochromatic radiance I_λ as if it were emitted by a black body, it can be converted into so-called *brightness temperature*, i.e. a virtual temperature of a black body emitting the same amount of radiation at a given wavelength. It can be calculated by applying the *inverse Planck function* (Houghton, 2002):

$$T_{brightness} = \frac{c_2}{\lambda \ln\left(\frac{c_1}{\lambda^5 I_\lambda} + 1\right)} \tag{3.19}$$

where c_1 and c_2 are the *first* and *second radiation constants*:

$$c_1 = 1.1911 \times 10^{-8}\,\mathrm{Wm^{-2}sr^{-1}}\left(\mathrm{cm}^{-1}\right)^{-4} \tag{3.20}$$

$$c_2 = 1.439\,\mathrm{K}\left(\mathrm{cm}^{-1}\right)^{-1} \tag{3.21}$$

Brightness temperature can be used when visualising MODIS thermal emission bands instead of monochromatic radiance.

Chapter 4

HDF4 Data Files

HDF4 (Hierarchical Data Format version 4) was chosen by the CALIPSO, CloudSat and MODIS missions as the primary file format for storage and distribution of down-linked scientific and ancillary data. It is a self-describing, platform-independent binary format designed for storage of large data sets and metadata, encapsulated together in a single file. Objects that can be contained in an HDF file include multi-dimensional arrays ('Scientific Data Set' or 'SDS'), tables ('Vdata'), raster images, palettes and annotations organised hierarchically in groups ('Vgroup'). Each object as well as the file itself can further be described by an arbitrary number of name-value pairs ('attribute').

Numerous NASA EOS missions, such as CloudSat and MODIS, use an extended version of HFD4 called HDF-EOS2, described later in this chapter.

HDF4 API (Application Programming Interface) is available for FORTRAN-77 and C, although various other languages are supported through third-party libraries. Additionally, a vast number of tools for manipulating these formats exist. A list such tools can be found on the web site of the *HDF Group* [http://www.hdfgroup.org] and the *HDF-EOS Tools and Information Center* [http://www.hdfeos.org/]. In particular, *HDFView* is a convenient GUI application for examining HDF4 files.

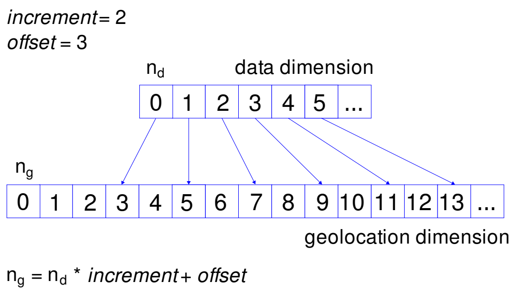


Figure 4.1 | Dimension mapping example. *Swath* data type allows indices of geolocation dimension and its associated data dimension to be in none-1:1 relationship. Geo-indices n_g are translated to data-indices n_d by multiplying by *increment* and adding *offset*.

4.1 Multi-dimensional Arrays, Dimensions and Attributes

Every SDS is associated with a number of dimensions, each of a particular *size* (or, in a special case, unlimited size). In HDF4 context, the number of dimensions of an array is called the

Table 4.1 | Attributes predefined by HDF4. Many product files do not follow the specification closely or invent their own attributes with a similar meaning (see footnotes). Note that this is not a full list of predefined attributes.

Data Object	Attribute Name	Description	Example
SDS/dimension	long_name	Name of the array.	Gaseous_Attenuation
SDS/dimension	units	Physical units of object items.	dBZe
SDS	valid_range	Minimum and maximum values.	0,1000[a]
SDS	__FillValue[b]	Value used to fill empty array items (expected, but did not appear).	65535
SDS	scale_factor[c]	Value by which each array item is to be multiplied.	100.0
SDS	add_offset[c]	Value to add to each array item.	0.0
SDS	missing_value[d]	Value used to fill empty array items (never expected to be filled).	-9999

[a] CALIPSO products denote valid_range as ‘<min>....<max>’.
[b] In CALIPSO products, this attribute is called *fillvalue*.
[c] Values in SDS can be scaled and shifted for space efficiency. In CloudSat products, these are called *factor* and *offset*.
[d] In CloudSat products, this attribute is called *missing*; additionally, attribute *missop* specifies operator (‘<’, ‘<=’, ‘==’, ‘>=’, or ‘>’) to be used for comparison of data items with *missing*.

rank. Array indices are counted from zero, and range up to *size*-1 (incl.). Dimensions can optionally be named. HDF4 standardises some predefined SDS and dimension attributes (Tab. 4.1).

4.2 HDF-EOS2

HDF-EOS2 is an extension to HDF4, which defines three new *data types* based on regular HDF4 structures, designed to accommodate data sets commonly produced by earth-observing missions:

1. Swath — time-ordered data such as series of scanlines or series of profiles (Fig. 4.2).
2. Grid — data geolocated on a rectilinear grid.
3. Point — sparsely geolocated data, such as records from ground stations.

Fields in HDF-EOS2 files are separated in *Geolocation Fields* and *Data Fields* groups. Fields, dimensions and relations between geolocation and data fields are described in the *HDF-EOS2 metadata*. Internally, this metadata information is stored as a continuous block of text inside the HDF4 file attribute *StructMetadata.0*, and encoded as PVL (Parameter Value Language), a markup language similar to XML. HDF-EOS2 library provides functions to access this information directly, effectively hiding the underlying structure from the programmer, and therefore alleviates the need to parse the language.

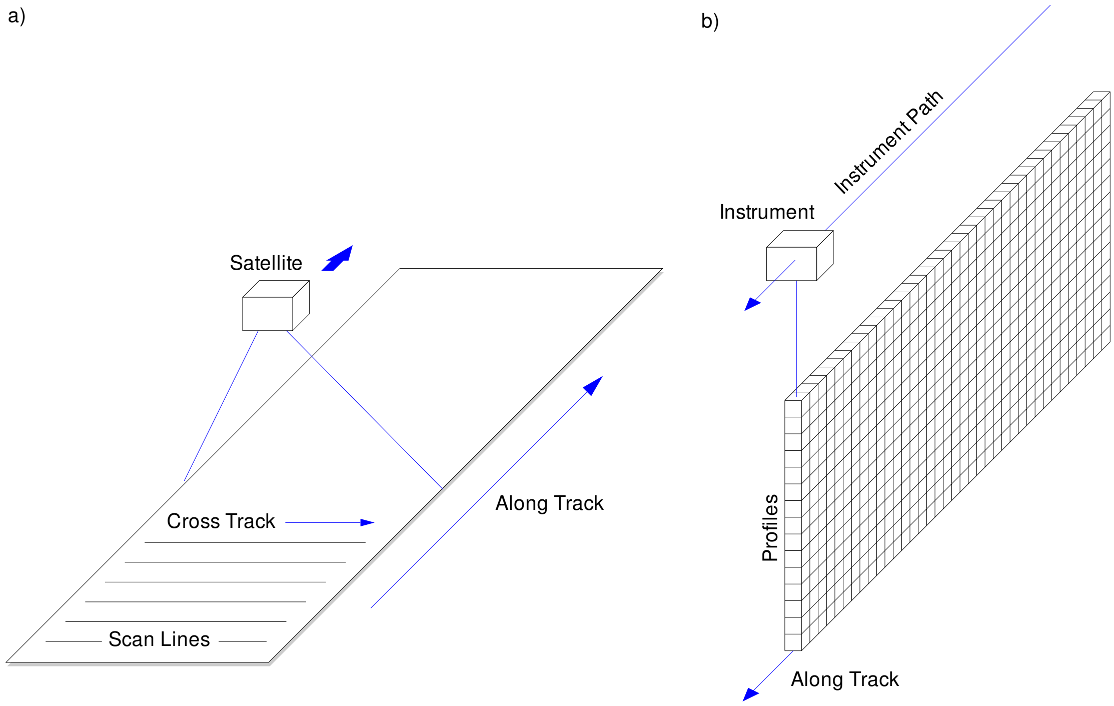


Figure 4.2 | HDF-EOS2 swath. Swath is typically deployed to store data from a **a**, scanning instrument, **b**, profiling instrument. [Adapted from HDF-EOS Library User's Guide Volume 1: Overview and Examples (2009).]

HDF-EOS2 files of MODIS contain another metadata structure — *ECS Core Metadata* stored in the *CoreMetadata.0* file attribute, similar to *StructMetadata.0*. Its aim is to provide information on spatial and temporal coverage, data quality and production status for searching purposes. *ECS Core Metadata* can be read with the *SDP Toolkit* available through the *HDF-EOS Tools and Information Center* [http://www.hdfeos.org/].

4.2.1 Dimension Mapping

Swath data type provides an optional feature called *dimension mapping*, which allows geolocation fields to have lower resolution than corresponding data fields. If dimension mapping is used, one has to distinguish between *geolocation dimensions* and *data dimensions*. The relationship between geolocation and data dimensions is linear, defined by two constants: *offset* and *increment*. Reversed dimension mapping, i.e. data fields of lower resolution than geolocation fields is also supported, although its applicability is likely to be not as high. The principle is illustrated in Fig. 4.1.

4.3 CALIPSO Products

CALIPSO mission deploys HDF4 format for product distribution. File naming convention is explained in Fig. 4.3. Generally, these products come in two kinds: profile products and layer products, as described in Section 2.1.2. The structure of CALIPSO products is flat; no

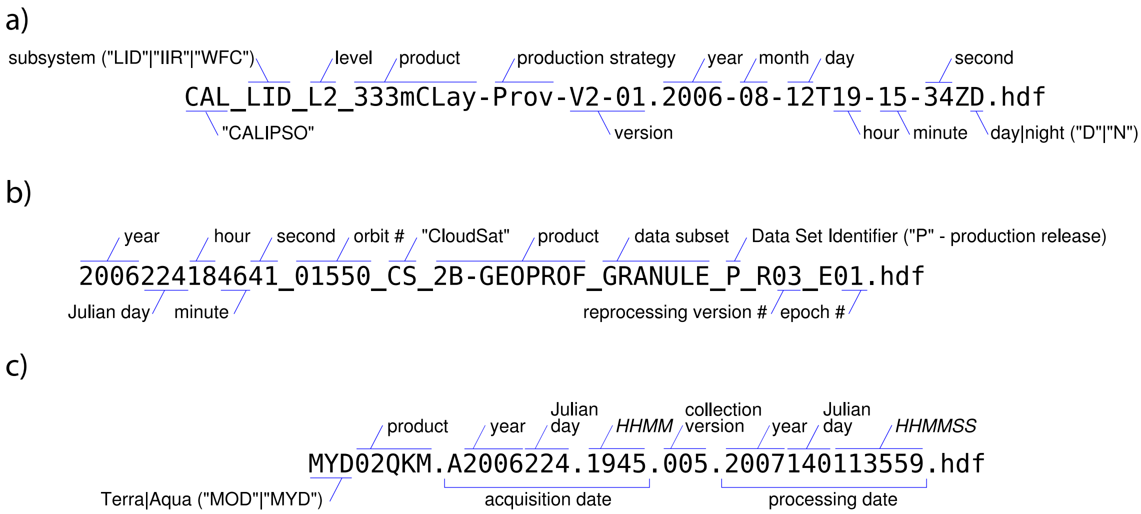


Figure 4.3 | File naming conventions. **a**, CALIPSO, **b**, CloudSat, **c**, MODIS (based on http://modis-atmos.gsfc.nasa.gov/products_filename.html).

explicit distinction is made between geolocation and data fields. Dimensions do not possess any explicitly meaningful names.

Let us consider the **333-m Lidar Level 2 Cloud and Aerosol Layer Product** as an example (Fig. 4.4). One-dimensional arrays ***Latitude*** [63120], ***Longitude*** [63120] and ***Profile_UTC_Time*** [63120] locate data sets spatially and temporally. In contrast with profile products, layer products are a expressed as a sequence of columns (in the along-scan direction) composed of 0-5 layers each. Number of layers in columns is stored in a one-dimensional array ***Number_Layers_Found*** [63120]. Base and top altitudes of the layers found are stored in two-dimensional arrays ***Layer_Top_Altitude*** [63120 × 5] and ***Layer_Base_Altitude*** [63120 × 5]. Finally, the actual data can be found in a two-dimensional array ***Integrated_Attenuated_Backscatter_532*** [63120 × 5], and in a number of other fields.

4.4 CloudSat Products

Data from the CloudSat mission are commonly distributed in per-granule HDF-EOS2 files. File naming convention is described in Fig. 4.3. The 2B-GEOPROF product contains a single swath called *2B-GEOPROF*. Two important dimensions are *nray*, which is the horizontal dimension (number of profiles), and *nbin*, which is the vertical dimension (number of bins). Data fields such as ***Gaseous_Attenuation*** [nray × nbin] are two-dimensional arrays, located spatially by one-dimensional arrays ***Latitude*** [nray], ***Longitude*** [nray] and ***Height*** [nray × nbin] and temporally by ***Profile_time*** [nray] (Fig. 4.5). Time corresponding to a particular ray is calculated by adding ***Profile_time*** to ***start_time*** (in UTC). The result is time in UTC, although it may differ from the proper UTC time in the rare event when a leap second is introduced in the time period covered by the granule. Other CloudSat products resemble a similar structure. Comprehensive documentation of the products can be found on the CloudSat DPC web site [http://www.cloudsat.cira.colostate.edu/].

4.5 Aqua MODIS Level 1B Products

There are three Aqua MODIS Level 1B products: MYD02QKM, MYD02HKM and MYD021-KM, described in detail in Section 2.3.2. They are distributed in HDF-EOS2 format. Every granule is either a '*day mode*', '*night mode*', or a '*mixed mode*' granule, depending on whether it contains RefSB bands on the entire swath, none of it, or a fraction of it (resp.). File naming convention employed by MODIS is described in Fig. 4.3.

Let us now consider a day mode MYD02QKM product as an example (Fig. 4.6). The HDF-EOS2 file contains a single swath called ***MODIS_SWATH_Type_L1B***. Geolocation dimensions are *Max_EV_Frames* and *10*nscans*. Their corresponding data dimensions are *4*Max_EV_Frames* and *40*nscans*. As you can see in Fig. 4.6, MODIS products utilise dimension mapping, so that geolocation fields can be specified more sparsely than data fields. ***Geolocation Fields*** group contains two two-dimensional arrays: ***Latitude*** [10*nscans × Max_EV_frames] and ***Longitude*** [10*nscans × Max_EV_frames]. ***Data Fields*** group contains a three-dimensional array ***EV_250_RefSB*** [Band_250M × 40*nscans ×, 4*Max_EV_frames] with the actual data. The dimension *Band_250M* is of size 2, because there are only two bands in this band grouping (see Tab. 2.2 in the previous chapter).

4.6 More Information

Much of the information in this chapter is based on the following documents:

- HDF-EOS Library User's Guide Volume 1: Overview and Examples (2009)
- HDF 4.2r4 User's Guide (2009)
- CALIPSO Data Products Catalog (2007)
- CloudSat Standard Data Products Handbook (2008)
- CloudSat DPC web product documentation at http://www.cloudsat.cira.colostate.edu/dataSpecs.php
- MODIS Level 1B Product User's Guide (2009)

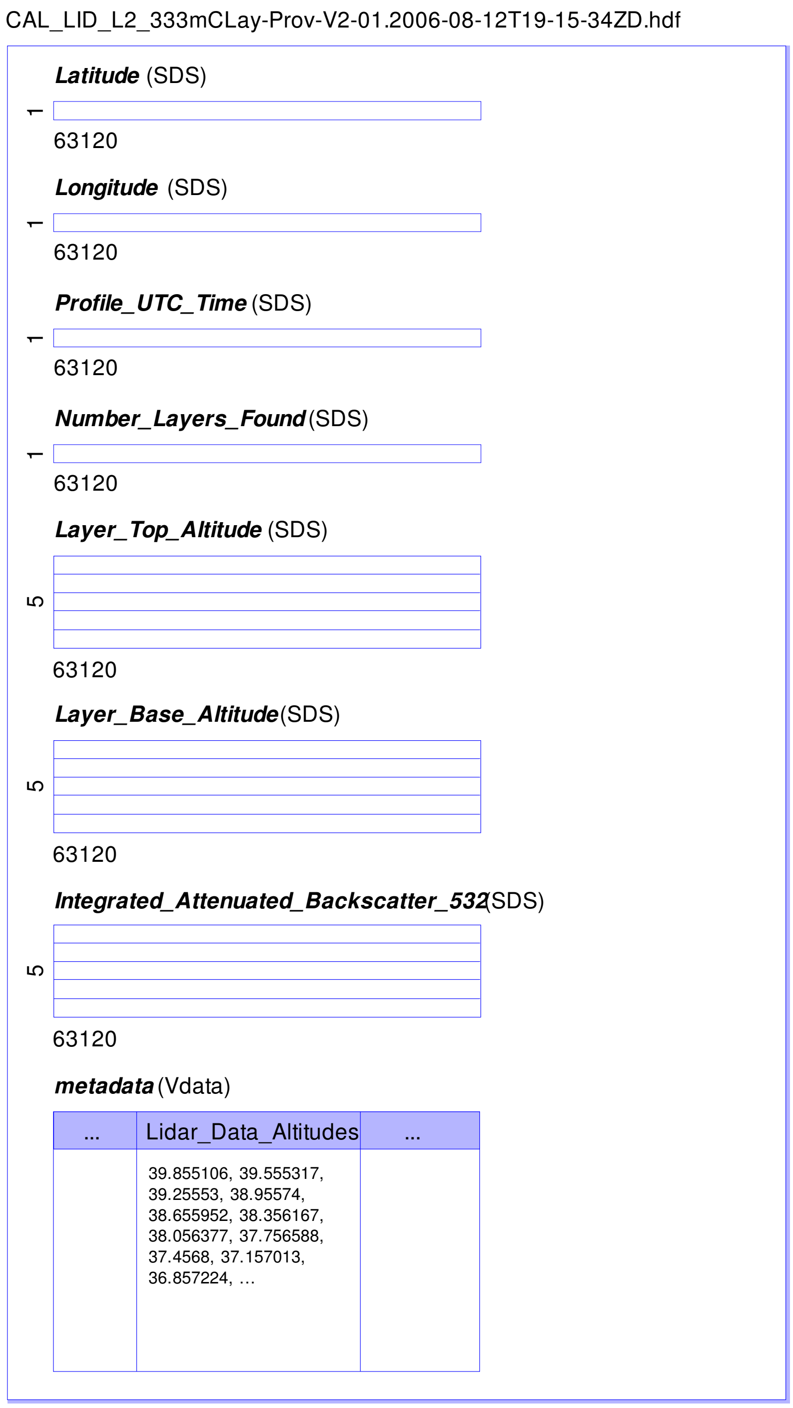


Figure 4.4 | CALIPSO HDF4 diagram. This is the structure of a typical CALIPSO Level 2 Layer Product. Note that ***metadata*** is the name of a Vdata object, and does not tally with the term '*metadata*' used elsewhere in this document, which refers to HDF4 attributes. Although the *Lidar_Data_Altitudes* field of the ***metadata*** table is not particularly relevant for *layer* products, it provides the only means how one can retrieve height information, essential for plotting *profile* products.

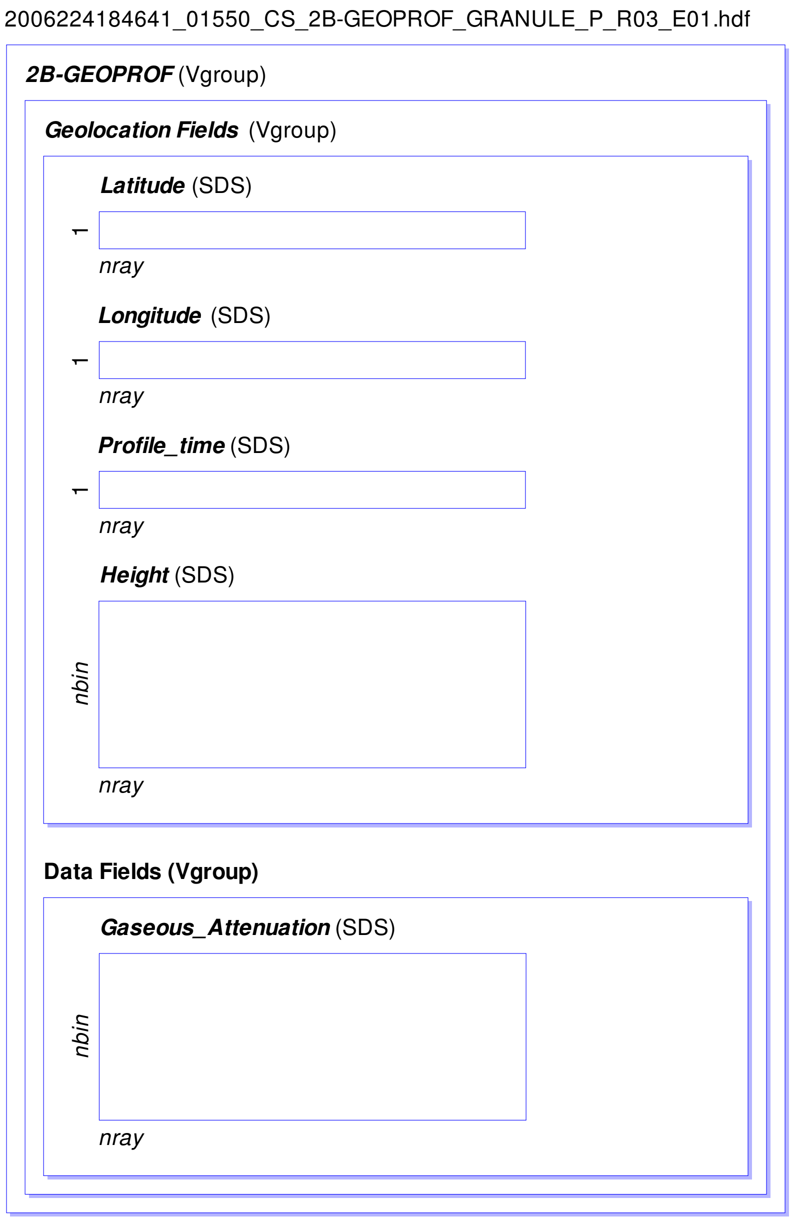


Figure 4.5 | CloudSat 2B-GEOPROF HDF-EOS2 diagram. This is the structure a typical CloudSat 2B-GEOPROF product.

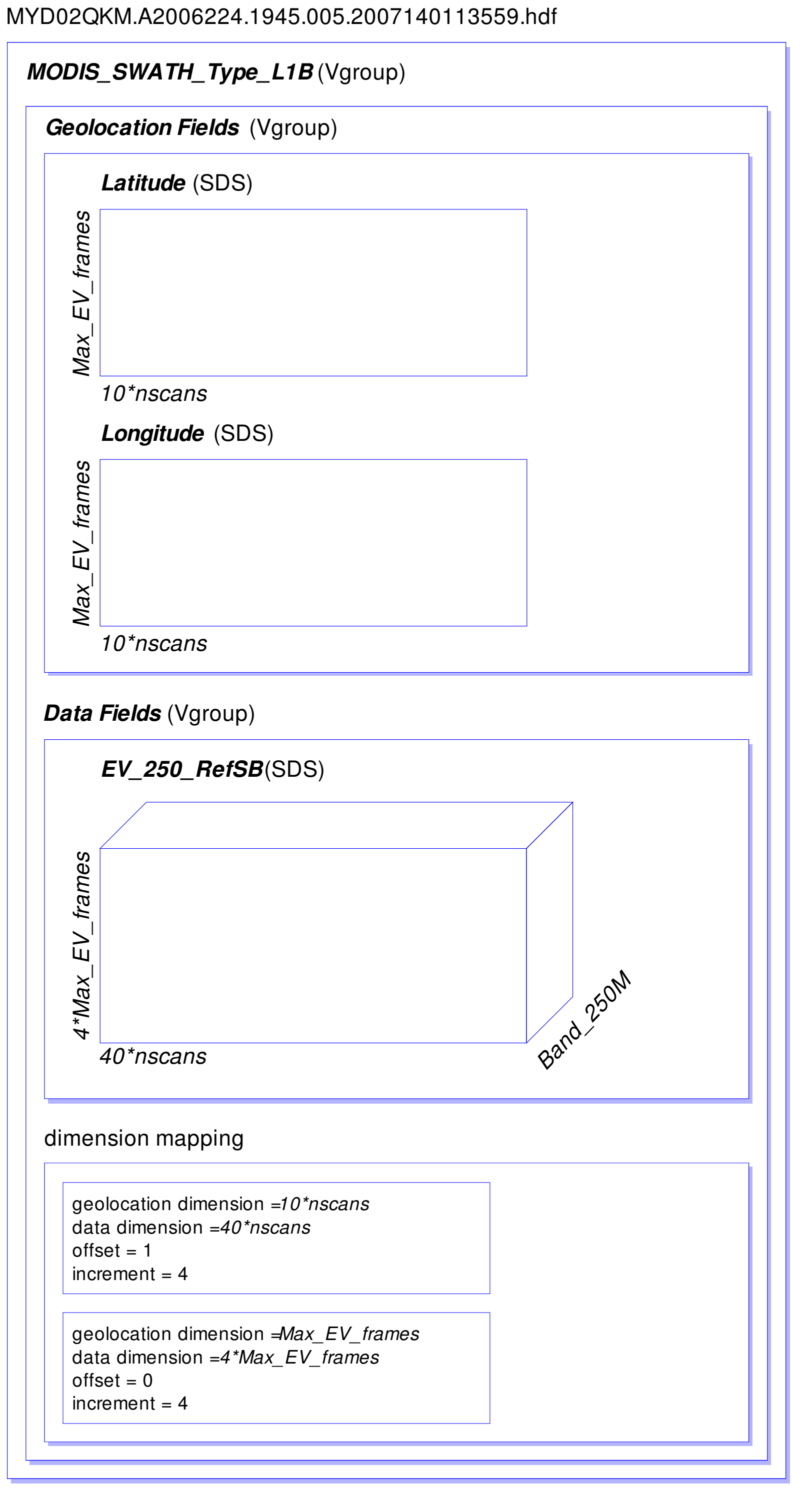


Figure 4.6 | MODIS Level 1B HDF-EOS2 diagram. This is the structure of a typical MODIS Level 1B product.

Chapter 5

Visualising CloudSat and CALIPSO Data

5.1 Introducing ccplot

ccplot is a platform-independent command-line program that can plot several types of data sets stored in CloudSat, CALIPSO, and Aqua MODIS HDF4 and HDF-EOS2 product files (Tab. 5.1). It is written in the open-source scripting language Python and uses the matplotlib plotting library for its output (see also Section 5.2). Some of the most important features of ccplot are:

- Support for a number of profile, layer, and swath products.
- Output in arbitrary quality, fine structure of data can be preserved.
- Region to be plotted can be selected easily.
- Suitable for being used by other programs or shell scripts.
- Colormaps can be customised.
- Publication-ready output.
- ccplot is free software released under the terms of the open-source-compatible, two-clause BSD license.

The following sections describe the way ccplot processes and visualises data. You may want to skip right to Chapter 6 if you are interested in how to use ccplot.

5.2 Components of ccplot

As has been mentioned earlier, ccplot is written in the scripting language Python[1]. Python is a byte-compiled programming language, which requires the user to have a copy of the python interpreter installed on their host system in order to run the program. Python was chosen for its suitability for scientific applications thanks to a set of libraries SciPy[2], including efficient array implementation numpy[3], state-of-the-art plotting library matplotlib[4] and projection toolkit basemap[5], and a library for reading HDF files PyNIO[6] made by NCAR

[1] http://www.python.org/
[2] http://www.scipy.org/
[3] http://numpy.scipy.org/
[4] http://matplotlib.sourceforge.net/
[5] http://matplotlib.sourceforge.net/basemap/doc/html/
[6] http://www.pyngl.ucar.edu/Nio.shtml

Table 5.1 | Plot types supported by ccplot.

Product	Data set	ccplot name
CloudSat 2B-GEOPROF	Radar Reflectivity Factor	cloudsat-reflec
CALIPSO Lidar L1B Profiles	Total Attenuated Backscatter 532nm Perpendicular Attenuated Backscatter 532nm Attenuated Backscatter 1064nm Attenuated Color Ratio 1064nm/532nm Depolarization Ratio	calipso532 calipso532p calipso1064 calipso-cratio calipso-dratio
CALIPSO Lidar L2 Cloud Layer Products (333m, 1km, 5km)	Integrated Attenuated Backscatter 532nm Integrated Attenuated Backscatter 1064nm Integrated Attenuated Total Color Ratio 1064nm/532nm Integrated Volume Depolarization Ratio Midlayer Temperature	calipso532-layer calipso1064-layer calipso-cratio-layer calipso-dratio-layer calipso-temperature-layer
Aqua MODIS L1B, CloudSat, CALIPSO	MODIS radiance and reflectance; CloudSat and CALIPSO trajectory	orbit, orbit-clipped

(The National Center for Atmospheric Reserch). To compensate for the performance-penalty inflicted by the use of a higher-level programming language, ccplot uses a set of computationally-intensive functions implemented in C as a python extension. This extension is called cctk. The diagram in Fig. 5.1 shows the relationship between various components of ccplot.

5.3 Data Reading, Processing and Visualisation

5.3.1 Data Reading

Data are read from data sets in a supplied HDF file. This is done by the PyNIO library. After that, dimension mapping is performed, missing values are masked (so that they are not taken into consideration in later processing), and data values are converted to scientific values by scaling and offsetting. Whether and how these operations are performed depends on the type of the product. For example, dimension mapping is only performed the on MODIS products, and scaling and offsetting is only performed on the CloudSat products.

The CALIPSO products store height information in a Vdata structure *metadata*. However, this is not supported by PyNIO at the moment, and a temporary solution of storing the height information inside ccplot was chosen. This was possible thanks to the fact that the sampling height levels are constant over all product files.

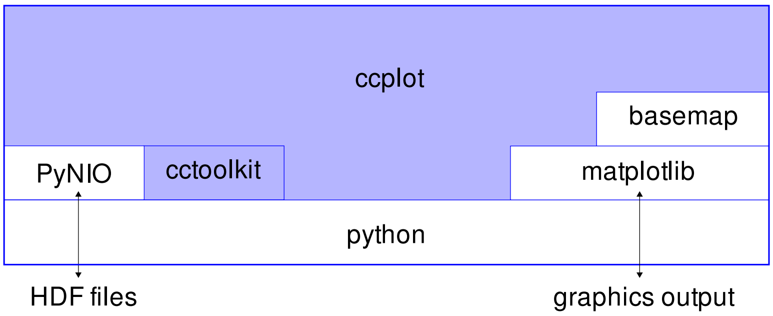


Figure 5.1 | Components of ccplot. The components that are a part of the ccplot code base are in blue.

5.3.2 Processing and Visualisation

a. Profile Products

Profile products are composed of a sequence of rays in the horizontal direction, and bins in the vertical direction. ccplot plots profile products on xy-plots, where the x-axis (horizontal) is linear with rays, and the y-axis (vertical) is linear with height. Linearity with rays implies linearity with time, because rays are sampled at a constant frequency of 6.25 Hz and 20.16 Hz[7] by CPR and CALIOP (resp.). Because the A-Train constellation travels at approx. constant velocity of 7 km s^{-1}, the x-axis is also linear with distance travelled.

Because bins are not sampled at regular altitudes, data points have to be interpolated on a regular grid before being plotted. This is done by the nearest-neighbour interpolation algorithm described in Section 5.3.3. The interpolation only needs to be performed vertically, therefore the horizontal cut-off radius $r_x = 0$. The vertical cut-off radius r_y is by default set to an equivalent of 800 m, recalculated to pixels according to the vertical extent, plot height, and DPI[8]:

$$r_y = \frac{800\,\mathrm{m}}{y_m - y_0} h \times \mathrm{DPI}$$

where h is axes height in inches, and y_0 and y_m are the lower and upper boundaries of the vertical extent (resp.) as introduced in Fig. 5.2. Typical bin height is 30 m to 300 m for CALIPSO products (Fig. 2.2), and 240 m for CloudSat products (Section 2.2). The vertical cut-off radius of 800 m was chosen large in order to err on the safe side.

In the current implementation, the axes height h is by default set to 4 in, and DPI is by default 300 px in^{-1}. This configuration results in 1200 px vertically regardless of the vertical extent to be plotted. This can be too little to plot all data points if the vertical extent is large, or unnecessarily much if the vertical extent is small. One way to mitigate this discrepancy is to increase or decrease (resp.) the plot height. Another way is to increase or decrease (resp.) DPI, although that may be restricted by publishing requirements.

[7] Applies to full resolution products. Others may be sub-sampled, but rays remain spaced regularly with time.

[8] DPI is the number of pixels per one inch. Typographical and vector graphics features of the plot such plot size, font, padding and line widths are measured in inches, while the profile raster is measured in pixels. DPI is the size translation factor between these two realms.

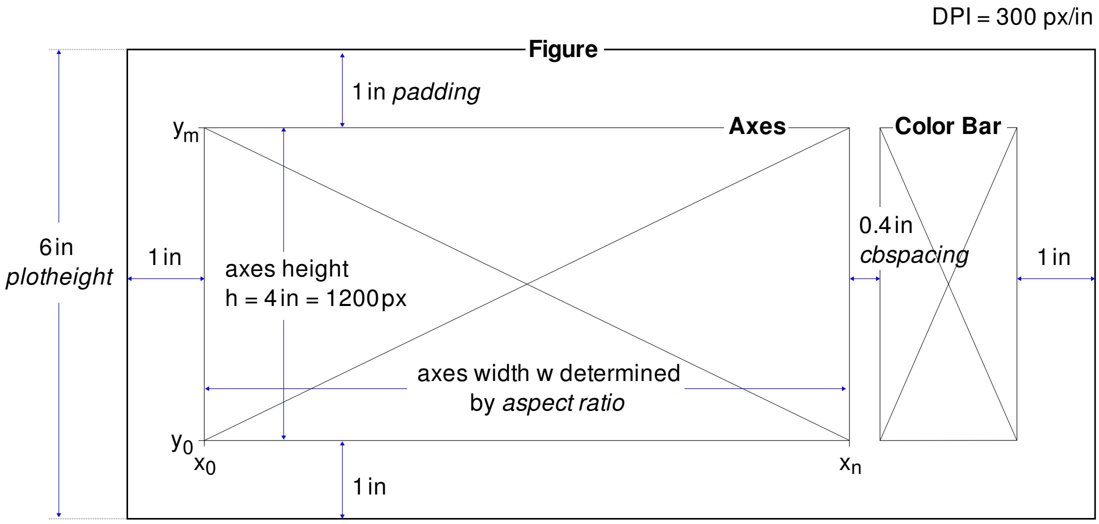


Figure 5.2 | Plot layout. The Figure contains two elements — the Axes and a Color Bar. The height of the Figure (*plotheight*) is by default 6 in regardless of the Axes content. 1 in *padding* on all sides of the Figure results in 4-inch-high Axes, which translates by DPI = 300 px in^{-1} to 1200 px vertically. x_0, x_n, y_0, y_m are the spatial coordinates of the Axes content. The Axes are by default separated from the Color Bar by *cbspacing* of 0.4 in.

The axes width is determined by the aspect ratio expressed as:

$$a = \frac{\Delta x_s}{\Delta y_s}$$

so that an atmospheric feature of a rectangular shape $\Delta x_s \times \Delta y_s$ is displayed square on the raster. The axes width w in inches is then calculated as:

$$w = \frac{h}{a}\frac{x_m - x_0}{y_m - y_0} = \frac{h}{a}\frac{(t_n - t_0)v_a}{y_m - y_0}$$

where x_0, x_m, y_0, y_m are as in Fig. 5.2, t_0 and t_n are the time of the first ray and the last ray (resp.), and v_a is the speed of the A-Train constellation, approximated by a constant of 7 km s^{-1}. At $a = 1.0$ atmospheric features may appear stretched in the horizontal direction, which is caused by the fact that the horizontal extent of clouds is normally far greater than the vertical extent. Aspect ratio is by default set to 14.0. If aspect ratio is set equally when plotting CloudSat and CALIPSO products, the appearance of atmospheric features is uniform, and therefore easily comparable.

Output fidelity could potentially be increased by taking into consideration that bins lying higher are shifted backwards horizontally relative to the bins lying close to the ground, i.e. by calculating the time it takes for a pulse to travel to a given range and back.

b. Layer Products

Layer products are plotted by filling a regular grid[9] with data values where there is any atmospheric feature. Although we could draw layer features as polygons, we chose not to,

[9] Regular with height in the vertical direction, and with rays in the horizontal direction.

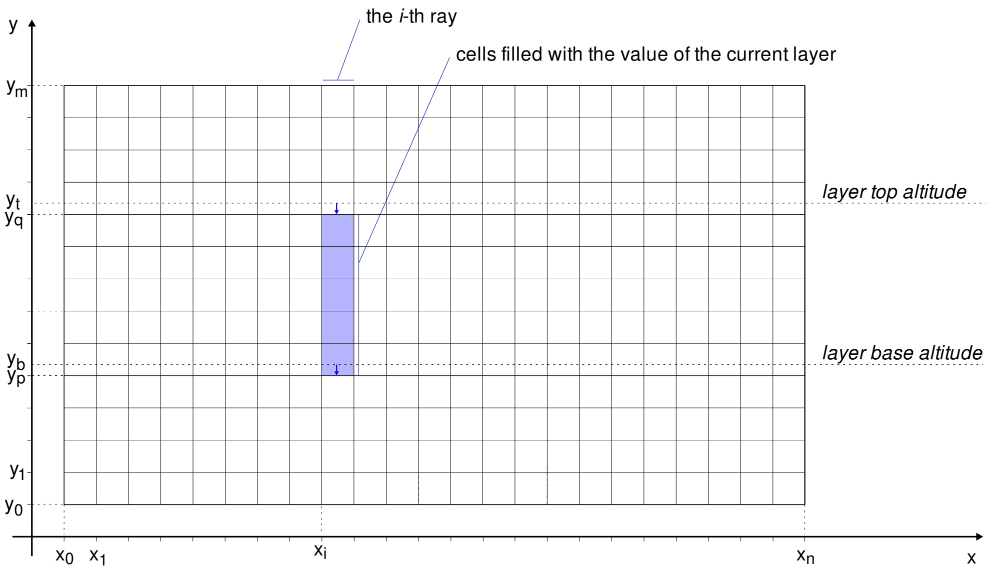


Figure 5.3 | The layer mapping algorithm. The algorithm works by iterating over all layers. Layers are localised by their base and top altitude y_b and y_t (resp.) and ray number i. The scheme shows a single iteration step. The coordinates of the low and high cell boundary y_p, y_q are calculated by rounding the base and top altitudes to the nearest horizontal cell boundary. (x_0, y_0) and (x_n, y_m) are the coordinates of the bottom-left and the upper-right corners of the grid (resp.).

because matplotlib cannot deal with large amounts of elements effectively. Instead, we use our own simple algorithm that fills the regular grid, which is then plotted as a raster. The algorithm is explained graphically in Fig. 5.3 and in a simplified pseudo-code in Fig. 5.5. The axes size is determined in the same way as for profile products described in the previous section.

c. Earth View Products and Trajectories

The Earth View products and trajectories are plotted by translating geographic coordinates of data and trajectory points into Cartesian coordinates on an xy-plane by the means of a map projection. This is handled by the basemap library. A large set of projections are supported by the library; however, our experience is that not all projections are properly implemented, and may fail when asked to translate points that do not lie in the typical region of the projection.

Because Earth View products data points are not positioned regularly with respect to Cartesian coordinates of any map projection, they have to be interpolated when they are to be plotted on the xy-plane. To accomplish that, the nearest-neighbour interpolation algorithm described in Section 5.3.3 is used. Default cut-off radii are calculated as:

$$r_x = \left\lceil \frac{2000\,\mathrm{m}}{x_n - x_0} w \times \mathrm{DPI} \right\rceil$$

$$r_y = \left\lceil \frac{2000\,\mathrm{m}}{y_m - y_0} h \times \mathrm{DPI} \right\rceil$$

Table 5.2 | Default values of some parameters in the standard and clipped regimes.

	Clipped	Not clipped
Major trajectory ticks	1 min	5 min
Minor trajectory ticks	10 s	1 min
Major parallels	5°	30°
Minor parallels	1°	10°
Major meridians	5°	30°
Minor meridians	1°	10°

The value of 2000 m was chosen as a large enough value suitable for all three MODIS resolutions (250 m, 500 m and 1 km). The cut-off radii can of course be set manually if any specific value is desired.

The axes height is by default fixed to 4 in, and the axes width is determined according to the aspect ratio reported by basemap. Earth View products plotting can operate in two regimes. The standard regime is not clipped, which causes the entire globe to be plotted. The other regime is clipped, which sets the projection parameters so that view is clipped optimally to MODIS swath. Default values of some other parameters are summarised in Tab. 5.2.

Setting central latitude and central meridian, latitude of true scale, projection centreline, bounding latitude for polar projections, and clipping region is not supported by the current implementation of ccplot, but are planned to be supported by future releases.

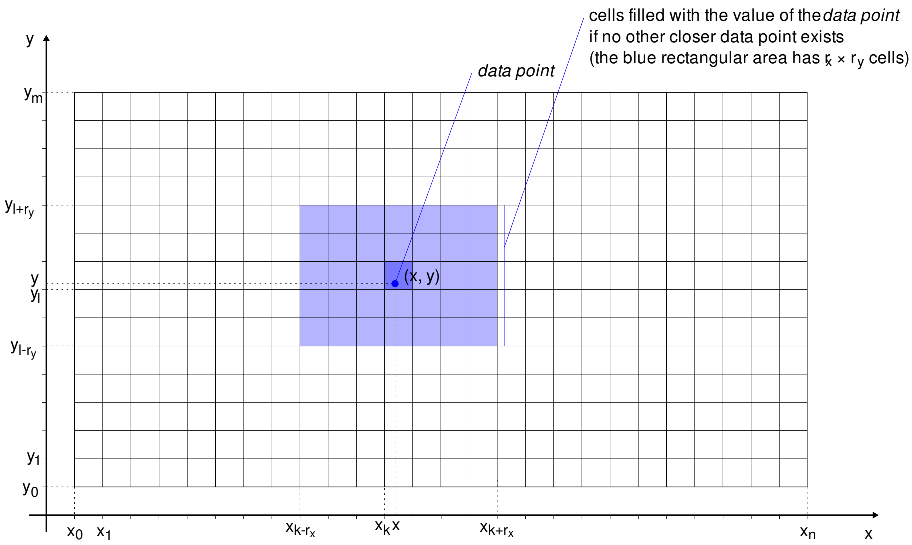


Figure 5.4 | The interpolation algorithm. The algorithm works by iterating over all source data points, and filling those cells of the regular grid which are within a rectangular area of $r_x \times r_y$ cells, and for which there have been no previous data points lying closer. The distance is calculated in screen coordinates. The scheme shows a single iteration step with a *data point* at (x, y). (r_x, r_y) are the cut-off radii, (x_k, y_l) are the coordinates of the cell lying closest to the data point, and (x_0, y_0) and (x_n, y_m) are the coordinates of the bottom-left and the upper-right corners of the grid (resp.).

5.3.3 The Interpolation Algorithm

Data from profile and MODIS swath products are not suitable for direct visualisation, because they are not distributed regularly with respect to desirable coordinates such as altitude in the vertical, or meters in the horizontal. In order to achieve that, we use a *nearest-neighbour interpolation algorithm* with an amendable *cut-off radius* in both directions, so that input samples are not taken as a source for far-enough points. This algorithm was used in an effort to present data with minimum distortion. Fig. 5.4 explains the interpolation algorithm by graphical means, and Fig. 5.6 contains a listing of the interpolation algorithm in a simplified pseudo-code. The actual implementation has been programmed in C, and as such scales well to large data sets.

```
# Performs mapping of CALIPSO layer data onto a regular grid.
#
# Arguments:
#
# data[n][U]     - array of data values, where n is the number of rays
#                  and U is the maximum number of layers per ray
# nlayer[n]      - array of number of layers in a ray
# basealt[n][U] - array of layer base altitudes
# topalt[n][U]  - array of layer top altitudes
# y0             - the y-coordinate of the bottom boundary of the grid
# ym             - the y-coordinate of the top boundary of the grid
# m              - number of grid cells in the y- direction
#
layermap(data[n][U], nlayer[n], basealt[n][U], topalt[n][U], y0, ym, m)
    grid[n,m] = array of NaN # The output raster.
                             # NaN stands for Not a Number,
                             # a value indicating an empty cell.

    # For each ray.
    for i from 0 to n-1:
        # For each layer in ray i.
        for j from 0 to nlayer[i]-1:
            yb = basealt[i][j]
            yt = topalt[i][j]
            pf = (yb - y0) / (ym - y0) * m
            qf = (yt - y0) / (ym - y0) * m
            p = round(pf)
            q = round(qf)

            for k from p to q-1:
                grid[i][k] = data[i][j]

    return grid
```

Figure 5.5 | The layer mapping algorithm in pseudo-code. The algorithm is supplied with a n×U array of scientific values data[n][U]. Only the first nlayer[i] items of data[i] contain meaningful values. The output is a regular grid of n×m cells. Also see Fig. 5.3 for a graphical explanation of the layer mapping algorithm.

```
# Implementation of the nearest-neighbour interpolation algorithm.
#
# Arguments:
#
# data[N]  - array of N data points
# coord[N] - array of N (x, y) pairs denoting the coordinates of
#            corresponding data points
# x0       - the x-coordinate of the left boundary of the grid
# xn       - the x-coordinate of the right boundary of the grid
# n        - number of grid cells in the x-direction
# y0       - the y-coordinate of the bottom boundary of the grid
# ym       - the y-coordinate of the top boundary of the grid
# m        - number of grid cells in the y-direction
# rx       - cut-off radius in the x-direction
# ry       - cut-off radius in the y-direction
#
interpolate(data[N], coord[N], x0, xn, n, y0, ym, m, rx, ry):
    grid[n][m] = array of NaN # The output raster.
                              # NaN stands for Not a Number,
                              # a value indicating an empty cell.

    distance[n][m] = array of +infinity # Distance of the nearest
                                        # data point as would appear
                                        # on the screen.

    # Interate over all data points.
    for i from 0 to N-1:
        value = data[i]
        (x, y) = coord[i]

        # Position of the data point on the grid.
        kf = (x - x0) / (xn - x0) * n
        lf = (y - y0) / (yn - y0) * m
        k = round(kf)
        l = round(lf)

        # For each cell within the cut-off distance.
        for p from -rx to rx:
            for q from -ry to ry:
                u = k + p
                v = l + q

                if not (0 <= u < n and 0 <= v < m):
                    continue

                d = (u - kf)^2 + (v - lf)^2
                if d < distance[u][v]:
                    distance[u][v] = d
                    grid[u][v] = value
    return grid
```

Figure 5.6 | The interpolation algorithm in pseudo-code. The algorithm takes an array of N input data points described by their value and coordinates, and parameters of a regular grid. The output of the algorithm is an n×m array — the grid. See also Fig. 5.4 for a graphical explanation.

Chapter 6

ccplot Manual

As a command-line application, ccplot is especially convenient for batch processing. On the other hand, the end user is required to know the names of command-line options and arguments in order to utilise the program. We provide an easy-to-follow tutorial on how to use ccplot in the next section.

6.1 Tutorial

6.1.1 Getting started

In this tutorial we suppose that you have access to a host system running unix-like operating system such as Linux with ccplot already installed[1], and you know how to use command-line programs. Moreover, it should be a host with at least 1 GB of physical memory, 4 GB is recommended. Start by simply running the program with the `-V` (print version) option:

```
$ ccplot -V
ccplot 1.31

Third-party libraries:
matplotlib 0.98.1
basemap 0.99.4

Copyright 2009, 2010 Peter Kuma.
This software is provided under the terms of a 2-clause BSD licence.
```

If no errors were reported, the required third-party libraries are present on the host system, and you can continue with the tutorial.

6.1.2 Getting Information

For brevity, we will assume that the shell variable `$HDF` is set to a directory where the HDF files reside. Prepare a CloudSat 2B-GEOPROF product such as *2006224184641_01550_CS_2B-GEOPROF_GRANULE_P_R03_E01.hdf* and enter:

[1] To install ccplot, download the source distribution of ccplot from http://www.ccplot.org, and follow the installation instructions included.

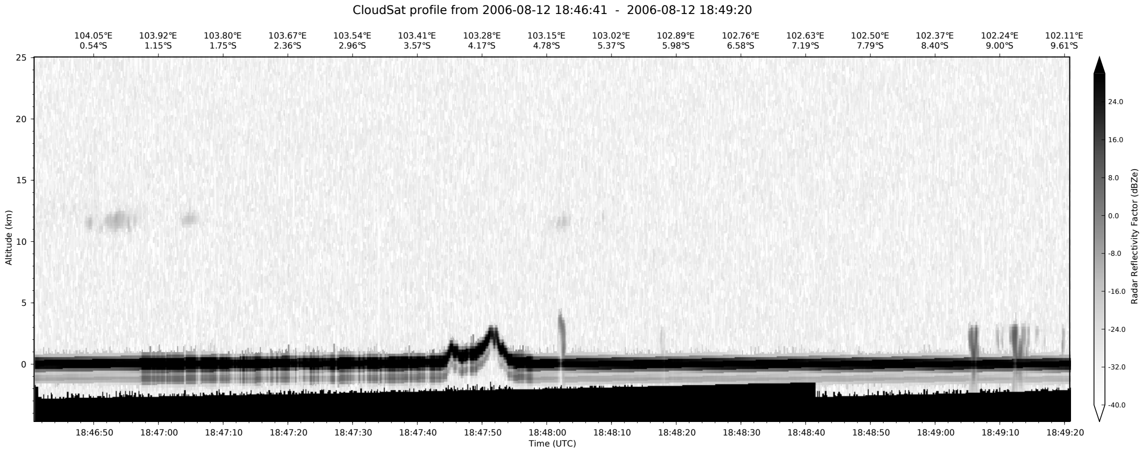


Figure 6.1 | cloudsat1.pdf

```
$ ccplot -i
$HDF/2006224184641_01550_CS_2B-GEOPROF_GRANULE_P_R03_E01.hdf
Type: CloudSat
Time: 2006-08-12 18:46:41, 2006-08-12 20:25:34
Height: -4874, 24865
nray: 37088
nbin: 125
Longitude: 104.171097, 79.441208
Latitude: 0.009954, -0.036672
```

The `-i` switch instructs ccplot to print summary information about the file.

6.1.3 Plotting Atmosphere Profiles

To plot the first 1000 rays of the Radar Reflectivity Factor data set and save it as *cloudsat1.pdf*, enter:

```
$ ccplot -o cloudsat1.pdf -x 0..1000 cloudsat-reflec
$HDF/2006224184641_01550_CS_2B-GEOPROF_GRANULE_P_R03_E01.hdf
```

You should get an image similar to that in Fig. 6.1. The `-x` option tells ccplot what extent to plot, and `ccplot-reflec` chooses the CloudSat Radar Reflectivity Factor as the input. The `-o` option selects the output file. The result may not seem very impressive, but we have not yet selected any colormap. Therefore, ccplot will use the default colormap, which is a black-and-white gradient spanning the entire valid range of the selected data set. Fortunately, ccplot comes with a set of colormaps that you can use without making your own. These are stored in `$PREFIX`*/share/ccplot/cmap*, where `$PREFIX` is the installation prefix, usually */usr* or */usr/local*. The one suitable for `cloudsat-reflec` is *cloudsat-reflectivity.cmap*. Let us use it in the next example (Fig. 6.2):

```
$ ccplot -o cloudsat2.pdf -x 0..1000
-c /usr/share/ccplot/cmap/cloudsat-reflectivity.cmap cloudsat-reflec
$HDF/2006224184641_01550_CS_2B-GEOPROF_GRANULE_P_R03_E01.hdf
```

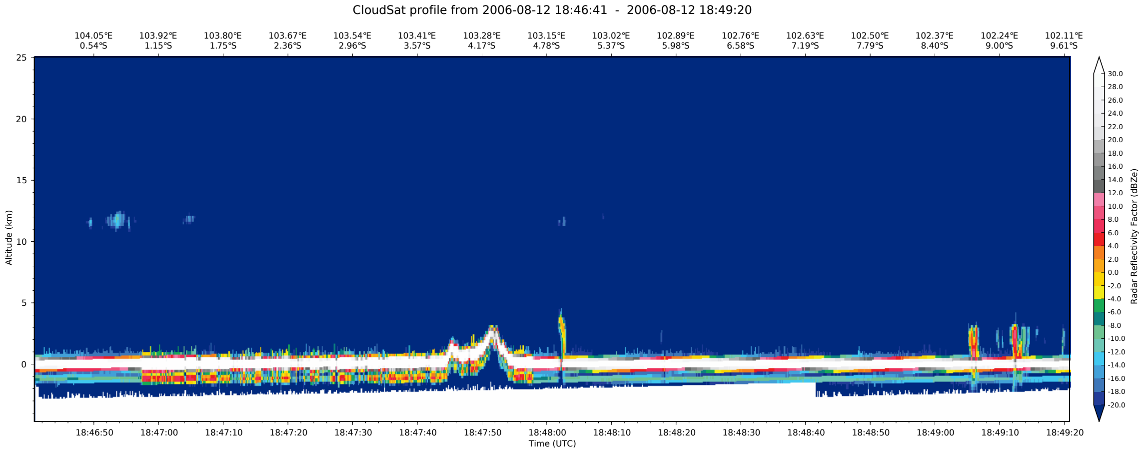


Figure 6.2 | cloudsat2.pdf

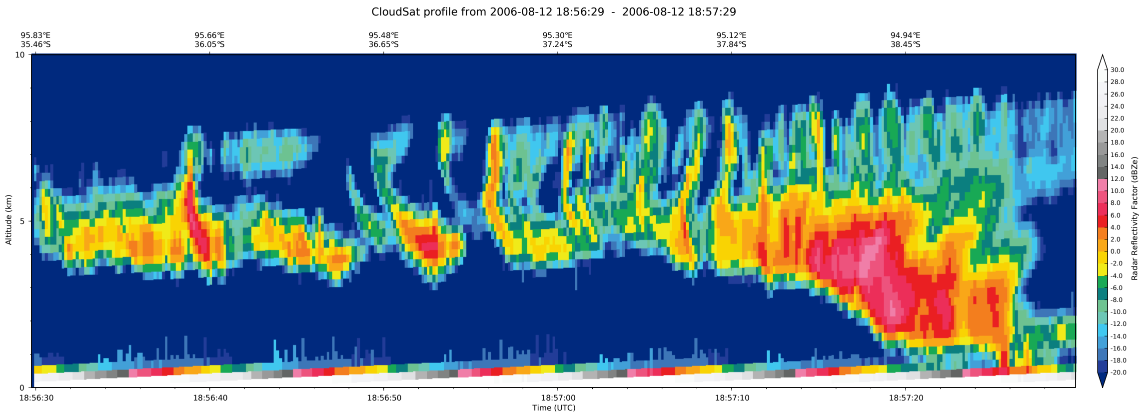


Figure 6.3 | cloudsat3.pdf

This demonstrates the use of the `-c` (colormap) option. Fig. 6.7 contains a summary of colormaps supplied with ccplot, and Section 6.2 will guide you through the process of crating your own colormap.

Suppose you know that there is an interesting feature between 18:56:30 and 18:57:30 UTC, which spans 0–10 km vertically. You can use the `-x` option with an absolute time, and select the vertical extent in meters with the `-y` option (Fig. 6.3):

```
$ ccplot -o cloudsat3.pdf -x 18:56:30..18:57:30 -y 0..10000
-c /usr/share/ccplot/cmap/cloudsat-reflectivity.cmap
cloudsat-reflec
$HDF/2006224184641_01550_CS_2B-GEOPROF_GRANULE_P_R03_E01.hdf
```

6.1.4 CALIPSO

Plotting CALIPSO products is almost identical to plotting CloudSat products. The only difference is that CALIPSO products are in higher resolution than those of CloudSat. Therefore, a 1000-ray plot of CALIPSO backscatter would likely be too short.

We will now focus on some of the advanced features. Prepare one CALIPSO L1B Profile product, and one CALIPSO L2 Layer product. Let us start with the L1B product, and use the

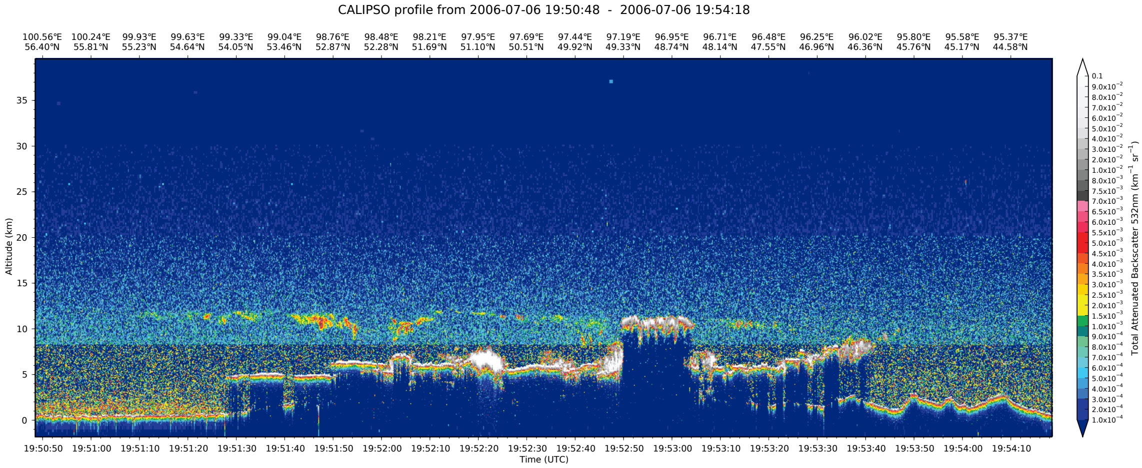


Figure 6.4 | calipso1.pdf

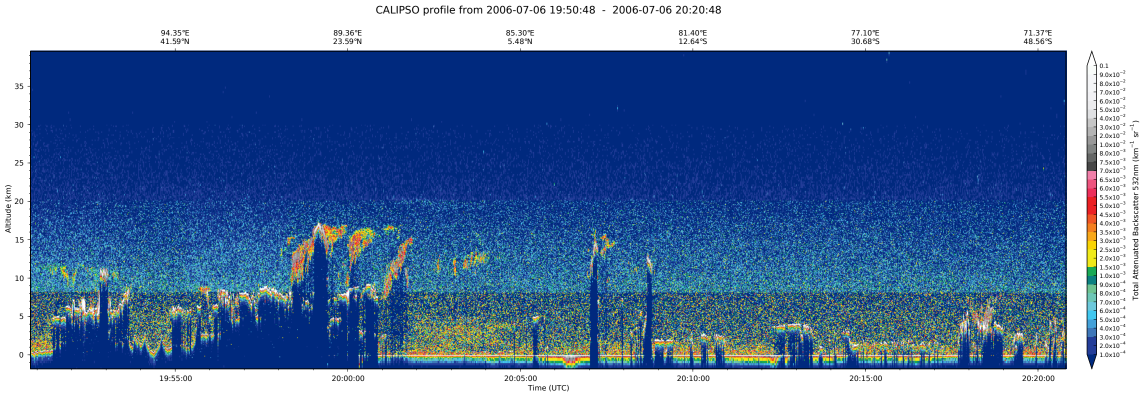


Figure 6.5 | calipso2.pdf

`-d` option to change the DPI of the resulting image. The default DPI is 300 pixels per inch. This time, we will use the `-x` option with a relative time in the format `(+|-)[HH]:MM:SS`. The preceding plus sign means '*relative to the beginning*', whereas the minus sign means '*relative to the end*'.

```
$ ccplot -o calipso1.pdf -d 100 -x +0:00..+3:30
-c /usr/share/ccplot/cmap/calipso-backscatter.cmap calipso532
$HDF/CAL_LID_L1-Prov-V2-01.2006-07-06T19-50-51ZN.hdf
```

This command plots the first three-and-a-half minutes of Total Attenuated Backscatter 532nm in 100 pixels per inch. The result is in Fig. 6.4. ccplot in its default configuration does not plot profiles in 1:1 aspect ratio, as the plots would appear squashed in the vertical direction. We chose the aspect ratio 14 as the default. For example, if you wanted to plot 30 minutes of a profile in one plot without it being too long, you could increase the aspect ratio to 1:10000 (Fig. 6.5):

```
$ ccplot -o calipso2.pdf -a 10000 -x +0:00..+30:00
-c /usr/share/ccplot/cmap/calipso-backscatter.cmap calipso532
$HDF/CAL_LID_L1-Prov-V2-01.2006-07-06T19-50-51ZN.hdf
```

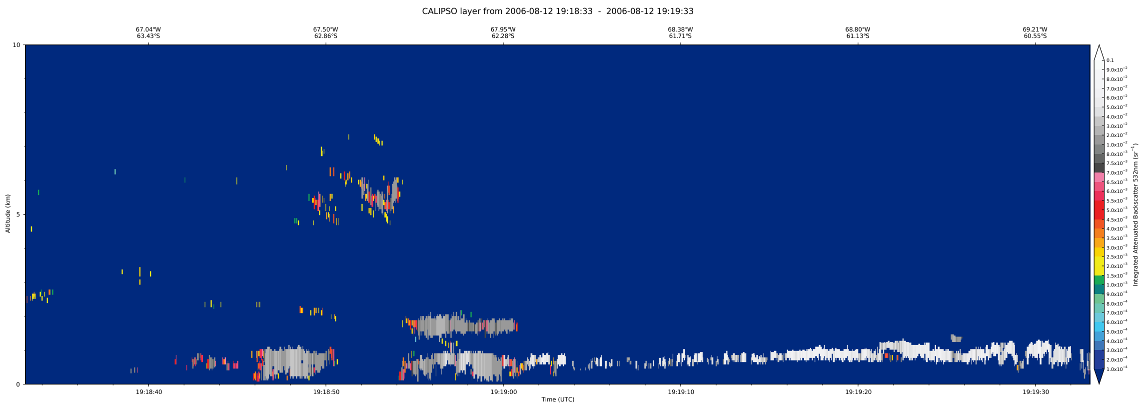


Figure 6.6 | calipso3.pdf

Last but not least, ccplot allow you to change the size of the plot in inches. You can change the height of the data part of the plot — the axes, but also the padding (space on the margins of the canvas), and spacing between the axes and the color bar. Supplementary options like these are covered by the `-z` option, which takes a list of comma-separated `name=value` pairs as its argument. The default value of the *plotheight* option is 6 in. Suppose you want to change the plot height to 8 in, the padding to 1.2 in, and the axes-color bar spacing to 0.1 in. We will try this new setting on a layer product (Fig. 6.6):

```
$ ccplot -o calipso3.pdf -x +3:00..+4:00 -y 0..10000
-z plotheight=8,padding=1.2,cbspacing=0.1 -c
/usr/share/ccplot/cmap/calipso-backscatter.cmap calipso532-layer
$HDF/CAL_LID_L2_333mCLay-Prov-V2-01.2006-08-12T19-15-34ZD.hdf
```

6.2 How to Create Your Own Colormap

If none of the colormaps supplied with ccplot suits your needs, you can create your own. ccplot colormaps are stored in simple ASCII text files. Some example colormaps are in Fig. 6.7. You can start by creating a copy of one of these files, and replacing the various sections of the file. As explained the previous section, colormaps can typically be found in */usr/share/ccplot/cmap* or */usr/local/share/ccplot/cmap*. A colormap file divided into four sections - `BOUNDS`, `TICKS`, `UNDER_OVER_BAD_COLORS` and `COLORS`. These can appear in an arbitrary order in the file. The start of a section is denoted by a section header (section name in capital letters). Blank lines are ignored.

`BOUNDS` This section describes the boundaries. Values that lie between two boundaries are mapped to the same colour. Boundaries are specified by ranges in the form `start stop step`, i.e. three floating point numbers separated by white space. For example, `0 10 2` would produce boundaries at 0, 2, 4, 6, 8. Notice that `stop` is not included in the range. `BOUNDS` section can contain multiple lines of one range per line. Ranges should be specified in an increasing order.

`TICKS` This section specifies where ticks on the colorbar should be placed. The format is the same as the format of `BOUNDS`.

a)

cloudsat-reflectivity.cmap

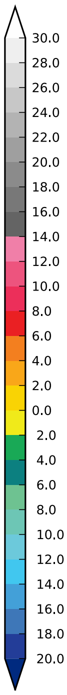
Suitability: cloudsat-reflec

```
BOUNDS
-20 32 2

TICKS
-20 32 2

UNDER_OVER_BAD_COLORS
0 42 127
255 255 255
0 42 127

COLORS
35 61 153
62 119 185
67 161 217
65 200 240
108 202 220
109 199 182
110 195 146
12 128 128
25 170 86
242 234 26
241 235 26
250 212 4
250 168 25
244 127 31
240 85 36
...
```



b)

calipso-temperature.cmap
modis-temperature.cmap

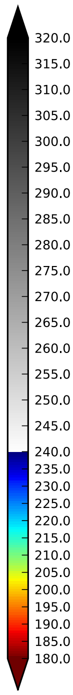
Suitability: calipso-temperature-layer, orbit, orbit-clipped

```
BOUNDS
180 240 0.75
240 320.5 0.5

TICKS
180 240 5
240 325 5

UNDER_OVER_BAD_COLORS
111 0 0
0 0 0
0 0 0

COLORS
111 0 0
134 0 0
146 0 0
157 0 0
169 0 0
184 0 0
196 0 0
208 0 0
220 0 0
231 0 0
245 0 0
...
```



c)

calipso-backscatter.cmap

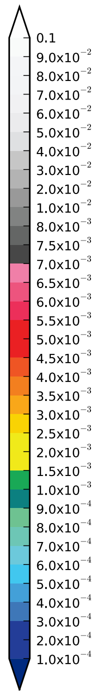
Suitability: calipso532, calipso532p, calipso1064, calipso532-layer, calipso1064-layer

```
BOUNDS
0.0001 0.001 0.0001
0.001 0.0085 0.0005
0.01 0.11 0.01

TICKS
0.0001 0.001 0.0001
0.001 0.0085 0.0005
0.01 0.11 0.01

UNDER_OVER_BAD_COLORS
0 42 127
255 255 255
0 42 127

COLORS
35 61 153
62 119 185
67 161 217
65 200 240
108 202 220
109 199 182
110 195 146
12 128 128
25 170 86
...
```



d)

calipso-cratio.cmap

Suitability: calipso-cratio, calipso-cratio-layer

```
BOUNDS
0 1.7 0.1

TICKS
0 1.7 0.1

UNDER_OVER_BAD_COLORS
0 0 0
155 155 155
0 0 0

COLORS
0 170 255
0 212 0
255 255 0
255 170 0
255 0 0
255 0 255
255 212 255
170 85 255
127 0 170
170 0 127
170 212 255
170 255 255
170 255 212
...
```

e)

calipso-dratio.cmap

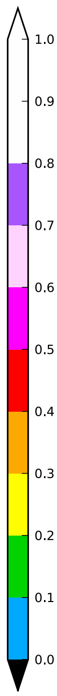
Suitability: calipso-dratio, calipso-dratio-layer

```
BOUNDS
0 1.1 0.1

TICKS
0 1.1 0.1

UNDER_OVER_BAD_COLORS
0 0 0
255 255 255
0 0 0

COLORS
0 170 255
0 212 0
255 255 0
255 170 0
255 0 0
255 0 255
255 212 255
170 85 255
255 255 255
255 255 255
255 255 255
```



f)

modis-reflectance.cmap

Suitability: orbit, orbit-clipped

```
BOUNDS
0 60 3.75
60 121.25 1.25

TICKS
0 60 10
60 125 5

UNDER_OVER_BAD_COLORS
0 0 0
255 255 255
0 0 0 0

COLORS
4 4 4
8 8 8
12 12 12
16 16 16
20 20 20
24 24 24
28 28 28
32 32 32
36 36 36
40 40 40
44 44 44
...
```

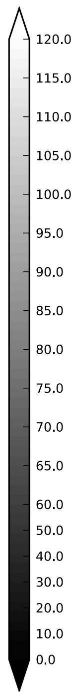


Figure 6.7 | Colormaps supplied with ccplot.

`UNDER_OVER_BAD_COLORS` This section contains three colours. The first one (*under*) is used for values that lie below the lowest boundary. The second one (*over*) is used for values that lie above the highest boundary. The third one (*bad*) is used for points where there is no valid data. Colours are specified by three (optionally four) numbers separated by white space. These are the RGB or RGBA (Red, Green, Blue, Alpha) components encoded in an 8-bit-per-channel base-10 format (i.e. values between 0 and 255, incl.).

`COLORS` This section contains the colours which data values lying between respective boundaries are mapped onto. The first colour following the section header is the one that lies between the first two boundaries, and so on. Colours in this section are in the same format as colours in the `UNDER_OVER_BAD_COLORS` section described above.

When creating custom colormaps, you should take into consideration that the performance of the current implementation of ccplot depends significantly on the number of color entries in the colormap. This is an inherent problem of the plotting library matplotlib, but we may be able to alleviate it in one of the future versions of ccplot.

Chapter 7

Conclusion

As stated in the *Introduction*, the aim of this thesis was to develop a tool called ccplot which would allow us to visualise data originating from CloudSat and CALIPSO. We developed and released this program under the open-source-compatible, two-clause BSD license. As such, ccplot and its source code is available to any one with no charge, and it can be modified and redistributed without restrictions. The third-party tools necessary to run ccplot are released under similar permissive licenses. It can be run on a number of unix-compatible operating system platforms including Linux. ccplot can be downloaded from http://www.ccplot.org. Presentation of three case studies of ccplot can be found in Appendix B.

The development of ccplot started with a simple goal of being able to visualise a few data sets from CloudSat, CALIPSO and MODIS products. Over the course of several months it grew from a few lines of code of the very first implementation into a much more complex program of more than 2700 lines. It is now able to handle more sophisticated extent selection, plot layout customisation, multiple projections and custom color maps. We started a web site to make it available to any one who needs it. By opening it as an open source project, we hope to attract new developers, encourage users to help with reporting and fixing of flaws in the program, and providing them with a place for discussion.

However, during the development we encountered many areas where improvement can be made. To mention just a few, some of the libraries can be replaced with alternatives that will provide greater performance and lower-level access, such as the cairo 2D drawing library or proj.4 map projection toolkit. More consistent application models for holding data structures can be introduced, so that support for new products can be added more readily. There are plans to build a GUI version to make the experience of working with ccplot more pleasurable to the user. Because there are many approaches to choose from, we want decide according to feedback from users of the current version of ccplot. For example, it can be designed to allow for a very detailed examination of a single product file, or it can be designed to combine many products effectively, thereby enabling the user to handle large amounts of data quickly and comprehensively. Last but not least, we would like ccplot to become a universal tool capable of visualising most scientific data coming from CloudSat and CALIPSO (and potentially other A-Train members as well), but that is a goal yet to be achieved.

Appendix A. ccplot Manual Page

NAME

ccplot — CloudSat and CALIPSO data plotting tool

SYNOPSIS

ccplot [**-a** *ratio*] [**-c** *cmapfile*] [**-d** *dpi*] [**-m** *band*] [**-o** *outfile*] [**-p** *projection*[:*projoptions*]] on [**-r** *radius*] [**-v**] [**-x** *extent*] [**-y** *extent*] [**-z** *options*] *type file ...*
ccplot **-i** *file*
ccplot **-h**
ccplot **-V**

DESCRIPTION

ccplot is a tool that produces 2D plots of data stored in CloudSat, CALIPSO and MODIS HDF files.

The plot *type* can be one of:

cloudsat-reflec	CloudSat Reflectivity Factor
calipso532	CALIPSO L1B Total Attenuated Backscatter 532nm
calipso532p	CALIPSO L1B Perpendicular Attenuated Backscatter 532nm
calipso1064	CALIPSO L1B Attenuated Backscatter 1064nm
calipso-cratio	CALIPSO L1B Attenuated Color Ratio 1064nm/532nm
calipso-dratio	CALIPSO L1B Depolarization Ratio
calipso532-layer	CALIPSO L2 Integrated Attenuated Backscatter 532nm
calipso1064-layer	CALIPSO L2 Integrated Attenuated Backscatter 1064nm
calipso-cratio-layer	CALIPSO L2 Integrated Attenuated Total Color Ratio 1064nm/532nm
calipso-dratio-layer	CALIPSO L2 Integrated Volume Depolarization Ratio
calipso-temperature-layer	CALIPSO L2 Midlayer Temperature
orbit	map projection of CALIPSO and CloudSat trajectory, and Aqua MODIS radiance or reflectance swath depending on files supplied
orbit-clipped	MODIS-region-clipped map projection of CALIPSO and CloudSat trajectory, and Aqua MODIS radiance or reflectance swath depending on files supplied

The options are as follows:

-a *ratio* Aspect ratio of profile and layer products in km horizontal per km vertical. Defaults to 14.0.

-c *cmapfile* Path to a cmap file defining a colormap *boundaries*, colorbar *ticks* and *colors*. This can be a filename relative to any path defined by the CCPLOT_CMAP_PATH environment variable. Such paths take precendence over the current working directory, unless *cmapfile* is an absolute path or begins with *./* or *../*. See the example cmap files that are distrubuted with **ccplot** for information about the format.

-d *dpi* DPI of *outfile* if a raster image is to be output.

-m *band* MODIS band specifier in the form r# for reflective bands and x# for radiation bands, where # is the band number.

-o *outfile* Output file. Format is determined by extension Supported formats are SVG (.svg), PNG (.png), PDF (.pdf), EPS (.eps) and PS (.ps). Defaults to ccplot.png.

-p *projection*[:*projoptions*] on *projection* specifies the mapping projection for orbit plots. Supported projection types are:

aeqd	Azimuthal Equidistant
poly	Polyconic
gnom	Gnomonic
moll	Mollweide
tmerc	Transverse Mercator
nplaea	North-Polar Lambert Azimuthal
gall	Gall Stereographic Cylindrical
mill	Miller Cylindrical
merc	Mercator
stere	Stereographic
npstere	North-Polar Stereographic

vandg	van der Grinten
laea	Lambert Azimuthal Equal Area
mbtfpq	McBryde-Thomas Flat-Polar Quartic
sinu	Sinusoidal
spstere	South-Polar Stereographic
lcc	Lambert Conformal
npaeqd	North-Polar Azimuthal Equidistant
eqdc	Equidistant Conic
cyl	Cylindrical Equidistant
aea	Albers Equal Area
spaeqd	South-Polar Azimuthal Equidistant
ortho	Orthographic
cass	Cassini-Soldner
splaea	South-Polar Lambert Azimuthal
robin	Robinson

projection can be followed by a comma-separated list of option-value pairs *projoptions*. Supported projection options are:

boundinglat	Bounding latitude for polar projections.
lat_0	Central latitude.
lat_1	First standard parallel.
lat_2	Second standard parallel.
lat_ts	Latitude of true scale.
lon_1	Longitude of one of the two points on the projection centerline for oblique mercator.
lon_2	Longitude of one of the two points on the projection centerline for oblique mercator.

Longitude and latitude have to be valid positive decimal numbers followed by E or W, or S or N literal (respectively) to indicate direction.

Use -p help to get a list of available projections.

-r radius
Interpolation radius in pixels. In profile products radius specifies vertical extent which a data point is mapped onto. If such vertical regions of two data points overlap value is determined by averaging with a weight coefficient of 1 over distance squared. The same holds for swath products, but here radius specifies a square. If radius is too low with respect to **dpi** data will be sparsely distributed on the image. Default is 3 for swath swath and a sensible value calculated from resolution for profile products.

-v
Enable verbose mode.

-V
Print version information and exit.

-x extent
Horizontal region to be plotted. extent can be specified in a number of formats depending on the plot type.

For profile and layer products extent can either be specified by rays or by a time interval. In the first case it takes the form from..to where from and to are the first and the last ray (resp.) to be plotted. In the latter case, extent can be an absolute time interval in the form hour:min[:sec]..hour:min[:sec]. or a relative time interval in the form +|-[hour:]min:sec..+|-[hour:]min:sec.

For swath products extent can be specified by scanlines (along-track) and samples (across-track), or by geographical coordinates. In the first case extent takes the form from..to,from..to where the first term is the first and the last scanline to be plotted, and the second term is the first and the last sample to be plotted. In the latter case extent takes the form lon(E|W)..lon(E|W),lat(S|N)..lat(S|N) where lon, lat are numbers (in degrees) and E, W, S, N are literals, (A|B) means either A or B.

-y extent
Vertical extent of CloudSat and CALIPSO profiles in meters in the form from..to.

-z options
Miscellaneous options that modifiy plot formatting. options is a list of comma separeted key=value pairs with no spaces in between. Supported general options are:

cbfontsize	color bar font size (defaults to 8)
cbspacing	spacing between the axes and color bar (defaults to 0.4)
drawelev (default to 1)	draw surface elevation line (CALIPSO)
elevlw (defaults to 0.5)	surface elevation line width
elevcolor (defaults to #FF0000)	surface elevation line color
fontsize	font size (defaults to 10)
padding	padding around the axes and color bar in inches (defaults to 1)
plotheight	plot height in inches (defaults to 6)
title	figure title (set automatically by default)

Supported options for orbit plots are:

coastlinescolor	coastlines color (defaults to #46396D)
coastlineslw	coastlines line width (defaults to 0.4)
countriescolor	countries outlines color (defaults to #46396D)
countrieslw	countries outlines line width (defaults to 0.2)
drawcoastlines	draw coastlines (defaults to 1)

drawcountries	draw countries outlines (defaults to 1)
drawlakes	draw lakes (defaults to 1)
drawlsmask	draw land-sea mask (defaults to 1)
drawmeridians	draw meridians (defaults to 1)
drawminormeridians	draw meridians (defaults to 1)
drawminorparallels	draw minor parallels (defaults to 1)
drawparallels	draw parallels (defaults to 1)
landcolor	land color (defaults to #E9E4F7)
majormeridianscolor	major meridians color (defaults to #000000)
majormeridianslw	major meridians line width (defaults to 0.3)
majorparallelscolor	major parallels line color (defaults to #000000)
majorparallelslw	major parallels line width (defaults to 0.3)
mapres	map resolution: c (crude), l (low), i (intermediate), h (high), f (full); (defaults to i)
minormeridianscolor	minor meridians color (defaults to #000000)
minormeridianslw	minor meridians line width (defaults to 0.1)
minorparallelscolor	minor parallels color (defaults to #000000)
minorparallelslw	minor parallels line width (defaults to 0.1)
trajcolors	list of trajectory colors (defaults to #FF0000:#0000FF:#00FF00)
trajlws	list of trajectory line widths (defaults to 0.5)
trajnminortics	number of minor ticks between adjacent major ticks or -1 for automatic selection (defaults to -1)
trajticks	base for trajectory major ticks in seconds or -1 for automatic selection (defaults to -1)
watercolor	water color (defaults to #FFFFFF)

Options that accept a list of values are specified in the form key=value1:value2[:value...].

Use -z help to get a list of available options.

ENVIRONMENT

CCPLOT_CMAP_PATH Colon-separated list of search paths for colormap files.

FILES

/usr/share/ccplot/cmap/* Example cmap files.

EXAMPLES

Plot the first 1000 rays of CloudSat reflectivity profile from 2006224184641_01550_CS_2B-GEOPROF_GRANULE_P_R03_E01.hdf using cloudsat-reflec.cmap colormap, and save it as cloudsat-reflec.png:

```
$ ccplot -x 0..1000 -c cloudsat-reflectivity.cmap
-o cloudsat-reflec.png cloudsat-reflec
2006224184641_01550_CS_2B-GEOPROF_GRANULE_P_R03_E01.hdf
```

Plot the first minute of CALIPSO backscatter profile from 0 to 20km using calipso-backscatter.cmap colormap, and save it as calipso532.png:

```
$ ccplot -y 0..20000 -x +0:00..+1:00 -c calipso-backscatter.cmap
-o calipso532.png calipso532
CAL_LID_L1-Prov-V2-01.2006-07-06T19-50-51ZN.hdf
```

Plot map projection of CALIPSO trajectory superimposed on Aqua MODIS band 31 radiance using modis-temperature.cmap colormap, and save it as orbit-calipso.png:

```
$ ccplot -m x31 -c modis-temperature.cmap -p tmerc
-o orbit-calipso.png orbit-clipped
MYD021KM.A2006224.1945.005.2007140113559.hdf
CAL_LID_L1-Prov-V2-01.2006-07-06T19-50-51ZN.hdf
```

SEE ALSO

CloudSat Standard Data Products Handbook, April 25th, 2008.

CALIPSO Data Products Catalog Release 2.4, December 2007.

MODIS Level 1B Product User's Guide, December 1, 2005.

AUTHORS

ccplot was written by Peter Kuma.

CAVEATS

Plot size is limited to 32767 pixels.

Appendix B. Case Studies

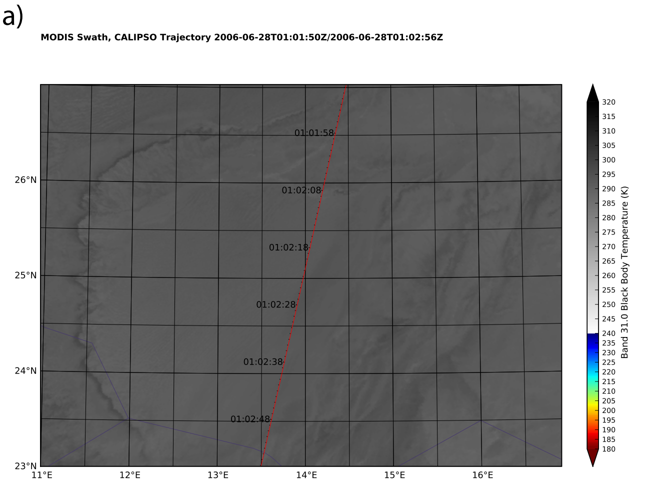
In the following sections we present three cases in which ccplot was used to produce plots of MODIS swath, CloudSat profile, and CALIPSO profile and layer products. A brief analysis is provided with each case.

Case 1: Sand over Sahara, 28 June 2006

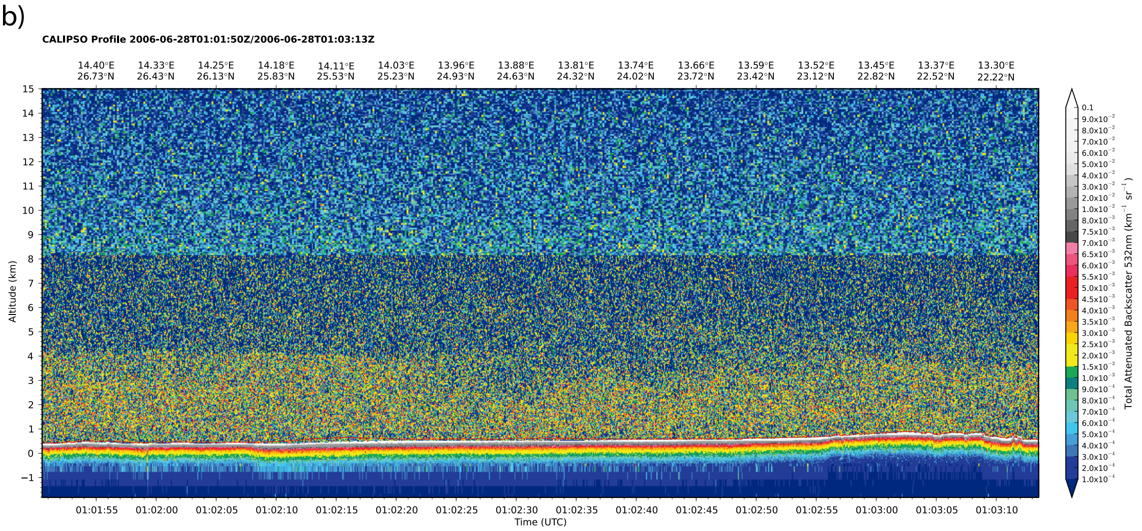
This case was chosen to demonstrate typical appearance of sand suspended in the lower troposphere in CALIPSO profiles.

a, presented is a track over an area called Murzuq Desert in the south west of Libya between 22° N and 27° N. **b**, a layer of sand stretches predominantly from the ground to 4 km. A conspicuous change in response occurs at 8.1 km. This is due to change in sampling resolution between Region 2 and Region 3 as explained in Fig. 2.2. The thick band of high backscatter below the ground (red line) is caused by oversaturation of detectors, as can be seen in most 532 nm profiles.

a)

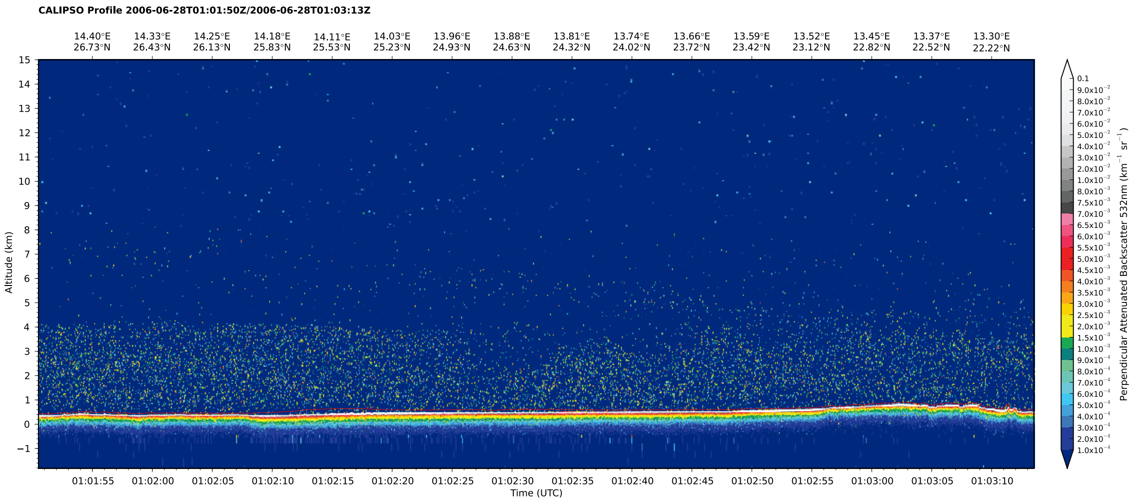


b)

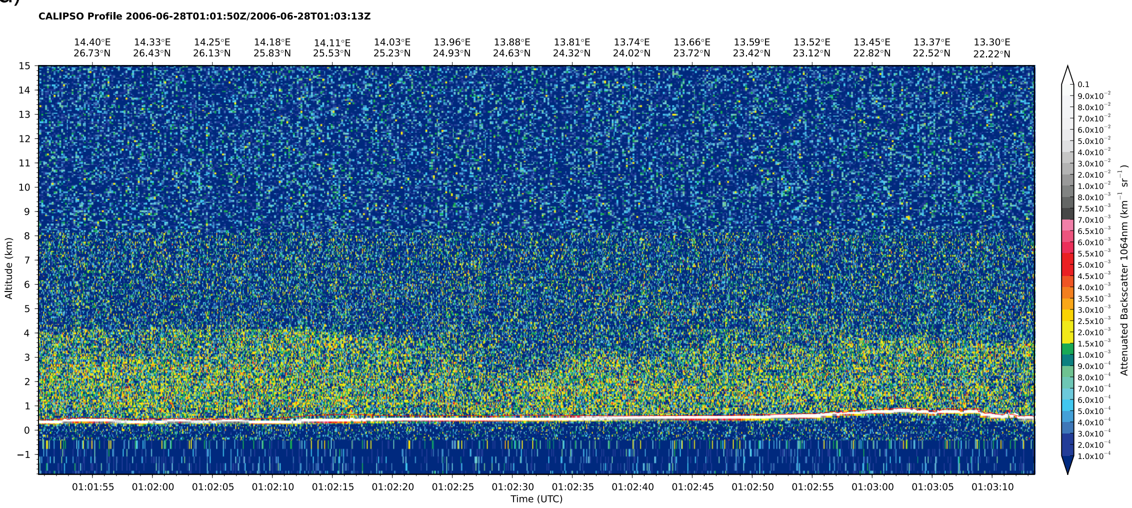


c, because sand particles are weak light polarisers, the response on Perpendicular Attenuated Backscatter 532 nm is scattered and low. **d**, response at 1064 nm is slightly lower than at 532 nm.

c)



d)

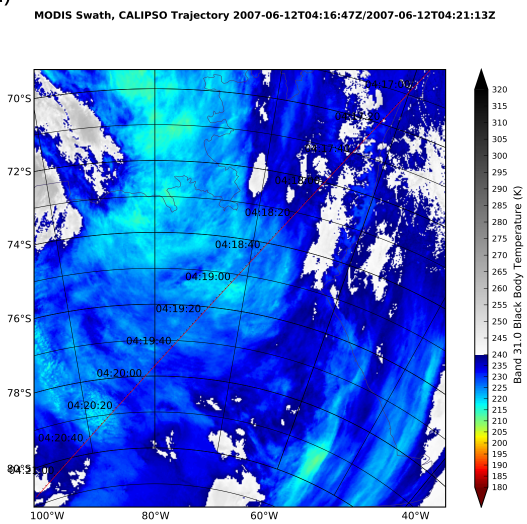


Case 2: Polar Stratospheric Clouds, Antarctica, 12 June 2007

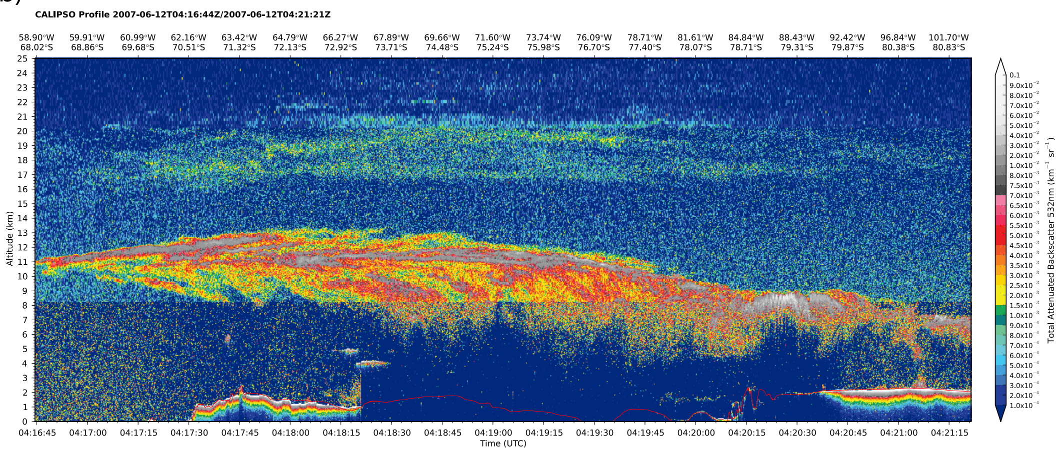
In this case we examine clouds inside the Antarctic Polar Vortex during the austral winter. These conditions favour formation of Polar Stratospheric Clouds (PSCs), which are crucial in converting reservoir species of chlorine into more active species, leading to strong ozone depletion when sun rises in the austral spring.

a, this case presents a track over Palmer Land at the base of Antarctic Peninsula between 68° S and 81° S, and 58° W and 102° W. **b**, visible are two clouds, the larger one stretches up to about 13 km. It has a bottom part that touches the ground, but it is only visible in the CloudSat profile, either because the attenuation by the overlying layers is too high, or because the bottom part is composed of larger particles such as snow pellets. A much more faint second cloud is visible at 20 km. **c**, light scattered from both clouds is polarised, which indicates ice-phase clouds, as we would expect in Antarctica in winter.

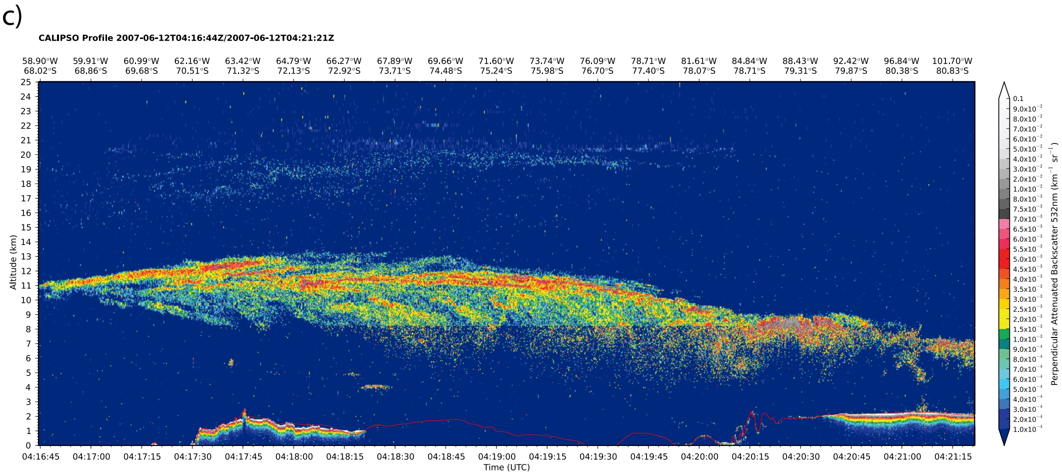
a)



b)

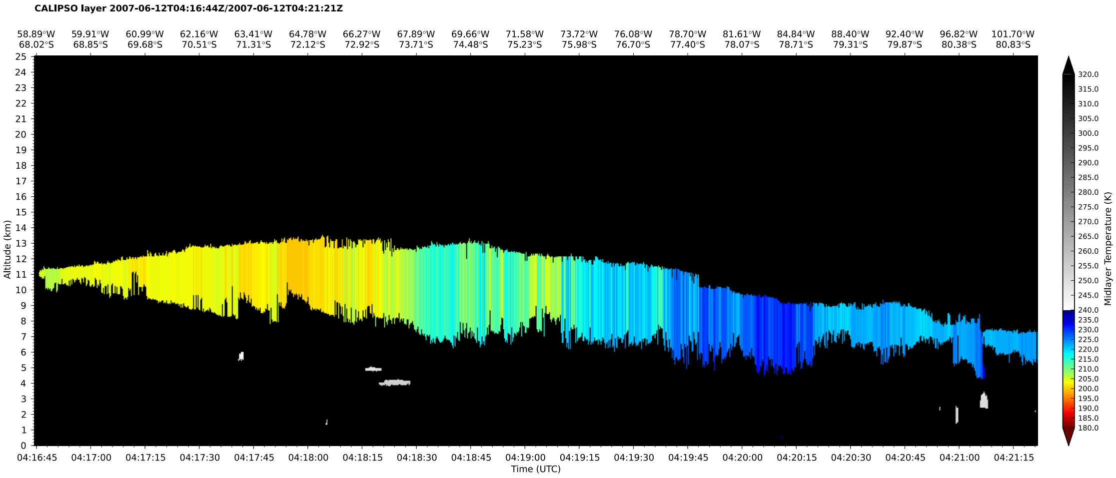


c)

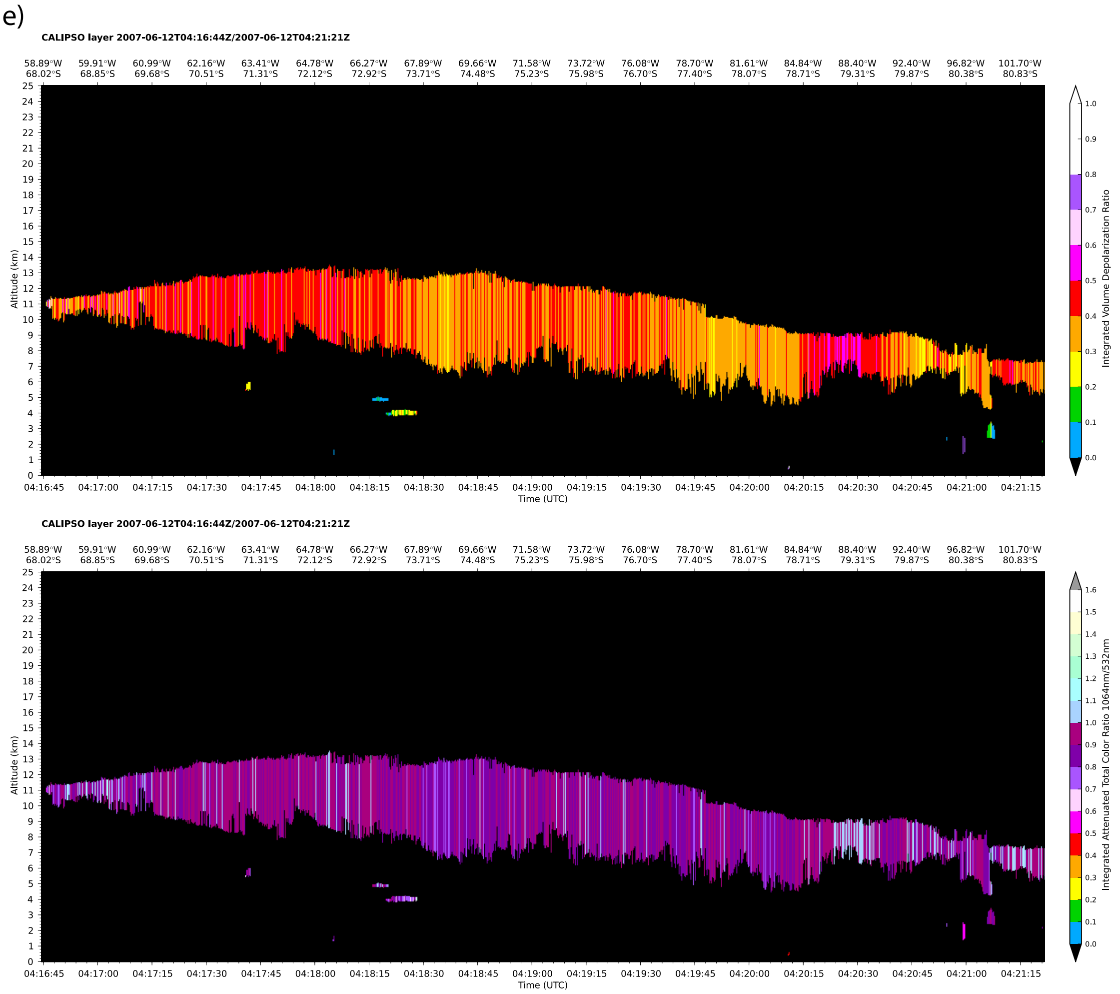


d, midlayer temperature of the lower cloud is greater than −78 °C, which is not enough for PSCs to form, although the fainter cloud visible in profile products could be a PSC. **e**, the larger cloud was well recognised by the layer detection algorithm.

d)

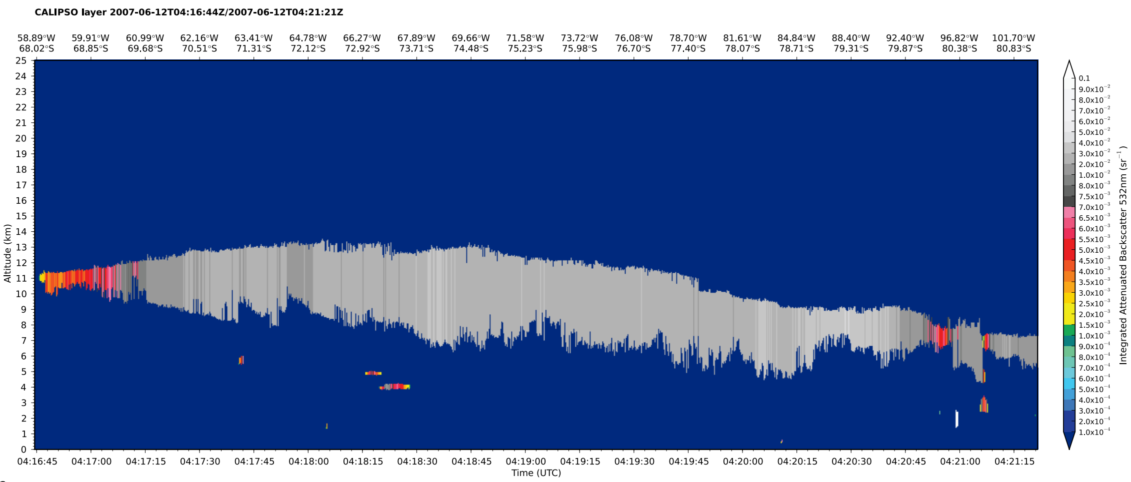


e)

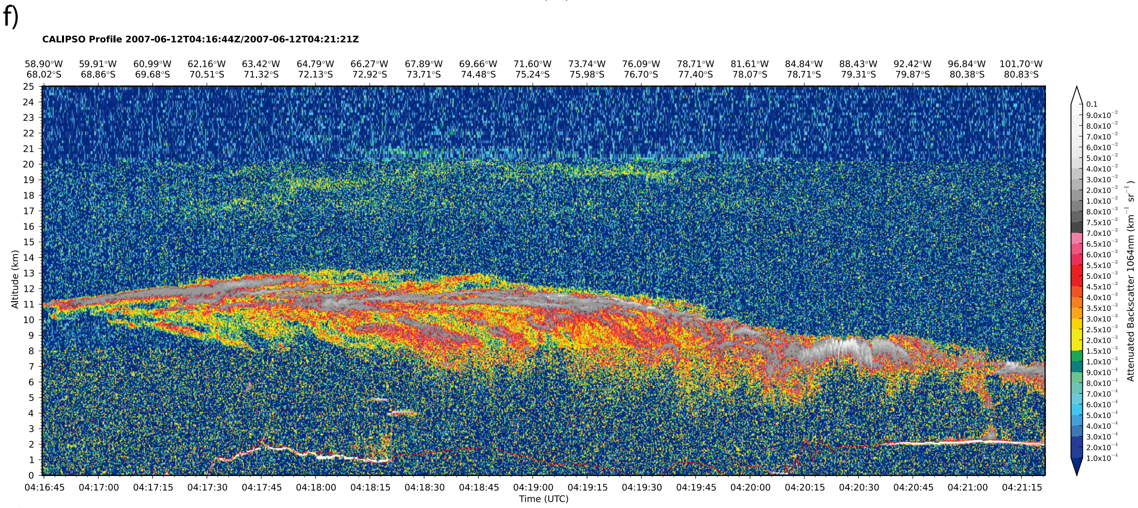


f, the 1064-nm channel is comparable to that of 532 nm both in terms of strength and detected features, but is contains more noise. **g**, the upper parts of the larger cloud were not captured by the millimetre-wave radar, but we can see a strong response from the parts below 9 km. This suggests that it is composed of different particles, presumably precipitation in the form of snow pellets.

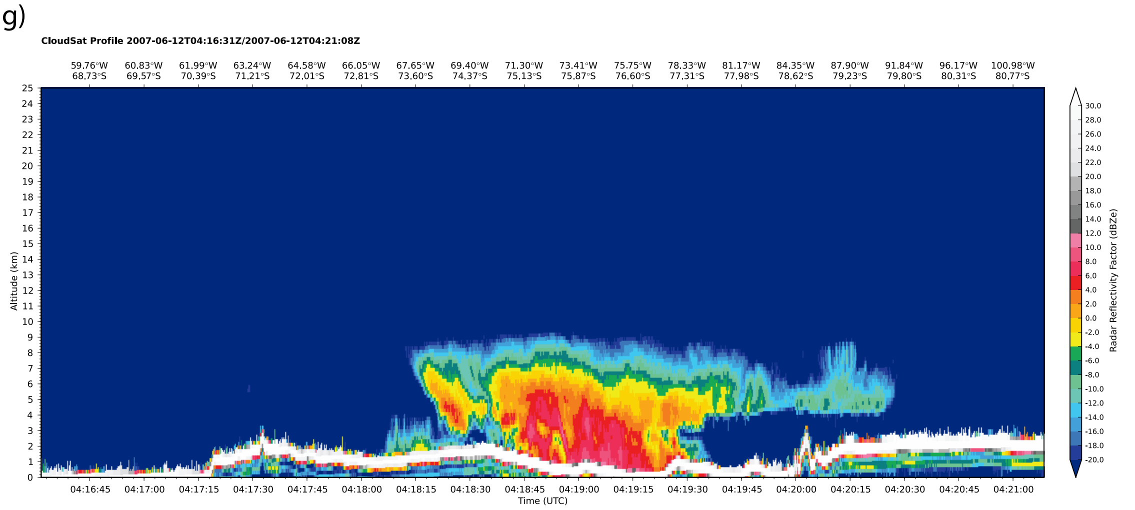
e, cont.)



f)



g)

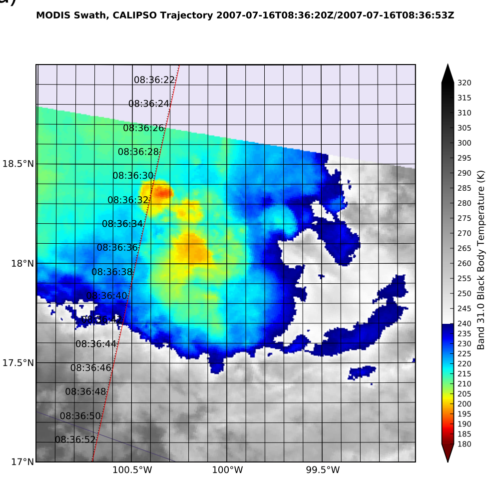


Case 3: Overshooting Top, Mexico, 16 July 2007

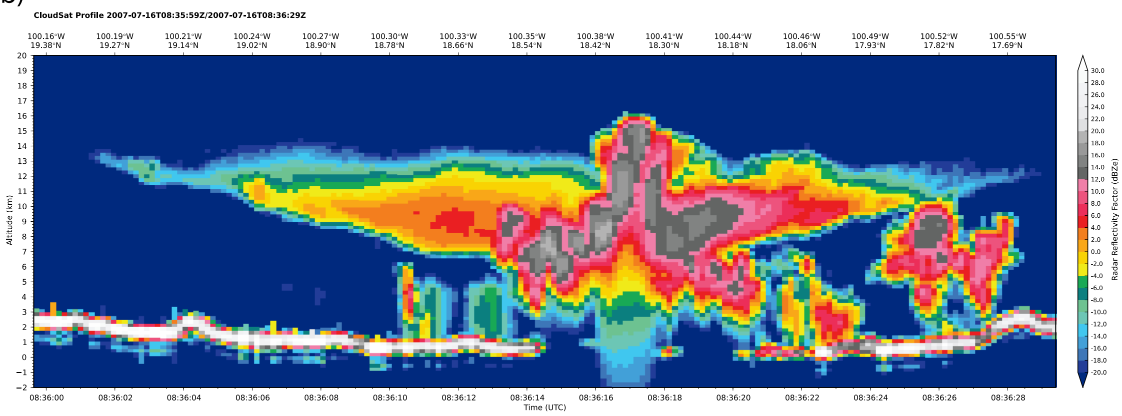
This case presents the appearance of a cumulonimbus (Cb) cloud with an overshooting top.

a, The Cb was located in the south of Mexico at 3:36 am local time. In particular, CALIPSO flew over its overshooting top at 8:36:31 UTC, as can be recognised on the swath by brightness temperature as low as −80 °C. **b**, the entire cloud is best observable with CPR. Reflectivity is strongest near the centre of the cloud, probably because it contains hail or partly melted ice particles, which generate high response at this wavelength. **c**, in contrast with CPR, CALIOP only captures the anvil and the overshooting top of the Cb. This lies at a very high altitude of about 14 km. Response is extremely strong from the overshooting top (more than 0.1 km^{-1} sr^{-1}).

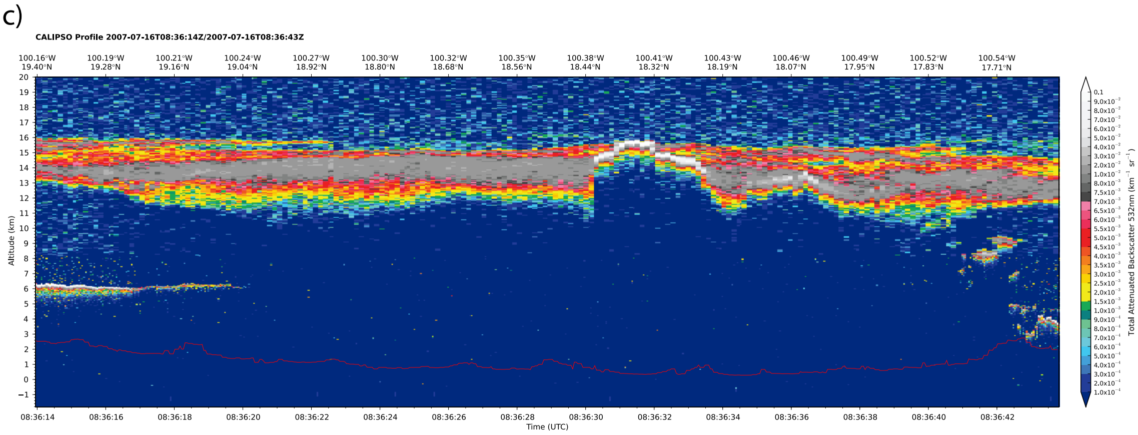
a)



b)

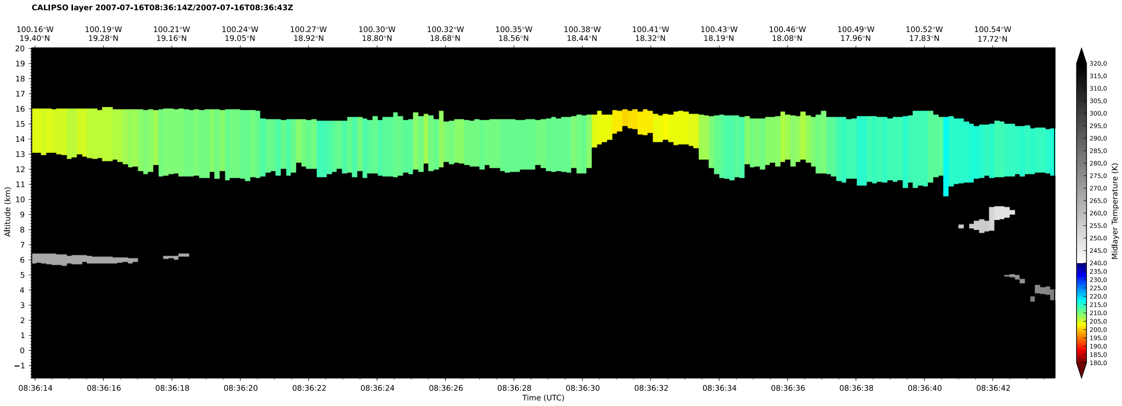


c)

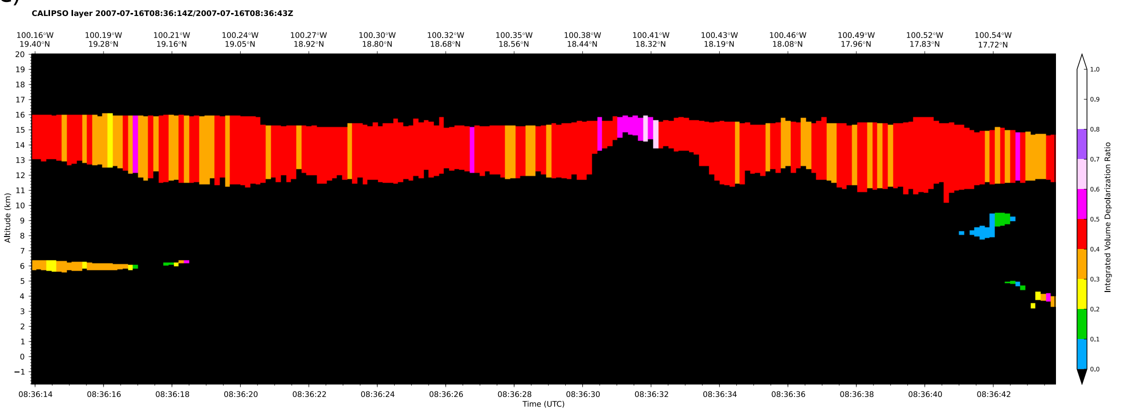


d, the overshooting top is much colder than the anvil, **e**, and polarises light more strongly.

d)



e)



References

1B-CPR_PDICD (2007). *Level 1 B CPR Process Description and Interface Control Document*. http://www.cloudsat.cira.colostate.edu/ICD/1B-CPR/1B-CPR_PDICD_5.3.pdf.

2B-GEOPROF_PDICD (2007). *Level 2 GEOPROF Product Process Description and Interface Control Document*. http://www.cloudsat.cira.colostate.edu/ICD/2B-GEOPROF/2B-GEOPROF_PDICD_5.3.doc.

A-Train Factsheet (2003). Formation Flying: The Afternoon "A-Train" Satellite Constellation. Fs-2003-1-053-gsfc, NASA. http://aqua.nasa.gov/doc/pubs/A-Train_Fact_sheet.pdf.

CALIPSO Data Products Catalog (2007). *CALIPSO Data Products Catalog*. http://www-calipso.larc.nasa.gov/products/CALIPSO_DPC_Rev2x4.pdf.

CALIPSO Quality Statements (2010, February). CALIPSO Quality Statements. http://eosweb.larc.nasa.gov/PRODOCS/calipso/Quality_Summaries/.

CALIPSO Quality Statements: Lidar Level 2 Cloud and Aerosol Profile Products (2009, July). CALIPSO Quality Statements: Lidar Level 2 Cloud and Aerosol Profile Products. http://eosweb.larc.nasa.gov/PRODOCS/calipso/Quality_Summaries/CALIOP_L2LayerProducts_2.01.html.

CloudSat Standard Data Products Handbook (2008). *CloudSat Standard Data Products Handbook*. http://www.cloudsat.cira.colostate.edu/cloudsat_documentation/CloudSat_Data_Users_Handbook.pdf.

Gutro, R. et al. (2005). CALIPSO, CloudSat, GRACE Science Writer's Guide. Technical report, NASA. http://www.nasa.gov/pdf/135705main_ScienceWriterGuideFinal10-11-05.pdf.

Gutro, R., K. Ramanujan, and J. Closs (2002). Science Writers' Guide to Aqua. Technical report, NASA. http://eospso.gsfc.nasa.gov/ftp_docs/Aqua_Sci_Writer%27s_Guide.pdf.

HDF 4.2r4 User's Guide (2009, June). *HDF 4.2r4 User's Guide*. ftp://ftp.hdfgroup.org/HDF/Documentation/HDF4.2r4/HDF42r4_UserGd.pdf.

HDF-EOS Library User's Guide Volume 1: Overview and Examples (2009, July). *HDF-EOS Library User's Guide Volume 1: Overview and Examples*. http://edhs1.gsfc.nasa.gov/waisdata/eeb/html/170eeb001.html.

Houghton, J. (2002). *The Physics of Atmospheres*. Cambridge University Press.

King, M. (2006, June). Editor's Corner. *The Earth Observer 18*(3). http://eospso.gsfc.nasa.gov/eos_observ/pdf/May-Jun06.pdf.

King, M., J. Closs, S. Spangler, R. Greenstone, and S. Wharton (2004, January). *EOS Data Products Handbook*, Volume 1. NASA Goddard Space Flight Center, Greenbelt, Maryland. http://eospso.gsfc.nasa.gov/ftp_docs/data_products_1.pdf.

Li, L., S. Sekelsky, S. Reising, C. Swift, S. Durden, G. Sadowy, S. Dinardo, F. Li, A. Huffman, G. Stephens, et al. (2001). Retrieval of atmospheric attenuation using combined ground-based and airborne 95-ghz cloud radar measurements. *Journal of atmospheric and oceanic technology 18*(8).

MODIS Level 1B Product User's Guide (2009). *MODIS Level 1B Product User's Guide*. http://www.mcst.ssai.biz/mcstweb/documents/M1054_RevC_PUG_022709_Update.pdf.

MODIS Specifications (2010, June). MODIS Specifications. http://modis.gsfc.nasa.gov/about/specifications.php, retrieved on 11 June 2010.

Palmer, P. (2009). Failure to Launch. *Nature Geoscience 2*(4), 247.

Parkinson, C. (2002). Aqua brochure. Technical report, NASA. http://www.nasa.gov/pdf/151986main_Aqua_brochure.pdf.

Parkinson, C. (2003). Aqua: An Earth-observing satellite mission to examine water and other climate variables. *IEEE Transactions on Geoscience and Remote Sensing 41*(2), 173–183.

PC-SCI-201 (2006). *CALIOP Algorithm Theoretical Basis Document, Calibration and Level 1 Data Products*. http://www-calipso.larc.nasa.gov/resources/pdfs/PC-SCI-201v1.0.pdf.

PC-SCI-202.01 (2006). *CALIOP Algorithm Theoretical Basis Document, Part 1: CALIOP Instrument, and Algorithms Overview*. http://www-calipso.larc.nasa.gov/resources/pdfs/PC-SCI-202.Part1_v2-Overview.pdf.

PC-SCI-202.02 (2005). *CALIOP Algorithm Theoretical Basis Document, Part 2: Feature Detection and Layer Properties Algorithms*. http://www-calipso.larc.nasa.gov/resources/pdfs/PC-SCI-202_Part2_rev1x01.pdf.

She, C. (2001). Spectral structure of laser light scattering revisited: bandwidths of non-resonant scattering lidars. *Applied Optics 40*(27). http://lamar.colostate.edu/~lidar/Publications/she_spectral-structure_2001.pdf.

Stephens, G., D. Vane, R. Boain, G. Mace, K. Sassen, Z. Wang, A. Illingworth, E. O'Connor, W. Rossow, S. Durden, et al. (2002). The CloudSat mission and the A-Train. *Bulletin of the American Meteorological Society 83*(12), 1771–1790.

Vaughana, M., S. Youngb, D. Winkerc, K. Powella, A. Omarc, Z. Liud, Y. Huc, and C. Hostetlerc (2004). Fully automated analysis of space-based lidar data: an overview of the calipso retrieval algorithms and data products. In *Proc. of SPIE Vol*, Volume 5575, pp. 16–30.

Wallace, J. and P. Hobbs (2006). *Atmospheric Science: An Introductory Survey, Second Edition*. Academic Press.

Winker, D., W. Hunt, and C. Hostetler (2004). Status and performance of the caliop lidar. In *Proc. SPIE*, Volume 5575.

Xiong, X. and W. Barnes (2006). An overview of MODIS radiometric calibration and characterization. *Advances in Atmospheric Sciences 23*(1), 69–79.

Abbreviations

AIRS	Atmospheric Infrared Sounder
AMSR-E	Advanced Microwave Scanning Radiometer - EOS
AMSU	Advanced Microwave Sounding Unit
BSD	Berkeley Software Distribution
CALIOP	Cloud Aerosol Lidar With Orthogonal Polarization
CERES	Clouds and the Earth's Radiant Energy System
IITVIS IDL	ITT Visual Information Solutions Interactive Data Language
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CNES	Centre National D'Etudes Spatiales
CPR	Cloud Profiling Radar
DPC	Data Processing Center
DPI	Dots per inch
EOS	Earth Observing System
FOV	Field of View
GUI	Graphical User Interface
HDF4	Hierarchical Data Format version 4
HDF-EOS2	Hierarchical Data Format - Earth Observing System version 2
HSB	Humidity Sounder for Brazil
LaRC	Langley Research Center
L1	Level 1
L2	Level 2
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Agency
NCAR	National Center for Atmospheric Research
OCO	Orbiting Carbon Observatory
UTC	Coordinated Universal Time
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
POSIX	Portable Operating System Interface
PSC	Polar Stratospheric Cloud
PRF	Pulse Repetition Frequency
PVL	Parameter Value Language
RSB	Reflective Solar Band
SDS	Scientific Data Set
TSB	Thermal Emissive Band
WFC	Wide-Field Camera
XML	Extensible Markup Language