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European Space Astronomy Centre (ESAC)
European Space Agency (ESA)
Camino Bajo del Castillo s/n
Urb. Villafranca del Castillo
28692 Villanueva de la Canada - Madrid
SPAIN

CILBO METEOR SPECTRA DATASET

Prepared by **S. Vicinanza, J. Zender**
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1. INTRODUCTION

1.1 Executive Summary

This dataset contains the products of the research on meteor spectroscopy, conducted by the Meteor Research Group (MRG) at the European Space Research and Technology Centre (ESTEC). Since 2012, the MRG operates the Canary Island Long-Baseline Observatory, i.e. CILBO (Koschny et al., 2013). This dataset includes the raw video images observed from CILBO (Level 0) and the products after the calibration (Level 1 and 2) and spectral analysis (Level 3) of the raw data. The calibration of the data includes: image processing, radiometric calibration, spectral calibration and intensity calibration. The spectral analysis involves the Bayesian inference of meteoroid chemical composition. The full pipeline is discussed by Zender et al. (2022).

1.2 Extended introduction

After the disintegration of asteroids and comets in space, "children" products, i.e. meteoroids and interplanetary dust, are generated and continue moving around space, generally along the orbit of their "parent" body. When the orbit of these bodies encounters the Earth, they collide with the Earth’s atmosphere. The interaction of meteoroids with the atmosphere heats the bodies to incandescence, resulting in luminous streaks in the sky: the meteors. The heating of space bodies in the atmosphere is a result of a process called meteor ablation. As the meteor ablates in the atmosphere, particles belonging to the meteoroid and atmosphere are excited.

These particles emit photons. The contributions of the wavelength-specific radiation generated by these emissions add together in the meteor spectrum. Meteor emission spectra are analysed using a technique called meteor spectroscopy, which allows to gain information about properties and chemical composition of the body generating the meteor event. Discoveries about space bodies’ compositions support different research areas, including Solar System evolution, astrobiology and planetary defense.

This dataset was the product of meteor spectroscopy research by the European Space Agency (ESA) MRG. The research used as the main data source the ground-based observations collected from CILBO observatory, operated by the MRG. CILBO has a double-station setup of intensified CCD video cameras (ICC). Three image-intensified cameras are mounted in two different locations: ICC8 and ICC7 mounted in Tenerife and ICC9 in La Palma. Data from ICC8 and ICC7 represent the primary source for this research. ICC7 records the zeroth order of meteors. ICC8 is equipped with an objective grating in front of its lens, optimised to record meteors’ first-order spectra. Both ICC8 and ICC7 have a frame rate of 25 frames per second, an image resolution of 768×576 px and 8 bit dynamical accuracy (Koschny et al., 2013).

The data in this dataset originated from the calibration and spectral analysis of CILBO meteor observations. The calibration includes: correction for dark current, flat-field and background (radiometric calibration), correction for atmospheric extinction and ICC8 spectral sensitivity (spectral calibration), and conversion from Arbitrary Digital Units to SI physical units (intensity calibration). The spectral analysis is used to infer the chemical composition of the meteoroids observed from CILBO. The meteoroid composition inference in this study was based on Markov Chain Monte Carlo (MCMC) Bayesian inference, described in more in-depth in section 3. Moreover, the full pipeline is described by Zender et al. (2022).

This research provides a large and diverse dataset, particularly useful for large-scale studies on the chemical composition of meteoroids and their parent bodies. Data belonging to this dataset include meteors belonging to more than 20 showers and span over more than 6 years, from 2012 to 2018. As such, it represents one of the most numerous meteor spectra databases in Europe.

1.3 CILBO METEOR SPECTRA DATASET Introduction

The purpose of this document is to describe the CILBO Meteor Spectra dataset, to guide future users on how to best use this dataset and benefit from its data. The main products which users will find in this dataset include:

- Raw data acquired from CILBO ICC8 and ICC7 cameras. These include video images of visible meteor observations in BMP format, and meteor trajectory data in INF, SNF and LOG format.
- Calibrated first-order meteor spectra in the visible band (350 nm to 850 nm). The data is given in FITS format.
- Ablation temperature, and line intensities and number densities of elements emitted by meteors observed from CILBO. The data is given in FITS format.

All the different data products are described in greater detail in section 4.

Future users of this dataset are welcome to contact the authors of this dataset for further information. The preferable means of contact is via email, using the following addresses:

- Salvatore Vicinanza (salvatorevicinanza@gmail.com)
- Joe Zender (joe.zender@esa.int).

1.4 Abbreviations and Acronyms

ADU - Arbitrary Digital Units

BMP - Windows Bitmap (data format)

CCD - Charge-Coupled Device

CILBO - Canary Island Long-Baseline Observatory

ESA - European Space Agency

ESTEC - European Space Research and Technology Centre

FITS - Flexible Image Transport System (data format)

ICC - Image-intensified CCD Camera

INF - Setup information (data format)

LOG - Common Log Format (data format)

MCMC - Markov Chain Monte Carlo

MRG - Meteor Research Group

PNG - Portable Network Graphics (data format)

SI - International System of Units

SNF - Server Normal Format (data format)

1.5 Reference and Applicable Documents

P. Jenniskens. Quantitative meteor spectroscopy: Elemental abundances. Advances in Space Research, 39(4):491 – 512, 2007.

D. Koschny, F. Bettonvil, J. Licandro, C. v. d. Luijt, J. Mc Auliffe, H. Smit, H. Svedhem, F. de Wit, O. Witasse, and J. Zender. A double-station meteor camera set-up in the Canary Islands –CILBO. Geoscientific Instrumentation, Methods and Data Systems, 2(2):339–348, 2013.

S. Löhle, M. Eberhart, F. Zander, A. Meindl, R. Rudawska, D. Koschny, and J. Zender. Extension of the Plasma Radiation Database PARADE for the Analysis of Meteor Spectra. Meteoritics & Planetary Science, 56(2):352–361, 2021.

S. Vicinanza, D. Koschny, R. Rudawska, W. van der Wal, and J. Zender. Spectral Calibration of Meteors: An Elevation-Dependent Atmospheric Correction. In J. Kac editor. International Meteor Conference, 25-26 September 2021, page nn.

2. SCIENTIFIC OBJECTIVES

<This section should cover the scientific objectives which led to the observations and the creation of this dataset. Additionally, the research method and/or analytical techniques utilised in the creation of the data will be explained here. The reference papers listed in bibliographical detail in the Introduction section should be referred to here as well (e.g. Smith et al. [2099]), with a bit of explanation on how those papers apply to this dataset. This section should provide more of a general overview, while the next will cover more details.>

[Refer back the references]

Meteor spectroscopy is based on remote observations of ablating meteoroids in the Earth's atmosphere, ca By analysing the spectra of meteors, one can acquire valuable information about the composition of their parent bodies (asteroids and comets).

2.1 Acknowledgements

The development of the calibration tool for the plasma radiation simulations (PARADE) was obtained through an ESTEC-supported scientific collaboration with Institute of Space Systems, Stuttgart, Germany, 2019.

The development of the Bayesian inference tool was supported by a thesis project from the Universiteit Leiden, conducted in ESTEC, Noordwijk, The Netherlands, 2020.

Finally, the development of the spectral calibration, intensity calibration and integration of all existing software tools was supported by an ESTEC-supported scientific collaboration with Technische Universiteit Delft, 2021.

If you use the data set in this archive, please make sure to acknowledge it in your research paper by using the following:

> European Space Agency, 2021 CILBO Meteor Spectra Dataset https://doi.org/<insert-doi>

and cite the papers by Vicinanza et al. (2021) and Zender et al. (2022).

3. DATA PRODUCT GENERATION

The data in this dataset is the result of calibration and spectra analysis processing of the CILBO meteor observations, from 2012 to 2018, containing visible first-order spectra. The full pipeline is described by Zender et al. (2022).

The calibration is made of three major steps:

1. The radiometric calibration allows to remove artifacts in the image which affect the appearance of spectra. Flat-field correction removes the effects of illumination variations in the optical system, like vignetting and distortions in the optical path. Dark current correction removes the effect of electrons which flow in the detector, even when there is no light incident on it. The background correction removes the effects of background illumination in the image. The output of this correction is Level 1 data.
2. The procedure developed for the spectral calibration corrects meteor spectra for the different extinction during a meteor's path in the atmosphere. The spectra are corrected for the direction of the incoming radiation and the scattering of gas molecules and aerosols, using an atmospheric correction vector. Then, the sensitivity correction is applied, which adjusts the intensity of the individual spectral lines based on ICC8 spectral sensitivity curve. An in-depth description of the spectral calibration (Level 2-A data) is given by Vicinanza et al. (2021).
3. The aim of the intensity calibration is to convert the spectral flux observed, measured in CCD pixel brightness and expressed in some Arbitrary Digital Units (ADU), to SI Physical units (W/m2/nm). This allows us to infer the true and absolute composition of elements in a meteoroid, during spectral analysis. To perform this intensity calibration, the method by Jenniskens (2007) was applied. The output of this correction is the Level 2-B data.

The spectral analysis is used to infer the chemical composition of meteoroids observed from CILBO. The meteoroid composition inference in this study was based on the Bayesian Markov Chain Monte Carlo (MCMC) spectral fitting of the calibrated observed meteor spectra with simulated synthetic spectra. The spectral fitting of ICC8 observed spectra, used for the estimation of the number densities of the meteor's radiating elements, is articulated in three main steps:

1. The synthetic spectra are simulated using an external tool, called PARADE (Löhle et al., 2021). For each radiating element, PARADE models first-guess synthetic spectra, by tuning several parameters (line intensities, N2 bands and ablation temperature).
2. Using a non-linear LSQ approach, an initial solution is obtained. This provides the estimate of all the unknown parameters, whose combination generates a complete synthetic meteor which best fits the ICC observed meteor spectrum.
3. The LSQ parameters' estimates are used as initial guesses for the successive MCMC. During the MCMC, for each meteor event 2000 iterations are run. Each iteration models a different synthetic spectrum using parameters which are sampled around the LSQ solution via MCMC affine-invariance sampling. The complete synthetic spectrum which best fits the ICC8 observed spectrum is inferred using Bayesian inference: Bayesian inference estimates the posterior distribution for all parameters. The results are the parameters for which the complete synthetic spectrum best fits the observed spectrum, thus those for which the posterior is highest.

The data provided in this data set was presented in a peer-reviewed paper by Zender et al. (2021), which was published by <name-of-journal>.

4. ARCHIVE FORMAT AND CONTENT

The dataset archived contains four levels of data, schematised in Table 1 and listed below:

- Level 0: BMP images recorded by ICC8 from 2012 to 2018; INF files, with celestial coordinates and times of meteor observation; SNF files, with .
- Level 1: FITS files, with raw meteor spectra collected by ICC8.
- Level 2: FITS files, with calibrated meteor spectra collected by ICC8 (Zender et al., 2022; Vicinanza et al., 2021).
- Level 3: FITS files, with spectral lines' intensities and emission number densities.

Table 1: Name, definition and format of the data archived.

Name	*Definition*	*Format Data*
Level 0	Raw data acquired by cameras at CILBO. No processing.	BMP (INF, LOG, SNF)
Level 1	Data after radiometric (dark current, flat-field, background subtraction) and wavelength calibration of Level 0 BMPS.	FITS
Level 2-A	Data after spectral calibration of Level 1 spectra. Correction for ICC8 sensitivity and altitude-dependent atmospheric extinction.	FITS
Level 2-B	Data after intensity calibration of Level 2-A spectra.	FITS
Level 3	Reduced data after MCMC Bayesian inference: chemical elements number density, ablation parameters and synthetic/observed spectra.	FITS, PNG

The INF, LOG and SNF files in Level 0 data can be opened using a text editor, like Notepad in Windows, and Vim in macOS and Linux. The BMP files in Level 0 data can be opened using image and graphics programs like Microsoft Windows Photos in Windows, Apple Photos in macOS and ImageMagick in Linux.

The FITS files from Level 1, Level 2 and Level 3 data can be opened using the interactive graphical program fv FITS Viewer, available for Windows, macOS and Linux.

5. KNOWN ISSUES

<Here is the place to report any known issues, if applicable. This information is important to provide to the user to avoid mis-usage of your products.>

6. SOFTWARE

The Python programs used to process the data in this dataset are:

- mrg_mess repository: all software used for the calibration of Level 0 meteor spectra, to obtain up to Level 2-B data.
- mrg_spectrum_bayesian repository: all software used for the spectral analysis of Level 2-B data, to obtain Level 3 data. The software is based on Bayesian inference of meteor spectra.

The aforementioned repositories are available via Gitlab. The following links could be used for the download of the software of (i) the mrg_mess and (ii) mrg_spectrum_bayesian repository:

(i) https://gitlab.com/mrg-tools/mrg_mess.git,

(ii) https://gitlab.com/mrg-tools/mrg_spectrum_bayesian.git .

A Python routine is provided to read the Level 1 and 2 files in the dataset, with a detailed description of the steps considered, in repository mrg_mess, under directory “analysis”. In repository mrg_spectrum_bayesian, directory “analysis” contains a Python routine to plot a ternary diagram, where the Level 3