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TECHNICAL NOTE

HotBird-13F and HotBird-13G / ICARE-NG² Level 1 data description

HotBird-13F and HotBird-13G / ICARE-NG² Level 1 datasets

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1. REFENCE DOCUMENTS AND ACRONYMS

1.1. Reference Documents

[RD 1] A. Boudouridis, J. V. Rodriguez, B. T. Kress, B. K. Dichter, and T. G. Onsager, “Development of a Bowtie Inversion Technique for Real-Time Processing of the GOES-16/-17 SEISS MPS-HI Electron Channels,” *Space Weather*, vol. 18, no. 4, p. e2019SW002403, Apr. 2020, doi: 10.1029/2019SW002403

[RD 2] https://swe.ssa.esa.int/fr/sparc-geo-ngrm-r170-federated

[RD 3] SEPEM reference data set (rds) v2.X 2017a, http://test.sepem.eu/help/SEPEM RDS V2-00.zip

[RD 4] I. Sandberg, P. Jiggens, D. Heynderickx, and I. A. Daglis, “Cross calibration of NOAA GOES solar proton detectors using corrected NASA IMP-8/GME data,” *Geophys. Res. Lett.*

[RD 5] P. Caron *et al.*, "In-flight Measurements of Radiation Environment Observed by Hotbird 13F and Hotbird 13G (Electric Orbit Raising Satellites)," in *IEEE Transactions on Nuclear Science*, 2024, doi: 10.1109/TNS.2024.3367730

[RD 6]

1.2. Acronyms

Acronym	Definition
EOR	Electric Orbit Raising
LEO	Low Earth Orbit
GEO	Geostationary Orbit
BT	Bowtie
RF	Response Function
PRF	Proton Response Function
ERF	Electron Response Function
FEIO	Omni-directional Integral Electron Flux
FPDO	Omni-directional Differential Proton Flux
FPIO	Omni-directional Integral Proton Flux

2. INTRODUCTION

2.1. Purpose

This document describes the main characteristics of HotBird-13F and Hotbird-13G/ICARE-NG² Level 1 (flux data) Version 1 datasets.

2.2. Background

ICARE-NG² is the third generation of the CNES-ONERA-EREMS radiation monitor. It benefits from more than 20 years of heritage. The very first unit, ICARE, flown on SAC-C at LEO and was launched in December 2000. Then a new generation was developed, reduced in size, ICARE-NG and flew on Jason-2 (LEO), SAC-D (LEO), Jason-3 (LEO) and E7C (EOR+GEO). The first ICARE-NG² unit was then implemented on Hotbird-13F (EOR+GEO) followed by a second one on HotBird-13G (EOR+GEO) and was respectively launched on 15-Oct-2022 and 03-Nov-2022.

Within "S2P S1-SW-10.01 SPACE WEATHER DATA SYSTEM ENHANCEMENT: ICARE-NG PDC" ONERA and Solenix were in charge of implementing the ICARE-NG² Payload Data Center. Part of this activity, the derivation of the response functions of ICARE-NG², accounting for HotBird spacecraft shielding, was done and Level 1 flux computed.

2.3. ICARE-NG² radiation monitor

The ICARE-NG² radiation monitor is dedicated to the measurement of electrons and protons. Three sensors are implemented on the instrument, two of them are composed of two silicon detectors with coincidence and anticoincidence logic and one of them is made of a single silicon detector. The sensors are shielded from the side with a minimum of 5 mm of aluminium. The field of view of the top Silicon detectors are 16°, 25° and 27°. A pulse height analyser allows building histogram of deposited energy in each silicon detector.

Figure 1 : The ICARE-NG² flight model for HotBird-13f with the sensors on the left of the instrument and the electronic box on the the right.

3. CALIBRATION OF ICARE-NG² INSTRUMENT

The radiation monitor has been calibrated under radiation sources at ONERA using the CIRIL facility. and by numerical means. The electron and proton response function of the three sensors have been derived from GEANT-4 simulation accounting for (1) ground calibration results and (2) the shielding from the spacecraft. Airbus Defense and Space provided the HotBird geometry in a FASTRAD sectoring analysis file.

The main response functions used here are provided below.

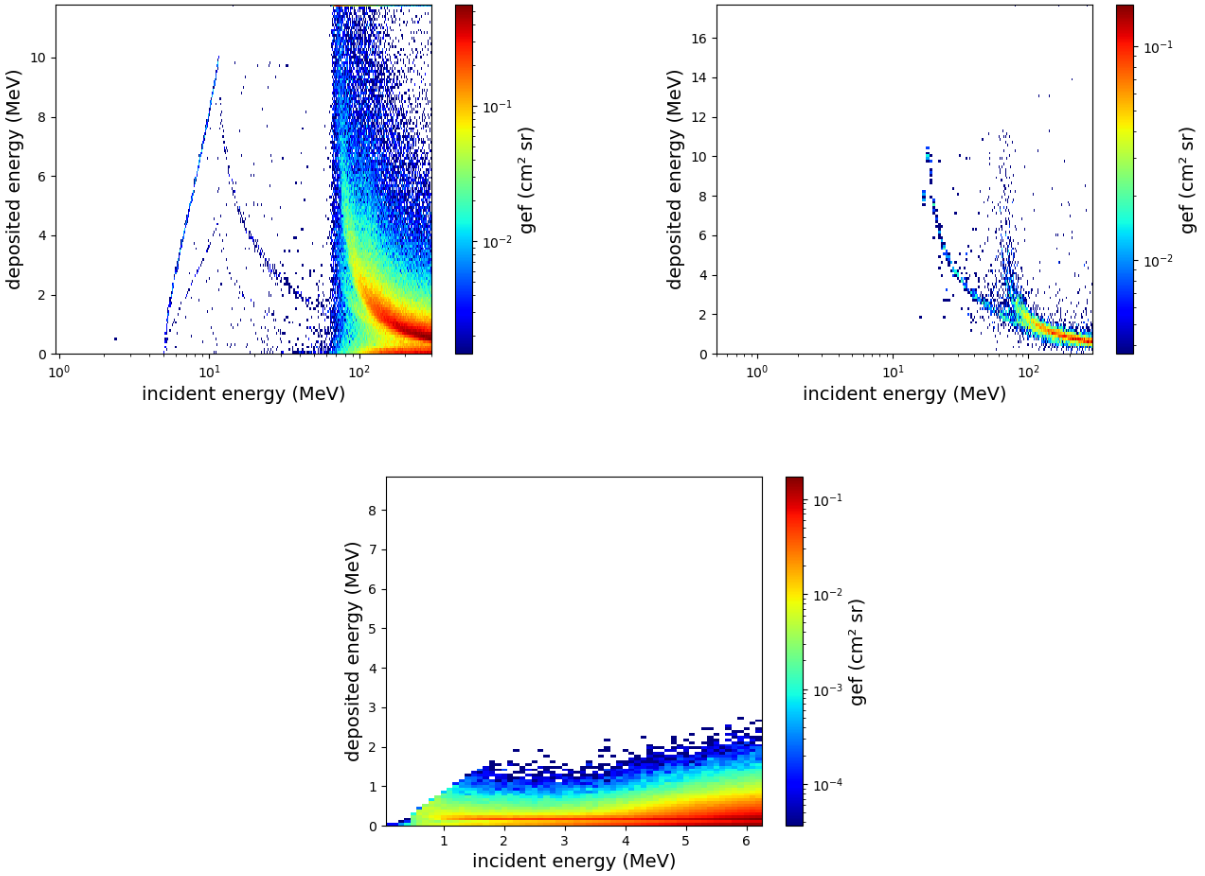

Figure 2: From left to right and top to bottom: PRF of the P2LE in anticoincidence mode, PRF of the PE2 in coincidence mode and ERF of the PE2 in anticoincidence mode

4. DATA CALIBRATION

ICARE_NG² provides counts integrated over a defined time window. The data recorded are therefore count rates C $(\#/s)$. The link between count rates and fluxes f_{diff} $(\#/\text{cm}^2/\text{MeV}/\text{sr}/\text{s})$ is given by the Fredholm integral equation of the first kind :

$$C = \int_0^\infty f_{\text{diff}}(E) \cdot \text{RF}(E) \cdot dE \tag{1}$$

Where RF describes the Response Function of the radiation monitor and E, the incident particle energy. Equation 1 is a typical example of an ill-posed problem and its solution is not guaranteed to be unique, nor a continuous function.

For the derivation of ICARE_NG² Level-1 fluxes, Bowtie method is used [RD 1]. The purpose of the bowtie analysis is to identify (effective/threshold energy - geometric factor) pairs that are applicable to a wide range of energy spectra and for which the reconstructed differential or integrated fluxes are the most representative. To do this, a virtual flux database is required. In the present case, the fluxes used come from other instruments (NGRM [RD 2] and SEPEM [RD 3]) and space environment models (AEP8 and AEP9).
The parameters (effective/threshold energy - geometric factor) are derived from the following relations :

$$GdE = \frac{\int_0^{\infty} f_{\mathrm{diff}}(E) \cdot \mathrm{RF}(E) \cdot dE}{f_{\mathrm{diff}}(E_{\mathrm{eff}})} \tag{2}$$

$$G = \frac{\int_0^{\infty} f_{\mathrm{diff}}(E) \cdot \mathrm{RF}(E) \cdot dE}{\int_{E_{\mathrm{th}}}^{\infty} f_{\mathrm{diff}}(E) \cdot dE} \tag{3}$$

Families of curves in $[GdE, E_{\mathrm{eff}}]$ and $[G, E_{\mathrm{th}}]$ spaces are generated from the virtual flux database to identify the best combination.

4.1. Proton Differential Flux Dataset: Level 1 Version 1

For the calculation of proton differential fluxes, a BT analysis of ICARE_NG² proton responses was applied using the Solar Energetic Particle Environment Modelling (SEPEM) reference dataset (SEPEM RDS) as a training dataset. SEPEM is based on NOAA GOES proton flux measurements cross-calibrated by [RD 4] using as reference the IMP-8 Goddard Medium Energy experiment. Hundreds randomly selected SEPEM spectra during solar particle events are extracted and used to perform BT analysis.

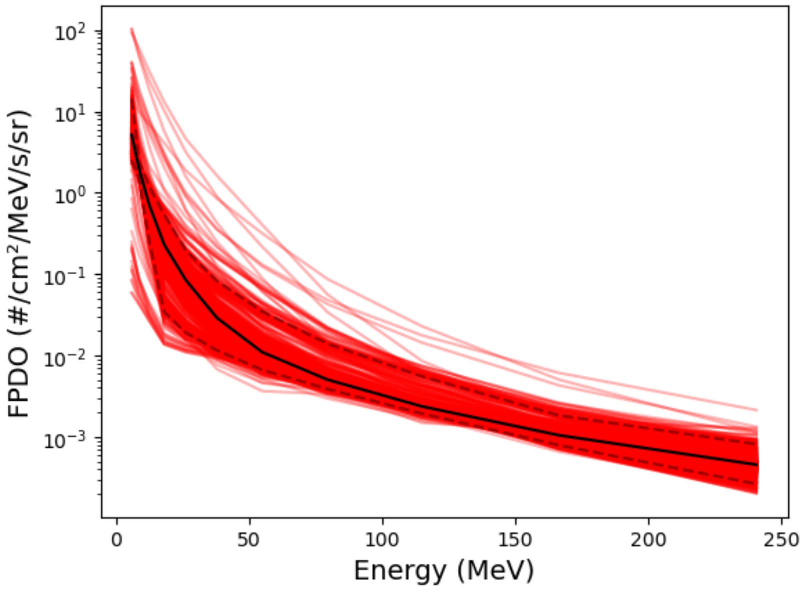

Figure 3: Randomly selected SEPEM spectra used to train the BT analysis. The solid black line is the median of the distribution while the dashed black lines are the 5th and 95th percentiles.

The common representation of the BT analysis are the $[GdE, E_{\text{eff}}]$ and $[G, E_{\text{th}}]$ plots (see Figure 4). The closer the curves are, the more the flux dynamics measured by the instrument at the given energy are effectively representative of the environment.

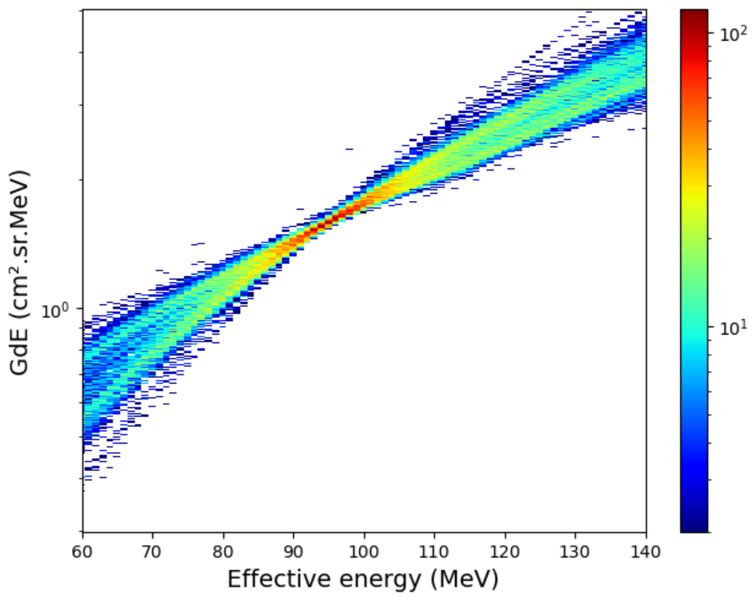

Figure 4: $[GdE, E_{eff}]$ binned plot for channel 11 of the PE2 detector. PRF in coincidence mode is used as RF the solve Equation 2.

Another way to represent the system is to calculate the error distribution for each $[GdE, E_{\text{eff}}]$ pair. The corresponding error is calculating as a function of the reconstructed flux compared to the expected flux. Figure 5 gives equivalent information to Figure 4 but represents the mean error for each bin.

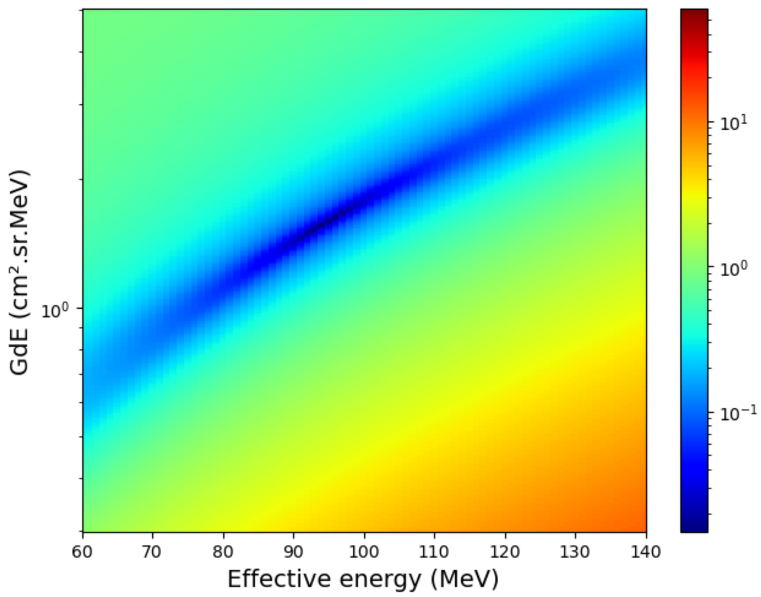

Figure 5: Binned mean errors of the $[GdE, E_{eff}]$ *plot*

The selected solution is the one associated with the minimum error. The procedure is repeated for all bowtie-shaped channels but only channels or pairs of channels with a solution associated with an error < 10% are used. Table I summarizes the results of the BT analysis, which provide the proton differential flux products in Level 1 dataset.

Table I: BT analysis results of L1 ICARE_NG² proton differential flux dataset

Head	Channels	FPDO Energy (MeV)	Mean error
P2LE	60-70	15.0	0.0356
PE2	70-80	23.0	0.0263
PE2	30-31	38.0	0.0410
PE2	20-24	54.0	0.0512
PE2	15-16	77.0	0.0122
PE2	11-12	98.0	0.0148

4.2. Electron Integral Flux Dataset: Level 1 Version 1

For the calculation of electron integral fluxes, equivalent BT analysis were performed but using EDRS-C NGRM measurements and engineering models (AE8 and AE9). Slightly higher error levels are accepted (up to 15%). Table II summarizes the results of the BT analysis, which provide the electron integral flux products in Level 1 dataset.

Table II: BT analysis results of L1 ICARE_NG² electron integral flux dataset

Head	Channels	FPDO Energy (MeV)	Mean error
PE2	11-12	0.65	0.1104
PE2	12-15	0.85	0.0812
PE2	14-18	1.00	0.0688
PE2	16-20	1.30	0.0650
PE2	15-22	1.40	0.0792
PE2	17-22	1.65	0.1024
PE2	19-21	2.00	0.1530

5. CONSIDERATIONS ON LEVEL-1 DATASETS

Instrument performances have been analysed and compared to third-party measurements during the cruise (EOR phase) [RD 5] and on-station (GEO).

- Electron fluxes are fully in line with EDRS-C/NGRM measurements (Figure 6). In the high energy end and low flux regime data may suffer from statistical issues.
- Proton fluxes could be compared to other measurements only during weak solar particle events. Highest energy channels could not be fully validated because of poor statistics in the count rates. A cross-comparison could be performed with EDRS-C/NGRM for the first 4 channels (Figure 7). It has been shown that HotBird-13F&13G underestimates EDRS-C/NGRM measurements by a factor 1.8 to 2. So far, because only weak solar particle events have been measured, data suffer from statistical issues.
- Electron channels may suffer from proton contamination during solar particle events
- Proton channels are free from electron contamination

- All channels may be affected by glitches, but only very few per month have been found so far.

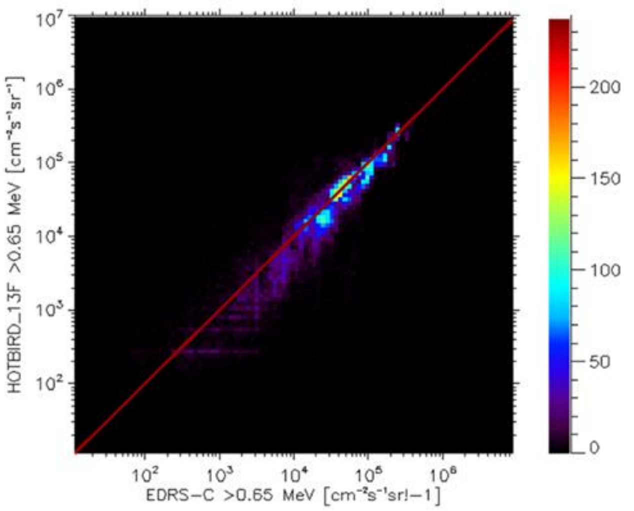

Figure 6: Cross comparison of HotBird-13F measurements with EDRS-C measurements during magnetic conjunctions found over the period 01/04/2023 to 31/12/2023. The color code represents the number of points in the bin. The red line indicates perfect match.

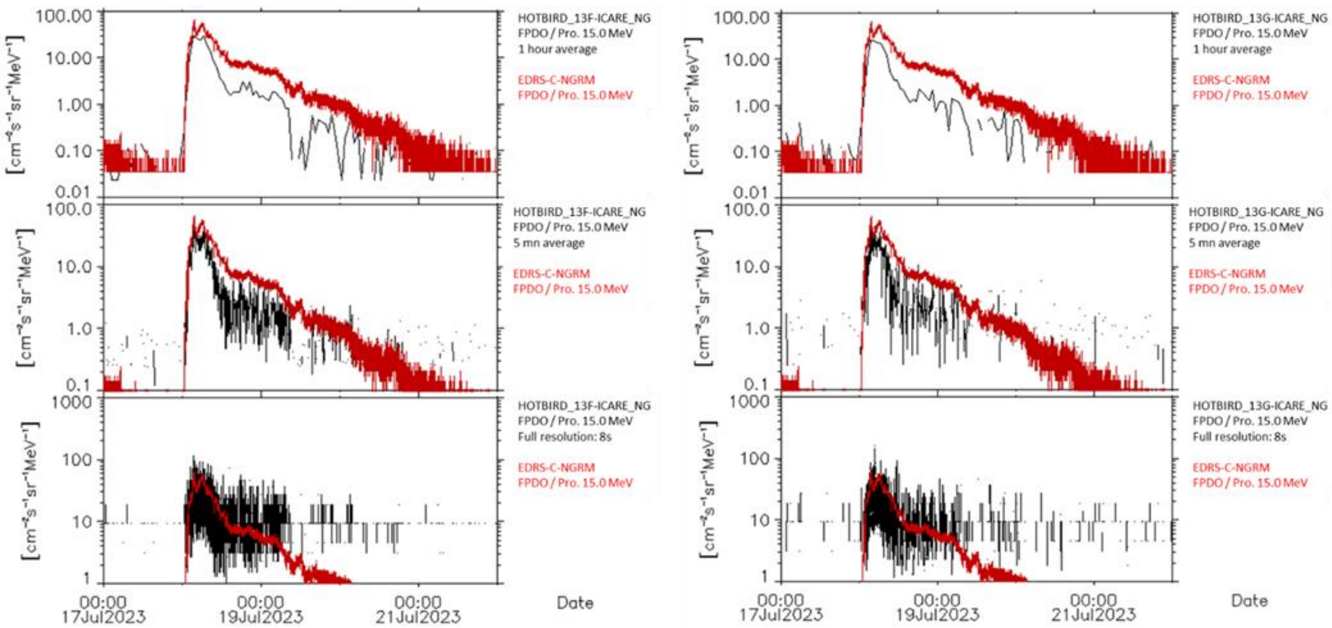

Figure 7: Comparison of 15 MeV differential proton flux measurements from EDRS-C-NGRM and HotBird-13F-ICARE-NG² (left) and HotBird-13G-ICARE-NG² (right) at three different time resolutions during the largest solar particle event observed between April 2023 and December 2023