Refined STACK-CNN for Meteor and Space Debris Detection in Highly Variable Backgrounds

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***Abstract*—In this article, we present cutting-edge machine learning-based techniques for the detection and reconstruction of meteors and space debris in the Mini-EUSO experiment, a detector installed on board of the International Space Station, and pointing toward the Earth. We base our approach on a recent technique, the STACKing method plus Convolutional Neural Network (STACK-CNN), originally developed as an online trigger in an orbiting remediation system to detect space debris. Our proposed method, the refined-STACKing method plus convolutional neural network (R-Stack-CNN), makes the STACKing method plus convolutional neural network (STACK-CNN) more robust, thanks to a random forest that learns the temporal development of these events in the camera. We prove the flexibility of our method by showing that it is sensitive to any space object that moves linearly in the field of view. First, we search small space debris, never observed by Mini-EUSO. Due to the limiting statistics, also in this case, no debris were found. However, since meteors produce signals similar to space debris but they are much more frequent, the R-Stack-CNN is adapted to identify such events while avoiding the numerous false positives of the Stack-CNN. Results from real data show that the R-Stack-CNN is able to find more meteors than a classical thresholding method and a new method of two neural networks. We also show that the method is also able to accurately reconstruct speed and direction of meteors with simulated data.**

***Index Terms*—Neural network applications, space technology.**

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I. Introduction

How safe is the space environment around the Earth? This is an important question that is worrying many space agencies and scientists in recent years. The exploration and utilization of Earth's orbit are no longer confined to the realms of governmental space agencies. The rapid growth of the commercial space sector has led to a new era of innovation and opportunity, with private companies launching satellites for telecommunications, Earth and space observation, and navigation, among other purposes.

Considering this evolving landscape, numerous questions and challenges emerge, demanding careful consideration and collaborative action. At the forefront is the pressing need for effective space traffic management. With an ever-increasing number of satellites, spacecraft, and space debris (SD) sharing the same orbital pathways, the risk of collisions and congestion poses a significant threat to the sustainability and safety of space activities.

In this article, we consider the problem of the detection of small SD [1], i.e., parts of defunct satellites and rockets in Earth orbit or re-entering the atmosphere. Debris are generated by events of fragmentation, including collisions, explosive break-ups, wear and tear, which generate entire populations that stagnate around the Earth. Because of their high speed, they pose a threat to functioning satellites in orbit, requiring them to perform dodging maneuvers.

According to ESA's 2023 space environment report [2], Space Surveillance Networks are tracking and maintaining in their catalogue about 34 810 debris but the vast majority of objects still remain unidentified. Statistical models by ESA estimate 36 500 SD objects greater than 10 cm, 1 million SD objects between 1 cm to 10 cm and 130 million SD objects between 1 mm and 1 cm. In order to avoid collisions with spacecrafts, unidentified debris should be detected, tracked to estimate their trajectory, and possibly removed from their orbit.

In this article, we propose an new strategy for the detection and tracking of SD around 10 cm-size, named *refined-STACKing method plus convolutional neural network* (R-Stack-CNN). This technique is based on the recent technique STACKing method plus convolutional neural network (STACK-CNN) [3], developed to trigger SD on board of space telescopes. Although the original method was effective and higher performing in simulated data, there were some challenges to be addressed. For example the method was not applied to real data, but only to simple simulated data. In this work we apply the Stack-CNN to real data, and we notice that there are many false positives events coming from highly variable background, causing a lack of reliability. To address this issue, we apply the R-Stack-CNN to the offline analysis of simulated and real data, showing its improvements in both cases.

Then we also demonstrate how this method can be adapted for the offline data analysis of meteors as they share similar properties as SD (similar magnitude and speed), leading to the R-Stack-CNN outperforming standard techniques and discovering new meteors and new events never found before.

The data come from the experiment Mini-EUSO, a telescope on board of the International Space Station (ISS) since 27 August, 2019. The instrument observes Earth in the UV range (290–430 nm) from a UV-transparent window in the Russian Zvezda module, aiming at the same scientific objectives of JEM-EUSO, among which are meteors and SD. Moreover, given that Mini-EUSO is co-moving with the ISS, the observed background is not static and extremely variable, with light emissions coming from cities, clouds, and moon reflections, making the detection of SD and meteors very challenging.

This is the first work that analyzes long sessions of Mini-EUSO data to find SD and meteors with the specific methodology proposed by the R-Stack-CNN.

The problem of detecting, tracking and possibly even removing SD of size 1–10 cm has already been studied in the context of JEM-EUSO collaboration [4], a future space-based detector flying attached to the ISS at an altitude of ∼400 km or on a free-flyer in low orbit (∼500 km) looking downward at Earth with a wide field of view (FoV, ± 20°–30°in the near-UV spectrum, 300–400 nm). The main operational procedure consists of online detection and tracking by the telescope, followed by the debris removal with laser ablation (see [5] for further information).

While the Stack-CNN was proposed to the online detection of SD in a future space detector, as a method that should be fast, accurate and with low memory, the R-Stack-CNN is an offline version of it, aiming to search SD already in Mini-EUSO data, making the method more robust to false positives and false negatives. The main difference of the R-Stack-CNN is the development of a random forest (RF) to distinguish the light curves of the interested objects, e.g., SD or meteors, from other light sources that could be triggered by the Stack-CNN, such as cities or aircraft. The light curve of an object refers to the variation in its brightness over time as observed from the detector. Moreover, the shape of a light curve can provide valuable information about the object's properties, such as its rotation rate, variability, and physical characteristics. Since different objects, such as debris and meteors, emit light in different ways, they will have different light curves. The Stack-CNN method does not consider the development of the light over the time, but only the object in a single frame (or more frames in a stacked image as described in the following sections), hence it loses an important feature to identify SD. To this aim, we propose an RF able to distinguish light curves of SD or meteors from that one of other events. It turns out that the Stack-CNN assembled with the RF makes the method more robust, excluding many events that are triggered by the Stack-CNN but that are not debris-like events. We present all the details of the RF, from the training strategy to the evaluations, providing also an ablation study to select the best hyperparameters of the R-Stack-CNN. Finally we show results in terms of performances and computational time and compare the R-Stack-CNN with the baseline Stack-CNN and a standard threshold-based algorithm.

In summary, here we list our contributions as follows.

1) We propose the *R-Stack-CNN*, an improved version of the Stack-CNN, aimed to work as an offline data analysis to detect moving space objects, such as SD and meteor.
2) We apply both the *Stack-CNN* and the *R-Stack-CNN* to search new events of SD and meteors in simulated data and Mini-EUSO data.
3) We demonstrate that the *R-Stack-CNN* is more robust against false positives, preserving high performances especially for the detection of faint events and finding new meteors events not found before.

The rest of this article is organized as follows. Section II gives details about similar works from which we took inspiration and highlights the advantages of our approach. Sections III and IV are, respectively, about the Mini-EUSO detector characteristics and the dataset we used to validate our method. In Section V, we explain our method and in Section VI we evaluate the performance on both real data and simulated data. Section VII presents the discussion. Finally, Section VIII concludes this article.

II. Related Work

In recent years many space agencies have been addressing the problem of SD removal by means of new techniques. For instance, in the work of Ruggiero et al. [8], a platform using electric propulsion is proposed. Another method for larger SD involves the use of adhesion properties to capture debris [9]. To the best of the authors' knowledge, there is no official technique for small debris removal. This is due to their small reflective surface and low albedo, reaching signal over noise ratio (SNR) of ∼1, that makes the signal related to these objects very faint and difficult to track.

The JEM-EUSO project [4] aims to detect, track and remove these objects by using an online detection and tracking by the telescope, followed by the debris removal with laser ablation [5]. For online detection the *Stack-CNN* is proposed in [3] as a trigger system to detect faint debris. In this article, we propose the *R-Stack-CNN* as an offline version to analyze data of the Mini-EUSO detector to search for debris and meteors.

The detection of debris and more generally of space objects has been studied for a long time through standard and advanced techniques. For example, Mohanty [10] presented an adaptive algorithm based on maximum likelihood ratio to reconstruct paths and positions of space objects. Another solution is to use

3-D filter theory [11] to match the possible trajectories of debris with known velocity and direction. A more feasible algorithm was proposed by Barniv [12] with a dynamic programming approach. SD are usually detected using ground-based telescopes pointed at the sky. Depending on exposure mode and times, debris can be seen as streak-like objects superimposed on a static background consisting of stars, or as point-like objects on a moving background. Given this nontrivial setup, traditional algorithms like the ones presented before might not be complex and powerful enough, although it is worth noting that they have the advantage of not requiring many computational resources.

In order to increase the performance, traditional machine learning techniques and more recent deep learning algorithms have also been investigated. Many recent techniques are based on this new paradigm with many applications on both meteors and SD. Regarding debris detection, in [13], SD are detected in a low SNR configuration and with high probability, using feature learning to extract the candidate regions and then classify the SD. Li et al. [14] showed how machine learning can also be used to model the orbital prediction errors of SD, thus correcting orbital prediction results. In [15], noisy labels in SD detection are mitigated using a new label-noise learning paradigm comprised of the mutual rectification of the two networks. This approach is shown to surpass previous state-of-the-art methods. Considering machine learning applications for meteors, an example is [16], where a feed forward neural network denoising method is applied to near-Earth-asteroids data obtained from the Goldstone Solar System Radar. A similar work is [17], where a deep learning method of object detection, YOLOv5, is improved via an attention mechanism able to detect small boulders from planetary images.

These previously cited algorithms have the advantage of being extremely powerful, but this comes also with a steep increase of the computational resources required, both during training and testing. On the contrary, given that our algorithm should be implemented as an online trigger in a field programmable gate arrays (FPGA), only shallow architectures (low parameters required) can be used. Thus, in [3], a stacking procedure similar to [18] and [19] is enhanced by a shallow CNN classifying right and wrong combinations of speed and direction of the moving object. CNNs are a specific type of neural networks, mostly used in computer vision tasks, such as image classification. The advantage with respect to classical methods is that image features are learnt implicitly during training instead of being hard-engineered by an human, thus increasing the overall performance (more details will be given in Section V).

One of the main challenges that these new methods have to address is the application to real data, since most of the works focus on simulated data, not considering many problems that could arrive from real data, such as pixels with outliers, weird light sources, and variable background. In this article, we are the first presenting a technique that has worked with real data for a total of $\sim$ 160 min of acquisition time. The data come from Mini-EUSO experiment on board of the ISS. Other experiments share a similar configuration with extremely variable background. An example is the orbital detector Tracking Ultraviolet Setup, onboard the Lomonosov Satellite [20], which showed promising results in meteor detection from space images. In parallel to this work, a new approach using a CNN and a fully connected network [21] is being investigated to find new meteors in some sessions of the Mini-EUSO data. Their approach still implements a CNN to select meteor images, and then a fully connected layer to classify pixels of such image containing meteor events. While they use real data to train the network, we base our method only on simulated data and then show the effectiveness on real data. Besides this, another difference is that the R-Stack-CNN finds automatically meteor pixels through the Stack-CNN classification (image classification) and then through a RF (light curve classification). We show a comparison in terms of new meteors found by both the methods in the Appendix.

III. Mini-EUSO Detector and its Acquisition Modes

The Mini-EUSO focal surface consists of 36 multianode photomultiplier tubes (MAPMTs) where each MAPMT has 8×8 pixels resulting in a total of 2304 channels, which can detect individual photon [see panel (c) of Fig. 1]. Given that the optical system is made of two Fresnel lenses of 25 cm each [see panel (b) of Fig. 1] with an FoV of $44° \times 44°$, each one of these pixels corresponds to a projected spatial resolution on Earth of $\sim$6.3 km, and $\sim$4.7 km at 100 km height where typically the meteor tracks develop in atmosphere. Mini-EUSO operates on three different data acquisition time scales (D1, D2, and D3), with different exposure times (2.5 μs, 320 μs, and 40.96 ms) making it capable of addressing events of varying duration. The D3 time scale is the one sensitive to meteor and SD events. Along this article we will call gate time units (GTUs) the acquisition time scales. As Mini-EUSO detects typically $\sim$1 photon count per GTU in D1 mode, thanks to its extremely high photon sensitivity, very often we will renormalize the photon counts detected in D3 mode to the D1 time scale by dividing them by 128×128 time which corresponds to the ratio between the two time frames. If not differently mentioned later on, the D3 GTU will be referred to as the nominal GTU within this article. Fig. 1(a) shows an example of a Mini-EUSO meteor observation. Other events and details regarding the instrument can be found in [6]. In this framework, the need to have a fast trigger system to find debris and possibly infer its direction and speed is crucial to activate the further operations in order to track and then deorbit the fragment.

IV. Physics of SD and Similar Events Detectable in Mini-EUSO

SD do not emit light by themselves, which makes them more challenging to detect. The phenomenon through which a sensor can detect them is known as albedo: the light coming from the Sun (or Moon) hits the debris and is reflected, making the object illuminated. Events that look very similar to SD are the meteors that are visible in the Mini-EUSO data as luminous tracks crossing the FoV. Here, we give a brief description of these events.

A. Twilight Configuration

Since the telescope is taking data only during night sessions (period of the ISS orbit spent behind the Earth's shadow), the

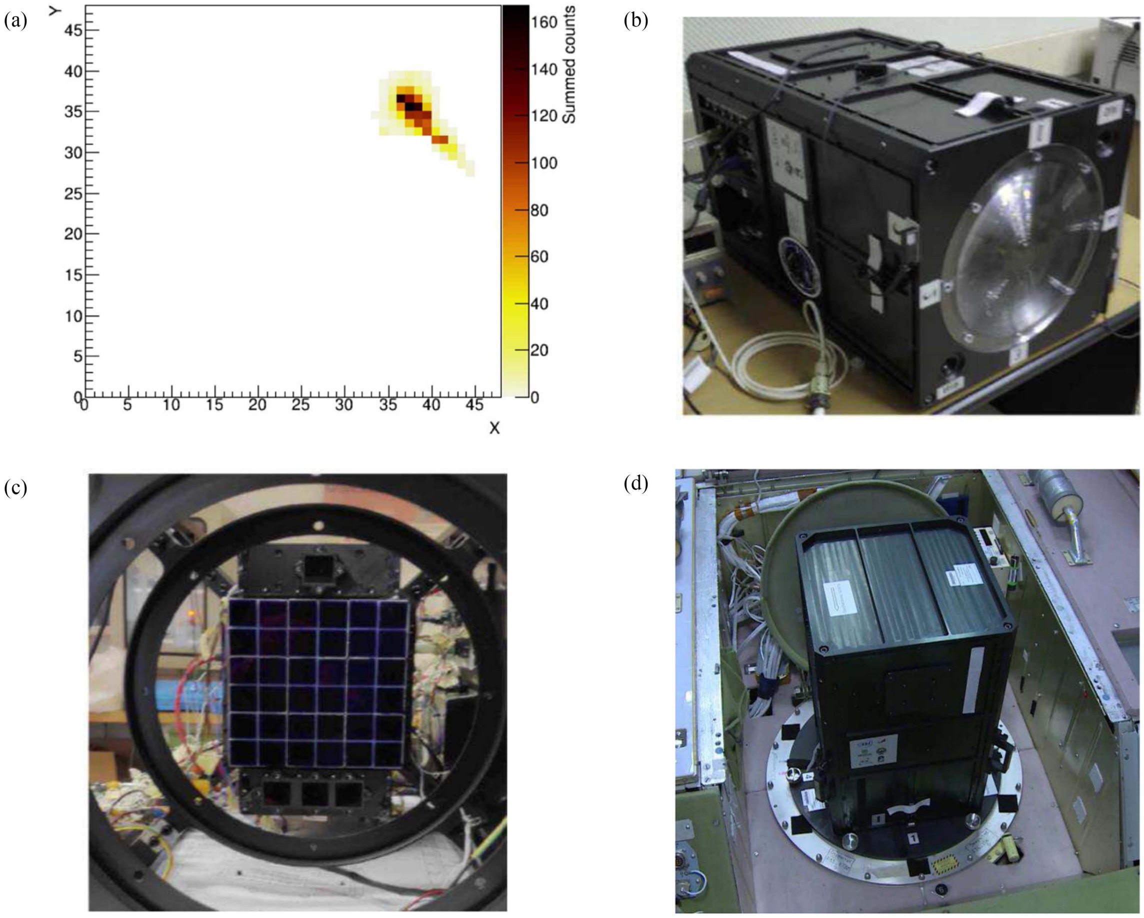

Fig. 1. Panel (a) displays an example of meteor track detected on Mini-EUSO focal surface. X and Y indicate the pixel coordinates and the color scale indicates the photon counts detected by each pixel in D3 mode rescaled to D1 mode. Panel (b) displays the Mini-EUSO detector facing its front lens during pre-launch tests. Panel (c) displays the Focal Surface of Mini-EUSO which is composed of 36 MAPMTS, each of them equipped with 64 photo-detecting pixels. Panel (d) displays Mini-EUSO detector mounted on the UV transparent window of the ISS Zvezda module (see text for details, figure adapted from [6] and [7]).

optimal configuration is at twilight, when the SD could still reflect sunlight and Mini-EUSO is still taking data (before sunrise or after sunset), see Fig. 2(a).

In over 37 Mini-EUSO sessions between October 2019 and August 2021 ($\sim$141 h 12 min 15 s) only $\sim$1 h 6 min 22 s of data (0.78%) correspond to this configuration. This is due to the fact that, since the telescope does not have a baffle to avoid sunlight and it is pointing nadir, the ISS is directly illuminated during the twilight situations, increasing background and compromising the possibility to test this approach. The observation of SD would be possible for Mini-EUSO if it would measure in the rare conditions in which the ISS has a roll angle of 90° or 180° opposite to the Sun. In those situations the ISS itself would shield Mini-EUSO from direct light. In addition to the above considerations and sticking to the nominal ISS orbiting condition, Mini-EUSO has a protection mechanism which reduces the gain of MAPMTs or turn them OFF to prevent damage to them from the intense sunlight. In this condition the pixels are not sensitive to the standard light levels. This procedure further decreases the real available dataset at twilight, which becomes just the 0.1% of the 37 Mini-EUSO sessions. In addition, the background distribution (median of data files) as visible in Fig. 2 that roughly only half of data files have background < 5 photon counts / D1 GTU, thus significantly reducing the SNR and consequently the possibility of identifying a debris.

B. Full Moon Albedo

An alternative albedo configuration could be full Moon reflection. This setup would have the advantage of an increased statistics since it concerns several entire Mini-EUSO sessions. On the other hand, the Moon light intensity increases significantly the atmospheric reflection and light diffusion as well as the reflection from objects at ground, resulting in a higher background.

Besides, the apparent magnitude of the full Moon is larger (fainter) than the Sun, respectively $\mathcal{M}_{\text{app}}^{\text{moon}} = -12.74$ and $\mathcal{M}_{\text{app}}^{\text{sun}} = -26.74$. Apparent magnitudes (indicated as $\mathcal{M}$) can be used to calculate the ratio of light intensities of Sun and full Moon using logarithmic properties

$$\mathcal{M}_{\text{app}}^{\text{sun}} - \mathcal{M}_{\text{app}}^{\text{moon}} = -2.5 \cdot \log_{10}\left(\frac{I_{\text{sun}}}{I_{\text{moon}}}\right). \quad (1)$$

As a consequence, the sunlight intensity is extremely higher than the moon light because of the logarithmic scaling

$$I_{\text{sun}} \sim 4 \cdot 10^5 I_{\text{moon}}. \quad (2)$$

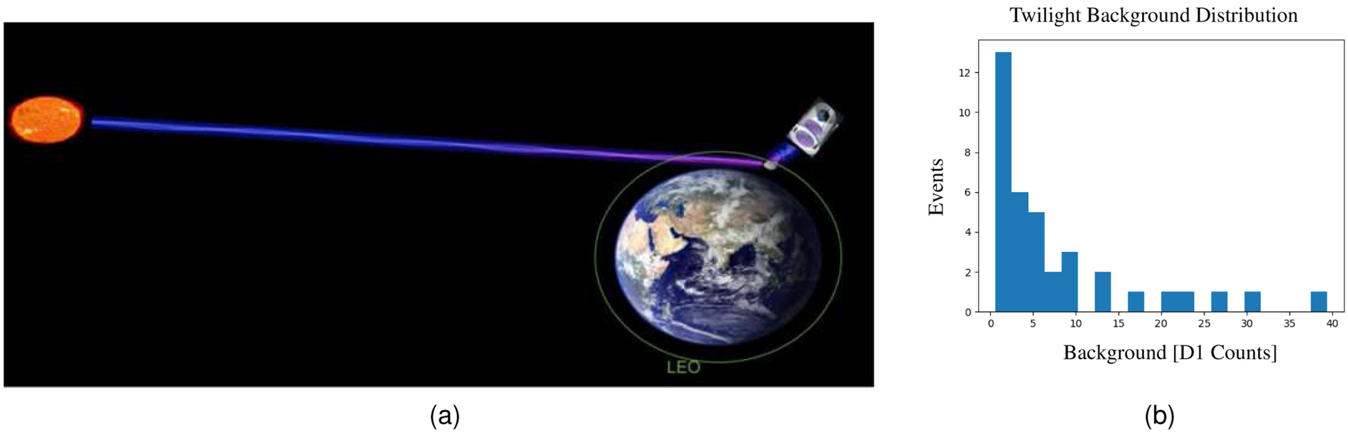

Fig. 2. Figure on the left (a) shows the observation principle of SD using albedo reflection from the Sun: Reflected UV light is shown as blue–violet wave. As can be seen, the detector itself is illuminated, causing an high background, visible on the right distribution (b) where the background is estimated as the median of the data file.

The reflected light depends on the size (square of the debris radius r^2), the light intensity of the source I_{source} (I_{sun} or I_{moon}) and the distance d from the detector to the debris by the inverse square law ($\frac{1}{d^2}$)

$$I_{\text{albedo}} \propto \frac{r^2}{d^2} I_{\text{source}}. \tag{3}$$

Thus, an algorithm can detect fewer debris as the distance grows, until a certain threshold is crossed and no objects can be detected. In [3], the performance of the Stack-CNN was tested using several distances and radius, using the Sun as the light source for the albedo in simulated data. It was shown that debris objects of radius ∼4 cm reflecting sunlight can be detected by the Stack-CNN up to a maximum distance of d ∼100 km with a 100% efficiency. A similar threshold can be adapted for Moon albedo

$$\left(\frac{r^2 I}{d^2}\right)_{\text{moon}} = \left(\frac{r^2 I}{d^2}\right)_{\text{sun}} \rightarrow \left(\frac{r^2}{d^2}\right)_{\text{moon}} \sim 6.4 \cdot 10^{-8}. \tag{4}$$

In other words, this means that a 10 cm-sized SD would be detectable up to a maximum distance of $\sim$ 200 m. At this altitude, the projected FoV is limited to ±80 m in both x and y directions, which means that the debris trajectory would need to be extremely close to the ISS.

Therefore, the probability of observing a 10-cm-sized debris within this distance is roughly of the same order of magnitude of the probability that the ISS is hit by the debris. ESA's models [2] estimate that the corresponding mean time between impact is ∼15 000 years, making this approach not suited for Mini-EUSO observations.

Thus, the current Mini-EUSO has not shown any observational usefulness for the detection of SD because it observes toward the Earth with high background, but if it were to observe darker directions in the sky, it would have a much higher probability of observing smaller and more distant debris.

C. Meteors

Despite the difficulty to test the method to detect SD, thanks to the flexibility of our approach, the Stack-CNN and the R-Stack-CNN can be applied to any object moving linearly in the FoV of a telescope, such as space debris, meteors, and cosmic rays. Therefore, the method was applied for meteors detection, as they share similar properties as SD (similar magnitude and speed) but they do not suffer from low statistics since they do not require albedo conditions. However, the highly variable background of Mini-EUSO adversely impacts its performance generating a lot of false positives. Since the telescope is pointed downwards the Earth, the observations contain the apparent motion of cities and clouds, hence distinguishing the meteors become challenging. Consequently, the R-Stack-CNN method is introduced to address such difficulties in order to be more efficient and more robust to noise with respect to the standard Stack-CNN and a classical thresholding method, using both real data and meteor simulations.

V. R-Stack-CNN Method

The proposed method for meteor detection and tracking is an offline version of the Stack-CNN, which is improved by means of a RF. The R-Stack-CNN is based on the Stack-CNN, with the additional implementation of a RF to make the method more robust, and to be used in offline data analysis of Mini-EUSO experiment. The R-Stack-CNN is comprised of three main techniques, a stacking procedure and a CNN (already presented in the Stack-CNN) and a final RF. Here, we describe the main components.

A. Stacking Method

The stacking method is applied to objects, e.g., SD or meteor, moving linearly in the FoV of the telescope with fixed apparent speed $\tilde{v}$ and direction θ. The speed and direction are apparent as the telescope is affected by the speed and azimuth of the platform on which is mounted (in case of Mini-EUSO, the ISS). The method can be described by two main operations, the shifting and the adding procedures. Considering n frames, each of them named I, of raw data depending on pixel position (x, y) and time t, $I(x, y; t)$, $t = \{0, \ldots, n-1\}$, the shifting is used to shift pixels in the opposite direction of the moving object's trajectory to match the further positions of the object in the initial position of the detector. The movement (dx, dy) depends on the time, speed and direction and it is used to roll the image back in the starting position (x_0, y_0).

In other words, the shifting operation is equivalent to assuming a constant optical flow with fixed speed and direction (opposite to the motion of the signal) over all the pixels of the image, and moving the whole image according to such flow to bring back the signal to its original starting position. This operation is repeated n times, where n is the number of frames. In our case, the n time frames correspond to the D3 GTUs of Mini-EUSO, the nominal GTUs in this article. The shift along x- and y-axes, corresponding to the intensity of the flow applied over each frame, is defined as follows:

$$\begin{cases} dx = \tilde{v} \cdot \cos(\theta) \cdot t \\ dy = \tilde{v} \cdot \sin(\theta) \cdot t. \end{cases} \tag{5}$$

Considering the object starts at the center of the pixel (x_0, y_0) and the xy grid is discrete, dx and dy are transformed into their closest integer value through the int() function (e.g., $dx = 0.4$, $dy = 1.7 \rightarrow dx = 0$, $dy = 2$)

$$I^{\text{shift}}(x, y; t) = I(\text{int}(x - dx), \text{int}(y - dy); t). \tag{6}$$

At this point the adding method is used to sum all the shifted images, to recover the moving signal in its starting position

$$I^{\text{stack}}(x, y) = \sum_{t=0}^{n-1} I^{\text{shift}}(x, y; t). \tag{7}$$

The main advantage of using $I^{\text{stack}}(x, y)$ is that it enhances the signal with respect to a single image. The SNR is defined as follows:

$$\text{SNR} = \frac{\text{Signal}}{\sigma_{bkg}} = \frac{\text{Signal}}{\sqrt{\mu_{bkg}}} \tag{8}$$

where the signal is meant to be the difference between the number of counts in a pixel and the average background level μ_{bkg}. If we consider the background to be Poissonian, its fluctuation (in terms of standard deviation) σ_{bkg} is equal to the square root of the background mean $\sqrt{\mu_{bkg}}$. The ideal average background value in the Mini-EUSO dataset is considered to be 1 photon count / D1 GTU, which corresponds to 128 × 128 counts / D3 GTU. The D3 counts are then rescaled by a factor 128 × 128, to avoid dealing with large numbers. However, observations also include dynamic background sources, such as cities and cloud reflections, which cause an increase in the average background value as well as its complexity, because it no longer can be modeled as Poissonian.

Nevertheless, we chose to consider a Poissonian background for the SNR estimation for the sake of simplicity. The stacked image exhibits an enhanced SNR due to the background that fluctuates between both positive and negative values, while the signal always remains positive, which makes the stacked signal $\sqrt{n}$ times brighter than the one in the single image

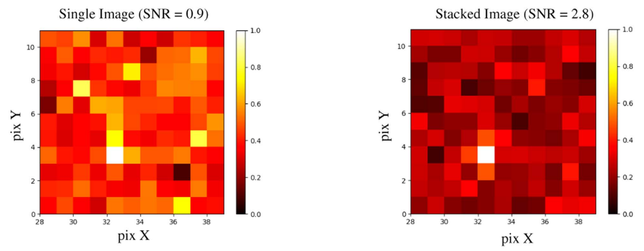

Fig. 3. SNR comparison between single image and stacked image using a simulated meteor of absolute magnitude $\mathcal{M}_{abs}$ = +6.

$$\text{SNR}^{\text{stack}} = \frac{\text{Signal} \cdot n}{\sqrt{\mu_{bkg} \cdot n}} = \sqrt{n} \cdot \text{SNR} \tag{9}$$

where n is the number of frames corresponding to the duration of the event that is assumed to emit constant light. According to the physics of the object this factor could variate. The denominator scales by a factor of $\sqrt{n}$ regardless of the object's presence. Therefore, it is crucial that the number of frames is as close as possible to the track's duration, otherwise the numerator will not scale with a factor of n and there would be only partial improvement on the SNR. Typical numbers for n are 20 (0.8192 s, the average meteor duration) and 40 (1.6384 s) for SD (a longer track since it is assumed that the debris crosses the entire FoV).

Fig. 3 shows the difference between the stacked image and the single image for a simulated meteor of $\mathcal{M}_{abs}$ = +6, for which the intensity of each pixel has been normalized from 0 to 1 for demonstration purpose. The single image is the one with the maximum signal in the meteor track, whereas the stacked one has been stacked with the true simulated speed, direction and duration of N_{GTU} = 13 GTUs. In the single image the meteor is barely visible and the SNR = 0.9, while in the stacked image the SNR is increased by a factor of 3.1 (SNR = 2.8) which is close to $\sqrt{13\text{ GTUs}} \sim 3.6$. Since the $(\tilde{v}, \theta)$ combination for a triggered object is not known, a significant sample of possible combinations are computed and a classifier is needed in order to distinguish the right combinations from the wrong ones. Here, is where the CNN comes into the game. The network is trained as a binary classifier for right (1) and wrong combination (0).

B. *Convolutional Neural Network*

CNNs are a class of artificial neural networks most commonly used in computer vision (image classification, video analysis,...). Their advantage with respect to other algorithms is that the network is computationally efficient (due to the convolutional operations involving shared weighted sum with small kernel size of the filter) and they extract image features most relevant to the relative objective, in our case the classification. The CNN implements filters (or kernels) that are optimized through automated learning and captures the spatial dependencies in an image. In the pre-deep learning era these filters were hard-engineered with human intervention and difficult to build. The name CNN is

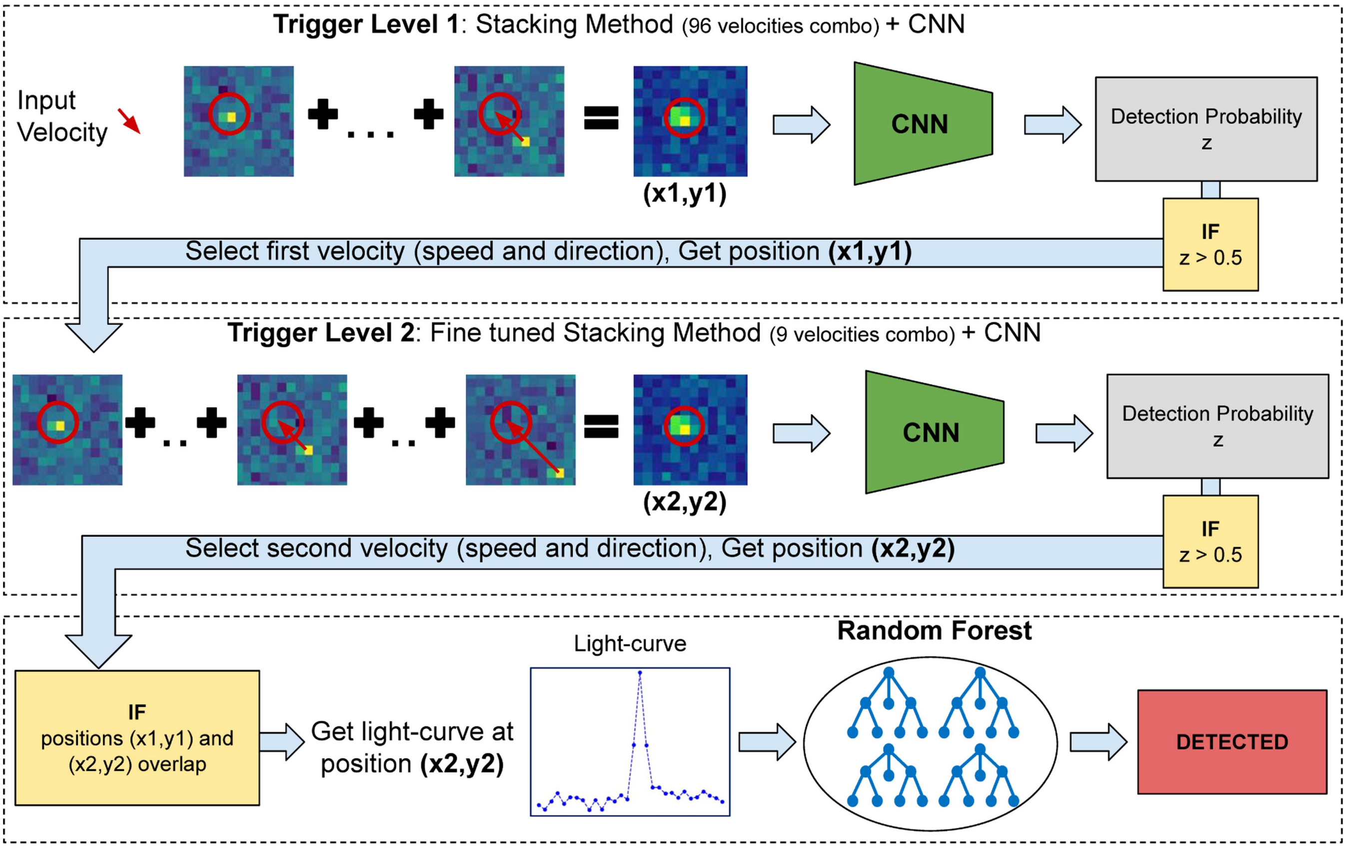

Fig. 4. R-Stack-CNN algorithm for SD and meteor detection (source: [3]).

originated with the design of LeNet-5 by Yann LeCun [22] in 1998, built for handwritten digit classification and it is the first architecture to implement backpropagation for automated learning in a CNN.

Newer architectures developed in the 2000 s thanks to the *ImageNet large scale visual recognition challenge (ILSVRC)* and to the usage of GPU during training, which strongly decreased computing time. ImageNet is a common dataset on which researchers tested new algorithms and the first GPU-based CNN to win the competition is AlexNet (2012) [23], which introduced ReLU activation functions and dropout layers for regularization. Similar but deeper architectures are called VGGNets [24], which prove that increasing the number of layers and parameters can yield an higher performance.

In 2015, Google presented GoogLeNet [25], winning ILSVRC by introducing the inception module, whose key idea is to parallelize pooling and convolutional layers.

Then, skip connections between layers were introduced by the ResNet architecture [26], addressing the gradient vanishing problem and achieving even higher performance. The concept was extended by DenseNets [27] with skip connections also between nonconsecutive layers.

In our work, the architecture also needs to be suitable for an on-board implementation in a SD remediation system. Hence, the CNN must be shallow because an higher number of parameters would require higher computational time and expensive resources. The number of total parameters is 16 825, divided across convolutional and fully connected layers, with ReLU activations in the hidden layers and a sigmoid function in the output layer. Regarding the training dataset, a total of 80 SD were simulated with ESAF [28], a software that generates point-like moving sources in the Mini-EUSO framework. The simulated background is Poissonian with mean value equal to 1 count / D1 GTU. See [3] for details about the event simulation, training, validation, and the architecture.

C. Stack-CNN

The Stack-CNN (see Fig. 4) combines the stacking procedure and the CNN in a detailed framework. The stacked combinations and the number of frames are chosen depending on the physics of the object (SD and meteor in this work), making this approach extremely versatile as it allows to use the neural network trained on SD even for meteors, and in principle to anypoint-like object moving linearly in the detector, e.g., cosmic rays. In this last example the method could be applied only offline due to the light-speed of such particles and the requirement to use D1 data. The Stack-CNN is divided in two processing levels. The former performs a rough track reconstruction, by generating 96 combinations of speed and direction. If the object is detected, the second level is implemented to fine-tune the reconstruction and suppresses false positives. For SD, the first level stacks 12 GTUs, where the considered directions go from 0° to 345° with steps of 15° while speed ranges from 5 to 11 km/s with steps of

2 km/s. It is assumed that the reference height is 370 km, which is below the International Space Station (∼420 km), but still in low Earth orbit. The range of the speed has been chosen depending on the typical order of the SD orbital speed in low Earth orbit, which is about ∼7–9 km/s, and to account for the relative motion of the ISS, which travels at ∼7.66 km/s. Then, the trained CNN is applied to each combination, which is positively classified if the output, indicated by y, is greater than 50%. The second level is used to fine-tune the triggered combination with ± 0.5 km/s and ± 5°steps. The number of stacked GTUs is increased to 40 to exploit the longer movement of a SD with respect to a background event. Finally, if the event is still positively classified by the neural network and the two triggered pixels overlap in a neighborhood of 2 pixels the SD event is triggered.

In our work, the Stack-CNN was adapted to meteors by modifying stacked frames and speed combinations, according to the meteor physics. The number of stacked GTUs in the first and second levels was changed to 8 GTUs (∼0.33 s) and 20 GTUs (∼0.82 s), respectively, because the duration of the event is shorter compared with SD. Meteor entry speed in the atmosphere is usually estimated using a reference height of 100 km, which is where the light emission starts [29]. Besides, the speed range is bounded by 11 and 72 km/s [30]. Thus, speed combinations have been chosen within a range from 10 to 70 km/s with step of 20 km/s. The fine-tuning steps have also been changed to 5 km/s. The advantage of using meteor events to test the Stack-CNN is that, unlike SD, the light emission phenomenon does not require any reflection of other light sources, making their observation more frequent in Mini-EUSO. Besides, the study of meteors in Mini-EUSO [31] could be useful because meteor observations are usually performed at visible wavelengths, while Mini-EUSO, operating in the UV range, could detect meteors in UV up to $\mathcal{M}_{abs} \geq +5$. Another advantage is that space observations are not affected by weather conditions like the ground observations and high statistics can be collected in a short time.

However, the CNN was trained using a simulated Poissonian background, which is a strong simplification with respect to real background from Mini-EUSO data. Hence, preprocessing is needed in order to recreate a configuration as similar as possible to the one used during the training procedure.

The background map is affected by the passage of the ISS over cities and clouds. The algorithm suppresses these contributions thanks to the normalization of each pixel by means of a moving median. The median is computed for each pixel and GTU, starting from GTU−4 to GTU+4. Then, the count of each pixel is divided by this value and the resulting background is normalized between 0 and 1. This is useful for discarding slow events (i.e., events that move at the apparent speed of the detector, which is the same of the ISS, i.e., ∼7.7 km/s), but it does not affect fast objects, such as meteors or SD. An example of a preprocessed background sample is given in Fig. 5. The threshold of the neural network was also increased to 90%, instead of the default value of 50%, in order to suppress as many false positives as possible. To improve the performance and lower the false positive rate coming from challenging background conditions and noisy pixels, the Stack-CNN is improved by adding a RF classifier, analyzing meteor light curves. We prove in the next chapter how the proposed method reaches better performance than the baseline Stack-CNN.

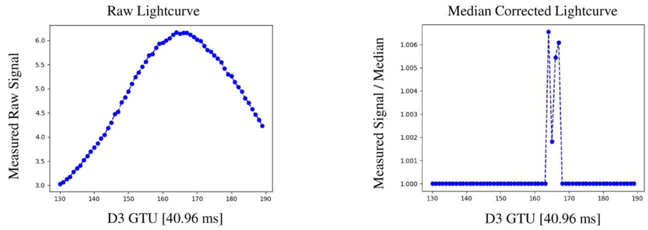

Fig. 5. Example of preprocessed light curve on cities observed by Mini-EUSO: raw light curve (on the left) is flattened to values close to 1 by a mobile median correction (on the right).

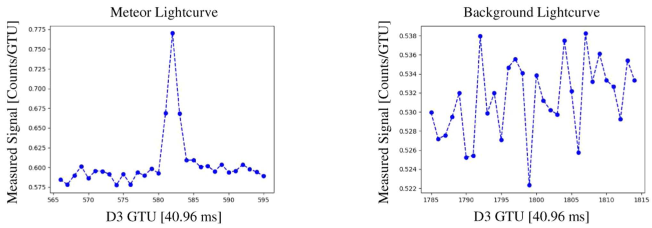

Fig. 6. RF training dataset: Binary classification of meteor light curves with output 1 (left) and background light curves with output 0 (right). The time range of each light curve is a portion of a complete data acquisition file, which lasts 3200 GTUs.

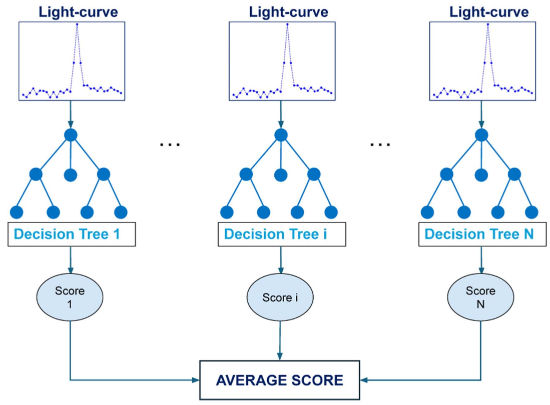

Fig. 7. RF, used in the R-Stack-CNN, processing meteor light curves. Each decision tree outputs a probability score for the recognition or not of a meteor, then the scores are randomly averaged across trees.

D. Random Forest

The RF is essential for the offline analysis of Mini-EUSO data to avoid many false positives coming from moving light sources (e.g., cities, ships, and lightning), while keeping a true positive rate as good as the original Stack-CNN. An illustration of the RF used in this article is in Fig. 7.

The classification is binary, i.e., an output of 0 for background light curves and 1 for meteor light curves. In astronomy, a light curve is a curve describing light intensity of celestial objects, in a particular frequency band, over a period of time. In the case of Mini-EUSO, the frequency band is UV, and light intensity is expressed as photon counts and time as GTUs. In this case the light curve can be considered as a time-series over the pixels illuminated by the signal. The fast movement of meteors (or SD) in the FoV generates an excess of signal counts in pixels hit by the track (see Fig. 6). In our framework, light curves are represented as univariate time series, i.e., series of time-ordered data of length T. With time series, features correspond to data values at each time frame, which means photon counts at every GTU for light curves.

We chose the RF for its robustness to limited train data and for its fast convergence during the train. RFs are an extension of decision trees, i.e., tree-like structures, where each internal node represents a decision on a feature, based on which the tree splits in branches.

RFs [32] minimize the tendency of decision trees to overfit, by averaging the output on a forest of bagged decision trees, with low correlation between each other, as they are trained on randomly extracted subsamples of the original dataset. The training and validation procedures were done using real data from an analysis performed on session 11 of Mini-EUSO. This session was chosen for the large statistics of detected meteors. First, a list of 553 events was obtained through the application of the standard trigger, which will be used as a baseline for all the results in this article. The standard trigger [33] does not implement machine learning techniques, it scans 25 virtual elementary cells, defined as 16 × 16 pixels, searching for an excess in neighboring pixels lasting five consecutive GTUs. The threshold for each pixel is 3σ above the mean background μ_{bkg} computed at every GTU ($\mu_{bkg} + 3\sigma$). Then, each event was visually inspected by an expert who verified if meteors were indeed moving objects hitting many pixels. Finally, the results consisted of 416 meteors, divided in two categories, 309 M and 107 $M^?$. The former class is used to classify objects with bright and long-duration movements. On the contrary, short-duration and fainter tracks are usually grouped in the latter class, labeled as $M^?$ with "?" indicating uncertain meteors. The reason for this distinction is that even if shorter tracks could come from real meteors, the physics reconstruction of speed and azimuth would be challenging and affected by high uncertainty. As for the positive events of the training dataset (output = 1), only certain meteors M were chosen, along with the two of the closest and most significant pixels in the meteor track. The meteor track is affected by blurring in the neighboring pixels, as described by the point spread function (PSF). Hence, the inclusion of light curves from closest pixels allows the correct classification of fainter events affected by the PSF, while also having the positive effect of increasing the training set size. Background events (see Fig. 6) were randomly chosen in the S11 dataset. In this way, events include both Poissonian fluctuations and cities, which would have been difficult to simulate. Finally, after visually inspecting the complete set of light curves, the size of the training dataset became 1384, equally distributed between positives and negatives (692 each). The preprocessing was limited to a normalization between 0 to 1 of the time series. Then, the dataset was split between training set S_{train} (60%), validation set S_{dev} for best model evaluation (20%) and test set S_{test} to quantify the performance in unseen data (20%). First, a validation set was used to tune the RF main hyperparameters, including the length of the time series, the number of decision trees and the maximum depth. Then, the model was trained with $S_{\text{train}} + S_{\text{dev}}$ and tested in S_{test} using the F1 metric, defined as the harmonic mean of precision and recall. The advantage compared to a symmetric metric like Accuracy is that F1 is used when true positives (TPs) are more important than true negatives (TNs), which means that an higher F1 tends to minimize false negatives (FNs). That makes it more suitable for this application, as it's crucial that the meteors found by the Stack-CNN must not be lost by the RF. The performance on the test set is summarized in Table I (FPs indicate false positives). The results are extremely promising as only an extremely low percentage of meteors are lost (3.4%) generating an high F1 score. Besides, most of the background events are correctly classified (97.7%) making the method robust to noise and background fluctuations.

TABLE I
RF PERFORMANCE ON TEST SET

TP	TN	FP	FN	Accuracy	F1
140	129	3	5	97.1 %	97.2 %

More details about the training and ablation of the RF along with definitions of used metrics are given in Appendix.

VI. APPLICATIONS OF STACK-CNN AND R-STACK-CNN TO REAL AND SIMULATED DATA

The R-Stack-CNN method was tested on both real data acquired by Mini-EUSO and simulated ones to study its performance in comparison with the original Stack-CNN and the standard trigger algorithm.

A. Real Data: Search for SD and Meteors

First, a dataset of 13 files from the Mini-EUSO session 6, which corresponds to roughly ∼28 min, has been used to quantify the improvement of the R-Stack-CNN with respect to the Stack-CNN.

Then, the entirety of Mini-EUSO session 14 has been used to compare the R-Stack-CNN results to the standard trigger. It is worth noting that because of the protection mechanism discussed in Section IV-A, the real available dataset is roughly ∼129 min, corresponding to $\sim 2 \times 10^5$ frames.

The Stack-CNN (see Table II) was able to find 89 new meteor candidates than the standard algorithm (32 M + 57 $M^?$), while losing only 13 meteors (2 M + 11 $M^?$) detected by the standard approach. However, the main problem is that 878 FPs were also triggered, making the final Precision (13) very low, 16.8%. The standard algorithm had an higher precision (85.6%) than the Stack-CNN (16.8%), making it more reliable even if fewer meteors were triggered. On the other hand, the R-Stack-CNN was able to find a total of 79 additional meteor candidates than the standard trigger (30 M + 49 $M^?$), while losing only 15 events (3 M + 12 $M^?$). The final precision was 88.2%, which is much better than the model without the RF (16.8%) and also an improvement on the standard algorithm (85.6%).

TABLE II
R-STACK-CNN ABLATION PERFORMANCE WITH MINI-EUSO DATASET FROM SESSION 6

Model	TP	TN	FP	FN	Precision	CPU Time
Standard Algorithm	101 (69 M + 32 $M^?$)	-	17	-	85.6 %	39 min
Stack-CNN	177 (99 M + 78 $M^?$)	-	878	-	16.8 %	65 min
R-Stack-CNN	165 (96 M + 69 $M^?$)	856	22	12 (3 M + 9 $M^?$)	88.2 %	247 min

TABLE III
R-STACK-CNN PERFORMANCE WITH MINI-EUSO DATASET FROM SESSION 14

Model	TP	FP	Precision	CPU Time
Standard Algorithm	196	100	66.2 %	180 min
R-Stack-CNN	276	119	69.9 %	1138 min

We evaluated also the computing time required to process these data files by each algorithm. As Table II shows, introducing the RF in the Stack-CNN increases the CPU time with a factor of 3.8. However, the increase in the precision is much higher, i.e., a factor of 5.25, meaning that using the RF is the optimal solution for tradeoff between time and performance.

Then, the R-Stack-CNN was tested using the complete Mini-EUSO session 14 (see Table III): the model R-Stack-CNN found 136 new meteor candidates (see Table III) than the standard algorithm (85 M + 51 $M^?$) while losing 56 meteors (26 M + 30 $M^?$). The model also detected 119 FPs, with an overall precision of 69.9%, which is slightly better than the corresponding 66.2% of the standard trigger. These results showed that, even for an extended set of data, our method outperformed standard techniques finding a larger number of meteors. It is also worth noting that, although our method proved to be the most powerful and accurate one, the standard algorithm remains a valid faster solution. In addition, we provide a comparison with another neural network-based method, and we show that the R-Stack-CNN finds more meteors than this. Further details are provided in the Appendix.

B. Simulated Data: Detection and Tracking of Meteors

In order to investigate the detection limit and true efficiency of the model, meteor events were also simulated. Considering that the Stack-CNN was originally planned for the online detection and tracking of SD, it is crucial that the speed and direction combination is as precise as possible. Hence, meteor simulations are also used to quantify the goodness of the speed and azimuth reconstruction.

An important feature of the simulations is that they involve a dynamical model, implementing analytical solutions [34] to the differential equations describing the physical problem of the meteor body deceleration in the atmosphere [35]. The simulated parameters were sampled from their known distributions [36] and the background maps were generated using a Poissonian distribution with an average of μ_{bkg} photon counts per GTU in D1 mode. An example of a simulated event of $\mu_{bkg} = 0.572$ and absolute magnitude $\mathcal{M}_{abs} = +4$ is given in the Appendix, Fig. 12. From now on the indicated magnitudes are meant to be positive even though the "+" sign is not explicitly indicated.

TABLE IV
SUMMARY OF SIMULATED ABSOLUTE MAGNITUDE $\mathcal{M}_{abs}$ AND MEAN BACKGROUND CONFIGURATIONS

Events	$\mathcal{M}_{abs}$	μ_{bkg}
100	4	{0.5:1}
100	5	{0.5:1}
100	6	{0.5:1}

TABLE V
SUMMARY OF THE R-STACK-CNN RESULTS WITH METEOR SIMULATED EVENTS

Events	$\mathcal{M}_{abs}$	R-Stack-CNN	Standard Trigger
100	4	88	77
100	5	70	50
100	6	6	5
300	{4,5,6}	164	132

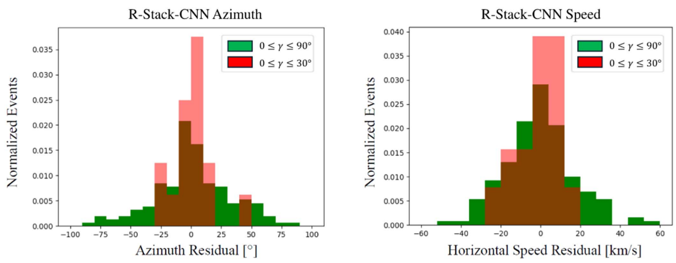

Fig. 8. Residual distribution of Stack-CNN reconstructed variables: Meteor azimuth is shown on the left and horizontal speed on the right. The green distribution refers to meteors with inclination 0°≤ $\gamma \leq$ 90°, while the red distribution refers to events with 0°≤ $\gamma \leq$ 30°.

A total of 300 events have been simulated for meteors of $\mathcal{M}_{abs} = \{4, 5, 6\}$ (100 each). Each event has been simulated with a random sampling of μ_{bkg} ranging from 0.5 to 1 photon counts per GTU in D1 mode.

The results using meteor simulations have been summarized in Table V and compared with the standard trigger results. The R-Stack-CNN found 32 additional meteors in 300 simulated events with respect to the standard trigger. However, only six meteors of $\mathcal{M}_{abs} =$ +6 were triggered by the algorithm, defining the detection limit. These events are indeed very faint and their tracks are often difficult to observe because of the background fluctuations. Fig. 9 shows, as an example, a lost event of $\mathcal{M}_{abs}$ = +6, with a horizontal purple line defining the $3\sigma_{bkg}$ range of background fluctuations, where $\sigma_{bkg} = \sqrt{\mu_{bkg}}$.

Then, the performance of the speed v and azimuth ϕ reconstruction has been estimated by using the standard deviations of the residual distributions of the triggered events.

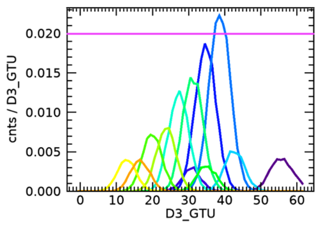

Fig. 9. Example of a meteor not found by R-Stack-CNN due to the low magnitude of $\mathcal{M}_{abs}$ = +6, $\mu_{bkg} = 0.716$. The plot shows a collection of light curves associated with the same meteor event, with signals hitting different pixels. The horizontal purple line shows the 3σ value of background fluctuations.

The azimuth is defined as the direction from the true North, whereas the speed refers only to the horizontal component of the meteor true speed. Since Mini-EUSO does not have a stereoscopic view, it would be impossible to estimate the transversal direction of speed.

Besides, it is important to note that since Mini-EUSO is mounted on the ISS, its variables (speed and direction) are affected by the position and speed of the ISS, that travels at ~7.66 km/s with an azimuth of ~51.6°. Therefore, both meteor horizontal speed and azimuth, i.e., the clockwise direction from the true North, were corrected. Moreover, the R-Stack-CNN often triggers the same meteor event more than once with different speed, direction and even starting GTU. Considering that images are processed sequentially, sometimes long tracks can surpass the 20 frames used in the stacking method, causing the event to be triggered more than once. Therefore, the best combination was chosen as the one with the highest number of counts in the maximum pixel of the stacked image. The residual distribution of the azimuth showed $\mu_\phi = (-3 \pm 4)°$and $\sigma_\phi = (46 \pm 3)°$(Fig. 8), whereas the longitudinal speed residual distribution had $\mu_v = (0 \pm 1)$ km/s and $\sigma_v = (17 \pm 1)$ km/s (see Fig. 8). However, these results refer to meteors with any value of inclination γ, which also means having vertical trajectories with few hit pixels. Hence, given that the goal is to investigate the precision of the Stack-CNN reconstruction of SD through meteors, the residual distributions were evaluated using mostly horizontal tracks, which resemble SD more accurately. Each meteor event has been simulated with a different inclination γ, with $\gamma = 0°$indicating an horizontal track and $\gamma = 90°$a completely vertical trajectory with respect to the Mini-EUSO focal surface. Thus, $0° \leq \gamma \leq 30°$has been set as the range used to define mostly horizontal tracks.

The results showed a great improvement, with $\mu_\phi = (1 \pm 4)°$, $\sigma_\phi = (15 \pm 3)°$for the azimuth and $\mu_v = (0 \pm 3)$ km/s, $\sigma_v = (10 \pm 2)$ km/s for the horizontal speed. These results show that the Stack-CNN could indeed be implemented in a SD remediation system with a reliable estimation of speed and direction. Besides, there is no bias in the reconstruction since both average values are compatible with 0.

VII. Discussion

Although the R-Stack-CNN has shown improvements with respect to the Stack-CNN, a standard thresholding method and another machine learning-based technique, it has some limitations. For example, our method, even if it suppressed the extreme number of FPs coming from the Stack-CNN, it lost some meteors that were detected by the latter. In future we want to study new strategies to avoid this loss, such as developing a recurrent neural network for the recognition of light curves. Another way to improve the whole framework could be training also the CNN with real data, but this would require a large amount of balanced and preprocessed data. Finally, even if we presented the R-Stack-CNN as an offline trigger we do not exclude the possibility to test it online with an FPGA and compare with the Stack-CNN.

VIII. Conclusion

In this article, we presented the R-Stack-CNN, a refined version of the Stack-CNN that serves as an offline data analysis to detect and track space objects that move linearly in the FoV of a telescope. In particular we applied the method to data of the experiment of Mini-EUSO, a UV telescope on board the ISS pointing on the Earth. With this configuration, the space objects that can be detected are meteors or SD. Unfortunately, the SD generally does not emit light themselves, therefore finding such events with a small aperture telescope at satellite orbit, such as Mini-EUSO described in this article, has turned out to be very difficult at the moment. However, similar phenomena to SD, but more luminous and more frequent, are meteors. We have shown that the R-Stack-CNN is an effective data analysis method for finding these events with higher precision than other methods. Specifically, the R-Stack-CNN found almost as many meteors as the Stack-CNN (which is the method that finds more meteors than the other methods), but with a FP rate much lower than that, avoiding to manually look at these events and discard them. With the development of a lightweight recurrent architecture, it is expected that the R-Stack-CNN can be improved to have even higher capabilities. The ability of the R-Stack-CNN to find events in real data, even though most of them are trained on simulated data, offers interesting prospects for applying this technique to other data, such as ground-based telescopes that point on the sky and can detect different space objects, e.g., SD, asteroids and meteors. Such an improved R-Stack-CNN could also be useful for the SD observations from the satellite orbit in future.

Appendix

In this section, we provide the Supplementary Material regarding our implementation of RF, the specific metrics we used, ablation and sensitivity studies.

A. RF Definitions

The RF is a traditional machine learning algorithm consisting of an ensemble of M decision trees, with M defining the forest size. The final output, indicated as $\bar{y}$, is defined as the average of each output y_i of each single decision tree. A sketch is shown in Fig. 7. As a consequence, the variance associated with the output depends on the correlation, indicated as ρ, between decision trees, as described by the following formula:

$$\text{Variance}\,[\bar{y}] = \rho \cdot \text{Variance}\,[y] + (1-\rho) \cdot \frac{\text{Variance}\,[y]}{M}. \tag{10}$$

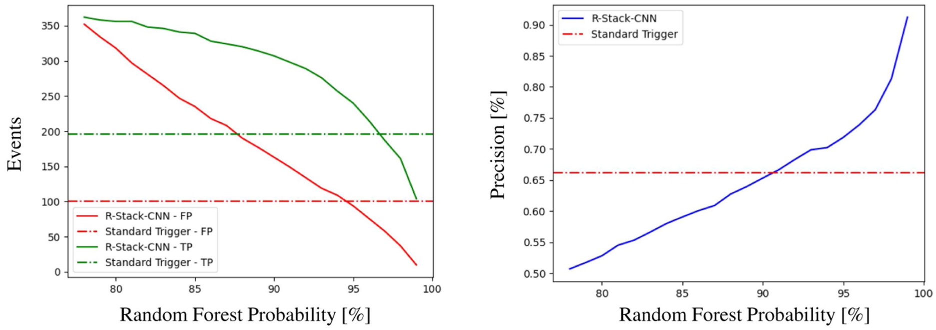

Fig. 10. Number of TPs and FPs on the left figure and precision on the right as a function of increasing RF threshold. Horizontal lines indicate the performance of the standard trigger.

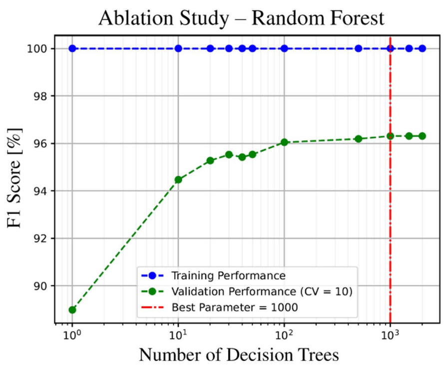

Fig. 11. Visualization of F1 metric computed on training (blue) and validation (green) datasets by iteratively removing decision trees from the RF. The best parameter is shown in red.

Therefore, the main objective of this algorithm is to decrease the correlation ρ, while also increasing the forest size M, so that the averaged variance is better than the single one. The technique is called bagging, it consists on training each decision tree with bootstrap samples, randomly chosen from the training dataset and replaced so that data can be used more than once. Besides, RF also decrease correlation by considering only a fraction of randomly selected features in each split node. The bias-variance tradeoff in RF is reflected by the fact that the chance of underfitting slightly increases because subsamples are smaller than the full dataset. Therefore, it is crucial to train RF with big enough datasets. Another disadvantage is that forests are less easy to visualize and interpret than single decision trees, but they are much more powerful.

We can also define the probability associated with its output as binomial (p_1 is the probability of having prediction equal to 1), with M being the forest size and N_1 the number of decision trees associated with output equal to 1

$$p_1 = \frac{N_1}{M}. \tag{11}$$

In Supplementary Material, we will also provide sensitivity analysis on this parameter, showing how it can deeply affect the performance of the R-Stack-CNN.

Given that our task was a classification task, i.e., time-series binary classification, we used a set of metrics suitable for our goal. In particular, accuracy is the baseline metric used to measure performance for finding positive and negative labels, precision is used to quantify the tradeoff between finding TPs and FPs, recall measures how many positive instances are detected from all the actual positive samples and finally F1 is defined as harmonic mean of precision and recall, giving a more complete and exhaustive view on the model performance. We provide the explicit definitions (TP, FP, TN, and FN)

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \tag{12}$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \tag{13}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \tag{14}$$

$$\text{F1} = \frac{2}{\frac{1}{\text{Precision}} + \frac{1}{\text{Recall}}} = \frac{\text{TP}}{\text{TP} + \frac{\text{FP}+\text{FN}}{2}}. \tag{15}$$

B. Ablation Study

In addition, an ablation study was performed to determine whether removing decision trees during training could drastically reduce the performance. The number of decision trees in the RF has been reduced iteratively from a maximum of 2000 to a minimum of 1, corresponding to a traditional decision tree. For each iteration, the performance has been estimated both in training dataset and validation dataset using the cross-validated F1 score on ten folds.

As can be seen from Fig. 11, the performance reaches a plateau with 1000 decision trees. Training with more iterations would be pointless as the model would preserve the same accuracy at the cost of an higher computational time.

Another study has been performed regarding the probability of the RF algorithm. The default value is set to 50%, meaning that if more than half of the decision trees have outputs 1, the overall output is also 1 (and vice versa). We investigated other possible values, by increasing and decreasing its value and estimating the R-Stack-CNN performance on real data.

The optimal performance of the R-Stack-CNN in session 6 (see Table II) has been achieved by increasing the RF threshold to 78%, meaning that at least 78% of decision trees have outputs 1. The threshold has been set by maximizing the F1 metric, which is

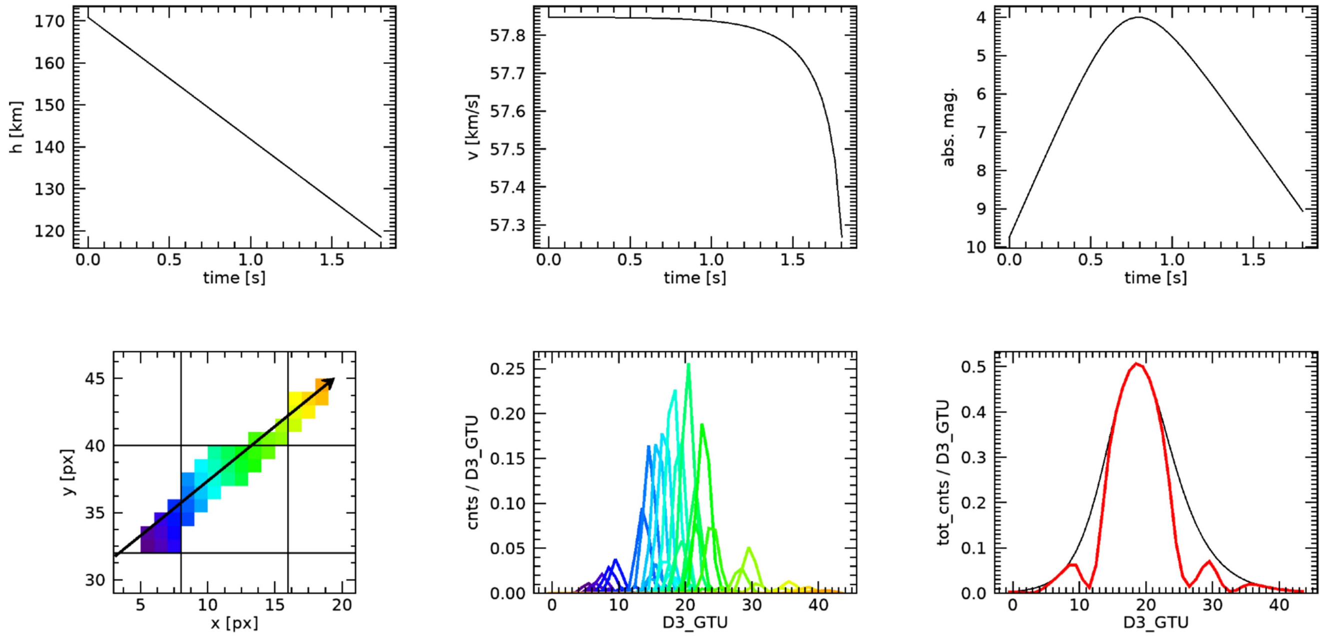

Fig. 12. Example of a simulated meteor event of $\mathcal{M}_{abs} =$ +4. The three plots on the top represent height, meteor speed and absolute magnitude as a function of time. The three plots on the bottom show the pixels hit by the meteor event (left), the respective photon counts per D3 GTUs (center) and the sum of the photon counts per D3 GTU (left), which have been indicated by the red curve. The black curve represents the expected meteor counts on the focal surface in the absence of dead spaces among MAPMTs.

TABLE VI
R-STACK-CNN PERFORMANCE WITH MINI-EUSO DATASET FROM SESSION 14

Model	Total meteors	New meteors
Standard Algorithm	196 (133 M + 63 $M^?$)	0
CNN + MLP	264 (97 M + 167 M?)	68
R-Stack-CNN	276 (192 M + 84 $M^?$)	80

equal at its maximum to 90.7%. The study was completed using session 14 of Mini-EUSO data: the R-Stack-CNN precision was estimated using different values of the RF probability threshold. Table VI and Fig. 10 show that by increasing the threshold more meteors are found with respect to the standard trigger. Using 78% threshold, the model found 193 new meteor candidates than the standard algorithm (115 M + 78 $M^?$) and lost only 27 meteors (10 M + 17 $M^?$) detected by the standard approach. Unfortunately, because of higher background configurations, 352 FPs were also triggered. Thus, an higher RF threshold has been set to eliminate as many FPs as possible and a study has been performed to estimate the optimal threshold: the precision, the number of TPs and the number of FPs were evaluated using increasing RF thresholds. The results in the left panel of Fig. 10 show that there is a strong decrease in the number of the R-Stack-CNN FPs with an increasing RF probability of 95%. On the other hand, the number of the R-Stack-CNN true positives decreases with a weaker slope, causing an increment in the precision as shown in the right panel. The optimal threshold has been set to 93% because with higher thresholds too many meteors would be lost. This setup has been used also to compare our method to another one, developed in parallel in the Mini-EUSO collaboration. This method implements a CNN trained to detect chunks of meteors in the FoV of the detector. Then, the algorithm searches for meteor light curves in meteor chunks and implements a multilayer perceptron (MLP) to classify them. We will refer to it by the acronym CNN + MLP. See [21] for more details. The overall structure is extremely similar to our method, as both algorithms implement CNNs to classify images, and then a light curve classifier is used to suppress FPs. In the alternative method the algorithm is a MLP while in our case it is a RF. A substantial difference, however, is that our CNN was trained on simulated data while in their case on the real data.

The results (see Table VI) show that the R-Stack-CNN was still the most performing method to find new meteor events (95 more meteors M were found). However, the CNN + MLP method was more precise (80% versus 69.9% of R-Stack-CNN). This behavior was probably caused by the different training dataset, which generates fewer FPs as data from Mini-EUSO sessions is more noisy and complex. An improvement of our method would probably fine-tune our CNN using real data, making it more robust to noise.

C. Illustration of a Simulated Meteor

An illustration of a simulated event with a background rate of $\mu_{bkg} = 0.572$ and an absolute magnitude of $\mathcal{M}abs = +4$ can be found in Fig. 12. Henceforth, the magnitudes mentioned are assumed to be positive, although the "+" sign is not explicitly stated. A total of 300 events have been simulated for meteors with absolute magnitudes of $\mathcal{M}abs = 4, 5, 6$ (100 events for each magnitude). Each event has been simulated with a random sampling of background rates, ranging from 0.5 to 1 photon counts per GTU in D1 mode.

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He is currently the Director of OMEGA Microelectronics Laboratory, Ecole Polytechnique CNRS/IN2P3, Palaiseau, France. He has coordinated ATLAS liquid Argon and CALICE electronics. His team has designed and produced many chips for calorimeter and SiPM readout, including PET applications. He contributed to the development of the front-end electronics of the experiments of the JEM-EUSO program.

Toshikazu Ebisuzaki received the Ph.D. degree in astronomy from the Graduate School of Science, University of Tokyo, Tokyo, Japan, in 1986.

He became a Resident Research Associate of National Research Council in USA at Marshall Space Flight Center, NASA. He came back Japan in 1989 and appointed as a Research Assistant of the Graduate School of National Science, Kobe University and Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo. In 1997, he moved to RIKEN and has worked as a Chief Scientist to lead Computational Astrophysics Laboratory until March 2024. He was the Principal investigator of the Japanese Exploratory Missions for the Extreme Universe Space Observatory (JEM-EUSO) collaboration from 2004 to 2010 and the deputy from 2011 to 2017. He has been an honorary Researcher with RIKEN, Tokyo, Japan, since April 1, 2024. He is a coauthor of more than 200 publications of refereed journals in the research field of astronomy, computational science, cosmic-ray physics, plasma physics, planetary science, and evolutional biology with an H index of 44 (Web of Science).

Johannes Eser received the Diploma in physics from the Karlsruhe Institute of Technologies, Karlsruhe, Germany, in 2012, and the Ph.D. degree in applied physics from the Colorado school of Mines, Golden, CO, USA, in 2018.

He is currently a Postdoctoral Fellow with the Astronomy and Astrophysics Department, the University of Chicago, Chicago, IL, USA. During his diploma, he worked on the radio detector of the Pierre Auger Observatory, and his Ph.D. research was within the international collaboration of the Joint Exploratory Missions for an Extreme Universe Observatory (JEM-EUSO). He was mainly involved in the balloon missions. He continues his research on EUSO-SPB2 in a leading role as a Postdoctoral Fellow first at the Colorado School of Mines and then at the University of Chicago. He is co-leading the OffLine working group inside JEM-EUSO and is the Project Manager of a new proposed balloon mission, POEMMA-Balloon with Radio (PBR). His research interests include ultra-high energy cosmic ray and very high energy neutrino science, in particular their detection from space.

Dr. Eser is a Member of international collaborations, such as JEM-EUSO, PBR, TERZINA, and nuSpaceSim.

Francesco Fenu received the bachelor's and master's degree in physics from the University of Trento, Trento, Italy, and the University of Tuebingen, Tübingen, Germany, in 2008, and the Ph.D. degree in physics from the University of Tuebingen, in 2013.

He is a technologist at the Italian Space Agency. During his Ph.D., he was invited as a Researcher with the Computational Astrophysics Laboratory, RIKEN, Tokyo, Japan, for 18 months. He was granted several postdocs at the University of Torino and at the Karlsruhe Institute of Technology, Karlsruhe, Germany, an invited Researcher position at the University of Alcala, Alcalá de Henares, Spain, a fixed-term Researcher position at the INAF Astrophysical Observatory of Torino, Pino Torinese TO, Italy, and a three years researcher position at the University of Pisa, Pisa, Italy. His research interest include cosmic ray science and high energy astrophysics. He currently works at the management of space projects at the Science and Research Directorate of the Italian Space Agency, Rome, Italy.

George Filippatos received the B.S. degree in pysics and astronomy and astrophysics, with a minor in mathematics from the Pennsylvania State University, State College, PA, USA, in 2018, and the Ph.D. degree in physics from Colorado School of Mines, Golden, CO, USA, in 2023.

He is currently a Postdoctoral Scholar with the Department of Astronomy and Astrophysics and an Associate Fellow with the Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL, USA. His research focuses on the study of ultra-high energy cosmic rays as a window into the most energetic environments in the universe.

Dr. Filippatos is a Member of the JEM-EUSO and POEMMA collaborations.

Massimo Alberto Franceschi received a degree in aerospace engineering from the Univ. Rome 'La Sapienza', Rome, Italy, in 1991.

Between 1993 and 1994, he was with Research Division/Collider Detector Department for CDF experiment, Fermi National Accelerator Laboratory, Chicago, IL, USA, for SVX II Silicon Detector mechanical design of whole detector, thermal and structural FEM analysis, mechanical and fluid dynamic design of Be bulkhead, and thermal and fluid dynamics tests; SVX' Silicon Detector Cooling system construction, test, and installation; and detector installation inside CDF experiment. Since 1995, he has been with Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati, Frascati, Italy. His major contributions to INFN particle physics experiments are: CUORE (LNGS) Engineering Coordinator in charge to integrate all the subsystems in an ultra-cold (1 ton detector at 0,01 K) and ultra-pure (radiation) experiment for Neutrino less Double Beta Decay study; in charge of mechanical installations in underground Lab, Experiment Local Coordinator (LNF); OPERA (LNGS) Project Leader of mechanical structure for target support (mass 1700 t, extra target material 0,4%); LNF responsible for target production (Brick Assembly Machine: 200.000 "bricks" in 1.5 years); KLOE (LNF) Responsible Engineer for design, construction, and installation of all the mechanical parts of the experiment; and coordinating roll-in, uplift, and aligning of the whole experiment (mass 1000 t).

Christer Fuglesang received the Ph.D. degree in experimental particle physics from Stockholm University, Stockholm, Sweden, in 1987.

He is currently an Astronaut and a Professor with KTH Royal Institute of Technology, Stockholm, while also working as a part-time Space Advisor for Saab. He has also worked for CERN and ESA. He has made two space shuttle missions to ISS and performed there five EVAs. He is the author of several books for children. His research focuses on particles in space: radiation on ultra-high energy cosmic rays and recently studying the possibility of putting sunshades in space to help control global temperature. He teaches a course in human spaceflight.

Dr. Fuglesang is Member of the Royal Swedish Academies of Science, Engineering Science, and War Sciences. He chairs the Boards for the Swedish National Museum of Science and Technology and Göran Gustafsson Foundation for Research in Natural Sciences and Medicine.

Alessio Golzio received the master's degree in physics from the University of Turin, Turin, Italy, in 2016, and the Ph.D. degree in environmental sciences from the University of Milan, Milan, Italy, in 2020, studying the interconnection between meteorology, climate, glaciers, and plant colonization of extreme mountainous habitat.

He is currently a meteorologist with the Piedmont Environment Protection Agency (ARPA), Turin. He had four years of postdoc contract with the University of Turin, related to the atmospheric physics and coworked with the National Institute of Nuclear Physics (INFN), Rome, Italy, about comic ray science and the interaction with atmosphere and the weather-related phenomena, especially inside the Joint Exploratory Missions for Extreme Universe Space Observatory (JEM-EUSO) Program. He organized field campaigns to investigate the planetary boundary layer, installing micrometeorological stations, devoted to better understand the atmospheric turbulence in mountainous terrain. He has coauthored 28 publications on refereed journals, with an H-index of six (Web of Science). His research interests include the Earth's atmosphere, and meteorology and climatology, especially in the planetary boundary layer over complex terrain, but also all the related disciplines.

Philippe Gorodetzky received the Ph.D. degree in physics from Strasbourg University, Strasbourg, France, in 1972.

He was Attaché Research with the National Center for Scientific Research, Strasbourg, in 1962–1975, Head Research in 1975–1986, and Director Research in 1986–1996, and he was with College France, Paris, France, in 1996. He has been listed as a noteworthy Physicist by Marquis Who's Who.

Dr. Gorodetzky is a Member of the American Physical Society, French Society Physics, and Audio Engineering Society. He is Member of the JEM-EUSO collaboration where he contributed to the development of the different detectors of the program.

Fumiyoshi Kajino received the Ph. D. degree in physics from Osaka City University, Osaka, Japan, in 1982.

He was a Research Associate with the Institute for Cosmic Ray Research, University Tokyo, Tokyo, Japan, and a Research Scientist with Virginia Polytechnic Institute and State University, USA, Blacksburg, VA, USA. He was also a Lecturer, an Associate Professor, and a Professor with Konan University, Kobe, Japan, where he is currently a Professor Emeritus. He is presently leading DIMS (Dark matter and Interstellar Meteoroid Study) project. His research interests include cosmic rays, high-energy particle physics, dark matters, and high-energy astrophysics.

Hiroshi Kasuga received the Ph.D. degree in information engineering from Saitama University, Saitama, Japan, in 2010.

From 2009 to 2023, he was with Technical Staff at RIKEN Advanced Science Institute. He is currently a Technical Scientist with RIKEN Center for Advanced Photonics. He is engaged in a research program about space debris.

Pavel Klimov received the master's degree in physics and the Ph.D. degree in high-energy physics from the Lomonosov Moscow State University, Moscow, Russia, in 2006 and 2009, respectively.

He is currently the Head of Ultra-High-Energy Cosmic Rays Laboratory, Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University (SINP MSU), Moscow. He teaches "Optical methods for observing the atmosphere from space" at the Faculty of Physics, MSU. He is a Member of the JEM-EUSO international collaboration (PI of Russian team of the collaboration) and PI of the TUS experiment on board the Lomonosov satellite. He is PI of Russian Mini-EUSO team and co-designer of the Mini-EUSO detector. He has coauthored about 250 publications on refereed journals, with an H-index of 19 (Web of Science). His research interests include the cosmic ray science, atmospheric science, aurora science and satellite-based scientific equipment development.

Viktoria Kungel received the Ph.D. degree in physics from the Colorado School of Mines, Golden, CO, USA, in 2023.

During her studies, she focused on the "Optics and pre-flight testing of the telescopes of the 'Extreme Universe Space Observatory on a Super Pressure Balloon II' (EUSO-SPB2) payload" as part of the JEM-EUSO collaboration. She led the high-energy laser efforts on the ground aimed attesting optical telescopes for UHECR and cosmogenic neutrinos, and determining atmospheric conditions for calibration.

Vladimir Kuznetsov received the master's degree in engineering from the Moscow State University of Engineering Ecology, Moscow, Russia, in 2003.

He is currently the Head of the department with S.P. Korolev Rocket Space Corporation, Moscow. He has coauthored about ten publications on refereed journals. He is responsible for Mini-EUSO integration on board and data taking during experiment sessions. He has worked on the numerous projects on board the ISS. His research interests include space-based systems and scientific equipment.

Massimiliano Manfrin received the master's degree in physics from the University of Turin, Turin, Italy, in 1997, and the Ph.D. degree in geophysics from the University of Genoa, Genoa, Italy, in 2003.

He is currently a Research Technician with the Physics Department, University of Turin. He had several contracts with the University of Turin, Istituto Fermi, Via Trionfale, Rome, and CSI Piemonte, Torino, Italy, and Environmental and Meteorological Department in Turin between 2002 and the end of 2007. Since 2007, he he has been with Physics Department, University of Turin, as a Research Technician. He also teaches experimental fluid dynamics and computer programming for geophysical applications such as model development. His research interests include the meteorological field through the use and development of models targeted for real time and case studies use and on experimental laboratory fluid dynamics performed in the world's second largest tank.

Laura Marcelli received the master's and Ph.D. degrees in physics from the University of Rome Tor Vergata, Rome, Italy, in 2004 and 2008, respectively.

Since 2016, she has been a Researcher with the National Institute for Nuclear Physics (INFN, Istituto Nazionale di FisicaNucleare), Division of Roma Tor Vergata, Rome. She is currently a Co-Principal Investigator of the Multiwavelenght Imaging New Instrument for the Extreme Universe Space Observatory (Mini-EUSO) experiment, part of the Joint Exploratory Missions for Extreme Universe Space Observatory (JEM-EUSO) program. She has coauthored about 200 publications on refereed journals, with an H-index of 35 (Scopus). Her research focuses on cosmic ray physics taking part in international collaborations, such as PAMELA and JEM-EUSO.

Gabriele Mascetti received the master's degree in mechanical engineering (cum laude) from the University Sapienza, Rome, Italy, in 2000 and second master's degree in space institutions and space law from International Organization Italian Society, Rome, Italy, in 2009.

He is currently the Head of ASI Scientific Coordination Unit, Head of Human Spaceflight Office, Italian delegate to the ESA Human Spaceflight, Microgravity and Exploration Program Board Member, ASI Program Manager for the International Space Station, and an Adjunct Professor for the Master in Space Missions Science, Design, and Application with Bologna University, Bologna, Italy. In 2002, he started his space adventure as Italian Space Agency representative at the NASA Johnson Space Center, Houston, TX, USA. He had previous experiences in big Italian companies in the fields of energy and high-speed trains. He authored or coauthored a guidebook for mountain bike trails in the region he lives in.

Włodzimierz Marszał received the postgraduate degree in electronics/automation from Vocational, Lodz, in 1980. He is currently an Electronics Engineer by education. He specializes in designing and building electronic devices. In 2016, he joined the Cosmic Ray Laboratory of the National Center for Nuclear Research, Lodz, Poland. Within this team, he participated in projects, such as EUSO-TA2, EUSO-SPB, EUSO-SPB2, MINI-EUSO, and the Baltic Sea Underground Innovation Network (BSUIN).

Marco Mignone received the Technical and Industrial High School Degree in electronics from the Istituto Tecnico Industriale Statale VIII of Torino, Turin, Italy, in 1991.

In 2001, he joined the Istituto Nazionale di Fisica Nucleare (INFN), Turin, where he is currently a Group Member of Technical Staff in Electronics Laboratory. His research focuses on the R&D of front-end electronics for nuclear physics experiments.

Hiroko Miyamoto received the Ph.D. degree in physics from Chiba University, Chiba, Japan, in 2007.

She is currently a Research Technician with Physics Department, University of Turin, Turin, Italy. At Chiba University, she worked on the simulation for extreme high energy (EHE) neutrino search and the hardware development, namely, 10-inch photomultiplier tubes (PMT) and the relevant detection and calibration system for the IceCube experiment located at the South Pole. Thereafter, she joined Max-Planck-Institute, Munich, Germany, as a Postdoctoral Researcher, where she worked on the development and application of Silicon Photomultipliers (SiPMs) for Astroparticle Physics (APP) experiments, such as MAGIC, MAGIC II, CTA, and Joint Exploratory Missions for Extreme Universe Space Observatory (JEM-EUSO). She had several postdoctoral contracts successively with RIKEN, Tokyo, Japan, LAL/University Paris-Sud XI/CNRS, Paris, France, University of Turin, Turin, Gran Sasso Science Institute, Italy, where she continued her research on the SiPM application in APP and in biomolecular science, worked on the development of front-end electronics and the simulations of Extreme Energy Cosmic Rays (EECR), meteor and space debris events for JEM-EUSO experiments, and applications of those techniques for the future space experiments, such as POEMMA and NUSES. Her research interests include developing and improving the photo-detection system for the ground, and balloon and future space experiments in view of UHECR and atmospheric Cherenkov detection. She is also interested in wide application of the technologies in other fields.

Alexey Murashov received the master's degree in radiophysics from the 'Moscow Power Engineering Institute, National Research University, Moscow, Russia, in 2010.

He is currently a Leading Engineer of Ultra-High-Energy Cosmic Rays Laboratory, Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University (SINP MSU), Moscow. He took part in several space-based projects: Mini-EUSO (on board the ISS), cubesats VDNH-80, DECART, and SATURN. He has coauthored about 30 publications on refereed journals. He is a co-designer of the Mini-EUSO detector. His research interests include space-based systems and scientific equipments.

Tommaso Napolitano received the master's degree in mechanical engineering from the University of Roma Tor Vergata, Rome, Italy, in 2003.

He is currently a technologist with the National Laboratory of Frascati, National Institute of Nuclear Physics (INFN), Rome. He contributed to the design and production of the mechanical structure of the Mini-EUSO experiment. His research interests include the design, production control, and installation of mechanical parts of numerous experiments of nuclear physics, and OPERA and CUORE experiments.

Hitoshi Ohmori received the graduation degree in optical engineering from the University of Tokyo, Tokyo, Japan, in 1986, and the Ph.D. degree in engineering from University of Tokyo, in 1991.

During his student hood, he invented the ELID method, which has been widely used for ultra/nanoprecision machining. He also has conducted various kinds of research and development on ultra/nanoprecision machining for optics and critical components for scientific and industrial demands. Combined processes with ELID-grinding, polishing, and surface modification have been proposed through his research activities, and have been applied to produce extremely high precision mirrors for X-ray laser reflectors and also for bio-implants. In his recent research topics, microfabrication and ultrafabrication for micro- to macro-sized machining with functional surface structures at a nanometric surface precision are being conducted to realize space observatories and solar collectors, and succeeded in manufacturing large Fresnel lenses more than 1m in diameter. He proposed "Picoprecision Technology" for the future manufacturing and has launched to develop its process and machine tool.

Angela Olinto received the B.S. degree in physics from the Pontifícia Universidade Católica, Rio de Janeiro, Brazil, in 1981, and the Ph.D. degree in physics from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 1987.

She was the Albert A. Michelson Distinguished Service Professor with the Department of Astronomy and Astrophysics, Kavli Institute for Cosmological Physics, and the Enrico Fermi Institute, University of Chicago, until February 2024. She was the Dean of the Division of the Physical Sciences from 2018 to 2024 and the Chair of the Department of Astronomy and Astrophysics from 2003 to 2006 and again from 2012 to 2017. She is currently a Provost, Professor of astronomy and astrophysics, and Professor of Physics with Columbia University, New York, NY, USA. She is best known for her contributions to the study of neutron stars, inflationary theory, cosmic magnetic fields, and the origin of the highest energy cosmic rays and neutrinos. She leads the POEMMA space mission concept and balloon payload, the EUSO on a super pressure balloon (SPB) two missions, and was a Member of the Pierre Auger Observatory.

Dr. Olinto is a Member of the National Academy of Sciences, the American Academy of Arts and Sciences, and of the Brazilian Academy of Sciences.

Étienne Parizot received the Ph.D. degree in theoretical gamma-ray astronomy from Service d'Astrophysique of CEA, Saclay, France, in 1997, and the Habilitation à Diriger des Recherches (HDR) in high-energy astrophysics in 2005.

After the Ph.D. degree, he obtained a European postdoctoral fellowship and worked at the Dublin Institute for Advanced Studies, Dublin, Ireland, on particle acceleration and spallative nucleosynthesis. He obtained a permanent position of Chargé de Recherche 1ère Classe with CNRS, Paris, in 2000, at the Institut de Physique Nucléaire d'Orsay, Orsay, France, and became a Member of the international Pierre Auger Collaboration to study Ultra-High-Energy Cosmic Ray (UHECRs). In 2006, he left CNRS to become a Full Professor with the Université Paris Diderot (now UPC). In 2010, he became a Member and the French National P.I. of the international Joint Exploratory Missions towards an Extreme Universe Space Observatory (JEM-EUSO) Collaboration to study UHECRs from space, of which he is currently the spokesperson. He is currently a Full Professor with Physics Department, Université Paris Cité (UPC), Paris, France, and a Member of the Astroparticle and Cosmology (APC) Laboratory, Paris. In this framework, he took part in several scientific balloon and space missions.

Piergiorgio Picozza received the degree in physics from the University of Rome 'La Sapienza', Rome, Italy, in 1964.

He is currently a Professor Emeritus with the University of Rome "Tor Vergata," Rome, Italy, and a Researcher Emeritus with INFN, Rome. For many years, his research in space focuses on stratospheric Balloons, satellites, and space stations, among them NINA, PAMELA, and JEM-EUSO. He is currently a Principal Investigator with the CSES-Limadou space mission, performed in collaboration with the Chinese Space Agency for the study of magnetosphere phenomena possibly connected with terrestrial catastrophic events. He is the author of more 600 articles published in the major international scientific journals. His research interests include the study of cosmic rays at low, medium, and ultra-high energy, indirect search of dark matter signals, energy gamma radiation, solar events, and a program of life science inside the MIR and ISS space stations.

Lech Wiktor Piotrowski received the master's degree in physics and the Ph.D. degree in particle physics from the University of Warsaw, Warsaw, Poland, in 2005 and 2011, respectively.

He is currently an Assistant Professor with the Department of Physics, University of Warsaw. He had several Postdoc positions with the Japanese Society for Promotion of Science, the Physics Department, Colorado School of Mines, Golden, CO, USA, and the Computational Astrophysics Laboratory of RIKEN, Tokyo, Japan. His research focuses mainly on experimental cosmic ray physics and transient phenomena in the sky and the atmosphere, realized through participation in international collaborations, such as JEM-EUSO, DIMS and GRAND.

Dr. Piotrowski is currently serving the role of the Software Coordinator and the Chair of the Membership Committee in the GRAND collaboration.

Zbigniew Plebaniak received the master's degree in applied physics from the Technical University of Łódź, Łódź, Poland, in 2011, and the Ph.D. degree in physics, with a focus on the modeling of ultra-high-energy cosmic ray interactions, from the National Centre for Nuclear Research, Otwock, Poland, in 2019.

Since 2013 and 2023, he has been respectively a Member and the P.I. of the Polish group in the JEM-EUSO Collaboration. Since 2014, he has been working on hardware and data analysis within the JEM-EUSO Collaboration. He was a Postdoctoral Researcher with the University of Turin, Turin, Italy, during 2020–2021, and has been a Postdoctoral Researcher with University of Tor Vergata, Rome, Italy, since 2023. His research interests include atmospheric physics and astrophysics, with a focus on cosmic ray physics.

Guillaume Prévôt received the master's degree in physics from the University of Evry, Evry, France, in 2004 and diploma degree in engineering from the Institut d'Optique Graduate School, Saclay, France, in 2007.

He is currently the Technical Director of the Laboratory of Astroparticle and Cosmology (APC), University Paris Cité, Paris, France. He participated to the development of the TARANIS, JEM-EUSO, and ASTRO-H space projects. For the JEM-EUSO program, he had the role of Project Manager of the EUSO-Balloon mission. He had a leading role in the development and assembly of the focal surface of the experiments of the JEM-EUSO program, including Mini-EUSO.

Enzo Reali received the Diploma at Industrial Technical High School for Nuclear Energy "E. Fermi" in Frascati, Italy, in 1979.

From 1983 to 1984, he was with InterLab, Ltd., as a Technical Assistant for electro-medical and scientific equipment. From 1984 to January 1991, he was with De Sistis as Electronic Technician. In the last two years, he had the responsibility of the Head of the R&D Electronics Department in the professional and artistic lighting field. Since February 1991, he has been with the Electronic Service of the Department of Physics, University of Rome Tor Vergata/INFN, Rome, Italy, initially as a Technical Assistant and currently as Technical Officer in the technical-scientific and data processing area. Since 1991, he has been involved in several experiments, performing work of electronic design, selection and procurement of components, characterization and market research. He is a coauthor of more than 50 publications of refereed journals with the h index of 16.

Marco Ricci received the master's degree in experimental physics from the University of Rome "La Sapienza," Rome, Italy, in 1985.

He was a Postdoc Fellow in experimental physics with CERN, Geneva, Switzerland, in 1986–1987 and a Postdoc Researcher with Frascati Laboratories, National Institute of Nuclear Physics (INFN) in 1988–1989. He became a Staff Researcher with INFN Frascati Laboratories in 1989, then Senior Researcher in 2002. He is currently a Senior Staff Researcher (Retired) with the Laboratories of Frascati, National Institute of Nuclear Physics (INFN), Rome. His main activity and scientific interests are related to the field of astroparticle physics and cosmic rays and experimental techniques in space, carried out with experiments placed on board Stratospheric Balloons, small- and large-size satellites and on the International Space Station, in the frame of international collaborations, such as WIZARD, PAMELA, Joint Exploratory Missions for Extreme Universe Space Observatory (JEM-EUSO), CSES-Limadou and the planned Probe of Extreme Multi Messenger Astrophysics (POEMMA). He has led the local groups of the INFN Frascati Laboratories in the abovementioned experiments and has hold the role of INFN National P.I. of the JEM-EUSO Italian Collaboration from 2013 to 2021. He is currently a Senior Staff Researcher (Retired) with the Laboratories of Frascati, INFN. He is the JEM-EUSO Country representative for the Italian Collaboration. He has coauthored about 300 publications on referred journals, with an H-index of 40 (Web Science).

Dr. Ricci is the Deputy Chairman of the JEM-EUSO Publication and Conference Committee.

Giulia Romoli is currently working toward the Ph.D. degree in physics with Physics Department, University of Rome Tor Vergata, Rome, Italy.

Her doctoral thesis focuses on the analysis of data from two detectors currently operating on board the International Space Station. The goal is to characterize the cosmic radiation environment inside the station by analyzing data acquired by the LIDAL particle detector, and to study an atmospheric phenomenon known as Emission of Light and Very Low Frequency perturbations due to Electromagnetic pulse Sources (ELVES) through the analysis of images acquired by the Mini-EUSO telescope. Her research interests include astrophysics, space science, and the study of Earth's atmosphere.

Naoto Sakaki received the Ph.D. degree in physics from the University of Tokyo, Tokyo, Japan, in 2003.

He was a Scientific Research Fellow with RIKEN, Tokyo, the University of Tokyo, and Karlsruhe Institute of Technology, Karlsruhe, Germany, and as an Assistant Professor with Aoyama Gakuin University, Tokyo, and Osaka City University, Osaka. He has more than 100 authored or coauthored publications. His research interests include the origin of cosmic rays at the high-energy end by observation on ground and from outer space, particle physics, and atmospheric and oceanic science.

Sergei Sharakin received the master's degree in physics and the Ph.D. degree in theoretical physics from Lomonosov Moscow State University (LMSU), Moscow, Russia in 1997 and 2000, respectively.

He is currently a Senior Researcher with the Skobeltsyn Institute of Nuclear Physics, LMSU. He is currently a Member of the Joint Exploratory Missions for Extreme Universe Space Observatory (JEM-EUSO) Program. He has coauthored about 130 publications on refereed journals, with an H-index of 12 (Web of Science). His research interests include the domain of cosmic ray science, physics of atmosphere, and data analysis.

Kenji Shinozaki received the Ph.D. degree in physics from the Saitama University, Saitama, Japan, in 2002.

Since 2020, he has been conducting research with Astrophysics Division, National Centre for Nuclear Research, Warsaw, Poland. His primary focus is on the experimental aspect of ultra-high energy cosmic ray physics. Beginning with his postgraduate study, he has been dedicated to ground-based air shower experiments, such as AGASA and Telescope Array. As a Postdoctoral Researcher in Japan, Germany, and Italy, he also actively participated in planned space-based experiments for air shower observation through the JEM-EUSO mission. His expertise include data analysis and simulations of air showers to uncover the chemical composition of cosmic rays. His research interests include very high-energy gamma-ray astronomy using the MAGIC telescope, studying hadronic interactions through air shower experiments on Mt. Chacaltaya, and recently searching for heavy dark matter as well as conducting meteor astronomy with the DIMS experiment at the Telescope Array site.

Jacek Szabelski received the Ph.D. degree in physics from the Faculty of Physics, University of Warsaw, Warsaw, Poland, in 1985.

For about 25 years, he has been the Head of the Cosmic Ray Laboratory of the National Center for Nuclear Research, Łódź, Poland. In 2008–2023, he was PI of the Polish group in the JEM-EUSO experiment. He contributed to hardware of two space experiments (POLAR and Mini-EUSO) and two stratospheric balloon experiments as well as to data analysis. He also participated in natural radioactive background measurements in underground laboratories as well as in data analysis. He is currently with the Stefan Batory Academy of Applied Sciences, Skierniewice, Poland. His research focuses on cosmic ray studies.

Yoshiyuki Takizawa received the master's degree in physics from the Gakushuin University, Tokyo, Japan, in 1995, and the Ph.D. degree in Earth and planetary science from the University of Tokyo, Tokyo, in 2003.

From 1998 to 2001, he became a Special Postdoctoral Researcher with RIKEN, where he was a Postdoc from 2001 to 2003 and became a Researcher of the Computational Astrophysics Laborator from 2003 to 2010. Since 2008, he has been a part-time Lecturer with the Faculty of Engineering, Saitama University, Saitama, Japan. In 2010, he became a Senior Researcher of RIKEN. Since 2018, he has been with Ultrahigh Precision Optics Technology Team of RIKEN. He is currently a Senior Researcher with RIKEN, Tokyo. He is also Japan spokesperson of the Joint Exploratory Missions toward an Extreme Universe Space Observatory (JEM-EUSO) Program. His research interests include the domain of cosmic ray science and its optical instrument development, such as telescopes of Mini-EUSO, EUSO-TA, EUSO-Balloon, EUSO-SPB, K-EUSO, EUSO-SPB2, and PBR.

Valerio Vagelli received the Ph.D. degree in physics from the Karlsruhe Institute of Technology, Karlsruhe, Germany, in 2014.

Since 2019, he has been a staff Researcher with ASI, where he pursues technological R&D for space-based particle detectors and contributes as ASI Program Manager and ASI Project Scientist to the programmatic and scientific contribution of Italian research institutes and universities to cosmic ray space missions, such as, e.g., AMS-02, HERD, EUSO-SPB2, and Mini-EUSO. He is currently a Staff Researcher with the Italian Space Agency (ASI), Rome, Italy. His Ph.D. thesis was on experimental astroparticle physics based on the analysis of the AMS-02 experiment onboard the International Space Station. His research activity at KIT, INFN, University of Perugia, and ASI has been contributing to experimental astroparticle physics research, focused on searches for new physics in space, ranging from technological developments to scientific data analysis for ground- and space-based experiments for measurement of cosmic rays, such as, e.g., AMS-02, DAMPE, CTA, HERD. He has coauthored about 90 publications on refereed journals, with an H-index of 30 as of 2024 (Web of Science).

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