

Autonomous image coverage and sharpness detection for hyperspectral data download prioritization – solution for the ASPECT payload of the Milani CubeSat (AIDA/ Hera mission)

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Introduction Hera [1] is the European part of the Asteroid Impact & Deflection Assessment (AIDA) project with NASA who is responsible for the DART (Double Asteroid Redirection Test) kinetic impactor spacecraft impacting Didymos/Dimorphos binary asteroid in January 2022. Hera will be launched in October 2024 and will arrive at Didymos in 2027. Milani 6U CubeSat [2] will be carried by Hera and is developed by a Czech-Finnish-Italian consortium. Milani has two payloads – ASPECT hyperspectral imager and VISTA thermogravimeter and aims to characterize surface and environment surrounding Didymos with special focus to map DART impact site from distance of 10 km down to 5 km.

ASPECT hyperspectral imager ASPECT is a hyperspectral imaging spectrometer [3] developed by VTT Technical Research Centre of Finland. Its key component is a tunable Fabry-Pérot Interferometer (FPI). ASPECT has spectral range from 500 nm up to 2500 nm divided into 4 measurement channels. VIS and NIR1/2 channels have imaging capability, while the SWIR channel is a single point spectrometer. Fe²⁺ absorptions, in dry silicates at ~1 and ~2 µm, Fe³⁺ absorption in hydrated silicates at ~0.7 µm, OH⁻ absorption at ~1.4 µm, and H₂O absorption at ~1.9 µm are all found within the ASPECT spectral range.

ASPECT imaging strategy and on-board algorithms for image quality detection A dedicated DPU (Data Processing Unit) based on Xiphos Q7S is integrated with ASPECT and is used to (1) autonomously execute pre-programmed hyperspectral data capture sequences, (2) reconstruct hyperspectral images from the raw data stream and store them in internal memory, (3) run set of pre-programmed algorithms to autonomously evaluate coverage and sharpness of the hyperspectral data cubes in order to select highest-quality data cubes for download to ground, and (4) compress downloaded data using lossless or near-lossless JPEG2000 compression. These features enable ASPECT imaging strategy based on performing multiple hyperspectral data cube acquisitions of each scene (target asteroid orientation) and downloading only the highest-quality data meeting criteria on coverage and sharpness. The DPU algorithms contain build-in flexible configuration settings to modify or bypass features through ground commanding. This enables in-flight algorithm configuration optimization based on actual target appearance (e.g., albedo variations, surface features) and ASPECT imager performance (e.g., noise levels, exposure time).

Algorithm architecture The image quality detection algorithm architecture is depicted in Fig. 1 and consists from four main blocks: **(1)** Global pixel statistics for global coverage evaluation, **(2)** Areal pixel statistics for coverage evaluation of individual objects (Didymos D1 vs. Dimorphos D2), **(3)** Laplacian filter convolution for sharpness detection, and **(4)** Artificial Intelligence (AI) experimental code for coverage and sharpness scoring. On input side single image from each datacube (at 500 nm, reconstructed from VIS channel RGB sensor green pixels) is extracted for quality check. This selection was based on the expected ASPECT high signal-to-noise ratio in this spectral region. Optional Gaussian convolution filter can be activated to remove noise. This step is important for proper coverage evaluation of images with substantial noise (where noise can confuse pixels statistics) but is skipped for sharpness evaluation (as Gaussian filter convolution intrinsically softens image boundaries). On output side, the individual coverage, sharpness, and AI scores are combined by decision logic as outlined in Fig. 1 and decision on data download is made. In the case the required object coverage was reached, the data cube with the highest Image Quality Score (IQS) and AI score is downloaded together with metadata. In the case the required object coverage was not reached, only metadata with image thumbnails are downloaded for detailed analysis on ground. The metadata contain information on pixel statistics thresholds as well as compressed Laplacian histograms and as option compressed evaluation image thumbnails. This enables to monitor the algorithm behavior on ground and adjust algorithm settings by commanding.

Pixel statistics For object coverage detection, thresholding is used to select proper part of image containing asteroids. To get proper threshold, we use weighted sum of two different algorithms joined by optional fixed threshold settings (relative or absolute). Apart from the standard Otsu thresholding algorithm [4] we developed one specific for bright asteroid(s) on black sky background based on the histogram shape. We can check either global pixel coverage without object detection or use different mode with exact object (D1 or D2) detection based on area selection using criteria like object size, shape, relative

position of binary components, or pixel density. Final coverage is normalized to (0,1) interval and compared to predefined minimum required asteroid coverage to check if desired coverage was achieved.

Laplacian filter convolution For sharpness detection, Laplacian filter convolution as a proxy to image second derivative provides reliable results because it is sensitive to sharp contrast boundaries within the image. Images with sharp boundaries have wider Laplacian histogram with higher maximal Laplacian values compared to smeared images where the histogram width and maximal Laplacian values are relatively reduced. Thus, the highest Laplacian values are used as an indicator of relative sharpness within an image series. The output is normalized into relative sharpness score in the range of (0,1).

AI experimental algorithm Two multi-label Convolutional Neural Networks (CNNs) have been created and trained, one for ranking images according to their coverage, and another according to their sharpness. The input images are reduced to 128x128 pixels to save DPU resources and then passed through three consecutive convolutional layers ending with a dense layer that outputs the selected label and its confidence value. The training sets consist of many synthetic images of the Didymos/Dimorphos system, created with a custom Python/Blender pipeline, with variations in coverage and sharpness added in post-processing. These training images have been manually labeled into one of four categories (“None”, “Low”, “Medium”, and “High”) for both coverage and sharpness. The trained networks are then able to process new images and choose the appropriate coverage and sharpness labels as values from 1 to 4.

Ground commanding and metadata content To tune the behavior of the whole image scoring pipeline in flight, we use several input parameters to either change basic building block behavior and/or to modify how elementary results are used in upper levels to produce final IQS. To monitor the image scoring we produce output metadata containing partial results to monitor each building block separately. Examples of input parameters and output metadata are:

Input parameters	Output metadata
<ul style="list-style-type: none"> Thresholding weights Image border size Sharpness and coverage weights for final IQS Enable/disable noise filtering for coverage tests Coverage detection mode (All, D1, D2, D1+D2) Required minimum asteroid coverage 	<ul style="list-style-type: none"> Compressed Laplacian histogram Partial threshold values, final threshold used Coverage statistics (coverage, border) Sharpness result (Laplacian histogram max.) Normalized coverage and sharpness Neural Network sharpness and coverage results

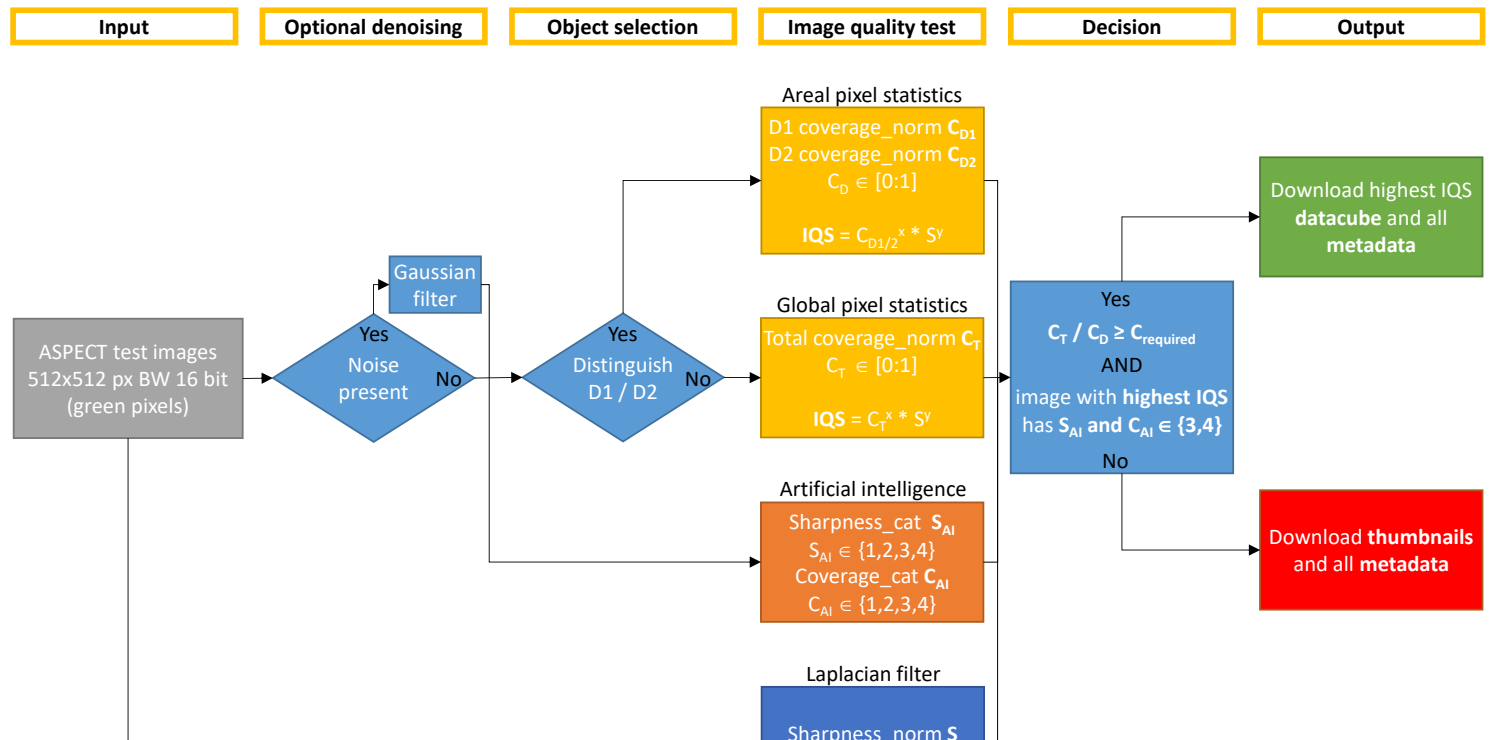


Fig. 1. On-board image quality detection algorithm architecture.