A Feasibility study of On-Board Data Compression for Infrared Cameras of Space Observatories*

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Abstract

In this paper, the feasibility of on-board data reduction/compression concept described in [1] is evaluated for infrared images taken from space observatories. The method described in [1], which was initially designed and developed for the PACS (Photodetector Array Camera and Spectrometer) instrument [10], makes use of on-board integration to achieve higher compression ratio (CR) for applications with modest telemetry rate. The evaluation of the reduction concept takes into account the visual performance (distortion) and the compression ratio. The distortion is assessed by calculating the reconstruction error using 4 metrics, namely, Root Mean Square Error (RMSE), Signal-to-Noise-Ratio (SNR), Peak-Signal-to-Noise-Ratio (PSNR) and Potential Information Loss (PIL). A quantitative evaluation of the on-board compression concept is performed on data from the infrared camera ISOCAM (Infrared Space Observatory CAMera). We conclude with a short summary.

1. Introduction

Data collected on-board space observatories (e.g. for infrared astronomy) impose enormous storage and bandwidth requirements for downlink, regarding the continuous observation and the high readout rates [4, 8]. Infrared detectors consist, as a rule, of fewer pixels than those for the visual range, but the design of multi-sensor instruments leads to even higher data volumes. If multiple detectors are operated in parallel to support multi-spectral or even hyper-spectral imaging, then, the data volumes multiply [4, 6, 11].

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Indeed, the classical data compression [9], transmission and processing technique is becoming inadequate for airborne or spaceborne missions, where the information rate largely exceeds channel capacity and high compression ratio is mandatory to fulfil the transmission requirements. In addition to that, the detectors are continuously exposed to high energy cosmic particles inducing a disturbance (glitches) of the readout voltage which decrease the signal-to-noise-ratio and hence the capability to achieve the required compression ratio even with the most powerful compression algorithms. For these reasons, a viable alternative is to use on-board data compression [1, 2], i.e. making the on-board sensor intelligent, and hence capable for interpreting the collected data.

It is to be noted that the requirements for the compression algorithm are governed by the limited resources on-board the spacecraft in such a way that the necessary compression hardware should be as simple as possible on-board. Furthermore, the spacecraft used for Deep Space missions are characterised by being restricted to low budget and consequently low data rate [9]. These make the compression tasks very challenging.

The on-board data reduction/compression concept presented in [1] deals with the removal of the redundancies in the data representing the signal. This redundancy is mainly caused by:

- the source information and its quality (noisy or not)
- the sampling rate
- the number of quantisation levels

Furthermore, the new concept, listed above, makes use of an on-board data reduction, by an integration over an adequate number of readouts, to offer a high compression ratio at a minimal data loss. This reduction makes the widespread distribution of digital image possible at the cost of introduction of artifacts. To control the introduction of potentially visible artifacts, a proper automated quality evaluation method is needed. Based on its simplicity, pixel-based Root Mean Square Error (RMSE) or its derivatives (Signal-to-Noise-Ratio (SNR) or Peak-Signal-to-Noise-Ratio (PSNR)) is dominant metric in practice [1, 12]. However, RMSE does not take into account the spatial property of human's visual perception that is the reason why it fails under many circumstances.To control the visual artifacts associated with lossy compression, a proper image quality evaluation metric is necessary. In this paper, we developed a statistics-based evaluation metric, Potential Information Loss (PIL), that exploits the property of visual perception. We are concerned with the imposing trade-off between parsimony and accuracy to assess the limitation of the on-board compression concept to achieve a high compression ratio for a given quality.

This paper is structured as follows: In Section 2, we present the evaluations criteria of the feasibility of the reduction/compression concept. In Section 3, the reduction/compression is summarized while compression performances are listed. Experimental results of the evaluation are given in Section 4. We conclude with a short summary.

2 Objective

The aim of this work is the evaluation of on-board compression concept on infrared data, showing the compression limit for a given image quality. Image distortion is evaluated by calculating the reconstruction error according to the following criteria:

- **RMSE:** Root Mean Square Error (see [1])
- **SNR:** Signal-to-Noise Ratio (see [1])
- **PSNR:** Peak Signal-to-Noise Ratio (see [1])
- **PIL** Potential Information Loss:

$$\mathrm{PIL} = 1 - \frac{\mathrm{PDF}(S_R(x))}{\mathrm{PDF}(S(x))} \tag{1}$$

where S is the original data, S_R is the reconstructed data and PDF is the Probability Density Function.

PIL is a new metric served for the evaluation of quality of the reconstructed image. This metric uses the assumption that an astronomical object in an image has a profile which is closer to a Gaussian curve [7]. Therefore, the peak of the curve is used as reference for the evaluation of the information loss.

The histogram (Figure 1) of the original and reconstructed images are used for the calculation of PIL by means of the difference between both histograms i.e. by computing the sum of the relative differences between all graylevel counts. We evaluate the compression method on several ISOCAM images [3] taken for objects in different wavelengths (see Figure 1). The representation of the object in these images depends on the wavelength chosen.

3 Signal Description

Infrared signal in astronomy consists of a combination of the telescope bias and the source signal. The goal is to transmit the source signal with a minimum data loss. Therefore, we make use of the redundancy of the data introduced by the telescope bias to achieve a high compression ratio.

The signal resolution of ISOCAM is 16 bits. The specification of the number of noise bits, in which the offset signal is coded, depends on the Signal-to-Noise-Ratio (SNR) of the telescope at specific wavelength ranges. Experiments have been made to assess the image quality, according to the criteria listed in Section 2, for several signal resolution.

The ISOCAM instrument on board the Infrared Space Observatory (ISO) was designed to map selected areas of the sky in the spectral region from 2.5 to 18 μm at various spatial and spectral resolutions. It contains two 32 x 32 pixels infrared detector array for short and long wavelength channel. Three ISOCAM images are used for the evaluation and are taken from the ISO database on [13]. Figure 1 depicts the three images (on the top) and their respective histograms (on the bottom). The histograms (counts in Y-axis) are computed respective to the graylevels (X-axis) in the images. Three different distributions of the data from compact to wide distribution – noticed in the X-axis where the range of the image graylevels is depicted – are chosen for the test, which lead to more constraints on the compression performance. The black column in the images of Figure 1 represents the dead pixels (detectors lost in flight).

4 Strategy and Realisation

4.1 Summary of on-board Reduction Concept

The data compression concept described in [1] consists of lossy and lossless compression modules:

• **Feature selection:** performs the data selection; for instance, to select only pixels are of interests e.g. non-defect pixels, pixels representing the object of interest, etc.

• **Glitch detection:** detects glitches to prevent the distortion of the relevant scientific data.

• **Averaging/Fitting module:** performs an averaging in photometry and ramp fitting in spectroscopy over a well defined number of samples for a reduction of the data.

• **Integration module:** integrates over successive averages/ramp fitting to allow additional compression ratio.

• **Redundancy reduction:** reduction of the signal amplitude by subtracting the offset signal (bias); in this case, the temporal (redundancy regarding the time) and spatial (redundancy between neighbouring pixels' data) redundancy reduction are used.

• **Lossless entropy coding:** as backend lossless compression the arithmetic coding [5] is used.

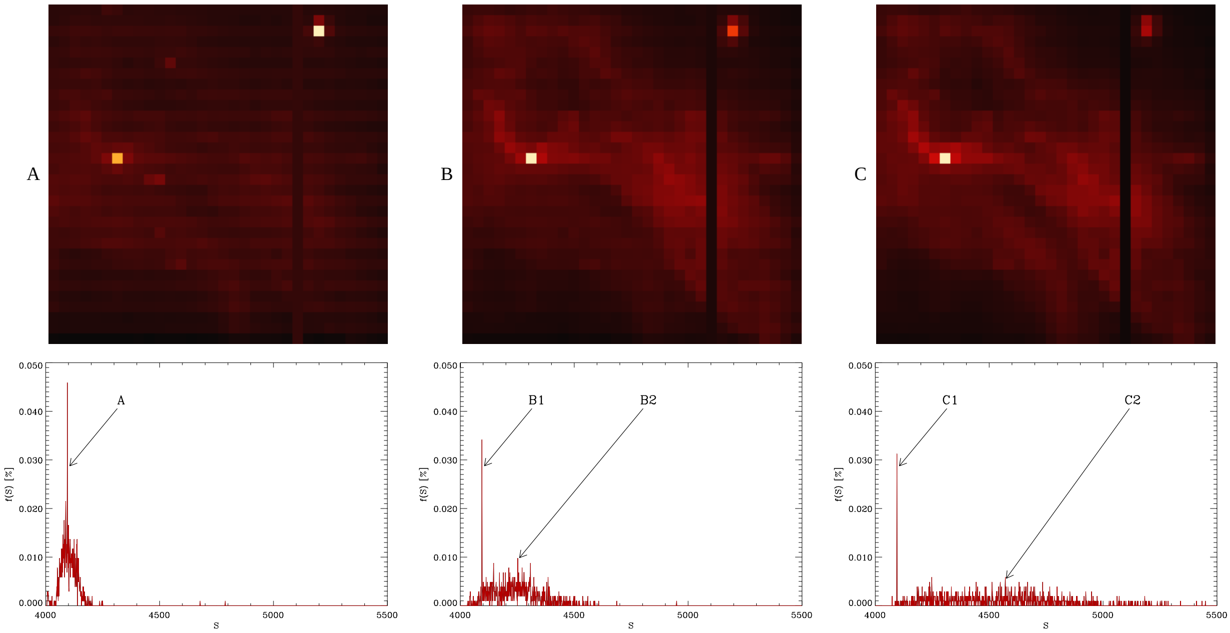

Figure 1. ISOCAM image and corresponding PDF in different Spectral Bands A, B and C.

The lossy part comprises items 1 to 4 and items 5 and 6 are the lossless part. More details on these modules can be found in [1, 2].

4.2 Compression Performance

We assume that a compression ratio of 4 is achieved by the averaging module while an additional ratio is achieved by the lossless entropy codecs (CR_{LLC}). Therefore, the total compression ratio can be calculated as follows:

$$CR_{tot} = 4\, CR_{LLC} \frac{n_{det}\ 16\text{bits}}{n_{ref}\ 15\text{bits} + n_{kept\_bits}\ n_{sel}} \quad (2)$$

where n_{ref} is the number of references taken and n_{kept_bits} is the number of bits/samples kept after quantization.

5 Experimental Results

In this paper, we are concerned with the lossy compression effects on the visual quality on the obtained images. Integration over 4 images and reduction of the signal resolution to 5 quantisation levels are evaluated for three ISOCAM images (see Table 1). The images quality is evaluated by calculating PIL, RMSE, SNR and PSNR. The achieved CR for all used quantisation levels is also given. Image A shows a very compact information due to the dense distribution of the data around the value 4100. Therefore, the PIL $< 0.6\%$ for a high CR of 40. Image B shows a wider distribution of the data than those in Image A, therefore, two reference peaks (B1, B2) have been used for compression. One

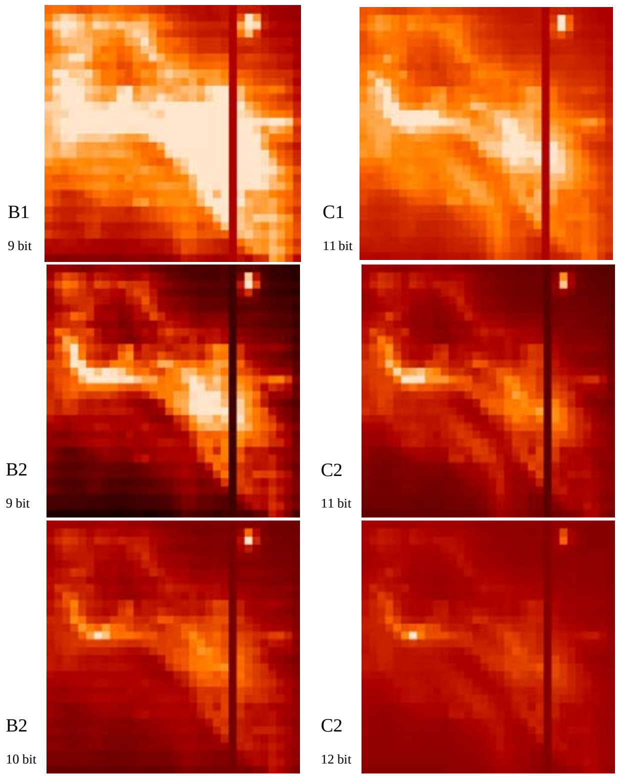

Figure 2. Reconstructed Images for different Reference Values and Number of Bits Kept.

Data Set	n_{kept_bits}	CR_{rr}	PIL in [%]	RMSE	SNR	PSNR
Image A	8	40.0	0.5859	22.7155	45.1347	0.6347
Reference A	9	35.4	0.1953	17.0563	47.6235	3.1235
	10	32.0	0.1953	6.0759	56.5890	12.0890
	11	29.0	0.0000	0.0000	Inf	Inf
	12	26.6	0.0000	0.0000	Inf	Inf
Image B	8	48.0	55.8594	107.634	31.9269	-7.2492
Reference B1	9	35.4	16.7969	57.9813	37.3001	-1.8759
	10	25.6	0.2939	30.7739	42.8022	3.6262
	11	23.2	0.0977	12.7500	50.4557	11.2796
	12	21.3	0.0000	0.0000	Inf	Inf
Image B	8	40.0	28.4180	53.4604	38.0052	-1.1708
Reference B2	9	28.3	2.1484	35.8143	41.4847	2.3087
	10	24.9	0.1953	24.5346	44.7703	5.5942
	11	22.6	0.0977	7.8438	54.6754	15.4993
	12	21.3	0.0000	0.0000	Inf	Inf
Image C	8	85.0	86.9141	422.271	20.6389	-12.2052
Reference C1	9	56.6	71.1914	330.418	22.7695	-10.0746
	10	32.0	38.0859	189.394	27.6034	- 5.2406
	11	22.0	3.1250	80.4544	35.0398	2.1957
	12	20.1	0.0977	38.9375	41.3434	8.4993
Image C	8	48.0	64.0625	199.731	27.1419	- 5.7022
Reference C2	9	35.4	37.4023	137.195	30.4040	- 2.4401
	10	24.9	3.8086	83.6831	34.6980	1.8539
	11	22.0	0.2930	56.4669	38.1149	5.2708
	12	20.1	0.0977	24.0625	45.5239	12.6799

Table 1. Number of Bits Kept vs. CR, PIL, RMSE, SNR and PSNR.

sees that B1 presents better results than B2, in term of high CR 25.6 for PIL $< 0.3\%$ for a 10 bits/samples kept. Image C depicts the widest distribution of the data than those in Image A and B, thus, two reference peaks (C1, C2) have been also used for compression. C2 presents better results than C1 such that for the same CR of 22, C2 has lower PIL ($< 0.3\%$) for 11 bits/samples kept. The reconstructed images on A, B and C for PIL $< 1\%$ is given in Figure 2. Obviously, compression on these ISOCAM images should take into account that 8 bits/resolution, 10 Bits/resolution and 11 bits resolution on respectively image A, image B (reference B1) and image C (reference C2) has to be kept. Comparing the reconstructed images with different reference values (Figure 2) shows that the choice of an appropriate reference level is a driving factor for minimisation of scientific data loss. Using more than one reference level is an alternative for additional compression ratio at the cost of a slightly increasing algorithmic complexity. Furthermore, the determination of the required resolution can be established by the calculation and comparison of the criteria for the reconstruction error. In the other hand, PIL provides a consistent evaluation and an objective measure of the distortion where RMSE, SNR and PSNR alone fail to provide.

6 Conclusion

This paper presents assessment results of the on-board compression concept on 3 different ISOCAM images. The compression ratio (CR), RMSE, SNR, PSNR and PIL are used for the evaluation. Initial results are very promising and show that the PIL combined with CR provides an objective measure for the compression performance and image quality. Depending on the source data distribution, we showed that the CR achieved by the compression method developed in [1] varies between 22 and 40 for an acceptable image quality (PIL $< 1\%$). The forthcoming perspective is the evaluation of this method on other infrared camera like PACS [10] using the same procedure.

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