FAPEC-BASED COMPRESSION RESULTS ON SATELLITE IMAGING DATA

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ABSTRACT

Satellite data compression is becoming essential for scientific missions owing to the increasing amount of data generated by modern instrumentation. Some examples of these missions are Euclid, Solar Orbiter and various Earth Observation missions. Given the very different goals and mission concepts, the optimum compression algorithm can be different for each of the cases. Here we study the performance of different compression solutions on image data. We aim to determine which is the best solution for each of these cases. This includes not only an assessment of the compression ratios but also of the corresponding computing load, to minimize the onboard processing requirements. We do this for four compression solutions, namely, the so-called Fully Adaptive Prediction Error Coder (FAPEC) – a new entropy-coding algorithm that provides an excellent coding efficiency even when large fractions of outliers are present in the data; the CCSDS 121.0 recommendation – which is based on the Rice coder; the CCSDS 122.0 recommendation for image compression – which is based on a Discrete Wavelet Transform (DWT) and Rice coding and allows lossy operation; and DWTFAPEC – a combination of FAPEC with the 122.0 standard which compresses non-scaled DC and AC coefficients from the DWT stage. All the tests have been done using a variety of images including color images, for which we have partitioned them into sub-streams (one for each of the color bands), thus making possible to use DWTFAPEC and FAPEC on them. Our results not only confirm the applicability of FAPEC to any space mission, but also reveal that in some cases and configuration options it offers the best results.

Keywords: Image data compression, satellite imaging, FAPEC, DWTFAPEC, lossless, lossy, CCSDS.

I. INTRODUCTION

Since the first payload was launched to space in 1957, space technologies have quickly evolved. Nowadays, with the development of new technologies in the space sector, from launchers to satellite subsystems, the amount of transferred data has increased to the order of gigabytes of daily telemetry, astronomical and communication data.

Unfortunately, data compression systems for satellite payloads have several tight restrictions. First, one must use small data blocks in order to avoid losing large amounts of data in the case of transmission errors. More precisely, data should be compressed in small independent data blocks. This is at odds with the fact that most adaptive data compression systems perform optimally only after a large amount of data is processed. Secondly, the processing power for software implementations (or electrical power, in hardware implementations) is limited in space. Therefore, the compression algorithm should be as simple and quick as possible. Finally, the required compression ratios are increasing as new missions, which handle huge data amounts of data, are conceived and launched.

The Consultative Committee for Space Data Systems (CCSDS) issued its 121.0 recommendation [1] for lossless data compression with the intention of offering a solution to data compression requirements in space missions. The proposed solution is a very simple (thus quick) algorithm that operates in blocks of just 8 or 16 samples and is able to achieve reasonable compression ratios with low processing requirements. The critical problem of this solution arises at the coding stage, as the Rice algorithm is not intended to compress noisy data. This is a major issue since most space-based measurements are contaminated with noise and outliers, mostly caused by prompt particle events.

This weakness is solved by the Fully Adaptive Prediction Error Coder (FAPEC), a highly-optimized entropy-coding algorithm for data compression which offers much better resiliency regarding outliers [2]. The typical application of FAPEC is as the coding stage of a data compression system, after a first stage performing some kind of pre-processing on the data to be compressed, leading to prediction errors – hereby the name of FAPEC. Such prediction errors, in the form of signed integer values, are expected to be much smaller than the original data, and from that FAPEC will generate short binary codes leading to an output smaller than the original data. Additionally, FAPEC has been designed to be extremely efficient regarding the processing requirements. An FPGA prototype is also available for FAPEC [3], thus demonstrating its feasibility and suitability for space missions.

On the other hand, there are compression systems specifically designed to work with images instead of generic data. The CCSDS released its 122.0 recommendation [4] to define a particular payload image data compression algorithm. The algorithm is intended to be suitable for use onboard a spacecraft. In particular, the algorithm complexity is designed to be sufficiently low to make a high-speed hardware implementation feasible. The compression technique described in the CCSDS standard can be used to produce both lossy and lossless compression. The compressor adopted in the CCSDS 122.0 standard relies on a Discrete Wavelet Transform (DWT).

II. THE DWTFAPEC IMAGE DATA COMPRESSOR

Previous studies investigated the right place of the implementation of the 122.0 standard where the FAPEC coder could be inserted to obtain a good performance. In order to have an optimal integration, it was decided to use the DC and AC non-scaled coefficients from the DWT stage, which lets the FAPEC compressor to achieve the best performance when integrated in the CCSDS 122.0 for both lossless and lossy compression (see Fig. 1). This compression system was called DWTFAPEC [5].

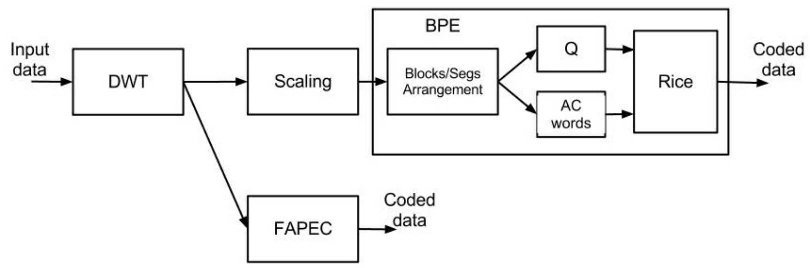

Fig. 1. DWTFAPEC concept compared to the 122.0 recommendation

As a further improvement to the original DWTFAPEC, a differential coding for the DC coefficients was added. That is, we take the DC coefficients generated by the DWT stage, determine the differences between consecutive coefficients, and provide them to the coder. In the decoding stage we just have to do the reverse operation – summing each new coefficient to the previous one in order to recover its original value.

In addition, in order to work with and compress RGB (Red-Green-Blue) colour images and avoid the 122.0 limitation to work only with greyscale images, a stream partitioner was devised to separate each colour band. Thus, we split each colour image into three sub-streams, each with a single band or colour. Then each sub-stream is compressed independently and finally, in decompression, the three bands are recombined to form the original image. This scheme will be integrated to the DWTFAPEC compressor/decompressor by means of interleaving.

III. TESTS AND RESULTS

Given the very different goals and mission concepts, the optimum compression algorithm can be different for each of the cases. Here we study the performance on simulated image data from Euclid, Solar Orbiter, and real data from various Earth Observation missions. We do this for the four compression solutions mentioned, namely, the so-called Fully Adaptive Prediction Error Coder (FAPEC), the CCSDS 121.0 recommendation, the CCSDS 122.0 recommendation, and the DWTFAPEC image compressor.

A. Improved DWTFAPEC results

As an initial test, we studied the performance of the new differential DC coefficients encoding as opposed to the previous scheme were the values of the DC coefficients were coded directly. Table 1 shows the results for a selected representative set of images of the different scenarios of satellite imaging data.

Table 1. DWTFAPEC compression ratios and times for a variety of image files

Image	**Absolute DC coding**		**Differential DC coding**	
	Ratio	CPU time (ms)	Ratio	CPU time (ms)
com0001.fits	2.03	152	2.06	152
for0001.fits	3.21	86	3.24	120
galaxy.fits	1.90	56	1.92	91
ngc0001.fits	1.69	146	1.69	162
sgp0001.fits	3.62	96	3.73	94
banyoles.raw	1.40	452	1.41	281
catedral.raw	1.14	352	1.14	301
eixample.raw	1.20	327	1.20	575
field.raw	1.31	839	1.32	285
pirineus.raw	1.41	586	1.41	282

As can be seen, the compression ratios have slightly increased for almost all the images. The CPU time required has also slightly increased yet not significantly. It is worth mentioning that, as otherwise expected, the image format does not affect the result considerably. The improvement achieved with this Differential DC Coding approach is marginal and depends on the image, but in almost all the lossless tests we have a larger compression ratio. The reason for such marginal improvement is the small number of DC coefficients with respect to the number of AC coefficients in the DWT stage. Regarding the compression time, in some cases it has increased, but in general the result is reasonable – especially considering the intrinsic inaccuracy when measuring the exact run time of the software.

Table 2 shows the overall results obtained for the case in which lossy compression is employed, selecting a quality level of 2 – that is, removing all the grandchildren AC coefficients [5]. As can be seen, better improvements are achieved in terms of compression ratio, while the processing times are still very similar. The reason of this significant improvement is that the DWTFAPEC code simply gets rid of many AC coefficients when selecting the lossy option. Thus, when coding the DC coefficients differentially we are affecting a larger fraction of the total number of coefficients.

Table 2. Compression ratios, times and PSNR for lossy DWTFAPEC on a variety of images

Image	**Absolute DC coding**		**Differential DC coding**		**PSNR (dB)**
	Ratio	CPU time (ms)	Ratio	CPU time (ms)	
com0001.fits	7.69	102	8.10	65	12.90
for0001.fits	8.97	58	9.28	43	12.82
galaxy.fits	6.59	26	6.80	26	19.63
ngc0001.fits	5.22	45	5.27	45	20.82
sgp0001.fits	10.61	28	11.66	28	19.22
banyoles.raw	4.37	142	4.45	138	11.53
catedral.raw	3.69	140	3.73	257	10.75
eixample.raw	3.80	144	3.85	255	10.92
field.raw	4.27	139	4.34	139	12.93
pirineus.raw	4.31	141	4.41	138	10.21

From the results obtained in the tests presented, the clear conclusion is that differential DC coding improves the compression ratios, both in the lossless case and (specially) in the lossy case. The compression time is just slightly increased with this technique, but in general it is better to use this as the default option for the DWTFAPEC compressor. In the lossless tests, the ratios are improved by up to 4%, whereas in the lossy tests the enhancement is of up to 12%. Using differential DC coefficients improves the final result of the DWTFAPEC compressor in any image format and also almost in any image type. The restored images after level 2 lossy compression also have an acceptable quality when compared to the original images, without much artefacts or noise in the images obtained.

B. Solar observation images

The goal of the Solar Orbiter mission is to address the central question of heliophysics, namely, how the Sun creates and controls the heliosphere. This, in turn, is a fundamental part of the second science question of the Cosmic Vision programme of ESA, namely, how the Solar System works. Solar Orbiter is specifically designed to identify the origins and causes of the solar wind, the heliospheric magnetic field, solar energetic particles, transient interplanetary disturbances, and the magnetic field of the Sun itself [6]. Fig. 2 displays an image kindly provided by the Solar Orbiter team. As can be seen, the image is mostly dark pixels, just with the solar corona around the dark circle (produced by the mask) in the centre of the image. The image is 1024x1024 pixels (16-bit greyscale).

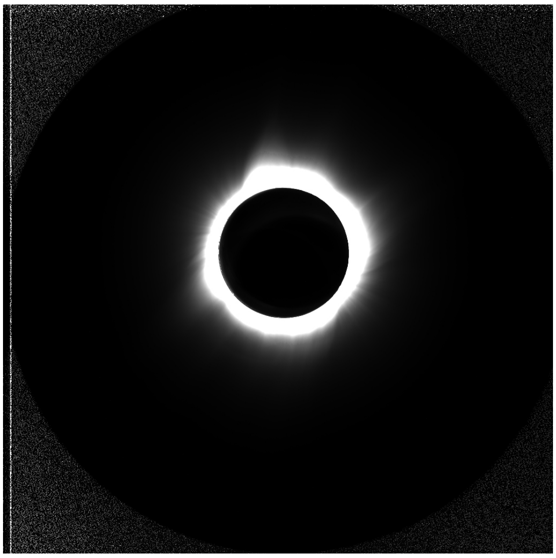

Fig. 2. Solar observation image used in tests

Table 3. Lossless compression ratios and times for the solar image

Image	**FAPEC**		**DWTFAPEC**		**CCSDS 121.0**		**CCSDS 122.0**	
	Ratio	CPU time (ms)	Ratio	CPU time (ms)	Ratio	CPU time (ms)	Ratio	CPU time (ms)
Mosaic10	2.41	120	2.26	540	2.51	128	2.55	693

Table 3 shows the results obtained with the four compression schemes mentioned before for the lossless case. We can see that for lossless compression of the solar image, the CCSDS recommendations outperform the FAPEC-based solutions in terms of compression ratios but with an important impact in the execution time. Nevertheless, for the Solar Orbiter mission, lossy compression is a requirement so we need to evaluate the performance of the image compressors that allow compression with losses (DWTFAPEC and CCSDS 122.0). We have tested four quality levels, that is, from 1 (higher quality) to 4 (lower quality). Table 4 shows the results for both compressors, where we can see that the highest compression ratios and shortest times have been achieved by DWTFAPEC – except for the lowest-quality levels where the times are slightly worse for DWTFAPEC.

Table 4. Compression ratios and times for lossy DWTFAPEC and CCSDS 122.0 on the solar image

Image	**Quality Level 1**		**Quality Level 2**		**Quality Level 3**		**Quality Level 4**	
Mosaic10	Ratio	CPU time (ms)	Ratio	CPU time (ms)	Ratio	CPU time (ms)	Ratio	CPU time (ms)
Lossy DWTFAPEC	3.21	440	8.41	260	10.79	430	26.22	330
Lossy 122.0	3.24	740	7.94	470	9.94	410	23.28	301

Finally, in order to get a quantitative evaluation of the lossy compression results, we determine the peak signal-to-noise ratio (PSNR) which shows the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation. PSNR is most commonly used to measure the quality of reconstruction of lossy compression CODECs (such as in our case, that is, image compression). The signal in this case is the original data, and the noise is the error introduced by lossy compression. For the lossy tests presented here, the PSNR has also been calculated and the results are summarized in Table 5. As a final conclusion for this test, we consider Lossy DWTFAPEC with quality level 2 as the best compromise between compression ratio, quality, and speed.

Table 5. PSNR results for lossy compression (DWTFAPEC and CCSDS 122.0) on the solar image

Image	**Level 1 PSNR**	**Level 2 PSNR**	**Level 3 PSNR**	**Level 4 PSNR**
Mosaic10	12.45 dB	11.98 dB	11.85 dB	11.70 dB

C. Euclid simulated images

Understanding the acceleration of the expansion of the Universe is one of the most compelling challenges of cosmology and fundamental physics. Euclid is an ESA mission to map the geometry of the dark Universe. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures. It achieves this by measuring shapes and redshifts of galaxies and clusters of galaxies to a look-back time of 10 billion years. It will therefore cover the entire period over which dark energy played a significant role in accelerating the expansion [7]. Fig. 3 illustrates some simulated images kindly provided by the Euclid team. From left to right and from top to bottom they are labelled as *30deg*, *60deg*, *90deg* and *VISCCD*. Note that we show them using a logarithmic scale in order to reveal the very faint details (specifically, using the *minmax log* scale of the *ds9* viewer). Nevertheless, as can be seen, the images are mostly dark pixels, just containing a few stars and also traces of cosmic rays or solar protons.

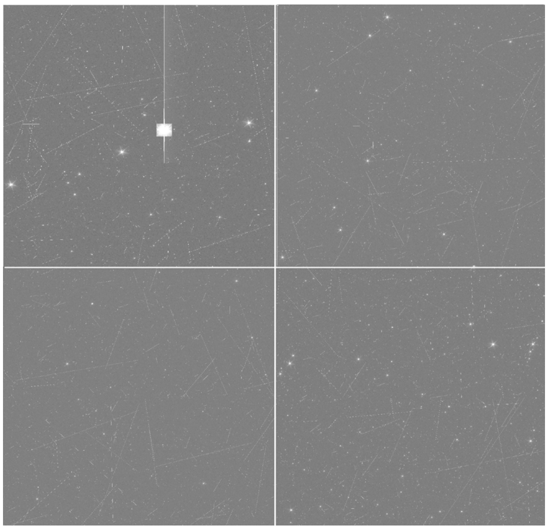

Fig. 3. Euclid images used in our lossless image compression tests

Table 6 shows the lossless compression results obtained with the four compression systems being studied. Lossy compression is not considered here, as the Euclid mission requirements impose lossless compression. As can be seen, the results indicate that FAPEC is definitely the best compression algorithm, both in terms of compression ratios and CPU load. FAPEC not only has the highest compression ratio, but when compared to CCSDS 121.0 and 122.0 standards, it is significantly quicker. Specifically, the FAPEC ratios are about 10% higher than those of 121.0, about 6% higher than those of 122.0, and about 5% higher than those of DWTFAPEC. Regarding the performance, it is about 40% faster than 121.0, 7 times faster than 122.0, and 6 times faster than DWTFAPEC.

Table 6. Lossless compression ratios and times for the Euclid images

Image	**FAPEC**		**DWTFAPEC**		**CCSDS 121.0**		**CCSDS 122.0**	
	Ratio	CPU time (s)	Ratio	CPU time (s)	Ratio	CPU time (s)	Ratio	CPU time (s)
30deg	3.63	1.51	3.45	9.07	3.26	2.22	3.43	10.44
60deg	3.69	1.47	3.49	8.92	3.30	2.25	3.47	10.56
90deg	3.68	1.47	3.49	8.96	3.29	2.21	3.47	10.57
VISCCD	3.61	1.47	3.45	9.05	3.26	2.22	3.43	10.72

D. Meteorological images

The various weather services are constantly striving to provide accurate forecasts, either in the form of actual data concerning current weather or in the form of a forecast of future conditions. In either case, the information provided is only as good as the weather data available to the meteorologist. The National Oceanic and Atmospheric Administration (NOAA) environmental satellites provide data from space to monitor the Earth to analyze the coastal waters, relay life-saving emergency beacons, and track tropical storms and hurricanes. NOAA operates two types of satellite systems for the United States – geostationary satellites and polar-orbiting satellites. Historical data from these satellites, and other air-based and ground-based observation platforms, is archived for public use at NOAA world-class national data centres [8]. On the other hand, the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is an intergovernmental organization and was founded in 1986. Its purpose is to supply weather and climate-related satellite data, images and products to the National Meteorological Services of the Member and Cooperating States in Europe, and other users worldwide [9]. Fig. 4 displays some test images selected from the NOAA (left) and EUMETSAT (right) websites, which we use here for the data compression tests. They are 3600×3000 pixels and 1420×1255 respectively, both with 8-bit three-band colour pixels. Using the stream partition scheme previously mentioned, we split each of the images into three sub-streams, each with a single band (or colour), and afterwards applied the four compression solution on each of the sub-streams. It is worth mentioning that, as otherwise expected, the individual ratios and times on each of the colour bands are extremely similar for each given image and compressor.

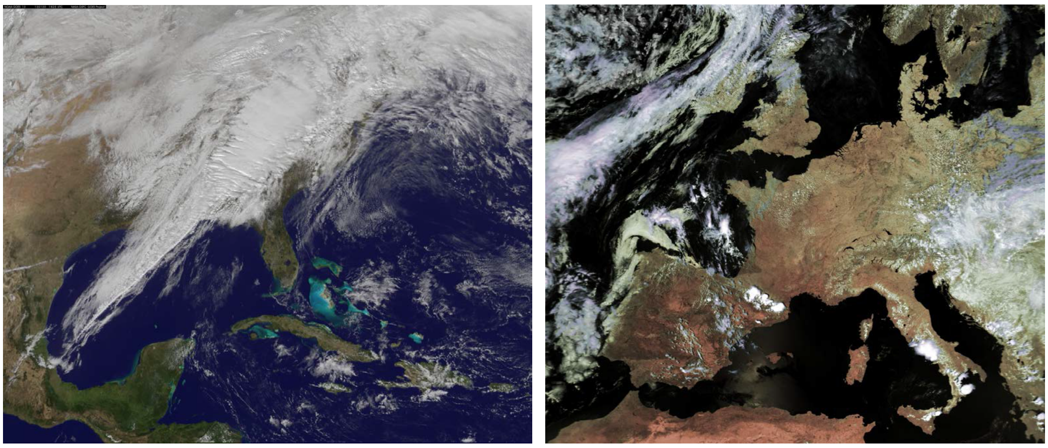

Fig. 4. *723585main* image from a NOAA satellite (left) and *Pyrenees* image from EUMETSAT (right)

Table 7 shows the results of the lossless compression tests. The ratios shown correspond to the overall ones on the three bands (that is, on the complete image), and so is the CPU time – showing the total time for the colour image. As can be seen, the best results are those obtained with the CCSDS 122.0 although at a very high cost in terms of CPU load. The fastest algorithm is FAPEC, overwhelming the performance of other compression algorithms, but unfortunately, the compression ratios are also the lowest of the four compressors compared.

Table 7. Lossless compression ratios and times for the meteorological images

Image	**FAPEC**		**DWTFAPEC**		**CCSDS 121.0**		**CCSDS 122.0**	
	Ratio	CPU time (s)	Ratio	CPU time (s)	Ratio	CPU time (s)	Ratio	CPU time (s)
pyrenees	1.61	0.5	1.80	4.12	1.72	0.84	1.93	3.81
723585main	1.87	3.46	2.07	23.81	2.00	6.16	2.26	27.00

Lossy compression is often a requirement for meteorological and Earth observation missions. The two lossy solutions are compared, namely the most frequently used one, that is, the CCSDS 122.0 standard and our own image compressor, DWTFAPEC. As usual, we provide compression ratios and CPU times. For each sub-stream in these simulations we have tested four quality levels for the losses, that is, from 1 (higher quality) to 4 (lower quality). The final results are summarized in Table 8.

Table 8. Lossy compression ratios and times for DWTFAPEC and CCSDS 122.0 on meteorological images

Image		**Level 1**		**Level 2**		**Level 3**		**Level 4**	
		Ratio	CPU time (s)	Ratio	CPU time (s)	Ratio	CPU time (s)	Ratio	CPU time (s)
pyrenees	**DWTFAPEC**	2.08	2.72	5.03	1.27	6.37	1.14	16.12	0.96
	122.0	2.25	3.39	4.82	1.83	5.87	1.73	13.78	1.25
723585main	**DWTFAPEC**	2.41	12.72	5.76	7.90	7.29	7.71	18.32	6.87
	122.0	2.62	16.07	5.54	10.57	6.73	10.09	15.72	7.60

For the lossy tests presented here with CCSDS 122.0 and DWTFAPEC, the PSNR has also been calculated and the results are summarized in table 9, which shows the average PSNR for the three bands. Based on these results, the highest compression ratio and the lowest compression load are achieved using DWTFAPEC. If the quality level is increased this difference becomes larger in terms of compression ratio and time, with very few artefacts in the reconstructed images.

Table 9. PSNR results for lossy compression on the meteorological images

Image	**Level 1 PSNR (dB)**	**Level 2 PSNR (dB)**	**Level 3 PSNR (dB)**	**Level 4 PSNR (dB)**
pyrenees	8.01	7.87	7.76	7.80
723585main	8.11	8.04	7.87	7.71

IV. CONCLUSIONS

We have proved that FAPEC can be efficiently used as the encoding stage of an image data compression system such as the CCSDS 122.0 standard. DWTFAPEC with its modifications has proven to be a better option than the CCSDS 122.0 standard when it comes to lossy image compression, whereas in the case of lossless compression the results are very similar. In almost all cases and also with different type of astronomical images, DWTFAPEC is significantly faster than the standard CCSDS 122.0. For the Solar Orbiter mission, lossy DWTFAPEC with a quality level of 2 (removing all grandchildren AC coefficients from the DWT) is the best compromise between compression ratio, quality, and speed, performing better than the CCSDS 122.0 standard. For the Euclid mission, our results demonstrate that FAPEC is definitely the best solution, both in terms of ratios and compression speed. Finally, by using the stream partitioning scheme we have proven the applicability of DWTFAPEC on colour images. In our tests we have obtained quite acceptable compression ratios, times and qualities for both NOAA and EUMETSAT images.

Summarizing, we have implemented and successfully tested a complete solution for image data compression, with selectable lossless/lossy operation and working also on colour images – or multi-band images in general. The resulting DWTFAPEC image compressor offers satisfactory results. It is a fast, quite simple and robust entropy coder capable of processing colour images yielding good compression ratios in almost any situation with very small processing requirements.

V. FUTURE WORK

In this work we have shown the integration of the FAPEC coding stage into the Nebraska C implementation of the CCSDS 122.0 standard. We plan to implement a solution doing it the other way around, that is, integrating an optimized DWT pre-processor into FAPEC to further improve the performance. In addition, the mentioned stream partitioning scheme will be integrated to allow the direct compression of colour and hyperspectral images in a transparent way for the user.

VI. ACKNOWLEDGEMENTS

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REFERENCES

[1] Consultative Committee for Space Data Systems, Lossless Data Compression, Blue Book. Technical Report CCSDS 121.0-B-1, CCSDS, 1993.

[2] J. Portell , A. G. Villafranca and E. Garcia-Berro, "Quick outlier-resilient entropy coder for space missions," *J. Appl. Remote Sens,* 2010.

[3] A. G. Villafranca, S. Mignot, J. Portell, and E. García-Berro, "Hardware implementation of the FAPEC lossless data compressor for space," in *NASA/ESA Conference on Adaptive Hardware and Systems*, 170–176 (2010).

[4] Consultative Committee for Space Data Systems, "Image Data Compression, Blue Book Technical Report CCSDS 122.0-B-1", CCSDS, 2005.

[5] G. Artigues, J. Portell, A. G. Villafranca, H. Ahmadloo and E. García-Berro, "Discrete wavelet transform fully adaptive prediction error coder: image data compression based on CCSDS 122.0 and fully adaptive prediction error coder," *J. Appl. Remote Sens,* 2013.

[6] "Solar Orbiter," ESA, 2014. [Online]. Available: www.sci.esa.int/solar-orbiter/

[7] "ESA Euclid," ESA, 2014. [Online]. Available: www.sci.esa.int/euclid/

[8] NOAA, "National Oceanic and Atmospheric Administration-NOAA," 2014. [Online]. Available: www.noaa.gov/

[9] EUMETSAT, "European Organisation for the Exploitation of Meteorological Satellites," 2014. [Online]. Available: www.eumetsat.int/website/home/index.html