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An Image Assessment Study of Image Acceptability of the Galileo Low Gain Antenna Mission

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ABSTRACT

This paper describes a study conducted by NASA Ames Research Center (ARC) in collaboration with the Jet Propulsion Laboratory (JPL), Pasadena, California on the image acceptability of the Galileo Low Gain Antenna mission. The primary objective of the study is to determine the impact of the Integer Cosine Transform (ICT) compression algorithm (Cham, 1989) on Galilean images of atmospheric bodies, moons, asteroids and Jupiter's rings. The approach involved fifteen volunteer subjects representing twelve institutions involved with the Galileo Solid State Imaging (SSI) experiment (Belton et al., 1990). Four different experiment specific quantization tables (q-table) and various compression stepsizes (q-factor) to achieve different compression ratios were used. It then determined the acceptability of the compressed monochromatic astronomical images as evaluated by Galileo SSI mission scientists. Fourteen different images were evaluated. Each observer viewed two versions of the same image side by side on a high resolution monitor; each was compressed using a different quantization stepsize. They were requested to select which image had the highest overall quality to support them in carrying out their visual evaluations of image content. Then they rated both images using a scale from one to five on its judged degree of usefulness. Up to four pre-selected types of images were presented with and without noise to each subject based upon results of a previously administered survey of their image preferences. Fourteen different images in seven image groups were studied. The results showed that: (1) Acceptable compression ratios vary widely with the type of images; (2) Noisy images detract greatly from image acceptability and acceptable compression ratios; (3) Atmospheric images of Jupiter seem to have higher compression ratios of 4 to 5 times that of some clear surface satellite images.

INTRODUCTION

The Galileo spacecraft was launched in October 1989, and it will reach Jupiter and its moons in late 1995. Its mission includes Io flyby, releasing a probe into the Jovian atmosphere, probe data capture and relay, Jupiter orbital insertion, and 10 satellite encounters with Ganymede, Callisto, and Europa. In April 1991, when the spacecraft first flew by Earth, the Galileo team commanded the spacecraft to open the 1.8m X-band high-gain antenna (HGA), but it failed to deploy. The only way to communicate between Earth and the spacecraft is now through the use of one of the two S-band low-gain

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antennas (LGA), which at Jupiter's range, can only support a telemetry data rate of 10 bit/second compared to the expected data rate of 134kbits/second in the HGA mode. Since the detection of the HGA anomaly, several unsuccessful attempts (including a major effort to perform hammering or pulsing of the deployment motor in December 1992) were made to free the HGA. A parallel effort was conducted from December 1991 through March 1992 to evaluate various options for improving Galileo's telemetry downlink performance in the event that the HGA would not open.

This contingency plan was known as the Galileo S-Band Contingency Mission, a mission based upon using the S-band LGA. This LGA mission includes major ground upgrades as well as inflight reprogramming of the Galileo spacecraft microprocessors to incorporate advance signal processing algorithms to boost the effective data rate. These onboard algorithms include advance error-correction coding, packetizing, and data compression schemes. A lossy image compression scheme known as the integer cosine transform (ICT) scheme [2] [3] was proposed, which is simple enough for spacecraft implementation. This scheme was extensively tested and was shown to provide good compression performance on images. It can also give a wide range of rate-distortion trade-offs for the image data, which accounts for over 70% of the total planned downlink data. In March 1993,the Galileo Project abandoned further attempts to free the HGA and adopted the LGA mission as the baseline.

ARC and JPL Collaboration. With ICT image compression algorithm baselined into the Galileo LGA mission, the evaluation and validation of this compression scheme with Galileo SSI principal investigators - in- the-loop is even more critical. The joint study conducted by ARC and JPL addressed this issue and resulted in validation of the ICT algorithm in terms of acceptability by the science user. The study incorporated representative images, anticipated noise and instrument signatures, quantization tables, expected compression ratios and most importantly, the science user community who evaluated and validated the expected compression scheme. Furthermore, the SSI principal investigators became more educated on the compression scheme and its effects on the visual quality of the Galilean images.

Ames' role was to develop the experimental design, implement the design, collect, and analyze the data from the subjects, and report findings and results. A pre-experiment survey of all members of the SSI was first conducted to collect preliminary information about the scientific interest of the expected imagery, what scientific questions are targeted for the images, how the questions are answered and what applications would be performed on the images. The survey results provided the basis for the PI-in-the-loop experiment. Subjective judgments and ratings were made by the scientists in a controlled environment at the Galileo SSI Compression Workshop held at NASA ARC. Ames collected, analyzed and reported the results to JPL.

JPL provided guidance to the ARC personnel and facilitated close communication with the SSI team members. JPL provided the ICT algorithm, library of representative images, quantization tables in support of the experiment.

ICT Algorithm. The ICT was chosen for the spacecraft because of its simplicity and performance. ICT can be thought of as an integer approximation of discrete cosine transform (DCT), which is regarded as one of the best transform techniques in image coding. The transform-based coding scheme consists of three stages: the data transform stage, the quantization stage, and the entropy coding stage. Both ICT and DCT are independent from source data statistics, and there are fast algorithms to perform ICT and DCT. Unlike DCT which requires floating-point or fixed-point operations, ICT requires only integer multiplications and additions, making it much simpler to implement than the

DCT. The elements in an ICT matrix are all integers, with sign and magnitude patterns that resemble those of the DCT matrix. Also the rows of the ICT matrix are orthogonal. The similarity of the ICT matrix to the DCT matrix, together with the orthogonality property of the ICT, guarantee that the ICT compression scheme performs almost as well as the DCT compression scheme, Joint Photographic Expert Group (JPEG).

METHODOLOGY

Basic Experimental Assumptions. We assumed that images can be grouped according to their visually based scientific features of interest and that experienced investigators having similar interests in these images have common requirements for acceptable visual fidelity. These assumptions permitted us to design an experiment around a reasonably small number of "representative" images as well as a manageable number of interested members of the SSI science team.

Experimental Design and Approach. The experimental design used to administer the variables of interest may be characterized as a 4 by 32 by 2 by 15 parametric design. The variables were:

q - Tables	4 tables
Quantization level	32 levels
Image type	2 (no noise; with noise)
Observers	15

Pair Comparison Method: Method of Paired Comparison was used [5]. Each observer was presented two compressed versions of the same image at a time side by side, varying only in their quantization level. They were not told anything about either image and only had to select which of the two possessed the highest overall quality to support them in conducting their visual examinations of that image. Then they rated each image on a scale from "1" to "5" where "1" represented a totally unacceptable scientifically-useless image, and "5" represented an image of the highest possible usefulness, value, or merit. A score of "3" was used as the threshold between acceptable and unacceptable for subsequent scoring purposes. No image pre-processing (contrast enhancement, stretching, etc.) were conducted on the images.

Method of Progressive Division: The Method of Progressive Division was used to quickly focus in and identify the optimal quantization level (q-level) for a given image and q-table, a group of observers were presented the same image and q-table with each person being presented a progressively smaller range of q-levels. The objective was to identify the quantization level(s) which separated an unacceptable from an acceptable rating. It will be recalled that a rating of "3" was considered as the threshold between an acceptable and an unacceptable image. Thus, images given a score that was higher or lower than "3" were used to determine when to decrease or increase the quantization levels, respectively, in subsequent testing. That acceptable half was presented to the next observer and bisected again, etc. This approach is based upon the (untested but reasonable) assumption that these observers possess a fairly consistent set of image evaluation criteria.

Observers: Fifteen people participated as subjects in the experiment. Six were SSI team members (representing six different institutions) while the remaining nine were participants at the workshop from another nine institutions. All possessed corrected or uncorrected 20:20 acuity and viewed the images on a high resolution SUN monitor.

Images Tested: Based upon meetings and telephone interviews with SSI team members at Ames and elsewhere we identified the following image classes of most interest to them. Images were selected for presentation for each of these seven classes from a larger image library provided by JPL. The experiment was conducted in a controlled environment at the SSI Compression Workshop held at Ames on July 22, 1993. Images were selected from each of the classes listed below, along with their respective noise-superimposed images.

Image Classes Studied

Solid surface with limb
Solid surface without limb
Solid surface with terminator
Gaseous surface without limb
Small bodies (e.g., asteroid)
Dark side phenomena/lightning
Rings

A total of fourteen separate images were studied in the experiment (cf. Table 1). Four represented the solid surface without limb category from Ganymede and Io. Three represented the solid surface with limb of Europa and Io, and another three represented a gaseous image without limb (all Jupiter). There was one image each representing a solid surface with terminator, small body (Gaspra), darkside phenomena (lightning), and rings (Saturn). All image files were cropped to fit side by side on the high resolution monitor and all but three were magnified x 2 in order to better demonstrate the effects of ICT compression. Four of the fourteen images were superimposed with noise frames.

Table 1 Image Details

Image Class Name	Body	File Name	Noise	Mag.	Q-tables (1)	(2)	(3)
Solid with Limb	Europa	r.6.r		x 2	0	1	2
	Europa	r6.noise.r	x	x 2	0	1	2
	Io	r.9.r		x 2	0	1	2
Solid - No Limb	Ganymede	r.4.r		x 2	0	1	2
	Ganymede	rq538.g.r	x	x 2	0	1	2
	Io	sr7.raw.r		x 2	0	1	2
	Io	sr7.noise.r	x	x 2	0	1	2
Solid with Termin.	Callisto	r.1.r		x 2	0	1	2
Gaseous - No Limb	Jupiter	r.14.r		x 1	0	2	3
	Jupiter	r.15.r		x 1	0	2	3
	Jupiter	rq538.j4o.r	x	x 1	0	2	3
Small Bodies	Gaspra	rq538.gas.r		x 2	0	1	2
Darkside/Lightning	Earth	rq538.litn.r		x 2	0	1	2
Rings	Saturn	r.11.r		x 2	0	1	2

q -Table Selection: Four quantization (q) tables were developed for use in this study by A. B. Watson of Ames Research Center [8]. Each was designed to produce maximal ICT compression for different types of image characteristics, e.g., low contrast soft-boundary details, medium to high contrast high spatial frequency details.

RESULTS

Final Results Summary

Compression as a Function of Image Type: In general it may be said that the maximum ICT compression level(s) cannot be predicted apriori for a given image type and/or q-table. Nor are the perceptual response characteristics of observers understood well enough to predict whether unacceptable distortions of useful features with the digital image will be produced by the ICT algorithm at different q-levels. Visual ratings and associated commentary made by experienced observers/scientists are needed in order to determine how well a particular q-table and quantization level handles certain kinds of details. Nevertheless, the present data does provide some useful insights into the relative magnitude of acceptable compression ratios for different classes of images, noise types, quantization matrices, and levels presented.

The present data were grouped into a low, medium, and high acceptable image ICT compression ratio category. The low compression ratio group was selectively defined as ranging from no compression (1:1) to 4:1 and 8:1. The four images having superimposed noise all fell into this category regardless of which q-table was used.

There were three images in the medium acceptable compression ratio category (i.e., from 8:1 to 17:1), viz., r.1.r, r.4.r, and r.6.r. All three are solid surface images characterized by the presence of high spatial frequency details such as craters, linear structures, and other varied shapes of medium to high contrast.

The highest acceptable ICT compression ratio group was, on the basis of the present results, defined as higher than 35:1. Six images fell into this group. They are all relatively diverse from one another in image detail and deserve detailed commentary. Table 2 is a summary of acceptable image quality for each image type and q-table. The "Safe" range of compression values cited represent a more conservative (wider range of values) estimate of acceptable compression. These values take into account response variability. The "Likely" range represents our estimate of the actual range of compression ratios for each condition.

Influence of Radiation Noise: Four image types contained superimposed noise which would be expected to influence its visual appearance after compression. Three types of simulated radiation noise were studied. Two (Noise type B and D specified by JPL) consisted of random dots and short lines at random inclinations. Noise type C specified by JPL consisted of identical pairs of dots and short inclined lines separated by about 1/20th of the frame dimension. In three of these cases both a noise and non-noise version of the same image was quantified. It was found that radiation noise greatly reduces the ICT compression ratio that is judged as being acceptable to these observers. In the most extreme case found (r.15.r of the gaseous atmosphere of Jupiter vs. the same image with noise [rq538.j4o.r]) compression was reduced from 57:1 down to <3:1 (q-table 2) by the noise alone. In a less extreme case (r.6.r vs. r6.noise.r of Europa), compression of the same image was reduced from about 12:1 down to 5:1 (for q-table 0) due only to noise. In a third case involving a solid image without limb and high spatial detail (r.4.r vs. rq538.g.r of Ganymede) compression was reduced from about 10:1 down to 8:1 (q-table

Table 2
Summary of Acceptable Image Quality
Compression Results by Type of Image and q-Table

Image Type	file	Acceptance Criterion	q = 0	q = 1	q = 2	q = 3
Solid Surface with Limb	r.6.r	Safe	8-12	9-15	4-12	-----
		Likely	8-12	9-15	8-12	-----
	r.9.r	Safe	37-42	35-46	44-46	-----
		Likely	37-42	41-46	44-46	-----
	r6.noise.r	Safe	1-5	< 2	< 3	-----
		Likely	4-5	< 2	< 3	-----
Solid Surface without Limb	r.4.r	Safe	9-10	6-9	8-12	-----
		Likely	9-10	6-9	8-12	-----
	sr7.raw.r	Safe	>38	23-41	23-36	-----
		Likely	>38	29-41	32-36	-----
	rq538.g.r	Safe	4-8	< 3	< 4	-----
		Likely	4-8	< 3	< 4	-----
	sr7.noise.r	Safe	1	< 2	< 2	-----
		Likely	1	< 2	< 2	-----
Solid Surface with Terminator	r.1.r	Safe	11-17	12-15	11-18	-----
		Likely	11-17	12-15	11-18	-----
Gaseous Surface without Limb	r.14.r	Safe	55-67	51-71	54-72	-----
		Likely	55-67	51-62	54-72	-----
	r.15.r	Safe	36-53	-----	42-57	48-53
		Likely	36-53	-----	42-57	48-53
	rq538.j4o.r	Safe	1	-----	< 3	6
		Likely	1	-----	< 3	6
Small Bodies	rq538.gas.r	Safe	35-61	37-50	36-54	-----
		Likely	35-61	37-50	36-54	-----
	rq538.litn.r	Safe	71-75	80-86	83-88	-----
		Likely	71-75	80-86	83-88	-----
Rings	r.11.r	Safe	> 36	> 45	> 48	-----
		Likely	> 36	> 45	> 48	-----

0). Each q-table used produced slightly different results but of a comparable magnitude. In another image involving radiation noise (rq538.j4o.rof Jupiter) the q-table 0 image could not be compressed at all and still be acceptable. However, only two observers rated this image and neither responded to the instructions very seriously. Results for the q-table 2 and 3 yielded compression ratios of less than 3:1 and 6:1, respectively.

Compression as a Function of q-Table: By scanning vertically down Table 2 for each q-table one can quickly gain an understanding of the relative effect each q-table had on acceptable compression ratio by image. Q-table 0 yielded the highest acceptable ICT compression in only two (14%) of the fourteen images studied [viz., sr7.raw.r; and rq538.g.r]. Both are solid surface without limb. Q-table 1 yielded the highest acceptable ICT compression from 9:1 to 15:1 in only one (1%) of the fourteen images ([viz., r.6.r]. Q-table 2 yielded the highest acceptable compression in eight (57%) of the fourteen images studied.

GENERAL CONCLUSIONS

Radiation noise tends to reduce ICT compression acceptance ratings if high frequency information is desirable. Radiation noise also degrades low frequency information if the ICT compression used also eliminates high frequency information. The results showed that: (1) Acceptable compression ratios vary widely with the images; (2) Noisy images detract greatly from image acceptability and acceptable compression ratios; (3) Atmospheric images of Jupiter seem to have higher compression ratios of 4 to 5 times that of some satellite images.

DISCUSSION

It is clear that the impact of compression algorithms on images need to be studied further for specific science domains and specific principal investigators' scientific use for the images. Further, the ICT compression scheme is a block transform coding scheme. It performs lossy image compression, and it exhibits blockiness and checkerboard artifacts to different degree in the reconstructed image, depending on the image background and compression ratio. These block-oriented artifacts are caused by quantizing the transform coefficients of the ICT, and there are standard techniques in the literature to "remove" or "hide" these artifacts subjected to certain visual criteria. Most of the standard techniques assume no knowledge of the original image. The Galileo image compression scheme operates in a unique scenario where an addressable 96 pixel x 96 pixel area in an image can either be losslessly compressed or uncompressed (truth window). This area can provide valid statistics and boundary information to facilitate image reconstruction and artifacts removal. New and modified image restoration and enhancement techniques are now being developed to take advantage of the information provided by the truth window. New experimental procedures can be designed to evaluate the restoration and enhancement techniques by comparing the reconstructed images (with and without enhancements) with the original images. The PI-in-the-Loop approach can be a good approach to assess the validity of the compression techniques.

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