A Comparative Study of SAR Data Compression Schemes

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I) INTRODUCTION

In spaceborne remote sensing, the amount of data collected has substantially increased in the last years. In the same time, the ability to store or transmit it has not increased as fast, so that there is a growing interest in developing compression schemes that could provide both higher compression ratios and lower encoding/decoding errors. In the case of the spaceborne Synthetic Aperture Radar (SAR) earth observation system developped by the French Space Agency (CNES), the volume of data to be processed is planned to exceed on-board storage capacities or telecommunication link. The objective of this paper is twofold:

- to present various compression schemes adapted to SAR data
- to define a set of evaluation criteria and compare the algorithms on SAR data.

In this paper, we review two classical methods of SAR data compression and propose novel approaches based on Fourier Transforms and spectrum coding.

II) DESCRIPTION OF ALGORITHMS

a) Block Adaptive Quantizer

The first algorithm presented in this paper is the Block Adaptive Quantizer (BAQ) which was first proposed for the Magellan mission to Venus ([1]). This method encodes data into 2 bits in the following way: one bit is the sign bit, the other indicates the signal level. The signal-level bit indicates whether the signal is above or below a rms dependant threshold S:

$$x(n) = "11" \text{ if } x < S$$
$$x(n) = "10" \text{ if } x \in [-S,0]$$
$$x(n) = "00" \text{ if } x \in [0,S]$$
$$x(n) = "01" \text{ if } x > S$$

In the decoding process, the signal y(n) is reconstructed as follows:

$$y(n) = (\text{sign}). \ \alpha.S \quad \text{if magnitude bit=0}$$
$$y(n) = (\text{sign}). \ \beta.S \quad \text{if magnitude bit=1}$$

The parameters α, β, S are chosen so as to minimize the encoding-decoding error:

$$\varepsilon = \int_0^S (x-\alpha S)^2 . p(x) \ dx \ + \int_S^\infty (x-\beta S)^2 . p(x) \ dx$$

where p(x) is the probability density function (pdf) of the data. In the case of SAR data, one can assume a normal distribution $N(0, \sigma^2)$. By setting $S=k \ \sigma$, it can be shown that the optimal choise k_{opt} of k is given by the minimizer of the following function:

$$J(k) = \frac{1}{2} - \frac{(1-e^{-k^2/2})^2}{\pi.\text{erf}(k/\sqrt{2})} - \frac{e^{-k^2}}{\pi.\text{erfc}(k/\sqrt{2})}$$

The optimal values of α, β are given by:

$$\alpha^{opt} = \frac{\sqrt{2}.(1-e^{-k_{opt}^2/2})}{k_{opt}.\sqrt{\pi}.\text{erf}(k_{opt}/\sqrt{2})}$$

$$\beta^{opt} = \frac{\sqrt{2}.e^{-k_{opt}^2/2}}{k_{opt}.\sqrt{\pi}.\text{erfc}(k_{opt}/\sqrt{2})}$$

Therefore, BAQ consists of the following steps:

1) select N samples
2) estimate σ from these samples
3) encode each sample as indicated above

The estimation of σ from the samples is not a direct estimation: it uses a mapping from the rms value to the average magnitude of the data ([1]): this method avoids multiplications and is therefore more attractive from an on-board point of view.

b) Block Floating Point Quantizer

The BFPQ method was proposed originally by Joo and Held ([2]) for the Magellan mission. As for BAQ, BFPQ uses results on gausian signals quantization: it is known ([3]) that for a k-bit uniform quantizer, there exists an optimal value σ_k^{opt} that minimizes the quantization

and saturation noise. **The principle of BFPQ is to adapt the rms level of data to this optimal value while decreasing the number of quantization bits.** If x(i) denotes the original m-bit quantized signal , the compressed signal y(i) is obtained by a simple division:

$$y(i) = \frac{x(i)}{C}$$

The constant C is determined using the fact that:
      i) y(i) should be quantized on k bits
      ii) the rms of y is optimal

Then, it is straigtforward to show that C is given by:

$$C = \frac{2.\sigma_x}{(2^k - 1).\sigma_k^{opt}}$$

where σ_x is the rms level of input data. The BFPQ encoding scheme consists of the following steps:

      1) acquire N samples x(i) i=1..N
      2) estimate σ_x
      3) calculate C
      4) divide the original data by C

There exists numerous versions of this algorithm that can simplify it:

      i) σ_x can be estimated either directly either using the mapping method
      ii) C is rounded to the nearest power of 2: this enables the division to become a simple bit shift

An interesting implementation of the algorithm is to establish a direct mapping of σ_x to C's nearest power of 2. In this case, BFPQ can be resumed by:

      1) acquire N samples
      2) estimate the average magnitude
      3) read in a table the corresponding value of the scaling factor

This version requires only simple operations on integers and can be directly implemented on board.

c) FFT

In this section, we propose a generalisation of the popular Discrete Cosine Transform method of image compression ([4]) to the case of SAR data. As a matter of fact, DCT concerns real data and can not be applied directly to SAR data, which, by definition, is complex. We then propose to replace the Discrete Cosine Transform by a 2D Fast Fourier Transform (FFT), the compression scheme being now modeled by the following figure:
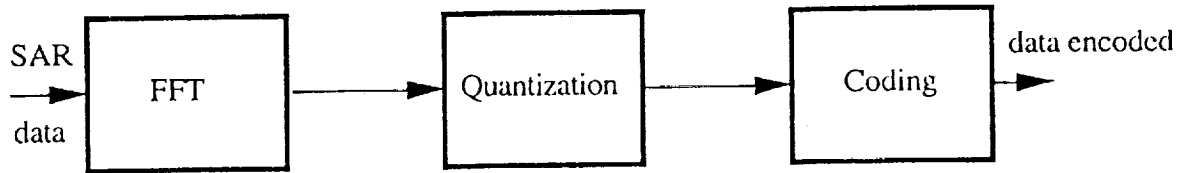
Figure 1: Block Diagram of FFT based SAR data compression

The original image is first partitioned into NxN pixel blocks and each block is independently transformed using the 2D Fourier Transform. The entropy of the transformed data is then estimated and the spectrum is quantized using 8 bits of resolution: given the original entropy, the quantization factor is chosen so that the entropy after quantization exactly matches the desired output bit rate. It is therefore supposed that the quantization process is optimal. Data is then coded using a loseless encoding algorithm (for instance, Huffman codes): since coding is supposed to be error free, it has not been simulated in this study. As can be seen, the algorithm used gives the optimal performance that can be acheived by this kind of method. It is to be noted that all the computations needed for this method were run using a floating point arithmetic, the analysis of errors due to fixed point implementation being beyond the scope of this study.

d) Presumming

The knowledge of some features of the radar signal suggests a more sensitive way to reduce the data flow in the spectral domain. In the range direction, the signal is shaped by the chirp generation which results in the spectral signature shown in figure 2:
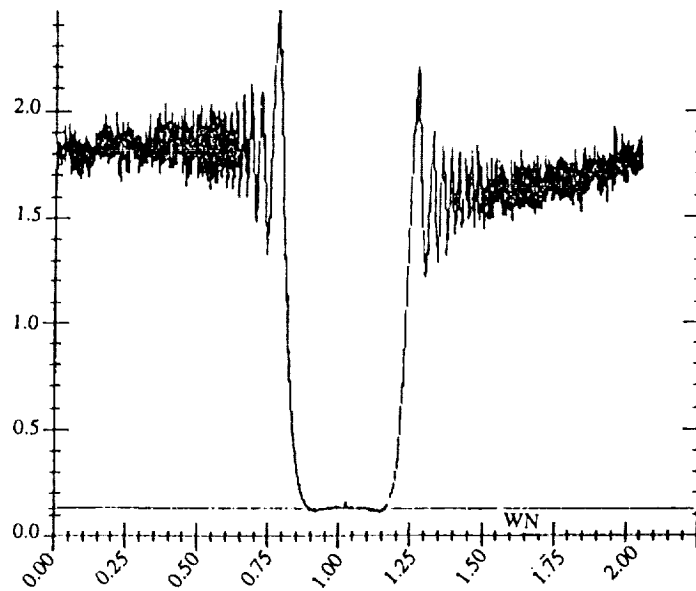

Figure 2: range spectral signature

The signal outside the "top hat" shape is noise and does not need encoding. In the azimuth direction, the signal is shaped by the antenna pattern once it has been aliased by the sampling phenomenon. Figure 3 shows an actual azimuth spectrum and, in dotted line, the actual shape of the antenna pattern once turned from the standard angular representation to the spectral representation. This spectral representation cannot be achieved in the real world due to unsufficient pulse rate of the instrument. As a result, the outermost contribution of the antenna pattern is aliased in the actual spectrum. The signal can then be modelled into three parts :

- a white noise floor WN
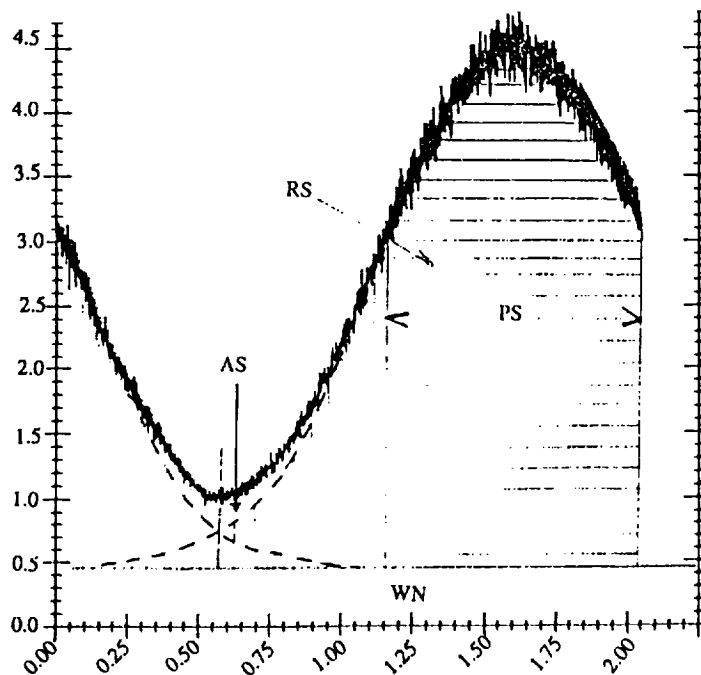- a useful radar signal RS
- a ambiguous radar signal AS

Figure 3: azimuth spectrum

The latter causes "ghosts" in the radar images, also called ambiguities, and should be eliminated. Standard compression schemes cannot make out a useful signal such as RS and an ambiguous signal AS since they have the same structure. It is also obvious that the signal to noise ratio is systematically greater in the central part of the spectrum.

The idea of presumming [5] is therefore to have a supervised coding of the 2D Fourier transform of the image. There would be no coding of the range region outside the useful signal (which results in a moderate saving of 20% or so). The coding in the azimuth spectrum would apply only to the central part where the signal to noise ratio is the highest. The loss of signal would amount to the vertically striped surfaces of figure 3, and the useful signal to the horizontally striped surface (the presommation span PS represented in figure 3 is just an illustration, not an actual value).

Presumming could easily achieve a factor of two in data compression with a minimal signal loss and an improvment of the quality due to the elimination of most of the ambiguous signal. This is true regardless of any further encoding of the conserved data.

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III) EVALUATION CRITERIA

a) SAR data

In order to evaluate the performances of the different algorithms, a set of criteria were developped for both SAR data and SAR image. In the following, we suppose an image of width LX and height LY and note z(i,j) (resp. z'(i,j)) the pixel of the ith raw and the jth column of the original (resp. encoded-decoded) data. The following criteria are considered for SAR data:

Mean Square Error (MSE):
$$MSE = \frac{1}{LX.LY} \sum_{i=1}^{LY} \sum_{j=1}^{LX} |z(i,j) - z'(i,j)|^2$$

Maximum error:
$$E_{max} = max \left[\frac{|z(i,j) - z'(i,j)|}{|z(i,j)|} \right]$$

Phase Mean Square Error:
$$MSE_\phi = \frac{1}{LX.LY} \sum_{i=1}^{LY} \sum_{j=1}^{LX} |\phi(i,j) - \phi'(i,j)|^2$$

Peak Signal to Quantization Noise Ratio:
$$PSQNR = 10.log \left[\frac{max(|z(i,j)|^2)}{MSE} \right]$$

Average Signal to Quantization Noise Ratio:
$$ASQNR = 10.log \left[\frac{\frac{1}{LX.LY} \sum_{i=1}^{LY} \sum_{j=1}^{LX} |z(i,j)|^2}{MSE} \right]$$

b) SAR image

An image acquired by ERS1 over southwest France in september 1991 was used as a testbed for the methods described in this paper. The image features ocean surface, homogeneous areas of forested or agricultural surfaces, highly contrasted areas such as the city of Bordeaux and some individual objects which are corner reflectors (two corner reflectors were placed in low backscatter regions) and which were shown to behave as corner reflectors (point targets).

A number of radar image quality criteria [6], which exceed the scope of this paper, were computed in addition to more standard data compression criteria, we may cite :

- range or azimuth resolution
- integrated sidelobe ratio
- ambiguous target ratio
- standard deviation/mean ratio over homogenous areas

More details about the results of this study are available in [7].

V) APPLICATION

The four above described methods were applied to an image provided from ERS1 and representing the scene of Cazaux (France). The original data had the following characteristics:

* data precision: 5 bits per I and Q sample
* data type: unsigned byte
* data range: [0,31]
* data entropy: approximately 4,7 bits
* data properties: approximately Gaussian distributed with mean and rms:

$$m = 15.31866 + j\ 15.37417$$
$$\sigma = 6.733508 + j\ 6.706872$$

* signal size: 10240 lines x 5616 complex samples

For all the methods, the image was partitioned into 128x128 blocks and each block was independently compressed and decompressed. The encoded/decoded data was then compared to original data by means of the above described criteria. The programs were written in Ansi C and run on a Sparc IPX station. The following tables show the SAR data evaluation criteria:

Criterion	BAQ	BFPQ(5,2)	FFT(5,2)	PRE(5,2)
mean	15.51 +j15.56	15.23 +j15.27	15.32 +j15.37	15.32 +j15.37
rms	6.94 +j6.92	4.67 +j4.64	6.86 +j6.83	6.4 +j6.386
MSE	9.758	19.625	**7.044**	12.8
E_{max}	6.4	1	9.487	14.56
MSE_ϕ	**1.13E-1**	1.17	6.65E-1	8.36E-1
PSQNR(dB)	17.2	14.165	**18.615**	16.02
ASQNR(dB)	9.7	6.67	**11.12**	8.53

*Table I: SAR data evaluation criteria for **2 bit compression***

Criterion	BFPQ(5,3)	FFT(5,3)	PRE(5,3)	PRE(5,3) no coding
mean	15.31 +j 15.35	15.32 +j 15.37	15.32 +j 15.37	15.32 +j 15.37
rms	5.7 +j 5.7	6.76 +j 6.74	5.23 +j 5.22	5.89 +j 5.88
MSE	5.28	**1.85**	9.957	19.048
E_{max}	**1**	5.385	13.93	17.09
MSE_ϕ	7.11E-1	**3.573E-1**	7.41E-1	9.547E-1
PSQNR(dB)	19.87	**24.42**	17.11	14.294
ASQNR(dB)	12.37	**16.92**	9.62	6.8

*Table II: SAR data evaluation criteria for **3 bit compression***

Concerning SAR data, it seems that the FFT provides either for 2 or 3 bits the best results. Nevertheless, in the case of 2 bit compression, BAQ is shown to perform nearly as well as FFT: more, the computational requirements for BAQ are very inferior compared to FFT. Consequently, for a 2 bit compression scheme, BAQ seems to provide the best trade-off between performance and complexity. In the case of 3 bit compression, it is more difficult to establish a hierarchy between the methods: if FFT is shown to have the best performances, this algorithm is more complicated than BAQ, BFPQ and Presumming with no coding.

The major conclusions of SAR image criteria [7] could be itemized below :

- all algorithms produce errors on the phase of image pixel,
- FFT algorithm reproduces images better than the other algorithms,
- Presumming algorithm is a very interesting algorithm : its performance is very near to FFT (its complexity is lower),
- BFPQ (5,3) and BAQ (5,2) are however very similar to FFT in terms of image quality for a city.

The images before and after compression-decompression can be found at the end of the paper.

V) CONCLUSION

We have presented in this paper four compression algorithms for raw SAR data. These algorithms have been developped in C language on a SUN station. Their performances have been studied and compared through image quality criteria, data criteria and complexity criteria on data supplied from ERS-1. The choice of the best algorithm (specially for space on-board application) is indeed a trade-off between performance and complexity.

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[7]   B. Rogron ,"Compression des données brutes SAR et Qualité des Images synthétisées", *Internal memo* CT/IA/QTIS/PR n°646 18-10-1993
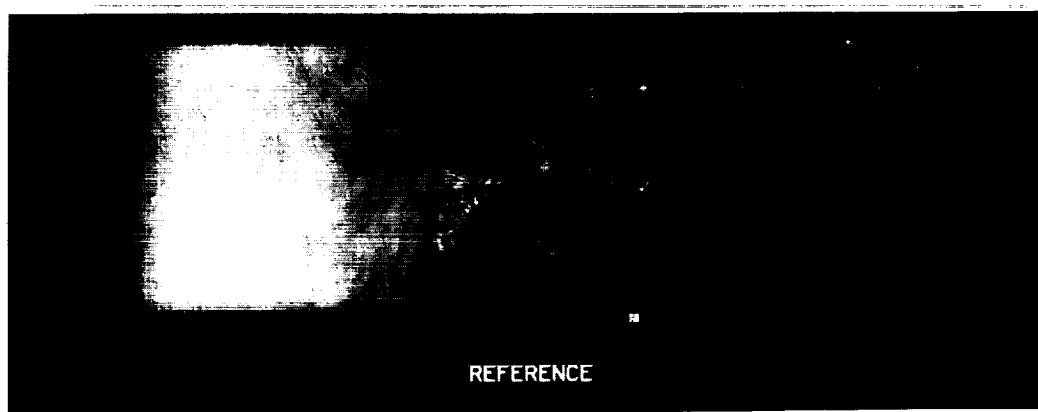
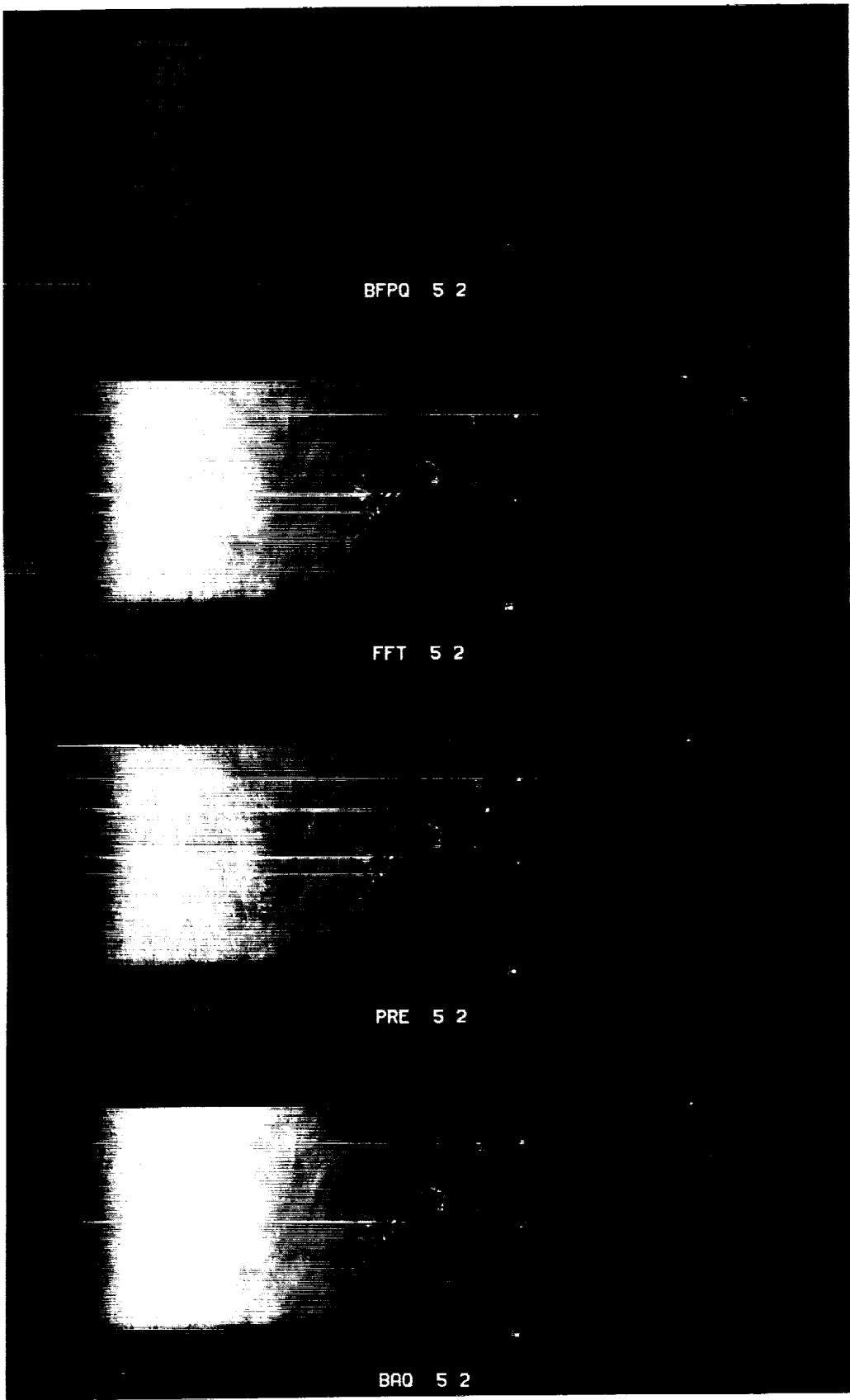*Figure 4: Reference image from ERS-1*
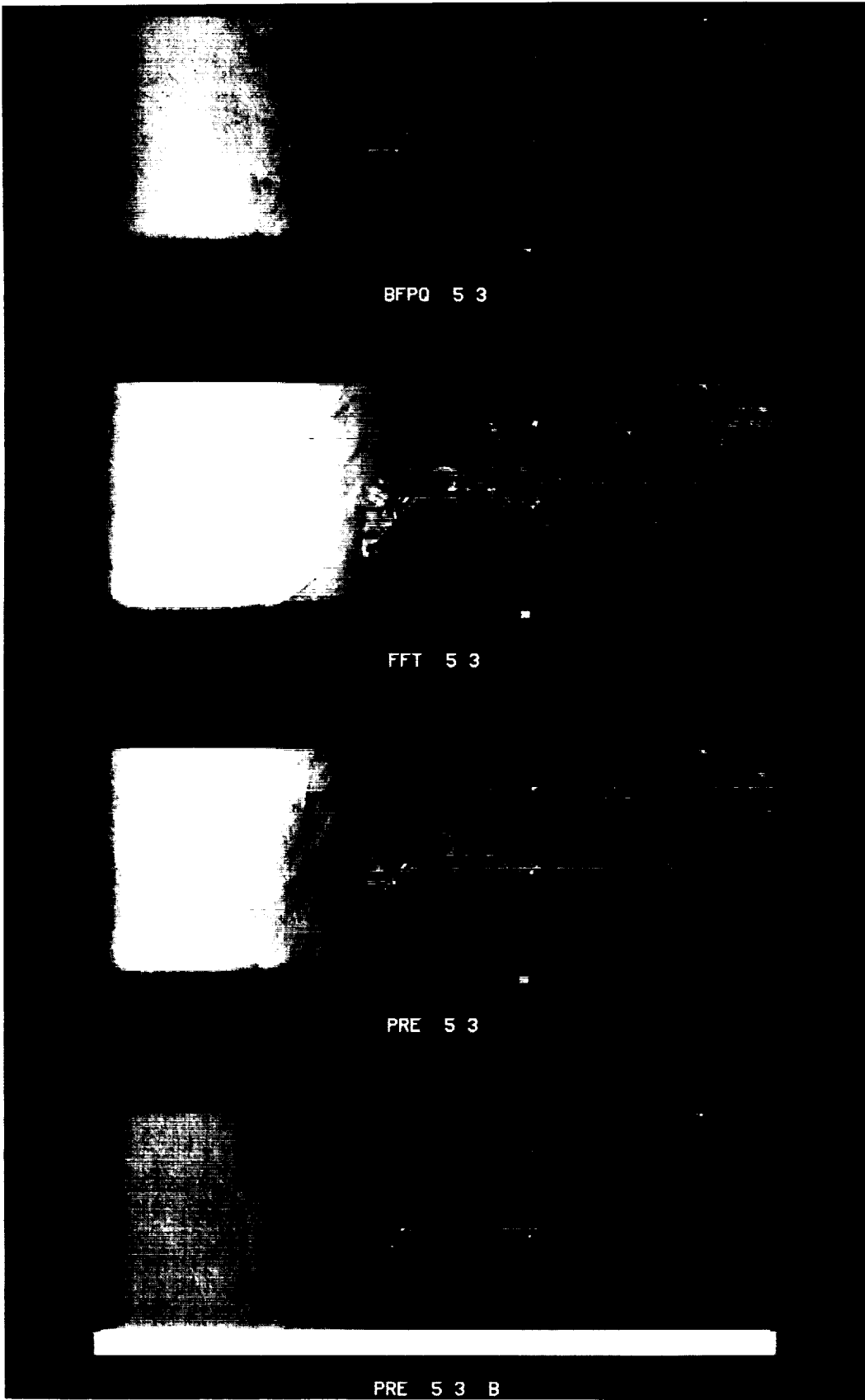
Figure 5: Image after 2 bit compression and decompression

Figure 6: Image after 3 bit compression and decompression