Data Rate Reduction Techniques Suitable for SAR Interferometer Application

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1. INTRODUCTION

A BAQ algorithm has been developed able to compress a 8 bit data stream into 2,3 or 4 bits.

The basic principle of the algorithm is the same of the one adopted for the Magellan Mission [KWO89] [GRA71][COL76], that's to estimate the power of the incoming signal, assumed Gaussian distributed, quantized into 8 bits for each I and Q component and requantized the signal with a non uniform 2, 3 or 4 optimum quantizer, the thresholds of which have been computed in order to cover the dynamic range estimated for the block of signal in use.

The great innovation in our approach is the reduced amount of memory for the quantizers threshold, with respect to the Magellan scheme, obtained by using only a limited number of quantizers to cover the 8 bit ADC dynamic range.

That has made the device feasible for 3 and 4 bit compression ratios, which following the Magellan scheme would have had an unacceptable memory requirement.

The algorithm has been tested on real data utilizing the ERS_1 data and AIR_JPL Data by quantizing the data by the BAQ algorithm and processing the quantized raw data by the SAR processor and successively comparing the resulting image with the one obtained from the original uncompressed raw data.

The performance have been measured by comparing the results in term of variation of the interferometric images correlation and also in terms of degradation of the single image quality by comparing the images obtained from the uncompressed raw data and the ones obtained from the compressed raw data.

At present a 4 bit BAQ is under study; the 4 bit BAQ has been simulated.

Results are much more promising for the 4 bit than for the 3 ones.

2. THE BAQ ALGORITHM

The basic principle of the BAQ algorithm is illustrated in figure 2-1 (see Annex) for the 3 bit version.

The figure shows the performance, in terms of Noise to Signal Ration of the 3 bit BAQ.

A -15 dB Noise to Signal Ratio at ADC output can be performed over a dynamic input range of about 33 dB. This range has to be handled by 16 3 bits optimum quantizers; each of them is capable of a N/S performance equal to -14.6 dB at best. Each curve in figure 2-1 represents the SNR performance of a 3 bit optimum quantizer.

Coverage is achieved by subdividing that range into 16 intervals each spaced 2.1 dB.

In such a way a whole dynamic range of 33.6 dB may be guarantied. Over such a range a minimum S/N performance of 13.5 dB is assured.

The right comparator is selected on the basis of an estimate of the signal power.

Such an estimate is carried out on a subset of a single PRF line 128 samples long.

The incoming signal has been supposed Gaussian and has zero mean on its In-phase and Quadrature components. That allows the computation of the signal variance throughout a the average of the mean of the absolute values of I and Q summed up together. The estimated probability of selecting the neighbouring comparator instead of the correct one is connected with the power of the particular block. Its expected value can be calculated as a weighted mean; for a Rayleigh power distribution mistaking probability is less then 2 % in our design. Performance loss in mistake case is less than 0.5 dB for a 2.1 dB spacing.

Implementation of the algorithm is fully digital. Each theoretical quantizer (analog) is defined by a set of 3 positive real threshold values, difficult to be dealt with. Then analog quantization problem has been converted into its numerical equivalent one, translating both threshold values and input signal values into numerical codes. A self-consistent analysis which takes into account all effects related numerical data handling has been carried out, and final results consider quantization, saturation, integer rounding and integer statistic distribution. The whole Noise/Signal performance is finally delivered.

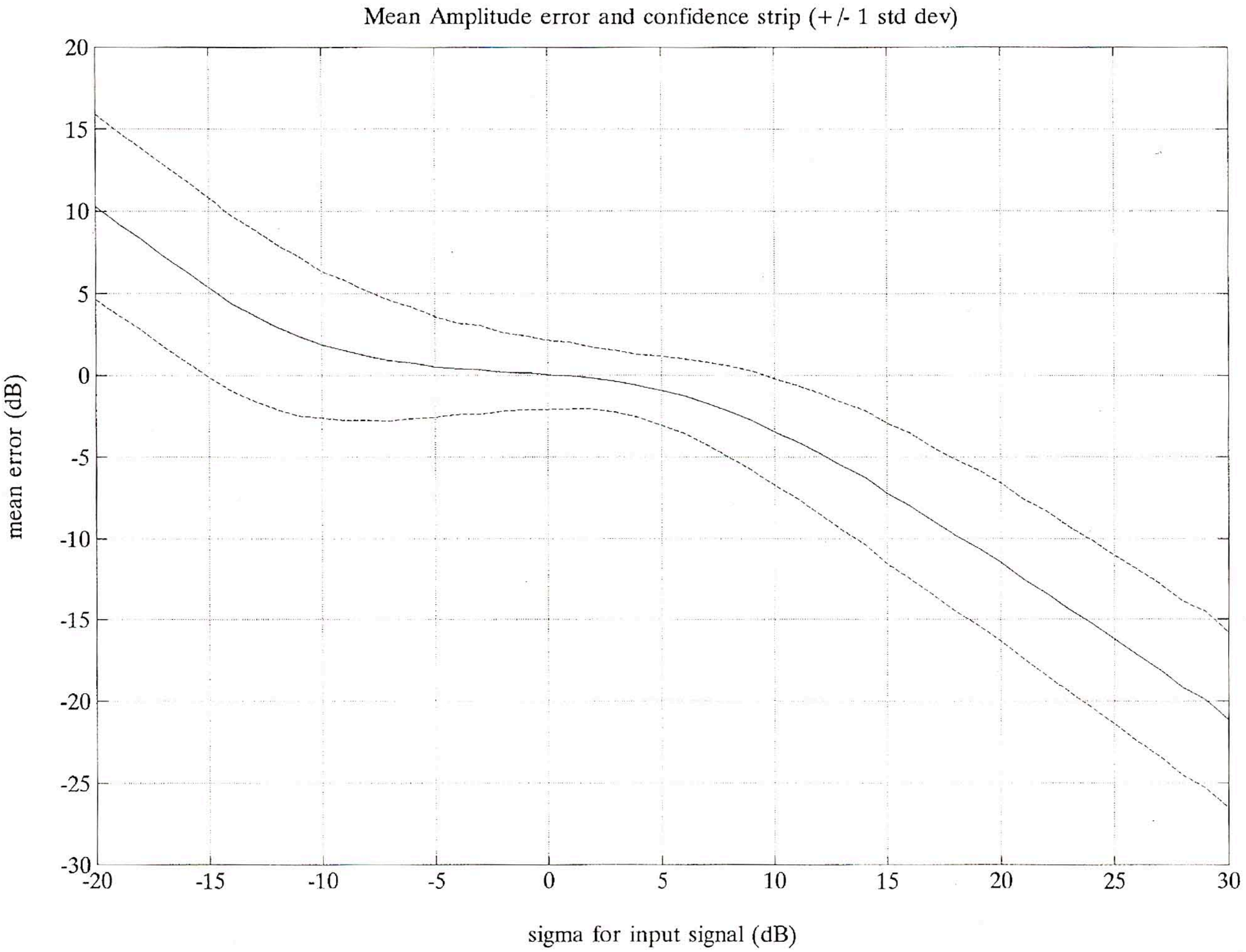

Figure 2-1. 3 bit BAQ performance.

3. ALGORITHM PERFORMANCE

Algorithm performance has been analytically evaluated in terms of:

- Quantization noise power and signal to noise power on the single I and Q component.
- Amplitude and Phase error for complex raw data.

Performance of an optimum quantizer for complex signals are analysed in a way as it's typically required for SAR systems analysis.

Let i(t) and q(t) be two independent stocastic processes with the following characteristics:

a) zero mean

b) Gaussian Distribution

c) Time slow varying variance (the same for i and q)

i (t) and q (t) are respectively the inphase and quadrature part of the signal

$$r(t) = m(t)e^{j\phi(t)}$$

where m and ϕ are real function of the variable t.

As it's well known, m is Rayleigh distributed and ϕ is uniformly distributed.

Let i (t) and q (t) be both quantized by the OQ (Optimum Quantizer) and determine for them the relevant amplitude and phase errors.

The phase error can be defined as:

$$\varepsilon_\phi (z) = arg(z_q) - arg\ (z) = \angle z_q - \angle z$$

where

$$z = i + jq$$

is the input signal and

$$z_q = i_q + jq_q$$

is its quantized version.

The mean square value of E_ϕ, can be computed

$$\overline{\varepsilon_\phi^2(z)} = \sum_{i=1}^{N_p} \int_{z\varepsilon 1(z_q)} (\angle z_q - \angle z)^2\ P\ (z)dz$$

The above equation can be written as

$$\overline{\varepsilon_\phi^2(z)} = 4 \sum_{l=1}^{4} \sum_{m=1}^{4} \int_{S_{l-1}}^{S_l} dx_I \int_{S_{m-1}}^{S_m}$$

$$(\Theta (y_l , y_m) - \Theta (x_I , x_Q))^2 P (x_I) P (x_Q) dx_Q$$

the values S_k, are the quantizers thresholds.
With the following assumptions:

$$\{S_k\}_{k=0,\dots,4} = (0 , \bar{S}_1 , \dots\dots \bar{S}_3 , \infty) \sigma$$

$$\Theta (x_l , x_Q) = \angle (x_l + jx_Q)$$

$$\Theta (y_l , y_m) = \angle (y_l + jy_m)$$

$$P (x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}$$

where $\bar{S}_K$
are the normal i z ed thre sholds.
Exploiting symmetry wrt the real and the imaginary part, the integral computation can be performed for the positive quadrant only.
The thresholds are the ones of the 3 bit OQ; the signal σ is assumed to be the same both for i(t) and q(t).
Similarly and amplitude error can be defined.

$$\varepsilon_g (z) = 20\log_{10} \frac{| z_q |}{| z |}$$

$$\overline{\varepsilon_g^2(z)} = 4 \sum_{l=1}^{4} \sum_{m=1}^{4} \int_{S_{l-1}}^{S_l} dx_I \int_{S_{m-1}}^{S_m} 20\log_{10}$$

$$\left(\frac{| z_q |}{| z |}\right)^2 P (x_I) P (x_Q) dx_Q$$

for which it has been assumed:

$$| z | = \sqrt{x_I^2 + x_Q^2}$$

$$| z_q | = \sqrt{y_l^2 + y_m^2}$$

Results are in figure 3-1. and 3-2. (See Annex) show $\overline{\varepsilon_g^2}$ and $\overline{\varepsilon_\phi^2}$ as a function of the standard deviation of the single channel σ_ε.

Let note, as it can be expected, $\overline{\varepsilon_g^2}$ is almost zero for $\sigma_\varepsilon = \sigma_{opt}$ $(OdBV)$ and $\overline{\varepsilon_\phi^2}$ has a minimum for

$$\sigma_{inp} = + 5dBV$$

This minimum is about 5° RMS. Integrals have been evaluated by means of stocastics method.

Noise to Signal ratio can be re-written as following :

$$\frac{N}{S} = \frac{1}{2\sigma^2} \sum_{l=1}^{S_l} \sum_{m=1}^{S_m} \int_{S_{l-1}}^{S_l} dx_I \int_{S_{m-1}}^{S_m}$$

$$| z_q - z |^2 P (x_I) P (x_Q) dx_Q$$

where a signal power tantamount the sum of the power on each channel x_I (σ^2) and x_Q (σ^2).
Result are shown in figure 3-3 (see Annex).

4. SIMULATION RESULTS

A couple of "accidental interferometric data" from Air-JPL airborne SAR have been used in our simulation. The data set used is relevant to Ventura California (see figure 4-1.) Raw data sets have been SAR processed by out in house SAR processor, with and without having been compressed by the BAQ algorithm. The final images (BAQ compressed and not) have been compared.
An error function between the original 8 bit image and the 3 bit compressed one has been defined.
The error figure has been defined as

$$\varepsilon (p) = 10\log_{10} \frac{A_{BAQ} (p)}{A_0 (p)}$$

where p is a generic pixel in the image and $A_{BAQ} (p)$ and $A_0 (p)$ are the image amplitude in the BAQ quantized image and in the original one respectively.
Of the above defined error figure they have been computed

$$\bar{\varepsilon} = < E (p) >$$

and

$$\sigma_\varepsilon = \sqrt{< \varepsilon^2 (p) > - < \varepsilon (p) >^2}$$

where the average is performed over the whole image.
$\varepsilon (p)$ shows the BAQ error contribution to radiometric accuracy error of the single resolution element, while $\bar{\varepsilon}$ and σ_ε are statistically related to the ground reflectivity function involved in the SAR image formation processing.
The result of simulation are shown in figure 4-2.
An histogram of such an error is shown in figure 4-3.
The colour image shows pixel by pixel the amplitude error caused on the compressed image by the BAQ re-quantization versus the image processed from the original data.
The chrome scale ranges from -0.8 dB (red) to +0.8 dB (Blue) with 0.1 db step.
The error is typically positive because of the quantization noise power that is added to the signal power.
It is well pointed out over low reflectivity regions (sea, rivers) which appear covered by noise.

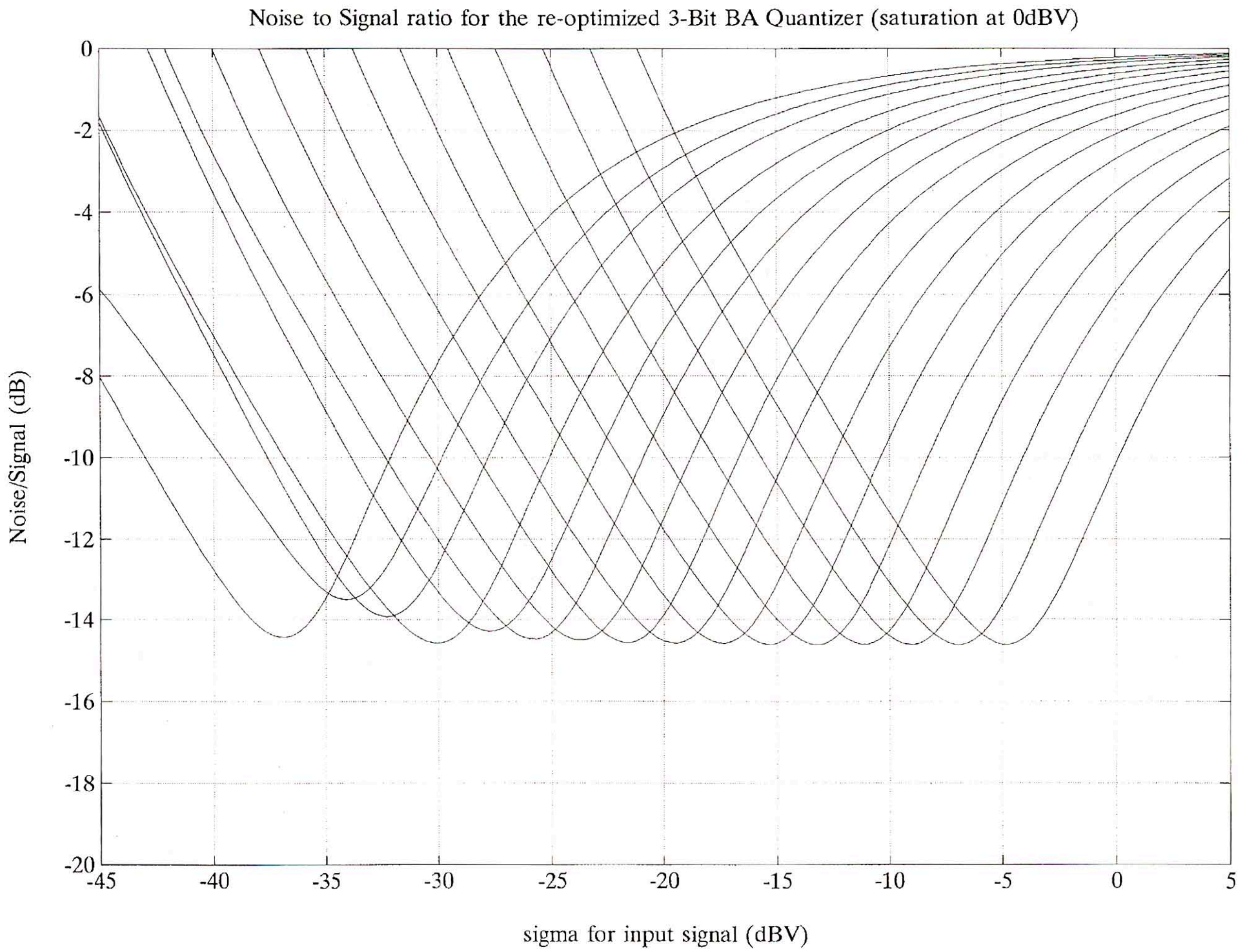

Figure 3-1. Amplitude error for 3 bit Optimum Quantizer.

In an analogous way the phase error on a single SAR image has been evaluated.
The error function has been defined as

$$\varepsilon_\varphi = \sqrt{\frac{\sum_{\iota=1}^{8} (\phi_\iota^B - \phi_\iota)^2}{8}}$$

Results are shown in figure 4-4.
The chrome scale ranges from 0 degrees (red) to 30 degrees dB (Blue) with 2 degrees step, typical values ranges from 6 to 12 degrees.
Obviously, features of the image can still be recognized as the phase error is inversely proportional to the pixel amplitude.
We also have simulated a 4 bit Block Optimum quantizer in order to estimate the improvement. Results are in figure 4-5., for what concerns the amplitude and 4-6. for what concerns the phase. Improvement is manifest. The phase error lowers down and dominant value ranges from 6 to 8.

5. EVALUATION OF THE INTERFEROMETRIC IMAGE COHERENCE FUNCTION

A further activity has ben carried out to evaluate the loss of images coherence due to BAQ quantization between two interferometric images.
Data of both the antennae have been SAR processed, the two resulting images have been registered and interpolated to a 1/8 of the pixel and the complex correlation coefficient y has been evaluated on four homogeneous subimages.

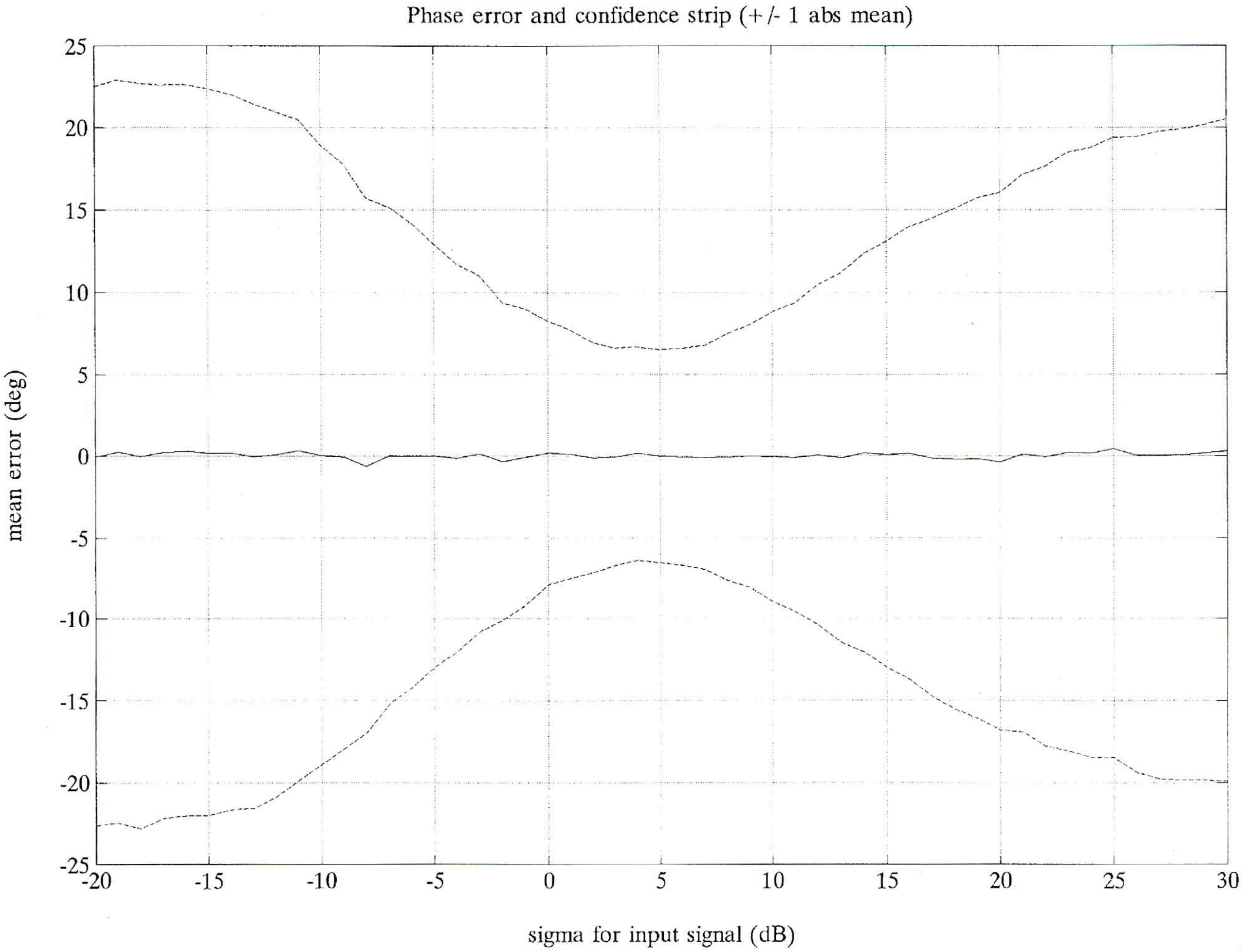

Figure 3-2. Phase error for a 3 bit Optimum Quantizer.

The same procedure has been applied to the data sets to which a 3 bit BAQ has been previously applied.
Results are shown on the side of each subimage (see figures 5-1.,2.,3. 4. and 5.) and summarized in table 5-a.

Table 5-a

SUBIMAGE	$\hat{y}$	$\hat{y}_{BAQ}$
Down left	0.810	0.780 (**.78**)
Down right	0.78	0.750 (**.753**)
Up right	0.897	0.892 (**.87**)
Up left	0.669	0.64 (**.65**)
Central	0.7	0.674 (**.68**)

y has been estimated as:

$$\hat{y} = \frac{< V_1 V_2^* >}{\sqrt{< V_1 V_1^* > < V_2 V_2^* >}}$$

The size of the area, inside the subimage, was 32 by 32 pixel.
The correlation coefficient y is bound to the SNR by the following relationship.

$$y = \frac{\alpha}{1 + SRN^{-1}}$$

α the geometric correlation has been estimated on the basis of the geometry of the system and a maximum residual registration error of 1/8 of the pixel.
alpha is about 0.9797.
Assuming the above value for α, the SNR can be derived.
The loss in SNR due to 3 bits quantization is known hence the y for 3 bit BAQ compressed data can be computed.
Computed values are in the right most column of table 5-a. in parenthesis.
Agreement of estimated and computed values is pretty high except for the up right subimage for which the value estimated over the image is higher than the expected one. That can be explained by the fact that the area is an urban one to which the correlation model can be applied.
We finally have carried out a preliminary analysis to relate phase error evaluated on a single image to improvement of interferometric phase uncertainty due to BAQ quantization.

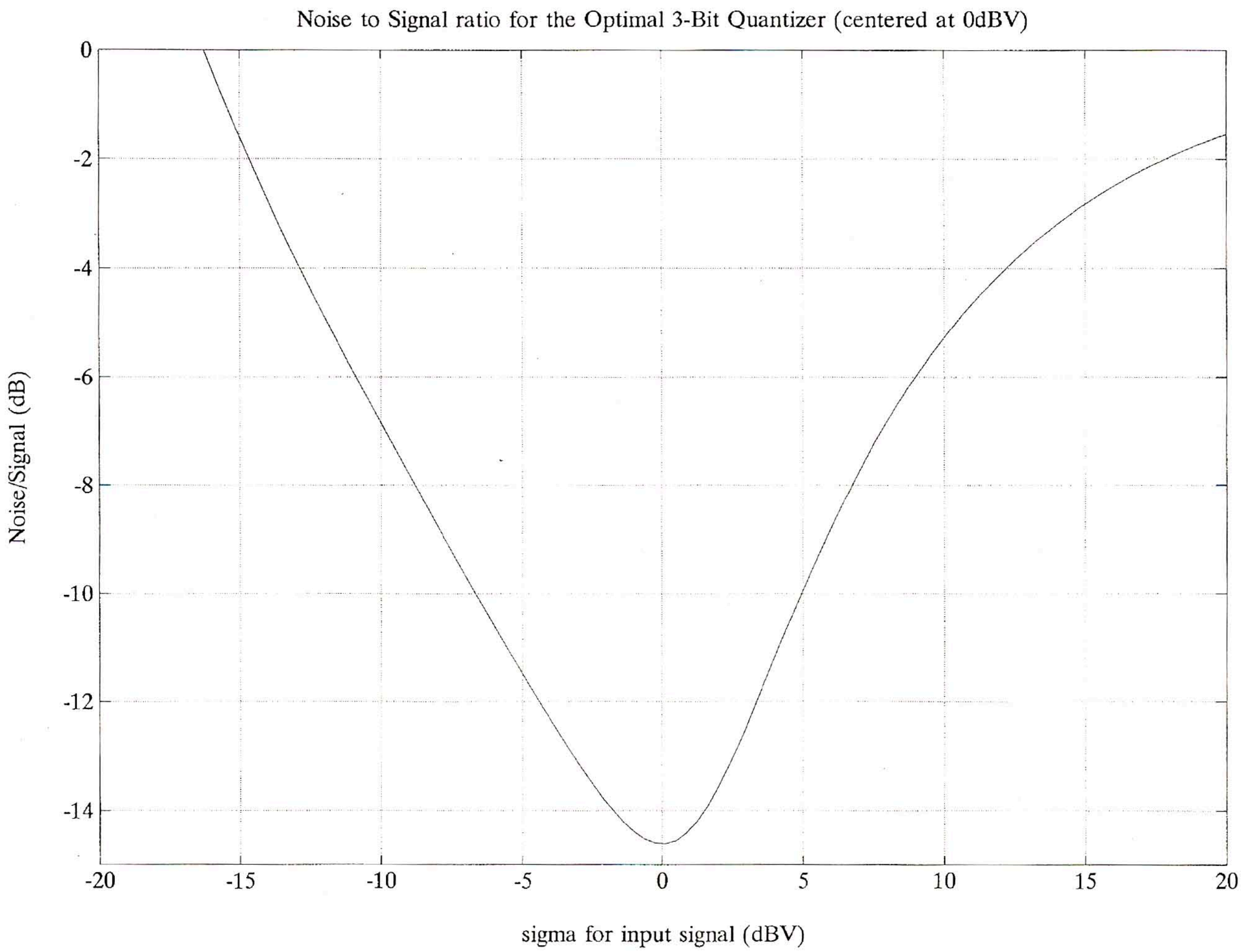

Figure 3-3. SNR for an Optimum 3 bit Quantizer.

Let σ_ϕ be the interferometric phase uncertainty of the original data set and σ_ϕ^B the one relevant to the BAQ Data sets. (Both raw data sets have been BAQ compressed before SAR and Interferometric processing).
It can be written

$$\sigma_\phi^B = <(\hat{\sigma}_\phi^B - <\hat{\sigma}_\phi^B>)^2>^{1/2}$$

where $<\sigma_\phi^B> = 0$ and $\phi^B = \Phi_{1B} - \Phi_2 B$ is the inteferometric phase computed on the compressed images.
Hence

$$\sigma_\phi = <(\hat{\sigma}_\phi)^2>^{1/2} = <(\Phi_1 - \Phi_2)^2>^{1/2}$$

$$\sigma_\phi^B = <(\hat{\sigma}_\phi^B)^2>^{1/2} = <(\Phi_{1B} - \Phi_{2B})^2>^{1/2}$$

The phase uncertainty with BAQ quantization related to the one without BAQ as:

$$(\sigma_\phi^B)^2 = \sigma_\phi^2 B^2 + \varepsilon_{\psi_1}^2 + \varepsilon_{\psi_2}^2$$

where ε_ψ is the RMS value of the phase error on the single image.
The above relationship has been verified on the down left frame of the scene.
Phase error E_ψ is the same for the two images.
Statistics of the phase error has been computed for all the sub image and separately for the upper and the lower part, results are in table 5-b.

Table 5-b

SUBIMAGE	$\bar{\varepsilon}_\psi$	σ_ψ
Whole	2.255°	11.60°
Upper part	0.9°	7.19°
Lower part	3.6°	14.62°

The expected interferometric phase error, computed by simulation, relevant to a y of **0.81 without BAQ** is, for single look interferogram, **50.66°**.

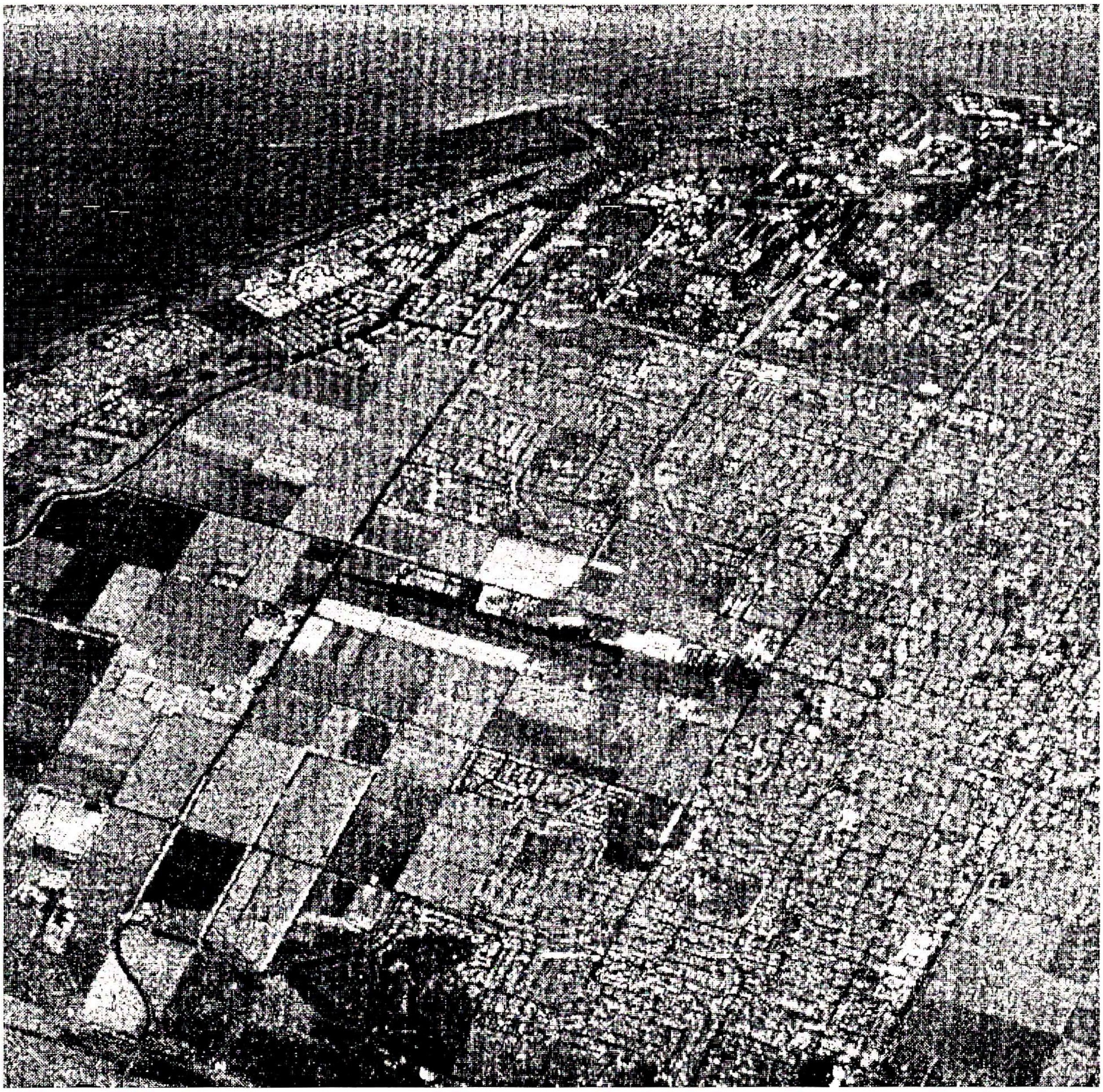

Figure 4-1. Ventura SAR Image.

For the same area the estimated y **with BAQ** is **0.78** to which a phase error of 54.9 corresponds.
Using the relation:

$$(\sigma_\phi^B)^2 = \sigma_\phi^2 B^2 + \varepsilon_{\psi_1}^2 + \varepsilon_{\psi_2}^2$$

we get

$$\sigma_\phi^B \sqrt{(50.66^2 + 2^* 14.62^2)} = 54.71$$

The higher value of 14.62° has been used since it has been estimated over the same area used for y estimation.

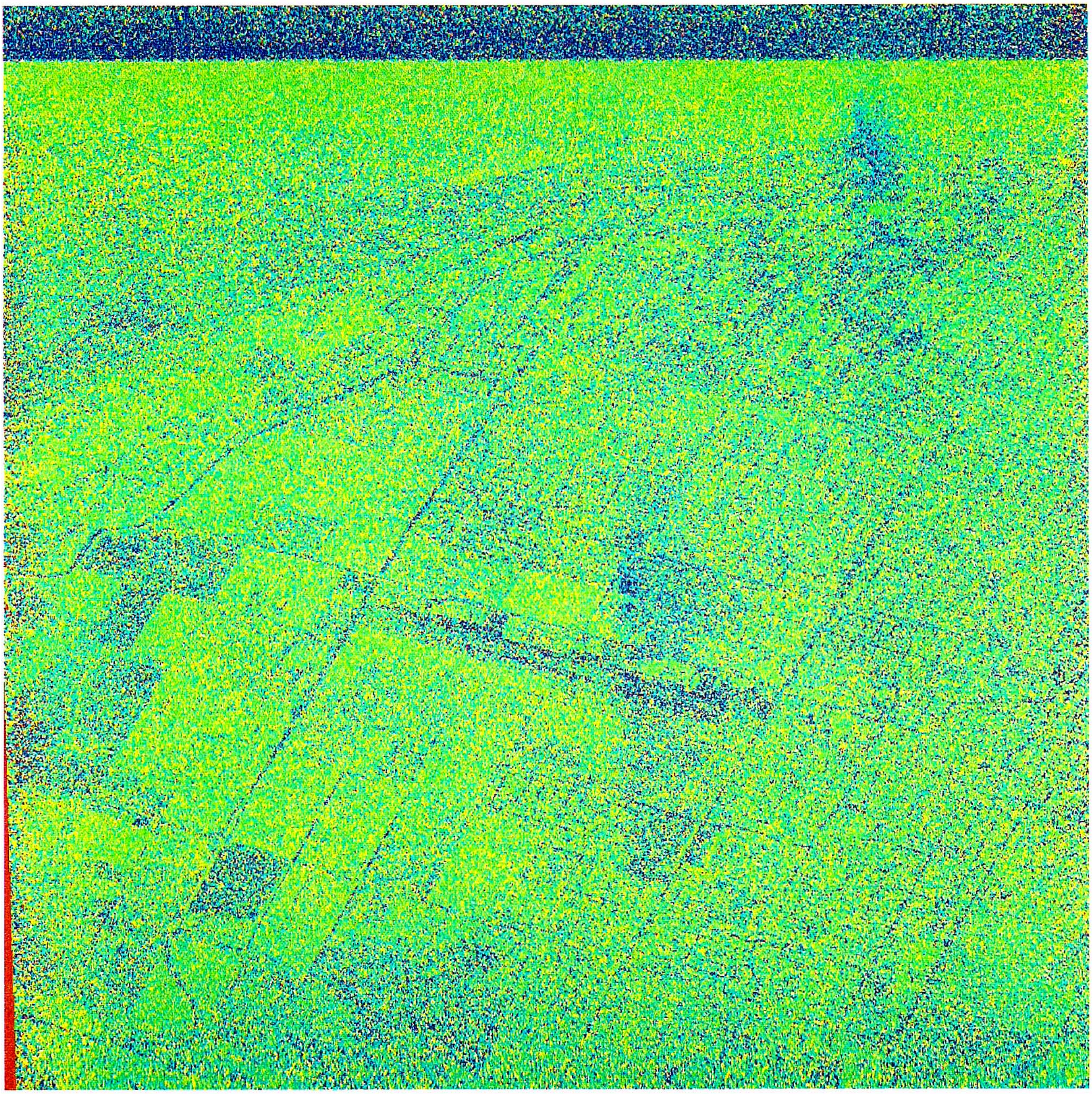

Figure 4-2. Amplitude error for Ventura image with and without 3 bit BAQ quantization.

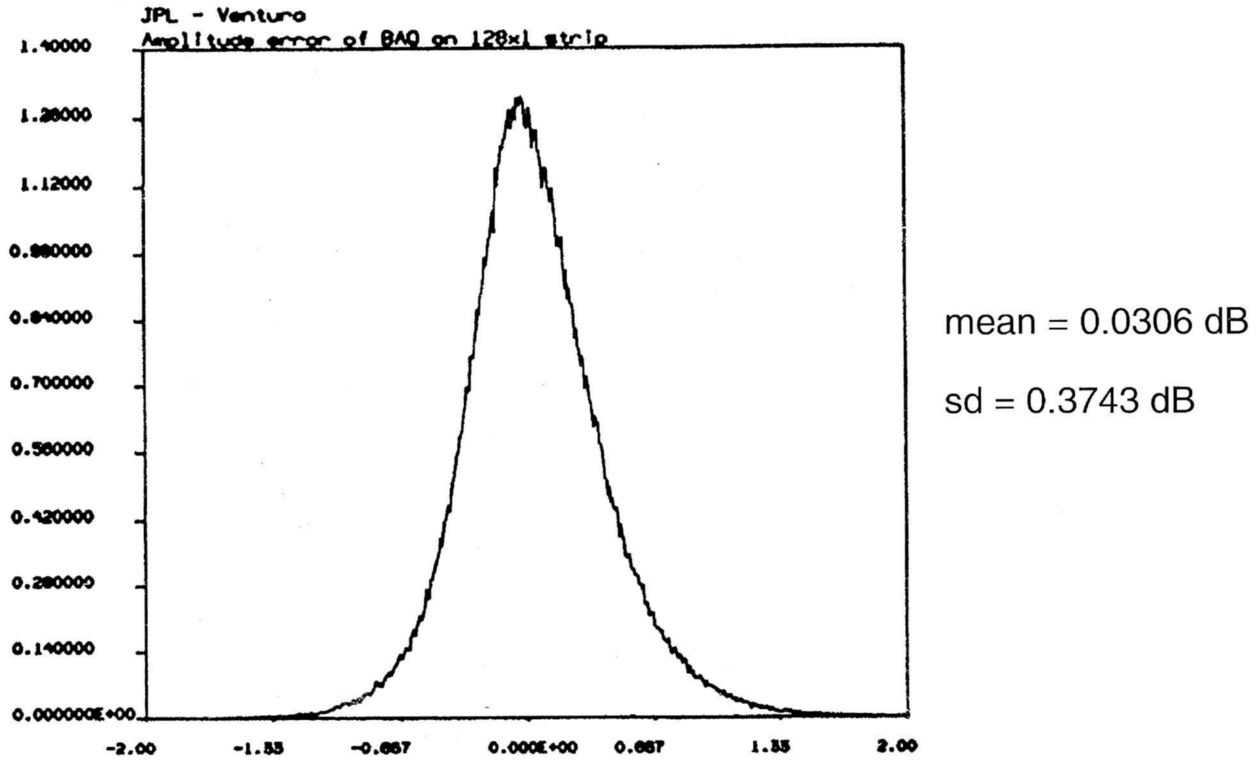

Figure 4-3. Histogram of the amplitude error for Ventura image with and without 3 bit BAQ quantization.

CONCLUSION

Effects of data compression on the error of the interferometric phase as been studied.
A method to relate interferometric phase error to the phase error on the single image has been derived.
Working on the phase of the single is much more simple since avoids phase ambiguity problems.
A four bit 4 BAQ, despite its higher complexity wrt a 3 bit ones, is of course more suitable then a 3 bit one for phase preserving. However, for example, a gamma increment from 0.81 to 0.78 (3 bit BAQ effect) for an 8 look image implies a change of interferometric phase error from 11.64° to 12.45° which correspond to a deterioration of the height estimate of 7%.
It must be keep in mind that we trade this worsening for a data rate reduction of 62 %.
It must be also pointed out that such a BAQ system accommodates a wide dynamic of the input signal 33.6 dB for the 3 bit (SNR>13 dB) BAQ and a 25.6 for the 4 bit one (SNR>13.5 db).

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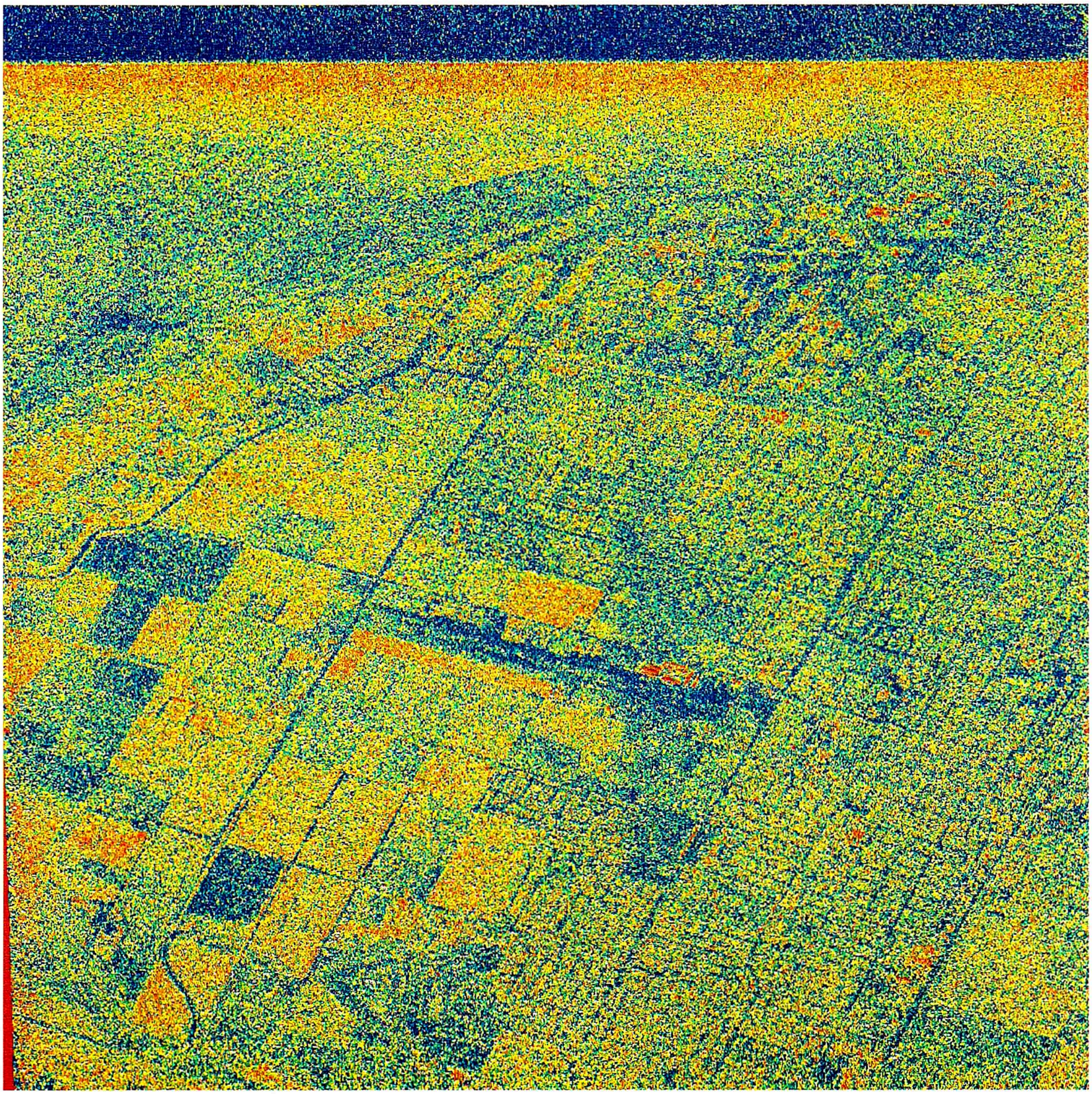


Figure 4-4. Phase error for Ventura image with and without 3 bit BAQ quantization.

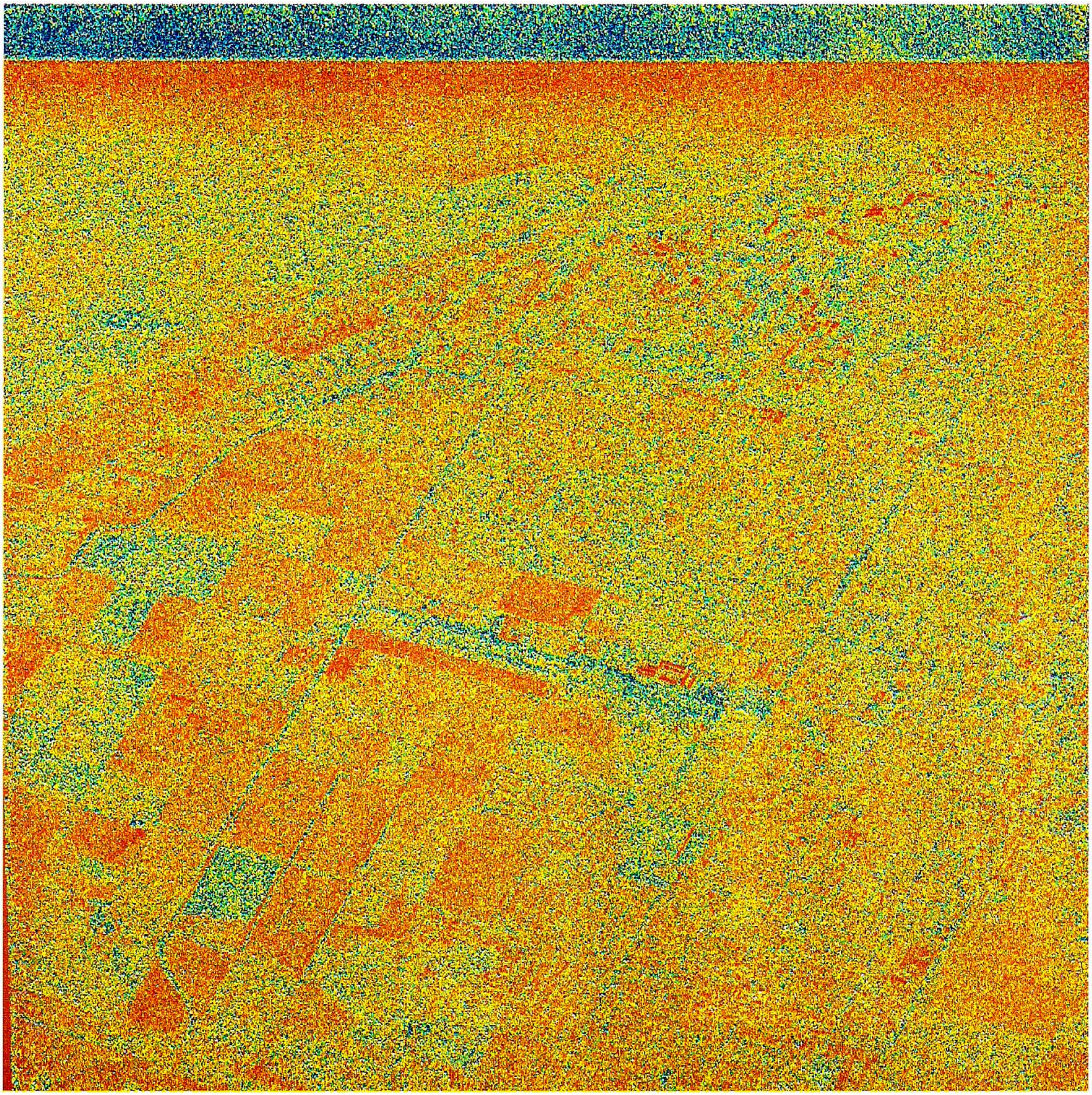


Figure 4-5. Amplitude error for Ventura image with and without 4 bit BAQ quantization.

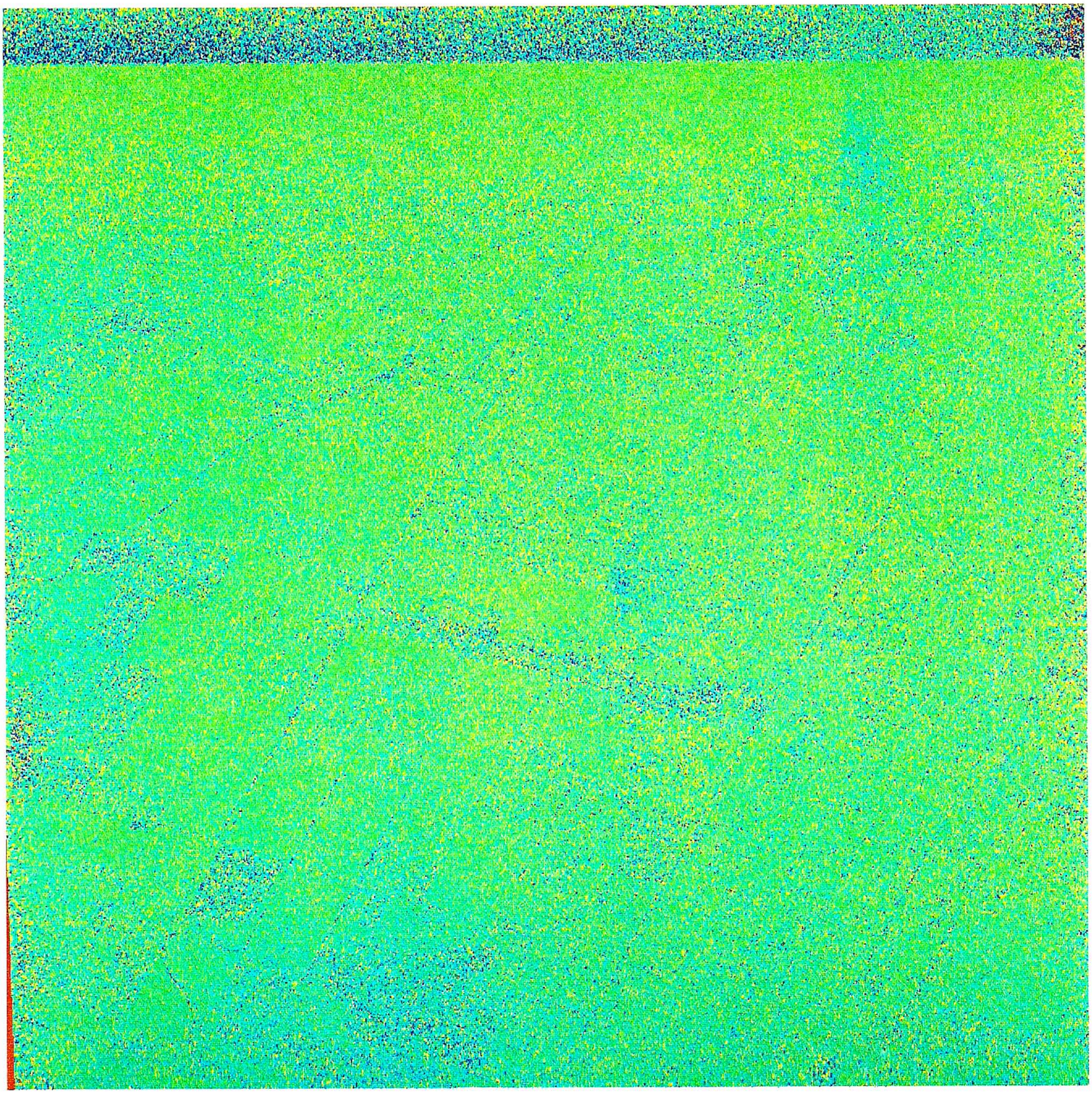


Figure 4-6. Phase error for Ventura image with and without 4 bit BAQ quantization.

POSITION IN WHOLE IMAGE :
AZIMUTH = (128, 256)
RANGE = (257, 512)

RANGE SHIFT = 2.125
AZIMUTH SHIFT = -12.750

CORRELATION COEFFICIENT γ :
WITHOUT BAQ PROC. = 0.669
WITH BAQ PROC. = 0.64

Figure 5-1. Correlation coefficient γ estimated for the upper left frame with and without 3 bit BAQ quantization.

POSITION IN WHOLE IMAGE :
AZIMUTH = (128, 256)
RANGE = (769, 1024)

RANGE SHIFT = 2.25
AZIMUTH SHIFT = -13.0

CORRELATION COEFFICIENT γ :
WITHOUT BAQ PROC. = 0.810
WITH BAQ PROC. = 0.780

Figure 5-2. Correlation coefficient y estimated for the lower left frame with and without 3 bit BAQ quantization.

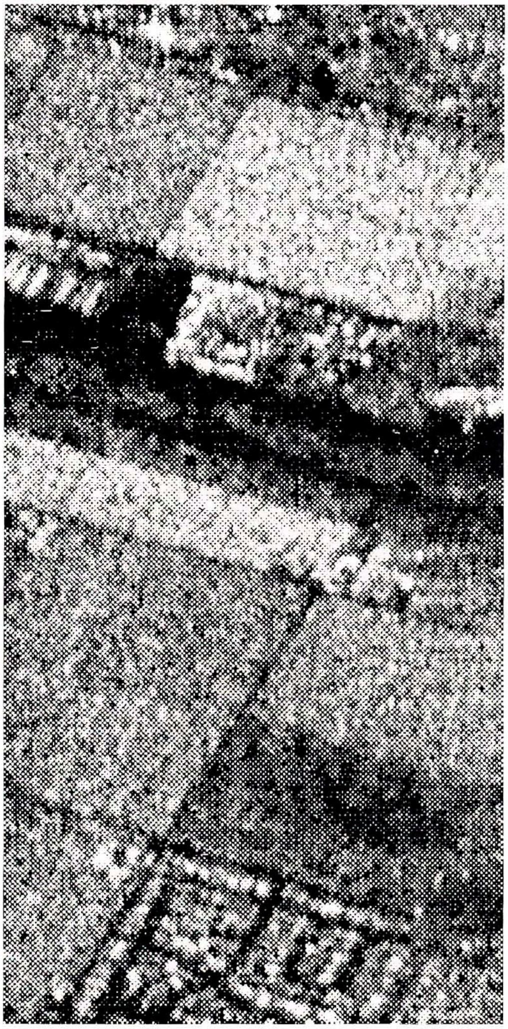


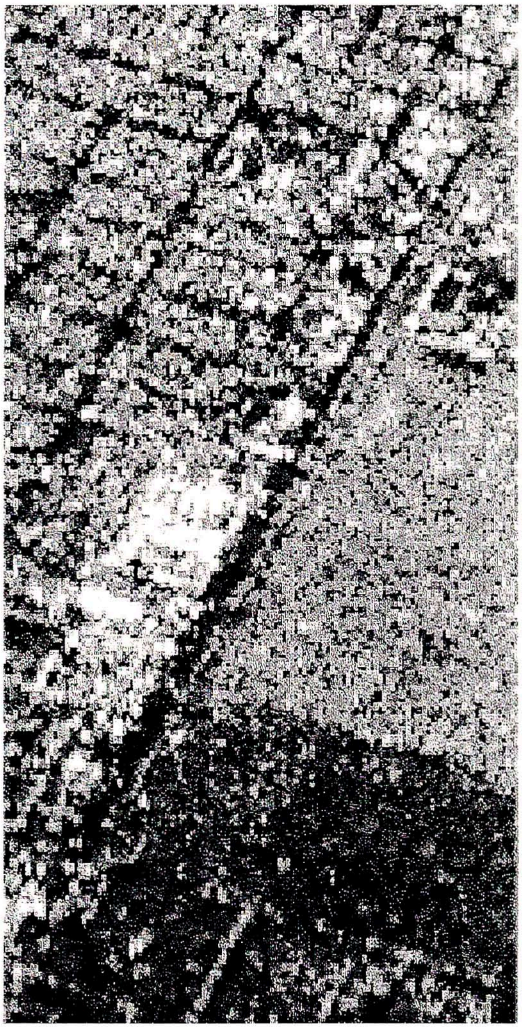
Figure 5-3. Correlation coefficient γ estimated for the central frame with and without 3 bit BAQ quantization.

POSITION IN WHOLE IMAGE :
AZIMUTH = (641, 768)
RANGE = (257, 512)

RANGE SHIFT = 2.125
AZIMUTH SHIFT = -12.750

CORRELATION COEFFICIENT γ :
WITHOUT BAQ PROC. = 0.897
WITH BAQ PROC. = 0.892

Figure 5-4. Correlation coefficient γ estimated for the upper right frame with and without 3 bit BAQ quantization.



POSITION IN WHOLE IMAGE :
AZIMUTH = (769, 896)
RANGE = (769, 1024)

RANGE SHIFT = 2.125
AZIMUTH SHIFT = -12.750

CORRELATION COEFFICIENT γ :
WITHOUT BAQ PROC. = 0.78
WITH BAQ PROC. = 0.75

Figure 5-5. Correlation coefficient y estimated for the lower. right frame with and without 3 bit BAQ quantization.