Reduction of JPEG Noise from the ALOS PRISM Products

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Abstract

PRISM images have radiometric noise caused by JPEG compression. In order to improve the image quality, low frequency components of the JPEG data were modified by assuming the image is smooth. The proposed method reduced the JPEG noise and helped interpretation of the image. This algorithm has been implemented into the system to produce PRISM standard products by JAXA.

1. Introduction

1.1 Overview of PRISM

ALOS (Advanced Land Observing Satellite) is an earth observation satellite launched on January 24, 2006 by JAXA (Japan Aerospace Exploration Agency). ALOS has three earth observation sensors: PRISM (Panchromatic Remote Sensing Instrument for Stereo Mapping), AVNIR-2 (Advanced Visible and Near Infrared Radiometer type 2), and PALSAR (Phased Array type L-band Synthetic Aperture Radar).

PRISM is an optical sensor designed for topographic mapping and DEM generation. PRISM has 3 monochromatic radiometers: forward-, nadir- and backward-looking, and observes the ground from 3 different directions within an orbit. Each radiometer has 6 or 8 linear CCDs. Neighbor CCDs have an overlap of 32 pixels on the focal plane using a half-mirror prism (Hamazaki, 1999; JAXA, 2007a).

The observed PRISM data are compressed in the JPEG format by onboard processing and the compressed data are downlinked. Odd and even CCD cells are independently compressed.

The JPEG algorithm compresses an image block by block; each block is 8 pixels by 8 lines. Therefore, a block of 16 pixels by 8 lines on a geometrically uncorrected image consists of 2 JPEG blocks: a block of odd pixels and a block of even pixels.

The process of the JPEG compression is as follows: (1) an 8 x 8 block is converted into frequency space using DCT (Discrete Cosine Transform); (2) DCT coefficients are quantized, i.e., divided by some number (usually integer) and rounded off; and (3) quantized coefficients are compressed by lossless compression methods (ITU, 1992). Data are lost only by the quantization of DCT coefficients.

1.2 Noise of PRISM Image

Though relative radiometric accuracy is reported as 1 digital number (Tadono, 2007) for level 1B2 (radiometrically and geometrically corrected products), PRISM image of level 1B1 (radiometrically corrected and geometrically uncorrected products) has three types of radiometric noise.

(1) Stripe noise
Brightness difference between odd and even pixels (Figure 1 (A)). Generally speaking, odd and even pixels of linear CCD are often driven by different hardware, such as carrier transfer channels, amplifiers, and A-D converters. The stripe noise is considered to be caused by characteristic difference between the odd and the even hardware.

(2) Brightness difference between CCDs
The difference is considered to be caused by the difference of the optical path and the difference of the CCD characteristics (Figure 2 (A)).

(3) JPEG noise
Noise caused by JPEG compression. There are typically two types of appearance. One is block noise. Block boundaries of JPEG compression are easily distinguished by the block noise especially in the horizontal direction (Figure 3 (A)). The block noise often appears in low-contrast parts, usually dark parts, such as water, forest, and wet paddy fields. The other is mosquito noise. This noise appears in low-contrast parts near high contrast parts, such as water area near the shore (Figure

4). Because JPEG is a lossy data compression method, complete correction of the JPEG noise is impossible.

Reduction of noise is important for image interpretation and image matching for DEM generation. This study aims at canceling or reducing these kinds of noise, especially the JPEG block noise.

Many methods for JPEG noise reduction have been proposed (Brailean et al., 1994; Xiong and Zhang, 1997), but independent JPEG compression for odd and even pixels is very special to the PRISM. The proposed method is for this special case.

2. ALGORITHM

Note that the following algorithms are applicable only to the level 1B1 products of ALOS PRISM. Because the original pixel structure is lost in the 1B2 or higher-level product, the following algorithms cannot be applied.

2.1 Histogram matching

Overlapping parts between CCDs observe the same object. It is also assumed that all even pixels and all odd pixels of a CCD observe statistically the same object. Therefore, two kinds of histogram matching are applied: histogram of the overlap parts shall be the same between CCDs to cancel the brightness difference between CCDs, and histogram of even pixels and histogram of odd pixels shall be the same in a CCD to cancel the stripe noise.

The first and the last pixels on a CCD are not used for the histogram matching, because these pixels are experimentally unreliable.

Histogram matching, or other processing to cancel the stripe noise, is necessary as preprocessing for the proposed JPEG noise reduction algorithm. JAXA (2007b) have implemented their own algorithm to cancel stripe noise since October 2007.

2.2 JPEG noise reduction

2.2.1 DCT and IDCT

DCT and IDCT (Inverse Discrete Cosine Transform) for a block is as follows; (1) is DCT and (2) is IDCT. Here s_{xy} are values in the real space and S_{uv} are in the frequency space. All indices start at 0.

$$S_{uv} = \frac{1}{4} C_u C_v \sum_{y=0}^{7} \sum_{x=0}^{7} s_{xy} \cos\left(\frac{(2x+1)u\pi}{16}\right) \cos\left(\frac{(2y+1)v\pi}{16}\right) \quad (1)$$

$$s_{xy} = \frac{1}{4} \sum_{v=0}^{7} \sum_{u=0}^{7} C_u C_v S_{uv} \cos\left(\frac{(2x+1)u\pi}{16}\right) \cos\left(\frac{(2y+1)v\pi}{16}\right) \quad (2)$$

where $C_u, C_v = \begin{cases} 1/\sqrt{2} & u \text{ or } v = 0 \\ 1 & \text{otherwise} \end{cases}$

2.2.2 Correction Formula

The cause of the JPEG noise is that correct values of S_{uv} are lost. Therefore, unknown correction values V in the frequency space are added to S_{uv} to get a smooth image. Because correction of all the components is considered impossible, and needs an impracticable calculation time, only n_K components of the total of 64 components are corrected.

$$\begin{aligned} O(x_B, y_B, p, x, y) &= I(x_B, y_B, p, x, y) + \frac{1}{4} \sum_{k=0}^{n_K - 1} C_{u(k)} C_{v(k)} V(x_B, y_B, p, k) \cos\left(\frac{(2x+1)u(k)\pi}{16}\right) \cos\left(\frac{(2y+1)v(k)\pi}{16}\right) \\ &= I(x_B, y_B, p, x, y) + \sum_{k=0}^{n_K - 1} E_{xy}^{k} V(x_B, y_B, p, k) \end{aligned} \quad (3)$$

where $E_{xy}^{k} = \frac{1}{4} C_{u(k)} C_{v(k)} \cos\left(\frac{(2x+1)u(k)\pi}{16}\right) \cos\left(\frac{(2y+1)v(k)\pi}{16}\right)$

I	Input values (CCT count)
O	Enhanced output values
V	Unknown correction values in the frequency space
(x, y)	Pixel and line number in a block
(x_B, y_B)	Block number in the pixel and line direction
p	Index for odd and even pixels (0 or 1)

Table 1 Value of u and v generated by k

v \ u	0	1	2	3	4	5	6	7
0	0	1	3	6	10	15	21	28
1	2	4	7	11	16	22	29	36
2	5	8	12	17	23	30	37	43
3	9	13	18	24	31	38	44	49
4	14	19	25	32	39	45	50	54
5	20	26	33	40	46	51	55	58
6	27	34	41	47	52	56	59	61
7	35	42	48	53	57	60	62	63

(u, v) Indexes in frequency space

k A value to generate u, v according to the JPEG storing order listed on Table 1. The lower k corresponds to the lower frequency.

n_K Number of correction values for a block

2.2.3 Observation Equations

In order to reduce JPEG noise, V in the correction formula (3) was adjusted by the following observation equations, where v_X, v_Y, etc. are residuals. The following observation equations minimize the brightness difference between neighbor pixels; between blocks in the pixel direction (weight w_x),

$$v_X = O(x_B, y_B, 1, 7, y) - O(x_B + 1, y_B, 0, 0, y) \qquad (0 \le x_B < n_{BX} - 1,\ 0 \le y_B < n_{BY},\ 0 \le y < 8)$$

between blocks in the line direction (weight w_Y),

$$v_Y = O(x_B, y_B, p, x, 7) - O(x_B, y_B + 1, p, x, 0) \qquad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY} - 1,\ p = 0,1,\ 0 \le x < 8)$$

and within a block in the pixel direction (weight w_I).

$$v_I = O(x_B, y_B, 0, x, y) - O(x_B, y_B, 1, x, y) \qquad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY},\ 0 \le x < 8,\ 0 \le y < 8)$$

$$v_{I'} = O(x_B, y_B, 1, x, y) - O(x_B, y_B, 0, x + 1, y) \qquad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY},\ 0 \le x < 7,\ 0 \le y < 8)$$

The following observation equations are for stability of solution; requesting correction values V are not large (weight w_V),

$$v_V = V(x_B, y_B, p, k) \qquad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY},\ p = 0,1,\ 0 \le k < n_K)$$

and requesting brightness does not change on image boundary to avoid periodical instability (weight w_B).

$$v_{BX} = M(0, y_B, 0, 0, y) \qquad (0 \le y_B < n_{BY},\ 0 \le y < 8)$$

$$v_{BX'} = M(n_{BX} - 1, y_B, 1, 7, y) \qquad (0 \le y_B < n_{BY},\ 0 \le y < 8)$$

$$v_{BY} = M(x_B, 0, p, x, 0) \qquad (0 \le x_B < n_{BX},\ p = 0,1,\ 0 \le x < 8)$$

$$v_{BY'} = M(x_B, n_{BY} - 1, p, x, 7) \qquad (0 \le x_B < n_{BX},\ p = 0,1,\ 0 \le x < 8)$$

where $M(x_B, y_B, p, x, y) = O(x_B, y_B, p, x, y) - I(x_B, y_B, p, x, y)$

(n_{BX}, n_{BY}) Number of blocks in the pixel and line direction

The above observation equations are transformed into the following matrix formula, where residuals are omitted.

$$\begin{bmatrix} A_{7y} & -A_{0y} \end{bmatrix} \begin{bmatrix} X^{1}_{x_B\, y_B} \\ X^{0}_{x_B+1\ y_B} \end{bmatrix} = \begin{bmatrix} L_1(x_B, y_B, y) \end{bmatrix} \qquad (0 \le x_B < n_{BX} - 1,\ 0 \le y_B < n_{BY},\ 0 \le y < 8)$$

$$\begin{bmatrix} A_{x7} & -A_{x0} \end{bmatrix} \begin{bmatrix} X^{p}_{x_B\, y_B} \\ X^{p}_{x_B\ y_B+1} \end{bmatrix} = \begin{bmatrix} L_2(x_B, y_B, p, x) \end{bmatrix} \qquad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY} - 1,\ p = 0,1,\ 0 \le x < 8)$$

$$\begin{bmatrix} A_{x\,y} & -A_{x\,y} \end{bmatrix} \begin{bmatrix} X^{0}_{x_B\,y_B} \\ X^{1}_{x_B\,y_B} \end{bmatrix} = \begin{bmatrix} L_3(x_B, y_B, x, y) \end{bmatrix} \quad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY},\ 0 \le x < 8,\ 0 \le y < 8)$$

$$\begin{bmatrix} A_{x\,y} & -A_{x+1\,y} \end{bmatrix} \begin{bmatrix} X^{1}_{x_B\,y_B} \\ X^{0}_{x_B\,y_B} \end{bmatrix} = \begin{bmatrix} L_4(x_B, y_B, x, y) \end{bmatrix} \quad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY},\ 0 \le x < 7,\ 0 \le y < 8)$$

$$[1][V(x_B, y_B, p, k)] = [0] \quad (0 \le x_B < n_{BX},\ 0 \le y_B < n_{BY},\ p = 0,1,\ 0 \le k < n_K)$$

$$[A_{0\,y}][X^{0}_{0\,y_B}] = [0] \quad (0 \le y_B < n_{BY},\ 0 \le y < 8)$$

$$[A_{7\,y}][X^{1}_{n_{BX}-1\ y_B}] = [0] \quad (0 \le y_B < n_{BY},\ 0 \le y < 8)$$

$$[A_{x\,0}][X^{p}_{x_B\,0}] = [0] \quad (0 \le x_B < n_{BX},\ p = 0,1,\ 0 \le x < 8)$$

$$[A_{x\,7}][X^{p}_{x_B\ n_{BY}-1}] = [0] \quad (0 \le x_B < n_{BX},\ p = 0,1,\ 0 \le x < 8)$$

where

$$X^{p}_{x_B\,y_B} = \begin{bmatrix} V(x_B, y_B, p, 0) \\ \vdots \\ V(x_B, y_B, p, n_K - 1) \end{bmatrix}$$

$$A_{x\,y} = \begin{bmatrix} E^{0}_{x\,y} & E^{1}_{x\,y} & \dots \end{bmatrix}$$

$$L_1(x_B, y_B, y) = -I(x_B, y_B, 1, 7, y) + I(x_B + 1, y_B, 0, 0, y)$$
$$L_2(x_B, y_B, p, x) = -I(x_B, y_B, p, x, 7) + I(x_B, y_B + 1, p, x, 0)$$
$$L_3(x_B, y_B, x, y) = -I(x_B, y_B, 0, x, y) + I(x_B, y_B, 1, x, y)$$
$$L_4(x_B, y_B, x, y) = -I(x_B, y_B, 1, x, y) + I(x_B, y_B, 0, x + 1, y)$$

L_1, L_2, L_3 and L_4 are differences of input values between neighbor pixels. These values are easily calculated from input values whose index is linear.

$$L_1(x_B, y_B, y) = D_X(x_O(x_B, 1, 7), y_O(y_B, y))$$
$$L_2(x_B, y_B, p, x) = D_Y(x_O(x_B, p, x), y_O(y_B, 7))$$
$$L_3(x_B, y_B, x, y) = D_X(x_O(x_B, 0, x), y_O(y_B, y))$$
$$L_4(x_B, y_B, x, y) = D_X(x_O(x_B, 1, x), y_O(y_B, y))$$

where

$$D_X(x_O, y_O) = I_O(x_O + 1, y_O) - I_O(x_O, y_O)$$
$$D_Y(x_O, y_O) = I_O(x_O, y_O + 1) - I_O(x_O, y_O)$$

I_O Input values (CCT count) with linear (not in block style) index

$x_O(x_B,p,x)$ Linear index for pixel

$y_O(y_B,y)$ Linear index for line

We need only input values by linear index (I_O), which is a normal image. Input values by block style index (I) are not used in the calculation.

D_X and D_Y are differences between neighbor pixels, which shall be adjusted into the same value by request of observation equation. This adjustment is based on the idea that the differences are caused by the JPEG compression. However if the difference is too large, it is not caused by the JPEG compression. That means whole value of D_X and D_Y should not be adjusted. Therefore, D_X and D_Y are cut off into range of $-D_{MAX}$ to D_{MAX}.

2.2.4 Normal Equations

Because all the observation equations are independent, the normal equation generated from the whole observation equations is the sum of the normal equations generated from each observation equation. Each normal equation is as follows. Weight shall be considered in the summation.

$$\begin{bmatrix} N^{7y}_{7y} & -N^{7y}_{0y} \\ -N^{0y}_{7y} & N^{0y}_{0y} \end{bmatrix}\begin{bmatrix} X^{1}_{x_B\, y_B} \\ X^{0}_{x_B+1\ y_B} \end{bmatrix} = \begin{bmatrix} L_1(x_B, y_B, y)A_{7y}{}^{T} \\ -L_1(x_B, y_B, y)A_{0y}{}^{T} \end{bmatrix} \qquad (0 \le x_B < n_{BX} - 1,\ \ 0 \le y_B < n_{BY},\ \ 0 \le y < 8)$$

$$\begin{bmatrix} N^{x7}_{x7} & -N^{x7}_{x0} \\ -N^{x0}_{x7} & N^{x0}_{x0} \end{bmatrix}\begin{bmatrix} X^{p}_{x_B\, y_B} \\ X^{p}_{x_B\ y_B+1} \end{bmatrix} = \begin{bmatrix} L_2(x_B, y_B, p, x)A_{x7}{}^{T} \\ -L_2(x_B, y_B, p, x)A_{x0}{}^{T} \end{bmatrix} \qquad (0 \le x_B < n_{BX},\ \ 0 \le y_B < n_{BY} - 1,\ \ p = 0,1,\ \ 0 \le x < 8)$$

$$\begin{bmatrix} N^{xy}_{xy} & -N^{xy}_{xy} \\ -N^{xy}_{xy} & N^{xy}_{xy} \end{bmatrix}\begin{bmatrix} X^{0}_{x_B\, y_B} \\ X^{1}_{x_B\, y_B} \end{bmatrix} = \begin{bmatrix} L_3(x_B, y_B, x, y)A_{xy}{}^{T} \\ -L_3(x_B, y_B, x, y)A_{xy}{}^{T} \end{bmatrix} \qquad (0 \le x_B < n_{BX},\ \ 0 \le y_B < n_{BY},\ \ 0 \le x < 8,\ \ 0 \le y < 8)$$

$$\begin{bmatrix} N^{xy}_{xy} & -N^{xy}_{x+1\ y} \\ -N^{x+1\ y}_{xy} & N^{x+1\ y}_{x+1\ y} \end{bmatrix}\begin{bmatrix} X^{1}_{x_B\, y_B} \\ X^{0}_{x_B\, y_B} \end{bmatrix} = \begin{bmatrix} L_4(x_B, y_B, x, y)A_{xy}{}^{T} \\ -L_4(x_B, y_B, x, y)A_{x+1\ y}{}^{T} \end{bmatrix} \qquad (0 \le x_B < n_{BX},\ \ 0 \le y_B < n_{BY},\ \ 0 \le x < 7,\ \ 0 \le y < 8)$$

$$[1][V(x_B, y_B, p, k)] = [0] \qquad (0 \le x_B < n_{BX},\ \ 0 \le y_B < n_{BY},\ \ p = 0,1,\ \ 0 \le k < n_K)$$

$$\left[N^{0y}_{0y}\right]\left[X^{0}_{0\,y_B}\right] = \vec{O} \qquad (0 \le y_B < n_{BY},\ \ 0 \le y < 8)$$

$$\left[N^{7y}_{7y}\right]\left[X^{1}_{n_{BX}-1\ y_B}\right] = \vec{O} \qquad (0 \le y_B < n_{BY},\ \ 0 \le y < 8)$$

$$\left[N^{x0}_{x0}\right]\left[X^{p}_{x_B\,0}\right] = \vec{O} \qquad (0 \le x_B < n_{BX},\ \ p = 0,1,\ \ 0 \le x < 8)$$

$$\left[N^{x7}_{x7}\right]\left[X^{p}_{x_B\ n_{BY}-1}\right] = \vec{O} \qquad (0 \le x_B < n_{BX},\ \ p = 0,1,\ \ 0 \le x < 8)$$

where $$N^{xy}_{x'y'} = A_{xy}{}^{T} A_{x'y'} = \begin{bmatrix} E^{0}_{xy}E^{0}_{x'y'} & \cdots & E^{0}_{xy}E^{n_K-1}_{x'y'} \\ \vdots & \ddots & \vdots \\ E^{n_K-1}_{xy}E^{0}_{x'y'} & \cdots & E^{n_K-1}_{xy}E^{n_K-1}_{x'y'} \end{bmatrix}$$

A^T is transpose of A, $\vec{O}$ is the zero vector.

2.2.5 Patching

The number of the unknowns n_N, i.e. order of the normal equation, is 2 $n_K\, n_{BX}\, n_{BY}$. Because the calculation cost to solve the linear equation is $O(n_N^3)$, the normal equation for the whole image cannot be practically solved. Therefore, the whole image was divided into patches with overlap; normal equations for all patches were solved; and patches were joined smoothly using the overlapping parts, i.e., each overlapping part is averaged by linear weight.

Because coefficient matrices of the normal equations are the same for all patches, the calculation cost to solve the linear equation is $O(n_N^2)$, not $O(n_N^3)$, after the LU or Cholesky decomposition. These decomposition need $O(n_N^3)$ of calculation cost, but the same decomposition result is applicable for all patches. Therefore, the patching reduces the calculation time dramatically.

3. Implementation and Experiments

The following parameter was used; $n_K = 15$, $w_x = w_Y = w_I = w_V = w_B = 1$, $D_{MAX} = 4$. A patch is 5 x 5 double-blocks, and the overlap is 1 double-block in the pixel and line direction, where a double-block is referred to as the 16 pixels by 8 lines, a pair of odd and even blocks. The program is coded by C++ using LAPACK and BLAS library to solve linear equation, and optional OpenMP support.

The proposed algorithms were applied to PRISM 1B1 products observing Fukuoka, Japan on August 25, 2006, and Nagasaki, Japan on July 27, 2006.

4. Results

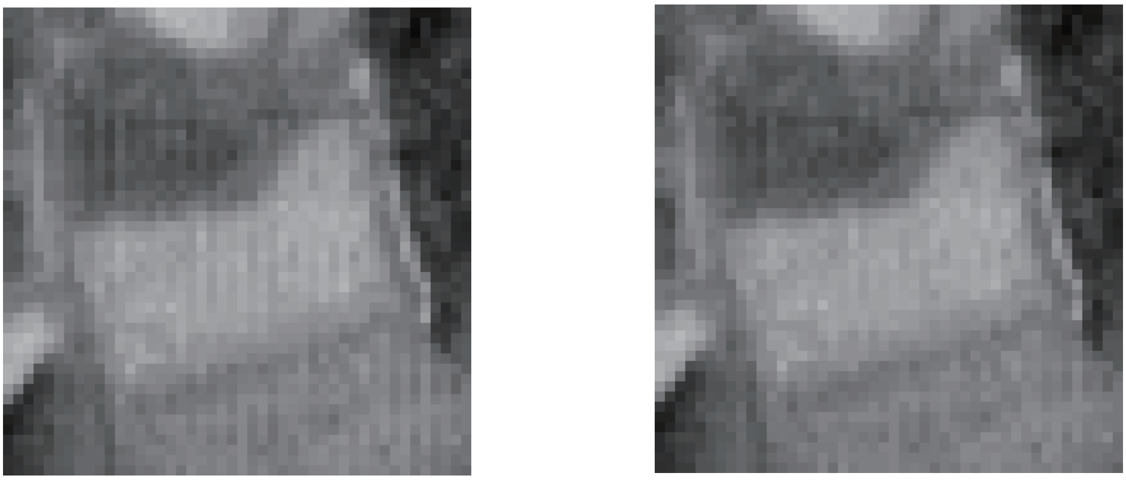
Figures 1 and 2 are the results of the histogram matching. Figure 1 focuses on the stripe noise. Figure 2 focuses on the brightness difference between CCDs. Figures 3 is the result of the JPEG noise reduction and the preprocessed histogram matching focusing on the JPEG block noise. Figure 4 is the result of the same process, but focusing on JPEG mosquito noise.

5. Discussion

The stripe noise was successfully reduced by the histogram matching in Figure 1, but stripe-like noise remained in Figure 3 (B). The stripe-like noise differs from the stripe noise in Figure 1 (A): bright or dark columns do not continue across block boundaries in many cases, and some columns in a block are bright in the upper part though dark in lower part. These facts cannot be explained by the actual brightness difference, or other characteristic differences, between odd and even pixels, but can be explained by odd/even independent JPEG compression. On the other hand, the stripe-like noise is reduced in Figure 3 (C). Therefore, I conclude that the stripe-like noise in Figure 3 (B) is caused by odd/even independent JPEG compression.

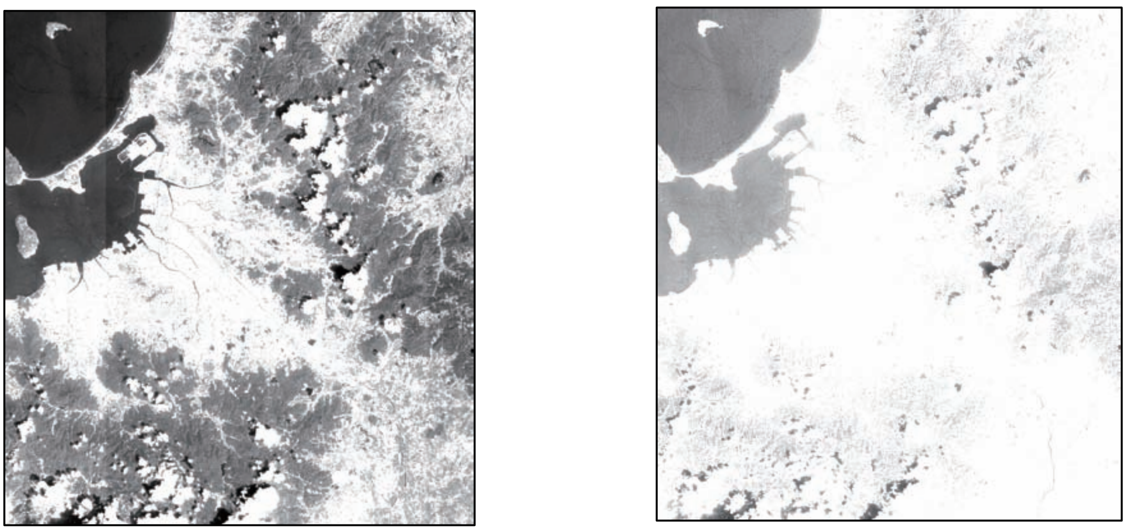
Mosquito noise remains after the processing. Because mosquito noise is caused by loss of the high frequency components, and the proposed method correct only the low frequency components, the mosquito noise is not suppressed.

Specialists in image interpretation in Geographical Survey Institute evaluated that interpretation was much easier after the image enhancement.



(A) Before (B) After

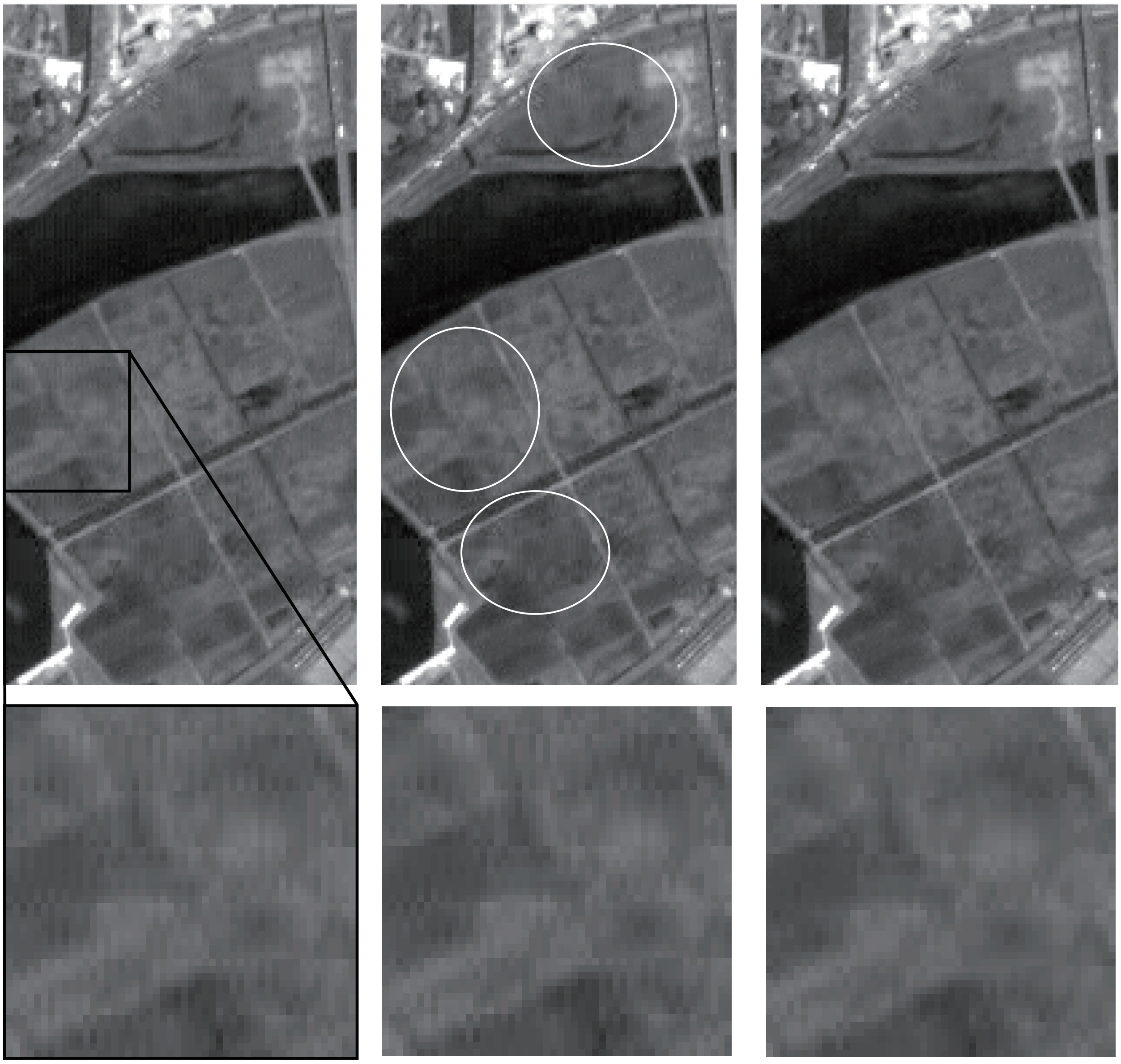
Fig.1 Result of the Histogram Matching (focusing on the stripe noise, part of the Fukuoka scene)



(A) Before (brightness stretched) (B) After (more stretched)

Fig.2 Result of the Histogram Matching

(focusing on the brightness difference between CCDs, the Fukuoka scene)



(A) Before the correction (B) After the histogram matching (C) After JPEG noise reduction

Fig.3 Result of JPEG Noise Reduction (focusing on block noise, part of the Nagasaki scene)

6. Conclusions

The stripe noise and the brightness difference between CCDs are successfully removed by the histogram matching. The JPEG block noise was reduced by the proposed JPEG noise reduction algorithm, but mosquito noise remains. These noise reductions help image interpretation and are expected to help image matching for DEM generation.

The noise reduction program for PRISM level 1B1 products is available on a web site (Kamiya, 2007). The JPEG noise reduction algorithm was implemented in the processing system for the PRISM standard products by JAXA (2008). It means not only level 1B1 products but all products except level 1A (radiometrically and geometrically uncorrected) are processed by this JPEG noise reduction algorithm.

Acknowledgment

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Fig.4 Result of JPEG Noise Reduction
(focusing on mosquito noise, part of the Fukuoka scene)

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