A Practical Method of
Remotely Sensed Digital Image's Resolving Power

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1. Abstract

A method which decides resolving power of digital remote sensing sensor in field experiment was developed. It was applied to MOS-1 airborne verification experiment and predicted a resolving power of MESSR on MOS-1 satellite.

An outline of this method is following. An airphoto signal, refrectance of which is like step function, is laid slightly obliquely (angle θ) to perpendicular to flying direction and observed (Fig. 1). It is equivalent to observing a object, radiance of which changes like step function, in various phases. A calculation method of PSF and MTF from the data was developed.

2. MOS-1 and MESSR

NASDA(National Space Development Agency of Japan) launched MOS-1(Marine Observation Satellite 1) in 1987. Before the launching, NASDA conducted MOS-1 airborne verification experiment in order to test sensor equipment. GSI(Geographical Survey Institute of Japan) took part in the experiment, and evaluated resolving power of MESSR(Multi-spectral Electric Self-scanning Radiometer). It is a visible and infrared image sensor on the MOS-1. Table 1 is selected technical data of the MOS-1 and the MESSR.

The MESSR employed linear CCD(Charge Coupled Device) sensor like SPOT HRV. One of the most significant difference between linear CCD sensor and scanner(ex. LANDSAT MSS, TM) is following. Scanner samples incident light in IFOV(Instantaneous Field of View) in a moment. But CCD accumulates incident light in IFOV while satellite moves corresponding length between two consecutive lines. So, the area that a detector observes changes during the accumulation. It contributes to lower resolving power in flying direction, but no contribution in perpendicular to the flying direction.

3. General idea of the method

In order to obtain PSF(Point Spread Function) in certain direction, it is enough to observe airphoto signal, refrectance of which changes like step function in the direction, in various locations of sensor relative to the edge. But it is impossible to design a airplane or satellite based experiment to fix a pixel to certain location. Also it is very difficult to observe the locations of pixeles in sub-pixel order. So, statistical processing of edge observation data, in which every locations were thought to appear in same probability, was used for field experiment to evaluate resolving power. But the statistical processing is not efficient usage of data.

In new method, an airphoto signal, refrectance of which changes like step function, is prepared. Now let us suppose to measure resolving power in flying direction. The airphoto signal is laid as its edge is slightly oblique to perpendicular to the flying direction. In this case, we can observe the edge in various locations of pixels in many columns. And the relative locations of the pixels in the flying direction to the edge(L_i) changes linear to the column number(i) (Fig. 2).

$$L_i = c + d*i \qquad (3\text{-}1)$$

Here, constant c is concern to only absolute geometric correction, and it is not important for our purpose. So if the airphoto signal is observed and the constant d is determined, it means that essential data to calculate PSF are obtained.

4. CCT-Column curve

It is convenient to plot CCT count to column number i of pixeles included in a line near the edge (Fig. 3). Lets us call it CC curve(CCT-Column curve). Because the edge is straight, and because the image has little distortion in small area even if no geometric correction, observed image of line l is similar to one of line l+1, and CC curves of the line l and l+1 have similar figures. In other words, if the CC curve of the line l is transferred in column direction, it overlaps to one of the line l+1. Using this fact, we can determine the constant d.

$$d = b/n \qquad (4\text{-}1)$$

Here, b is pixel size in line direction, n is number of columns to transfer in CC curve(real number).

5. Calculation algorithm

Now, CC curve can be thought usual edge observation data, x axis of which is space coordinate in tangent to the edge, y axis of which is CCT count, supposing one column equal to length d (=b/n). So, standard algorithm to calculate PSF from edge observation data can be applied. Radiance(R(x), relative vale) of airphoto signal is

$$R(x) = \begin{cases} Rb & (x < 0) \\ Rw & (x > 0) \end{cases} \qquad (5\text{-}1)$$

Here, x : space coordinate in tangent to the edge.
the edge is corresponding to x = 0.
Rw : Radiance of black part of the airphoto signal.
Rb : Radiance of white part of the airphoto signal.
CCT count of observed image(I(x)) is expressed as following.

$$I(x) = \int_{-\infty}^{+\infty} R(x) * PSF(x-x')\, dx' \qquad (5\text{-}2)$$

$$= Ib + (Iw-Ib) \int_{-\infty}^{x} PSF(x')\, dx' \qquad (5\text{-}3)$$

Here, PSF(x) : Point spread function (normalized).
Ib = I($-\infty$) = Rb : CCT count of the black part of the airphoto signal.
Iw = I($+\infty$) = Rw : CCT count of the white part of the airphoto signal.

Point spread function can be calculated from I(x)

$$PSF(x) = \frac{1}{Iw-Ib} \frac{d}{dx} I(x) \qquad (5\text{-}4)$$

Here, I(x), I_b and I_w can obtain from CC curve, i.e. PSF can calculate from only observed image data.

6. A constraint condition formula

As for flying direction, PSF is broadened by the moving of the satellite through the accumulation as mentioned in section 2. A constraint condition formula on observed image I(x) will be derived. The effect of moving is expressed as follow.

$$PSF(x) = \int_{x-b/2}^{x+b/2} PSF0(x')\,dx' \qquad (6\text{-}1)$$

Here, PSF0(x) : PSF, assuming the sensor dose not move.
Differentiating and using PSF0(x)$\rightarrow$0 (x$\rightarrow -\infty$), PSF0(x) can calculate from PSF(x)

$$PSF0(x) = \sum_{j=0}^{\infty} \frac{d}{dx} PSF(x-b/2-j*b) \qquad (6\text{-}2)$$

Using PSF0(x)$\rightarrow$0 (x$\rightarrow +\infty$),

$$\sum_{j=-\infty}^{+\infty} \frac{d}{dx} PSF(x+j*b) = 0 \qquad (6\text{-}3)$$

As $|(d/dx)PSF(x)| \rightarrow 0$ ($|x| \rightarrow \infty$), (6-3) can be written in finite expression.

$$\sum_{j=-m}^{+m} \frac{d}{dx} PSF(x+j*b) = 0 \qquad (6\text{-}4)$$

Here, m and x are supposed m>>b and x<<m.
Substituting (5-4) into (6-4) and integrating twice,

$$\sum_{j=-m}^{+m} I(x+j*b) = A*x + B \qquad (6\text{-}5)$$

Here, A and B are integration constant.
Subtracting (6-5) from (6-5) substituted x+1 in x, value of constant A can be calculated as A = I(x+(m+1)*b) - I(x-m*b) = Iw-Ib. So, (6-5) is expressed,

$$\sum_{j=-m}^{+m} I(x+j*b) = (Iw-Ib)*x + B \qquad (6\text{-}6)$$

This is the constraint condition formula for CCT count of observed image I(x) in flying direction.

7. Application to the MOS-1 airborne verification experiment

The experiment was executed in 1984 winter and 1985 summer (Table 2). The oblique airphoto signals were placed on roof of GSI in the both experiment. Because adjustment of offset was too small in the winter experiment, CCT count of the black part of the airphoto signal(Ib) was 0. It meant that Ib could not be determined correctly, and that the data could not be used for the analysis. All MESSR images of the summer experiment including the airphoto signal were checked, and it appeared that complete (continue from Ib to Iw) CC curve was obtained from only one image for PSF in the flying direction, and no image for perpendicular to the flying direction. The image was taken on September 6, 1985 (reference number MCC85-278-2). Following analysis was executed to the image. PSF and MTF of all bands were obtained in flying direction.

MESSR images had alternative vertical stripes, which were caused by existence of two shift registers in a semiconductor chip. First, radiometric correction was executed, assuming odd number detectors and even number detectors observed same sample(same mean and same standard deviation). The stripes were removed by the correction. Generally speaking, round error into integer was significant in processing of CCT data. So the CCT count was multiplied by 5 in this correction.

Actually, CC curve of any one line of the image was not complete. Partial CC curves were obtained from two lines l and l+1. They had overlapping part, so n(number of columns to transfer) and d could be measured(Fig. 4). The CC curve of line l was shifted n columns, and complete CC curve was synthesized. Here after, CC curve and observed CCT count I(x) express this synthesized one. What mentioned above as 'complete CC curve was obtained' means these contents.

Next, the CC curve was smoothed. It really important process, because the curve would be differentiated. If there had been no smoothing, effective result had not been obtained because of noise(especially quantization noise). Observed values I(x) were not located in same distance in x coordinate of CC curve, because the curve was synthesized. It is convenient for following processing and application of the constraint condition(6-6) that observed values I(x) was interpolated into linear grid in same time. Distance of the grid(D) was selected near d and diving b(pixel size) into integer N (b=n*d=N*D).

The smoothing was executed minimizing sum of two terms(S) under the constraint condition. The first term was sum of square of difference between observed value and smoothed value. The second term was sum of square of second order differential of smoothed CC curve.

$$S = \sum_{j=1}^{J} (Is(x_j) - I(x_j))^2 + W \sum_{k=1}^{K} (2*Is(x_k) - Is(x_{k-1}) - Is(x_{k+1}))^2 \quad (7-1)$$

Here, $I(x_j)$: Observed value(CCT count).
j : Index of observed value.
J : Number of observed values.
$Is(x_k)$: Smoothed observed value. Value of $Is(x)$ was defined only on the linear grid, so it was linearly interpolated to x_j in the first term. $Is(x)=Ib$ $(x<=x_1)$, $Is(x)=Iw$ $(x>=x_K)$. $Is(x_k)$ $(k=2,3,...,K-1)$ should be determined.
k : Index of smoothed observed value.
K : Number of smoothed observed values.
x_k: Grid point $(x_k=(k-1)*D+x_1)$.
W : Weight of smoothing.

The constraint condition formula(6-6) was transformed into discrete expression and applied.

$$\sum_{k=k0,k0+N,K0+2*N,...}^{M} Is(x_k) = (Iw-Ib)*D*k0 + B \quad (7-2)$$

Here, M : The smallest multiple of N greater than or equal to K.
B : Constant.
KO : 1,2,...,N.

Formula(7-2) had N constraint conditions (the formula substituted k0=N+1 was equivalence to k=1). Canceling constant B, (7-2) has N-1 independent constraint conditions. Using Lagrange's method of undetermined multipliers, smoothed observed value $Is(x_k)$ were obtained by minimizing formula (7-1) under the N-1 constraint conditions(7-2). Using (5-4), PSF was obtained.

8. Estimation of PSF of the MESSR on the MOS-1 satellite

The obtained PSF in section 7 was PSF of the MESSR on the airplane. If it had been PSF in perpendicular to the flying direction, or if the MESSR had employed scanner, PSF on satellite had been same without effect of small angle scattering of atmosphere. But they were not same in this case.

Accumulation and sampling time interval of the MESSR was designed as long as the time to move an IFOV on satellite, i.e. pixel size in flying direction (b) is equal to an IFOV on the satellite. The same sampling interval was used in the air borne experiment, but speed height ratio of platform was different between from satellite. Actually pixel size b was much longer than an IFOV.

The estimation was executed in two steps. The first step transformed PSF from condition of speed height ratio of the airplane to stationary status using (6-2). The second step transformed PSF from stationary status to the ratio of the satellite using (6-1). In the second step, b of (6-1) should changed to a(pixel size in perpendicular to flying direction, it was equal to an IFOV), and unit of length should be interpreted as a is pixel size in satellite case. The ratio of a and b were obtained by measurement of the airphoto signal.

MTF was calculated from PSF by usual algorithm.

$$MTF(\omega) = Norm \int PSFs(x) * e^{-i\omega x} dx$$

Here, MTF : Modulation transfer function.
PSFs : PSF on satellite calculated by above method.
Norm : Normalization constant $(1 / \int PSFs(x)\, dx)$.

Fig. 5 is obtained MTF of the MESSR on the MOS-1 satellite

9. Conclusion

The practical method to obtain PSF and MTF of digital image sensor in field experiment was developed in this study. The method uses information of phase effectively by slightly oblique airphoto signal. This is the most excellent point of the method, which other methods do not have.

Following conditions of airphoto signal are very important for the method.
(1) Refrectance of the airphoto signal shall change like step function.
(2) Black part and White part of the airphoto signal shall be uniform, shall not be saturated in CCT count, shall have great difference in CCT count.
(3) Edge of the airphoto signal shall be straight line.
(4) Length of edge and oblique angle shall adjusted in order to obtain complete CC curve.
These conditions are so critical that it is difficult to use natural target instead of airphoto signal. In addition, smoothing mentioned in section 7 and measure against round error are very important, because quantization error can not be ignored.

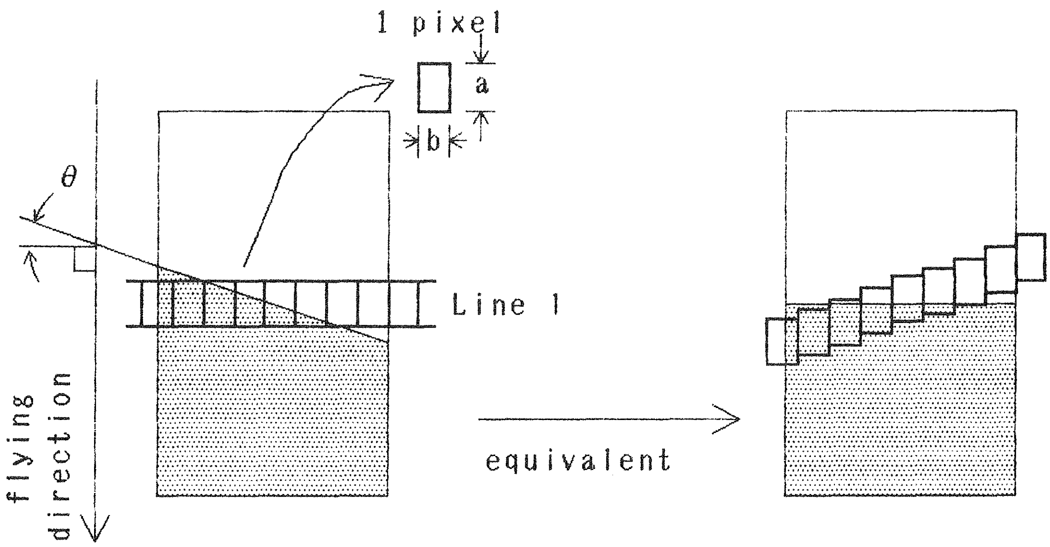

Fig. 1 Basic idea of the PSF measurment

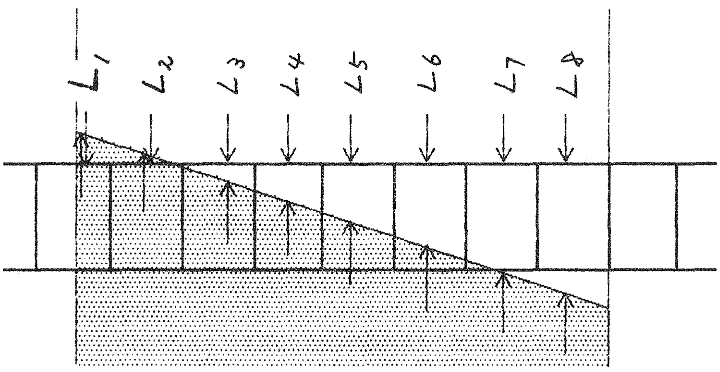

Fig. 2 Relative locations of pixels to the edge

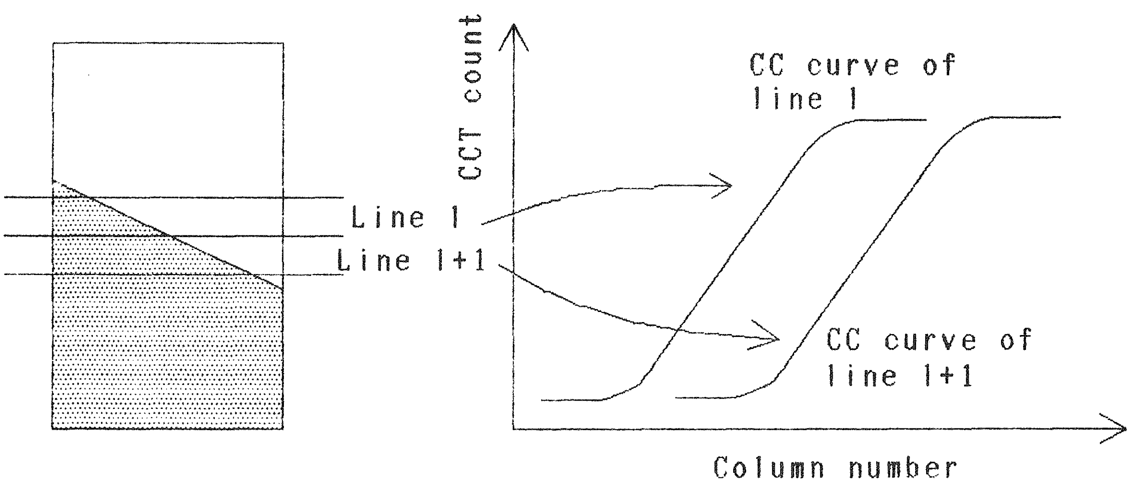

Fig. 3 CC curve of line l and l+1

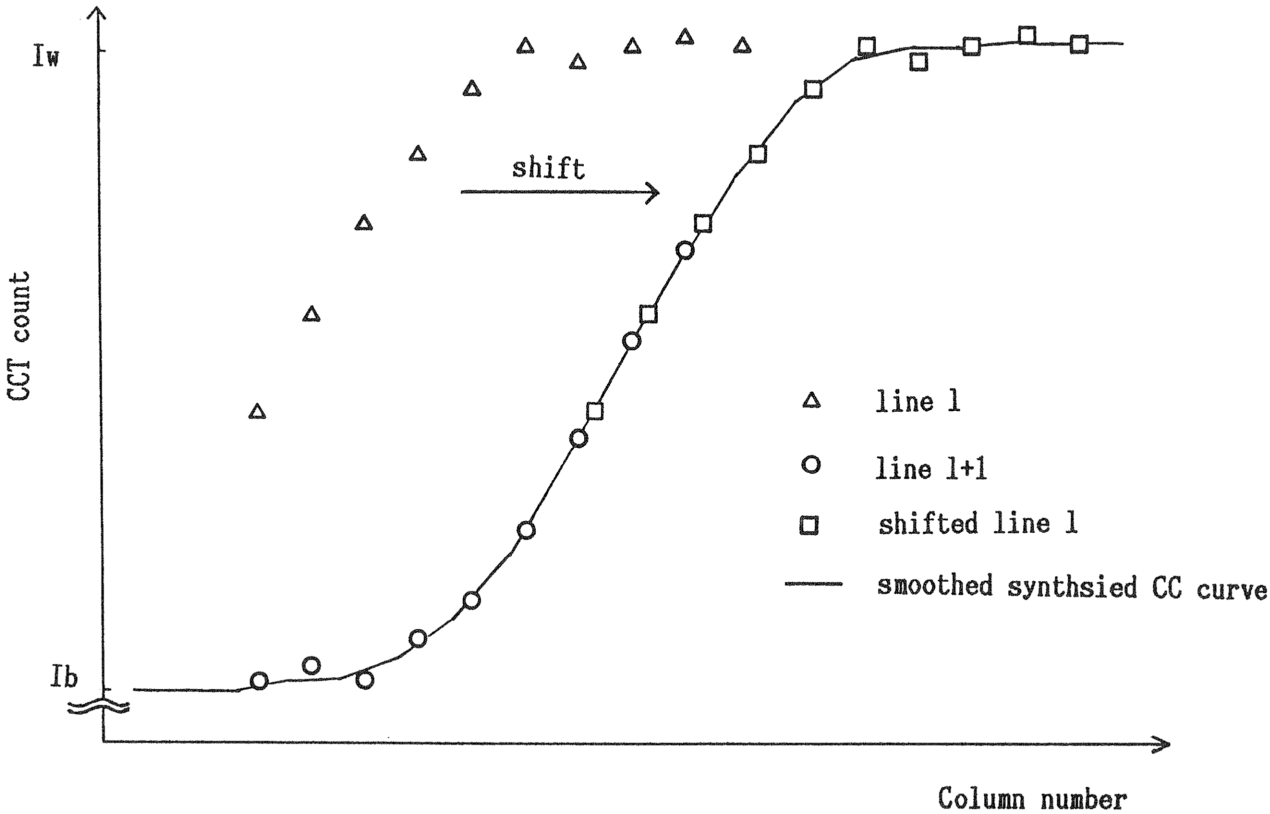

Fig. 4 Synthesis of CC curve

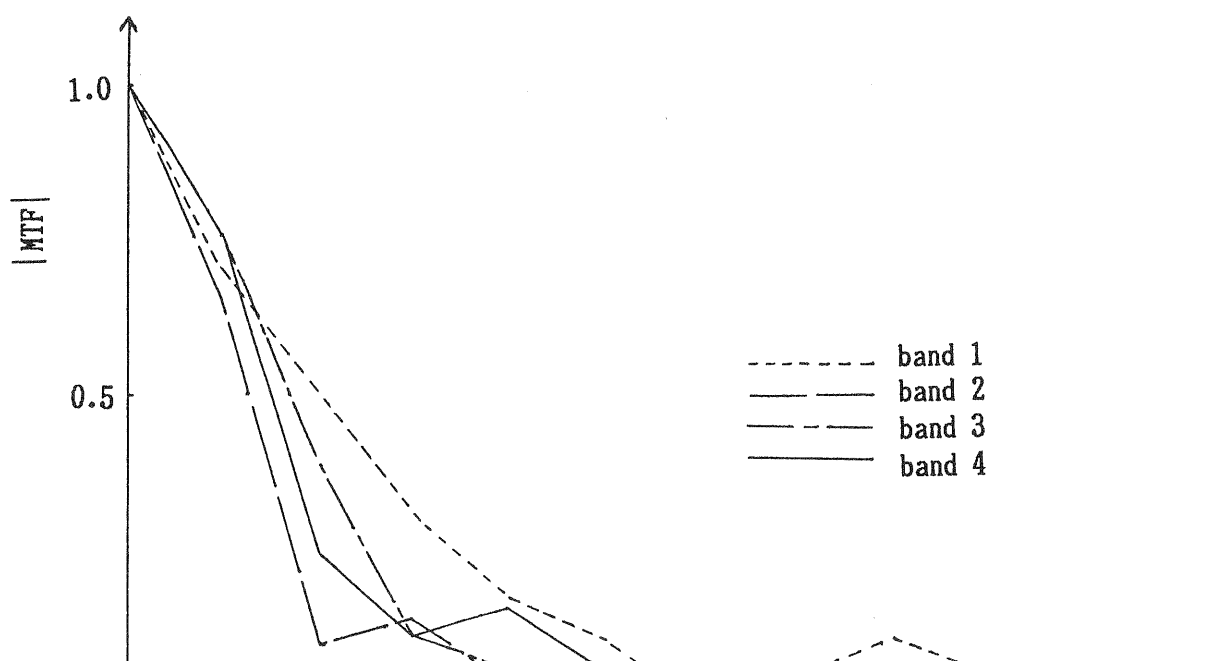

Fig. 5 Estimated MTF of the MESSR on the MOS-1 satellite

launching	Feb. 19, 1987	IFOV	54.7 μrad (50 m at ground)
orbit hight	909 km		
wave length (μ)	0.51-0.59(band1) 0.61-0.69(band2) 0.72-0.80(band3) 0.80-1.10(band4)	quantization levels	64 (128 at the verification experiment)
		detector	2048 cells linear CCD
scan width	100km×2 systems	scan period	7.6 m sec.

Table 1　Selected technical data of the MOS-1 and the MESSR

Place	Date	Hight
Tsukuba - Kashimanada	Nov. 22, 1984 Dec. 8, 1984 Dec. 13, 1984	1,000 m / 7,000 m
	Jul. 18, 1985 Sep. 5, 1985 Sep. 6, 1985	1,000 m / 6,000 m

The airphoto signal was placed at Tsukuba. Experiment at other area is omitted.

Table 2　MOS-1 airborn verification experiment