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Fidelity of Space TV

The rms geometric distortion of ESSA-7, Surveyor-7 and Mariner-4 was less than 1.6 TV lines.

INTRODUCTION

PLANETARY MAPPING FROM television photographs requires the highest geometric fidelity in the received imageries. At a photography scale of 1:1,000,000, for example, a displacement of 1 millimeter on the photograph will result in a location error of 1 kilometer. In an attempt to establish the potential of space TV systems in photogrammetric mapping, an investigation was made to study the distortion characteristics of three space systems; namely: ESSA-7, SURVEYOR-7 and MARINER-4. These three systems were chosen because each had a calibrated reseau on the target plate of its vidicon tube. Results from the experiment have determined the following parameters for each system:

- Magnitude of geometric distortions,
- Magnitude and pattern of the systematic component,
- Magnitude of the random component,
- Consistency and stability of the distortion characteristics,
- Effectiveness of image correction using a reseau.

Table 1 gives a summary of the characteristics of the three TV systems. ESSA-7 was a weather satellite in polar orbit around the earth. SURVEYOR-7 was a lunar vehicle that soft landed on the lunar surface on January 10, 1968. Its photographic mission lasted until February 21, but most of the television photographs were obtained during the first lunar day between the 10th and 25th of January. MARINER-4 flew by the planet Mars on July 14, 1965 and transmitted a total of 22 pictures back to Earth.

METHOD OF ANALYSIS

MAGNITUDE OF GEOMETRIC DISTORTION

This study was based primarily on the reseau pattern on the target plate of a vidicon tube. As each exposure was made and transmitted back to earth, the reseau imagery underwent the same electronic processes as the photographic imagery and was shown on every film negative. Should there be a complete absence of geometric distortion in the entire television system, then the final reseau image would be a simple enlargement of the original reseau.

Let the position of a reseau point on the target be defined by its coordinates $\bar{x}_j$, $\bar{y}_j$ which could be measured during the manufacturing of the tube. Correspondingly, let the position of the same reseau point on the exposure be defined by a pair of photo coordinates x_j, y_j. The relationship between the two sets of coordinates may be expressed by the simple formulas of conformal transformation. That is,

$$x_j = x_0 + \lambda \cos\theta \bar{x}_j - \lambda \sin\theta \bar{y}_j \quad (1)$$

$$y_j = y_0 + \lambda \sin\theta \bar{x}_j + \lambda \cos\theta \bar{y}_j \quad (2)$$

where x_0, y_0 represent a translation of the coordinate axes, λ is a scale factor and θ is an angle of rotation. Considering a displacement of V_{x_j} and V_{y_j} on the coordinates x_j and y_j, respectively, Equations 1 and 2 may be written as:

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TABLE 1. CHARACTERISTICS OF THE THREE SPACE TV SYSTEMS

System	*Mission*	*Camera*	*Focal Length*	*Raster Size (inches)*	*No. of Scan Lines*	*Frame Size*	*Line Width on Frame*
ESSA-7	Earth-Satellite	Vidicon	0.230 inch	0.475×0.475	833	20×23 mm.	24 μm
SURVEYOR-7	Moon Lander	Vidicon	Variable: 25 to 100 mm.	0.465×0.465	600	49×47 mm.	82 μm
MARINER-4	Mars Flyby	Vidicon	12 inches	0.22×0.22	200	9×10 mm.	46 μm

ABSTRACT: *The geometric distortions in the television systems of ESSA-7, Surveyor-7 and Mariner-4 were highly systematic. Although the total geometric distortions were between 5 and 10 TV lines at one-sigma level, the random components amounted to less than 0.5 TV line. The distortions were also found to be perfectly stable in both magnitude and shape between successive exposures. Results showed that a major portion of geometric distortion in the TV systems was caused by the difference in scale distortions in the horizontal and vertical directions. In all instances, after separate scale corrections in these two directions, the* rms *error of the image coordinates was less than 1.6 TV lines.*

$$V_{x_j} + x_j = x_0 + a_1\bar{x}_j - a_2\bar{y}_j \quad (3)$$

$$V_{y_j} + y_j = y_0 + a_2\bar{x}_j + a_1\bar{y}_j. \quad (4)$$

In a given exposure, each reseau point generates two such equations. Twenty-five reseau points then generate 50 equations altogether. The method of least-squares can then be used to solve these equations to produce the most probable set of transformation constants as well as image residuals V_{x_j}, and V_{y_j}. These residuals represent the total distortions that are present at the reseau points on that given exposure.

Equations 3 and 4 use a common scale factor for both x and y coordinates. In actuality, because of the intrinsic characteristic of line scanning, the scales in the x and y directions are rarely identical. Therefore, the equations for affine transformation represent a more realistic description of the relationship between the target coordinates $\bar{x}_j$, $\bar{y}_j$ and the image coordinates x_j, y_j. These equations allow different scales in the x and y directions and may be written as:

$$\dot{V}_{x_j} + x_j = x_0 + a_1\bar{x}_j + a_2\bar{y}_j \quad (5)$$

$$\dot{V}_{y_j} + y_j = y_0 + a_3\bar{x}_j + a_4\bar{y}_j. \quad (6)$$

Again, using all the reseau points in an exposure and the method of least-squares, the most probable set of residuals $\dot{V}_{x_j}$, $\dot{V}_{y_j}$ for that exposure can be determined. Here the residuals $\dot{V}_{x_j}$, $\dot{V}_{y_j}$ represent distortions which cannot be accounted for by scaling.

In this experiment, each exposure was analyzed using first Equations 3 and 4 and then Equations 5 and 6.

SYSTEMATIC AND RANDOM COMPONENTS

The image residuals $\dot{V}_{x_j}$ and $\dot{V}_{y_j}$ from Equations 5 and 6 may be considered to consist of systematic components $\dot{r}_{x_j}$, $\dot{r}_{y_j}$ and random components r_{x_j}, r_{y_j}. That is,

$$\dot{V}_{x_j} = \dot{r}_{x_j} + r_{x_j} \quad (7)$$

$$\dot{V}_{y_j} = \dot{r}_{y_j} + r_{y_j}. \quad (8)$$

The systematic components $\dot{r}_{x_j}$, $\dot{r}_{y_j}$ are distortions that remain at the same image point j of every exposure in a given sequence of exposures. The random components r_{x_j}, r_{y_j}, however, follow a normal distribution with mean 0. Hence, the systematic and random components of distortion may be determined using the following procedure:

1. Consider a sequence of N successive exposures. Equations 5 and 6 were used to determine the distortion at each exposure. Let $(\dot{V}_{x_j})_i$ and $(\dot{V}_{y_j})_i$ denote the residual of reseau point j at the ith exposure, then the systematic components of distortion at point j can be computed using:

$$\dot{r}_{x_j} = \frac{1}{N}\left[\sum_{i=1}^{N} (\dot{V}_{x_j})_i\right] \quad (9)$$

$$\dot{r}_{y_j} = \frac{1}{N}\left[\sum_{i=1}^{N} (\hat{V}_{y_j})_i\right]. \qquad (10)$$

The quantities $\dot{r}_{x_j}$, $\dot{r}_{y_j}$ are computed for all reseau points.

2. Correct the image coordinates x_j, y_j for systematic distortion using $\dot{r}_{x_j}$ and $\dot{r}_{y_j}$. Equations 5 and 6 are then used to perform a second transformation for each exposure. That is, substituting Equations 7 and 8 into 5 and 6 respectively we, have

$$r_{x_j} + (\dot{r}_{x_j} + x_j) = x_0 + a_1\bar{x}_j + a_2\bar{y}_j \qquad (11)$$

$$r_{y_j} + (\dot{r}_{y_j} + y_j) = y_0 + a_3\bar{x}_j + a_4\bar{y}_j. \qquad (12)$$

The residuals r_{xj}, r_{yj} are then the random components of geometric distortion.

A sample size of $N=12$ was found to be adequate for this experiment.

STABILITY OF DISTORTION CHARACTERISTICS

The geometric stability of a space TV system can be evaluated by collecting a sample of exposures from each day of the mission. The pattern of systematic distortion during each day can be determined as described above. Then by comparing the distortion patterns for successive days, the geometric stability of the system can be analysed. Change in the distortion pattern may be due to change in environmental conditions around the TV camera, aging of the electronic components, and/or programmed adjustment of ground receiving systems.

MATERIALS AND EQUIPMENT

An adequate sample of exposures was collected for each of the ESSA-7, SURVEYOR-7 and MARINER-4 television systems. All exposures were film negatives obtained through the National Space Science Data Center. The photographic content in these exposures was of no significance in this experiment. The only criteria for selecting the samples was that as few of the reseau points be obscured by image detail as possible.

All coordinate measurements were made at the Mapping Science Laboratory, NASA Manned Spacecraft Center at Houston using a Mann monocomparator. This comparator has a least count of 0.5 μm. Each frame was measured independently by two different operators. Each operator made one pointing at each reseau point. The mean of the two sets of readings was used as the measured photo coordinates. Besides the reseau images, the coordinates of the four corners of each frame were also measured. The photo coordinate system x, y was defined with the origin at the center of the frame, and the x-axis bisecting the frame in the horizontal direction.

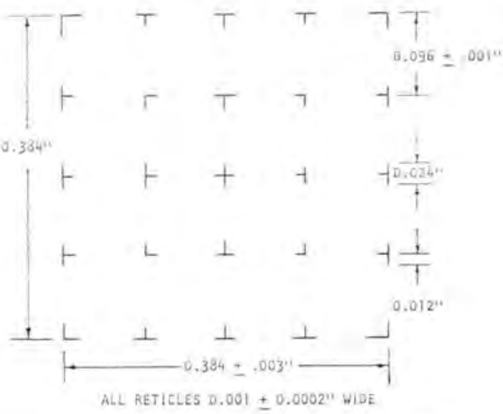

FIG. 1. ESSA-7 vidicon reseau map. (Dimensions are shown in inches.)

ESSA-7 PHOTOGRAPHY

The sample of ESSA-7 exposures consisted of 7 groups of 12 frames each. Within each group, the 12 frames were successive exposures along one earth orbit. The exposure interval was 4 minutes and 20 seconds. Two groups were studied from two successive orbits for each of the dates: January 24, 1969, February 14, March 7, and March 28. Thus the exposures were sampled regularly over a period of two months and provided an adequate period for a study of the geometric stability of the system.

Figure 1 illustrates the spacing of the reseau marks on the ESSA-7 vidicon tube. No problems were encountered in measuring the reseau images on the film negatives although occasional reseau marks were obscured by image detail. The standard deviations in the image measurements were: $\sigma_x = \pm 4\mu$m and $\sigma_y = \pm 4\mu$m.

SURVEYOR-7 PHOTOGRAPHY

Exposures from the SURVEYOR-7 mission were sampled from-Days 13, 16, 19, 21 and 22 of the SURVEYOR's pnotographic life. At least 10 exposures were used for each day. The first photographic day was designated as Day 10. Thus, all the exposures used in the experiment were made during the first lunar day and were spread over a period of 9 Earth-days.

Figure 2 illustrates the reseau pattern in the Surveyor-7 vidicon tube. It consisted of 25 circular dots arranged in rectangular arrays Table 2 shows the coordinates of the points.

The reseau images on the SURVEYOR-7 photography were found to be noticeably

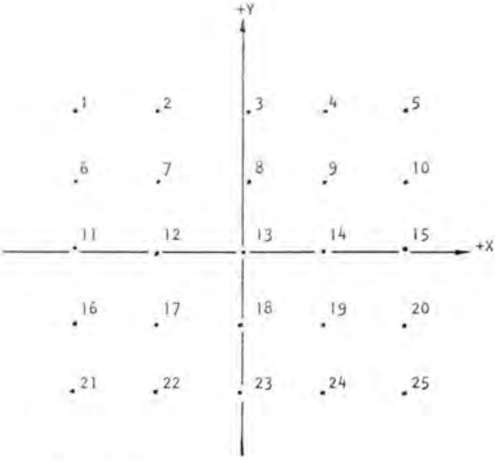

FIG. 2. Surveyor-7 vidicon reseau map.

inferior to those of ESSA-7 photography. Due to a defocusing of the electron beam in the vidicon tube, the bottom row of reseau marks appeared blurry and out of focus in all of the available exposures. Moreover, due to the finite aperture of the scanning beams, the images of the circular reseau marks appeared irregular in shape with an average diameter of about 0.250 mm. These effects resulted in poor pointing arccuracy in coordinate measurement. It is for this reason that two operators were employed to reduce errors caused by personal bias. The measured coordinates were estimated to have $\sigma_x = \pm 10\mu m$ and $\sigma_y = \pm 11\mu m$.

TABLE 2. COORDINATES IN INCHES OF POINTS SHOWN IN FIGURE 2

Pt.	*X*	*Y*	*Pt.*	*X*	*Y*
1	−.18848	+.18690	14	+.09352	.00000
2	−.09500	+.18685	15	+.18727	+.00014
3	−.00152	+.18675	16	−.18614	−.09361
4	+.09197	+.18675	17	−.09278	−.09368
5	+.18554	+.18680	18	+.00079	−.09373
6	−.18773	+.09335	19	+.09489	−.09331
7	−.09420	+.09328	20	+.18802	−.09382
8	−.00069	+.09329	21	−.18534	−.18686
9	+.09287	+.09335	22	−.09202	−.18697
10	+.18644	+.09326	23	+.00139	−.18704
11	−.18689	+.00006	24	+.09490	−.18705
12	−.09342	+.00004	25	+.18847	−.18711
13	.00000	.00000			

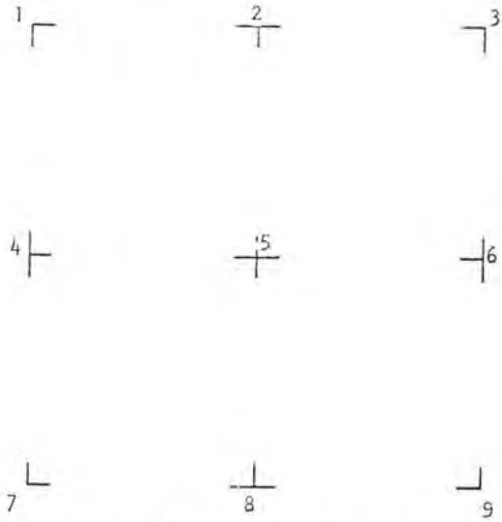

FIG. 3. Mariner-4 vidicon reseau map.

MARINER-4 PHOTOGRAPHY

MARINER-4 transmitted 22 pictures of Mars back to Earth in July, 1965. As the picture sequence was transmitted twice, two samples of 22 pictures each, were obtained. Both samples were available for these experiments. However, due to the loss of reseau images in several frames, only 13 frames were used in Sample 1 and 15 frames were used in Sample 2.

The MARINER-4 reseau had nine reseau marks as shown in Figure 3 and Table 3. The calibrated coordinates of these reseau marks were given in terms of rows and elements. The unit length of a row and that of an element were not known and that they were not necessarily the same. This resulted in uncertainty in the scale relationship between the negatives and the target. However, the calibration data was found to be adequate for distortion study.

TABLE 3. ROWS AND COLUMNS OF POINTS SHOWN IN FIGURE 3

No.	*Element No.*	*Row No.*
1	−72	75.5
2	−1	77
3	69	79
4	−71	−2
5	0	0
6	70.5	2
7	−70	−88
8	1	−86
9	72	−84

TABLE 4. *RMS* ERRORS OF IMAGE COORDINATES FOR ESSA-7

Photo Group	No. of Frames	σ ($\mu m.$)			σ_x ($\mu m.$)			σ_y ($\mu m.$)		
		Conformal	Affine	Random	Conformal	Affine	Random	Conformal	Affine	Random
124a	11	232	34	6	221	36	7	232	32	7
124b	11	239	35	7	230	34	6	235	32	7
214a	12	238	33	6	233	34	6	230	34	7
214b	12	241	33	7	229	34	7	240	31	7
307a	12	226	32	6	217	34	5	224	31	6
307b	12	237	32	7	226	34	6	235	31	7
328a	12	261	33	7	246	35	6	261	30	7
328b	12	188	33	7	195	35	7	169	31	8
Mean ($\bar{\sigma}$)		233	33	7	225	35	6	228	32	7
Equivalent TV Lines		9.2	1.4	0.3	9.3	1.5	0.3	9.5	1.4	0.3

RESULTS

ESSA-7

Table 4 is a summary of the results obtained for the ESSA-7 photography. The mean of the root-mean-square (*rms*) errors for the image coordinates after conformal transformation was found to be ± 0.233 mm., which was equivalent to the width of 9.7 TV lines. This represented the total geometric distortion of an image point in both the x and y directions at one-sigma level. The mean *rms* error after affine transformation was ± 0.033 mm. or 1.4 TV lines. Thus, a major portion of the geometric distortion was accounted for by the difference in scale between the x and y directions. The mean *rms* error for the random components was only ± 7 μm or 0.3 TV line. No significant difference in geometric accuracy between the x and y coordinates seemed to exist.

During the two-month period covered by the photography, the systematic component of distortions remained very stable in both magnitude and shape. Figure 4 shows the systematic distortion at the 25 reseau points for photo group 307a. The same distortion pattern was manifested by the other groups of ESSA-7 negatives.

SURVEYOR-7

Results from the SURVEYOR-7 photography are tabulated in Table 5. The mean *rms* error after conformal transformation was ± 0.428 mm. or 5.2 TV lines. After affine transformation, the mean *rms* error was ± 0.131 mm. or 1.6 TV lines. Again, as in the case of ESSA-7, this showed that a great percentage of geometric distortion was due to the difference in scale between x and y directions. The mean *rms* error for the random component of distortion was ± 23 μm or 0.3 TV line. Comparison between σ_x and σ_y showed that the SURVEYOR-7 photographs had a slightly higher fidelity in the y-direction.

Figure 5 illustrates the systematic component of distortion for the TV system on Day 16. The same pattern was displayed by the system during other days. However, a noticeable change occurred in the magnitude of systematic components between successive days. This may be caused by the temperature

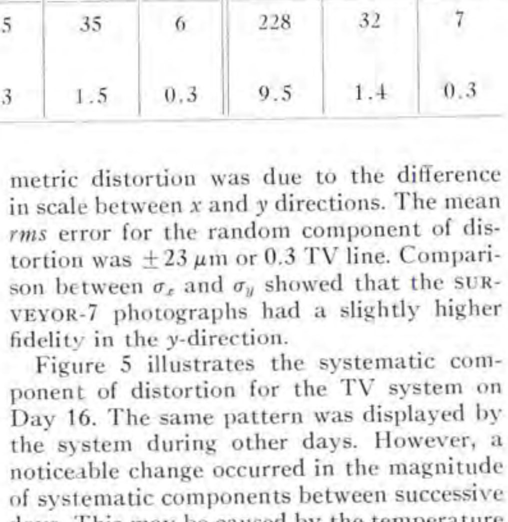

FIG. 4. Typical distortion pattern in ESSA-7 photographs. (Photo group 307a.)

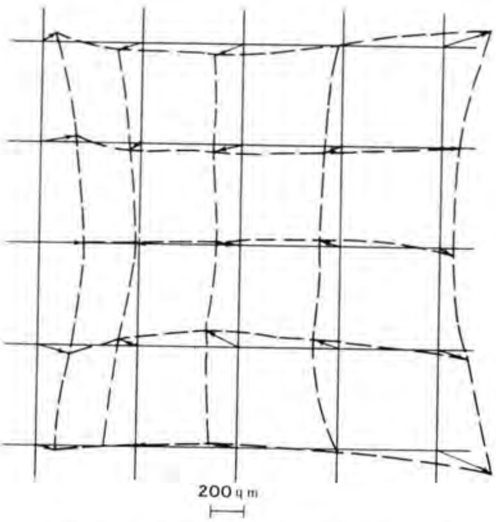

FIG. 5. Distortion pattern of Surveyor-7 on Day 16.

change in the vidicon tube during the lunar day as the sun angle changed. It could also be caused by the daily adjustment of ground receiving system.

MARINER-4

The MARINER-4 TV system behaved in about the same manner as ESSA-7 and SURVEYOR-7, as shown by the results listed in Table 6. The distortion was highly systematic and a large percentage was caused by scale difference in the x and y directions. The mean *rms* errors were:

$$\sigma \text{ (conformal)} = \pm 0.235 \text{ mm. or } 5.1 \text{ TV lines}$$
$$\sigma \text{ (affine)} = \pm 0.013 \text{ mm. or } 0.3 \text{ TV line}$$
$$\sigma \text{ (random)} = \pm 5 \mu\text{m. or } 0.1 \text{ TV line}$$

It should be remembered that part of the residuals in conformal transformation could be due to the possibly unequal units of row and element in the calibration data. The tremendous improvement in using affine transformation (from 0.235 mm. to 0.013 mm.) further showed that the unit lengths of a row and an element were not identical.

The MARINER-4 photography had the same order of fidelity in both vertical and horizontal directions.

Figure 6 illustrates the distortion pattern of the MARINER-4 system. No appreciable dif-

TABLE 5. *RMS* ERRORS OF IMAGE COORDINATES FOR SURVEYOR-7

Photo Group	No. of Frames	$\sigma(\mu m.)$			$\sigma_x(\mu m.)$			$\sigma_y(\mu m.)$		
		Conformal	*Affine*	*Random*	*Conformal*	*Affine*	*Random*	*Conformal*	*Affine*	*Random*
Day 13	12	464	137	21	507	167	19	389	88	22
16	22	446	124	14	472	167	12	397	53	16
19	10	406	130	23	416	168	21	373	71	26
21	11	432	129	29	445	163	25	395	80	32
22	10	391	135	28	400	172	24	361	82	30
Mean ($\bar{\sigma}$)		428	131	23	448	167	20	383	75	25
Equivalent TV Lines		5.2	1.6	0.3	5.5	2.0	0.2	4.7	0.9	0.3

TABLE 6. *RMS* ERRORS OF IMAGE COORDINATES FOR MARINER-4

Photo Group	No. of Frames	(σm).			$\sigma_x(\mu m.)$			$\sigma_y(\mu m.)$		
		Conformal	*Affine*	*Random*	*Conformal*	*Affine*	*Random*	*Conformal*	*Affine*	*Random*
1	13	233	12	4	233	7	6	202	16	3
2	15	236	13	5	235	9	6	204	17	3
Mean ($\bar{\sigma}$)		235	13	5	234	8	6	203	17	3
Equivalent TV Lines		5.1	0.3	0.1	5.1	0.2	0.1	5	0.4	0.06

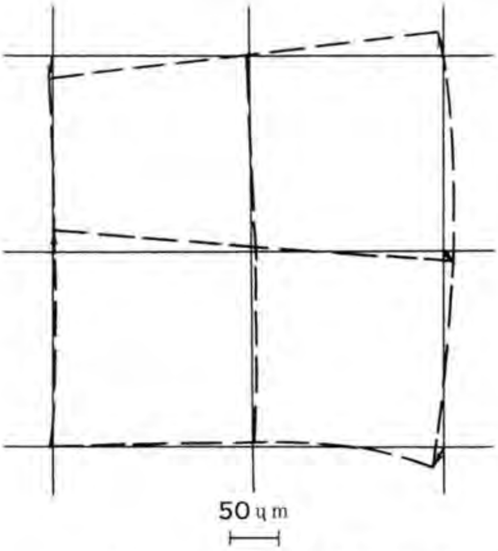

FIG. 6. Distortion pattern of Mariner-4 photographs. (Sample 1.)

ference existed between the distortion characteristics of the two photographic samples.

SUMMARY AND CONCLUSIONS

The results from this investigation showed that geometric distortions in the three space TV systems are highly systematic. This supported the conclusions drawn from a previous theoretical study by the author. Although the total geometric distortions in the ESSA-7, SURVEYOR-7 and MARINER-4 systems were between 5 and 10 scan lines (at one-sigma level), the random components amounted to less than 0.5 scan line.

In all three systems the systematic component of distortion appeared perfectly stable in both magnitude and shape between successive exposures. The systematic component can be separated from the random component with excellent reliability using a sequence of 10 or more successive exposures. The ESSA-7 photography displayed excellent stability in the distortion characteristics throughout the given period of two months. However, the SURVEYOR-7 did have a significant variation in the magnitude of distortion between successive days.

Another significant conclusion from this study is that a major portion of geometric distortion in the TV system was caused by scale distortion in the horizontal and vertical directions. In all instances, the *rms* error in the image coordinates after affine transformation was less than 1.6 TV lines.

TABLE 7. MEAN *rms* ERRORS REDUCED TO A COMMON FRAME SIZE

TV System	$\bar{\sigma}$ *in micrometers (with respect to a frame size of 49×47 mm.)*		
	Conformal	*Affine*	*Random*
ESSA-7	571	81	17
SURVEYOR-7	428	131	23
MARINER-4	1278*	71	27

* Includes errors due to unequal units of the calibrated *x* and *y* coordinates.

As the three TV systems have basically different design characteristics, no conclusions can be drawn on the relationship between geometric distortions and the number of scan lines. To provide a comparison on the relative fidelity of the three systems, the mean *rms* errors were reduced to a common frame size of 49×47 mm. and listed in Table 7. Comparing the total geometric distortions, the SURVEYOR-7 system had the best fidelity.

In view of the low magnitude of random distortions, space television systems seem to have excellent potential for geometric measurements using methods of analytical photogrammetry. Its potential in topographical mapping, however, will depend laregely on how much of the systematic distortions can be corrected over an entire frame by electronic processing. Research efforts are being continued to study this problem.

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