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ANNA Satellite Yields Photogrammetric Parameters

Future optical geodetic satellite applications will have improved precision because of knowledge gained relative to flash intensity, range, exposure and image diameter.

(*Abstract is on page 343*)

Introduction

On October 31, 1962 with the launch of the Satellite ANNA 1-B* into a nearly circular orbit of approximately 600 nautical miles (Figure 1) a new era in the sciences of photogrammetry and geodesy was started.[1] This geodetic satellite (designed for six months' operation) continues to be productive some 22 months later. The name ANNA reflects its four United States sponsors, the Air Force, Navy, NASA and the Army. The Army was responsible for the electronic ranging system known as Secor; the Navy was responsible for the electronic doppler system and integration of the satellite payload; the Air Force was to develop the flashing light system; and NASA was to assist in the optical observational program. This paper will cover only those aspects contributing to the optical phases of the active ANNA program.

* Although it is not the subject of this paper, it is deemed appropriate to note that the ANNA 1-B satellite has satisfied many objectives of our original research program, in that results have clearly proven the feasibility of using multi-angulation space-surveying techniques to obtain highly reliable geodetic data. The results of our Long Line Azimuth and Gulf test reductions have demonstrated that Air Force PC-1000 geodetic stellar cameras are capable of extending geodetic control to a proportional accuracy of greater than 1/100,000 when cameras in a network simultaneously observe a flashing beacon such as that carried on ANNA. The results are described in AFCRL Environmental Research Papers No. 21, "Long Line Azimuths from Optical Observations of the ANNA Flashing Satellite," by A. Mancini, June 1964 and No. 35, "Geodetic Positioning from Simultaneous Optical Observations of the ANNA 1-B Satellite," by L. L. Sheldon and D. H. Eckhardt, July 1964.

† Presented at the Tenth Congress, International Society of Photogrammetry, Lisbon, Portugal, September 1964.

In January 1963, after more than two months of excellent performance, a defective capacitor bank caused a malfunction in the optical system. The output of the light system was reduced to about 25% to 30% of its original value and this condition remained in effect into July. Therefore, between January and July only a limited program of flash transmissions took place, and while usable camera data was still received it was for the most part not up to original expectations.

Prior to the capacitor problem in the satellite, geodetic stellar cameras obtained an excellent series of photographs. The image diameter of the flash recorded on 103-F emulsion averaged 70 microns on the PC-1000's and approximately 50 microns on the BC-4-300 plates. In mid-July 1963, the light output returned to normal and good data was again obtained. Because of normal solar cell deterioration, only 7 flash sequences a day can currently be programmed as opposed to the original 30 sequences.

Due to the condition of the main battery controlling the command system and the lack of doppler tracking data, the Applied Physics Laboratory, Johns Hopkins University, suggested to Air Force Cambridge Research Laboratories in October 1963 that we operate the flashing light by employing our alternate logic (Figure 2). The emergency over-ride system (EMOS) had been developed to provide the necessary redundancy for the optical operations, and this bit of foresight continues to pay dividends. The EMOS system consists of a World Timing System accurate to one millisecond, a transmitter, a linear amplifier, and an antenna system. The cycle for interrogating the light, from the time the pulse is initiated until the flash is

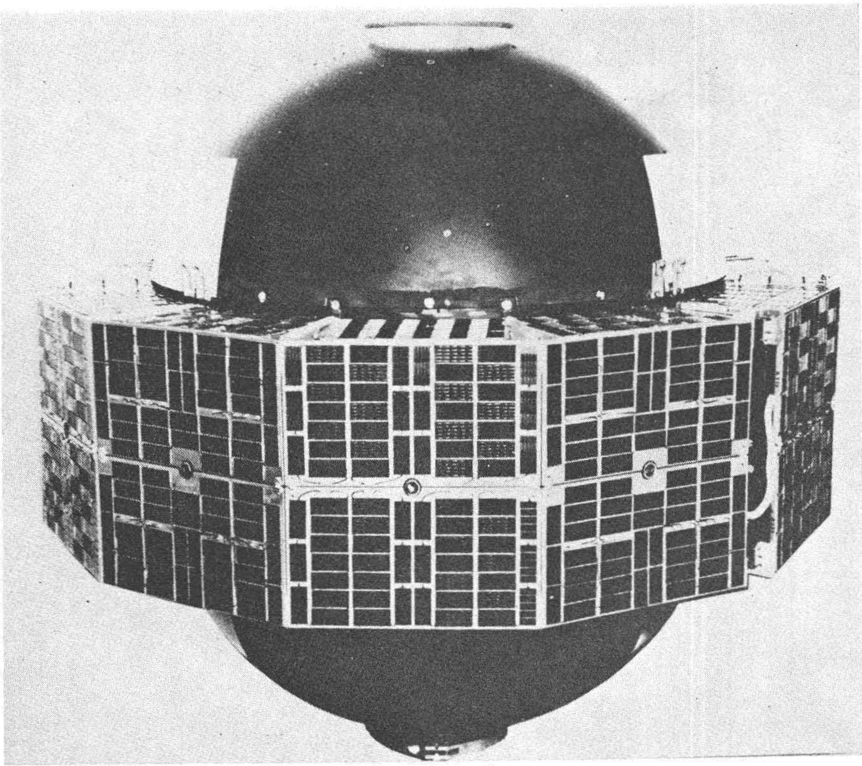

FIG. 1. The ANNA 1-B Geodetic Satellite.

activated, is less than 2 seconds.

Although AFCRL generated about 175 flash sequences employing EMOS from Bedford, Massachusetts through January 1964, and thereby permitted about 400 successful observations of ANNA, the system is now being operated by Air Photographic and Charting Service, Orlando, Florida, in support of their geodetic stellar activities.*

DESCRIPTION OF BEACON

The ANNA optical beacon, developed for AFCRL by Edgerton, Germeshausen and Grier, Inc. (EG & G) consists of two pairs of xenon-filled stroboscopic lamps with reflectors, one pair on the north face of the solar cell panel and one pair on the south face (Figure 3). When either set of lights is triggered by the satellite memory or by EMOS, a series of 5 flashes, 5.6 seconds apart having a duration of 1.2 milliseconds from $\frac{1}{3}$ peak to $\frac{1}{3}$ peak is produced.[2] An enlargement of a part of one of the first photographs of ANNA clearly demonstrates the above mentioned spacing (Figure 4).

Each of the flashes produces a light output of about 8800 candle seconds. The light has a cone angle of 150° so that each flash is visible over a large portion of the earth. The beacon operates in conjunction with the magnetic stabilization feature of the satellite such that one set of lights will be visible when the satellite is north of the magnetic equator and the other set south of the magnetic equator.

LIGHT INTENSITY

The light intensity of the ANNA beacons is not constant over the light angle but varies as shown by a dotted line in Figure 5 while the solid line shows the intensity used to predict the image sizes for ANNA. Light intensity was also measured as a function of increasing longitudes around the satellite and at various angles above the satellite's equator.[3]

COMPUTATION OF IMAGE SIZE

Equations used to compute image sizes, d,

* The third member of the Air Force team is the Aeronautical Chart and Information Center (ACIC) located in St. Louis, Missouri. ACIC is responsible for initially locating the flash images from the satellite and for performing the plate measuring and the preliminary reduction of data.

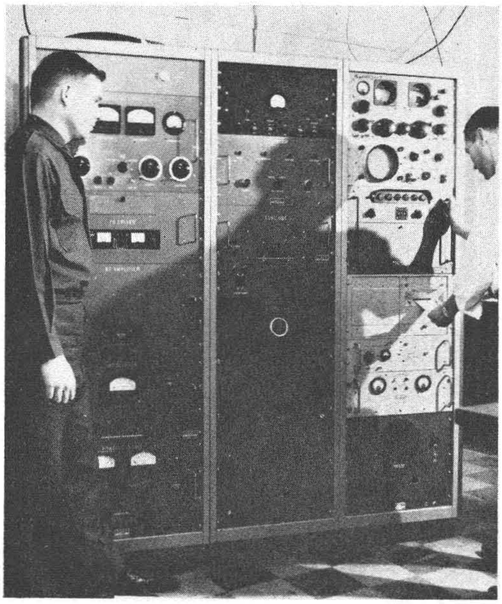

FIG. 2. The Emergency Over-ride System.

FIG. 4. ANNA 1-B Strobe Light Images (1962 Beta Mu-1).

recorded on a photographic plate of ANNA are given by

$$d = A_1 q + A_2 q^2 + A_3 q^3$$

The constants A_1, A_2, and A_3 are used in the computation for a 103F emulsion developed in 8 minutes in D-19 at 68°F and are as follows:

$$A_1 = 7.4680$$
$$A_2 = 0.112237$$
$$A_3 = 0.0008352$$

These values were obtained by means of a least-squares fit of the polynomial q to the E_d vs. d curve of 103F emulsion. This was determined by D. Brown from recordings of Vega[4] through neutral density filters (Figure 6).

$$q = \frac{D}{S} (TB)^{1/2} P$$

D = camera aperture in microns

T = lens transmission factor

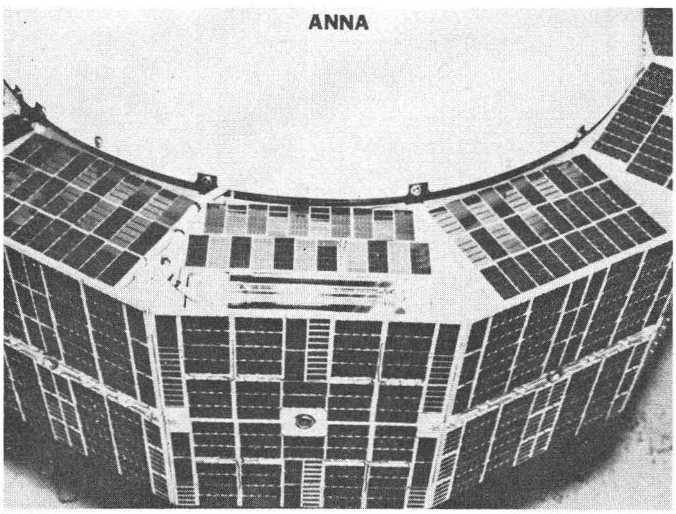

FIG. 3. A Close View of One of the Four Strobe Lights Located on the ANNA Geodetic Satellite.

Abstract: *One of the major considerations associated with Satellite Geodesy using photogrammetric techniques is the critical design of a minimum-weight, minimum-power strobe light which produces a photographable intensity consistent with camera systems used in the optical program. The relationship between flash intensity and range (or image diameter) has been approximated, but the theoretical formulae need to be validated and improved.*

This paper presents an evaluation of these computations as derived from actual photographic plates taken during the ANNA Geodetic Satellite Program. The light-intensity and light-pattern measurements performed on the ANNA light prior to launch and the known ranges and position of the satellite available from the orbit analysis will serve as constraints to investigate other photographic parameters. The relationship between flash intensity, range, and exposure versus image diameter curves will be presented and the results extrapolated to other geodetic satellite programs.

For various cameras these factors are:

Camera	*Aperture D*	*Lens Transmission T*
BC-4 210 mm	5×10^4 microns	70%
BC-4 300 mm	1.17×10^5 microns	70%
PC-1000	2×10^5 microns	85%
600 mm	3×10^5 microns	60%

B is the light intensity in beam candle-seconds.

The light output

$$B = 9000, \quad \text{if } \theta \leq 45^\circ$$

or

$$B = 150(105 - \theta) \quad \text{when } \theta > 45^\circ.$$

is the angle at the satellite from the light axis to an observer. S is the slant range from an observer to the satellite in meters.

$$P = \exp\left(\frac{-0.46\Delta m}{\sin h}\right)$$

h = elevation angle of satellite

The atmospheric extinctions in stellar magnitudes is Δm. The value $\Delta m = 0.25$ is used for clear conditions and $\Delta m = 1.25$ for moderate haze conditions. An example of the relationship between image size and a change in the angle θ for a 600 nm orbit is found in Figure 7. Note: These equations are more valid over the range of 40 to 100 microns than those image sizes less than or more than the specified spread.

Validity of Equations

During the development phase of ANNA the above equations for moderate haze conditions (1.25) were used to predict the image size on Air Force PC-1000 geodetic stellar camera plates. Currently, two groups, EG & G and Duane Brown Associates, Inc., have examined some of the ANNA PC-1000 plates to determine the validity of the equations. The results of the EG & G analysis of 32 images on 8 plates are shown in Table 1. These measurements were performed on a Mann screw-driven Micro-comparator and they adopted the value $\Delta m = 1.25$ in their reductions.

Duane Brown Associates analyzed 88 images on 20 different plates taken from six different PC-1000 cameras.[5] The plates were selected to be representative of different cameras, different locations, and a wide range of

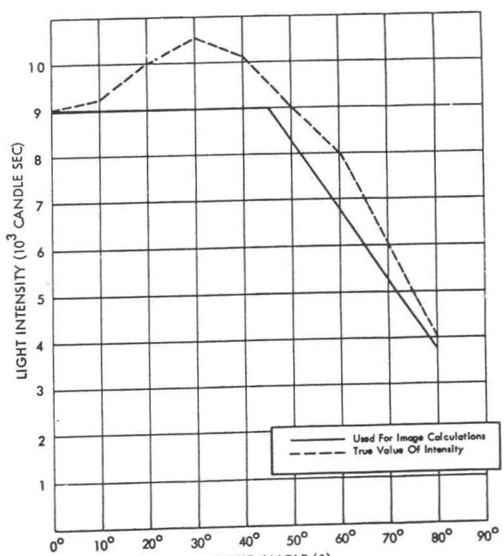

Fig. 5. Light Pattern

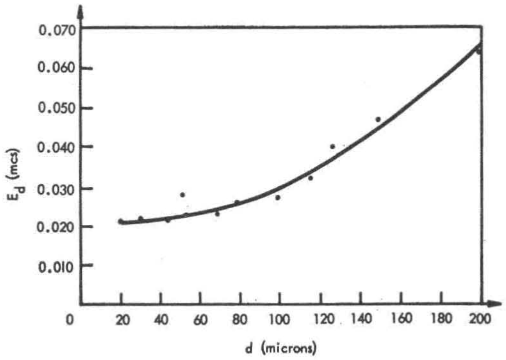

FIG. 6. Exposure vs. Image Diameter Curve of 103F Emulsion from Recordings of Vega Through Neutral Density Filters.

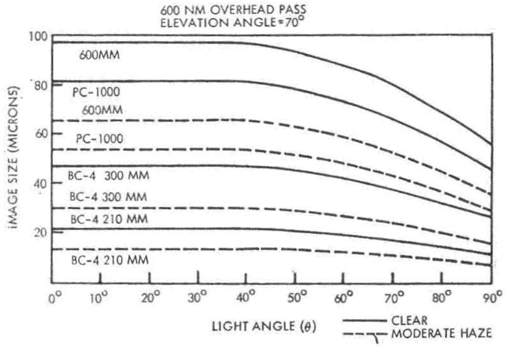

FIG. 7. Relationship Between Image Size and a Change in the Angle θ for a 600 nm orbit.

TABLE 1

PLATE MEASUREMENTS FROM EG & G PHOTROGAPHIC PLATE STUDY

Date (Day in 1962)	*Time (Z)*	*Camera Location*	*Slant Range (nm)*	*Elevation Angle (degrees)*	*Angle off Beacon Axis (degrees)*	*Image Number (Left to Right)*	*AFCRL Computed Image Diameter (microns)*	*EG & G Meas. Image Diameter (microns)*	*Light Intensity Calculated from EG & G Meas. Image Diameters (candle-sec)*	*Deviation from Known Source Light Intensity of 8800 Candle-sec (percent)*
325	09:37:37	0654 Ft. Wayne, Ind.	783.2	48.2	38.3	1	38	37		
						2		51*		
						3		40		
						4		39*	7445	−15
						5		39*		
334	03:46:37	0654	888.4	42.8	50.5	**	30	**		
						2		40*		
						3		46*	8772	0
						4		42*	10,005	14
						5		37*		
335	01:12:44	0654	703.6	63.0	36.8	1	47	52*		
						2		35		
						3		43	7524	−14
						**		**		
						**		**		
335	03:07:23	0656 Oscoda, Mich.	748.2	55.4	41.1	1	43	37		
						2		36*		
						3		42	7497	−15
						4		50		
						5		45		
336	08:06:46	0653 Las Cruces, N. M.	658.0	83.3	33.9	1	53	35	4070	−64
336	00:30:57	0654	878.9	41.5	34.1	1	31	32		
						2		33	6447	−27
						3		29		
						4		36		
						5		**		
336	02:28:24	0656	750.2	56.6	40.3	1	43	55		
						2		52		
						3		50	10,347	18
						4		44		
						5		46		
338	04:56:43	0654	701.3	63.2	35.9	1	47	32	4376	−50
						2		34		
						3		29		
						4		36		
						**		**		

* Poor image quality.
** No visible image.

TABLE 2

D. BROWN DATA SHEET: ANNA FLASH IMAGE DIAMETER VS. SLANT RANGE STUDY

Station: Orlando, Florida
Camera No.: 104
Focal Length (mm): PC-1000
Identification: 3-217-02-56-43
Plate No.: 118

Azimuth: 357°.8
Zenith Distance: 38°.8
Slant Range (nm): 802.0
Flash Nos. 1, 2, 3, 4, 5
No. Flashes: 5

MEASUREMENTS:

Flash No.		*First Setting (mm)*	*Second Setting (mm)*	*Average Setting (mm)*	*Horiz. Diameter (microns)*	*Vertical Diameter (microns)*	*Dispersion About Grand Mean (microns)*
	X Rt.	131.070	131.066	131.068			
1	X Left	131.136	131.140	131.138	70.0		H. −6.1
	Y Bot.	137.911	137.910	137.9105			
	Y Top	137.973	137.976	137.9745		64.0	V. −12.1
	X Rt.	151.749	151.755	151.752			
2	X Left	151.810	151.820	151.815	63.0		H. −13.1
	Y Bot.	122.893	122.890	122.8915			
	Y Top	122.951	122.960	122.9555		64.0	V. −12.1
	X Rt.	172.059	172.055	172.057			
3	X Left	172.142	172.144	172.143	86.0		H. 9.9
	Y Bot.	108.079	108.072	108.0755			
	Y Top	108.164	108.159	108.1615		86.0	V. 9.9
	X Rt.	192.049	192.049	192.049			
4	X Left	192.132	192.130	192.131	82.0		H. 5.9
	Y Bot.	093.445	093.442	093.4435			
	Y Top	093.542	093.545	093.5435		100.0	V. 23.9
	X Rt.	211.721	211.723	211.722			
5	X Left	211.801	211.795	211.798	76.0		H. −0.1
	Y Bot.	078.993	078.999	078.996			
	Y Top	079.070	079.062	079.066		70.0	V. −6.1

Grand Mean $=76.1\ \mu$
Pooled Standard Error of Horizontal and Vertical Diameters $=12.2\mu$

image diameters. Both horizontal and vertical components of the image diameters were also measured on a Mann comparator. Four settings were made on each image, two on the horizontal diameter and two on the vertical diameter, and all recorded flash images were measured on each plate. Ten plates had five flash images each, eight had four, and two had three. The horizontal and vertical diameters were averaged for each image and these averages were in turn averaged for each plate. The average slant range and the average zenith distance of the flashes on a given plate were provided by AFCRL and these were associated with the average image diameter of the plate.

The known brightness of the ANNA flashes, together with their known slant ranges and zenith distances were entered into the above formulae to compute the expected diameters of images. Inasmuch as atmospheric extinction at the zenith (Δm) was not measured, the value $\Delta m = 0.40$ magnitudes was adopted in all reductions.

The data sheet for a typical plate is reproduced (Table 2). The dispersion of image diameters is seen to be rather large. For instance, the smallest vertical diameter in Table 2 is 64 μ and the largest is 100 μ, a range of 36 μ on a single plate. In Table 2, the standard error of the diameter of the individual image about the mean diameter is 12.2 μ. The pooled mean error from all 20 plates is somewhat smaller, being 10.0 μ. This figure applies to individual images.

The key results of the study are summarized in Table 3. In four instances where a pair of cameras was employed at the same station

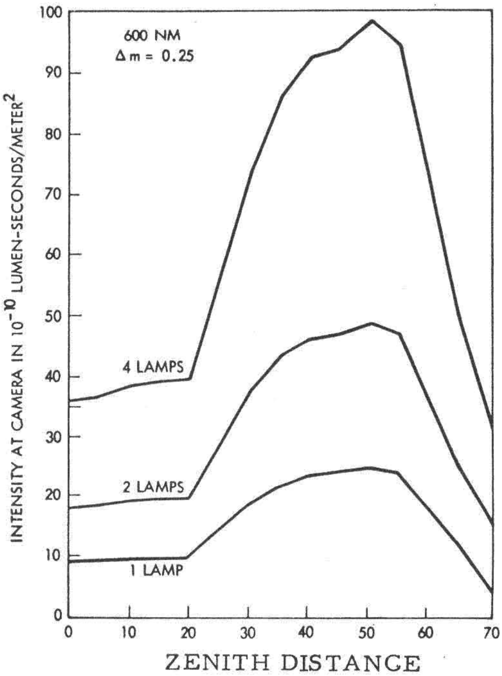

FIG. 8. Intensity at Camera as a Function of Zenith Distance. $\Delta m = 0.25$ for Atmospheric Extinction at 600 nm.

the pairs are bracketed in the first column of the table. In the four cases in which cameras 104 and 121 were employed in side-by-side operations, the mean image diameters from 104 turn out to be consistently and significantly larger than those from 121; on the average, images from camera 104 are 23 microns larger than paired images from camera 121. This convincingly demonstrates that significant differences may exist in the capabilities of cameras of the same type. It follows that for *maximum predictive accuracy*, the exposure vs. image diameter curve (E_d *vs.* d) should be calibrated for individual cameras.

Of interest is the fact that although EG&G and D. Brown used the two different values for Δm in their reductions, a remarkable degree of consistency resulted between their values.

Results Applied as Planning Factors

Recent developments in the area of beam "tailoring" and flash tube reflectors will permit greater efficiency in future geodetic satellite operations.[6] Furthermore, the verified validity of our original calculations on light intensity, expected image diameter, and so forth, have permitted the application of these factors in satisfying the planning objectives of the Geodetic Explorer Project. To provide both redundancy and a choice of light intensities, the optical beacon to be used in the GEOS I spacecraft will have four independent xenon-lamp capacitor-bank assemblies. These lamps will operate in multiple flash sequences, with any selected combination of from one to four lamps being used in each sequence. Planning estimates considering intensity and beamwidth as a function of the two Δm values for atmospheric extinction at 600 nm appear in Figures 8 and 9.

Conclusions

On the whole, agreement between theory and observation is considered to be sufficiently good (13.4 micron mean error) for the theory to be used for purposes of general planning. Significant changes in the coefficients of the basic E_d vs. d curve (A_1, A_2, A_3) are not warranted on the basis of the present sample. However, the results do indicate that the predictive accuracy of the theory can be significantly upgraded for individual cameras if *individually* calibrated E_d vs. d curves were employed in place of an average curve.

It is suggested that such a calibration would best be performed on the ground using the actual flashing light unit to be mounted in the satellite. A wide range of distances could be simulated with the flashing unit at a fixed distance from the camera provided that appropriate neutral density filters were employed in front of the camera lens. With individually calibrated E_d vs. d curves coupled with field measurements of atmospheric extinction, it is estimated that the predictive accuracy of the formulae could be improved from about 13 microns to about 5 microns at

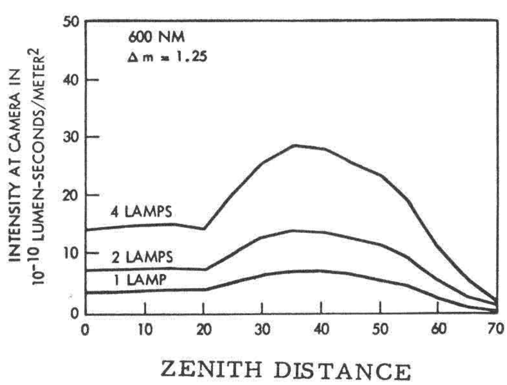

FIG. 9. Intensity at Camera as a Function of Zenith Distance. $\Delta m = 1.25$ for Atmospheric Extinction at 600 nm.

TABLE 3

SUMMARY OF KEY RESULTS OF IMAGE DIAMETER STUDY BY D. BROWN

Plate No./(No. Flashes)	*Camera No.*	*Av. Slant Range (miles)*	*Av. Zenith Distance (degrees)*	*Slant Range Normalized to Zenith (miles)*	*Computed Image Diameter (microns)*	*Average Image Diameter (microns)*	*Standard Error of Individual Image Diameter (microns)*	*Difference between Observed and Computed Diameters (microns)*
{1 (4)	121	934	50.8	1006	55.8	43.2	6.6	12.6
{2 (5)	104	934	50.8	1006	55.8	71.8	13.4	−16.0
{3 (5)	121	921	49.1	986	56.7	62.9	11.8	− 6.2
{4 (5)	104	921	49.1	986	56.7	72.6	6.2	−15.9
5 (5)	110	873	46.0	925	60.0	47.8	6.2	+12.8
6 (5)	104	846	45.7	986	61.6	60.6	12.2	+ 1.0
7 (5)	104	831	42.7	876	63.0	77.4	11.8	−14.4
8 (4)	110	804	42.3	844	64.9	65.6	10.4	− 0.7
{9 (5)	121	802	38.8	836	65.4	58.0	8.4	+ 7.4
{10 (5)	104	802	38.8	836	65.4	76.1	12.2	−10.7
11 (4)	121	776	35.8	804	67.6	51.7	10.6	+15.9
12 (3)	104	760	33.5	785	69.1	81.6	9.7	−12.5
13 (3)	108	759	31.3	781	69.3	58.0	10.8	+ 4.1
14 (4)		752	34.2	777	70.0	44.7	7.9	+25.3
15 (5)	101	720	25.6	736	72.9	67.3	6.3	+ 5.6
16 (5)	104	702	25.7	718	74.4	63.2	7.2	+11.2
17 (4)	107	690	21.5	703	75.7	56.8	6.3	+18.9
{18 (4)	121	680	15.8	690	76.8	58.9	8.0	+17.9
{19 (4)	104	680	15.8	690	76.8	95.0	16.0	−18.3
20 (4)	112	638	10.3	646	81.0	81.6	14.3	− 0.6

RMS Difference = 13.4μ

the one sigma level. (This figure refers to the mean of five images on a given plate.)

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