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The Determination of Exhaust Cloud Dimensions From Films of Space Shuttle Launches

R. A. Zak
ST Systems Corporation (STX)
Hampton, Virginia

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SECTION 1 - INTRODUCTION

Photogrammetry, the technology of obtaining quantitative information about objects through the use of photographic images, has been applied to many disciplines in the past. More recent applications have evolved from remote sensing activities in space. Of particular interest is the digital processing of multispectral images from weather satellites and earth observation platforms for the purpose of stereographic measurements of three-dimensional clouds. Quantitative processing of cloud images from cameras both on the ground and aloft provide the ground truth for many meteorological and earth sciences experiments where the "laboratory" is the real atmosphere and where little, if anything, can be controlled in the usual laboratory sense. For a discussion of some of these applications see Holle, (1982).

The purpose of this report is to document cloud dimensions from 16 mm films of the Space Shuttle launches from Kennedy Space Center, Florida. The dimensions of the ground cloud formed from the rocket exhausts will be the ground truth for numerical simulations of such clouds in different atmospheric conditions.

SECTION 2 - DATA SOURCES

Motion picture films were taken from Kennedy Space Center by TGS Technology Inc. in order to record the Shuttle exhaust cloud near the ground. These films were taken for three Shuttle launches: Mission 41C (April 6, 1984), Mission 41D (August 30, 1984), and Mission 51A (November 8, 1984). Kodak 7239 16 mm color film was used in Mitchell cameras with an exposure time of 1/108 second. Different lenses were used to capture both the full ground cloud and the horizon in each frame in order to facilitate quantitative analysis. Copies of these films were provided for this study.

For each launch, films were taken from three different Universal Camera Sites (UCS) whose locations are described by Figure 1. The focal lengths of the camera lenses and speeds of the films are shown in Table I. Unfortunately, the film from UCS 9 for Mission 51A was overexposed and unavailable for analysis. The locations of the camera sites, launch pads, and other structures were determined from detailed maps provided by Kennedy Space Center.

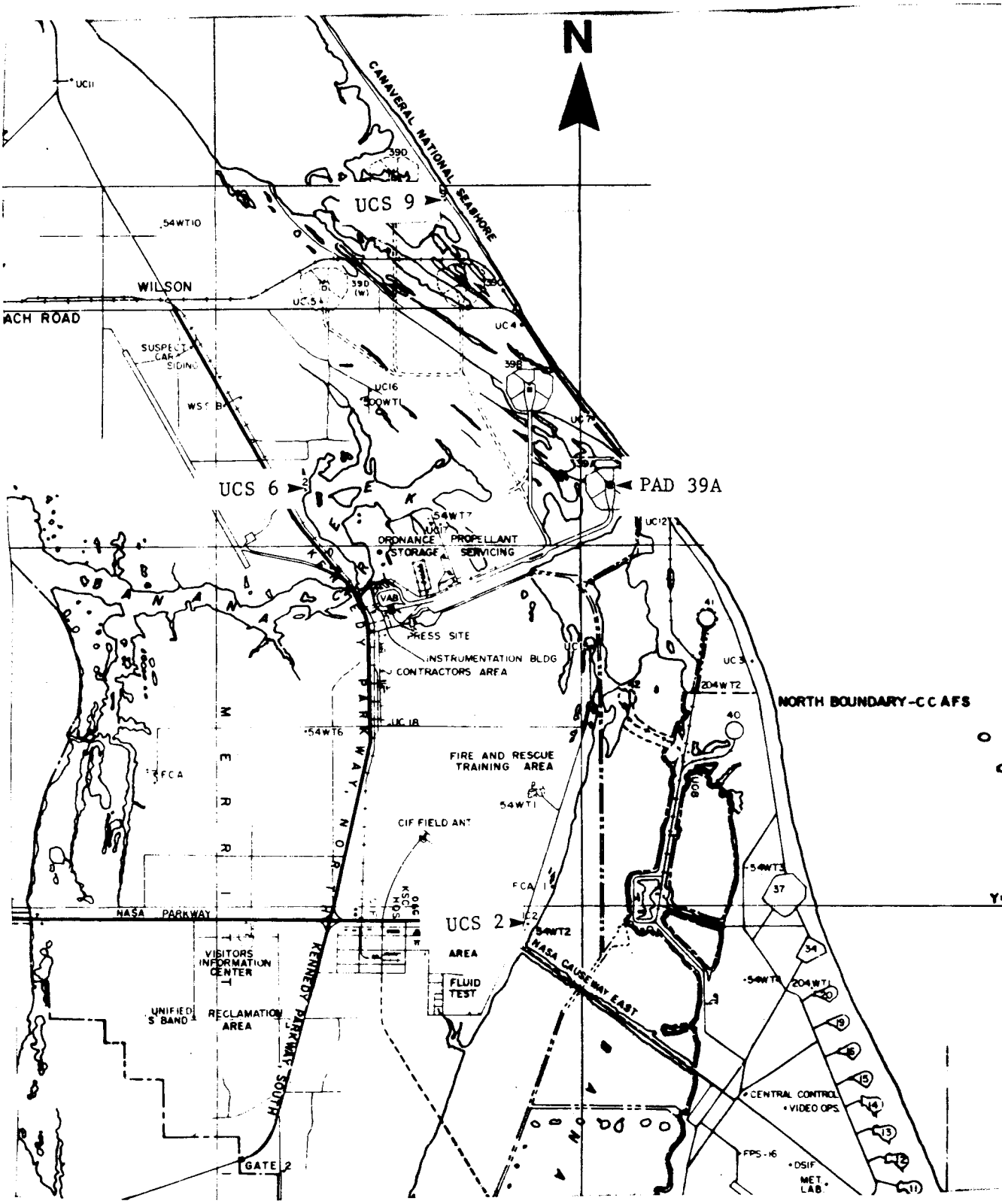

Figure 1. Locations of camera sites

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TABLE 1: CAMERA LOCATIONS AND FOCAL LENGTHS

Mission	Date	Liftoff (GMT)	Camera Site	Camera Location (From Pad 39A)	Focal Length	Film Speed (Frames/Sec)
41C	4/6/84	13:58:00	UCS 2	190.6° at 9330 m	15 mm	18.6
			UCS 6	270.0 at 6320	15	19.5
			UCS 9	331.2 at 6975	10/15	18.7
41D	8/30/84	12:41:50	UCS 2	190.6 at 9330	15	3.0
			UCS 6	270.0 at 6320	10	3.0
			UCS 9	331.2 at 6975	15	3.0
51A	11/8/84	12:15:00	UCS 2	190.6 at 9330	15	3.0
			UCS 6	270.0 at 6320	15	3.0
			UCS 9	--------UNAVAILABLE----------		

In order to permit reconstruction of the proper time history of the Shuttle launches and ground clouds, each film was imprinted with a special NASA-developed timing code known as IRIG Format 'B'. The films with 20 frames/second speed were coded with 100 pulse per second (pps) IRIG code, while the films at 3 frames/second speed were coded with 10 pps code. The formats of the two codes are identical except that the 10 pps code does not include the straight binary time representation at the end of each sequence and the pulse sequences repeat every 10 seconds instead of each second (see Figure 2). The time indicated by each pulse sequence corresponds to the frame nine inches (30 frames) behind the point on the film where the first pulse of that sequence is printed.

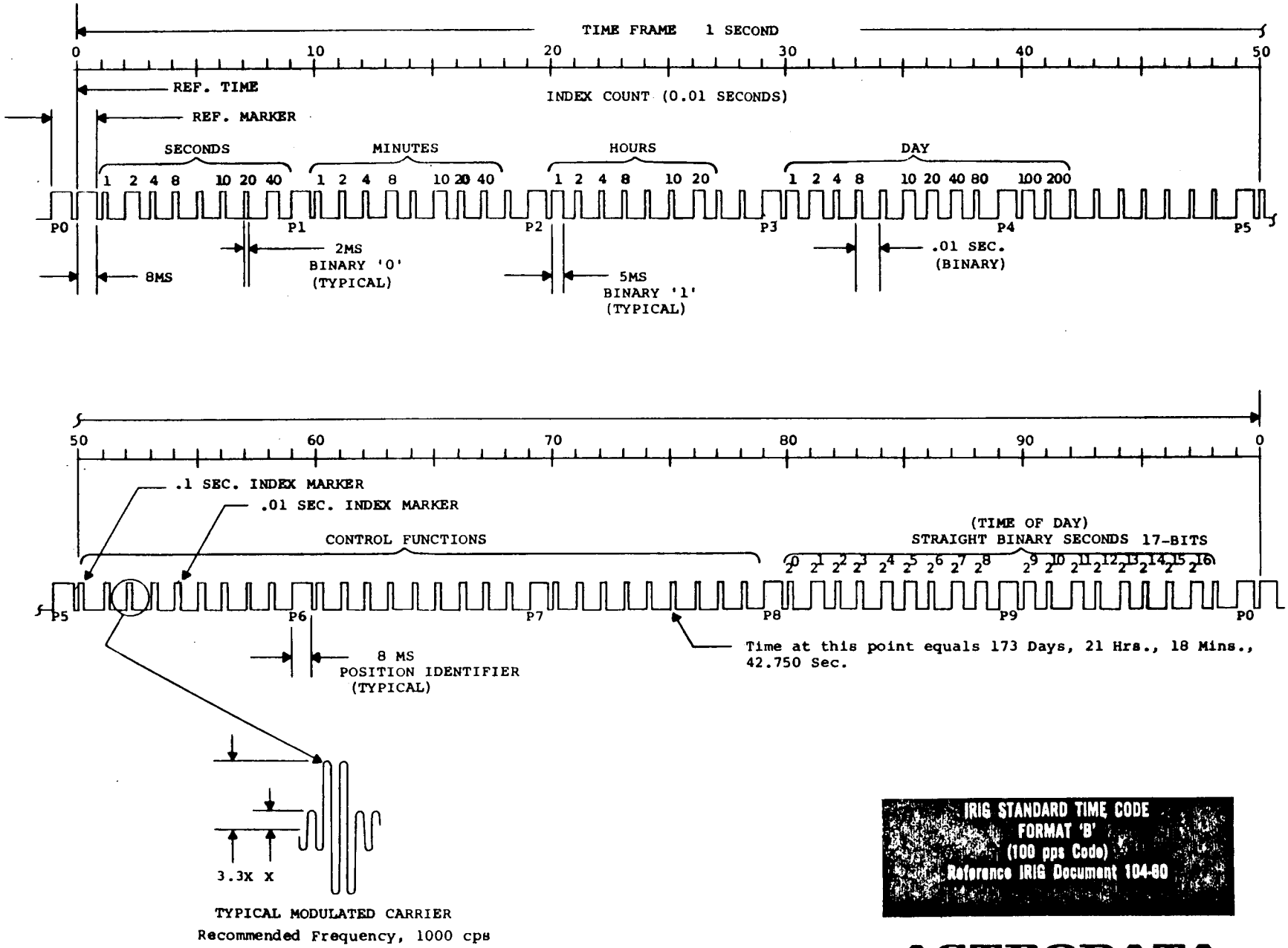


Figure 2. IRIG Code

SECTION 3 - METHODS

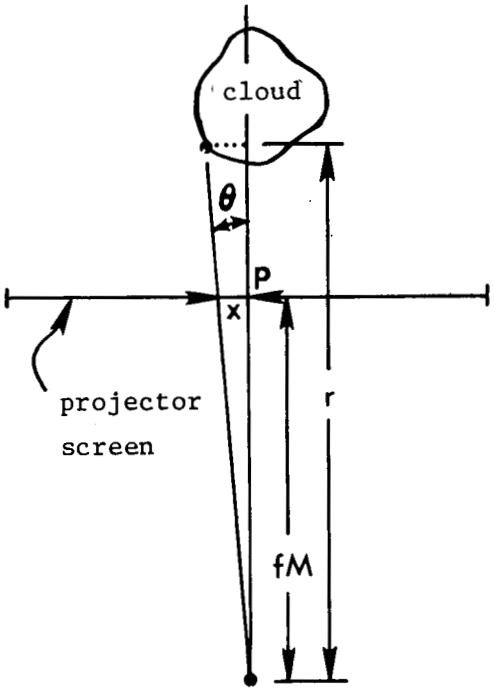
Outlines of the cloud were traced onto paper for subsequent analysis using a 16 mm stop-action projector. The projector magnification (ratio of projector's screen dimensions to those of the film) was adjusted to be 83.4 for all tracings. At one-minute intervals for each film, the cloud outline was traced along with the screen's Principal Point (the exact center of the frame), the horizon, and any ground features such as launch assemblies for Pads 39A, 39B and buildings or towers. In addition, the positions of the Shuttle itself were noted for each film at 5-second intervals while the vehicle was within the camera's field of view; these Shuttle positions were used to check equations for range and height by comparing the calculated heights to altitudes on detailed Ascent Trajectory Listings from Johnson Space Flight Center.

Ground-Based Photogrammetry

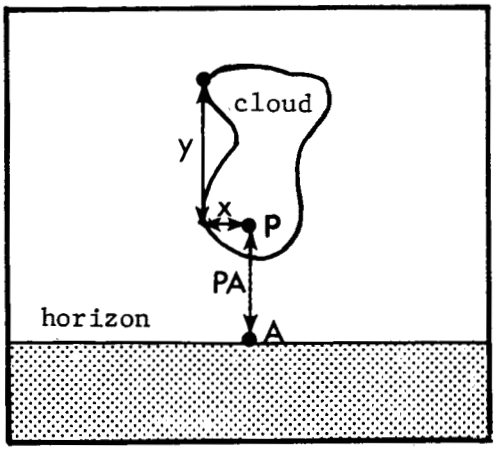
Heights and widths of objects on the projector screen can be converted to actual distances. To locate a point on the exhaust cloud, it is necessary to calculate two angles (see Figure 3): θ, the horizontal angle (projected onto the Earth's surface plane) from the Principal Point 'P' to the cloud point with the camera site as the center; and σ, the vertical angle from the ground to the cloud point.

The equations to determine these angles are (Holle, 1982):

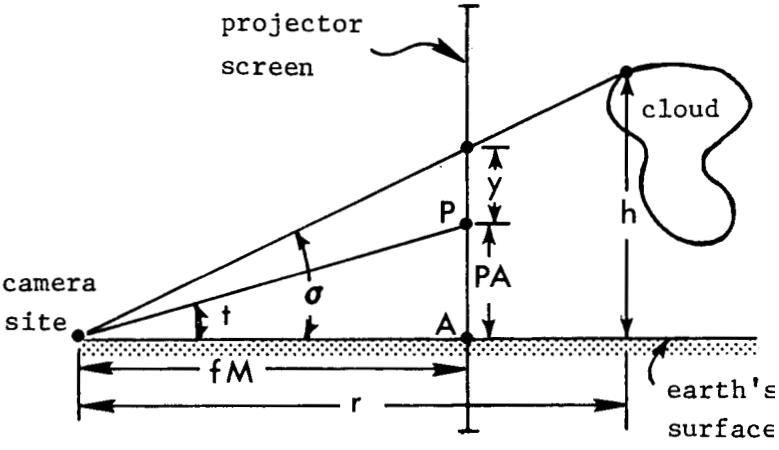
$$\tan(\theta) = \frac{x}{fM\cos(t) - y\sin(t)} \qquad (1)$$



AERIAL (TOP) VIEW



PROJECTOR (FRONT) VIEW



SIDE VIEW

Figure 3. Variables used in photogrammetry equations

and

$$\tan(\sigma) = \frac{\cos(\theta)[y\cos(t) + fM\sin(t)]}{fM\cos(t) - y\sin(t)} \tag{2}$$

where 't' is the camera tilt (with respect to horizontal) given by

$$\tan(t) = -\frac{PA}{fM} \tag{3}$$

and the other parameters (which must all have the same units) are indicated on Figure 3 and defined in Table 2.

TABLE 2: PARAMETERS USED IN PHOTOGRAMMETRY EQUATIONS

Parameter	Description
PA	Vertical distance from Principal Point to horizon (measured on projector screen)
f	Focal length of camera
M	Magnification of the projector
x	Horizontal distance from Principal Point to cloud point on projector screen
y	Vertical distance from Principal Point to cloud point on projector screen

Once the angles θ and σ have been calculated, the height (h) of a cloud point can be determined from

$$h = r\tan(\sigma) \tag{4}$$

where 'r' is the range (ground distance) to the cloud point from the camera site. In addition, the width (w) between two cloud points can be calculated from

$$w = r\tan(\theta_2 - \theta_1) \tag{5}$$

Cloud Dimensions

Four different quantities were calculated for the exhaust cloud in each film: the altitudes of the top and base, the maximum width (near the top of the cloud), and the average width. Figure 4 illustrates the greater width of the ground cloud near the top and the irregular shape of the cloud in general. The altitude of the top was considered to be the highest point on the cloud. The height of the base, however, was selected according to where the cloud material appeared to become more dense and better defined. The smaller "pieces" of the cloud that protruded beneath the dense areas were not considered in defining the cloud base. The maximum width was specified to be near the top of the cloud in order to exclude from consideration the inactive elements near the base which frequently extended beyond the main body of the cloud. The average width was estimated to give a general horizontal dimension to the cloud despite its non-uniform shape.

Cloud Ranges

When the range 'r' is known for one camera site, the cloud dimensions can be calculated from that film. However, for the Shuttle exhaust cloud, the range from one camera site must be determined from at least two different

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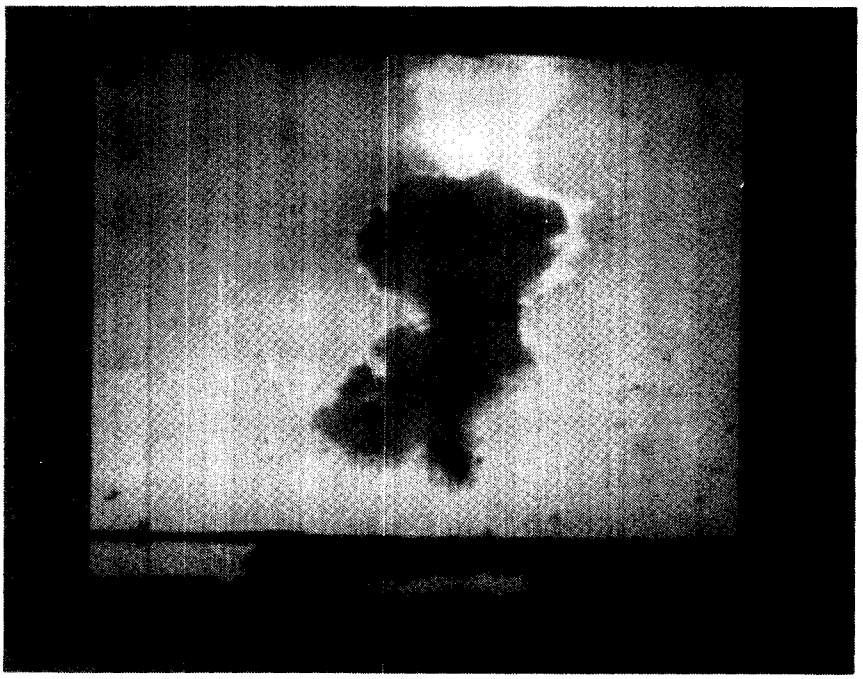


Figure 4. Photograph of a 512 x 512 digitization of a film frame for Mission 41D at nine minutes after liftoff. This picture was taken from camera site UCS-6 looking east.

films for each launch. Since the launch assembly on Pad 39A (from which the Shuttle was launched in each case) was visible in films taken from UCS 6 and UCS 9, the cloud's distance from Pad 39A in these two views was used to triangulate the cloud's position. Since the UCS 9 film was not available for Mission 51A, a straight line approximation was employed to represent the cloud's movement and to calculate its ranges from the camera sites of the other two films. On all films taken from UCS 2, the horizon, launch assemblies, and other ground objects are obscured by foliage near that camera site; these films could not be used to triangulate positions of the clouds.

Ranges for Missions 41C, 41D

The coordinates of the exhaust cloud with respect to UCS 6 (r_6, ϕ_6) and UCS 9 (r_9, ϕ_9) were determined in two steps: (1) the angles ϕ_6 and ϕ_9 were determined from quantities measured on the projector screen at each selected time throughout the cloud's duration; and (2) the ranges r_6 and r_9 were calculated based on these angles and the locations of the camera sites and Pad 39A.

From Figure 5, the angles ϕ_6 and ϕ_9 are determined by

$$\phi_6 = \arctan(l_6/fM_6) + \arctan(c_6/fM_6) \tag{6}$$

and

$$\phi_9 = \arctan(l_9/fM_9) + \arctan(c_9/fM_9) + 28.8^{\circ} \tag{7}$$

The parameters in these equations are described in Table 3.

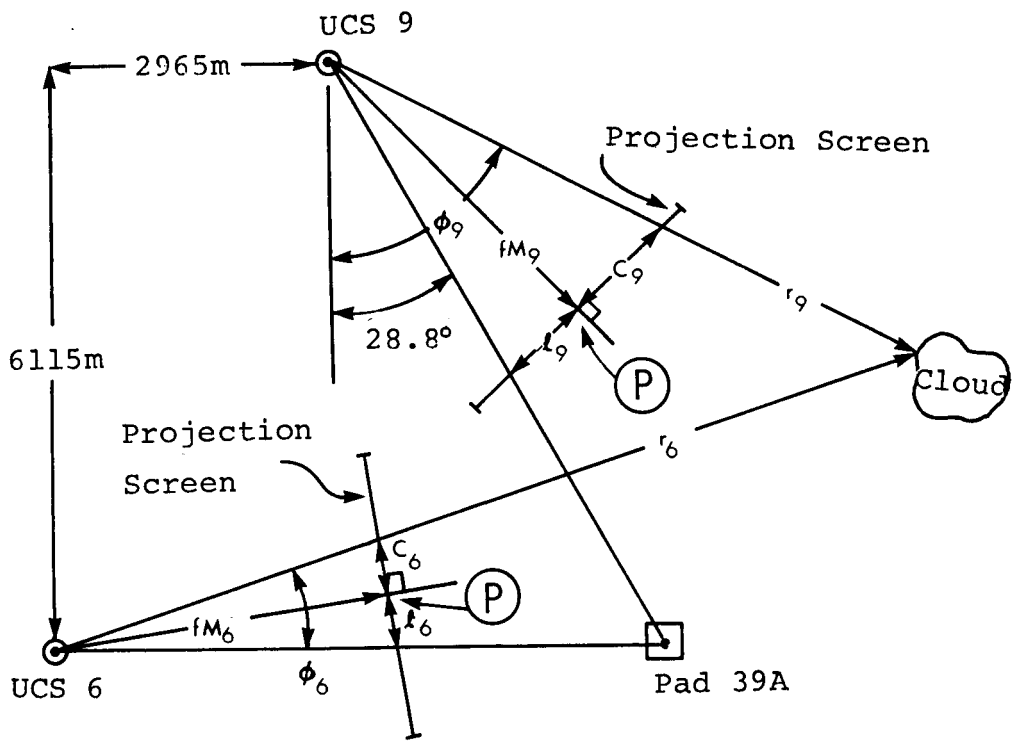


Figure 5. Ranges and azimuths of exhaust cloud from camera sites

TABLE 3: PARAMETERS USED IN RANGE EQUATIONS (6) and (7)

Parameter	Description
l_6 and l_9	Distance on the projector screen from Principal Point 'P' to Pad 39A, defined as positive when Pad 39A is to the right of 'P'
c_6 and c_9	Distance on the projector screen from 'P' to the cloud point, defined as positive when cloud point is to the left of 'P'
fM_6 and fM_9	Products of the focal lengths and magnification factors defined previously

Once the angles ϕ_6 and ϕ_9 have been computed, the ranges can be found by equating the following distances on Figure 5:

East-West distance from UCS 6 to cloud: $r_6 \cos \phi_6 = r_9 \sin \phi_9 + 2965$

North-South distance from UCS 6 to cloud: $r_6 \sin \phi_6 = 6115 - r_9 \cos \phi_9$

(the distance unit is meters)

Solving for r_6 and r_9 yields

$$r_6 = \frac{(2965) + (6115)\tan\phi_9}{\cos\phi_6 + \sin\phi_6 \tan\phi_9} \tag{8}$$

and

$$r_9 = \frac{(6115) - (2965)\tan\phi_6}{\cos\phi_9 + \sin\phi_9 \tan\phi_6} \tag{9}$$

Ranges for Mission 51A

Since the UCS 9 film was unavailable for Mission 51A, a different method was used to calculate the cloud ranges. The UCS 2 and UCS 6 films showed the

cloud to be above the Vertical Assembly Building (VAB) at T + 10 minutes. The cloud's movement was approximated to be along a straight line from PAD 39A to the building. Since the range of the building is approximately 2940 m from UCS 6 and 7135 m from UCS 2, the following equations were developed to describe the cloud's range with time from each camera site:

$$r_6 = 6320 + \frac{2940 - 6320}{10 \text{ min.}} (T) = 6320 - 338(T) \tag{10}$$

$$r_2 = 9330 + \frac{7135 - 9330}{10 \text{ min.}} (T) = 9330 - 219.5(T) \tag{11}$$

SECTION 4 - METHOD CONFIRMATIONS

The equations used to calculate cloud ranges and heights were tested on objects visible on the films whose positions and dimensions were known from other sources. For example, the ranges to the launch assembly of Pad 39B (which is near Pad 39A) were calculated and compared to distances measured on detailed maps from Kennedy Space Center. In addition, the photogrammetry equations were used to calculate the height of the Verticle Assembly Building as well as the altitude of the Shuttle during its first 30 seconds of flight. The calculated height of the VAB was compared to that given by construction drawings (furnished by Kennedy Space Center), and the Shuttle heights were compared to Ascent Trajectory Listings from Johnson Space Flight Center.

Range Comparisons

The range equations, Eqns. (6) through (9), were used to find the distances from Pad 39B to UCS 6 and UCS 9 for Mission 41D at T + 5:00 minutes. The variables c_6 and c_9 represent the horizontal distance from 'P' to the launch assembly of Pad 39B instead of to a cloud point. The data and results of this comparison are shown in Table 4.

TABLE 4: COMPARISON OF RANGES TO PAD 39B:
CALCULATED VALUES VS. MAP MEASUREMENTS

Camera Site	Cloud Data (cm) l	c	fM	Calculated Quantities ϕ (deg.)	Range (m)	Map Ranges (m)	Error
UCS 6	5.6	31.8	83.4	24.7	5120	5120	0
UCS 9	8.3	-21.1	125.1	23.0	4320	4390	1.6%

From both cameras, the calculated ranges are very close to those measured from maps.

Photogrammetry Comparisons

The photogrammetry equations, Eqns. (1) through (5), were used to calculate the height of the VAB (which appears at T + 8:00 minutes on UCS 6 and UCS 2 films for Mission 51A). The height calculated in each view was compared to that specified on a drawing containing the building plans. The results of this comparison are shown in Table 5.

TABLE 5: COMPARISON OF HEIGHTS OF VAB:
CALCULATED vs. ACTUAL (FROM ENGINEERING DRAWING)

Camera Site	Cloud Data (cm) PA	fM	x	y	Calculated Quantities t^o	θ^o	tan	r(m)	h(m)	Actual Height (m)	Error
UCS 6	26.4	125.1	0.0	-19.8	11.9	0.0	.0511	2940	150	160	6.2%
UCS 2	27.4	125.1	40.6	-24.4	12.4	17.7	.0223	7135	159	160	0.6%

The photogrammetry equations were also used to calculate the altitude of the Space Shuttle during its first 30 seconds of flight for Mission 41C. The range equations were used to locate the Shuttle as it moves away from the

camera sites. The calculated heights were compared to one-second Ascent Trajectory Listings from Johnson Space Center (JSC). The results of these comparisons are shown in Table 6.

TABLE 6: COMPARISON OF SHUTTLE ALTITUDES:
CALCULATED VS. DATA FROM ASCENT TRAJECTORY LISTINGS

Time (s)	JSC Data	UCS 2	UCS 6	UCS 9	Ave. Error
T + 15	670 m	715 m	765 m	750 m	10.4 %
T + 20	1241	1285	1335	1325	6.0
T + 25	2000	2025	2130	2120	4.5
T + 30	2940	3005	------	3090	3.6

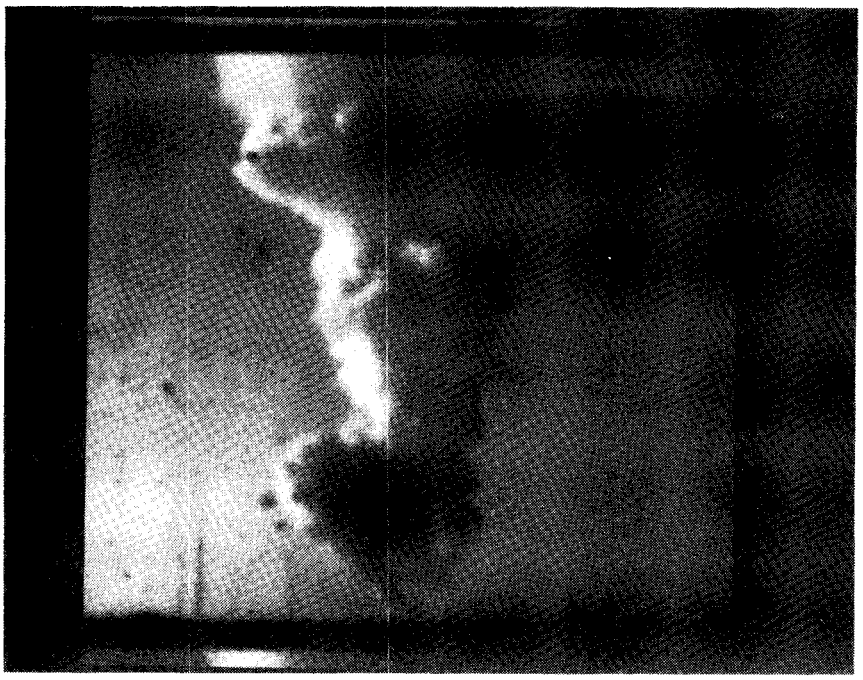
In all cases, the heights calculated from the equations agree well with reliable ground truth data.

SECTION 5 - RESULTS

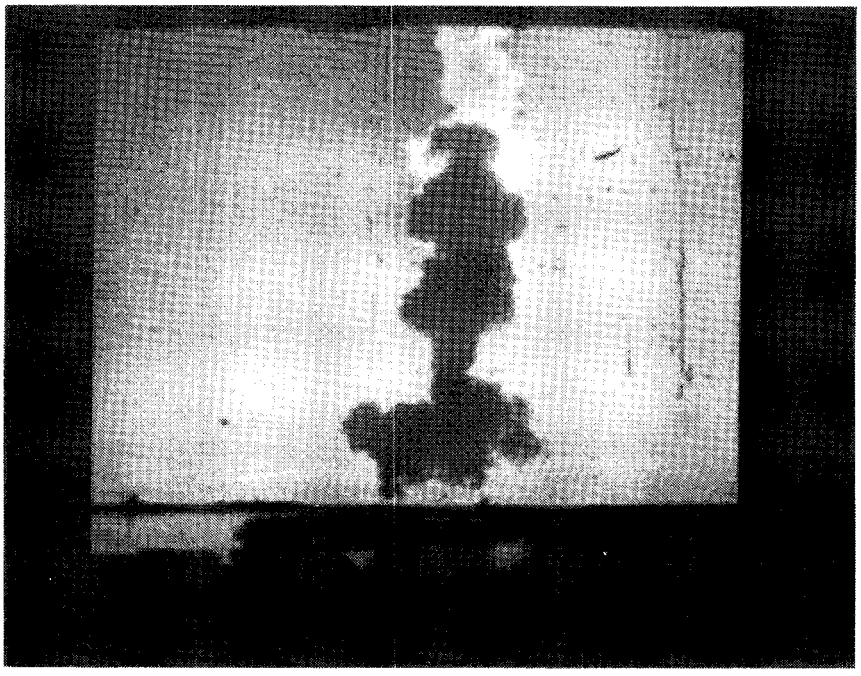
From Equations (1) through (11), the altitudes of the top and base and the maximum and average widths of the Shuttle exhaust cloud were calculated for each film tracing at one-minute intervals. Since the shapes of the sides and bases of the cloud were irregular, the altitudes of the base and average widths were estimated and indicated on each tracing. In general, the ground cloud develops from the combination of portions of the exhausts coming from the vehicle itself and the flame trenches which are separated by 180 degree and into which deluge water is sprayed for cooling. The cloud rises to its maximum altitude depending on atmospheric conditions. For these three launches the cloud reaches its maximum altitude in 3 to 5 minutes then descends slightly due to the influence of the environment.[1]

The Shuttle turns East just after launch, and the ground cloud tended to follow this tilted exhaust channel as shown in Figure 6a. Notice the irregular shape. Contributing to this asymmetry were wind shear (really only for Launch 51A), the tilt of the rocket exhausts as the Shuttle turned East, and the three channels for exhaust near the ground (rocket engines after they clear the pad, and the two pieces from the flame trenches). These pieces are somewhat visible from the films in the early few minutes of cloud formation (Figure 6b). The top of the cloud in Figure 6b is tilted into the picture and corresponds to the left (Eastward) tilt in Figure 6a. The data for all cloud measurements are presented in Appendix A.

[1]A temperature inversion was present just below the maximum altitude; this creates a situation whereby cloud parcels cooling as they rise, reach a temperature which is colder than the environment whereby these parcels descend to an equilibrium temperature near the level of the inversion.



(a) UCS 9 View (looking South)



(b) UCS 6 View (looking East)

Figure 6

Photographs of 512 x 512 digitizations for Mission 41D at three minutes after liftoff.

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Results For Mission 41C

The calculated cloud top and base are shown for UCS 6 and UCS 9 films in Figure (7a). Measurement from these camera views showed the altitude of the cloud top to reach a peak of 2200 m at T + 4:00 minutes followed by a rapid decline to 1700 m by T + 6:00 minutes. The top remained at approximately 1700 m until the cloud began to dissipate after T + 9:00. The base of the cloud rose steadily after T + 1:00 and approached an asymptote of 1000 m at T + 10:00. The altitudes calculated from the two different camera views agreed to within 160 m for the cloud top and to within 110 m for the base.

The calculated maximum cloud widths near the top and the average widths from UCS 6, UCS 9, and UCS 2 (Fig. 7b) show the cloud to be quite asymmetrical. The cloud appeared to be much wider after T + 6:00 in the North-South direction (UCS 6) than in the East-West direction (UCS 2, 9). The maximum width near the top as measured from UCS 6 increased almost linearly with time to 2500 m at T + 10:00, while that measured from UCS 2 reached a peak of 1800 m at T + 7:00 and subsequently decreased. The maximum width from the UCS 9 view peaked at 1500 m at T + 4:00 and remained between 1300 m and 1500 m afterwards. Figure (7b) indicates that the cloud's orientation may have shifted between T + 6:00 and T + 9:00 possibly as a result of a change in wind directions. Figure (7c) shows the average width measured from UCS 6 after T + 6:00 to be about 800 m greater than the stable 1200 m width measured from both the UCS 2 and UCS 9 views.

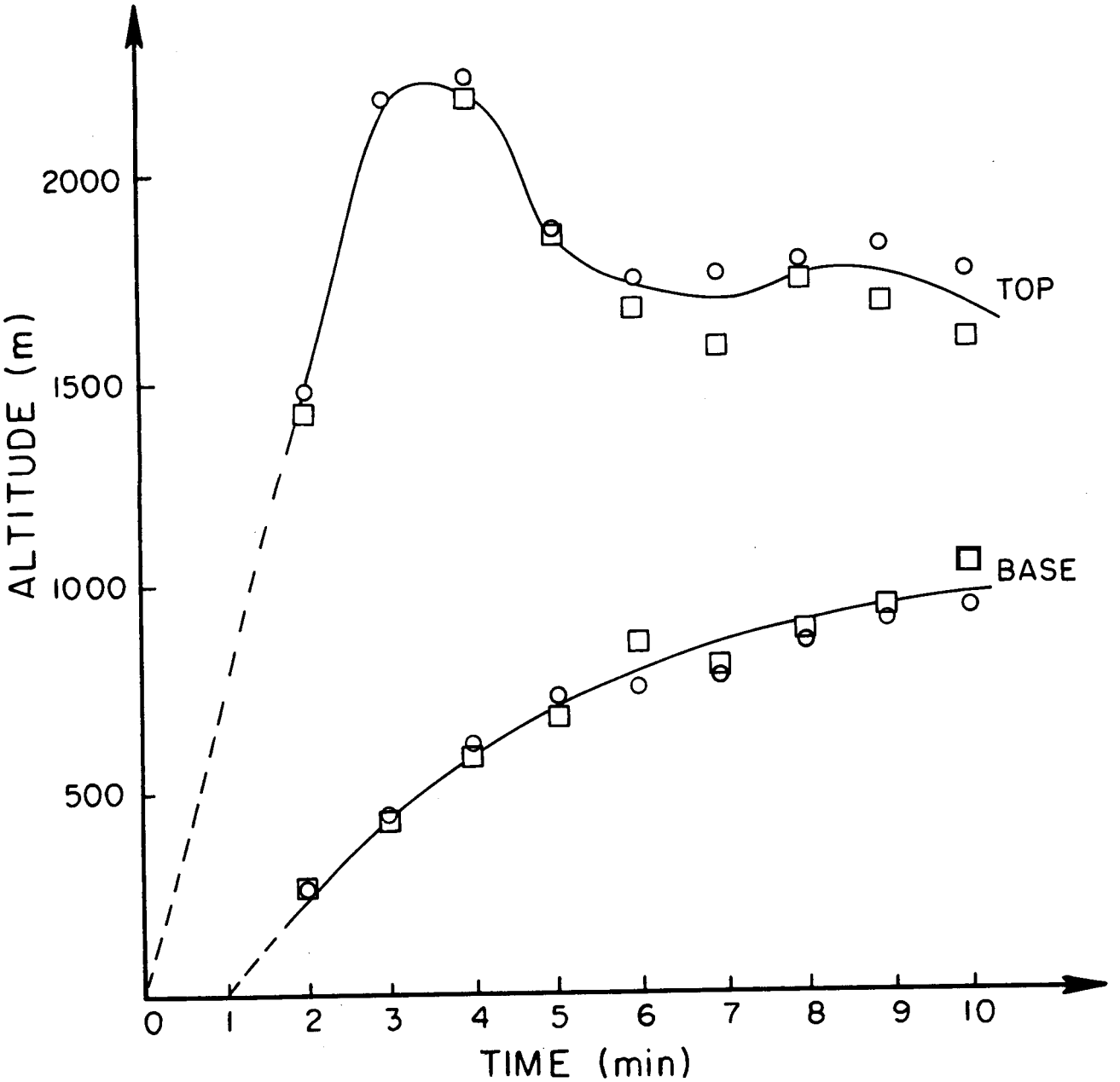

Figure 7a. Altitude of top and base of Shuttle exhaust cloud vs. time Mission 41C

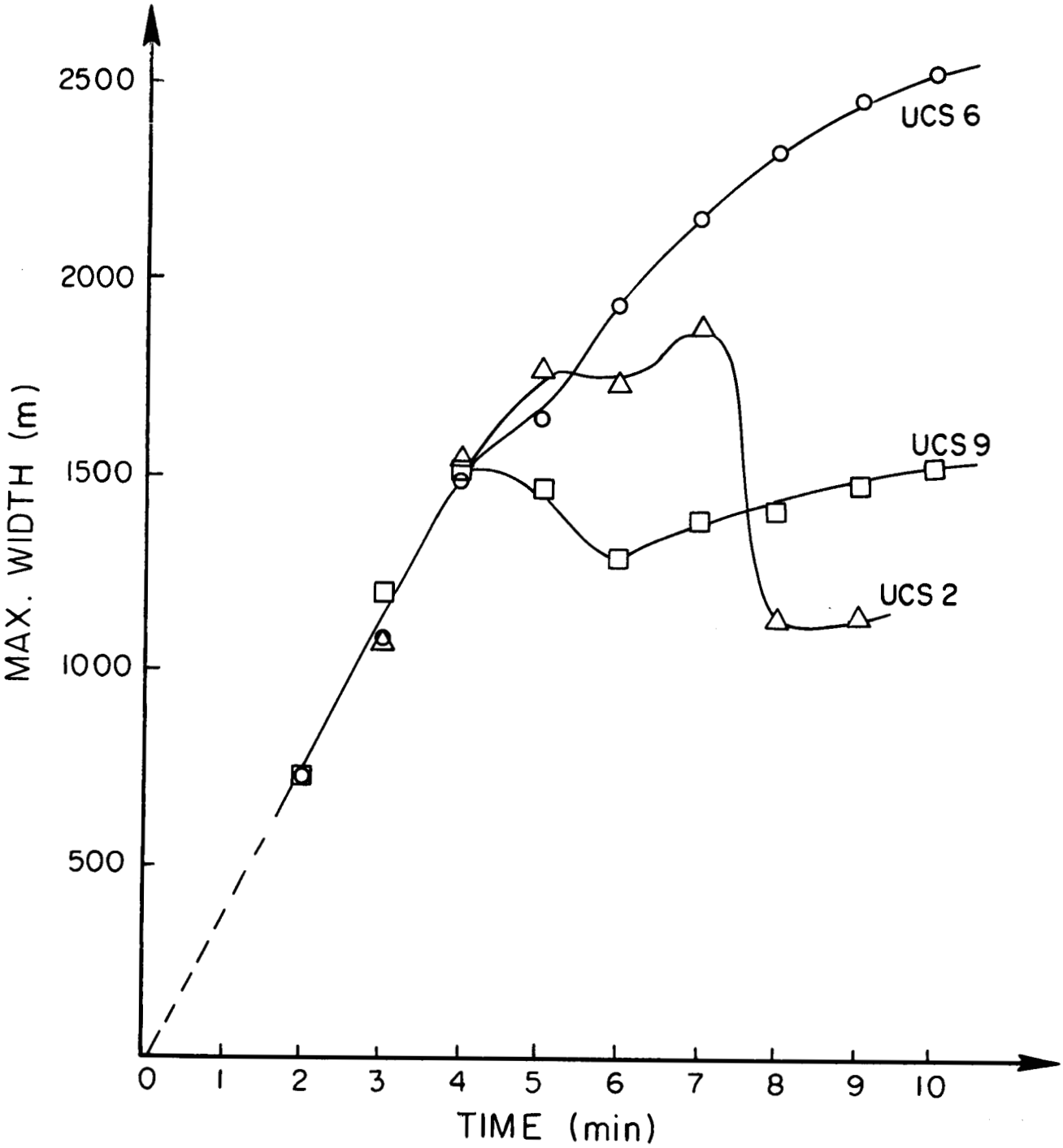

Figure 7b. Maximum widths (at top) of Shuttle exhaust cloud vs. time Mission 41C

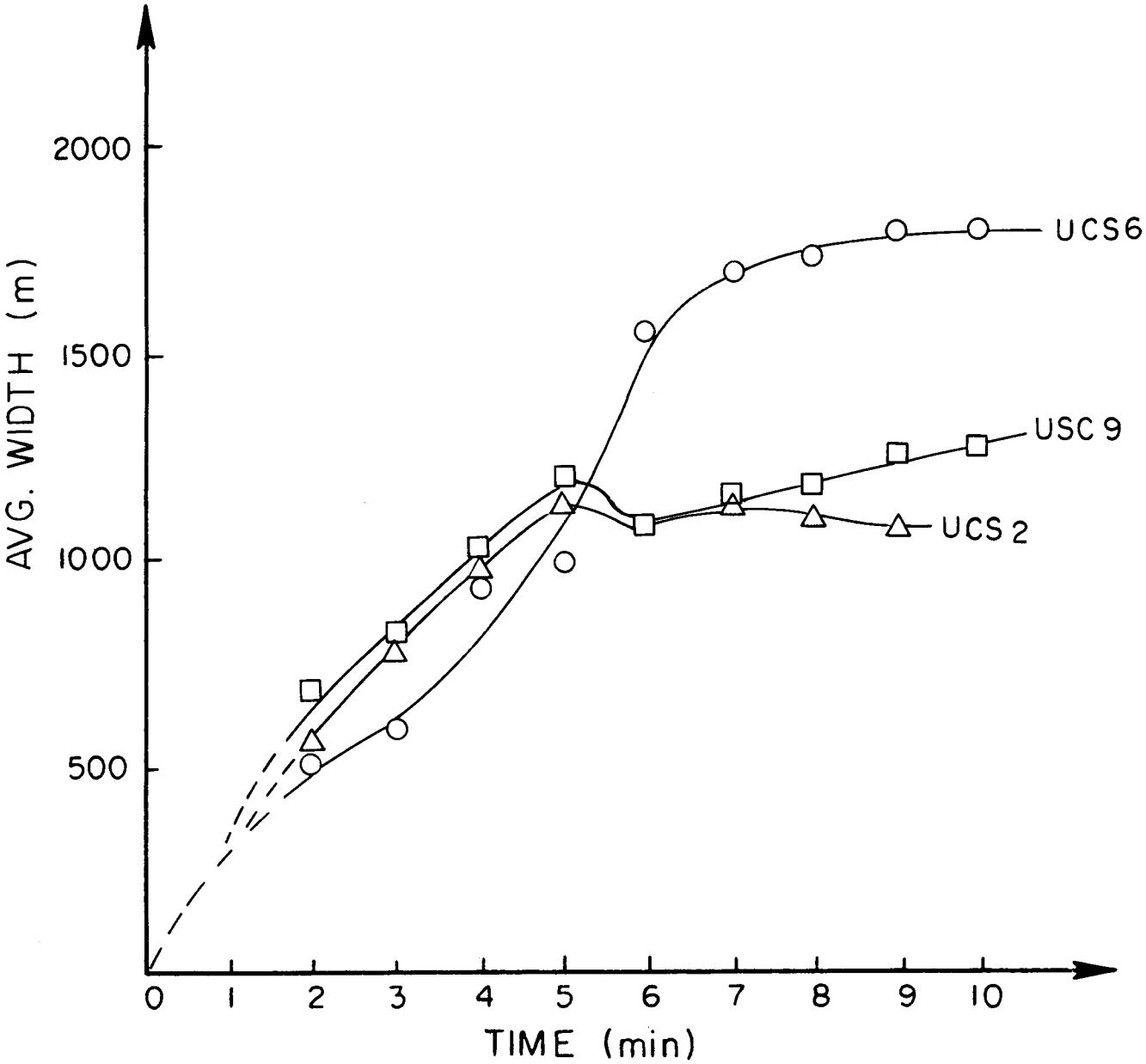

Figure 7c. Average widths of Shuttle exhaust cloud vs. time
Mission 41C

Results For Mission 41D

The cloud top and base for Mission 41D were calculated from UCS 6 and UCS 9 films and are shown in Figure (8a). Measurements from these camera views showed the altitude of the cloud top to reach a peak of 3500 m at T + 5:00 followed by a gradual decline to 3000 m at T + 10:00. In general, the cloud top for Mission 41D rose to a much higher altitude and remained there for a longer time than that of Mission 41C. Like that of Mission 41C, however, the base of the cloud for 41D rose steadily after T + 1:00 and reached 1000 m at T + 10:00. The altitudes calculated from the two different camera views agreed to within 190 m for the cloud top and to within 100 m for the base, which was difficult to estimate for most of the tracings because of its non-uniformity.

The maximum widths (near the cloud top) and the average widths are shown in Figure 8b. The calculated maximum cloud widths from UCS 6 and UCS 9 show the cloud to be quite asymmetrical near the top. For this launch, the cloud was up to 700 m wider in the East-West direction (UCS 9) than in the North-South direction (UCS 6) between T + 4:00 and T + 7:00. At the other times, however, the view-to-view width difference was less than 200 m. The maximum width near the top measured from both UCS 6 and UCS 9 rose asymptotically towards 1200 m at T + 10:00.

The volume was estimated for the ground cloud at 5 minutes after launch. At this time the first convective element was at its maximum altitude (which was also the absolute maximum) but the main bubble was still rising and the cloud from the North trench was dissipating. The extemely irregular shape of the cloud, the fact that different convective elements were rising or dissipating at different rates and that these convective elements were

overlapping to varying extents makes any precise volume calculations impossible using only ground-based photographs. Nevertheless geometric approximations were made to represent the cloud at the 5 minute point. Two methods were used. In the first a rectangular solid represented the bottom part with dimensions of 1548 m x 1305 m x 840 m. A cylinder of radius 525 m and height 1627 m was the central case and a half sphere of radius 520 m was the top. The volume was calculated to be 3.37×10^9 m^3 for this method. In method 2 an overlapping and offset to the North sphere of radius 507 m was the base. A cylinder of 525 m radius and height of 1776 m was the center with an overlapping sphere of radius 581 m to represent the main convective bubble still rising but below the top bubble by about 800 m. The top was a half sphere of radius 520 m the same as in method 1. The volume this time was 3.05×10^9 m^3. These numbers turned out to be surprisingly close despite the difference in assumed shapes.

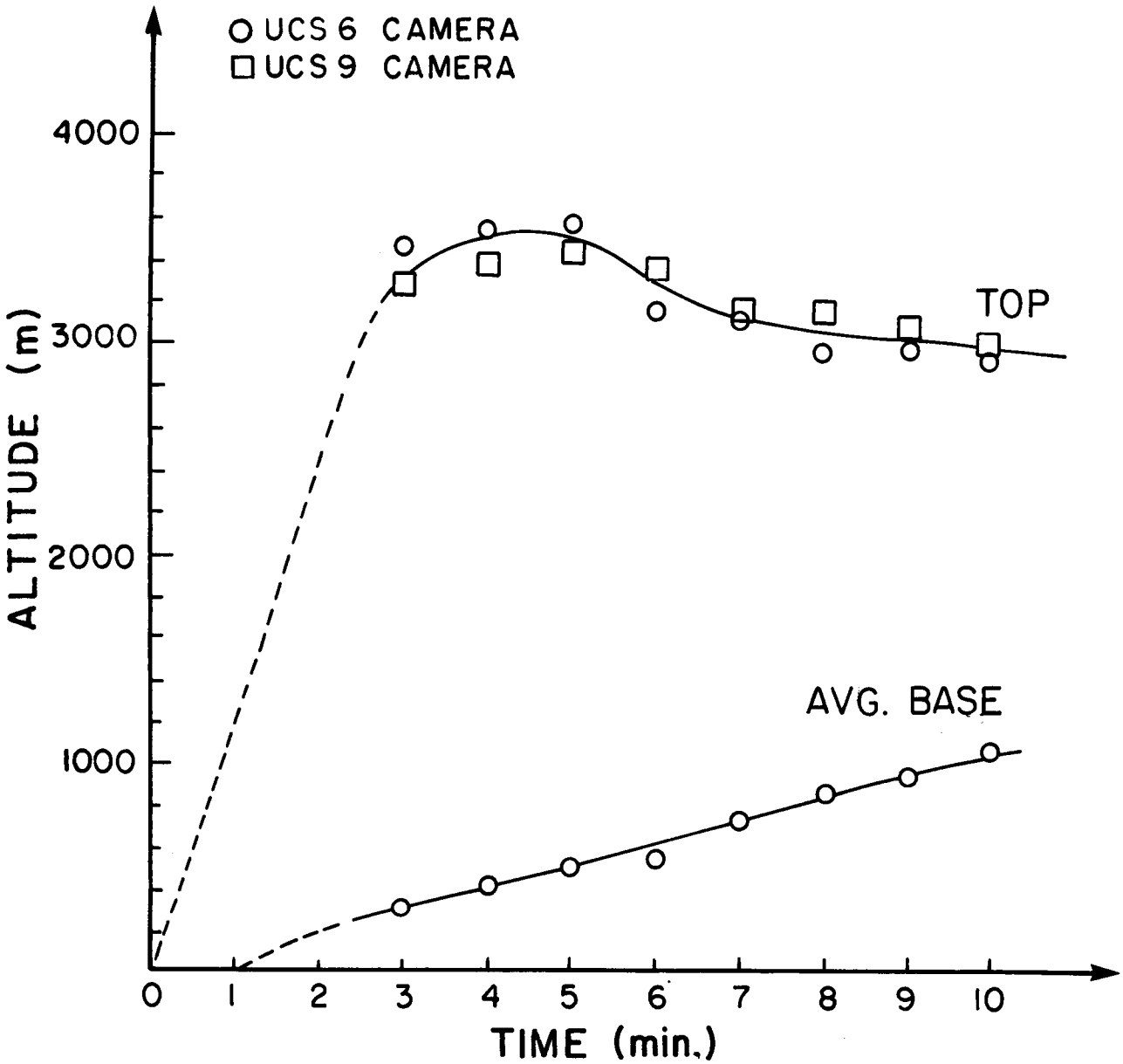

Figure 8a. Altitude of top and base of Shuttle exhaust cloud vs. time Mission 41D

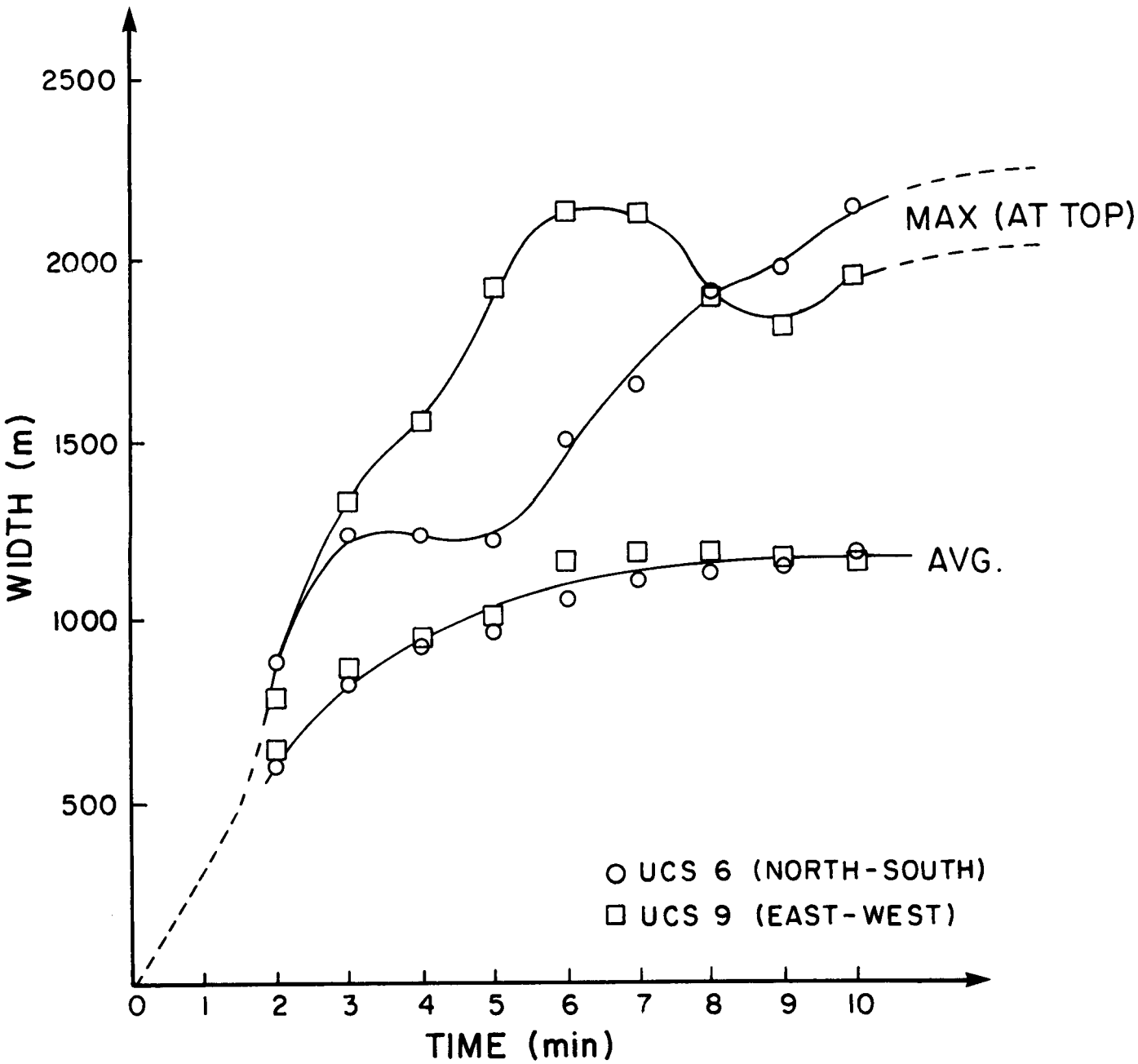

Figure 8b. Average widths and maximum widths (at top) of Shuttle exhaust cloud vs. time Mission 41D

Results For Mission 51A

For Mission 51A, the UCS 9 film was unavailable for this study. In addition, much of the cloud was obscured by environmental clouds in the UCS 2 view. Consequently, most cloud measurements were forced to be taken from the UCS 6 film alone. Only the average width could be estimated from the UCS 2 view based on the lower, visible portion of the cloud.

The calculated cloud top and base are shown for the UCS 6 films in Figure 9a. The altitude of the cloud top was estimated to reach a peak of about 2400 m at T + 4:00, since the cloud extended above the camera's view. After T + 5:00, the cloud top fell rapidly to 1800 m by T + 8:00. The cloud base, similar to those of the other launches, rose steadily after T + 1:00 and reached about 900 m at T + 8:00. By T + 8:00 after launch, the cloud had spread out considerably and moved too close to the camera site to be entirely contained within picture frames.

The average and maximum cloud widths for Mission 51A are shown in Figure 9b. The calculated maximum cloud width from UCS 6 reached a peak of 1700 m at T + 6:00, but was difficult to estimate afterwards. The average width was calculated from UCS 6 and estimated from UCS 2 based on what was visible beneath the environmental cloud cover. The UCS 2 calculations showed the average width to be up to 700 m wider than that from UCS 6. However, since the cloud shape was diagonal from top to bottom in the UCS 6 view, the average width was measured diagonally across the cloud (perpendicular to its sides) in order to provide a more accurate width that could be used in a rough volume estimate. As a result, the UCS 6 width may have been considerably less than that which was measured horizontally (because of the limited visibility of the cloud) from the UCS 2 view.

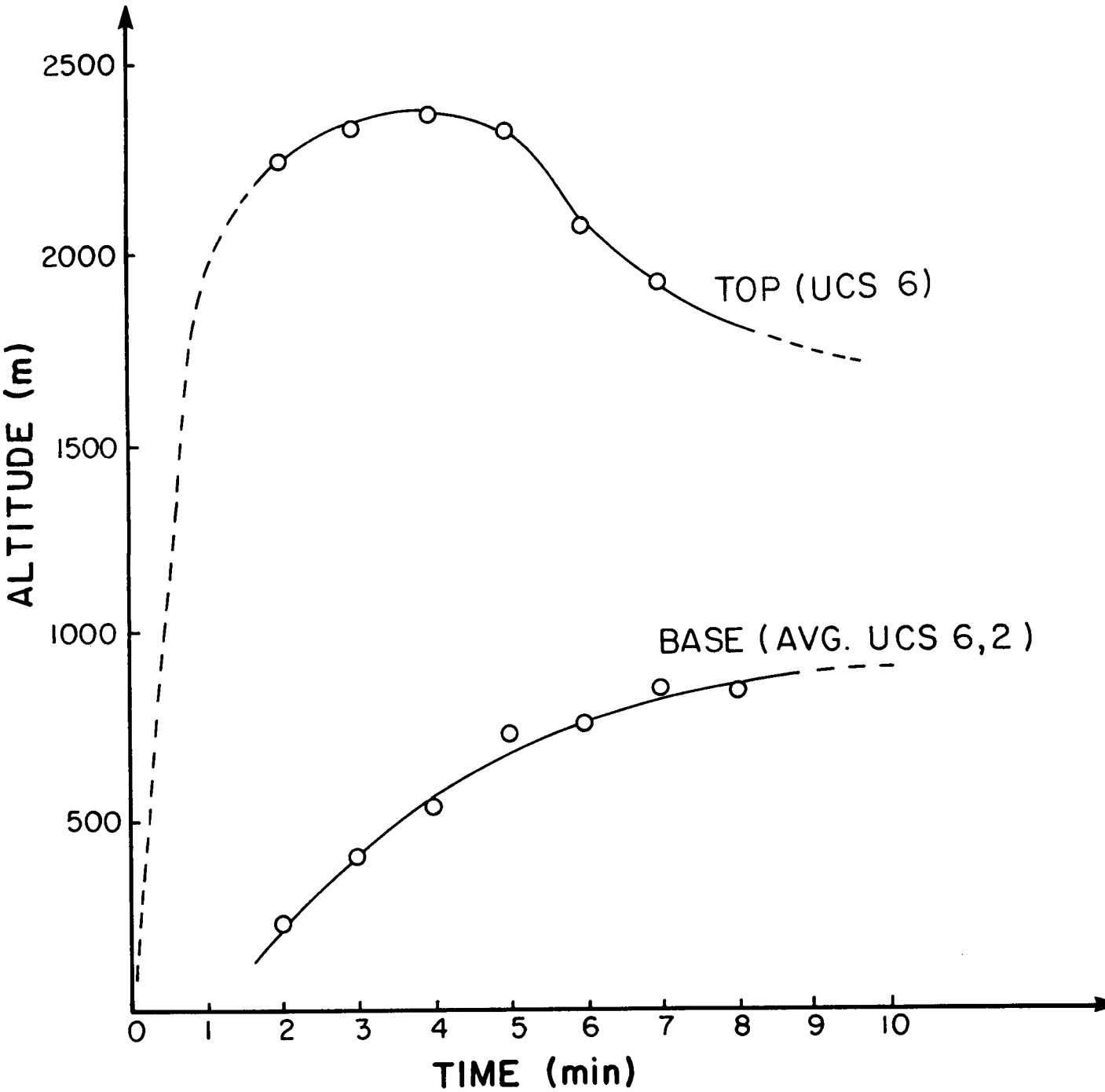

Figure 9a. Altitude of top and base of Shuttle exhaust cloud vs. time Mission 51A

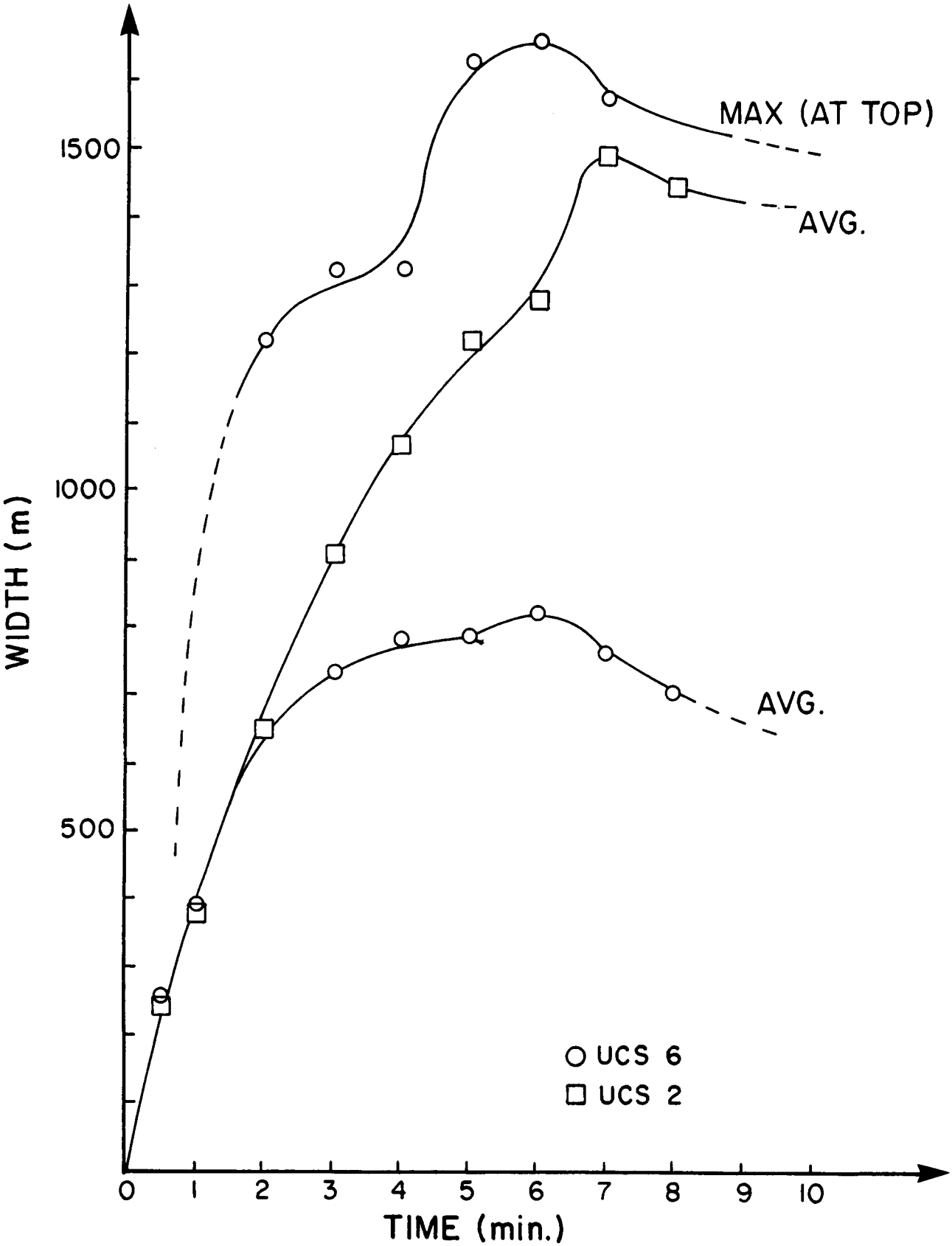

Figure 9b. Average widths and maximum widths (at top) of Shuttle exhaust cloud vs. time Mission 51A

SECTION 6 - UNCERTAINTIES AND ERROR SOURCES

The errors and uncertainties can be separated into three main categories: random errors, errors due to the limited visibility of the exhaust cloud, and errors due to the cloud's non-uniform shape. The random errors, caused by uncertainties in direct measurements, had a relatively small effect on the results of this study. The errors due to limited visibility of the cloud and its non-uniform shape were significant and caused some measurements to be estimated or abandoned. Most of the errors in heights or widths were due to these factors. Considering all sources of errors and uncertainties, the results can be considered accurate to within about 350 m.

Random Errors

The random errors in calculating the exhaust cloud dimensions were those due to uncertainties in measuring distances from maps and from the cloud tracings. Since the map distances were read to the nearest 10 m, their uncertainties had little effect on the accuracy of the cloud calculations. Likewise, the uncertainties in measuring distances from the tracings of the clouds were negligible. The effects of these uncertainties were determined by varying the measured parameters by about 3 mm (which was the approximate measuring uncertainty) in different combinations and observing the effect on ranges and cloud dimensions. The ranges and dimensions typically varied less than 100 m. The estimated positions of the horizon in the UCS 2 views can also be considered measurement uncertainties; their effects were circumvented by using the two other views for Missions 41C and 41D and were irrelevant for 51A because the cloud itself was obscured. Thus, random errors had a minimal

effect on the calculated cloud dimensions.

Errors Due To Limited Visibility Of The Exhaust Cloud

For Missions 41C and 51A, the cloud is obscured in one or more views either by bright, light-saturated portions of the film (UCS 6, 41D), environmental clouds (UCS 2, 51A), the cameras' limited fields of view (UCS 9, 41D; UCS 6, 51A), or an unusable film (UCS 9, 51A). For 41D, the severity of these problems was lessened by the availability of other views. Estimations were made for the measurements of the cloud when it was partially obscured (which only occurred for a few of the tracings). Since these estimations agreed well with information from the other views, they were not disregarded. For Mission 51A, however, only the UCS 6 view was usable for cloud measurements. After T + 7:00, though, the cloud began to extend beyond the camera view, rendering further measurements inaccurate.

The limited cloud visibility for Mission 51A also decreased the accuracy of all range calculations which, in turn, affected the calculated cloud dimensions. The straight-line range approximation employed for 51A was only accurate to within about 200 m because the entire cloud was not visible in both views. Moreover, since the cloud in the UCS 6 view spread out horizontally (in the direction of travel), the points selected for measurements may have been up to 500 m away from the center point corresponding to the calculated range. This can cause an error of about 250 m. Since there were no identifiable ground features to use as position references, it was impossible to accurately compensate for these range differences. Therefore these range uncertainties probably caused errors in the cloud dimensions of up to 300 m for Mission 51A.

Errors Due To The Exhaust Cloud's Non-Uniform Shape

Since the exhaust cloud was non-uniform in shape and quite wide near the top for all launches, it was difficult to determine if the cloud top seen on the films was the actual maximum height or a lower height closer to the camera. Since the cameras were located relatively close to the cloud and on the ground, the vertical angle (σ) to the cloud top was 20-30 degrees. If the slope of the top part of the cloud from its sides to its center maximum is less than the vertical angle, the absolute maximum will not be seen on the film. In addition, because the cloud appeared to be rather non-uniform in shape and the camera sites are not the same distance away, the altitude of the apparent cloud top may differ from view to view. Thus, the shape of the cloud not only causes errors in the calculated heights, but also creates discrepancies between views.

Since an error of 400 m in the range will cause an error of up to 200 m in the cloud height, it is important to determine the correct range to the point selected as the cloud top. However, the cloud shape makes accurate range determinations difficult. For example, (see Figure 10) if the range to the top is taken to be where the cloud center is located and the absolute top is not visible, the calculated height will be too large. In contrast, if the apparent cloud top is estimated and the range calculated for that point, the altitude will be too low (since the apparent top is lower than the actual top).

Finally, because of the size of the exhaust cloud, it is virtually impossible to locate a particular cloud point in two different camera views. Therefore, determining the ranges is only accurate to about 500 m. The combination of errors due to the cloud shape probably causes the calculations of the cloud tops and widths to have errors of up to 250 m for all launches.

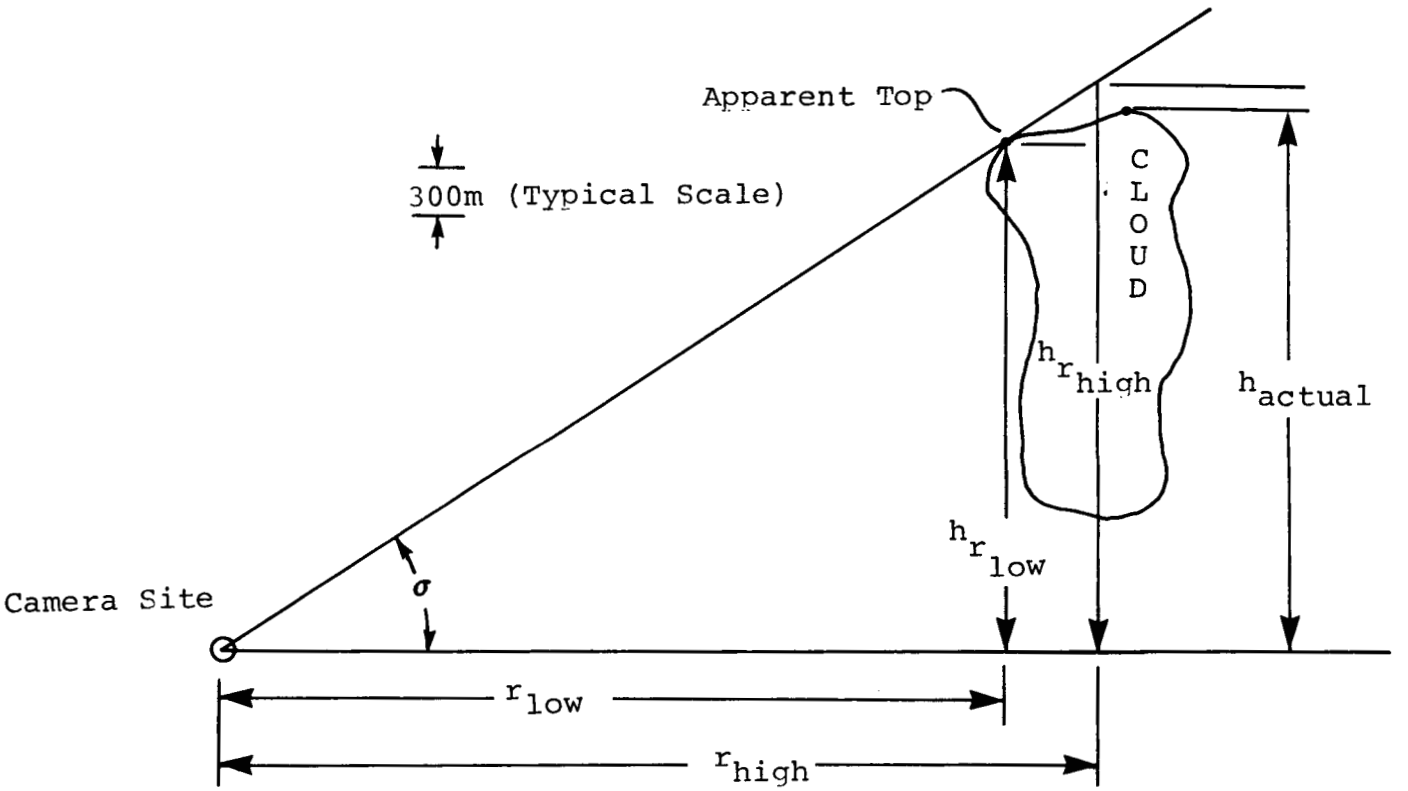

Figure 10. Errors caused by cloud asymmetries and large widths

SECTION 7 - REFERENCES

Holle, R. L., 1982. Photogrammetry of thunderstorms. Thunderstorms: A Social, Scientific and Technological Documentary, E. Kessler, Ed. U.S. Department of Commerce.

APPENDIX A

SHUTTLE EXHAUST CLOUD MEASUREMENTS

SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41C | LIFTOFF: T = 13 : 58 : 00 (Z) | DATE: 4-6-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	FM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	CLOUD TOP X (in.)	Y (in.)	θ (Deg.)	tanθ	H (ft.)	H_{ABT} (ft.)	H (m)	$H_{AV}/\Delta H$ (m)
2:00	6			7.1		-3.25	0			0	3.9			4835	5370	1475	
	9			3.0		3.6	-3.85			-3.85	6.3			4630	4900	1410	
	2			11.1		—	—			2.0	-.6			6030	6335	1835	
3:00				6.5		-5.8	0			0	7.7			7150	7305	2180	
				4.2		3.7	-.75			-.75	8.65			7165	7255	2185	
				10.5		—	—			—	.7			6415	6570	1955	
4:00				7.5		-9.3	2.6			2.6	5.95			7270	7490	2215	
				5.75		4.3	.7			.7	6.4			7160	7545	2180	
				11.6		—	—			—	1.2			7195	7195	2200	
5:00				7.5		-11.2	2.6	(-2.3)		2.6	4.6			6125	7060	1865	
				6.45		4.7	-2.8	(0)		-2.8	4.0			6050	6830	1845	
				11.1		—	—			—	1.5			6695	6925	2040	
6:00				7.3		-12.2	2.6	(-4.5)		2.6	3.6			5690	6705	1735	
				6.6		5.75	-3.3			-3.3	2.6			5480	6295	1670	
				11.65		—	—		26815	—	1.0			6540	6920	1995	
7:00				7.3		-13.2	2.6	(-4.5)		2.6	3.3			5705	6970	1740	
				6.15		7.0	-4.1			-4.1	2.3			5180	6115	1580	
				11.65		—	—			—	.7			6510	6780	1985	
8:00				7.3		-14.9	-2.8			-2.8	1.5			5805	6045	1770	
				5.9		7.2	-3.0	0		-3.0	1.5			5635	5635	1720	
				10.9		—	—			—	1.5			6600	6740	2010	
9:00				7.3		-16.1	-2.5			-2.5	1.2			5925	6220	1805	
				5.9		8.05	-3.0	0		-3.0	1.0			5505	5565	1680	
				11.4		—	—			—	.7			6570	6615	2005	
10:00				7.3		-16.7	-2.5			-2.5	.8			5780	6065	1760	
				5.7		8.25	-3.0			-3.0	.7			5220	5285	1590	

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41C | LIFTOFF: T = 13:58:00 (Z) | DATE: 4-6-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	FM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	CLOUD BASE X (in.)	Y (in.)	Θ (Deg.)	tanσ	H (ft.)	H_{ADJ} (ft.)	H (m)	H_{AV}/ΔH (m)
2:00	6			7.1		-3.25	0			0	-5.3			855		260	
	9			3.0		3.6	0			0	-1.4			835		255	
	2			11.1		—	—			0	-9.4			950		290	
3:00				6.5		-5.8	0			0	-3.7			1400		425	
				4.2		3.7	0			0	-1.8			1330		405	
				10.5		—	—			0	-80			1380		420	
4:00				7.5		-9.3	0			0	-3.85			1970		600	
				5.75		4.3	0			0	-2.65			1885		575	
				11.6		—	—			0	-8.1			1685		515	
5:00				7.5		-11.2	0			0	-3.4			2330		710	
				6.45		4.7	0			0	-2.95			2245		685	
				11.1		—	—			0	-7.4			2260		690	
6:00				7.3		-12.2	0			0	-3.3			2410		735	
				6.6		5.75	0			0	-2.5			2765		845	
				11.65		—	—		26815	0	-7.3			2290		700	
7:00				7.3		-13.2	0			0	-3.3			2580		785	
				6.15		7.0	0			0	-2.5			2610		795	
				11.65		—	—		26945	0	-7.3			2300		700	
8:00				7.3		-14.9	1.0			1.0	-3.1			2770		845	
				5.9		7.2	0			0	-2.0			2855		870	
				10.9		—	—		26860	—	-4.9			3200		975	
9:00				7.3		-16.1	1.0			1.0	-3.1			2945		900	
				5.9		8.05	0			0	-2.0			3025		920	
				11.4		—	—		27020	—	-5.4			3210		980	
10:00				7.3		-16.7	1.0			1.0	-3.1			3015		920	
				5.7		8.25	0			0	-1.4			3415		1040	
				—													

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41C | LIFTOFF: T = 13 : 58 : 00 (Z) | DATE: 4-6-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	fM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	MAX. CLOUD WIDTH (Near Top) Y (in.)	X_1 (in.)	X_2 (in)	θ_1 °	θ_2 °	$\tan(\theta_1-\theta_2)$	W (ft.)	W (m
2:00	6			7.1		-3.25	-2.0		22845	2.8	-2.5	2.5	2.960	—	.1037	2370	720
	9			3.0		3.6	-2.5		25965	5.6	2.2	-2.2	2.580	—	.0903	2345	715
	2			11.1		—	—		28680	-2.2	2.1	-2.1	2.478		.0867	2485	755
3:00				6.5		-5.8	-1.0		23800	5.4	-3.6	3.6	4.278	—	.1505	3580	1090
				4.2		3.7	-2.0		27125	6.0	-3.5	3.5	4.122	—	.1449	3930	1200
				10.5		—	—		28120	-.6	3.05	-3.05	3.614		.1268	3565	1085
4:00				7.5		-9.3	0		26920	3.0	4.35	-4.35	5.153	-5.153	.1818	4895	1490
				5.75		4.3	0		30125	3.8	3.95	-3.95	4.658	-4.658	.1640	4940	1505
				11.1		—	—		28710	-1.4	4.2	-4.2	4.964	—	.1750	5025	1530
5:00				7.5		-11.2	0		28325	3.0	4.55	-4.55	5.388	—	.1903	5390	1645
				6.45		4.7	0		31840	2.4	3.65	-3.65	4.302	—	.1513	4820	1470
				11.6		—	—		27465	-1.4	5.05	-5.05	5.974		.2116	5810	1770
6:00				7.3		-12.2	0		29980	1.3	5.05	-5.05	5.941		.2104	6310	1925
				6.6		5.75	0		33450	-.8	3.1	-3.1	3.626		.1273	4255	1295
				11.65		—	—		26815	-.7	5.05	-5.05	5.995		.2124	5695	1735
7:00				7.3		-13.2	0		32055	1.3	5.3	-5.3	6.233		.2211	7085	2160
				6.15		7.0	0		35425	-.4	3.15	-3.15	3.684		.1293	4580	1395
				11.05		—	—		26945	-3.5	5.5	-5.5	6.439		.2286	6160	1880
8:00				7.3		-14.9	+1.0		32775	-1.0	5.6		6.537		.2322	7610	2320
				5.9		7.2	0		36225	0	3.1		3.627		.1273	4610	1405
				10.9		—	—		26860	0	3.3		3.926		.1379	3705	1130
9:00				7.3		-16.1	1.0		34865	-1.0	5.6		6.537		.2322	8095	2465
				5.9		8.05	0		38360	0	3.1		3.627		.1273	4885	1490
				11.4		—	—		27020	0	3.3		3.934		.1382	3735	1140
10:00				7.3		-16.7	+1.0		35676	-1.0	5.6		6.537		.2322	8290	2525
				5.7		8.25	0		39260	0	3.1		3.626		.1273	4995	1520

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41C | LIFTOFF: T = 13 : 58 : 00 (Z) | DATE: 4-6-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	fM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (Feet)	AVE. CLOUD WIDTH Y (in.)	X_1 (in.)	X_2 (in)	θ_1 °	θ_2 °	$\tan(\theta_1-\theta_2)$	W (ft.)	W (m
2:00	6			7.1		-3.25	-2.0		22845	0	-1.75	1.75	2.056	—	.0719	1640	500
	9			3.0		3.6	-2.5		25965	0	2.1	-2.1	2.446	—	.0856	2220	675
	2			11.1		—	—		28680	0	1.5	-1.5	1.788	—	.0625	1790	545
3:00				6.5		-5.8	-1.0		23800	0	-2.0	2.0	2.346	—	.0821	1955	595
				4.2		3.7	-2.0		27125	0	2.4	-2.4	2.800		.0981	2660	810
				10.5		—	—		28120	0	2.2	-2.2	2.615	—	.0915	2575	785
4:00				7.5		-9.3	0		26920	0	2.7	-2.7	3.174	—	.1112	2995	915
				5.75		4.3	0		30125	0	2.7	-2.7	3.159	—	.1107	3335	1015
				11.1		—	—		28710	0	2.65	-2.65	3.157		.1106	3175	970
5:00				7.5		-11.2	0		28325	0	2.8	-2.8	3.291	—	.1154	3270	995
				6.45		4.7	0		31840	0	3.0	-3.0	3.515		.1235	3925	1195
				11.6		—	—		27465	0	3.2	-3.2	3.819		.1341	3685	1125
6:00				7.3		-12.2	0		29980	0	4.1	-4.1	4.810	—	.1695	5080	1550
				6.6		5.75	0		33450	0	2.6	-2.6	3.049	—	.1068	3575	1090
				11.65		—	—		26815	0	3.2	-3.2	3.820		.1341	3595	1095
7:00				7.3		-13.2	0		32055	0	4.2	-4.2	4.927		.1737	5565	1695
				6.15		7.0	0		35425	0	2.6	-2.6	3.045		.1067	3780	1150
				11.65		—	—		26945	0	3.3	-3.3	3.939		.1384	3730	1135
8:00				7.3		-14.9	1.0		32725	0	4.2		4.927		.1737	5695	1735
				5.9		7.2	0		36225	0	2.6		3.043		.1066	3860	1175
				10.9		—	—		26860	0	3.2		3.807		.1337	3590	1095
9:00				7.3		-16.1	1.0		34865	0	4.1		4.810		.1695	5910	1800
				5.9		8.05	0		38360	0	2.6		3.043		.1066	4090	1245
				11.4		—	—		27020	0	3.1		3.696		.1297	3505	1070
10:00				7.3		-16.7	1.0		35695	0	4.0		4.694		.1655	5900	1800
				5.7		8.25	0		39260	0	2.6		3.042		.1066	4185	1275

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41D | LIFTOFF: T = 12 : 41 : 50 (Z) | DATE: 8-30-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	fM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	CLOUD TOP X (in.)	Y (in.)	θ (Deg.)	tanσ	H (ft.)	H_{ADJ} (ft.)	H (m)	$H_{AV}/\Delta H$ (m)
3:00	6		32.835	9.20	15.65	1.20	0	2.09	21375	0	7.10	0	.5284	11295		3440	3365
	9		49.252	11.00	12.59	.55	1.50	31.1	22520	1.50	11.40	1.88	.4793	10795		3290	150
	2		49.252	11.40	13.03	0	.60	11.3	31460	.60	4.70	.733	.3342	10515			4.5%
4:00				9.30	15.81	2.15	-.40	3.05	21310	-.40	7.30	-.773	.5395	11495		3505	3435
				11.00	12.59	2.30	0	31.42	22175	0	12.20	0	.4986	11055		3370	135
				11.10	12.70	—	—	10.51	31815	0	5.50	0	.3457	11000			4.0%
5:00				9.20	15.65	2.20	0	3.83	21635	0	7.50	0	.5434	11755		3580	3500
				11.48	13.12	3.25	0	32.53	22070	0	12.10	0	.5078	11208		3416	165
																	4.8%
6:00				9.20	15.65	3.50	-1.65	3.21	19730	-1.65	7.10	—		10410		3170	3265
				12.10	13.80	4.50	-5.35	27.77	21420	-5.35	11.90	—		11020		3360	185
																	5.6%
7:00				9.20	15.65	3.50	0	6.08	20095	0	6.60	—	.5099	10245		3120	3135
				12.00	13.69	4.70	-3.80	29.79	20655	-3.80	11.30	—	.4993	10313		3145	20
																	.6%
8:00				9.20	15.65	3.65	-.30	5.82	19045	-.30	6.55	—	.5080	9675		2950	3040
				12.00	13.69	6.50	-8.05	26.99	20340	-8.05	11.80	—	.5051	10275		3130	180
																	6.0%
9:00				9.20	15.65	3.80	.60	7.65	19645	.60	6.20	—	.4951	9725		2965	3010
				11.95	13.80	6.65	-6.25	29.21	19980	-6.25	11.60	—	.5023	10035		3060	95
																	3.2%
10:00				9.30	15.81	3.75	.80	7.91	19755	.80	5.60	—	.4766	9415		2870	2925
				12.00	13.69	8.15	-7.40	29.60	19940	-7.40	11.10	—	.4898	9765		2975	105
																	3.6%

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41D | LIFTOFF: T = 12 : 41 : 50 (Z) | DATE: 8-30-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	FM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	CLOUD BASE X (in.)	Y (in.)	θ (Deg.)	tan σ	H (ft.)	H_{ADJ} (ft.)	H (m)	$H_{AV}/\Delta H$
3:00	6			9.20		1.20	0		20605	0	-7.40			1060			
	9			11.00		.55	0		22155	0	-8.80			950			
	AVE													1005		305	
4:00				9.30		2.15	0		21175	0	-7.10			1335			
				11.00		2.30	0		21880	0	-7.80			1375			
														1355		415	
5:00				9.20		2.20	0		21635	0	-6.50			1685			
				11.48		3.25	0		22070	0	-7.50			1720			
														1700		520	
6:00				9.20		3.50			21800		-6.40			1765			
				12.10		4.50			21400		-7.60			1755			
														1760		535	
7:00				9.20		3.50			21895		-5.50			2355			
				12.00		4.70			21440		-6.15			2470			
														2410		735	
8:00				9.20		3.65			22730		-4.90			2855			
				12.00		6.50			21760		-5.60			2755			
														2805		855	
9:00				9.20		3.80			22745		-4.50			3135			
				11.95		6.65			21680		-5.00			2985			
														3060		930	
10:00				9.30		3.75			23525		-4.0			3671			
				12.00		8.15			22105		-4.7			3200			
														3435		1045	

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41D | LIFTOFF: T = 12 : 41 : 50 (Z) | DATE: 8-30-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	fM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	MAX. CLOUD WIDTH (Near Top) Y (in.)	X_1 (in.)	X_2 (in)	θ_1°	θ_2°	tan(θ_1-θ_2)	W (ft.)	W (m)
2:00	6			9.30		.90	0		22185	2.8	2.0	-2.0	3.712	-3.712	.1303	2890	880
	9			11.4		.45	2.90		23095	5.90	5.50	+.30	6.724	+.368	.1114	2575	785
	AVE																
3:00				9.20		1.20	-.30		22710	3.5	2.4	-3.0	4.474	-5.586	.1774	4030	1230
				11.00		.55	3.75		23370	8.0	8.0	-.60	9.798	-.742	.1861	4350	1325
4:00				9.30		2.15	-1.1		22985	4.3	1.6	-3.7	3.011	-6.935	.1754	4030	1230
				11.00		2.30	2.6		23430	8.7	7.6	-2.4	9.347	-2.856	.2181	5110	1555
5:00				9.20		2.20	-1.3		23080	5.2	1.3	-3.9	2.464	-7.355	.1731	3995	1215
				11.48		3.25	1.7		23570	8.4	7.75	-4.35	9.551	-5.385	.2669	6290	1915
6:00				9.2		3.5	-1.65		22745	3.0	1.65	-4.95	3.066	-9.128	.2161	4915	1500
				12.1		4.50	.6		22835	7.5	7.5	-6.3	9.252	-7.712	.3066	7000	2130
7:00				9.2		3.5	-1.6		22510	3.0	2.05	-5.3	3.807	-9.761	.2413	5430	1655
				12.0		4.70	0		22685	7.6	7.0	-6.75	8.643	-8.338	.3054	6925	2110
8:00				9.2		3.65	-2.2		22465	3.7	2.0	-6.4	3.737	-11.806	.2781	6245	1905
				12.0		6.50	-2.2		22925	6.4	7.0	-5.35	8.591	-6.586	.2713	6220	1895
9:00				9.2		3.80	-2.2		22755	2.9	2.1	-6.55	3.896	-11.993	.2846	6475	1975
				11.95		6.65	-1.7		22990	6.3	4.2	-7.60	5.175	-9.306	.2583	5935	1810
10:00				9.3		3.75	-2.1		23555	3.15	2.0	-7.0	3.723	-12.831	.2972	7000	2135
				12.0		8.15	-1.7		23390	7.75	4.5	-7.9	5.585	-9.741	.2741	6410	1955

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 41D | LIFTOFF: T = 12 : 41 : 50 (Z) | DATE: 8-30-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	FM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	CLOUD WIDTH (AVE) Y (in.)	X_1 (in.)	X_2 (in)	θ_1 °	θ_2 °	$\tan(\theta_1-\theta_2)$	W (ft.)	W (m)
2:00	6	✓		9.3		.90	0		20655	0	1.5	-1.5	2.718	-2.718	.0952	1965	600
	9	✓		11.4		.45	0		22340	0	2.5	-2.0	2.982	-2.387	.0940	2100	640
	AVE																620
3:00		✓		9.2		1.20	0		21115	0	2.0	-2.0	3.620	-3.620	.1270	2680	815
		✓		11.00		.55	1.0		22395	0	4.0	-2.0	4.757	-2.383	.1253	2805	855
																	835
4:00		✓		9.30		2.15	-1.25		21225	0	1.3	-3.2	2.356	-5.784	.1430	3035	925
		✓		11.00		2.30	-.75		22615	0	2.5	-4.0	2.977	-4.757	.1358	3070	935
																	930
5:00		✓		9.20		2.20	-.85		21425	0	1.5	-3.2	2.716	-5.779	.1494	3200	975
		✓		11.48		3.25	-1.0		22460	0	2.5	-4.5	2.984	-5.360	.1467	3295	1005
																	990
6:00		✓		9.20		3.50	-2.0		22025	0	.5	-4.5	.906	-8.100	.1585	3490	1065
		✓		12.10		4.50	-1.0		22675	0	3.0	-5.0	3.589	-5.968	.1684	3820	1165
																	1115
7:00		✓		9.2		3.50	-2.5		22500	0	0	-5.1	0	-9.163	.1613	3630	1105
		✓		12.00		4.70	-.7		23205	0	3.3	-4.7	3.945	-5.610	.1683	3905	1190
																	1150
8:00		✓		9.2		3.65	-2.5		22755	0	0	-5.1	0	-9.163	.1613	3670	1120
		✓		12.00		6.50	-1.9		23255	0	2.6	-5.4	3.110	-6.438	.1682	3910	1190
																	1155
9:00		✓		9.2		3.80	-2.5		23395	0	0	-5.1	0	-9.163	.1613	3775	1150
		✓		11.95		6.65	-.8		23510	0	3.0	-4.70	3.587	-5.608	.1619	3805	1160
																	1155
10:00		✓		9.30		3.75	-1.90		24260	0	.6	-4.5	1.088	-8.107	.1619	3925	1195
		✓		12.00		8.15	-.3		23665	0	3.5	-4.2	4.183	-5.016	.1619	3830	1165
																	1180

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 51A | LIFTOFF: T = 12 : 15 : 00 (Z) | DATE: 11-8-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	fM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	CLOUD TOP X (in.)	Y (in.)	θ (deg.)	tan θ	H (ft.)	H (m)	ΔH (m, %)	H_{AV} (m)
2:00	G		49.252	8.3 / 1	9.57				17585	0	11.4	.0	.4162	7320	2230		
3:00				10.3					16515	0	11.3	0	.4607	7610	2320		
4:00				10.4					15445		13.0 *		.5032	7770	2370		
5:00				10.4					14375		14.0 *		.5270	7575	2310		
6:00				10.25					13305		13.5 *		.5114	6805	2075		
7:00				10.3					12235		13.5 *		.5126	6270	1910		
8:00				10.2					11165		13.0 *		.5102	5565	1695		

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 51A | LIFTOFF: T = 12 : 15 : 00 (Z) | DATE: 11-8-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	fM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	CLOUD BASE X	Y	θ	tan θ	H (ft.)		H(m)	
2:00	6		49.252	8.3					18875	0	−6.5	0	.0358	675			
	2			10.8							−9.3			735			
	AVE													705		215	
3:00				10.3					17515		−6.2		.0811	1420			
				10.8							−8.3			1230			
														1325		400	
4:00				10.4					16445		−5.1		.1053	1730			
											−7.3			1730			
														1730		525	
5:00				10.4					15375		−2.7		.1645	2375			
											−6.1			2335			
														2355		720	
6:00				10.25					14305		−1.9		.1682	2405			
											−5.8			2490			
														2450		745	
7:00				10.3					13235		−1.5		.1775	2350			
											−4.5			3155			
														2750		835	
8:00				10.2					12165		−1.1		.1839	2235			
											−4.4			2205			
														2720		830	

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 51A LIFTOFF: T = 12:15:00 (Z) DATE: 11-8-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	fM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	MAX. CLOUD WIDTH (Near Top) Y (in.)	X_1 (in.)	X_2 (in)	θ_1 °	θ_2 °	$\tan(\theta_1-\theta_2)$	W (ft.)	W (m)
2				8.3					17585	8.0	-5.3	5.3	-6.402	6.402	.2273	3995	1220
3				10.3					16515	8.0	-6.0	6.0	-7.341	7.341	.2620	4325	1320
4				10.4					15445	11.0	-6.0	6.7	-7.445	8.302	.2820	4355	1325
5				10.4					14375	12.2	-11.0	5.5	-13.543	6.867	.3721	5350	1630
6				10.25					13305	10.0	-11.7	6.5	-14.217	8.012	.4087	5435	1655
7				10.3					12235	11.0	-14.5	4.3	-17.511	5.345	.4215	5155	1570

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SHUTTLE EXHAUST CLOUD MEASUREMENTS

STS 51A | LIFTOFF: T = 12:15:00 (Z) | DATE: 11-8-84

TIME (T+)	CAMERA (UCS)	FRAME CODE	FM (inches)	PA (in.)	TILT (Deg.)	ℓ_{REF} (in.)	C (in.)	Ø (Deg.)	RANGE (feet)	AVE. CLOUD WIDTH Y (in.)	X_1 (in.)	X_2 (in)	θ_1 °	θ_2 °	$\tan(\theta_1-\theta_2)$	W (ft.)	W (m)
2:00	6			8.3					18585	0	-1.0	4.5	-1.180	5.294	.1135	2110	645
	9			10.8					29240	0	-3.0	.5	-3.568	.5955	.0728	2130	650
	AVE																650
3:00	6			10.3					17515	0	-2.2	4.4	-2.613	5.215	.1375	2410	735
	9			10.8					28560	0	-3.5	1.5	-4.161	1.786	.1042	2975	905
																	820
4:00				10.4					16445	0	-1.0	6.5	-1.189	7.682	.1561	2565	780
				10.8					27880	0	-3.5	2.5	-4.161	2.975	.1252	3490	1065
																	920
5:00				10.4					15375	0	-1.0	7.0	-1.189	8.265	.1665	2560	780
				10.8					27200	0	-3.0	4.0	-3.568	4.753	.1463	3980	1215
																	1000
6:00				10.25					14305	0	-2.0	7.0	-2.375	8.260	.1878	2685	820
				10.8					26520	0	-3.0	4.5	-3.568	5.344	.1568	4160	1270
																	1045
7:00				10.3					13235	0	-2.0	7.0	-2.375	8.262	.1878	2485	760
				10.8					25840	0	-4.0	5.0	-4.753	5.933	.1887	4875	1485
																	1120
8:00				10.2					12165	0	-2.0	7.0	-2.375	8.258	.1877	2285	700
				10.8					25160	0	-4.0	5.0	-4.753	5.933	.1887	4745	1445
																	1070
:30	2			10.8					30600	-10.0	1.3	0	1.482	0	.0259	790	240
1:00	2			10.8					30600	-5.0	2.0	0	2.329	0	.0407	1245	380
:30	6			6.7					20725	-6.2	4.0	2.0	4.607	2.307	.0402	830	255
:00	6			6.7					20725	0	3.0	0	0	3.518	.0615	1275	390

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Technical Monitor: B. J. Anderson. Prepared for Structures and Dynamics Laboratory, Marshall Space Flight Center, Alabama 35812.

16. ABSTRACT

Principles of photogrammetry are used to calculate the dimension of ground clouds produced from the Space Shuttle launch system at Kennedy Space Center, Florida. For each of three launches (Missions 41C, 41D, and 51A), a 16 mm camera recorded the ground cloud from three different locations (two for 51A). A NASA timing code (IRIG) was imprinted on the film for precise time determination of each frame. Measurements were made from outlines of the cloud and other features of interest which were traced onto paper at one minute intervals using a 16 mm stop-action projector. These measurements were converted into cloud dimensions through equations developed for each camera location. Cloud characteristics such as top, max width at top, average width, and base are presented as a function of time. Two different methods were used to check results of the quantitative photogrammetric analysis: the known position of the rocket as it ascended in the film field of view, and the known dimensions of buildings appearing in selected film frames.

For each of the three launch days, a temperature inversion was present and the cloud responded by first rising into the inversion then desending to about the inversion height. Max tops were achieved in about 3 to 5 minutes and ranged from 2200 m for Mission 41C to 3500 m for Mission 41D. Cloud bases rose steadily to between 700 and 1000 m after 10 minutes. Average widths ranged from 500 to 1700 m depending on mission and camera. Photographs of digitizations of selected film frames are included in the report to show the irregular cloud shapes. Error sources for this analysis are also discussed.

17. KEY WORDS		18. DISTRIBUTION STATEMENT
Space Shuttle	Kennedy Space Center	Unclassified - Unlimited
Exhaust Cloud	Measurements	
Dimensions	Photogrammetry	
STS-41C		
STS-41D		
STS-51A		Subject Category 45

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