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Anomalous Phenomena in Space Shuttle Mission STS-80 Video

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Abstract

Analysis of video from Space Shuttle mission STS-80 provides new insight into a number of unusual events captured by a camera aboard the space shuttle Columbia in 1996. Three different phenomena are analyzed: 1) two slow moving circular objects, 2) a number of fast moving objects in space near the shuttle, and 3) a strange luminous apparition near the earth's surface. The two slow moving circular objects have attracted a great deal of popular interest due to their disk-like shape. One seems to appear out of a cloud layer, the other moves into the camera's field of view. It is argued that both are likely to be pieces of shuttle debris emerging from the spacecraft's shadow. The fast moving objects in space near the shuttle appear as bright streaks moving rapidly across the video frame. Analysis of their speeds and directions implies that they are not shuttle debris or meteors. Perhaps the most interesting observation is a rapidly moving burst of light that appears near the earth's surface off the east coast of Puerto Rico. Occurring well before sunrise, away from thunderstorm activity, and moving at an estimated speed of over 500 miles/sec., this is one of the most unusual phenomena observed to date by the shuttle. Its similarity to certain ground-based sightings suggests that it might represent the first observation of a new kind of atmospheric phenomenon from space.

1. Introduction

On November 19, 1996, the space shuttle Columbia (STS-80) began a 17-day mission to deploy and retrieve two satellites and conduct two space walks. On December 2, at about 7:57 GMT, the video camera in the payload bay recorded a number of disk-like objects near the shuttle. In response to popular interest in these objects, space expert James Oberg examined the video. According to Oberg, "When I asked crewman Story Musgrave, who is not shy about talking about anomalies of any kind, he assured me he saw nothing unusual on the flight, at this point or at any other." In a February 1997 web posting¹, Oberg dismisses the event as being "identical in origin to the infamous STS-48 scenes and to numerous others throughout the shuttle flight program."

In September 1991, live video showing as many as a dozen objects moving in unusual trajectories was captured by cameras aboard shuttle mission STS-48. One of the objects appears at a point near the horizon and moves in a path that seems to follow the horizon. After a flash, the object abruptly changes direction and speed. This is followed a few seconds later by a streak that moves rapidly across the field of view and crosses the path of the object. NASA's assessment was that the objects were orbiter-generated debris illuminated by the sun, the flash of light was a thruster firing, and the change in motion of the particles resulted from the impact of gas jets from the thrusters².

Independent analysis of the STS-48 video led to a different conclusion. Jack Kasher produced five proofs that the objects seen in the video could not be ice particles disturbed by a thruster firing³. Carlotto found that instead of following linear paths, a number of the objects travel in circular arcs, which implies the objects were far from the shuttle and moving at a high rate of speed⁴. The estimated speed of one of these objects, about 35 km/sec, is approximately the same as that of a "fastwalker" tracked by the North American Air Defense Command in 1984⁵. Oberg⁶ claimed that the flash in the STS-48 video was from a thruster firing. However, Lan Fleming⁷ has argued that telemetry data does not support this claim.

A similarity between the STS-48 and STS-80 events mention above is that objects in space near the shuttle "appear" at sunrise. According to Oberg⁸,

"When sunrise occurs (due to the Orbiter's motion along its orbit), even though the Orbiter is now bathed in sunlight, the camera is still trained on the dark side of Earth. But now the floating particles which routinely accompany every shuttle flight (often ice particles, sometimes junk from the payload bay, pieces of insulation blankets, a dozen or more distinctly different sources) can become visible in the sunlight, sometimes even moving into sunlight from the umbra of the Orbiter (and thus 'appearing suddenly'). These are close to the camera, sometimes a few feet, at most a few hundred feet. Sometimes they are hit by pulses of gas from the RCS jets as they automatically fire to gently nudge the spaceship back towards a preset orientation."

In reviewing an extended version of the STS-80 video, a number of other unusual events can be seen over the period of time leading up to the appearance of the disk-like objects. This paper presents an analysis of the disks and other objects seen earlier in the video. After defining the chronology of events (Section 2), three sets of anomalies are examined in Sections 3-5.

- 1) A rapidly moving burst of light that appears on, or near, the surface off the east coast of Puerto Rico. Unlike other anomalies observed in shuttle video, this event occurs well before sunrise and away from thunderstorm activity.
- 2) A number of fast moving objects that appear as bright streaks moving rapidly across the video frame. After establishing a lower bound on their distance from the camera, it is shown that at least some of the objects are probably not shuttle debris, or meteors.

3) The disk-like objects. One seems to appear out of a cloud layer, the other moves into the camera's field of view. It is argued that both are probably pieces of shuttle debris emerging from the spacecraft's shadow, and slowing moving away from the shuttle.

Section 6 discusses ground sightings and related atmospheric/meteorological phenomena. Four appendices (A-D) detail the geometrical models used in the analysis.



Fig. 1 Key frames from STS-80 mission video. In some images the brightest features appear gray due to the automatic gain control of the video camera.

2. Overview of Video Sequence

The video sequence considered here starts at 7:52:08 GMT (Day 337). The shuttle was at an altitude of about 218 miles (342 km) in an orbit inclined 28.45°. Its camera was zoomed out looking back at the earth's limb (Fig. 1a). We see clouds illuminated by moonlight as the camera zooms in on a cluster of lights on the surface (Fig. 1b). A short time later, a fast moving object (Fig. 1c) appears, moves rapidly across the field of view of the camera, and disappears. We designate this as event F1. The camera zooms back as if the operator were

looking for the object (Fig. 1d). Next, as the shuttle enters sunlight 2-1/2 minutes later (Fig. 1e), a large slow moving object enters from the upper right and moves into the center of the field of view (Fig. 1f). This object is designated U1. Other objects including slowly moving points of light and fast moving streaks (Fig. 1g) also appear at this time. Ten streaks designated S1-S10 were selected for study. A second large slowly moving object (U2) suddenly appears in the middle of the field of view and slowly moves away from the shuttle (Fig. 1h). Toward the end of the video sequence activity similar to that seen in STS-48 near the limb is observed (Fig. 1i). The total elapsed time is about 5 minutes. These events, which occur over a period of about 5 minutes, are summarized in Table 1.

Time Code	Event
7:54:04	Shuttle in darkness, event F1 occurs (geodetic location 19.02 N, 53.09 W)
7:56:49	Sun rises on shuttle (Earth below is in darkness)
7:57:25	Object U1 moves into field of view from the upper right
7:57:42	Streak S1 appears (heading 322°)
7:58:04	Two streaks S2 (heading 292°) and S3 (heading 357°) appear
7:58:17.25	Streak S4 appears on left and disappears near center of FOV (heading 317°)
7:58:17.69	Streak S5 appears (heading 337°)
7:58:30	Streak S6 appears (heading 307°)
7:58:38	Streak S7 appears (heading 92°)
7:58:40.12	Streak S8 appears (heading 297°)
7:58:40.63	Streak S9 appears (heading 122°)
7:58:43	Streak S10 moves through center of FOV (heading 332°)
7:58:46	Object U2 appears near center of FOV

Table 1 Key events in STS-80 video. Heading angles are clockwise relative to north, and were determined from measured angles in the video imagery and the estimated direction of view of the camera.

3. Event F1

The object in event F1 appears at 7:54:04.4, grows in size as it moves across the camera's field of view and disappears under the time code field in the video at 7:54:05.1. Fig. 2 presents a sequence of video frames bracketing the event. The clamping effect of the camera's automatic gain control causes bright lights to appear gray.



Fig.2 Sequence of cropped video frames of the F1 event (from 7:54:04.4 to 7:54:05.1 GMT at about 0.05 sec/frame).

At 7:54:04 GMT the shuttle was located at about 19.02 N, 53.6 W, which is east of Antigua⁹. At an altitude of 345 km, the distance from the sub-spacecraft point to the horizon is about 2042 km (Appendix A). By measuring the apparent direction of motion of the stars, the approximate look direction of the camera with respect to the direction of motion of the shuttle can be determined (Appendix B). We obtained a value of 49.6° which gives an azimuth of about 289°. As shown in Fig. 3 the shuttle's camera was looking roughly west toward Puerto Rico, 1328 km away.



Fig. 3 Approximate shuttle-ground geometry at the time of event F1.

Neither the object nor the shuttle are in sunlight at this time. Therefore, the appearance of the object cannot be a result of it moving out of the sun's shadow cast by the orbiter, as is sometimes the case for objects that seem to appear at sunrise. The moon was roughly behind the shuttle (azimuth 121.5°, elevation 71°, and phase 58%). That the object might be emerging from the moon's shadow is a possibility. However it is considerably brighter than the moonlit clouds, appearing to be comparable in brightness to the lights on the ground.

Fig. 4a shows a video frame from just before the event. The frame has been rotated so that the shuttle is to the right. Fig. 4b is the cluster of lights stretched in range (horizontal direction) by 1/f = 7.2 (720%) to correct for foreshortening. A map of Puerto Rico (Fig. 4c) matches the shape of the corrected pattern of lights (Appendix C), establishing the location of the event just off the east coast of Puerto Rico, near Vieques.



Fig. 4 Visual correlation of shuttle image taken just before event F1 with a map of Puerto Rico.

Fig. 5 shows three key frames from F1. The images have been compensated for camera motion and rotated so that range is in the vertical direction (look direction is slightly north of west). The object first appears just off the eastern coast of Puerto Rico (Fig. 5a). The moon is above and behind the shuttle at this time. Bright diffuse areas are clouds illuminated by moonlight. The darker region between the island and the first cloud bank is either water or a shadowed cloud bank. It is conjectured that the object is either emerging from a cloud bank or rising up out of the water. A tail forms behind the object as it moves in the direction of the shuttle (Fig. 5b). The object increases in size as it moves toward the camera and begins to wiggle back and forth leaving a faint vapor-like trail (Fig. 5c). It then passes under the time code field and disappears. As noted earlier the camera operator zooms out at this point in the video, and seems to be searching for the object. A careful examination of the video shows no sign of the object after it disappears.



a) Object appears south of Vieques island off Puerto Rico.

b) Tail forms behind object.

c) Object wiggles left to right.

Fig. 5 Close up of F1 event. Images have been shifted to remove camera motion, and rotated so that range is in the vertical direction. Down is in the direction of the shuttle (slightly south of east). Images are distorted in the vertical direction due to foreshortening.

Fig. 6 is a time lapse photograph of the event. The object appears to be moving at a relatively constant speed. Assuming it originates at or near the surface, the object travels about 200 miles (320 km) in 0.4 seconds, which yields a speed of 500 miles/sec (assuming that it is moving parallel to the surface). Due to the clamping effect of the camera's automatic gain control, it is not possible to measure the change in luminosity of the object as it moves in the direction of the shuttle. Although the appearance of the object could be the result of it moving out of the moon's shadow as noted above, it's shape and motion are not consistent with typical orbiting debris.



Fig. 6 Time lapse photograph showing object moving at constant speed toward the shuttle (elapsed time ~0.4 sec)

4. Objects S1-S10

A number of fast moving objects, some of which appear as streaks, are seen in the video just after sunrise. It has been noted that bright objects near the shuttle often leave streaks. We show that at least one, and possibly two of the streaks are probably far from the shuttle, moving at high speed. Three of the objects (S4-S6) are analyzed in detail.



Fig. 7 Time exposure showing streaks S4 and S5. S4 disappears as it moves into the center of the field of view. S5 moves across the video frame in about 1.2 seconds.

Fig 7 is a time exposure capturing streaks S4 and S5. S5 moves across the full width of the video frame in about 1.2 seconds. A lower bound on the distance S5 must be from the shuttle

can be inferred from information provided by S4. S4 disappears as it approaches the center of the field of view of the camera. The sun has risen on the spacecraft by this time (7:58:17). Estimating the shuttle's ground track has moved to about 25° N, 24° W at 7:58:17, the azimuth and elevation of the sun are about 113° and 22°, respectively. The camera's look direction is 289° and depression angle is about 70° (elevation angle -20°) as shown in Appendices B and C. This means that the sun is almost directly behind the shuttle, antiparallel to the direction of view (Fig. 8). The shuttle's shadow is thus cast in the middle of the field of view. If the sun were a point source, the shadow would extend to infinity. But since it has non-zero angular extent ($\delta \approx 0.009$ radian), the shadow has a finite depth. Using a value of 70 feet for the spacecraft's wingspan, the depth of the shadow is 2.4 km. This means that objects closer than 2.4 km may be shadowed by the shuttle (depending on where they are in the field of view), while those farther than 2.4 km will never be shadowed. It is conjectured that S4 disappears into the shadow, and that S5, which appears 1/2-second later, must be at least 2.4 km away from the observer since it is not shadowed as it crosses through the center of the video frame. By measuring the decrease in brightness of the object as it moves across the field of view we can estimate the increase in distance. This, together with knowledge of the camera's field of view allows us to estimate the object's speed. If the object is at least 2.4 km away when it first appears at the edge, its estimated speed as it moves across the camera's field of view is at least 4 km/sec (Appendix D).



Fig. 8 Estimated shadow-casting geometry for analysis of events S4 and S5.

Fig. 9 is a montage of frames from 07:58:30.9 to 07:58:31.3 showing streak S6 moving across the center of the field of view. Occurring only 24 seconds after S5, the shadow-casting geometry is essentially the same. As an object moves away from the observer at constant speed, its angular motion (apparent speed) decreases as the object moves toward the vanishing point. This phenomenon is exploited in Appendix D to develop a 3-D motion model for S6. If its initial range when it appears at the edge of the video frame is 2.4 km, its range on the opposite side is 5.16 km. The distance traveled in 0.25 sec is about 3 km which yields a speed of about 12 km/sec. The actual speeds of S4 and S6 may be more similar, depending on how far each really is from the camera.



Fig. 9 Frames from 07:58:30.9 - 07:58:31.3 showing streak S6.



(a) Time exposure. Objects U1 and U2 decrease in size as they move away from the shuttle.
 (b) Orthogonal projection of video data showing vertical displacement of objects as a function of time.
 Fig. 10 Time exposure and projection of video data showing U1, U2, and other objects.

5. Objects U1 and U2

Two objects have generated a great of popular interest due to their disk-like shape. Fig. 10 are time-exposures showing the tracks of objects U1 and U2, along with a number of other objects exhibiting similar behaviors over time. U2 has generated significant interest and speculation in the way it suddenly appears in the video. In the previous section we determined that the center of field of view is in shadow at 7:58:17 with the sun behind the shuttle. When U2 appears about 30 seconds later, the sun's position has shifted only about 2°. With reference to Fig. 11a, the streak S4 disappears into the shadowed region at 7:58:17. The arc indicates part of the hypothesized boundary of the shadow region. Object U2 would appear to be moving out of the bottom of the shadowed region (through the penumbra) as depicted in Fig. 12. If the object were a small particle floating very close to the camera, it would be out of focus and appear as a blurred circle. The proposed explanation is that U2 is initially in shadow (Fig. 11a), becomes gradually illuminated as it moves through the penumbra (Fig. 11b), and reaches full brightness upon existing the shadow (Fig. 11c).



Fig. 11 Evidence that U2 emerges from the shadowed region in the center of the camera's field of view.



Fig. 12 Probable explanation for U2. Object initially in shuttle's shadow a). U2 becomes gradually illuminated as it moves through penumbra b). Object becomes smaller as it moves away, behind and below the orbiter.

As seen in Fig 10, U1 and U2 become smaller as they move away from the shuttle. The shape of their trajectories indicate that U1, U2, as well as many of the other objects are slowly receding from the spacecraft. It is conjectured that drag forces are acting on these objects, slowing them down, and thus causing them to move away from shuttle¹⁰. For data collected during the STS-3 mission at an altitude of 241 km, the ambient pressure can vary by 2 orders of magnitude depending on the attitude of the shuttle relative to the velocity vector¹¹. The most likely explanation is that U1 and U2 are ice particles or other relatively small objects in close proximity to the orbiter.

6. Discussion

Assuming that S5 is not self-luminous, if one accepts that the presence of a cast shadow from the shuttle is responsible for the sudden appearance of U2 as it moves out of the shadow zone, then S5 must be several km away since is passes through the same zone without being affected. S5 would seem to be of considerable size, moving at high speed with respect to the shuttle. This implies that S5 is not a piece of shuttle debris.



Fig. 13 Polar plot of S1-S10 heading angles (directions of travel).

Fig. 13 plots estimated heading angles for S1-S10. With the exception of S7 and S9, all of the other objects are moving generally in a northwest direction $(\pm 45^{\circ})$. Typically, artificial satellites have orbital inclinations in the range 0-90°. If we suppose that these objects are satellites, they are in retrograde orbits, which would be highly unlikely. Meteors are another possible explanation. The Geminid shower occurs from December 6-19. At the time of the video, the constellation Gemini is to the west, about 62° above the horizon. The streaks cannot be Geminid meteors because they are moving in the wrong direction.

During the period of time S1-S10 were observed, lighting flashes could be seen below as the shuttle traveled over the eastern Caribbean. Could these streaks be related to sprites, jets, and other high-altitude phenomena¹² that occur above thunderstorms? The flashes typically emanate up to about 45 km from thunder clouds at speeds around 100 km/sec. One reported

case¹³ involved a mysterious glowing ball (ball lightning?) 80 km in altitude moving up at about 3000 km/sec observed a few months earlier in 1996. Where spites and jets move upwards (Fig. 14), the streaks in the shuttle video appear to be moving parallel to the earth's surface. They are also much higher in altitude than thunderstorm-related electrical activity.



Fig. 14 High-speed photography showing the evolution of a sprite¹⁴ (Courtesy New Mexico Tech).

F1 is difficult to explain in terms of its sudden appearance and disappearance, and its speed. The object appears to originate south of the island of Vieques¹, off the east coast of Puerto Rico (Fig. 5). If such a phenomenon occurred over a populated area, it is likely that there would be corroborating ground-based sightings. No known reports of the sighting have been found, although strange phenomena have since been reported in the area¹⁵.

Sightings of similar phenomena can however be found in UFO archives. For example, in a report made to the Australian UFO Research Network in September 2002¹⁶ an observer

"...saw a red light appear in the sky to the front of the vehicle, and then there was a bright blue flash. The blue flash vanished just like a light bulb being switched off. A crooked trail of "smoke" was left in the sky for some time. The pre-smoke observations' duration was a "couple of seconds." No sound was heard above the noise of the vehicle."

In November 1995, Lufthansa flight 405 reported "a big bright white light on the front, and a greenish tail coming out the back" moving several thousand feet above them. The sighting was confirmed by another aircraft in the area. This and other similar sightings in this area, the same area TWA flight 800 came down, has lead to speculation that the objects might be surface to air missiles.

¹ Until recently, the US Navy owned over two-thirds of Vieques. Military exercises were conducted on the island for more than 60 years until the Navy withdrew in 2003. The withdrawal resulted in part from a bombing accident in 1999. Vieques is also known for its bioluminescent bays, one of which (Mosquito Bay) is on the south side of the island.

A surface-to-air missile accelerates at launch to its maximum speed toward burnout. F1 cannot be a missile because it is moving at a constant speed from the point it is first seen, off the east coast of Puerto Rico, to the point it disappears. It is also moving much too fast – its estimated speed is within the range of jets, sprites, ball lightning, and other previously documented phenomena. Could F1 be still another mysterious kind of atmospheric phenomena?

October 11, 1492 several hours before their historic landing in the New World, Columbus and his men saw "a light, … perceived it once or twice, appearing like the light of a wax candle moving up and down, which some thought an indication of land¹⁷." Columbus made landfall in the Bahamas not far from Puerto Rico. Although we will never know what these men saw, one has to wonder if these flashes and streaks are not UFOs (in the usual sense), not surface-to-air missiles, but something completely different.

Was it a coincidence that the shuttle's video camera was zoomed in on the region precisely at the time F1 took place? Was the camera operator looking for the object after it disappeared? Why is there no mention of this event in the mission? Is there an official explanation?

Hopefully, if future shuttle sightings can be quickly detected and a search for corroborating ground-based and aircraft reports made, a better understanding of these phenomena can be achieved.

Appendix A – Horizon Geometry

If R is the radius of the earth and h is altitude of the shuttle, the distance to the horizon is

$$d_0 = \sqrt{\left(R+h\right)^2 - R^2} \tag{A-1}$$

For the shuttle's altitude h = 345 km., this distance $d_0 = 2115$ km. The angle between the horizon and the spacecraft (Fig. A-1)

$$\alpha_0 = \cos^{-1} \left(\frac{R}{R+h} \right) \tag{A-2}$$

is about 18.4°. The distance from the horizon to the sub-spacecraft point (the point on the surface directly below the shuttle) is $\alpha_0 d_0 = 2045$ km.



Fig. A-1 Approximate horizon geometry for STS-80.

Appendix B – Estimating the Direction and Field of View

For an orbital inclination of $i = 28.5^{\circ}$, the flight path azimuth at a latitude¹⁸ $L_0 = 19.02$ is

$$\beta_0 = \sin^{-1} \left(\frac{\cos i}{\cos L_0} \right) = 68.2^{\circ} \tag{B-1}$$

Fig. B-1a is a time exposure just before the camera zooms in to observe event F1. Stars are setting at an angle of about 49.6° relative to the horizon. The view azimuth is $68.2 + 180 + (90 - 49.6) = 289^{\circ}$.

The field of view (in radians) is

$$\theta = A/d_0 \tag{B-2}$$

where d_0 is the distance to the horizon and A is the distance along the horizon (Fig, B-1b). To determine the distance along the horizon, one must solve the transcendental equation

$$2\left(\frac{A}{C}\right)\sin\left(\frac{\theta}{2}\right) = \theta \tag{B-3}$$

for θ using image measurements of A and C in pixels. For A = 677 and C = 664, θ = 19.7°. The length of the arc is $A = d_0 \theta$ = 703 km, which yields a resolution of 703 km/677 pixels = 1.04 km/pixel along the horizon. The instantaneous field of view (IFOV) is 19.7°/677 pixels = 0.03°/pixel².

A c ~49.6°



a) Time exposure before event F1 showing direction of b) Geometry for estimating the field of view from the shuttle video. movement of stars with respect to the horizon.



² The airglow layer is visible in the actual images (Fig B-2b,d). The height of the layer at maximum intensity is about 87 km. At a range of 2115 km, the airglow layer is about 87/2115 = 0.04 rad. = 2.35° above the horizon. Its measured location in the image is about 52 pixels above the horizon. This yields a scale factor of $2.35^{\circ}/52 = 0.045^{\circ}/pixel$. The discrepancy between the two IFOV estimates (0.03 and 0.045°/pixel) imply a measurement error of about $\pm 20\%$.



a) Predicted view at 7:52:00 GMT (Az. = 313°, FOV = 20°).



b) Actual view. At this point the camera is aimed north of the event F1 location.



= 283°, FOV = 18°)

c) Predicted view just before F1 at 7:53:20 GMT (Az. d) Actual view. At this point the camera is aimed slightly south of the cluster of lights seen in the event F1.

Fig. B-2 Predicted and actual sky views just before the F1 event.

To verify the direction and field of view estimates, the program *Expert Astronomer* was used to generate predicted views of the sky as seen by the shuttle at the corresponding times. Fig B-2 identifies stars seen in the video around the time of event F1. (The depression angle was adjusted by hand and so the actual and predicted images are shifted relative to one another in the vertical direction.) The width of the cluster of lights (Fig. B-2d) in the cross-range direction is about 51 pixels. This corresponds to a physical dimension of 53 km or about 33 miles, which is about the width of the island of Puerto Rico.

Appendix C – Visual Navigation

Although the width of the cluster of lights in Fig. B-2d suggests that it could be Puerto Rico, the shape is wrong. The long dimension of the island, which is about 100 miles, is viewed along the range direction. The size of a resolution cell is changes as a function of range because the earth's surface slopes away from the observer. This effect, which is known as

foreshortening, causes an object to appear shorter than it really is. For a point on the earth's surface, if β is the look angle from the shuttle to that point, and γ is the tangent angle, the foreshortening factor is

$$f = \sin(\gamma - \beta) \tag{C-1}$$

For example, directly below the shuttle, the look angle is zero, the tangent angle is 90°, and the foreshortening factor is 1.0 (i.e., the object's shape is not distorted). As we move towards the limb, the foreshortening factor decreases toward zero, and the object appears increasingly compressed in the range direction.



With reference to Fig. C-1, $\alpha = 90 - \gamma$ is the angle between a point on the earth's surface and the sub-spacecraft point relative to the center of the earth. Define a similar angle β relative

to the location of the shuttle in space. The two angles are related by the transcendental equation

$$\tan\beta = \frac{R\sin\alpha}{R(1-\cos\alpha)+h}$$
(C-2)

which is tabulated in Table C-1. The distance from the shuttle to a point on the surface subtending the angle α is

$$d = \sqrt{\left[h + R(1 - \cos\alpha)\right]^2 + R^2 \sin^2\alpha}$$
(C-3)

which reduces to

$$d_0 = \sqrt{\left(R+h\right)^2 - R^2} \tag{C-4}$$

when

$$\alpha = \cos^{-1} \left(\frac{R}{R+h} \right) \tag{C-5}$$

Alternatively, that same angle can be expressed in terms of the arc distance

$$\alpha = a/R = 1328/6370 = 11.9^{\circ} \tag{C-6}$$

which is the value between the sub-spacecraft point and Puerto Rico. From the table, β =70° corresponds to α =12°. Thus the foreshortening factor is

$$f = \sin(90^\circ - \alpha - \beta) = \sin(90 - 12 - 70) = \sin(8^\circ) = 0.14$$
 (C-7)

Fig. C-2a shows a map of Puerto Rico and a portion of the STS-80 imagery (Fig. C-2b) stretched by 1/0.14=7.2 (720%). Also shown is a map of the area (Fig. C-2c) and registered Earth light data (Fig. C-2d) from the Defense Meteorological Satellite Program (DMSP). The cluster of lights is clearly Puerto Rico based on it size, shape, and distance from other bright clusters of lights in the regions.



a) Puerto Rico (Courtesy Microsoft Map)



b) STS-80 image stretched by 720% in the horizontal (range) direction. The dark blotch (top middle), an artifact of the video camera, is bright lights in and around San Juan.



c) Caribbean region



d) Earth light data derived from DMSP imagery registered to map. This is consistent with the shuttle video showing an isolated cluster of lights.

Fig. C-2 Visual correlation of imagery with map data establishing that the cluster of lights in the video is the island of Puerto Rico.

Appendix D – Motion Analysis

Fig. D-1 plots the brightness of S5 it moves across the field of view. From the inverse-square radiation law, intensity is inversely proportional to the square of the distance,

$$\frac{R_2}{R_1} = \sqrt{\frac{I_1}{I_2}} = \sqrt{\frac{164}{28}} = 2.4 \tag{D-1}$$

Thus if the initial range is R, the range after 1.2 seconds is 2.4R.



Fig. D-1 Plot of S5 brightness vs. position in video frame.

The S5 geometry is depicted in Fig. D-2 where the field of view is 19.7° (Appendix B). The minimum distance traveled is obtained using the law of cosines:

$$c^2 = a^2 + b^2 - 2ab\cos C \tag{D-2}$$

which yields:

$$\sqrt{R_1^2 + (2.4R_1)^2 - 2R_1^2 \cos(19.7)} \approx 2R_1.$$
 (D-3)

Thus the minimum distance traveled is about 4.8 km, and the minimum speed is 4.8/1.2 = 4 km/sec.





Streak S6 is moving faster across the camera's field of view and so a different approach is used to determine its motion away from the observer. Fig. D-3a is the imaging geometry. If d(t) is the object's displacement along its flight path as a function of time, its projections in and out of the imaging plane are:

$$u(t) = d(t)\cos\alpha$$

$$v(t) = d(t)\sin\alpha$$
(D-4)

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The relation between the direction of motion of the object α (which is assumed constant) and the observed angular coordinate $\theta(t)$ is

$$\theta(t) = \tan^{-1} \left(\frac{d(t)\sin\alpha + v_0}{d(t)\cos\alpha} \right)$$
(D-5)

In the limit as $d(t) \rightarrow \infty$, the object appears to slow down as it approaches the vanishing point

$$\tan[\theta(t)] = \tan\alpha + \frac{v_0}{d(t)\cos\alpha} \to \tan\alpha$$
 (D-6)

Fig. D-3b plots $\theta(t)$ vs. d(t) for different values of α and v_0 . As $d(t) \rightarrow \infty$, $\theta(t) \rightarrow \alpha$ asymptotically.



a) S6 geometry. v is in the view plane and u is orthogonal (away from the observer).



Fig. D-3 Geometrical analysis of S6.

Fig. D-4a plots measurements of S6's motion in the video frame (IFOV = 0.04° /pixel). The geometry resulting from these measurements is shown in Fig. D-4b. Using the law of sines, if the initial range when the object appears on the left is 2.4 km, the range as it approaches the right side of the video frame is 5.16 km and so the distance traveled in 0.25 sec is about 3 km which yields a speed of about 12 km/sec.

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$
(D-7)
$$\frac{2.4}{\sin 15.3} = \frac{R_2}{\sin 145.4} = \frac{d}{\sin 19.3}$$

If S5 is farther away than we have assumed and S6 is closer, the speeds of the two objects might be more similar.



a) S6 measurements. Curve fit gives estimated asymptote of about 25°.

b) Estimated S6 geometry based on measurements. Fig. D-4 S6 trajectory estimation

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