6.5 EFFECT OF CLOUDS ON OPTICAL IMAGING OF THE SPACE SHUTTLE DURING THE ASCENT PHASE: A STATISTICAL ANALYSIS BASED ON A 3D MODEL

David A. Short*, Robert E. Lane, Jr.*, Katherine A. Winters[+], and John T. Madura[#]
NASA / Kennedy Space Center / Applied Meteorology Unit / *ENSCO, Inc.
[+]45th Weather Squadron, Patrick Air Force Base, FL
[#]NASA / Kennedy Space Center / Weather Office, FL

1. INTRODUCTION

Clouds are highly effective in obscuring optical images of the Space Shuttle taken during its ascent by ground-based and airborne tracking cameras. Because the imagery is used for quick-look and post-flight engineering analysis, the Columbia Accident Investigation Board (CAIB) recommended the return-to-flight effort include an upgrade of the imaging system to enable it to obtain at least three useful views of the Shuttle from lift-off to at least solid rocket booster (SRB) separation (NASA 2003).

The lifetimes of individual cloud elements capable of obscuring optical views of the Shuttle are typically 20 minutes or less. Therefore, accurately observing and forecasting cloud obscuration over an extended network of cameras poses an unprecedented challenge for the current state of observational and modeling techniques. In addition, even the best numerical simulations based on real observations will never reach "truth."

In order to quantify the risk that clouds would obscure optical imagery of the Shuttle, a 3D model to calculate probabilistic risk was developed. The model was used to estimate the ability of a network of optical imaging cameras to obtain at least N simultaneous views of the Shuttle from lift-off to SRB separation in the presence of an idealized, randomized cloud field.

2. SIMULATION MODEL

The model was executed in 3D Earth Centered Earth Fixed (ECEF) coordinates on an oblate spheroidal earth. Clouds were represented as 6-sided rectangles with faces parallel to lines of latitude, longitude, and the earth's tangent plane below each cloud. The heights of cloud bases and tops and the horizontal dimensions of cloud elements were specified, whereas cloud locations were randomized. Camera sites, including airborne cameras, were fixed. The Shuttle position was represented at 0.1-second intervals for 124 seconds from lift-off to SRB separation.

An efficient numerical scheme was developed to determine if any cloud elements were in the line-of-sight between each camera site and the Shuttle. The equation of the line connecting each camera and the Shuttle was computed in ECEF coordinates and used to determine if the line pierced any of the cloud elements within the relevant domain. This computation was done for each camera within the network and initially for each 0.1-second time interval during the ascent. Later testing indicated that a 0.5 second interval could be used without significantly affecting the results.

*Corresponding author address: David A. Short, ENSCO, Inc., 1980 N. Atlantic Ave., Suite 230, Cocoa Beach, FL 32931. Email: short.david@ensco.com

3. SHUTTLE ASCENT IMAGING NETWORK BEFORE AND AFTER UPGRADE

In response to the CAIB recommendation, the Intercenter Photo Working Group (IPWG) proposed several possible upgrades to the imaging network. These upgrades included additional long-range ground-based and airborne cameras. Figure 1 shows 11 ground-based, and 2 airborne long-range camera sites included in a proposed upgrade. Prior to the upgrade the network consisted of five long-range camera sites at Shiloh (N), Playalinda Beach (N), Universal Camera Site (UCS) 23 (S), Cocoa Beach (S) and Patrick Air Force Base (PAFB; S). The proposed upgrade initially involved dropping the PAFB site and adding ground based sites at Ponce Inlet (N), Apollo Beach (N), Launch Complex (LC) 46 (S), UCS-11 (N), UCS-3 (S), and UCS-25 (S), for a total of 10 ground-based long-range camera sites. Sites north and south of the ground track are denoted by (N) and (S), respectively, above. The upgrade proposal also included airborne cameras to be located 15 n mi NW and SE of the SRB separation point, at 65 000 ft altitude. The IPWG also considered an upgrade of the ground-based network with only 8 camera sites by dropping the Shiloh and UCS-25 sites, marked with open triangles in Figure 1.

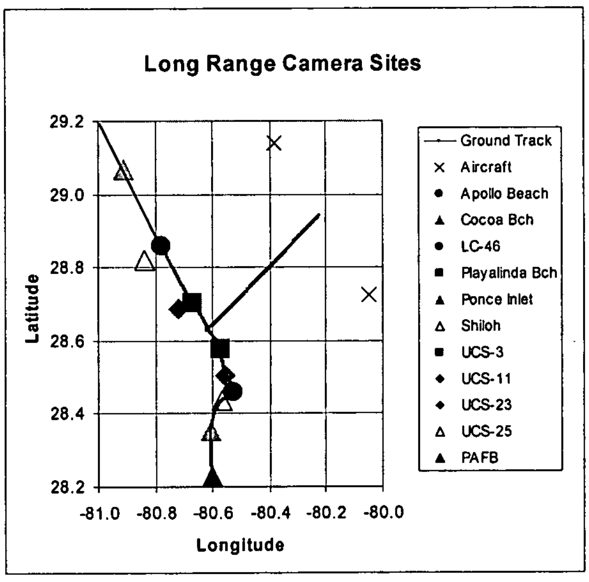

Figure 1. Locations of all pre- and proposed-upgrade long-range camera sites. Airborne cameras are at 65 000 ft 15 n mi NE and SW of the SRB separation point. The solid line shows the ground-track of a Shuttle ascent trajectory to the International Space Station from lift-off to SRB separation.

4. PERFORMANCE COMPARISON BETWEEN PRE- AND POST-UPGRADE CAMERA NETWORKS

The capabilities of the pre-upgrade and proposed-upgrade camera networks for providing at least three simultaneous views of the Shuttle were compared. A cloud field with 8000 ft bases and a 500 ft thickness was used. An 8000 ft ceiling is operationally significant because that is the lowest ceiling that satisfies launch commit criteria and return-to-launch site flight rules.

Cloud elements with horizontal extents of 1, 4, and 8 n mi were used and cloud cover was varied from clear to overcast by 1/8s. For each cloud size and each cloud coverage, 1000 trials were executed with cloud elements randomly positioned for each trial.

Figure 2 shows the average percent of time from lift-off to SRB separation that the Shuttle was viewable simultaneously by at least three cameras. The percent viewable time is 100% under clear conditions and decreases to 22% for overcast conditions because it takes approximately 27 seconds for the Shuttle to reach cloud base and to be completely obscured from all the ground-based cameras. For this cloud scenario medium and short-range cameras do not affect the results because their useful imagery is limited to the time from lift-off to when the Shuttle reaches an altitude of 7000 ft, which is below the chosen cloud base.

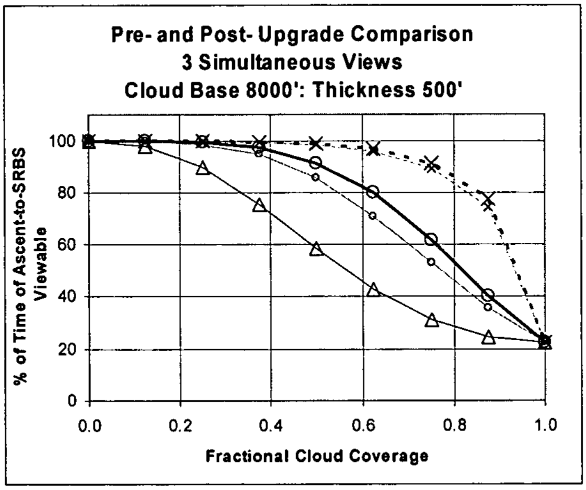

Figure 2. Fractional cloud coverage versus % of ascent-to-SRB separation time period that the Shuttle is viewable simultaneously by at least 3 cameras for several configurations of the camera network: Pre-upgrade (Δ), Post-upgrade with 8 ground-based long-range cameras (o), Post-upgrade with 10 ground-based long-range cameras (O), Post-upgrade with 8 ground-based and 2 airborne long-range cameras (x), and Post-upgrade with 10 ground-based and 2 airborne long-range cameras (X).

Figure 2 shows that as cloud cover was increased from clear to 0.5 coverage, the percent viewable time for the pre-upgrade network decreased to just under 60%, whereas the upgraded networks decreased more slowly to 85% or better. As cloud cover was increased from 0.5 up to 0.75, the percent viewable time decreased to less than 80% for all configurations, except those that included the airborne cameras. As cloud coverage approached overcast conditions, all network configurations rapidly converged to the 22% level.

5. LINES-OF-SIGHT AND CLOUD OBSCURATION ZONES

The line-of-sight from a tracking camera to the Shuttle sweeps across the sky as the Shuttle travels along its ascent trajectory. Figure 3 shows a 2-dimensional cross section of the azimuth and elevation angles followed by a camera at UCS-3 as it moved across the sky, tracking the Shuttle. Earth curvature effects are evident at the SRB separation point as the elevation angle is decreasing, even though the Shuttle continues to ascend.

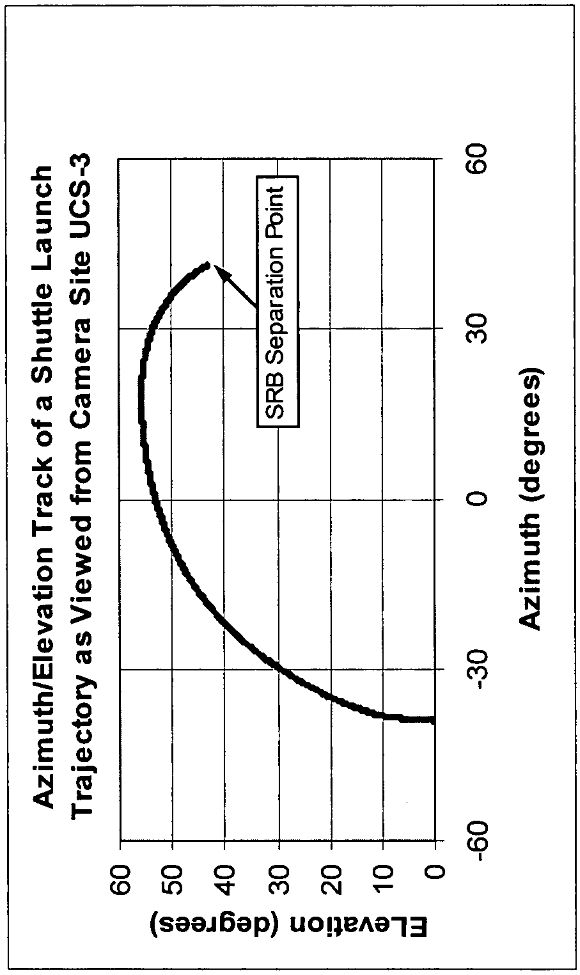

Figure 3. Azimuth/elevation cross section of a Shuttle launch trajectory as viewed from UCS-3.

Figure 4 shows a schematic 2-dimensional cross-section of an instantaneous line-of-sight from a camera (lower left) to the Shuttle during any moment in time from lift-off to SRB separation at 155 000 ft. The bottom line at the Earth's surface is divided into regions A, B and C. The boundaries have been determined by a cloud base altitude (CB), a cloud top altitude (CT), and the elevation angle of the line-of-sight. If cloud elements with the prescribed bases and tops were present within region B they would obscure the line-of-sight from the camera to the Shuttle at that moment in time. Similar cloud elements within region A could not obscure the view as the line-of sight would pass beneath them. Similar cloud elements in region C could not obscure the line-of-sight as it would pass above them.

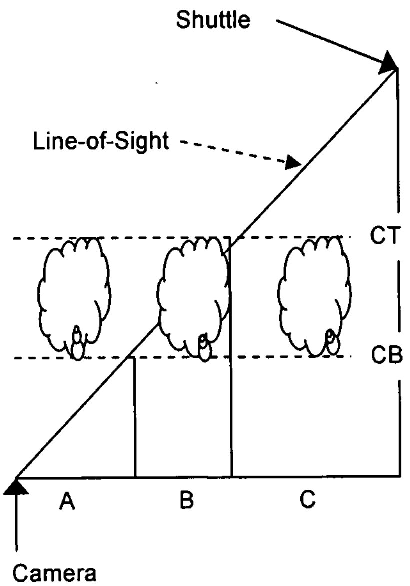

Figure 4. Schematic view of the line-of-sight from a camera site in the lower left-hand corner to a Shuttle at a particular point in its ascent trajectory from lift-off at the launch site to SRB separation at 155 000 ft above the Earth's surface. Region B is the domain where cloud elements with bases at altitude CB and tops at altitude CT would obscure the line-of-sight from the camera to the Shuttle.

The geographic boundaries of the domain labeled B in Figure 4 can be computed for any camera site for all moments from lift-off to SRB separation and for any prescribed CB and CT. Figure 5 shows a composite of the zones susceptible to cloud obscuration for the post-upgrade long-range camera network shown in Figure 1 with CB at 3000 ft and CT at 27 000 ft. This cloud scenario could be representative of late morning convective elements during the warm season (May – September) or frontal clouds during the cool season (October – April). The zones susceptible to cloud obscuration shown in Figure 5 are mostly off-shore and are confined to within less than 10 n mi of the coast.

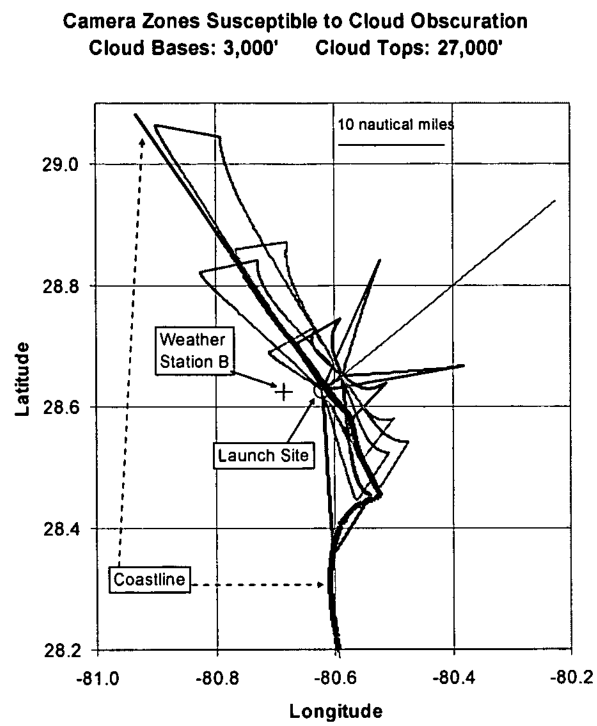

Figure 5. Geographical pattern of camera zones susceptible to cloud obscuration for the upgraded long-range camera network with cloud bases at 3000 ft and cloud tops at 27 000 ft. The weather station (+) near the Shuttle landing facility is where routine surface-based observations of cloud height and cloud amount are obtained.

The complex geographical pattern shown in Figure 5 provides an indication of the difficult challenges that would have to be overcome in order to provide an accurate, deterministic forecast of the effect of clouds on viewing conditions from a network of cameras. Although it may be possible to diagnose an existing cloud geometry over the region with advanced instrumentation such as cloud radars, cloud lidars and high-resolution satellite observations, an accurate 15-minute forecast of the cloud geometry would be even more challenging.

6. DISCUSSION AND RESULTS

The goal of this study was to determine the effects of clouds on optical imaging of the Space Shuttle during its ascent from lift-off to SRB separation, by ground based and airborne tracking cameras. This effort was motivated by Recommendation R3.4-1 from CAIB Report for Space Shuttle return-to-flight that stated: "Upgrade the imaging system to be capable of providing a minimum of three useful views of the Space Shuttle from liftoff to at least Solid Rocket Booster separation, along any expected ascent azimuth. The operational status of these assets should be included in the Launch Commit Criteria for future launches. Consider using ships or aircraft to provide additional views of the Shuttle during ascent."

In response to the CAIB recommendation the Kennedy Space Center (KSC) Weather Office tasked the Applied Meteorology Unit (AMU) to develop a model to forecast the probability that at any time from launch to SRB separation, at least three of the Shuttle ascent imaging cameras will have a view of the Shuttle unobstructed by cloud. Because current observational and modeling capabilities do not permit accurate forecasts of cloud morphology and location, a statistical modeling approach was selected by a team composed of the Shuttle Launch Director, The NASA Intercenter Photo Working Group, the KSC Ice and Debris Team, the KSC Weather Office, the 45th Weather Squadron and the AMU. The AMU formulated a 3D model to calculate lines-of-sight from tracking camera locations to the Shuttle during its ascent and to simulate obscuration of the lines-of-sight by an idealized cloud field placed randomly within the 3D domain. Following are the primary elements of the model:

- An ascent trajectory from Space Launch Complex 39B to the International Space Station.

- The network of ground-based cameras prior to upgrade and the network of ground-based and airborne cameras after the upgrade, including 2 airborne cameras.

- 19 basic cloud scenarios with realistic and operationally significant values for cloud base height, cloud thickness, horizontal cloud dimensions, fractional cloud cover varying from clear (0) to overcast (1) in 1/8 increments and randomized cloud locations.

For each random realization of a cloud field scenario, the number (N) of simultaneous views of the Shuttle were determined from the line-of-sight data between lift-off and SRB separation. Then the average percent of time with N simultaneous views was computed from 1000 random realizations of each scenario. N was varied from 2 to 6 and particular attention was paid to simultaneous views from both the north and south sides of the camera network, defined with respect to views of the right (north) and left (south) sides of the Shuttle after its roll to a heads-down attitude. Analyses of the percent of time viewable were made to determine its sensitivity to cloud amount, cloud base height, cloud thickness, cloud horizontal dimensions, and the upgrade of the camera system.

The results are summarized as follows:

- For overcast conditions, the recommendation for at least three simultaneous views could only be met while the Shuttle was below cloud base. The maximum percent of time viewable for a high overcast of cirrus clouds with bases at 30 000 ft would be less than 50%. Broken cloud cover, that is 5/8 to 7/8 coverage, generally would allow 80% or less viewable time, without airborne cameras. When the network includes two airborne cameras, the probability of 90% or better time viewable with at least three cameras simultaneously extends from clear conditions up to approximately 6/8 cloud coverage.

- The impact of upgrading the ground-based network was found to be roughly equivalent to decreasing the cloud cover by approximately 2/8 in terms of the increased percent of time viewable, except for overcast conditions as noted above. The addition of airborne cameras was roughly equivalent to decreasing the cloud cover by about 4/8, except for overcast conditions.

- The required number of simultaneous views had a significant impact on the average percent of time viewable. For the case with at least three simultaneous views of both sides of the Shuttle (at least six views total) with 4/8 cloud coverage, bases at 8000 ft and tops at 8500 ft the upgraded network with 2 airborne cameras provided 65% time viewable. For the case with at least three simultaneous views, regardless of which side the cameras were on, with the same cloud conditions and the same network configuration, the percent viewable time was 99%.

- Cloud thickness was the next most important variable with thicker clouds being more efficient at reducing the percent of time viewable. At the typical viewing angles, < 60° above the horizon, the effective cloud cover is increased by the sides of the clouds. An increase in cloud thickness from 500 ft to 5000 ft was roughly equivalent to increasing the fractional cloud cover by an amount in the range between 1/8 and 2/8.

The AMU also mapped out the geographic boundaries of the domain where clouds could potentially obscure imagery of the Shuttle from individual cameras within the network. If developed into an overlay for satellite imagery, this product could provide real-time, subjective operational guidance to the Shuttle Launch Weather Officer regarding the susceptibility of various camera sites to cloud obscuration.

Additional details of the study have been described in quarterly reports that are posted to a publicly accessible website (http://science.ksc.nasa.gov/amu). A final report will be posted in the near future.

Acknowledgement: We thank Mr. Michael Leinbach, the Shuttle Launch Director, for his guidance and support.

7. REFERENCE

National Aeronautics and Space Administration, 2003: Columbia Accident Investigation Board Report: Volume I. Government Printing Office, Washington D.C., 248 pp.