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# **8.3** TRIGGERED LIGHTNING RISK ASSESSMENT FOR RLVS AT THREE COMMERCIAL SITES IN CALIFORNIA, NEW MEXICO AND OKLAHOMA

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## 1. INTRODUCTION

We present the findings of a study sponsored by the Federal Aviation Administration Office of Commercial Space Transportation (FAA/AST) to assess the risks from triggered lightning during suborbital launches and landings of four concept reusable launch vehicles (RLVs) from three proposed sites. These are the Southwest Regional Spaceport (now known as Spaceport America) in New Mexico, the Oklahoma Spaceport in Burns Flat, Oklahoma and the Mojave Spaceport in California. Three areas were addressed: (1) observed frequencies of cloud-to-ground lightning at the proposed spaceports, including estimates of violation frequencies of the existing lightning flight commit criteria (LFCC), (2) estimates of the ambient fields required for triggering by each of the concept vehicles, including consideration of methods for estimating the probability of encountering these field magnitudes from the measured radar returns of thunderstorm anvil clouds, and (3) review of the current LFCC to determine if these criteria are relevant to each suborbital RLV concept. We also examined the local geographical effects pertaining to each spaceport to determine whether additional LLCC are necessary to conduct safe launch operations in that location.

Diurnal and seasonal variability of natural cloud-to-ground lightning at the proposed spaceports were compared to existing federal launch ranges at Cape Canaveral, Florida (CAPE) and Vandenberg Air Force Base, California (VAFB) in order to assess relative lightning risk.

## 2. TRIGGERED LIGHTNING

At least 80 - 90% of all lightning strikes to aircraft and spacecraft in-flight are “triggered,” in the sense that they are initiated locally by the introduction of a large conductor into a pre-existing electric field that is sufficiently large-scale and sufficiently strong. Recordings of currents and electric-field changes on board aircraft have been interpreted to indicate that triggered strikes invariably begin with a positive leader propagating away from an extremity on which positive charge was induced by the ambient field; followed after a few milliseconds by the development of a negative leader propagating in the opposite direction away from a negatively charged extremity, [e.g., Boulay et al., 1988; Mazur, 1989]. Here the term, “leader,” denotes a highly ionized, conducting, filamentary channel. The term, “positive streamer,” in contrast, will always refer to the poorly conducting “corona” space-charge waves [e.g.; Dawson and Winn, 1965; Phelps and Griffiths, 1976] that are an important component of the advancing “head” of a positive leader.

Detailed study of the triggering phenomenon (as well as other important aspects of lightning) has been facilitated by rocket-triggering techniques where triggering is initiated by a small rocket lifting a grounded wire aloft under a thunderstorm [Newman et al. [1958, 1967; St. Privat D'Allier Group, 1985]. The key to success is likely a hypothesis by Brook et al. [1961] that the sufficiently rapid introduction of a grounded conductor into a high-field region might initiate the discharge.

It is now well established that classical rocket-triggered lightning normally begins with an upward-propagating, positive leader that moves from the tip of the triggering wire toward a negatively charged cloud in common with most “upward-initiated” discharges to towers [Uman, 1987, Chapter 12].

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Very similar positive leaders have been shown to initiate “altitude” triggered lightning [e.g., Laroche et al., 1989] produced when a small rocket lifts an ungrounded wire aloft. Altitude triggered discharges are believed to be a good analog for lightning strikes to flying aircraft and spacecraft. For these reasons, we focus on the extended development of a positive leader as the proximate cause of triggered strikes to spacecraft, and we use triggering conditions derived from experiments with classical rocket-triggered lightning to estimate the conditions for such strikes.

Laboratory studies and to a lesser extent studies of discharges in the free atmosphere [*e.g.*; Bazelyan and Raizer, 1998, 2000; Willett *et al.*, 1999] indicate that there are at least three conditions that must be satisfied in order to initiate and propagate a positive leader. First, electrical “breakdown” must occur in a small volume of air near the surface of the object in question, in order to produce free electrons in sufficient quantities to carry an electric current. This means that at normal temperatures and pressures the local electric field must reach a value near 3.0 MV/m, and when this occurs, a phenomenon called “glow corona” is produced. Second, the current in the corona region must be amplified to the point where positive streamers occur. These streamers propagate outward from the breakdown region, further heating a small volume that is called the “stem,” and the stem is where the positive-leader channel begins. Third, the ambient field must be large enough over a sufficiently large volume of space that the positive leader, once it has been initiated, will continue to grow and propagate (i.e., the potential at its tip will remain large enough relative to the local ambient potential to sustain propagation). We refer to this last condition as “leader viability.”

It appears that it is the amplitude and extent of the ambient field, rather than the locally enhanced field at the extremities of a flying object, that are the key determinants for triggering lightning. The net charge on a flying vehicle is usually unknown, making it difficult or impossible to calculate the conditions for localized breakdown by the familiar enhancement-factor approach. The enhancement factor of the vehicle, which can be estimated from the nose radius of curvature and the effective length (including the exhaust plume) of any of the RLVs of interest here (assuming it to be uncharged), predicts the onset of electrical breakdown at a higher ambient field than the field that is required to produce leader viability (as determined from the data and model described in Section 4). Thus the leader-viability approach affords a margin of safety in these cases.

## 3. POSSIBLE SOLUTIONS

There are two ways to reduce the risk of triggered lightning: hardening the vehicle against the effects of a lightning strike or avoiding the hazard. Avoidance is the focus of the present study.

### 3.1 *In Situ E* Field Measurements

*In situ* measurement of the ambient electrostatic field is undoubtedly the best way to determine whether any particular cloud along or near the planned flight path has created an electric field that poses a triggered-lightning hazard to any particular RLV. This is because most clouds do not give a clear indication with any known remote-sensing technique (*e.g.*, morphology or radar reflectivity) of whether they are electrified and capable of triggering lightning. The obvious exceptions are cumulonimbus clouds and any clouds that are producing natural lightning; clearly, any such clouds should always be avoided. Developing cumulus clouds should also be avoided because they are capable of becoming electrified very rapidly.

Unfortunately, the only appropriate method of obtaining in situ electric field measurements -- a high-performance aircraft instrumented with five or more field mills (an Airborne Field Mill, or ABFM, system) -- is expensive and both technically and operationally difficult.

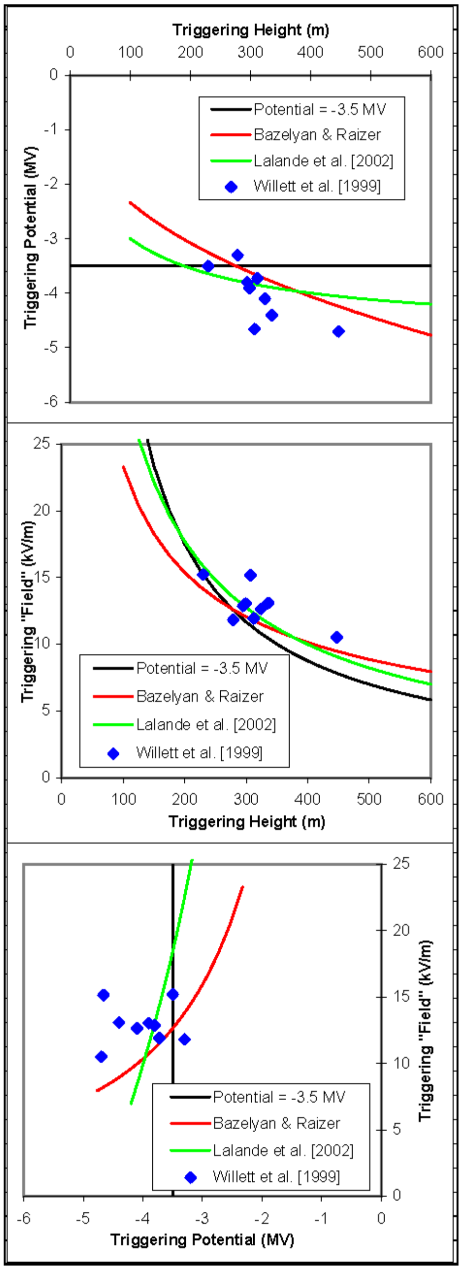


Figure 1. Comparison of the "Constant-Potential-Spanned," Bazelyan and Raizer [2000], and Lalande *et al*. [2002] Positive-Leader Models with the Data of Willett *et al*. [1999].

### 3.2 Cloud-Based Rules

The existing LLCC are examples of cloud-based avoidance criteria. Although they are believed to be very safe, these rules were developed for large orbital boosters like the Titan and the Space Shuttle, and they do produce false alarms and reduce launch availability. Nevertheless, they should be applied to flight operations of the RLVs of interest here until and unless an operational ABFM and/or further statistical analysis of existing ABFM experiments enable some of the rules to be tailored to smaller launch vehicles.

### 3.3 Ground-Based E-Field Measurements

Measurements of surface electric fields using a Ground-Based Field-Mill system (GBFM) are incorporated into certain of these LLCC, where they are important for both adding safety (detection of additional hazards) and providing some relief from the otherwise very conservative cloud-based rules. We emphasize that a GBFM is not a substitute for an ABFM because of the electrical charges on screening layers that can accumulate in the atmosphere and at the cloud boundaries.

## 4. TRIGGERING MODELS

We now briefly review four models for predicting the viability of a positive leader, a lower bound on the triggering conditions in classical rocket-triggered lightning. In this section, we will only consider triggering at altitudes near the surface, *i.e.*, at standard temperature and pressure (STP).

A) A leader might become viable when the magnitude of the ambient field is larger than the longitudinal potential gradient found in a DC arc that carries the same current -- only a few kilovolts per meter at leader currents of a few Amperes. This is probably a necessary condition, but it is not sufficient.

B) It has been suggested that triggering can occur when the potential "spanned" by the triggering wire exceeds about 3.5 MV. However, this turns out to be overly simplistic when compared to more sophisticated models of leader propagation that cannot be discussed in any detail here.

C) Aleksandrov et al. [2005] have presented a formula corresponding to a model that was developed previously by Bazelyan and Raizer [2000].

D) Lalande et al. [2002] gave a comparable formula corresponding to their very different physical model.

In Figure 1 we show the predictions of models B, C, and D, plotted together with the direct measurements of Willett et al. [1999]. (Note that we are plotting the average measured electric field between the surface and the triggering height, as opposed to the field at the triggering height, because models C and D both assume a uniform ambient field.) The black curves in Figure 1 represent the assumption that a viable positive leader will be initiated whenever the potential spanned by the triggering wire exceeds a constant threshold of 3.5 MV -- model B above. The red curves are for model C of Bazelyan and Raizer, and the green curves are for model D of Lalande et al. The data of Willett et al. [1999] agree reasonably well with all three of these models, giving little to recommend one over any of the others. Nevertheless, the relatively limited data available from lightning strikes to instrumented aircraft (not shown) appears to conclusively rule out model B and to favor model C over model D. For this reason, and because the Bazelyan and Raizer model is safer -- it predicts a smaller triggering field for a conductor of any given length in the size range relevant to our RLVs -- we favor model C. Clearly, however, more work needs to be done on the models of triggering and their validation.

## 5. ALTITUDE AND VELOCITY DEPENDENCE OF TRIGGERING

The altitude dependence of electrical breakdown in long sparks is essentially unknown. The triggering field threshold for any given vehicle might scale anywhere from a $p^{3/2}$ dependence on ambient pressure at constant temperature, such as that found for the positive-streamer "stability field" by Phelps and Griffiths [1976], down to the $p^{1/3}$ dependence that has been measured for the voltage drops in DC arcs [see Raizer, 1991, Fig. 10.15], or even lower. Here we compromise and use a $p^1$ dependence that is implied by Paschen's Law at constant temperature, with the understanding that this behavior is still quite uncertain.

## 6. VEHICLE TYPES AND SPACEPORTS

### 6.1 Representative Suborbital Vehicle Concepts

In order to determine the electric fields that could trigger lightning to suborbital vehicles, the types of vehicles and their trajectories must be known. Because this information is difficult to obtain or is simply not available for the four suborbital vehicle concepts being considered, representative vehicle configurations were developed that closely resemble the currently proposed suborbital vehicle concepts. The four vehicle configurations are described below.

<u>Horizontal takeoff and landing (HTHL) vehicle with jet engines and rocket engines:</u> This vehicle takes off using jet engines and proceeds to an airborne launch point, where it then climbs to apogee using rocket power and glides to a landing on a runway. It is similar to the Rocketplane “XP” concept.

<u>Ferried takeoff and horizontal landing vehicle with rocket engines (referred to as “Air Launch vehicle”)</u>: The vehicle is carried aloft to the drop point by a carrier aircraft where it is released and climbs to apogee using rocket power, and glides to a landing on a runway. It is similar to the Scaled Composites “SpaceShipOne” concept.

<u>HTHL vehicle with rocket engines:</u> This vehicle takes off using rocket engines, climbs to apogee using rocket power, and glides to a landing on a runway. It is similar to the XCOR Aerospace “Xerus” concept.

<u>Vertical takeoff and landing (VTVL) vehicle with rocket engines:</u> This vehicle takes off vertically using rocket engines, coasts to apogee, and lands by rocket-powered descent, similar to the Armadillo Aerospace “Black Armadillo” concept.

### 6.2 Spaceports

The site for the Southwest Regional Spaceport (SWRS) is near Upham, New Mexico, approximately 45 miles north of Las Cruces and 30 miles east of Truth or Consequences. This location is along the western boundary of the White Sands Missile Range.

The site for the Oklahoma Spaceport (OS) is the Clinton-Sherman Industrial Airpark at Burns Flat, Oklahoma, approximately 100 miles west of Oklahoma City.

The site for the California site is the Mojave Spaceport located adjacent to Edwards Air Force Base.

## 7. ESTIMATION OF VEHICLE PLUME LENGTHS

The electrical conductivity of an exhaust plume is primarily a function of electron density; the particle content might also be a secondary factor. The electron density is strongly dependent on the temperature and the presence of easily ionized trace species, mainly sodium and potassium compounds in the fuel. Soot particles are produced by the combustion of hydrocarbon fuels such as

JP-1 and RP-1 with liquid oxygen or nitrogen/ oxygen compounds used as oxidizers. One possible effect of these particles might be the thermionic emission of electrons subsequent to their reaction with entrained air. The governing plume parameter for triggering lightning is assumed to be an effective conducting length that can be combined with the vehicle body length. The question is how to define an effective plume length with respect to the electrical conductivity.

Here we base our estimates of the conducting lengths of RLV plumes on (A) the visible plume length scaled from two video images of SpaceShipOne during a test flight and (B) scaling to the other vehicles in proportion to the square root of engine thrust, on the assumption of single nozzles with the same expansion ratios and fuel-oxidizer mixtures in all cases. We further assume (C) that these plumes are all under-expanded throughout the altitude range of interest for triggered lightning (roughly 0 - 10 km), so that their lengths do not change appreciably with altitude. The results, given in the third column of Table 1, are obviously quite uncertain in terms of the actual conductive lengths of these plumes.

The overall effective electrical length of each vehicle during the boost phase has been estimated as one half of the sum of vehicle length plus the conducting plume length, and the values are listed in the last column of Table 1. For a long, thin, uncharged conductor of actual length equal to this sum, this value of electrical effective length, when multiplied by the ambient-field magnitude (assumed uniform and parallel to the conductor's long dimension), would give the correct potential difference between each tip of the conductor and the nearby ambient atmosphere. Nevertheless, the proper value of electrical effective length to use in the Bazelyan and Raizer model might range from something less than half the vehicle length (if the plume actually has no effect at all) to as much as the sum of vehicle plus plume length (if the tip of the conducting plume acts as a potential equalizer), so this value is also quite uncertain.

## 8. TRIGGERING CONDITIONS

The ambient electric-field thresholds that are required for triggering have been estimated for each of the concept RLVs at two altitudes, 0 and 10 km, both during boost phase (with the exhaust plume) and during landing (without the plume). Similar estimates for the Titan IV indicate triggering thresholds of 16 and 5 kV/m at the surface and 10 km, respectively, based on an effective electrical length of 180 m. Triggering conditions during the glide phase have not been given for the concept 4 vehicle because this vehicle is designed to land vertically, breaking first with a parachute and then with its rocket motor. Thus, the exhaust plume may play a role during landing as well as during launch.

Table 1. Estimated Plume Lengths

| System | Vehicle length, m | Conducting plume length, m | Electrical effective length, m |
|---|---|---|---|
| Concept 1 | 12.2 | 29 | 21 |
| Concept 2 | 6.5 | 13 | 10 |
| Concept 3 | 7.4 | 16 | 12 |
| Concept 4 | 7.1 | 18 | 13 |

Table 2. Estimated Electric Fields for Triggering

| System | Boost Phase | | Glide Phase | |
|---|---|---|---|---|
| | Surface, kV/m | 10 km, kV/m | Surface, kV/m | 10 km, kV/m |
| Concept 1 | 60 | 20 | 125 | 42 |
| Concept 2 | 93 | 31 | 182 | 61 |
| Concept 3 | 83 | 28 | 169 | 56 |
| Concept 4 | 79 | 26 | -- | -- |

Although these field thresholds are quite uncertain in absolute terms, they should be reasonably comparable between vehicles at the same altitude.

## 9. LIGHTNING CLIMATOLOGY

In support of this effort, we studied lightning climatology data for the period 1990 - Sept 2004 for sites with locations nearly identical to the above spaceports (Clinton-Sherman AFB, White Sands Missile Range and Edwards AFB) in order to assess the diurnal and seasonal probability of naturally occurring lightning. Frequency of natural lightning, percent of cloud cover, and cloud top temperatures were analyzed to determine the risk of natural or triggered lightning to anticipated suborbital launch activity at these sites. Diurnal and seasonal variability of natural cloud-to-ground lightning at the proposed spaceports was compared to existing federal launch ranges at Cape Canaveral, Florida (CAPE) and Vandenberg Air Force Base, California (VAFB) in order to assess relative lightning risk. The southern portion of White Sands Missile Range (WSMR) -approximately 40 miles distant from SWRS -was also included in this study.

### 9.1 Data

A nearly fifteen year lighting climatology [Schaub, 1996a,b] of all cloud-to-ground lightning strikes detected by the National Lightning Detection Network (NLDN) within a 100 km radius from various sites was collected. The climatology includes periods before and after an NLDN upgrade in 1995. Only periods after the upgrade were selected for further analysis.

We also analyzed the correlations between naturally occurring lightning and convective cloud types for the months of January and July 1999. Three-hourly data from the Cloud Depiction and Forecast System (CDFS2), which incorporates Defense Meteorological Satellite Program (DMSP) cloud sensors, was used. CDFS2 is a global cloud analysis product, which uses data from the DMSP Satellites. It identifies clouds by types, percent coverage, and top and base heights for up to four layers. Temperatures from the European Center for Medium Range Forecasting global analysis model grid were also used.

Since the analysis uses data from three independent databases they cannot establish that a particular cloud generated lightning. The temperatures were obtained from a global analysis model and do not represent the actual temperatures inside a cloud.

### 9.2 Lightning Climatology

The climatology of naturally occurring cloud-to-ground lightning at all five sites was examined for seasonal and diurnal variability. The percentage of 1-hour periods that are lightning free are shown in Figures 2-4 for SWRS, CSAFB and Edwards AFB, respectively. The percentage by hour is shown in Figures 5-7 for the same sites.
The scatter in Figures 2-4 comes from the diurnal variation as well as day-to-day variability. In terms of daily mean percentages the minimum values for the summer months are ~ 55, 70 and 75% for SWRS, Edwards and CSABF, respectively. Somewhat surprisingly the lightning frequency at Edwards and CSAFB are similar. The hourly climatology (Figures 5-7) shows, as expected, that diurnal variability (along with the overall frequency) is less. The summertime diurnal variation is least for the Oklahoma site. The peak values are similar for all three locations, being close to 90%. However the frequency stays fairly high (above ~ 70%) for CSAFB, but drops as low as 45% for Edwards and near 20% for SWRS.

Results were compared to Vandenberg and Cape Canaveral (not shown). Vandenberg is shown to be nearly lightning-free year round. Cape Canaveral is less than 80% likely to be lightning-free for May 30 – October 7 or ~130 days a year. CSAFB is less than 80% likely to be lightning-free for May 25 – September 7 or ~105 days a year. The proposed SWRS is less than 80% likely to be lightning-free for June 19 September 27 or ~105 days a year. Edwards is similar to SWRS. The natural lightning seasons at the potential spaceport sites are nearly one month shorter than for Cape Canaveral, the most lightning-prone of the existing launch sites.

### 9.3 Local Effects

Initially, the southern end of the WSMR had been used as a proxy for the proposed SWRS location. The two sites were expected to be similar as they are adjacent and have similar elevations. However, despite their proximity, significant differences in the lightning climatology for WSMR and SWRS were seen. WSMR experienced roughly half as many lightning strikes as the proposed SWRS. The likelihood that WSMR will be lightning-free on any given day is similar to that for SWRS, except the duration of the lightning season lasted approximately two weeks longer (Sep 17 – Oct 2) for SWRS. Even though CSAFB and SWRS had identical lightning probabilities at the sites, the 100-km radius area near the proposed SWRS experienced twice the number of lightning strikes and for more hours per day (in season) as CSAFB.

The site of the proposed SWRS is near a bend in a small mountain range on the western edge of WSMR. The mountain range between the WSMR and the SWRS appears to block the flow of monsoonal moisture from the southwest. A graph of the latitude and longitude coordinates of measured lightning strikes near SWRS in July 1999 (not shown) illustrates this effect. The density of lightning strikes is much higher to the west of the proposed SWRS and the mountain range. WSMR, which is inside of a protected valley, experienced many fewer lighting strikes in the same time period.

### 9.4 Cloud Analysis and Lightning

Several LLCC [Krider et al., 1999] developed for Expendable and Reusable Launch Vehicles on the federal ranges require that launches be delayed if lightning storms are in the area and if the associated clouds remain in the vicinity of the launch area. Lightning and convective cloud data were combined to clarify the correlations. The purpose was to assess the utility of the cloud data for identifying electrified cumulus clouds, and not to establish a correlation between cumulus clouds and lightning since these are known to be correlated.

The dates and hours of observed convective clouds and lightning strikes within a 100 km radius circle of the proposed SWRS and CSAFB were plotted (not shown). As expected, there was a correlation between observation of cumulus and cumulonimbus clouds and lightning occurrence. However, a high correlation was also observed between altocumulus clouds and lightning occurrence indicating that the CDFS2 system can misidentify cumulus clouds as altocumulus clouds, possibly because satellite inferences can sometimes give cloud top heights that are too high by up to 3 km [Naud *et al.*, 2004].

### 9.5. Cloud Temperature-Based LLCC

Some of the cloud-based LLCC are based on cloud temperature. They specify that the flight path must not come within 0, 5 or 10 nautical miles of cumulus clouds with cloud tops colder than the -5ºC, -10ºC and -20ºC, respectively. Since this requires knowledge of the heights where these temperatures occur at specific times and places and CDFS2 does not give this information, we used data from the European Center for Medium Range Forecasting (ECMWF) global analysis model.

The geopotential heights for 5°C, -5°C, -10°C, and -20°C (red, green, aqua, blue lines) are shown in Figures 8 and 9. Comparison of the July 1999 and 2004 data show that the cumulus (and possibly also the altocumulus) cloud tops at the proposed SWRS reach the -10°C, and -20°C isotherm altitudes more frequently than those at CSAFB. This increases the chances of violating the LLCC that depend on cloud top temperatures. There were no noticeable differences in the cumulonimbus cloud top temperatures.

### 9.6. Climatology Summary

A nearly 15-year climatology of naturally-occurring cloud-to-ground lightning strikes showed that the proposed SWRS experiences significantly more lightning strikes overall than CSAFB and Edwards. However, year-to-year variability is high, and cloud-to-ground data from July 2004 indicated twice the amount of lightning strikes at the proposed OS than at the proposed SWRS.

All proposed launch sites are more than 20% likely to experience lightning for roughly the same number of days a year (105), but the peak season begins at the end of May and lasts through early September in Oklahoma, and in New Mexico begins in mid-June and lasts until early October. A more detailed discussion with many additional graphs can be found in the final report for this study [Krider *et al.*, 2006].

## 10. WORK IN PROGRESS

We are now in the process of refining and expanding our knowledge about the characteristics of electrified clouds and lightning in the above areas. We will also investigate the hazards to a vehicle's safety critical systems, and will discuss the impact of any new findings on the current Lightning Flight Commit Criteria.

## 11. ACKNOWLEDGEMENTS

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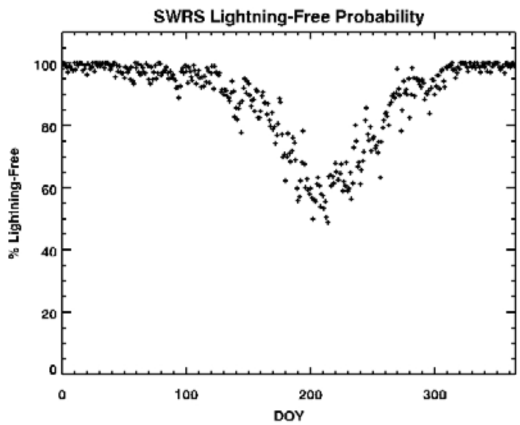


Figure 2: Lightning free percentage by day-of-year for the SouthWest Regional Spaceport, New Mexico. Occurrence statistics are based on NLDN data for lightning occurrences within 100 km for 1-hour periods.

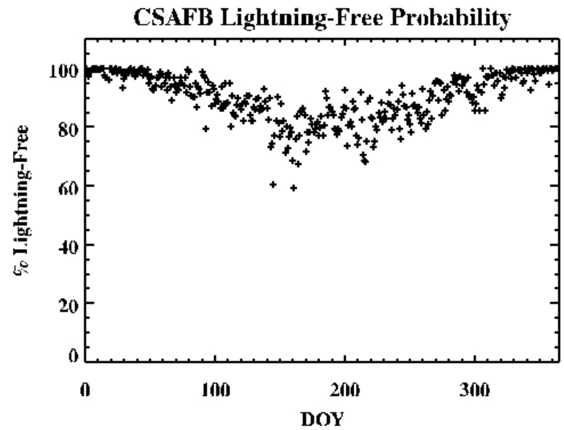


Figure 3: Same as Figure 2 but for Clinton-Sherman AFB, Oklahoma.

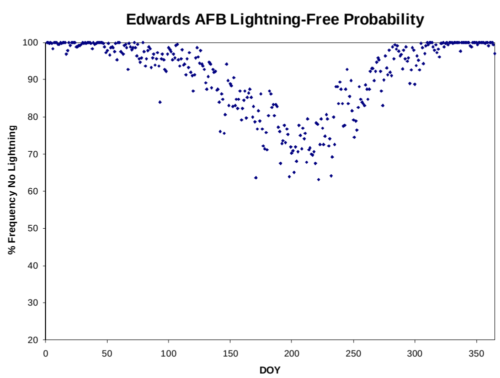


Figure 4: Same as Figure 2 but for Edwards AFB, California.

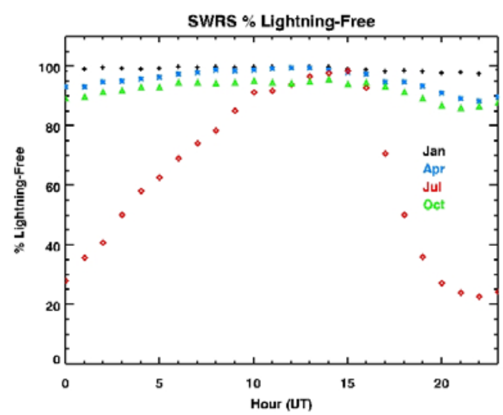


Figure 5: Lightning free percentage by hour for various months for the SouthWest Regional Spaceport, New Mexico. Occurrence statistics are based on NLDN data for lightning occurrences within 100 km for 1-hour periods.

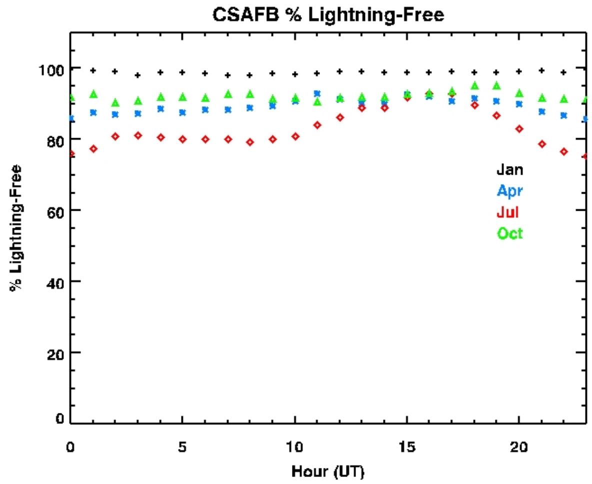


Figure 6: Same as Figure 5, but for Clinton-Sherman AFB, Oklahoma

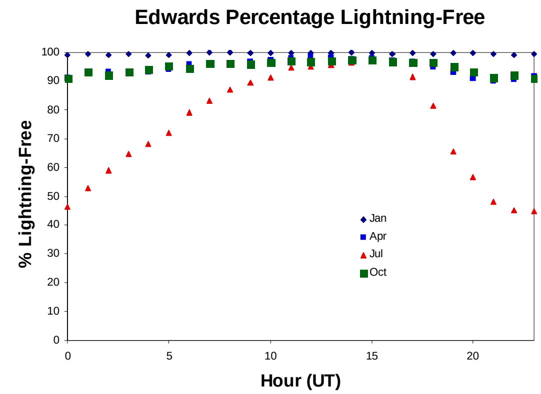


Figure 7: Same as Figure 5, but for Edwards, AFB, California

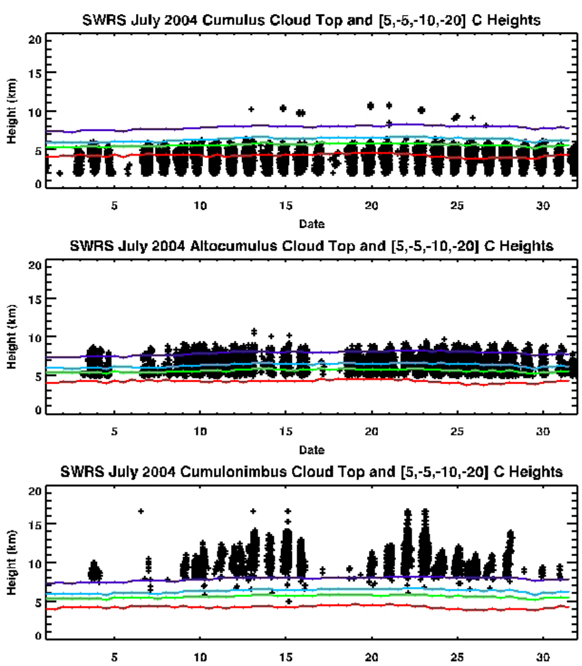


Figure 8. Cloud top heights for selected cloud types are shown in black (+). Isotherm heights for 5, -5, -10 and -20 C are shown in red, green, aqua and blue respectively.

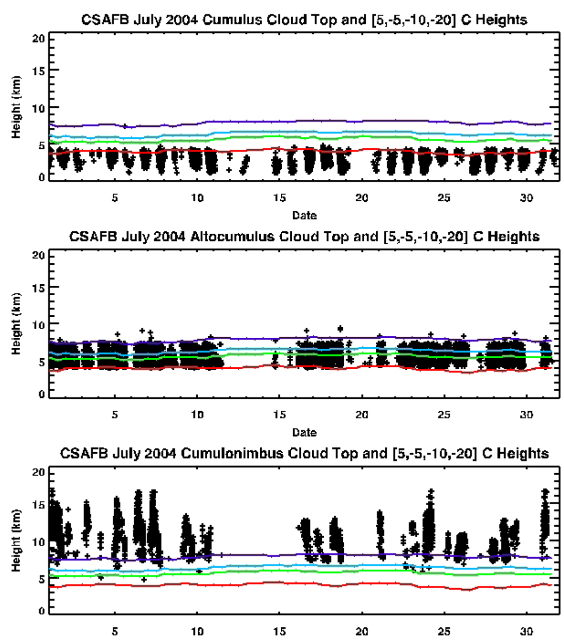


Figure 9. Cloud top heights for selected cloud types are shown in black (+). Isotherm heights for 5, -5, -10 and -20 C are shown in red, green, aqua and blue respectively.