

Establishing cause and effect relationships between lightning flash data and airplane lightning strike damage

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ABSTRACT

Commercial airplanes are, on the average, struck by lightning once per year. Knowing the intrinsic properties of the lightning strike that caused the damage to the airplane, as well as the exact time and location would add to the understanding of which lightning characteristics cause specific types of damage to airplanes. Knowledge of the lightning strike environment and other weather conditions present at the time the airplane was struck could help avoid similar conditions in the future. In regions of the world where Lightning Detection Networks (LDN) obtain good detection coverage, a unique opportunity presents itself to correlate detected lightning flash information and other meteorological data with the airplane flight tracks for flights where the airplane was struck by lightning. In this paper we address the approaches and challenges there are for determining the probability that a given lightning flash detected by a Lightning Detection Network is the flash which caused the lightning damage to a particular airplane.

ACRONYMS AND SYMBOLS

ATM (Air Traffic Management); CG (Cloud-to-Ground); DARPA (Defense Advanced Research Projects Agency); FAA (Federal Aviation Administration); GLD360 (Global Lightning Detection); GMT (Greenwich Mean Time); IFR (Instrument Flight Rules); kA (kilo amps); Knots (nautical mile); LDN (Lightning Data Network); MPH (Miles Per Hour); neg (negative); NLDN (National Lightning Data Network); NOAA (National Oceanic and Atmospheric Administration); NWS DIFAX (National Weather Service Digital Facsimile); U.S. (United States of America)

Background

Why are we interested in which lightning strike struck an airplane?

Lightning strikes to in-service airplanes impact the airlines in the form of inspection times and the costs and schedule impacts related to repairs. A better understanding of what types of lightning, and which lightning characteristics are responsible for the specific airplane damage we see can assist the airplane manufacturer in tailoring lightning protection to minimize these impacts. Additionally, an understanding of the weather and specifically the lightning environment present just before and at the time the airplane was struck, can shed light on ways to better avoid airplane lightning strikes.

What we currently know about lightning strikes to airplanes

We know that airplanes do get struck by lightning, and the statistical global average rate for lightning strikes to airplanes is stated to be once per year per airplane. In reality, the probability that an airplane will be struck by lightning varies greatly depending on several factors. Among the most influential factors increasing the likelihood of a lightning strike are: 1) the size of the airplane, 2) the flight profile of the airplane, and 3) the geographical area of operation.

- 1) **Airplane Size** - Airplane size influences lightning strike rate probability. Large airplanes can actually “trigger” a lightning strike because the presence of a large airplane disturbs the electric field allowing lightning leader formation at a lower electric field intensity than would be required if the airplane were not present [1]. This effect can be seen in Figure 1 which presents the reported lightning strikes per cycle for various sizes of commercial transport airplanes.
- 2) **Airplane Flight Profile** - The flight profile of the airplane influences the probability it will be struck by lightning because the probability that an airplane will be struck by lightning is strongly a function of flight altitude. Airplanes that spend more time at lower altitudes have an increased probability of being struck by lightning since most lightning strikes to airplanes are seen to occur between the altitudes of 5,000 feet and 15,000 feet (1,524 to 4,572 meters) [2]. An airplane flying short haul routes between closely situated cities will spend a greater percentage of its total flight time in the takeoff and landing phases where there is a greater probability of encountering lightning. Figure 2 shows reported lightning strikes to airplanes as a function of flight phase. The chart shows the flight phase distribution for over 2700 lightning strikes to airplanes reported between the years 2002 and 2009 and for which the flight phase was clearly specified. These results clearly show that the majority of lightning strikes to airplanes occur during takeoff/climb and descent/approach flight phases. These findings are consistent with previous studies of lightning strikes to commercial airplanes, including those detailed in references [5] and [6].
- 3) **Geographic Area of Operation** – Airplanes are designed to fly in all global lightning conditions, so the lightning requirements provide for safe operations worldwide. However, to avoid or minimize the impacts of lightning strikes to airlines, consideration of global variations may be useful.

Thunderstorms and lightning are not evenly distributed across all geographic locations on earth. Figures 3 and 4 show some of the global lightning variation studies that have been reported. Figure 3 depicts average lightning strike densities for various locations on the earth. The figure is color coded to show the number of lightning strikes per square kilometer per year experienced at the various locations on the earth. The areas of highest lightning activity are shown as orange, red, brown and black. In general the density of lightning strikes is greatest near the equator, where warmth in the region gives rise to convection which is part of the thunderstorm formation process. Even within the continental United States, significant lightning density variations exist. For example, parts of Florida experience an average of 100 days of thunderstorm activity, while areas along the West Coast, such as Seattle, typically see only 10 thunderstorm days per year.

Figure 4 is a map showing the average peak current amplitudes of a lightning strike as a function of geographic location. This chart was generated by DARPA based on data collected from the GLD360 network [3]. The global map prepared by DARPA and presented in Figure 4 indicates that 30kA is the average peak amperage of lightning strikes for a majority of the earth covered by land mass. Regions where the average peak current of a lightning strike is shown as above 30kA are mostly over the ocean. The uncertainties associated with oceanic LDN measurements may to some extent contribute to these variations. DARPA is conducting lightning investigation activities at this time to investigate oceanic lightning strikes.

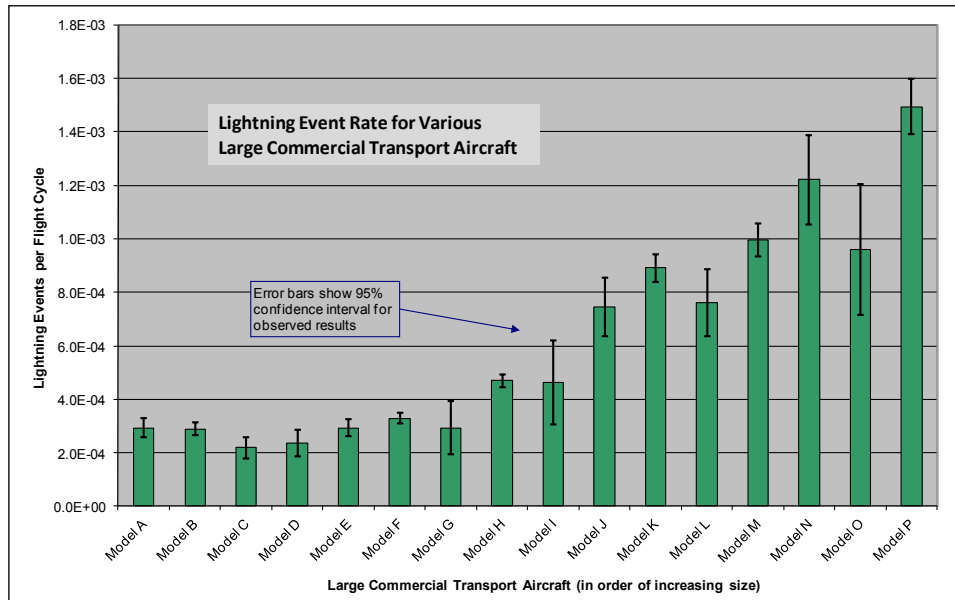


Figure 1 - Reported Strikes for Commercial Transport Aircraft (according to size)

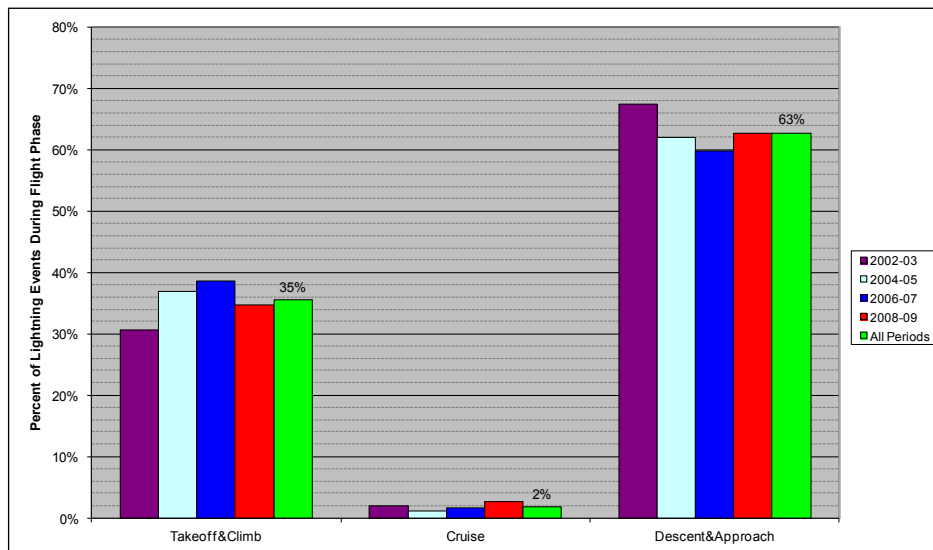


Figure 2 Lightning Distributions with Flight Phase

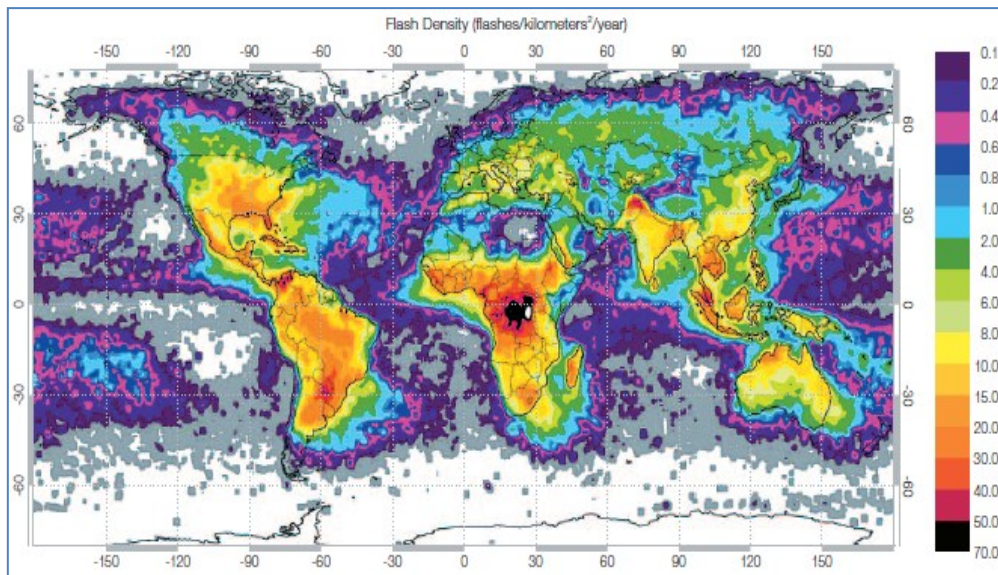


Figure 3 Lightning Densities for April 1995 through February 2003 [2]

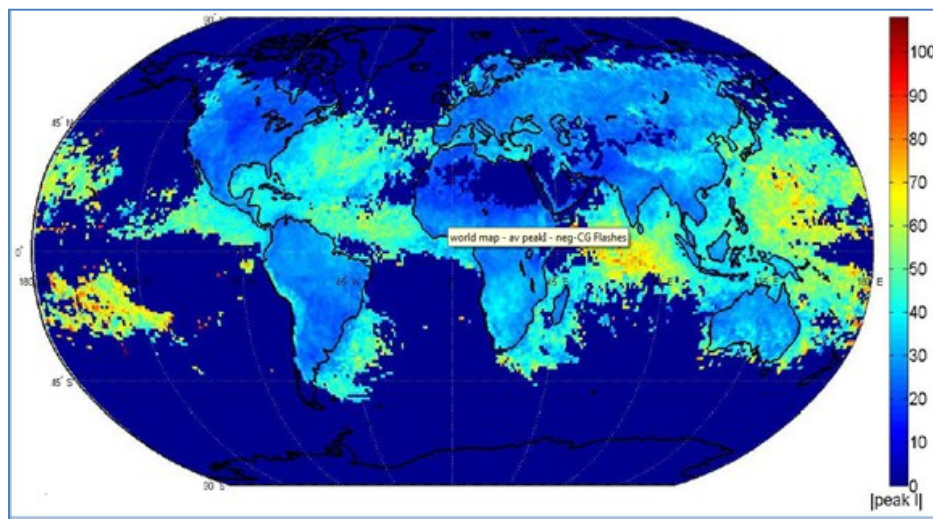


Figure 4 Average Peak Current of Initial Strokes in Kiloamps (cloud-to-ground) [3]

Data needed to determine which lightning strike struck a specific airplane

When an airplane is struck by lightning, the airline generally provides a report to the airplane manufacturer. Reports typically include the date and flight number, and photos of the lightning damage. Lightning strike reports provided by the airlines are our primary source for notification that a lightning strike has occurred to an airplane. Not all lightning strikes are reported. In particular, small strikes may occur that do not result in damage or that are not observed and therefore go unreported. Other sources of data needed to conduct our analysis include FlightAware®, recorded lightning strike events data from a lightning detection network, and weather data. There are several independent lightning detection networks operating at differing locations around the world. Coverage areas, sensor sensitivities/ accuracies, and detection probabilities and methods vary considerably among the different LDNs.

- 1) **Airline Reports of lightning strikes to their airplanes** - The date, flight number, time or flight phase for when the airplane encountered the lightning strike is important information. It allows us to narrow down or isolate the key parameters of time and geographical location. Knowledge of specific damage caused by the lightning strike; description of damage, photos, etc., is important to correlate to the likely environment that caused the damage. It also provides for a “sanity check” when our analysis gives more than one possible lightning strike candidate.
- 2) **Flight track data for the flight that was struck by lightning** - Historical archived airplane flight track information is obtained from FlightAware®, who obtains their data from a variety of sources including the FAA Aircraft Situation Display to Industry (ASDI) real time data feed. Data records for track information are given at approximately one minute intervals between data records, from takeoff “wheels up” to landing “wheels down.” Each record contains: date/time, airplane location (latitude, longitude, and altitude in hundreds of feet above sea level), ground speed in MPH/KPH, orientation (course, direction), reporting facility and information identifying the airplane/flight.
Complete flight track data sets are available from data feeds for airplanes operating on IFR flight plans within the U.S. airspace. For flights outside US airspace, the available flight track information is dependant on airplane equipment and locations of ground receiving equipment. All or portions of FlightAware® entries for flights outside of US airspace are listed as “estimated.” This is seen for flights that, for example originate at an airport location with a flight track ground receiver which reports location data for a flight until the airplane flies out of range. Flight track data records may exist locally at international airports or with airlines; however, it is not readily accessible or incorporated into the FlightAware® database.
- 3) **Lightning Data Network (LDN) data** - Data spanning the approximate time and for the approximate location corresponding to when and where the airplane was struck by lightning is required for this analysis.
- 4) **Weather data for the time and location of the airplane lightning strike** - Extensive historical weather data, Doppler radar and satellite Images are available through the National Oceanic and Atmospheric Administration (NOAA), National Weather Service Observed Weather Stations, National Doppler Radar Sites, Geostationary Satellite Servers, as well as a number of University-based atmospheric research databases. Observed Weather Station data is reported every 15 to 30 min. and includes a variety of observed weather variable observations including wind speed.

CASE STUDY – Correlate Flight Track Data and LDN data for a known lightning strike to an airplane in US airspace

To show viability of concept, that is, to show that it is possible to determine which lightning strike struck an airplane, we chose a known lightning strike to an airplane as a test case. Our test case was an airplane that was struck while enroute into Houston International airport during the winter months. We choose this airplane lightning strike report in part because we had a good idea of the magnitude and type of damage the lightning strike caused to the airplane, including photographs of the damage. Knowledge of the type of damage caused by the lightning strike is important in the event that more than one lightning strike is determined as a potential candidate.

Using flight track data for the test case airplane lightning strike, lightning location data from Vaisala® NLDN, and weather data from local weather sources, we were able to reconstruct the atmospheric present at each location of the airplane (latitude/longitude and altitude) and time during the airplane's flight path. This allowed us to determine which lightning strike struck the airplane with a high degree of certainty, from a subset of possible lightning strikes. From this correlation, we are able to know the recorded amplitude (and waveform characteristics in some cases), as well as the weather conditions present at the time of the lightning strike. The recorded lightning strike amplitude compared well with the photos of the airplane damage further assuring us that our correlation had identified the correct lightning strike responsible for the airplane damage.

Figure 5 illustrates the damage done to the airplane by the test case lightning strike. Initial lightning attachment was to a fastener connecting the nose radome to the fuselage. A post flight inspection found 14 additional attachment points along the lower fuselage and wing-to-body fairing. This is a typical swept stroke pattern where the path of the lightning attachments follows the airflow. The "swept stroke" phenomenon leaves evidence of an initial attachment point and subsequent re-attachment points along the body of the airplane. This pattern results from the fact that the duration of a lightning event is on the order of milliseconds and the airplane is moving forward at a constant velocity during the lightning event. The airplane essentially flies through the lightning channel which continues reattaching to points farther aft of the initial attachment point as the airplane flies forward. Figure 6 depicts this phenomenon of an initial lightning attachment and subsequent re-attachments.

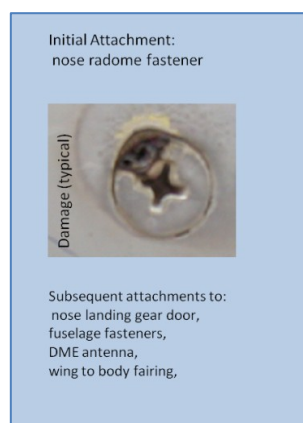


Figure 5 - Case Study Lightning Damage

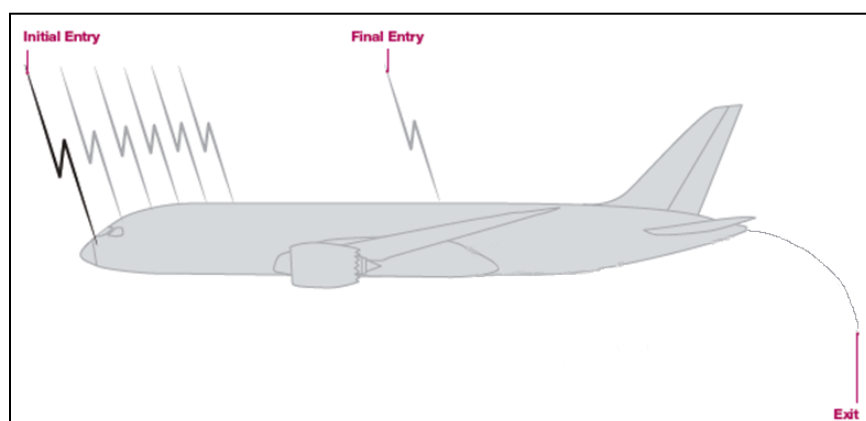


Figure 6 – Example of Swept Stroke Lightning Phenomenon

Key data elements that were assembled into a Matlab® Mapping Toolbox®-based numerical model include the trajectory of the airplane from the FlightAware®, and the relevant lightning strike locations and times reported by the NLDN sensors during the time and at the location represented by the airplane flight track. The test case flight originated from Houston Intercontinental Airport in Houston Texas, extended over the Gulf of Mexico about 160 miles from Houston and completed a figure eight maneuver before returning to the airport of origin. The NLDN lightning strike events were collected for the period of time of the airplane flight and within a 200 statute mile radius of the Houston airport, thereby capturing all lightning events relevant to the case study flight. Figure 7 illustrates the flight path of the test case airplane and all lightning strikes reported by the NLDN during the duration of the flight.

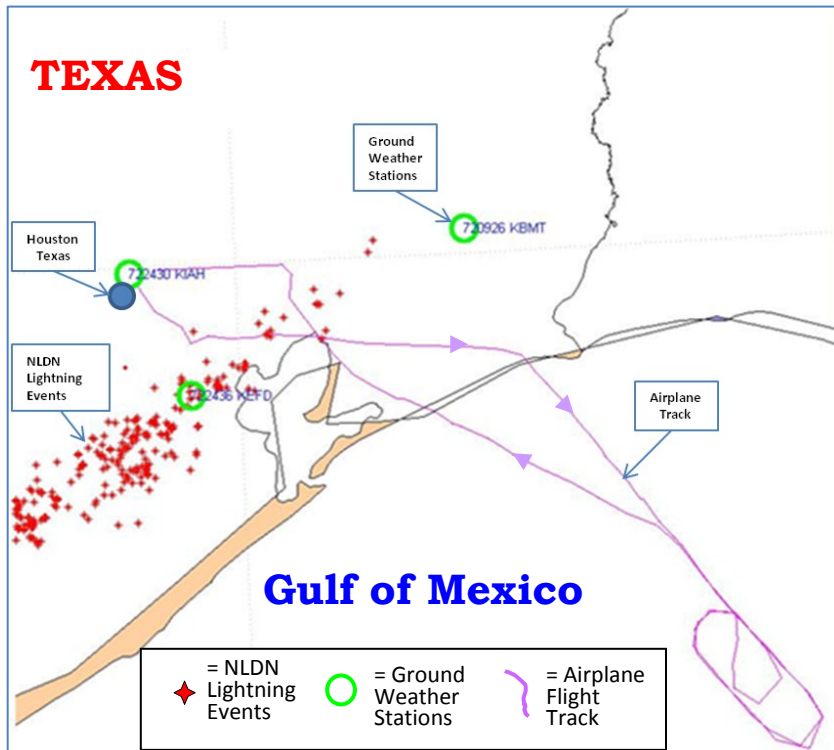


Figure 7 - Case Study Flight Path and Lightning Discharge Plots

The NLDN data coverage and probabilities of detection are quite good for this test case. Uncertainty associated with each detected strike location for our area of interest is also very reasonable. Figures 8 and 9 are the NLDN coverage and location uncertainties associated with our Houston test case.

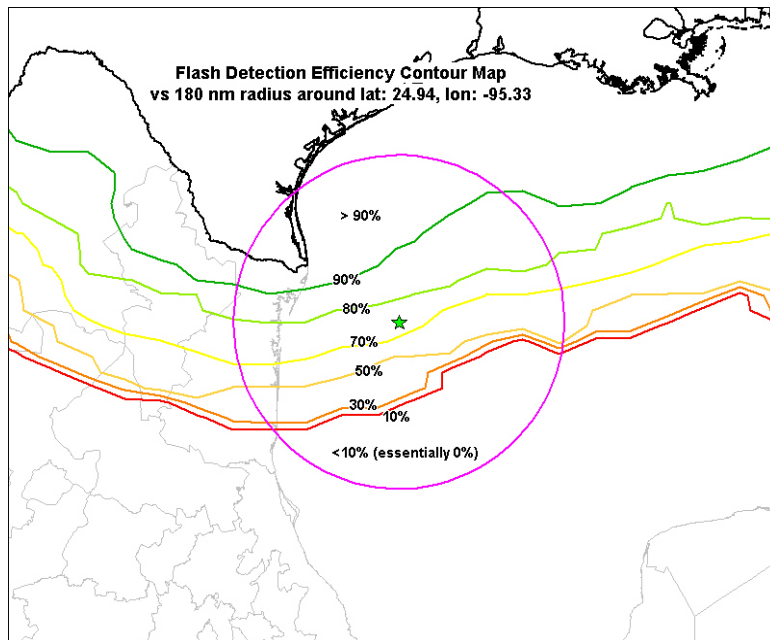


Figure 8 - Detection Efficiency Contour Map for NLDN coverage southern Texas/Gulf of Mexico

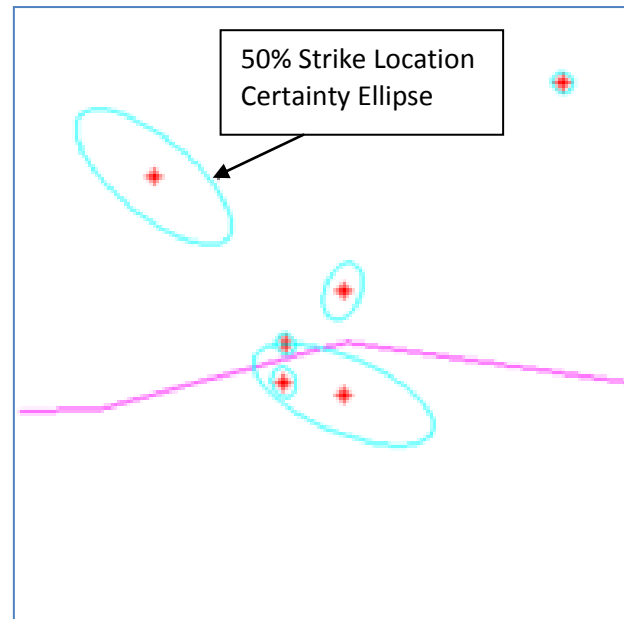


Figure 9 – 50% Strike Location Certainty Ellipses For NLDN data from test case

To perform the correlation analysis and determine the lightning strike responsible for the damage to the airplane, lightning events are extracted from the NLDN data file in chronological order and added to the Matlab® model. Upon insertion into the model, the lightning event time stamp is used to compute the current location of the airplane using the previously loaded flight track data.

Figure 10 presents a histogram of the airplane flight in time from takeoff, versus the mean distance between the airplane and the closest lightning strike event recorded at that time in the flight. The NLDN detected 477 lightning strikes occurring during the duration and in the vicinity of the test case flight. The first 250 lightning strikes and their respective distances from the airplane are shown in the top histogram in figure 10. The remaining 227 lightning strikes are presented in the lower histogram. The scale of the y-axis is from 0 miles at the bottom of the histogram, to 200 miles at the top, depicting distance between the airplane and the closest detected lightning strike. The times correlating to the lightning strike report are highlighted in the lower histogram. This figure does not show the altitude that the airplane was at when each of the 477 lightning strikes occurred, which is an important factor, however, it offers a good visual showing those strikes that occurred close to the airplane in a two dimensional plane (latitude/longitude.) Altitude is discussed later in this paper.

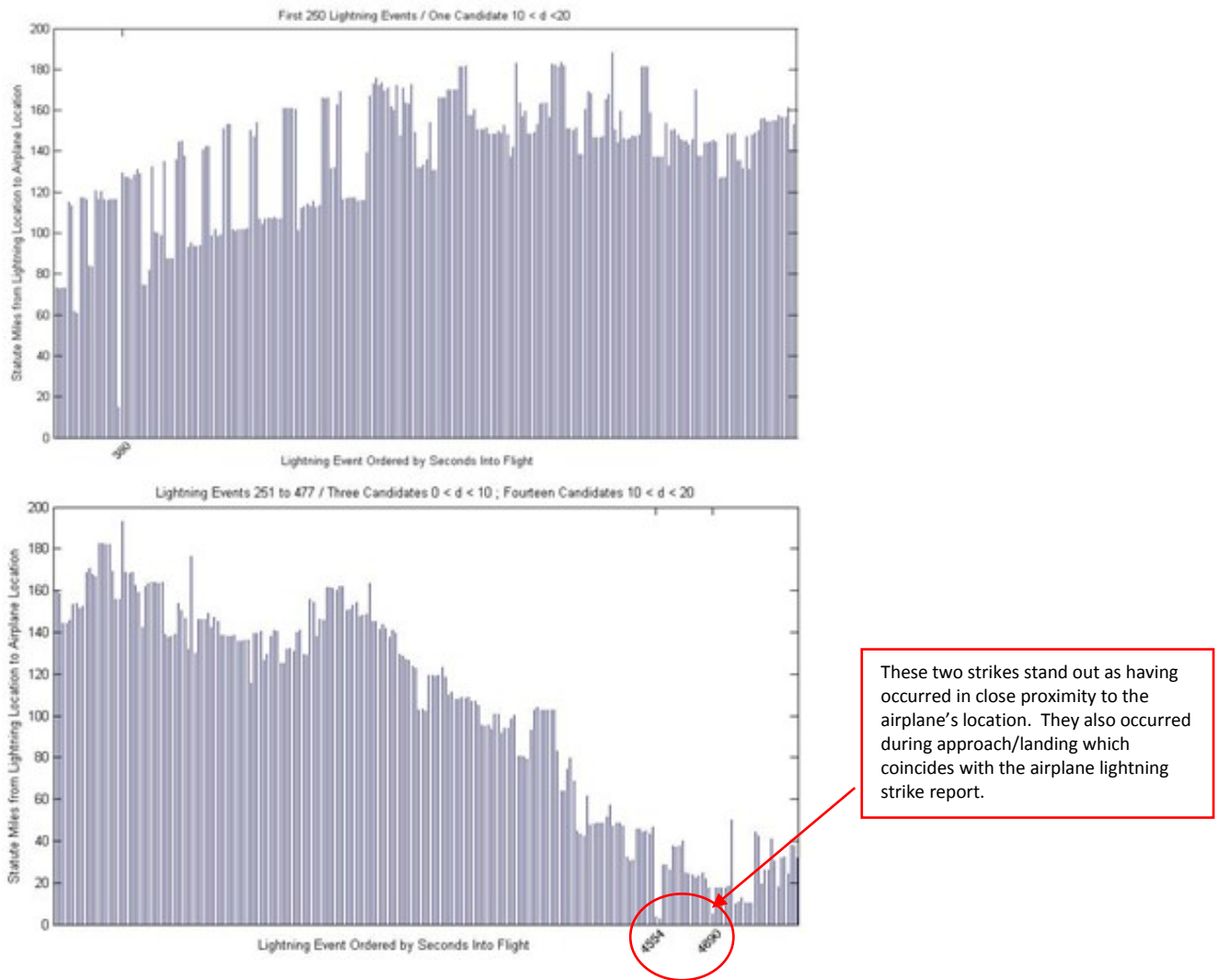


Figure 10 – Flight time verses distance to closest detected lightning strike

The distances in the histograms presented in Figure 10 represent the distances between the location of the airplane and the mean location of where the strike event was measured to have struck the earth which is not the same location as where the lightning struck the airplane. The NLDN measures the location of a lightning strike at approximately 200 to 300 meters above the ground. As discussed earlier in this paper, most lightning is seen to strike airplanes between the altitudes of 5,000 feet and 15,000 feet (1,524 to 4,572 meters). Figure 2, which is a graph showing the percentage of airplane lightning strikes as a function of flight phase clearly shows that the majority of lightning strikes to airplanes occur during takeoff/climb and descent/approach, during which the airplane transitions through the altitudes of 5000 – 15,000 feet (1,524 – 4,572 meters).

There can be a difference of 1000's of meters between the altitude at which lightning strikes an airplane and the altitude at which NLDN measured the location of that lightning strike, therefore, lightning's ability to travel horizontally some number of miles before connecting with the earth needs to be taken into consideration.

Table 1 summarizes the NLDN discharge events that are measured at less than 20 miles from the location of the airplane and during the flight phase that the lightning strike was observed to have occur.

	Time from beginning of flight in seconds	Distance from Airplane in miles	Airplane Altitude in feet	Peak Amperage in kA	Strike Type
1	4554	2.62	8733	-22	G
2	4554	2.62	8730	-15.9	G
3	4690	17.67	7601	-28.6	G
4	4690	4.83	7601	21.7	G
5	4690	17.63	7601	-25.6	C
6	4690	17.62	7600	-54	C
7	4690	17.65	7600	-12.8	C
8	4690	17.60	7596	-35	C
9	4690	18.61	7595	-31.1	G
10	4788	10.01	7000	22.3	C
11	4788	10.74	7000	-107.2	G
12	4788	12.64	7000	8.7	C
13	4788	10.39	7000	-37.6	G
14	4788	10.20	7000	-18.5	G
15	4788	10.23	7000	-9.6	G
16	4941	19.56	6541	20.1	C
17	5081	17.74	4420	62.5	G

Table 1 Airplane Lightning Strike Candidates

For each candidate lightning strike shown in Table 1, the seconds since the beginning of the flight, the distance from the airplane, the airplane altitude, the peak amperage of the discharge and the type of strike; cloud-to-cloud (C) or cloud-to-ground (G), is given. This table presents all lightning strikes that occurred during the decent/landing phase, and where the recorded lightning strike location (lat/long) and the airplane location (lat/long) are separated by a distance of 20 miles or less at the time the lightning strike was recorded by the NLDN. Three of the lightning strikes listed in Table 1 occurred less than 5 miles from the airplane's location. The remaining lightning strikes in Table 1 occurred more than 10 miles from the airplane.

Figure 11 visually depicts the airplane lightning strike candidates that are listed in Table 1. For the purposes of clarity, only the lightning events that took place less than 12 miles from the airplane are illustrated in Figure 11.

When distance alone between the airplane and the lightning event measurement is taken under consideration, two cloud-to-ground lightning events stand out. The locations of both lightning strikes were measured by the NLDN at a distance of approximately 2.62 miles from the airplane. The strikes were measured to have occurred approximately 0.3 seconds apart. During that time, the airplane, traveling at over 231mph, has moved approximately 100ft.

The NLDN recorded these two lightning strikes as negative cloud-to-ground strikes with magnitudes of -22 kilo-amps and -15.9 kilo-amps, occurring 0.3 seconds apart. The lightning damage reported for our test case and summarized in Figure 5, is consistent with the damage expected from a lightning strike and re-strike of this magnitude.

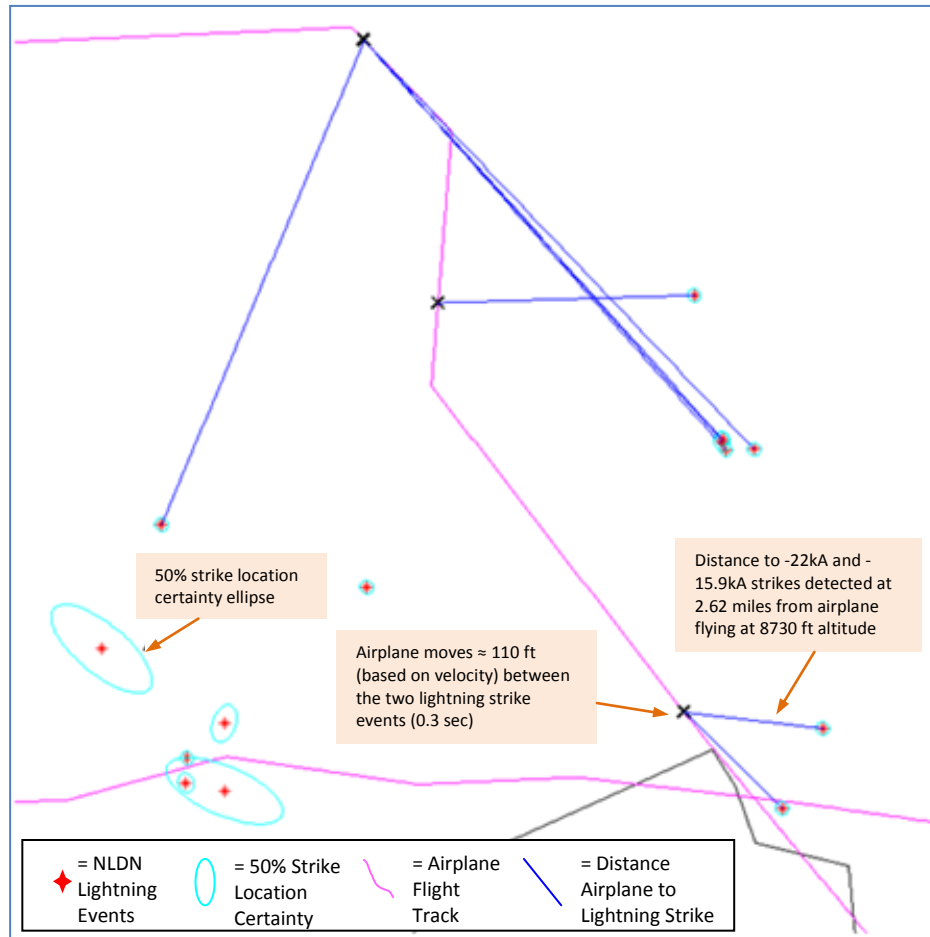


Figure 11 - Lightning Discharge Candidate

Weather conditions at time of lightning strike to the airplane

It is possible to collect a variety of on-line weather data records for the location and time of the candidate lightning discharges in order to reconstruct the atmospheric conditions associated with the airplane lightning strike. Figures 12 – 14 present weather data from various sources for the weather conditions present during the time span and at the location of our test case lightning strike.

Figure 12 shows the NWS DIFAX 700mb chart extracted from an open atmospheric research archive maintained at Colorado State University. The 700mb chart corresponds to measurements taken at an altitude of approximately 10,000ft where the steering winds are located. The steering winds are associated with the movement of storm cells. In Figure 12 the circled reading indicates that in the Houston area during the time of our test case airplane lightning strike, the wind was coming from the southwest and moving at a speed of 35 Knots or 40mph.

Figure 13 is an archived Doppler radar chart showing the location of the storm system in the Houston area at a time that correlates with our test case. The areas of intense storm activity, and hence intense lightning activity, are colored in red and are clearly visible. The successive Doppler radar images taken during the day of our test case lightning strike show the movement of storm centers. Figure 14 shows a satellite image of the storm clouds over the Houston area for the time of our test case lightning strike.

Identifying specific weather conditions or patterns that contribute to an increased probability of an airplane being struck by lightning can shed light on methods for avoiding airplane lightning strikes in the future.

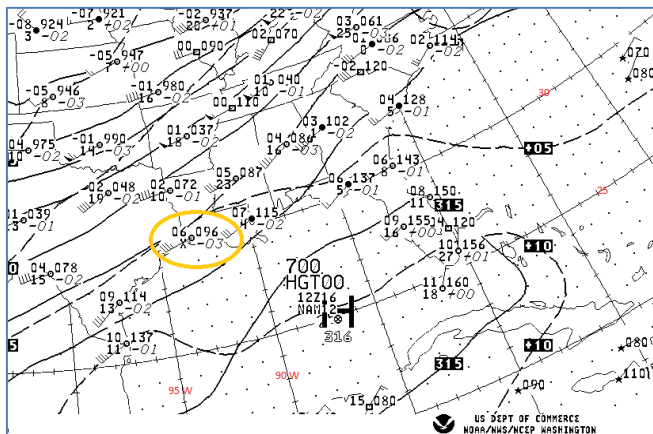


Figure 12 - 700mb Chart illustrating Steering Wind Currents for Case Study Storm

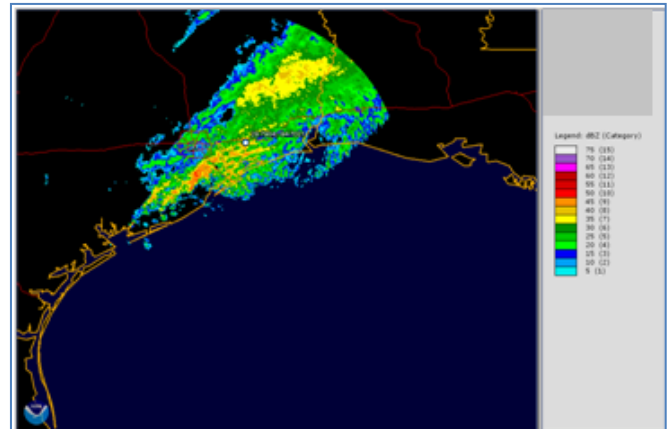


Figure 13 - Case Study Storm Doppler radar Image

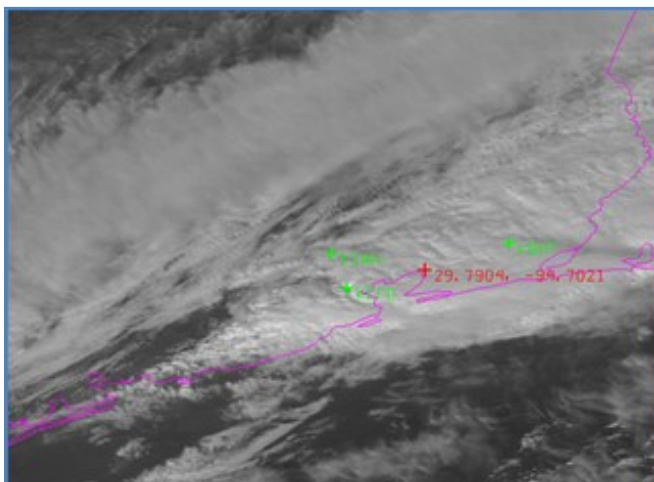


Figure 14 – Case Study Storm Satellite Image

Correlating an airplane location with a lightning strike location introduces uncertainties

Lightning is a phenomenon occurring in 3 dimensions. What we refer to as a lightning strike is actually a complex electrical discharge which can have several branches and cover a 3 dimensional area on the order of cubic miles. In a lightning strike to an airplane, the airplane becomes part of the electrical circuit however, the airplane is extremely small (approx 150 feet) compared with a total length of a lightning channel from a cloud formation to the ground (kilometers). Both vertical and horizontal distances typically span on the order of kilometers. An airplane, if part of the circuit, comprises a very small portion of this span.

Cloud to ground lightning may travel horizontally some distance between the cloud charge center and the point where it discharges to the ground. If the lightning discharge has struck an airplane, then the channel may travel horizontally some distance before entering the airplane at its attachment point, then travel some distance from the airplane exit point to the ground. This is illustrated in Figure 15.

In order to evaluate the probability that a lightning discharge may have travelled at least as far as the distance between the near ground LDN measurement and the position of the airplane, we turn to a study that focused on the issue of horizontal travel. In a 2000 thesis study conducted using NLDN data, Parsons [4] was able to generate statistical distributions for the horizontal distances traveled by cloud-to-ground lightning. Parsons divided the United States into six geographical regions and evaluated NLDN lightning event discharge records captured for a period of five years during the months from March to November.

The region of interest for our case study is called region 4 and is bound by latitude 28.0 to 37.0 North and longitude 88.0 to 102.0 west. In both Parsons' work and earlier research, lightning discharge detections given to us through the NLDN are classified as either clustered discharges or isolated. Two lightning discharges belong to the same cluster if they meet specified temporal and geographic constraints. Clusters of lightning discharges are thought to be distributed around the storm center. Parsons did not conduct the analysis for the months of December through February in view of the assumption that the winter months present the least lightning activity during any given year. We are also confined to applying these statistics to cloud-to-ground lightning discharges and not cloud-to-cloud discharges. We note that in Parsons' March to November data, while the flash frequencies vary significantly, the summer frequencies being the highest, the horizontal distances traveled appear to be more stable. For this reason, we can reasonably use the weighted mean of approximately 5.13 miles traveled with a pooled standard deviation of 4.11 miles for clustered flashes. It may be possible to use this and other weather related analysis to improve the relative probability estimates for our candidate airplane lightning strikes.

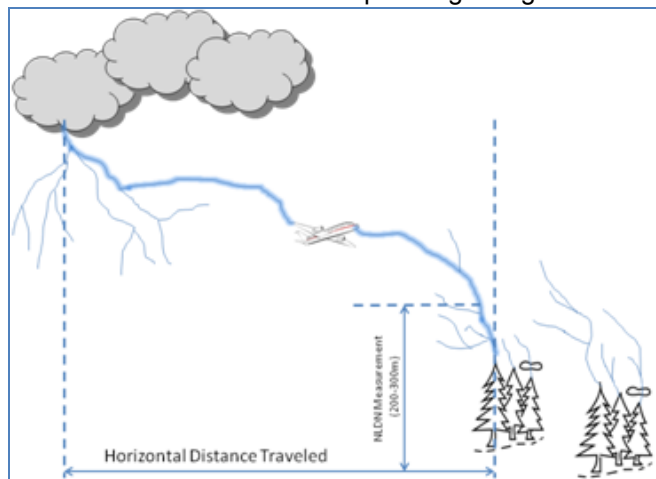


Figure 15 – Horizontal travel of a lightning strike

CONCLUSIONS AND FUTURE WORK

In summary, we have shown that it is possible to determine the measured characteristics of the lightning strike responsible for causing damage to a specific airplane in flight. Our analysis combined information on a known lightning strike to an in-flight airplane with key meteorological data for the region of the airplane's flight, including data from an LDN.

We are now attempting to correlate flight track data with LDN data for airplane lightning strikes outside of US airspace, specifically in Japan. Uncertainties which are not bounded or quantified and some inconsistencies have been found. The uncertainties include: 1) accuracy of flight track data entries for flights outside of US

airspace, 2) LDN data outside the US; coverage, sensitivities, probability of detection, and accuracy of detected values.

An example of an inconsistency is highlighted in Figure 16. This figure presents measured values of peak lightning strike currents on a log-normal scale as first observed by Cianos and Pierce [6]. The graph shows that 50% of all lightning strikes have peak amplitudes lower than 20kAmps, with 50% higher than 20kAmps. The graph also shows that 98% of all lightning strikes have peak amplitudes below 140kAmps. The linear curve is interpolated between observed measurements as are the extremes; the max and min amplitude values. The red circle on Figure 16 represents a lightning amplitude value recorded by an LDN for a time period and location of interest outside of US airspace.

This data is inconsistent with the knowledge base of measured lightning amplitudes as it exceeds the highest peak amperage value ever recorded for a lightning strike.

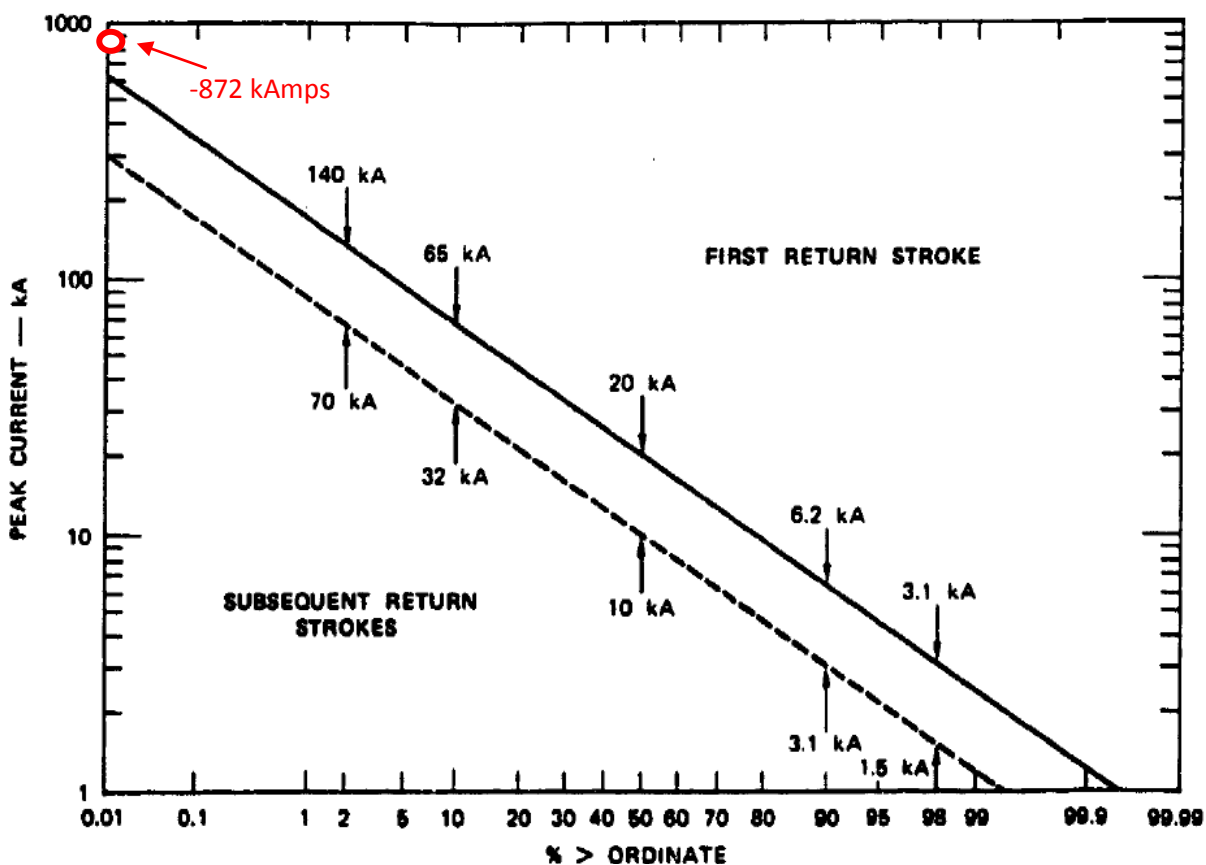


Figure 16 - Distribution of Peak Lightning Current Amplitudes - direct measurements extrapolated curve [10] with recent LDN measurements noted in red

A better understanding of uncertainties and methods of calculating amperages is needed before LDN data can accurately be applied to the effort of correlating lightning strike waveform characteristics to in-flight airplane damage reports.

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