10.4 METRICS FOR EVALUATING THE IMPACT OF WEATHER ON JET ROUTES

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1. ABSTRACT

In this paper, we analyze the impact that convective weather has on Route Availability (RA) and evaluate Route Blockage (RB) statistics. In this research, the analysis is spatially confined to lateral regions, left and right of the centerline of a jet route. The analysis applies to transition arrival and departure routes, as well as en route jet routes. We explore the relationship between the amount of convective weather present in the vicinity of a jet route, and the amount of traffic that is able to use the jet route without having to deviate to a nearby route. A MaxFlow/Mincut technique is used to quantify the permeability of the airspace near the filed flight plan, and this is compared to the permeability of the actual route flown. Real convective weather data and current routing structures are used in this analysis. Air Traffic Management (ATM) personnel can use these results for planning the safe and efficient use of jet routes through the National Airspace System (NAS).

2. BACKGROUND

ATM requires weather translation models to transform weather forecast data into ATM impact information. Research has addressed how various weather phenomena (e.g., convection, terminal and en route winds, turbulence, icing, volcanic ash, winter weather, and space weather) impact sector capacity, airport arrival and departure rates, route availability, runway availability, and other ATM parameters; see, for example, surveys by Krozel [K10, K11]).

In this paper, we analyze a specific ATM impact, RA, and the relationship between RA and the amount of convective weather present in the vicinity of a jet route. We are particularly interested in the transition airspace routes around major airports in the NAS, including the Standard Terminal Arrival Routes (STARs) into an airport. We focus primarily on arrival traffic in the transition phase of flight, roughly from top of descent to the arrival metering fixes of the terminal area – that is, a range from 200 nmi to 40 nmi from the runway.

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We begin with a brief literature review of two RA components:

1. The Convective Weather Avoidance Model (CWAM), including Weather Avoidance Fields (WAFs) at different altitudes, and
2. The use of the MaxFlow/Mincut model to perform RA or RB assessment.

2.1 Convective Weather Avoidance Models

CWAM addresses how convective weather impacts traffic in en route or transition airspace. CWAM was built by analyzing historical traffic and weather data to determine when pilots choose to deviate *vs.* penetrate convective weather constraints. Both precipitation intensity as well as echo tops data are important factors in CWAM. In the linear, deterministic CWAM model (Figure 1), pilots deviate according to the flight altitude above the 90% percentile of the echo top, with increasing clearance over the echo top required as the severity of the weather coverage below the aircraft increases. As an output of CWAM, WAFs are computed as a function of observed and/or forecast weather to determine 2D or 3D grids retaining either a probability of deviation (0% to 100%, as illustrated in Figure 2(a)) or a binary deviation decision value (0 or 1, as used throughout this paper). Two approaches have been taken to model and validate weather-avoidance deviations using trajectory and weather data: trajectory classification [RKP02, DE06, DRP08, DRE08, CRD07] and spatial cross-correlation [PBB02, Ku08]. Recent work on CWAM involves the evaluation or assessment of CWAM for NAS operations [CDM10, DCF09, MD10a, MD10b, RD10].

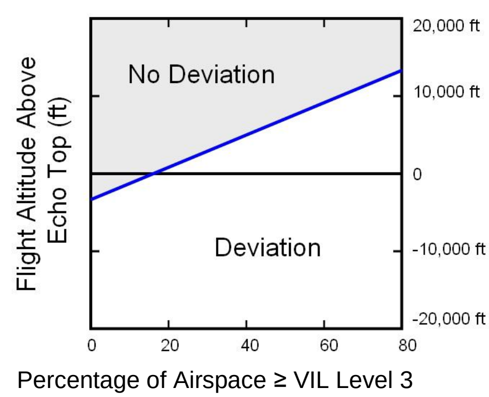
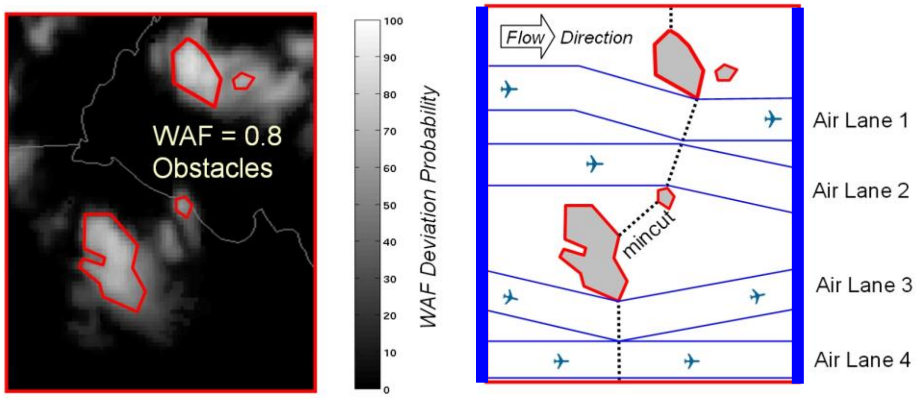


Figure 1: The deterministic CWAM model.



(a) Weather hazard defined by WAF threshold

(b) Mincut bottleneck and maximum number of lanes of traffic that may pass through the airspace

Figure 2: The translation of convective weather WAF data into maximum ATM throughput based on mincut analysis.

The CWAM model for en route airspace is expected to be different than the CWAM model for terminal/transition airspace. Terminal/transition area WAFs must reflect the fact that nominal descent (ascent) trajectories for arrivals (departures) do not allow for pilots to fly over hazardous weather cells – as is the case for en route CWAM. Pilots flying at low altitudes in the terminal area appear to penetrate weather that en route traffic generally avoids [RP99, RBB00, Ku08]. We find in this current paper that pilots also penetrate hazardous weather when approaching the arrival metering fixes of an airport. The willingness of pilots to penetrate severe weather on arrival increases as they approach the ground [RP99].

Furthermore, CWAM arrival models incorporate pilot behaviors that are different from those used in CWAM departure models. For instance, arrivals have a limited amount of remaining fuel, so the pilots feel pressure to avoid excessive delays and holding while avoiding weather cells. In contrast, departures can wait on the ground until the weather is more favorable. In another example, departures typically climb out at full power and hence have little opportunity to deviate to avoid weather in the first few minutes of flight; arrivals have flexibility to maneuver until the final approach. Finally, arrivals descending from above the cloud base have less visual information about the severity of the weather below than departures climbing from the ground.

2.2 MaxFlow/Mincut

Mincut algorithms have been shown to apply to several aviation applications [KMZ09, Ki10, LL10, Z10]. For a given region of airspace (e.g., a grid cell, sector, center, or flow constrained area (FCA)), the maximum capacity of an airspace region may be determined using geometric MaxFlow/Mincut Theory [AMO93, Mi90, KMP07a], which is based on an extension of the standard network MaxFlow/Mincut Theorem to continuous domains [Mi90, Ir79, St83] and to measuring the maximum number of disjoint air lanes ("thick paths") that can be routed from a source to a destination across a given airspace [P07]. The theory is suitable for estimating the maximum throughput across an en route airspace given one of the following sources of demand: a traffic flow pattern [SWG08], a uniform distribution of flow monotonically traversing in a standard direction (e.g., East-to-West) [ZKK09], or random, Free Flight conditions [KMP07a, KMP07b]. The maximum throughput of transition airspace can be determined, at least approximately, by transforming the problem into an analysis over an ascent or descent cone that models terminal/transition airspace for arrival and departure flows [KPM08].

Figure 2(b) illustrates the MaxFlow/Mincut model [MPK06]. Given convective weather constraints and a method of defining the weather hazard (e.g., the appropriate en route or terminal CWAM model and WAF threshold, as shown in Figure 2(a)), a geometric hazard map of polygonal constraints is identified. In the figure, a simple rectangular airspace is shown, with flow from the source (left side, highlighted blue) to the right side (highlighted blue). The *continuous* mincut is shown (dashed); it is the "shortest" path from the "bottom" boundary of the rectangle to the "top" boundary, treating the polygonal constraints as "free" regions through which the mincut path can travel at zero cost. The continuous mincut is a measure of the maximum amount of "fluid" that can flow from source to sink. There is also a notion of a *discrete* mincut, which is a measure of how many air lanes can be routed from source to sink through a given constrained airspace. In order to speak of the discrete mincut, we assume the specifications include the width of an air lane (equivalently, the required gap size between adjacent hazardous weather cells) that is required for a flow of traffic passing through the airspace in a given period of time. This parameter may be expressed in terms of Required Navigation Performance (RNP) requirements for air lanes. An algorithmic solution identifies the discrete mincut bottleneck in much the same way as the continuous mincut – the discrete mincut determines the maximum capacity in terms of the maximum number of air lanes that can pass through the gaps between weather hazards as a function of time, given a weather forecast.

In this paper, we use the continuous mincut to characterize the "permeability" of the airspace around an aircraft, characterizing the permeability of the gaps between weather cells in front of or near an aircraft filed route or actual route flown.

2.3 Route Blockage / Route Availability

RB/RA models have previously been proposed in the literature to assess the convective weather impacts on jet routes in the NAS [KPP04, MED06, WEW06, KPP07, Ma07, MWD09, DRD10, TSM10]. The terms RB and RA have been used interchangeably in the literature.

3. APPROACH

Next, we review our approach to this study. We study specific airspaces that capture transition airspace arrival traffic into major airports in the NAS. We compare scenarios with and without convective weather constraints. We define metrics that (1) capture the magnitude of the pilot deviation away from the jet route centerline, (2) measure the significance of the weather constraints in terms of mincut metrics, and (3) assess the operational flexibility in routing around hazardous weather cells.

3.1 Airspace Boundaries of Interest

We consider transition airspace to be between 40 nmi and 200 nmi of a major airport. A "major" airport is one of the top 35 airports in terms of overall volume of traffic; such airports are traditionally called the Operational Evolution Plan (OEP)-35 airports. We center an "area of interest" moving window around the actual route flown, as well as along the filed route (Figure 3), in order to assess the permeability of the airspace around both routes.

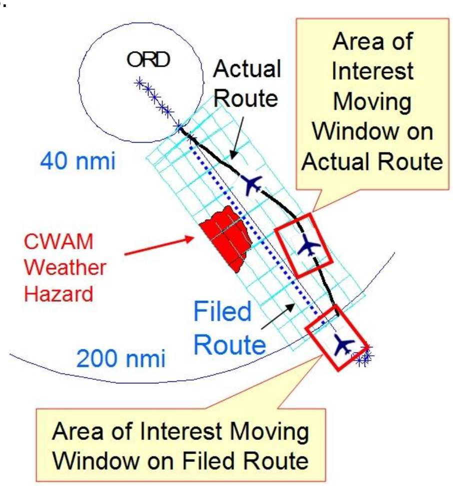


Figure 3: Airspace boundaries of interest.

We consider areas of interest centered on the jet route as well as on the actual route flown. The area of interest is defined by a parameter *w*, specifying the distance to the left/right of the route centerline (red box in Figure 4). We expect that aircraft fly within ±4 nmi to the left or right of a jet route centerline, corresponding to *w*=4. However, we consider other values of *w* relative to either the jet route or the actual route.

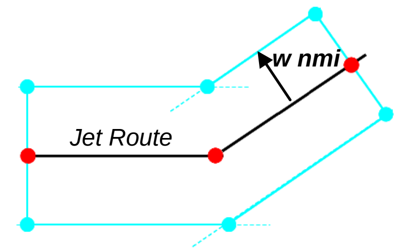


Figure 4: Specification of the airspace region of interest relative to a jet route.

3.2 Route Deviation Metric

We track how far pilots deviate from a nominal routing structure during weather avoidance maneuvering, and study these weather avoidance trajectories to generate route deviation statistics. The deviation at an instant of time is measured as the shortest distance between the flight's actual position and the filed route (Figure 5).

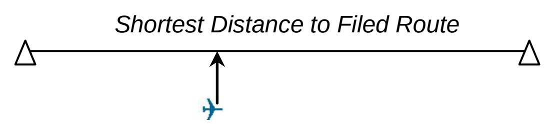


Figure 5: Deviation from the filed route.

3.3 Operational Flexibility Metrics

In order to study the relationship between pilot deviations and weather constraints near a routing structure, we define operational flexibility metrics that quantify the degree to which weather permits an aircraft to reroute from a jet route and still be considered within the jet route's structure. The metrics are based on the weather constraints in a sector of airspace and where the weather constraints reside relative to a routing structure and sector boundaries. Operational flexibility metrics formalize and measure the amount "wiggle room" around a routing structure.

Operational flexibility metrics are described in some detail in [KYM11]. There, four metrics are suggested:

1. Unconstrained Airspace Metric (UAM): The volume of airspace that is not impacted by weather hazard constraints and is "close" to the original route structure.
2. Constrained Airspace Metric (CAM): The volume of airspace not impacted by weather that is "close" to the original route structure, where closeness explicitly takes into account the weather constraints through which the route structure passes.
3. Operationally Accessible Airspace Metric (OAAM): The volume of airspace that can be utilized for off-nominal rerouting according to standard procedures.
4. Maxflow Metric (MM): A permeability estimate in the vicinity of the route structure in terms of the number of available air lanes; determined by maxflow-mincut methods.

For each metric, one can distinguish between its *local* and its *global* version. A *local* operational flexibility metric measures flexibility that exists locally, particularly "close" to the original route structure, according to some meaningful notion of "close." Local operational flexibility allows for relatively minor adjustments to routing without the need to relocate traffic to different destination locations (e.g., metering fixes) or to define a new "topology" for routes. Closeness is quantified by a locality parameter that specifies the maximum distance a reroute is to be from the nominal route. In contrast, a *global* metric measures flexibility that allows for reroutes that are at a considerable (geometric) distance from the original and that are "far" from the original route, yet bounded by sector boundaries.

In this study, we use a basic form of the MM metric, using the continuous mincut within the airspace area of interest to estimate the operational flexibility and to quantify the severity of the weather hazard relative to the jet route. For example, for an area of interest with width *w*=4 (i.e., ±4 nmi to the left or right of the route centerline), the continuous mincut value will range from 0 nmi (the rectangular region of interest is completely blocked by hazardous weather) to 8 nmi (no weather hazards present in the region of interest). We do not explicitly implement local/global versions of the metric; however, we do vary the width parameter *w*. The parameter *w* serves as a measure of locality.

In our experiments, we use a moving window specifying an area of interest that slides along the flight route (actual or filed), with widths *w*=4, 5, 8, or 10 nmi and lengths defined by four data points (Figure 6), one minute apart from one another.

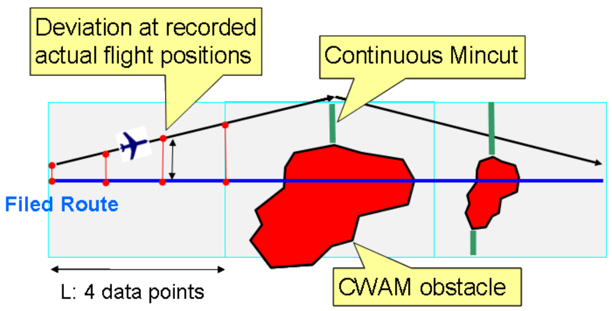


Figure 6: Illustration of methodology for measuring deviation and mincut.

3.4 Time Periods of Interest

We are interested in time periods within which there was major weather activity and also there were moderate to heavy traffic loads on major airport arrival routes. With this goal in mind, for this particular study we selected the following four time periods:

1. July 13, 2010
   - From 10:45 AM to 12:00 PM for arrivals
   - From 10:00 AM to 12:00 PM for weather data
2. July 13, 2010
   - From 16:05 AM to 17:20 PM for arrivals
   - From 15:20 AM to 17:20 PM for weather data
3. July 22, 2010
   - From 10:45 AM to 12:00 PM for arrivals
   - From 10:00 AM to 12:00 PM for weather data
4. July 22, 2010
   - From 15:45 AM to 1700 PM for arrivals
   - From 15:00 AM to 17:00 PM for weather data

The total number of arrivals within the above four specific time periods is 3,535. Traffic Flow Management System (TFMS) data were used to obtain filed and actual flight track data.

3.5 Weather Data and CWAM Obstacles

In this study, we use precipitation intensity and echo top data as provided by the Corridor Integrated Weather System (CIWS). We implement the linear, deterministic CWAM weather hazard model (Figure 1). The weather hazard is labeled the CWAM WAF obstacle in our work, and this weather obstacle is a function of the current altitude of the aircraft being analyzed. WAF polygon obstacles are based on actual weather (nowcasts), at 10-minute intervals, within the periods of interest specified in Section 3.4 and for every 1,000 ft from 5,000 ft to 35,000 ft. CWAM WAF polygon altitudes ranged from 5,000 to 35,000 ft in increments of 1,000 ft.

4. ANALYSIS

We divided our analysis into two efforts: flight-based and incident-based.

4.1 Flight-Based Analysis

Results of the flight-based analysis are presented first.

4.1.1 Clear-Weather Baseline for Deviations

As a clear-weather baseline, we measured the deviation from the filed route at any given data point for flights that had no weather activity within ±10 nmi of actual/filed route centerline. Figure 7 and Figure 8 show the distribution of the number of flights as a function of maximum deviation and average deviation, respectively.

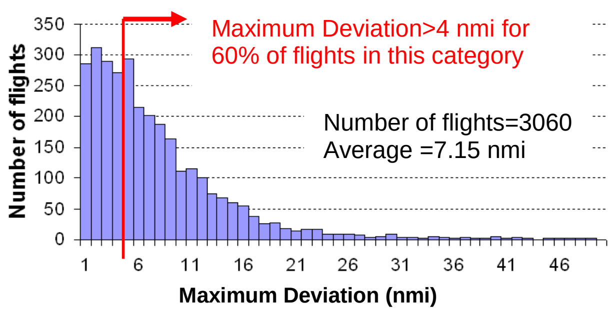


Figure 7: Distribution of the number of flights as a function of maximum deviation.

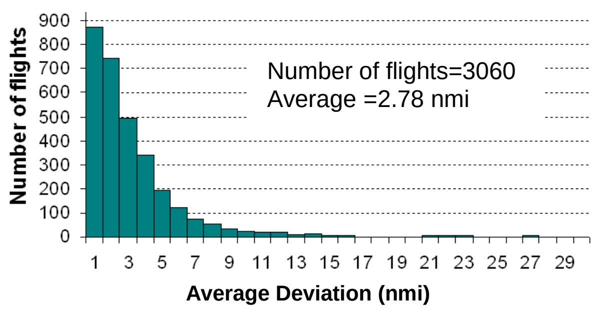


Figure 8: Distribution of the number of flights as a function of average deviation.

Under normal clear-weather conditions, controllers expect pilots to fly within 4 nmi from the jet route centerline. Thus, in Figure 7 we indicate a 4 nmi threshold. In the absence of any weather activity, the reasons for deviation above 4 nmi include direct-to routing, path stretching, flight technical errors, conflict avoidance, and other causes. No aircraft in holding patterns were included in these statistics.

4.1.2 Route Blockage and Penetrations

Next, we characterize statistics for flights penetrating hazardous weather with complete route blockage. We measured the deviation from the filed route at any given data point for flights whose filed route penetrated hazardous weather at some point in the transition airspace. In this case, a flight penetration is an indication of both the actual route and the filed route being completely blocked within 10 nmi of the actual/filed route centerline by hazardous weather according to the CWAM model.

Figure 9 and Figure 10 show the distribution of the number of flights that penetrated the weather as a function of the maximum deviation and the average deviation, respectively.

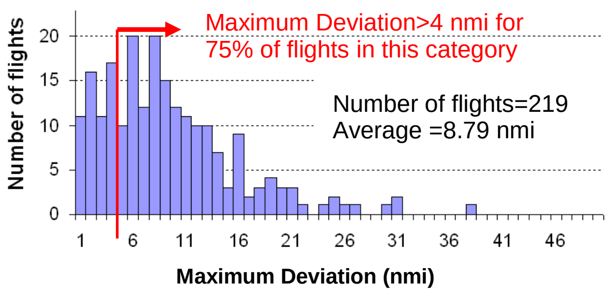


Figure 9: Distribution of the number of flights with penetration as a function of maximum deviation.

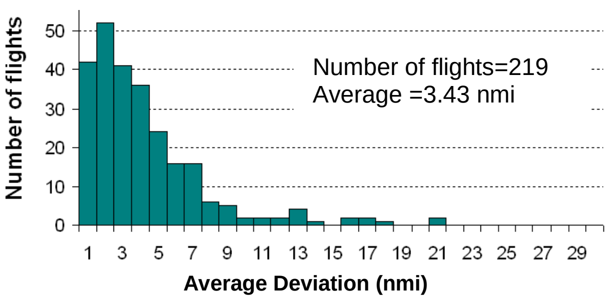


Figure 10: Distribution of the number of flights with penetration as a function of average deviation.

Figure 11 shows the maximum deviation percentile, which is the percentage of the number of flights for which the maximum deviation is less than a certain number. Black refers to all flights in our analysis (3,535 flights), red refers to flights that are weather free (Section 4.1.1), purple refers to flights not represented by the red line (474 flights), and green refers to flights with complete route blockage (Section 4.1.2)

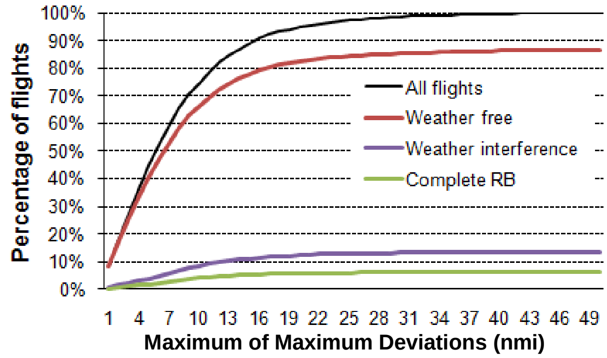


Figure 11: Maximum deviation percentile.

4.2 Incident-based Analysis

Results from the incident-based analysis are presented next.

4.2.1 Actual Route Permeability vs. Range

We studied the relationship between the flights' actual route permeability and their range from the arrival airport. The following conditions define occurrences of penetration and deviation:

- A penetration incident occurs at a given point of flight track data if:
  - (i) The deviation is less than 4 nmi from the centerline, and
  - (ii) The mincut value within 10 nmi of the actual route centerline is less than 10 nmi (or 8,6,4,2 nmi).
- A deviation incident occurs at a given point of flight track data if:
  - (i) The deviation at least 4 nmi,
  - (ii) The mincut value within 10 nmi of the actual route centerline is more than 10 nmi, and
  - (iii) The minimum mincut value within 10 nmi of the filed route centerline, from the given point to the arrival fix, is less than 10 nmi.

Figure 12 shows two examples of these conditions.

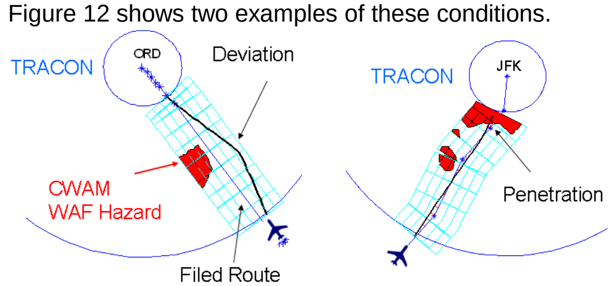


Figure 12: Examples of CWAM weather hazard deviation (left) and weather hazard penetration (right).

Figure 13 shows the results of our incident-based analysis and compares the number of penetration incidents with the number of deviation incidents with respect to the range from the airport. The number of penetration incidents increases and the number of deviation incidents decreases as flights get closer to the arrival metering fixes (roughly 40 nmi from the airport). The occurrence of a penetration incident is subject to the existence of a weather hazard; thus, we only apply this analysis to cases in which weather was present.

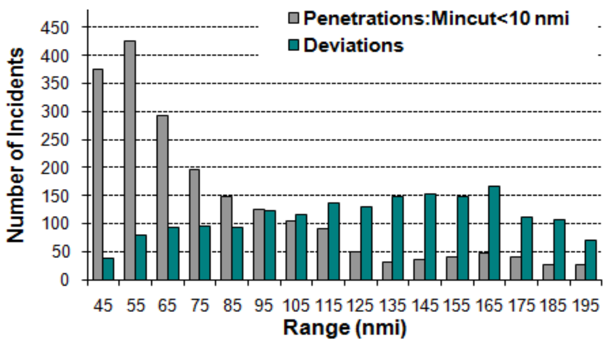


Figure 13: Number of incidental penetration and deviation as a function of distance from the airport.

Figure 14 compares the number of penetration incidents for different mincut thresholds defining a penetration incident. Results show that the further the flights are away from the arrival metering fix, the less likely an incident will be classified as a penetration no matter what mincut threshold is chosen. Close to an arrival metering fix, larger mincut thresholds (the gap size between hazardous weather cells is larger) result in more situations being classified as penetration incidents.

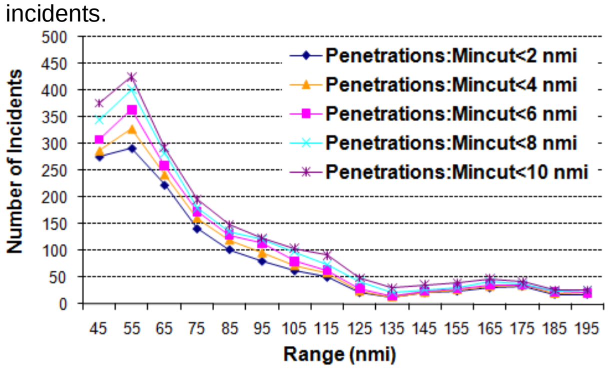


Figure 14: Penetration incidents as a function of range from the airport for different definitions of penetration.

4.2.2 Deviation vs. Actual/Filed Route Permeability

Figure 15 and Figure 16 show the deviation as a function of the filed route mincut and actual route mincut, respectively, at any given data point. In this analysis, we only selected incidents in which the largest gap within 8 nmi of the filed route centerline was less than 6 nmi (indicating there is no flyable gap between hazardous weather cells).

As expected, the deviations decrease as the filed route mincut increases. In other words, the less severely a filed route is blocked by hazardous weather, the less a pilot needs to deviate away from the filed route to find a flyable gap between or beyond hazardous weather cells. Many flights still intersect with a WAF polygon even though they deviate. Therefore, to gain a better insight, we have partitioned the incidents into those for which flights successfully avoid the WAF polygons (blue dots) and those for which flights intersect with a WAF polygon (pink pluses). The separation threshold is set at actual route mincut being equal to 4 nmi. The actual route mincut greater than 4 nmi indicates the flight successfully avoiding the weather, and vice versa.

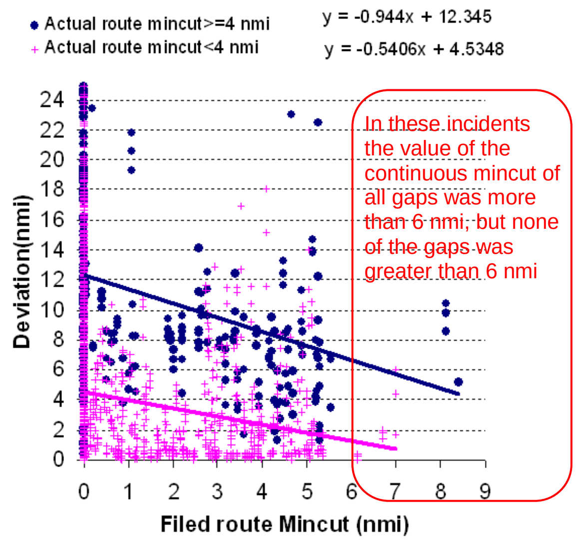


Figure 15: Deviation as a function of the filed route mincut for all incidents with filed route blockage.

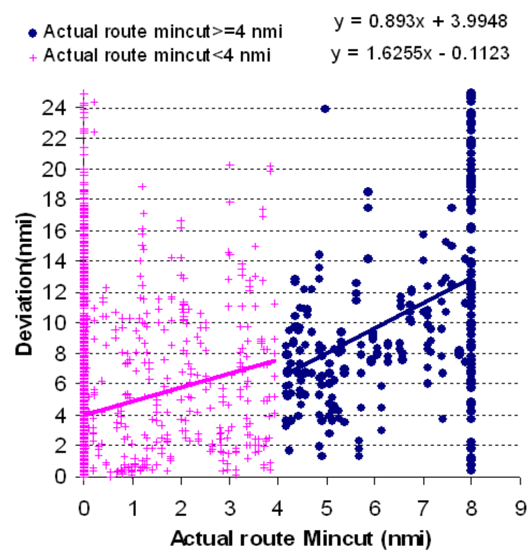
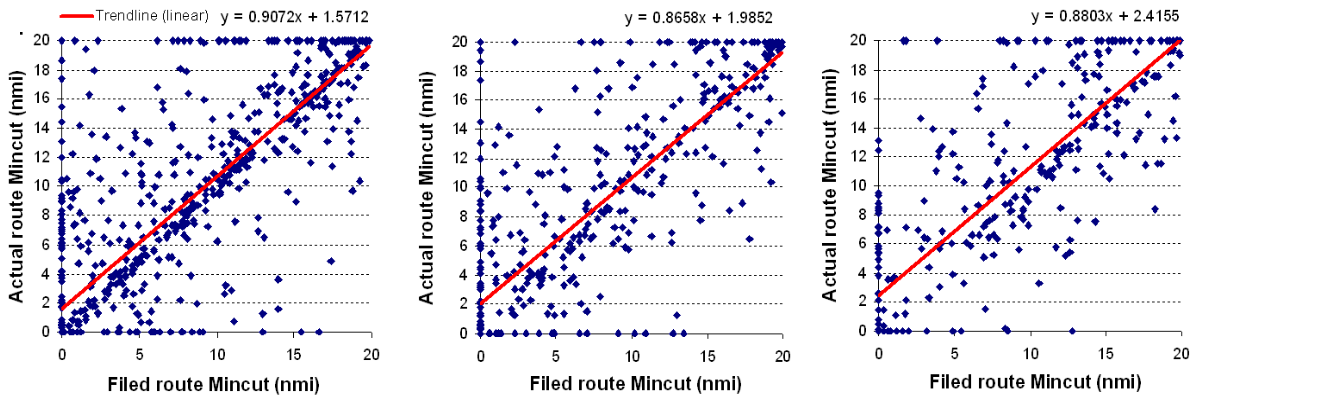


Figure 16: Deviation as a function of the actual route mincut for all incidents with filed route blockage.

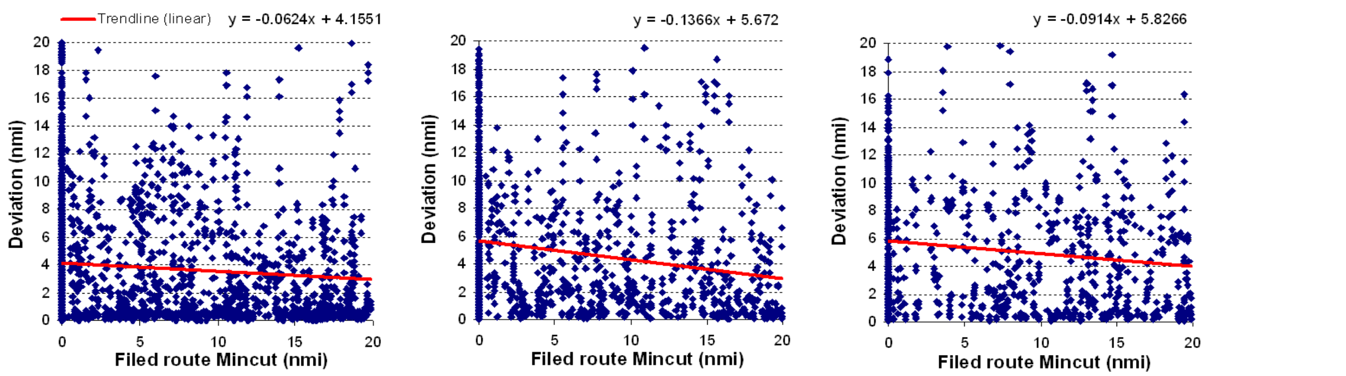
As shown in Figure 15, the average deviation for flights successfully avoiding the WAF polygons is 12.3 nmi when the filed route is completely blocked (mincut = 0 nmi), and decreases to about 7 nmi as the mincut increases to 6 nmi. The average deviation for flights that did not successfully avoid the WAF polygons is much less and ranges from 4.5 nmi to about 1.5 nmi for filed route mincut from 0 to 6 nmi.

Figure 16 shows the relationship between deviation and the actual route mincut. The result indicates that pilots needed to deviate, on average, 7 nmi or more in order to successfully avoid the CWAM WAF polygons.



(a) 40 ≤ Range < 80 nmi (b) 80 ≤ Range < 120 nmi (c) 120 ≤ Range < 200 nmi

Figure 17: Permeability of the actual route vs. permeability (mincut) of the filed route for (a) near, (b) far, and (c) very far away from the arrival metering fix.



(a) 40 ≤ Range < 80 nmi (b) 80 ≤ Range < 120 nmi (c) 120 ≤ Range < 200 nmi

Figure 18: Relationship between the magnitude of the deviation and filed route permeability (mincut).

4.2.3 Actual vs. Filed Route Permeability

Figure 17 and Figure 18 provide insight as to how the relationship between actual versus filed route permeability varies with range from the airport.

In this incident-based analysis, we chose all incidents for flights that at some point along their filed route, had presence of weather activity within 10 nmi of the filed route centerline. Figure 17 shows that as pilots choose to deviate away from the filed route, they found gap sizes between hazardous weather cells that are, on average, about 2 nmi larger than the gap sizes between weather cells on or near the filed route. In other words, these pilots found permeability properties of the airspace away from the filed route to be more attractive than the permeability of the weather near the filed route.

Figure 18 shows that pilots that were further away from the metering fix were willing to fly further away from the filed route to find benefits in permeability of the airspace. As previously shown, the deviations were smaller near the metering fixes (40 ≤ range < 80 nmi) compared to farther away.

5. CONCLUSION

We studied the permeability of the airspace on the filed route versus the actual route flown around weather constraints for transition airspace arrival traffic into major airports in the NAS. A mincut metric was used to quantify the permeability of the airspace in the vicinity of a route. Data indicates that when hazardous weather is present in transition airspace:

- Pilots are more likely to penetrate weather or penetrate through smaller gap sizes between weather cells the closer they are to the arrival metering fixes;
- The magnitude of route deviations decreases as the filed route permeability (mincut) increases;
- Route deviations from the filed route increase as the range from the metering fixes increases; and,
- Route deviations from the filed route results in 2 nmi (in general) or more increase in gap size (permeability), illustrating the typical benefit of deviation away from the filed route.

Ongoing/future work is to explore alternative metrics for characterizing and quantifying the airspace flexibility to accommodate weather avoidance routing. Our goal is to identify metrics that, when crossing a threshold value, indicate that aircraft are more likely to deviate away from the filed route in order to seek out airspace with acceptable permeability. We would like to eventually evaluate if the gaps between weather hazard cells will be large enough to allow for pilot deviations to occur safely, or if penetrations will be likely or unavoidable, given the weather forecast and associated uncertainty.

ACKNOWLEDGEMENTS

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REFERENCES

[AMO93] Ahuja, R., Magnanti, T., and Orlin, J., *Network Flows: Theory, Algorithms, and Applications*, Prentice Hall, Englewood Cliffs, NJ, 1993.

[CDM10] Crowe, B., DeLaura, R., and Matthews, M., "Use of Aircraft-Based Data to Evaluate Factors in Pilot Decision Making in Enroute Airspace," *14th Conf. on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Atlanta, GA, Jan., 2010.

[CRD07] Chan, W., Rafai, M., and DeLaura, R., "An Approach to Verify a Model for Translating Convective Weather Information to Air Traffic Management Impact," *AIAA Aviation Technology, Integration, and Operations Conf.*, Belfast, Ireland, Sept., 2007.

[DCF09] DeLaura, R., Crowe, B., Ferris, R., Love, J. F., and Chan, W. N. "Comparing Convective Weather Avoidance Models and Aircraft-Based Data," *89th AMS Annual Meeting, ARAM Special Symposium on Weather-Air Traffic,* Phoenix, AZ, Jan., 2009.

[DE06] DeLaura, R., and Evans, J., "An Exploratory Study of Modeling Enroute Pilot Convective Storm Flight Deviation Behavior," *Proc. of the 12th Conf. on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Atlanta, GA, Jan./Feb., 2006.

[DRD10] Davison, H., Reynolds, R., DeLaura, R., and Robinson, M., "Field & (Data) Stream: A Method for Functional Evolution of the Air Traffic Management Route Availability Planning Tool (RAPT)," *54th Annual Meeting of the Human Factors and Ergonomics Society*, San Francisco, CA, Sept./Oct., 2010.

[DRE08] DeLaura, R., Robinson, M., and Evans, J. "Modeling Convective Weather Avoidance in Enroute Airspace," *13th Conf. on Aviation, Range and Aerospace Meteorology*, American Meteorological Society, New Orleans, LA, Jan., 2008.

[DRP08] DeLaura, R., Robinson, M., Pawlak, M., and Evans, J., "Modeling Convective Weather Avoidance in Enroute Airspace", *13th Conf. on Aviation, Range and Aerospace Meteorology,* American Meteorological Society, New Orleans, LA, Jan., 2008.

[Ir79] Iri, M., *Survey of Mathematical Programming*, North-Holland, Amsterdam, Netherlands, 1979.

[K10] Krozel, J., "Survey of Weather Impact Models used in Air Traffic Management," *AIAA Aviation Technology, Integration, and Operations Conf.*, Ft. Worth, TX, Sept., 2010.

[K11] Krozel, J., "Summary of Weather-ATM Integration Technology", *Second Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration,* American Meteorological Society, Seattle, WA, Jan., 2011.

[Ki10] Kim, J., *Algorithms for Optimizing Multiple Routes Through Constrained Geometric Domains*, Ph.D. Dissertation, Stony Brook University, Stony Brook, NY, Aug., 2010.

[KMP07a] Krozel, J., Mitchell, J.S.B., Polishchuk, V., and Prete, J., "Airspace Capacity Estimation with Convective Weather Constraints," *AIAA Guidance, Navigation, and Control Conf*., Hilton Head, SC, Aug., 2007.

[KMP07b] Krozel, J., Mitchell, J.S.B., Polishchuk, V., and Prete, J., "Maximum Flow Rates for Capacity Estimation in Level Flight with Convective Weather Constraints," *Air Traffic Control Quarterly*, Vol. 15, No. 3, 2007.

[KMZ09] Kim, J., Mitchell, J. S. B., and Zou, J., "Approximating Maximum Flow in Polygonal Domains using Spanners," *21st Canadian Conf. on Computational Geometry*, pp. 115–118, Vancouver, BC, Canada, Aug., 2009.

[KPM08] Krozel, J., Prete, J., Mitchell, J.S.B., Kim, J., and Zou, J., "Capacity Estimation for Super-Dense Operations," *AIAA Guidance, Navigation, and Control Conf*., Honolulu, HI, Aug., 2008.

[KPP04] Krozel, J., Penny, S., Prete, J., and Mitchell, J.S.B., "Comparison of Algorithms for Synthesizing Weather Avoidance Routes in Transition Airspace," *AIAA Guidance, Navigation, and Control Conf*., Providence, RI, Aug., 2004.

[KPP07] Krozel, J. Penny, S., Prete, J., and Mitchell, J.S.B., "Automated Route Generation for Avoiding Deterministic Weather in Transition Airspace," *J. Guidance, Control, and Dynamics*, Vol. 30, No. 1, Jan./Feb., 2007.

[Ku08] Kuhn, K., "Analysis of Thunderstorm Effects on Aggregated Aircraft Trajectories," *J. Aerospace Computing, Information and Communication*, Vol. 5, April, 2008.

[KYM11] Krozel, J., Yang, S., Mitchell, J.S.B., and Polishchuk, V., "Strategies to Mitigate Off-Nominal Events in Super Dense Operations", *AIAA Guidance, Navigation, and Control Conf.*, Portland, OR, Aug., 2011.

[LL10] Layne, G., and Lack, S., "Methods for Estimating Air Traffic Capacity Reductions due to Convective Weather for Verification," *14th Conf. on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Atlanta, GA, Jan., 2010.

[Ma07] Martin, B. D., "Model Estimates of Traffic Reduction in Storm Impacted En route Airspace," *AIAA Aviation Technology, Integration and Operations Conf.*, Belfast, Ireland, Sept., 2007.

[MD10a] Matthews, M. , and DeLaura, R. "Evaluation of En route Convective Weather Avoidance Models Based on Planned and Observed Flight," *14th Conf. on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Atlanta, GA, Jan., 2010.

[MD10b] Matthews, M. and DeLaura, R., "Assessment and Interpretation of En route Weather Avoidance Fields from the Convective Weather Avoidance Model," *AIAA Aviation Technology, Integration, and Operations Conf.*, Ft. Worth, TX, Sept., 2010.

[MED06] Martin, B. D., Evans, J., and DeLaura, R. "Exploration of a Model Relating Route Availability in En Route Airspace to Actual Weather Coverage Parameters," *12th Conf. on Aviation, Range and Aerospace Meteorology*, American Meteorological Society, Atlanta, GA, Jan., 2006.

[Mi90] Mitchell, J. S. B., "On maximum Flows in Polyhedral Domains," *J. Computer and System Sciences,* Vol. 40, pp. 88-123, 1990.

[MPK06] Mitchell, J.S.B., Polishchuk, V., and Krozel, J., "Airspace Throughput Analysis considering Stochastic Weather," *AIAA Guidance, Navigation, and Control Conf*., Keystone, CO, Aug., 2006.

[MWD09] Matthews, M., Wolfson, M., DeLaura, R., Evans, J., Reiche, C., Balakrishnan, H., and Michalek, D. "Measuring the Uncertainty of Weather Forecasts Specific to Air Traffic Management Operations," *Aviation, Range, and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration*, Phoenix, AZ, Jan., 2009.

[P07] Polishchuk, V., *Thick Non-Crossing Paths and Minimum-Cost Continuous Flows*, Ph.D. Dissertation, Dept. of Applied Mathematics and Statistics, Stony Brook University, Stony Brook, NY, Aug., 2007.

[PBB02] Post, J., Bonn, J., Bennett, M., Howell, D., and Knorr, D., "The Use of Flight Track and Convective Weather Densities for National Airspace System Efficiency Analysis," *21st Digital Avionics Systems Conf.*, Piscataway, NY, Oct., 2002.

[RBB00] Rhoda, D., Boorman, B., Bouchard, E., Isaminger, M., and Pawlak, M., "Commercial Aircraft Encounters with Thunderstorms in the Memphis Terminal Airspace," *9th Conf. on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Orlando, FL, Sept., 2000.

[RD10] Rubnich, M. and DeLaura, R., "An Algorithm to Identify Robust Convective Weather Avoidance Polygons in En route Airspace," *AIAA Aviation Technology, Integration, and Operations Conf.*, Ft. Worth, TX, Sept., 2010.

[RKP02] Rhoda, D. A., Kocab, E. A. and Pawlak, M. L., "Aircraft Encounters with Thunderstorms in Enroute vs. Terminal Airspace above Memphis, Tennessee," *10th Conf. on Aviation, Range and Aerospace Meteorology*, American Meteorological Society, Portland, OR, May, 2002.

[RP99] Rhoda, D. A. and Pawlak, M. L., "The Thunderstorm Penetration / Deviation Decision in the Terminal Area," *8th Conf. on Aviation, Range and Aerospace Meteorology*, American Meteorological Society, Dallas, TX, Jan., 1999.

[St83] Strang, G., "Maximal Flow through a Domain," *Mathematical Programming*, Vol. 26, pp. 123-143, 1983.

[SWG08] Song., L., Wanke, C., Greenbaum, D., Zobell, S, and Jackson, C., "Methodologies for Estimating the Impact of Severe Weather on Airspace Capacity," *26th Intern. Congress of the Aeronautical Sciences,* Anchorage, AK, Sept., 2008.

[TSM10] Taber, N., Song, L., Masalonis, A., and DeLaura, R., *Demand and Capacity Models for Integrated Departure Route Planning*, MITRE CAASD Tech. Report MTR090473, March, 2010.

[WEW06] Weber, M., Evans, J., Wolfson, M., DeLaura, R., Moser, B., and Martin, B., Improving Air Traffic Management During Thunderstorms, *12th Conf. on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Atlanta, GA, Jan./Feb., 2006.

[Z10] Zou, J., *Geometric Algorithms for Capacity Estimation and Routing in Air Traffic Management*, Ph.D. Dissertation, Stony Brook University, Stony Brook, NY, Aug., 2010.

[ZKK09] Zou, J., Krozel, J., Krozel, J., and Mitchell, J.S.B., "Two Methods for Computing Directional Capacity given Convective Weather Constraints," *AIAA Guidance, Navigation, and Control Conf*., Chicago, IL, Aug., 2009.