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An examination of the potential impact of 5G on air travel in the U.S.

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ABSTRACT

The rollout of 5G wireless service has been much anticipated by consumers across the U.S. since it will bring faster data download speeds and expanded service; however, the impact to aviation and air travel are as a major issue and the potential impact to aviation has not been estimated or assessed. This paper fills that gap and provides the first analysis of the potential number of flights impacted by 5G at ten of the busiest airports in the U. S. Using detailed historical weather and flight data in 2019 at 10 large hub airports, we find that nearly 15,700 flight arrivals could be directly impacted annually, at the ten airports considered. The geographical and seasonal impact varies significantly with more flights affected by the potential for 5G interference at airports in Seattle and Dallas Fort-Worth and relatively few flights affected at airports in Phoenix and Las Vegas. A case study examining ten years of data at Chicago O'Hare International, a hub for two major airlines, suggests that over 2,400 flights every year could be impacted by 5G interference. Fortunately, there has been increasing cooperation between the cell phone industry and aviation stakeholders to ensure a safe rollout of 5G C-band; this paper provides a significant contribution by documenting the issues and context for aviation operations.

Introduction

The rollout of 5G wireless service has been much anticipated by consumers across the U.S. as data download speeds will be increased and service expanded. 5G C-band enables data intensive technology for personal and business use, ranging from entertainment such as video games to critical communications for public services (Pham et al, 2020), and provides more consistent, faster speeds and increased capacity. The communications band or "C" band was originally designated for industrial applications and satellite communications and were repurposed for 5G wireless between 3.7 and 3.98 GHz. C-band is one component of the mid-band frequency between 3.3 and 4.2 GHz. The benefits of the new 5G C-band service have been contraindicated near airports by the aviation industry due to the potential for negative operational and safety impacts. Since the 5G C-band frequencies is very close to the Aeronautical Radionavigation Service (ARS) spectrum (as shown in Fig. 1), there is a potential for signal interference which could potentially disrupt the operation of the radio/radar altimeter equipment on many transport aircraft. This equipment is necessary to conduct certain low visibility procedures when weather conditions do not permit use of standard precision or non-precision procedures. The inability of aircraft to safely perform these procedures could generate flight disruptions throughout the system. This fact was underscored by the acknowledgement that over 100 pilot reports of potential 5G interference have been made in the first few weeks of 5G rollout (Levin and Shields, 2022). Additionally, the U.S. Transportation Secretary noted that these issues will not be fixed by the summer flying season (Reardon, 2022).

As the debate continues related to the rollout of 5G, the potential impact is unclear which shrouds the discussion between stakeholders. This paper is the first to provide an analysis of the implications of 5G C-band use on the operations of airlines. Several studies have examined the impact of weather delays on air travel (e.g., Mangortey et al, 2019, Chen and Wang, 2019, Grabbe, Sridhar & Mukherjee, 2014). Weather delays are caused by weather too severe for safe landing, the need for increased separation between aircraft, and the inability of aircraft to land during low visibility when the conditions are below the minimum thresholds for the instrument landing system (ILS), due to either the ground-based equipment or the aircraft equipment. The systems that enable aircraft to land during some weather conditions (namely low visibility) may be compromised by interference from 5G systems, however, there has been no published research quantifying the potential impact of 5G interference on aircraft operations.

Using data from the top ten busiest airports in the U.S. in 2019 as a baseline, the potential number of impacted flights are estimated. The remaining sections of this paper are organized as follows. Section 2

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provides a background on 5G and a context for its impact on aircraft operations. Section 3 describes the data and methodology used in this research. Section 4 discusses the results of the estimation of number of potential flights that could be impacted. Section 5 provides a summary of conclusions related to policy implications and paths for future research.

Background

It is helpful to understand the framework for the use of ILS in aviation, and the use of aircraft equipment such as radar altimeters for aviation operations in the context of the potential impacts of interference from 5G C-band.

Critical phases of a commercial aircraft flight include the approach to landing and landing at the destination airport (FAA, 1981). During approach, the aircraft must descend through the terminal area to properly align the aircraft and land on the appropriate runway. During inclement weather and low visibility conditions, the pilot requires support from instrumentation to safety complete the approach and landing. ILS precision approaches provide a precise path to safely land the aircraft on the runway (FAA, 2017) and these precision approach procedures allow aircraft to operate in adverse weather conditions with reduced visibility and cloud clearance. There are different categories, based on when the pilot must make the decision to land (aka, Decision Height or DH) and the runway visual range (RVR), which reflects how far the pilot can see, as shown in Table 1.

Table 1
ILS categories and associated minimums.

ILS Category	DH (in ft)	RVR and required ground and airborne system components
Cat I	200 ft	2,400 ft (with touchdown zone and centerline marking, RVR 1,800 ftOr Autopilot or FD (flight director) or HUD (head up display) , RVR 1800 ft
Special Authorization Cat I	150 ft	1,400 feet, HUD to DH
Cat II	100 ft	1,200 ft (with autoland or HUD to touchdown and noted on authorization, RVR 1,000 ft)
Special Authorization Cat II with Reduced Lighting	100 ft	1,200 with autoland or HUD to touchdown and noted on authorization, RVR 1,000 ft
Cat IIIa	No DH or DH < 100 ft	>700 ft
Cat IIIb	No DH or DH < 50 ft	<700 ft but > 150 ft
Cat IIIc	No DH	No RVR limitation

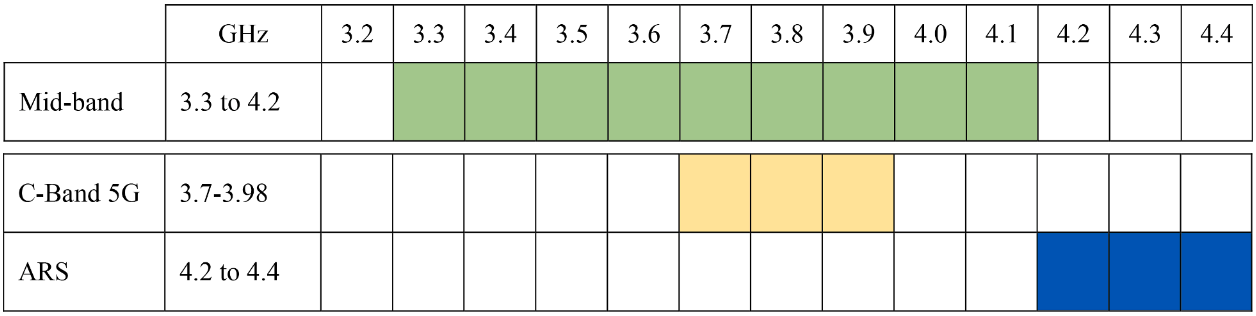
Source: FAA, 2017.

The three classification of ILS approaches are CAT I, II, and III. A higher CAT level is associated with a lower decision height, and allows a safe landing in more restricted conditions with lower visibility. The decision height is the minimum height on the approach to landing at which the pilot must make a decision to land that the aircraft or execute a missed approach procedure, which might occurs if the runway is not visible (e.g., due to fog or other environmental conditions). Fig. 2 provides the minimum decision heights and visibility restrictions for each category of ILS approach per the FAA Instrument Procedures Handbook (FAA, 2017). ILS CAT I approaches do not require the use of radar altimeters and this information is consistent with the information in Table 1. In addition to potentially affecting CAT II and III ILS procedures, 5G also restricts the use of Area Navigation (RNAV) Required Navigational Performance (RNP) procedures. RNAV RNP are procedures used under instrument flight rules (IFR) that are based on selection of a course within the limits of a network of navigation beacons at the airport, rather than use of a specific and designed flight path as is used for ILS approaches. RNAV RNP requires on-board monitoring and alerting systems as well use of a radar altimeter.

CAT II and III approaches allow an aircraft to operate in and land in reduced visibility conditions, since they are possible with lower decision heights. Use of higher precision approaches (e.g., CAT III and III) requires special authorization (SA) from the operating carrier (e.g., the airline), special equipment in the aircraft, and pilot certification to ensure the strict requirements for precise operation are met. Not all runways have ILS equipment, due to the expense associated with installation and maintenance. Higher categories of ILS require more precise and expensive equipment ground equipment and are installed only where they are warranted. Similarly, not all aircraft have the equipment required for higher precision approaches. One special equipment item required to conduct these precise CAT II and III approaches is the radar/radio altimeter.

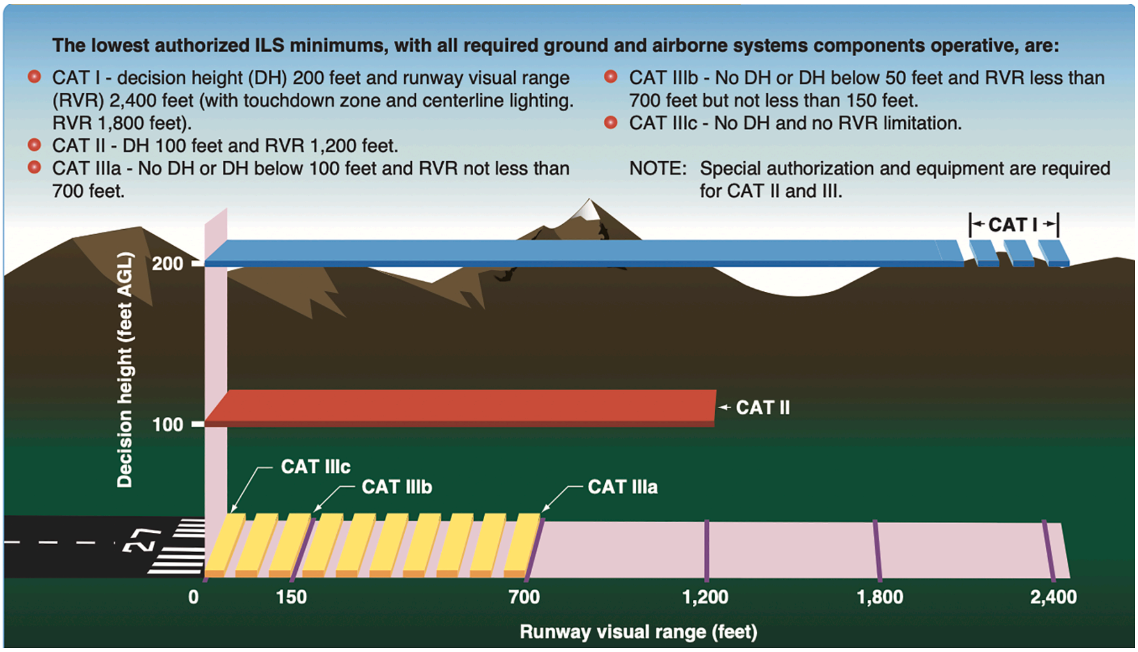
Radar altimeters on aircraft are used during several phases of flight to ensure the aircraft is safe from collision with terrain and obstacles. Radar altimeters provide the flight crew with the aircraft's precise above ground level (AGL) altitude that is not measured by the aircraft's pressure altimeter. These radar altimeters operate in the Aeronautical Radionavigation Service (ARS) spectrum from 4.2 to 4.4 GHz and allow an aircraft to perform low-visibility instrument procedures such as CAT II, III and RNP. Use of the spectrum from 3.7 to 3.98 GHz for 5G has introduced the possibility of interference with the operation of aircraft mounted radar altimeters. Although this topic has recently captured the attention of the media, the issue has been under investigation for some time.

In October 2020, RTCA published findings in RTCA Paper No. 274–20/PMC-2073 (RTCA, Inc. , 2020). This report presents compelling results that 5G C-band presents a major risk to radar altimeters for all kinds of aircraft; these results are based on evaluation of numerous operational scenarios. These findings are critical since radar altimeters are the only sensor on the aircraft that provides a measurement of the actual distance between the aircraft and the ground or other obstacles. The RTCA report was published prior to the FCC authorizing (and auctioning new licenses) for use of the frequency spectrum from 3.7 to



	GHz	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4
Mid-band	3.3 to 4.2		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
C-Band 5G	3.7-3.98						🟨	🟨	🟨					
ARS	4.2 to 4.4											🟦	🟦	🟦

Fig. 1. Spectrum Allocation.

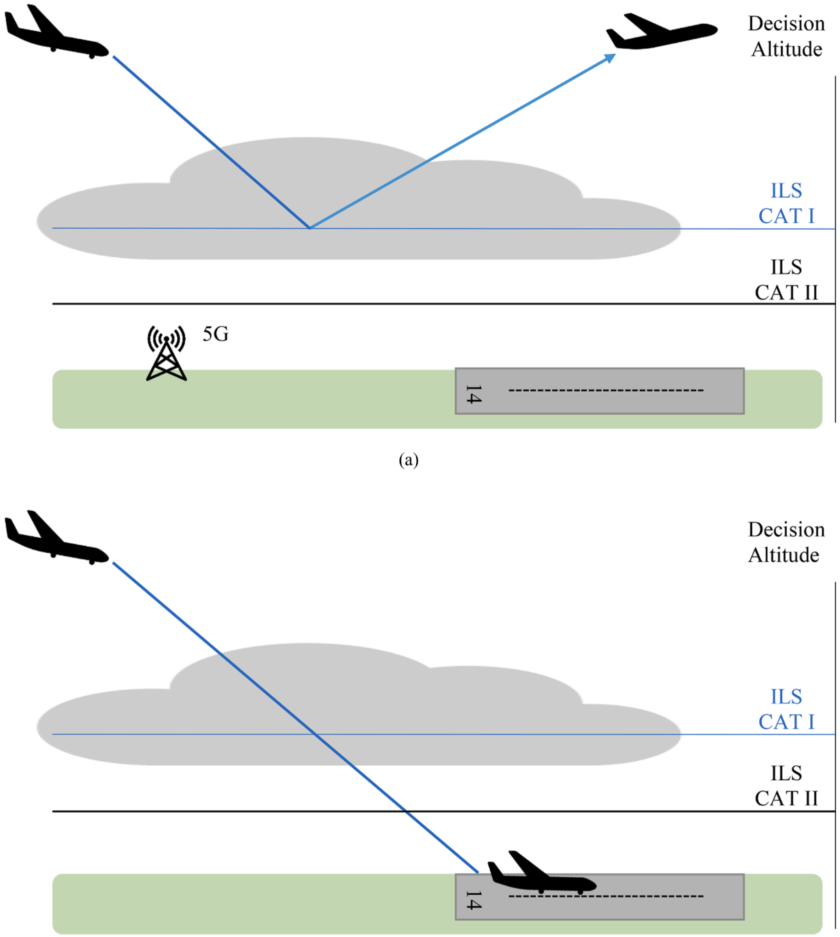


The lowest authorized ILS minimums, with all required ground and airborne systems components operative, are:

- CAT I - decision height (DH) 200 feet and runway visual range (RVR) 2,400 feet (with touchdown zone and centerline lighting. RVR 1,800 feet).
- CAT II - DH 100 feet and RVR 1,200 feet.
- CAT IIIa - No DH or DH below 100 feet and RVR not less than 700 feet.
- CAT IIIb - No DH or DH below 50 feet and RVR less than 700 feet but not less than 150 feet.
- CAT IIIc - No DH and no RVR limitation.

NOTE: Special authorization and equipment are required for CAT II and III.

Fig. 2. ILS minimums by category from the FAA Instrument Procedures Handbook. Source: FAA (2017).



(a)

(b)

Fig. 3. Example of an aircraft flying an (a) ILS CAT I because of 5G NOTAM and (b) an ILS CAT II without a 5G NOTAM due to weather below ILS CAT I minimums, but above ILS CAT II minimums.

3.98 GZ, which began in December 2020.

On December 9, 2021, the FAA issued the airworthiness directive (AD) 2021-23-12. This AD, directed to all transport and commuter aircraft equipped with a radio altimeter, requires that aircraft limit certain operations that require the radio altimeter in low visibility conditions, when there is the potential for 5G C-band interference as communicated by a NOTAM (notice to air mission). The procedures addressed by the AD include CAT II, CAT III and RNP procedures that require the use of a radar/radio altimeter to assist the flight crew in flying the aircraft through the weather and safely landing the aircraft in instrument meteorological conditions (IMC).

The prohibited procedures referenced by the AD when 5G NOTAMs will result in aircraft that are unable to land during periods of low visibility. Fig. 3 provides an example of a low visibility weather day at an airport (a) impacted by a 5G NOTAM, and (b) not impacted by a 5G NOTAM. In the case of a 5G NOTAM, the aircraft would be unable to perform the low visibility approach (Cat II ILS) and would be required to hold (circle the airport) or divert to another airport where visibility is better. When a 5G NOTAM does not exist, the aircraft is able to safely conduct a low visibility approach and safely land at the airport.

After the FAA published CE 2021-23-12, Boeing published a Multi Operator Message (MOM-22-0001-01B) on January 3, 2022, and a Flight Crew Operations Manual Bulletin (TBC-119) addressing the radio altimeter anomalies due to interference from 5G C-band on January 5, 2022. Interference may affect numerous systems including the autopilot flight director system, autothrottle, engines, thrust reversers, flight controls, flight instruments, traffic alert and collision avoidance system, and ground proximity warning system. As of mid-January, FAA continues to analyze data to determine the impact on different aircraft models. On January 19, FAA published an AD for Boeing Company Airplanes 787–8, −9, and −10 with the determination that these aircraft cannot be relied upon if they experience interference from 5G C-Band (2022, Jan 19c). Challenges for these Boeing Aircraft include the lack of proper transition from AIR to GROUND mode used to tranisiton aircraft systems for stopping after landing, and associated degradation in performance (e.g., longer landing distances, etc.) that require revised calculations for landing distance (FAA, 2022c).

The uncertainty of the impact of 5G C-Band on aircraft operations is a significant challenge, and understandably a concern for FAA, aircraft manufacturers and airlines. There is some confusion since 5G-Band C has been used in some locations in Europe without compromising aircraft operations. However, consider 5G in the US compared to France as an example (FAA, 2022a):

- Different signal strength: 5G signal strength in the US is 1585 W, >2.5 times the signal strength in France (631 W).
- Antenna angle: In the US, the antenna are pointed at a 90 degree angle, whereas in France the antenna are angled downward.
- Airport buffer zones: In the US, there is a six month temporary hold on 5G C-band at 50 airports, whereas in France there are permanent safeguards in place. The buffer zone in the US is targeted to protect aircraft for 20 s of flight on the approach, whereas the buffer zone in France is targeted to protect aircraft for 96 s of flight on the approach. Since a Boeing 787–8 aircraft has an approach speed of 145 knots (166.86 mph) (Boeing, 2016), the US buffer zone of 20 s correlates with a buffer zone of less than a mile (0.93 mile) whereas the French buffer zone of 96 s correlates with a buffer zone of over 4.4 miles.

On January 13, 2022, FAA issued NOTAMs throughout the system warning pilots of the potential for 5G C-band interference. NOTAMs became active on January 19, 2022 and end January 19, 2024. Both Aerodrome (airport) and Procedure NOTAMs were issued, with reference to Airworthiness Directives 2021-23-12 and 2021-23-13. These NOTAMs were issued not only for large airports that serve commercial service, but also for general aviation airports throughout the country. Sample NOTAMs are shown in Fig. 4. Chicago Executive Airport (PWK) is a reliever airport that serves business aircraft and general aviation; PWK is 18 miles northwest of Chicago and about 10 miles north of Chicago O'Hare International Airport.

On January 19, 2022, FAA published a list of 87 airports with low visibility approaches (CAT II & III, RNP AR) in 5G deployment ((FAA, 2022b)). FAA has also published a list of fifty airports that will be provided a 5G buffer zone of 20 s, as shown in Table 2 . The choice of these airports was determined by examining the rollout cities for 5G C-band operations and the number of low-visibility operations at each airport. The list includes many of the busiest airports; however, several airports that will rollout 5G C-band networks were not included in the list of airports with buffer zones. These airports could experience disruptions to operations due to 5G NOTAMS and low-visibility operations.

Note that the airports in Table 2 include nineteen (of thirty) large hub airports in the US. These airports are the backbone of the commercial passenger aviation system. In addition to serving passenger service, there are 37 airports that are designated Cargo Airports by FAA since they serve over 100,000 lb of air cargo annually (landed weight). General aviation (GA), National Airports also play an important role in the aviation system by serving general aviation aircraft (smaller aircraft) including business jets. GA airports do not serve scheduled passenger service so for these airports, the number of aircraft operations (take-offs and landings) is provided in addition to the annual enplanements, because operations is a better measure of airport activity at GA airports. The airports in Table 2 all play an important role in our national aviation system. While this research focuses on quantifying disruption to passenger service, it is valuable to recognize the impacts of 5G disruption extend beyond passenger service.

The next section discusses the methodology used to quantify the expected number of aircraft flights that would be affected by 5G interference, based on historical data. While the current focus of FAA, airlines and media is on large airports that serve commercial passenger service and cargo, the potential for disruption to safe operations at thousands of GA airports across the country is also significant.

Data and methodology

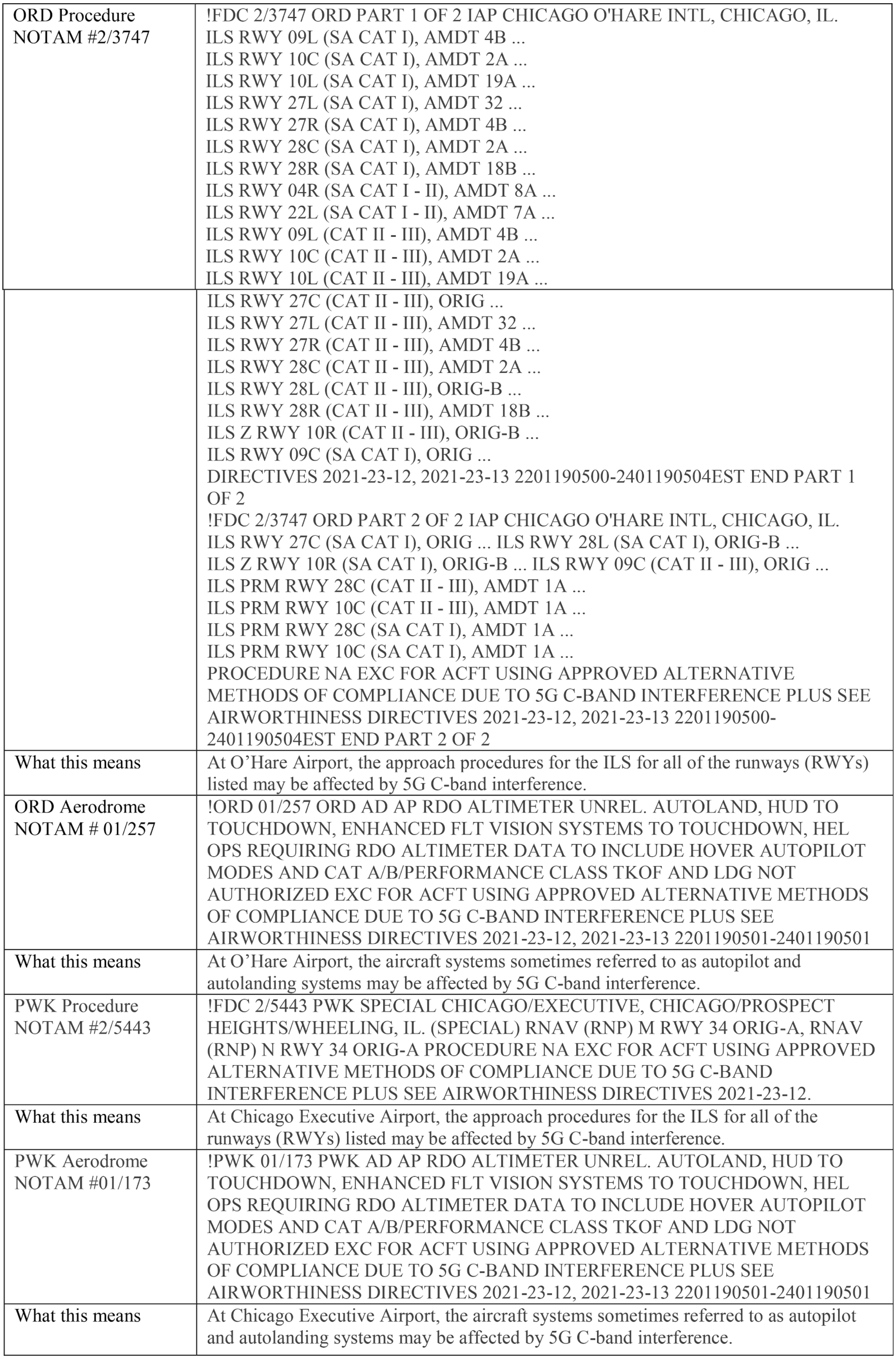
This section described the data sources and the methodology used to estimate the potential impact of 5G C-band on aircraft operations at major airports in the US. The methodology includes:

- Identification of ten large airports where 5G C-band service is proposed for deployment.
- Evaluation of weather data and NOTAMS at these airports in 2019 to identify time periods in which ILS is required to land.
- Evaluation of flight records and approach procedures to identify flights that would be affected by potential interference from 5G C-band.
- Development of descriptive statistics to quantify and describe impact of 5G C-band interference on aircraft operations for ten airports in a one year period. To provide a multi-year perspective of the potential impact, a case study assessing the impact over a ten-year period on operations at O'Hare International Airport is presented.

Additional details about the data and methodology is presented below.

Data

Every two years, the FAA updates the National Plan of Integrated Airport Systems and identifies large hub airports based on the number of passenger enplanements at each airport. There are approximately 30 large hub airports, and collectively these airports serve about 70% of all commercial passenger flights and represent the busiest airports in the nation (FAA, 2020a,b). The list of large hub airports was then



ORD Procedure NOTAM #2/3747	!FDC 2/3747 ORD PART 1 OF 2 IAP CHICAGO O'HARE INTL, CHICAGO, IL. ILS RWY 09L (SA CAT I), AMDT 4B ... ILS RWY 10C (SA CAT I), AMDT 2A ... ILS RWY 10L (SA CAT I), AMDT 19A ... ILS RWY 27L (SA CAT I), AMDT 32 ... ILS RWY 27R (SA CAT I), AMDT 4B ... ILS RWY 28C (SA CAT I), AMDT 2A ... ILS RWY 28R (SA CAT I), AMDT 18B ... ILS RWY 04R (SA CAT I - II), AMDT 8A ... ILS RWY 22L (SA CAT I - II), AMDT 7A ... ILS RWY 09L (CAT II - III), AMDT 4B ... ILS RWY 10C (CAT II - III), AMDT 2A ... ILS RWY 10L (CAT II - III), AMDT 19A ... ILS RWY 27C (CAT II - III), ORIG ... ILS RWY 27L (CAT II - III), AMDT 32 ... ILS RWY 27R (CAT II - III), AMDT 4B ... ILS RWY 28C (CAT II - III), AMDT 2A ... ILS RWY 28L (CAT II - III), ORIG-B ... ILS RWY 28R (CAT II - III), AMDT 18B ... ILS Z RWY 10R (CAT II - III), ORIG-B ... ILS RWY 09C (SA CAT I), ORIG ... DIRECTIVES 2021-23-12, 2021-23-13 2201190500-2401190504EST END PART 1 OF 2 !FDC 2/3747 ORD PART 2 OF 2 IAP CHICAGO O'HARE INTL, CHICAGO, IL. ILS RWY 27C (SA CAT I), ORIG ... ILS RWY 28L (SA CAT I), ORIG-B ... ILS Z RWY 10R (SA CAT I), ORIG-B ... ILS RWY 09C (CAT II - III), ORIG ... ILS PRM RWY 28C (CAT II - III), AMDT 1A ... ILS PRM RWY 10C (CAT II - III), AMDT 1A ... ILS PRM RWY 28C (SA CAT I), AMDT 1A ... ILS PRM RWY 10C (SA CAT I), AMDT 1A ... PROCEDURE NA EXC FOR ACFT USING APPROVED ALTERNATIVE METHODS OF COMPLIANCE DUE TO 5G C-BAND INTERFERENCE PLUS SEE AIRWORTHINESS DIRECTIVES 2021-23-12, 2021-23-13 2201190500-2401190504EST END PART 2 OF 2
What this means	At O'Hare Airport, the approach procedures for the ILS for all of the runways (RWYs) listed may be affected by 5G C-band interference.
ORD Aerodrome NOTAM # 01/257	!ORD 01/257 ORD AD AP RDO ALTIMETER UNREL. AUTOLAND, HUD TO TOUCHDOWN, ENHANCED FLT VISION SYSTEMS TO TOUCHDOWN, HEL OPS REQUIRING RDO ALTIMETER DATA TO INCLUDE HOVER AUTOPILOT MODES AND CAT A/B/PERFORMANCE CLASS TKOF AND LDG NOT AUTHORIZED EXC FOR ACFT USING APPROVED ALTERNATIVE METHODS OF COMPLIANCE DUE TO 5G C-BAND INTERFERENCE PLUS SEE AIRWORTHINESS DIRECTIVES 2021-23-12, 2021-23-13 2201190501-2401190501
What this means	At O'Hare Airport, the aircraft systems sometimes referred to as autopilot and autolanding systems may be affected by 5G C-band interference.
PWK Procedure NOTAM #2/5443	!FDC 2/5443 PWK SPECIAL CHICAGO/EXECUTIVE, CHICAGO/PROSPECT HEIGHTS/WHEELING, IL. (SPECIAL) RNAV (RNP) M RWY 34 ORIG-A, RNAV (RNP) N RWY 34 ORIG-A PROCEDURE NA EXC FOR ACFT USING APPROVED ALTERNATIVE METHODS OF COMPLIANCE DUE TO 5G C-BAND INTERFERENCE PLUS SEE AIRWORTHINESS DIRECTIVES 2021-23-12.
What this means	At Chicago Executive Airport, the approach procedures for the ILS for all of the runways (RWYs) listed may be affected by 5G C-band interference.
PWK Aerodrome NOTAM #01/173	!PWK 01/173 PWK AD AP RDO ALTIMETER UNREL. AUTOLAND, HUD TO TOUCHDOWN, ENHANCED FLT VISION SYSTEMS TO TOUCHDOWN, HEL OPS REQUIRING RDO ALTIMETER DATA TO INCLUDE HOVER AUTOPILOT MODES AND CAT A/B/PERFORMANCE CLASS TKOF AND LDG NOT AUTHORIZED EXC FOR ACFT USING APPROVED ALTERNATIVE METHODS OF COMPLIANCE DUE TO 5G C-BAND INTERFERENCE PLUS SEE AIRWORTHINESS DIRECTIVES 2021-23-12, 2021-23-13 2201190501-2401190501
What this means	At Chicago Executive Airport, the aircraft systems sometimes referred to as autopilot and autolanding systems may be affected by 5G C-band interference.

Fig. 4. Sample NOTAM Warning Pilots of 5G C-Band Interference. Source: FAA, 2022b.

Table 2
Airports with 5G buffer (2020).

Code	Airport Name	State	Category	Enplanements[1]	Cargo (lbs)[2]
AUS	AUSTIN-BERGSTROM INTL	Texas	Medium hub	7,714,479	607,956,455
BED	LAURENCE G HANSCOM FLD	Massachusetts	Non-hub	10,194	
BFI	BOEING FLD/KING COUNTY INTL	Washington	Non-hub	18,586	714,618,694
BHM	BIRMINGHAM-SHUTTLESWORTH INTL	Alabama	Small hub	1,457,562	173,209,320
BNA	NASHVILLE INTL	Tennessee	Medium hub	8,017,347	286,833,754
BUR	BOB HOPE	California	Medium hub	2,680,240	
CAK	AKRON-CANTON	Ohio	Non-hub	449,731	
CLT	CHARLOTTE/DOUGLAS INTL	North Carolina	Large hub	352,816	784,913,564
DAL	DALLAS LOVE FLD	Texas	Medium hub	8,011,221	
DFW	DALLAS-FORT WORTH INTL	Texas	Large hub	32,821,799	4,515,027,123
DTW	DETROIT METRO WAYNE COUNTY	Michigan	Large hub	17,436,837	888,306,650
EFD	ELLINGTON	Texas	GA, Natl[2]	245 *(87,485)* [3]	538,620
EWR	NEWARK LIBERTY INTL	New Jersey	Large hub	22,797,602	2,986,808,278
FAT	FRESNO YOSEMITE INTL	California	Small hub	853,538	146,444,940
FLL	FORT LAUDERDALE/HOLLYWOOD INTL	Florida	Large hub	17,612,331	391,351,570
FNT	FLINT MICHIGAN	Michigan	Non-hub	361,709	87,139,300
HOU	WILLIAM P HOBBY	Texas	Medium hub	7,053,886	109,280
HVN	NEW HAVEN	Connecticut	Non-hub	38,991	
IAH	GEORGE BUSH INTCNTL/HOUSTON	Texas	Large hub	21,157,398	2,458,897,596
IND	INDIANAPOLIS INTL	Indiana	Medium hub	4,655,847	5,653,005,700
ISP	LONG ISLAND MAC ARTHUR	New York	Small hub	811,535	
JFK	JOHN F KENNEDY INTL	New York	Large hub	30,620,769	3,431,222,328
LAS	HARRY REID INTL	Nevada	Large hub	23,795,012	457,181,050
LAX	LOS ANGELES INTL	California	Large hub	42,624,050	13,171,992,460
LGA	LAGUARDIA	New York	Large hub	15,058,501	
LGB	LONG BEACH (DAUGHERTY FLD)	California	Small hub	1,908,635	112,561,460
MCI	KANSAS CITY INTL	Missouri	Medium hub	5,790,847	595,447,328
MCO	ORLANDO INTL	Florida	Large hub	23,202,480	1,292,668,960
MDT	HARRISBURG INTL	Pennsylvania	Small hub	636,756	448,263,880
MDW	CHICAGO MIDWAY INTL	Illinois	Large hub	10,678,018	
MFE	MCALLEN INTL	Texas	Non-hub	347,440	
MIA	MIAMI INTL	Florida	Large hub	21,021,640	9,929,929,001
MSP	MINNEAPOLIS-ST PAUL INTL	Minnesota	Large hub	18,361,942	1,102,871,589
ONT	ONTARIO INTL	California	Medium	2,498,993	5,220,302,257
ORD	CHICAGO O'HARE INTL	Illinois	Large hub	39,873,927	7,877,649,208
PAE	SNOHOMISH COUNTY (PAINE FLD)	Washington	GA, Natl	3,037 *(115,201)* [3]	198,726,000
PBI	PALM BEACH INTL	Florida	Medium hub	3,270,605	
PHL	PHILADELPHIA INTL	Pennsylvania	Large hub	15,292,670	3,148,398,964
PHX	PHOENIX SKY HARBOR INTL	Arizona	Large hub	21,622,580	2,423,935,280
PIE	ST PETE-CLEARWATER INTL	Florida	Small hub	1,115,886	
PIT	PITTSBURGH INTL	Pennsylvania	Medium hub	4,670,033	547,841,586
RDU	RALEIGH-DURHAM INTL	North Carolina	Medium hub	6,258,101	631,531,300
ROC	FREDERICK DOUGLASS/GREATER ROCHESTER INTL	New York	Small hub	1,281,908	310,801,664
SEA	SEATTLE-TACOMA INTL	Washington	Large hub	24,024,908	2,715,552,788
SFO	SAN FRANCISCO INTL	California	Large hub	27,790,717	1,245,566,300
SJC	NORMAN Y MINETA SAN JOSE INTL	California	Medium hub	7,032,851	226,218,750
SNA	JOHN WAYNE/ORANGE COUNTY	California	Medium hub	5,201,642	
STL	ST LOUIS LAMBERT INTL	Missouri	Medium hub	7,631,953	500,158,300
SYR	SYRACUSE HANCOCK INTL	New York	Small hub	1,139,568	422,563,500
TEB	TETERBORO	New York	GA, Natl	19,242 *(86,372)* [3]	

[1] 2020 emplanements; 22,020 Landed cargo weight in pounds for cargo airports; 3 The number of aircraft operations (landings or take-offs) is provided in parenthesis in addition to the number of enplanements for General Aviation, National airports. Since these airports do not provide scheduled commercial service, operations data provides a better measure of airport activity. Sources: (FAA, 2022e, Jan7) (FAA, 2020a; FAA, 2020b).

crosschecked with the list of cities that will be the first to rollout 5G C-band networks (Federal Communications Commission (FCC), 2010). Table 3 provides a list of the cities, corresponding airports, the airport category, and number of enplanements for the airports studied. Each of these airports serves one percent or more of the annual U.S. commercial enplanements (FAA, 2021a) and plays an important role in the national airport system. Note that the airport ranked the busiest in the U.S., Hartsfield-Jackson Atlanta International, as well as several other top ten busiest airports are not included in this analysis. These airports were not included in the 5G C-band rollout and therefore will not experience an impact to their low visibility flight operations (i.e., these low visibility procedures will not be prohibited). Each of the airports in Table 3 were included in the first notice to air missions (NOTAMs) issued by the FAA related to 5G (FAA, 2021b).

At each of the selected airports, weather data is gathered from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information database (NOAA, 2021). These data include historical meteorological aerodrome reports (METARs) observed at each airport. METARs include periodic weather observations throughout the day and contain information related to ceiling and visibility which drive the type of instrument approach procedure to be used by flights to land at that airport. These are released every hour unless a significant weather change occurs such as a transition to low visibility due to precipitation.

Data related to each airports' instrument procedures currently used are provided by Jeppesen Flitedeck (Jeppesen, 2021). These data

Table 3
Cities and corresponding airports where 5G C-band rollout will occur.

City	Airport Name (FAA Ranking)	Airport Code	Airport Category	Enplanements in 2019
Los Angeles, CA	Los Angeles International (2)	KLAX	Large Hub	42,939,104
Chicago, IL	Chicago O'Hare International (3)	KORD	Large Hub	40,871,223
Fort Worth, TX	Dallas-Fort Worth International (4)	KDFW	Large Hub	35,778,573
New York, NY	John F. Kennedy International (6)	KJFK	Large Hub	31,036,655
San Francisco, CA	San Francisco International (7)	KSFO	Large Hub	27,779,230
Seattle, WA	Seattle-Tacoma International (8)	KSEA	Large Hub	25,001,762
Las Vegas, NV	Harry Reid International (9)	KLAS	Large Hub	24,728,361
Orlando, FL	Orlando International (10)	KMCO	Large Hub	24,562,271
Charlotte, NC	Charlotte/Douglas International (11)	KCLT	Large Hub	24,199,688
Phoenix, AZ	Phoenix Sky Harbor International (13)	KPHX	Large Hub	22,433,552

Sources: Federal Communications Commission (FCC) (2010); FAA (2020a,b).

include approach and arrival procedures specific to each airport and runway. Archival NOTAM data for each airport is from the FAA FNS NOTAM search page (FAA, 2021). These data provide information related to ILS equipment outages and runway closures pertinent to this analysis.

Daily flight data for each airport are collected from the Department of Transportation using Cirium's Diio Mi database (Cirium, 2021). The Diio Mi database is updated weekly and provides custom reporting of Department of Transportation data. These flight data consist of the time of arrival for each flight and number of seats on the aircraft. Table 4 provides a summary listing of the data and sources used.

Methodology

The methodology to determine the number of flights using low visibility approach procedures that would be prohibited under a 5G NOTAM is as follows. First, each airport's published precision approaches are examined to determine the availability and usage of the prohibited low visibility approaches listed under the FAA AD. These procedures are necessary to safely land during low visibility weather conditions but would be prohibited when the airport is operating under a NOTAM related to 5G. After confirming the availability of low visibility approach procedures, the historical METAR data is examined for each airport over the entire year studied (2019, in this case). This weather data is filtered to determine dates and times that the METAR indicates low visibility conditions exist at the airport. For example, Fig. 5 provides a graphical representation of the METAR data in a meterogram for Chicago O'Hare International Airport on December 24, 2019 (Plymouth Weather Center, 2021). During the hours between 0900Z to 1500Z, the METAR indicated that the vertical visibility was 100 feet about the runway environment with visibility of ¼ mile and runway visual range (RVR) of<1400 feet for Runway 10*L*. These weather conditions are below the required minimums for a CAT I ILS (vertical visibility or ceiling of 200 feet, visibility of ½ mile, and RVR 1800), but within the limits required to perform a CAT II (or III) ILS approach. Therefore, aircraft arriving at Chicago O'Hare International on December 24, 2019 during these hours would be required to conduct an ILS CAT II (or III) approach to safely land at the airport. If a CAT II (or III) approach cannot be completed, the aircraft would be required to hold until weather conditions improve or the aircraft would be required to divert to an alternate airport with more favorable conditions (either more favorable weather or lack of potential interference from 5G C-band). In this example, if a 5G C-band NOTAM was active for the airport, then arriving aircraft would be unable to complete the required approach to land at Chicago O'Hare International and would be required to hold until conditions improved, divert, or cancel the flight at their destination before departing for Chicago O'Hare International. Note that diversion to other airports may be challenging, since other airports in the area may have similar weather and may have the potential for 5G C-band interference; furthermore, there are a limited number of airports that can accommodate the large aircraft landing at large hub airports.

Table 4
Data sources.

Data	Date Range	Number of Observations	Source
METAR Reports	All Airports – 2019 KORD – 2009–2019	264,540	National Oceanic and Atmospheric Administration
NOTAMs	All Airports – 2019 KORD – 2009 – 2019	3,044	Federal Aviation Administration FNS NOTAM Database
Flights	All Airports – 2019 KORD – 2009–2019	5,067,533	Cirium Diio Mi
Approach Procedures	All Airports – 2019	440	Jeppesen Flitedeck

Source: Authors' calculations.

Once a date and time is identified as having low visibility weather conditions from the METAR data, we reference the NOTAMs in place for that airport. If certain instrument landing equipment is out-of-service or any other prohibition on using low visibility approach procedures exists, then we annotate that date to ensure the flight data corroborates that no flights were conducted using these types of operations. All arriving flight data for that date and time are then matched from the low visibility timeframe. A flight arriving within the time window of low visibility weather is considered to have conducted a low visibility approach because low visibility approaches are the only authorized procedure given the prevailing weather conditions. For example, based on the METAR data on December 24, 2019, at Chicago O'Hare International (as displayed in Fig. 5) we find that 258 flights arrived during the timeframe when the airport operated under weather conditions requiring the use of an ILS CAT II or III approach procedure. These flights accounted for approximately 26% of the total flights arriving at Chicago O'Hare International that day. These 258 flights would not have been authorized to land if a 5G NOTAM was active for the airport which would ultimately result in numerous delayed, cancelled, or diverted flights.

The above-mentioned procedure is conducted for the ten airports listed in Table 3 to provide an overview of the potential impact of 5G C-band on airline operations. Additionally, to better understand the magnitude of the impact on airline operations over a longer time horizon, we provide a decade-long perspective using Chicago O'Hare International as the case airport. Ten years of weather, flight, and NOTAM data are compiled for Chicago O'Hare International between 2009 and 2019. This longer time horizon analysis will provide an understanding of the variation across months, seasons, and years that 5G could impact.

The monthly number of commercial and cargo flights using low visibility approach procedures at each airport are provided in Fig. 6. This figure provides a baseline visual representation of the seasonal impact 5G could have on flight operations across these airports. Low visibility approaches were not conducted uniformly over the 12-month period at any of the studied airport; however, some airports experienced seasonality in the number of low visibility weather days and therefore flights impacted. For Charlotte/Douglas, Dallas-Fort Worth, and San Francisco International airports, winter season flights were more impacted than the flights in summer. The winter season

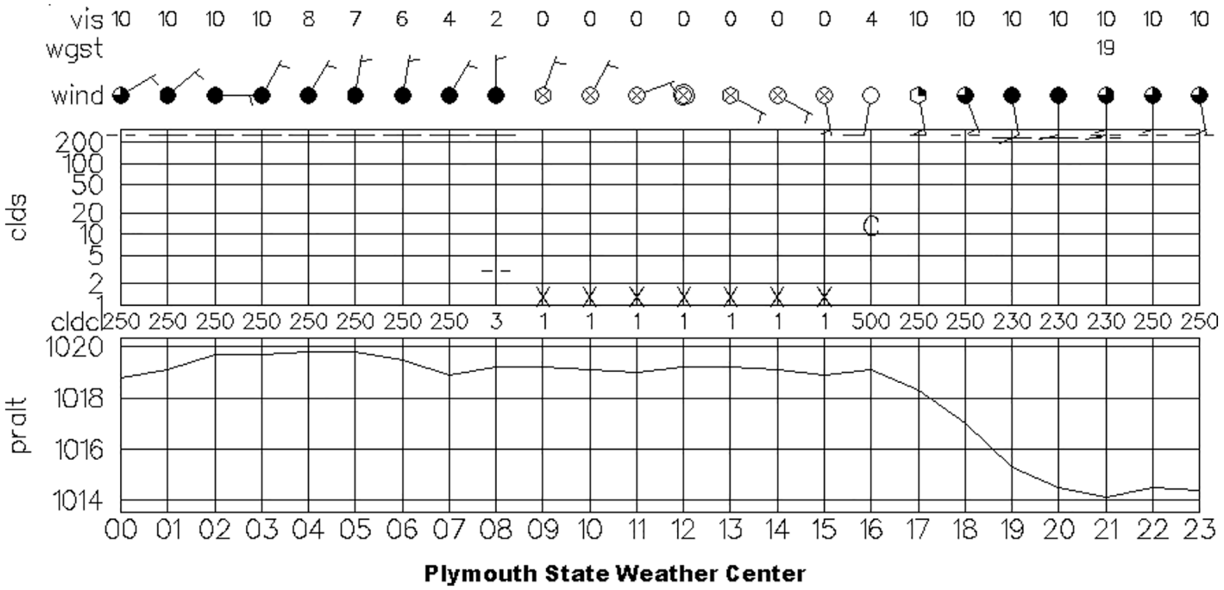


Fig. 5. Meteogram data from Chicago O'Hare International (KORD) showing visibility, wind, cloud cover, and pressure altitude on 24 December 2019. *Source: Plymouth State Weather* Center (2021).

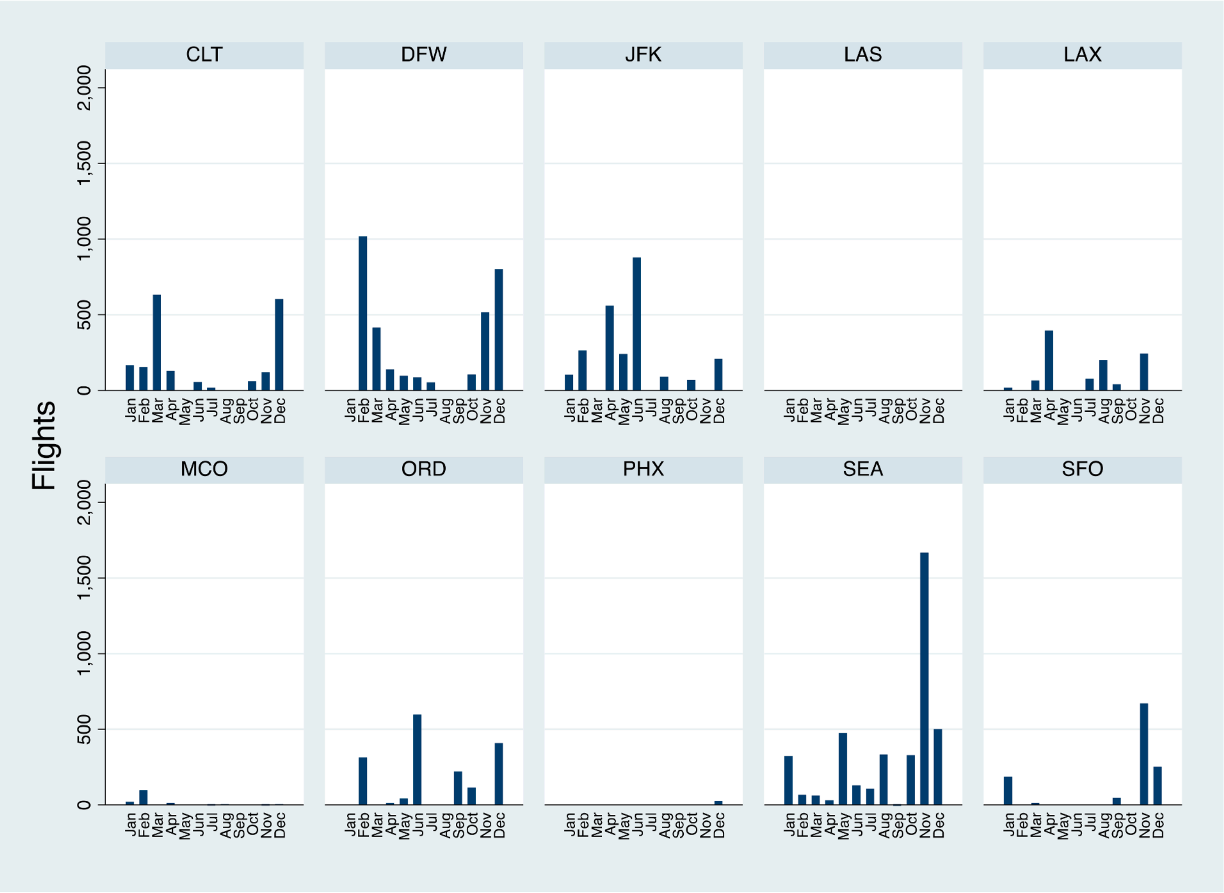


Fig. 6. Monthly flights performing low visibility precision approaches at each airport in 2019.

encompasses several significant holiday travel periods and with a 5G NOTAM in place there would be numerous delays, diverts, or cancellations at these busy airports. Los Angeles and Chicago O'Hare International experienced a more uniform spread of flights performing low visibility approaches. If a 5G NOTAM had been in place, then flight disruptions would have occurred regularly throughout the year. Orlando International had very few low visibility approaches in the early part of 2019, and Phoenix Sky Harbor International had few low visibility approaches in December only. Harry Reid International in Las Vegas did not have any flights conduct low visibility approaches over the time studied. Noticeably, the impact of potential flight disruptions from 5G varies across seasons as well as geographically.

The variation of the monthly low visibility flights at each airport are provided in Fig. 7(a). Seattle-Tacoma International had the highest median number of low visibility flights that would be impacted by 5G, while Phoenix Sky Harbor and Las Vegas had the lowest median number of flights that would be impacted.

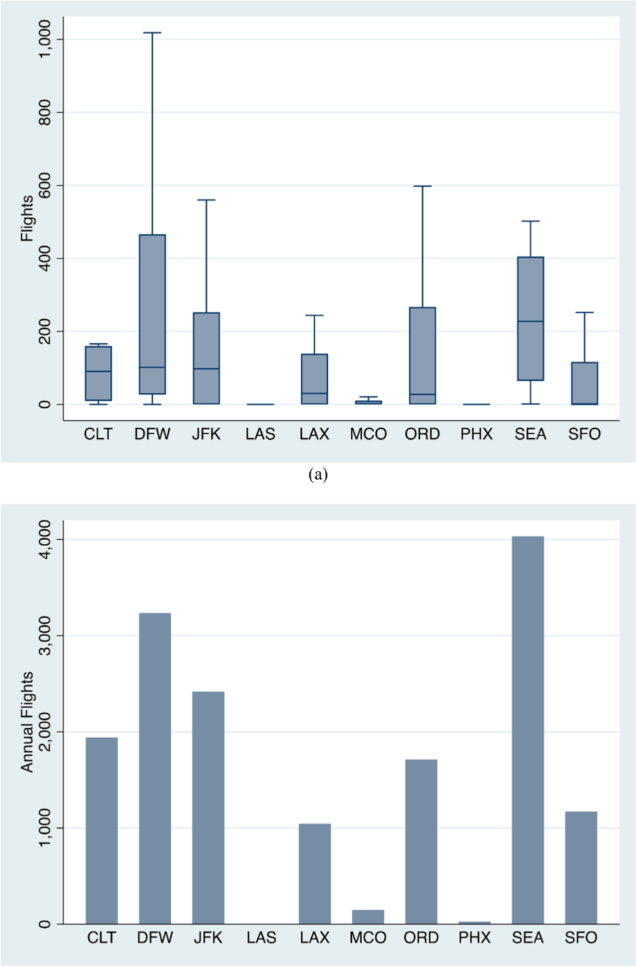
Dallas Fort-Worth International had the greatest monthly variation in flights conducting low visibility approach while Harry Reid International had the lowest with no low visibility flights. Fig. 7(b) provides the aggregate number of low visibility flights that would have been impacted by 5G. Seattle-Tacoma International had the highest total number of low visibility flights that would have been impacted by 5G at over 4,000 flights. Dallas Fort-Worth International had over 3,200 flights followed by Charlotte/Douglas International with over 1,900 flights that would have been impacted by 5G. In total, for these ten airports studied, over 15,700 flights would have been either delayed, diverted, or cancelled due to 5G.

The annual summary for each airport is provided in Table 5. Seattle-Tacoma experienced the most days with low visibility weather and experienced the highest number of low visibility flights among the studied airports. Of the total number of flights arriving at Seattle-Tacoma International, almost 2% would have been impacted by 5G resulting in a delay, divert, or cancellation. John F. Kennedy International had over 1% of their flight operations using low visibility approaches that would be impacted by 5G. Dallas Fort-Worth International had 26 days with timeframes of low visibility weather resulting in nearly 1% of their flights requiring these procedures. Phoenix Sky Harbor International and Harry Reid International in Las Vegas had the least days experiencing low visibility weather and would have experienced the smallest impact from 5G.

Table 5
Annual summary data for each airport.

Airport	Low Vis Days in 2019	Low Vis Flights in 2019	Total Flights in 2019	Percent of Total Flights
CLT	31	1,941	270,553	0.72%
DFW	26	3,235	345,317	0.94%
JFK	27	2,417	214,337	1.13%
LAS	2	0	183,834	0.00%
LAX	15	1,044	315,195	0.33%
MCO	10	148	168,238	0.09%
ORD	13	1,711	450,384	0.38%
PHX	1	26	190,150	0.01%
SEA	48	4,032	215,162	1.87%
SFO	10	1,170	214,363	0.55%

Source: Authors' calculations.



(a)

(b)

Fig. 7. Each of the busiest airport's (a) box and whisker plot of monthly flights and (b) aggregate annual flights conducting p low visibility precision approaches in 2019. *Notes: Outlier values not shown on box plots for readability. Source: Authors' calculations.*

Finally, the results from analyzing a decade of weather and flight data at Chicago O'Hare International are provided in Fig. 8. The monthly variation across the decade is displayed in Fig. 8(a). July and August experienced the least low visibility flights, while December through February experienced the highest number of low visibility flights. These results suggested that the late summer months could experience the smallest impact while the winter months would experience the highest impact from 5G flights disruptions. The aggregate number of low visibility flights is provided in Fig. 8(b). In 2015, over 4,000 flights performed low visibility approaches accounting for 1% of total arrivals into Chicago O'Hare International; however, in 2013<1,000 flights conducted low visibility approaches at Chicago O'Hare International. The average number of flights conducting low visibility approaches that would be impacted by 5G at Chicago O'Hare International is over 2,400 per year. In total, Chicago O'Hare International had 27,139 flights conduct low visibility procedures over the 11-year period.

Conclusions

As the U.S. and other countries introduce 5G C-band, the need to understand the potential disruption to air travel is apparent. This paper provides the first estimates of the number of flights that could be potentially impacted at ten of the busiest airports in the U.S. These flights conducting low visibility procedures could be delayed, diverted, or cancelled. The number of flights conducting these low visibility approaches varies across seasons and location. Some airports, such as Seattle-Tacoma International could experience a significant impact to flight operations while others such as Harry Reid International in Las Vegas could be minimally impacted. Dallas Fort-Worth International, which area serves as several major airline hubs and headquarters, experiences numerous low visibility flight operations with the greatest monthly variation. The systemic impact from disruptions out of these ten busy hub airports presents a significant risk to travelers and airline operations. These risks include delays and cancelations as well as their direct and indirect economic costs. Further, to highlight the significant potential impact we determined that Chicago O'Hare International had over 27,000 flights conduct low visibility operations in the decade from 2009 to 2019.

Our analysis provides a baseline for discussion and future cost benefit analysis. Unfortunately, the exact number of low-vibility days that may occur at a given region is uncertain; however, the historical analysis we provide can afford stakeholders a lens into the likely

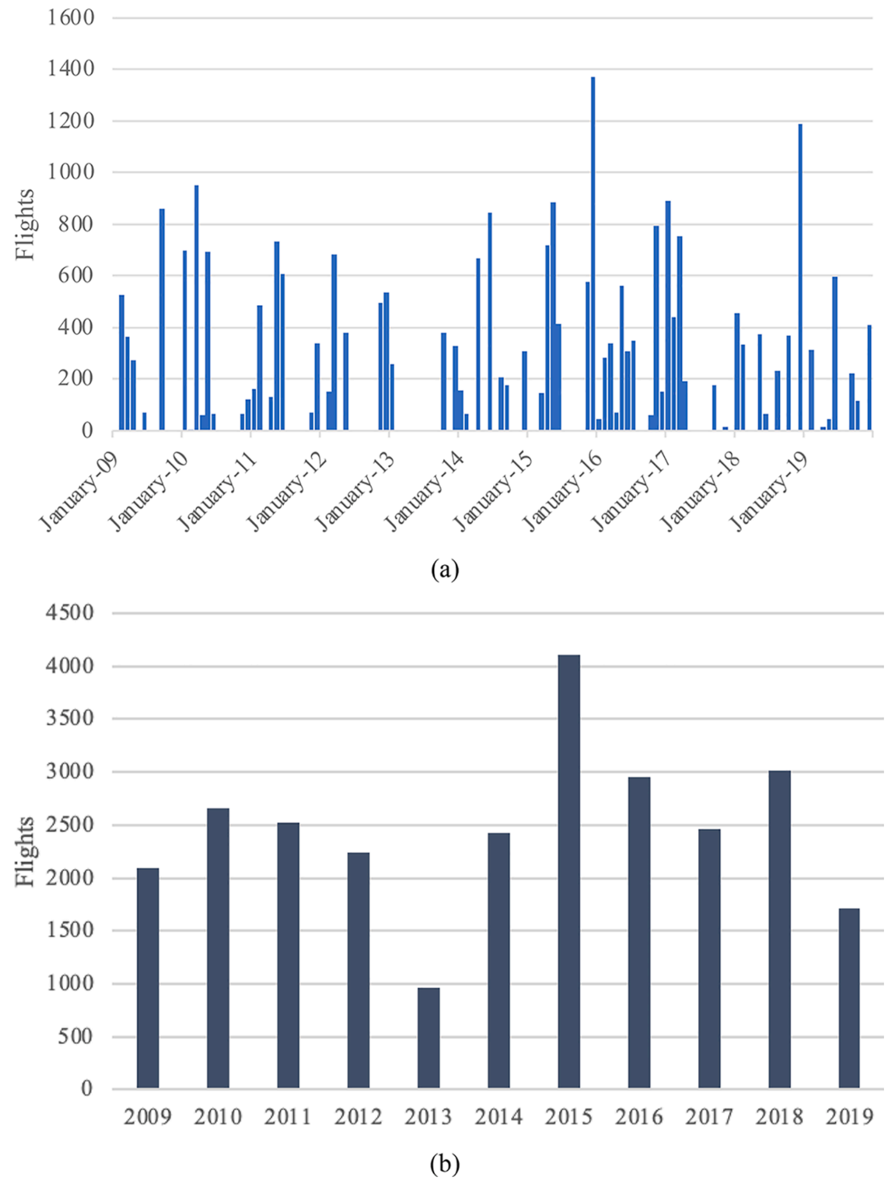


Fig. 8. Chicago O'Hare International Airport's (a) monthly and (b) annual number of low visibility approaches from January 2009 to December 2019. *Source: Authors' calculations.*

significance of the issue. Some stakeholders have already altered their behavior due to these potential issues. Recently, Emirates Airlines preemptively cancelled flights into several destinations to include Chicago O'Hare International due to concerns related to the prohibition on low visibility operations caused by 5G (Singh, 2022). Given the numerous pilot reports of potential 5G interference in the first few weeks of the rollout, the likelihood of future disruptions has increased (Levin & Shields, 2022). These potential and now realized disruptions from the restriction on low visibility approaches caused by 5G not only impact the travelling public and airline operators, but also potentially pose a significant safety risk. Aircraft requiring the use of Autoland due to numerous emergency reasons may be unable to safely land at airports impacted by these 5G NOTAMs. Policymakers have discussed buffer zones that afford aircraft the opportunity to safely operate in the terminal environment without interference from 5G such as those used in France (Patterson, 2022). These may provide aircraft operators the margin of safety necessary to continue low-visibilty operations even with the presence of 5G. Technical solutions from the aerospace industry could also provide for the safe operation of aircraft when 5G NOTAMs exist. Future work could quantify the impact to emergency aircraft at these airports thus providing more urgency for an appropriate buffer zone or technological fix. Prospective research could also uncover the indirect network effects that will likely propogate from these issues. As 5G rollout continues, the issues related to aviation will continue to be a necessary topic of research and discussion.

CRediT authorship contribution statement

Joseph B. Sobieralski: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Sarah M. Hubbard:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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