Final

Aviation GPS incidents show importance of backup systems. Policy makers should take note

High level assessment of the impact of GNSS disruption at Dallas Fort Worth and Denver airports

May 2024

London Economics

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Aviation GPS incidents show importance of backup systems, Policy makers should take note

Incidents of GPS disruption lasting 24 hours or more at two major US airports in 2022 caused no observable impact. Backup systems at both airports saved operations and maintained service in the absence of the aviation sector's foremost navigation aid. These findings underline the value of redundancy and bring ongoing developments in nav rationalization in the US and Europe into sharp focus. Is it right to seek marginal efficiencies in normal times at the expense of business continuity when things go wrong?

Global Navigation Satellite Systems (GNSS) refers to the constellations of satellites that provide position, navigation, and timing (PNT) information to users around the globe. The unique characteristics of GNSS have enabled it to be the position, navigation, and timing (PNT) solution of choice in a wide range of applications, including Critical National Infrastructure (CNI). Mobile applications like aviation that have a global footprint are also well served by GNSS.

Historically, aviation has been inextricably linked with GNSS. It was following the Soviet shootdown of Korean Air Lines Flight 007 in 1983 that the, then, military-only GPS was opened for civilian use. In 2003, the Federal Aviation Administration (FAA) developed and launched the Wide Area Augmentation System (WAAS), a Satellite-Based Augmentation System (SBAS) for aviation. In 2011, the safety-of-life service of the European SBAS, EGNOS, became available for aviation.

WAAS in conjunction with GPS offer pilots and airlines access to more than 4,000 runway ends in the US, allowing planes to land in adverse weather conditions and land more efficiently than using alternative systems, including ground-based navigation aids. The expected and realized benefits of SBAS cover both efficiency and safety, such as reduced fuel burn from reduction in track miles, enabled by the SBAS landing procedure, and the ability to reduce delays, diversions, and cancellations in bad weather. Safety benefits are gained through reductions in Controlled Flight Into Terrain (CFIT). As SBAS landing procedures and aircraft equipage reach critical mass, its proponents argue that rationalisation of nav infrastructure on the ground results in CAPEX and OPEX savings. Currently, more WAAS landing procedures have been published in the US than for other systems, extending the availability of landing procedures to a wider range of locations.

The American Global Positioning System (GPS), the first GNSS and the only one certified for flight, serves key roles at all stages of flight, and has therefore become critical to aviation. For example, GPS, in conjunction with WAAS, allows pilots to land more safely and efficiently, and in adverse weather conditions. GPS also enables higher volumes of aircraft movements, improved traffic management and collision avoidance, and optimized fleet management of ground assets. The reliance on GPS also extends outside certified aviation applications, as aircrew, airport staff, passengers, and cargo freight are often aided by GNSS-enabled services (GPS and the complementary systems, Galileo, GLONASS, BeiDou). GNSS is thus a critical enabler to the safe and efficient functioning of aviation in the US and globally.

While the economic impact of real-world disruption to airports has not previously been studied, a hypothetical case study of a spoofing event around London's Heathrow Airport (London Economics) in 2021 predicted minimal airside disruption due to existence of backup inputs and GNSS independent systems, but a potentially compounding impact from landside transport disruption. A similar analysis of potential disruption in the US context has not previously been published, but the UK findings can largely be adapted to US airports with some allowances for US-specific practices, such as the push to decommission non-GPS infrastructure and achieve cost savings.

The present study, commissioned by the Resilient Navigation and Timing Foundation and delivered by London Economics considers two separate incidents of GPS/GNSS disruption at Dallas Fort Worth and Denver International Airports in 2022. The incidents lasted 24 hours and 33 hours, respectively, with pilot reports confirming loss of GPS as they approached and landed at both airports, before restoring access to GPS once on the ground. Dallas Fort Worth (DFW) and Denver International Airports (DEN) are key transport hubs in the US, ranking second and third for passenger traffic, and third and fourth for aircraft movements globally in 2022.

The cause of the disruptions to GPS

At 10:33pm on Friday January 21st 2022, an advisory Notice to Airmen (NOTAM) was issued, advising pilots of widespread GNSS disruption in the area around the Denver International Airport. The affected area covered a 50 nautical mile radius around the airport, spanning approximately 8,000 square nautical miles. The Cybersecurity and Infrastructure Security Agency (CISA) have since released a report highlighting some details of the event. The report confirms the event lasted 33 hours and was caused by a source unintentionally emitting an L1 frequency signal that interfered with GPS. This interference impacted flights in the affected region at altitudes up to 36,000ft, and also suggests the range might have stretched much farther afield, perhaps reaching 230 nautical miles from the interference source. It has not been confirmed whether L5 was affected as well.

A similar Air Traffic Control System Command Center (ATCSCC) advisory was issued at 4:51pm on Monday 17th October 2022 warning pilots of GPS anomalies in the airspace around Dallas Fort Worth International Airport. Although original reports of the disruption suggested the event lasted for 44 hours, subsequent research by a group at Stanford University identified a more realistic timeline of significant GPS jamming from 2:21pm on October 17th, to 2:10pm on October 18th, roughly 24 hours. This spanned periods of both high and low flight traffic throughout the day, and led to the closure of a runway. The source of interference was never identified, and the disruption ended on its own.

The effect of the disruptions to GPS

No effect of the GPS disruption could be observed at either airport, despite the closure of a runway at DFW. For both locations, airside delays, diversions, and cancellations were comparable to the annual average, with no observable difference from the previous week. Both incidents occurred outside of major travel days, so there is no evidence to conclude that air traffic was disrupted as a result of the GPS interference. Aircraft that lost GPS during approach and landing switched to backup systems such as Instrument Landing System (ILS), Very high-frequency Omni-directional Range (VOR), and Distance Measuring Equipment (DME). As such, some of the marginal benefits of WAAS-based landing procedures may have been lost (i.e. more fuel may have been burnt), but no concrete testimony exists to this effect. The relatively short duration of both disruptions also means they are unlikely to have had a meaningful impact on pilot workload and fatigue.

The readily available backup systems at DFW and DEN, and the aircraft's immediate ability to revert to these systems has preserved value and prevented disruption. For a cautionary tale on what happens in the absence of such systems, one only needs to consider Tartu Airport, the second-largest airport in Estonia, whose only international route (to Finland) was suspended on 29 April 2024 due to GPS interference and lack of ground-based systems. The ongoing war in Ukraine and the repeated and widely publicized jamming activity in the area has rendered the airport, which does not have backup navigation aids, unusable. To mitigate against the disruption of service arising from the GPS interference, Tartu Airport is reinforcing GPS-independent ground navigation equipment. The Finnair route is expected to resume on 2 June 2024.[1]

Beyond airspace operations, the expectation would be that GNSS applications within or in the vicinity of the airport would be disrupted. Ground equipment in large airports is often GNSS tracked (using GPS and often a combination of Galileo, GLONASS, and BeiDou), to improve efficiency and ensure the closest set of stairs, tug, or baggage cart is deployed to incoming aircraft. However, as many pilots reported that GPS was restored once on the ground (with only a small minority reporting that issues continued after landing), these ancillary applications are not likely to have observed a loss of GNSS – indeed, there are no reports to the contrary.

Activities in the vicinity of the airports, including passenger and crew transport would be affected by a loss of GNSS in theory, but in practice it appears that availability of GNSS on the ground was unaffected, thus leaving those applications able to operate continuously. Additionally, there is no evidence on whether L5 was affected by the disruptions. As such, ground-based applications incorporating dual-frequency receivers may have maintained continuity through the use of L5.

Conclusion and lessons learnt

Two instances of GPS disruption at major US airports resulted in no discernible impact on operations. We can deduce two main reasons for this. Firstly, the disruption did not reach the ground level, either because it was directed upwards or because buildings or terrain shielded the ground level, and, secondly, because both airports, and smaller airports in the vicinity, had retained legacy ground-based navigation aids, allowing aircraft to seamlessly revert to working solutions. As evidenced in Tartu in Estonia, the impact of GNSS disruption on air transport is on a completely different scale when such backup systems are not readily available.

The United States intends to move towards a Minimum Operation Network (MON), which will decommission a lot of the existing infrastructure for non-GPS navigation and leave a minimum viable capacity for non-GPS navigation at a selected few airports. MON airports will be spread across the country ensuring no aircraft is more than 100 nautical miles from a MON airport. The impact of GPS disruption on aviation at DFW, DEN, and Tartu advises caution with the move towards MON. Firstly because the traffic patterns at the largest airports make it extremely challenging to divert to smaller sites with fewer runways and infrastructure, and secondly, because the impact of a more widespread GPS outage (e.g. space weather) would make the increased demand on MON airports from many more locations much more complex to tackle, especially with prolonged disruption.

The legacy systems for aviation have long faced calls for retirement. The spectrum they occupy is desired by many other applications and the fact that GPS works almost all the time means the value of a backup is increasingly difficult to argue. The events at DFW and DEN bring the value of a backup into sharper focus, and policy makers must ensure that rationalisation of ground infrastructure can be achieved without losing the backup capability. In fact, policy makers ought to notice the success with which DFW and DEN rode the GPS outage, and consider whether developments should instead be towards a more widely applicable source PNT – one that could benefit other critical and even consumer applications as well.

This study is based on publicly available information. Although individuals in the US Government expressed eagerness to support this effort, they were ultimately unable to gain permission to do so.

[1] FlightGlobal (2024). *Finnair to restore Tartu service after GPS alternative implemented in Estonian airspace*. Available at: https://www.flightglobal.com/air-transport/finnair-to-restore-tartu-service-after-gps-alternative-implemented-in-estonian-airspace/158324.article

1 Context

In the modern aviation landscape, widespread adoption of GPS enabled technology has revolutionized the global aviation industry. GPS provides real-time positioning, navigation, and timing signals to an accuracy of high degree, and adaptations to procedure have been made worldwide to allow for its advancements in the industry. The advantages of these modifications are unequivocal, and overall safety and efficiency in the aviation field has been widely advanced as a result of this and many other developments. However, with GPS at the forefront of continuous technological advances, it is pertinent to consider the potential effects of heavily relying on GPS signals to inform all procedures.

In 2022, the USA saw two significant GPS disruptions at Denver International Airport and Dallas Fort Worth International Airport. The purpose of this research is to identify observable impacts of the incidents, and to determine how they can inform aviation and PNT policy in the future.

Dallas Fort Worth International Airport (DFW) and Denver International Airport (DEN) are two key transport hubs in the United States (US). In 2022 they ranked second and third in the world in terms of passenger traffic, serving over 73 and 69 million passengers respectively.[2] In terms of aircraft movements, they place third and fourth respectively with more than 650,000 and 600,000 take-offs and landings occurring in 2022.[3] This means that on an average single day in 2022, there were more than 1,600 take-offs and landings, and more than 189,000 passengers passing through each of these transport hubs. These airports serve flights at nearly all hours of the day, with reduced numbers between midnight and 6am. To accommodate such high volumes of air traffic requires efficient and reliable operating systems that are resilient to disruption. These airports generate annual economic impacts of over USD $36 billion each[4,5] and represent major air freight hubs in their own right[6] so even minor disruptions to the regular operations of these airports could produce drastic impacts to the regional economy and the US more broadly.

Table 1 2022 Airport statistics

Airport	Passengers	Aircraft movements	Average daily passengers	Average daily aircraft movements
DFW	73,362,946	656,676	200,994	1799
DEN	69,286,461	607,786	189,826	1665

Source: Airports Council International (2023). 'International travel returns: Top 10 busiest airports in the world revealed', accessible at: https://aci.aero/2023/04/05/international-travel-returns-top-10-busiest-airports-in-the-world-revealed/

What, then, would happen in the event of a major disruption? How resilient are the operations at these airports? 2022 provided two major disruption events that allow investigation of such questions in a real-life context. These events involved widespread interference of Global Navigation Satellite System (GNSS) signals in the airspace in the vicinity of DEN on 21-22 January 2022, and DFW on 17-18 October 2022. GNSS is a critical part of navigation, arrivals and departures, and safety-of-life systems onboard aircraft in the US. The loss of such a key system could have severe impacts

[2] Airports Council International (2023). 'International travel returns: Top 10 busiest airports in the world revealed', accessible at: https://aci.aero/2023/04/05/international-travel-returns-top-10-busiest-airports-in-the-world-revealed/
[3] Airports Council International (2023). 'International travel returns: Top 10 busiest airports in the world revealed', accessible at: https://aci.aero/2023/04/05/international-travel-returns-top-10-busiest-airports-in-the-world-revealed/
[4] Dallas Fort Worth International Airport (2024). 'About DFW & Fast Facts', accessible at: https://www.dfwairport.com/business/about/facts/
[5] City and Council of Denver Department of Aviation (2024). 'Airport Info and Fast Facts', accessible at: https://www.flydenver.com/about-den/
[6] Federal Aviation Administration (2023). CY 2022 Qualifying Cargo Airports, Rank Order, and Precent Change from 2021, accessible at: https://www.faa.gov/sites/faa.gov/files/2023-08/CY2022-All-Cargo-airports.pdf

without suitable redundancies in place. These events thus enable a unique analysis of the real impacts of GNSS disruption at two of the largest airports in the world and a test of their resilience.

1.1 The importance of GNSS

Global Navigation Satellite Systems (GNSS) refers to the constellations of satellites that provide position, navigation, and timing (PNT) information to receivers around the globe. The Global Positioning System (GPS) is the American GNSS and was the first to achieve full operational capability (FOC). GPS is present in all GNSS receivers while the complementary systems from Europe (Galileo), Russia (Glonass) and China (BeiDou) are widely used in consumer electronics. The global coverage, low implementation cost, commitment to continuity, and usually high availability and reliability have enabled GNSS to be the PNT solution of choice in a wide range of applications such as financial transactions, location-based services for consumer devices, transport, and Critical National Infrastructure (CNI). Mobile applications like aviation that have a global footprint and operate in a high vertical plane (altitude) are also well served by the unique characteristics of GNSS.

As reliance on GNSS has increased and its applications become higher value and more critical, such as timing for CNI, it has also attracted increasing threats to disrupt, degrade or deny service. Unfortunately, the characteristics of GNSS means that this is relatively easy to achieve. In particular, the orbital height, low power, and relatively low frequency of GNSS signals (L band is at the lower end of the microwave range) means that GNSS signals from space are weak by the time they reach the ground. Interference with these signals (whether malicious or otherwise) is relatively easy to achieve with consumer grade devices, and is not uncommon.

There is currently no universally applicable alternative to GNSS that is fully GNSS independent for positioning and navigation requirements. For example, current sources suggesting that Iridium's STL is GNSS dependent, albeit with internal holdover that can ensure continuity of approximately one day. Loss of GNSS-based timing can be mitigated using adequate oscillators in the GNSS receiver that can hold time for a certain holdover period, ranging from a few minutes to months or through the use of caesium or rubidium clocks. However, the cost of holdover increases as the period of holdover increases, so long-term holdover is limited to only the most critical applications. Loss of position and navigation can be mitigated using alternative (local) systems or sophisticated inertial sensors, although are not yet available in the mainstream.

Loss of GNSS would therefore still affect sectors that rely on PNT, with the extent of loss dependent on the quality of holdover and other mitigation strategies in place. A range of studies have sought to qualify and quantify this impact, suggesting significant disruption and costs across numerous sectors, even accounting for existing holdover and mitigation strategies. However, it should be noted that GNSS as a utility is difficult to value, and absent large-scale natural experiments that can unearth the true reliance on GNSS, the studies remain theoretical. Notable studies include:

- London Economics (LE)'s 2017[7] and 2021[8] studies on the economic impact of a loss of GNSS assessed the exposure of UK economic sectors to outages of GNSS signals (and timing specifically) and found that even short disruptions would cause billions of pounds of economic losses.

[7] i London Economics (2017). 'The economic impact on the UK of a disruption to GNSS', accessible at https://londoneconomics.co.uk/wp-content/uploads/2017/10/LE-IUK-Economic-impact-to-UK-of-a-disruption-to-GNSS-FULLredacted-PUBLISH-S2C190517.pdf

[8] London Economics (2023). 'The economic impact on the UK of a disruption to GNSS', accessible at https://assets.publishing.service.gov.uk/media/652eb0446b6fbf000db7584e/20231018_London_Economics_Report_GNSS.pdf

- In 2019, the National Institute of Standards and Technology commissioned a report[9] to estimate the potential economic impacts of a GPS outage on the US private sector. The report found that the US economy would lose an estimated $30.3 billion over a 30-day outage of GNSS. Importantly, the impact of a GPS outage was only considered for those industries that derive marginal service improvements from GPS (therefore excluding sectors that use GPS but do not require the precision benefits) and assumed a hypothetical scenario where pre-GPS processes and would be readily implementable. As GPS has enabled a wide range of efficiencies, however, the feasibility of achieving the same output based on a pre-GPS mode of operation is questionable. For example, the skills required to navigate 'from A to B' are dwindling in the population, as GPS has enabled assisted navigation 'from me to B'.
- A 2021 US study from the RAND corporation[10] estimated a range of potential losses from a nationwide GPS disruption of $785-1,318m per day – a figure that is small given the availability of alternative GNSS, complementary PNT, and back-up technologies, and therefore likely to be significantly higher if a general disruption to GNSS were to occur.

1.2 GNSS in aviation

Historically, aviation has been inextricably linked with GNSS. It was following the Soviet shootdown of Korean Air Lines Flight 007 in 1983 that the, then, military-only GPS was opened for civilian use. Twenty years later, in 2003, the Federal Aviation Administration (FAA) developed and launched the Wide Area Augmentation System (WAAS), a Satellite-Based Augmentation System (SBAS) to support aviation. WAAS in conjunction with GPS offer pilots and airlines access to more than 4,000 runway ends in the US, allowing planes to land in adverse weather conditions and land more efficiently than using alternative systems, including ground-based navigation aids. More WAAS procedures have been published than other systems, extending the availability of landing procedures to a wider range of locations.

There is a trend towards using SBAS-based landing procedures as these require less ground infrastructure, saving capital and maintenance costs. This trend can be observed in all regions covered by SBAS, for example in the EU, where the Performance Based Navigation (PBN) regulation *"paves the way for rationalisation of conventional navigation procedures"*.[11] GPS remains the only GNSS certified for flight. However, ground operations and applications incidental to the airport increasingly integrate all available GNSS signals to provide the best performance to the user.

Table 2 lists a range of use cases of GPS (and GNSS) in aviation and related applications, with more detail in the write-up below.

Table 2 Uses of GNSS in aviation

Phase	Use case	Description
In-flight	RNAV (Area Navigation) departures and arrivals	Approach procedures that do not require additional ground infrastructure.
	En-route navigation	Efficient navigation with reduced aircraft spacing enabled by GPS

[9] National Institute of Standards and Technology. (2019). 'Economic Benefits of the Global Positioning System (GPS)'. Available at: https://www.rti.org/sites/default/files/gps_finalreport.pdf

[10] U.S. Department of Homeland Security. (2020). 'Report on Positioning, Navigation, and Timing (PNT) Backup and Complementary Capabilities to the Global Positioning System (GPS)', available here: https://www.rand.org/pubs/research_reports/RR2970.html

[11] European GNSS Agency (2020). *EGNOS Grant Plan 2020*. Available at: https://www.euspa.europa.eu/sites/default/files/gsa-egn-pm-pl-a02355_3.0_egnos_grant_plan_2020.pdf [quotation from page 7].

Phase	Use case	Description
	ADS-B	Transponder used for tracking aircraft and in collision avoidance systems.
	Terrain awareness and warning system (TAWS)/ Enhanced Ground Proximity Warning System (EGPWS)	Warns pilots if in close proximity to terrain.
	Runway Overrun Prevention System (ROPS)/ Runway Warning System (ROW)	Determines if the runway is too short to stop.
	Transponders	Communicates information to air traffic controller and other aircraft.
	Satellite Communications	Timing signal for satcoms in oceanic and remote airspaces comes from GPS
	Controller Pilot Data Link Communications (CPDLC)	Efficient communication that requires GPS for time-sync.
	Traffic Alert and Collision Avoidance System (TCAS)	Monitors airspace for transponder equipped aircraft, determines collision threats, and provides warnings to pilots.
	Emergency Locator Transmitter (ELT)	Locators for search and rescue in the event of a crash
	Electronic Flight Bags	Can be use GPS to provide a moving map display
	Emergency Divert Programmes	Route planning for emergency diversions
Ground Operations	Ground vehicle and asset tracking	GNSS trackers, combined with other technology, used to track airport equipment.
	Runway incursion warning	Alerts when vehicles enter runways.
	Taxiing	Measuring taxi speeds
	ADS-B (Vehicle Movement Area Transmitters, VMATs)	Surface vehicles can be equipped with ADS-B
	Air traffic control (ATC) radars	Time synchronisation
Airport adjacent	Vehicle navigation	Navigation
	Rail	Positive Train Control (PTC) for tracking train movements and accident prevention. Accurate information of location and arrival times.
	Buses	Locations and accurate arrival times
	Rideshare	Location and navigation
	Telecommunications	Synchronisation and operational efficiency. Allows for more effective sharing of limited spectrum.
	Smart phones	Navigation and location information e.g. for emergency calls.

GPS has thus become ubiquitous in global aviation and serves important roles at all stages of flight. It has been a crucial component in the modernization of the US National Airspace System (NAS) by the FAA. This initiative, known as the Next Generation Air Transport System (NextGen), takes advantage of GPS signals in modern approach and departure procedures, en-route navigation, and collision avoidance systems. The accuracy provided by GPS allows for reduced separation between aircraft, as well as enabling more direct and shorter routes using area navigation (RNAV)[12], and GPS-based RNAV approaches allow for higher volumes of arrivals and departures[13] - enabling an improvement in passenger throughput with existing airport infrastructure. On-board Automatic Dependent Surveillance-Broadcast (ADS-B) transponders communicate GPS-derived and other information to other aircraft and ground stations, enabling accurate tracking for traffic management and collision avoidance.[14] These capabilities provide benefits in reducing delays and fuel consumption as well as increasing safety. NextGen as a whole contributed an estimated USD 10.9

[12] Eno Center for Transportation (2012). 'NextGen: Aligning Costs, Benefits and Political Leadership', accessible at: https://enotrans.org/wp-content/uploads/2023/02/NextGen-paper1.pdf
[13] Jack Herstam (2023). 'A Pilot's Guide To The Role Of GPS in Aviation', Simple Flying, accessible at: https://simpleflying.com/gps-in-aviation-pilots-guide/
[14] Flightradar24 (2024), 'An introduction into ADS-B', accessible at: https://www.flightradar24.com/blog/ads-b/

billion worth of benefits from 2010-2023.[15] Many of these benefits are underpinned by the accurate positioning information provided by GPS.

As part of the transition to NextGen, and the increased use of GPS in aviation, much of the existing infrastructure required for non-GPS navigation and airport approaches is being decommissioned to leave a Minimum Operational Network (MON) of very high frequency omni-directional range (VOR) and ILS approaches (ground-based approaches that do not rely on GPS).[16] This is an attempt to save money since these approaches require expensive ground equipment, while GPS based approaches do not, and are therefore much cheaper.[17] The MON provides a reduced backup network for use in the event of widespread GPS outage, where flights will always have an airport within 100 nautical miles where VOR or ILS approaches are possible.[18] It is not necessarily the largest or busiest airports that are included in the MON,[19] and other airports might still support non-GPS approaches that require other specific on-board equipment, such as Distance Measuring Equipment (DME) or Automatic Direction Finder (ADF). Therefore, the backup systems available for GPS approaches will largely be dependent on the aircraft and airport involved, and some airports would need to redirect flights to the nearest suitable airport in the event of GPS outage. These differences drive different outcomes to those predicted for the hypothetical Heathrow case study.

In addition to airborne applications, including incoming and outgoing flights, ground operations are vital to the smooth running of an airport. Various ground vehicles, including cargo pallets, passenger boarding stairs, refuelling trucks, and pushback tugs, need to be accurately located and tracked with GNSS[20], and can also incorporate ADS-B systems[21]. This tracking is also important for the prevention of runway incursions which pose major risks to airport staff and passenger safety.[22] Furthermore, pilots use GPS for determining ground speed during taxiing.[23]

The reliance on GNSS, however, does not end with airport applications. Passengers and staff must also travel to and from the airport. This transport could be via personal vehicles and involve navigation using GNSS (i.e. GPS plus a combination of complementary systems). GNSS is also crucial for rideshare apps to communicate accurate pickup locations and navigate efficiently. If travelling by public transport, GNSS still plays a key role in tracking buses and providing accurate arrival times.[24] GNSS is also important in positive train control (PTC) that helps maintain the safety and operation of US rail transport, and GNSS locations are used to provide accurate station arrival times for passengers.[25] While these applications of GNSS sit outside the aviation sector, they represent

[15] Federal Aviation Administration (2024). 'NextGen: Performance Reporting and Benefits', accessible at: https://www.faa.gov/nextgen/reporting-benefits

[16] Federal Aviation Administration (2022). 'Navigation Programs – Very High Frequency Omnidirectional Range Minimum Operation Network (VOR MON)', accessible at: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gbng/vormon

[17] Fred Simonds (2020). 'ILS on the Block', IFR, accessible at: https://www.ifr-magazine.com/charts-plates/ils-on-the-block/

[18] Thomas A. Horne (2021). 'On instruments: The GPS backup. New life for old VORs and ILSs', Aircraft Owners and Pilots Association, accessible at: https://www.aopa.org/news-and-media/all-news/2021/july/pilot/on-instruments-the-gps-backup

[19] Jason Blair (2023). 'Flying the MON', Flying, accessible at: https://www.flyingmag.com/flying-the-mon/

[20] Teltonika (2024). 'Airport Ground Vehicle and Asset Tracking', accessible at: https://teltonika-gps.com/use-cases/telematics/airport-ground-vehicles-and-assets-tracking

[21] Federal Aviation Administration (2023). 'Airport Surface Detection Equipment, Model X (ADSE-X)', accessible at: https://www.faa.gov/air_traffic/technology/asde-x

[22] Skybrary (2024). 'Runway Incursion', accessible at: https://skybrary.aero/articles/runway-incursion

[23] Jack Herstam (2023). 'Taxi Speeds: The Rules, Procedures & Practices That Influence Taxiing', Simple Flying, accessible at: https://simpleflying.com/taxi-speeds-guide/

[24] Regional Transportation District (2023). 'Mobile Apps', accessible at: https://www.rtd-denver.com/open-records/open-spatial-information/mobile-apps

[25] the National Coordination Office for Space-Based Positioning, Navigation, and Timing (2021). 'Rail', accessible at: https://www.gps.gov/applications/rail/

crucial enabling infrastructure for airports as transport for aircrews, airport staff, aviation logistics, passengers, and cargo freight.

1.3 Projected impacts of GNSS disruption at an airport

While the economic impact of real-world disruption to airports has not previously been studied, the hypothetical impact has previously been studied by London Economics in 2021. This report on the projected impacts of a loss of GNSS in the UK included a case study on the impact of GNSS disruptions in the area around Heathrow Airport.[26] Drawing on interviews with experts and desk-based research of aviation infrastructure and sources of resilience, the report predicted minimal airside disruption but a potentially compounding impact from landside transport disruption. Specifically, inbound flights to the airport would be minimally impacted due to the existence of backup inputs and GNSS-independent systems such as the instrument landing system (ILS). The main predicted impact was on road traffic, where GNSS disruptions would lead to slowed traffic into and out of the airport. These delays are also predicted to have cascading effects such as missed and delayed flights due to passenger and crew delays which would compound over the period of outage.

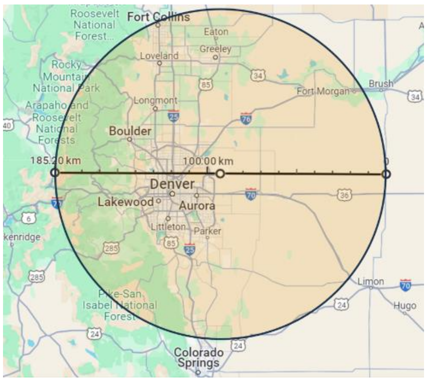
This analysis was performed on a UK airport but can largely be adapted to US airports with some allowances for US-specific practices. Ground transport is predicted to be impacted in a similar way, with the potential for cascading effects on outbound flights. However, the extent of back-up systems available as alternatives to GPS for flights in the US is being reduced.

2 Scope of the GNSS disruption events

2.1 Denver International Airport

At 10:33pm on Friday January 21st 2022, an advisory Notice to Airmen (NOTAM) was issued, advising pilots of widespread GNSS disruption in the area around the Denver International Airport. The affected area covered a 50 nautical mile radius around the airport (Figure 1), spanning approximately 8,000 square nautical miles.[27]

Figure 1 Map of are of GNSS disruption around Denver International Airport



Note: 50 nautical mile radius drawn using google maps. 1 nautical mile = 1.852km.

Source: Google maps

The Cybersecurity and Infrastructure Security Agency (CISA) have since released a report highlighting some details of the event.[28] The report confirms the event lasted 33 hours and was caused by a source unintentionally emitting an L1 frequency signal that interfered with GPS. This interference impacted flights in the affected region at altitudes up to 36,000ft, and also suggests the range might have stretched much farther afield,

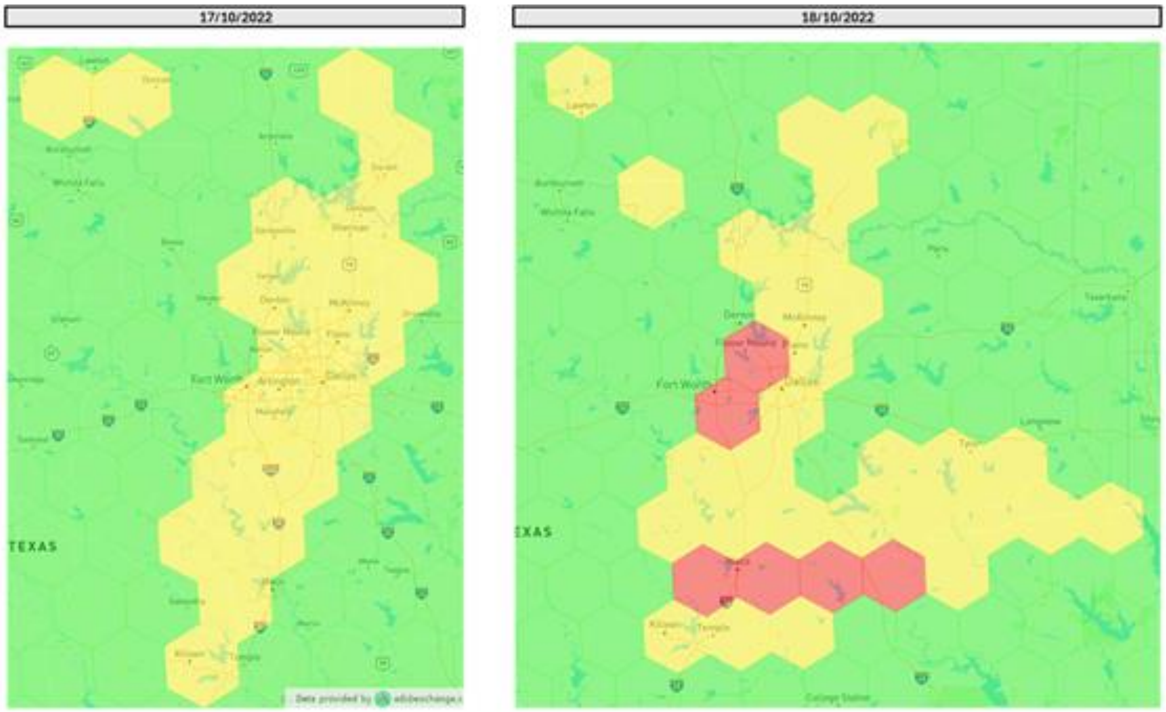
[26] London Economics (2023). 'The economic impact on the UK of a disruption to GNSS'.
[27] Dana A. Goward (2022). 'What happened to GPS in Denver', GPS World, accessible at: https://www.gpsworld.com/what-happened-to-gps-in-denver/
[28] Cybersecurity & Infrastructure Security Agency (2022). 'Global Positioning System (GPS) Interference', accessible at: https://www.cisa.gov/sites/default/files/publications/CISA-Insights_GPS-Interference_508.pdf

perhaps reaching 230 nautical miles from the interference source. While the exact timing of the event is unknown, it is likely to have begun at or before 15:30 on January 21st, as a report of GPS interference in the area at this time was submitted to the United States Coast Guard Navigation Center (NAVCEN)[29]. As the disruption lasted for more than 24 hours it spanned periods of both high and low flight traffic throughout the day. This event ended when the source of the interference was eventually located and terminated. January 21-22 were a Friday and Saturday outside of school or public holidays, and are therefore characterized by average levels of passenger traffic.

2.2 Dallas Fort Worth International Airport

A similar Air Traffic Control System Command Center (ATCSCC) advisory was issued at 4:51pm on Monday 17th October 2022 warning pilots of GPS anomalies in the airspace around Dallas Fort Worth International Airport.[30] The region of disruption can be viewed using an online tool for examining GPS interference developed in July 2022 (Figure 2).[31]

Figure 2 Map of GPS interference around Dallas Fort Worth International Airport



Note: Map showing extent of GPS disruption on both days of GNSS disruption around Dallas Forth Worth.

Source: John Wiseman (2022). 'GPSJAM', accessible at: https://gpsjam.org/?lat=31.29129&lon=-96.96985&z=5.4&date=2022-10-17

Although original reports of the disruption suggested the event lasted for 44 hours[32], subsequent research by a group at Stanford University identified a more realistic timeline of significant GPS jamming from 2:21pm on October 17th, to 2:10pm on October 18th, or roughly 24 hours[33]. This spanned periods of both high and low flight traffic throughout the day. The source of this

[29] Report found on United States Coast Guard Navigation Center (NAVCEN) on 01/21/2022 at 1530 Mountain Standard Time, accessible at: https://www.navcen.uscg.gov/gps-problem-report-status

[30] Joerger, M., Fan, C., Jada, S., (2023). 'The Unsolved Mystery of the 2022 Texas Interference', Inside GNSS, accessible at: https://insidegnss.com/the-unsolved-mystery-of-the-2022-texas-interference/

[31] John Wiseman (2022). 'GPSJAM', accessible at: https://gpsjam.org/?lat=31.29129&lon=-96.96985&z=5.4&date=2022-10-17

[32] Resilient Navigation and Timing Foundation (2022). 'DOT Must Warn Public During GPS Disruptions – PNT Advisory Board', accessible at: https://rntfnd.org/2022/11/19/dot-must-warn-public-during-gps-disruptions-pnt-advisory-board/

[33] Liu, Z., Blanch, J., Lo, S., Walter, T. (2022). 'Investigation of GPS interference events with refinement on the localization algorithm', Proceedings of the 2023 International Technical Meeting of The Institute of Navigation, (January), pp. 327-338

interference was never identified, and the disruption ended on its own. However, research has showed the source caused substantial jamming in a 200km radius around DFW and impacted aircraft at all altitudes.[34] The same research suggested that the interference might have been directional and upward facing, potentially changed direction on October 18th, and had minimal impact on ground GPS receivers. However, the disruption to GPS on-board aircraft led to the closure of a runway at DFW.[35] October 17-18 were a Monday and Tuesday outside of school or public holidays, and are therefore characterized by average levels of passenger traffic.

3 Quantifiable impact

3.1 Air traffic

3.1.1 Denver International Airport

The most obvious initial line of investigation for GNSS disruption across a major airport is the impact on commercial flight services. Aircraft rely on GNSS for navigation and tracking, and also for air traffic management, separation distances, and take-off and landing procedures. Within the week commencing 17th January 2022, Denver International Airport saw a total of 9,801 arrivals and departures.[36] Analysis of the flight data indicates no unusual pattern in the cancellation, delay, and diversion rates on the days of interference. Surprisingly, with respect to the week before, these factors actually improved during the period of GPS disruption – as seen in Table 3 and Table 4.

Table 3 Inbound flight disruptions at Denver International Airport

	21 -22 Jan 2022 (disruption)	14 – 15 Jan 2022 (week before)	2023 Average	2022 Average (Feb – Dec)
Percent flights cancelled	3.46%	3.82%	1.53%	2.24%
Percent flights diverted	0.00%	0.00%	0.38%	0.31%
Percent flights delayed	16.29%	19.49%	20.97%	19.93%

Note: Comparison of inbound flight disruptions during GPS interference to the week before, the average for 2023, and the average for the remaining months in 2022

Source: Data obtained from the Bureau of Transportation Statistics, 'Airline On-Time Statistics', accessible at: https://www.transtats.bts.gov/ONTIME/Index.aspx

Table 4 Outbound flight disruptions at Denver International Airport

	21 -22 Jan 2022 (disruption)	14 – 15 Jan 2022 (week before)	2023 Average	2022 Average (Feb – Dec)
Percent flights cancelled	3.24%	4.33%	1.43%	2.13%
Percent flights diverted	0.00%	0.22%	0.26%	0.25%
Percent flights delayed	19.51%	24.96%	26.65%	28.07%

Note: Comparison of outbound flight disruptions during GPS interference to the week before, the average for 2023, and the average for the remaining months in 2022

Source: Data obtained from the Bureau of Transportation Statistics, 'Airline On-Time Statistics', accessible at: https://www.transtats.bts.gov/ONTIME/Index.aspx

[34] Joerger, M., Fan, C., Jada, S., (2023). 'The Unsolved Mystery of the 2022 Texas Interference', Inside GNSS, accessible at: https://insidegnss.com/the-unsolved-mystery-of-the-2022-texas-interference/

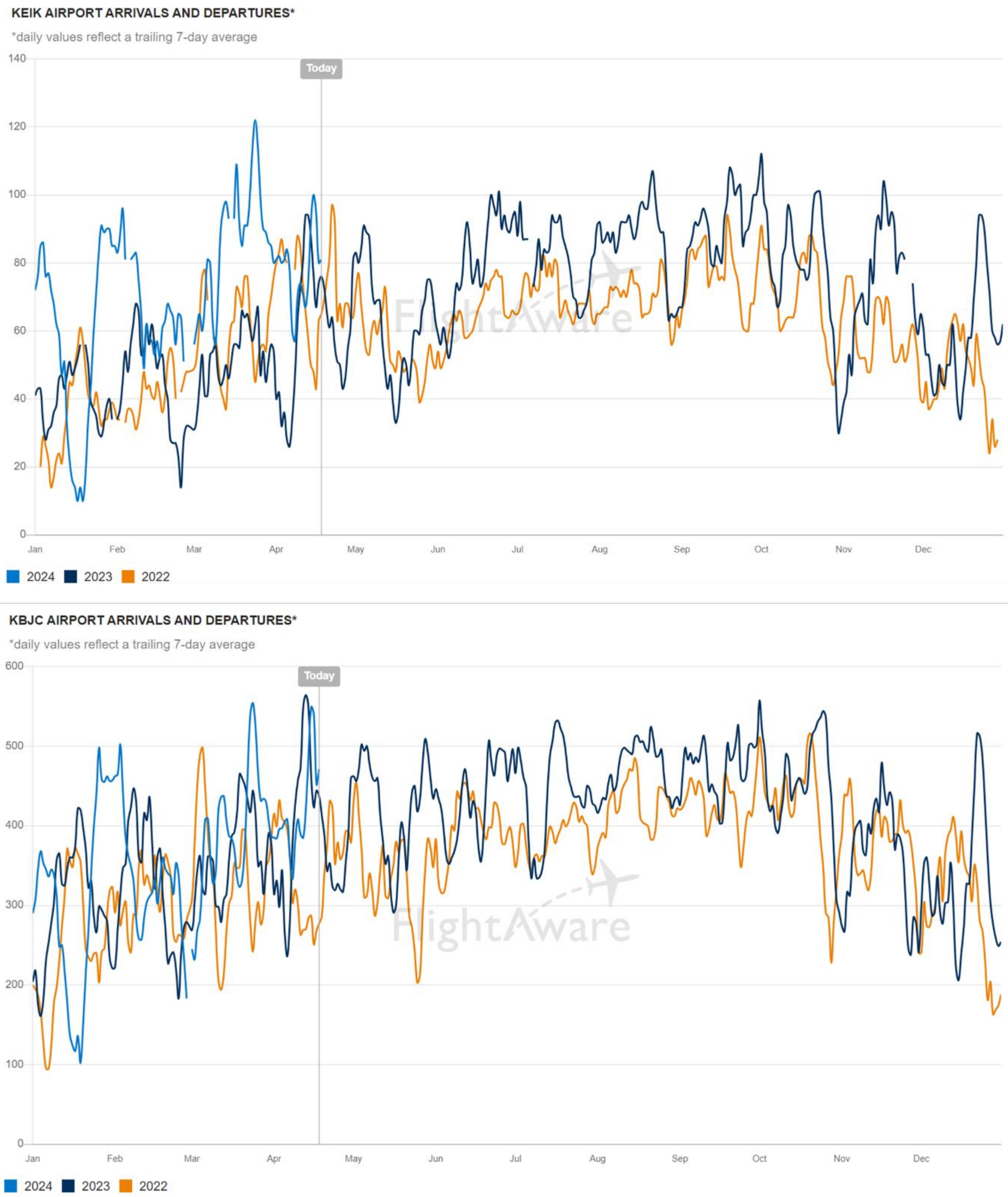
[35] Dan Goodin (2022). 'GPS interference caused the FAA to reroute Texas air traffic. Experts stumped', ars technical, accessible at: https://arstechnica.com/information-technology/2022/10/cause-is-unknown-for-mysterious-gps-outage-that-rerouted-texas-air-traffic/

[36] Data obtained from the Bureau of Transportation Statistics, 'Airline On-Time Statistics', accessible at: https://www.transtats.bts.gov/ONTIME/Index.aspx

While Denver International Airport is the largest airport in the impacted area, it is also worthwhile investigating the smaller surrounding airports that might have also felt the impact of a GNSS outage. Erie Municipal Airport and Rocky Mountain Metropolitan Airport are two applicable examples that lie within the locality of the GNSS interference (19 and 21 nautical miles north-west and west of DEN respectively).

Figure 3 illustrates the number of arrivals and departures at both airports by day and indicate there is no clear disruption on either of the affected dates.[37]

Figure 3 Flight data for Erie Municipal Airport and Rocky Mountain Metropolitan Airport



Note: Number of arrivals and departures at Erie Municipal Airport (top) and Rocky Mountain Metropolitan Airport (bottom)

Source: figures obtained from FlightAware, accessible at: https://www.flightaware.com/live/

[37] Data obtained from FlightAware, accessible at: https://www.flightaware.com/live/

Pilots arriving and departing from DEN also reported instances of GPS interference using NASA's Aviation Safety Reporting System (ASRS). A total of 19 reports were identified by the Resilient Navigation and Timing Foundation (RNTFND) as relating to GPS problems during this period.[38] A further 28 reports were identified from January 2022 in Colorado as likely being linked to this disruption. These reports highlight that pilots experienced issues with their GPS, ADS-B, transponders, terrain warning systems, and traffic alert and collision avoidance systems (TCAS). Many pilots reported experiencing these issues, but also that they landed or departed uneventfully, with systems returning on landing or travelling far enough from the airport (though in some cases the disruption was reported to continue after landing). There were only two disruptions reported that were of any consequence. In one instance, one plane followed a level off resolution advisory after a warning from its collision avoidance system, where no prior warning was produced before this immediate action was required. Ordinarily the TCAS would first provide a traffic advisory (which does not require imminent response) that may then escalate into a resolution advisory requiring action from the pilots to avoid collision.[39] The other aircraft involved reported receiving no advisory from their TCAS. Another pilot reported executing a go-around (an aborted approach requiring restarting the approach to land safely) after losing auto-pilot and radio altimeter. Other pilots also reported minor mistakes that were in part due to the distracting warnings produced by this disruption, or while attempting to avoid the disrupted airspace.

These reports show that the disruption detrimentally impacted in-flight systems, but combined with the lack of impact observed on arrivals and departures shows that suitable back-ups were in place at DEN to prevent this causing disruption to airport operations.

3.1.2 Dallas Fort Worth International Airport

In 2022, Dallas Fort Worth Airport was the second busiest airport in the world by passenger traffic and boasted a 77% on-time arrival rate.[40] On the two days of GNSS interference, DFW saw 2,991 successful inbound and outbound flights and, similarly to Denver, there is insufficient statistical evidence to conclude that there was a material impact on commercial flights.

The flight data analysis produced a result remarkably comparable to that for the disruption around Denver Airport, the difference being that the delay rate of both inbound and outbound flights seems larger in comparison to the week before disruption. However, against the average for 2023 and taking into consideration the expectation of flight delay numbers for an interference of this magnitude, the figures still portray minimal disruption. The primary airline at DFW airport (American Airlines) stated to the press that the GPS issue did not affect business, and Southwest Airlines further confirmed that it was not experiencing any disruptions.[41]

[38] Resilient Navigation and Timing Foundation (2022). 'ASRS Reports of GPS problems, Denver, January 2022', accessible at: https://rntfnd.org/wp-content/uploads/ASRS-Reports-of-GPS-Problems%5eJ-Denver%5eJ-January-2022.pdf

[39] Pete (2021). 'TCAS – A Definitive Guide for Pilots', Aviation Matters, accessible at: https://www.aviationmatters.co/tcas-guide/?utm_content=cmp-true

[40] Alexandre Skores (2023). 'DFW Airport, Dallas Love Field ranked high for flight delays in 2022', The Dallas Morning News, accessible at: https://www.dallasnews.com/business/airlines/2023/03/22/dfw-dallas-love-field-lag-compared-to-other-major-airports-for-on-time-arrivals

[41] Airguide (2022). 'Mysterious GPS Disruptions Spread Across Texas; FAA Issues Warning to Pilots', accessible at: Mysterious GPS Disruptions Spread Across Texas; FAA Issues Warning to Pilots – AirGuide Business – Air and Travel Business News :: AirGuide.info – Pyramid Media Group

Table 5 Inbound flight disruptions at Dallas Fort Worth International Airport

	17 – 18 Oct 2022 (disruption)	10 - 11 Oct 2022 (week before)	2023 Average	2022 Average (Jan – Sep)
Percent flights cancelled	0.06%	0.2%	1.63%	3.39%
Percent flights diverted	0.00%	0.13%	0.32%	0.38%
Percent flights delayed	20.16%	9.58%	20.77%	18.62%

Note: Comparison of inbound flight disruptions during GPS interference to the week before, the average for 2023, and the average for the remaining months in 2022

Source: Data obtained from the Bureau of Transportation Statistics, 'Airline On-Time Statistics', accessible at: https://www.transtats.bts.gov/ONTIME/Index.aspx

Table 6 Outbound flight disruptions at Dallas Fort Worth International Airport

	17 – 18 Oct 2022 (disruption)	10 - 11 Oct 2022 (week before)	2023 Average	2022 Average (Jan – Sep)
Percent flights cancelled	0.00%	0.06%	1.58%	3.29%
Percent flights diverted	0.13%	0.00%	0.28%	0.26%
Percent flights delayed	17.69%	11.28%	23.11%	21.52%

Note: Comparison of outbound flight disruptions during GPS interference to the week before, the average for 2023, and the average for the remaining months in 2022

Source: Data obtained from the Bureau of Transportation Statistics, 'Airline On-Time Statistics', accessible at: https://www.transtats.bts.gov/ONTIME/Index.aspx

While deemed minor next to DFW, Dallas Love Field Airport is an established airport in its own right, conducting 226,591 flight operations in 2022[42], residing only 10 nautical miles east of DFW, and within the area of GNSS disruption. Upon investigation, arrival and departure trends at Dallas Love Field Airport also demonstrated lack of impact.

Table 7 Inbound flight disruptions at Dallas Love Field Airport

	17 – 18 Oct 2022 (disruption)	10 - 11 Oct 2022 (week before)	2023 Average	2022 Average (Jan – Sep)
Percent flights cancelled	0.24%	0.00%	1.57%	3.30%
Percent flights diverted	0.00%	0.00%	0.35%	0.41%
Percent flights delayed	14.93%	15.42%	19.31%	24.38%

Note: Comparison of inbound flight disruptions during GPS interference to the week before, the average for 2023, and the average for the remaining months in 2022

Source: Data obtained from the Bureau of Transportation Statistics, 'Airline On-Time Statistics', accessible at: https://www.transtats.bts.gov/ONTIME/Index.aspx

Table 8 Outbound flight disruptions at Dallas Love Field Airport

	17 – 18 Oct 2022 (disruption)	10 - 11 Oct 2022 (week before)	2023 Average	2022 Average (Jan – Sep)
Percent flights cancelled	0.00%	0.00%	1.50%	3.18%
Percent flights diverted	0.00%	0.24%	0.22%	0.21%
Percent flights delayed	23.19%	20.15%	23.72%	32.25%

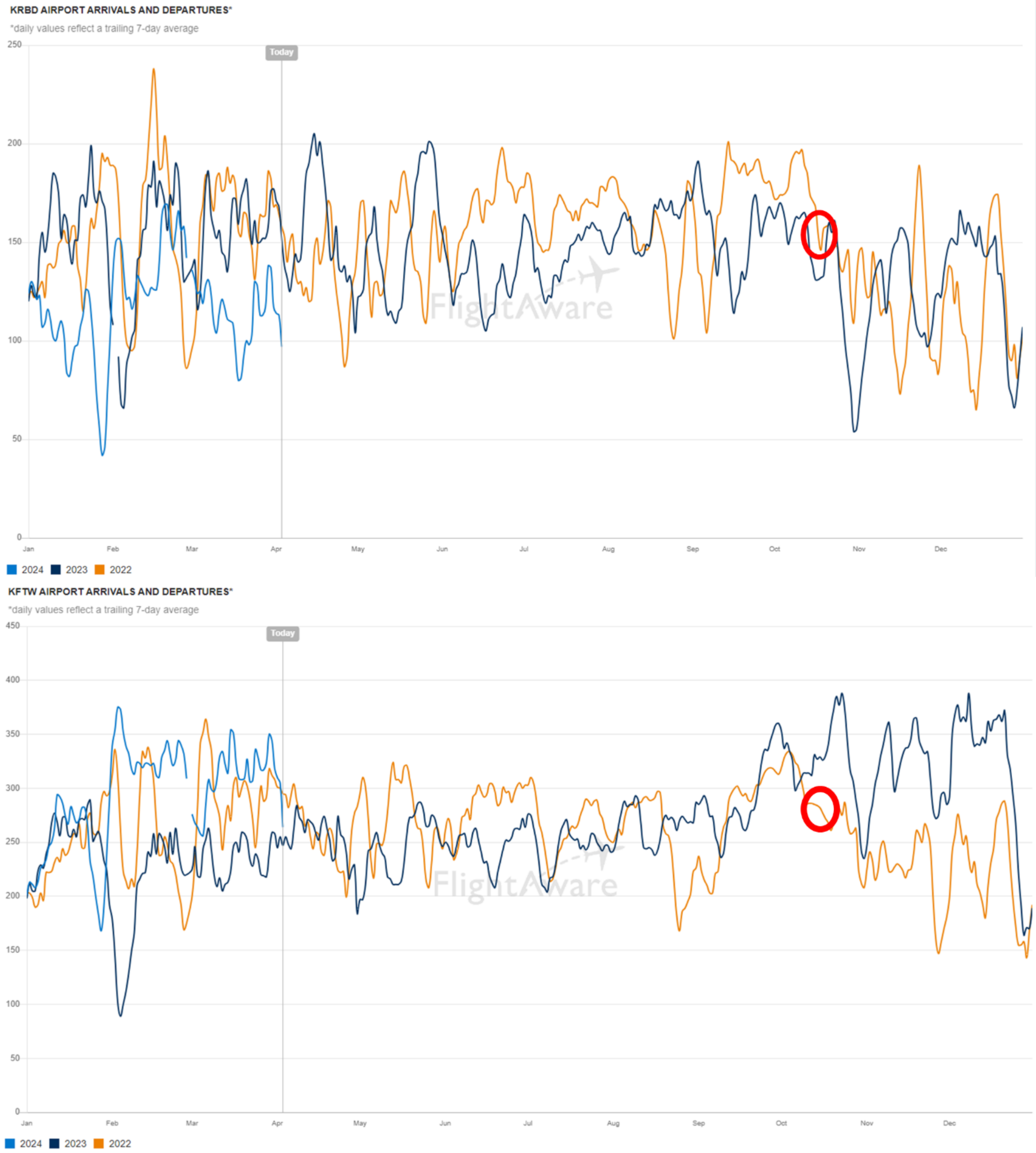
Note: Comparison of inbound flight disruptions during GPS interference to the week before, the average for 2023, and the average for the remaining months in 2022

Source: Data obtained from the Bureau of Transportation Statistics, 'Airline On-Time Statistics', accessible at: https://www.transtats.bts.gov/ONTIME/Index.aspx

[42] Dallas Love Field (2022). '2022 Annual Report', accessible at: dallas-lovefield.com/home/showpublisheddocument/2747/638079354892330000

The flight patterns of smaller airports surrounding DFW were also considered during this analysis. The most relevant examples were Dallas Executive Airport and Fort Worth Meacham International Airport (16 nautical miles south east, and 17 nautical miles north west of DFW respectively), both of which seemed resilient to the surrounding disruption, as per Figure 4.

Figure 4 Flight data for Dallas Executive Airport and Fort Worth Meacham International Airport



Note: Number of arrivals and departures at Erie Municipal Airport (top) and Rocky Mountain Metropolitan Airport (bottom)

Source: figures obtained from FlightAware, accessible at: https://www.flightaware.com/live/

During the time of interference, there was only one ASRS report relating to GPS issues made by pilots flying in or around DFW, with only one further report related to the outage when widening the search to Texas.[43] One was a report stating that manual landing was required due to autopilot

[43] ASRS database online, DFW, October 2022, accessible at: https://akama.arc.nasa.gov/ASRSDBOnline/QueryWizard_Display.aspx?server=ASRSO

failing to intercept the inbound course. A safe visual landing was carried out and no further impact or danger was reported. The other mentioned descending 200ft below an assigned altitude, that was caused by an autopilot issue attributed to the GPS outage.

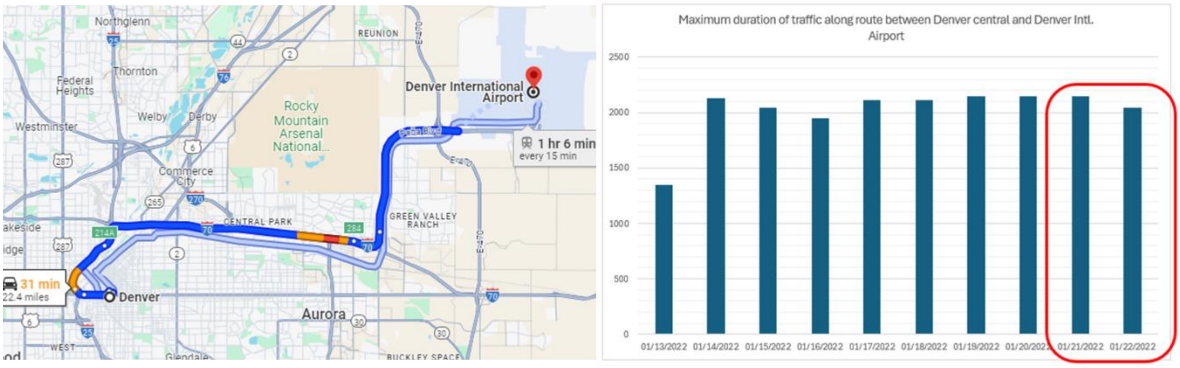
3.2 Ground Operations

A holistic assessment of the impact of GNSS disruption on airports requires an assessment of the impact on enabling systems and infrastructure that serve airports and may therefore represents a secondary source of disruption. Ground operations is one such area.

For example, road transport is reliant on GNSS for optimized navigation and fleet management. A US study in 2022 indicated heavy automobile driver reliance on GNSS.[44] 93% of respondents to this survey admitted to being dependent on their navigation system, and both Denver and Fort Worth placed in the top five cities in which the most drivers admitted to being *extremely* dependent on GPS for navigation. A disruption to GNSS could therefore be expected to have a significant impact on traffic navigation and management within the vicinity of interference. If this were to persist for an extended period, the interruption in passenger, aircrew, airport staff, aviation logistics, and freight could be expected to have a cascading effect on airport operations, airline performance, and ultimately the supply-chains that are reliant on air freight.

In practice, the traffic congestion data for routes between central Denver or Boulder (north west of Denver) and Denver International Airport on the days of GNSS disruption presents no clear indication of impact – see Figure 5 and Figure 6.[45] These routes were selected by google maps as the best routes from these locations and follow two different main roads to the airport.

Figure 5 Map of route and travel times from central Denver to DEN



Note: Map of route from central Denver to DEN (left). Graph of maximum travel times for this route during the disruption and the week leading up to disruption

Source: map: google maps. Travel times: Data obtained using Outscraper, accessible at: https://outscraper.com/google-maps-traffic-extractor/

[44] Unitedtires library (2022). 'Study Reveals Where Drivers Are Most Reliant on Their GPS', accessible at: Study Reveals Where Drivers Are Most Reliant on Their GPS - Tire Reviews, Buying Guide & Interesting Facts - Utires.com
[45] Data obtained using Outscraper, accessible at: https://outscraper.com/google-maps-traffic-extractor/

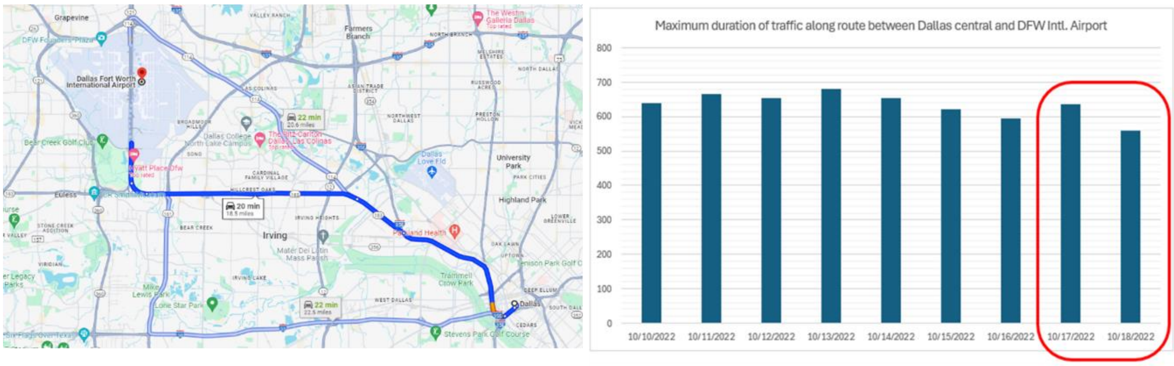
Figure 6 Map of route and travel times from Boulder to DEN

Note: Map of route from Boulder to DEN (left). Graph of maximum travel times for this route during the disruption and the week leading up to disruption

Source: map: google maps. Travel times: Data obtained using Outscraper, accessible at: https://outscraper.com/google-maps-traffic-extractor/

The same analyses were conducted for the routes from Dallas and Fort Worth to Dallas Fort Worth Airport, and the results produced a relatively identical conclusion, shown in Figure 7 and Figure 8, that traffic management in the area was not affected by the outage of GNSS. The routes chosen were again selected by google maps as the best routes from the centres of Dallas and Fort Worth, and approach the airport along the main road from opposite directions.

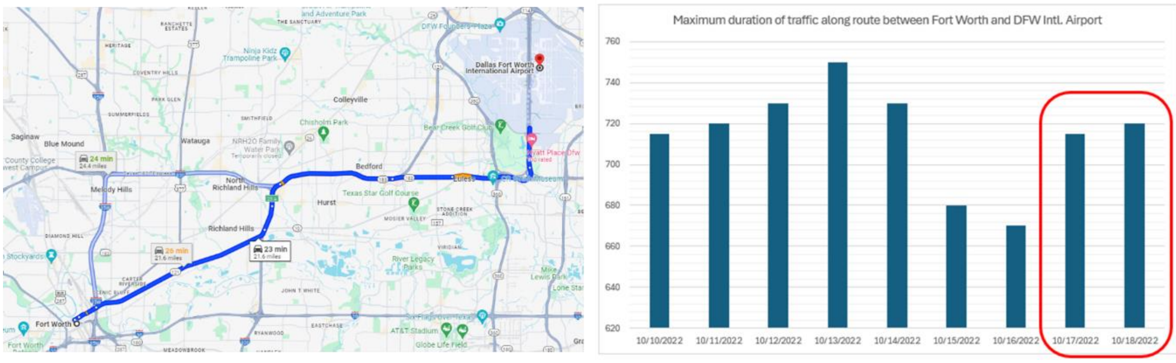
Figure 7 Map of route and travel times from Dallas to DFW



Note: Map of route from Dallas to DFW (left). Graph of maximum travel times for this route during the disruption and the week leading up to disruption

Source: map: google maps. Travel times: Data obtained using Outscraper, accessible at: https://outscraper.com/google-maps-traffic-extractor/

Figure 8 Map of route and travel times from Fort Worth to DFW



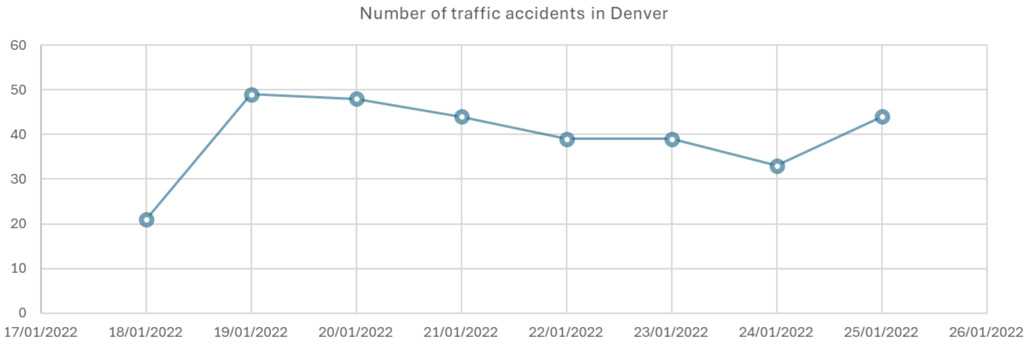
Note: Map of route from Dallas to DFW (left). Graph of maximum travel times for this route during the disruption and the week leading up to disruption

Source: map: google maps. Travel times: Data obtained using Outscraper, accessible at: https://outscraper.com/google-maps-traffic-extractor/

Along a similar line of discourse, GNSS not only provides navigation systems with the means to deliver accurate routing but also to alert road users to potential hazards. Drivers, particularly those visiting the city, rely heavily on directional guidance and so it is sensible to expect an uplift in traffic accidents amid a period of GPS loss.

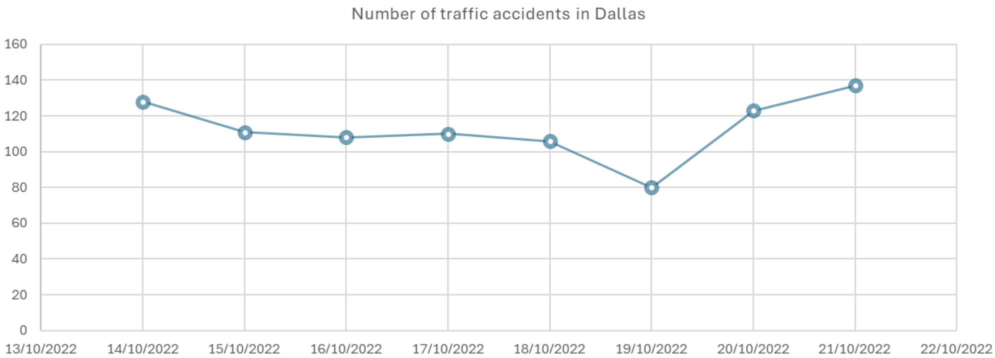
However, the statistics of traffic accidents in the cities of both Denver and Dallas over the course of their respective GNSS outages implies that crash numbers were unaffected by interruption in both cases, as demonstrated in Figure 9 and Figure 10.

Figure 9 Graph showing the number of traffic accidents in Denver by day.



Source: Data was obtained from the City of Denver Open Data Catalog, accessible at: https://www.denvergov.org/opendata/dataset/city-and-county-of-denver-traffic-accidents. Data is available under the license CC BY 3.0: http://creativecommons.org/licenses/by/3.0/.

Figure 10 Graph showing the number of traffic accidents in Dallas by day.

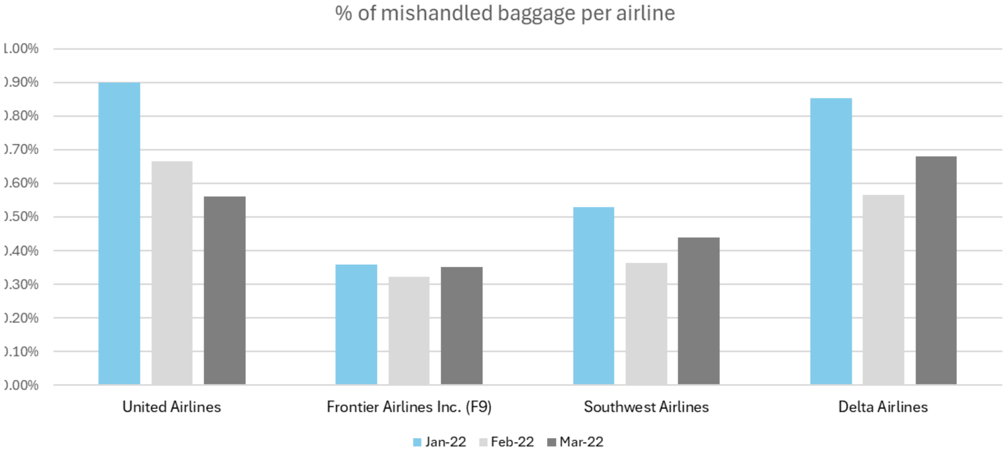


Source: Data was obtained from the Texas Department of Transportation, Crash Records Information System, accessible at: https://cris.dot.state.tx.us/public/Query/app/home

Seemingly minor yet pertinent indicators of impact during loss of GNSS signals are ground handling services. Flight delays and diversions, as well as congestion, contribute to the mishandling of passenger luggage, so it is assumed that we would likely see a spike in lost or misplaced luggage during GPS disruption. As such, the statistics for mishandled baggage have been analysed.

Figure 11 shows the percentage of passenger baggage that was mishandled by the primary airlines that fly through Denver for January 2022 alongside February and March for reference.

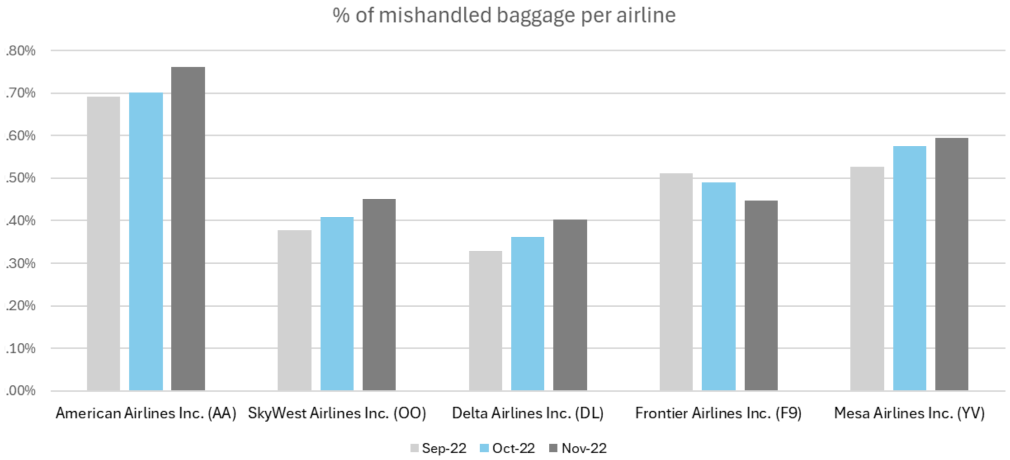
Figure 11 Graph showing the percentage of mishandled baggage by month and airline.



Source: U.S. Department of Transportation (2023). 'Air Travel Consumer Reports for 2022', accessible at: https://www.transportation.gov/individuals/aviation-consumer-protection/air-travel-consumer-reports-2022

The results show an increase in January, which could be interpreted as an indicator of interference impact at ground level. However, this data is for these airlines across the whole country, and not for these airports specifically and so any impact is diluted by all other airports served by these airlines. Taking United Airlines as an example, Denver was their second most visited airport in 2022 but were among 342 others and there is no data indicating that this increase was seen specifically at Denver. Turning to the figures for DFW's primary airlines in October 2022, no significant impact can be deduced, and the same caveats apply.

Figure 12 Graph showing the percentage of mishandled baggage by month and airline.



Source: U.S. Department of Transportation (2023). 'Air Travel Consumer Reports for 2022', accessible at: https://www.transportation.gov/individuals/aviation-consumer-protection/air-travel-consumer-reports-2022

One impact was identified on the ground was the loss of sync between base transceivers in Aurora Colorado (within the range of the Denver jamming) on 21st January 2022. This was reported to NAVCEN, and identified that three sites in Aurora were affected as well as a public safety communication system.[46]

[46] Report found on United States Coast Guard Navigation Center (NAVCEN) on 01/21/2022 at 1530 Mountain Standard Time, accessible at: https://www.navcen.uscg.gov/gps-problem-report-status

3.3 Other

DEN and DFW are two of the busiest airports in the world, respectively serving 69.3 million and 73.4 million passengers in 2022.[47] This passenger volume, alongside a study that showed 14% of surveyed US adults had made a complaint about travel or tourism via social media within the last 6 months[48], creates an expectation of a large number of public posts to be made during disruption of airports of this magnitude. Nevertheless, the digital footprint of both events on social media was minimal and less than 5 complaints were found online coinciding with each of them.

In regard to the Dallas event, there were more tweets posted by people having successfully flown through DFW than those of a complaining nature. For Denver, the Federal Aviation Administration was posting photos of the weather on January 21st, warning customers that low visibility may actually be the cause of any delays at Charlotte Douglas and Denver International Airport.[49]

Figure 13 Tweet from the Federal Aviation Administration on potential disruption at DFW

Source: Twitter

Aside from complaints, there were some general discussions about the events online, albeit not as many as expected. One Reddit thread discussed the disruption at Denver, with pilot(s) flying in and out of nearby Centennial airport mentioning issues they experienced with GPS.[50] The thread mentions that zero RNAV approaches were performed because of this disruption. Another thread shows an email from a flight school. This says that pilots would be grounded if their ADS-B failed (which was likely in the current circumstances).[51]

In an aviation online forum, a member of the site claimed to be sitting in the jump seat of an Airbus A320 about 40 miles South of DFW at FL350 during the Dallas disruption. This passenger alleged they heard 'lots of chatter on the radio' and their GPS was blank for roughly 20 minutes but reported no further impact.[52]

Annex 1 presents a selection of social media posts concerning DEN and DFW during the disruptions.

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[47] Airports Council International (2023). 'International travel returns: Top 10 busiest airports in the world revealed', accessible at: https://aci.aero/2023/04/05/international-travel-returns-top-10-busiest-airports-in-the-world-revealed/

[48] Bhavika Bansal (2023). 'Are Britons and Americans likely to use social media for complaints with automotive brands?', YouGov, accessible at: https://business.yougov.com/content/47137-are-britons-and-americans-likely-to-use-social-media-for-complaints-with-automotive-brands

[49] Twitter post on January 21 2022, accessible at: https://twitter.com/FAANews/status/1484530469618204672

[50] Reddit thread on January 23 2022, accessible at: https://www.reddit.com/r/flying/comments/safwek/cause_of_den_gps_issues/?rdt=62786

[51] Reddit thread on January 23 2022, accessible at: https://www.reddit.com/r/aviation/comments/sawzrx/got_this_email_from_my_flight_school_yesterday/

[52] Van's Air Force thread, October 20 2022, accessible at: https://vansairforce.net/threads/mysterious-gps-outage-around-dfw.210956/

4 Conclusion

The analysis undertaken for this study has shown that despite heavy reliance of systems in and around airports on reliable GPS data, these two instances of widespread GPS interference durations are characterized by limited real world impact. How and why was this the case? There are two main reasons for this. One is that functional back-up systems were in place for aircraft GPS enabled systems. The other is that ground-based systems were mostly unaffected in these events.

Both airports had runways with the infrastructure to support ILS/DME approaches[53,54] which allowed for safe approaches and landings despite the GPS issues. Several pilots reported making use of these systems during the outage.[55] While it is commonplace to use GPS-based approaches, many aircraft and airports are still equipped with the technology for performing alternative, ground-based approaches with equivalent levels of safety. These incidents demonstrate why redundancy is critically important.

However, with the US moving towards the Minimum Operational Network (MON) in an effort to cut costs, the number of airports with suitable back-up systems is being reduced.[56] The airports in this study are not part of the list of MON airports[57] due to the dependence of their Instrument Landing Approaches (ILS) approaches on Distance Measuring Equipment (DME) (whereas MON airports support ILS or Very High Frequency Omnidirectional Range (VOR) approaches that do not rely on GPS or DME[58,59]). Only aircraft that are not equipped with DME would have been unable to land using an instrument approach at DEN or DFW. It is therefore lucky that these airports had plenty of runways supporting these approaches; if they had not the economic impact of rerouting flights to neighbouring airports could have been more severe.

Such extensive back-up systems are not necessarily in place for ground-based GPS users. Are there equivalent suitable backup systems for rail, buses, and rideshares? What about for other drivers and general smartphone users? Due to the lack of impact on ground receivers in these events we do not have specific evidence of the impact GNSS loss would have. However, the outcome of a theoretical analysis of GNSS in the UK[60] are likely to hold true in the US. This theoretical analysis accurately predicted that the impact on flights would be minimal due to alternative landing procedures. Further predictions suggested that GNSS disruption near the airport could have much stronger impacts on road traffic, and cascading effects on flights due to passenger and staff delays if disruption were to persist. The economic impacts are expected to be much more severe if ground receivers were also impacted by this interference. It is therefore fortuitous that the disruptions of both DEN and DFW were restricted to the airspace, with the ground-level kept free of disruption.

The focus of this report was on two specific incidents of GPS disruption in the US in 2022. looking further afield and more recently, 46,000 flights have experienced GPS interference between August

[53] AirNav (2024). 'KDEN: Denver International Airport, Denver, Colorado, USA', accessible at: https://airnav.com/airport/kden
[54] AirNav (2024). 'KDFW: Dallas-Fort Worth International Airport, Dalla-Fort Worth, Texas, USA', accessible at: https://www.airnav.com/airport/KDFW
[55] Resilient Navigation and Timing Foundation (2022). 'ASRS Reports of GPS problems, Denver, January 2022', accessible at: https://rntfnd.org/wp-content/uploads/ASRS-Reports-of-GPS-Problems%5eJ-Denver%5eJ-January-2022.pdf
[56] PilotWorkshops.com featuring John Krug (2023). 'The VOR Phase-Out', accessible at: https://pilotworkshop.com/tips/vor-decommissioning-as-of-2023/
[57] Federal Aviation Administration (2024). 'Digital – Chart Supplement (d-CS)', accessible at: https://www.faa.gov/air_traffic/flight_info/aeronav/digital_products/dafd/
[58] Jason Blair (2023). 'Flying the MON', Flying, accessible at: https://www.flyingmag.com/flying-the-mon/
[59] Federal Aviation Administration (2022). 'Navigation Programs – Very High Frequency Omnidirectional Range Minimum Operation Network (VOR MON)', accessible at: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gbng/vormon
[60] London Economics (2023). 'The economic impact on the UK of a disruption to GNSS'.

2023 and March 2024 in the Baltic, Black Sea, and eastern Mediterranean regions.[61] Tartu Airport in Estonia has dramatically suffered from GPS jamming, with all flights to and from this airport suspended from April 29th until the end of May 2024.[62] This occurred after two Finnair flights diverted back to Helsinki after being unable to land at Tartu due to GPS interference. Tartu Airport relies heavily on GPS for aircraft approaches, and despite having ILS in place, requires GNSS for the initial approach to make use of this[63]. Tartu exemplifies the kind of airport that suffers the most during GNSS disruption. In recognition of this, Tartu Airport will introduce alternative approach procedures at the airport for safe landing without reliance on GPS signals during the period of flight suspension.[64]

Airports like Tartu are not a rarity in the US. 22 and 97 airports were identified in Colorado and Texas respectively as having exclusively GPS-reliant instrument approach procedures.[65] On a national scale, there are over 900 airports in the US and its territories where all available instrument approaches require GPS. [66] In the event of GPS jamming such as that seen in the Baltic (or DEN and DFW in 2022), at one of these vulnerable airports we would expect to see similar consequences to Tartu including diverted and cancelled flights. All the airports assessed in this report, including the smaller airports within the range of GPS disruption, had alternatives to GPS-based approaches available (including ILS or VOR), thus mitigating the potential effects on aviation during these specific events. This provides a direct contrast to the recent Tartu disruptions and shows just how important these redundancies are at limiting the consequences of GPS interference in an airport context. This can call into question proposed rationalization of alternative infrastructure (e.g. ILS) in the US[67] and Europe[68]. Given current threats to GNSS signal integrity, such outages must be considered as real possibilities in weighing the cost and benefits of removing this infrastructure.

The primary conclusion that can be taken away from the incidents at DFW, DEN, the Baltic, Tartu, and many others, is that alternative reinforcements are fundamental for locations with essential procedures that rely on GPS to operate. The lack of quantifiable impact observed in Dallas and Denver during their respective disruption periods is not representative of the potential impact of these events had alternative means of positioning, navigation, and timing not been implemented at the locations of interference.

[61] Sarah Hooper (2024). 'Major airline cancels flights to European city over Russian 'GPS hacking', METRO, accessible at: https://metro.co.uk/2024/04/29/two-passenger-planes-turned-around-gps-jammed-russia-20738997/

[62]Jesse Khalil (2024). 'Finnair cancels flights amid increased GNSS jamming', GPS world, accessible at: https://www.gpsworld.com/finnair-cancels-flights-amid-increased-gnss-jamming/

[63] AIRAC AMDT (2022). 'Instrument Approach Chart – ICAO', accessible at: https://eaip.eans.ee/2024-04-18/graphics/eAIP/AIRAC-AMDT-13-2022/AD_2_EETU_IAC_26_4_en.pdf

[64] FlightGlobal (2024). *Finnair to retore Tartu service after GPS alternative implemented in Estonian airspace*. Available at: https://www.flightglobal.com/air-transport/finnair-to-restore-tartu-service-after-gps-alternative-implemented-in-estonian-airspace/158324.article

[65] Data on airport approach procedures available from Airnav.com at: https://www.airnav.com/airports/

[66] GPS Innovation Alliance (2023). 'Aviation and GPS', accessible at: https://www.gpsalliance.org/aviation

[67] Fred Simonds (2020). 'ILS on the Block', IFR, accessible at: https://www.ifr-magazine.com/charts-plates/ils-on-the-block/

[68] EASA (2024). 'Transition to Performance based navigation (PBN) operations: in the single European sky', accessible at: https://www.easa.europa.eu/en/domains/air-traffic-management/transition-pbn-operations

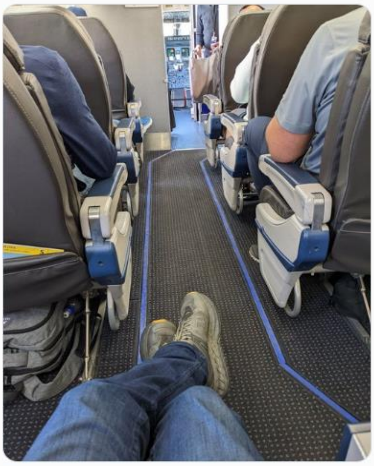
ANNEXES

Annex 1 Social media

Posts of successful flights through DFW

ryndon.eth .lens .com (🌸, 🌿) @ryndon · Oct 17, 2022

They assigned me the best seat in the house on my **flight** from **Dallas** TX to Idaho Falls. #AmericanAirlines #getlucky



1

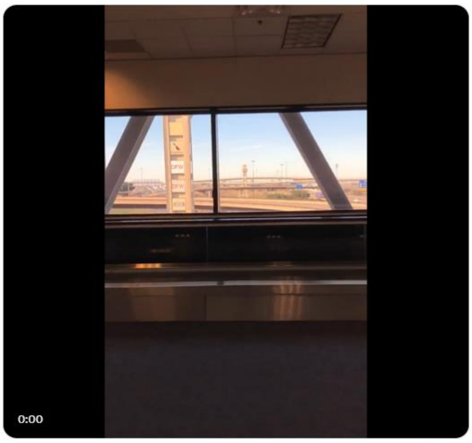
Jerry Zgoda
@JerryZgoda

It's Game Day with a plane full of #MNUFC supporters headed to Dallas this morning

8:43 PM · Oct 17, 2022

Eric Dreshfield (He/Him) @ericdresh · Oct 17, 2022

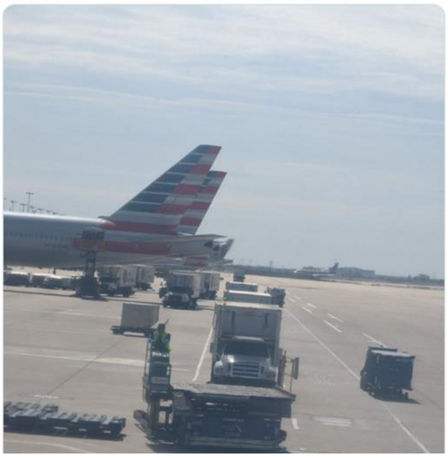
Waving to all my #DFW friends as I make my way from @DFWAirport B4 to C31. I'm headed for @AUStinAirport on @AmericanAir (as usual!)



2 7

Shelby
@FlyAArmy

Hello 👋 HOME!!!!; (@ Dallas Fort Worth International Airport in Grapevine, TX) swarmapp.com/c/6QWspLu6d7E



DFW Airport
@DFWAirport

And just as fervently, we're waving back right at you, hoping to see you again at DFW Airport! Have a great journey! 😊

11:16 PM · Oct 17, 2022

Posts of complaints - DFW

Cakes2022
@mat_zebrowski

@AmericanAir Your Airline sucks. Worst experience ever. How do I arrive at 5PM in Dallas just to have gates moved 5 times and my flight postponed for now until 11PM just to get to San Antonio.

3:05 AM · Oct 17, 2022

JB🐊
@gatorblunt2

Flight been delayed four times somehow will make it Dallas to miss a connecting flight with no flights out tomorrow either thanks @AmericanAir

1:58 AM · Oct 17, 2022 from Florida, USA

cas 🦝
@casssierolls

I LOVE GETTING DELAYED. I LOVE NOT GETTING HOME TILL WELL PAST MIDNIGHT. I LOVE THE DALLAS FORT WORTH AIRPORT. WOOOOOOO YEAHHHHHHHHH

1:29 AM · Oct 17, 2022

Posts of complaints - Denver

@SouthwestAir seriously every time I fly you guys to Demver you [redacted] up everyone's checked bags. Over an hour wait. Get your [redacted] together #denverairport

1:38 AM · Jan 22, 2022

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