RTO 66
Analysis of En route Sector Demand Prediction Accuracy and Quantification of Error Sources

Final Report

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ABSTRACT

In this report, we present results for an investigation into en route sector demand prediction accuracy. Through interviews with air traffic controllers and personnel from the Air Traffic Control System Command Center (ATCSCC), error sources were identified and ranked in terms of their influence on sector demand prediction accuracy. Error sources the highly affect sector demand prediction accuracy: departure time prediction, prediction of Traffic Flow Management (TFM) restrictions and Air Traffic Control (ATC) actions, horizontal route prediction accuracy. Error sources that have a medium affect on sector demand prediction accuracy: vertical route prediction accuracy, flight speed prediction accuracy, changing airspace adaptation data. And finally, error sources that have a low affect on sector demand prediction accuracy: weather and winds aloft forecast accuracy, the accuracy of surveillance data, flight technical errors and operational errors, and accuracy of the trajectory models. The majority of the analysis performed focused on the error sources that ranked highest. This study is primarily based on Enhanced Traffic Management System (ETMS), Official Airline Guide (OAG), and Aircraft Communications Addressing and Reporting System (ACARS) data sources. TFM initiatives and ATC control actions data were drawn from Historically Validated Restriction (HVR), Miles-In-Trail (MIT), Ground Stop (GS), and Ground Delay Program (GDP) data. Aggregate sector demand prediction data was generated using NASA's Future ATC Concept Evaluation Tool (FACET) to predict future trajectories, and ETMS for comparison. Given these data sources, the aggregate characteristics of errors in sector entry time and sector demand were identified. Detailed explanations of the sources of demand prediction error are identified and their contribution to the total error is quantified.

List of Acronyms

AAR....................Airport Arrival Rate
AATT..................Advanced Air Transportation Technologies project of NASA
ACARS...............Aircraft Communications Addressing and Reporting System
ACES..................Adaptation Controlled Environment System
ADL....................Aggregate Demand List
ADS-B................Automatic Dependent Surveillance – Broadcast
AF.......................ETMS Flight Plan Amendment
APREQ...............APproval REQuest or "call for release"
ARTCC...............Air Route Traffic Control Center
ARTS..................Automated Radar Terminal System
ATC....................Air Traffic Control
ATCSCC............Air Traffic Control System Command Center
ATCT..................Air Traffic Control Tower
ATM...................Air Traffic Management
AZ.......................ETMS Arrival
BTS....................Bureau of Transportation Statistics
CCFP..................Convective Current Forecast Prediction
CCSD................. Common Constraint Situation Display
CDM..................Collaborative Decision Making
CDR...................Coded Departure Route
CIWS.................. Corridor Integrated Weather System
CONUS..............Continental United States
CTAS.................Center TRACON Automation System
CTD...................Controlled Time of Departure
DZ......................ETMS Departure
ETA...................Estimated Time of Arrival
ETMS.................Enhanced Traffic Management System
FAA...................Federal Aviation Administration
FACET...............Future ATC Concept Evaluation Tool
FAST..................Final Approach Spacing Tool
FCFS..................First Come, First Served
FL.......................Flight Level
FMS...................Flight Management System
FS.......................ETMS Scheduled Flight Plan
FSM...................Flight Schedule Monitor
FTE.....................Flight Technical Error
FZ.......................ETMS Flight Plan
GA......................General Aviation
GDP...................Ground Delay Program
GMT ....Greenwich Mean Time
GS......................Ground Stop
HVR..................Historically Validated Restrictions
IFR.....................Instrument Flight Rule
ITWS..................Integrated Terminal Weather System
LAADR.............Low Altitude Arrival and Departure Route

LAT....................Look-Ahead Time
LOA....................Letter of Agreement
MA.....................Monitor Alert
MIT....................Miles In Trail
MOU..................Memorandum Of Understanding
NAS....................National Airspace System
NASA.................National Aeronautics and Space Administration
nmi......................Nautical Mile
OAG...................Official Airline Guide
OOOI.................Out, Off, On, In
PDC....................Pre-Departure Clearance
PIREP................. Pilot Weather Report
POET..................Post Operations Evaluation Tool
RS.......................ETMS Scheduled Flight Cancellation
RTO....................Research Task Order
RUC...................Rapid Update Cycle
SID.....................Standard Instrument Departures
SOP....................Standard Operating Procedures
SPO....................Strategic Plan of Operations
SPT.....................Strategic Planning Team
STAR..................Standard Terminal Arrival Routes
SUA....................Special Use Airspace
TFM...................Traffic Flow Management
TMA...................Traffic Management Advisor
TMC...................Traffic Management Coordinator
TSD....................Traffic Situation Display
TSD....................Traffic Situation Display
TZ.......................ETMS Position Update
US.......................United States
USA....................United States of America
UZ.......................ETMS Center Boundary Crossing
VA......................Virginia, USA
Z..........................Zulu Time
ZAU....................Chicago Center
ZFW...................Fort Worth Center
ZOB....................Cleveland Center

1 Introduction

Given the complexities of Air Traffic Control (ATC) in our country today, NASA's Future ATC Concept Evaluation Tool (FACET) [BSC00] hold the potential to reduce inefficiencies in Traffic Flow Management (TFM) [No94] and en route segments of National Airspace System (NAS) operations. Previous studies have addressed the identification of the range of such inefficiencies. Through such studies, Metron has identified a significant obstacle to improving NAS TFM operations: the lack of accurate en route sector demand prediction. In this Research Task Order (RTO) 66 effort, we characterize and quantify the error sources responsible for the lack of accuracy. The key is to develop logical relationships between various potential error sources and the sector demand. Then, recorded data can be used to "identify" the finer details within these logical relationships so that effects of various error sources on the demand prediction can be quantified. These logical relationships may change over the time of flight and thus as the prediction time horizon changes. By performing this task, we point the way for NASA to enhance the FACET system to improve sector demand prediction. This study will support further research and analysis of capabilities to be added to FACET to directly address NAS TFM inefficiencies.

In the **Initial Analysis,** aggregate data supporting an investigation of trajectory prediction accuracy and error sources was collected. Our initial analysis effort focused primarily on error sources associated with 'operational' aspects of trajectory generation [BWH00], as opposed to issues that relate to the technical aspects of trajectory generation (which is well covered in the literature). As such, we focused our analysis on error sources such as departure time prediction accuracy, effects of TFM actions [FAA98], accuracy of prediction of horizontal flight route, and effects of ATC/airspace procedures. **Table 1** reports the error sources that were found to most influence sector demand.

Table 1. Error Sources and their Level of Influence on Sector Demand Prediction.

Level of Influence	Error Source
High Influence	Departure Time Prediction
	Prediction of TFM Restrictions and ATC Actions
	Horizontal Route Prediction Accuracy
Medium Influence	Vertical Route Prediction Accuracy
	Flight Speed Prediction Accuracy
	Changing Airspace Adaptation Data
	Weather and Winds Aloft Forecast Accuracy
Low Influence	Accuracy of Surveillance Data
	Flight Technical Errors and Operational Errors
	Accuracy of the Trajectory Models

In the **Final Analysis**, we identify detailed relationships between error sources and operational data collected through on-site visits. Using FACET, we generate predictive trajectories for flights during the on-site visit dates. Using the resultant trajectory database, we generate statistics of sector demand prediction accuracy and factors that influence the trajectory predictions and sector demand. Specific examples are given based on the data collected during the on-site visits.

1.1 Objectives

The objectives of this final analysis are:

- Identify specific error sources affecting FACET's trajectory modeling, focusing on 'operational' error sources, and
- Evaluate and quantify the detailed effects and significances of these error sources.

This research evaluates operations as they are currently conducted in the NAS, with specific emphasis on the Air Route Traffic Control Centers (ARTCCs):

- Chicago Center (ZAU)
- Cleveland Center (ZOB), and
- Fort Worth Center (ZFW).

1.2 Technical Approach

The technical approach for the initial analysis is as follows.

1.2.1 Characterize the Operations at 3 Focus ARTCCs

Based on on-site visits and data analysis, we characterize the operations at ZFW, ZOB, and ZAU centers.

1.2.2 Specify Data Collected and used in the Detailed Analysis

For the detailed analysis, we specify sources and dates of the data collected for the analysis.

1.2.3 Conduct Detailed Analysis

Our analysis quantifies the accuracy of FACET's sector demand prediction. From the Initial Analysis ranking, we focus on the most influential elements contributing to sector demand prediction, namely, departure time prediction, prediction of TFM restrictions and ATC actions, and horizontal/vertical route prediction. For example, the sector demand prediction is evaluated before and after departure, including errors in modeling departure procedures. We also investigate before and after the last flight route amendment of a flight prior to take off. To conduct this analysis, we use specific operational data from the NAS and in particular, data collected for the 3 focus ARTCCs on the on-site collection dates. Using FACET, we generate predictive trajectories for each of the flights in the operation. Using the resultant trajectory database, we generate detailed analysis statistics of sector demand prediction accuracy.

2 Three Focus Centers

In this chapter, we briefly describe the operational conditions at three focus centers:

- Chicago Center (ZAU)
- Cleveland Center (ZOB)
- Ft. Worth Center (ZFW)

Figure 1 illustrates the relative location of these centers.

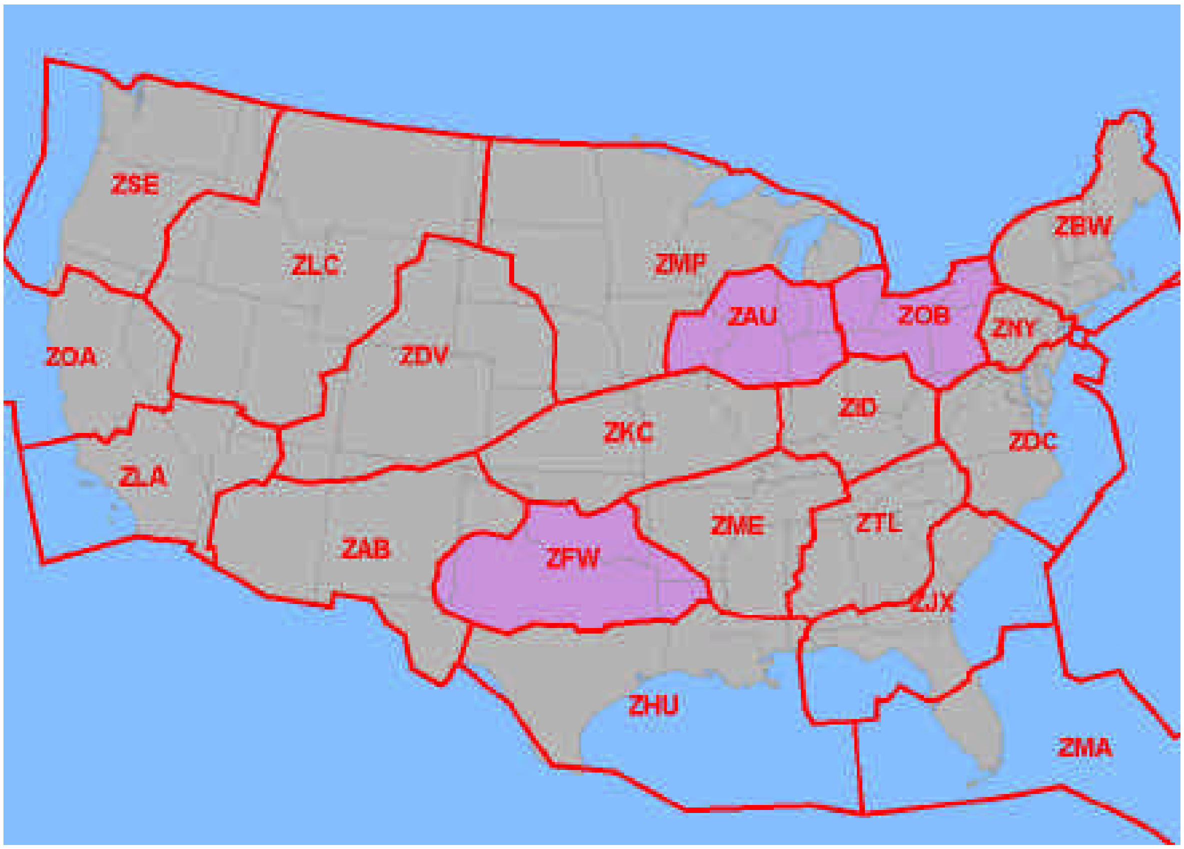


Figure 1. The 20 ARTCCs in the Continental US (CONUS) and 3 focus centers.

2.1 Chicago Center (ZAU)

The Chicago airspace has been designed with the primary concern of handling arrivals and departures to the Chicago O'Hare airport (ORD). Indeed, this airport is one of the busiest in the country, capable of handling 100 arrivals per hour. This is in contrast to the Cleveland Center (ZOB) airspace, which is designed to handle primarily en route traffic with internal releases from much smaller airports in comparison to ORD. According to ZAU traffic managers, most congestion problems at ZOB are handled by passing Miles In Trail (MIT) restrictions back to adjacent centers, including ZAU to the west and New York Center (ZNY) to the east. At ZAU, congestion problems are handled by implementing Ground Delay Programs (GDPs) or Ground Stops (GSs) for ORD. Chicago center does not face the same en route congestion issues as Cleveland center, and under normal conditions is usually capable of absorbing MIT restrictions rather than passing them back to a second tier. Because of traffic and handling of ZOB restrictions, the east side of ZAU is typically much busier than the west.

In addition to ZOB, ZAU is adjacent to Minneapolis (ZMP), Kansas City (ZKC), and Indianapolis (ZID) centers. Jet Routes J60, J64, J94, J16, and J18 handle most of the east-west en route traffic through Chicago to these centers, and J80, though not within the ZAU airspace, is near enough that it contributes to ZAU controller workload through “point out” operations. Routes J89, J101, J105, J35 and J19 handle the north-south en route traffic through the airspace. The airspace is divided into eight areas, each area responsible for traffic in a certain section of ZAU. Each area is further divided into six to eight sectors, where one or more controllers is responsible for the flights within each individual sector. In addition to these eight local areas is the Traffic Management Unit (TMU) that handles traffic at the “flow” or strategic level. Within the ZAU TMU a restriction coordinator handles airspace restrictions, a departure coordinator departures from (primarily) ORD and MDW, an arrival coordinator arrivals to ORD, an en route coordinator flights en route, and a weather coordinator weather effects. The departure coordinator and the en route coordinator positions are infrequently staffed and often combined with the arrival coordinator position. ORD arrivals pose the biggest challenge in the TMU and this position is always staffed.

Both local controllers and the TMU have access to track data on the radar at the respective positions and to data from the Enhanced Traffic Management System (ETMS), presented on the Traffic Situation Display (TSD) in the area. The TMU uses ETMS to view general traffic flows, but known problems with the accuracy of altitude and position data limit its usefulness as a strategic planning tool. ETMS also has congestion prediction capabilities, but these too are used infrequently because of observed reliability problems. Because of its relatively slow update rate and data quality issues ETMS is not used by local controllers for aircraft monitoring or separation. The TMU also has access to ITWS weather data that it uses to monitor weather changes.

Figures 2 and **3** illustrate the low and high altitude sectors for ZAU. Sector ZAU83 resides in the center where ORD airport is located, and the surrounding sectors are shaped to lead traffic to and from this central airport and sector.

The routes that receive the most attention at ZAU are those for arrivals and departures to ORD. **Figure 4** and **5** illustrate the arrival and departure traffic streams for ORD. Midway airport, a regional airport near ORD, represents an interesting case in that it can handle more than 40 arrivals per hour, and Midway traffic must be crossed and merged with that of O’Hare. Typically, Midway flights arrive and depart below those of O’Hare.

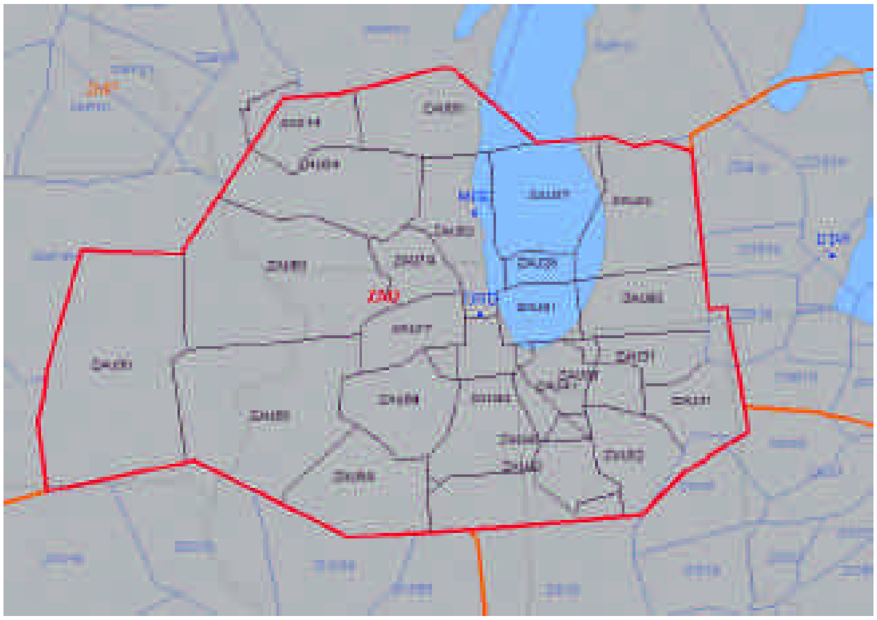


Figure 2. Chicago (ZAU) center, low altitude sectors, and the primary internal airport ORD.

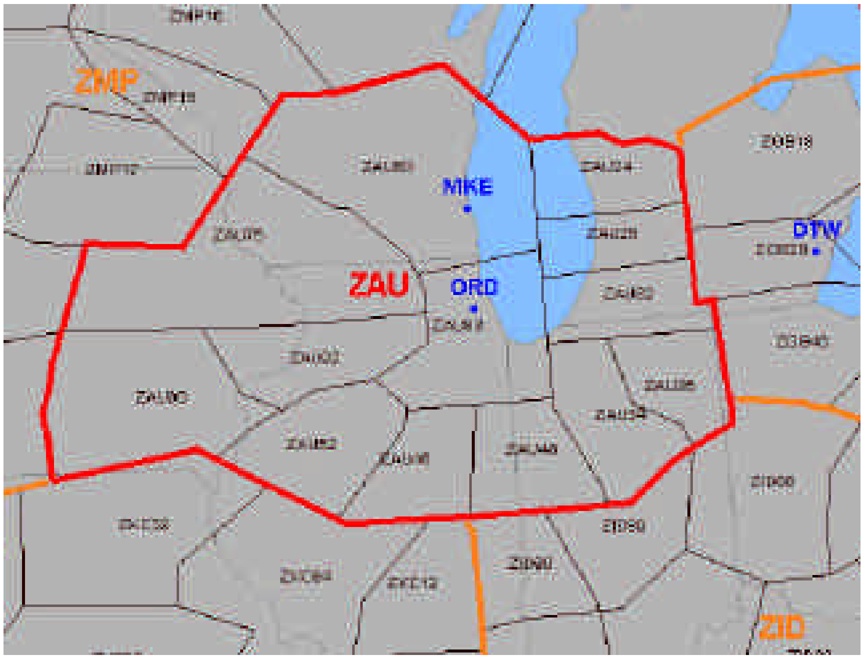


Figure 3. Chicago (ZAU) center, high altitude sectors, and the primary internal airport ORD.

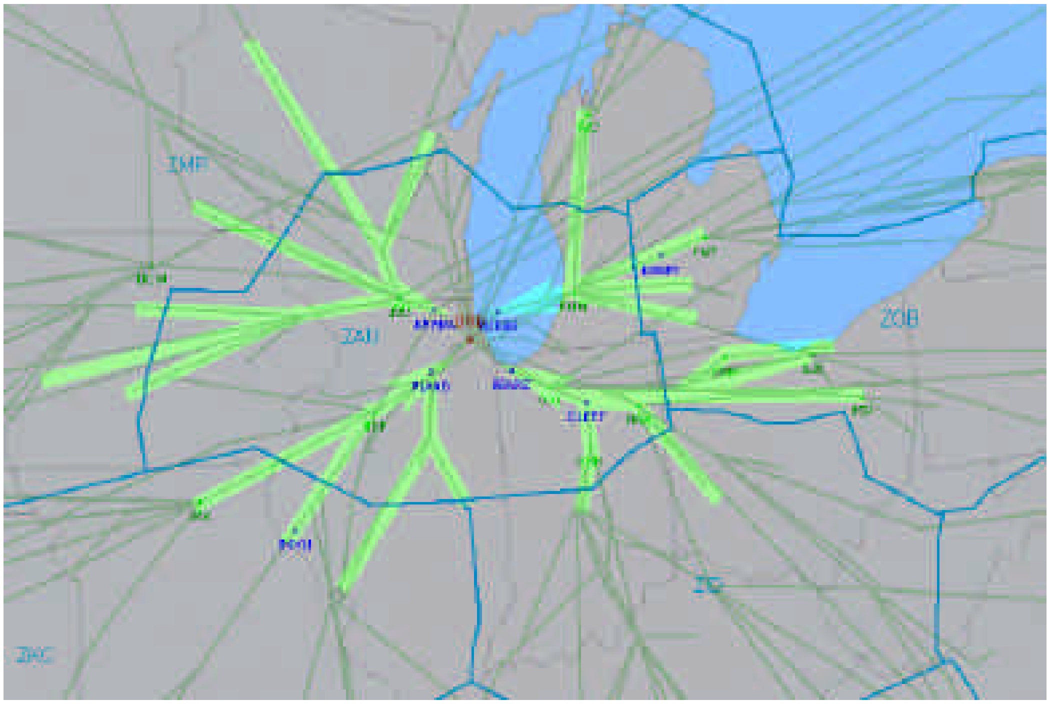


Figure 4. Chicago (ZAU) traffic arriving to ORD.

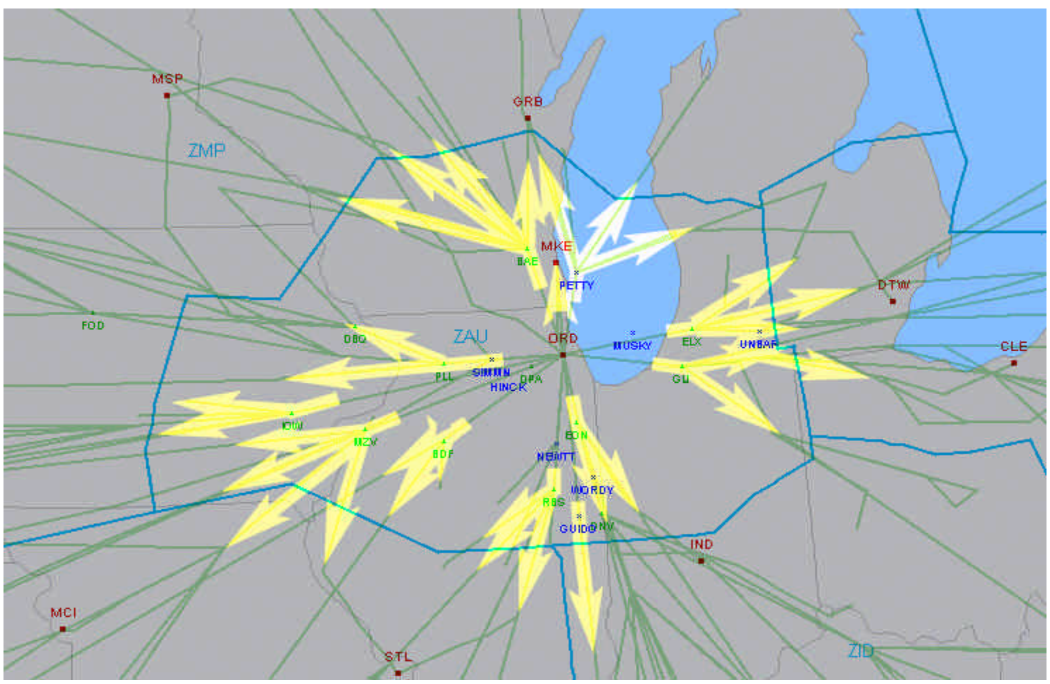


Figure 5. Chicago (ZAU) traffic departing from ORD.

For departures and overflights, the most significant **MIT restrictions** for ZAU come from ZOB, in particular for Newark (EWR) and Kennedy (JFK) arrivals. ZOB requests these MIT restrictions daily, generally starting at about 11:30 local time. The MIT restriction requested depends on the traffic situation on that day, and can range from 10 to 30. This is a frequent point of frustration for ZAU personnel, as it often appears to them that ZOB requests unnecessarily high restrictions on some days. Conferences are held frequently between ZAU, ZOB and the Air Traffic Control System Command Center (ATCSCC) to negotiate restrictions, as an inaccurate forecast of congestion can put undue work on either facility. Unless there is severe weather in the vicinity during the restriction, ZAU typically works to absorb all of the restriction requested by ORD without passing a subsequent restriction for flights inbound from ZKC or ZMP. The TMU handles most of the mitigation of traffic to meet MIT restrictions into ZOB. Radar scopes in en route area of the TMU are set to show only flights to which the restrictions apply. For example, if ZAU is restricted to 30 miles in trail for EWR arrivals, the traffic manager at the en route scope can observe all applicable flights in the entire airspace and plan ahead to meet the 30 MIT restriction. This is a relatively large distance for a local controller to apply, considering many of the sectors are less than 80 miles across. The TMU works with the area managers to anticipate these problems before they happen.

Another way that ZAU deals with restrictions is by asking for “offload” routes. These are alternate routes to the destination airport that are exempt (to a point) from the restrictions. Typically, Toronto Center will allow ZOB two to four offload flights per hour through its airspace. ZOB may pass the benefit of two of these offloads back to ZAU, easing its burden to absorb the restriction.

For arrivals ORD requires 7 MIT over each arrival fix during normal conditions, which translates into a 10 MIT for arrivals from ZOB. This 10 MIT restriction rarely changes (even under abnormal circumstances), as ZAU deals with congestion that it cannot absorb for ORD arrivals by running GDPs or GSs. The 7 MIT restriction, however, fluctuates with the ORD arrival rate. The center responds to a decreased arrival rate by increasing this restriction, usually favoring (by restricting less) the busier side of the airport.

The single largest source of disruption within the Chicago airspace is **weather**. During the winter the weather is relatively predictable; at worst, it can snow the airport in, but typically just reduces the ORD Airport Arrival Rate (AAR). This is mitigated with GDPs and GSs. In storm season weather is unpredictable, exacerbated by “lake effect” fronts from the Great Lakes. The sudden and severe convective activity frequently results in significant delays and airborne holding. The center facility includes a meteorology department that gives weather briefings twice daily and works with the TMU to develop strategies. The TMU, in turn, works with the Airline Operations Centers (AOCs) to exchange information and with ORD, ZOB and the ATCSCC to implement AARs and other restrictions.

The effect of the jet stream is an often-overlooked element of weather in the airspace. It is difficult for center personnel to predict how airlines will try to take advantage of the jet stream, and what effect that will have on the traffic situation for any given day. When the jet stream passes through ZAU airspace, normal arrival rushes tend to occur at different times or not at all, as long-haul flights get out in front of the flow.

Because of the combination of O’Hare and Midway airport arrivals, overflights and weather, the ZAU airspace is relatively complex, particularly in the low and high southern and eastern sectors. Here many flows cross and merge, climb and descend as they depart from and arrive to ORD. **Figure 6** shows complex crossings for climbing and descending streams in ZAU46. One particularly interesting issue pertaining to workload and complexity occurs when flights cut corners of adjacent sectors, or otherwise come within two miles of them. This occurrence requires an operation called a “point-out” in which the controller controlling the aircraft alerts controllers in the adjacent centers of its presence. As many as four point out operations can occur for one flight in rapid succession as it climbs through and traverses stacked and adjacent sectors

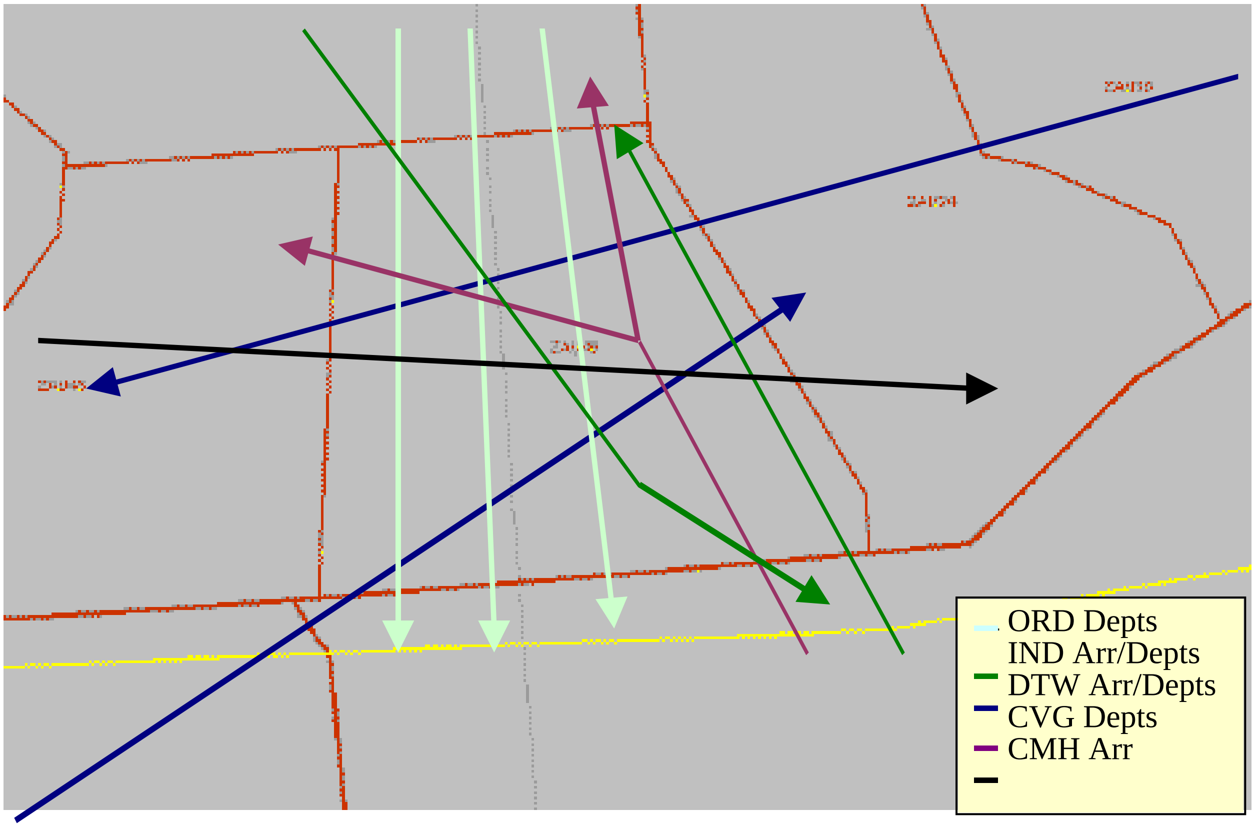


Figure 6. Crossing arrival and departure flows create complexity in ZAU sectors.

2.2 Cleveland Center (ZOB)

Cleveland ARTCC (ZOB) is situated in a critical segment of the NAS; it is responsible for aircraft transitioning to and from the New York/Philadelphia metro areas, the Chicago metro areas, and the most heavily traveled section of Canadian airspace including Canadian and International flights into the US. Its complexity means that much of the operational environment of the airspace is often driven by fixed procedures codified in Letters of Agreement (LOAs) with other facilities and internal Standard Operating Procedures (SOPs). ZOB borders Canadian airspace (to the North) and is surrounded by several other busy centers:

- ZNY is adjacent to the East. ZNY has a main emphasis to work on departures.
- ZID is adjacent to the South. Several flows from ZID pass through ZOB.
- ZAU is adjacent to the West. ORD within ZAU has a major influence on ZOB.

Other centers ZMP, ZBW, and ZDC play less of a role in the traffic of ZOB. Regional differences are significant, and traffic management techniques within ZOB may be considered unique to ZOB. Ordinarily, the center in which a major airport is based lines up the traffic for delivery to the airport. However, the proximity of ORD and the New York airports to the ZOB boundaries pushes this responsibility upstream to ZOB. As such, ZOB is essentially taking on a major workload on behalf of ZAU and ZNY.

As shown in **Figure 7** and **8**, the primary internal releases in ZOB are from DTW, CLE, and PIT airports. There is also an external influence from Toronto. There are complications in the proximity of these airports. The inbounds fix for CLE is also a departure fix for DTW. ZOB experiences a high volume of over flight traffic. Each of these three major internal airports requires sequencing and spacing for both departing and arriving traffic. They also require Approval Requests (APREQs) for internal releases into the overhead steams going to major airports both within and external to ZOB. ZOB is characterized by a lot more transitioning traffic compared to other center airspaces.

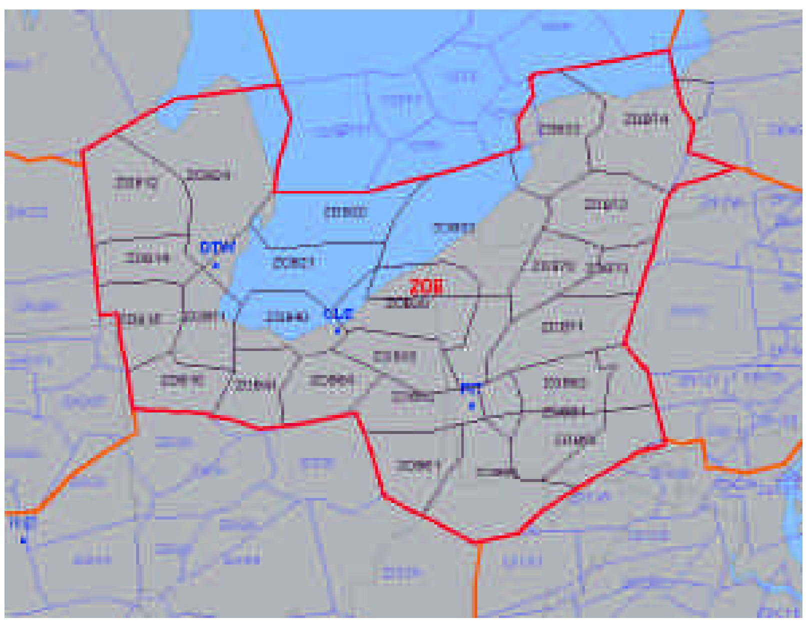


Figure 7. The ZOB center, low altitude sectors, and the primary internal airports.

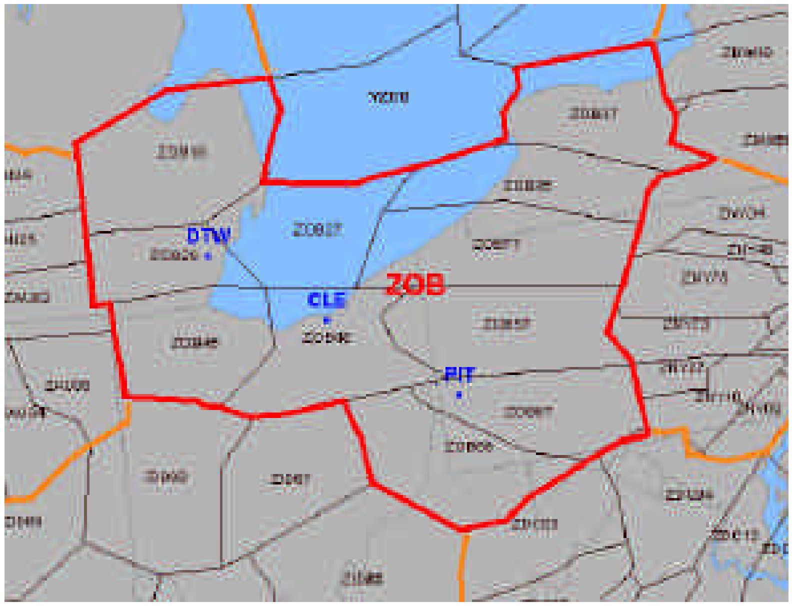


Figure 8. The ZOB center, high altitude sectors, and the primary internal airports.

Currently the ZOB air traffic management facility is divided into two major parts, the TMU and Traffic Services. The TMU is responsible for things such as monitoring traffic through the center, posting and enforcing MIT restrictions on flights leaving and entering the center, posting GDPs, communicating with the local TRACONs, communicating with the TMU from other centers and communicating with the ATCSCC to coordinate restrictions and GDPs.

The TMU uses radar data and ETMS data to observe both currently active flights as well as predicted future flights. They also watch current and historical weather data, and communicate directly with other centers and the ATCSCC. The Great Lakes have a significant impact on the weather in the ZOB airspace. Mountains to the East also create turbulence at certain times of the year. Although the controllers have access to weather and ETMS data, their primary means of observation comes from radar data and through communication with pilots. All communication is done via a headset worn by the controllers. The traffic coordinators at the TMU use telephones.

ZOB Traffic Services is divided into seven areas, each area responsible for traffic in a certain section of the ZOB airspace. Each area is further divided into sectors, where one or more controller is responsible for the flights arriving and departing (as shown in **Figures 9** to **11**) and within each individual sector. Note that the airspace is stratified both laterally and vertically, creating "stacks" of sectors on top of one another. For example, CRL Sector 40 extends from the surface to 23000 ft, while RAV Sector 48 extends from FL240 to FL310. Above RAV is a super-high LOR Sector 49 which covers FL330 and above. Note that the "shape" of the stacked sectors is typically not identical and often times a given high sector will sit atop low sectors from a number of different areas. This fact can be inferred by overlaying the low and high sector diagrams given in **Figures 7** and **8**. There are also sectors that combine and split at different times of the day; e.g., ZOB18/19 are considered by controllers to be one sector with the exception of a one-hour peak period – we combine them as one in our analysis. Controllers in a given sector talk directly to pilots, to controllers in surrounding sectors, and to the TMU.

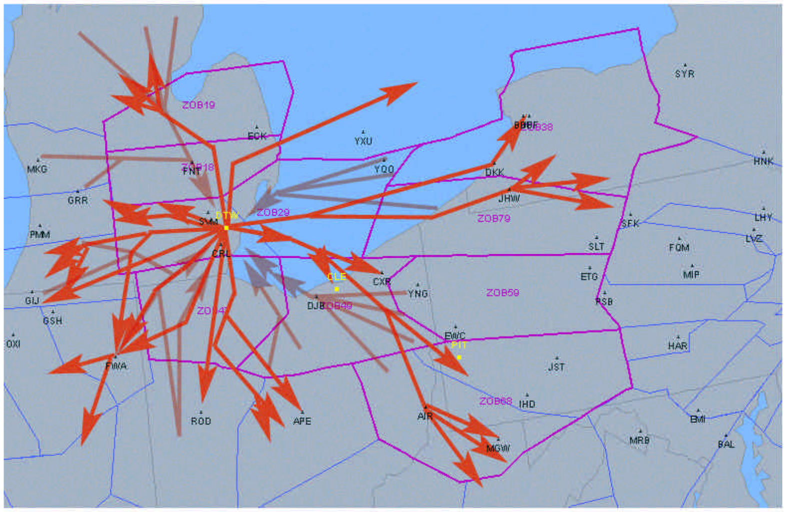


Figure 9. DTW internal releases for ZOB.

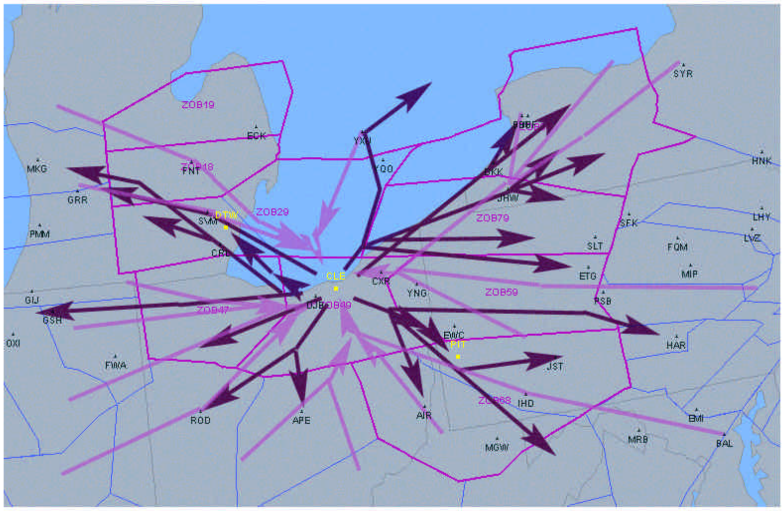


Figure 10. CLE internal releases for ZOB.

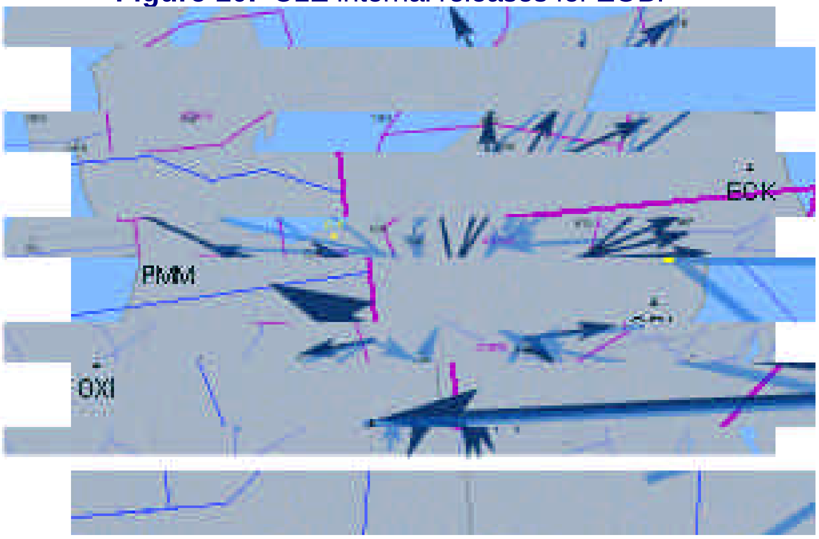


Figure 11. PIT internal releases for ZOB.

ZOB runs En Route Spacing Programs (ESPs) into certain busy airports at different times of the day. These ESPs are performed at dedicated Traffic Management Coordinator (TMC) positions and display in the TMU. Flows passing over ZOB into Chicago Airport (ORD) are as shown in **Figure 12**. Because of the volume into ORD, one TMC position is dedicated to this ORD flow every day. Typically, there are two sets of MIT restrictions placed on these flows, as shown with the 10 over PMM and 30 over OXI routes. This 10/30 combination is considered the Historically Validated Restriction (HVR) for these routes. LOAs set these constraints regardless of how large the AAR is at ORD. As a default, a LOA calls for delivery of 30 MIT over OXI. The two Southern flows over routes J60 and J64 are treated as one, or as the controllers say: "two as one". The Southern flow has a 30 MIT restriction on it because there are typically two other flows that are coming into the Southeast metering fix into ORD from ZID airspace. Since ORD sees this as one flow, they put 30 MIT on each of the 3 streams that make up the flow. At times, on this route, if a TMC is having trouble meeting the 30 MIT, they may look over the flows over ZID to see if they are heavy or not. If there is room, they may call up ZAU to ask if they can relax the 30 MIT restriction given that the sum of the 3 flows is not likely to push the 10 MIT restriction that is on the metering fix at ORD. Sometimes they get the OK, sometimes not.

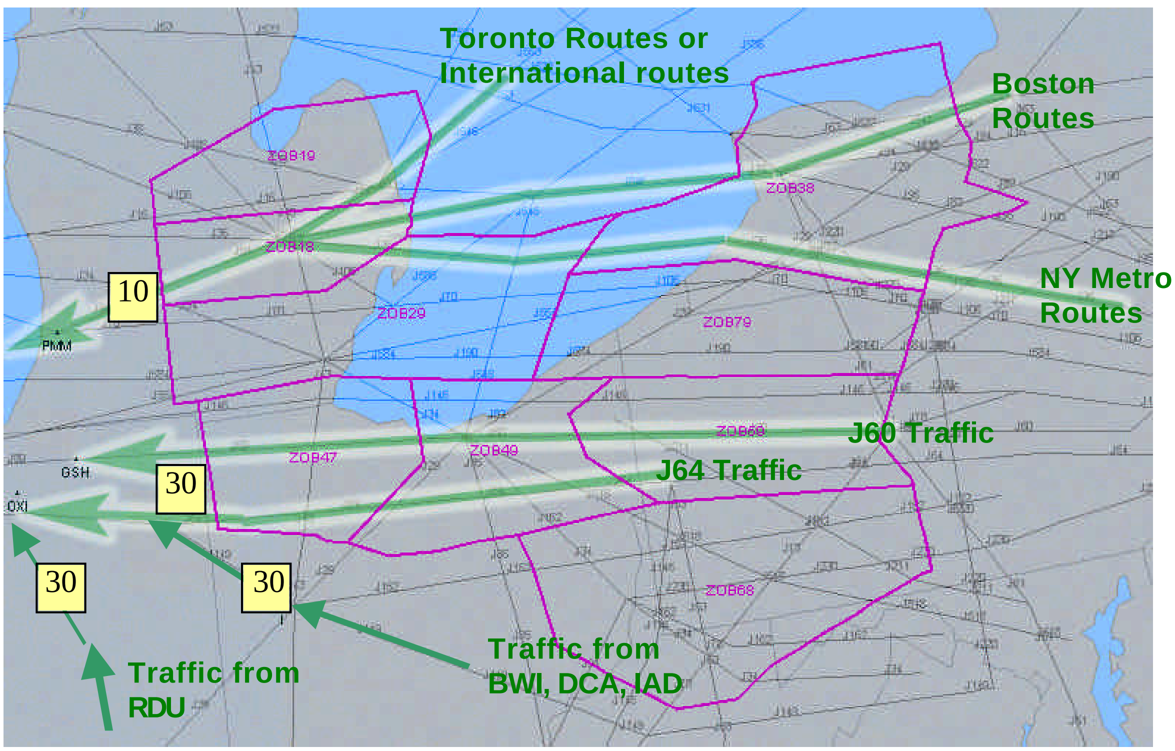


Figure 12. ZOB West flow into ORD and the pass back of MITs to ZNY.

Airborne holding is also an issue for ZOB. If Newark EWR changes runways, then it will cause a 15-minute delay. This could cause airborne holding in ZNY that can sometimes create airborne holding in ZOB. These airborne holds will occur at SLT first, and if too many aircraft are holding at SLT (usually 6 aircraft are allowed), then another holding pattern in ZOB is used for any remaining traffic that needs to be held

2.3 Ft. Worth Center (ZFW)

Ft Worth ARTCC (ZFW) is located in the south-central US and is centered around the Dallas Ft. Worth (DFW) airport. The low and high sectors for ZFW are shown in **Figure 13** and **14**.

Traffic in ZFW is dominated by the arrivals (**Figure 15**) and departures (**Figure 16**) of Dallas Ft. Worth (DFW).

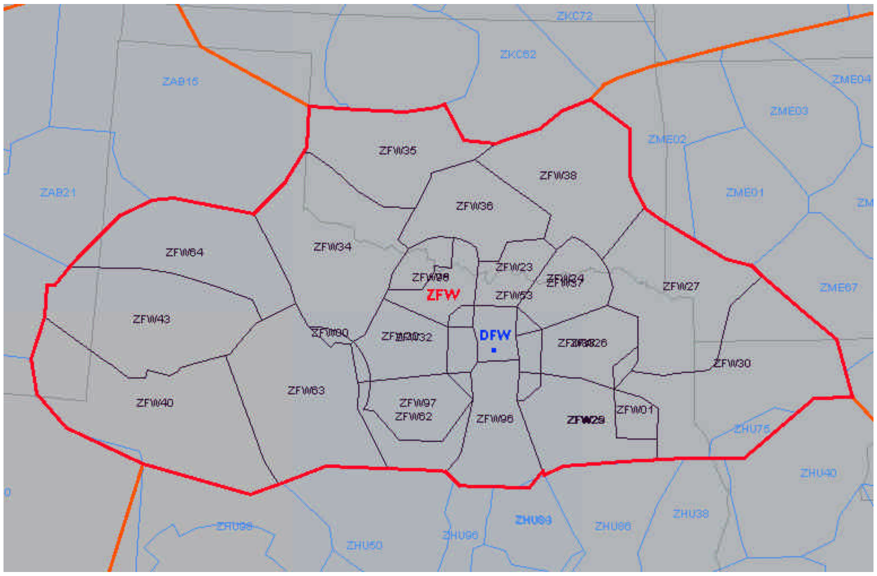


Figure 13. ZFW center, low altitude sectors, and the primary internal airport DFW.

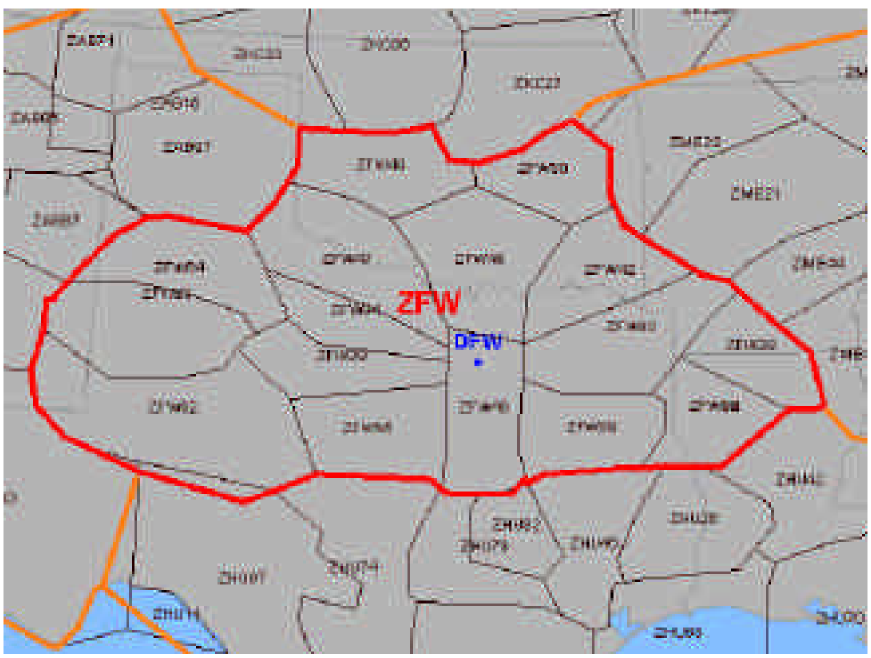


Figure 14. ZFW center, high altitude sectors, and the primary internal airport DFW.

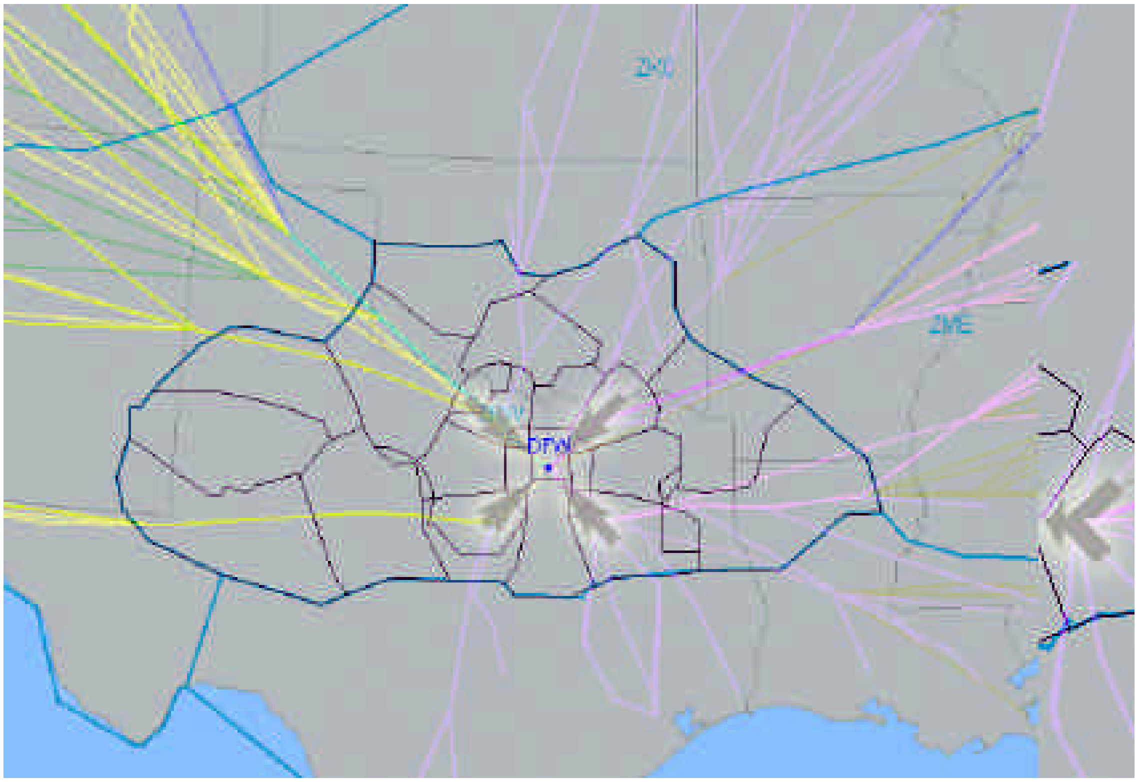


Figure 15. DFW arrivals relative to ZFW center.

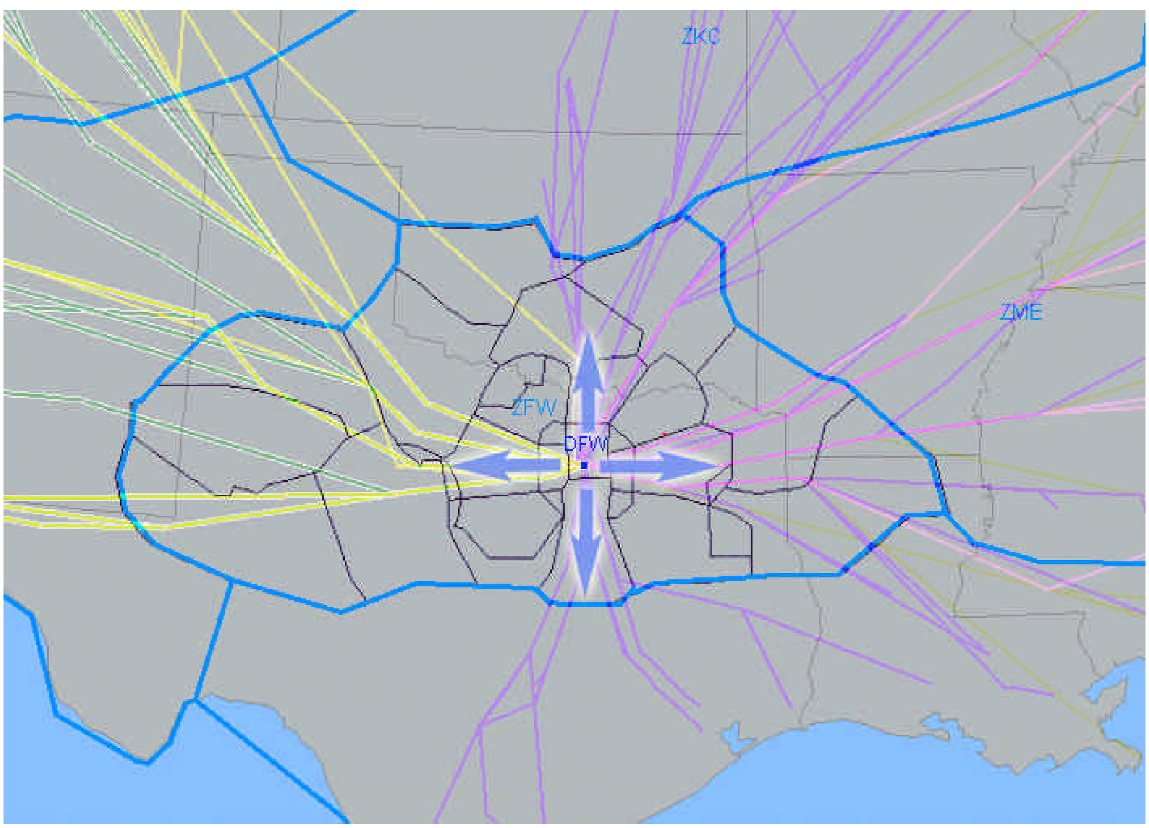


Figure 16. DFW departures through ZFW center.

3 Data Collected for Detailed Analysis

In this section, we present data sources used in the detailed analysis. In general, the data collection dates and locations used were as follows:

- Jan. 14, 2002 ZFW
- Jan. 28 – Feb. 1 ZAU, ZOB

Not all data was collected for all days. Due to complications in data collection, some data are missing from a complete set. Note: Because it is not convective weather season yet, no CCFP data was collected in this study (that is, it was not available at the time of the study).

3.1 ACARS Data

Bureau of Transportation Statistics (BTS) Out, Off, On, In (OOOI) data was collected for the following time periods:

- Jan. 14, 2002 (05:00Z) to Jan. 15, 2002 (05:00Z)
- Jan. 28, 2002 (05:00Z) to Feb. 2, 2002 (05:00Z)

These data are published monthly on the website www.bts.gov and is generally available 40 days after the end of the reporting month.

3.2 ETMS Data

ETMS data for all flights in the NAS was collected for the following time periods:

- Jan. 13, 2002 (00:00Z) to Jan. 15, 2002 (05:00Z)
- Jan. 27, 2002 (00:00Z) to Feb. 2, 2002 (05:00Z)

ETMS provides flight information on all flights that are operating and all flights planned to operate in the NAS. Flight data is loaded into the live database fifteen hours before its scheduled departure. ETMS also receives the NAS state messages such as shown in **Table 2**. ETMS track data is currently received every 1 minute. These track data is presented to the nearest minute of latitude and longitude.

Table 2. ETMS data identifiers, descriptions, and purpose.

Identifier	Description	Purpose
FS	Scheduled Flight Plan	Scheduled flight plan ahead of the filed flight plan
RS	Scheduled Flight Cancellation	Cancels a scheduled flight previously fed into ETMS
FZ	Flight Plan	Flight Plan as filed with the NAS
AF	Flight Plan Amendment	Amendment to flight plan as filed with the NAS
RZ	Cancellation	Cancels a flight plan previously filed with the NAS
DZ	Departure	Signifies the activation of a proposed flight
UZ	Center Boundary Crossing	Current flight plan data as sent from ARTCC from which flight is leaving to the ARTCC which the flight is entering
TZ	Position Update	Current position, altitude, and speed of a flight as tracked by the NAS
AZ	Arrival	Signifies the termination of an active flight

3.3 CM_Sim Host Data

CM_Sim host data for ZFW was collected the following time period:

- Jan. 14, 2002 (00:00Z) to Jan. 14, 2002 (23:59Z)

CM_Sim host data for ZFW comes from radar hits on all aircraft within a certain radius of DFW. The coverage radii for arrivals to and departures from DFW are 314 nmi and 361 nmi, respectively. The data includes horizontal position (*x*,*y*) and altitude (*z*) measurements updated once every 4 to 7 seconds. This is considered to be the most accurate data source available for this type of information. For our analysis, the A/C Data field was used. Each line (one per flight per time update) contains the flight ID, call sign ID, arrival airport, departure airport, POSIT time (seconds from start time), horizontal position (*x*,*y*) nmi from DFW, and altitude (*z*) in feet. The CM_Sim start time is given in HHMMSSZ.

3.4 RUC Winds Aloft Data

Rapid Update Cycle (RUC) data provides wind and other data. Data was collected each hour for the following time periods:

- ruc2a.020114 January 14, 2002 (00:00Z to 23:00Z)
- ruc2a.020128 January 28, 2002 (00:00Z to 23:00Z)
- ruc2a 020129 January 29, 2002 (00:00Z to 23:00Z)
- ruc2a 020130 January 30, 2002 (00:00Z to 23:00Z)
- ruc2a 020131 January 31, 2002 (00:00Z to 23:00Z)
- ruc2a 020201 February 1, 2002 (00:00Z to 23:00Z)

RUC is an operational atmospheric prediction system comprising primarily of a numerical forecast model and an analysis system to initialize that model. The RUC has been developed to serve users needing short-range weather forecasts, including those in the US aviation community. We used RUC40 (RUC-2) that has 40-km horizontal resolution and a computational grid of 151x113. RUC40 also has 40 levels of vertical resolution. For this effort, FACET used the horizontal and vertical wind components from the RUC data in order to perform its trajectory calculations.

3.5 Nexrad Weather Data

NEXRAD plots show the NCWF/NCWD products that have to do with convective weather. Data was collected each hour for the following time periods:

- Jan. 14, 2002 (00:00Z) to Jan. 14, 2002 (23:59Z)
- Jan. 28, 2002 (00:00Z) to Feb. 1, 2002 (23:59Z)

Both precipitation (in dBZ) as well as convective activity were recorded for Jan. 28 – Feb. 1, 2002, as shown in **Figure 17**. Note that even though the precipitation maps indicate that there is weather present in the ZAU and ZOB centers, the controllers at these facilities said that there was not enough convective activity (as illustrated in the right side of the figure) to cause any concern. As one controller commented, the aircraft are just going to fly right over this weather. Thus, the convective activity plots, which show relatively low levels of convectivity, are more important to this study than the precipitation maps.

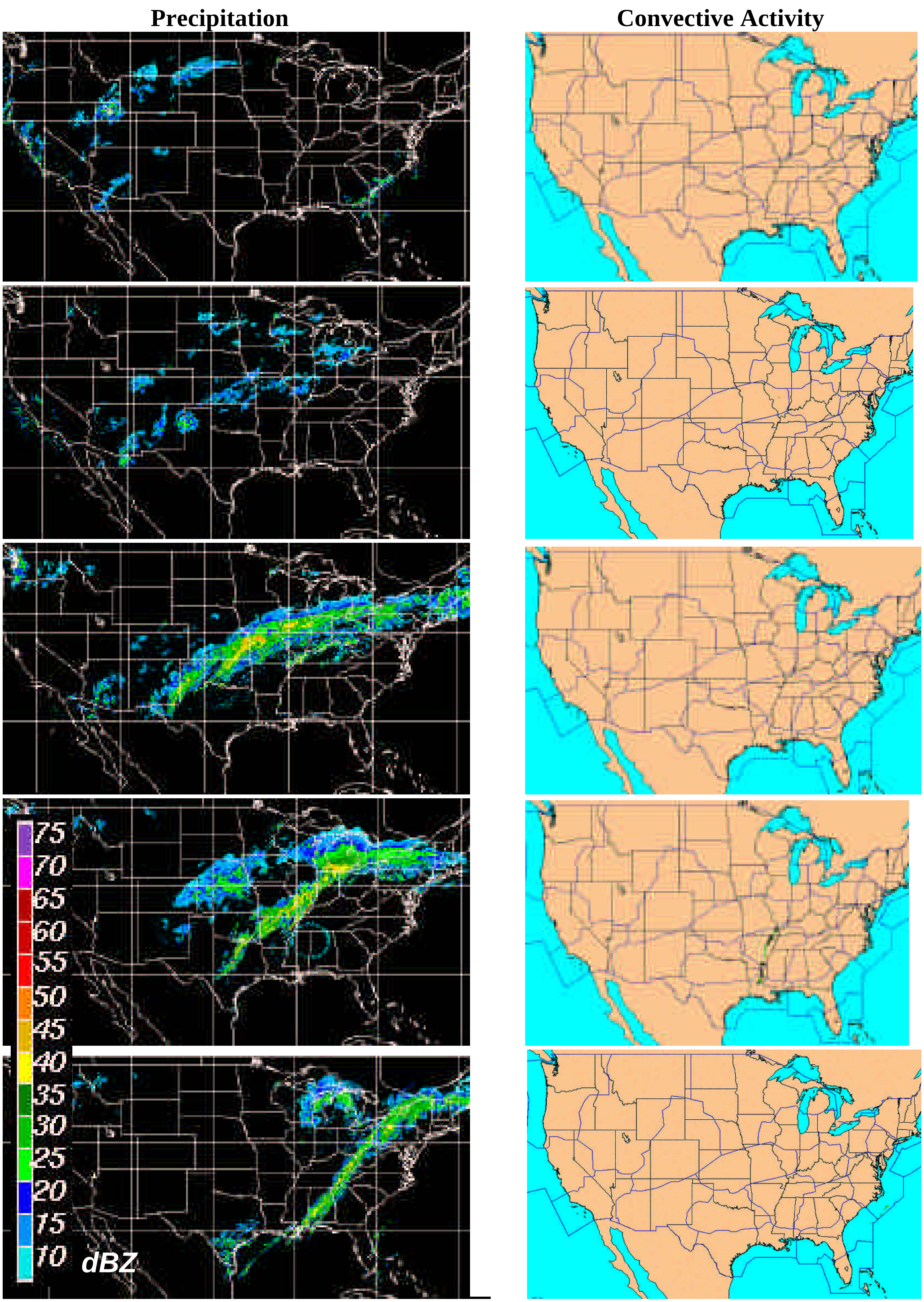


Figure 17. Precipitation and Convective Weather for 1/28/02 – 2/1/02.

3.6 Sigmets and Airmets

Airmets and Sigmets data was collected each hour for the following time periods:

- Jan. 14, 2002 (14:00Z) to Jan. 15, 2002 (06:00Z)
- Jan. 24, 2002 (20:00Z) to Feb. 3, 2002 (03:00Z)

Airmets and Sigmets, for example as shown in **Figure 18** through **21**, were automatically downloaded hourly from the following web pages:

1. Airmets - http://aviationweather.noaa.gov/awc/awc-airmets.html
    a. IFR / Mountain Observations (airmet_s.gif)
    b. Turbulence (airmet_t.gif)
    c. Icing (airmet_z.gif)
2. Sigmets - http://aviationweather.noaa.gov/awc/domestic_sigmets.html
    a. Western US (wsigmet.gif)
    b. Eastern US (esigmet.gif)

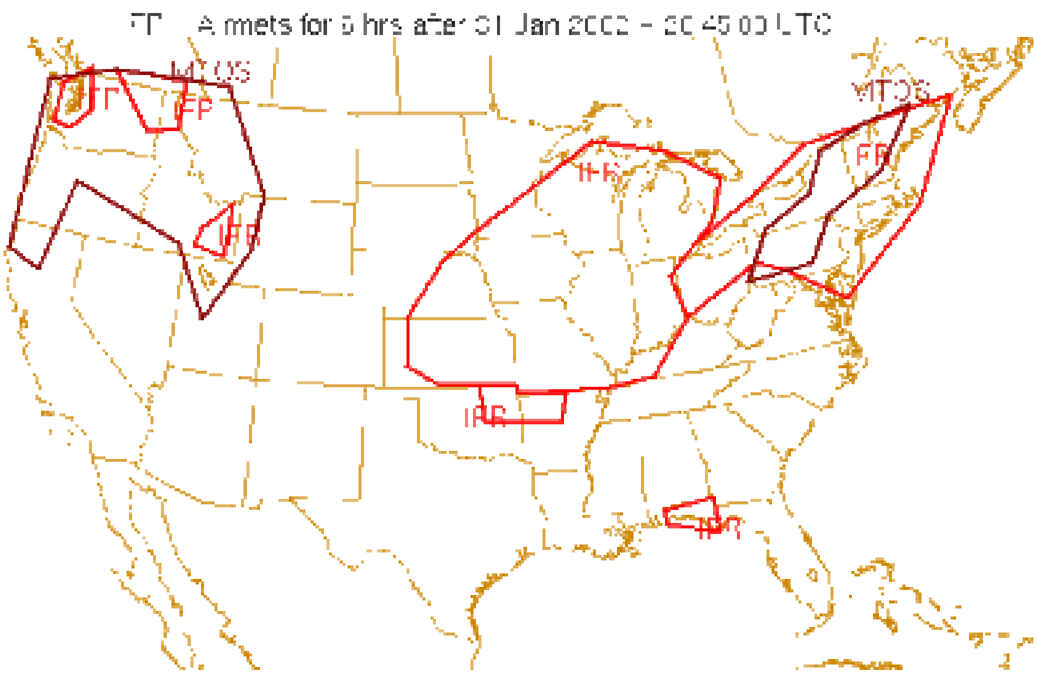


Figure 18. IFR AIRMET Jan 31, 2002 at 21:00Z.

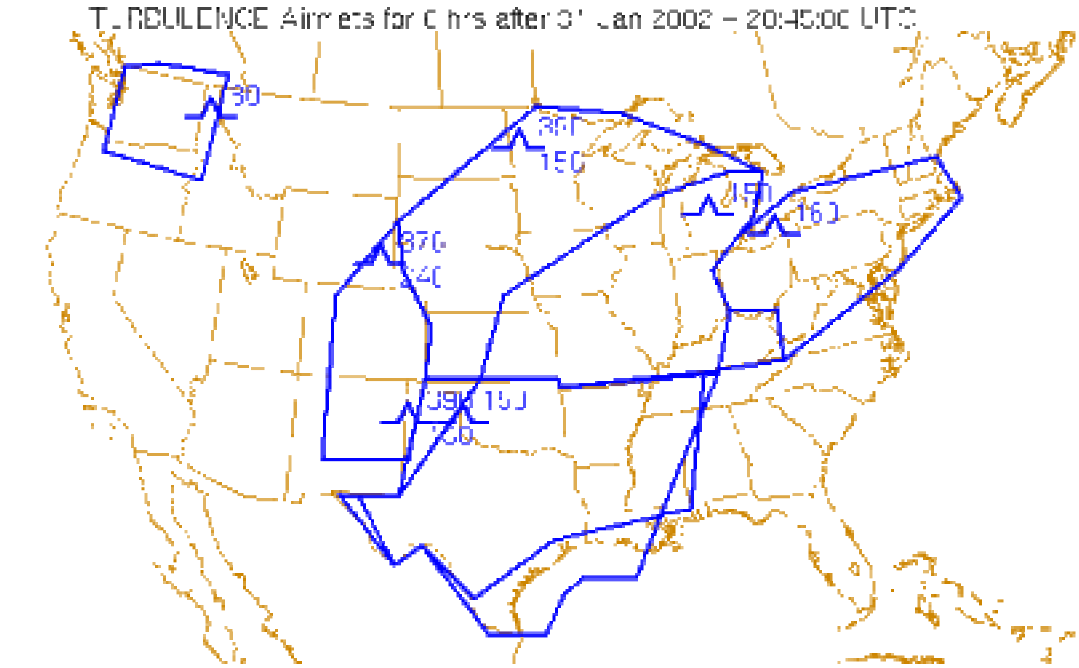


Figure 19. Turbulence AIRMET Jan 31, 2002 at 21:00Z.

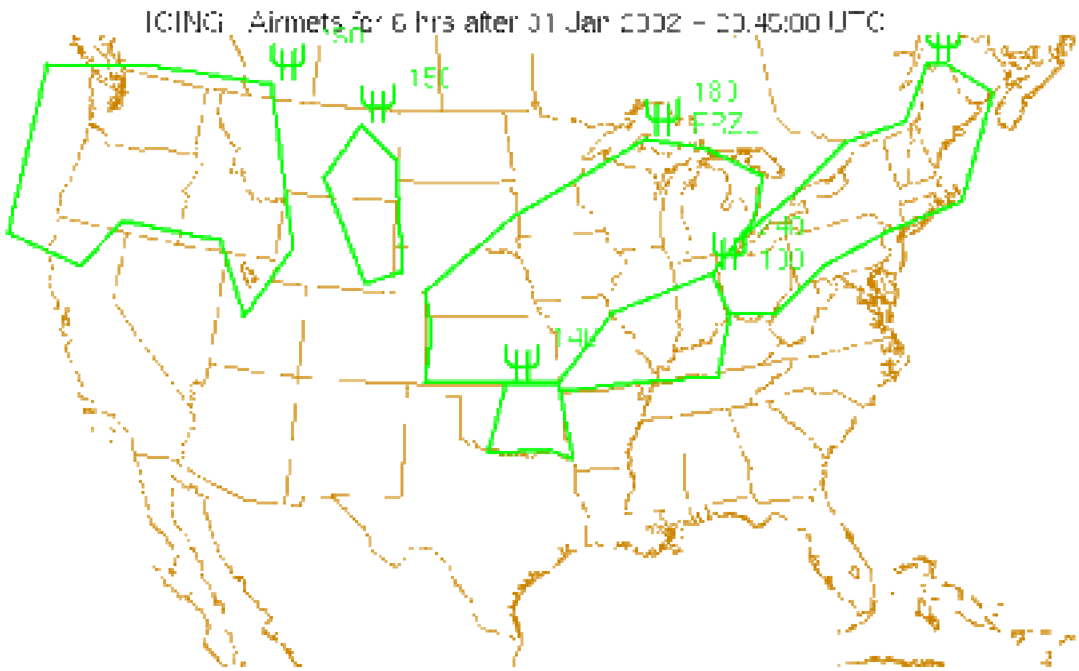


Figure 20. Icing AIRMET Jan 31, 2002 at 21:00Z.

Figure 21. Western and Eastern SIGMETs for Jan 31, 2002 at 21:00Z.

3.7 ARTCC TMU Log

Paper copies of ARCCC TMU logs for ZFW were collected for the following day:

- Jan. 14, 2002

TMU logs provide TRACON restrictions, monitor alerts, traffic management restrictions with a short narrative, summary of weather conditions, traffic summary and a metering log.

3.8 ATCSCC National Logs

ATCSCC position logs were collected for the following days:

- Jan. 14, 2002
- Jan. 28, 2002 to Feb. 1, 2002

Position logs provide advisory information and comments on discussions / coordination with the facilities. Data is added to these files only when a facility contacts the ATCSCC to report the restriction. There are different types of position logs. Severe Weather Area log – provides a summary of activity and lists the specific events by time. East and West area logs provide (1) weather data; (2) staffing and outage information concerning centers; (3) GDP code, outage, arrival and departure runways configurations, and arrival/departure rates; (4) detailed listing of events including MITs, GSs, and GDPs; and (5) a short narrative at the end summarizing the shift.

Sample MIT restrictions from ATCSCC Logs are as follows. MIT restrictions are formatted (for the most part) as:

time stamp (Zulu) || Center From/TO ... # MIT, issuing constraint, time periods, reason for MIT and/or additional constraints.

For example: “1640 | | ZOB/ZID...20 MIT, O/MIZAR DTW, 1700-1745, COMPACTED DEMAND. “ says that at 1640 ZOB tell ZID starting at 1700 lasting until 1745 give 20 MIT for flights arriving DTW over MIZAR because of compacted demand. Inconsistencies may exist since this is not an automated process (there is no standard template). Example restrictions from 1/29/02 are (miscellaneous messages have been filtered out) are shown in **Figure 22**.

```
1106 | | ZOB/ZNY...20 MIT, ORD, 1145-1230, TERM VOL. ZAU/ZOB 10/30 MIT.
1106 | | ZOB/ZBW...20 MIT, ORD, 1115-1230, TERM VOL. ZAU/ZOB 10/30 MIT.
1106 | | ZOB/ZBW...20 MIT, MDW, 1200-1300, TERM VOL.
1106 | | ZOB/ZNY...20 MIT, MDW, 1200-1300, TERM VOL.
1110 | | ZOB/ZBW...25 JETS MIT, CLE, 1230-1315, ZOB30.
1110 | | ZOB/ZDC...25 JETS MIT, CLE, 1230-1315, ZOB30.
1110 | | ZOB/ZNY...25 JETS MIT, CLE, 1230-1315, ZOB30.
1157 | | ZOB/ZBW...30 MIT, ORD, 1245-1345, TERM VOL. ZAU/ZOB 15 MIT V/PMM.
1157 | | ZOB/ZNY...30 MIT, ORD, 1245-1345, TERM VOL. ZAU/ZOB 15 MIT V/PMM.
```

Figure 22. Example MIT restrictions recorded in the ATCSCC National Logs.

3.9 ATCSCC Advisories

ATCSCC advisories were downloaded (http://www.fly.faa.gov/advisories/) for the following days:

- Jan. 14, 2002
- Jan. 28, 2002 to Feb. 1, 2002

Each advisory contains a message, an effective time and a signature as shown in **Figure 23** and **24**. There are many different types of advisories, as listed below.

- Miles in Trail restrictions
- Ground Stops
- Ground Delay Programs
- Strategic plans of operation
- Scheduled facility outages
- Weather impact and update
- Arrival/departure rerouting
- Enroute rerouting
- Airport runways and AARs
- Airport information
- Proposed compression
- Special operations

ATCSCC Advisory	
ATCSCC ADVZY 021 ORD/ZAU 01/28/2002 CDM GROUND DELAY PROGRAM	
MESSAGE:	AIRPORT: ORD ADL TIME: 14:55Z PROGRAM TYPE: RBS PP ARRIVALS ESTIMATED FOR: 281800Z - 290059Z PROGRAM AAR: 78 ALL CENTERS ARE INCLUDED IN THE PROGRAM. THE FOLLOWING SHALL APPLY FA DELAYS: All EXEMPTED AIRPORTS: NONE MAXIMUM DELAY: 83 AVERAGE DELAY: 33 REASON: WEATHER, LO CIGS/REDUCED AAR REMARKS:
EFFECTIVE TIME:	281458 - 290159
SIGNATURE:	02/01/28 14:59 FSB.//wkstn13a 703-708-5113

Figure 23. Sample ATCSCC Advisory Messages for a GDP collected during the study.

ATCSCC Advisory	
ATCSCC ADVZY 020 IAH/ZHU 01/28/2002 CDM GROUND STOP	
MESSAGE:	AIRPORT: IAH ADL TIME: 14:36Z GROUND STOP PERIOD: 1426Z - 1559Z FACILITIES INCLUDED: (Manual) ZFW ZME ZTL REASON: WEATHER, FOG REMARKS: EXPECT UPDATE: 1600Z ZHU INTERNAL DEPARTURES WILL BE RELEASED FROM STOP AS AIRBORNE INVENTORY AND WX DICTATES..
EFFECTIVE TIME:	281442 - 281559
SIGNATURE:	02/01/28 14:46 FSB.//wkstn24 703-708-5124

ATCSCC Advisory	
ATCSCC ADVZY 022 IAH/ZHU 01/28/2002 CDM GS CNX	
MESSAGE:	AIRPORT: IAH ADL TIME: 15:21Z GS CNX PERIOD: 1521Z - 1559Z REASON: WEATHER, IMPROVED REMARKS: RELEASED FACILITIES: ALL
EFFECTIVE TIME:	281523 - 281659
SIGNATURE:	02/01/28 15:24 FSB.//wkstn24 703-708-5124

Figure 24. Sample ATCSCC Advisory Message for a GS collected during the study.

4 Detailed Analysis

The detailed analysis results are combined with aggregate analysis results and presented in this section. The ZFW center data is used for the basis of vertical prediction analysis, and ZAU and ZOB centers are used for the basis of horizontal prediction analysis.

4.1 Accuracy of ETMS Data

Since the basis of our scientific investigation into sector demand prediction accuracy is formulated on ETMS data, we start by analyzing the accuracy of ETMS data relative to Host data. Since FACET trajectory predictions are based on ETMS data, all predictions carry with them the inherent error in ETMS data.

Discrepancies occurring as a result of ETMS data processing lead to estimation errors in the **vertical dimension**. To document the potential error within ETMS data, we analyze Host data vs. ETMS processed data for the ZFW data set of Jan 14, 2002. A sample of flights departing (542 flights; 22361 data points) and arriving (672 flights; 31995 data points) at DFW are included in this analysis. **Figures 25, 26** and **27** illustrates the aggregate difference in reported aircraft altitude according to Host vs ETMS data sources.

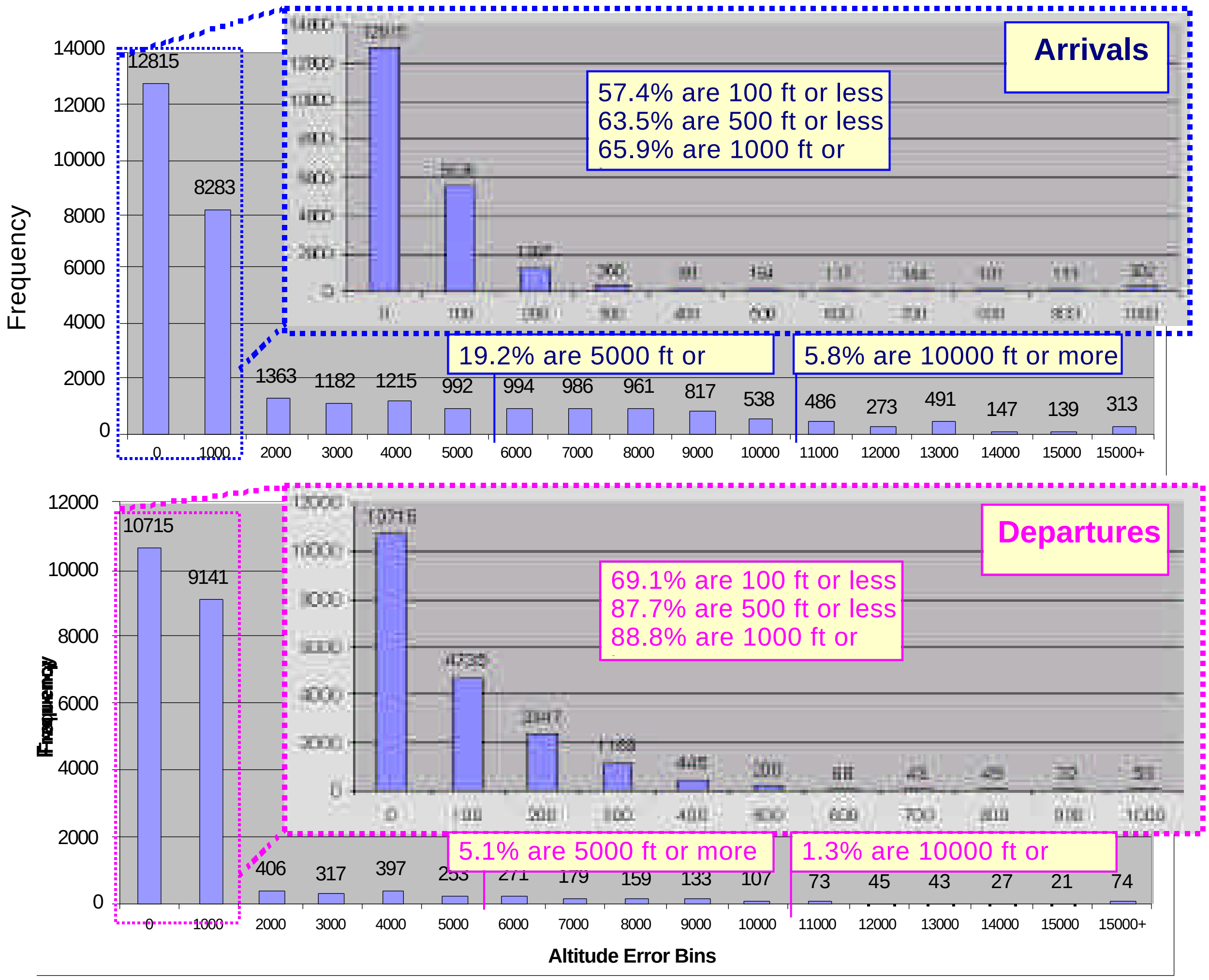


Figure 25. Absolute difference between Host and ETMS altitude data for ZFW (1/14/02).

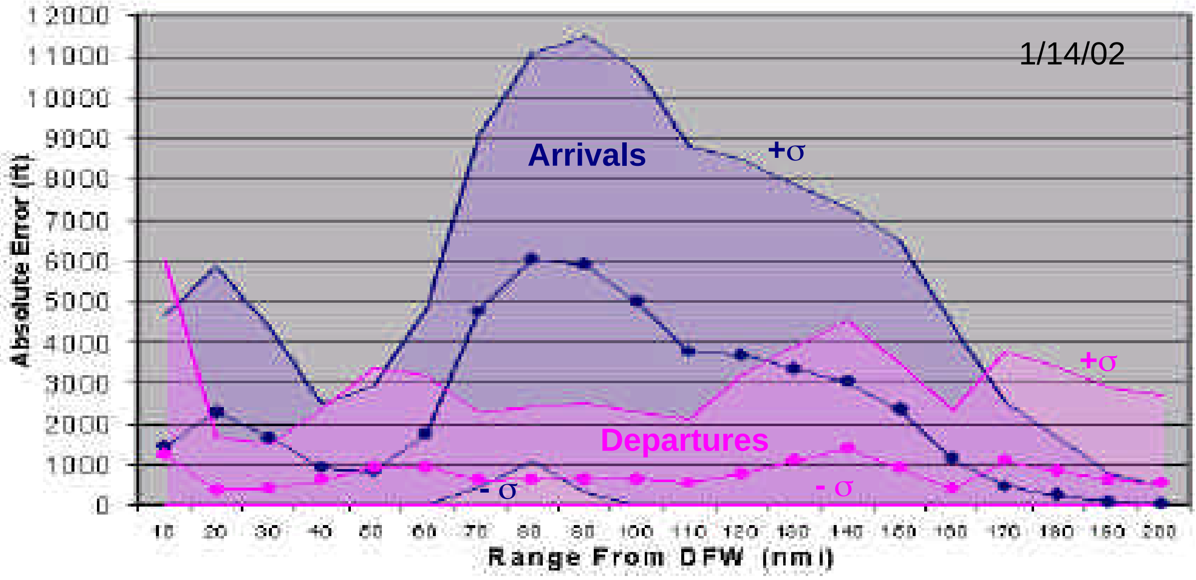


Figure 26. Absolute error between Host and ETMS altitude data as a function of range to DFW.

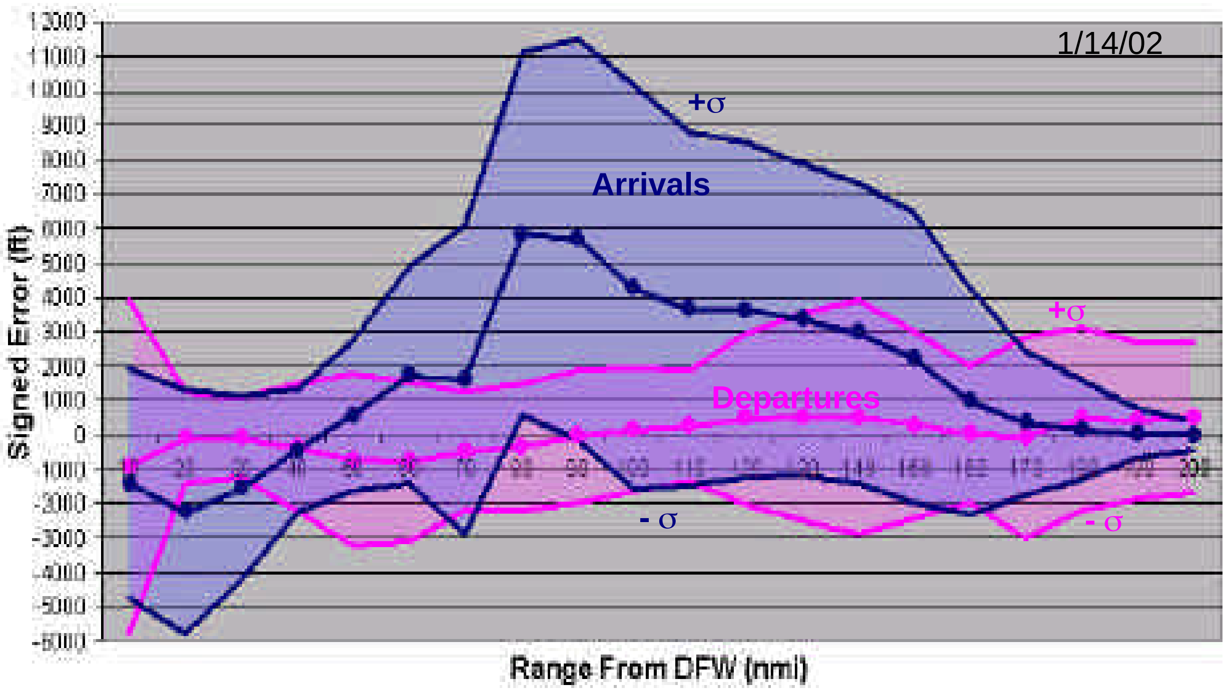


Figure 27. Signed error between Host and ETMS altitude data as a function of range to DFW.

The statistics for arrivals and departures out of DFW differ for ETMS vs Host data. On average, the ETMS departure data has much less error than ETMS arrival data. In terms of accuracy, ETMS altitude data is within 100 ft or less 57.4% of the time for arrivals and 69.1% of the time for departures. ETMS altitude data is within 1000 ft or less 65.9% of the time for arrivals and 88.8% of the time for departures. On the other extreme, ETMS altitude data has large errors in the order of 10000 or greater 5.8% of the time for arrivals and 1.3% of the time for departures. These outlier data points are most problematic to causing sector demand prediction errors.

To understand the differences between arriving and departing traffic, **Figure 26** and **Figure 27** plot the absolute and signed altitude error as a function of range from DFW airport. Again, the data reveals a difference in error statistics between arrival and departure data. The data associated with departing aircraft exhibits better characteristics compared to the arrivals. First, the departure data is smaller in mean and variance. Also, the mean and variance for the departure data is more "behaved" and does not vary as a function of range from DFW. On the other hand, the data associated with arrival traffic has a mean that varies as a function of range from DFW as well as a variance that varies as a function of range from the airport.

In order to understand the nature of the errors observed in these data sets, we investigate a detailed analysis of some of the problematic cases. **Figure 28** illustrates the data for an aircraft departing out of DFW on Jan. 14, 2002. The Host data indicates a steady climb out to 33,000 ft. However, the ETMS data indicates that the aircraft apparently goes to 20,000 ft, holds, and then climbs a while until it quickly goes to 28,000 ft. The rate at which these "jump" climbs in the ETMS data occur is suspect. This characteristic of ETMS data can be attributed to temporary altitude clearances or "T altitudes". Controllers enter a temporary altitude into the Host computer to assign an altitude to an aircraft. Unfortunately, this altitude takes precidence in the ETMS data feed over the Host altitude as determined by radar. So the ETMS data feed reports the T altitude rather than the radar altitude. For any system (e.g., FACET) that is based on the ETMS data feed, this will cause an error in the altitude reading. To characterize the error in sector demand, we place a line that separates where the low altitude sectors and high altitude sectors in ZFW meet, namely at 24,000 ft. Another example of this type of T altitude error is presented in **Figure 29**.

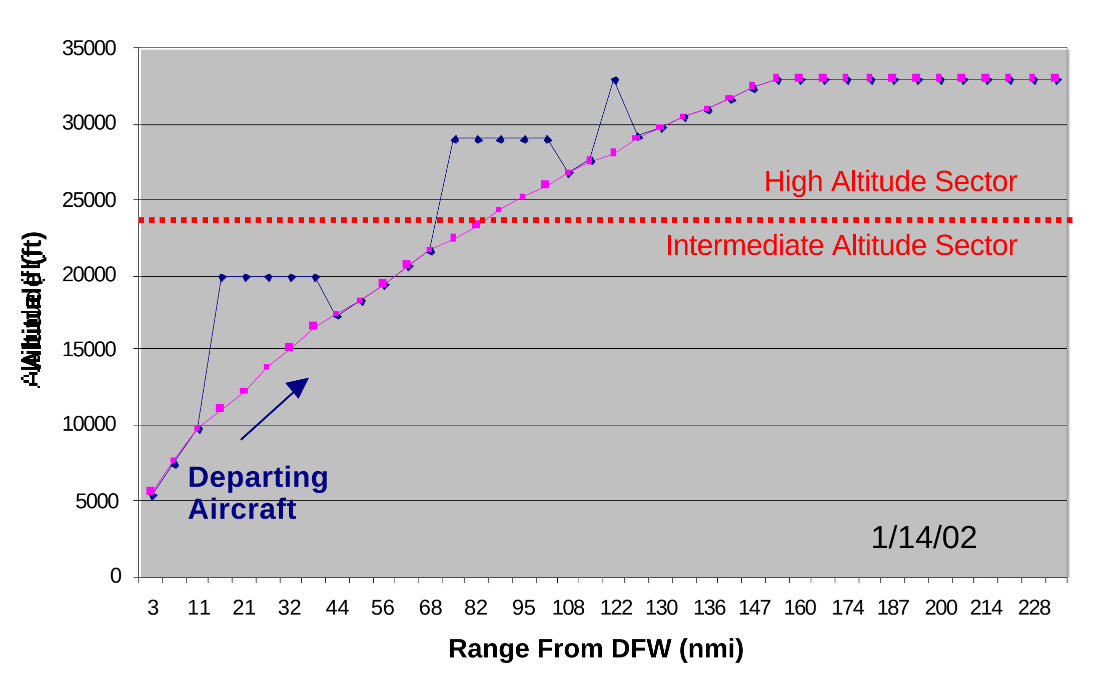


Figure 28. Example ETMS altitude data problem exhibited in DFW departures data.

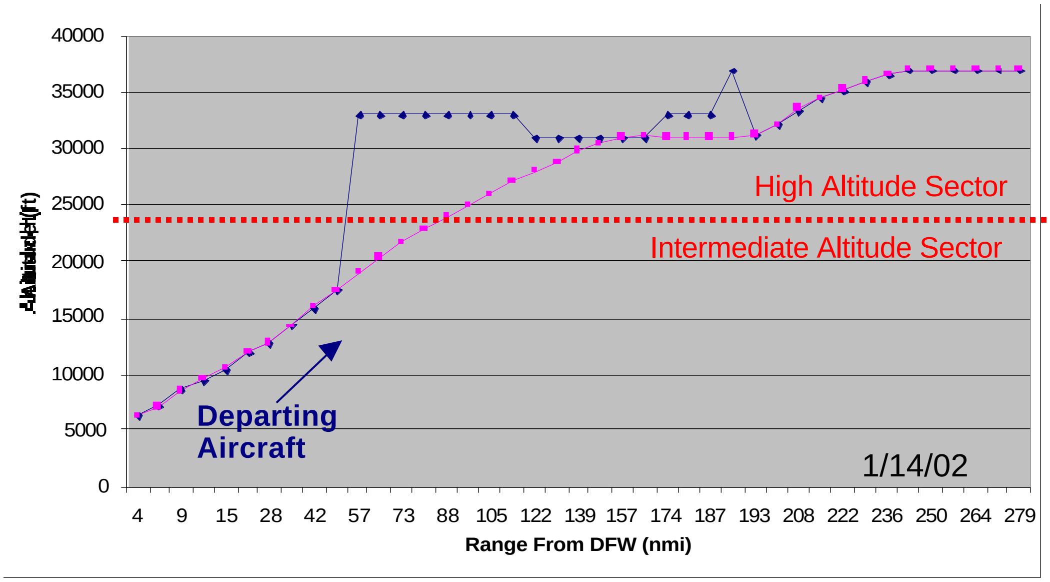


Figure 29. Another example ETMS altitude data problem exhibited in DFW departures data.

Similar effects are observed in the arrival data. As flights descend from their cruise altitude, approx 70 to 110 nmi outside of DFW, they are issued a T altitude which ETM carries over until ARTS takes over for the Host computer. As shown in **Figure 30**, the T altitude for an arrival into DFW is at 11,000 ft. The aircraft cannot physically descend at the rate that the ETMS altitude data reveals. To expalin the ratcheting that occurs within 45 nmi of DFW, we first must understand the transition of data collecting. After a flight reaches a certain threshold about 40 to 50 nmi from DFW, the Host stops collecting data and is transferred to ARTS; from there, CM Sim collects directly from ARTS, while ETMS gets is data from ARTS going through HOST, thus being a time lag which can account for altitude descepencies. The zig zag affect is attributed to T altitudes, CM Sim is gathering data from ARTS while ETMS still has the T altitudes. A similar example is shown in **Figure 31**.

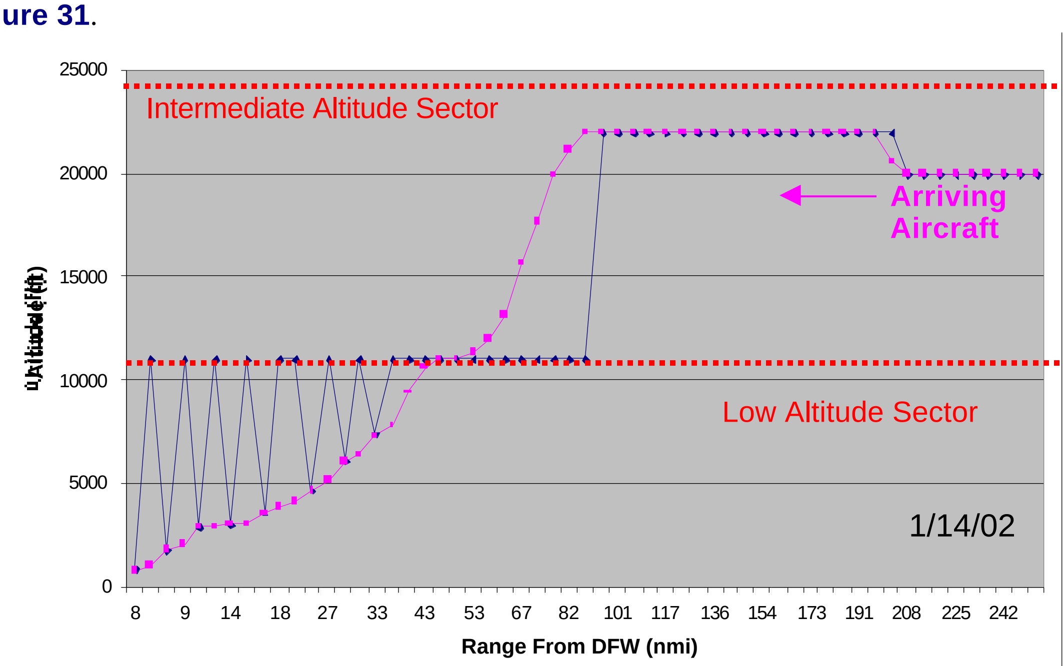


Figure 30. Example ETMS altitude data problem exhibited in DFW arrival data.

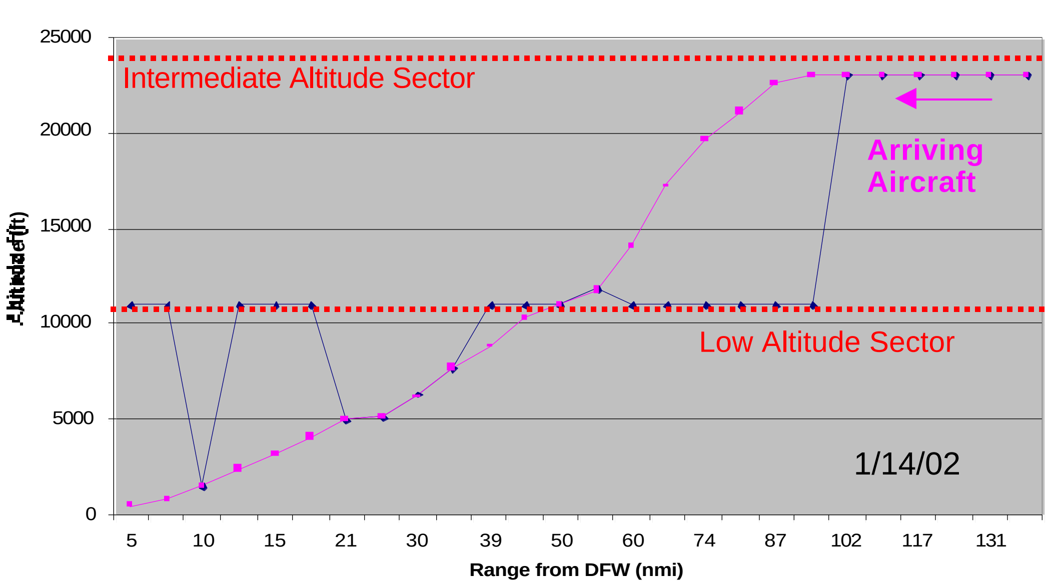


Figure 31. Another example ETMS altitude data problem exhibited in DFW arrival data.

Note that in **Figure 30** and **31** the line that separates the low altitude sectors from the high altitude sectors appears. Note that aircraft are typically descended into the low altitude sectors prior to the final descent to DFW. Because of this, these ETMS erros due to T altitudes are not likely to cause an error in classifying the aircraft in the wrong high or low altitude sector since the effect is seemingly contained in the low altitude sector. Thus, the error in ETMS data relative to Host data for arrival aircraft is less likely to cause an error in sector count in comparison to the departure data.

Returning to the absolute altitude error plot of **Figure 27**, arrivals, approximately 70 to 110 nmi contains the most error, this can be attributed to T altitudes that are generally being used in approximately the same range from the airport.. During these ranges where T alititudes are issued, largre errors are recorded between Host and ETMS altitude data.

Finally, there is reason to believe that these types of T altitudes will not appear very often in the ETMS data feed in the future. As shown in **Figure 32**, the occurrence of T altitudes in the ETMS data are greatly reduced in the most recent data from ZAU. ZAU has installed a HOST patch (on roughly 3/3/02 according to the data in the figure) that re-orders the T altitude to be used only when there is no other data available for altitude. In this patch, the Mode C altitude has highest priority and is reported in the ETMS data feed unless it is not present at the time of the reporting. Prior to the patch, the Mode C altitude had lowest priority in the ordering. At this time, ZOB and other centers are experimenting with this proposed patch. Most recent data has indicated that further centers appear to have installed the patch as of 5/16/02. By "appear to", we identify centers where the number of observed altitudes of type "T" have significantly dropped since data collected on 3/3/02. As shown in **Figure 33**, the only centers that seem not to have employed the patch are: ZAB, ZFW, and ZID.

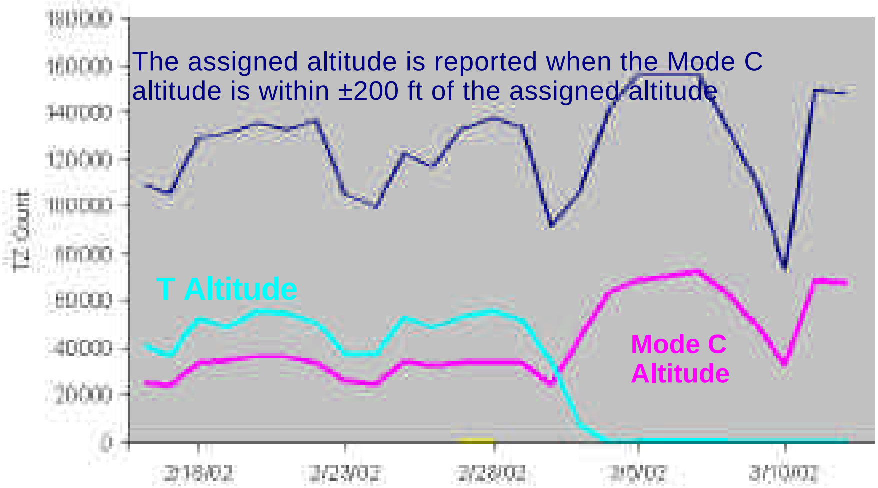


Figure 32. ETMS TZ altitude data for ZAU indicates that T altitudes are beginning to appear much less frequently compared to the time period before 3/3/02.

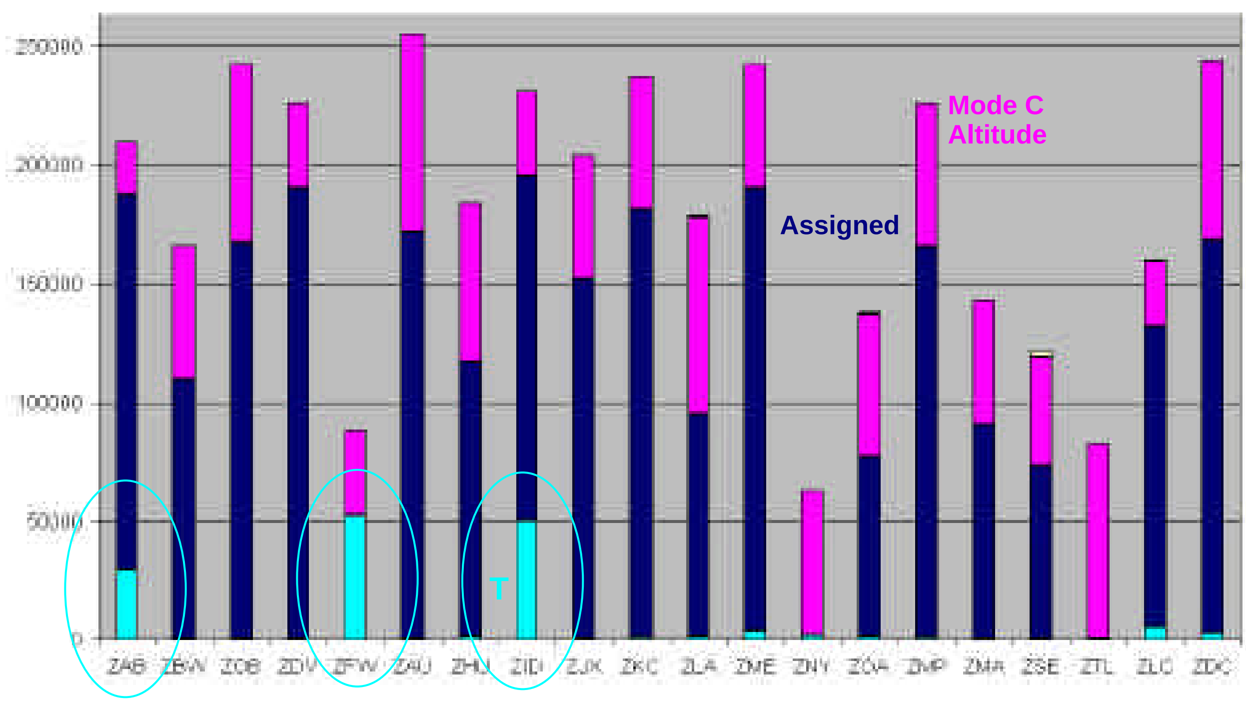


Figure 33. ETMS TZ altitude data for all centers (5/16/02) indicates that T altitudes are beginning to appear a small percentage of the time.

Next, for the **horizontal dimension**, we compare host data to ETMS data to identify the accuracy of ETMS data. **Figure 34** represents the aggregate difference in reported aircraft position according to Host vs. ETMS data sources.

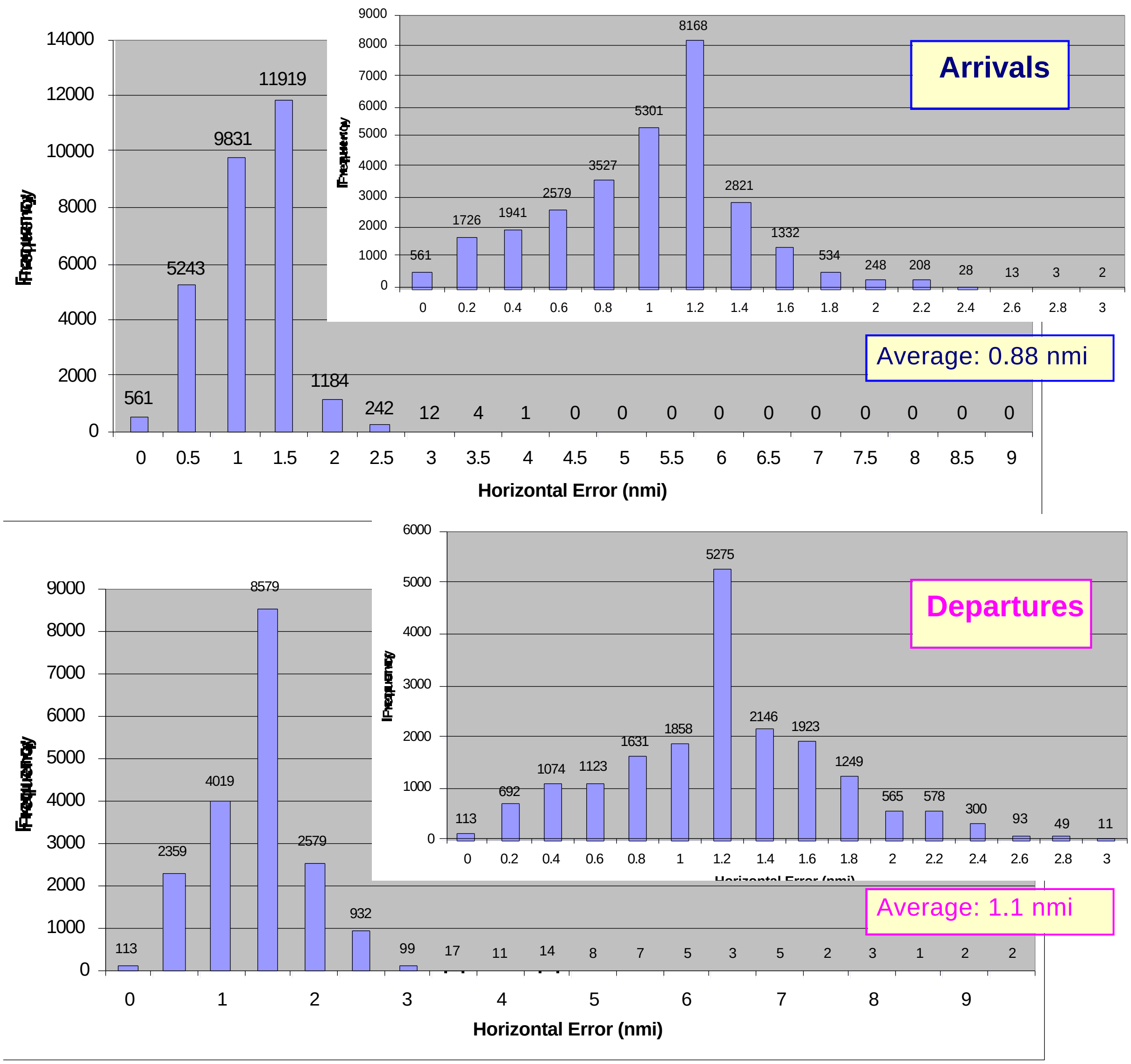


Figure 34. Absolute difference between Host and ETMS position data for ZFW (1/14/02).

There are several sources of error for the horizontal position data. First, the ETMS latitude and longitude coordinates have been truncated to the nearest minute (ETMS stores lat / longs as minutes) resulting in an average error of 0.5 nmi in each direction, or a total error of 0.7 nmi in horizontal range. Historically, this truncation has been attributed to the fact that some ETMS users have to trade off between bandwidth (limited by 9600 baud models for some ETMS sites) and required accuracy. The primary (original) purpose for the ETMS TZ messages was so that the TSD could plot an icon on the display to represent the current location of a particular flight for TFM purposes (not ATC purposes). A resolution to the nearest minute of lat/long is sufficient for this purpose. This factor accounts for most of the average error in our FACET error analysis study. Another form of error can be associated with time lag between the ARTS data sources and the ETMS data source. Depending on time lag, ETMS and the Host data can differ as much as 0.5 nmi (5 second lag), assuming that in one second an aircraft can travel 0.1 nmi (i.e., a speed is 360 nmi per hour).

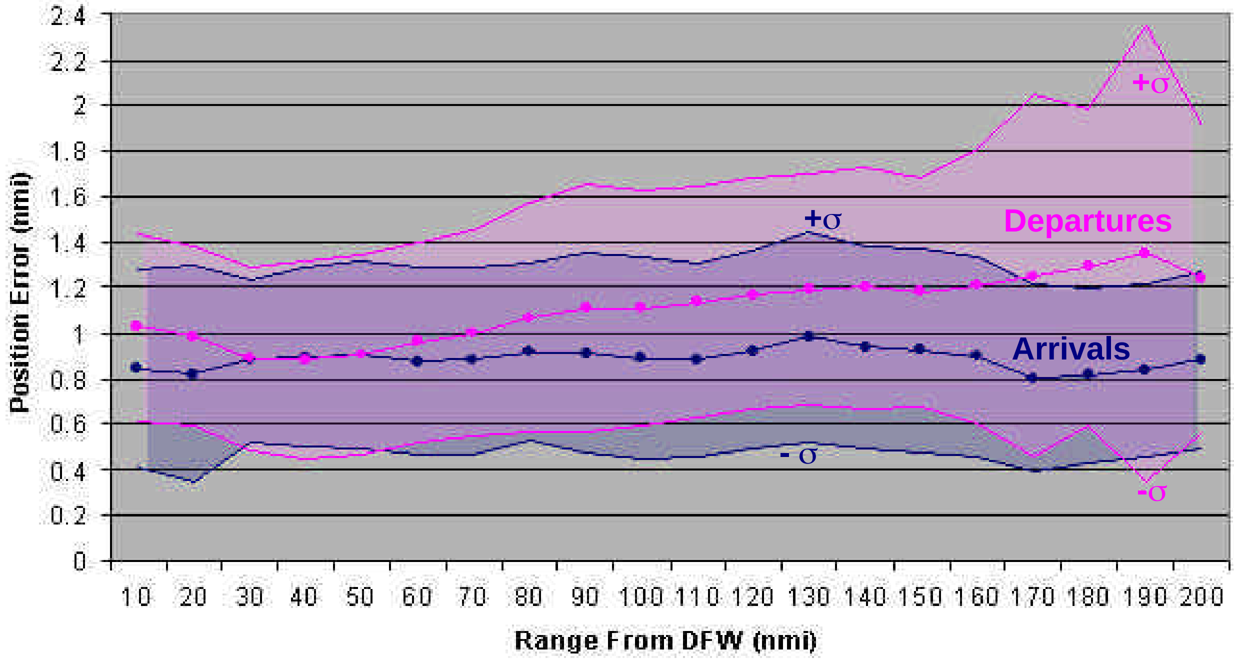


Figure 35. Absolute difference between Host and ETMS position data as a function of range from ZFW (1/14/02).

Figure 35 shows that the arrivals are pretty consistent through out the range, with potential errors described in the above paragraph. The departures on the other hand are a little more disconcerting, the increasing trend of position error as the range increases tells as a the flight increases in distance from DFW, that the error increases. The problems lie in the peak around the 190 range bin.

Finally for the **time dimension**, we compare the first data point of ETMS to the wheels off time to identify the accuracy of the take off time based on ETMS data. The most accurate wheels off time currently comes from ACARS data. In order to understand the nature of the errors involved, an analysis of 20 large airports in the US was performed. The average statistics for all 20 large airports in our focus group is shown in **Figure 36**. Based on this plot, one can conclude that, on average, ETMS is about 1 minute off on its first data point that identifies when a takeoff has occurred. These data vary by airport based on the terrain, buildings, and the locations of radar. **Figure 37** illustrates the statistics for 4 airports in the 3 centers that are the focus of this study (ORD in ZAU, CLE in ZOB, DFW in ZFW, and DTW in ZOB). The worst average statistics for any airport occurs for DTW in ZOB airspace. In these plots, items entered in "More" are considered outlier data points. These results agree with the work of [KCH97] who showed that ETMS DZ times are typically 0–2 minutes after the actual wheels off time, and ETMS AZ times are typically between 1–4 minutes after the actual wheels on time.

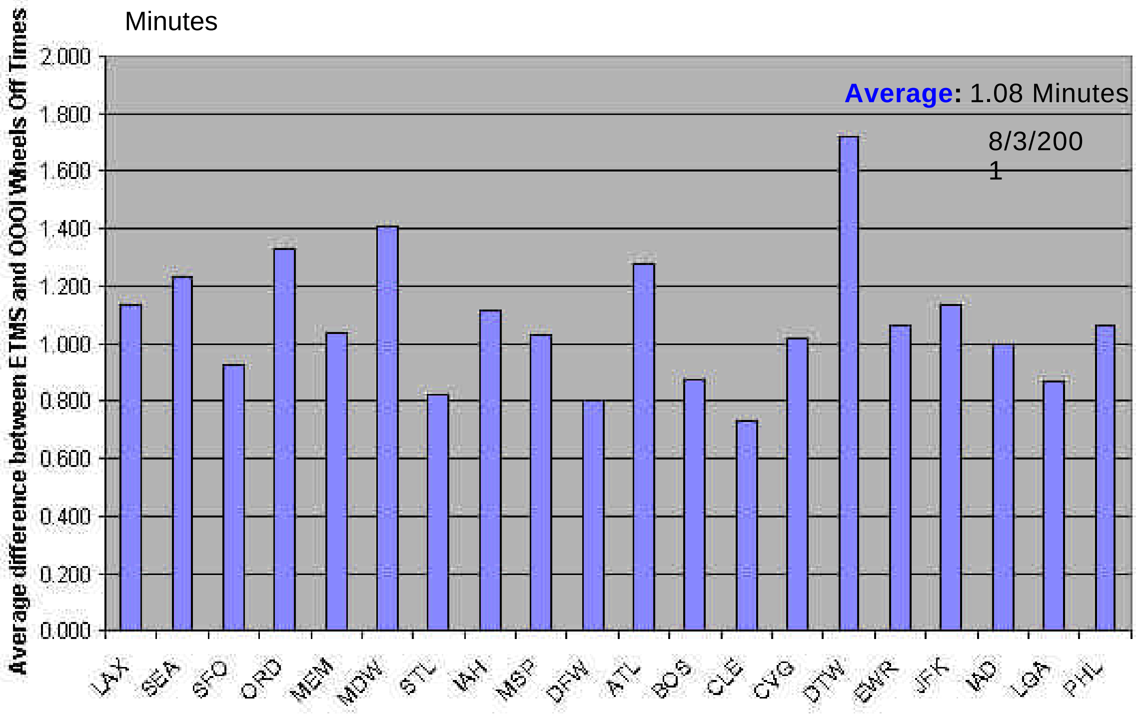


Figure 36. Error between first ETMS data point and ACARS OOOI wheels off time for 20 major airports in the NAS.

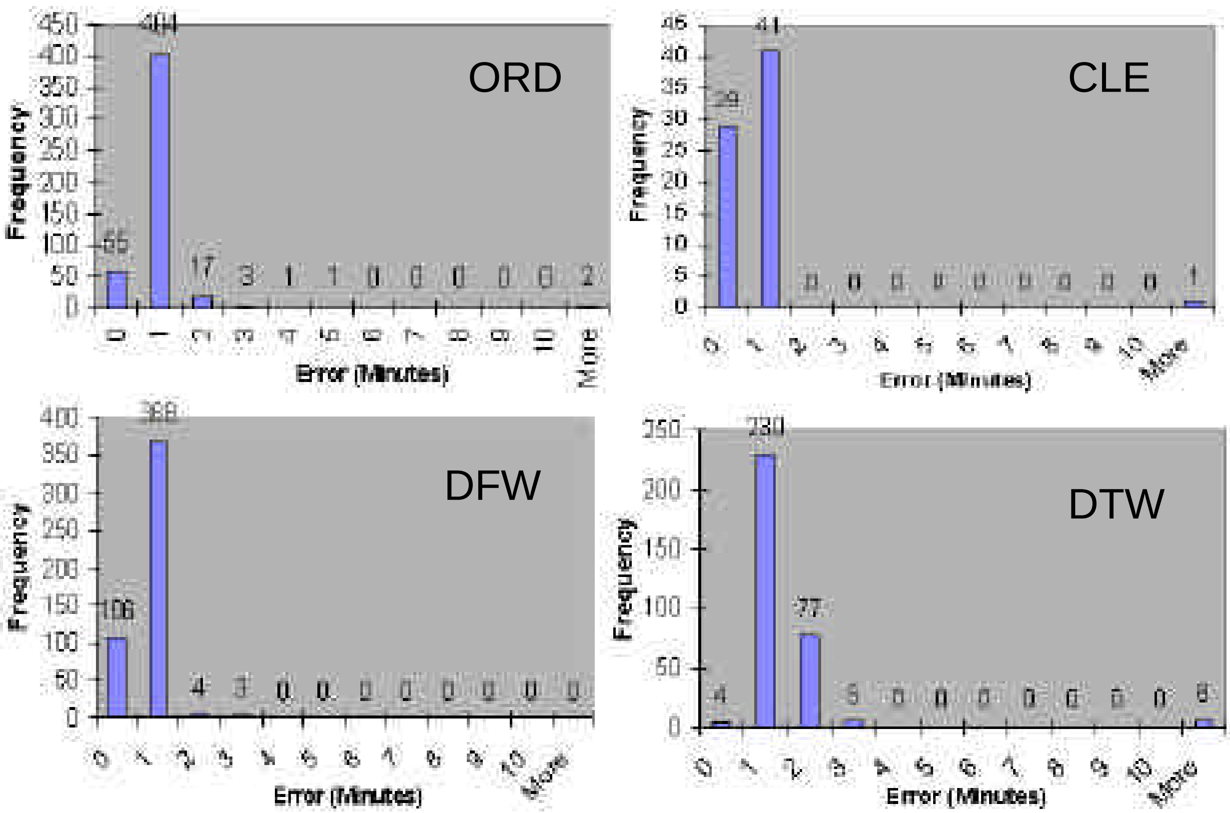


Figure 37. Statistics for error between OOOI wheels off time and the first ETMS data point for several airports in the NAS.

Figure 38 illustrates the accuracy of the **ETMS scheduled departure time** relative to the OOOI wheels off time. These data illustrate the errors made when ETMS departure times are used to predict take off times and errors that exist in trajectory predictions that are made prior to take off. On average across 20 airports, there is about an 8 min. difference. Once an aircraft takes off, the ETMS position data is fairly accurate, so these errors are immediately nullified. However, prior to takeoff, these errors characterize the trajectory prediction error.

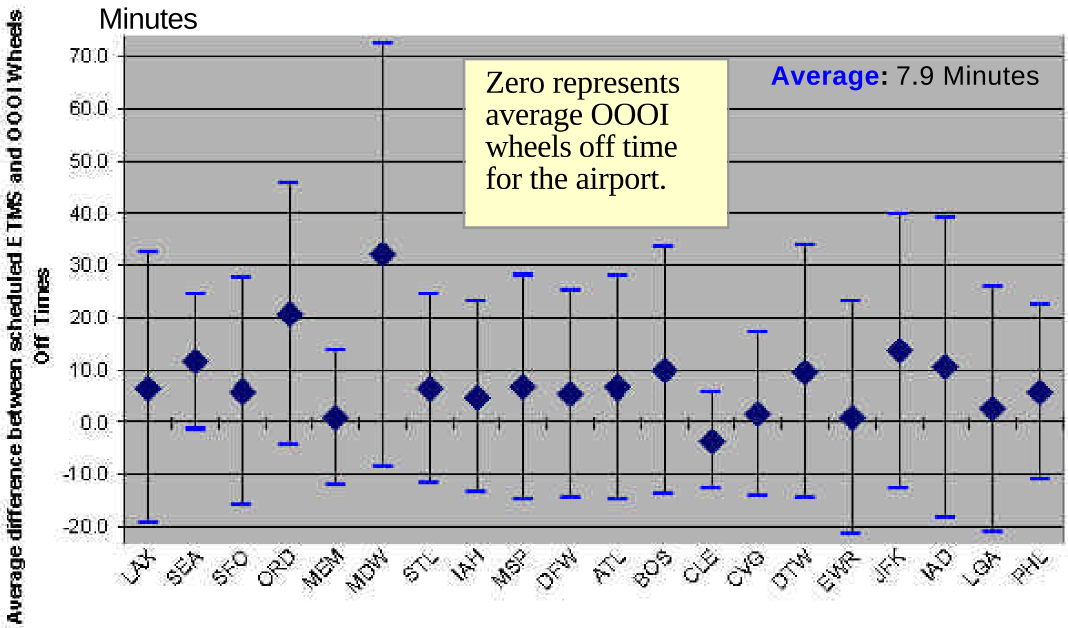


Figure 38. Error between ETMS scheduled departure time and OOOI wheels off time.

Next, we consider what happens during de-icing conditions at an airport, since this affects the error between the ETMS schedule take off time and the actual OOOI wheels off time. In our on-site observations at the ZOB center, we specifically saw a difference in the way APREQs were performed on days that had de-icing conditions compared to days where there was no de-icing. On de-icing days, aircraft were immediately released from CLE and DTW, presumably so that they would not have to de-ice twice and disrupt airport operations. As shown in **Figures 39** and **40**, the data for DTW airport reveals that the taxi times during the time period when de-icing was recorded is on average more than double the taxi time during days when there was no de-icing. Furthermore, when de-icing operations are performed, the variance in the taxi time is greatly increased (most likely due to the amount of de-icing to be performed and the queue for de-icing). At DTW, a flight pushes back from the gate (starting the taxi timer) then travels to the "de-icing zone", gets de-iced, then proceeds to be inserted in the departure queue. However, on days where there was no de-icing, the APREQs were used to hold aircraft until gaps opened up in the streams into ORD, for example. Thus, there will be a drastic difference in the taxi times and predicted departure times between these days. **Figure 41** shows that when this is taken in perspective with respect to the ETMS scheduled take off time, the de-icing seemingly causes the error to increase in time.

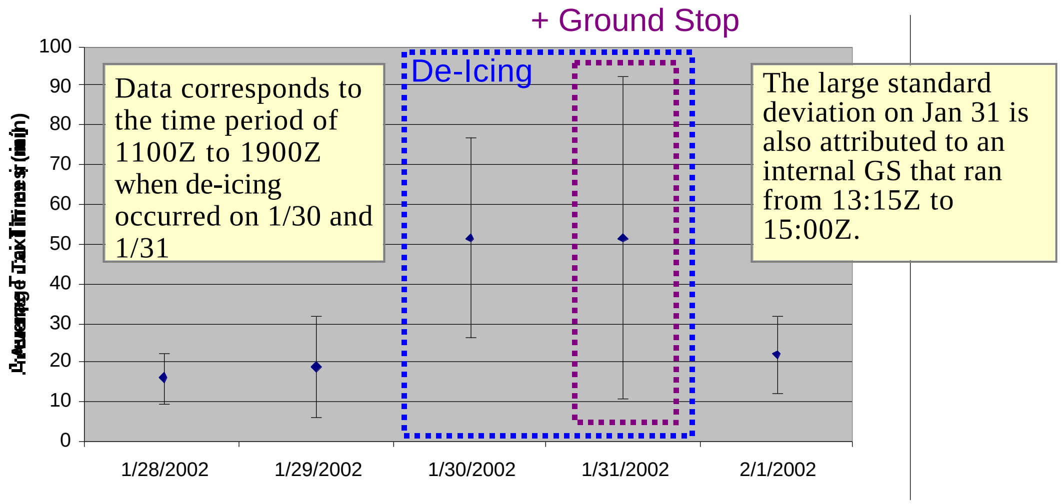


Figure 39. Average taxi time for DTW indicates the effect of de-icing operations.

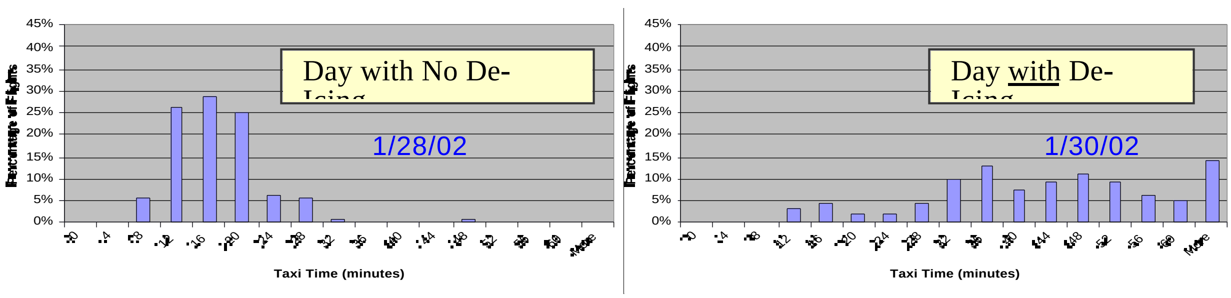


Figure 40. Histogram plots for taxi times for DTW indicates the effect of de-icing operations.

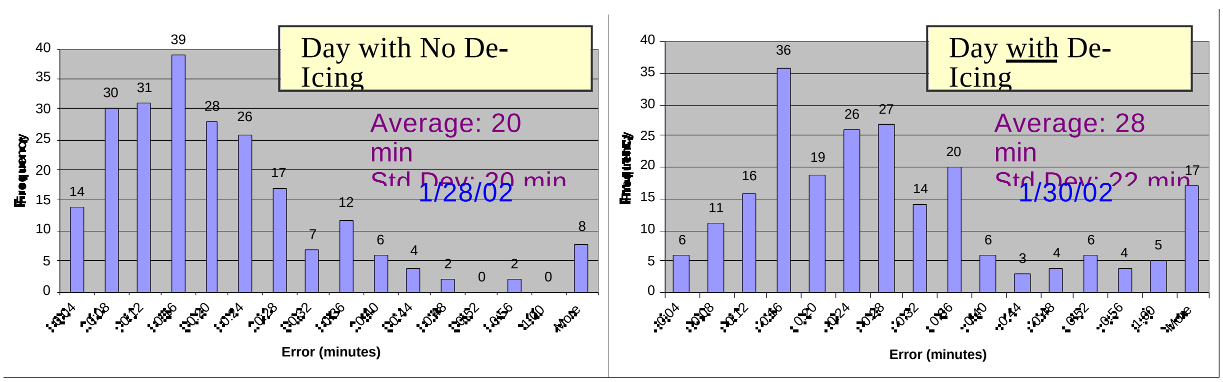


Figure 41. Error between OOOI wheels off time and the Scheduled ETMS Departure Time for DTW airport indicates a greater average error the day when de-icing occurs.

4.2 Sector Demand Prediction by FACET

In order to analyze the effects of various sources of error on sector demand, we fist identify the sector demand performance metrics that are most important to our study and the general characteristics of these metrics for the focus centers of our investigation.

4.2.1 Scope of Analysis

There are two factors that play an important role in our analysis:

- Law of diminishing returns – very long look ahead times do not reveal much new information.
- Active vs Proposed flights. Active flights, or those that are currently en route, are separated in our analysis from proposed flights, those that are on the ground at the time of estimating the sector demand.

As **Figure 42** shows that most en route flights (93%) became airborne within a 120 minute look ahead time. To look any further back in time for analyzing en route flights does not have a high payoff. Thus, we investigate trends in active flights for look ahead times from 0 to 120 minutes, and for proposed flights from 0 to 240 minutes.

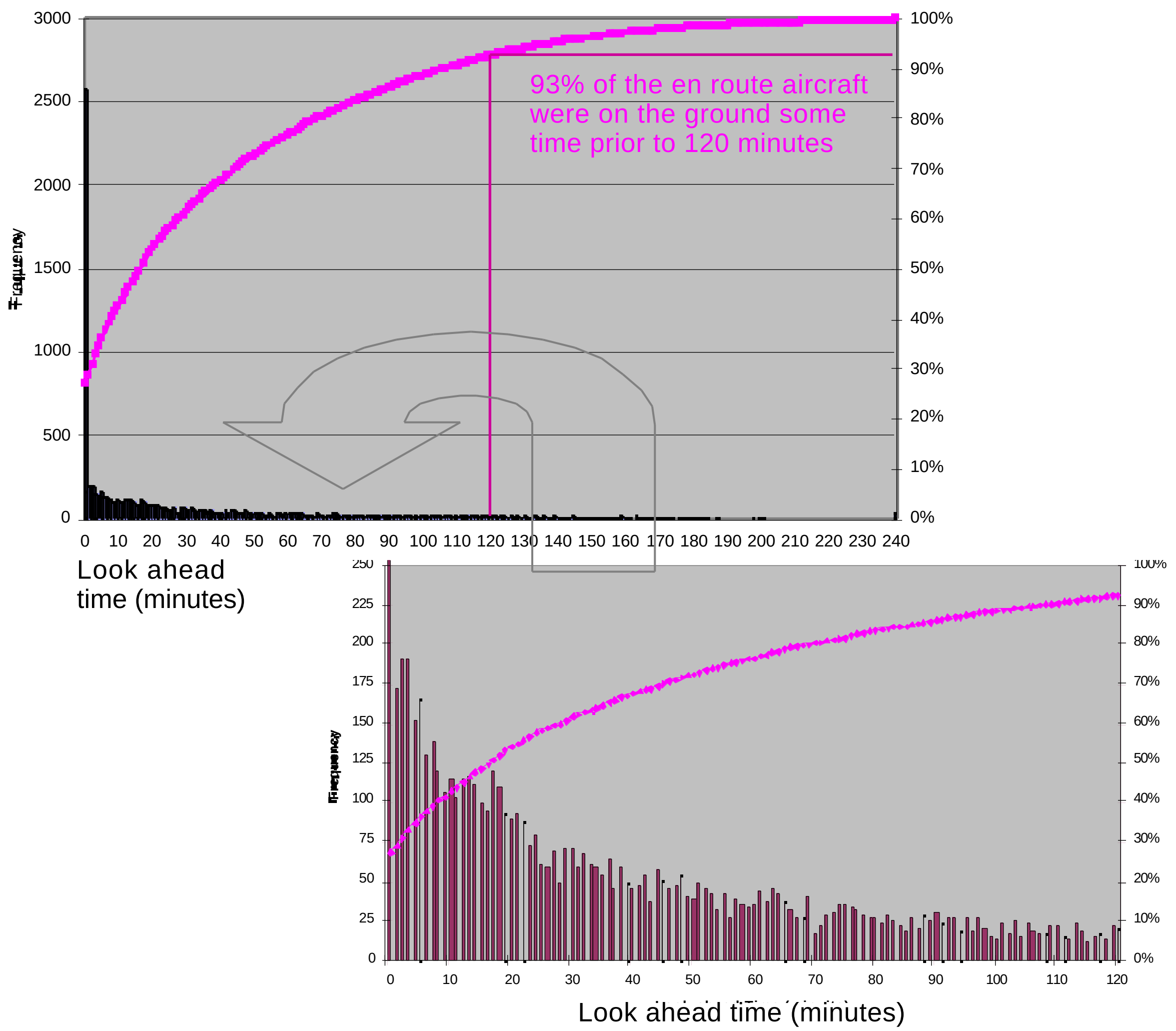


Figure 42. Most en route flights took off within a window of120 minutes.

One additional assumption that the analysis of sector demand errors makes is to assume that the ETMS data is truth data. The previous section discussed how ETMS data is in error in comparison to Host data, however, these errors are most pronounced in the terminal area close to airports. The majority of the sector demand error analysis is performed for high altitude en route airspace where ETMS data is more accurate in comparison to Host data. Nevertheless, ETMS data does have its limitations, and we note that our conclusions are only as good as the ETMS data that we base our conclusions on.

Certain color schemes were chosen in the analysis to assist in interpreting the data and statistics related to the data. In general, when we are directly comparing statistics of ZAU to ZOB, we color ZAU data blue and ZOA data red. When a focus is made between adjacent sectors between ZAU and ZOB, or within either of ZAU or ZOB, we use the colors identified in **Figure 43** to help identify data. We associate adjacent sectors through the use of common colors in ZOB and ZAU according to the major jet routes between them; ZOB18/19 with ZAU25, ZOB28/29 with ZAU82, ZOB46 with ZAU36. The two additional sectors, ZOB48 and ZAU24 are colored yellow.

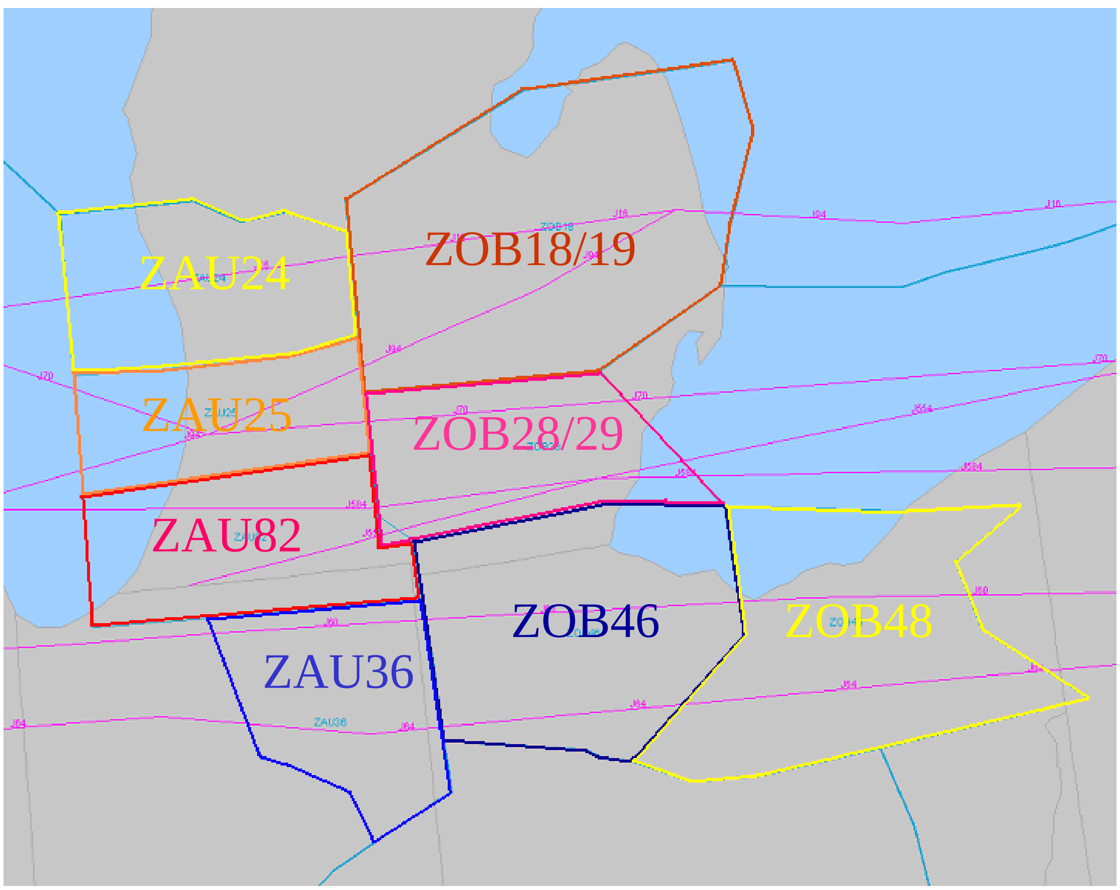


Figure 43 Color scheme for ZAU and ZOB sectors called out in the study.

4.2.2 Sector Entry Time

Since a focus of this report concerns ARTCC sector demand, we analyze the events of aircraft entering and exiting sectors. This is highly contingent on the accuracy of trajectory prediction, which is why trajectory prediction accuracy is covered in this chapter with equal importance. In this section, we consider the accuracy of FACET in predicting sector entry events, as shown in **Figure 44**. While a similar study could be carried out for sector exit events, it would yield no additional insight.

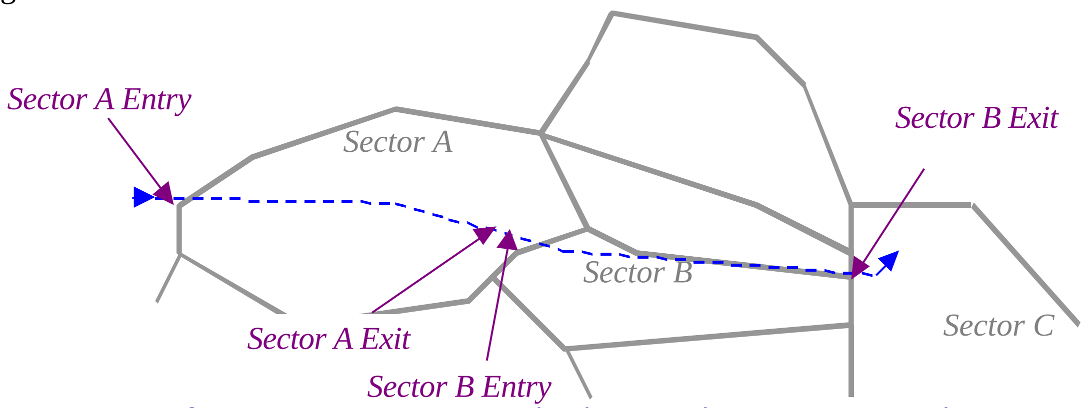


Figure 44. Sector Entry and Exit Events in Sectors A, B and C.

The plots presented in this section serve to answer how well actual entry time into a sector was predicted. Small deviations in sector entry time can cause large errors in peak sector counting. Many of the graphs are produced by "pushing" predictions forward in time. For example, if a prediction was made for a flight at 1000Z, the filled predictions show the effect of using that prediction for 1005Z, 1010Z, 1015Z, etc., until the next actual prediction was made. These plots only look at predicted flights that actually entered a particular sector.

Figure 45 through **50** show the signed and absolute sector entry time prediction error for proposed and active flights for ZAU and ZOB airspaces. The signed sector entry time is the predicted minus the actual time of entry into a sector. The absolute sector entry time is the absolute value of the predicted minus the actual time of entry. The absolute sector entry time errors for the active flights are very similar between the two days (1/29/02 and 1/30/02), showing increased error as look-ahead time increases. Note that the sector entry time error for ZOB is almost always larger than ZAU results, at lease with look ahead times up to 120 minutes.

Sector entry time errors for proposed flights appear to get better as look ahead time increases up to look ahead times of 80 to 100 minutes, then proceed to get worse. There are relatively few unique flights that make up the data points with short look-ahead times. These few flights that make up the early part of the proposed curve are heavily biased towards data anomalies, for instance, the error associated with T-altitudes that are set as the initial condition for when an aircraft enters a high altitude sector. In addition, only internal center departures or other short flights make up the smaller look-ahead times and they are more likely to be delayed than en route flights. Also, we receive very few flight amendments less than a half hour before take off which translates into no new information with which to improve our trajectory predictions for short look ahead times.

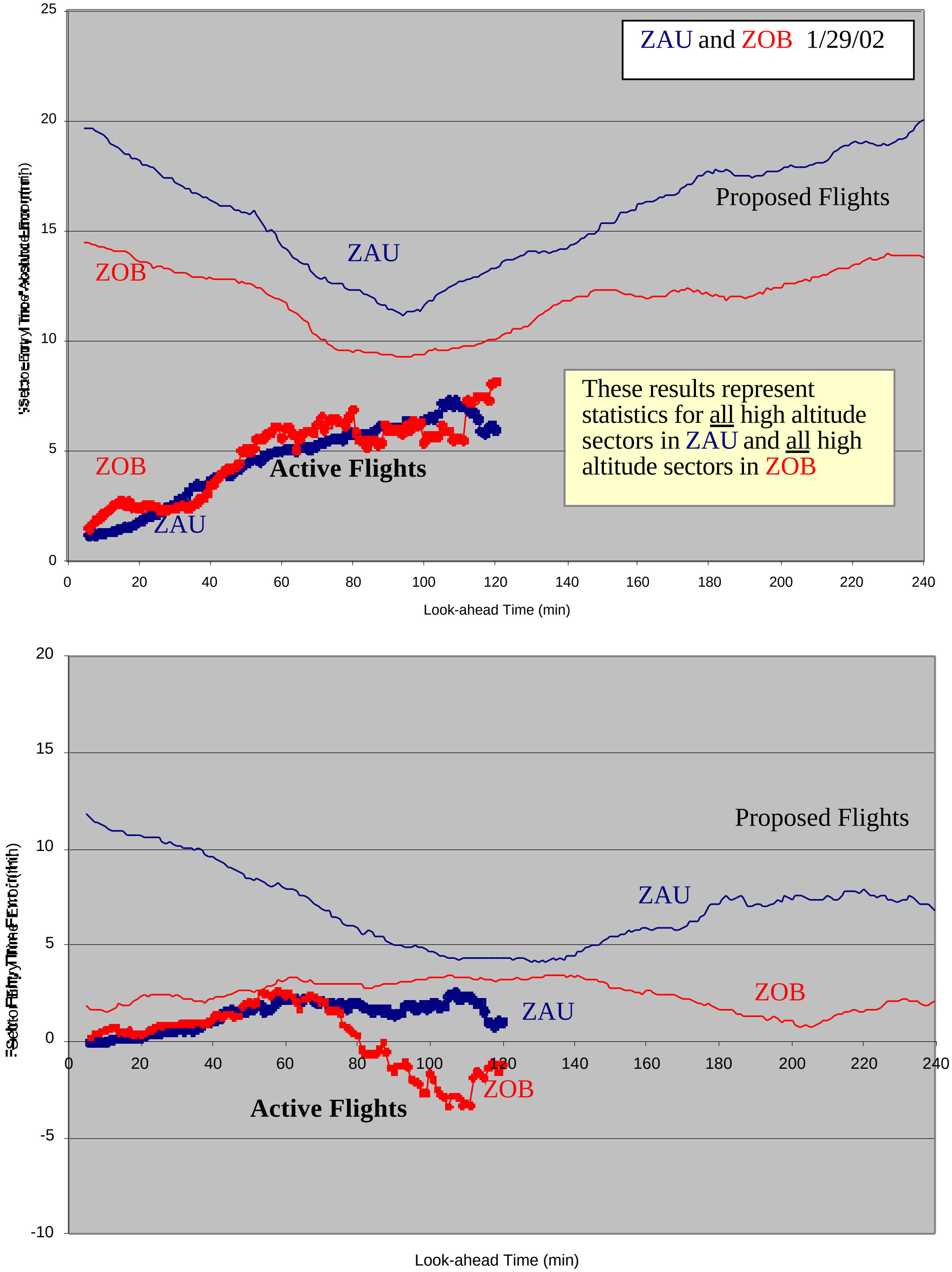
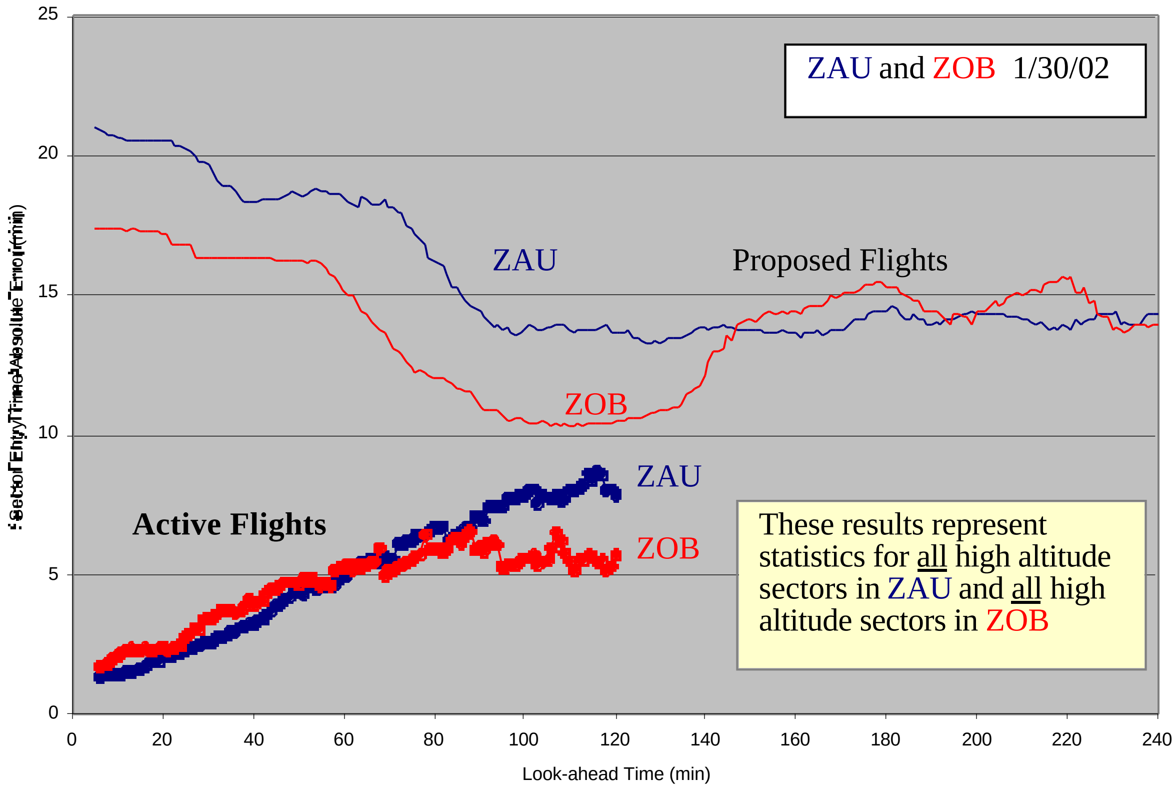


Figure 45. Sector Entry Time Error (signed and absolute) for predictions made prior to take off (proposed) and after take off (active) for ZAU and ZOB on 1/29/02.



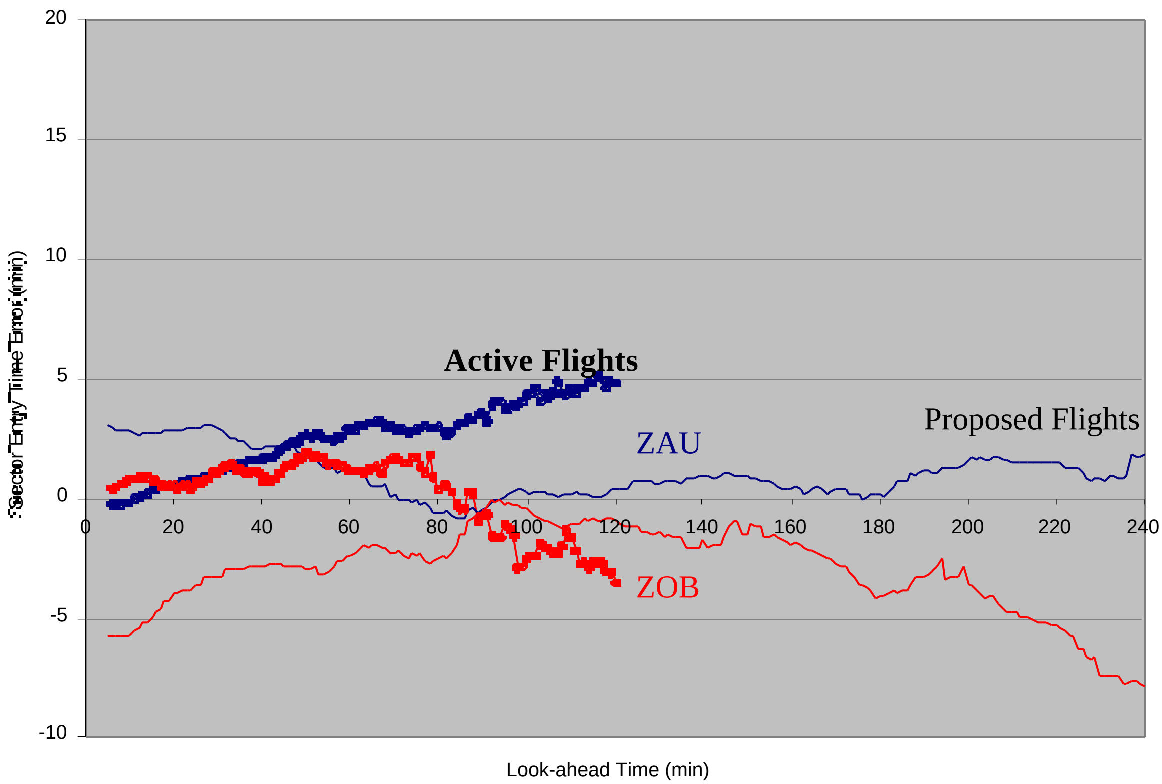


Figure 46. Sector Entry Time Error (signed and absolute) for predictions made prior to take off (proposed) and after take off (active) for ZAU and ZOB on 1/30/02.

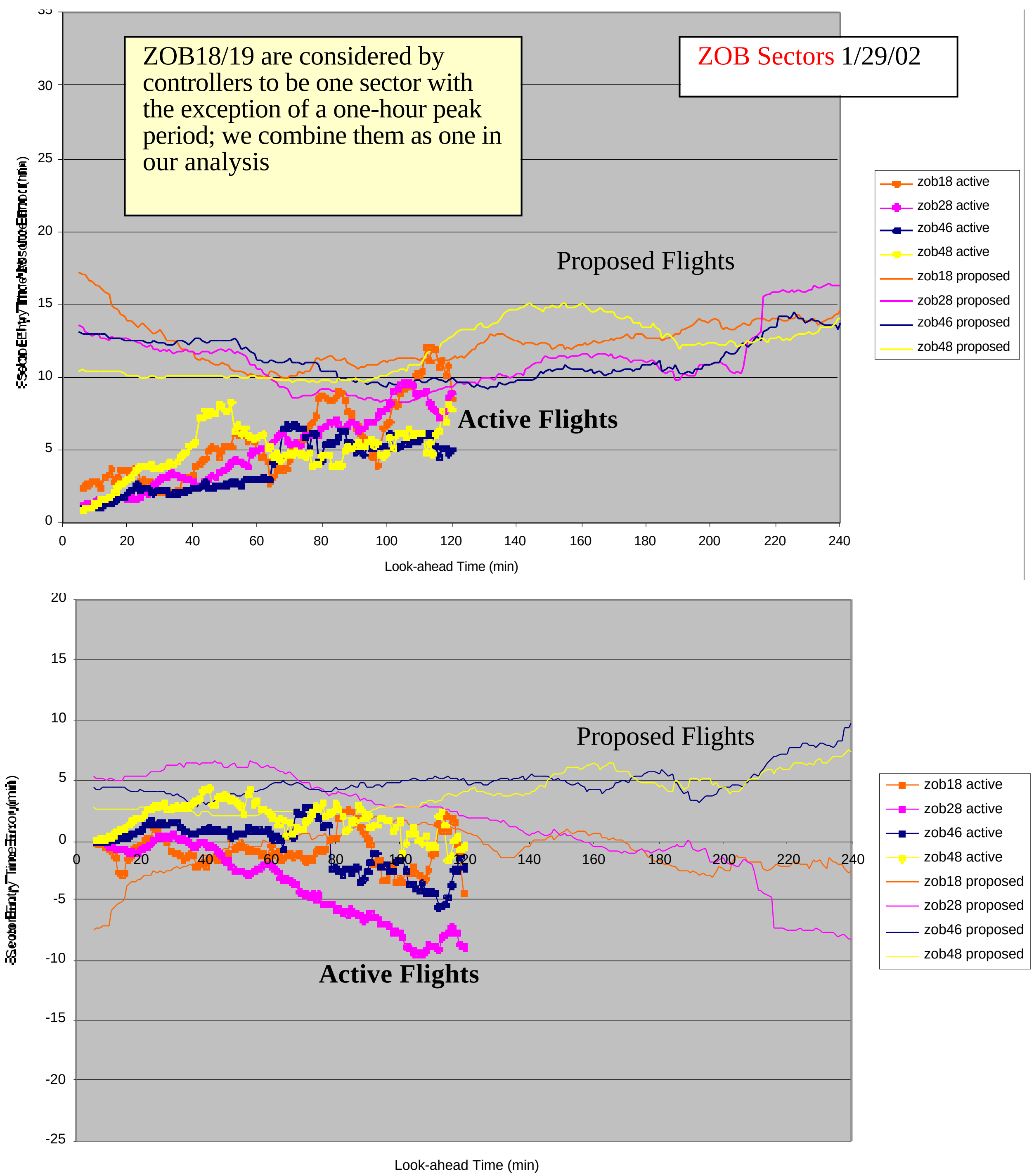


Figure 47. Sector Entry Time Error (signed and absolute) for predictions made prior to take off (proposed) and after take off (active) for selected sectors within ZOB.

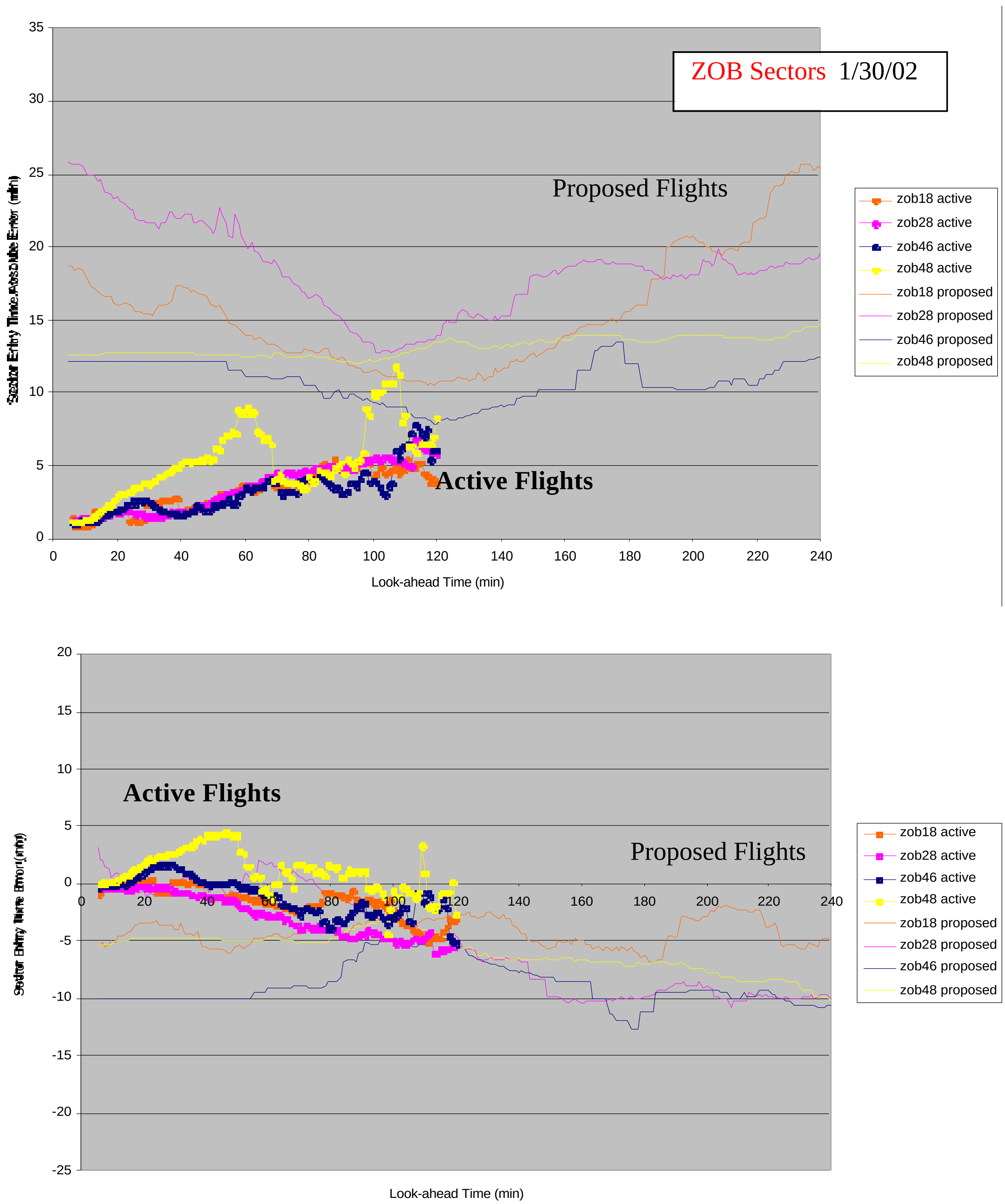


Figure 48. Sector Entry Time Error (signed and absolute) for predictions made prior to take off (proposed) and after take off (active) for selected sectors within ZOB.

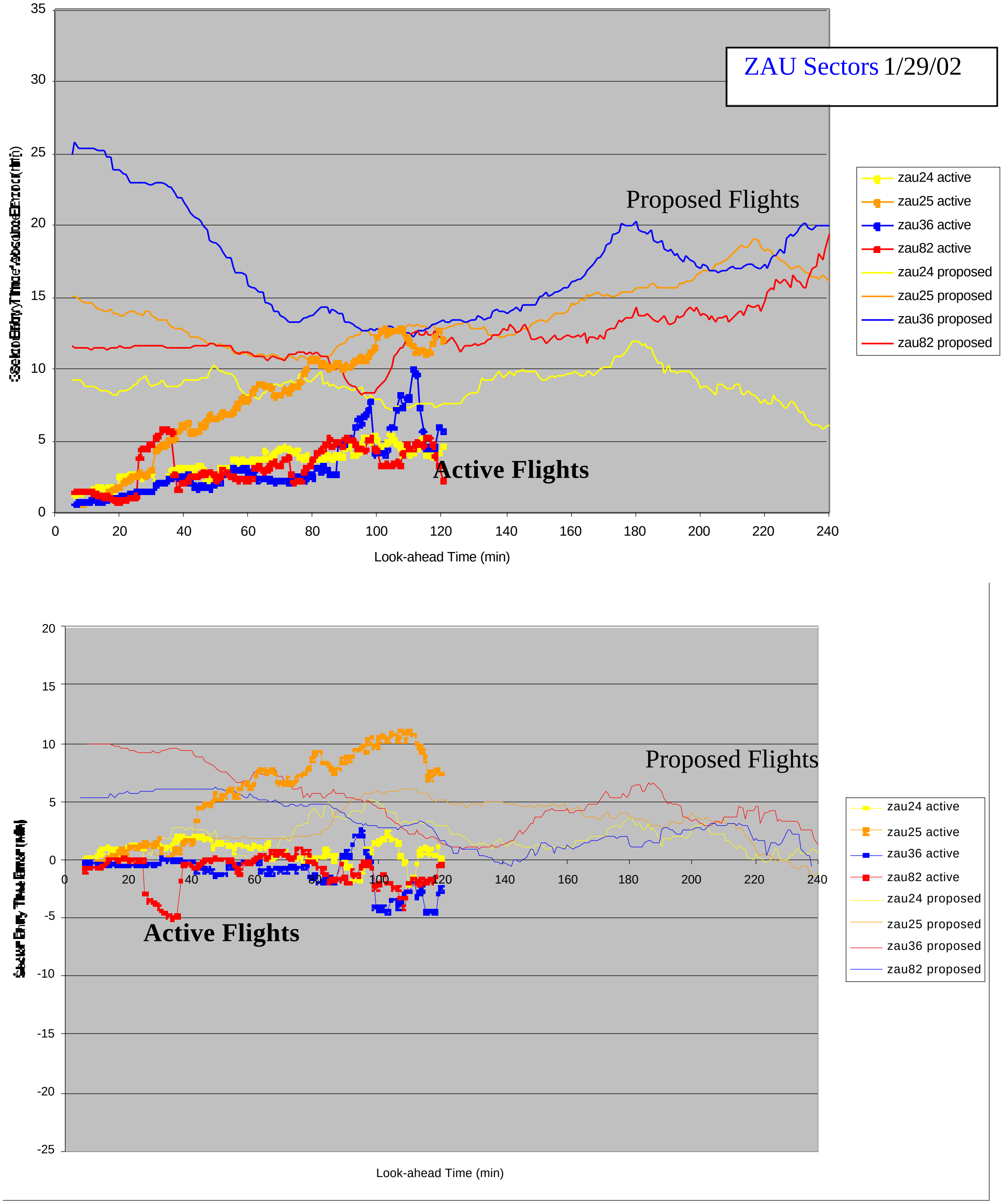


Figure 49. Sector Entry Time Error (signed and absolute) for predictions made prior to take off (proposed) and after take off (active) for selected sectors within ZAU on1/29/02.

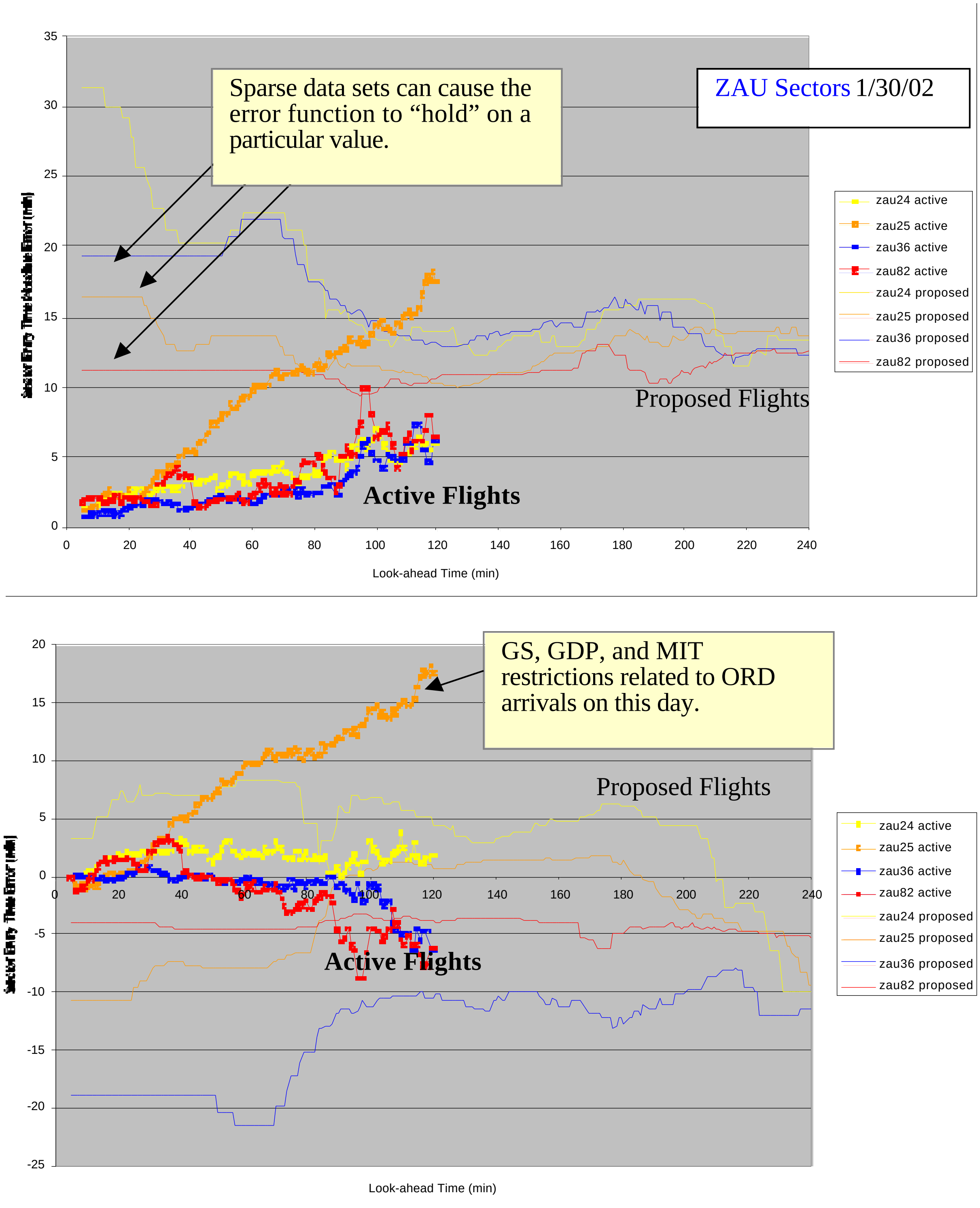


Figure 50. Sector Entry Time Error (signed and absolute) for predictions made prior to take off (proposed) and after take off (active) for selected sectors within ZAU on 1/30/02.

These plots indicate the trends in sector entry time predictions over two adjacent centers. The following general points can be made from these plots:

- Active flights generally have an error plot that is fairly linear starting near zero with very small look-ahead times.
- Results from 1/29/02 and 1/30/02 are similar, which builds our confidence that there are not any major flaws in our trajectory prediction results.
- When looking at the signed error of active flights in ZAU for both days, there is a tendency to over predict more than in ZOB.
- In general, ZOB has a tendency to have less error than ZAU. One possible explanation for these results is that ZAU contains Chicago O'Hare (ORD) airport, one of the most congested airports in the NAS where there is often unexpected airborne holding.
- There were a lot of ground stops that were executed on 1/30/02, which might explain why the absolute error for sector counts are high for short look-ahead times, in comparison to results from 1/29/02, when there were fewer ground stops and less weather.
- In all of these figures, the active performance metrics are significantly better than the proposed ones. This is expected because with active flights we have a known departure time which is the greatest source of error for trajectory prediction of proposed flights.

Furthermore, there are several causes of the errors in these plots. These include:

- Aircraft sector entry times that are late due to path stretching or vectoring for conflict detection and resolution by ATC, as shown in **Figure 51**.
- Circular holding, as seen in **Figure 52,** can possibly cause multiple sector entries (but this is rare), and causes en-route delay that is not taken into account by FACET in advance. This generally adds to the sector entry time error as FACET predicts the aircraft will proceed forward.
- Direct-to routes (e.g., **Figure 53**), which FACET does not know about, will result in the aircraft flying shorter route than the FACET trajectory prediction which will follow the filed flight plan.
- Some flights have abnormal behavior that may be impossible to predict, as shown in **Figure 54** and **Figure 55**.

Figure 51. Vectoring is the most prevalent cause for sector entry time error in ZAU25.

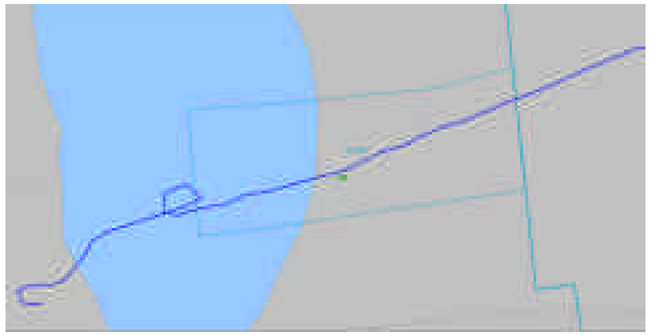


Figure 52. ORD circular holding causes sector entry time and sector count errors in ZAU25.

Figure 53. A Direct-to route (to DEWIT) actually reduces sector entry time.

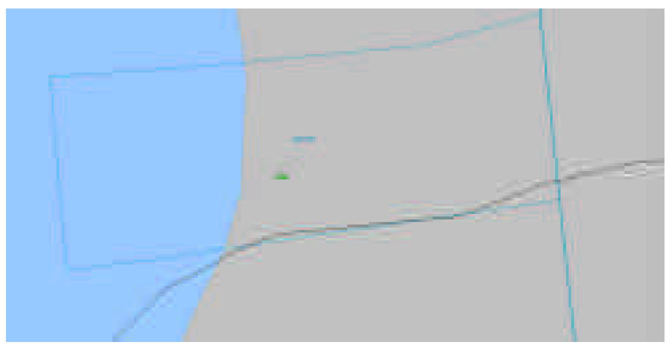


Figure 54. A flight vectoring on the southern boundary of ZAU25 exits and enters ZAU25 multiple times.

Figure 55. An abnormal flight pattern causes large errors in sector entry time and sector counts.

4.2.3 Sector Count

The analysis of this section is concerned with FACET's ability to predict sector counts. Sector count prediction is the ability of a tool to predict for any sector the number of aircraft to be in that sector at some time in the future. Predicted sector counts allow center controllers and TMUs to change the flow of traffic to prevent future airspace overloads – which lead to high workload for controllers – and possibly limit unnecessary airspace and ground restrictions. There is a caveat that is important to note: analyzing predicted sector count vs. a truth data set fails to address the accuracy of how individual flights contribute to those counts[1]. For example as shown in **Figure 56**, an aircraft may be predicted to occupy a sector that it never actually enters. Another aircraft, *not* predicted to enter the sector does in fact enter it at around the same time the first aircraft was predicted to do so. The sector count prediction for this particular sector would have been correct, although two aircraft actually occupied unpredicted sectors. Data from our experiments confirms that this effect happens; **Figure 57** shows an example of an aircraft trajectory predicted to occupy a sector that it never actually enters (according to ETMS data).

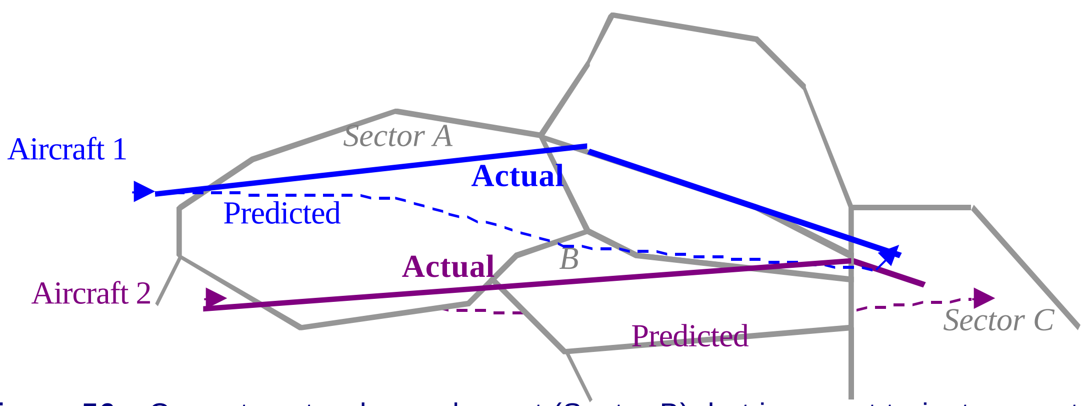


Figure 56. Correct sector demand count (Sector B), but incorrect trajectory contribution (sector count contribution predicted from Aircraft 1 but ultimately produced by Aircraft 2).

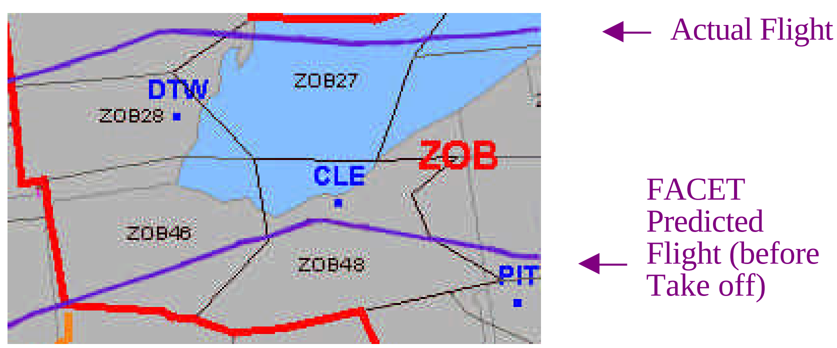


Figure 57. Example flight predicted to pass through one sector (ZOB48) but actually flown through another neighboring sector (ZOB27).

The results of these analyses are presented as an aggregate of all flights and events over a certain prediction time horizon. Sector count is defined as the maximum instantaneous count over a fifteen minute time period. We are approximating this by looking at 15 consecutive one-minute bins and taking the maximum of those values. Then to get signed sector count error, we

[1] The sector hit rate of FACET is a comparison of the accuracy of FACET in simply predicting that an aircraft entered a sector at all. While this may not be significant in a tool that involves prediction in the aggregate, namely the sector count, it is vital to the operation of a tool depicting contributions by unique flights.

take predicted minus actual sector counts. To get absolute sector count error, we simply take the absolute value of this difference. Furthermore, it is often helpful to split presentation of the data into different types of flights (active or proposed) to gain insight into the source of error being due to poor departure time prediction, horizontal position error, or other error sources.

For proposed flights we would expect sector count contributions of 0 for look ahead times at or near 0 for the simple reason that flights so near to entering a sector (particularly high sectors ZFW50, etc.) would be airborne, and therefore active. Data seems to contradict this because of limited departure delay information and the lack of cancellation message handling within FACET. As shown in **Figure 58**, we illustrate this effect with the following example: consider a flight that is predicted by FACET to depart at time t_0, and predicted to enter a sector x minutes later. For whatever reason, that flight gets delayed (e.g., with a ground stop) on the ground for a total of y minutes ($y > x$), but this information is never captured in the FACET input data. At time t_0+x, the aircraft is still predicted to enter the sector at time t_0+x (for a look ahead time of 0), when in fact the aircraft has not left the ground. In this case, the information does not get correctly updated until some time after t_0+y when the aircraft becomes active and first track is detected. The example can be extended to show the effect of cancellations, in which case information is never correctly updated.

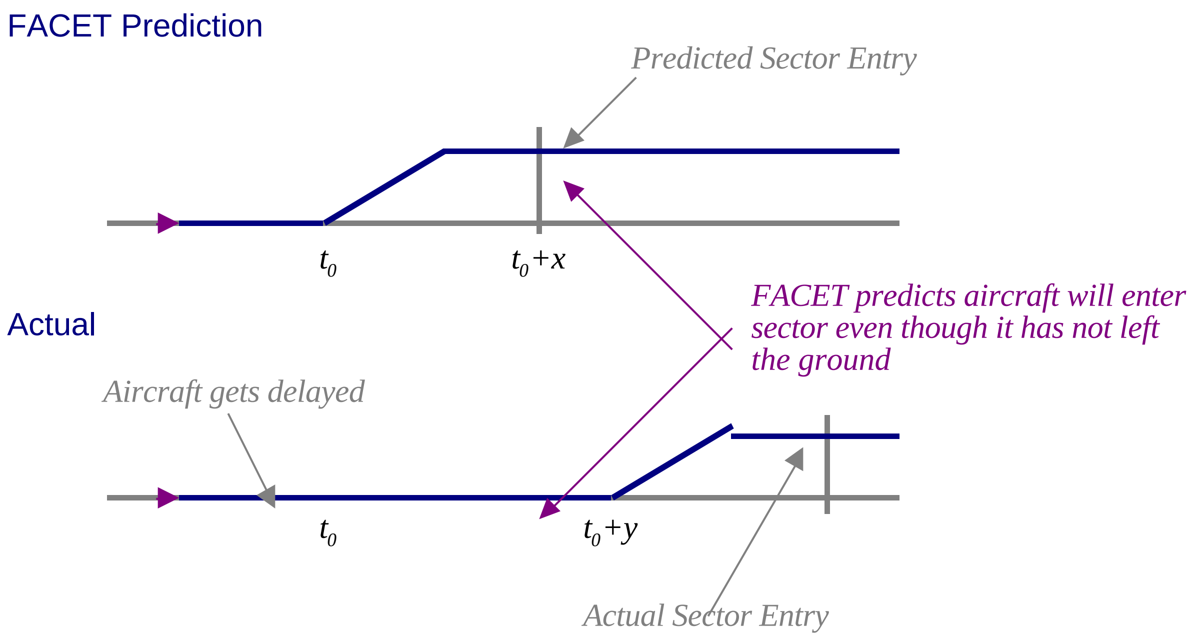


Figure 58. A sector count at 0 look ahead is reported for a proposed aircraft.

Figure 59 through **64** show the signed and absolute sector count prediction errors for proposed flights for selected sectors during the on-site visits. The truth set for actual sector counts are taken from the ETMS track data. For active flights, we would expect smaller look ahead times to be associated with less prediction error. In dealing with proposed flights, however, we actually see smaller look ahead times to be associated with slightly higher demand errors. This is due to the way we compute sector count error for active flights. There is a heavy bias towards zero as the prediction look ahead time increases because there are so few active flights that are included in the statistics for large look ahead times. In order to understand this better, we created a plot based on percent error. By looking at the absolute percentage error graphs, we see that, in fact, active sector count error increases as look ahead time increases.

For active flights on both 1/29/02 and 1/30/02, ZAU exhibits higher sector count errors than ZOB. This can be largely attributed to ORD in ZAU. More last minute vectoring and circular holding in ZAU results in higher sector count errors. The opposite is true for proposed flights – ZOB shows more sector count errors than ZAU. This is likely due to the complexity of ZOB. ZOB handles many internal departures from airports such as Cleveland, Detroit, and Pittsburgh, as well as transcontinental traffic. This complexity leads to numerous traffic management initiatives are not taken into account in filed flight plans. Another thing to note about the absolute charts is for 1/30/02. On 1/30, the absolute total error appears to be less than for proposed flights. Intuitively, this may not make sense because the total is usually the sum of the proposed and active flights. Because we are dealing with absolute errors, the average absolute value of the proposed flights plus the average absolute value of the active flights is not equal to the average absolute value of the active and proposed flights.

The behavior of error statistics depends on the sector in ZOB for proposed flights. We would expect proposed flights to show increased sector count errors as look ahead times increase. This is not the case for ZOB18/19 and ZOB28/29. ZOB18/19 and ZOB28/29 are sectors that feed ZAU25, a sector that contains an important ORD arrival fix. These flights tend not to be rerouted very often. ZOB48 and ZOB46 exhibit more sector count errors. Because adjacent sectors ZOB46 and ZOB48 share jet routes located very close to their southern boundary of ZOB, vectoring and reroutes are more likely to take aircraft in these adjacent sectors.

Figures 61 through **64** show graphs for the absolute and signed sector error counts on 1/29/02 and 1/30/02. Note the compactness of the proposed and active flights in **Figure 63** and **64** when compared to **Figure 61** and **62**. Also, the errors for individual ZAU sectors are less than those for individual ZOB sectors. This is consistent with **Figure 59** and **60** that showed the ZOB high sectors in aggregate having more error than their ZAU counterpart. Looking at the sectors geographically, we see that those sectors that are farther north (ZAU24 and ZOB18) exhibit less error and less under prediction than southern sectors (ZAU82, ZOB46 and ZOB48). This may be occurring because the northern sectors border Canadian airspace and thus have less flexibility for vectoring and reroutes than the southern sectors.

Note that signed sector count error graphs have a tendency to under-predict the actual sector counts. One reason we are under-predicting is because there are many GA and military pop-up flights that FACET has no way of knowing about because these aircraft don't submit a filed flight plan through ETMS. These pop-ups are in the 10-15% range. Currently, there is no good way to account for pop-up flights to improve the overall sector count error statistics.

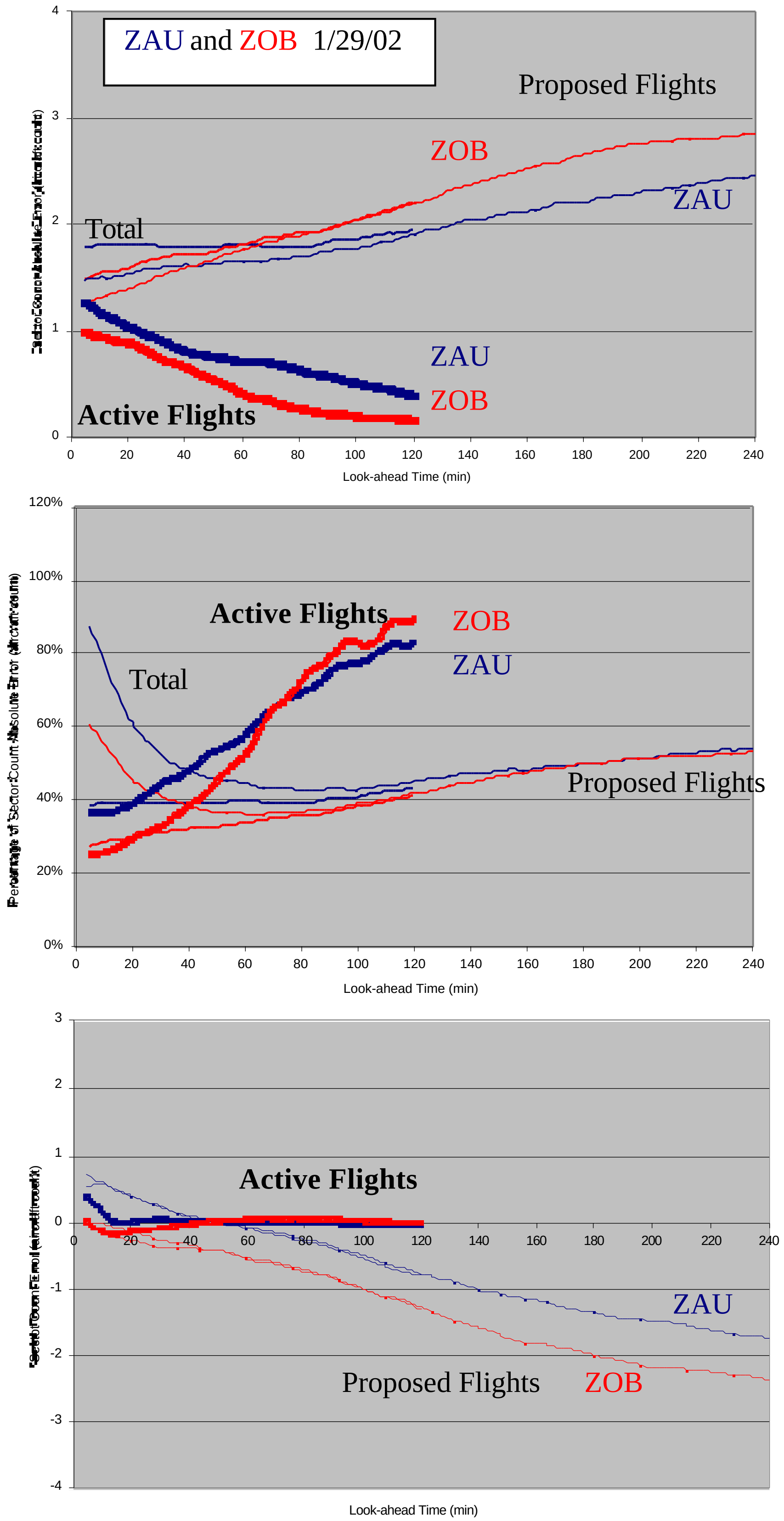


Figure 59. Sector Count Errors for active and proposed flights in ZOB and ZAU on 1/29/02.

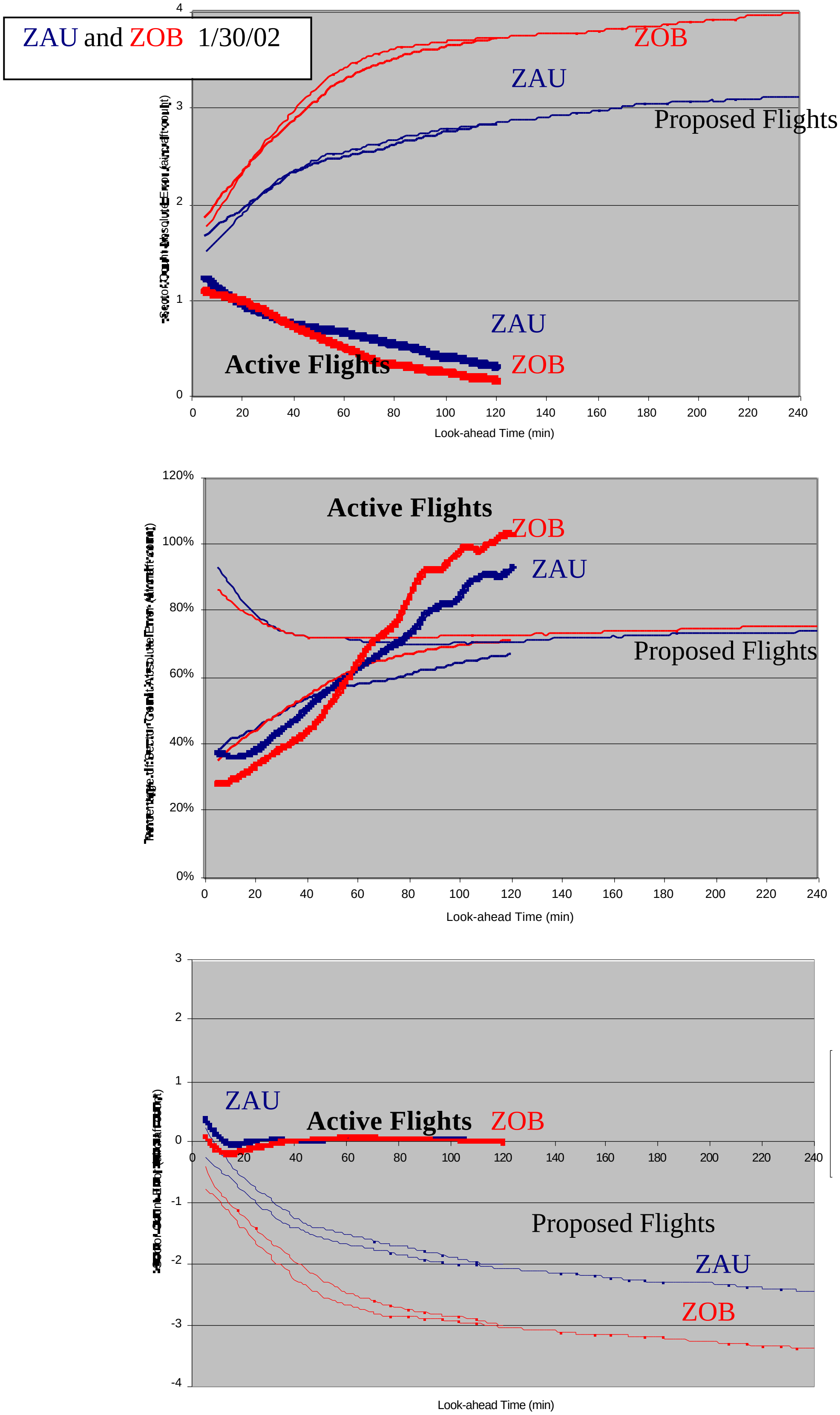


Figure 60. Sector Count Errors for active and proposed flights in ZOB and ZAU on 1/29/02.

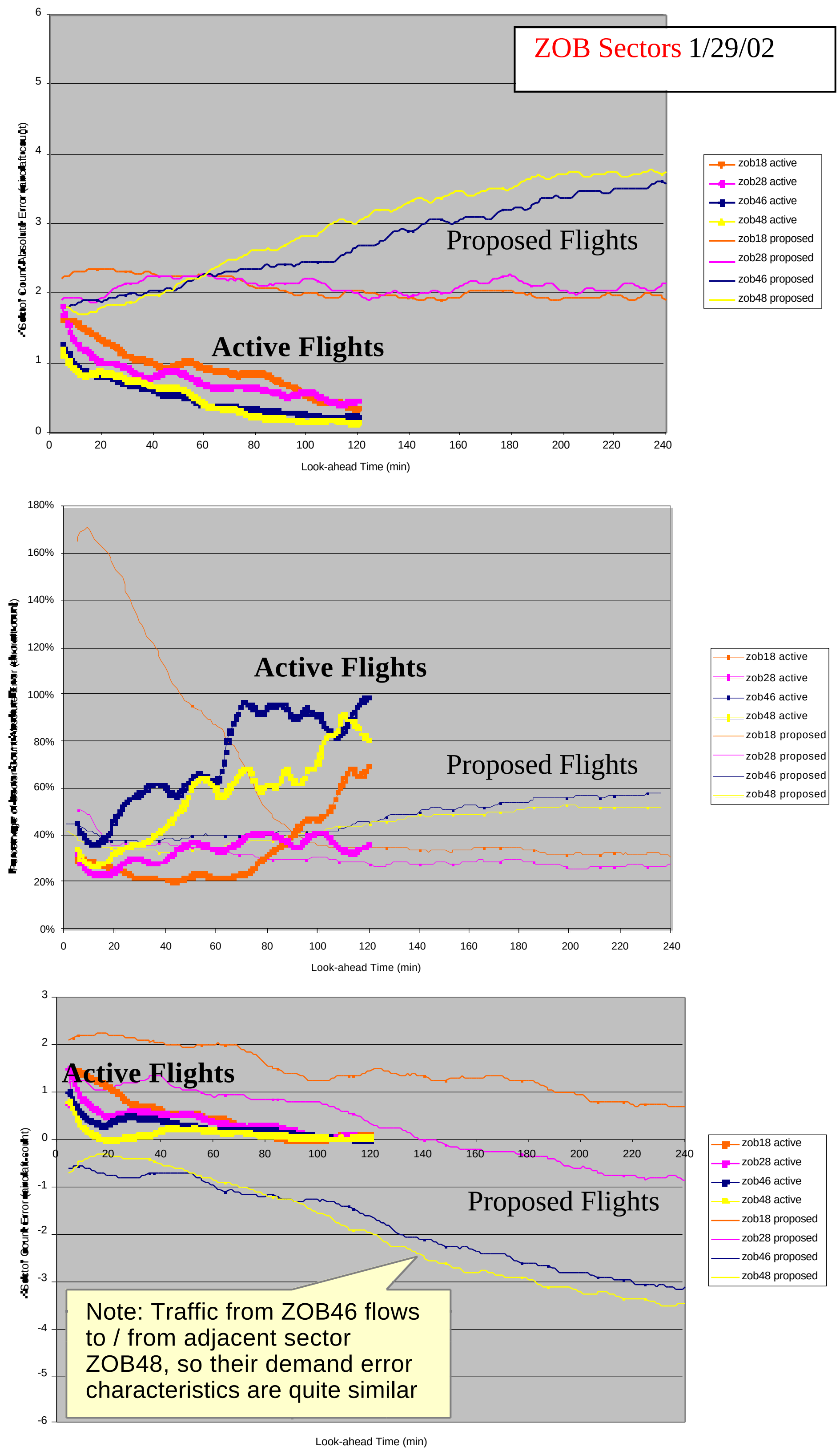


Figure 61. Sector Count Errors for active and proposed flights in selected ZOB on 1/29/02.

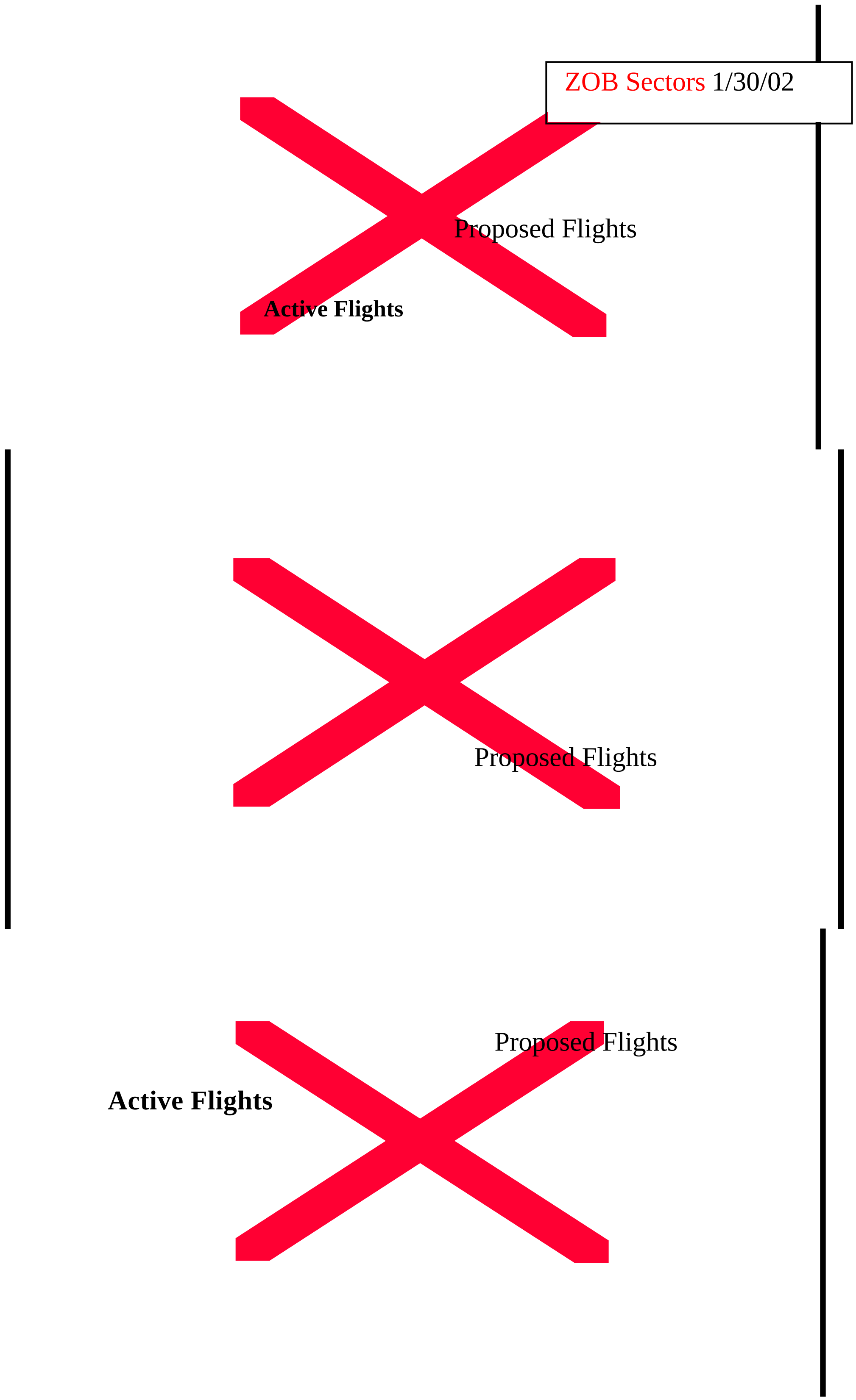


Figure 62. Sector Count Errors for active and proposed flights in selected ZOB on 1/30/02.

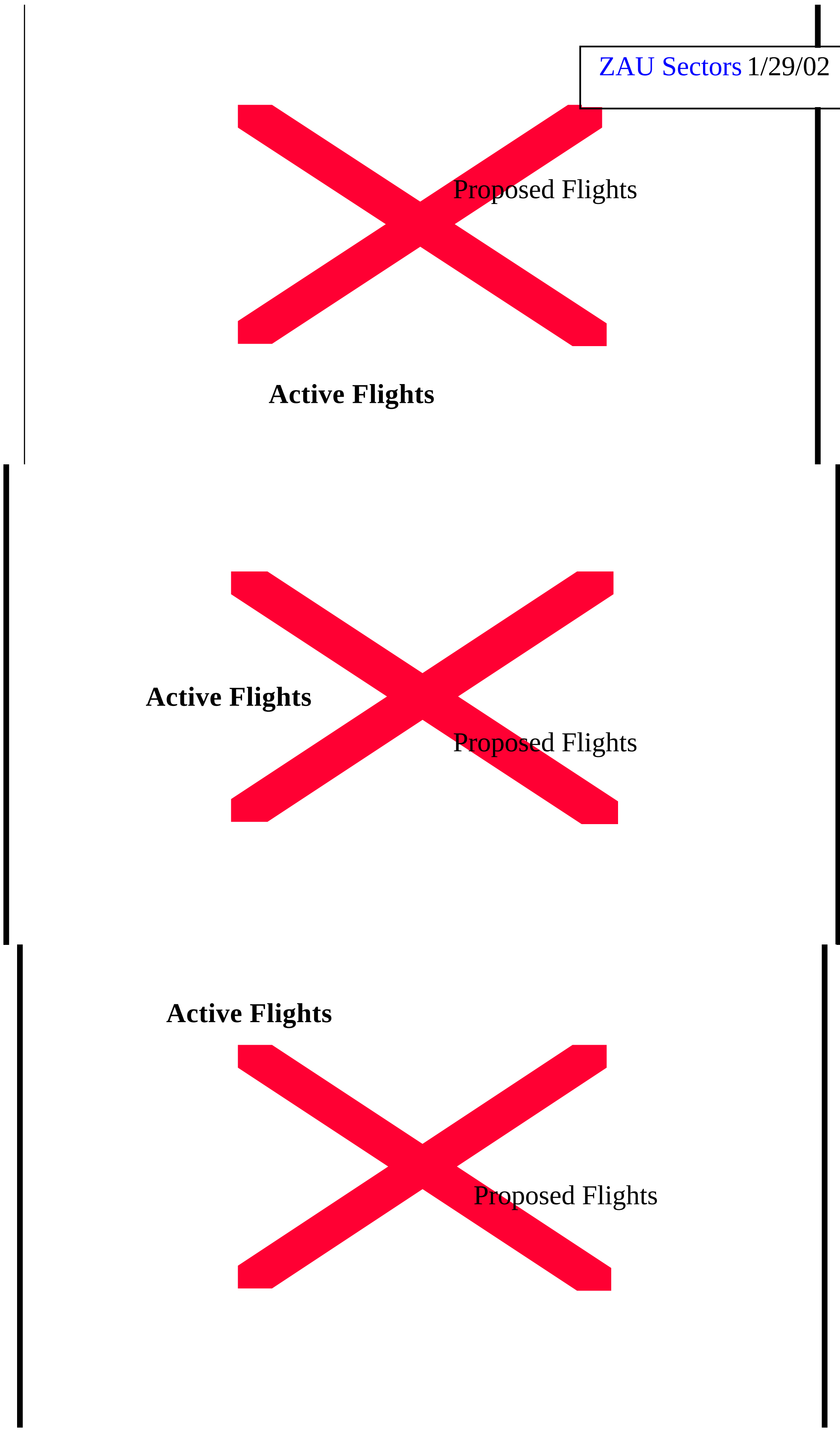


Figure 63. Sector Count Errors for active and proposed flights in selected ZAU on 1/29/02.

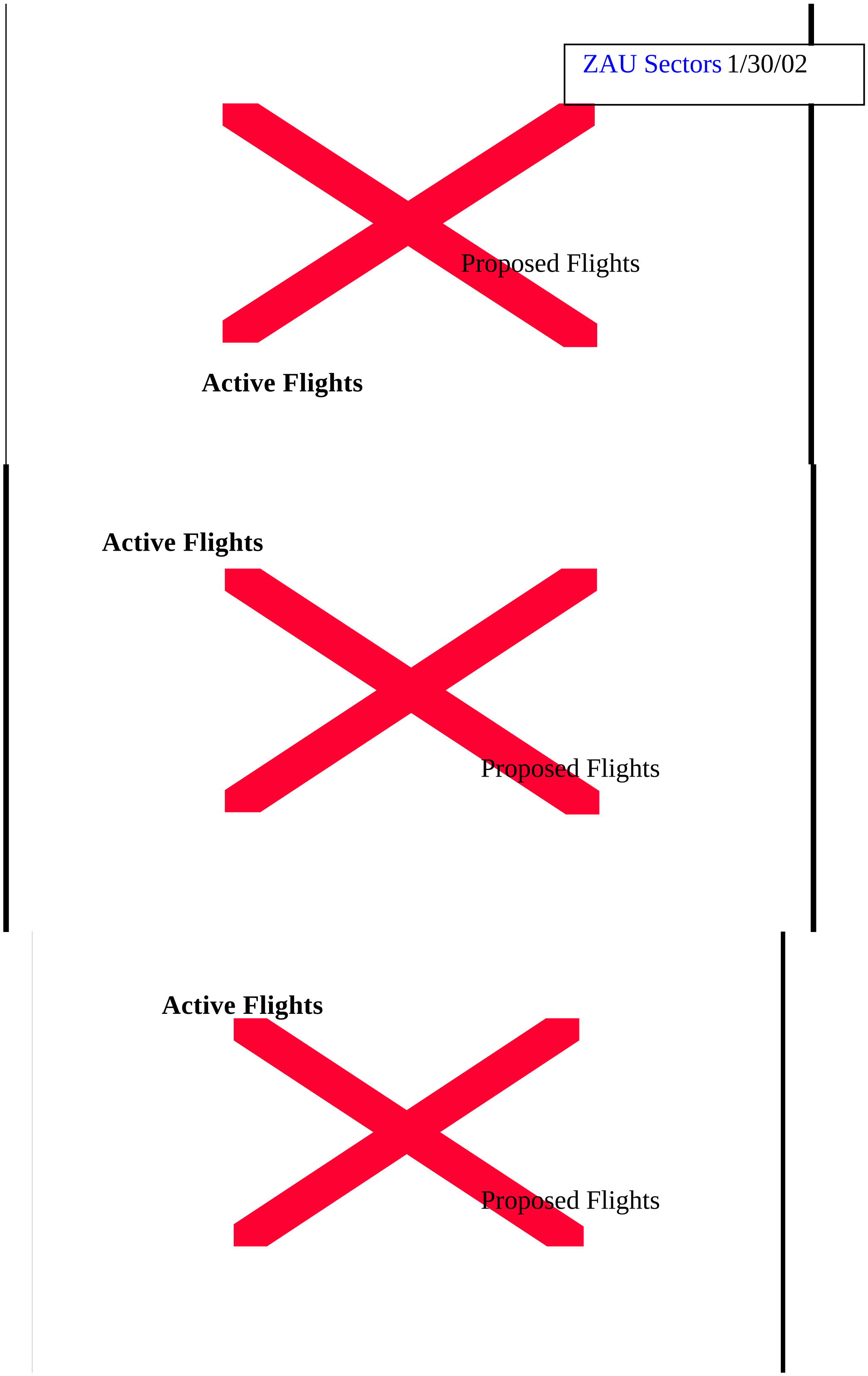


Figure 64. Sector Count Errors for active and proposed flights in selected ZAU on 1/30/02.

As shown in previous figures, depending on the sector that is analyzed, the sector entry time error varies across individual sectors as well as during the time of the day. Next, we investigate the variation in the sector demand error as a function of time of day and as a function of quantity of proposed vs. active flights. **Figure 65** and **66** identify how the sector count varies with respect to the time of day for various prediction look ahead times. While ZOB48 seems to have fairly constant results over the course of the day and over various look ahead times, the results for other sectors, ZOB18, ZOB25, and ZOB36, vary with time of day and look ahead time.

Figure 67 and **68** identify how the sector count varies with respect to the composition of the prediction results in two sets:

- Contribution due to aircraft on the ground when the prediction is made, and
- Contribution due to aircraft currently en route when the prediction is made.

Note that the prediction of the sector demand is dominated by the aircraft that are on the ground when the prediction is made. Over 60% of the aircraft are on the ground when 30 minute look ahead time predictions are made, and when longer look ahead times are used, as with 120 minute and 240 minute look ahead times, the percentage of aircraft that are on the ground when the trajectory prediction is 98% or above. **Figure 67** and **68** indicate that the sector demand error is due to error causes from aircraft on the ground prior to take off more than for errors associated with aircraft currently en route when trajectory predictions are made. If the demand prediction is mostly in error due to errors in prediction take off times, then these plots indicate the degree to which the errors associated with predicting take off time will become a factor in the sector demand predictions.

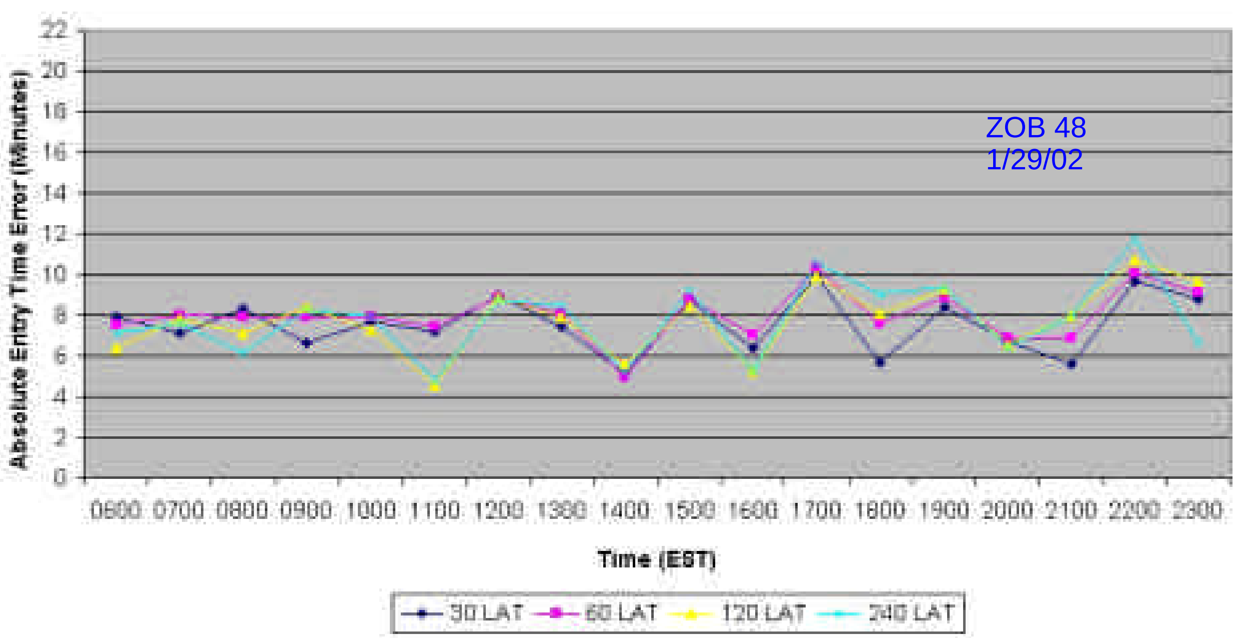


Figure 65. Sector Entry Time error for predictions made various look ahead times (LATs) for ZOB 48 airspace (1/29/02)

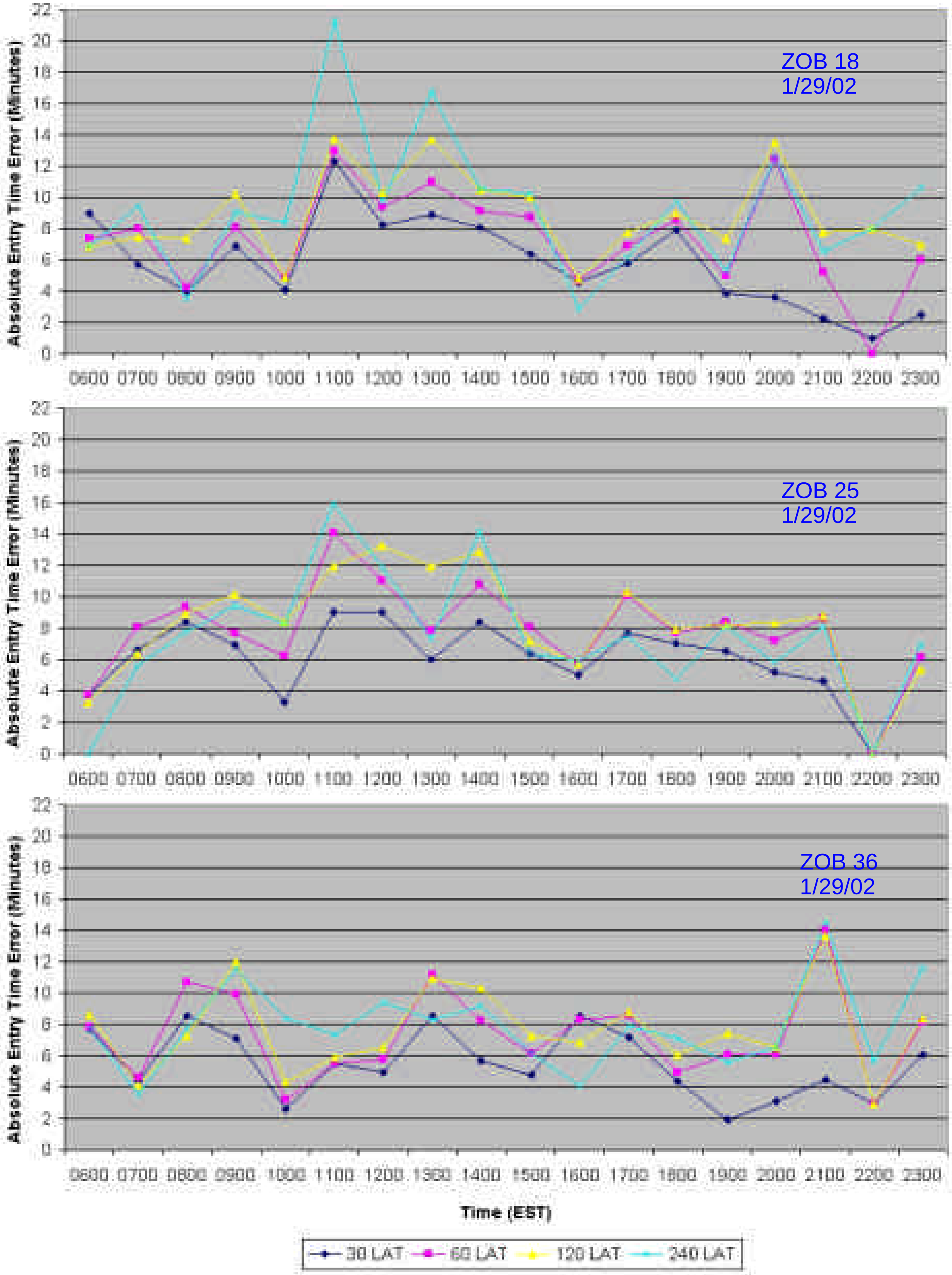


Figure 66. Sector Entry Time error for predictions made various look ahead times (LATs).

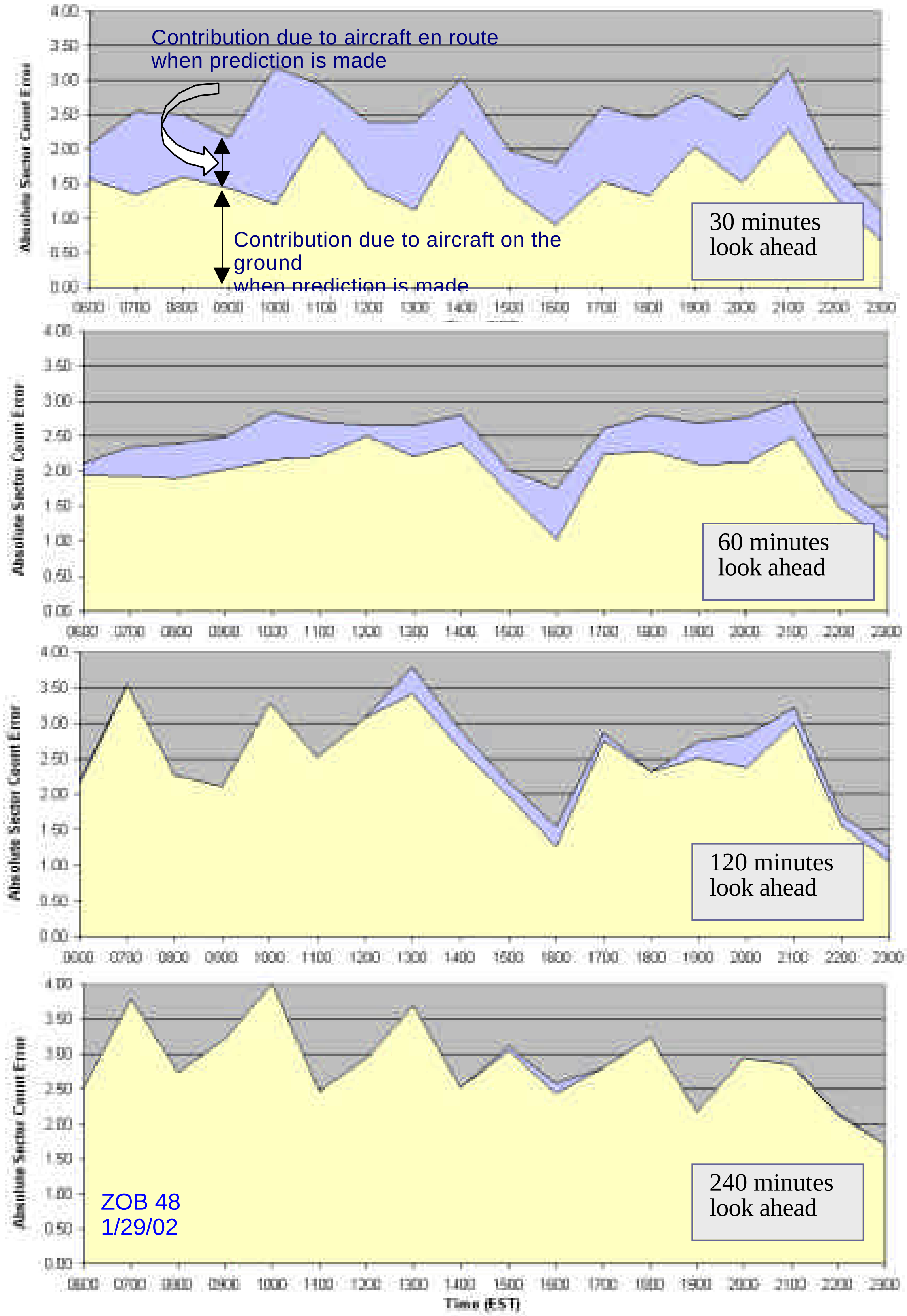


Figure 67. Sector Count error for on the ground vs en route at different times of the day.

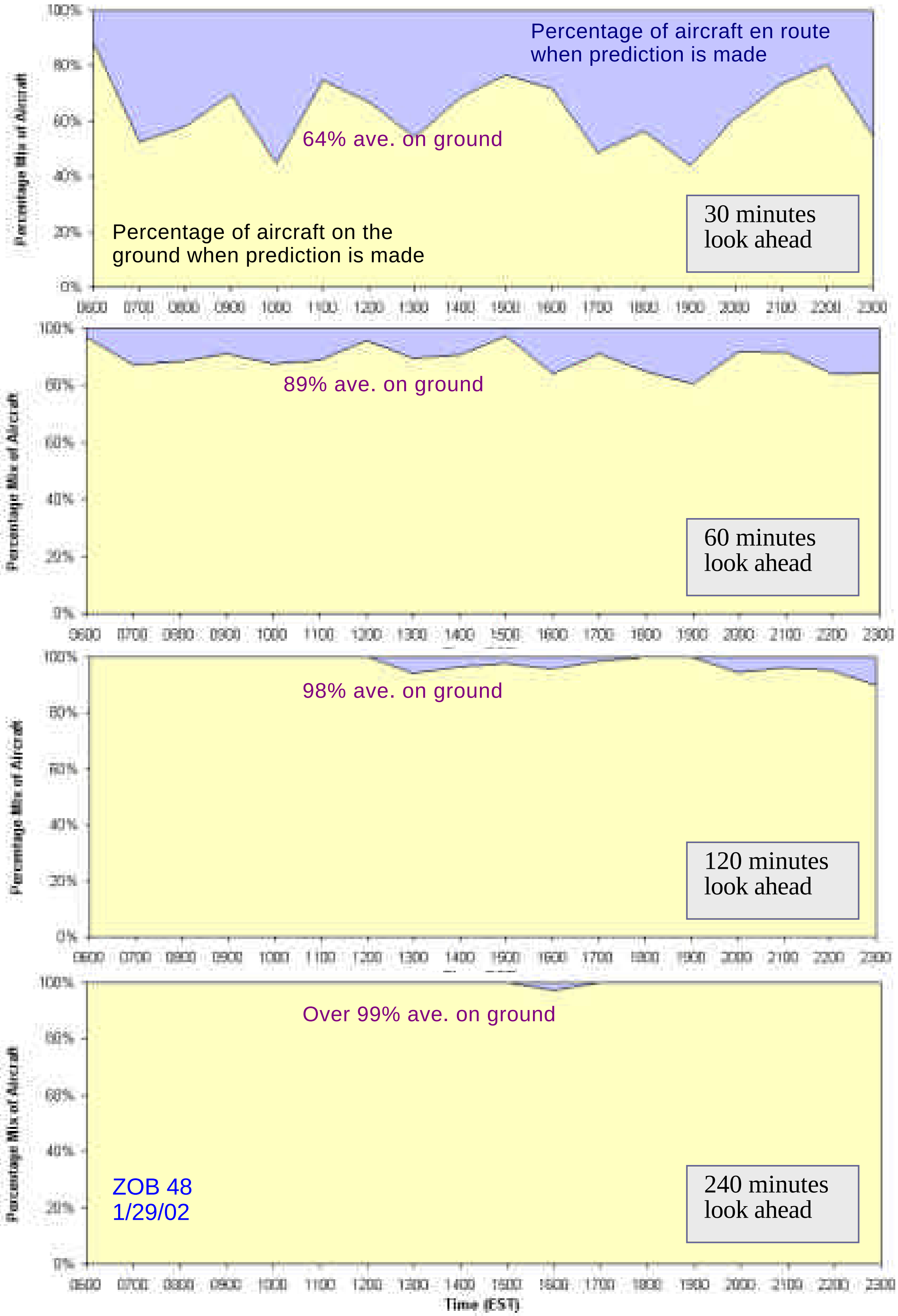


Figure 68. Percentage of aircraft on the ground vs en route at different times of the day.

4.3 Effect of Departure Time Prediction on Sector Demand

Several studies were performed to investigate departure time prediction accuracy and its effect on sector demand.

4.3.1 The Effect of Cancellations on Sector Demand

FACET does not process any ETMS cancellation messages. Thus, cancelled flights, while known to be cancelled in ETMS data, are assumed to take off within FACET at their scheduled take off times. To characterize the error imposed by this assumption, we investigate the characteristics of cancelled flights relative to the scheduled take off times. The POET archived ETMS database was used to query cancellations data from 21 major airports for the week of January 28, 2002 through February 1, 2002. All departures and cancelled departures were counted at each airport. **Figure 69** illustrates the percentage of all departure flights that were cancelled at each airport. The majority of these airports have cancellation percentages between 3% and 10% for departures, with an average of 6.2%.

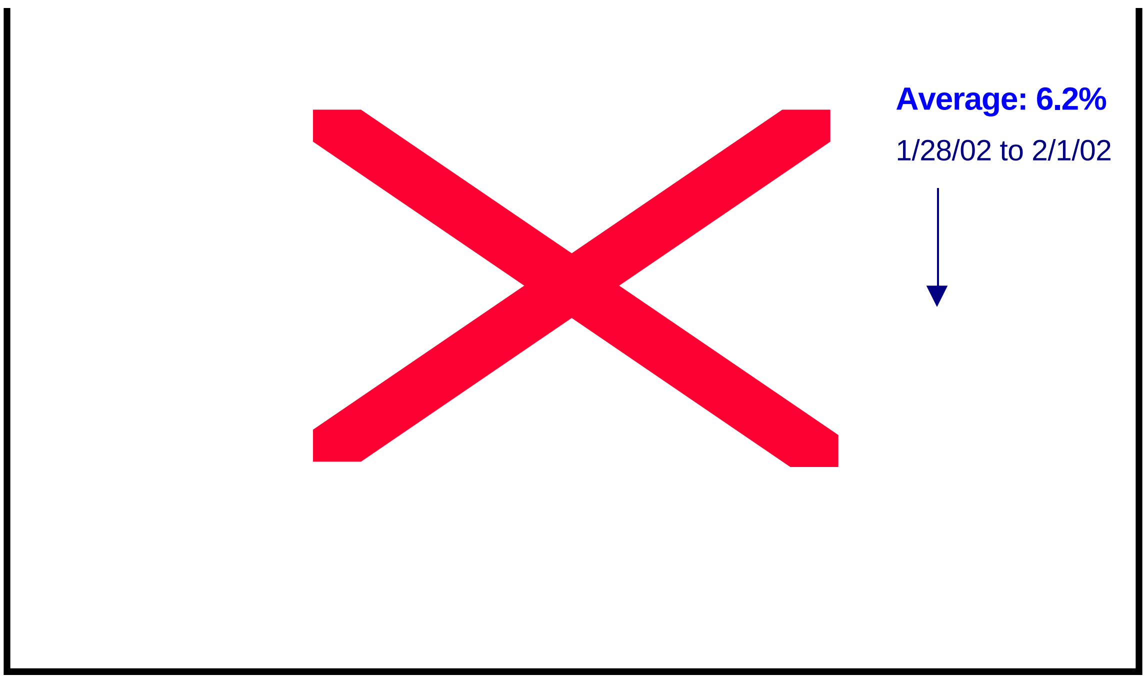


Figure 69. Departure cancellations at 21 major airports.

A flight is considered cancelled if the scheduled flight received an ETMS RS, RZ, FX, or TO cancellation message. An RS message is an internal ETMS message generated when a specialist takes an Original Airline Guide (OAG) flight out of the database. An RZ message indicates a flight was cancelled in a NAS flight plan. An FX message is the CDM message used by an airline to indicate that a flight is not operating. A flight is timed out by ETMS and receives a TO message if it does not submit an activation message within 1 hour after the departure time for NAS or CDM cancelled messages. This time out period is 5 minutes if only OAG data has been received.

This set of cancelled flights does not include those flights that are considered "cancelled but flew", or regular controlled flights. A "cancelled but flew" flight is a flight that received a cancellation message and still flew. This happens if a flight was cancelled but ETMS received an activation message within a certain time of the predicted departure time. An airline will issue cancellation messages when substituting flights during a GDP. Also, flights that are diverted to an alternate destination will receive a cancellation message. These are all examples of flights that received cancellation messages but flew.

The effect of these cancellations on FACET prediction accuracy depends on the look-ahead time of prediction. The amount of look-ahead time determines the percentage of cancelled flights that are known to FACET at the time of prediction. If a prediction is made with a large look-ahead time, e.g., 4 hours, then flights that are cancelled after the prediction look-ahead time will be predicted to fly. This will directly contribute to an error in sector demand due to an inability to predict the cancellation. **Figure 70** displays the number of flights that are cancelled *x minutes* before departure, grouped in 1-hour bins. **Figure 71** displays the same data in more detail with smaller 15-minute bins. **Figure 72** depicts 5-minute bins and a closer look at the period 4 hours prior to departure and 1 hour after departure. **Figures 71** and **72** show two clusters of departure cancellations, one around 15 hours and one about 2 hours prior to departure. Although the airlines may submit cancellations days or even weeks before departure, Volpe does not synchronize the airline CDM data with ETMS data until 15 hours before departure time. This explains the large spike in the cancellation data at 15 hours prior to departure, which accounts for approximately 38% of the cancellations. These plots also show that flights are often cancelled at or after scheduled departure times.

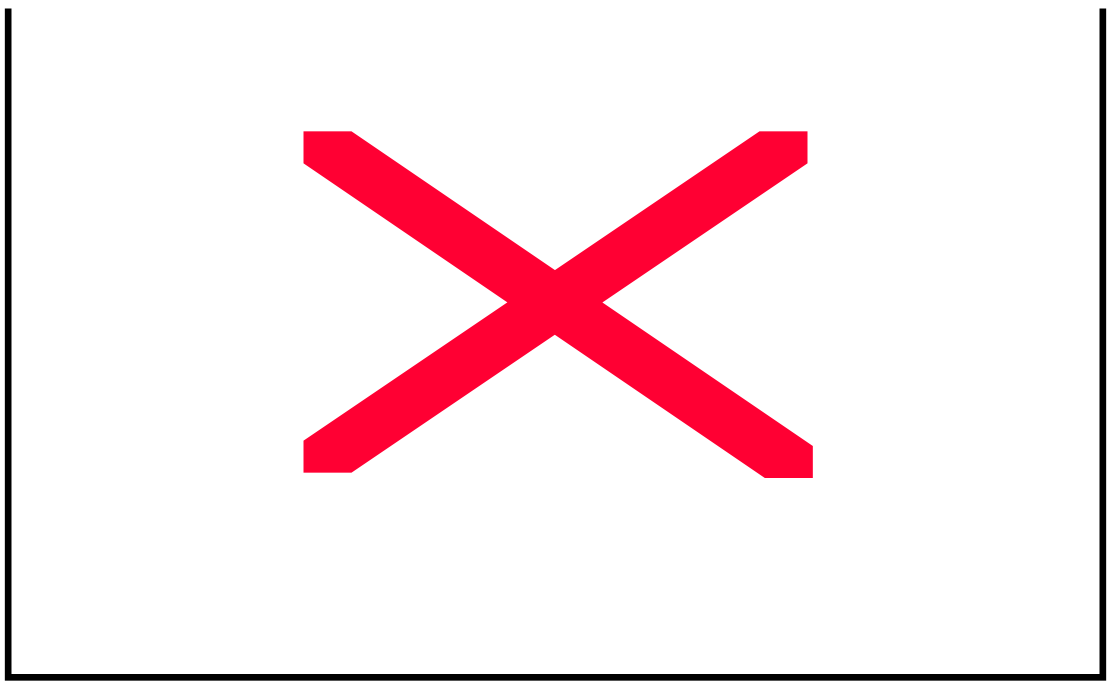


Figure 70. Cancellation times relative to scheduled take off time grouped by 1-hour bins.

Figure 71. Cancellation times relative to scheduled take off time grouped by 15-minute bins.

Figure 72. Cancellation times relative to scheduled take off time grouped by 5-minute bins.

Figure 73 illustrates the percentage of all departure flights that FACET could know about from ETMS cancellation messages as a function of look-ahead time. This represents the amount of cancellations that FACET could correctly account for if FACET were to correctly process all cancellations in the ETMS data feed. Note that FACET could never know about *all* the cancellations, since many of them occur outside the look ahead time or even after the scheduled time of departure (about 8% of the cancellations occurred after the scheduled take off time).

Figure 73. Cancellations unknown at the time of prediction.

Perfect knowledge of cancellations cannot be fully realized. The statistics for aircraft prior to take off must take into account the time when the cancellation occurs. That is, if a cancellation is not known until just prior to the scheduled take off time (or even after the scheduled take off time), then FACET must assume that the aircraft will take off at the scheduled take off time until a cancellation notice actually comes in. This is problematic when predictions must be made ahead of the cancellation time and far ahead of the scheduled take off time. Cancelled flights, especially for long look ahead times, will be included in the trajectory predictions and sector demand predictions. This cannot be avoided.

4.4 Effect of TFM and ATC Restrictions on Sector Demand

In order to generalize the aggregate statistics for TFM and ATC restrictions, we present data that represents the Miles-in-Trail Restrictions (MITs), Ground Stops (GS), and Ground Delay Programs (GDPs). These are data collected from the ATCSCC (Herndon, VA), and only include data that are recorded at the ATCSCC; so, if restrictions are imposed within a center without affecting another center, they are not revealed in these data. We start by reviewing MIT, GS, and GDP data, and then identify the detailed effects of these data on sector demand.

4.4.1 MIT Restrictions

Based on an earlier Metron study of airline deviations [KGL99], aggregate trends in MIT restrictions were established. These results are presented in **Figure 74** in comparison to the data points that represent the on-site data collection dates for this RTO 66 study. In general, the number MIT restrictions tend to follow the growth in the week of number of flights, peaking midweek. However, while the amount of traffic in our current study is actually slightly less than the amount of traffic in RTO 37 study, the amount of MIT restrictions used in the NAS is currently more. This may reflect a change in the way controllers are currently using MIT restrictions.

Figure 74. In general, the number of MIT restrictions mirrors the number of flights during the week. (based on [KGL99]).

NAS data for the dates that correspond to our on-site visits, as shown in **Figures 75** and **76,** illustrate how MIT restrictions were distributed geographically across the NAS for this time period. Clearly, there are portions of the NAS where there simply are very few MIT restrictions used, primarily in the Northwest. Also, the extreme Northeast (ZBW) and Southeast (ZJX and ZMA) used very few MIT restrictions. The most MIT restrictions are occurring in ZOB and ZNY centers. The conclusion to be drawn from these MIT data is that FACET does not have to model the effects of MIT restrictions everywhere in the NAS; modeling MIT restrictions in a few centers (particularly ZNY and ZOB) may provide the most benefit for the least amount of modeling effort.

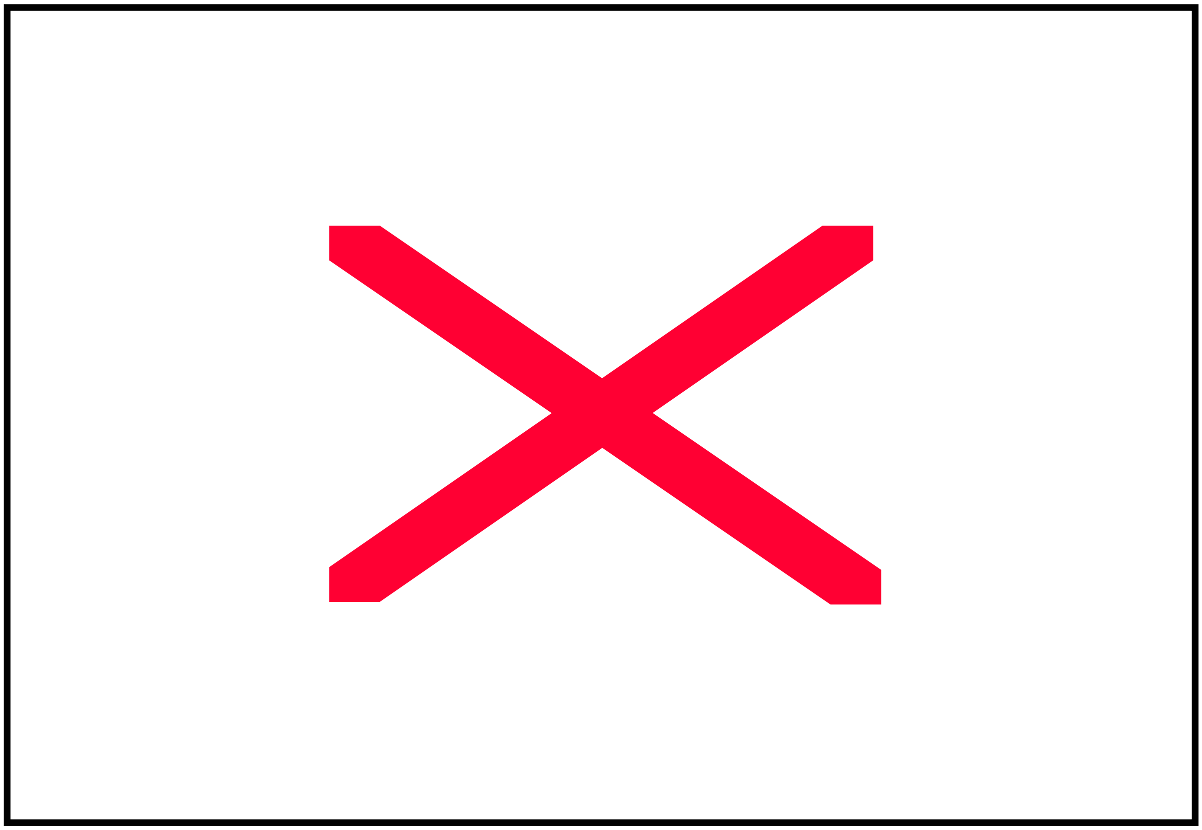


Figure 75. Average number of MIT restrictions per center (recorded at the ATCSCC) for Jan. 28 through Feb. 1, 2002; (note: centers with an average less than 1 are not shown).

MIT restrictions affect trajectory predictions and sector demand predictions. While MIT restrictions can be modeled in FACET, they are not used while making trajectory predictions in FACET. This is in part because there is no predictor of when MIT restrictions are likely to occur. Nonetheless, MIT restrictions are still used in the NAS and they represent a source of error in making trajectory predictions and sector demand predictions. Our approach is to study specific instances of the use of MIT restrictions in order to understand how they affect sector demand prediction.

Jan. 28, 2002

235 MIT Restrictions in the NAS

Jan. 29, 2002

261 MIT Restrictions

Jan. 30, 2002

250 MIT Restrictions

Jan. 31, 2002

189 MIT Restrictions

Feb. 1, 2002

192 MIT Restrictions

Figure 76. Geographical distribution of MIT restrictions (recorded at the ATCSCC).

Consider the west flows of traffic in ZOB where on a daily basis there is an ESP performed. In this ESP, as shown in **Figure 77**, MIT restrictions are set at the ZAU border, and they are often "passed back" from ZAU to ZNY. This passback is most effective when given with 1.5 to 2 hr advance notice. There are two primary flows from the east to west across ZOB. The northern flow is an ESP set up to control traffic into ORD through the Pullman (PMM) fix. This flow combines Toronto and International traffic from the north (which they almost never restrict), Bostron (BOS) routes passing over J547, and New York City (NYC) Metro area routes passing over J36. When analyzing the flow of traffic over PMM, we must take note that on a typical day, for all the traffic that exists in ZOB, only 3.0% of that traffic passes over PMM to ORD. An even smaller percent are subject to MIT restrictions.

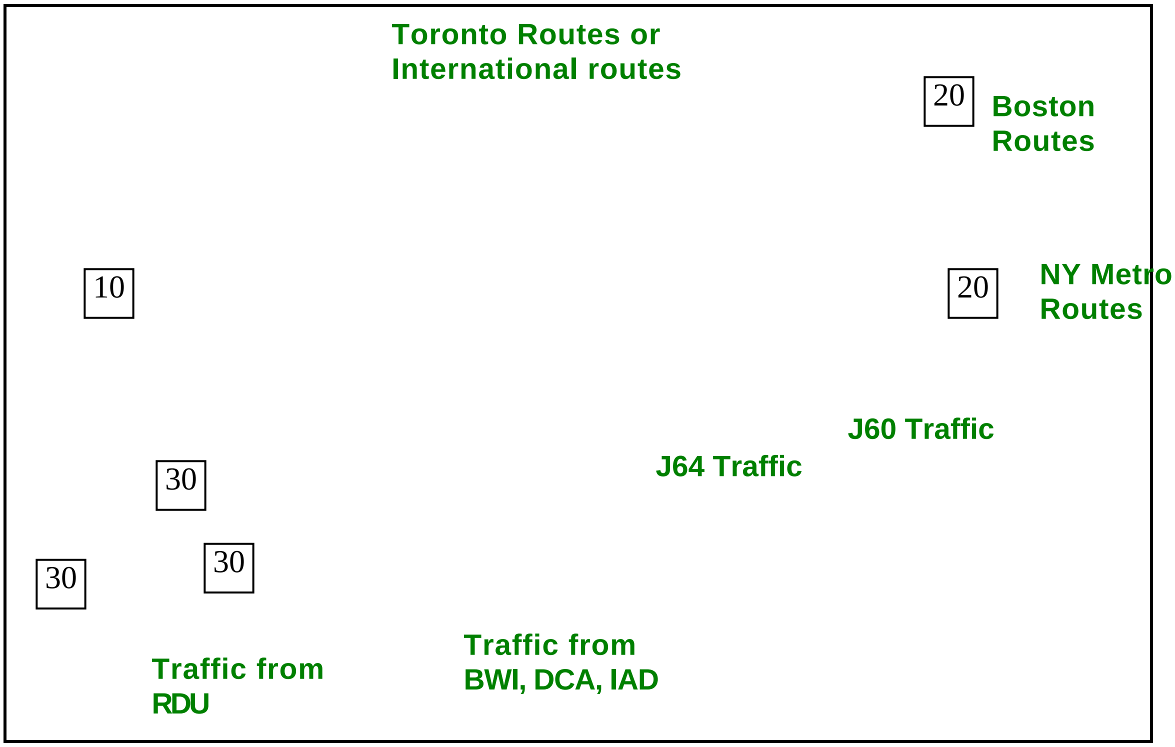


Figure 77. ZOB West flow into ORD and the pass back of MITs to ZNY.

There are several MIT possibilities in the "system" described in **Figure 77**. For example, combinations could include those in **Table 3**. Not all these combinations were observed during the site observation period (1/28/02 – 2/1/02). Also, the ATCSCC logs and the TMU logs do not always correspond 1-to-1 in terms of the magnitude and duration of the MIT restrictions data. **Table 4** identifies the data for the observations and the discrepancies in the logs.

Table 3. Typical MIT restrictions for ZOB routes leading to ORD over PMM.

10	0	0	HVR
10	20	20	Needs traffic padding
10	25	10	BOS rush coming
10	30	10	BOS rush + weather
10	10	25	NYC rush coming
10	10	30	NYC rush + weather
15	20	20	ORD AAR reduced
15	30	30	ORD AAR + rush
Etc.	Etc.	Etc.	Increasing complexity due to Weather and Traffic

Table 4. Actual MIT restrictions for ZOB routes leading to ORD over PMM.

												1/28/02
ATCSCC	10	1215-1700					10	2330-0130				
TMU	10	1215-1700	15	1745-1830	10	1830-2130	10	2230-0100				
												1/29/02
ATCSCC	15	1230-1637	10	1637-1715	10	1845-2000	10	2045-2145	10	2230-0030	15	0030-0200
TMU	10	1215-1637	10	1637-1715	10	1845-2000	10	2045-2145	10	2230-0030	15	0030-0200
												1/30/02
ATCSCC	15	1230-1515	15	1515-1630	15	1630-1830	15	1830-2014	15	2014-0300		
TMU	15	1230-1515	10	1515-1630	15	1630-1830	10	1830-2014	15	2014-0300		
												1/31/02
ATCSCC	10	1815-2015	10	2115-0100								
TMU	10	1815-2015	10	2330-0015								
												2/1/02
ATCSCC	10	1230-1330	15	1330-1530	10	1530-1630	10	1730-1945	10	2230-0200		
TMU	10	1230-1330	15	1330-1430	10	1530-1630	10	1815-2230	10	2330-0200		

To determine MITs over J547 and J36, the TMC analyzes the traffic counts expected over a time horizon. A TSD list of BOS traffic and a TSD list of NY Metro traffic over certain metering fixes are used. Alternatively, some TMCs use the TSD list for all traffic heading into ORD over PMM and count up or separate the BOS and NY Metro traffic counts. Reasons to add to the MIT restrictions on J547 or J36:

- Traffic count is high (combines the J547 and J36 traffic with Internal releases expected in the time horizon of 1 to 2 hours)
- Turbulence reports over the East airspace in high altitude Area III (this adds extra talk over the frequency, and adds to controller workload)

- Wx adds MIT (look at WARP display to check ceilings and precip extent)

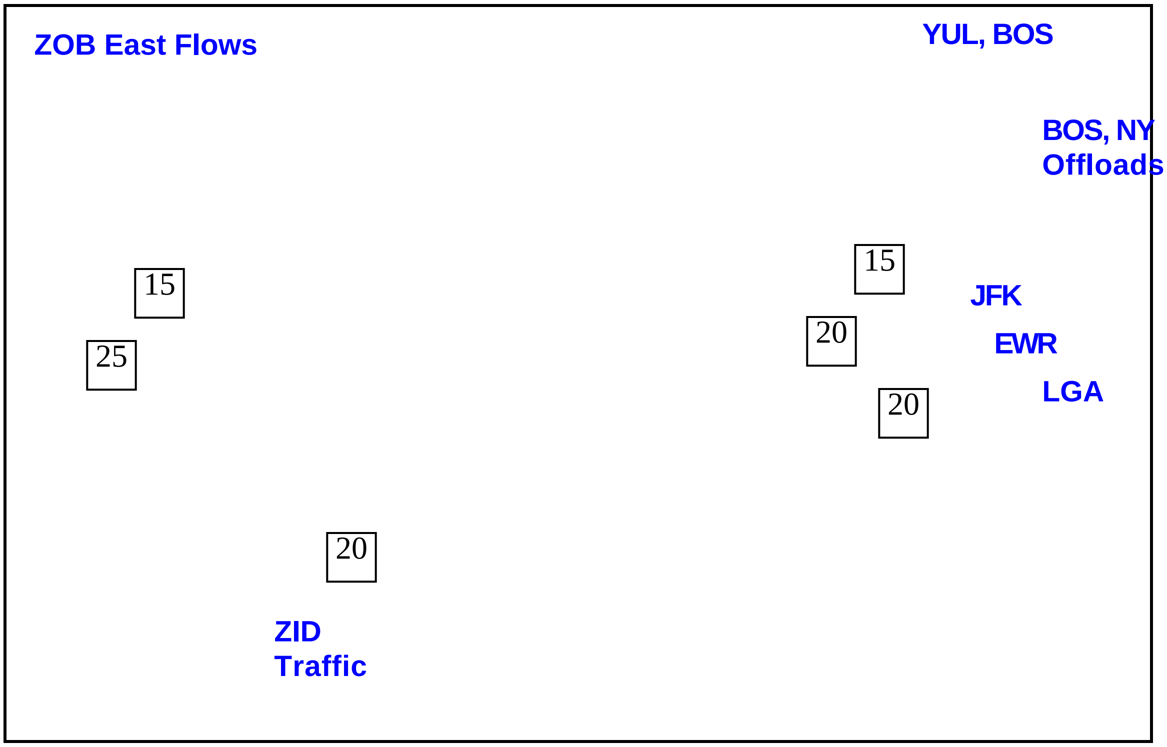


Figure 78. ZOB East flow into BOS, JFK, EWR, and LGA.

Typical East flows in ZOB and MIT restrictions are shown in **Figure 78**. ZNY basically reacts to what the NY TRACON sets for MITs. They simply add a 5 MIT increment to the MIT as a "compression factor". E.g., a 20 MIT into the NY TRACON will cause a 25 MIT restriction at the ZNY border. ZNY center does not have a TMU position specifically looking at traffic backing up into ZOB… it is more an automatic thing than an analysis. ZOB automatically passes back MITs to ZAU. Note that two of these flows JFK and EWR pass through the same sector ZOB79 in parallel. This does not leave much room for vectoring for delays like in other parts of the ZOB center. Also a holding pattern exists at SLT in ZOB79 so that too, when used, really limits the possibilities for vectoring traffic. ZID traffic may typically get 20 or 25 or 30 MIT. When analyzing the flow of traffic over OXI, we must take note that on a typical day, for all the traffic that exists in ZOB, only 3.7% of that traffic passes over OXI to ORD. An even smaller percent are subject to MIT restrictions.

4.4.2 Ground Stops

Figure 79 shows the aggregate GS data across the NAS for the year 2001. The increase during the summer months is primarily resulting from the convective weather season. In September, a drop in the traffic volume across the NAS occurred after the September 11 tragedy, and thus, the number of GSs during the remainder of the year were low. Across the NAS over 2001, there were an average of 2.6 ground stops per day.

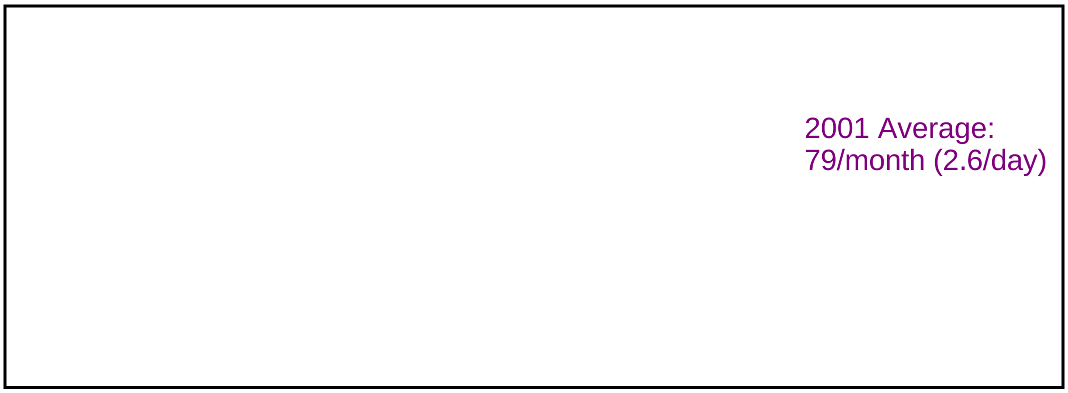


Figure 79. The number of ground stops issued per month in 2001.

Figures 80 and **81** shows the geographic distribution of GS data across the NAS for the given time period of the on-site visits. The Northeast corridor exhibits a large portion of these data, however, there is no one sector that seems to appear as one that consistently uses GSs more than the others. The use of ground stops seems to vary by day.

Figure 80. Geographical distribution of all ground stops issued during Jan. 28 – Feb. 1, 2002.

Jan. 28, 2002

5 Ground Stops
in the NAS

Jan. 29, 2002

2 Ground Stops

Jan. 30, 2002

8 Ground Stops

Jan. 31, 2002

10 Ground Stops

Feb. 1, 2002

10 Ground Stops

Figure 81. Centers where GSs occurred in the on-site visit period.

4.4.3 Ground Delay Programs

Figure 82 and **Table 5** show the aggregate GDP data across the NAS for the years 1998 through 2001. These data indicate an increase in the use of GDPs each year. **Figure 83** shows the geographic distribution of GS data across the NAS for the given time period of the on-site visits. There is not enough data to generalize where the GDPs are occurring based on our on-site visit days. However, when all the GDPs issued in 2001 are analyzed, as shown in **Figure 84**, it is clear that there are certain airports for which GDPs are issued more than others. These airports are: ATL, BOS, EWR, LAX, LGA, ORD, and SFO.

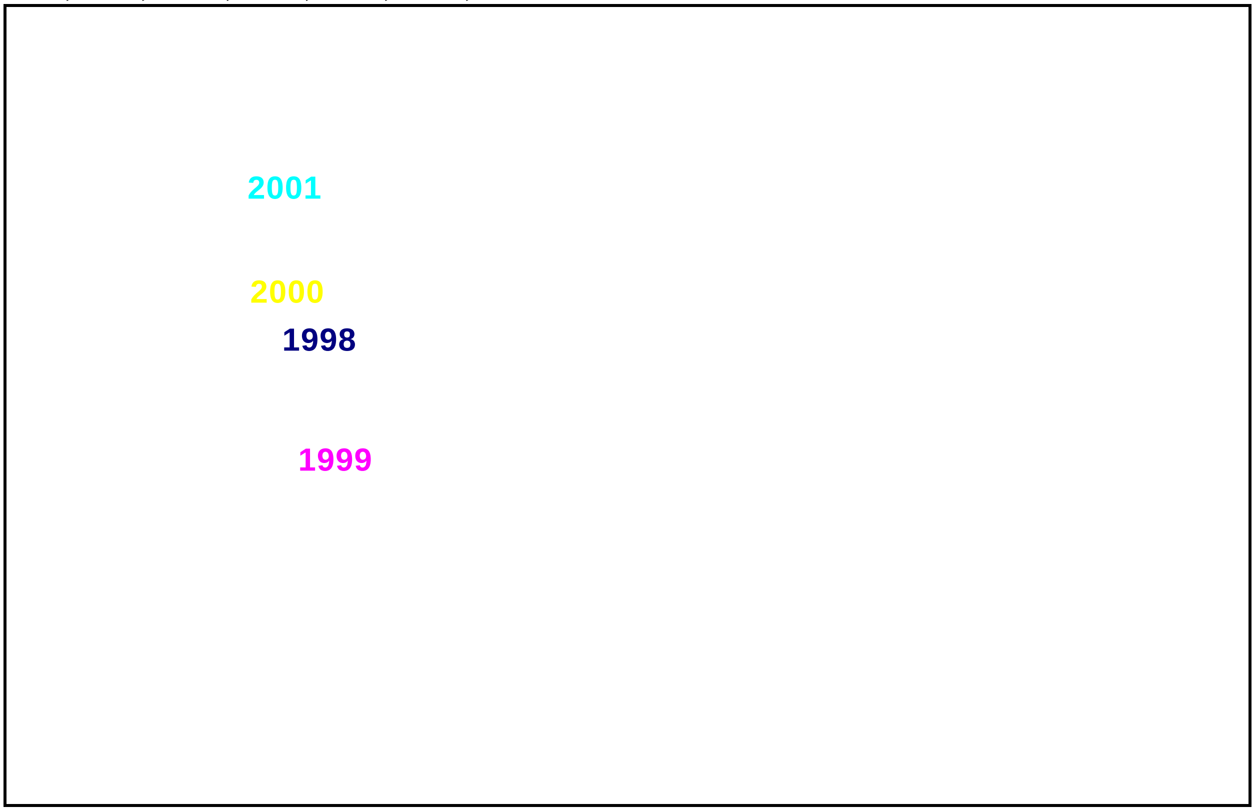


Figure 82. The number of GDPs issued per month in 1998 through 2001.

Table 5. Statistics for GDPs issued during 1998 through 2001.

1998	513	1.4
1999	705	1.9
2000	1083	2.9
2001	799	2.8

*Note: The 2001 average is determined using Jan. – Aug. (243 days) data only.

Jan. 28, 2002 — **2** GDPs in the NAS

Jan. 29, 2002 — **3** GDPs

Jan. 30, 2002 — **3** GDPs

Jan. 31, 2002 — **5** GDPs

Feb. 1, 2002 — **5** GDPs

Figure 83. Centers where GDPs occurred in the on-site visit period.

Figure 84. Airports where GDPs occurred in 2001.

4.4.4 Effect of MIT Restrictions, GSs, and GDPs on Sector Demand Prediction Accuracy

In order to address the net affect that TFM restrictions cause on sector demand errors, we compare time periods when the ATC restrictions are in effect vs time periods when there are no restrictions in effect. In terms of Eastern Standard Time (EST), our base line for no ATC restrictions is determined by data from 1/29/02 from 5:00 – 6:30pm. The conditions of 30 MIT restrictions are for 1/29/02 from 6:30 – 8:30 pm, and GS data is from 1/28/02 from 12:00 – 1:00 am, and GDP conditions are for 1/30/02 from 6:30 – 8:30pm. **Figures 85** through **90** illustrate the GDPs, GSs, and MIT restrictions put into effect for 1/28/02 through 1/30/02 for ZAU and ZOB.

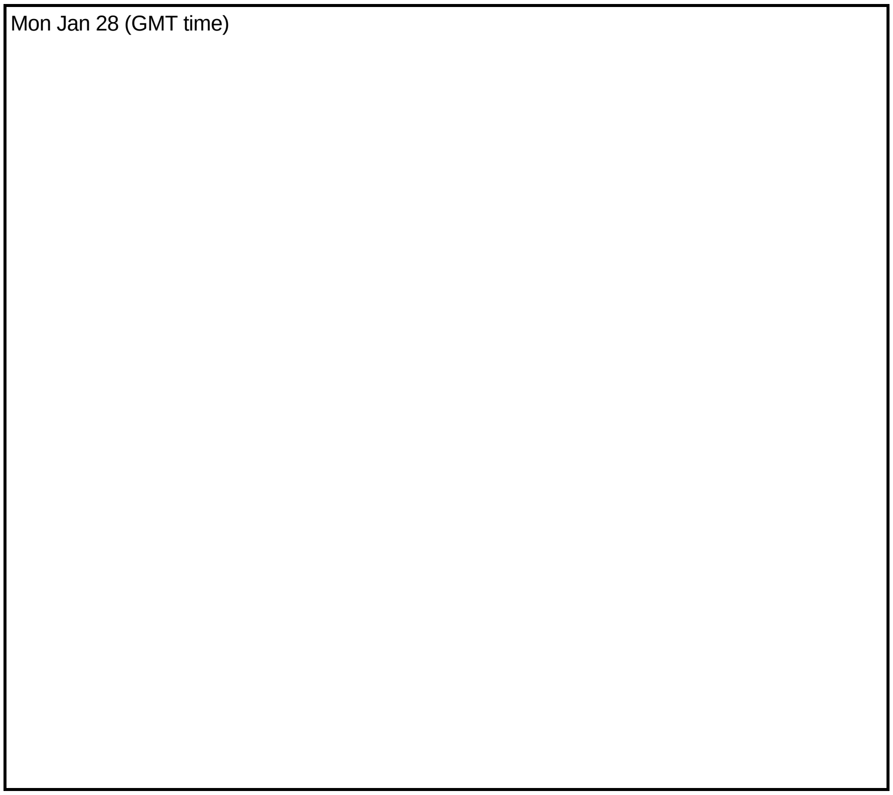


Figure 85. GDP, GS, and MIT data for ZAU on Jan. 28, 2002 local time.

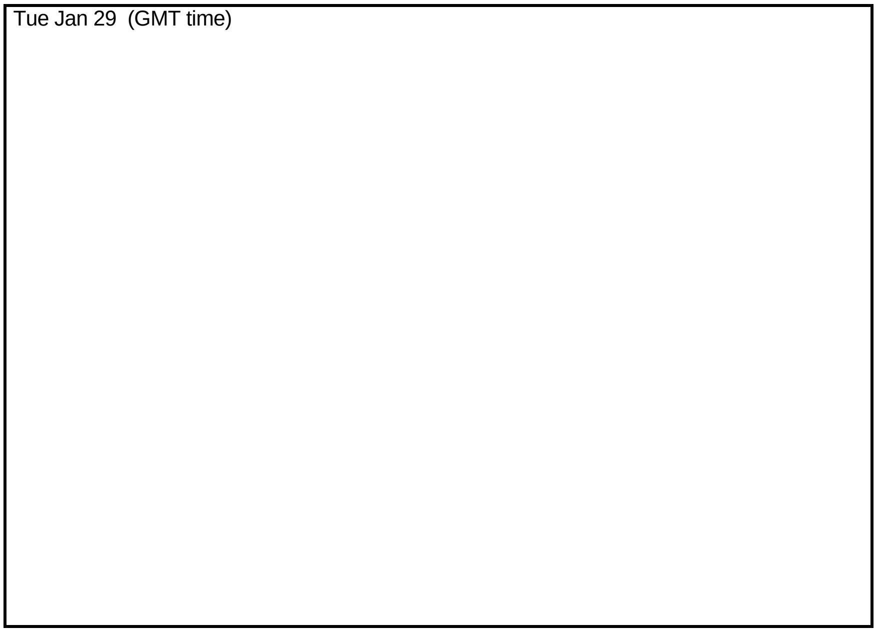


Figure 86. GDP, GS, and MIT data for ZAU on Jan. 29, 2002 local time.

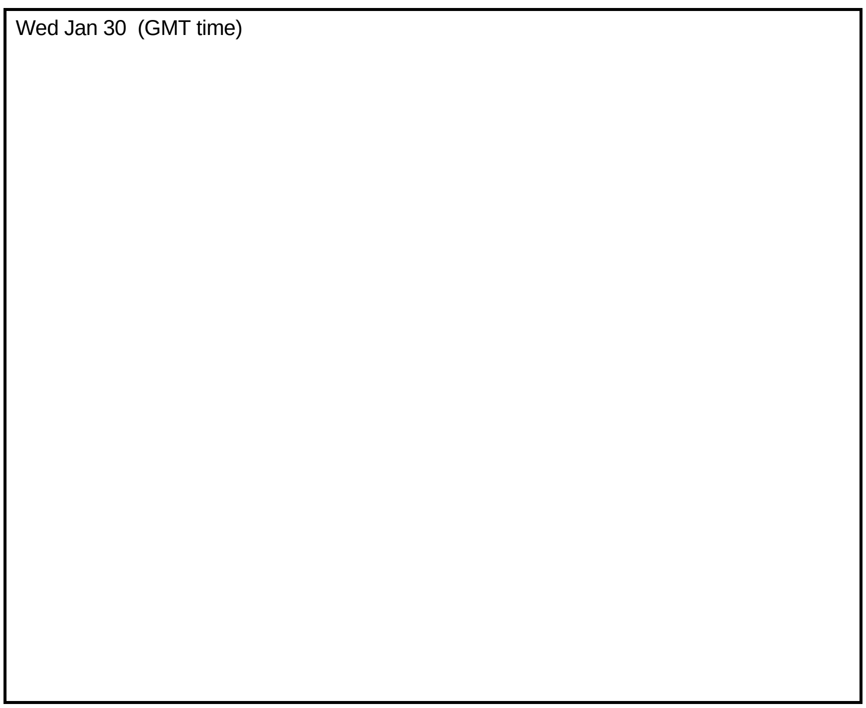


Figure 87. GDP, GS, and MIT data for ZAU on Jan. 30, 2002 local time.

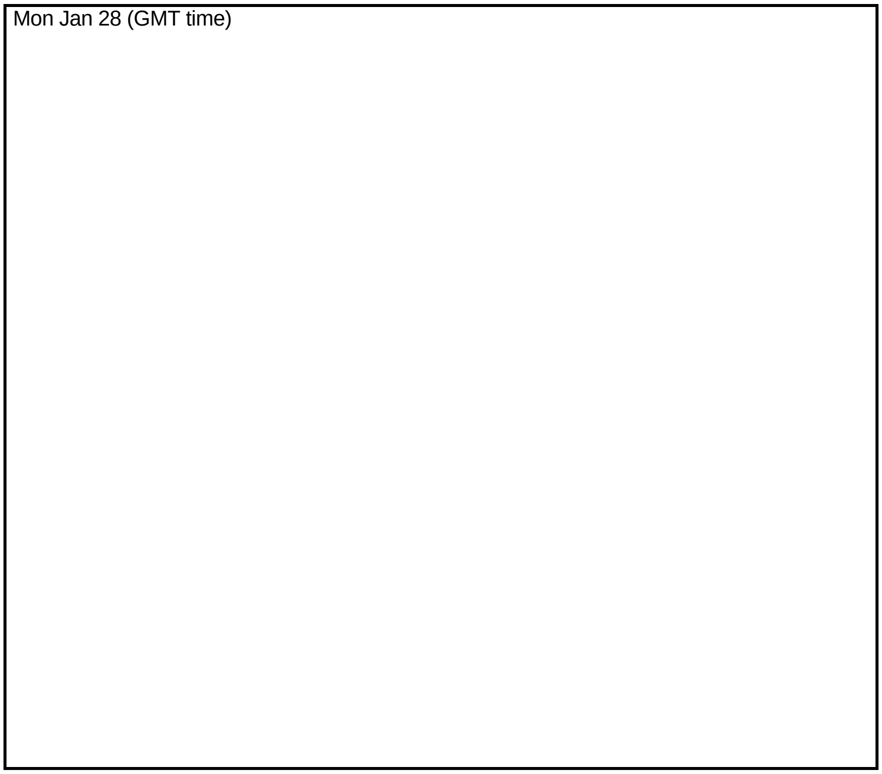


Figure 88. GDP, GS, and MIT data for ZOB on Jan. 28, 2002 local time.

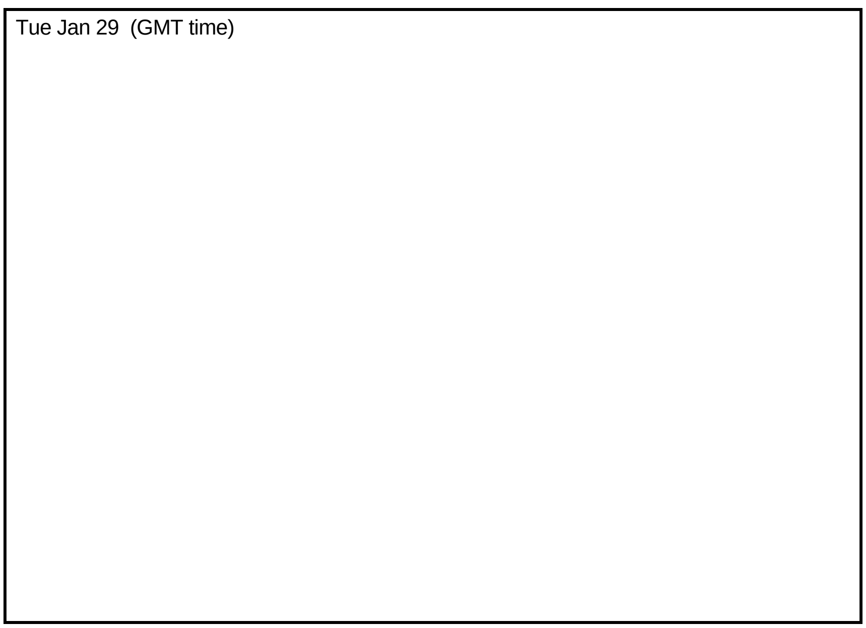


Figure 89. GDP, GS, and MIT data for ZOB on Jan. 29, 2002 local time.

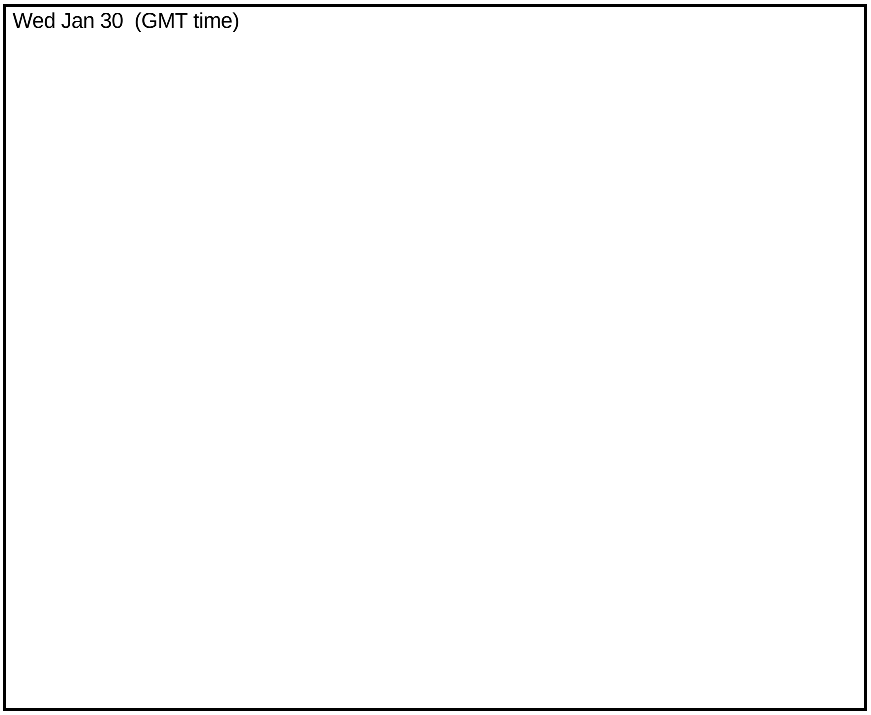


Figure 90. GDP, GS, and MIT data for Jan 30, 2002 local time.

Figure 91 illustrates a comparison between the effects of ATC restrictions on the sector count error. For MITs, a slight over prediction occurs with small look-ahead times but as the look ahead time gets larger, the affect on sector count error is small. First, the MIT restrictions that were in place were over OXI, and roughly 3.7% of all traffic in ZOB in a given day is involved with the jet route that passes over OXI. The number of flights that are actually subject to MIT restrictions is thus quite small, and the total sector count error will thus be small as well. Furthermore, MIT restrictions are used only as long as they are needed to solve the problem, so they are not used for long periods of time, and they do not seemingly affect the sector demand prediction results for long look ahead times. According to one air traffic controller, until MIT restrictions are above 30 to 40, there is not likely to be a noticeable difference in terms of sector demand error and how flights are handled.

Since a GDP occurs prior to take off and since our baseline data is en route data, the GDP results show insignificant effects when in comes to contributing significantly to errors in sector count. Most of the data for short look ahead times is far after take off, and only a few aircraft may still be on the ground due to a GDP (perhaps delayed because of other reasons like de-icing or taxi traffic). The effect of a GDP is showing up only at long look ahead times, as seen in the figure.

The most significant contribution to sector count errors for active flights comes from ground stops (GSs). For a GS, results indicate under predicting for the majority of look ahead times, with the most pronounced effect occurring at short look ahead times. This may be due to upstream en route restrictions – airborne holding as evident in **Figure 92**. Recall that GSs are usually issued as a last resort due to adverse NAS conditions (e.g., congestion causing holding patterns or severe weather), so their effect is going to be immediate and they are typically used only for as long as they are needed.

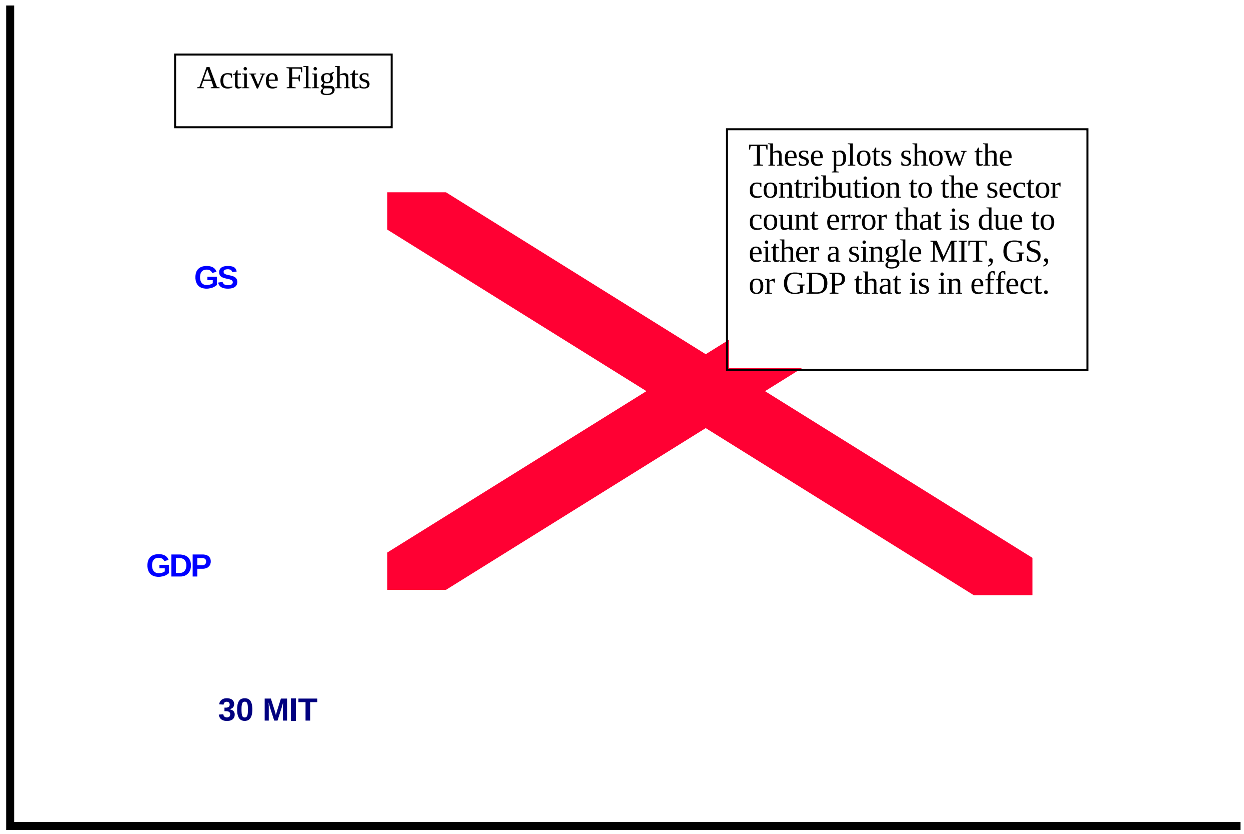


Figure 91. The net effect of MITs, GSs, and GDPs comparing time periods when the ATC restrictions were on to time periods when the ATC restrictions were off.

Figure 92. Ground stops were coupled with upstream holding patterns that caused the ground stops.

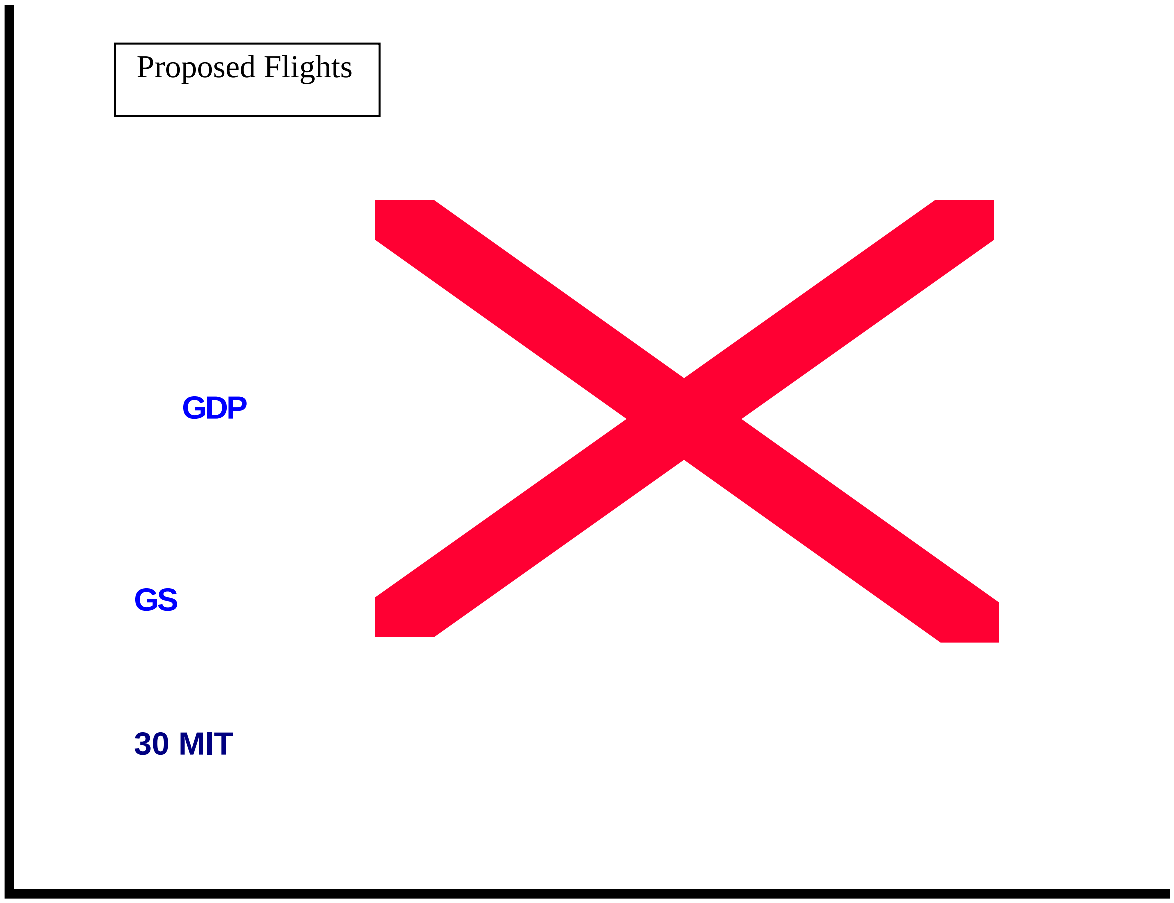


Figure 93. The net effect of MITs, GSs, and GDPs comparing time periods when the ATC restrictions were on to time periods when the ATC restrictions were off.

In order to understand the relationship between an EDCT time submitted in a GDP and its potential to influence the predicted sector demand, the rules for when to send a EDCT message need to be reviewed:

1. If no EDCTs have been sent yet, hold all EDCTs until 60 minutes before each departure.
2. If an EDCT has previously been sent, look to see if the new EDCT time is earlier or later than the previously sent one.
   a. If the new EDCT time is earlier than the existing EDCT, send it 60 minutes before the new EDCT time.
   b. If the new EDCT is after the existing EDCT, send the new time 30 minutes before the existing EDCT time.

For example, if BLR32 has a Ptime of 1500 and gets an EDCT of 1630, the ATCSCC would not send the EDCT until 1400 (60 minutes before Ptime). If after 1400 (once the first EDCT had been sent out) the flight was involved in a GDP revision, when a flight plan amendment would occur depends on the new ECDT. If the new EDCT was earlier - like a 1615 departure, the new EDCT would not be sent out until 1515 (60 minutes before the new EDCT). If the revision had moved the EDCT later in the day - like a 1700 EDCT, the new EDCT would not be sent out until 1600 (30 minutes before the existing EDCT time).

The algorithm used in the GDP for setting the EDCT time and reporting it as a flight plan amendment influences trajectory predictions for proposed flights. The EDCT time is the most accurate estimate of the take off time, however, it is not reported until either 1:00 prior to take off or 30 minutes prior to take off, depending on the case described above. This is one possible explanation to why the sector count error peaks locally at 30 and 60 minute look ahead times for proposed flights, as shown in **Figure 93**.

4.4.5 Effect of Airborne Holding Patterns on Sector Demand

Holding patterns are used for en route aircraft when sudden changes in the traffic flow inhibit aircraft from landing or from entering into neighboring centers (e.g., exiting ZOB into ZNY). Often, airborne holding is preceded by a ground stop or some other event, like a sudden change in MIT restrictions at a sector boundary. Thus, a GS or a MIT restriction change may be a predictor (although perhaps a weak predictor) of a need for holding.

Figure 94 illustrates the frequency of holding patterns in ZAU and ZOB. **Figure 95** illustrates the spatial distribution of these holding patterns in ZAU and ZOB for a particular day. In general, ZOB tends to have more holding patterns than ZAU, most likely because of the number of airports internal to ZOB being more than ZAU.

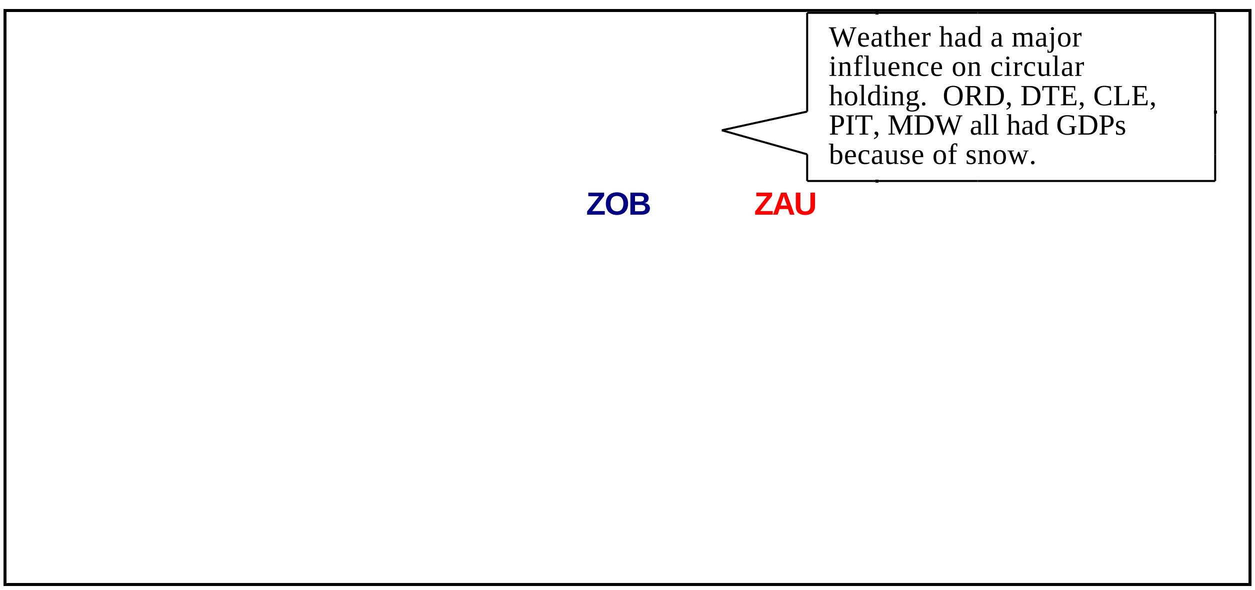


Figure 94. Frequency of circular holding in ZAU and ZOB during 3/18/02 through 3/31/02.

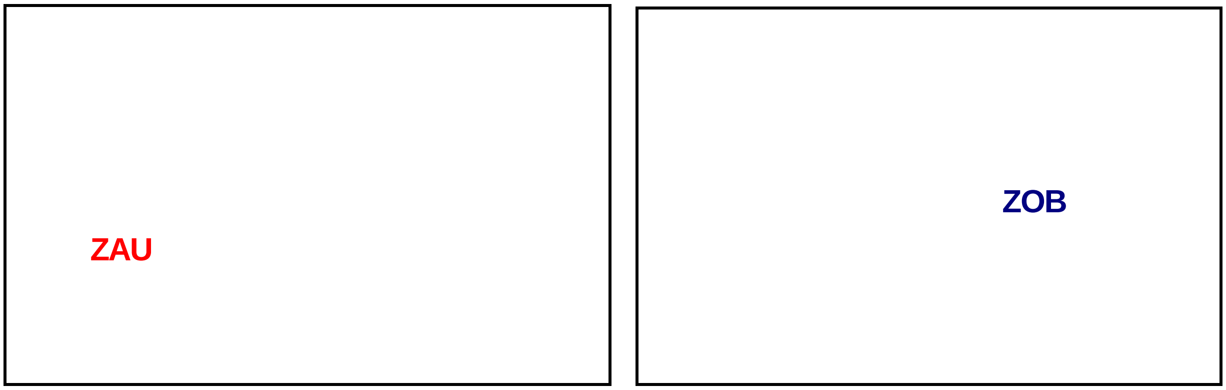


Figure 95. Spatial distribution of circular holding in ZAU and ZOB during 3/25/02.

When modeling the affects of holding patterns, one must account for the following factors:

- TFM generally prefers to absorb a rush or traffic closer to an airport than further
- Holding patterns in the TRACON (lower altitudes) are generally likely to be used up first and then when full, holding further upstream will begin (generally at higher altitudes), as shown in **Figure 96**,
- Holding patterns in the center with the problem are likely to be used up before another center is asked to begin to set holding patterns,
- Holding patterns that are passed back to an upstream center will begin at the closest available holding pattern to the center boundary and propagate back upstream across the center, and
- Holding patterns generally "stack" aircraft and accommodate from 6-8 aircraft depending on the airspace.

Given these conditions, aircraft that are en route could fly several hundred miles before they get to the holding pattern that other aircraft are currently holding within. So the propagation of flow upstream takes a long time and if potentially problematic, will cause additional TFM initiatives to take into effect (e.g., ground stops for traffic going to the problem airport or problem center).

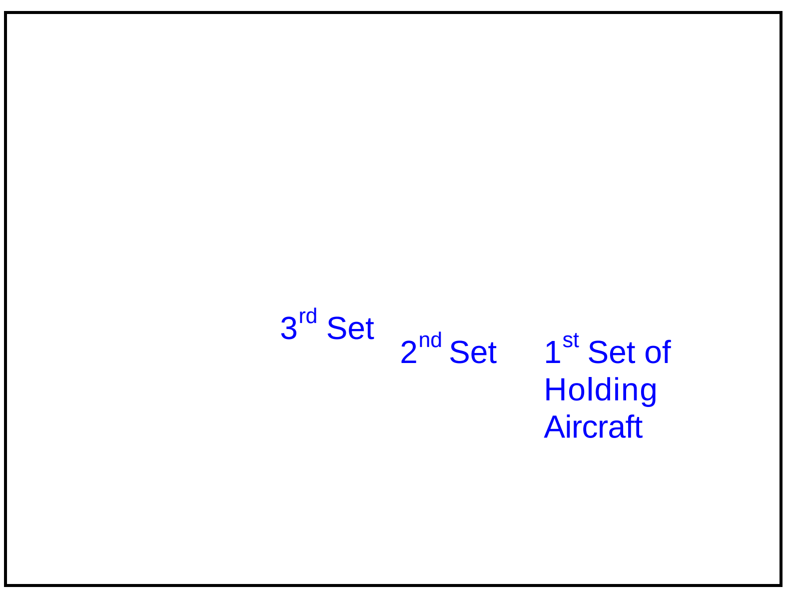


Figure 96. Airports where GDPs occurred in 2001.

Data from on-site observations at ZOB for 1/31/02 indicate holding patterns as follows:

20:30Z ZNY calls and indicates they are in holding. ZOB identifies how many aircraft Area 7 can handle in holding; Area 7 indicates 6 can be accommodated. ZAU says that they have no aircraft coming out into ZOB airspace in the next 30 minutes. Best case is to hold as close as possible to the troubled airport. The need to break the flow and let the leaders go into the ZNY airspace and into their holding patterns in ZNY. Then the remainder will be put into ZOB holding patterns. If during this time an APREQ occurs, then they have to keep track of how many are in the holding pattern and how many more can be added from internal releases. At this time, they estimate that the aircraft are going to be in holding for about 20 minutes. For the internal releases, they can take off or be held on the ground, and they will be given the choice.

20:49Z Slate Run (SLT) has a left turn holding pattern that is soon to be used. NWA672 is not in it yet but close. NWA672 will be the first to ask to hold.

20:53Z NWA672 goes into a holding pattern at FL290 at SLT (**Figure 97**)

21:04Z NWA672 still in holding pattern at SLT. UAL 8159 and BTA3544 to soon be added to holding pattern as soon as they get there (**Figure 97**). Different holding pattern altitudes are assigned for each aircraft, and aircraft are ascending to those altitudes before reaching SLT.

21:07Z A call is made to ZAU to warn that the first holding pattern will fill at SLT for any aircraft coming in from ZAU. Any more will have to start into a second holding pattern in Area 2 at Keeho.

21:20Z ZNY took the NWA672 out of the holding pattern at FL290 at SLT. The UAL8159 is holding at FL350 and the BTA3544 is still holding at FL370.

21:25Z ZNY accepts UAL8159 out of the holding pattern. Also, BTA3544 is accepted out next. ZNY is requesting 25 MIT out of the holding pattern. Not an easy thing to do because the timing of the loop in the pattern is not controlled. Another aircraft flying along the jet route might get through before the BTA3544 gets out of the holding pattern. Just the luck of the draw.

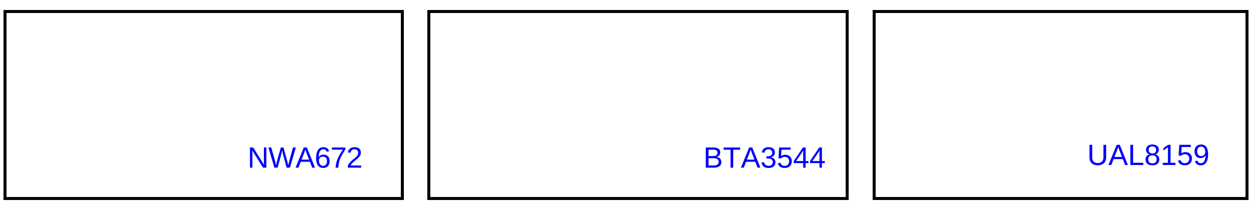


Figure 97. Three aircraft put into holding at Slate Run (SLT) on 1/31/02.

FACET does not have any information that an aircraft is in a holding pattern, so FACET will predict that an aircraft will fly through a sector without holding. The transit time is likely to be along the line of the average transit time across ZOB77, as shown in **Table 6** and **Figure 98**. In POET, a pattern recognition algorithm is used to detect holding patterns, and we are able to identify the flights that experience circular holding and separate them from the ones that do not. In doing so, we establish an average time for aircraft to pass west to east over J584 through SLT in ZOB77 (or the super high sector ZOB79 above ZOB77). The aircraft that experience circular holding remain within ZOB77 (or ZOB79) a considerable amount of time above and beyond the average. This additional time is not accounted for in FACET trajectory predictions.

Table 6. Statistics for ZOB77 during holding.

Non-Holding Average	None	18	-
BTA 3544	1 Loop	30	67%
UAL 8159	1 Loop	29	61%
NWA 672	3 Loops	46	156%

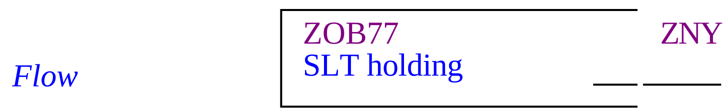


Figure 98. The sector where the holding pattern is taking place will experience sector count errors and will contribute to sector entry time errors downstream.

Note that holding patterns not only cause an error in sector demand for the sector where the holding occurred, however, it also causes the prediction of where the aircraft will be in the future to be wrong for all downstream locations. Once the holding pattern causes the delay, there is nothing in FACET that accounts for the delay for the rest of the flight. Thus, the error is going to remain with the aircraft for the rest of its flight.

4.4.6 Effect of SOPs and LOAs on Sector Demand Prediction

Each center has its own Standard Operating Procedures (SOPs) and Letters of Agreement (LOA) with neighboring centers. These SOPs and LOAs can establish rules and restrictions that will limit aircraft trajectories. Additionally, these SOPs and LOAs also affect trajectory predictions.

SOPs provide relevant specifications for, but not limited to:

- Traffic Management Programs
- TMU/Sector communication and coordination
- Combining and de-combining a sector
- Coordination for Direct Flights
- Lowest usable Flight Level
- Preferred Routings
- Processing of weather information (PIREPs, forecasts, SIGMETs, AIRMETs, etc.)
- Special Use Airspace

Some examples from ZOB SOPs are as follows:

- The radar controller shall not assign or allow to be assigned a flight level to an aircraft that will operate within the sector that is lower than the **lowest usable flight level**.
- When accepting a handoff on an aircraft that is assigned an **interim altitude** directly above or below the altitude stratum of your sector, you may enter an interim altitude allowing aircraft to climb/descend into your sector.
- The following types of **flight plans** may be **processed manually** (without entering into the Host computer):
    - Flights that will remain within the sector's airspace

- Flights that are executing a missed approach or making practice approaches
- Flights that are a point-out to the sector

· **Special Use Airspace** is identified in the SOP.

LOAs typically point out restrictions related to:
a. Traffic Flow
b. Handoff Procedures
c. Point-out Procedures
d. Canadian Airspace

Some examples from the ZOB LOAs are as follows.

The IHD Sector 53 has several restrictions in place:
- No direct routes to ZNY at or below FL180.
- PIT arrivals via V12 should be rerouted via THS.V474.NESTO, MON - SAT 1130Z - 1430Z and 1900Z - 0000Z.
- Restrictions on PIT arrivals from ZCW and ZNY are provided by the Traffic Management Unit on a dynamic basis.
- Five miles in-trail on all traffic over NESTO Intersection from CKB Approach.

The following restrictions are for the BKI Sector 57:
- All CLE arrival traffic must cross 20 DME east of the YNG VOR at FL240.
- All DTW and DTW satellite traffic (DET, PTK, YQG, TOL) must cross the BKI/RAV boundary at or below FL280.
- All YYZ arrivals via DKK VOR must enter the WRN Sector at or below FL330 descending to FL310
- All traffic enroute to BUF, ROC, and IAG must enter the WRN Sector at or below FL310 descending to FL280.

Restrictions from YQG Sector 21 indicate specific interim altitudes that are used, for example:
- Those DTW area departures filed over JHW, DKK, or SLT requesting at or above FL240, are issued an interim altitude of FL230 and handed off to the HUD Sector. The HUD Controller will issue a higher altitude via the interim altitude message.
- Those DTW area departures filed over ACO and CXR , requesting at or above FL240, are issued an interim altitude of FL230 and handed off to the RAV Sector. The RAV controller will issue higher via the interim altitude message. Depending on the aircraft's rate of climb, the YQG controller must point-out this aircraft to the HUD Sector or the YNG Sector. Care must be taken on those aircraft proceeding direct CXR to ensure YQG Sector points out any aircraft that might infringe on the WRN/DKK Sector.

Issues related to FACET modifications from SOPs and LOAs are as follows:
- Individual LOAs may identify a specific altitude or location that an aircraft may be expected to cross a sector boundary. However, even though this may be used to modify trajectory predictions that greatly deviate from the LOA, such rules are very specific to individual jet routes and sectors. Coding of such rules is very difficult to generalize and may not have the pay off in comparison to the cost of coding such rules into FACET.
- Specific rules and procedures can often be “over-ruled” by controller judgment, so there may still be errors between what the rule says and what is observed in the data.
- LOAs and SOPs change over time so any software modifications made to FACET based on LOAs and SOPs would have to be monitored periodically.

4.4.7 Effect of SUA use on Sector Demand

There was no SUA used in the time period of our on-site visits. However, there was an AWACS aircraft that reserved an amount of airspace that eliminated a jet route during a certain time period.

Such an event would bring down the sector count to zero. This event was not analyzed in further in this study since the occurrence is not typical. Furthermore, it would be difficult for FACET to know of such events prior to when they occur.

4.4.8 Effect of Adverse Weather on Sector Demand

Unfortunately, while there was weather present during our on site visits, the convective weather was very low, and we could not make any conclusions in this study due to the influence of convective weather on sector demand prediction accuracy. Air traffic controllers at the ZOB facility commented that most aircraft were going to easily climb over the weather that was present and the controllers were not having to make any special changes in their control actions for the day due to convective weather.

5 Conclusions and Recommendations

This chapter states the conclusions and some recommendations for future work.

5.1 Conclusions

There is a large collection of potential error sources that affect sector demand prediction. The error sources were classified into the following sets. Error sources that highly affect sector demand prediction accuracy are:

- Departure time prediction, *
- Prediction of TFM restrictions and ATC actions*, and
- Horizontal route prediction accuracy. *

Error sources that have a medium affect on sector demand prediction accuracy are:

- Vertical route prediction accuracy, *
- Flight speed prediction accuracy,
- Changing airspace adaptation data.

And finally, error sources that have a low affect on sector demand prediction accuracy are:

- Weather and winds aloft forecast accuracy,
- Accuracy of surveillance data,
- Flight technical errors and operational errors, and
- Accuracy of the trajectory models.

The majority of the analysis performed in this study focused on the error sources that ranked highest. These are marked with an asterisk (*).

Through interviews with air traffic controllers and personnel from the ATCSCC, we identified many factors that influence the error sources affecting sector demand prediction accuracy. These factors range from ones that are predictable, but have a low probability of occurrence, to ones that are unpredictable. The majority of the factors were classified into the areas of departure time prediction and prediction of TFM initiatives and ATC actions. Examples for departure time prediction include: abnormal events (runway and taxiway closures, obstructions on runways or taxiways, snow and/or ice removal, de-icing operations, runway direction reversals), unavailable gates, lack of information about GA aircraft, the effects of adverse weather, accidents, and incidents. Examples for predictions of TFM initiatives and ATC actions include: non-standard procedures across sectors and centers, style and preferences of controllers, lack of data on TFM initiatives or ATC actions (procedures typically avoid unnecessary data entry), daily trends due to weather and congestion, and seasonal trends.

Our study started by analyzing the accuracy of ETMS data relative to Host data in the terminal area of an airport (DFW). The following issues were identified:

- Errors in the vertical dimension were far larger than errors in the horizontal dimension, which is a widely known flaw of ETMS data.
- Errors in the vertical dimension were worse for arrivals in comparison to departures.
- Vertical errors for arrivals as well as departures were largely a result of the use of temporary altitudes called T-altitudes. T-altitudes assist controllers in performing hand offs and for directing an aircraft to hold at an altitude, but they are troublesome because they do not reflect the actual aircraft altitude.
- Analysis of recent ETMS data from all the centers in the NAS reveal that the majority of the centers no longer assign T-altitudes as the first preference for the ETMS data feed; thus, the errors associated with the T-altitudes are likely to be eliminated from the system soon.

- Horizontal errors for arrivals and departures were much more similar in comparison to the statistics of the vertical errors.
- The majority of the error between the horizontal ETMS and Host data is due to the fact that ETMS latitude and longitude coordinates have been truncated to the nearest minute resulting in an average error of 0.5 nmi in each direction, or a total error of 0.7 nmi in horizontal range. The primary (original) purpose for the ETMS TZ messages was so that the TSD could plot an icon on the display to represent the current location of a particular flight for TFM purposes (not ATC purposes). A resolution to the nearest minute of lat/long was sufficient for this purpose.
- Another form of horizontal error can be associated with time lag between the ARTS data sources and the ETMS data source. Depending on time lag, ETMS and the Host data can differ as much as 0.5 nmi (5 second lag), assuming that in one second an aircraft can travel 0.1 nmi (i.e., a speed is 360 nmi per hour).

The majority of our study analyzed data associated with sector demand prediction. The most important factor in sector demand prediction was identified as the accuracy of predicting take off time. Over 60% of the aircraft are on the ground when 30 minute look ahead time predictions are made. When longer look ahead times such as 120 and 240 minutes, the percentage of aircraft that are on the ground when the trajectory prediction is made is above 98%. There are several contributing factors and issues related to takeoff time prediction:

- Accuracy of the 1st ETMS data point, which was shown to be generally 1 minute late in comparison to the actual take off time (based on ACARS OOOI data).
- Scheduled take off times (from ETMS) are generally 8 minutes off from actual take off times (based on ACARS OOOI data).
- Average taxi times (from ACARS OOOI data) exhibit a variance smaller than the scheduled take off time variance. However, the lack of readily accessible data for either OOOI out times nor data for parking gate information (arrivals/departures) inhibits better predictions prior to take off.
- De-icing affects the take off time based on two cases: if de-icing occurs prior to pushback vs. if de-icing occurs after pushback, for instance, when there is a remote location where all de-icing takes place. When de-icing is in effect and when the airport performs de-icing at a remote location, then the taxi time as well as the variance in taxi time are greater due to de-icing.
- The scheduled ETMS take off time is in greater error (error magnitude and variance) during days when de-icing is taking place.
- When de-icing operations are in effect, air traffic controllers are more likely to increase the MIT restrictions used in an En Route Spacing Program in order to insure that an aircraft can immediately take off after de-icing and have a space to fit into in the overhead traffic stream.
- Cancellations occur often enough (up to 9% for the 20 airports studied) to justify including cancellation data into the FACET trajectory prediction and sector demand prediction processes; these cancellations eventually affect the sector demand prediction accuracy.
- Two clusters of data exist for departure cancellations, one around 15 hours and one about 2 hours prior to departure. Although the airlines may submit cancellations days or even weeks before departure, Volpe does not synchronize the airline CDM data with ETMS data until 15 hours before departure time. This explains the large

spike in the cancellation data at 15 hours prior to departure, which accounts for approximately 38% of the cancellations.

- A small percent (roughly 8%) of cancellations occur after the scheduled take off time of a flight; in general, there is no way for FACET to know about such a cancellation with any look ahead time, so such flights must be assumed by FACET to take off at their scheduled take off time.

From the perspective of TFM initiatives and ATC control actions, the following factors were identified:

- MIT restrictions data are available at the ATCSCC, however, the data is recorded only if it affects a neighboring center; MIT restrictions within a sector are not recorded at the ATCSCC, nor is it available electronically elsewhere.
- MIT restrictions data recorded at the ARTCC did not always match the MIT restrictions data recorded at the ATCSCC; this is true for both the magnitude of the MIT restriction as well as the time duration for the restriction. Data discrepancies occurred every day during on site observations.
- In comparison to RTO 37 results, the number of MIT restrictions used in a day are more today than several years ago, even though the traffic level today is smaller than several years ago (due to a reduction in traffic volume associated with the 9/11 events). These data indicate that MIT restrictions are being used more often than they used to be, relative to a constant traffic volume.
- Centers in the Northeast corridor experience the most MIT restrictions, with ZNY and ZOB clearly exhibiting the most MIT activity in the NAS over the week of observations.
- Until a reliable electronic source of MIT restrictions data becomes available, Historically Validated Restrictions (HVRs), which are MIT restrictions that occur on a repeatable basis from day to day, offer the best data for incorporating into trajectory prediction or sector demand prediction.
- Ground Stops (GSs) and Ground Delay Programs (GDPs) are announced through the ATCSCC website, and thus are available in electronic form for possible input into prediction algorithms. However, these are not in a friendly format for reading by computer automation.
- GS and GDPs occur all across the NAS, without any one particular geographical location where they are consistently used on a daily basis; ORD, SFO, and LGA exhibit the highest occurrences of GDPs.
- Between MITs, GDPs, and GSs, the most significant contribution to sector count errors for active flights (predictions made for aircraft that are currently en route) comes from GSs. The error is most likely caused by airborne holding patterns near the GS airport, which in turn, are the result of a GS.
- Between MITs, GDPs, and GSs, the most significant contribution to sector count errors for proposed flights (predictions made for aircraft that are currently on the ground) comes from GDPs. GDPs, by their very nature, are announced either 30 or 60 minutes in advance of the EDCT time, which does not help when it comes to making sector demand predictions for large look ahead times.

Analysis of aggregate sector demand prediction data indicated the following:

- The active aircraft sector demand prediction results are generally significantly better than the proposed aircraft results. This is expected because with active flights, there is a known departure time that is the greatest source of error for trajectory prediction of proposed flights.
- While sector entry time predictions associated with very short look ahead times generally were at or near zero for active flights, the predictions for proposed flights

(predictions made for aircraft that have not yet take off) generally did not start at or near zero. The effects associated with airborne holding were the primary reason for this "offset".

- In the worst case, horizontal errors may be large enough so that an aircraft predicted to enter a sector prior to take off may never pass through the sector, thus effecting sector count statistics.
- Sector demand predictions do not vary much over the course of the day; errors at different times of the day may be attributed to specific causes more than any particular generalization of the time of day.
- As expected, the data suggests that predictions based on OAG data are worse than predictions based on the filed flight plan in ETMS.
- Pop up flights (aircraft that do not have a filed flight plan at the time of take off, for instance, GA aircraft) are not accounted for in the ETMS flight plan data, but do appear in ETMS track data. Pop up flights are a cause for under-predicting sector counts.
- Total absolute sector count error for all sectors in ZOB or ZAU typically ranged from 1-4 aircraft for up to 4 hour predictions, with individual sector counts in error as much as 5 aircraft.
- Absolute sector entry time error for all sectors in ZOB or ZAU typically ranged up to 20 minutes for proposed flights for up to 4 hour predictions, with individual sector entry time errors varying as much as 30 minutes in error.

Unfortunately, while there was weather present during our on site visits, the convective weather was very low, and we could not make any conclusions in this study due to the influence of convective weather on sector demand prediction accuracy. Air traffic controllers at the ZOB facility commented that most aircraft were going to easily climb over the weather that was present and the controllers did not have to make any special changes in their control actions for the day due to convective weather.

5.2 Recommendations

The following recommendations are ordered in terms of order of importance. Items that can be immediately addressed to improve FACET with little difficulty are placed highest on the list. Items that would require systems or inputs that are not currently available are placed at the end of the list.

Flight Cancellations

FACET does not record when a flight is cancelled. However, this information is currently available in the ETMS data feed and is available in electronic format. At the present time, FACET will assume that a cancelled flight will take off at it's scheduled take off time and continue to predict the trajectory of the path based on the scheduled take off time. This causes sector demand errors since an aircraft will be counted in a sector when it actually never departed. Two possible mitigation strategies exist for this problem:

1. Modify the ETMS data parser for FACET to include the ETMS RZ flight cancellation messages so that FACET can then delete the flight from the list of active flights, or
2. Write software that infers a flight cancellation within FACET by assuming a flight is cancelled if a flight plan is filed but a track message does not appear within a certain amount of time relative to the scheduled take off time.

Since cancellations occur every day (roughly 9% for the 20 airports studied), the majority of the cancellation data are known roughly 2 hours prior to take off, and cancellations are directly connected with the largest factor in sector demand prediction error (namely, the prediction of take off time), there is a very good benefit to including cancellations data into FACET. The final recommendation is to suggest that the ETMS data parser or FACET be modified to include cancellation messages.

ETMS T-Altitude Data Suppression

FACET uses the ETMS TZ altitude data to establish the location of an aircraft and to predict the future location. However, as pointed out in this study, the TZ altitude data in ETMS at times holds T-Altitude data in place of the altitude. When this happens, the altitude based on ETMS TZ data may skip from an altitude that is relatively close to the actual aircraft altitude to an altitude that is very far from the last data point. If taken literally, an aircraft could not physically fly such a route. When T-altitudes are used in the ETMS data stream, FACET should suppress the T-altitude and use the last data point, an extrapolation forward in time based on previous data, or a filtered data point. The most recent data collected for this study shows that this problem is becoming a non-issue as more and more centers adapt a "patch" that re-orders the altitude data supplied in the ETMS TZ message. As of May, 2002, the only centers that seem not to have employed the patch are: ZAB, ZFW, and ZID. There is no recommendation to alter FACET to account for T-altitude data, since it looks like these patches should take care of the problem and all centers will soon have this patch installed.

ETMS Data Bias Adjustments

ETMS data, on average, is about 1 minute off on its first data point that identifies when a takeoff has occurred. This offset can be adjusted in FACET to change the initial conditions of a flight such that the initial conditions more closely match actual take off times. Furthermore, this offset can be adjusted on an airport by airport basis if it proves useful. It is unlikely that this offset affects long term trajectory predictions, since ETMS TZ messages will update the most current track information. However, if there is a significant amount of time between the ETMS DZ message and the first TZ message, the bias can eliminate a small amount of sector entry time error. Such a change to FACET is very easy to implement.

ATCSCC Data Dissemination

FACET does not have a reliable source of TFM control action data from the ATCSCC that is easily readable by computer automation. GS, GDP, and MIT restrictions data are potentially available in electronic format at the ATCSCC, and there is a benefit to having this data placed in a location where FACET can read the data in a well defined format. The ATCSCC web site provides such data, but the format is not computer friendly and is based on communicating to a human user rather than for a computer system (e.g., FACET). At this time, we recommend that NASA and the ATCSCC work together to establish an experimental connection (e.g., FTP site) to TFM control action data that resides at the ATCSCC. If such a data connection is established in a well defined format, and if reliable data is placed at such a location, then there may be benefit to trajectory predictions and sector demand predictions. The magnitude of such a benefit needs to be investigated in future research. MIT restriction data is currently being stored electronically through testing of the National Log Program. It remains to be seen whether this data is entered in a timely and consistent enough fashion to be of use for real time trajectory prediction. NASA should also explore getting access to GS and GDP messages that get issued by the ATCSCC through TSD and FSM. This would allow FACET to have access to EDCT data that could greatly improve predictions during GSs and GDPs.

Airborne Holding Prediction

In this study, we noted that airborne holding is a significant event that is not currently identified in FACET, it occurs on average every day, it can be detected fairly easily by an algorithmic filter, and is an event that is associated with sector demand prediction errors. While this is primarily a problem for short look ahead times, there are some algorithmic solutions that can be investigated to improve trajectory predictions and sector demand predictions while airborne holding is present in real-time data. First, we observed that airborne holding is often the result of ground stops or reductions in airport arrival rates. Thus, ground stops or changes of airport arrival rates may be used in a predictive model. Also, we noted that airborne holding propagates upstream. Thus, if airborne holding is occurring downstream, it is possible that it can propagate to an aircraft upstream, and this also something that can be incorporated into a predictive model. The difficulty with airborne holding, as observed in the on site observations, is that once an aircraft is placed into a holding pattern, there is no particular order for which it will be taken out of the circular holding pattern if more than one aircraft is in airborne holding. There is no first in first out rule; as an air traffic controller explained, the first aircraft that is in a good position to exit the airborne holding pattern is taken out simply because the aircraft was fortunate enough to be at the right location at the right time for exiting the airborne holding. Airborne holding, in the form of a circular holding pattern, is relatively easy to detect algorithmically (for instance, POET provides a simple algorithm that detects circular holding patterns). There are two directions that we recommend pursuing:

1. Identify the initial conditions that are likely to trigger airborne holding within the TRACON. Such events are likely to be a reduction of airport arrival rate or a ground stop. Given a large collection of data for such cases, these data should be analyzed and a model should be built that predicts the amount of airborne holding that is likely to result given the airport arrival rate reduction or the time duration after a ground stop.
2. Identify the initial conditions of aircraft in circular holding patterns downstream (in the TRACON or en route airspace) that are likely to propagate upstream and cause traffic to be put into airborne holding. Given a large collection of data for such cases, these data should be analyzed and a model should be built that predicts the amount of airborne holding that is likely to result given the time and location of airborne holding downstream.

Future research is needed to establish these predictive models and to establish the benefit of such predictive models. It is likely that such models may only assist in short term trajectory predictions and will have limited benefit or limited accuracy in the long term. The final recommendation is for these limits to be explored in future research.

Takeoff Time Prediction Based on ACARS or SMS Data

In the future, there may be a source for ACARS on times or pushback times available to FACET. If so, then there is a possibility that the pushback time and the average taxi time could be used to predict the take off time. Additionally, historical data could assist in such a prediction, as we discuss in **Appendix A**. Another alternative is to exploit SMS taxi and take off time predictions to determine a better estimate for take off time. Such a prediction for the takeoff time of an aircraft may prove to be a better estimate than the filed flight plan take off time, however, future research should be performed to build an appropriate model and to verify this proposition.

En Route Spacing Prediction

Direct-to routes, path stretching, MIT restrictions, and speed control are used in En Route Spacing Programs to adjust the flow rate to a fix location. For example from our on site observations, we observed a series of such control maneuvers used to adjust the flow rate properties of traffic going to ORD over the PMM fix and yet another case of adjusting the flow rate properties of traffic going to ORD over the OXI fix. These adjustments are to some degree predictable, however, they affect traffic only for short look ahead times. The degree to which these can be modeled so that the model for predicting the route and time that an aircraft will arrive at the fix location should be explored in future research. Such a model may depend on historical data, as we discuss in **Appendix B**. The payoff of such modeling is not expected to be as high as other FACET improvements, e.g., inclusion of cancellations, since modeling of En Route Spacing Programs would only apply to traffic flying over a particular fix and not to all traffic within the center. No recommendation is made at this time to include such a predictive model into FACET, since our research does not indicate that there will be a large benefit from adding such prediction capabilities to FACET.

Parking Gate Information

There is long term potential to use parking gate information in the ETMS data feed to improve departure time predictions. It is currently very difficult to obtain information about the 'line of flight' of an aircraft. This line of flight refers to the sequence of an airline's flights that are conducted using a specific aircraft. Knowledge of the line of flight would allow systems to more accurately predict the departure time of an outbound flight. If the inbound flight of the aircraft that will make up an outbound flight is late, then it is reasonable to predict that the outbound flight will depart late, unless there is slack in the scheduled turn-around time for the aircraft.

One way by which the line of flight information could be inferred and predictions of departure times improved is by inclusion of the parking gate in the ETMS data feed. The aircraft used for the arrival flight assigned to a parking gate will likely also be the aircraft used for the next departure flight assigned to that parking gate. With this information, the departure time of the departure flight can be estimated based on the arrival time of the arrival flight at the same parking gate. Line of flight information would greatly benefit long term trajectory predictions and long term sector demand predictions. Without such information, long term predictions are currently limited.

Note that airlines have many operational options available to them to deal with situations in which arrival flights are late. A different aircraft may be assigned to the departure flight if the arrival flight is late. Other parking gate changes required by maintenance or other factors may also reduce the accuracy of the line of flight data derived from parking gate information.

Ultimately, parking gate information would potentially allow predictions of take off times to be done prior to the filed flight plan and are likely have better accuracy than the OAG scheduled take off time. This would need to be investigated in a future effort to establish the value of such information.

Future Steps Concerning FACET Software

There are several areas where Trajectory Prediction, TP, and FACET interface, and where there are potential areas of improvement:

- Configuring and running TP for the conditions of RTO 66 was troublesome. It depends heavily on editing a configuration file. Locations of many of its data files are hard-coded, and it's method of handling wind data is cumbersome. We suggest creating a startup panel for TP that would allow the user to set the necessary parameters and then initiate processing. The locations of its required data files could be set in this panel instead of being hard-coded in the software.
- A better way of handling the winds data would be for TP to send a message to FACET and have FACET retrieve the ruc files from a specified location, eliminating the need for the RUCRendevous file.
- TP should also be modified to use POET adaptation data where possible. Both TP and FACET should automatically update their adaptation data every 56-days, like other operational tools that are used at the ATCSCC.
- One of the issues TP had during the RTO 66 project was the speed at which it was able to update the database tables. Some means to do this more speedily needs be found whether through some form of bulk insert or more efficient code. A replacement for TP is close to being completed that allows for multiple "trajectory writers" that can run on any machine on the network.
- The current method by which TP requests trajectories from FACET is a serial one, with TP processing a list of flights, sending each flight over, and receiving the trajectory. FACET has other capabilities, such as deconfliction, that cannot be used when flights are sent in this manner. It may be possible to modify the TP/FACET interface in such a way that TP could send all the flights expected to be in the air

during a specified time frame and have FACET crunch the numbers and send back all the trajectories that result.

- One of the changes from last year's version is that FACET has encrypted its adaptation data. This prevents other applications, such as TP, from using its adaptation data and it also prevents us from, for instance, modifying POET adaptation data to be used by FACET.
- An area that FACET may want to address in the future to improve its trajectory predictions are airports where altitude restrictions exist for arriving flights. This is a complex area both in terms of creating an adaptation to represent the restrictions and in calculating the trajectories themselves.

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Appendix A: Prediction of Aircraft Take Off Time

By Yijuan Zhao

We wish to develop a mathematical model for accurately predicting aircraft takeoff times at a given airport on a given day for specified look-ahead times, based on all (easily) available information. Obtaining good estimates on takeoff times is essential to accurate trajectory predictions and the prediction of sector demands.

(A.1) Approach

For the convenience of discussions, we index all flights scheduled to depart from a given airport by two integers: flight , where represents the day of the year, and corresponds to the numbering of flights scheduled to depart from the given airport within a 24-hour period,

Many factors influence the actual takeoff times. After careful examination of all these different factors, we propose a four-term model for predicting takeoff times. On a particular look-ahead day (is fixed), the predicted takeoff time at a certain look-ahead time of the th flight is given by:

where:

Time for which takeoff time prediction is made,

The current time,

The look-ahead time,

Takeoff time predicted at the current time () for the time for the th aircraft on the th day,

Nominal takeoff time predicted for the time for the th flight of the day, calculated at the current time ().

Estimation correction based on historical data,

Corrections based on adapting to airport conditions, and

Effects of random events and estimation errors

A hidden term in this prediction model is the scheduled takeoff time based on flight plans. It affects the nominal takeoff time.

Expressions of Individual Terms

Scheduled Takeoff Time

Scheduled takeoff times reflect desired takeoff times specified by the airlines in absence of any aircraft movement or specific airport conditions, and can be obtained from Official Airline Guide (OAG), flight plans, and/or amended flight plans. In general, the scheduled takeoff time may depend on the day of the year.

For a specified flight , check OAG, ETMS, and Host computers

If the flight has been cancelled

Deduct this flight from prediction program

Else if a flight plan or amended flight plan is available,

is the takeoff time filed in the (amended) flight plan

Otherwise

can be obtained from OAG

<u>Nominal Takeoff Time</u>

Nominal takeoff times represent <u>planned takeoff times</u> incorporating considerations of airline desired takeoff times, airport conditions, and air traffic control measures currently employed at the airport. They reflect reality-constrained departure time plans at a given airport. .

At the time of estimation and for a specified flight , one first needs to check ACARS data, if available, to see if the flight has already taken off or has pushed back.

<u>(1) If the aircraft has taken off</u>

Use ACARS and ETMS data to determine actual takeoff time, for example

*where is the actual takeoff time of the th aircraft on the th day, and represents errors between actual takeoff time and ETMS recorded takeoff time (which may be based on the first radar hit). can be determined from historical data and has been studied in a previous Metron report [*KCH97*].*

<u>(2) Otherwise, if the aircraft has pushed back but has not taken off</u>

Use SMS data or ADS-B data (if available) to determine current aircraft location in the airport, and estimate takeoff time as a function of this location. SMS may provide an accurate estimate on the takeoff time. If SMS data is not available, proceed to use raw ADS-B data or the same method as below.

<u>(3) If the aircraft has not pushed back yet</u>

If the airport is closed or will be closed before

Else if GS or GDP is in effect or will be in effect before

Else if de-icing program is in effect or will be in effect before

Else

In the above, the terms are defined:

is the estimated length of airport close time and should be available from the Tower control authority,

is the estimated length of takeoff delay caused by ATC actions (GS or GDP) and is also available from the Tower control authority,

is the estimated length of time required for the de-icing process at a given airport. Historical data is used to obtain estimates of the de-icing time by fitting these data according to season of the year and time of the day (morning, afternoon, evening, and night),

is either 1 or 0, indicating whether the current aircraft will go through the de-icing process or not.

Since the decision on which aircraft will need to go through the de-icing process depends on both the weather and the pilot, not every aircraft affected by the weather would go through the de-icing process. If the decision on which aircraft will go through the de-icing process is known at the time of prediction (), then

If this decision is not known at the time when prediction is being made, whether a specific aircraft will go through de-icing may be a random number.

The de-icing probability can be determined from historical data. This model may not result in the correct prediction for individual aircraft, but will help to improve the prediction of sector demands given a large set of aircraft

Historical Data Corrections

Historical data can be used to improve estimates of takeoff times through corrections over the scheduled takeoff times. These corrections reflect historical trends on the differences between scheduled takeoff times and actual takeoff times at a given airport around a certain time, caused by salient characteristics of factors such as rush hours, rush patterns over the week, and seasonal effects. In essence, they provide more accurate estimates of aircraft taxi times.

Historical data can be used to different extents or in different ways. For example, where aircraft are selected to obtain a historical average from all aircraft on previous days of the same season with scheduled takeoff times within a certain window of :

where represents past days but in the same season as , and may need to be on the same day of the week as . Historical data can be utilized in additional ways, such as by dividing the data on individual airlines, destinations, weather conditions, etc.

Learning adaptation to airport conditions

Estimation corrections based on historical data may not be able to model effects of special episodic factors of the day, such as accidents/incidents, aircraft failed parts, specific weather conditions of the day, and other local, abnormal events. Effects of these special factors may be captured through learning adaptations.

The idea of learning adaptation is to improve the takeoff time predictions of later flights based on observing the differences between actual and predicted takeoff times of earlier flights from the same airport. This is based on the intuition that delay build-up or reduction is a continuous process. In other words, if an immediate previous flight is delayed, it is likely that the current flight will be delayed also.

At the time of prediction (*t*), it is assumed that the special airport condition may cause additional takeoff delays at a future time according to some function . Let's use a second-order model to explain the idea of learning adaptation.

where the coefficients can be trained periodically using data from immediate past flights. For example, let's say that flights have taken off from the same airport in the last time frame (e.g. half an hour to two hours). These coefficients can then be determined from the following parameter optimization (or identification) problem

Learning adaptation is most useful when is relatively small, because it uses past data to predict future trends. When this time difference is too large, the learning adaptation term should not be used.

Effects of Random Events

It may not be possible to predict the takeoff times perfectly, because of various abnormal or random events (e.g. airline human factors, etc.). It is then useful to develop some understanding about the stochastic nature of takeoff time predictions. This understanding can be used to develop bounds around the predicted takeoff times; so as to obtain estimates on the valid range of trajectory predictions or sector bound estimations.

The probabilistic distributions for the term are obtained from plotting and examining historical data.

(A.2) Incorporating Flight Cancellations into Sector Demand Predictions

Flight cancellations directly affect both trajectory predictions of individual aircraft and sector demand predictions. Effects of flight cancellations may be incorporated into FACET in one of two ways.

(1) Process ETMS cancellation message for the predictions of individual aircraft trajectories and takeoff times. This can directly improve the prediction accuracy for studying individual aircraft.

or

(2) Use historical data on flight cancellations on individual airports to improve sector demand predictions. In doing so, three variables need to be modeled using historical data:

   a. The average number of flight cancellations on this day with scheduled takeoff times around : ;
   b. Percentage of these aircraft that would go through a specified sector ; and
   c. The typical time of flight from the given airport to the specified sector .

Then, the number of aircraft that will not pass through a given sector at a specified time is given by

Realistically, FACET could never know about all the cancellations, since many of them occur outside the look-ahead time or even after the scheduled time of departure. Therefore, there is a certain randomness in the prediction of sector demands. Stochastic distributions of these random components may be identified through historical data and used to obtain bounds on the predictions of sector demands.

Appendix B: Prediction of Traffic Flow

By Yijuan Zhao

We wish to develop a convenient mathematical model for predicting traffic flows over a specified sector or center, and to determine effective MIT measures and/or internal release rates so that a desired level of traffic can be controlled.

(B.1) A Sector/Center Model for Traffic Flow Prediction

For the purpose of traffic flow predictions, the following generic model may be used to describe a given sector or center.

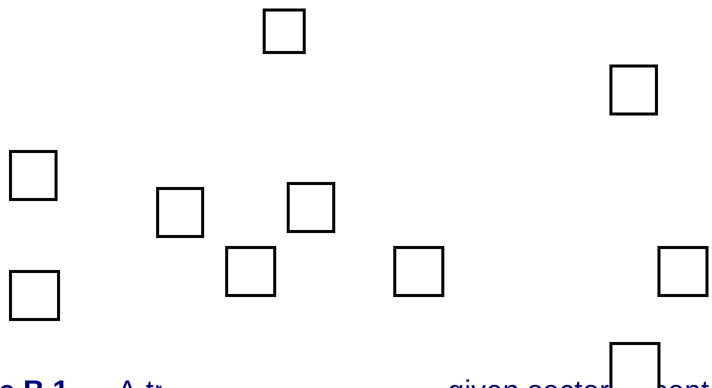

Figure B.1. A tr… given sector or center.

In **Figure B.1**, symbols have the following meanings.

- arriving traffic flow rate (number of flight arrivals at a certain boundary point per unit time);
- departing or landing traffic flow rate (number of flights that leave the specified area or land within per unit time);
- fixed arrival rate reflecting arrivals from International routes;
- traffic arrival rate from a certain domestic route where ;
- takeoff rate from internal airport releases where ;
- rate of traffic leaving the specified area at a certain boundary point where ; and
- landing rate into internal airports where .

Define:

traffic increase rate

traffic reduction rate

the number of flight within the specified area can be predicted as

(B.1)

where .

Traffic Flow Prediction

The number of traffic within the specified area is affected by both and , which depend on MIT restrictions, arrival rate, traffic leaving rate, takeoff rate, and landing rate. These rates may be changed from time to time, but stay roughly constant between changes. For example, MITs are in general implemented in 15-minute blocks of time.

For a time window over which all these rates are roughly constant, the number of traffic within the specified area can be predicted as

(B.2)

where is a random number reflecting prediction uncertainties and whose stochastic characteristics may be determined by examining historical data. A steady-state number of flights can be achieved by having

(B.3)

Therefore, the traffic flow prediction problem can be solved as follows. Divide the look-ahead time interval into subintervals where in each subinterval, both the traffic increase rate and the traffic reduction rate are constant.

(B.4)

In other words, whenever a change occurs in MIT restrictions, arrival rates, or landing rates, etc., a new subinterval should be defined. Then, all it takes is to apply Eq. (B.2) repeatedly over these subintervals with different values of and .

Effects of MIT Restrictions on Traffic Arrival/Departure Rates

Figure B.2. Effects of MIT restrictions on l or departure rate.

Determinations of and from MIT restrictions are now discussed. Consider the arrival traffic at a certain boundary point. If the average flight speed at this point is and the MIT restrictions for traffic entering into this point is , then from **Figure B.2**,

(B.5)

Similarly, (B.6)

Further Expansions of the Prediction Model

Differences between predicted traffic flow and measured traffic flow can be used to modify the above prediction model or to develop learning capabilities if measured traffic flow is frequently available in real time.

Alternatively, this above model can be used to “identify” actual controller strategies in MIT restrictions by comparing measurements and predictions of traffic flows.

(B.2) Control of Traffic Flow

The above traffic flow prediction model can be used to proactively develop flow control methods to stabilize the number of traffic within a given area. For example, let represents the desired number of flights (or the maximum number of flights acceptable). Based on Eq. (B.2), a desired traffic increase rate may be selected to achieve this specified number of flights from

(B.7)

We have (B.8)

Different strategies or distributions of MIT restrictions may be used to implement this desired traffic increase rate.