Use of Next-Generation Satellite Systems for Aeronautical Communications: Research Issues

DRAFT PROJECT FINAL REPORT

prepared by

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The introduction of Next-Generation Satellite Systems (NGSS) into the global telecommunications landscape offers the potential to revolutionize how consumers and business entities communicate in the future. Aviation is also currently undergoing major changes in its telecommunications infrastructure with modernization efforts underway to convert from the current analog, primarily voice-based system to a digital voice and datalink system for both Air Traffic Management (ATM) as well as airline operational (AOC)-type communications. The future air-ground aeronautical telecommunications infrastructure will be a hybrid, made up numerous terrestrial and space-based links such as VDL-Modes 2 and 3, Mode S, SATCOM, HF to name a few. Each of these will have their own specific link characteristics in terms of technical performance and cost as well as applicability to aircraft platform. Traditionally, air-ground aeronautical communications in domestic airspace has been considered primarily from the ground-based provider perspective. The application of NGSS systems for aviation offers the potential to greatly change how aeronautical communications is performed in the future. NGSS stands to offer a new alternative to the mix of candidate communications links for future ATM and AOC communications.

This project had two inter-related goals. The first was to assess future aeronautical communications applications. Our work developed a traffic scenario for the year 2020 and then estimated associated bandwidth requirements for advanced weather applications. Included is a model in which aircraft act as sensors and feed back readings, which are fused by a weather model. The resultant weather information would then be sent to all interested aircraft.

The second goal involved the investigation of the use of next generation satellite technology to support these advanced applications. We developed a model that supports the comparison of broadcast, uni-cast and hybrid broadcast/uni-cast satellite systems for the delivery of weather and other information to aircraft. This model allows for the estimation of the bandwidth requirements for future aeronautical communications applications. It also is supports the comparison, based on bandwidth requirements and processing cost, of broadcast or hybrid LEO/MEO architectures, broadcast or hybrid GEO architectures and general unit-cast architectures.

Section 1 of the report describes the satellite communications model and summarizes the overall results of the project. Section 2 described a methodology to estimate aircraft flows in NAS. Section 3 provides the results of future aeronautical communications applications research.

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1 Communications Requirements and Solutions

1.1 Overview

We can generally classify aeronautical communications applications into those that are specific to a single aircraft and those that are of interest to multiple aircraft within a geographic region. An exchange related to a route modification would fall into the former category and dissemination of weather information would fall into the latter. Both types of communications could be sent to an aircraft via a uni-cast link. However, a broadcast link may offer a more attractive alternative for the latter type of communications. We develop bandwidth requirements associated with next generation aviation communications applications for both the case of uni-cast-only links and the case of a hybrid uni-cast/broadcast architecture. In the hybrid case, we specifically take into account the characteristics of next generation satellite systems.

We model the broadcast applications by associating a region of interest (ROI) with each aircraft at any particular time during its flight. We assume that all required broadcast information can be represented as attributes of this (geographic) ROI. The ROI can be conceptualized as map whose attributes are dynamically updated over time and whose center changes as the flight moves through space. As the flight progresses the ROI would change. In general, an aircraft could be interested in three different ROIs: a tactical ROI, a near-term strategic ROI and a far-term strategic ROI. At certain times during a flight the pilot and/or aircraft control systems could be interested in any one the three ROIs, while at other times, e.g. during final approach, there would be only one of interest. We model the requirements of each separately and implicitly assume that overall bandwidth requirements are obtained by summing the requirements of each application. We leave to future research methods for efficiently handling the three simultaneously. We assume that each of the three ROI types have appropriate sizes, which increase as one progress from tactical to near-term strategic to far-term strategic and resolutions, which decrease as a function of the same progression. A refresh rate would also be associated with an ROI. This is the frequency at which the information in the ROI is updated. Since between successive updates some of the underlying information will remain the same, we also associate an update factor for this process, which is the fraction of the ROI's information content that must be changed between successive updates.

The principle focus of our analysis is the modeling and evaluation of next generation satellite communications technologies to support future aeronautical communications. However, we will also be able to draw some conclusions related to terrestrial cellular communications systems.

Next generation satellites are equipped with directional antennae with multiple spot-beams. Thus, the footprint of a satellite is covered by multiple cells, each of which is served by a spot-beam. LEO/MEO satellites have steered antennae so that as the satellites move along their orbit, the area illuminated by their spot-beams remain fixed with respect to Earth coordinates. For example, the Teledesic proposal describes such a system. Thus, both GEO and LEO/MEO satellites cover the Earth with multiple stationary cells. From the perspective of our model, the only difference between the two is the size of the cells. As the aircraft (or user of any sort) traverses different cells, it is handed-over to different spot-beams or satellites. In this work we assume that hand-over issues such as call-blocking and call-dropping are solved by employing similar hand-over strategies developed for terrestrial cellular networks. The focus of our work is on determining the bandwidth requirements for the down-link to aircraft for successful on-time delivery of weather information.

1.2 Communications Model

We model the ROI as a square with the aircraft at the center of this square. Thus, the aircraft is interested in the region ahead of it as well as the region it has passed. During take-off and final approach, the aircraft generally will be interested in the on-going events (in this case weather information) in all directions, since the air traffic density in these regions is high, which may cause the aircraft to make frequent maneuvers to approach/leave the airport. However, during the en-route portion of a flight an aircraft is likely to be principally interested in a very large area ahead of it and a relative small portion of the area that it has already passed. Thus, this assumption represents a somewhat coarser approximation in the en-route case.

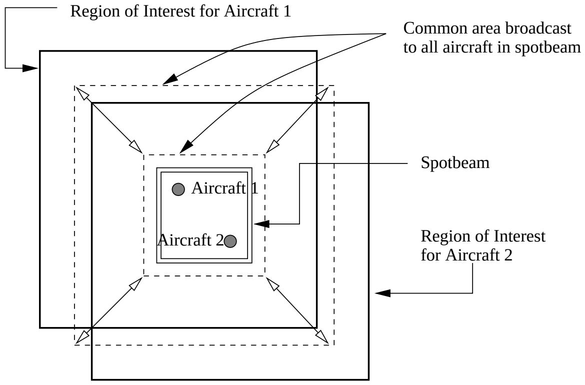


Figure 1: Region of Interest of different aircraft in a spot-beam.

We consider LEO and GEO satellites and compare the bandwidth requirement of the two. The LEO satellite spot-beam is also modeled as a square with an area of 2500 km^2, while the GEO satellite spot-beam has an area 40000 km^2. The size of ROI for tactical, near-term strategic and far-term strategic weather applications are 47000 km^2, 424000 km^2 and 2700000 km^2 respectively. Thus, spot-beam sizes are usually much smaller than ROI. We consider the aircraft traffic to be uniformly distributed in a spot-beam. For those aircraft in the same spot-beam, there is substantial overlap for ROIs that can be exploited for efficient delivery of information.

Each aircraft has two active channels: broadcast and uni-cast. In the hybrid communications case, which is the subject of our optimization model, any aircraft-specific communications would be carried over the uni-cast channel, while the communications of interest to multiple aircraft would be sent using a combination of the broadcast and uni-cast channels. Every aircraft in the same spot-beam tunes in to the same broadcast channel. A large portion of information that is common to all ROI of the aircraft in the spot-beam is delivered on this channel. However, the uni-cast channel of each aircraft is specific to that aircraft; it is used to transmit the information for the portion of the ROI not transmitted over the broadcast channel. Our objective is to determine the optimal size of the area that needs to be broadcast over the broadcast channel for optimal bandwidth and processing efficiency.

We consider two factors in determining the optimal broadcast area (BA) per each spot-beam: Bandwidth and processing costs. The bandwidth cost is the total amount of information transferred to the aircraft per unit time. This is the usual metric that considers the bandwidth of the pipe from the satellite. The processing cost is the amount of processing that has to be performed to convert the received information into a format that is suitable to be displayed on a cockpit monitor. In our work, we assume that the weather information is transmitted from a central processor to the aircraft in a format that is ready to be displayed. The processing cost must be incurred because the amount of information transmitted is greater than the amount needed by the aircraft (i.e. a portion of weather map is out of the scope of ROI); the excess information must be filtered out by the aircraft. Since we are dealing with future applications, one can only speculate as to the cost of this processing relative to the bandwidth cost. One could argue that processing power has become very cheap, however, history indicates that on-board processing power is limited, and the priority should always be given to more time-sensitive processes. Consequently, some cost must be associated with the extra amount of information delivered to the aircraft.

In our analysis we determine the average total cost of bandwidth and processing in a spot-beam for a given traffic density. We consider a certain area to be transmitted over the broadcast channel to all aircraft in the spot-beam. This broadcast area (BA) is a square with its center coinciding with the center of the spot-beam (Figure 1). As the BA increases, the amount of information transferred over the uni-cast channel decreases. However, beyond a certain BA size, the processing cost starts increasing, since unnecessary information has to be filtered out by each aircraft. Thus, there is an optimal BA size that minimizes the sum of bandwidth and processing costs. We assume that the bandwidth and the processing costs are directly related to the size of the area that is broadcast, where the bandwidth per unit area is derived from the analysis given later in this report. We consider that each aircraft can be at any location in the spot-beam at a given time, so we determine the total bandwidth and processing cost of an aircraft with respect to its location. The bandwidth cost of each aircraft is the bandwidth of its uni-cast channel. Then, since the aircraft are uniformly distributed over the spot-beam, we average these quantities. This gives us the average total bandwidth and processing requirement per aircraft in a spot-beam. We then multiple this quantity by the number of aircraft in the spot-beam at any given time and add the total bandwidth cost of the broadcast channel to determine the average total bandwidth and processing costs in the spot-beam.

1.3 Bandwidth and Processing Cost Analysis

Figure 2 depicts the set-up for our analysis. Consider a single spot-beam. Let the origin be placed at the lower left corner of this spot-beam. The length of a side of the spot-beam is 2 units. The length of a side of the BA is $2d$, while the length of a side of the ROI is $2K$. In Figure 2, $A1$ and $A2$ corresponds to the locations of two aircraft in the spot-beam. The ROIs for A1 and A2 are also shown in the figure. Let C_p and C_b denote the cost of processing and cost of bandwidth for unit area of weather information. Clearly, the average bandwidth cost of broadcast channel is $C_b(2d)^2$. From Figure 2 it is easy to observe that for $K \geq d+1$, the complete area that is broadcast is required by all aircraft in the spot-beam. Thus, for $K \geq d+1$ the processing cost $p(x,y)$ for any aircraft at location (x,y) is zero. The additional bandwidth (over the uni-cast channel) $u(x,y)$ that is required by an aircraft at location (x,y) is $u(x,y) = C_b((2K)^2 - (2d)^2)$. The average additional bandwidth cost is $\overline{u}(d) = C_b((2K)^2 - (2d)^2)$.

On the other extreme if $K < d-1$, then $u(x,y) = 0$, and the processing cost $p(x,y) = C_p((2d)^2 - (2K)^2)$.

For $d \leq K < d+1$, there is both bandwidth and processing cost for each aircraft. Notice that under the uniform distribution assumption, it is sufficient to focus on a single quadrant in the spot-beam. We can calculate the total requirements for the spot-beam from symmetry. Thus, we consider the aircraft to be located in the region $0 \leq x < 1$ and $0 \leq y < 1$. For the calculation of bandwidth and processing costs of an aircraft located at (x,y), we can identify three different cases

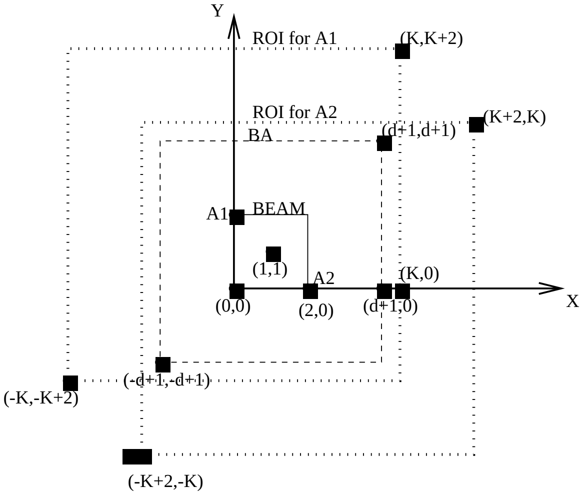
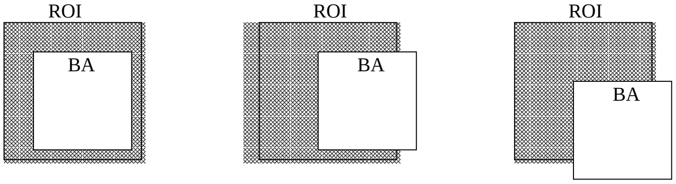


Figure 2: Set-up for the analysis.



(1) (2) (3)

Figure 3: Three possible cases for the overlap of ROI and BA when $d \leq K < d+1$.

which correspond to three cases shown in Figure 3:

1. $(K+x \geq d+1, K+y \geq d+1)$:

   For this case, as illustrated in Figure 3, the ROI completely covers the BA. This is exactly the same situation as for the case $K \geq d+1$. $u_1(x,y) = C_b((2K)^2 - (2d)^2)$, while $p(x,y) = 0$.

2. $(K+x < d+1, K+y \geq d+1)$ OR $(K+x \geq d+1, K+y < d+1)$:

   The shaded area in Figure 3 corresponds to the area that needs to be transferred over the uni-cast channel, i.e. the source of the additional bandwidth cost. This area is given by $(2K)^2 - 2d(K+x+d-1)$. The additional bandwidth cost for aircraft at location (x,y) is $u_2(x,y) = C_b((2K)^2 - 2d(K+x+d-1))$. Right now, we focus on the calculation of the additional bandwidth costs. In the end we will show that processing costs can be derived from the bandwidth costs by symmetry.

3. $(K+x < d+1, K+y < d+1)$:

   The area of the corresponding shaded region in Figure 3 is $(2K)^2-(K+x+d-1)(K+y+d-1)$. The additional bandwidth cost for aircraft at location (x,y) is $u_3(x,y) = C_b((2K)^2 - (K+x+d-1)(K+y+d-1))$.

The aircraft are uniformly distributed over the area of the spot-beam. The average bandwidth cost per aircraft, $\overline{u}(d)$, is calculated by averaging these quantities:

$$\begin{aligned}\overline{u}(d) &= (K-d)^2((2K)^2-(2d)^2)+2(d+1-K)(K-d)\int_0^{d+1-K}\int_{d+1-K}^{1} u_2(x,y)\,dy\,dx \\ &\quad +(d+1-K)^2\int_0^{d+1-K}\int_0^{d+1-K} u_3(x,y)\,dy\,dx\end{aligned}$$

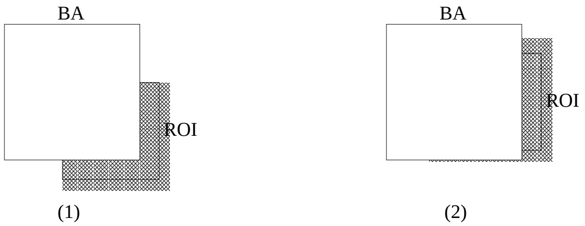


Figure 4: Two possible cases for the overlap of ROI and BA when $d-1 \le K < d$.

When $d-1 \le K < d$, for additional bandwidth cost we only need to consider the two cases depicted in Figure 4:

1. $(K+x < d+1, K+y < d+1)$:
   $u_1(x,y) = C_b((2K)^2-(K+x+d-1)(K+y+d-1))$.
2. $(-K+y > -d+1, -K+x \le -d+1)$ OR $(-K+y \le -d+1, -K+x > -d+1)$:
   $u_2(x,y) = C_b(2K(K-x-d+1))$.

For $K+x > d+1, K+y > d+1$, BA completely covers ROI, so there is no information transfered over the uni-cast channel. The average bandwidth cost per aircraft, $\overline{u}(d)$, is calculated by averaging these quantities:

$$\overline{u}(d) = (d+1-K)^2\int_0^{d+1-K}\int_0^{d+1-K} u_1(x,y)\,dy\,dx + 2(d+1-K)(K-d)\int_0^{d+1-K}\int_{d+1-K}^{1} u_2(x,y)\,dy\,dx$$

The processing cost can be determined from the bandwidth cost by symmetry. Notice that while the shaded area in Figure 3 corresponds to the bandwidth cost for the case $d \le K < d+1$, it also corresponds to the processing cost for the case $d-1 \le K < d$. Similarly, the shaded areas in Figure 4 correspond to the bandwidth cost for $d-1 \le K < d$, but also the processing cost of $d \le K < d+1$. Consequently, the average processing per aircraft can be given as $\overline{p}(d) = \frac{C_p}{C_b}\overline{u}(2K-d+2)$ for $d > K-1$. As we have mentioned before, $\overline{p}(d) = 0$ for $d \le K-1$.

1.4 Numerical Results

We calculate the unit bandwidth costs from the weather radar information. Table 1 summarizes these costs for Tactical, Near-Term Strategic and Far-Term Strategic types of weather applications.

For the numerical studies we assumed that complete weather map (tactical, near-term strategic or far-term strategic) is delivered to the aircraft completely, periodically and continuously. We do not consider differential information delivery solutions where only the data that has changed from the previous refresh period is delivered to the users. We also assume that the data transmitted is not compressed. The compression of data requires higher processing on-board aircraft.

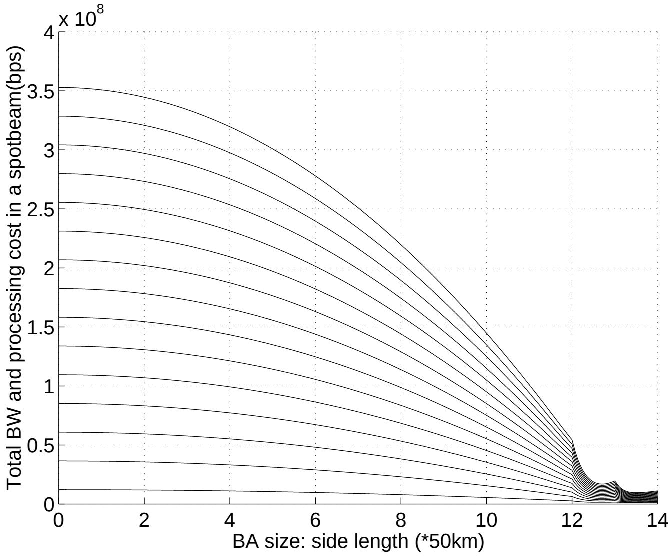


Figure 5: Total bandwidth and processing cost per spot-beam for Near-Term Strategic weather applications by LEO satellites vs. the size of the broadcast area for varying air traffic densities. Air traffic density changes between 0.5 and 15 aircraft per 100 km2.

Domain	**Region Size (km^2)**	**Bandwidth per km^2 (bps)**
Tactical	$4.71 \cdot 10^4$	13.58
Near Strategic	$4.24 \cdot 10^5$	2.31
Far Strategic	$2.7 \cdot 10^6$	0.02

Table 1: Unit Bandwidth costs.

Typically, the on-board processing resources are more easily available than the bandwidth resources. We assume that unit processing cost is ten times smaller than the unit bandwidth cost, and both of them is measured in terms of bits per second (bps).

Figure 5 depicts the results of this analysis for delivering Near-Term Strategic Weather information by using LEO satellites.The figure displays the variation of total cost versus the varying sizes of BA for different air traffic densities. The interesting result of this analysis is that the optimal BA size is less than the size of ROI by only a small fraction. For the analysis in Figure 2, the optimal diameter of BA is 25 km less than ROI. Furthermore, this optimal point is independent of the air traffic density. Although this result may seem counter-intuitive, it is reasonable due to following reasons. First, the ROI of each aircraft is much larger than the area of the spot-beam. In the worst case, where all aircraft are collected at the opposite corners of the spot-beam, the ROI of these aircraft still overlap considerably. Consequently, it is better to broadcast a large area. Second, we assumed that the aircraft are uniformly distributed over the geographical area corresponding to the spot-beam. Thus, even though there may be quite few (or quite large on the other extreme) aircraft in the spot-beam, since any aircraft may be located at any location in the spot-beam with equal probability, on the average the optimal broadcast area will be the same for both low and high traffic density.

Figure 6 depicts the optimal BA size for delivering Near-Term Strategic weather information by GEO satellites. Similar arguments discussed for the LEO case apply here as well.

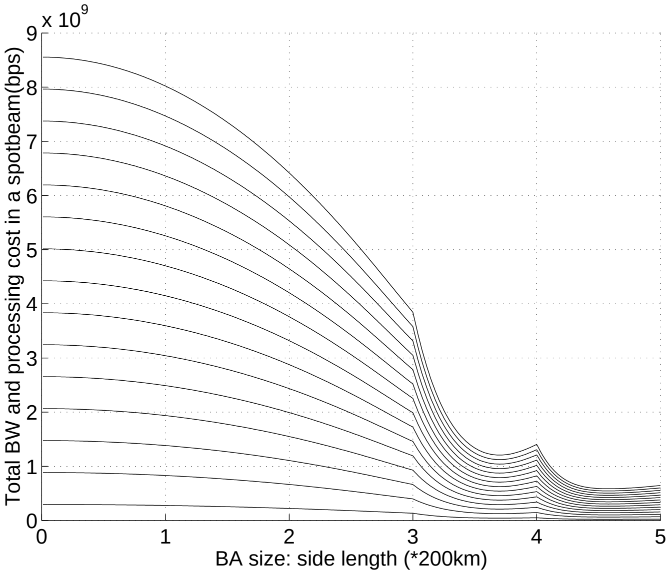


Figure 6: Total bandwidth and processing cost per for Near-Term Strategic weather applications by GEO satellites vs. the size of the broadcast area for varying air traffic densities. Air traffic density changes between 0.5 and 15 aircraft per 100 km2.

We also investigated the variation of the optimal BA size with respect to the processing cost. Figure 7 depicts the variation of total cost with respect to BA size for varying unit processing costs. We observe that as the processing cost increases the optimal BA size that minimizes the total cost decreases. Notice that when the unit processing cost is low, then the total cost mainly consists of bandwidth cost. It is clear that in order to minimize bandwidth cost, it is always better to broadcast as much as possible.

In Figure 8 we investigate the variation of optimal BA size with respect to the processing cost. It is interesting to observe that the optimal BA size decreases with a *jump* as the processing cost increases. This jump arises from the nonlinearity of the total cost function as depicted in Figure 7.

In Figure 9 we observe the variation of optimal bandwidth cost with respect to the processing cost. The bandwidth cost increases as the unit processing cost increases. The optimal bandwidth cost also increases with a jump like the optimal BA size. This result is not as surprising as it first seems. Notice that our optimization objective is the minimization of total bandwidth and processing costs. As the processing cost is varied, the total cost changes continuously, but one of its components namely the bandwidth cost may not.

In the following analysis the unit processing cost is set to one tenth of the unit bandwidth cost. In Figures 10 and 11 we compare the bandwidth requirements for each type of weather information with LEO and GEO satellites with respect to varying air traffic densities. For each curve we consider that optimally sized BA is broadcast at the broadcast channel. Thus, the bandwidth requirement for each curve is the minimum for that type of application. In Figure 11 we focus on the variation of bandwidth requirements for far-term strategic weather applications served by LEO and GEO satellites.

We can observe that the derivative of total bandwidth requirement for LEO case is smaller than the GEO case. Notice that LEO satellites have smaller spot-beams. The ROI of each aircraft in a LEO spot-beam substantially overlap. The broadcast channel of a LEO satellite can deliver this

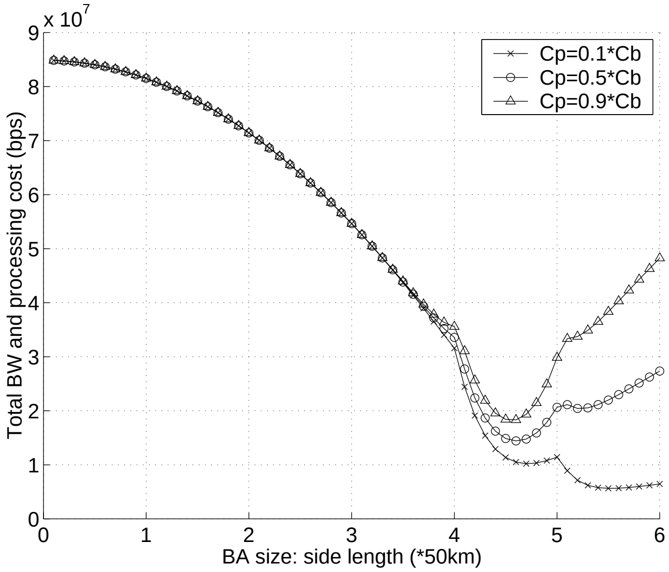


Figure 7: Total Bandwidth and processing cost compared for varying processing cost for Tactical weather application via LEO satellites. Air traffic density is 4 aircraft per 100 square km area.

large portion of overlapped region for a more customized view. Consequently, each aircraft requires less information to be transferred over the uni-cast channel. Since less information is transferred over the uni-cast channel, the total bandwidth requirement does not increase as fast as the GEO case as the air traffic density increases. However, in order to cover the same area as a GEO satellite spot-beams we require multiple LEO spot-beams. Each LEO spot-beam has a broadcast channel which delivers the information that is little different compared to the broadcast channels of the adjacent LEO spot-beams. Thus, in order to deliver comparable service to a same sized area LEO satellite solution consumes larger bandwidth over the broadcast channels compared to the GEO case. This leads to higher bandwidth requirements for LEO solution compared to the GEO case when the air traffic density is low .

In Figure 10 we observe that when the air traffic density is below 8 aircraft per 100 km^2 GEO satellites require less bandwidth for the delivery of Near-Strategic weather information. For Far-term Strategic applications, however; we notice that (Figure 11) the GEO solution is always better than the LEO solution.

In Figures 12, 13 and 14 we compare the bandwidth requirements of and broadcast-only solutions with the hybrid case. As depicted in these figures, uni-cast-only solution is the worst. In the broadcast-only solution the country is still divided into cells, however; in each cell there is single channel which broadcasts the required information for all aircraft. The broadcast-only solution appears to be the better than the hybrid LEO case when the air traffic density is very low, since for the broadcast-only case we assumed larger cell sizes. For low air traffic density, the hybrid GEO solution appears to be the best. The hybrid GEO combines the best of two counterparts: broadcast and uni-cast. GEO satellites have larger spot-beams which leads to efficient use of broadcast channel, and they have additional uni-cast channel for delivering unique information for each aircraft. However as the air traffic density is higher we observe that hybrid LEO solution is better than the hybrid GEO solution. LEO satellites due to their smaller spot-beams can deliver more customized view for each aircraft over the broadcast channel. Thus, each aircraft require less

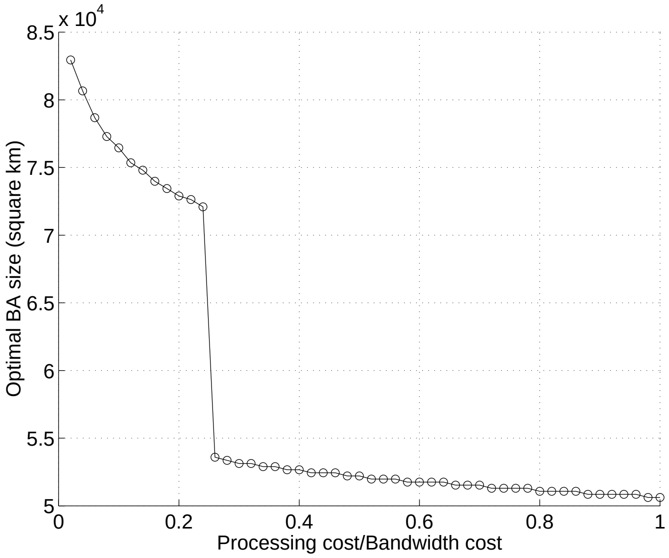


Figure 8: Optimal BA size for varying processing cost for Tactical weather application with LEO satellites. Air traffic density is 4 aircraft per 100 square km area.

information to be transferred over the uni-cast channel. However, broadcast-only solution is the best solution for high air traffic densities. Notice that our optimal BA size is very close to the convex hull of the ROIs of the all aircraft in the spot-beam. In the broadcast-only solution we broadcast this convex hull of all ROIs, so as the aircraft density is higher the total cost of uni-cast channels becomes larger than sending the additional area of the convex hull over the broadcast channel.

1.5 Discussions and Remarks on the System

We can arrive at a few conclusions from this theoretical analysis. Our first conclusion is that the optimal area that leads to minimum total bandwidth and processing costs is relatively independent from the air traffic density. This result enables a single static solution that can be applied throughout the country. Although the optimal broadcast area does not change with respect to the air traffic density, for low air traffic densities hybrid-GEO solution can provide better bandwidth efficiency. And when the air traffic density is high broadcast-only solution appears to be the best considering the bandwidth efficiency. For TRACONs and the region close to the airports the broadcast of weather information can provide lower bandwidth requirements. However, for the en-route aircraft that is interested in Far-Strategic weather information using hybrid-GEO solution can provide better bandwidth utilization.

We also demonstrated that future weather applications would require high bandwidth communication links. This also supports the use of next generation satellite systems as an alternative to the current terrestrial systems. Table 2 summarizes the bandwidth requirements for different weather applications under different delivery options.

An issue that arises in a broadcast cellular system with mobile nodes is the timing of the broadcast information in the adjacent cells. Like any other broadcast information delivery systems, the information is broadcast according to a schedule. Assume for the sake of discussion, same

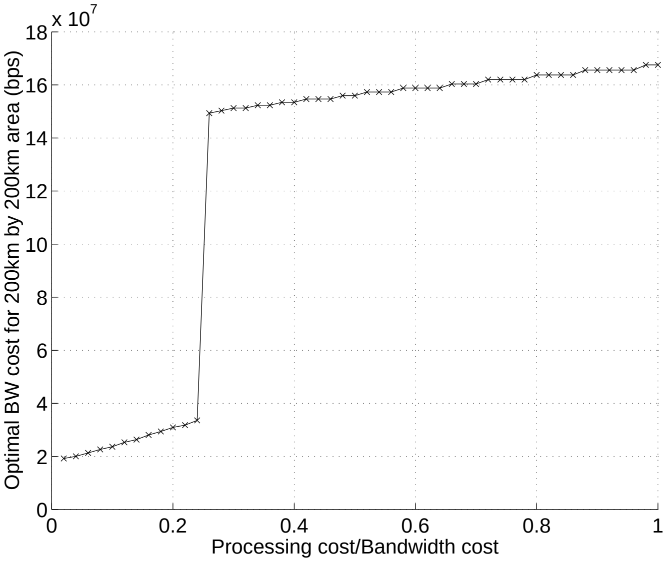


Figure 9: Optimal total Bandwidth cost per 200km by 200km area for Tactical weather application with LEO satellites. Air traffic density is 4 aircraft per 100 square km area.

information is broadcast in two adjacent cells. A mobile user traversing different cells may encounter a different portion of the schedule in the new cell it entered than the portion of the schedule in the cell it left, if the schedules are not perfectly synchronized. In the worst case, the mobile user may have to wait for the whole duration of the broadcast schedule to receive the part of information that it requires. In our case, the information that is broadcast, is not exactly the same though a large portion is common in all adjacent cells. For this reason, synchronizing the schedules is not possible. To ensure all information in the ROI of the aircraft is updated according to refresh rate, we may increase the broadcast transmission rate, and the aircraft may request certain information that is *late* according to the schedule via the uni-cast channel. This type of information request for the unarrived data will be only once every time an aircraft changes spot-beams. Thus, the effect of this transient behavior will be low on the uni-cast channel bandwidth requirements.

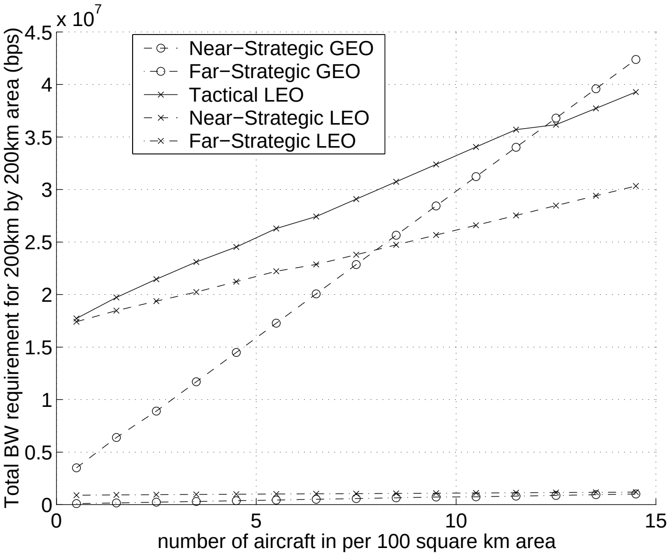


Figure 10: Total bandwidth requirements for different weather applications when served by LEO and GEO satellites for varying air traffic densities.

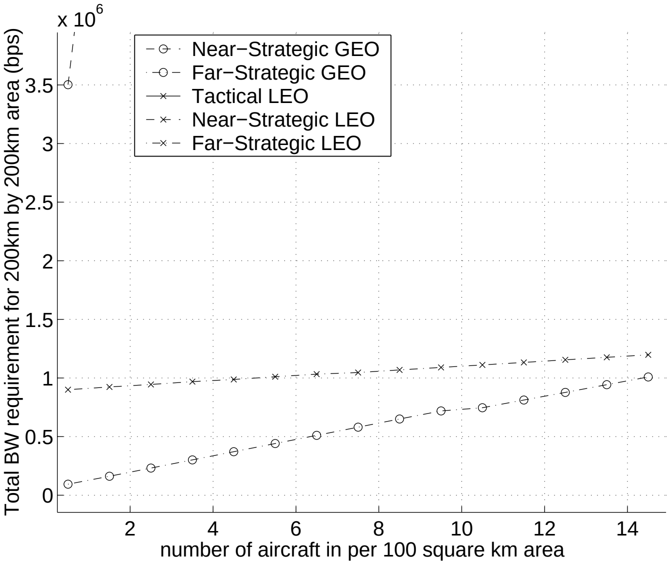


Figure 11: Total bandwidth requirements for different weather applications when served by LEO and GEO satellites for varying air traffic densities.

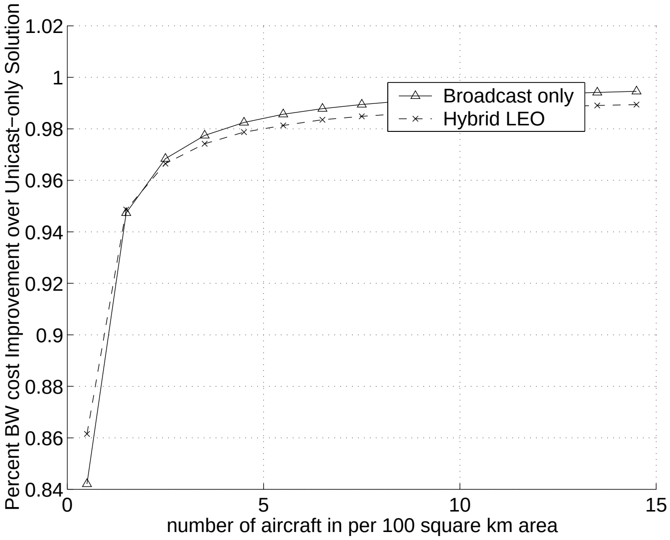


Figure 12: Total bandwidth requirements for Tactical Weather Application under different delivery options. Total bandwidth requirement for broadcast-only solution is 20.214 Mbps.

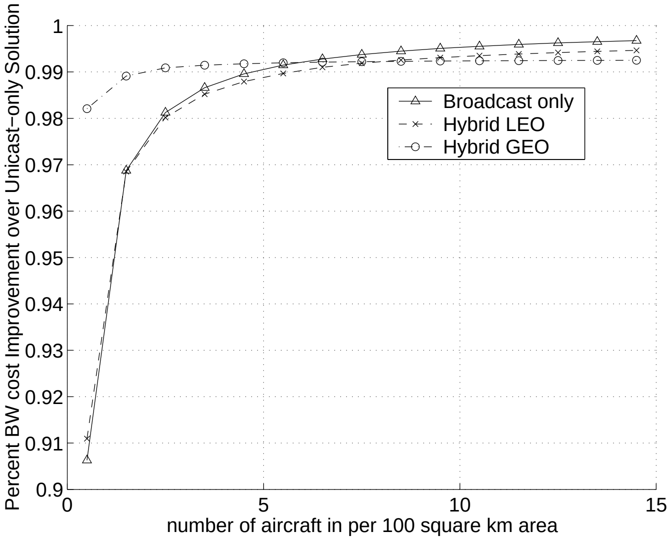


Figure 13: Total bandwidth requirements for Near-Term Strategic Weather Application under different delivery options.

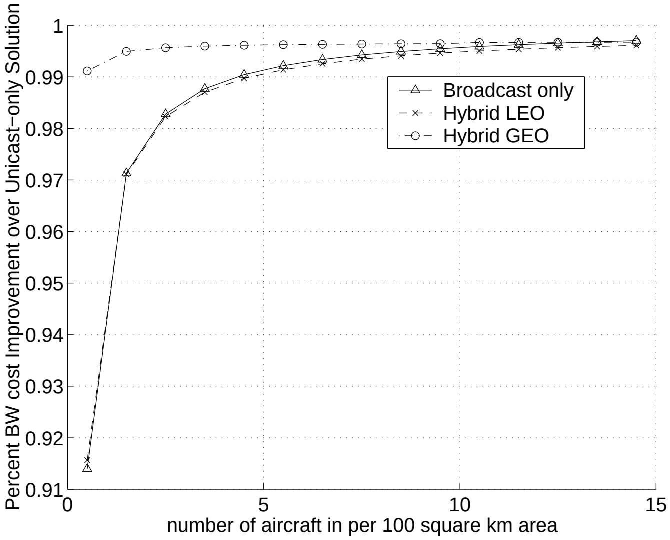


Figure 14: Total bandwidth requirements for Far-Term Strategic Weather Application under different delivery options.

	Tactical	**Near-Strategic**	**Far-Strategic**
Unicast BW requirement per aircraft	640 kbps	977 kbps	53 kbps
Unicast BW requirement per aircraft with differential transmission (30% updated)	192 kbps	293.1 kbps	15.9 kbps
Unicast BW requirement per aircraft when aircraft acts as a sensor with differential transmission	577 kbps	1.42 Mbps	49.63 kbps
Percent reduction in BW requirement by broadcast GEO at nominal air-traffic density	0.86	0.905	0.91
Percent reduction in BW requirement by hybrid GEO at nominal air-traffic density		0.98	0.99
Percent reduction in BW requirement by hybrid LEO at nominal air-traffic density	0.88	0.91	0.91

Table 2: A Summary of Bandwidth Requirements under Different Approaches at nominal air traffic densities.

2 Modeling NAS Operations

This section describes the methodology employed to derive realistic aircraft traffic flows in the horizon year of our analysis (the year 2020). The section starts with a brief description of the existing concept of operations in the National Airspace System (NAS). Then it expands to the concept of operation expected to be in place in the year 2020. The section ends with the mathematical description of a Lumped Air Traffic Flow Model (LATFM) used to derive various aeronautical communication services associated with multiple airborne platforms sharing a large region of airspace over time.

Modeling operations in the future National Airspace System (NAS) is a difficult proposition. This is specially true when the analysis is expected to derive results two decades into the future. Generally speaking, the Federal Aviation Administration (FAA) performs forecasts ten and fifteen years into the future (FAA, 2000). For this project, we relied on a combination of FAA statistics and forecasts (up to the year 2010 typically), and simple forecast models derived from historical data considering possible capacity constraints in the system.

2.1 Scenario Development

The current state of NAS is a complex combination of airports, airspace, airlines and assets, corporate and general aviation users and air traffic control facilities and personnel. The communication between these entities plays an important role in the operational capabilities of NAS and without doubt, contributes in some measure to the capacity of the system. Figure 15 illustrates some of the current communication links used in NAS. These include services stated in Table 3 encompassing three categories of service: surveillance, navigation, and communication services.

The functional requirements for a future NAS system are derived here under the premise that users would want to exploit some of the advanced communication capabilities of a moderately developed Airborne Transportation Network (ATN). Deriving functional requirements two decades ahead of time is a difficult proposition. Nevertheless, some assumptions are needed to derive feasible operational scenarios in the future NAS. The scenarios presented here represent a more aggressive plan than that planned under NAS plan 4.0. An attempt is made here to prototype scenarios that would enhance the safety and efficiency of operations.

While developing a suitable end-state scenario with future communication applications it is relevant to understand a proposed classification of services to be provided in the future NAS. In our opinion, communication channels can be effectively used in the following areas:

¥ Air traffic management
  - Strategic traffic flow management
  - Tactical (air traffic control)
¥ Aircraft status information
¥ Commercial services and cockpit applications
  - Weather services to the cockpit
  - Internet access
¥ Aircraft as weather sensor
¥ Airport and terminal area status

¥ Airline operating center related information

¥ General NAS status

More details about these applications will be provided in the following sections of the report.

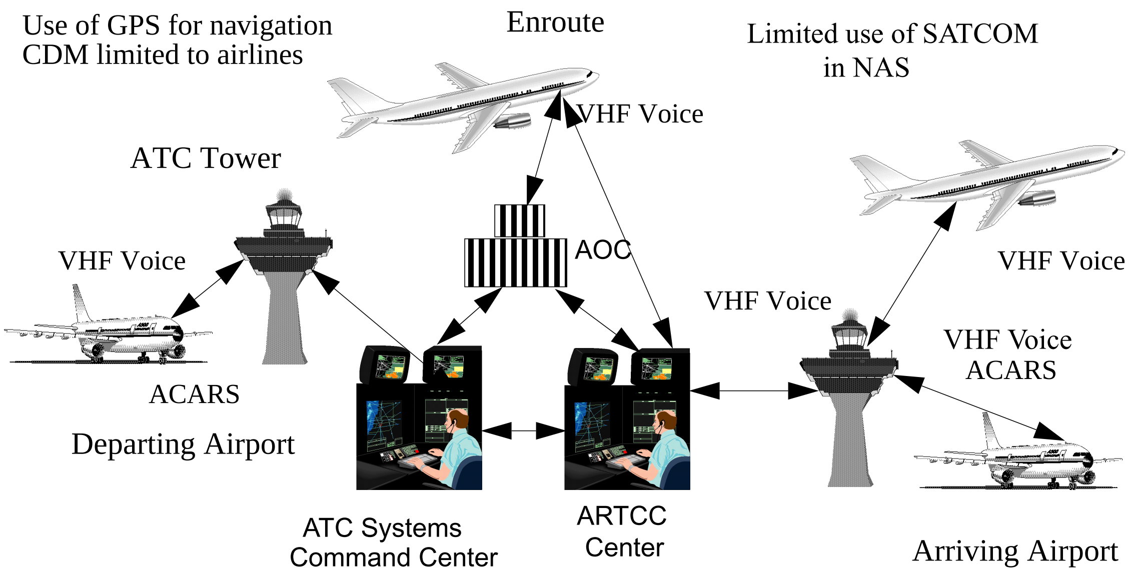


Figure 15: Current operational concept in NAS.

Service	System	Remarks
Surveillance	Long range radar	Primary surveillance mechanism
	Mode C and S	Secondary radar
	Automated Dependent Surveillance (ADS-B)	Oceanic surveillance function Limited use in continental NAS
Navigation	VORTAC and DME	Enroute navigation
	ILS and MLS	Precision approach NAV tool
	GPS	Enroute and non-precision approaches
Communication	ACARS	Clearance delivery
	VHF Voice	Primary ATC-Pilot Communication channel
	Dedicated Datalinks	Limited use (weather information such as Arnav system)

Table 3: Current communication services offered in NAS.

2.2 Concept of Operations in NAS 2020

This scenario presents a more mature ATC and ATM system beyond of the NAS Plan 4.0 deployment. Figure 16 illustrates the possible evolution of the NAS system showing a substantial use of satellite technology for communication, navigation and surveillance tasks. The 2020 scenario represents a new era in ATC and ATM services. The control and responsibility of aircraft separation services is a decentralized service managed by aircraft (in the air or on the ground) and ATC controllers (on the ground). Various forms of on-board automation exist to provide pilots with enhanced situational awareness of neighboring traffic included new versions of Cockpit Traffic Information Displays (CTID) that fuse information from advanced versions of the Automated Dependence Surveillance (ADS-B) and Traffic Collision Advisory System (TCAS). Coordination of aircraft separation is a highly decentralized activity with ATC ground controllers making final conflict resolution decisions when on-board sensors and aircraft logic cannot coordinate acceptable resolution advisories for multiple vehicles. An array of cockpit services are commonplace providing pilots with advanced weather information services critical to the conduct of flight operations in a single IFR environment.

The Wide Area Augmentation System (WAAS) has been deployed successfully and hundreds of airports have dedicated Local Area Augmentation Services (LAAS) in support of Category II and III precision approaches. Services provided by WAAS include safety-critical services such as enroute and precision approach navigation (equivalent to Category I today). Ground radar systems are only available for backup surveillance tasks. Mode C and S secondary radars play now (in 2020) a similar back-up role played by primary radar in the 1980s and 1990s. The primary surveillance function in NAS is provided using satellite-based systems in the Continental U.S.

Voice communications are only used for critical NAS communications. The role of the ATC personnel is to act as a broker and supervisor in a distributed ATC/ATM environment. ATC benefits from aircraft sensors and position information to control traffic flows in congested TRACON and enroute airspace. At the end of this period (circa 2020) it is possible to envision up to 75-80% of the ATC/ATM message exchange actions be given over a dedicated datalink environment.

In the derivation of communication requirements for each one of the three applications presented in this report required some fundamental assumptions regarding the technology available in the year 2020. Some of these assumptions are:

- The growth rate of the aircraft fleet and aircraft operations in NAS follows the FAA predicted pattern until the year 2010. A 1.75% growth in aircraft operations per year is assumed thereafter.
- The equipage rate of aircraft having onboard weather sensors is assumed to be 100%.
- The equipage rate of aircraft having advanced weather displays is 100% across all four classes of aircraft discussed in the report.
- The number of aircraft having access to traffic information services is also assumed to be 100%.

These assumptions are based on the premise that in a steady-state scenario all aircraft flying in NAS will require some form of weather information in the cockpit, act as a weather sensor, and require traffic information services in order to conduct safe operations across NAS. The authors believe that this worst-case scenario assumptions should provide a best example of the cumulative effect of large numbers of airborne platforms requesting various services.

2.3 NAS Traffic Flows in 2020

The growth in NAS over the period 2000-2020 is expected to grow at a rate of 4-5% per year. NAS capacity limitations will play an important role at ultimately dictating how the demand function for air transport services will grow over time. The FAA has made estimates of demand growth until 2012 that can be then extrapolated to predict demand flows in 2020 (FAA, 1999). Table 4 illustrates some of the predicted demand flows for the complete NAS per year.

The statistics shown in Table 4 illustrate the high utilization of air carrier aircraft (around 2,400 hours per year) versus only 144 hours per year for the average General Aviation (GA) aircraft. Using simple estimates of the traffic growth patterns expected in NAS into the next two decades one might conclude that up to **1450 operations per hour** (includes air carrier, corporate jets and GA users) could fly over some of the most congested airspace in the country (for example over Indianapolis and New York ARTCC Centers). These numbers need to be adjusted by dwell times inside the area of interest in order to estimate the number of aircraft soliciting communication services. This analysis is explained in the following section.

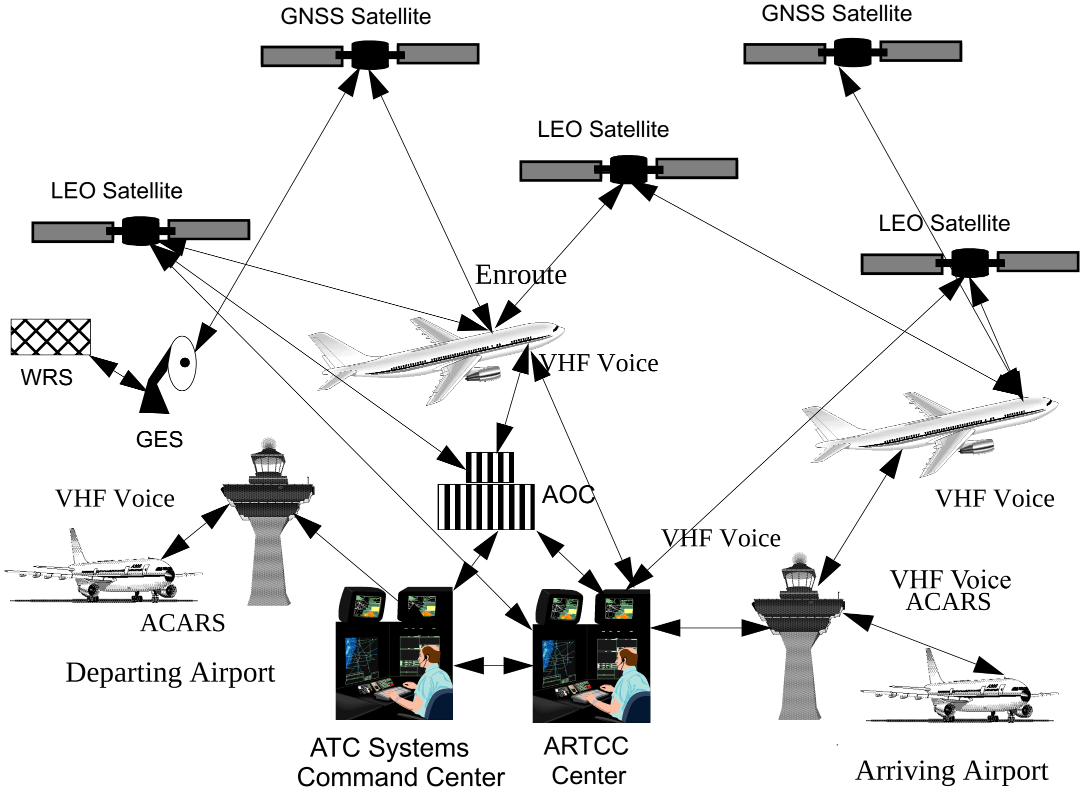


Figure 16: Conceptualization of future NAS air traffic services (circa 2020).

Measure	Current (1998)	2010	2020	Remarks
Number of Operations (per year)	65,300,000	81,200,000	97,360,000	1) Based on FAA Forecasts until 2010 2) 1.75% growth factor after 2010
Enplanements (per year)	643,000,000	991,000,000	1,232,000,000	1) Based on FAA Forecasts until 2010 2) 3% growth factor after 2010
Number of Air Carrier Aircraft in US (jets only)	5,850	8,284	10,200	Our estimates
Number of GA Aircraft	206,500	242,500	277,500	Our estimates
Hours Flown by Air Carriers	13,600,000	21,292,160	26,615,200	Our estimates
Hours Flown by GA Aircraft	29,800,000	38,494,673	44,050,605	Our estimates

Table 4: Current and projected air traffic operations in NAS.

2.4 Lumped Air Traffic Flow Model

In order to quantify aircraft traffic flows over large regions of airspace we developed a Lumped Air Traffic Flow Model (LATFM). This model is based on the principles of Systems Dynamics (SD) and continuous simulation modeling to model aggregate traffic flows. LATFM uses the premise that aircraft inside a region of airspace (say an Air Route Traffic Control Center - ARTCC) can be in any one of eight possible states (3 enroute, 2 terminal area, and 3 airport states described in the sequel). These states represent different phases of flight or idle conditions on the ground and each one have specific communication requirements. Each state dwell time has been derived from actual flow analyses using FAA Enhanced Traffic Management System (ETMS) data (FAA 1998). The data used in our analysis is representative of traffic flows inside the Indianapolis ARTCC for the sake of discussion. However, the model can be tailored to represent any region of airspace desired with minor modifications to some model parameters. So far the model development of this prototype model has been carried out using STELLA II - a Systems Dynamics software package developed by High Performance Systems of Nashua, New Hampshire. The model equations are presented in Appendix A of this report.

The structure of the model is illustrated in Figure 17. Model inputs are the demand functions defining aircraft movements inside the region of interest. The model tracks the aggregate number of aircraft over time (Traffic Flow Module) and computes communication data size requirements for various aeronautical services such as weather products in the cockpit (Aviation Weather Module), aircraft as weather sensor (Aircraft as Weather Sensor Module), and flight information services (Flight Information Services Module).

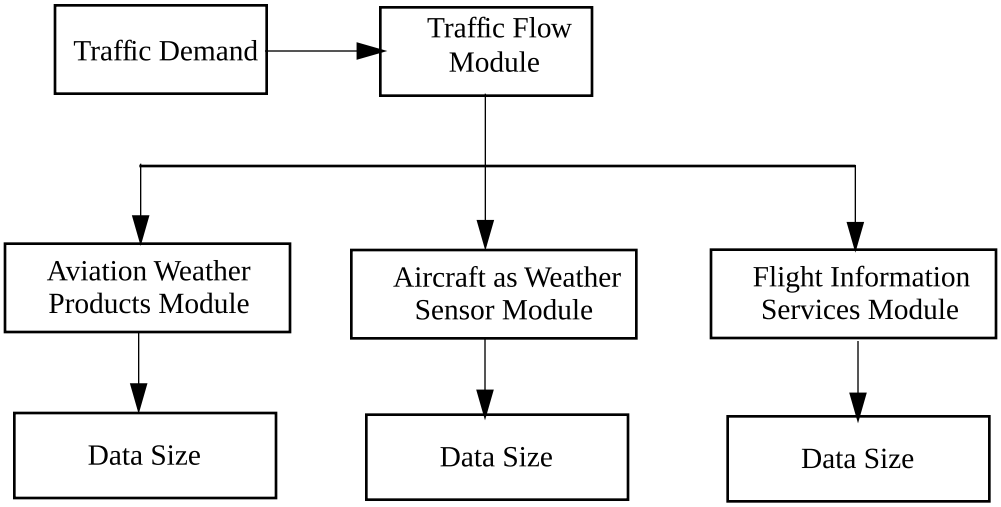


Figure 17: Organization of the Lumped Air Traffic Flow Model (LATFM).

It is important to recognize that when modeling communication service requirements in NAS one can adopt two distinct points of view: 1) an aircraft centered view point to understand the communication services required by an individual flight and 2) an air traffic control and management centered perspective to view systematically multiple flights traversing regions of airspace and requiring communication services. Both of these view points are useful in our analysis since the derivation of communication requirements across NAS requires an understanding of both operations densities across NAS (obtained using the air traffic control and management centric approach) and individual services provided to the cockpit (derived from an aircraft centered view point). The relationship between these different viewpoints is illustrated in Table 5. Here we contrast the sizes of traditional air traffic service areas (i.e., Air Route Air Traffic Control Center, Terminal Approach Control Areas, and Airport Control Zone) with the aircraft centered view point regions of interest (i.e., far-strategic, near-strategic, and tactical regions).

	Name of the Region	Typical Shape and Size (for modeling purposes)	Typical Area (km^2) (for modeling purposes)
ATC-Centered Regions	**Enroute Air Traffic Control Center**	Rectangle w = 600 km, h = 280 km	168,000
	Terminal Approach Control Area	Circular R=110 km	38,000
	Airport Control Zone	Circular R=10 km	314
Aircraft-Centered Regions	**Far-strategic Region**	Rectangle variable dimensions	up to 2,700,000 in CONUS
	Near-strategic Region	Trapezoidal wedge w=600 km, h1=300,h2=900 km	424,000
	Tactical Region	Conical wedge	47,100

Table 5: Definition of various regions of analysis.

LATFM Model Equations

A causal diagram depicting the possible transitions of flights inside the ARTCC center is shown in Figure 18. The diagram distinguishes between information flows (dashed arrows) and accumulation flows (solid arrows) to showcase eight aircraft states (boldfaced names) inside the volume of airspace of interest. Causal diagrams are standard techniques used in Systems Dynamics modeling (Trani, 1988). The polarity of the causal relationships shown in the diagram represent the general trend of the slope relating two immediate variables. For example, the Inbound Aircraft Demand Function (IADF) “causes” an increase in the Number of Aircraft Entering the Enroute Airspace (NAENO) and in the Number of Inbound Transient Aircraft in the Enroute Airspace (NITAER). The nomenclature used in this diagrams is explained in the following paragraphs as the equations of motion of the model are introduced.

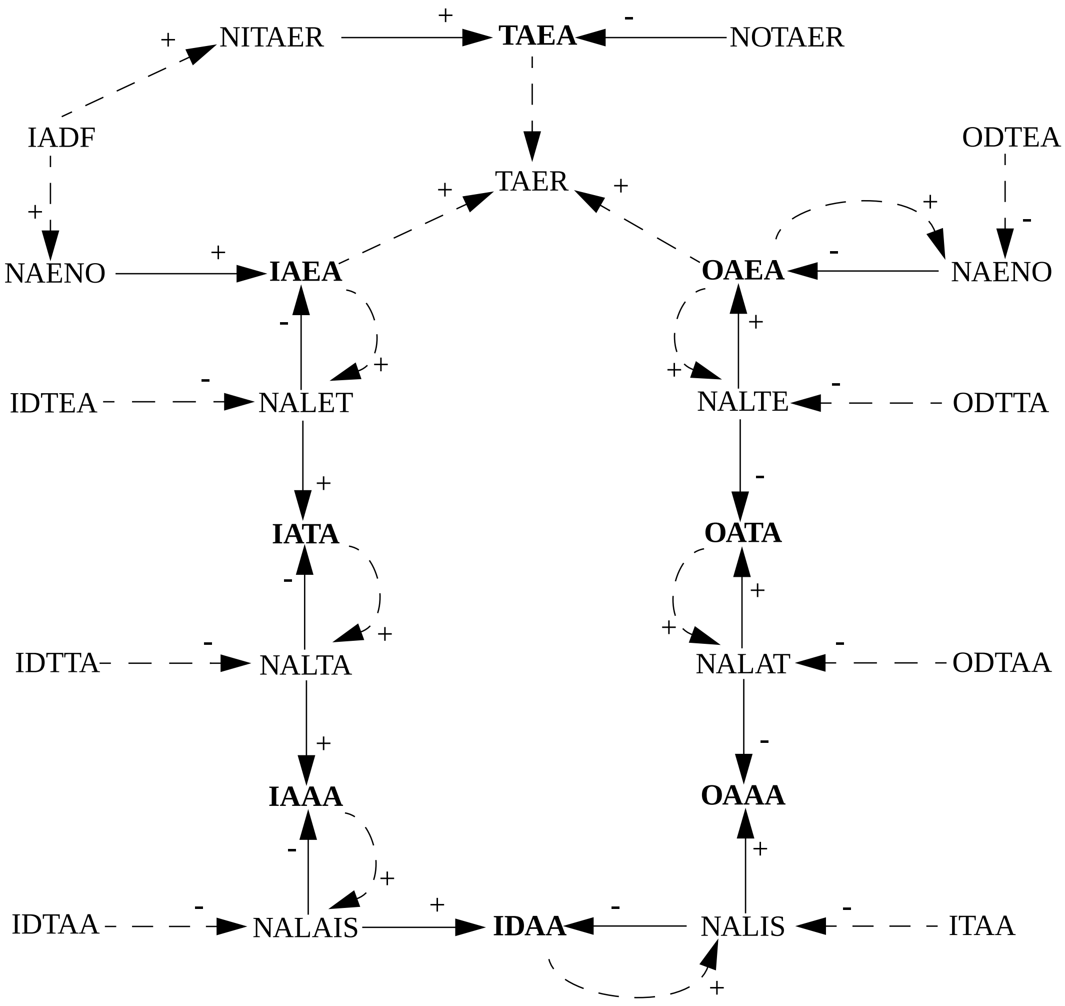


Figure 18: Causal diagram of aircraft states inside ARTCC region.

Using the causal diagram as a starting point we define eight rate equations, one for each aircraft state in the system.

$$\frac{d}{dt}(TAEA_t) = NITAER_t - NOTAER_t \tag{1}$$

$$\frac{d}{dt}(IAEA_t) = NAENO_t - NALET_t \tag{2}$$

$$\frac{d}{dt}(IATA_t) = NALET_t - NALTA_t \tag{3}$$

$$\frac{d}{dt}(IAAA_t) = NALTA_t - NALAIS_t \tag{4}$$

$$\frac{d}{dt}(IDAA_t) = NALAIS_t - NALIS_t \tag{5}$$

$$\frac{d}{dt}(OAAA_t) = NALIS_t - NALAT_t \tag{6}$$

$$\frac{d}{dt}(OATA_t) = NALAT_t - NALTE_t \tag{7}$$

$$\frac{d}{dt}(OAEA_t) = NALTE_t - NALEO_t \tag{8}$$

where the **state variables** are:

$TAEA_t$ is the Total Aircraft in the Enroute Airspace system (aircraft) at time t, $IAEA_t$ is the number of Inbound Aircraft (aircraft) in the Enroute Airspace system at time t, $IATA_t$ is number of Inbound Aircraft in the Terminal Areas (aircraft) at time t, $IAAA_t$ is the number of Inbound Aircraft in the Airport Areas (aircraft) at time t, $IDAA_t$ is the number of Idle Aircraft at Airports (aircraft) at time t, $OAAA_t$ is the number of Outbound Aircraft at Airport Areas (aircraft) at time t, $OATA_t$ is the number of Outbound Aircraft in Terminal Areas (aircraft) at time t, and $OAEA_t$ is the number of Outbound Aircraft in the Enroute Airspace (aircraft) at time t. These state variables are represented as a system of eight first-order differential equations (Equations 1-8) that are solved numerically using STELLA's built-in integration algorithms (see Appendix A for details of the model).

The **rate variables** of the system are defined as follows:

$NITAER_t$ is the Number of Inbound Transient Aircraft in the Enroute Airspace (aircraft/hour) at time t, $NOTAER_t$ is the Number of Outbound Transient Aircraft in the Enroute Airspace (aircraft/hour) system at time t, $NAENO_t$ is the Number of Aircraft Entering the Enroute Airspace (aircraft/hour) at time t, $NALET_t$ is the Number of Aircraft Leaving the Enroute airspace for Terminal Airspace (aircraft/hour) system at time t, $NALTA_t$ is the Number of Aircraft Leaving the Terminal airspace for Airport Areas (aircraft/hour) at time t, $NALAIS_t$ is the Number of Aircraft Leaving the Airport Areas for Idle State (aircraft/hour) at time t, $NALIS_t$ is the Number of outbound Aircraft Leaving the airport Idle State (aircraft/hour) at time t, $NALAT_t$ is the Number of outbound Aircraft Leaving the Airport Areas for Terminal Airspace (aircraft/hour) at time t, $NALTE_t$ is the Number of outbound Aircraft Leaving the Terminal areas for Enroute airspace (aircraft/hour) at time t, and $NALEO_t$ is the Number of outbound Aircraft Leaving the Enroute Airspace (aircraft/hour) system at time t.

The dwell times of aircraft in every one of the eight possible states are explicitly represented in the model. These key variables are: $IDTEA$ is the Inbound aircraft Dwell Time in the Enroute Airspace system (hours), $IDTTA$ is the Inbound aircraft Dwell Time in the Terminal Airspace system (hours), $IDTAA$ is the Inbound aircraft Dwell Time in the Airport Areas (hours), $ITAA$ is the Idle

Time at the Airport (hours), $ODTAA$ is the Outbound aircraft Dwell Time in Airport Areas (hours), $ODTTA$ is the Outbound aircraft Dwell Time in the Terminal Airspace areas (hours), and $ODTEA$ is the Outbound aircraft Dwell Time in the Enroute Airspace (hours).

In this first iteration of the model these dwell times are assumed to be constants and thus have not been subscripted as a function of time. However, with minor variations the model can represent dynamic dwell times to incorporate the effect of congestion in any one of the eight state of the system. Dwell times are typically extracted by close examination of the FAA Enhanced Air Traffic Management data base (FAA, 1998). For example, enroute air carrier overflights dwell 0.4 hours (on the average) over a busy ARTCC Center like Indianapolis if free flight routes are considered. Similarly, if an air carrier flight ends or originates inside the volume of airspace assigned to the ARTCC in question the expected value of the dwell time would increase to 0.52 hours accounting for times in the descent and climb profiles (whichever is applicable). General aviation flight dwell times are higher since the average speeds of these aircraft are 150 knots in cruise and 130 knots inside the terminal area. However, GA aircraft trip lengths are far shorter thus producing dwell times of 0.85 hours per ARTCC center on the average. Using these parameters Table 6 illustrates a typical load scenario for a single ARTCC with 8 terminal areas (1 large hub, 2 medium size hubs, 2 small size hubs, and 3 regional airports), 20 utility General Aviation airports and 100 public general aviation with small traffic loads inside the region of interest volume. Figure 19 illustrates two sample demand functions representing the aircraft movements per hour at a large hub and a regional airport. These demand functions can be obtained (for the baseline year) from the Consolidated Delay and Airport System database (CODAS) (FAA, 2000) and adjusted to represent year 2020 conditions.

The numbers reflect first-order approximations to be used in the load analysis of traffic and weather information services of a busy region within NAS in the design year (2020). These numbers do not incorporate any assumptions regarding the presence of Small Aircraft Transportation System (SATS) aircraft.

LATFM Model Interface

To simplify the interaction between a user and the model a simple Graphic User Interface (GUI) was developed for LATFM. GUIs are standard features in the modeling approach adopted in STELLA II (Richmond, 1999), the simulation language used to prototype LATFM. Figures 20 through 24 illustrate five screens available as interface elements in LATFM. These screens represent input-output graphic user interfaces for each one of the 4 computational analysis modules available in LATFM: 1) traffic flow, 2) aircraft weather services, 3) aircraft as weather sensor, and 4) flight information services. Figures 20 through 23 illustrate the computational module screens in LATFM. A fifth screen is included representing an introduction to the model (Figure 24).

2.5 Critical Air Traffic Densities

The critical air traffic density for a complex airspace that combines airport, terminal, and enroute services has been estimated at 0.0090 aircraft/km^2. This density would be consistent with the most demanding situation expected for a tactical region of analysis (aircraft-centered region). The densities of airport areas are much higher (at 0.1630 aircraft/km^2 because they involve aircraft moving on ground requesting COM services).Enroute densities are projected to be around 0.0055 aircraft/km^2 under the most demanding conditions. This situation would be analogous to the near-strategic region scenario.

FAA Service Area	Aircraft Type	Total Aircraft inside Region of Interest (Aircraft per hour)	Instantaneous Aircraft inside Region of Interest
Airport	General Aviation	231	35
	Corporate	32	5
	Commuter	140	28
	Transport-Type	245	61
	Total	**647**	**128**
Terminal Area	General Aviation	128	128
	Corporate	16	16
	Commuter	66	66
	Transport-Type	101	101
	Total	**311**	**311**
Enroute	General Aviation	516	438
	Corporate	71	32
	Commuter	312	156
	Transport-Type	547	219
	Total	**1446**	**845**

Table 6: Predicted peak aircraft traffic in region of interest (includes aircraft classes breakdown).

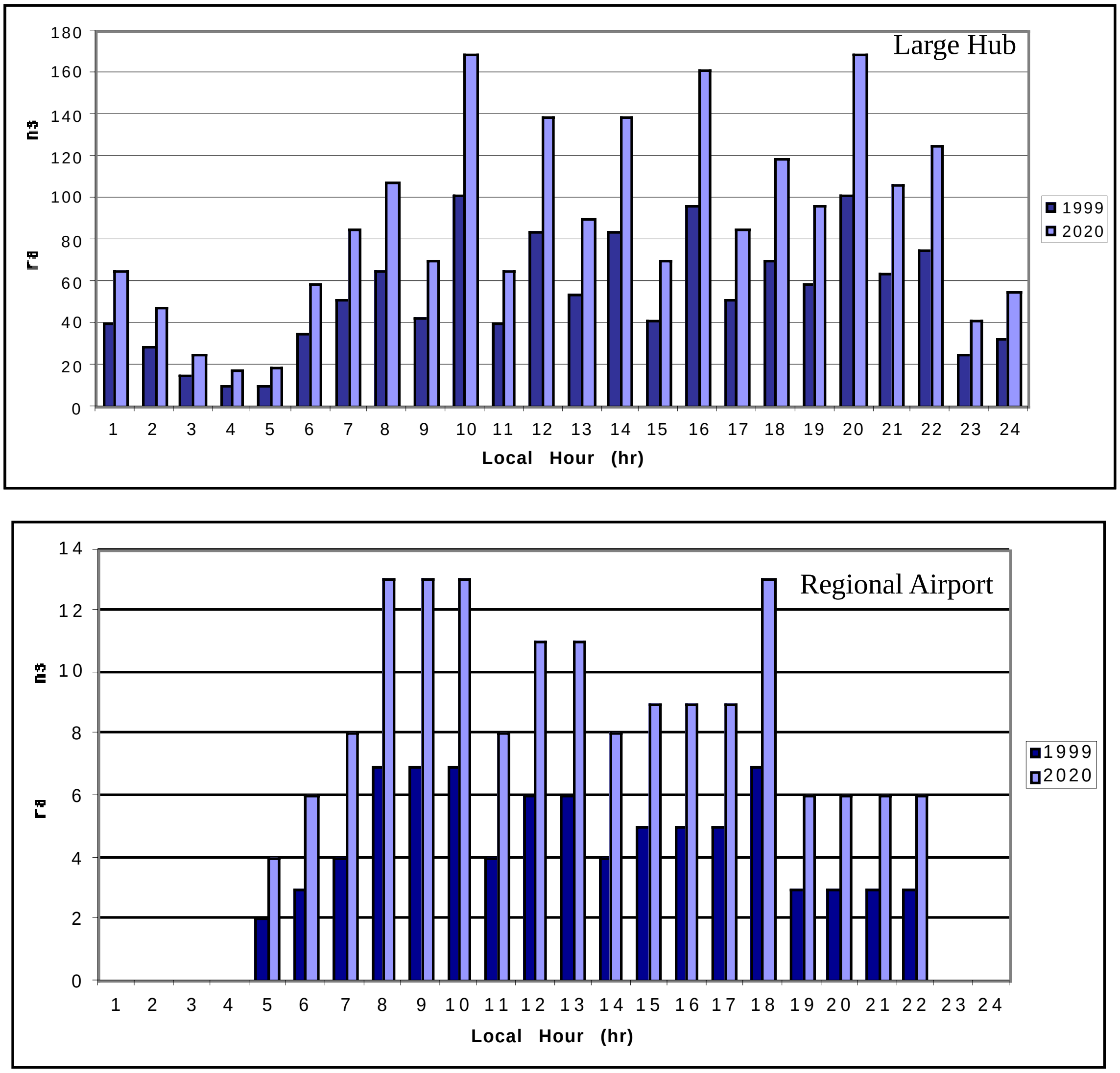


Figure 19: Sample data input to LATFM (Large Airport Hub and Regional Airport Demand Function).

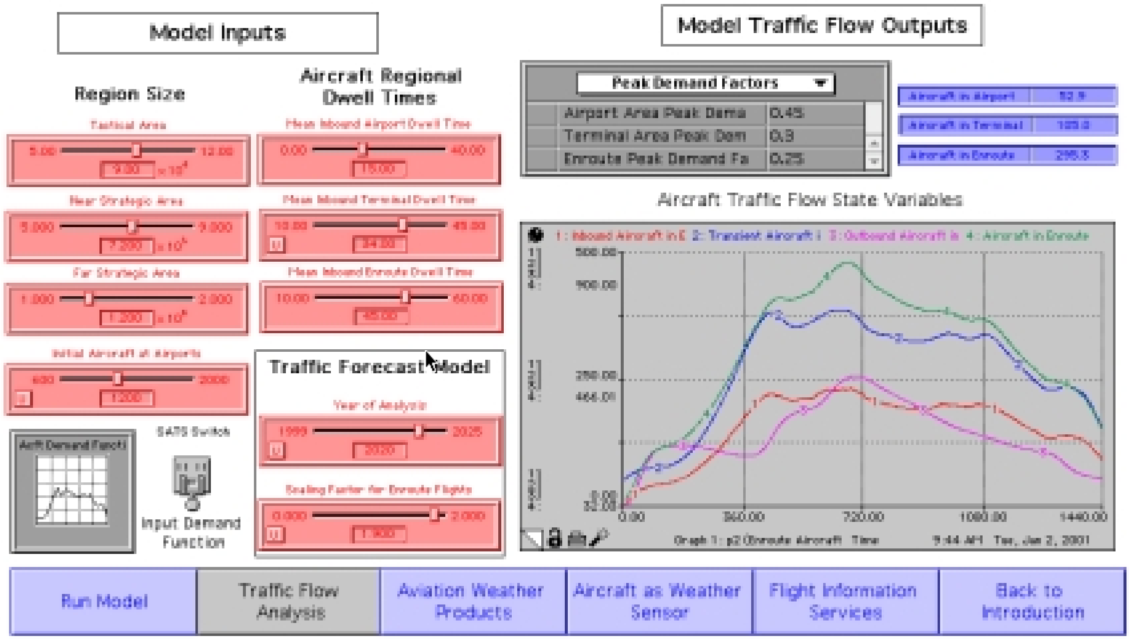


Figure 20: Traffic flow screen in LATFM.

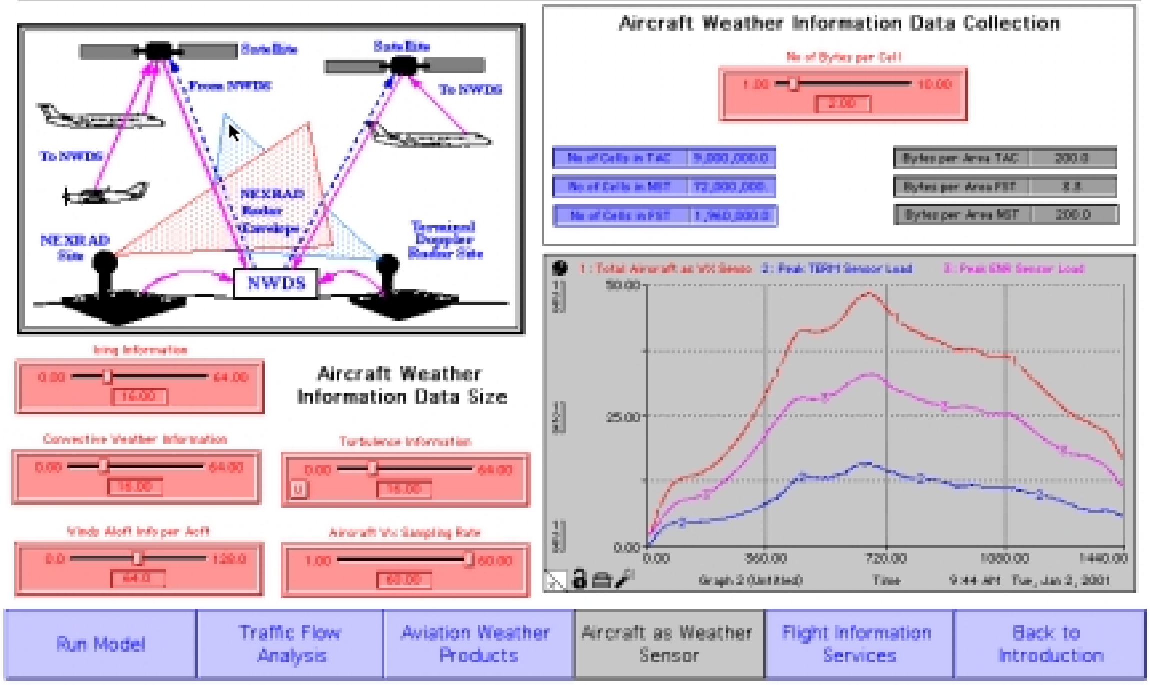


Figure 21: Aircraft as a sensor screen in LATFM.

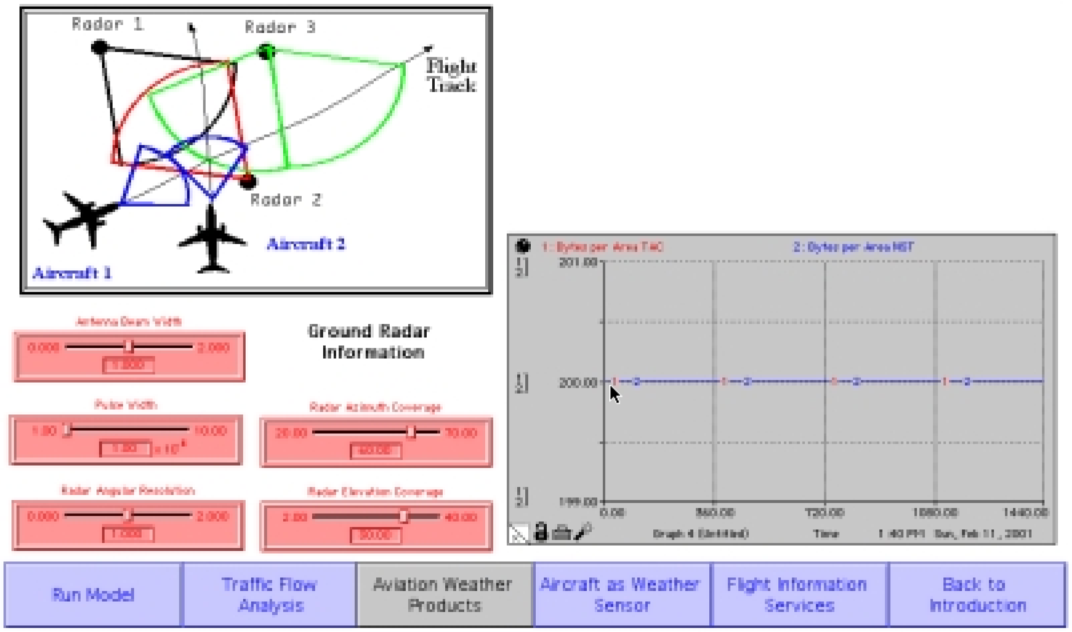


Figure 22: Aviation weather products screen in LATFM.

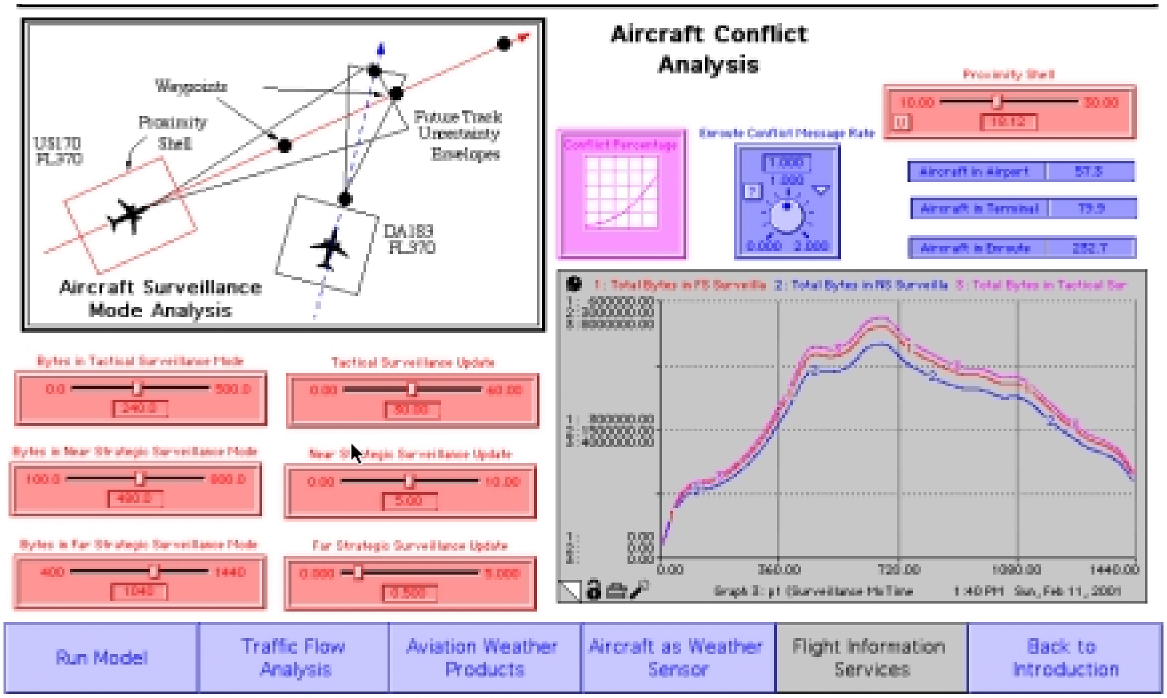


Figure 23: Aircraft flight information screen in LATFM.

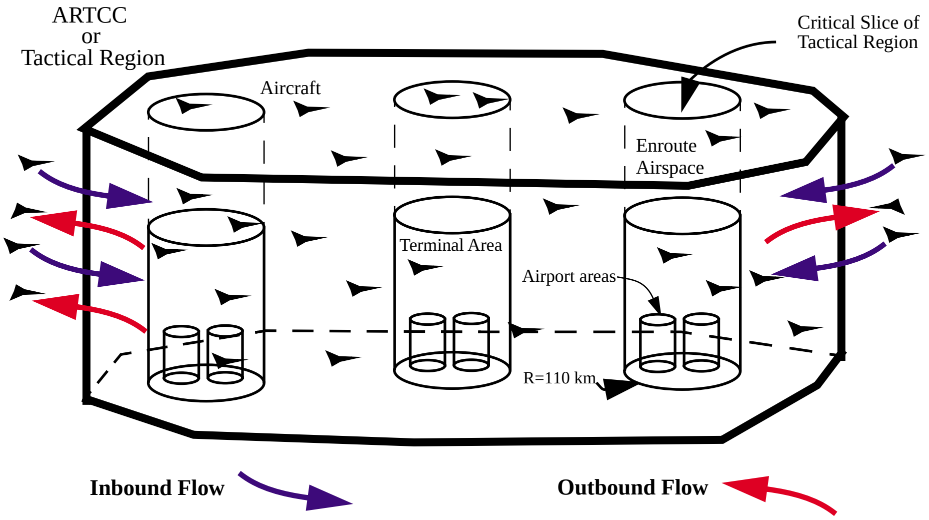


Figure 24: Introductory screen in the LATFM model.

3 Aeronautical Applications

There future aeronautical applications studied in this project are classified into three domains: 1) applications of weather information to the cockpit, 2) aircraft as a weather sensor, and 3) flight information services to help air traffic management. The following sections of the report describe in detail some of the applications considered relevant in future NAS operations.

3.1 Weather in the Cockpit Applications

Aviation weather is perhaps the most prominent application in the future of NAS operations. According to statistics compiled by the National Transportation Safety Board (NTSB) and the FAA a large percentage of the accidents in aviation are either Controlled Flight into the Terrain (CFIT) or weather related accidents (FAA, 2001). In the last decade 22.3% of the accidents reported in the U.S. were classified as weather related. Part 91 operators account for 85% of the total accidents reported (4,245 total accidents by Part 91 operators). These statistics are compelling to suggest that better weather information systems in the cockpit could benefit the entire aviation community, and especially those operators that lack on-board weather radars and other weather detection systems (i.e., stormscopes, etc.). The impact of timely weather information to the cockpit can improve pilot situational awareness and warn pilots of dangerous phenomena both during terminal area and enroute airspace operations. According to NTSB records 33% of the weather related accidents are related to low visibility and ceiling conditions at the airport. The remaining 67% of the remaining weather-related accidents involve enroute operations (FAA, 2001). It is clear that timely weather information to the cockpit, coupled with more accurate weather forecasting models should enhance the safety of the aviation system at all levels.

In our analysis we first derive aviation weather data communications needs for a single aircraft. Extensions based on predicted aircraft flows at airport, terminal areas and enroute airspace are then made to derive communication requirements for large regions of interest in a dynamic traffic flow environment. Both ground and airborne weather gathering sources are considered in this problem.

Today, the primary source for ground-based weather component is advanced Doppler radar (NEXRAD). There are 147 Doppler radar stations across NAS to facilitate data collection of several weather data products ranging from base reflectivity to storm total precipitation. Doppler radars provide accurate information on weather phenomena at ranges of up to 400 km. from the radar antenna (Mahapatra, 1999). Doppler radar update rates vary according to the data products derived but under ideal conditions total scans of 3-4 minutes are the best sampling rates possible with the current state-of-the-art radars such as the WSR-88D (NCDC, 1988). To derive weather data communication requirements in the future it is necessary to assume an advanced form of Doppler radar system information available to pilots. Our analysis considers that in twenty years time a technical multiplier of 3-4 will be achieved in sampling rates available (equating to a 60 second sampling rate across various weather products). Moreover, the minimum cell resolution of advanced Doppler radar applications assumed in this analysis is expected to be down to 1 microsecond of radar pulse width. These technical parameters are needed to derive future weather applications in the cockpit.

The primary source for airborne-based weather information is the airborne weather radar of each aircraft in the area of interest. The information gathered by airborne radars is more limited in scope (due to power limitations of the radar) and the physical tilt limitations of the onboard the radar antenna. Nevertheless, weather information gathered by onboard sensors could play a significant role to improve the accuracy of the weather picture of a region if fusion algorithms are developed to synthesize onboard and ground information weather data. The use of onboard weather information by pilots today is limited to the near-term strategic scenario (discussed in Section 1) given the power limitations and cell resolution of onboard weather radars.

Aviation Weather Resolution Levels

The flight planning decision making process employs weather information of various degrees of resolution. These resolution levels are necessary because a pilot planning detours around a large weather front 600 km. away can afford to inspect the macroscopic trend of the weather pattern with moderate resolution. The same pilot performing storm cell avoidance maneuvers in the terminal area would require a finer detail in the weather picture to help in the decision making process. In this project we define three boundaries for pilot decision making: 1) **tactical** (20 minutes ahead), 2) **near strategic** (20-60 minutes ahead), and 3) **far strategic** (>60 minutes ahead). These boundaries are defined in terms of time to avoid complexity when dealing with dissimilar performance aircraft. Time variations allow pilots to make better weather avoidance decisions throughout a typical flight (Figure 25).

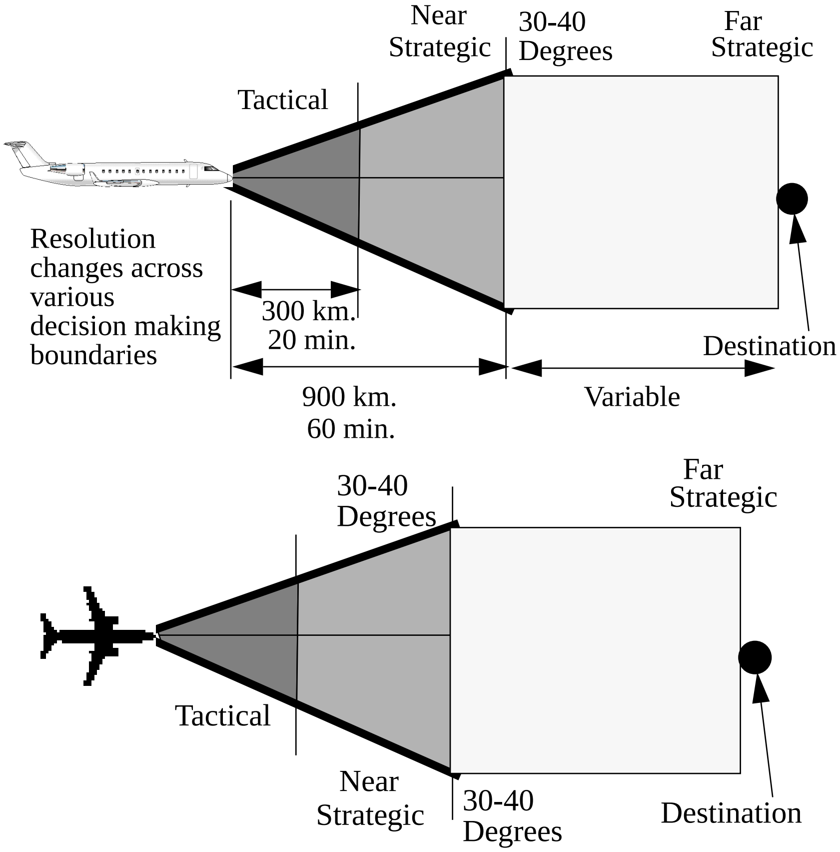


Figure 25: Decision domains for airborne weather advisory systems.

In the current and future NAS, the resolution of aviation weather services improves as each flight transitions from ARTCC to the airport area due to the physical resolution of the weather sensors (i.e., Doppler radar, Low Level Wind Shear, etc.) installed near or at the airports. Figure 26 illustrates the FAA requirements for weather radar coverage in NAS (FAA, 1981). The figure includes the resolution required for various ATC domains. The hypothesis in this study is that these levels of weather radar resolution would be surpassed by a **factor of three** in the horizon year of our analysis (i.e., 2020).

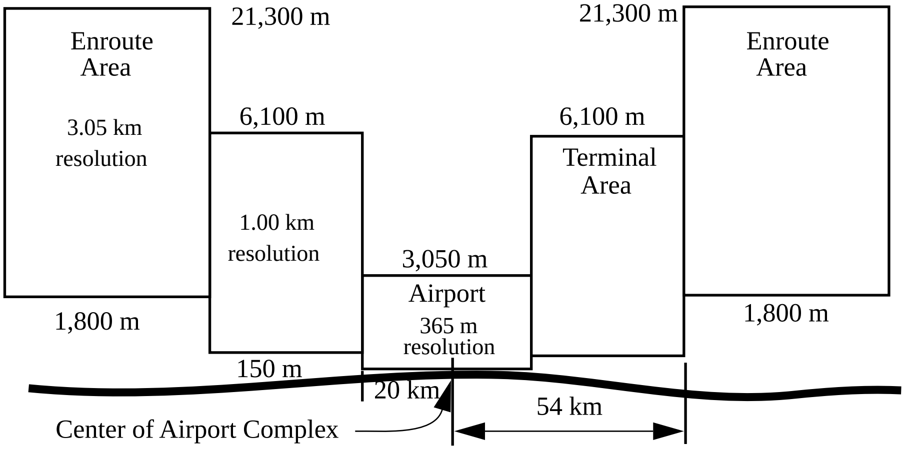


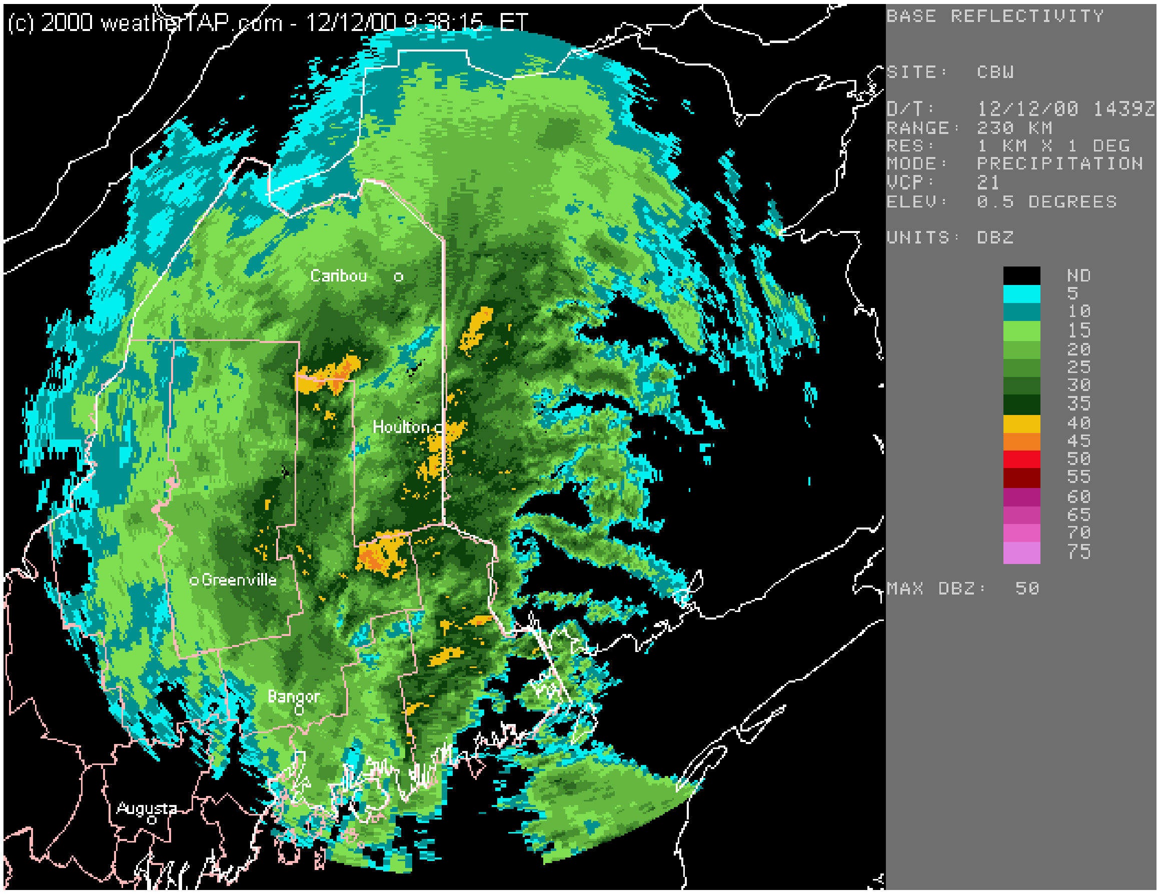
Figure 26: Spatial resolution of ground-based radars (Mahapatra, 1999).

The resolution of the weather information provided to the cockpit today and in future applications changes as a function of time and space over NAS for three fundamental reasons: 1) ground-based Doppler radar information has uneven volume resolutions as the target moves away from the radar antenna, 2) the airborne sensor information (i.e., weather radar and other sensors) are limited in scope due to power limitations of the sensor, 3) the distribution of both ground and airborne sensors is not even across NAS. Fortunately, the most advanced weather sensors are usually located near large airports thus contributing to better weather volume resolutions in the critical phases of flight (landing and takeoff).

Table 7 presents the most useful Doppler radar products used by pilots in flight planning. These products are available today at all National Weather Service stations across NAS via PLan Position Indicator displays (PPI). Figures 27 through 31 illustrate graphically some of these products in the WeatherTap^{TM} interface available through the internet (WeatherTap, 2000). The basic assumption in deriving weather applications in this project is the availability of these products in the future to the cockpit with higher resolutions (**3 times the resolution** available today using WSR-88D radars.

Product Number	**Product Identifier**	**Product Description**
19	R	Base reflectivity - 230 km. range (4 elevation angles)
20	R	Base reflectivity - 460 km. range (lowest elev. angle)
38	CR	Composite reflectivity - 16 levels (precipitation and clear air modes)
65,66,90	LRM	Layer composite reflectivity (three layers)
41	ET	Echo tops
57	VIL	Vertical integrated liquid
27	V	Base radial velocity (lowest 4 elevation angles)
56	SRM	Storm relative mean radial velocity (2 elev. angles)
48	VWP	Velocity azimuth display (VAD) winds
78	OHD	Surface rainfall accumulation - one hour total
80	STP	Surface rainfall accumulation - storm total
81	DPA	Hourly digital rainfall array

Table 7: Summary of weather data products available from ground-based Doppler radars.



BASE REFLECTIVITY

SITE: CBW

D/T: 12/12/00 1439Z
RANGE: 230 KM
RES: 1 KM X 1 DEG
MODE: PRECIPITATION
VCP: 21
ELEV: 0.5 DEGREES

UNITS: DBZ

MAX DBZ: 50

Figure 27: Base reflectivity weather data product available today (WeatherTap, 2000).

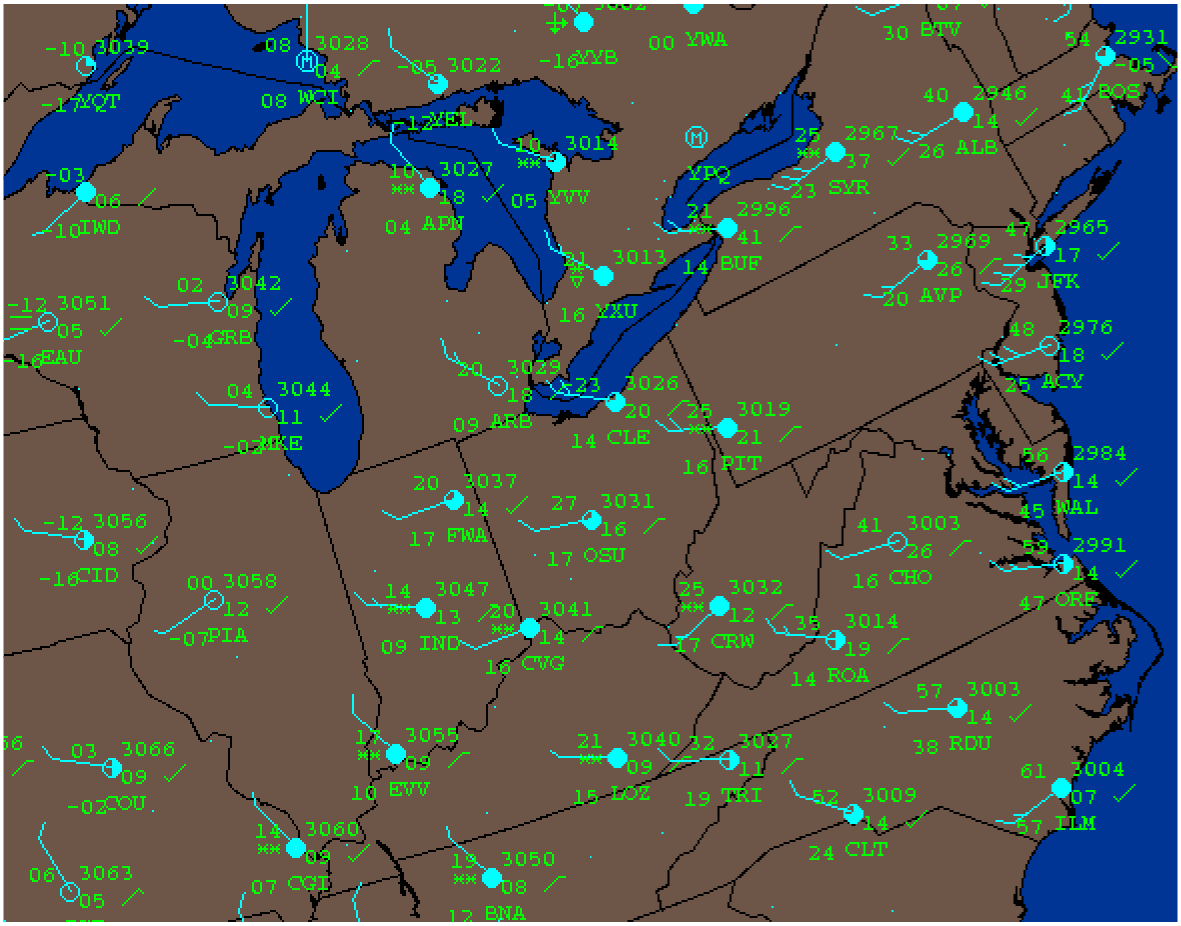
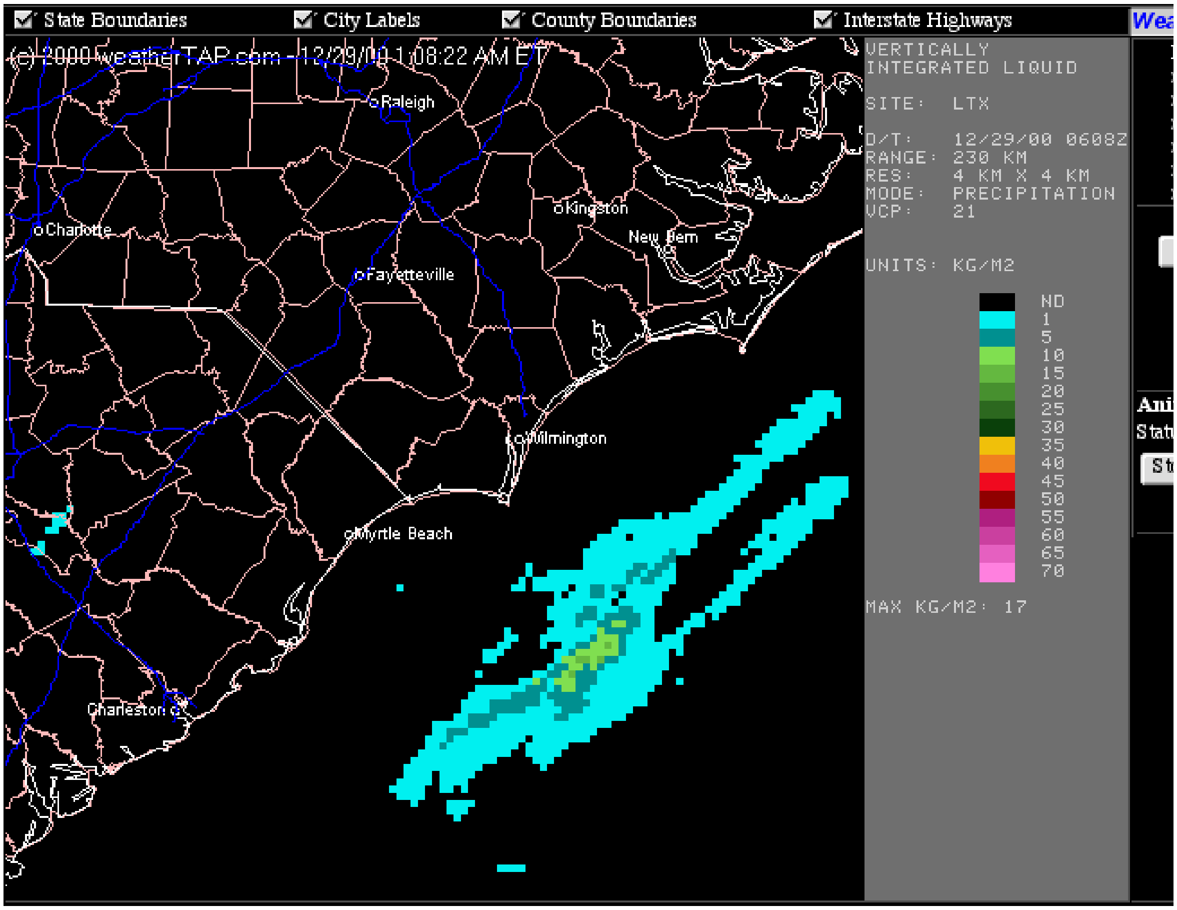


Figure 28:Winds at altitude weather data product available today (WeatherTap, 2000).



VERTICALLY
INTEGRATED LIQUID

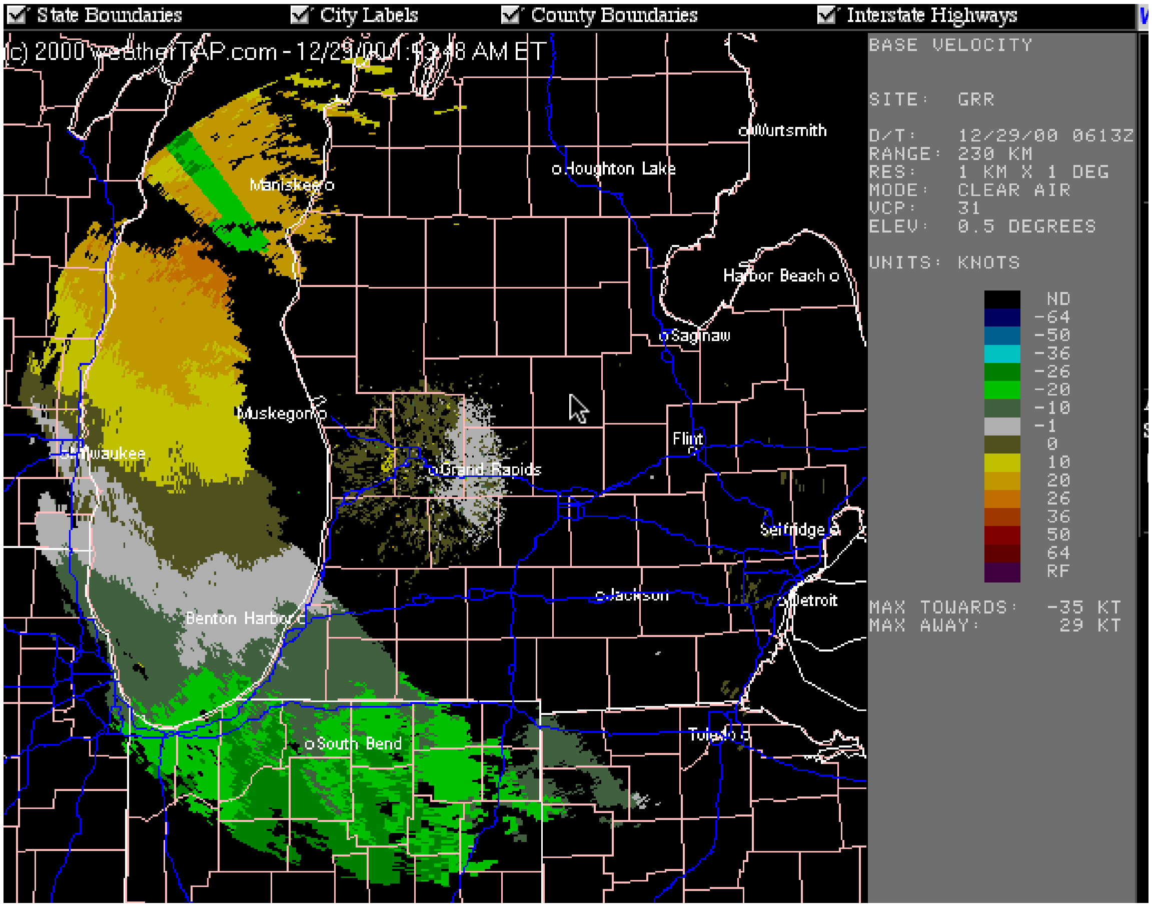
SITE: LTX

D/T: 12/29/00 0608Z
RANGE: 230 KM
RES: 4 KM X 4 KM
MODE: PRECIPITATION
VCP: 21

UNITS: KG/M2

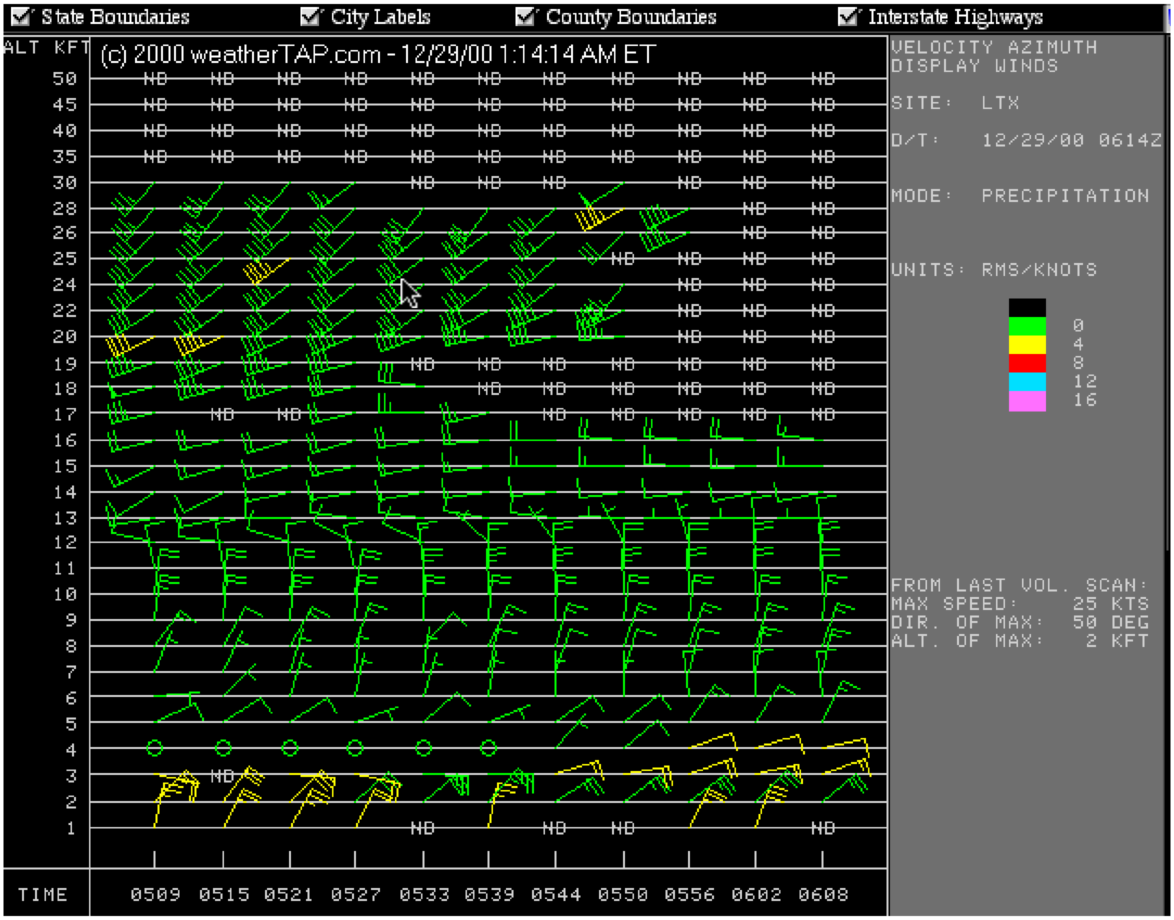
MAX KG/M2: 17

Figure 29:Echo tops weather data product available today (WeatherTap, 2000).



```
BASE VELOCITY

SITE:   GRR

D/T:    12/29/00 0613Z
RANGE:  230 KM
RES:    1 KM X 1 DEG
MODE:   CLEAR AIR
VCP:    31
ELEV:   0.5 DEGREES

UNITS:  KNOTS

MAX TOWARDS:   -35 KT
MAX AWAY:       29 KT
```

Figure 30:Base velocity weather data product available today (WeatherTap, 2000).



VELOCITY AZIMUTH DISPLAY WINDS

SITE: LTX

D/T: 12/29/00 0614Z

MODE: PRECIPITATION

UNITS: RMS/KNOTS

FROM LAST VOL. SCAN:
MAX SPEED: 25 KTS
DIR. OF MAX: 50 DEG
ALT. OF MAX: 2 KFT

Figure 31:Vertical velocity weather data product available today (WeatherTap, 2000).

Communication Requirements Analysis

The following steps are necessary to derive realistic communication requirements associated with aviation applications: 1) derive a concept of operations (include interactions between aircraft, ATC and weather information services); 2) define the type of weather information derived from ground and airborne sensors. This will include assessment of data structures of weather information and sampling rates used in the collection of the weather data and the distribution of it to airborne users; and 3) determine possible communication modes of operation (segregated channel vs. broadcast mode, etc.). Once this last step is concluded the derivation of communication requirements can be executed if dynamic traffic flows across the region of interest are known (i.e., through the use of dynamic traffic flow models such as LATFM).

The estimation of communication data requirements to bring advanced weather to the cockpit is executed for two types of aircraft: 1) those having an onboard weather detection equipment, and 2) those without it. As aircraft move in their flight paths, they traverse various ground and airborne weather sensor sites resulting in a non-uniform distribution of the resolution volumes gathered from ground sensors. This is illustrated in Figure 32. The first-order analysis performed in this project provides a static snapshot of the worst possible requirements for weather in cockpit applications.

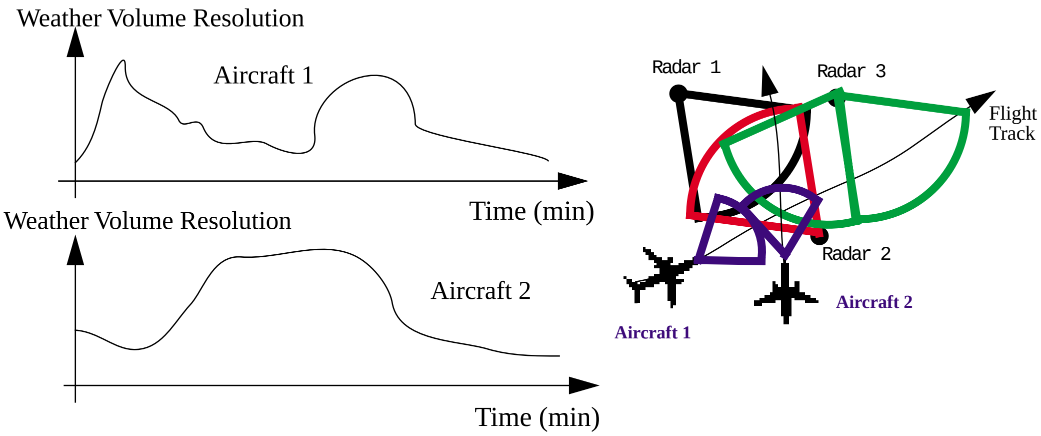


Figure 32: Composition of weather information.

Data Analysis of Weather Information

A first-order analysis of the data size requirements to bring high quality weather information to the cockpit is illustrated in Figure 33. In the tactical domain weather information is assumed to be the resolution cells of the ground sensor. A worst case scenario (from a data size viewpoint) occurs when the aircraft flies near the ground sensor as the cell resolution of the ground sensor is highest. Using 30 degrees in elevation and 60 degrees of azimuth coverage provided by ground sensors spaced every degree requires 4.8 million bytes of information for a complete tactical region coverage.

In the near-strategic domain weather information is assumed to be the resolution cells of the ground sensors available in the flight track (no collaborative weather information is assumed for airborne sensors). The desired range of weather information precludes the use of onboard sensors. A total of 28 million bytes of information will be required for a complete weather picture. In the analysis we have assumed the resolution of information to be the same as that of the tactical boundary. In the far-strategic domain weather information is assumed to be the resolution cells of the ground sensors available in the flight track with some loss in the quality of the image provided (5 pixels into 1).

Techniques to reduce communication bandwidth requirements are data compression techniques and a data validation and adaptive filtering algorithms to refresh weather cell elements that change from successive observations. It has been estimated that up to 25% of the weather information content could change between successive radar samples (using 60 second refresh rate) for a high-speed subsonic aircraft in the cruise mode. Anecdotal information from the AWIN program shows that tactical weather information savings are substantial using these two techniques. In one case the data filtering algorithms changed 41 kilobytes of a complete weather display (several Mbytes of information at 8 bit resolution).

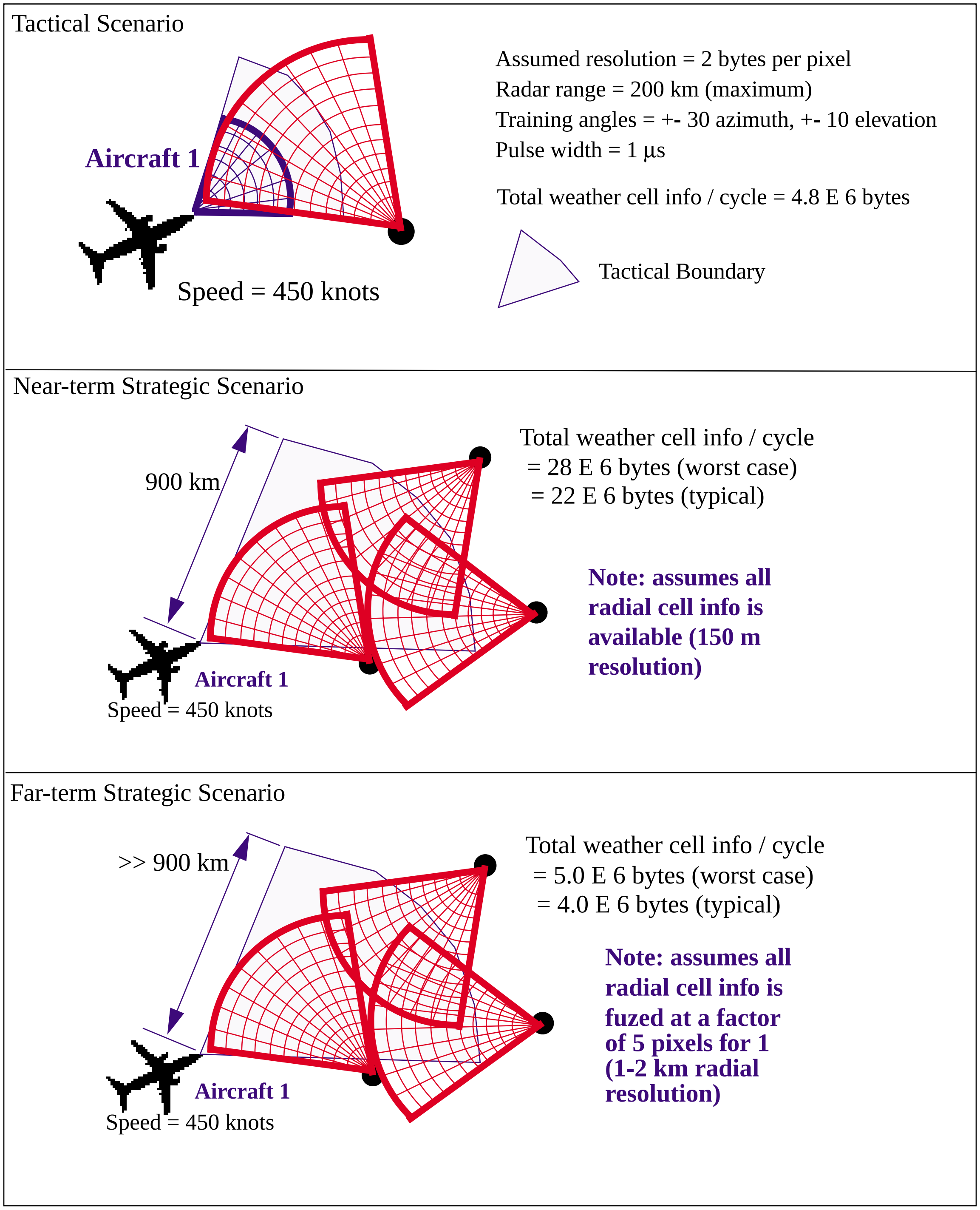


Figure 33: Weather information analysis for various decision-making flight regions.

The refresh rates of weather information are assumed to be consistent with the technology expected to be in place in the horizon year. In our analysis we assumed a technology multiplier that will provide faster sampling rate (down to one minute in 2020 for airport services).The tactical domain matters the most and has the fastest update cycle (60 seconds). This level of detail over time would be sufficient to detect most of the harmful convective weather phenomena in the terminal area. Table 8 summarizes the weather information including sampling rates projected for the weather data sets in each domain. The communication requirements shown in Table 8 apply to individual aircraft.

Domain	**Total Weather Data Size (bytes)**	**Region Size[a] (km^2)**	**Data (bytes per sq. km)**	**Sampling Rate (seconds)**
Tactical	4.8 E 6	4.71 E 4	101.85	60
Near-term Strategic	22 E 6	4.24 E 5	51.86	180
Far-term Strategic	4.0 E 6	2.700 E 6	1.48	600

a. For a typical transport-type aircraft traveling at 900 km/hr. (460 knots).

Table 8: Summary of weather information data to the cockpit.

3.2 Aircraft as Weather Sensor

So far the discussion has been centered around the use of airborne and ground-based weather sensors to detect two types of weather services: 1) convective weather (from doppler and airborne radar sources, and 2) wind information (collected from tracers detected by doppler radar). Many aircraft have multitude onboard sensors that, under current conditions, are not exploited to provide information to others. The availability of aircraft-derived weather information could provide valuable point measurements of weather-related services useful to pilots. Examples of these are: 1) wind data along the flight track (derived from FMS, INS or GPS sensors), 2) turbulence levels derived from aircraft accelerator sensors, 3) convective weather information, and 4) icing information along a route.

In this applications aircraft would provide relevant weather information to a centralized **National Weather Database System (NWDS)** at predetermined intervals. NWDS would collect these data and apply tactical weather models and algorithms to complement ground-based products derived from long-range Doppler radar, terminal doppler radar and other ground sensors. The information derived from NWDS system is sent to pilots (via satellite) at predetermined intervals (see Figure 34). The main advantage of this concept is that many of the current voids in weather information would be closed with the presence of aircraft at various flight levels (Figure 35).

Given the randomness of flight tracks across NAS the number of data points and the time and spatial distribution of the information will vary substantially. The NWDS will fuse all data collected and provide a common format to all requesting aircraft, The data format assumed for this analysis is a rectangular grid provided to all aircraft. Table 9 contains a description of the aircraft as weather sensor data products prototyped in this model. Table 10 summarizes the data size requirements to make aircraft be collaborative sensors across NAS. The sampling rate assumed in this analysis is 60 seconds.

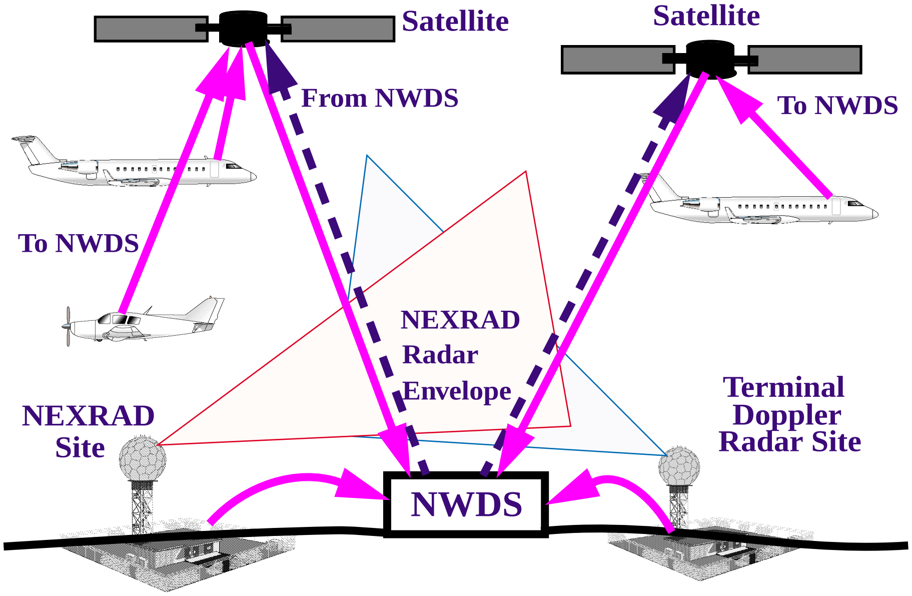


Figure 34: Aircraft as a sensor diagram.

Service Type	Sources of Data	Sampling Rate	Data Size
Winds Aloft along the flight track	Air data, FMS, GPS derived wind data	Continuous variables reported (direction, magnitude, location, time) every 10 seconds for all aircraft types	512 bits[a] per aircraft per measurement aircraft ID wind direction wind magnitude 3D location time tag
Icing	Vehicle icing sensors and on-board temperature gradient measurements	every 10 seconds (all types of aircraft) reported as	64 bits per aircraft per measurement
Turbulence	Vehicle accelerometers, mechanically measured	every 10 seconds (all types of aircraft) reported as	64 bits per aircraft per measurement
Convective	Moisture content instruments, Pressure, etc.	every 10 seconds (all types of aircraft) reported as	128 bits per aircraft per measurement

a. Assumes no compression

Table 9: Aircraft as a weather sensor communication information data sets.

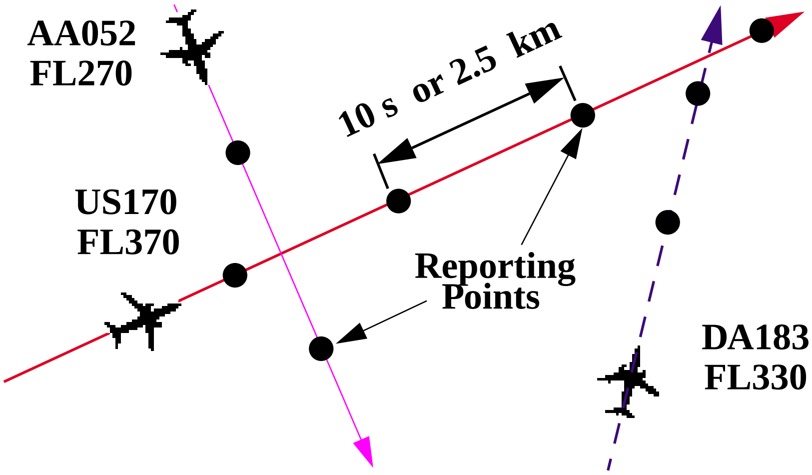


Figure 35: Spatial retrieval information for aircraft as a weather sensor.

Domain	Total Weather Data Size (bytes)	Region Size (km^2)	Average Data Set (bytes[a] per sq. km)	Sampling Rate (seconds)
Tactical	1.8 x 10^5 rectangular 9.0 x 10^4 triangular	9.0 x 10^4 rectangular 4.5 x 10^4 triangular	2.0 in both cases	60
Near Strategic	1.44 x 10^6 rectangular 7.2 x 10^5 triangular	7.2 x 10^5 rectangular 3.6 x 10^5 triangular	2.0 in both cases	180
Far Strategic	2.48 x 10^5 rectangular (4 km grid size)	up to 2.7 x 10^6 rectangular	0.19	600

[a] Assumes 8 bit data representation, 8 bit error correction scheme and 1 km grid.

Table 10: Aircraft as a sensor data size with low sampling rate.

Aircraft in flight will probably require several of these data products on a continuous basis. The most demanding situation will be for all aircraft requesting simultaneous services for all data sets. This will imply for example 8 bytes/km^2 (4 weather products times 2 bytes/km^2) in the tactical region of analysis. In the analysis using the LATFM model described in Section 2 we assumed Peak Demand Factors (PDF) of 0.4, 0.30 and 0.25 for every ATC centered service (airport, terminal and enroute services, respectively) to obtain peak demand loads for the most critical region. A sample output from LATFM is shown in Figure 36. Peak demand factors represent an accumulation of traffic density in congested regions of airspace. PDF is the ratio of aircraft traffic in congested airspace and the aircraft traffic in all the region of interest.

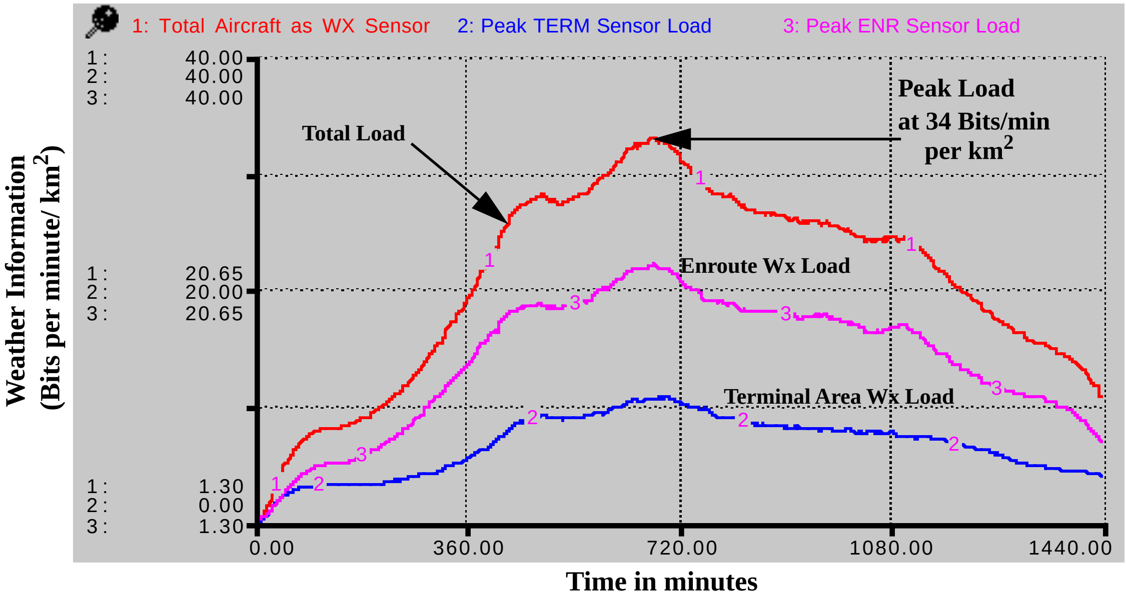


Figure 36: Aircraft as weather sensor results shown in the LATFM model.

One of the advantages of using a dynamic model to predict communication loads is its ability to adapt to a multitude of design conditions. Table 10 shows the resulting data sets associated with weather products derived using NWDS with aircraft sampling rates once every second (grid size is 0.1 km). The matrix below represents the data sets for each product per aircraft. It is obvious that a multiplicative growth results in the amount of information generated by unit area.

Domain	**Total Weather Data Size (bytes)**	**Region Size (km^2)**	**Average Data Set (bytes[a] per sq. km)**	**Sampling Rate (seconds)**
Tactical	1.8×10^7 rectangular 9.0×10^6 triangular	9.0×10^4 rectangular 4.5×10^4 triangular	200 in both cases	60
Near Strategic	1.44×10^8 rectangular 7.2×10^7 triangular	7.2×10^5 rectangular 3.6×10^5 triangular	200 in both cases	180
Far Strategic	3.96×10^6 rectangular (1km grid size)	up to 2.7×10^6 rectangular	3.14	600

[a] Assumes 8 bit data representation and 8 bit error correction scheme and **0.10 km grid size**.

Table 11: Aircraft as a sensor data size with high sampling rate.

3.3 Flight and Traffic Information Service Applications

Flight information services constitute another important area where satellite communications are changing the nature of aviation operations. Examples of current Traffic Information Services (TIS) are: 1) TCAS - the Traffic Collision Avoidance System, and 2) ADS-B systems based on air-to-ground VHF data link (using either satellite or land datalinks).

Future Air Traffic Management systems are likely to implement advanced forms of Collaborative Routing (CR). Under CR the premise is for flights to take both tactical and strategic actions on the ground or in flight to minimize conflicts with others and increase the efficiency of operations (i.e., reduce delays). Collaborative routing strategies might be directed by a centralized facility (i.e., an airline operations center, or air traffic control) or by decentralization of ATC/ATM services to neighboring flights. Under CR flights have primary flight plans filed before departure. As each flight progresses a number of events in NAS can change the character of the best strategy to conduct each flight. At the tactical level each flight will alter their course to avoid others (TCAS type service). In the context of airline services, the airline operations center has no role in this resolution strategy. Aircraft require real-time position information, real-time conflict detour strategies considering *n* flights and *m* possible flight plan alternatives.

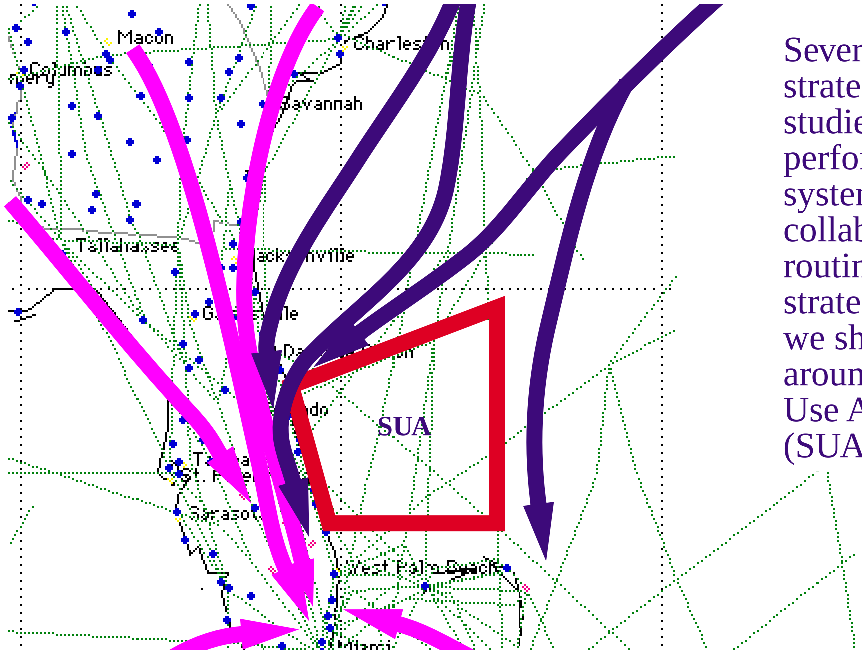
In the near-term and far-term strategic domains each flight will probe conflicts and sector capacity boundaries to plan a system-optimal detour strategy. Figure 37 illustrates an example of system-optimal detours around a Special Use Airspace region in Florida. In this instance plan-ahead traffic information solution in the near-term strategic boundary. The character of the messages requires real-time information but have less priority that the previous case. Enroute and terminal ATC sectors and boundaries are modeled in moderate detail (a single lumped queueing model is enough).The role of the airline operations center is critical in the decision making process. Failure to plan a detour strategy considering other traffic could result in longer delays at critical points in the airspace system.

Air Traffic Management Concept of Operations (Circa 2020)

Our assumptions for a concept of operations in 2020 ADS-B surveillance information is widely available to all airspace users. LEO communications are used in two ways: 1) as backup system for ADS-B (critical element of ground surveillance), and 2) as service provider of traffic information services - collaborative routing and self-separation information - to aircraft in the airspace (in all phases of flight). Aircraft communications messages can, once again, be catalogued into three distinct groups:1) tactical decision making information (typically flight critical), 2) near-term strategic information (aircraft to AOC for example), and 3) far-term strategic information (for long-range strategic planning).

Under this concept of operations aircraft constitute a distributed network of intelligent agents (Figure 38). Distributed control algorithms devise aircraft maneuvers (advanced real-time tactical and strategic flight plan functionality). Other services exist (TCAS) for last-minute conflict resolution strategies. For initial conceptualization we assume that most of the ATM system-wide optimization computations occur at a ground facility (called ATM Center - part of ARTCC or TRACON) where faster CPUs exist. In advanced version of this system aircraft could collaborate in the computational tasks if they have idle CPU resources available.

In order to understand the communication loads required with advanced ATM applications for each one of the areas of interest we use a prototype flight plan shown in Figure 39. This flight plan structure contains information typically stored in the current FAA ETMS system.



Several detour strategies need to be studied while performing system optimal collaborative routing strategies. Here we show detours around Special Use Airspace (SUA)

Figure 37: Sample collaborative routing around a warning area (SUA).

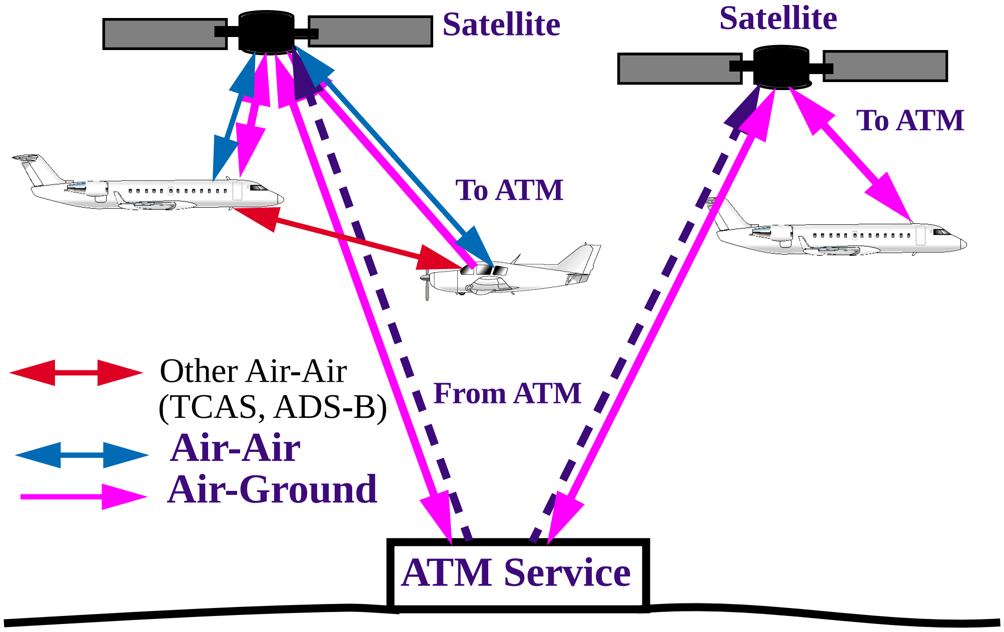
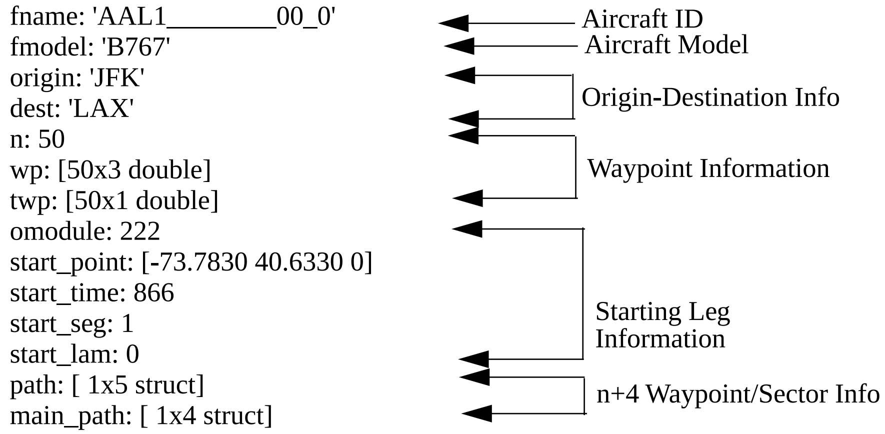


Figure 38: Traffic information services.



```
fname: 'AAL1________00_0'
fmodel: 'B767'
origin: 'JFK'
dest: 'LAX'
n: 50
wp: [50x3 double]
twp: [50x1 double]
omodule: 222
start_point: [-73.7830 40.6330 0]
start_time: 866
start_seg: 1
start_lam: 0
path: [ 1x5 struct]
main_path: [ 1x4 struct]
```

Total Data Set = 3708 bytes (using double precision for all numeric data)

Figure 39: Prototype flight plan data structure.

The average flight plan in ETMS today has 34 waypoints of information. This represents an average of 3,350 bytes of information per flight (using double precision data types for most of the numerical information). The modeling assumption is that in the future NAS most of the flights will operate under an equivalent IFR flight plan for safety reasons. In the tactical domain *n+4* waypoint information is used to probe and schedule detours. In the near-term strategic domain we assume *n+10* waypoints used in the elaboration of surrogate flight plans for optimal detour strategies. An initial estimate of the communication requirements in a future NAS requires an estimate of the number of messages produced by every agent in the system. An assumption made here is that the number of messages will be correlated to the number of conflicts that are likely to occur in the system.

A study by Trani et al.(1998) using 6000 random flights in ZMA and ZJX under current NAS system conditions reported that about 4.7% of the flights in the enroute airspace are in conflict (9.26 km. shell). Under Reduced Vertical Separation Mode (RVSM) conditions the number of blind conflicts is expected to decrease to 3.1% and the geometries of the conflicts will change moderately. Other studies confirm that random airspace conflicts grow quadratically with the number of flights. Figure 40 illustrates possible ways to study airspace conflicts including a notional conflict rate diagram.

System-wide optimal airspace models would employ this information to generate flight planning advisories to every flight. A sample Airspace Planning Model is reported by Sherali et al. (2000). Traffic information plans (solutions of the APM model) are transmitted from the ATM Center to each aircraft at predetermined intervals. These intervals are dictated by the quickness of the APM solver. Tables 12 and 13 illustrate the typical sampling rates and data sizes of the various TIS messages assumed in this analysis. Figure 41 illustrates a sample screen in the LATFM model showing dynamic communication requirements for the region of interest modeled.

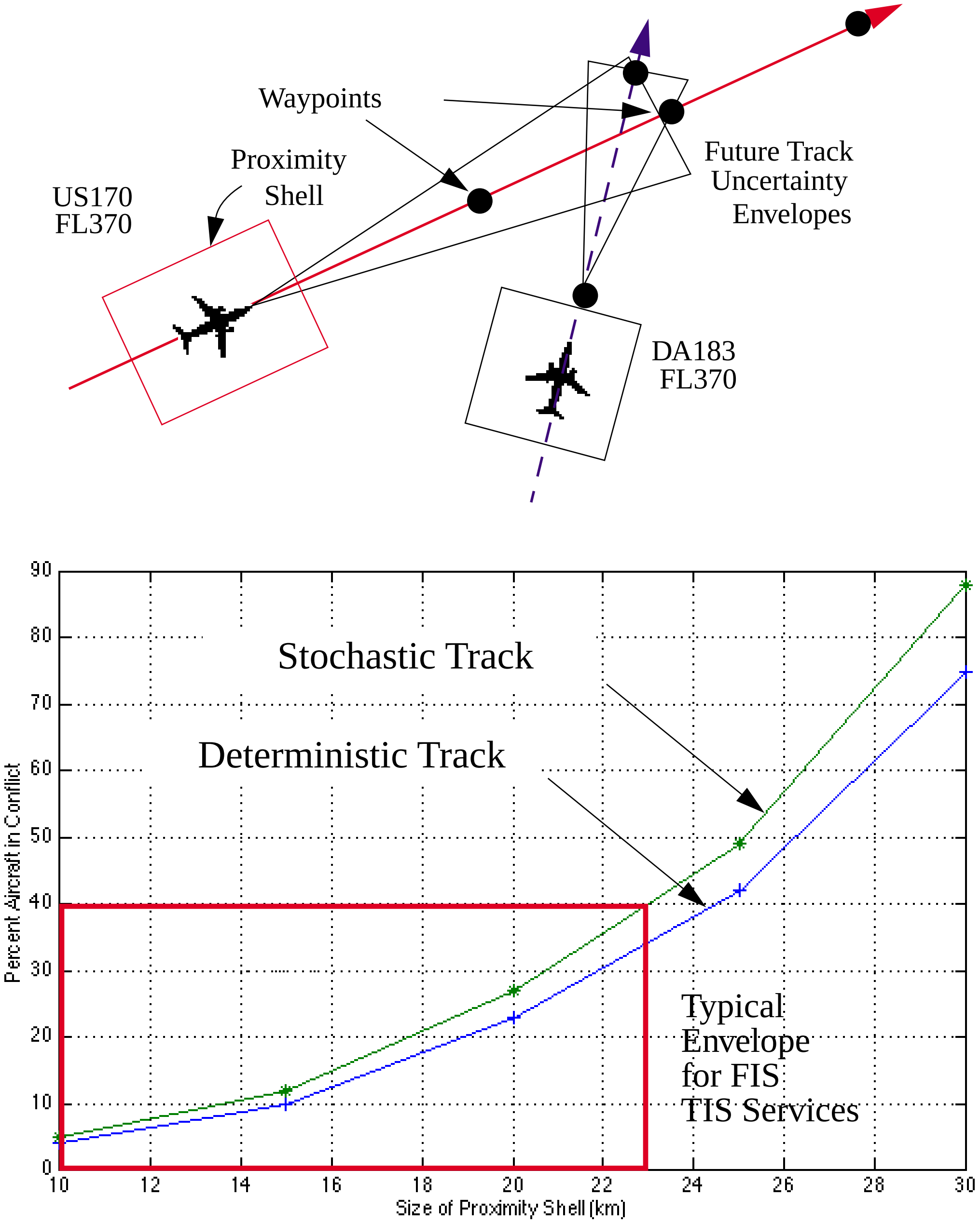


Figure 40: Estimating airspace conflicts (stochastic and deterministic flight tracks).

Domain	Message Size (bytes)	Typical Message Update Rate (messages per minute)
Tactical	240	30
Near Strategic	480	5
Far Strategic	512	0.5

Table 12: First-order TIS surveillance information.

Domain	Message Size (bytes)	Update Rate[a] (messages / minute)
Tactical	512	1
Near Strategic	1024	1/2
Far Strategic	4700	1/6

[a] Represents how fast the decision-making Airspace Planning Optimization model can produce a new system-wide flight plan solution.

Table 13: First-order TIS information (ATM mode).

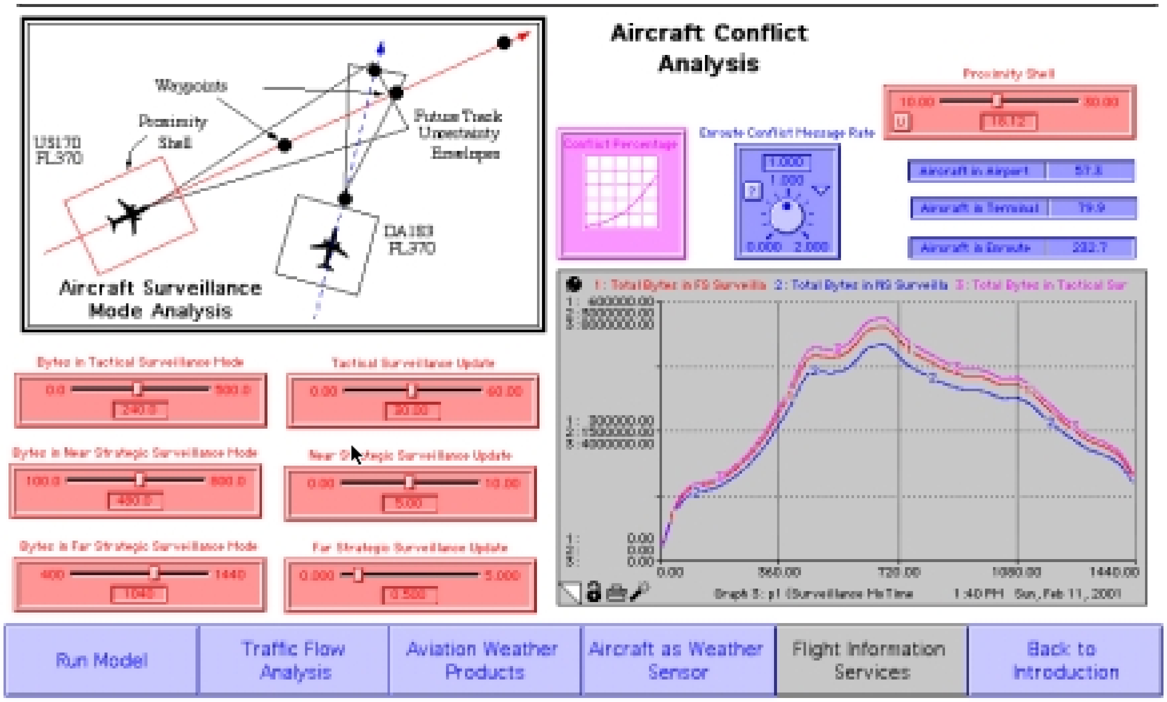


Figure 41: Aircraft flight information screen in LATFM.

4 Conclusions and Recommendations

This report has presented various modeling strategies for evaluating future aeronautical applications that could benefit from the deployment of Low Earth Orbit satellites. The project had two interrelated goals. The first one was to assess the future aeronautical communication applications. Our work developed a traffic scenario for the year 2020 using the Lumped Air Traffic Flow Model (LATFM) and then estimated associated bandwidth requirements for advanced weather applications. Included is a model in which aircraft act as sensors and feed back information to a centralized ground database system, which are fused by a weather model. Another application uses ground radar information to deliver detailed weather products to the cockpit. A final application studied possible uses of LEO satellites to support an advanced Air Traffic Management (ATM) system where Traffic Information is made available to all airborne platforms in NAS.

The second goal involved the investigation of the use of next generation satellite technology to support these advanced applications.We developed a model that supports the comparison of broadcast, uni-cast and hybrid broadcast/uni-cast satellite systems for the delivery of weather and other information to aircraft. This model allows for the estimation of the bandwidth requirements for future aeronautical communications applications. It also is supports the comparison, based on bandwidth requirements and processing cost, of broadcast or hybrid LEO/MEO architectures, broadcast or hybrid GEO architectures and general unit-cast architectures.

In the derivation of communication requirements for each one of the three applications presented in this report required some fundamental assumptions regarding the technology available and the number of operations in the year 2020. Some of these assumptions are:

- The growth rate of the aircraft fleet and aircraft operations in NAS follows the FAA predicted pattern until the year 2010. A 1.75% growth in aircraft operations per year is assumed thereafter.
- The equipage rate of aircraft having onboard weather sensors is assumed to be 100%.
- The equipage rate of aircraft having advanced weather displays is 100% across all four classes of aircraft discussed in the report.
- The number of aircraft having access to traffic information services is also assumed to be 100%.

These assumptions are based on the premise that in a steady-state scenario all aircraft flying in NAS will require some form of weather information in the cockpit, act as a weather sensor, and require traffic information services in order to conduct safe operations across NAS. The authors believe that this worst-case scenario assumptions should provide a best example of the cumulative effect of large numbers of airborne platforms requesting various services.

A flexible computer simulation model (called Lumped Air Traffic Flow Model - LATFM) has been developed and tested using data from an Air Route Traffic Control Center. This model can be employed to study the impact of future aeronautical applications as they affect communication data requirements. The model tracks the aggregate number of aircraft over time (Traffic Flow Module) and computes communication data size requirements for various aeronautical services such as weather products in the cockpit (Aviation Weather Module), aircraft as weather sensor (Aircraft as Weather Sensor Module), and flight information services (Flight Information Services Module). The development of this prototype model has been carried out using STELLA II - a Systems Dynamics software package developed by High Performance Systems of Nashua, New Hampshire. The model can be easily adapted to study the effects of variable aircraft demands inside an ARTCC on communication data requirements.

Some of the conclusions of the broadcast trade-off model developed are:

- The optimal area that leads to a minimum total bandwidth and processing costs is relatively independent from the air traffic density. This result enables a single static solution that can be applied throughout the country.
- Future aeronautical applications would require high bandwidth communication links. This supports the use of next generation satellite systems as an alternative to current terrestrial systems.

Conclusions of the traffic flow model are:

- The growth in the demand function expected in the next two decades assumed in this project produced estimates of up to 1450 operations per hour (including air carrier, corporate jets and GA users) in congested Air Route Air Traffic Control (ARTCC) centers such as Indianapolis and New York. When these operations are viewed as instantaneous operations produce 800-850 aircraft requesting communication services inside an ARTCC area.

Future recommendations of this work are:

- Improvements to the broadcast model could be made to study hybrid terrestrial and satellite networks.
- Improvements to the integration between the broadcast and the air traffic models. This integration could take the form of better input-output file parser development. The benefits of such integration would be the added flexibility to run multiple variations of communication scenarios faster.
- Improvements to the traffic flow modeling scheme used in LATFM could incorporate feedbacks between airport resources and traffic dwell times to better characterize delays at congested airports and their impact on communication requirements.
- Improvements to the traffic flow model to accommodate other aeronautical applications such as Airline Operations Center messages, ground-based flight data recorder style applications, etc. These would present a more complete picture of the overall communication requirements across dense regions of NAS
- Adaptation of the traffic model to hybrid aircraft equipage. This will provide a better assessment of the evolution of NAS communication requirements over time.
- Adaptation of the existing LATFM model to account for a larger growth in aircraft operations consistent with the deployment of SATS type aircraft technologies. These aircraft would require better airborne services and perhaps drive the bandwidth requirement of the LEO satellite network in the future. The current

LATFM model has a SATS switch to represent a probable growth in aircraft operations in the future. However, the current representation is very crude and should be studied in more detail if the results are to be considered reliable. At this point the CNS requirements of SATS are still sketchy to understand their full implication on future CNS NAS requirements.

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Appendix A. LATFM Stella II Source Code.

The following equations constitute the basis for the Lumped Air Traffic Flow Model. LATFM has been prototyped using STELLA II (a trademark software of High Performance Systems in Nashua, New Hampshire). The model representation of eight state variables implies a solution to eight coupled first order differential equations with variable coefficients. The STELLA II software handles the solution to this system of equations automatically.

State Variables

```
Idle_Aircraft_at_Airport(t) = Idle_Aircraft_at_Airport(t - dt) + (To_Idle_State - Out_of_Idle_State) * dt
INIT Idle_Aircraft_at_Airport = Initial_Aircraft_at_Airports

INFLOWS:
To_Idle_State = NALAIS
OUTFLOWS:
Out_of_Idle_State = Idle_Aircraft_at_Airport/Dwell_Time_at_Airport
Inbound_Aircraft_at_Airports(t) = Inbound_Aircraft_at_Airports(t - dt) + (NALTA1 - NALAIS) * dt
INIT Inbound_Aircraft_at_Airports = 0

INFLOWS:
NALTA1 = NALTA
OUTFLOWS:
NALAIS = Inbound_Aircraft_at_Airports/Inbound_Airport_Dwell_Time
Inbound_Aircraft_in_Enroute_Airspace(t) = Inbound_Aircraft_in_Enroute_Airspace(t - dt) + (NAENO - NALET) * dt
INIT Inbound_Aircraft_in_Enroute_Airspace = 0

INFLOWS:
NAENO = Acft_Demand_Function*Time_Scale_Factor*SATS_Scaling_Factor
OUTFLOWS:
NALET = Inbound_Aircraft_in_Enroute_Airspace/Inbound_Dwell_Time_Enroute
Inbound_Aircraft_in_Terminal_Areas(t) = Inbound_Aircraft_in_Terminal_Areas(t - dt) + (NALET1 - NALTA) * dt
INIT Inbound_Aircraft_in_Terminal_Areas = 0

INFLOWS:
NALET1 = NALET
OUTFLOWS:
NALTA = Inbound_Aircraft_in_Terminal_Areas/INbound_Dwell_Time_Terminal
Outbound_Aircraft_at_Airports(t) = Outbound_Aircraft_at_Airports(t - dt) + (NAEOIS - NALAT) * dt
INIT Outbound_Aircraft_at_Airports = 0

INFLOWS:
```

NAEOIS = Out_of_Idle_State
OUTFLOWS:
NALAT = Outbound_Aircraft_at_Airports/Outbound_Airport_Dwell_Time
Outbound_Aircraft_in_Enroute_Airspace(t) = Outbound_Aircraft_in_Enroute_Airspace(t - dt) + (NALTE1 - NALEO) * dt
INIT Outbound_Aircraft_in_Enroute_Airspace = 0

INFLOWS:
NALTE1 = NALTE
OUTFLOWS:
NALEO = Outbound_Aircraft_in_Enroute_Airspace/Outbound_Dwell_Time_Enroute
Outbound_Aircraft_in_Terminal_Areas(t) = Outbound_Aircraft_in_Terminal_Areas(t - dt) + (NALAT1 - NALTE) * dt
INIT Outbound_Aircraft_in_Terminal_Areas = 0

INFLOWS:
NALAT1 = NALAT
OUTFLOWS:
NALTE = Outbound_Aircraft_in_Terminal_Areas/Outbound_Dwell_Time_Terminal
Transient_Aircraft_in_Enroute_Airspace(t) = Transient_Aircraft_in_Enroute_Airspace(t - dt) + (NAERC_in - NAERC_out) * dt
INIT Transient_Aircraft_in_Enroute_Airspace = 50

INFLOWS:
NAERC_in = Scaling_Factor_for_Enroute_Flights*NAENO*SATS_Scaling_Factor
OUTFLOWS:
NAERC_out = Transient_Aircraft_in_Enroute_Airspace/TD_ENER_cr

Rate and Auxiliary Variables

Aircraft_in_Airport_Areas = Inbound_Aircraft_at_Airports+Outbound_Aircraft_at_Airports
Aircraft_in_Enroute_Region = Inbound_Aircraft_in_Enroute_Airspace+Outbound_Aircraft_in_Enroute_Airspace+Transient_Aircraft_in_Enroute_Airspace
Aircraft_in_Terminal_Areas = Inbound_Aircraft_in_Terminal_Areas+Outbound_Aircraft_in_Terminal_Areas
Aircraft_Wx_Sampling_Rate = 60
Airport_Area = 314
Airport_Area_Peak_Demand_Factor = .45
Antenna_Beam_Width = 1
Average_Airport_Density = Aircraft_in_Airport_Areas/Total_Airport_Areas
Average_ENR_Density = Aircraft_in_Enroute_Region/Total_ARTCC_Area
Average_TERM_Density = Aircraft_in_Terminal_Areas/Total_Terminal__Areas_Footprint
Bytes_in_Far_Strategic_Surveillance_Mode = 1040
Bytes_in_Near_Strategic_Surveillance_Mode = 480
Bytes_in_Tactical_Surveillance_Mode = 240

Bytes_perTerminal_Conflict_Message = 512

Bytes_per_Area_FST = Total_Bytes_FST_Service/Far_Strategic_Area

Bytes_per_Area_NST = Total_Bytes_NST_Service/Near_Strategic_Area

Bytes_per_Area_TAC = Total_Bytes_TAC_Service/Tactical_Area

Bytes_per_ENR_Conflict_Message = 1048

Convective_Weather_Information = 128/8

Convective_Wx_Sampling_rate = Aircraft_Wx_Sampling_Rate

Elevation_Multiplier = Radar_Elevation_Coverage/Antenna_Beam_Width

Enroute_Area = 168000

Enroute_Conflict_Message_Rate = 1

Enroute_Peak_Demand_Factor = .25

Exchange_Messages_Enroute = Enroute_Conflict_Message_Rate*No_of_Enroute_Conflicts

Exchange_Messages_terminal = No_of_Terminal_Conflicts*Terminal_Conflict_Message_Rate

Far_Strategic_Area = 1.2e6

Far_Strategic_Surveillance_Update = .5

Icing_Information = 16

Icing_Sampling_Rate = Aircraft_Wx_Sampling_Rate

Inbound_Airport_Dwell_Time = NORMAL(Mean_Inbound_Airport_Dwell_Time,3)

Inbound_Dwell_Time_Enroute = NORMAL(Mean_Inbound_Enroute_Dwell_Time,5)

INbound_Dwell_Time_Terminal = NORMAL(Mean_Inbound_Terminal_Dwell_Time,5)

Initial_Aircraft_at_Airports = 1200

Mean_Inbound_Airport_Dwell_Time = 15

Mean_Inbound_Enroute_Dwell_Time = 45

Mean_Inbound_Terminal_Dwell_Time = 34

Near_Strategic_Area = 7.2e5

Near_Strategic_Surveillance_Update = 5

No_of_Airports = 24

No_of_ARTCCs = 1

No_of_Bytes_per_Cell = 2

No_of_Enroute_Conflicts = Aircraft_in_Enroute_Region*Percent_of_Aircraft_in_Conflict/100

No_of_Terminal_Areas = 8

No_of_Terminal_Conflicts = Aircraft_in_Terminal_Areas*Percent_of_Aircraft_in_Conflict/100

Outbound_Airport_Dwell_Time = 12

Outbound_Dwell_Time_Enroute = 40

Outbound_Dwell_Time_Terminal = 18

Peak_Airport_Density = Aircraft_in_Airport_Areas*Airport_Area_Peak_Demand_Factor/Airport_Area

Peak_Convective_Downlink_ENR = Enroute_Peak_Demand_Factor*Total_Convective_Wx_ENR/Terminal_Area

Peak_Convective_Downlink_TERM = Terminal_Area_Peak_Demand_Factor*Total_Convective_Wx_TERM/Terminal_Area

Peak_Enroute_Density = Enroute_Peak_Demand_Factor*Aircraft_in_Enroute_Region/Terminal_Area

Peak_ENR_Sensor_Load = Peak_Convective_Downlink_ENR+Peak_Icing_Downlink_ENR+Peak_Turbulence_Downlink_ENR+Peak_Winds_Downlink_ENR

Peak_Icing_Downlink_ENR = Enroute_Peak_Demand_Factor*Total_Icing_Info_ENR/Terminal_Area

Peak_Icing_Downlink_TERM = Terminal_Area_Peak_Demand_Factor*Toal_Icing_Info_TERM/Terminal_Area

Peak_Terminal_Density = Aircraft_in_Terminal_Areas*Terminal_Area_Peak_Demand_Factor/Terminal_Area

Peak_TERM_Sensor_Load = Peak_Convective_Downlink_TERM+Peak_Icing_Downlink_TERM+Peak_Turbulence_Downlink_TERM+Peak_Winds_Downlink_TERM

Peak_Turbulence_Downlink_ENR = Enroute_Peak_Demand_Factor*Total_Turbulence_Info_ENR/Terminal_Area

Peak_Turbulence_Downlink_TERM = Terminal_Area_Peak_Demand_Factor*Total_Turbulence_Info_TERM/Terminal_Area

Peak_Winds_Downlink_ENR = Total_Winds_Aloft_ENR*Enroute_Peak_Demand_Factor/Terminal_Area

Peak_Winds_Downlink_TERM = Terminal_Area_Peak_Demand_Factor*Total_Winds_Aloft_TERM/Terminal_Area

Percent_of_Aircraft_in_Conflict = Conflict_Percentage*Traffic_Multiplier

Proximity_Shell = 10

Pulse_Width = 1e-6

Radar_Angular_Resolution = 1

Radar_Azimuth_Coverage = 60

Radar_Elevation_Coverage = 30

Radar_Range = 450

Radial_Distance_per_Pulse = Speed_of_Light*Pulse_Width/2

Sampling_Rate_of_Aircraft_Sensor = MAX(Convective_Wx_Sampling_rate,Icing_Sampling_Rate,Turbulence_Sampling_Rate,Winds_Aloft_Sampling_Rate)

SATS_Scaling_Factor = if SATS_Switch = 1 then

1.60

else

1.0

SATS_Switch = 1

Scaling_Factor_for_Enroute_Flights = 1.9

Speed_of_Light = 3e5

Tactical_Area = 9e4

Tactical_Surveillance_Update = 30

TD_ENER_cr = 40

Terminal_Area = 38000

Terminal_Area_Peak_Demand_Factor = .30

Terminal_Conflict_Message_Rate = 3

Toal_Icing_Info_TERM = Icing_Sampling_Rate*Aircraft_in_Terminal_Areas*Icing_Information

Total_Aircraft_as_WX_Sensor_Load = Peak_Convective_Downlink_ENR+Peak_Convective_Downlink_TERM+Peak_Icing_Downlink_ENR+Peak_Icing_Downlink_TERM+Peak_Turbulence_Downlink_ENR+Peak_Turbulence_Downlink_TERM+Peak_Winds_Downlink_ENR+Peak_Winds_Downlink_TERM

Total_Airport_Areas = No_of_Airports*Airport_Area

Total_ARTCC_Area = Enroute_Area*No_of_ARTCCs

Total_Bytes_for_Enroute_Conflicts = Bytes_per_ENR_Conflict_Message*Exchange_Messages_Enroute

Total_Bytes_for_Terminal_Conflicts = Bytes_perTerminal_Conflict_Message*Exchange_Messages_terminal

Total_Bytes_FST_Service = No_of_Cells_in_FST*No_of_Bytes_per_Cell

Total_Bytes_in_Air_to_Air_Mode = Total_Bytes_for_Enroute_Conflicts+Total_Bytes_for_Terminal_Conflicts

Total_Bytes_in_FS_Surveillance =

(Aircraft_in_Airport_Areas+Aircraft_in_Enroute_Region+Aircraft_in_Terminal_Areas)*Bytes_in_Far_Strategic_Surveillance_Mode*Far_Strategic_Surveillance_Update

Total_Bytes_in_NS_Surveillance = (Aircraft_in_Airport_Areas+Aircraft_in_Enroute_Region+Aircraft_in_Terminal_Areas)*Bytes_in_Near_Strategic_Surveillance_Mode*Near_Strategic_Surveillance_Update

Total_Bytes_in_Tactical_Surveillance = (Aircraft_in_Airport_Areas+Aircraft_in_Enroute_Region+Aircraft_in_Terminal_Areas)*Bytes_in_Tactical_Surveillance_Mode*Tactical_Surveillance_Update

Total_Bytes_NST_Service = No_of_Bytes_per_Cell*No_of_Cells_in_NST

Total_Bytes_TAC_Service = No_of_Bytes_per_Cell*No_of_Cells_in_TAC

Total_Convective_Wx_ENR = Convective_Weather_Information*Aircraft_in_Enroute_Region

Total_Convective_Wx_TERM = Convective_Weather_Information*Convective_Wx_Sampling_rate*Aircraft_in_Terminal_Areas

Total_Icing_Info_ENR = Icing_Information*Aircraft_in_Enroute_Region*Icing_Sampling_Rate

Total_Terminal__Areas_Footprint = No_of_Terminal_Areas*Terminal_Area

Total_Turbulence_Info_ENR = Turbulence_Information*Aircraft_in_Enroute_Region*Turbulence_Sampling_Rate

Total_Turbulence_Info_TERM = Aircraft_in_Terminal_Areas*Turbulence_Information*Turbulence_Sampling_Rate

Total_Winds_Aloft_ENR = Aircraft_in_Enroute_Region*Winds_Aloft_Info_per_Acft*Winds_Aloft_Sampling_Rate

Total_Winds_Aloft_TERM = Aircraft_in_Terminal_Areas*Winds_Aloft_Info_per_Acft*Winds_Aloft_Sampling_Rate

Traffic_Multiplier = (Time_Scale_Factor+SATS_Scaling_Factor)^2

Turbulence_Information = 16

Turbulence_Sampling_Rate = Aircraft_Wx_Sampling_Rate

Winds_Aloft_Info_per_Acft = 64

Winds_Aloft_Sampling_Rate = Aircraft_Wx_Sampling_Rate

Year_of_Analysis = 2020

Table Functions

Acft_Demand_Function = GRAPH(time)

(0.00, 1.00), (60.0, 1.00), (120, 1.00), (180, 1.50), (240, 2.40), (300, 3.50), (360, 4.80), (420, 5.40), (480, 4.40), (540, 4.80), (600, 5.20), (660, 5.10), (720, 4.30), (780, 4.40), (840, 4.20), (900, 4.30), (960, 4.60), (1020, 4.20), (1080, 4.60), (1140, 3.70), (1200, 3.20), (1260, 2.80), (1320, 3.20), (1380, 2.70), (1440, 1.20)

Conflict_Percentage = GRAPH(Proximity_Shell)

(10.0, 4.00), (15.0, 10.0), (20.0, 22.0), (25.0, 43.0), (30.0, 75.0)

Dwell_Time_at_Airport = GRAPH(time)

(0.00, 300), (60.0, 300), (120, 300), (180, 250), (240, 250), (300, 250), (360, 250), (420, 120), (480, 120), (540, 120), (600, 75.0), (660, 60.0), (720, 60.0), (780, 60.0), (840, 60.0), (900, 69.0), (960, 90.0), (1020, 111), (1080, 146), (1140, 200), (1200, 243), (1260, 285), (1320, 700), (1380, 700), (1440, 1000)

Grid_Size_of_Cell_Map = GRAPH(Sampling_Rate_of_Aircraft_Sensor)

(6.00, 1.00), (15.0, 0.85), (24.0, 0.7), (33.0, 0.55), (42.0, 0.4), (51.0, 0.25), (60.0, 0.1)

No_of_Cells_in_FST = GRAPH(Grid_Size_of_Cell_Map)

(0.1, 2e+06), (0.25, 1.2e+06), (0.4, 0.00), (0.55, 0.00), (0.7, 315000), (0.85, 0.00), (1.00, 123000)

No_of_Cells_in_NST = GRAPH(Grid_Size_of_Cell_Map)

(0.1, 7.2e+07), (0.25, 1.6e+07), (0.4, 6e+06), (0.55, 3e+06), (0.7, 1.5e+06), (0.85, 1e+06), (1.00, 720000)

No_of_Cells_in_TAC = GRAPH(Grid_Size_of_Cell_Map)

(0.1, 9e+06), (0.25, 2e+06), (0.4, 900000), (0.55, 500000), (0.7, 183000), (0.85, 100000), (1.00, 90000)

Time_Scale_Factor = GRAPH(Year_of_Analysis)

(1999, 0.46), (2001, 0.51), (2004, 0.582), (2006, 0.648), (2008, 0.708), (2011, 0.774), (2013, 0.851), (2016, 0.923), (2018, 0.96), (2020, 1.00), (2023, 1.06), (2025, 1.09)

Appendix B. Sample FAA ETMS Data.

The following dataset showcases the structure of the streamlined FAA Enhanced Traffic Management System flight plan information. This information was used in this research project to study air traffic flows around congested regions of airspace in NAS. These traffic flows serve as the basis for the derivation of aeronautical communication requirements in the LATFM model.

The data presented below illustrates a typical flight plan from New York John F. Kennedy International Airport (KJFK) to Los Angeles International (KLAX). The flight is performed with a Boeing 767 aircraft by American Airlines (AA). Figures B1 and B2 illustrate graphically the spatial trajectory of the filed flight plan.

```
AAL1________00_0 YYY B767 YYY YYY   1
AAL1________00_0  JFK   LAX    40.640   73.779  866   33.943  118.408 1152  14:26   286 0 C  50
IZYYYYYY  40.633   73.783   0  866.000    123   123
YYYYYYYY  40.417   74.143 112  871.885    330   304
YYYYYYYY  40.200   74.500 208  875.749    386   345
YYYYYYYY  40.285   74.988 282  879.526    441   386
YYYYYYYY  40.369   75.477 330  882.941    477   413
YYYYYYYY  40.450   75.967 347  886.272    477   411
YYYYYYYY  40.500   76.283 348  888.425    477   412
YYYYYYYY  40.550   76.600 349  890.573    477   412
YYYYYYYY  40.592   77.016 350  893.360    477   413
YYYYYYYY  40.633   77.433 350  896.142    477   414
YYYYYYYY  40.650   77.800 350  898.568    477   414
YYYYYYYY  40.687   78.282 350  901.762    477   415
YYYYYYYY  40.723   78.765 350  904.951    477   416
YYYYYYYY  40.756   79.249 350  908.132    477   417
YYYYYYYY  40.787   79.732 350  911.305    477   418
YYYYYYYY  40.817   80.217 350  914.472    477   419
YYYYYYYY  40.900   81.683 350  923.999    477   424
YYYYYYYY  40.900   81.817 350  924.854    477   425
YYYYYYYY  40.967   84.200 350  940.081    477   430
YYYYYYYY  40.983   85.183 350  946.289    477   433
YYYYYYYY  41.167   86.583 350  955.179    477   437
YYYYYYYY  41.167   89.583 350  973.665    477   448
YYYYYYYY  40.550   91.400 350  985.723    477   455
YYYYYYYY  40.417   91.783 350  988.259    477   455
YYYYYYYY  40.283   92.183 350  990.891    477   457
YYYYYYYY  40.133   92.583 350  993.574    477   456
```

YYYYYYYY	39.783	94.183	350	1003.617	477	459
YYYYYYYY	39.633	94.800	350	1007.519	477	459
YYYYYYYY	38.933	97.617	350	1025.428	477	461
YYYYYYYY	37.917	100.733	350	1046.062	477	461
YYYYYYYY	36.500	104.867	350	1074.123	477	457
YYYYYYYY	35.483	108.867	350	1100.881	477	456
YYYYYYYY	34.933	111.383	350	1117.655	477	458
YYYYYYYY	34.700	112.483	350	1124.986	477	461
YYYYYYYY	34.567	113.633	350	1132.452	477	456
YYYYYYYY	34.550	113.683	350	1132.802	477	459
YYYYYYYY	34.465	114.101	350	1135.583	477	459
YYYYYYYY	34.378	114.518	350	1138.365	477	459
YYYYYYYY	34.290	114.935	350	1141.146	477	459
YYYYYYYY	34.200	115.350	350	1143.926	477	460
YYYYYYYY	34.117	115.767	350	1146.704	477	466
YYYYYYYY	34.109	116.250	348	1149.798	438	427
YYYYYYYY	34.100	116.733	275	1153.199	435	419
YYYYYYYY	34.075	116.983	234	1155.014	429	410
YYYYYYYY	34.050	117.233	191	1156.889	409	393
YYYYYYYY	34.033	117.400	162	1158.184	393	381
YYYYYYYY	34.017	117.633	129	1160.075	369	361
YYYYYYYY	34.000	117.767	113	1161.221	345	340
YYYYYYYY	33.975	118.083	66	1164.440	252	253
LZYYYYYY	33.950	118.400	0	1168.621	219	225

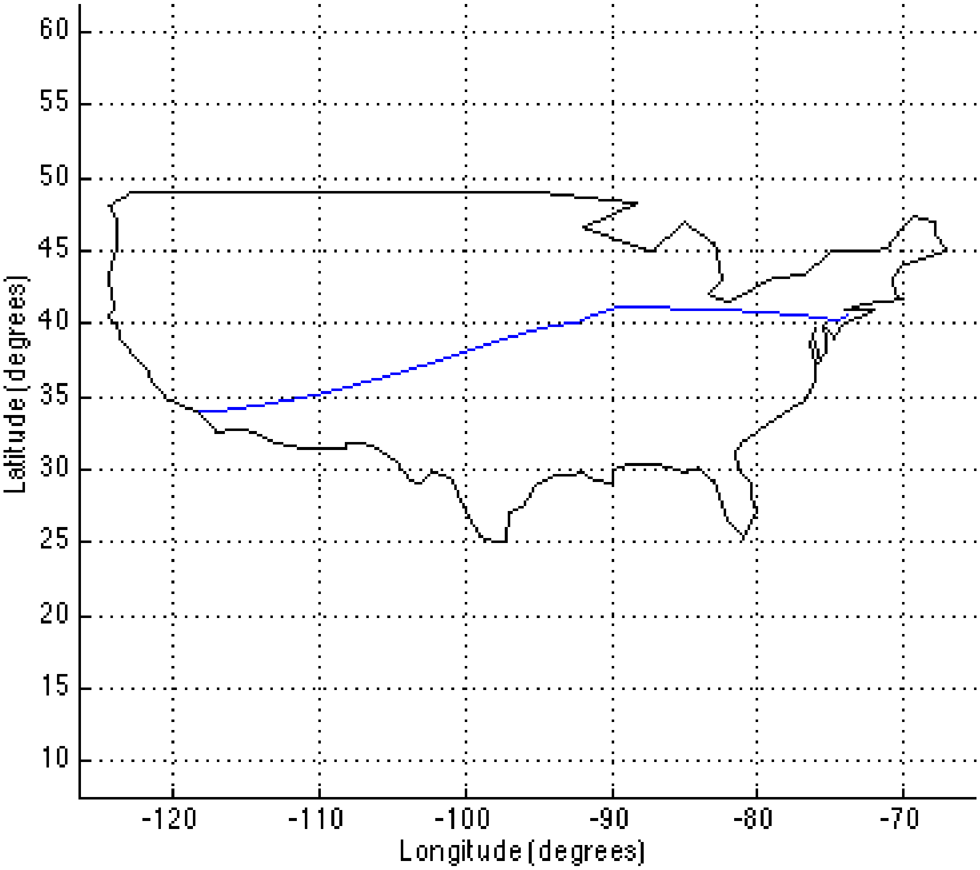

Figure B1. Graphical depiction of the ETMS filed plan.

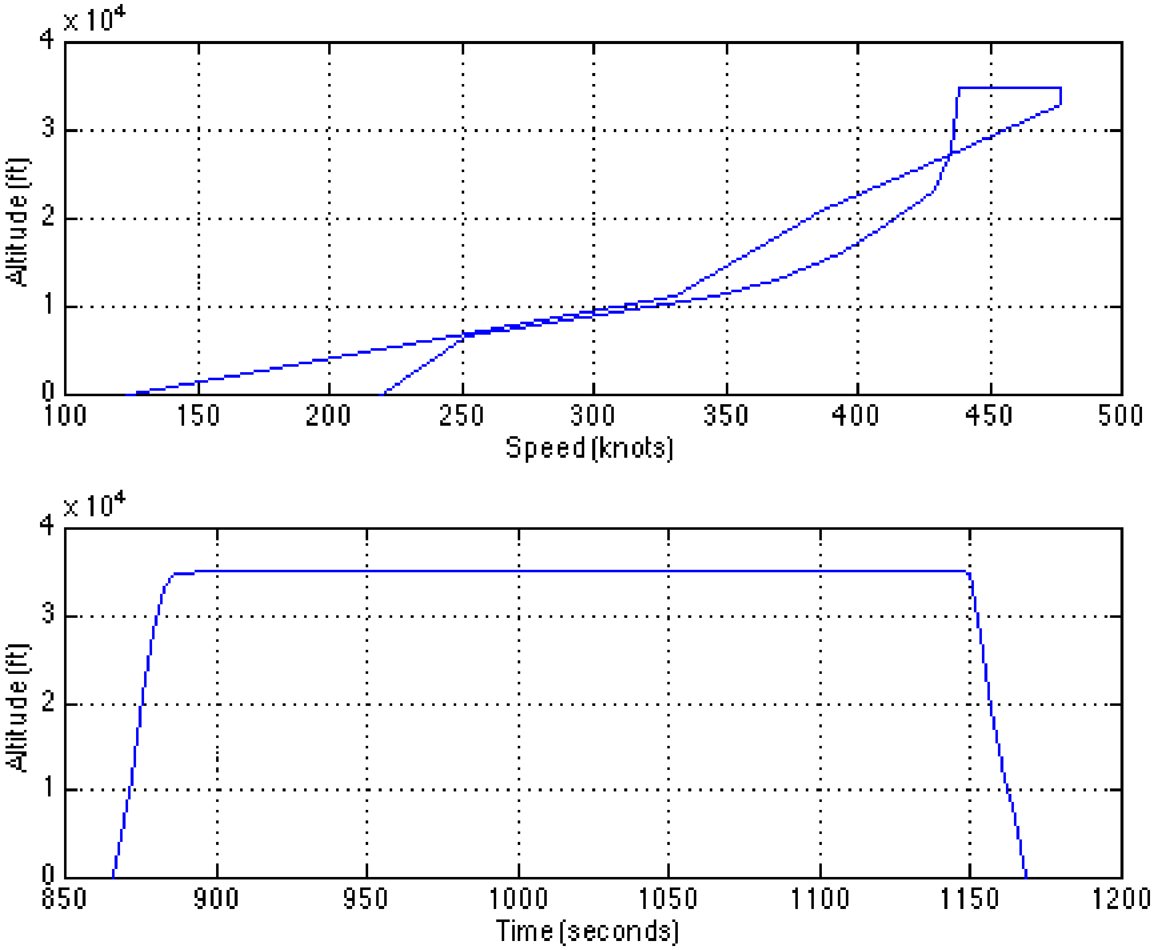

Figure B2: Speed and altitude profiles of the ETMS flight plan.