Commercial Aircraft Sensor Improvements Required

For A Successful Implementation of NextGen

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1. Introduction

The Next Generation Air Transportation System (NextGen) is in the planning stage. The Concept of Operations (ConOps) by the Joint Planning and Development Office (JPDO) is an iterative and evolutionary process that allows input and feedback from the entire aviation community. NextGen involves complex changes in the way air traffic management is performed. Virtually every facet of NextGen involves weather and the environment, with many organizations and individuals involved in various aspects of weather applications. This discussion is this document is framed around the results of the JPDO Weather Functional Study Team, who have produced a document "Four Dimensional Weather Functional Requirements for NextGen Air Traffic Management", available on the internet and dated January 18, 2008.
No overlap is intended here as the radar, satellite, and modeling aspects of aviation weather are covered elsewhere. **Only current and future in situ sensor systems on board commercial and business aircraft that measure key atmospheric parameters are addressed in this document. These sensors provide measurements of the three fundamental fields of the atmospheric that are central to aviation weather and weather prediction in general: water vapor, temperature, and wind fields.**

A spectrum of time horizons must be addressed in NextGen – these include planning, aspects of en route and cruise operations, ascent and descent phases of flight, and terminal operations. This document will be organized about these points. Section 2 defines a few key terms in NextGen, including the Automatic Dependent Surveillance- Broadcast (ADS-B) system and Trajectory **based Operations (TBO).** The success of **TBO** will depend upon aircraft having a 4-D trajectory – a precise description of the aircraft's path in space and time. Knowledge of the position of every aircraft, and the uncertainty in that position, is crucial for future aviation operations in the national airspace system (NAS). Section 3 reviews the sources of uncertainties associated with the aircraft position over time. This section reveals the necessity for improved sensors on the aircraft for optimizing the safety and efficiency of TBO. Section 4 indicates the impacts of uncertainties on several operational examples drawn from the spectrum of NextGen **functional categories** defined over time. These examples can be updated with the methodology employed to help evolve optimal NextGen procedures.

More than just aircraft position accuracy is at stake. The weather's role is vital in all NextGen activity. The improved information from the aircraft sensors, combined with all other sources of weather information, contribute a quantum leap forward for aviation weather and weather prediction in general. Section 5 concludes with a summary of required actions for the provision of important sensors that must be added to commercial and business aircraft to help meet NextGen objectives throughout the NAS. Arguments for accelerating Federal Aviation Administration (FAA) actions to provide these accurate sensors for commercial and business aircraft are provided in this Section.

The final message is this document is clear -- the atmosphere is a chaotic system in perpetual motion! Unless there is near unanimous participation of commercial and business aircraft in equipping necessary sensors on such aircraft – in order to reduce position and velocity uncertainties, and to help improve our knowledge of the thermodynamic state of the atmosphere, the NextGen will fail to achieve its goals.

2. Definition of NextGen Terms

2.1 Automatic Dependent Surveillance – Broadcast (ADS-B)

The Automatic Dependent Surveillance –Broadcast (ADS-B) is a cooperative surveillance technique for air traffic control and related applications. An ADS-B equipped aircraft determines its own position using a global navigation satellite system and periodically broadcasts this position and other relevant information to ground stations and other aircraft with ADS-B receiving equipment. ADS-B is more accurate than today's air-traffic control secondary radar, which measures the range and bearing of the aircraft. An ADS-B based system is more accurate as it listens for position reports broadcast by the aircraft. These position reports are based upon accurate navigation systems, such as the Global Positioning System **(GPS).** The accuracy is now determined by the accuracy of the navigation system and unaffected by range.

Detecting aircraft **velocity** changes via the radar requires tracking the received **position** data. Changes can only be detected over a period of radar sweeps that are several seconds apart. With ADS-B, **velocity** changes are broadcast more frequently as part of the State Vector report. Under ADS-B, a vehicle (aircraft or ground) broadcasts without knowing what other vehicles or entities might be receiving it, and without expectation of an acknowledgement or reply – hence it is **automatic**. It is **dependent surveillance** in the sense that the surveillance information so obtained depends on the suitable navigation and **broadcast capability** in the source vehicle.

The broadcast capability for the ADS-B version used in the United States is designed as two different systems operating in the L-band (microwave signals with good range, but unable to penetrate buildings or mountains). This duel broadcast link uses the **1090 MHz Mode S Extended Squitter** (ES) and **978 MHz** Universal Access Transceiver (UAT) as mediums. The 1090 MHz ES **ADS-B link** is for air carrier and private/commercial operators of high performance aircraft, and the UAT **ADS-B link** is for the typical general aviation user. Information can be sent from the ground to the aircraft via **ADS-B** and other legacy communication systems.

2.2 Trajectory Based Operations (TBO)

The expected capacity, efficiency, and safety increases in the next generation air traffic management system are based upon a significant change – moving from an air traffic management system (ATM) based upon clearance – based operations to **TBO.** The success of **TBO** will depend upon aircraft having a four dimensional trajectory – a precise description of the aircraft's path in space and time. With accurate **TBO,** the precise management of an aircraft's current and future position enables major increases in air traffic throughput. This trajectory prediction capability facilitates separation assurance in the airspace; it further allows the delegating of separation to capable aircraft for some operations, further improving efficiency and throughput. Peak demand at the busiest airports is accommodated with **super-density arrival/departure operations,** in which advanced aircraft and Air Navigation Service Providers **(ANSP)** capabilities support optimized and efficient runway throughput. The ANSP personnel are aided by sophisticated automation of weather information for both en route and air terminal operations.

Using **TBO** and probabilistic decision making for weather events, entire flows of aircraft and individual trajectories can be dynamically adjusted to take advantage of opportunities – avoiding weather constraints safely and efficiently while reducing the overall impact of these events. To accomplish these trajectory actions, digital data exchange of trajectories becomes the primary mode of communication between the **ANSP** and flight operators, replacing verbal delivery of clearances.

2.3 Communications Update Rate

There remains an important research question to be carefully answered "what tolerances in the **time dimension** are needed to make the 4-dimensional trajectories (**4DT)** practical and at the same time safe for aviation applications?" One of these key tolerance questions refers to the **update rate** of the **4DT** information across the communication system. The **update rate** is the frequency with which 4DT and other information is simultaneously upgraded across the Net-enabled Information network (NEI) – creating situation awareness for all elements of the NAS. The communication system must be capable of a communicating without interference. With 14,000 aircraft in the air (expected in 2025), additional **TBO** data sets, today's communications of highly used reports (Out, Off, ON, IN [OOOI] reports, engine performance analysis data, meteorological data), and a host of other information items, a seamless communication system must be created.

The **update rate** will evolve as the NEI network evolves. This evolution requires the linking of legacy systems with new **ADS-B** systems so that information can be exchanged seamlessly. Communication architecture is being developed by a few large and knowledgeable companies in a joint effort called System-Wide Information management (SWIM) to provide this capability. The **update rate** may be different for different NextGen **Functional Categories** (flow corridors [perhaps 12 to 20 seconds], continuous descent approach, etc.).

2.4 Required Navigational Performance

Related to the **update rate** is another key parameter. This is the **Required Navigation Performance (RNP) Level (X)**, where **X** is a value, in **nautical miles (nm),** from the intended horizontal position within which an aircraft would be at least 95% of the total flying time. The **RNP-X** is the required navigation performance accuracy necessary for operation within a defined airspace. An **RNP = 0.3 means the aircraft is within 0.3 nautical miles of its intended horizontal position 95% of the time, and within 0.6 naut. mi. 99.999% of the time.**

Clearly, X will be determined by several factors – first and foremost will be safety, followed by efficiency (capacity). What is the value of X that will assure safety and yet maximize efficiency and capacity? Obviously, X is also related to the **update rate** as a longer **update rat**e will lead to greater uncertainty in aircraft position.

2.5 Atmospheric Model Refresh Rate

The tools of ADS-B and TBO are powerful, but it remains to be proven how safe they will be when **operating in the Earth's complex chaotic atmosphere.** Any individual aircraft can obtain a quite accurate position and velocity from GPS every second. But for everybody (all the aircraft and the ANSP operating in a portion of the NAS) to be on the same page, the current position and **future position (the projected 4DT)** of all those aircraft must be uplinked to the aircraft. Between update times the aircraft will move and have positions with some uncertainty based upon uncertainties in the true air speed and upon the uncertainties of the **background atmospheric wind field** in which the aircraft fly.

One cannot measure the **future** wind field, but one can predict it with a numerical model with some uncertainty. The accuracy of the prediction will depend upon the both the **accuracy and frequency** of the data input to the model, and upon the settling time for the model to equilibrate (dynamic mathematical adjustment between the data and the model). The uncertainty of the wind field will be a part of the projected **4DT**, thus the **refresh rate** is important.

The communication **update rate** will be on the order of seconds (perhaps 8 to 20 seconds), while the model **refresh rate** on the order of minutes (ranging from a minimum of 5 minutes in the terminal area and longer for other applications)**.** Clearly, more accurate aircraft sensors can help with model accuracy – lowering **position uncertainty** and the **RNP.**

3. Error Sources in Aircraft Position over Time

It has been indicated that the atmosphere is a chaotic system in perpetual motion! The three critical fields of water vapor, temperature, and winds interact with each other in a nonlinear fashion over all time scales. This document addresses these critical fields and how they impact the two aviation weather missions of NextGen: (1) maintaining navigational accuracy and integrity (this Section) and (2) providing the thermodynamic basis for analysis and prediction of aviation weather phenomena that impact the NextGen **functional categories** (see Section 4).

The first consideration for the NextGen TBO is to have all **users** on the same page referencing an **accurate data set** of the four dimensional trajectory of each aircraft in the national air space. An accurate data set will include the current position and velocity of the aircraft and all **future** positions and velocities along the intended trajectory. Obviously, providing this accurate data set will entail **position accuracy**, **velocity accuracy**, the effective **update rate** at which all users have access to each aircraft's TBO data, the **density of traffic** in a given airspace, and the final agreed upon allowable **separation distance** for each application air space type or **functional category.**

The analysis of position uncertain **(ΔP)** for any given aircraft will have components of initial uncertainty from the GPS [**ΔP (GPS)**], and other velocity components [**ΔV (X)**] multiplied by some **function of time** – where the X will take on one of three forms discussed below. **The function of time is discussed in Section 3.4.** Only positive error values for position and velocities are given in the sections below, but of course these errors could be plus or minus values.

3.1 GPS Position and Velocity Errors

The GPS is quite accurate. The position error for the en route phase is 30 meters or 0.016 nautical miles (nm). Note that for terminals with Wide Area Augmentation System available the position error is 10 meters. Thus the initial position error is **ΔP (GPS) = 0.016 nm.** Today, with the combined use of INS, the Global Positioning System (GPS), and the software tool of the

Kalman filter, the **initial velocity** errors can be quite small. The **ΔV (GPS)** error has been estimated from a collocation study of winds from the Aircraft Communications Addressing and Reporting System (ACARS) reports from commercial aircraft. Benjamin, et al (1999) indicated an error of about **1.8 meters/second (m/s).** Today's GPS/INS systems should be able to lower this to **1.0 m/s.** Thus for the initial velocity error due to GPS will be **ΔV (GPS) = 1.0 m/s.** The error in position due to the velocity error is shown in Section 3.4.

3.2 Errors in True Air Speed

True air speed (TAS) is obtained from the **indicated air speed** [Mach number (M)] times the **speed of sound**. The speed of sound is a function of the ambient temperature; thus, **TAS** is a function of the local ambient temperature **(T_S)** at flight level. The Mach number (the **indicated air speed**) is obtained from a pitot tube which measures both **impact pressure** (also referred to as dynamic pressure or **total pressure)** and the **static pressure** (also called the outside air or ambient pressure). The relationship between the **total pressure (P_T)** and **static pressure (P_S)** is given by:

$$P_T = P_S \, (1 + 0.2\, M^2)^{3.5} \qquad (1)$$

The relationship between the dynamic temperature **(T_T)** and static temperature **(T_S) is:**

$$T_T = T_S \, (1 + 0.2\, M^2) \qquad (2)$$

The total pressure and temperature are due to the kinetic energy of the moving aircraft.

TAS of an aircraft in the atmosphere is given by:

$$TAS = (M)\,([\text{Speed of sound}]) = (M)\,[(\gamma\, R\, T)]^{1/2} = (M)\,[(1.4)(287.05)\,)(T)]^{1/2}$$

$$TAS = (M)\,[(401.87)\,(T)]^{1/2} \qquad (3)$$

where T = T_S in degrees Kelvin and TAS is in m/s with the above constants used in Eq (3).

The Mach number (M) can be obtained by inverting Eq. **(1)**:

$$M = \{ (5)\,[(P_T / P_S)^{2/7} - 1] \}^{1/2} \qquad (4)$$

The ambient atmospheric temperature (**T_S**) is obtained from Eq. (2), with a measurement of **T_T** from a total air temperature **(TAT)** probe. The scientific community has been assessing the accuracy of **T_S** from aircraft – using the data as initial conditions in weather prediction models.

There are a number of concerns with today's TAT sensors (Fleming, 1996, 2008). The evaluated accuracy in the best of conditions is about 0.6 to 0.8 ºC. There is ample evidence that the errors, both **random** errors and systematic **biases,** are often much larger than this (Stickland, 1996; Baker, 1998; Pauley, 2000). The growth of real time transmission of aircraft temperatures and winds has exposed this temperature data to the scientific community. Significant **biases** have been determined, varying with different aircraft types (AMDAR Panel, 2004). Both the **random** error and the **biases** are apparently affected by the **environmental influences** on the TAT probe itself.

Both the **random error** and **bias error** of the **T_S** must be inserted into Eq. 3 to obtain the error in **TAS.** One can consider the **random error as $\Delta T = 0.7$** degrees (a compromise value) and then use this ΔT in Eq. (3) to compute **$\Delta V(TAS)_{Random}$**. The systematic bias error for this document will be set to the value of **$\Delta T = 2.0$** degrees, and then used in Eq. (3) to compute **$\Delta V (TAS)_{Bias}$.** This may be considered conservative by some as Pauley (2000) has found military aircraft communicating real time temperature data with systematic biases of 5 and 6 degrees. The error in position due to the error in TAS requires multiplying by some function of time. Since one error is **random** and the other is **biased**, this **time function** will be discussed in Section 3.4.

3.3 Errors in Atmospheric Model Winds

The **TBO f**or each aircraft in the NAS requires the current position and velocity and **future position and velocity** of the aircraft along its intended flight path. That future velocity will depend upon a predicted wind field from a numerical weather prediction model with a high

refresh rate. The predicted wind uncertainty will depend upon the accuracy of the initial analysis of the atmosphere and upon the skill of the model itself.

The **numerically analyzed wind field at a given time** will be a blending of the three fields (winds, temperature, and water vapor) **predicted** for that location **at that time,** plus all the available **observational data** of those fields – **merged dynamically in space and time** to optimize the analyzed fields as initial conditions for the next forecast integration. The analysis/prediction cycle repeats – today usually at a one or three hour cycle. The cycle (or **refresh rate**) will have a higher frequency (as low as 5 minutes) for NextGen.

The wind prediction capability of current models can be seen in Figure 1. The **blue curve on the left (labeled 0 h)** is the initial analysis error (numerical analysis minus observations).

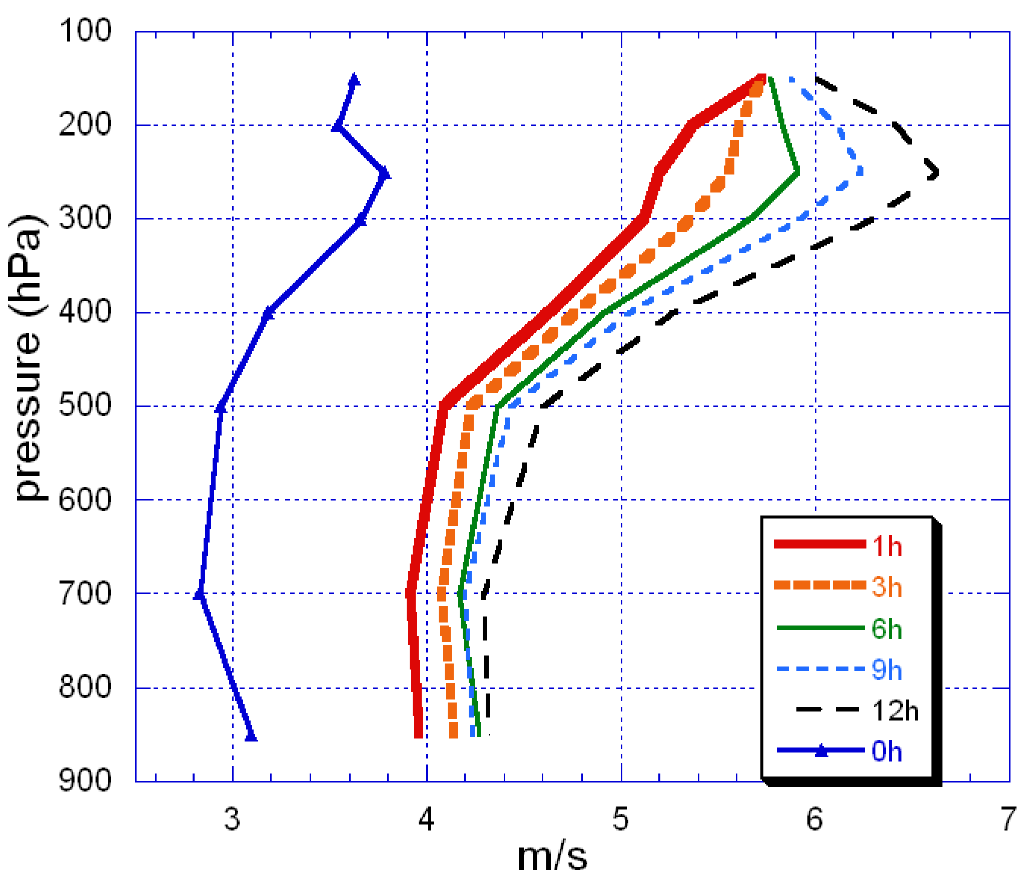

Figure 1. Forecast wind errors as a function of decreasing pressure (from NOAA/FSL)

The **numerically analyzed wind field** will be **smoothed** for more accurate wind predictions. This smoothing filters out non-representative errors (small scale turbulence, and fine scale structure in space and time). This filtering introduces a very small non-representative error that can be absorbed into the initial velocity error **ΔV (GPS), but now call it ΔV (OBS)** -- for use in Section 4.

The other labeled curves are for various prediction periods from 1 hour to 12 hours. These errors are quite substantial and one can see the need for a greater number of aircraft winds, and a need for significant improvement in numerical models prior to NextGen. **One can be optimistic that the error growth will be substantially less when all commercial aircraft are providing wind, temperature, and water vapor information in real time to the forecast models in use for NextGen.** In this document we will use an optimistic value for the model prediction error of the wind as **ΔV (ATM) = 3 m/s.**

3.4 Final Position Errors Due to All Sources.

The position errors from the velocity errors discussed in Section 3.1 to 3.3 are multiplied by a function of time to obtain the **ΔP f**or each. This function could be just "time" itself. For example, the **ΔV (TAS)** $_{\mathbf{Bias}}$ is a constant over time so the **ΔP = [ΔV (TAS)** $_{\mathbf{Bias}}$ **] [time] where time is in seconds.**

The velocity terms **ΔV (TAS)** $_{\mathbf{Random}}$ and **ΔV (GPS)** can be considered random and Gaussian over some time interval, but over the short time intervals of the **update rate** it would be unwise to think **these velocity errors** average out to a zero. A conservative policy (keeping aircraft safely separated) would be to hold these velocity errors constant over the length of the **update rate, but not increase the position error beyond that time.** The aircraft's ΔP would be limited to an increase of **[ΔV (TAS)** $_{\mathbf{Random}}$ **+ ΔV (GPS)] [time]** where time is limited – beyond which ΔP does not change.

The velocity term **ΔV (ATM)** is a hybrid term in that it actually increases over time as seen in Figure 1. The initial error value chosen (e.g., 3 m/s) can be considered constant over the short refresh rate of 5 minutes. However, for calculated uncertainties in position for forecast periods of 1-2 hours for moving flow corridors, or longer periods for planning purposes, this value must increase.

4. Impact of Uncertainties in Various NextGen Operations

The results of Section 3 can now be summarized into a single equation for the uncertainty in position of any given aircraft as a function of **update rate** and **model refresh rate:**

$$\Delta P = \Delta P\,(GPS) + [\Delta V\,(TAS)_{Random} + \Delta V\,(TAS)_{Bias} + \Delta V\,(GPS) + \Delta V\,(ATM)]\,[Time] \qquad (5)$$

Time	ΔP(GPS)	ΔP(OBS)	$\Delta P(TAS)_{Ran}$	$\Delta P(TAS)_{Sys}$	ΔP(ATM)	ΔP(TOT)
30,000 ft	M = 0.8	ΔV = 1.0	ΔT = 0.7	ΔT = 2.0	ΔV = 3.0	
12 sec	0.016	0.006	0.002	0.007	0.019	0.051
16 sec	0.016	0.009	0.009	0.009	0.026	0.069
20 sec	0.016	0.011	0.011	0.011	0.032	0.082
10 min	0.016	0.011	0.011	0.344	0.972	1.353
20 min	0.016	0.011	0.011	0.687	1.944	2.669
40 min	0.016	0.011	0.011	1.374	3.888	5.300
1 hour	0.016	0.011	0.011	2.061	5.832	7.931
2 hour	0.016	0.011	0.011	4.123	11.663	15.824
40,000 ft						
12 sec	0.016	0.006	0.003	0.007	0.019	0.052
16 sec	0.016	0.009	0.010	0.010	0.026	0.070
20 sec	0.016	0.011	0.012	0.012	0.032	0.083
10 min	0.016	0.011	0.012	0.359	0.972	1.369
20 min	0.016	0.011	0.012	0.719	1.944	2.701
40 min	0.016	0.011	0.012	1.438	3.888	5.364
1 hour	0.016	0.011	0.012	2.157	5.832	8.026
2 hour	0.016	0.011	0.012	4.314	11.663	16.015

Table 1. Total Position error (all in + / - nautical miles) for the en route phase of flight. The contribution of $\Delta V\,(TAS)_{Random}$ and ΔV(GPS) are zero beyond 20 seconds – that is, the position error does increase from these terms beyond 20 seconds.

Table 1 above summarizes these total position errors for a given aircraft in the en route phase of flight. The top half of the Table covers position errors at 30,000 ft and the bottom half for errors at 40,000 ft. The assumed errors for the GPS position and the various velocity errors are shown in **red.**

The **functional categories** of NextGen are presented over time—from the longest to the shortest time interval. The JPDO Weather Functional Requirements Study Team has recommended forecast increments and **forecast refresh rates** for the various NextGen **functional categories**. These range from a 3-hour forecast increment with a **1-hour refresh rate** for **longer term planning**, down to a 10-minute forecast increment with a **5-minute refresh** rate for **the case of convection in the terminal area.**

4.1 Improved Planning

Most air carrier plans need to be made at least 8-hours in advance. Unfortunately, the chaotic nature of the atmosphere and the lack of **quality measurements** of the three key fields over the four dimensions of space and time leave these forecasts with significant error as seen in Fig. 1. The **stability** of the atmosphere (controlled by both **temperature** and **water vapor)** dictates the degree of weather impact on aviation activities. Both temperature and moisture contribute to the stability of the atmosphere. Warm air is lighter than cold air. Moist air is lighter than dry air. Moisture is a key ingredient for atmospheric stability and a significant source of heat exchange as water changes its phase from ice to liquid to gas (water vapor). **Atmospheric water vapor affects virtually every aspect of aviation weather. Moisture affects ceiling and visibility, the type and amount of precipitation, and atmospheric convection (microbursts, thunderstorms, severe thunderstorms with hail, and tornados.)**

In view of the paucity of quality data in the vertical dimension, it is imperative that aviation helps itself by measuring the water vapor, temperature, and wind fields accurately from the aircraft platform itself! The information from balloon launches every 12 hours does not serve aviation requirements. Moreover, the water vapor information is poorly measured from the balloons and other systems. **Figure 2.** dramatically reveals how bad the water vapor variable is measured and predicted. Shown in the Figure is **relative humidity (RH)** [but it could as well have been the **dew point** values or the **water vapor mixing ratio** – all are related to each other when pressure and temperature are known]. The initial analysis has errors ranging from 8-10%. The errors in the predictions are very poor at all forecast periods -- showing pathetic errors from

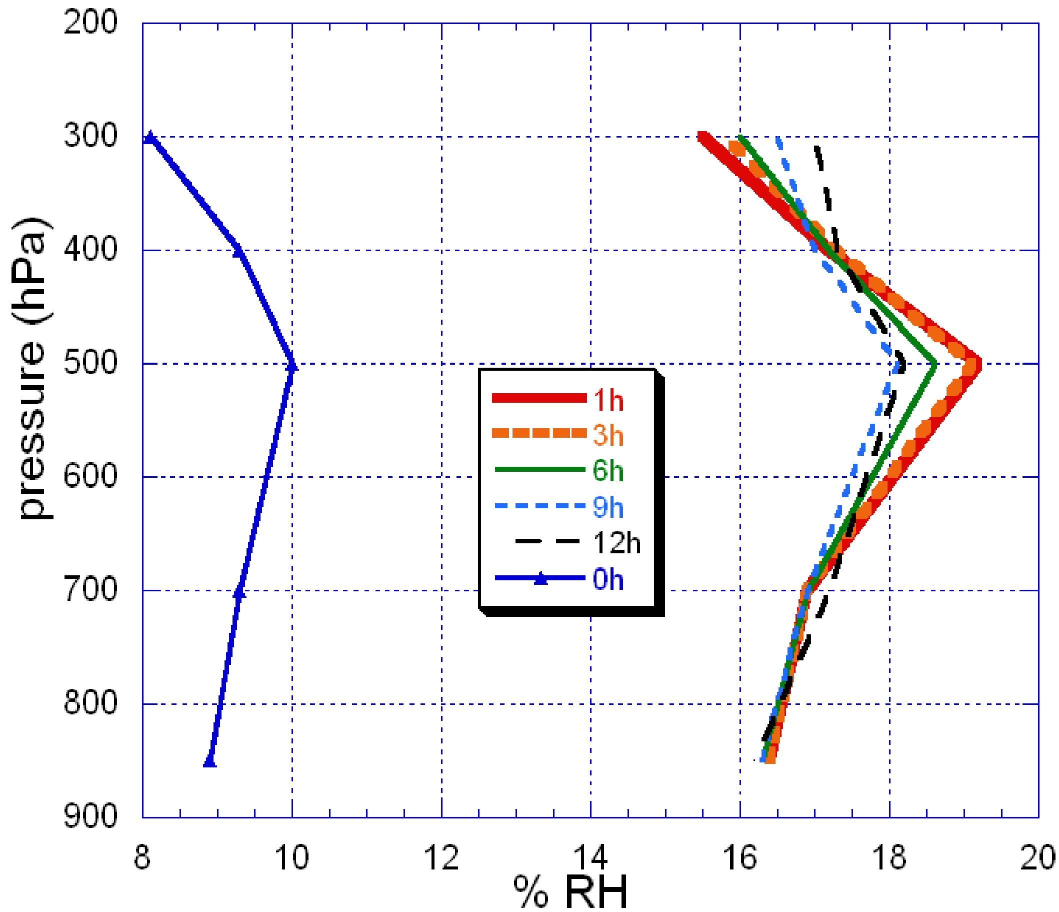

Figure 2. Forecast errors of RH as a function of pressure (from NOAA/FSL)

16 to 19% for all periods – whether 1-hour forecasts or 12 hour forecasts they are all quite bad.

Reliable detection of hazardous weather and predictions thereof for **several hours in advance** are essential for advanced planning. Perhaps far more important are the occasional very rapid developments of **convective systems** that can impact **all** the NextGen **functional categories. Accurate water vapor information from all commercial and business aircraft is crucial for convective prediction in NextGen.**

4.2 Improved En Route Operations and Flow Corridors

There are different distinct types of airspace use for en route and cruise envisioned, but all require **4DT on aircraft with increased 4DT capability.** The first is for oceanic and remote airspace. The current separation requirement in ocean air space is 120 nm. One goal expressed in internet articles on NextGen is to reduce this separation to 5 nautical miles (nm). **Here there is a potential problem in meeting this goal unless all aircraft are properly equipped.**

For areas outside the NAS the model horizontal resolution is 10 km and the forecast **refresh rate is 30 minutes**. An aircraft may have an updated forecast right after it was issued or may have one that is 30 minutes old. Therefore, on average, one may assume an **average effective refresh rate** of 15 minutes. Interpolating Table 1 for 15 minutes (using 10 min and 20 min values) the tabular value is + / - 2.01nm or a ΔP of 4.02 nm. Multiplying by a factor of three for safety provides an uncertainty of **12.06 nm** – more than twice the goal of 5 nm. However, as the community moves toward these better sensors for aircraft, one can eliminate the temperature bias error, and one can expect to have the model wind error from 3 m/s to 1.5 m/s. Using these values and the same **refresh rate** the tabular rate from Eq. (5) becomes + / - 0.767 nm or a ΔP of 1.534 nm. Multiplying by the safety factor of three provides an average RNP value of **4.6 nm** which meets the goal.

The second level of airspace use is for more capable aircraft which would occupy the **more efficient routes and altitudes.** When demand is very high, the ANSP may implement "flow corridors" for large numbers of separation-capable aircraft traveling in the same direction on very similar routes. Flow corridors consist of long tubes or "bundles" of near-parallel **4DT** assignments, which consequently achieve a very high traffic throughput. The airspace for aircraft operating in flow corridors is protected; aircraft not part of the flow do not penetrate the corridor.

The 4DT assignments in a flow corridor do not ensure that conflicts never occur, but do ensure they are resolved with **small speed or trajectory adjustments.** The corridor is large enough for aircraft to use their separation capabilities for entering and leaving the corridors -- accomplished with well-defined procedures to ensure safety. The flow corridors would be at such levels to take advantage of jet stream conditions for west to east flow between major hub terminals, and the corridors would be moved appropriately to minimize head winds for all traffic.

Using Table 1 for this case and an update rate of **20 seconds** reveals that the uncertainty in position would be **+ / -** 0.082 nm or that **ΔP** would be 0.164 nm. Using a safety factor of three times this number would give a **final ΔP = 0.492 nm.** Thus, the **X** value in **RNP value** would be **0.5 nm. Note that eliminating the temperature bias error and halving the ΔP (ATM) error would permit a RNP value of 0.26 nm.**

These numbers need not be exact now. They are acceptable for the flow corridor application under normal weather conditions. **However, a corridor may have to be dynamically shifted to avoid severe weather. This will make the real time transition of the corridor more challenging. This is where the vastly improved water vapor field will help make convection prediction several hours in advance a tractable problem – where it is not being adequately performed now. Then the critical task of optimally moving the flow corridors will be substantially easier.**

4.3 Choreographed Arrival/Departure Operations

The greatest improvements in air traffic control within NextGen will occur in the terminal environment. This is where the information from sensors on the aircraft can be provided with such high density and clarity that the three dimensional atmospheric structure around the airport becomes crystal clear – safely allowing enormous improvements in aircraft arrival and departure capacity. Not every automated thermodynamic report needs to be transmitted from every aircraft in the terminal near-surround. Pre-selected densities of reports can be established for a variety of weather scenarios. If a frontal system with a significant wind shift is bearing down on the terminal, then the density of thermodynamic reports can be dynamically increased appropriately to capture the precise time when runway usage must be changed. Other examples of scenarios abound.

Airspace around airports serving trajectory –based traffic is ANSP-managed, but aided with advanced automation – including the 4D atmospheric fields generated by the **aircraft thermodynamic reports,** satellite images, radar data, and conventional weather information. The

JPDO Weather Study Team (2008) has described a network-enabled four-dimensional weather data cube (4-D Wx Data Cube) as the best choice to ensure that accurate weather information is integrated into NextGen operational decision making. A subset of this 4-D Wx Data Cube, known as the Single Authoritative Source **(4-D Wx SAS),** provides seamless, consistent weather information for ATM decisions.

Integrating arrival/departure procedures with improved airport surface management will ensure that arrival flows match airport capacity for improved overall throughput. The entire integrated procedure will eliminate today's low-altitude path-stretching and holding patterns. A further service at major airports with peak periods of heavy traffic will have **super-density arrival/departure operations** for high-capability aircraft. This is only implemented when warranted by demand; at other times operations revert back to accepting **all trajectory-based traffic.**

With the full gamut of information available in the terminal area, it will be possible to have aircraft approaching from all four quadrants surrounding the terminal. All aircraft can be choreographed to spiral down in curved paths in **continuous descent approach (an uninterrupted descent from cruise altitude to near touchdown with near-idle power).** The position and velocity adjustments can be accurate enough to produce a landing sequence that is extremely safe and efficient! **Continuous descent approach** has already been tested in Louisville, KY and shown to produce significant (34%) fuel savings.

A high density of aircraft thermodynamic reports sent to the 4D atmospheric data base for the terminal area must be maintained for another reason. Modern 4-dimensional data assimilation methods (4DDA) and proper data base managements methods can gather statistics of individual aircraft over time and detect sensors that have **anomalous behavior**. This will add **further quality to the 4DT data for all other airspace applications.**

Table 2 is a revised version of Table 1 with lesser errors in two categories, and the Table applies to the **terminal area (thus ΔP (GPS) is now only 10 meters versus 30 meters).**The Table only covers the 30 minute arrival/departure optimization process. The numbers are approximate in the Table as the **average Mach number was used for the track from 30,000 feet to 2000 feet.** In NextGen's terminal computer, the actual Mach and temperature at each altitude would be provided with great accuracy. The **top of the table** has the original current estimate of **temperature bias of 2 degrees** and the **ΔV (ATM) = 3 m/s.** The **bottom of the table** has the temperature **bias removed** and **ΔV (ATM) was reduced from 3 m/s to 1.5 m/s.**

Time	ΔP(GPS)	ΔP(OBS)	$\Delta P(TAS)_{Ran}$	$\Delta P(TAS)_{Sys}$	ΔP(ATM)	ΔP(TOT)
16,000 ft	M = 0.5	ΔV = 1.0	ΔT = 0.7	ΔT = 2.0	ΔV = 3.0	
12 sec	0.005	0.006	0.002	0.004	0.019	0.037
16 sec	0.005	0.009	0.005	0.005	0.026	0.051
20 sec	0.005	0.011	0.007	0.007	0.032	0.062
1 min	0.005	0.011	0.007	0.020	0.097	0.145
5 min	0.005	0.011	0.007	0.101	0.486	0.615
10 min	0.005	0.011	0.007	0.203	0.972	1.202
20 min	0.005	0.011	0.007	0.406	1.944	2.377
30 min	0.005	0.011	0.007	0.608	2.916	3.551
16,000 ft	M = 0.5	ΔV = 1.0	ΔT = 0.7	ΔT = 0.0	ΔV = 1.5	
12 sec	0.005	0.006	0.002	0.000	0.010	0.023
16 sec	0.005	0.009	0.005	0.000	0.013	0.027
20 sec	0.005	0.011	0.007	0.000	0.016	0.032
1 min	0.005	0.011	0.007	0.000	0.049	0.072
5 min	0.005	0.011	0.007	0.000	0.243	0.266
10 min	0.005	0.011	0.007	0.000	0.486	0.509
20 min	0.005	0.011	0.007	0.000	0.972	0.995
30 min	0.005	0.011	0.007	0.000	1.458	1.481

Table 2. Position Uncertainties in arrival/departure airspace (see text for details).

Using the update rate of 16 seconds with the current error estimates (top of the table) provides a RNP value of 0.31 nm. **Using the lower error rates expected from the improved data from the air carriers (from the bottom of the table) provides a RNP value of 0.16 nm.**

5. Required Actions for Aircraft Sensor Upgrades

The atmosphere, a chaotic system, it is not *perfectly* predictable at any time scale. Methods of four dimensional data assimilation (4DDA) blend **predicted fields and data** over time in an optimal fashion. The data can come from various sources, and can be combined to produce fields that are dynamically consistent.

The real time data available from aircraft (in quantity and quality) is still far from what is needed to serve aviation interests today and even farther from the requirements for NextGen. More accurate temperature reports from the aircraft are needed. Water vapor sensors on aircraft are just becoming available and need to be on every aircraft. **All future aircraft in NextGen need to accurately measure all three fields of winds, temperature, and water vapor.**

5.1 Temperature Sensors

The aircraft **thermodynamic reports** provide spatial and temporal gap filling in areas not covered by weather balloon data. Errors in **ground speed** are given by the sum of errors in **true air speed (TAS)** plus errors in the **wind speed.** Errors in TAS are due to random temperature errors and systematic bias errors of the TAT probe. The predicted wind errors can be reduced by accurate aircraft data available in real time providing information on **all three important fields**.

Removal of the **temperature bias error** is absolutely essential for NextGen. There may be other new temperature sensors that will come along and do this, but one such sensor has already been explicitly designed to remove this bias. This is the SpectraSensors, Inc. (SSI) Mobile Temperature Sensor and is described in Fleming (2007 and 2008). Details can be found in those references, **but the key is to isolate the sensors from the effects of nature – thus eliminating the bias error.** A clever insulation scheme and precision machinery can place two identical (thus redundant) temperature sensors just inside the walls of the measurement cell. The air intake is flush mounted – **removing the requirement of a heater and eliminating TAT probe drag.** The surface friction effect on the flush mounted air intake is only moderate, but can be accurately modeled. A prototype of this sensor has been proven in wind tunnel tests. The mathematical modeled within the software produces a random error that is 50-60% less than the current TAT probe. Global Aerospace, LLC and SpectraSensors, Inc. (SSI) are patent partners in this product, but it may be manufactured in an avionics company other than SSI.

5.2 Water Vapor Sensors

Water vapor information for the aviation industry is crucial for the industry to help itself with its own weather improvements – leading to fuel savings and less carbon dioxide emissions. The United States National Weather Service has embarked on a program to add water vapor sensors on commercial aircraft. The FAA has endorsed this as part of NextGen.

SSI is the recognized leader in the water vapor sensor technology. Efforts are underway within many national weather services to have a moisture sensor on commercial aircraft. SSI has recently won a competitive government contract to supply the National Weather Service with a water vapor sensing system (WVSS-II) for commercial aircraft. The description of the laser technology behind the WVSS-II is described in May (1998). The description of the WVSS-II system is found in Fleming and May (2004). SSI manufactures and markets the product.

The first systems will go on United Parcel Service (UPS) and Southwest Airlines aircraft. The technology is a laser for measuring water vapor, similar to the product used by SSI in their rapidly growing natural gas pipeline business -- where they now have a dominant market share. The system has been certified on B-757 aircraft and certification on the B-737 is in progress.

5.3 Total Fleet Involvement – Beginning Now

All commercial and business aircraft need accurate sensors onboard for a successful

NextGen. Moreover, the implementation of these sensors needs to begin at an accelerated pace now. There are **two strong reasons** for this accelerated total commitment. The **first reason** deals with the unstable price of fuel and the need to decrease global carbon dioxide emissions.

Acceleration of the certification and installation of these new **accurate sensors** on all aircraft types can be fostered by the aviation community through the acceptance of new weather sensors on aircraft as carbon credits. This concept was introduced by the author at various international aviation meetings. The concept is gaining acceptance as a workshop on the subject was held between the International Civil Aviation Organization (ICAO) and the World Meteorological Organization in June of 2008 (ICAO, 2008). **Achievable sensor accuracies for water vapor, temperature, and winds are: 5%, 0.3 degrees C, and one m/s, respectively.**

The Director General and CEO of the International Air Transport Association (IATA) has indicated that shaving even a minute off every commercial flight has the potential to save 5 million metric tones of CO_2 and $3.8 billion annually (Bisignani, 2007). The capability of these improved sensors combined with the next generation ATM systems, would bring about efficiencies in aircraft operations – equal to or exceeding the IATA claim.

The NextGen must also face the issue of global warming -- a major concern for the aviation industry. The addition of better sensors for the aforementioned fields and potential future laser sensors for greenhouse gases are likely candidates for carbon credits. Such carbon credits are far more palatable for aviation than some of the existing carbon emission trading schemes that have been proposed for the aviation community.

The **second reason** for accelerating the sensors on commercial aircraft has to do with the current state of prediction and the progress required in time for NextGen. There is a sign of concern that sends a shrill warning to the atmospheric science community preparing to support

NextGen. In August of 2007 there was a test of the fleet of TAMDAR equipped aircraft looking at the prediction of low cloud ceilings. The results showed negative impact of the data.

Some 50 Saab turboprop aircraft operated by Mesaba Airlines over the Great Lakes region participated. The data was filtered by the company providing the TAMDAR data, so only data considered good was released for the 10-day test period. **The data did include the three primary fields of information needed: winds, temperature, and water vapor.** There are several possible factors in this negative result **(probably all contributed to some unknown degree).** These factors are (1) the aircraft data were not accurate enough, (2) the settling time or dynamic adjustment time, and (3) modeling improvements yet to be added.

Throughout this document the emphasis has been on **accurate sensors** for aircraft. Merely being able to measure a quantity is not sufficient. The accuracy has to be sufficient to add positive information to the dynamic model of the atmosphere. History has shown this to be true since the inception of numerical weather prediction. It took several years for satellite data to become effective in actually improving numerical predictions – this occurred through improvements in the satellite data and in learning how to use the data effectively.

TAMDAR **winds** not as accurate as other aircraft winds data (due to relatively poor heading information from the turboprop aircraft). TAMDAR **temperature** data has a slightly higher random error than traditional jet aircraft, and the temperature **bias** is just as bad as for the traditional jet aircraft.

The acquisition of **accurate** water vapor information from commercial aircraft has also gone through an evolutionary process (Fleming, et al, 2002). Several years of operation on UPS aircraft revealed multiple problems with measuring water vapor information via RH sensors – and later, the advantages of the laser approach to measure water vapor mixing ratio. The laser approach on commercial aircraft also had early problems not seen in the SSI water vapor sensors in the natural gas pipeline business. It took a major re-engineering effort by SSI to fix problems associated with the first prototype laser based water vapor sensor. The first effort was based upon research aircraft experience – not the daily grind of commercial aircraft operations over a wide spectrum of operating temperatures.

The TAMDAR RH sensor gets wet in clouds and/or precipitation. The sensor wetting influences both the RH sensor and the temperature sensor as seen in research aircraft results. When both the RH and laser sensors are working properly, the laser approach of measuring mixing ratio is more accurate at all levels, but especially at higher aircraft speeds. **Cloud formation is very sensitive to accurate stability analysis and moisture amounts.**

Model adjustment time is crucial to NextGen. The government lab involved in these tests used the method of handling dynamic imbalances (diabatic digital filter initialization), and suggests that further filtering may be required. The first issue is whether this is the best approach to perform dynamic adjustment. A much deeper concern is that these results are for 1-hour forecasts with a similar **refresh rate**. Considerable progress must be made in achieving dynamic model adjustment to get down to the **5 minute refresh rate envisioned for NextGen.**

Predicting low level ceilings involves the proper parameterization of moist physics – for which there are approximately 25 tuning knobs with assigned values to be determined. Some of these knobs are not precisely known. Considerable research with actual **accurate data** is needed to advance the physical parameterization in these models.

The solution for NextGen is for the FAA to assist the NWS in advancing the necessary **accurate sensors** in sufficient quantity to achieve progress across all three of these factors (accurate data, faster model adjustment, and model improvement). The time to begin is now.

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