8.4 TRAJECTORY-BASED WEATHER-ATM INTEGRATION AT THE FLORIDA NEXTGEN TEST BED

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ABSTRACT

One of the objectives for NextGen is to maximize capacity during adverse weather without compromising safety and efficiency. In the current National Airspace System (NAS), convective weather events such as thunderstorms can cause major delays due to their impact on traffic flow in the airspace system. The integration of more sophisticated forecast tools, such as the Corridor Integrated Weather System (CIWS) and trajectory-based weather detection services, with traffic flow automation decision support systems could help to improve air traffic management. To this end, the FAA defined a demonstration task called "Task N" with Embry-Riddle Aeronautical University (ERAU) using the Florida NextGen Test Bed (FTB), a NextGen research and demonstration facility at the Daytona Beach International Airport in Florida. The FTB is a cooperative FAA / academia / industry initiative to foster NextGen partnerships with industry, academia, and government by providing a facility where new prototype capabilities can be rapidly integrated into a NAS-like environment for demonstration and evaluation of NextGen Operational Improvements (OIs) and Enablers. The Task N project builds upon the work completed in 2008 on Task A – Integrated Traffic Management Advisor (TMA), En-Route Automation Modernization (ERAM), and 4D Predictive Weather project. Task N integrates a Lockheed Martin prototype trajectory-based weather conflict detection service developed in 2010 with TMA arrival decision support tool. Together with NNEW capabilities, gridded weather avoidance products (provided by ENSCO), and a SWIM-based infrastructure (provided by Harris), TMA has been enhanced under Task N to 1) display net-enabled CIWS weather products and prototype WAF data on the Planview Graphical user Interface (PGUI) display, 2) integrate weather data into TMA decision support algorithms with delay impacts shown on the TMA Timeline Graphical User Interface (TGUI) display and 3) reflect weather deviation impact to metering times on the ERAM R-Position display. These innovative enhancements demonstrate the integration of network-enabled weather with en route decision support tools to allow arrival time-based metering to continue while the airspace is impacted by hazardous convective weather.

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KEY WORDS

NextGen, weather avoidance, integration, trajectory based, NNEW, CSS-Wx, TMA, TBFM, SWIM, NEMS, DEX

1. INTRODUCTION

In the fall of 2008, an FAA demonstration project known as Task A demonstrated an early concept of integrating 4-D predictive weather with the Traffic Management Advisor (TMA) and En-Route Automation Modernization (ERAM), (Burkle and Montgomery 2008). The results of Task A indicated that there is value gained by integrating weather forecasts for planning purposes, but 1) the forecasts need to be accurate, 2) the concept for tactical routing of aircraft around weather cannot conflict with the overall traffic management workflow, and 3) there has to be minimal or no impact to the workload of the air traffic controller.

In 2012, FAA conducted a follow-on demonstration project: Task N – Convective Weather Integration into Traffic Management Advisor. For this task, enhancements were made to a TMA platform based on the currently deployed operational TMA (version 3.12) that was configured as the Jacksonville ARTCC (ZJX) TMA with current ZJX adaptations.

This paper makes reference to both TMA and TBFM. Time Based Flow Management (TBFM) is a continuation of TMA that will fulfill the operational user needs of NextGen. These needs include all of the functions of TMA plus enhancements including a re-architecture, flexible scheduling, extended metering and an integrated departure/arrival capability. Hence, the term TBFM will be used from this point forward.

2. Operational Problem

TBFM is deployed throughout the NAS to help maximize arrival rates into major airports. It accomplishes this by using a technique known as Time-Based Metering (TBM). TBM is a method of controlling traffic flow by scheduling the time when an aircraft should cross a defined point or "meter fix," (FAA 2008). TBM, and hence TBFM, is less effective however, when convective weather causes aircraft to deviate from their expected flight paths, which in turn causes aircraft to arrive at the TBFM metering points late. TBFM can cope with an aircraft projected to arrive at the meter point too early, in which case the controller simply delays the aircraft by extending its flight path or slowing it down. But when an aircraft arrives too late, there is no option available to make up the lost time. This late arrival at the TBFM metering points occurs because the Host Computer flight plan is not typically updated for the added flight time around the weather. Thus, the TBFM-calculated Estimated Time of Arrival (ETA) is no longer valid. In addition, TBFM does not currently have the ability to display graphical weather information that would provide better situational awareness to the Traffic Management Coordinator (TMC).

Since the current TBFM system does not account for unexpected deviations around convective weather, traffic managers typically stop using TBFM for TBM and resort to the much less efficient miles-in-trail (MIT) technique. This reduces the arrival rate at the airport, which can have a ripple effect of flight delays throughout the rest of the NAS.

Thus, TBFM's capability shortfall is its inability to take into account pilot deviations around weather. It receives no convective weather information and its schedule time calculations have no way of adjusting for an aircraft deviating around weather. The objectives of Task N are to help TBFM remain effective even when there are thunderstorms.

3. Functional Enhancements

To address the TBM and TBFM challenges during convective weather, the following adjustments to the current capabilities needed to be made for Task N:

a) TBFM needed forecasts from the current time to approximately 40 minutes in the future of areas where aircraft would need to avoid thunderstorm activity,

b) TBFM delay and scheduling algorithms needed to be modified to account for these Weather Avoidance Fields (WAFs) and estimate the added flight time aircraft will likely need take to deviate around them,

c) TBFM displays needed to be modified to show which flights have an added weather delay in their scheduled times so traffic managers would be aware of this and plan accordingly, and

d) The en route sector controller needed an indication that a flight's schedule time at the meter fix includes a weather deviation.

Each of these enhancements along, with the peripheral processes that support, them are described below.

a) Convective Forecasts – ENSCO Weather Avoidance Field (WAF)

In the summer of 2010, Lockheed Martin and ENSCO Inc. collaborated to develop a prototype WAF that could be used for integration with a trajectory-based approach in classifying aircraft conflicts or impacts with convective weather according to the estimated hazard severity of the storm. The work was presented at the ATCA 54th Annual Conference in 2010 (Avjian et al. 2010). Additionally, the WAF and the aircraft trajectories were translated to a grid-based construct to implement a weather conflict detection service. For Task N, ENSCO developed a WAF service which received archived Corridor Integrated Weather System (CIWS) Vertically Integrated Liquid (VIL) and Echo Top (ET) forecasts from the NextGen Network-Enabled Weather (NNEW) server at the Florida Test Bed (FTB) via the Harris NAS Enterprise Messaging System (NEMS). It translated VIL and ET into the WAF using a look-up table. This process is shown below in Figure 1.

The ENSCO WAF look-up table is shown in Figure 2. The ENSCO approach is similar to the one used by (Matthews and DeLaura 2010). The basic concept is that precipitation intensity and storm top are good indicators of the updraft strength which in turn is a good indicator of the storm's overall danger to aviation. The stronger the storm, the more risk it presents to an aircraft and thus the more leeway a pilot should give the storm as he/she deviates around it. The ENSCO WAF depicts four categories of risk; slight, moderate, high, and extreme. The colors depicted on the TBFM PGUI correspond to these risk categories. The WAF used for this demonstration has been optimized for summertime convection over Florida. This look-up table would likely need to be modified for other regions and seasons.

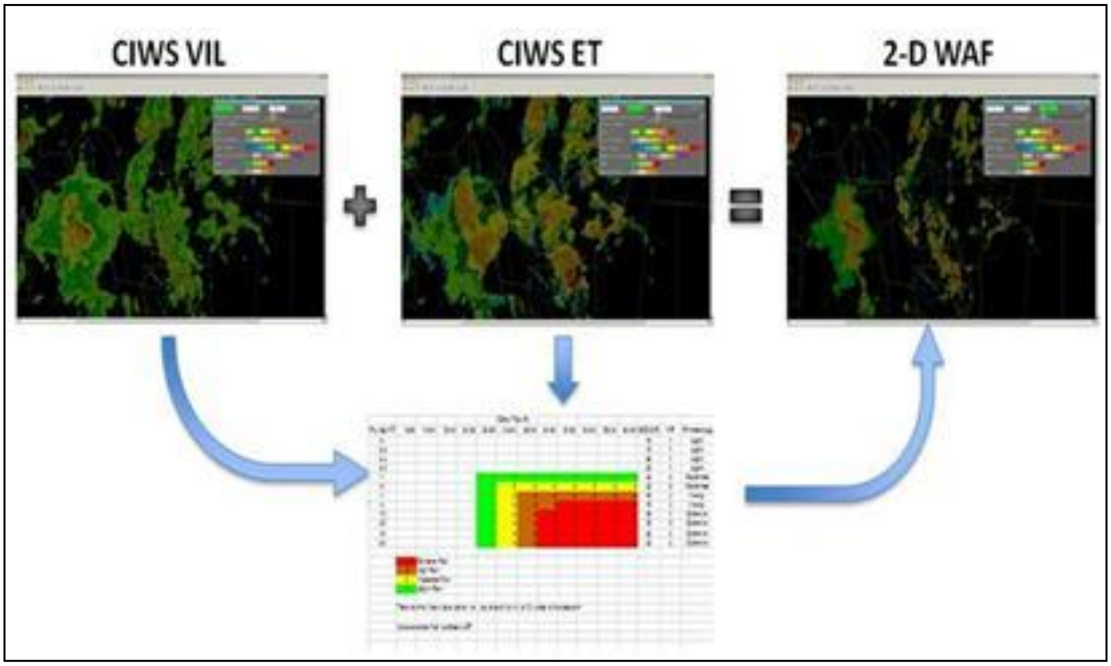


Figure 1. CIWS VIL/ET Translation to WAF

						Echo Top (ft)									
VIL (kg/m^2)	5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000	55,000	60,000	dBZ (CR)	VIP	Phraseology
0													10	1	Light
0.2													15	1	Light
0.3													20	1	Light
0.5													25	1	Light
1					1	1	1	1	1	1	1	1	30	2	Moderate
2					1	2	2	2	2	2	2	2	35	2	Moderate
4					1	2	3	3	3	3	3	3	40	3	Heavy
8					1	2	3	3	4	4	4	4	45	3	Heavy
15					1	2	3	4	4	4	4	4	50	4	Extreme
25					1	2	3	4	4	4	4	4	55	5	Extreme
40					1	2	3	4	4	4	4	4	60	6	Extreme
60					1	2	3	4	4	4	4	4	65	6	Extreme
	4	Extreme Risk													
	3	High Risk													
	2	Moderate Risk													
	1	Slight Risk													
	Treat storms like a layer cake - i.e. you should not try to fly under a thunderstorm														
	Color extends from surface to ET														

Figure 2. ENSCO WAF Lookup Table

b) Weather Integrated TBFM delay and scheduling algorithms

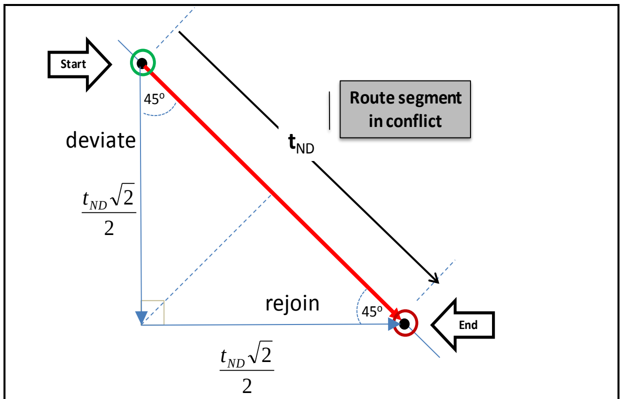
Before the weather impact to the TBFM schedules can be computed, the impact of hazardous convective weather, as defined by the WAF, to aircraft trajectories must first be determined. To accomplish this, Task N used Lockheed Martin's Weather Conflict Detection Service (WCDS) which was previously described in (Avjian et al. 2010). The difference between the 2010 WCDS and the 2012 WCDS is that whereas the 2010 WCDS handled a few set of trajectories, the 2012 WCDS evaluates 4D aircraft trajectories against 4D WAF fields every 12 seconds. It does this using a sampling frequency that captures every flight's trajectory update from TBFM. It did this processing for approximately 30 flights over a two hour duration.

Once the impact is determined, the WCDS passes the impacted trajectory segments to TBFM. TBFM then evaluates the delay associated with the impacted segments and estimates the time needed by the aircraft to deviate around the impacting WAF as shown in Figure 3. This is only an estimate of the approximate amount of deviation, not based on the aircraft's actual planned deviation trajectory. This estimate is a very rough order of magnitude and is considered a placeholder for a more accurate estimate of the deviation time. A more complete weather conflict resolution service as described in (Avjian and Dehn 2011) would provide an improved estimate and one that accounts for other aircraft in the solution as well. However, the pilot, with controller coordination, ultimately determines the avoidance route.

c) TBFM Display Enhancements

The enhanced TBFM PGUI with the current and forecast VIL and ET incorporated into the display is shown in Figure 4. The CIWS products are overlaid onto the entire PGUI display. The TBFM user is able to toggle on and off the VIL and ET overlays. The display controls also include a toggle control to turn off and on the current and forecast WAF displays.

The enhanced TBFM TGUI with weather impact symbology is shown in Figure 5. The only difference from the current TBFM is the addition of red symbols to the left of the ETAs indicating aircraft which ETAs have a weather deviation included in their flight-time estimate.



$$t_{WD} = 2 * \frac{t_{ND}\sqrt{2}}{2} = t_{ND}\sqrt{2}$$

$$\boxed{\Delta t_{WD} = t_{WD} - t_{ND} = t_{ND}\left(\sqrt{2} - 1\right)}$$

t_{ND} - estimated time to fly segment with no weather impact

t_{WD} - estimated time to fly segment with weather deviation

Δt_{WD} - **net additional time estimated to fly segment with weather deviation**
This is the [WX n] time displayed on TGUI

Figure 3. Placeholder Technique to Estimate Weather Deviation

d) En Route Sector Display Enhancements

For Task N, it was desired to provide some indication to the sector controller using the R-Pos that the metering times reflected added time due to a flight's expected weather deviation delay. To avoid having to make changes to the ERAM R-Pos Computer-Human Interface (CHI), a simple offset value was added to the Delay Countdown Time (DCT) value that is sent from TBFM and shown on ERAM. Because the DCT value displayed on ERAM only takes on a 2-digit value, a sufficiently large value (of 80) was added to the DCT number to distinguish it from a non-weather impacted value. See Figure 6.

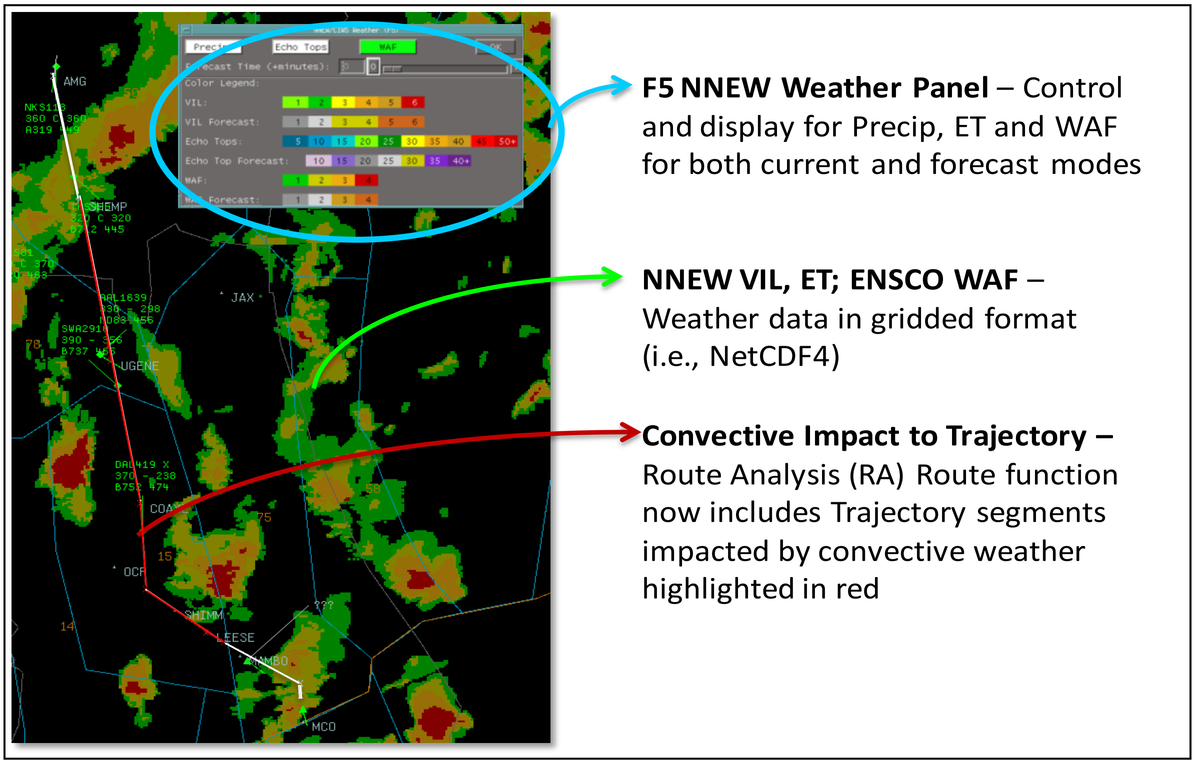


Figure 4. TBFM PGUI Enhancements

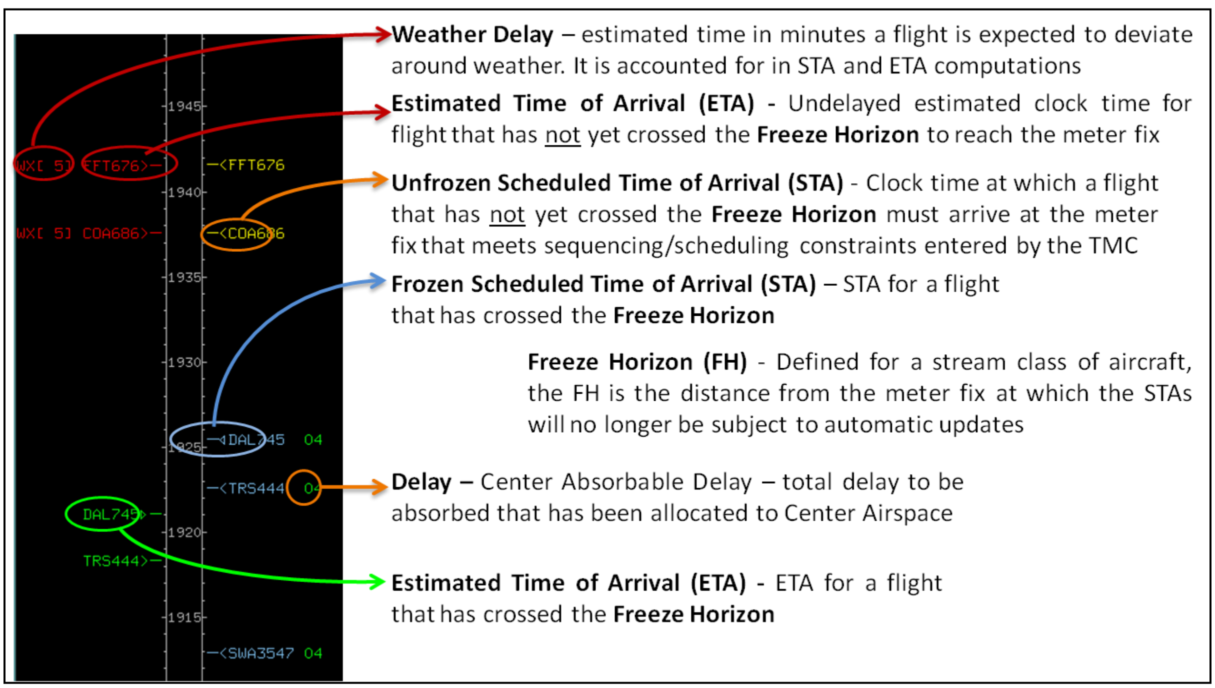


Figure 5. TBFM TGUI Enhancements

For example, the value “**1853 86**” next to flight DAL744 indicates the weather-impacted STA is 1853 and the DCT equal 6 min. The 8 indicates the STA and DCT are weather-adjusted. For flight TRS561, a DCT value of 80 indicates the STA is weather–adjusted, but the constraint-related delay is zero. This method allows for up to 19 (99-80) minutes of weather-impacted delay, and was chosen just as a prototype approach. It is understood that the approach would need to be revised for actual operational considerations.

Figure 6. Metering Times Adjustment on R-Pos

In summary, modifications included:
- Display convective weather products on Planview Graphical User Interface (PGUI)
- Corridor Integrated Weather System (CIWS) precipitation product or Vertically Integrated Liquid (VIL)
- CIWS Echo Tops (ET)
- ENSCO Weather Avoidance Field (WAF) as derived from CIWS VIL and ET

4. System Architecture

The Task N architecture diagram shown in Figure 7 depicts the high-level data flow among the system components. The boxes in gray represent the systems (AT Coach, ERAM, HADDS) used in Task N that remained unchanged, while the remaining components are systems that were modified or new for this task. Beginning at the lower, far left area of the diagram, the CSS-Wx (NNEW) On Ramping Service pulls data from the FTB CSS-Wx (NNEW) servers and sends the VIL and ET data to TBFM for display on the PGUI and also to the ENSCO WAF service. The ENSCO WAF service converts the VIL and ET data into a WAF as described above. The ENSCO WAF service then sends the ENSCO WAF data to the weather conflict detection service (WCDS) and TBFM. The WCDS calculates the segment(s) of a trajectory that were impacted by the WAF data and then publishes these segments to TBFM. TBFM evaluates the time associated with the impacted segments and estimates the time needed by the aircraft to deviate around the impacting WAF as described previously.

Continuing from right to left in the upper portion of Figure 7, TBFM uses this information to calculate revised delay times which are forwarded to ERAM via the Host Air Traffic Management Data Distribution System (HADDS). The sector controller uses the delay information displayed on ERAM to adjust the aircraft flight paths so they arrive at the metering point on time. The controller does this through radio voice communications with the pilot. The sector controller works with the pilot to continue to control the trajectory of the aircraft as they do so today. That is, the pilot requests deviations around the thunderstorm and the controllers accommodate these requests while taking into account other ATC considerations and limitations. The only difference is that TBFM has already taken the deviations into account in creating its arrival sequence into the airport.

From the Task N architecture in Figure 7, there are two components that warrant further discussion: the weather conflict detection service and the NNEW On-ramping service.

Weather Conflict Detection Service

The Weather Conflict Detection Service (WCDS) was first described in (Avjian et al. 2010) and will not be repeated in its entirety here. The fundamental functions WCDS performs are:

1) Test for WAF Existence – determines if there are WAF fields in the grid field
2) Bounding Volume Intersection Test – determines if there is an intersection between an aircraft trajectory (including buffers) and the WAF regions at a gross level
3) WAF Search Algorithm to determine aircraft-to-WAF conflicts by evaluating each grid cell that the trajectory (including defined buffer) traverses through against those grid cells occupied by weather to find the WAF conflict for the appropriate forecast time interval (there are grids at 5 minute intervals that represent time up to 25 minutes into the future). The 25 minute lookahead is a tunable parameter and was suggested by TMC subject matter experts for this demonstration

Because the WCDS was to be integrated with a version (i.e., 3.12) of TBFM that was operational in the field as of 2010, the WCDS needed to be improved in order to meet the timing constraints of current/forecast weather and a 12 second track update rate.

The 2010 WCDS prototype was based on a single-threaded design. For Task N, WCDS \was updated to a multi-threaded design as shown in Figure 8. This design implements two processing loops: 1) the main detection and track update processing loop using the active grid, and 2) the weather data ingest processing loop where weather data received from the NEMS is read into the standby grid. As soon as the main loop is finished, the active grid is replaced with the new grid contain fresh current weather data and (when available) forecast weather data.

NNEW On-Ramping Service (NOS)

The NNEW On-ramping service acts as an NNEW client and forms Open Geospatial Consortium (OGC) defined Weather Coverage Service (WCS) Reference Implementation (WCSRI) (NCAR 2008) client requests for CIWS VIL and ET data in a rectangular geographic bounding area suitable for the Task N Area of Interest. The subset bounding box is specified in geodetic latitude and longitude points in accordance with the NNEW WCS.

The NNEW On-Ramping Service to NNEW Interface provides archived VIL and ET data to the NNEW server as if it were current live data. The NOS synchronizes time using the NEMS Time Service to track the simulation time. As simulation time runs, the NOS copies the archive data that would have been current at the simulation time from the archive into an NNEW ingest folder. The NOS acts as an intermediary between NEMS and NNEW by subscribing to NNEW products and publishing them to NEMS. The NOS – NNEW interface is implemented using the NNEW WCSRI Notification message exchange pattern. The flow of message date from NOSNI to NEMS is shown in Figure 9.

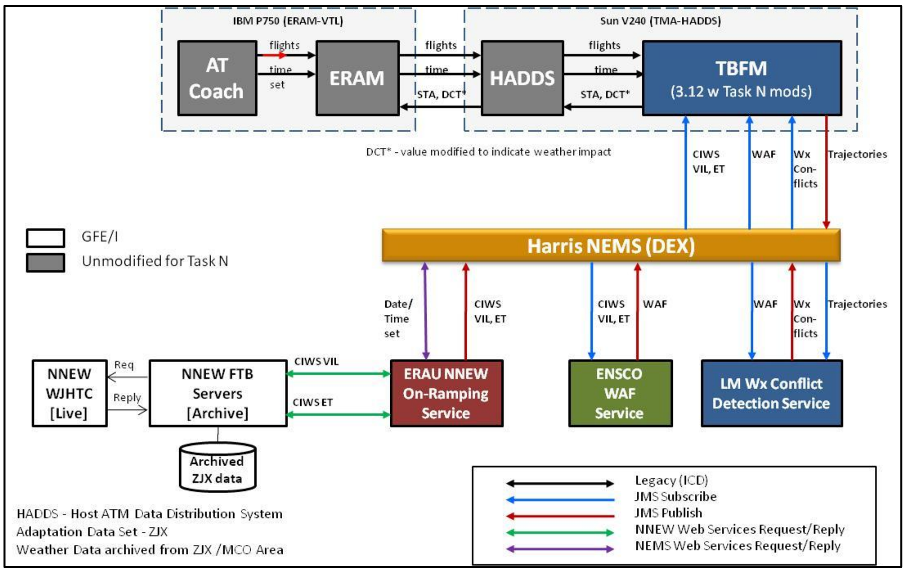


Figure 7. Task N System Architecture

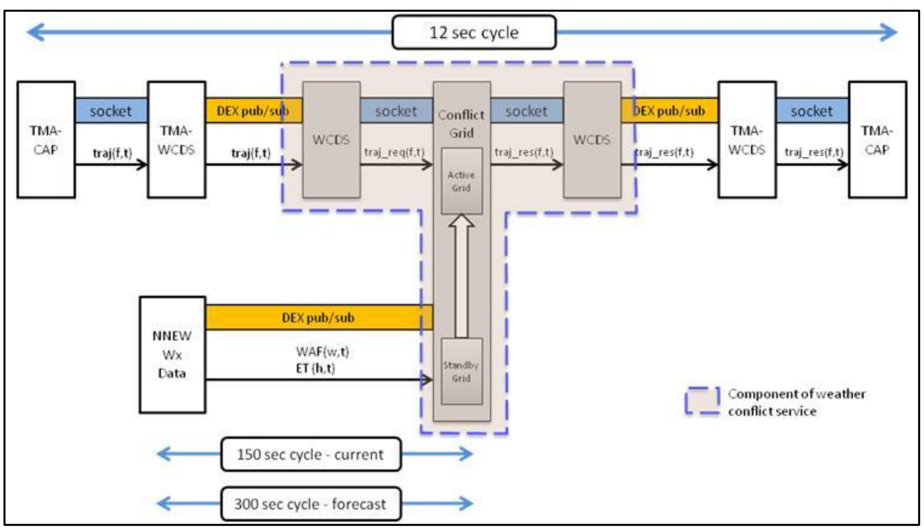


Figure 8. Weather Conflict Detection Service Multi-Threaded Processing

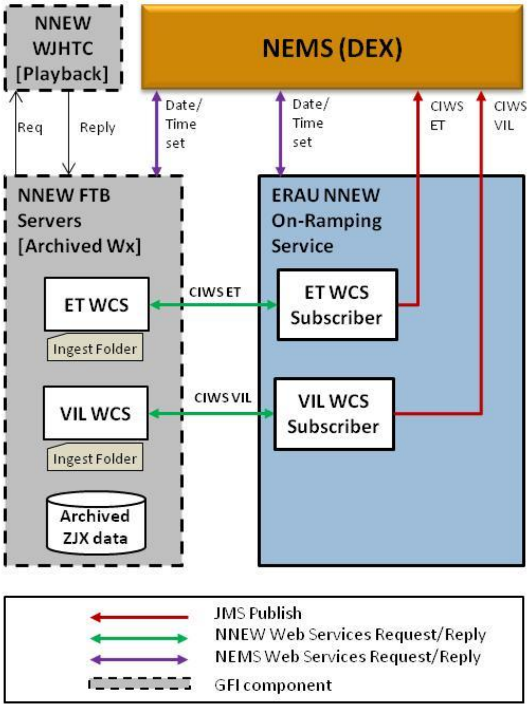


Figure 9. NNEW On-Ramping Service

5. Capability Demonstration

The demonstration of the Task N system enhancement was conducted in the Demonstration Suite at the Florida NTB on Tuesday, June 26, 2012. Attendees included individuals from the FAA, ERAU and private industry. The demonstration included the following:

- A presentation describing the Task N project overview, the concept of operations, architecture and simulation scenarios
- A set of recorded videos highlighting to the audience the following: a) arrival scheduling using the current TBFM-ERAM system on a clear day, b) arrival scheduling using current TBFM-ERAM system on a convective weather day, and c) arrival scheduling using Task N enhanced TBFM-ERAM system on a day with convective weather
- An interactive human-in-the-loop (HITL) simulation demonstrating a) how trajectory segment weather conflicts on the PGUI translate to weather deviation delay times on the TGUI, b) how weather deviation times appear on the ERAM R-Position and relate to delay times on the TGUI, c) what happens when weather-impacted fights do NOT deviate around weather, d) how flight trajectory segments are impacted by forecasted weather, e) how flight ETAs align with their STAs at the meter fix, thus showing that TBM can be continued while convective weather impacts arrival operations.

6. Evaluation Results

Following the capability demonstration, to test the hypothesis that the Task N modifications to TBFM would enable controllers to continue to use TBFM during thunderstorm activity, a series of experiments were conducted using students from ERAU. For each experiment, the students performed the roles of air traffic management controller, air traffic controller, and pseudo pilot. The same real-world traffic captured from a typical afternoon over northern Florida was used for each experiment. The pilots and controllers were allowed to maneuver their aircraft or direct air traffic as they saw fit during each experiment.

The team conducted a total of nine experimental runs. For one run, a clear weather day was used. For the other eight runs, real weather captured during an active thunderstorm day over northern Florida was incorporated. During four of the thunderstorm day runs, the Task N TBFM enhancements were turned off, and for the remaining four runs, the TBFM enhancements were turned on.

To compare the runs, a performance score called the normalized failure rate (NFR) was calculated. The NFR score compared the actual arrival time at the meter fix with the scheduled time. A low NFR indicates a good performance in meeting the TBFM scheduled times of arrival at the meter fix; a high NFR score indicates a poor performance in meeting the TBFM scheduled times at the meter fix.

With the current, non-enhanced TBFM, the results showed that the NFR was significantly better (0.21) during clear weather than the average (0.55) for the days with thunderstorms present. The NFR for the thunderstorm days with the Task N enhancements turned on scored slightly better (0.51) than the runs with the enhancements turned off (0.55). Although this difference is small, it should be noted there was considerable difference between individual runs. Recall from Figure 3 the estimated weather avoidance estimate is based on a simplistic path stretch. Thus, the change in predicted arrival times at the meter fix will be better than before, but do not necessarily match the deviation that a pilot might make. Considering the small NFR difference, the scatter in the data, and the limitation of using only one weather test case, the results are not completely conclusive. However, now that the Task N system is in place at the FTB, more thorough experiments are possible with little start-up effort to obtain a statistically significant sample.

In general the results support the following hypothesis:

The enhanced TBFM takes into consideration the additional time needed for aircraft to deviate around storms, enabling controllers to better meet STA times and continue using time-based metering.

During clear weather the controllers were able to get the aircraft to the meter fix generally on time. During the thunderstorm day, controllers had more difficulty getting aircraft to the meter fix on time. The NFR on the clear day example was much better than the average NFR on the thunderstorm day.

The true benefit of this limited study is that the team learned a great deal while conducting the experiments and the infrastructure is now in place to conduct a more robust set of experiments with minimal effort required.

In reviewing the video recordings of several of the cases, both with and without the enhancements turned on, it is apparent that the enhanced version did provide a means for accounting for the aircraft deviations around thunderstorms. Although the NFR scores were not overwhelming, the potential benefits still appear to be valid.

Finally, one of the interesting aspects of this concept of operations is that the CIWS forecast does not need to be precise for this system to be successful. As long as it is accurate enough to predict the deviation times, that's all that is needed. If the pilot chooses to go around the storm to the left or right is immaterial, as long as the predicted time to get around the storm is reasonably accurate.

7. Next Steps

Task N provided an opportunity to collect the team's thoughts and lessons learned and put forth a number of recommendations on next steps or follow on work.

- Investigate variable weather scenarios at different regions and airports
- Demonstrate the concept with increased traffic simulation complexity, and even with live flights
- Replace the simple path stretch calculation with a weather conflict resolution service to get more accurate weather deviation times
- Provide a more accurate depiction of the weather for the pilots
- Provide a simulated WARP NEXRAD mosaic for the ERAM controllers

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