Offshore Precipitation Capability for ATC

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Introduction

Weather radar map depictions available on the Corridor Integrated Weather System (CIWS) and Weather and Radar Processor (WARP) are critical tools for ATC to manage the flow of air traffic in the NAS, particularly during convective weather events.[1–6] Although radar coverage is available throughout the continental United States (CONUS), other regions such as Alaska, Hawaii, and much of the wider NAS do not have accurate and timely weather information, particularly offshore and out of range of land-based weather radar assets. This deficiency especially affects airspace covering routes in the southeastern United States, over the Gulf of Mexico, the Caribbean, and extending to Puerto Rico and the US Virgin Islands.

Unfortunately, planes encounter storms and turbulence in these areas, sometimes resulting in serious injuries to passengers and crews. Table 1 shows recent encounters in or near the Caribbean that resulted in 32 injuries in a single year.[7-11] These "turbulence" events are often associated with convection in the vicinity, and may be avoided if the flight crew and ATC are aware of the storms.

This paper describes the development and evolution of the Offshore Precipitation Capability (OPC), which is a tool that provides radar-like imagery for offshore and other radar-deficient regions to help mitigate these encounters, and improves safety and efficiency.

Offshore Precipitation Capability

The FAA, in coordination with the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL), has developed a capability to generate synthetic weather radar,[12-14] called OPC. OPC uses modern ML algorithms to predict maps of precipitation intensity (Vertical Integrated Liquid Water [VIL]), storm tops (echo tops), and composite reflectivity from available non-radar weather data. ML algorithms are game-changing technologies, and continue to prove valuable in many fields from image processing, medicine,

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speech recognition, financial analysis, fluid flow, and wave modeling.[15-19] In this system, these algorithms "learn" what a radar signature will look like by comparing a large radar data set against non-radar data available offshore, namely visible and infrared satellite imagery, lightning, and numerical model data. The algorithms thereby can predict synthetic radar signatures by using this proxy weather data.

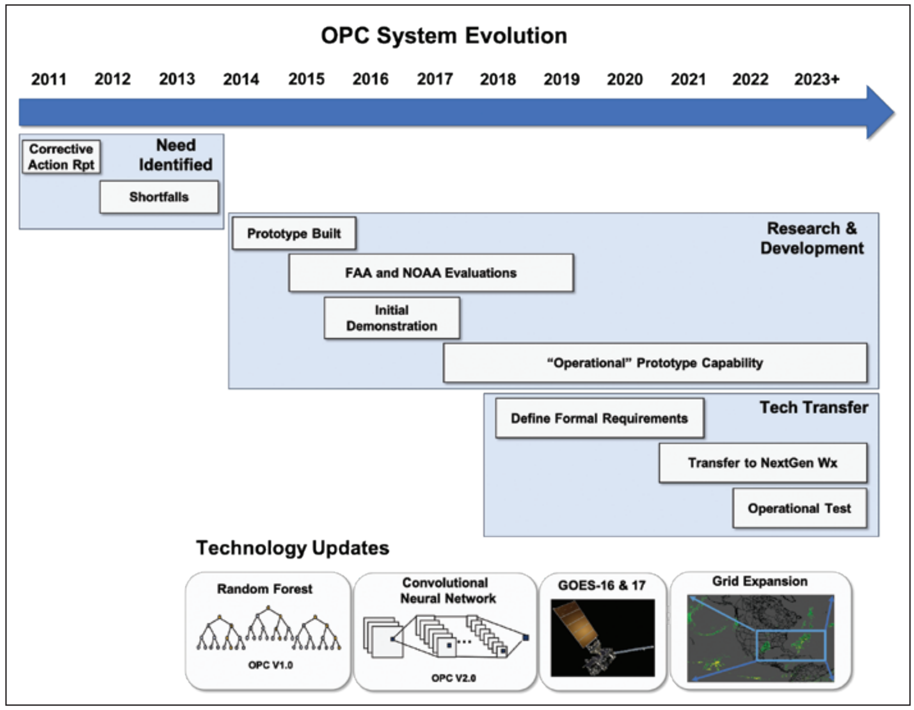

Figure 1. The evolution of the OPC system from initial identification of ATC needs to deployment on to FAA systems in the future.

OPC Demonstration and Evaluation

Ample evidence suggests that precipitation depictions like VIL and echo tops are useful predictors of pilot avoidance in and around convective storms.[20-21] VIL and echo tops products are currently available from the CIWS on the Traffic Situation Display in major FAA facilities, which serves as one of the current legacy operational radar products for the NAS. WARP is available on the En Route Automation Modernization (ERAM) displays in the Air Route Traffic Control Centers (ARTCC) for en route operations. Although widely used in day-to-day operations, CIWS and WARP technologies are being surpassed by more accurate, lower latency depictions available through the FAA's NextGen Weather system programs: the NextGen Weather Processor (NWP) and Common Support Services for Weather (CSS-Wx).[22-24] The FAA is actively implementing these systems for Initial Operational Capability within the next few years.

OPC Evolution

Figure 1 shows OPC prototype capability's development evolution. In 2011, the FAA issued a Corrective Action Report in response to an Air Traffic Safety Action Program report issued by a Miami (ZMA) ARTCC controller who identified a safety risk due to reduced and/or absent radar coverage in offshore areas. As safety is the FAA's highest priority, the agency acted quickly to correct this deficiency. It completed a shortfalls analysis in 2013 that identified approximately 23 million square miles of limited or no weather radar coverage, resulting in an estimated 15,000 hours of annual flight delays with $35 million in wasted fuel costs. One key finding that this study identified was that the capability must be able to adapt to the increased demands of ERAM to be technically feasible (i.e. the precipitation data must be displayed on ERAM).[25] Subsequently, in 2014, MIT LL initiated a study to produce synthetic radar products using a ML technique called Random Forests (RF), which had showed promise for predicting storm initiation precipitation.[26-28] However, instead of forecasting storm growth, the MIT LL study sought to estimate precipitation intensities and echo tops in areas where radar data were absent (i.e. create a precipitation proxy similar to work by Iskenderian,[29] which used a probability-matching scheme). The results of the MIT LL study were promising and as a result, the FAA moved forward on developing the algorithm.

From 2015–2017, an initial prototype was developed and deployed as an experimental system to a limited number of controllers in the ZMA and Houston (ZHU) ARTCCs. This initial domain was designed to address ATC needs in the Caribbean, southern US, western Atlantic Ocean, and Gulf of Mexico airspaces. The geographic footprint of the OPC demonstration appears in Figure 2. Shown are VIL and echo tops, both without synthetic radar on top (panels a and b), and radar data merged with synthetic products on the bottom (panels c and d).

Table1. Injuries from encounters with turbulence in offshore areas between Feb. 2019 and Feb. 2020.

Date	Airline/Type	Location	Preliminary Cause	Injuries
23-Jan-20	Avianca A319	Off NW Colombian Coast	Gravity wave	6 passengers 2 crew
15-Dec-19	Air Canada A320	Descent into Varadero, Cuba	Sudden strong down/ up draft	4 passengers 3 crew
2-Aug-19	Thomas Cook A330	Over the Atlantic (Cuba to UK) about 150 nm NE to Grand Bahama	Severe turbulence	2 crew
5-May-19	British Airways B777	About 500 nm NE of Bermuda	Turbulence	12 passengers 2 crew
5-Feb-19	American Airlines B737	Enroute Costa Rica to Miami, FL	Severe turbulence	1 crew

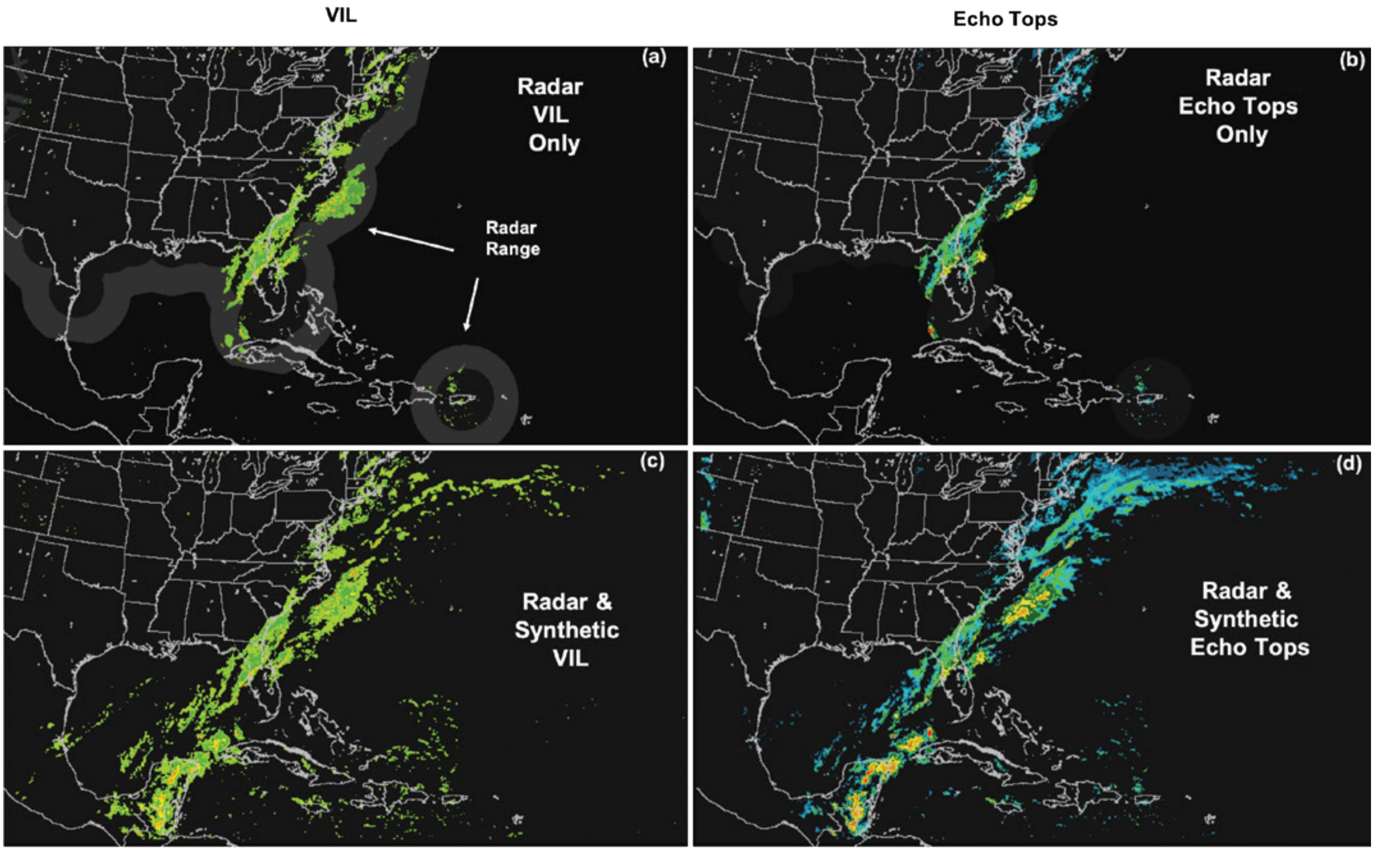

Figure 2. The OPC domain of the operational prototype on Dec. 17, 2019, with radar VIL only in panel (a), radar echo tops only in panel (b), radar VIL merged with synthetic VIL in panel (c), and echo tops merged with synthetic echo tops in panel (d).

The FAA's Aviation Weather Research Program (AWRP) sponsored a cross-organization evaluation that assessed:

1. OPC's baseline scientific performance via scoring against radar truth metrics, conducted by National Oceanic and Atmospheric Administration's Earth Systems Research Laboratory (NOAA/ESRL) (2016-NOAA Evaluation).[30]
2. The usability of OPC by conducting a "user" evaluation which was done by the Aviation Weather Demonstration and Evaluation (AWDE) Services of the FAA.[31-32]

The 2016-NOAA Evaluation showed that the performance of the synthetic radar products for VIL, echo tops, and composite reflectivity did correlate well with radar signals on land. However, in areas offshore where there was no radar coverage, the performance was degraded and variable when compared to NASA's Global Precipitation Measurement (GPM) data, indicating more development work was necessary to address the performance.

In parallel, the AWDE team conducted laboratory-based user evaluation field studies with subject matter experts (SMEs) from the ZHU and ZMA ARTCCs to determine the operational suitability of the OPC product. Seventeen en route air traffic controllers and four traffic management coordinators

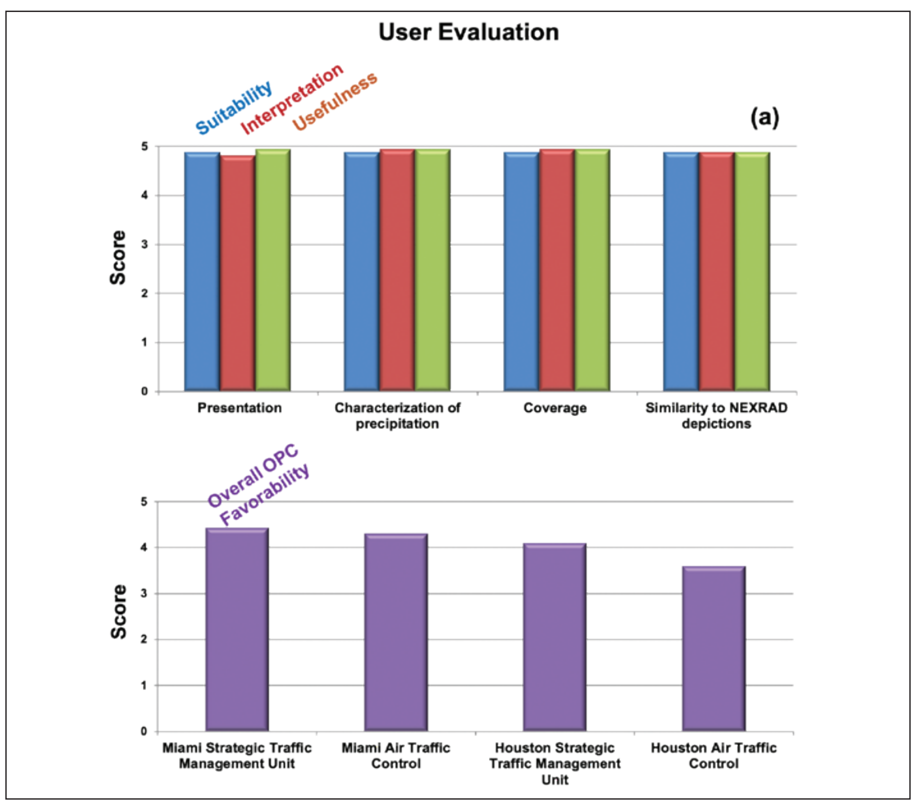

Figure 3. Results from an FAA-conducted user evaluation of OPC during the initial operational demonstration at ZHU and ZMA in summer 2016. ATC SMEs representing enroute ATC and Traffic Management Unit (TMUs) found OPC favorable on a scale of zero to five, with zero being unfavorable, and up to five with the highest favorability. Panel (a) shows favorability of suitability, interpretation, and usefulness for various characteristics. Panel (b) shows the overall favorability rating from different ATC facilities. Figure is taken from [32].

participated in the study, which considered several objectives. Findings are summarized in Table 2.[32]

Under all categories, the SME users found OPC a viable concept product.

The SMEs were also asked to rate the favorability of the OPC product, including how realistic the coverage and depictions are with respect to Next Generation Radar (NEXRAD) depictions. The users rated each category on suitability, interpretation, and usefulness. A rating scale from zero to five was adopted, where "zero" was unfavorable and "five" was the highest favorability. In almost every category, the OPC product typically rated high (see Figure 3 for a summary of the scores).

Key takeaways from this analysis include:

- Controllers were very enthusiastic about the usability and look of the OPC product.
- The study showed that there are significant user needs that could be met by this technology.
- Controllers indicated that this information should be available on their ERAM displays.

Even though the OPC product's aggregate statistics showed variability and some bias in the NOAA/ESRL study, users found the products sufficient for experimental operations. As a result, the FAA initiated an operational demonstration that began in the summer of 2017. The initial research technology was hardened for operations, and dedicated computer hardware was procured for real-time operations. In addition, the FAA supplied dedicated displays at Houston, Miami, New York, and San Juan, Puerto Rico, and at the Air Traffic Control System Command Center outside of Washington, D.C.

The OPC system continues to run in a prototype environment and has undergone several improvements. Although the initial ML algorithm based on RF methods produced promising results, with advances in deep learning neural networks such as Convolutional Neural Networks (CNNs)[33-35] and the addition of better offshore model training and validation from GPM radar, the initial RF algorithm was replaced with a better performing CNN algorithm.[13] NOAA/ESRL conducted an additional evaluation on the new algorithm to assess its performance.[36] The CNN model showed improved performance and is now the default model for OPC operations.

Other improvements were made in 2019, including an upgrade to inputs via the GOES East and West satellites (GOES 16 & 17). An expansion of the OPC domain to cover the CONUS, Alaska, Hawaii, and the eastern Pacific Ocean was implemented. This grid expansion was possible because the US Air Force (USAF) funded a re-engineering of the OPC technology so synthetic radar could be created globally. This program is called the Global Synthetic Weather Radar (GSWR),[37] and its primary goal is to serve USAF remotely piloted aircraft operations. Although OPC and GSWR are built on similar platforms, the USAF has different operational needs, which do not necessarily align with the FAA's. Therefore, the FAA may desire to leverage the USAF technology while designing the ATC systems to meet the agency's own operational goals.

Testimonials

Representatives from NATCA organized a meeting with ZMA and ZHU OPC users on July 31, 2020, with the goal of collecting feedback from current users to understand better the future needs that OPC could meet. A summary of the outcomes is provided in Table 3. Overall, the users found OPC very effective and view it as an essential safety product for ZMA and ZHU operations. One key takeaway expressed by users was a strong need for OPC on the ERAM scopes. The following paraphrased comments were noted:

- Weather and air traffic must be merged to be effective.
- Goal is to get OPC on the ERAM scope and call weather with aircraft.
- Users expect that OPC will be on ERAM.
- Users want and need OPC on ERAM scopes.
- One hundred percent support for OPC on ERAM scopes.
- OPC is an essential safety product and no longer optional.

Due to the overwhelming success of the OPC initial demonstration prototype, the FAA is exploring including OPC on the NWP and CSS-Wx platforms. In the near term, OPC was not included in the initial baseline for NextGen Weather, mainly

Table 2. User evaluation findings.

Objective	Findings
Safety Decisions	Enhances communication and collaborations, safer reroutes and deviations, improved situational awareness (SA).
Sector Efficiency Decisions	Predicts deviations, efficient planning, predicts opening/closing of routes, improved communication with pilots, anticipates pilot requests.
Airspace Efficiency Decisions	Proactive traffic management planning.
Suitability	High suitability for air traffic and flow, supports timeliness and effectiveness of duties, TMU reported workload decrease, but ATC is concerned with increased workload calling weather for pilots.
Situational Awareness	Significant increase in SA, more detailed and informed decisions, improved SA between airlines, Command Center, and ARTCCs.
Presentation (Display)	Highly effective, easy to interpret, usefull, realistic precipitation, suitable for ERAM display, echo tops, lightning, and overlays highly effective.

Table 3. Summary of User-Needs Feedback from the NATCA Meeting on July 31, 2020.

Topic	Description	Priority
Situational Awareness	• OPC provides overall better or enhanced SA. • Controllers have experienced significant benefits from using OPC. • OPC has become an essential part of oceanic operations. • Controllers strongly stated that weather must come from the same source, and be displayed on a common display with air traffic. • Operations need the most accurate and timely weather possible. • OPC is used extensively in ZHU oceanic operations to help anticipate where planes coming from Mexico will approach during weather.	High
Safety	OPC is an essential safety product and no longer considered an 'optional' capability.	High
Display	• Controllers expressed a strong need to have OPC precip. on the glass (i.e. ERAM). • Current demonstration display configuration is unacceptable, difficult to use, and unusable for some controllers: - Displays are not in good locations and are too far from ERAM. - Increases workload lining up weather and traffic. - Cannot be used for planes close to military airspace as there is no time to look at both screens and make critical safety decisions.	High
Precip Products	Controllers indicated that Composite Reflectivity layers are desirable for enroute operations, i.e. 0-60 kilofeet (kft), 0-24 kft, 24-60 kft, and 33-60 kft layers.	High
Auxillary Products	Users indicated they wanted Storm Cell Information, Storm Extrapolated Position and possibly Growth and Decay for OPC, not on ERAM, but on a separate display (e.g. Aviation Weather Display).	Moderate
Forecast Products	• An eight- to 12-hour forecast would be useful for TMU to plan routes and anticipate future deviations. However, must be on separate display from ERAM. • One oceanic airspace controller indicated that forecasts in oceanic areas may be useful up to two hours, but not to eight or 12 hours.	Moderate

because the technology was not ready in time for the development phase of the schedule. However, OPC is being considered for the next enhancement package in the mid-2020s. At present, initial analysis and assessments have been conducted for operational shortfalls, ConOps, and preliminary requirements.

Technology

The software platform on which the OPC system was developed was based on a "branch" from the NWP platform that split into a separate development path in 2017. At this time, the NWP system was already several years into a "system-hardening" or "refactoring" phase in preparation for transfer to industry. Therefore, OPC uses the same architecture and inherited many of the improvements already available to the FAA from NextGen Weather. The USAF system was applied to this same development thread. The two systems can be configured under the same software so an OPC or GSWR instance can be run using the same base code, but trained under different inputs and truth datasets. The radar target used for training/validating the OPC algorithm can be either land-based radar such as the NEXRAD, Terminal Doppler Weather Radar (TDWR), Canadian Radars (CANRAD), or space borne radar such as NASA's GPM satellite.

Figure 4 shows a schematic of the software. The base system in gray consists of a Portable Operating System Interface (POSIX) operating system (e.g. Linux) and other freely available open-source software. The light blue boxes represent the weather algorithmic processing platforms and consist of common software libraries (e.g. image processing, meteorology packages, geospatial packages, communication layers, input and output utilities, and process drivers). The green layers are the NextGen Weather platform and represent software necessary for the ML components, and consist of a training package, database infrastructure, and Python scientific tools (NumPy, TensorFlow, etc.).[38] The base layer has about 90 percent in common with the NextGen Weather system and the upper (green) layer consists of an additional package that is about 10 percent the size of the NextGen Weather system. Merging OPC back onto the NextGen Weather platform is straightforward because the two systems share the same architecture, operating system, data formats, and base libraries.

Data Flow and Processing

This section covers the data flow and processing steps with OPC included on the NextGen Weather platform. The current NextGen Weather system ingests data from three types of radars, including NEXRAD, TDWR, and CANRAD into a preprocessing system, applies a series of data quality steps, and then mosaics the radars together using a maximum plausible logic scheme for precipitation and weight distance averages for echo tops.[22-23] To add OPC's synthetic weather radar to the existing radar mosaics, the system ingests and preprocesses the satellite, lightning, and numerical model

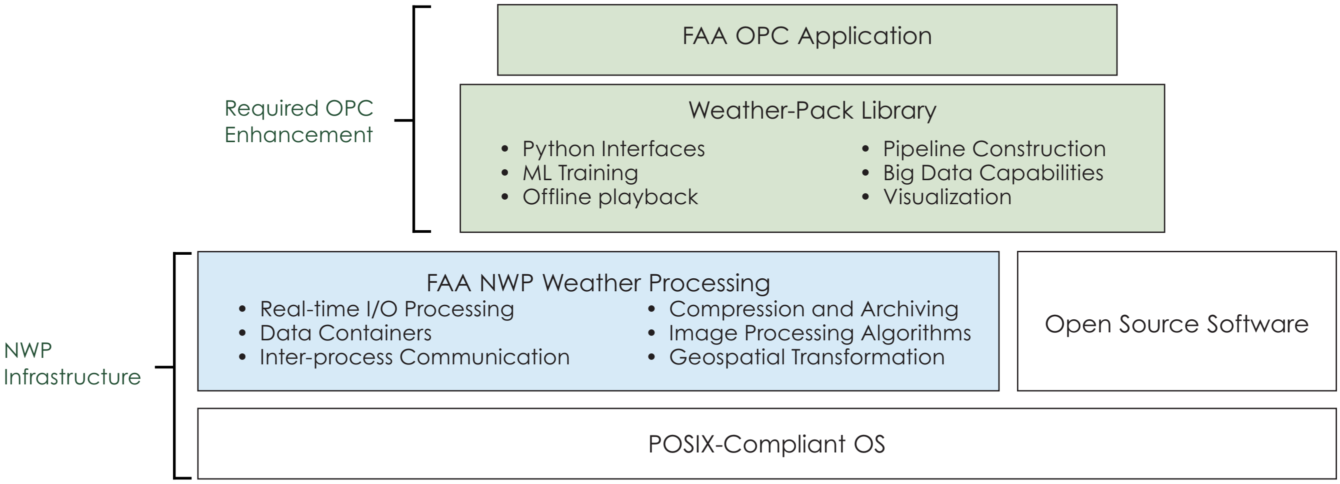

Figure 4. Software architecture for the OPC system.

data which is then processed by the CNN model (previously trained on NEXRAD or GPM data set offline) to derive a prediction of the radar precipitation intensity for VIL, composite reflectivity, and echo tops.

The radar mosaic and synthetic radar grids are then combined in a merge process (Figure 5). At boundaries between limited-long range coverage (230 to 460 kilometers [km]) and no coverage (> 460 km), a weighted average scheme is applied that smoothly blends in the synthetic radar. The weighting function is based on a logistic sigmoid function[13] that begins at 230 km from the radar and ends at 460 km from the radar. Within this zone, the maximum of the radar return, or the maximum of the weighting function, determines the final value. This leaves mostly real radar returns in the interior (< 230 km) where there is radar coverage, only synthetic radar in no coverage areas, and a weighted average or radar maximum between the two in the transition. In some areas like the US Rocky Mountains, where there is radar blockage of beams, synthetic radar may be used to enhance the interior in degraded areas; R&D funded by FAA AWRP is actively exploring these concepts.

Data Distribution and Display

ERAM is the backbone of the ATC tools available at 20 ARTCCs. ERAM provides ATC flow and satellite-based flight surveillance, communications, trajectory modeling, conflict detection services, and radar weather. An example of the ERAM display is shown in Figure 6 in three-level controller colors. There are four layers of composite reflectivity radar weather products available: zero to 60 kft, zero to 24 kft, 24 to 60 kft, and 33 to 60 kft to allow controllers to filter weather levels of interest.

The NextGen Weather CSS-Wx service already supports the publishing of products to ERAM through the User Display System interface.[39] In addition to ERAM, OPC could be displayed on the Advanced Technologies and Oceanic Procedures or Microprocessor En Route Automated Radar Tracking System if desired.

The NextGen Aviation Weather Display (AWD) consolidates the legacy weather systems from CIWS and WARP onto a single

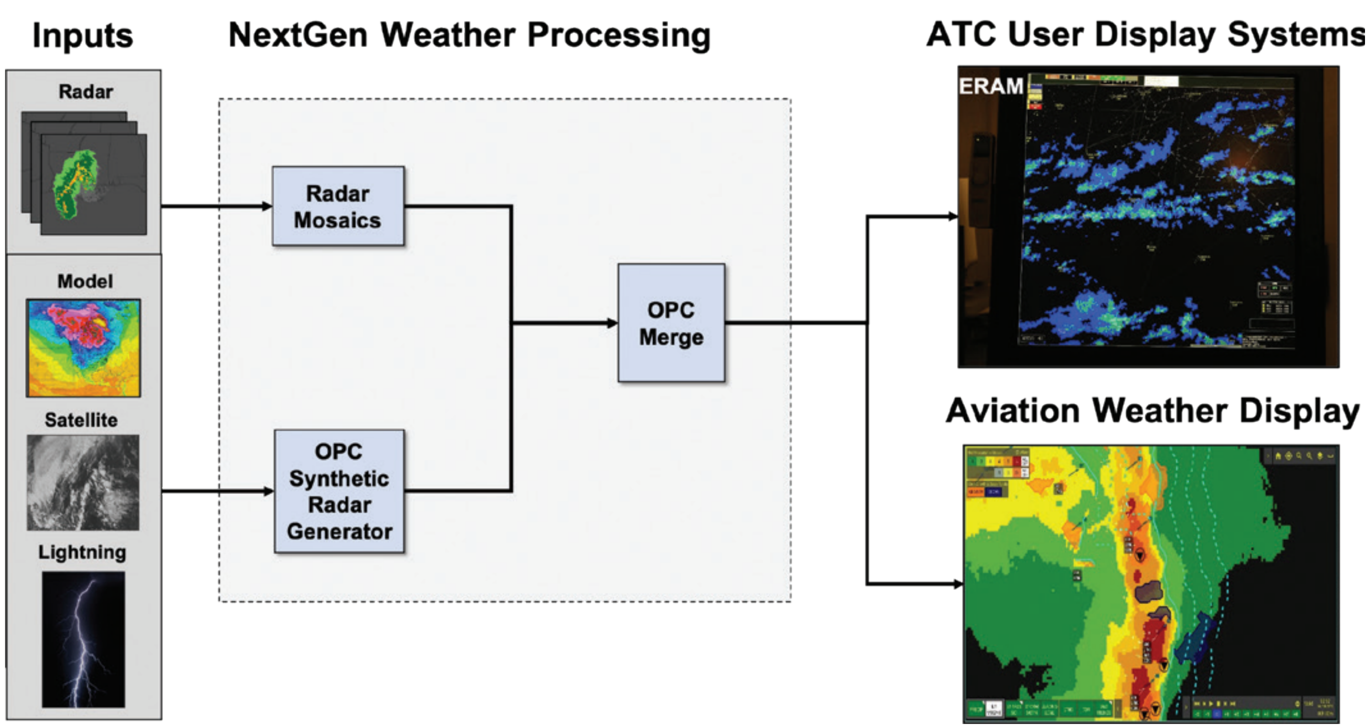

Figure 5. The high-level flow of the OPC system on the NextGen Weather system.

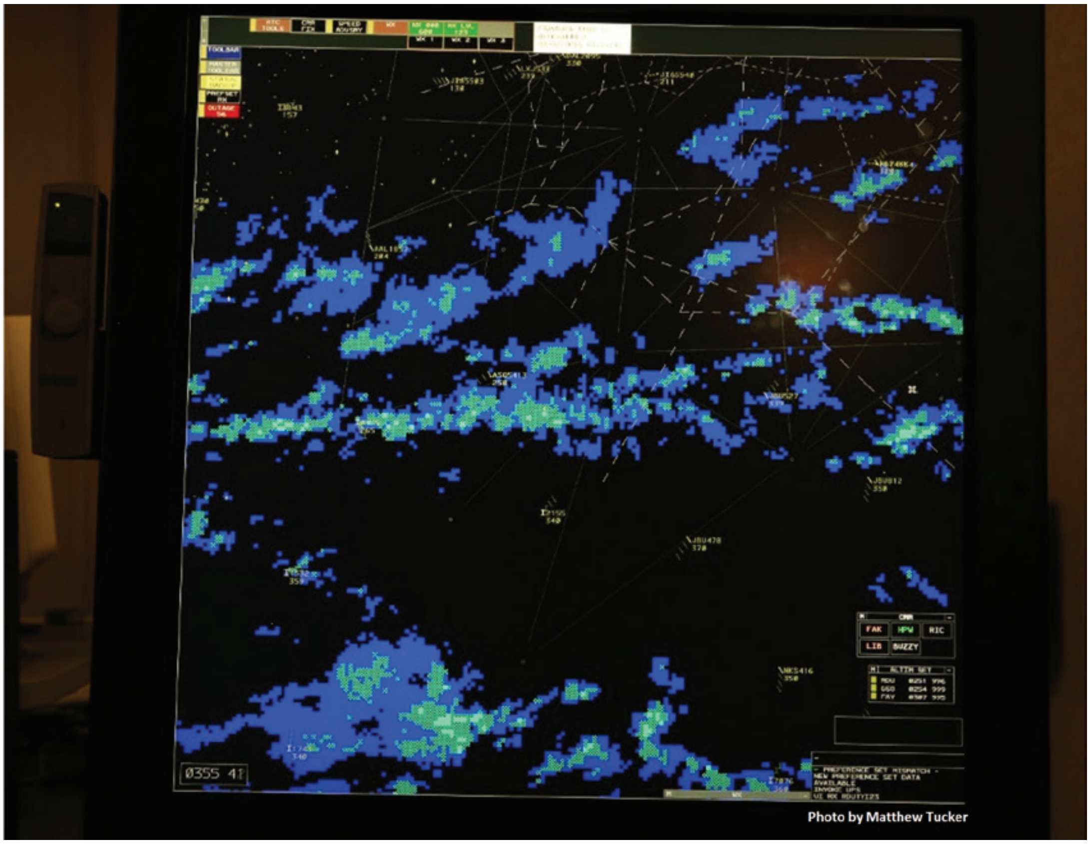

Photo courtesy of Matthew Tucker

Figure 6. Shown here is the ERAM user display provided at the ARTCCs within the NAS.

display platform so weather can be provided at "a glance." The current design for NextGen Weather provides weather information internal to the NWP system through local web services. Adding OPC VIL, echo tops, and composite reflectivity information to AWD is a low-risk engineering modification.

Summary

OPC has proven valuable to ATC in initial experimental operational environments. The FAA has invested a considerable amount of resources, effort, and time into developing this product for operational use. The initial payoff for the FAA investments is evident through several independent analyses that have shown the OPC product has operational utility and can sufficiently provide indications of convective precipitation in areas where radar data is either deficient or non-existent.

Although an experimental prototype continues to serve a small number of ATC operations, the safety issue identified by ZMA ATC in the 2011 Corrective Action Report has not been officially closed and remains unresolved for much of the NAS. Offshore radar coverage is not available on official FAA operational platforms such as ERAM and the NextGen Weather AWD, and will likely not be available until sometime after 2025. A clear low-risk path for OPC to operations has been identified through the NextGen Weather systems program; development teams are currently spun-up. A transition of OPC to operations would be a major payoff of the FAA's investment in this key technology.

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