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# **Enhancing Aviation Safety and Efficiency Through Advanced Weather Sensing and Forecasting**

**Tim Bonin**

**8 May 2025**





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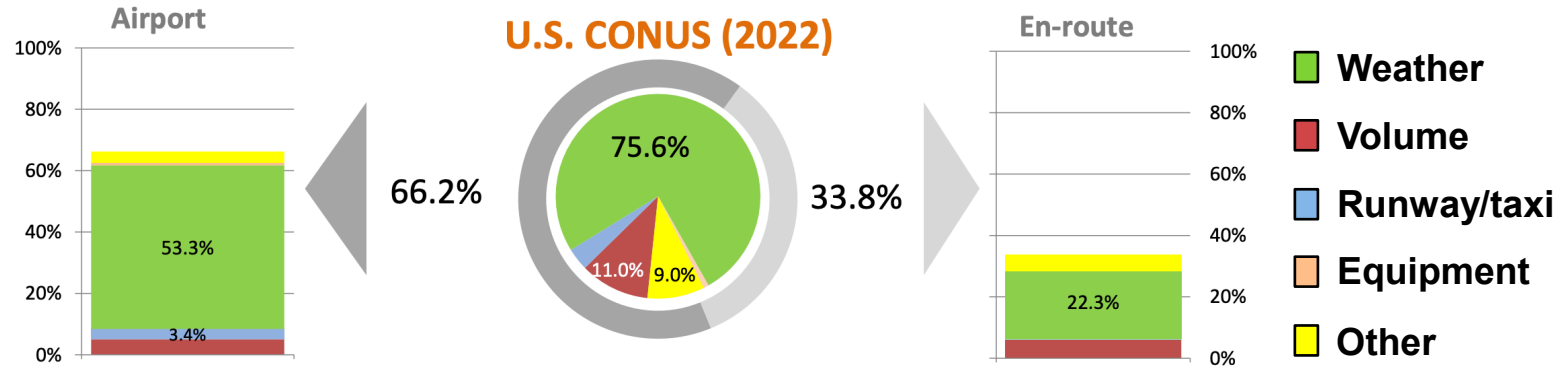
**\*Except where marked "This material is based upon work supported by the Observations Program within NOAA/OAR Weather Program Office under Award No. NA23OAR4590397."**





# Motivation

Air Traffic Control Delays by Cause



- **Weather is the primary disrupter to air traffic in the US**
  - Significant implications for the safety and efficiency of the National Airspace System (NAS)
  - Weather is a significant driver of flight delays & cancelations
- **Weather sensing and forecasting aids Air Traffic Control (ATC) with both tactical and strategic planning**





# Primary Weather Conditions Impactful to Aviation

En-route



Convection and Thunderstorms



Icing

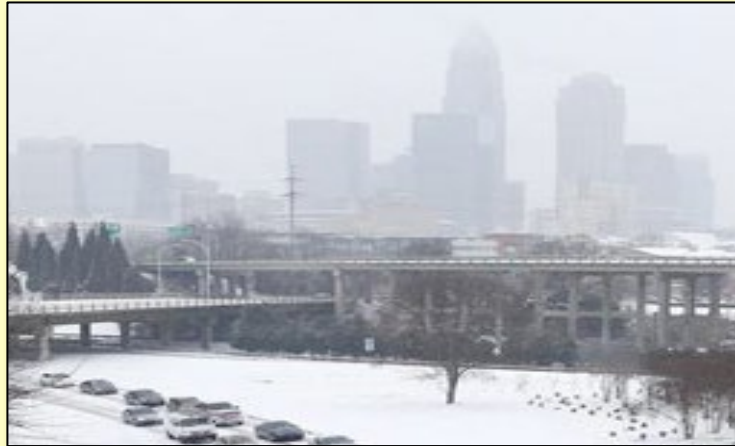


Turbulence

Airport



Wind Shifts and Shear



Winter Precipitation



Low Ceiling and Visibility



# Weather Products Needed to Aid in Decision Making

En-route

- Composite reflectivity
  - Flexible layers
- Echo tops
- Forecasted airspace permeability

Convection and Thunderstorms

- Icing hazard layers
- Supercooled large droplets (SLD) layers

Icing

- Turbulence hazard layers
  - Clear-air turbulence
  - Mountain wave
- Convective growth products & reflectivity
  - Convectively induced turbulence

Turbulence

Airport

- Microburst & gust front detections
- Wind shift forecasting
- Headwind/crosswind
  - Runway configuration
  - Wake vortex separation assurance
- Wind gust potential

Wind Shifts and Shear

- Precipitation type/intensity sensing and forecasting
  - Snow
  - Ice Pellets
  - Freezing rain / drizzle
  - Mixed
- Frost forecasting

Winter Precipitation

- Forecasts of visual flight rules (VFR) or instrument flight rules (IFR) conditions
- Fog / stratus dissipation or burn off timing

Low Ceiling and Visibility



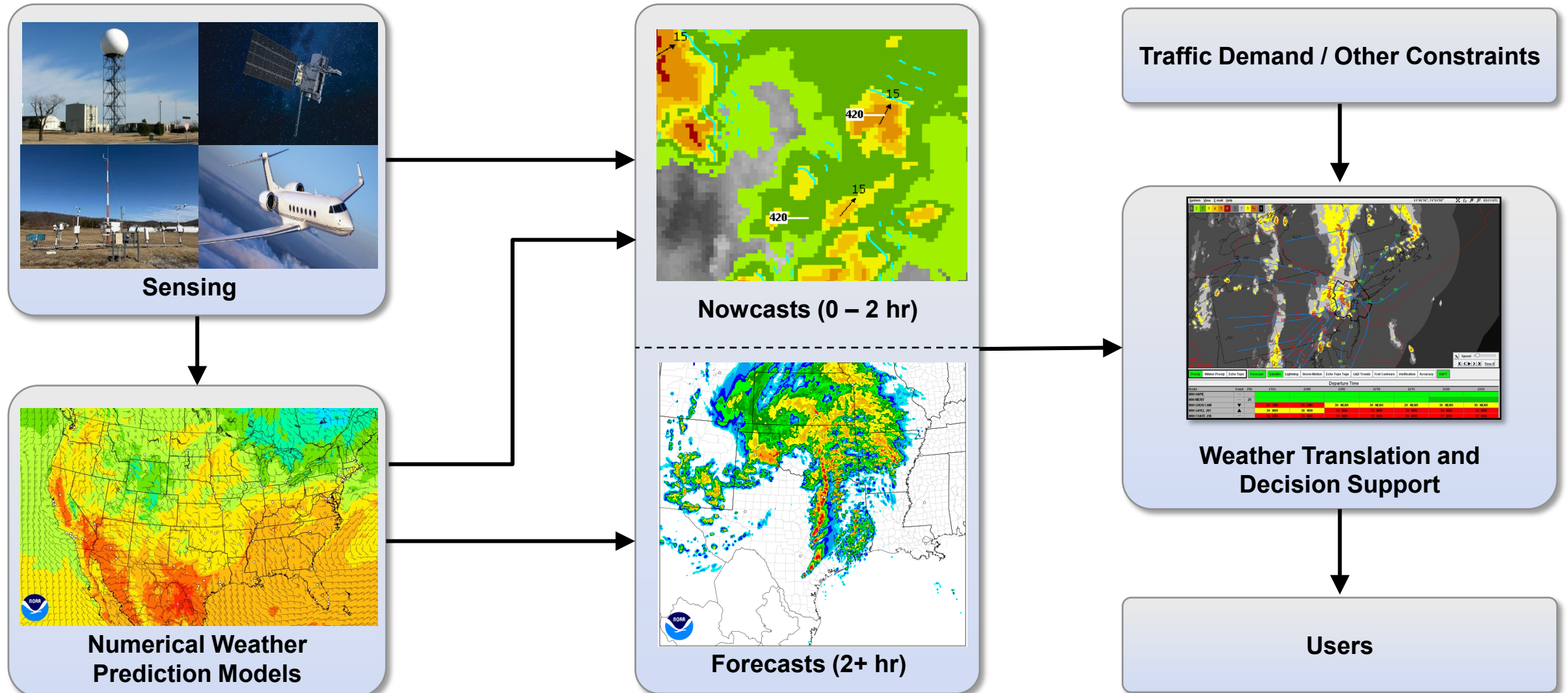
# Outline

- **Motivation**
- ➔ • **Weather Sensing and Forecasting for Aviation**
  - **Airport Sensing and Forecasting**
  - **En-route Sensing and Forecasting**
- **RF Issues**
- **Summary**





# Generalized Weather Information Pipeline





# Tactical Airport Weather Sensing (0-2 Hours)

## Integrated Terminal Weather System (ITWS)



**NEXRAD  
(S-band)**



**TDWR  
(C-band)**



**ASR-9  
(S-band)**



**Lightning Detector**



**LLWS**

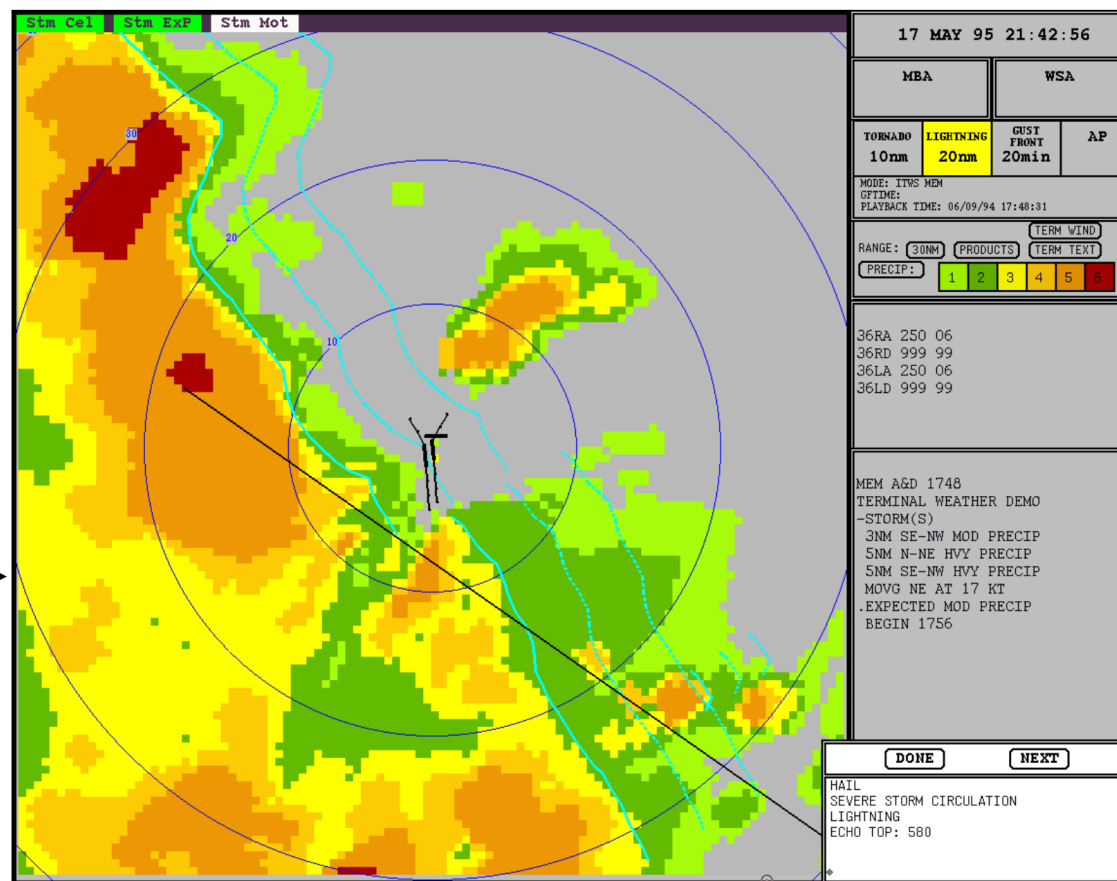


**ASOS**



**Aircraft Observations**

**Integrated Terminal  
Weather System**



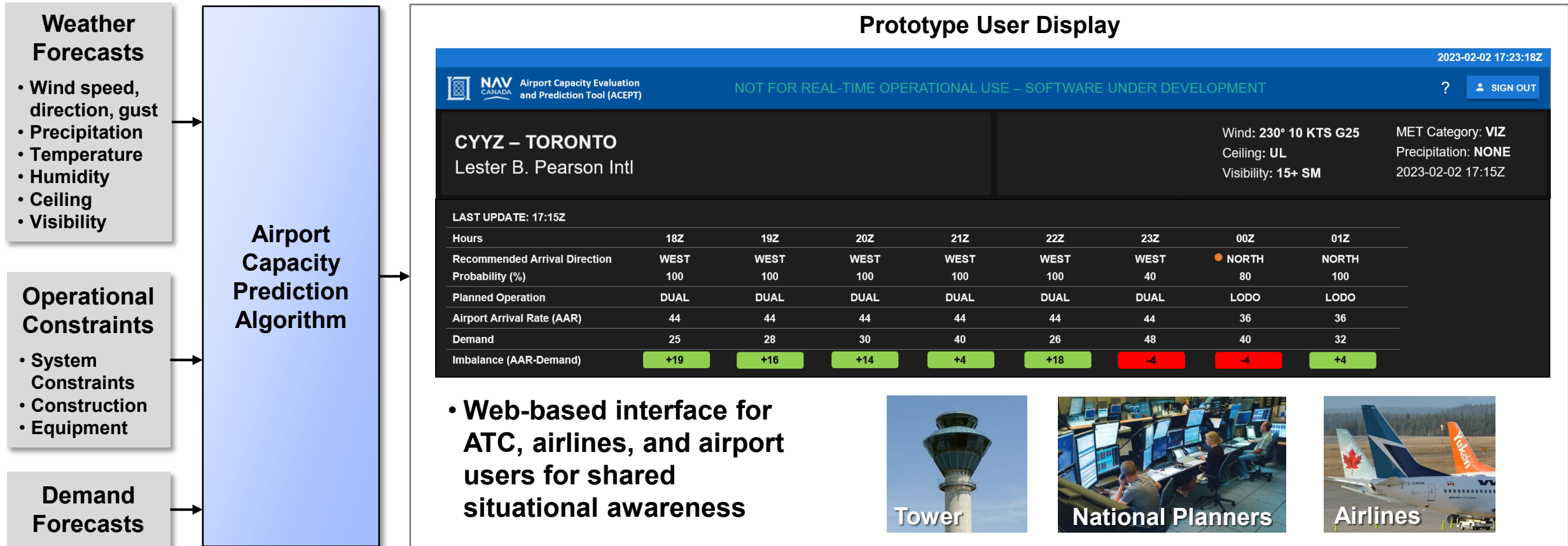
### Products:

- Gust front detection and forecasts
- Storm location and motion
- Winds in terminal area and routes
- Tornado and lightning alerts



# Strategic Airport Weather Forecasting (2+ Hours)

## Airport Capacity Evaluation and Prediction Tool (ACEPT)



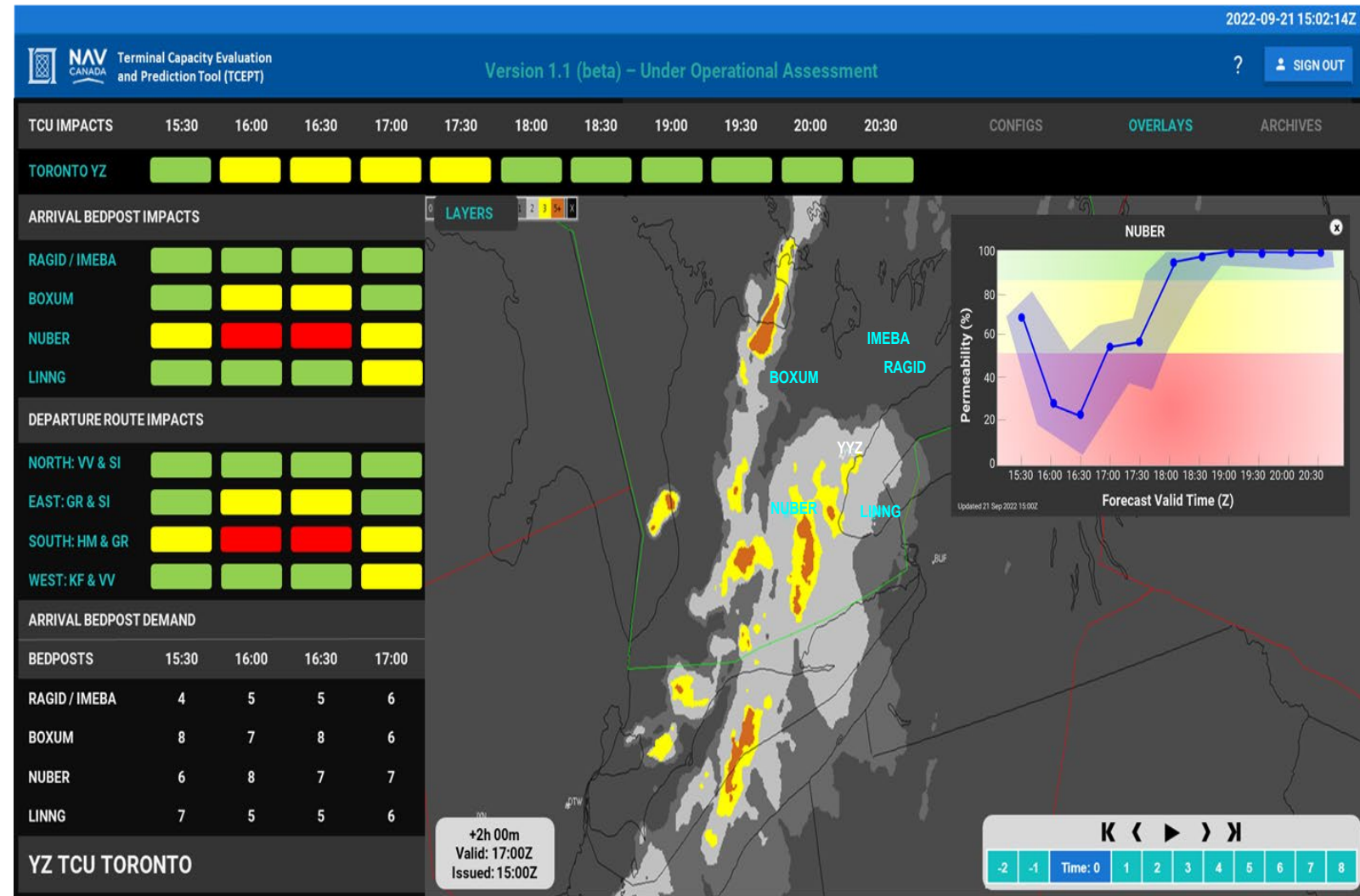
**ACEPT predicts airport weather, recommended runway arrival direction, resulting airport capacity, and identifies demand imbalances 8 hours into future to support effective collaborative decision making**





# Terminal Airspace Weather Forecasting Terminal Capacity Evaluation & Prediction Tool (TCEPT)

- Terminal airspace bridges the gap between airport and en-route operations
- TCEPT predicts waypoint availability & capacity to guide planning in convective weather
  - Assess availability of departure/arrival routes
  - Complementary to ACEPT
- Weather depicted from radar mosaics and HRRR model output
  - Radar-based at short time horizons
  - HRRR-based at long time horizons (2+ hours)







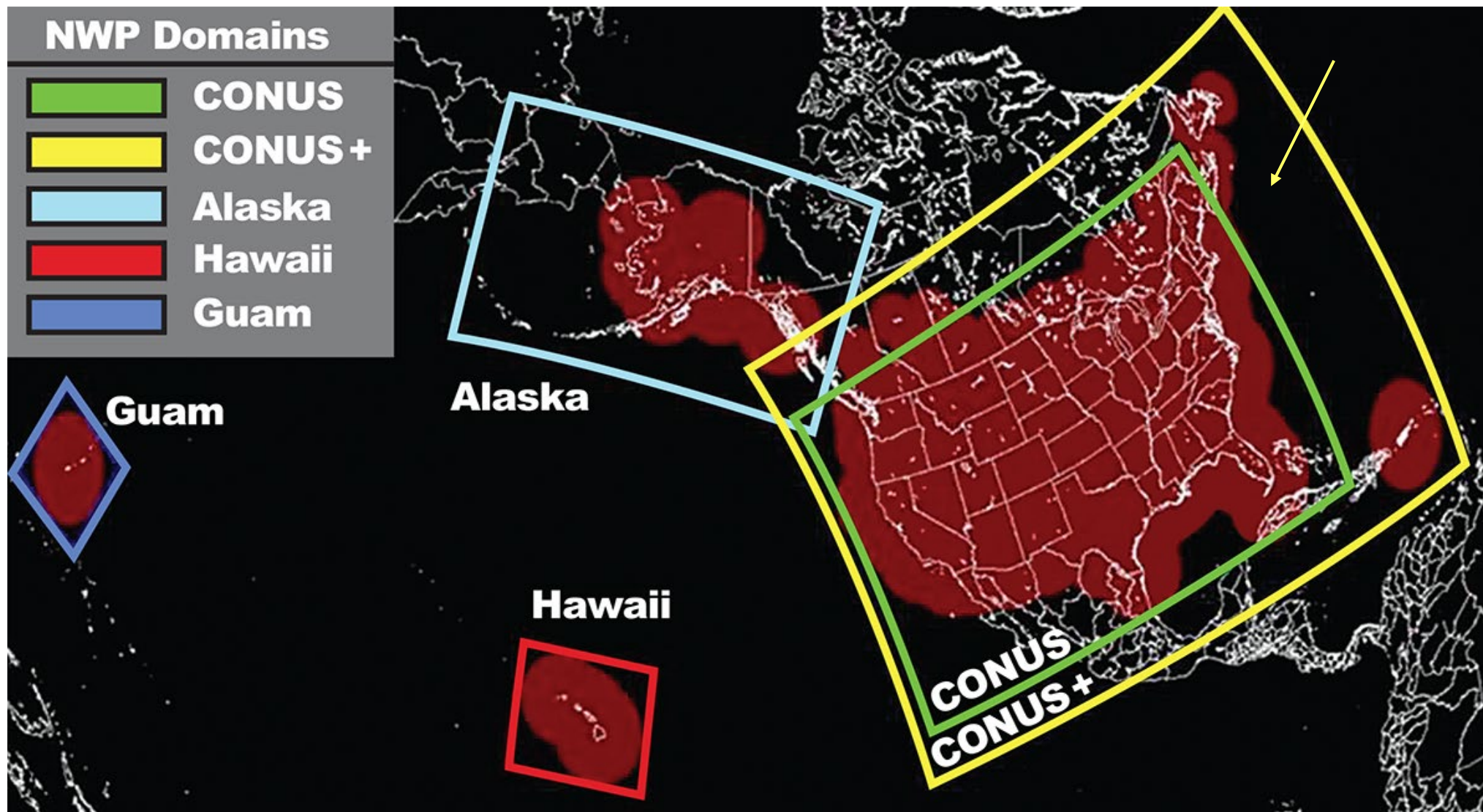
# **En-route Weather Sensing and Forecasting**

## **The NextGen Weather Processor (NWP)**

- **NWP developed to provide a “Common weather picture”**
  - Available to all stakeholders
  - No conflicting weather information from multiple sources
  - Synthesizes many weather products (e.g., weather radar, geostationary satellite, weather models, surface weather observations, etc.)
- **Improved safety:**
  - Accurate storm location, size, shape, height, intensity through advanced mosaicking
  - More timely weather hazard information (25 sec updates)
- **Improved efficiency:**
  - Anticipation of airspace capacity impacts
  - Prediction of route availability and flow constrained areas
  - Support development of precise traffic flow initiatives
    - Miles-in-Trail restrictions, Ground Delay Programs and Airspace Flow Programs

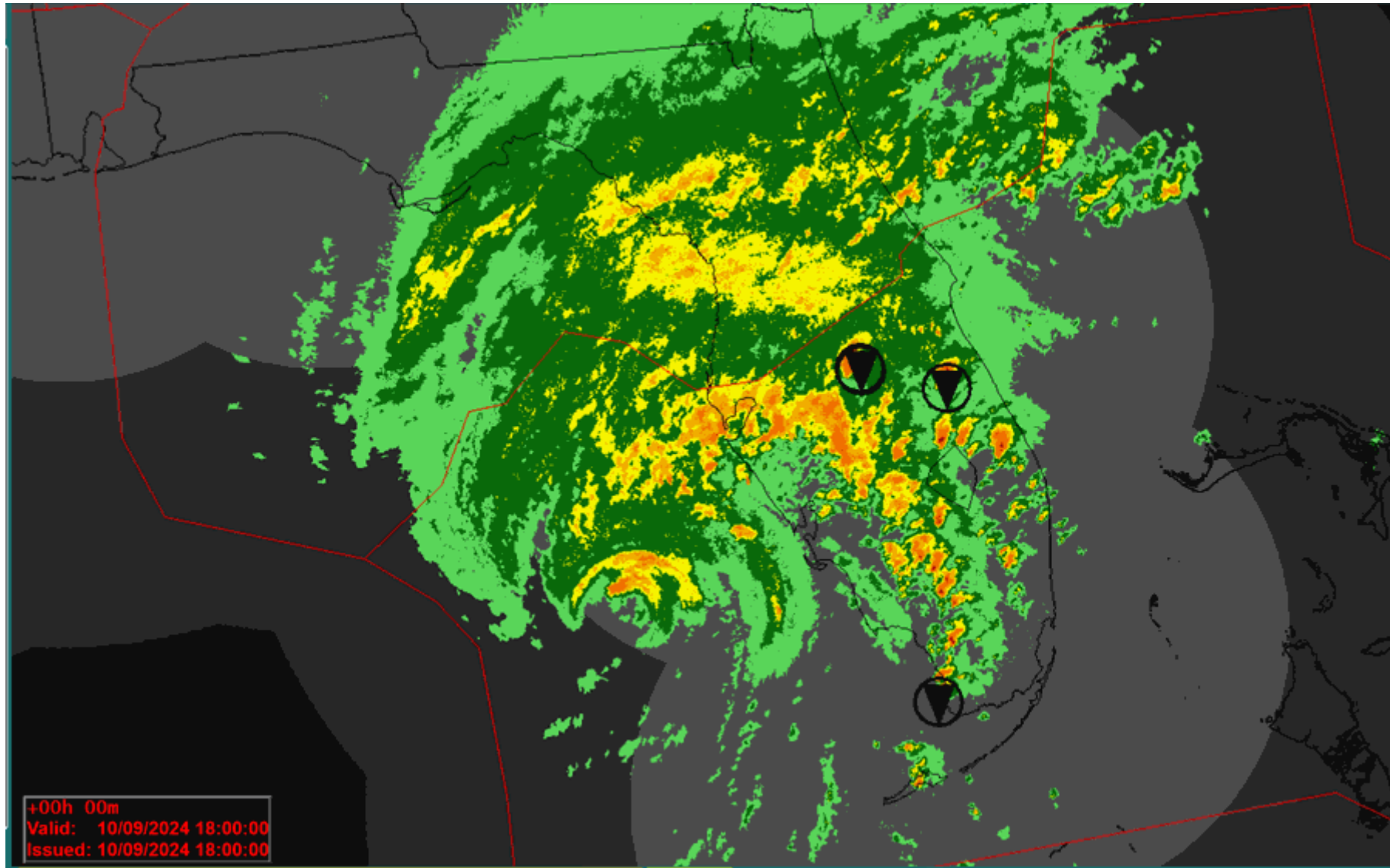


# NWP Coverage





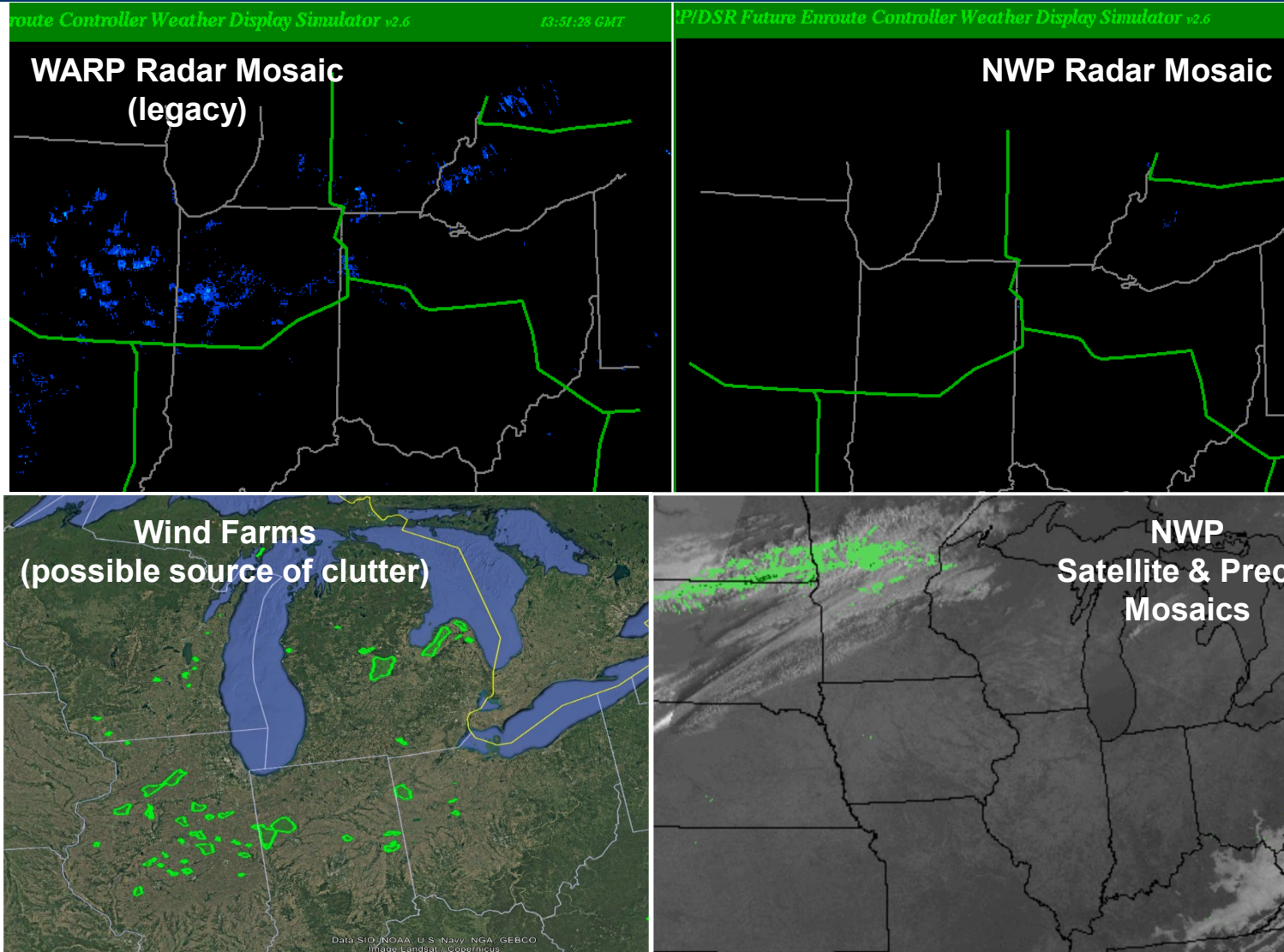
# NWP Depiction of Hurricane Milton – 25 sec CompRefl







# NWP Mitigates of Wind Farms in Legacy Systems



Courtesy of  
Tri Nguyen  
and  
Dave Keifer  
10/3/2024

- Wind farms create clutter that is notoriously difficult to remove in weather radar measurements
- Able to identify and remove through use of geostationary satellite imagery
- Mitigates non-weather echoes compared to legacy systems

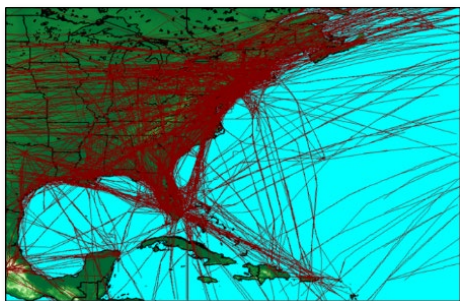




# En-route Weather Sensing and Forecasting: The Need for *Synthetic* Weather Radar

## FAA

Domestic Jet Routes

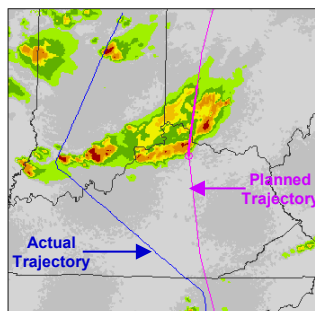


Current Radar Analysis



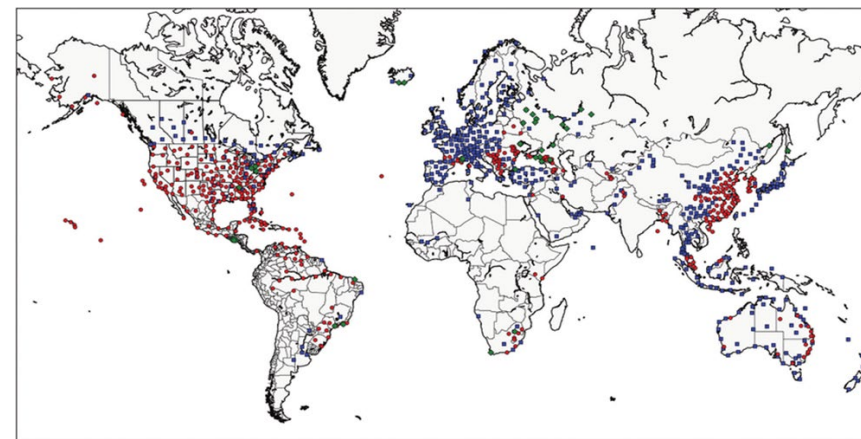
- Piloted aircraft need to avoid hazardous weather for safety reasons
- Air Traffic Controllers lack sufficient weather radar coverage in offshore areas of the National Airspace System
- Controllers are unable to provide timely and accurate weather information to pilots in these regions

Weather Avoidance



MITLL Solution:  
Offshore Precipitation Capability (OPC)

## DoD



Location of X- (green), C- (blue) and S- (red) band radars<sup>1</sup>

- Weather radar information is non-existent or not accessible in many high interest areas
- Other forms of weather information (e.g., satellite, numerical models) may be insufficient to support operations

MITLL Solution:  
Global Synthetic Weather Radar (GSWR)

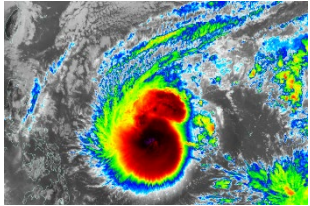


# Using Machine Learning to Extend Weather Radar Coverage

## Model Training

### Historical Input Data

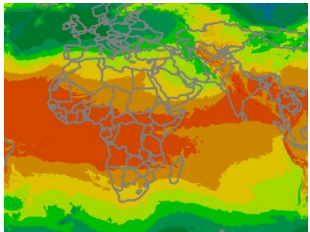
Satellite



Lightning

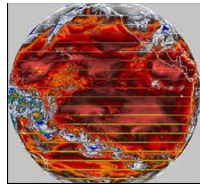


Numerical Model

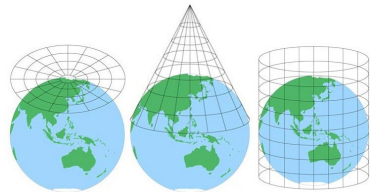


### Preprocessing

Data Quality

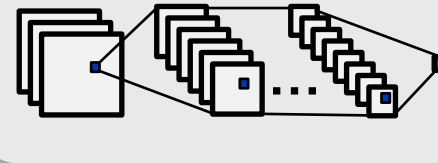


Common Projection

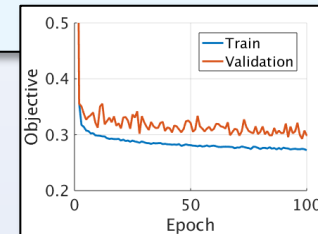


### Training

ML Model



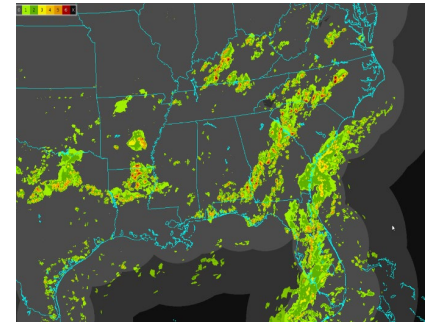
Objective



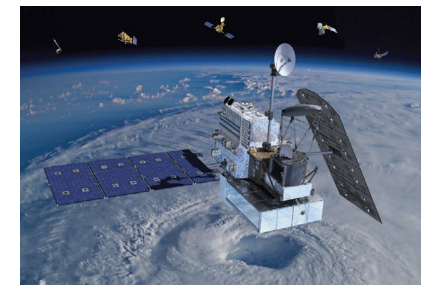
MSE Loss

### Truth Data

Ground Radar



Satellite Radar



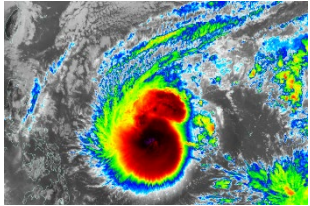


# Using Machine Learning to Extend Weather Radar Coverage

## Model Execution

### Real-time Input Data

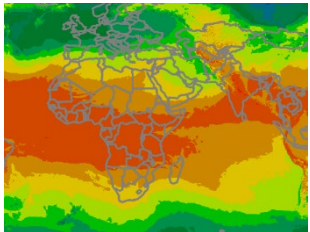
Satellite



Lightning

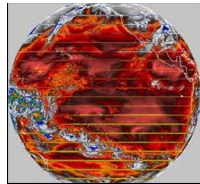


Numerical Model

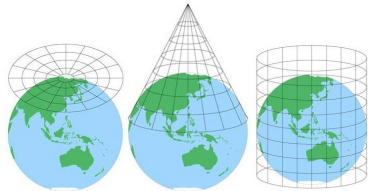


### Preprocessing

Data Quality

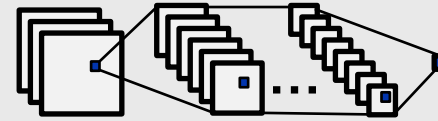


Common Projection



### Execution

ML Model

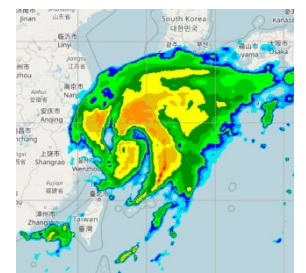


### Output

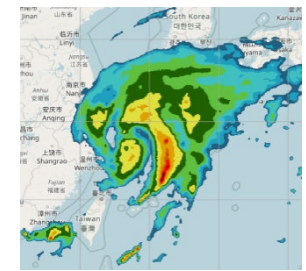
Vertically-Integrated Liquid



Composite Reflectivity



Echo Top



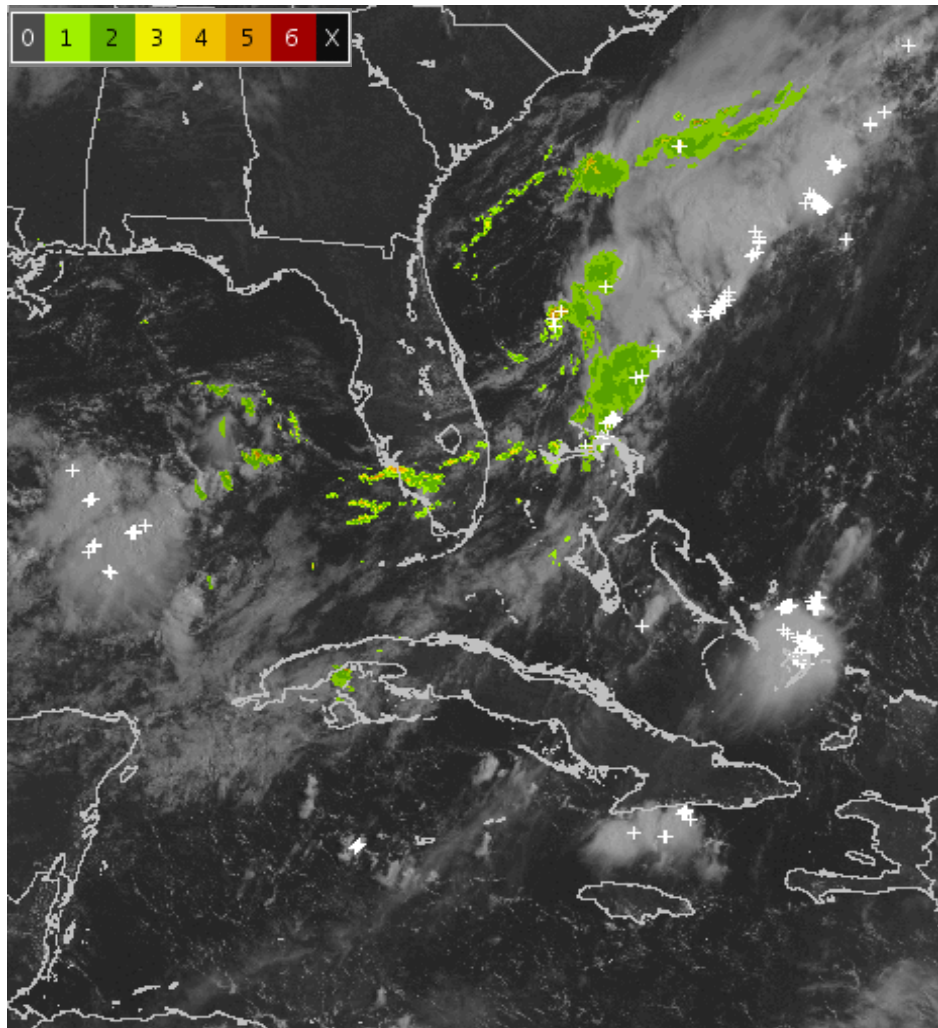




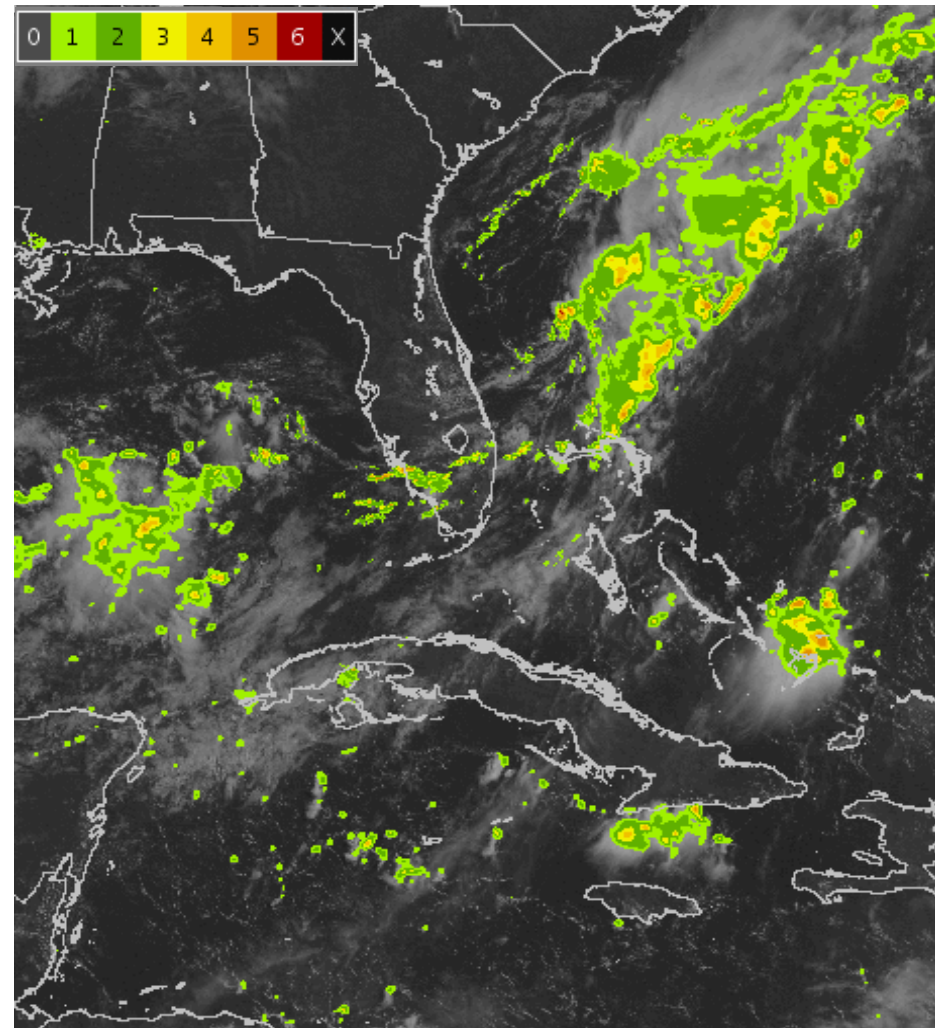
# Offshore Precipitation Capability (OPC)



NEXRAD + Satellite + Lightning



Synthetic + Satellite



1 August 2017 1400 – 1700 UTC every 5 minutes





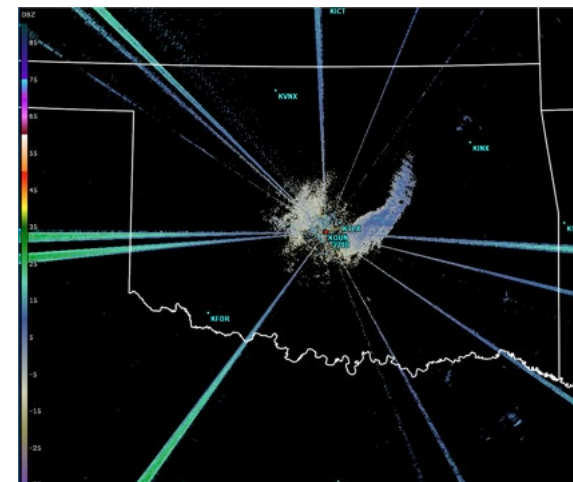
# Outline

- **Motivation**
- **Weather Sensing and Forecasting for Aviation**
- ➔ • **RF Issues**
  - **Weather Radar Radiofrequency Interference**
  - **Usage of Aviation Bands for Weather Information**
- **Summary**

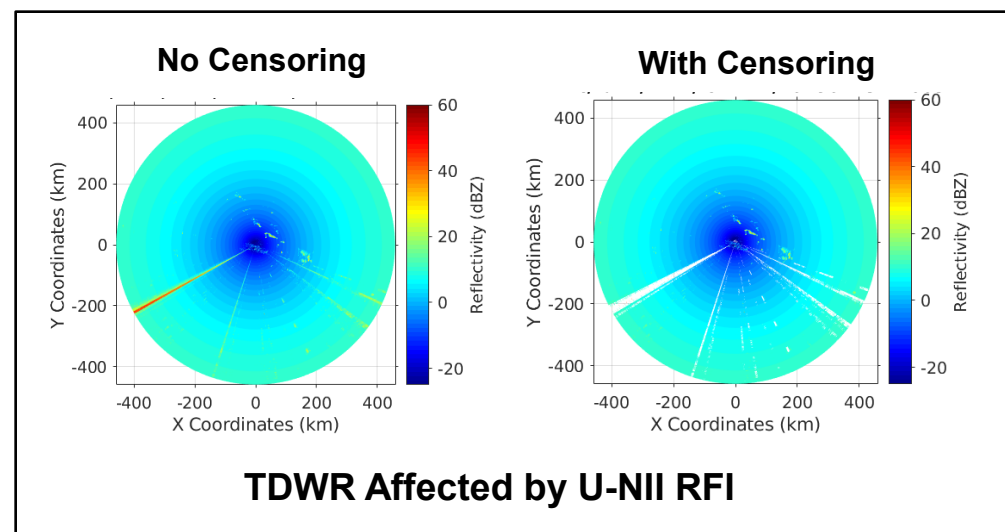


# Weather Radar Radiofrequency Interference (RFI)

- **RFI is a common problem for weather radars**
  - **NEXRAD (S-band) most frequent sources:**
    - Airport Surveillance Radars (ASRs)
    - Cell towers (4G LTE and 5G in the 2496-2690 MHz band), with out-of-band emissions up to 2765 MHz (see NTIA Report 13-490)
  - **TDWR (C-band) most frequency source is Unlicensed National Information Infrastructure (U-NII) sources**
    - Difficult to filter out due to high duty cycle and white noise in Doppler spectrum domain
    - Half of all sites experience RFI from U-NIIs
    - Dynamic Frequency Selection (DFS) function is required in this band, but improper installation, use, and failure to detect TDWR is problematic
- **RFI can largely be censored but not filtered**
  - May miss detections (e.g., wind shear events)



**NEXRAD Affected by Cell Tower RFI in November 2019**



**TDWR Affected by U-NII RFI**



# Potential to Greatly Increase Weather Observations with Novel Low-Cost System

- **The Portable Aircraft Derived Weather Observation System (PADWOS) can obtain dense observations**
  - Low-cost (~\$12K) requiring only 28 W
  - Interrogates aircraft within 60 nm range
  - Able to retrieve temperature, wind speed, and wind direction aircraft is experiencing from received data
  - Transmits at 1030 MHz, aircraft replies at 1090 MHz
  - Initial test network set up around New England and the Southeastern United States
- **Numerous potential uses of these measurements**
  - Improve accuracy of weather models
  - Inform ATC operators of real-time conditions
  - Leverageable to enable time-based separation\*





# Challenges of Deployment of PADWOS Network

- **PADWOS transmits at 1030 MHz, within the 960-1164 MHz band allocated for aeronautical radionavigation service (ARNS)**
  - **Managed domestically by the FAA**
- **Definition from NTIA: “The ARNS is a radionavigation service *intended* for the benefit and the *safe operation* of aircraft. There are numerous types of aeronautical radionavigation systems *primarily used to ensure safety of flight* and to support precision approach and landing of aircraft.”**
- **Initial PADWOS installations have operated under a 2-year authorization from the FAA\***
  - **Authorization has recently expired and have been unable to obtain extended / new licenses for continued operations**
  - **Contend that PADWOS does benefit the safe operation of aircraft through enhanced weather situational awareness directly, and improved weather forecasts indirectly**





# Summary

- **Weather is a significant challenge to the safety and efficiency of flight**
  - **Plethora of weather conditions can affect operations at any stage of flight**
- **Transformational weather sensing and forecasting technologies and systems have been developed to improve the safety of flight**
  - **Continue to be enhanced to address emerging problems as density of operations increases**
- **Radiofrequency allocation and usage has posed increasing challenges for advanced weather sensing**

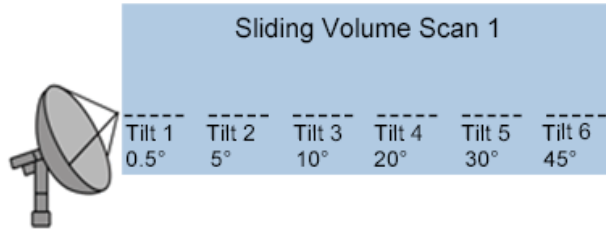


# Backup

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# NWP Rapid Update Mosaic Techniques



## NWP Mosaic Techniques

- **Sliding Volume updates**: Compute new radar volume with every new tilt (15-40 sec)

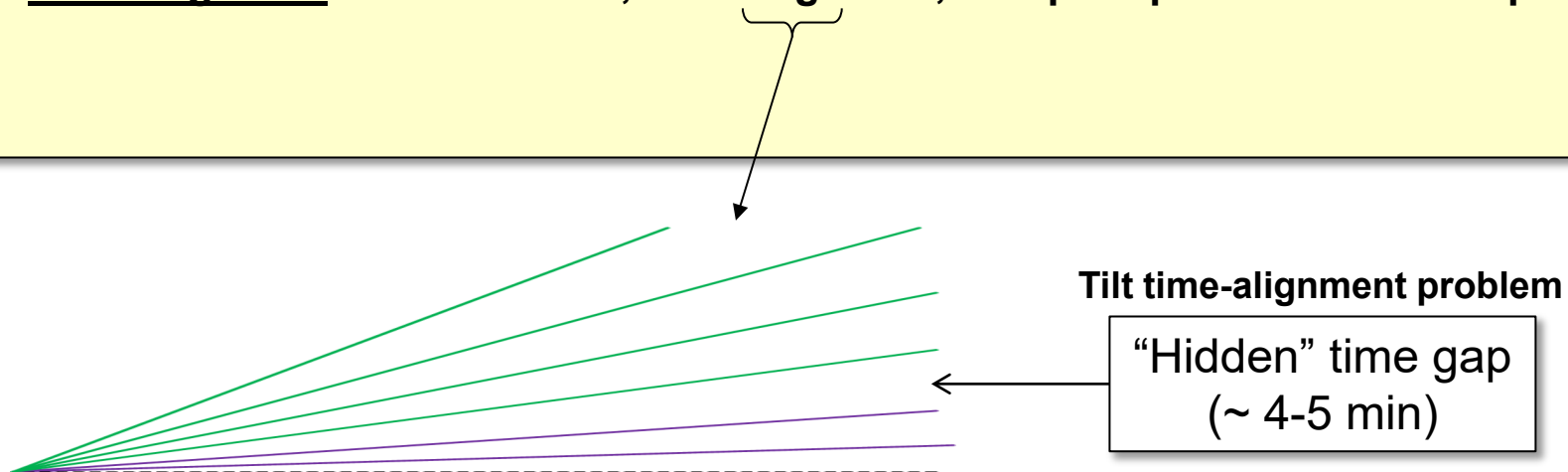


# NWP Rapid Update Mosaic Techniques



## NWP Mosaic Techniques

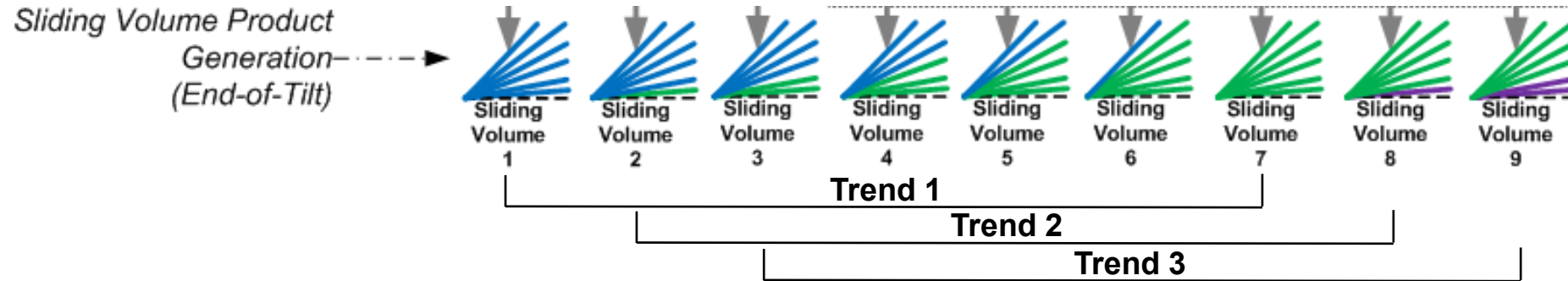
- **Sliding Volume updates**: Compute new radar volume with every new tilt (15-40 sec)
- **Time-align tilts**: Track storms; time-align tilts; compute per-radar volume products





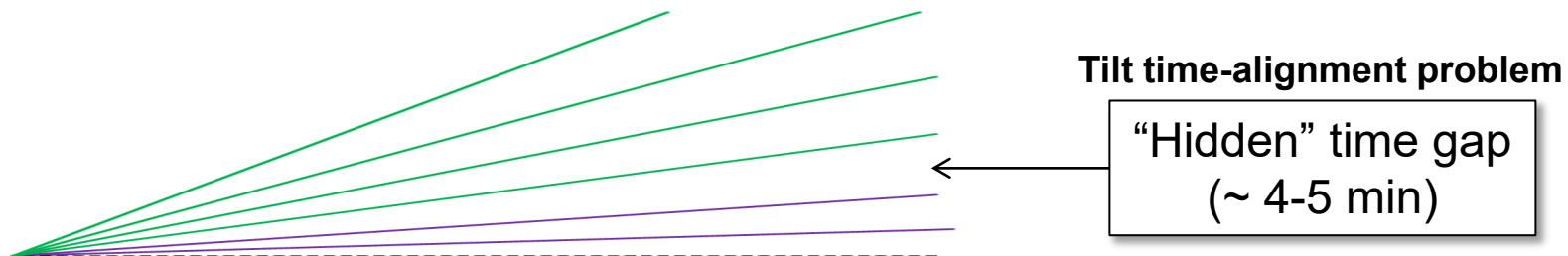


# NWP Rapid Update Mosaic Techniques



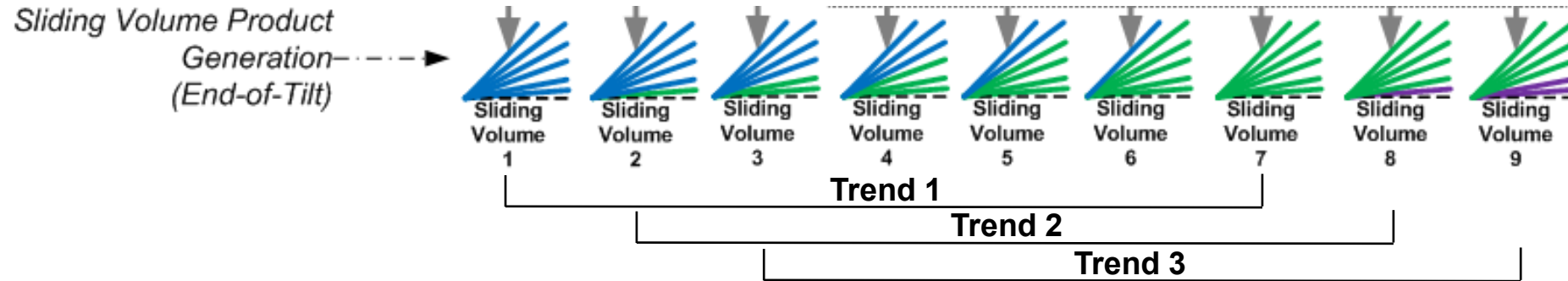
## NWP Mosaic Techniques

- **Sliding Volume updates**: Compute new radar volume with every new tilt (15-40 sec)
- **Time-align tilts**: Track storms; time-align tilts; compute per-radar volume products
- **Respect radar scan strategy**: Compute trends only from “like” volumes



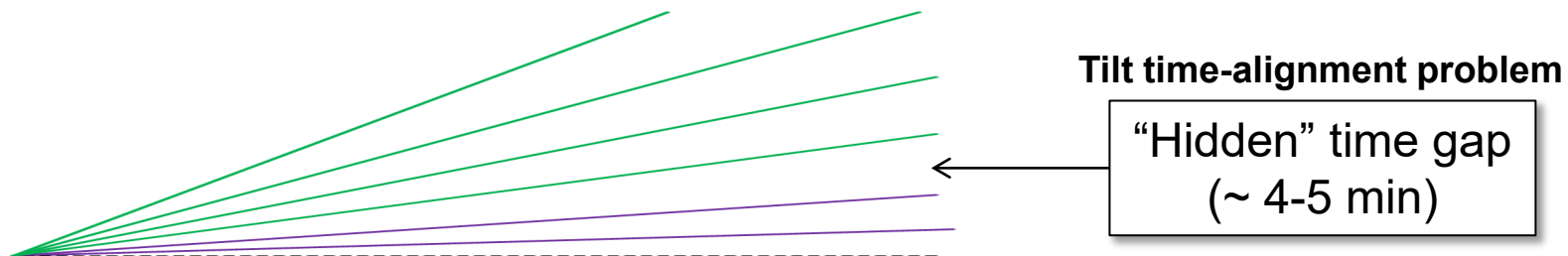


# NWP Rapid Update Mosaic Techniques



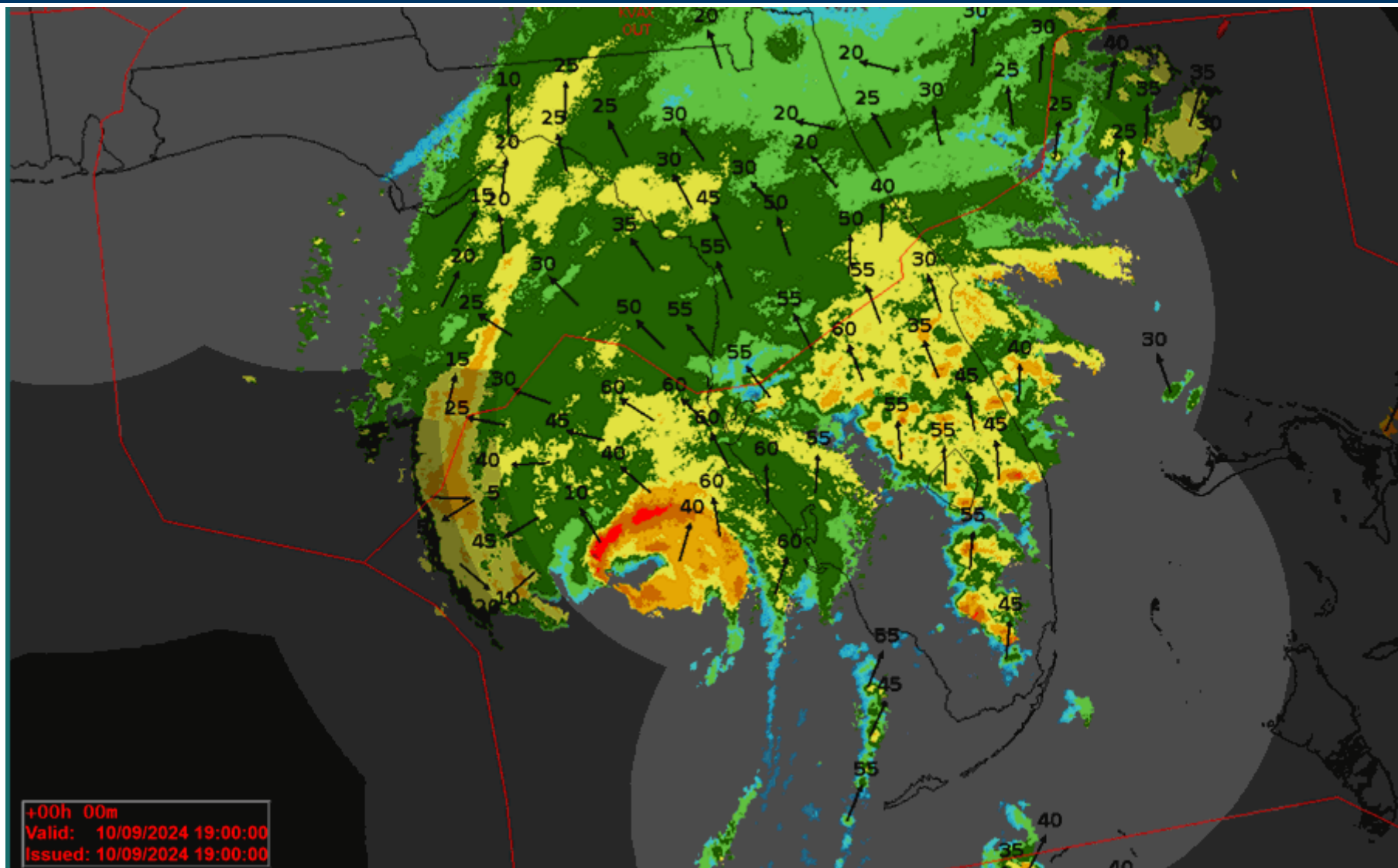
## NWP Mosaic Techniques

- **Sliding Volume updates**: Compute new radar volume with every new tilt (15-40 sec)
- **Time-align tilts**: Track storms; time-align tilts; compute per-radar volume products
- **Respect radar scan strategy**: Compute trends only from “like” volumes
- **Make mosaics**: Motion-compensate all volumes to common mosaic time



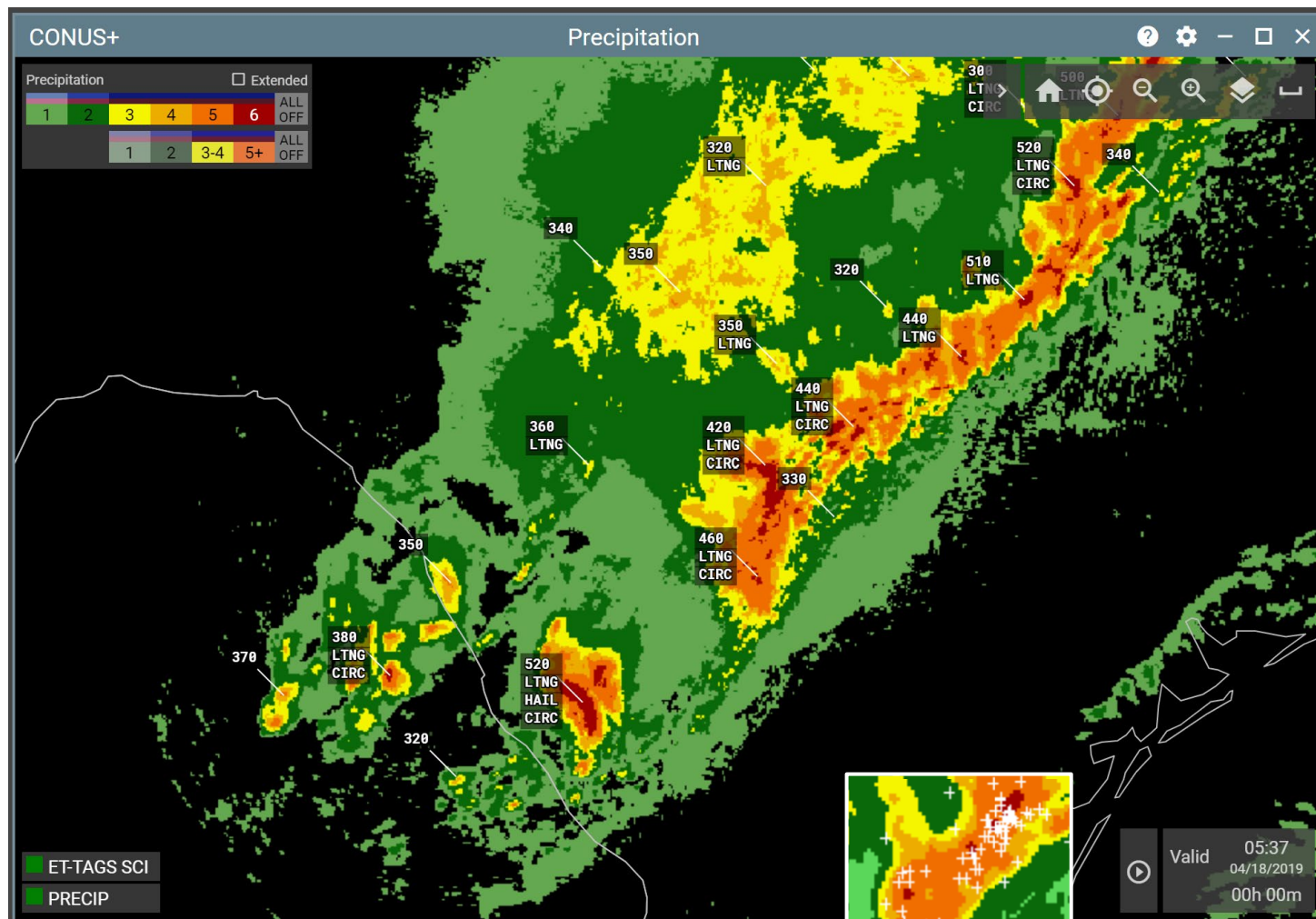


# Hurricane Milton – 2.5 min Echo Tops





# Storm Hazard Tags



In addition to Echo Tops Tags, NextGen Weather provides Storm Hazard Tags as selectable option

**LTNG**  
(from FAA contract Lightning feed)

**HAIL**  
(based on Nexrad Hail product)

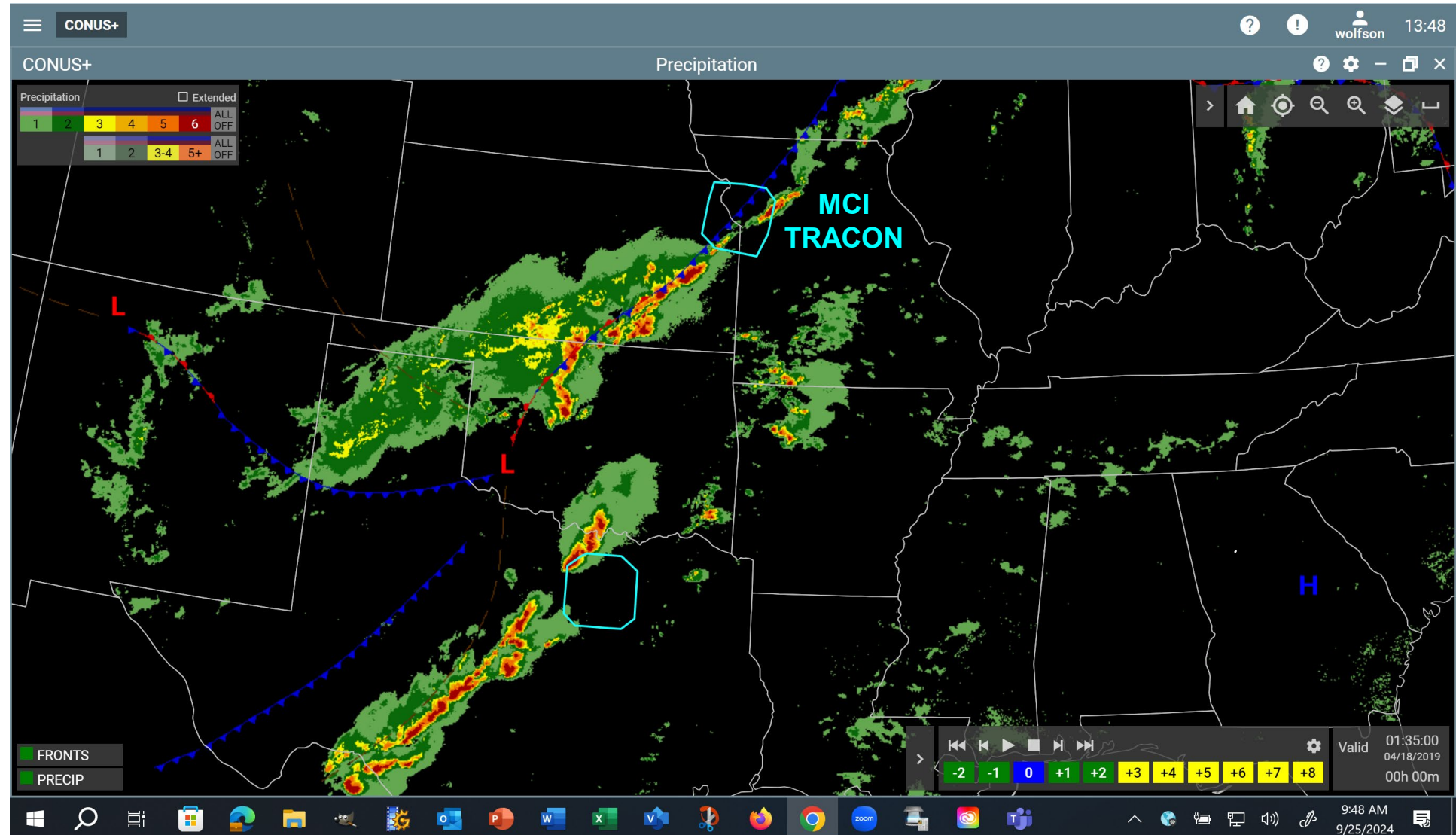
**CIRC**  
(based on Nexrad Mesocyclone product)

← Alternative lightning display  
(Can obscure Precip in severe lightning)



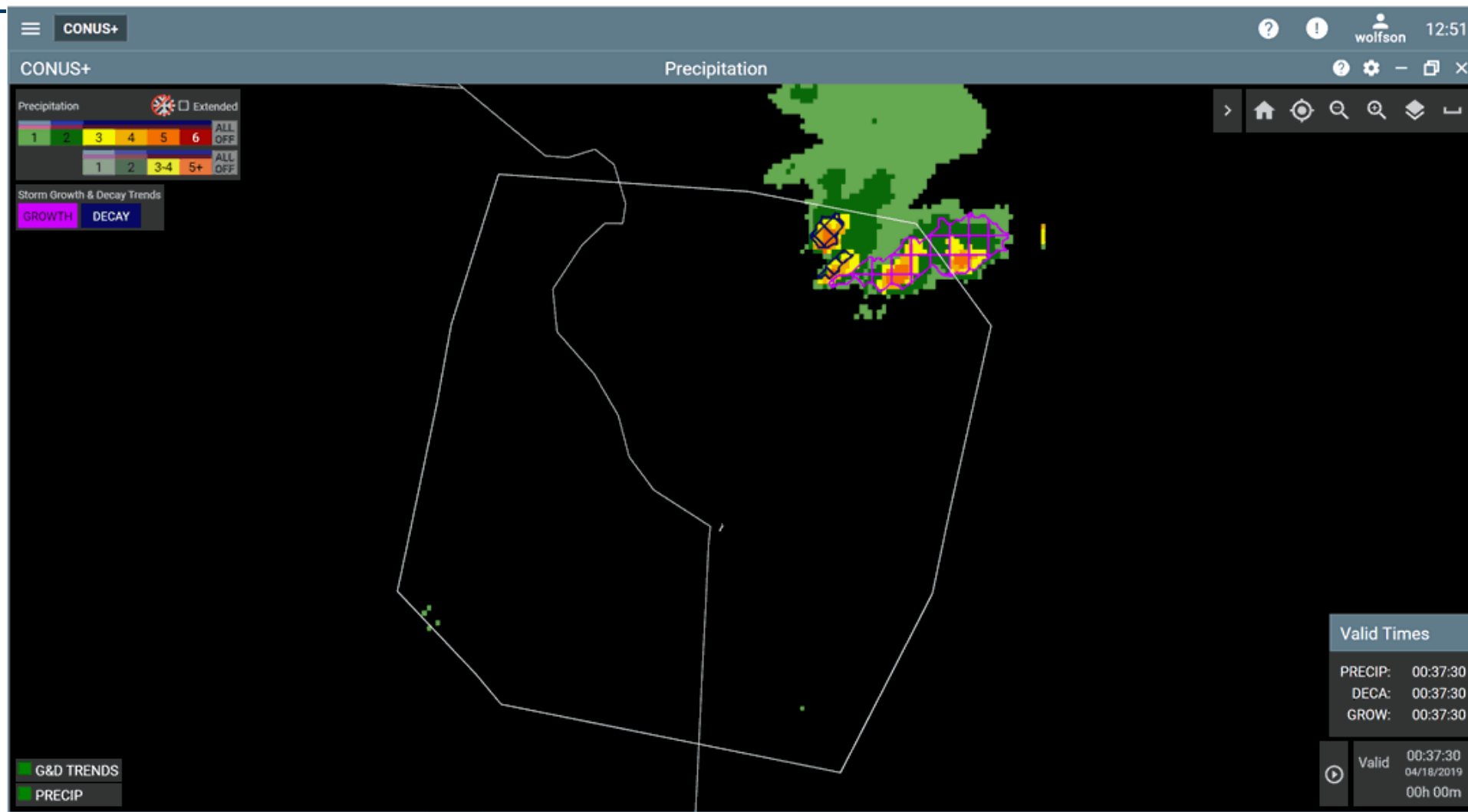


# Example Mosaics in a Rapid Growth Scenario – Frontal Forcing





# Rapid Storm Growth Indicated through Detectors

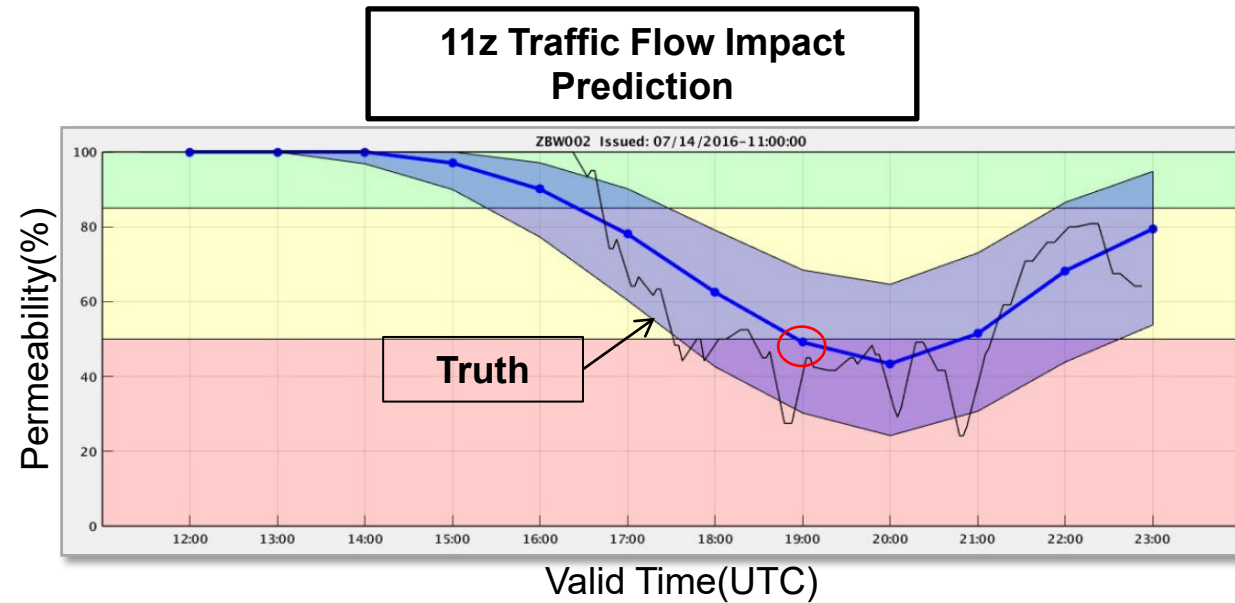


Excellent storm tracking allows accurate diagnosis of Trends

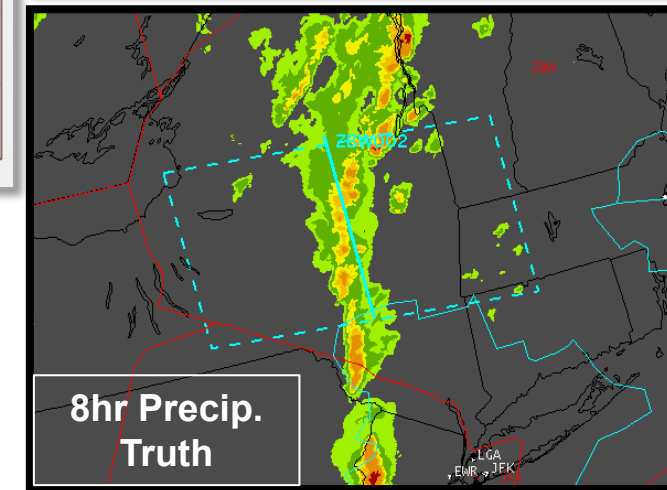
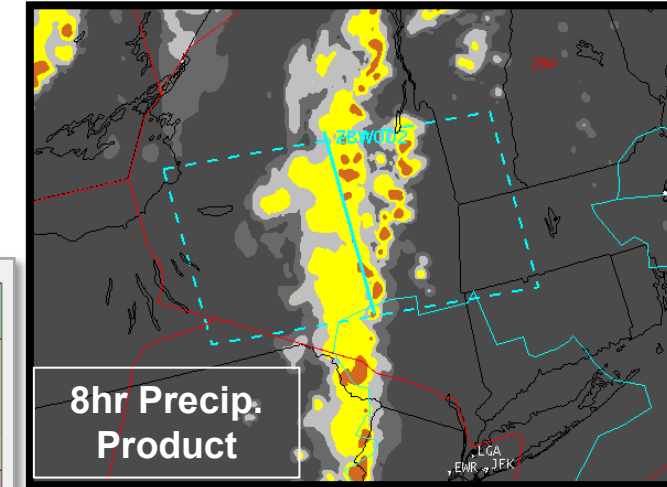
Precip updates: 2.5 min  
Trend updates: 25 sec



# Traffic Flow Impact Predictions

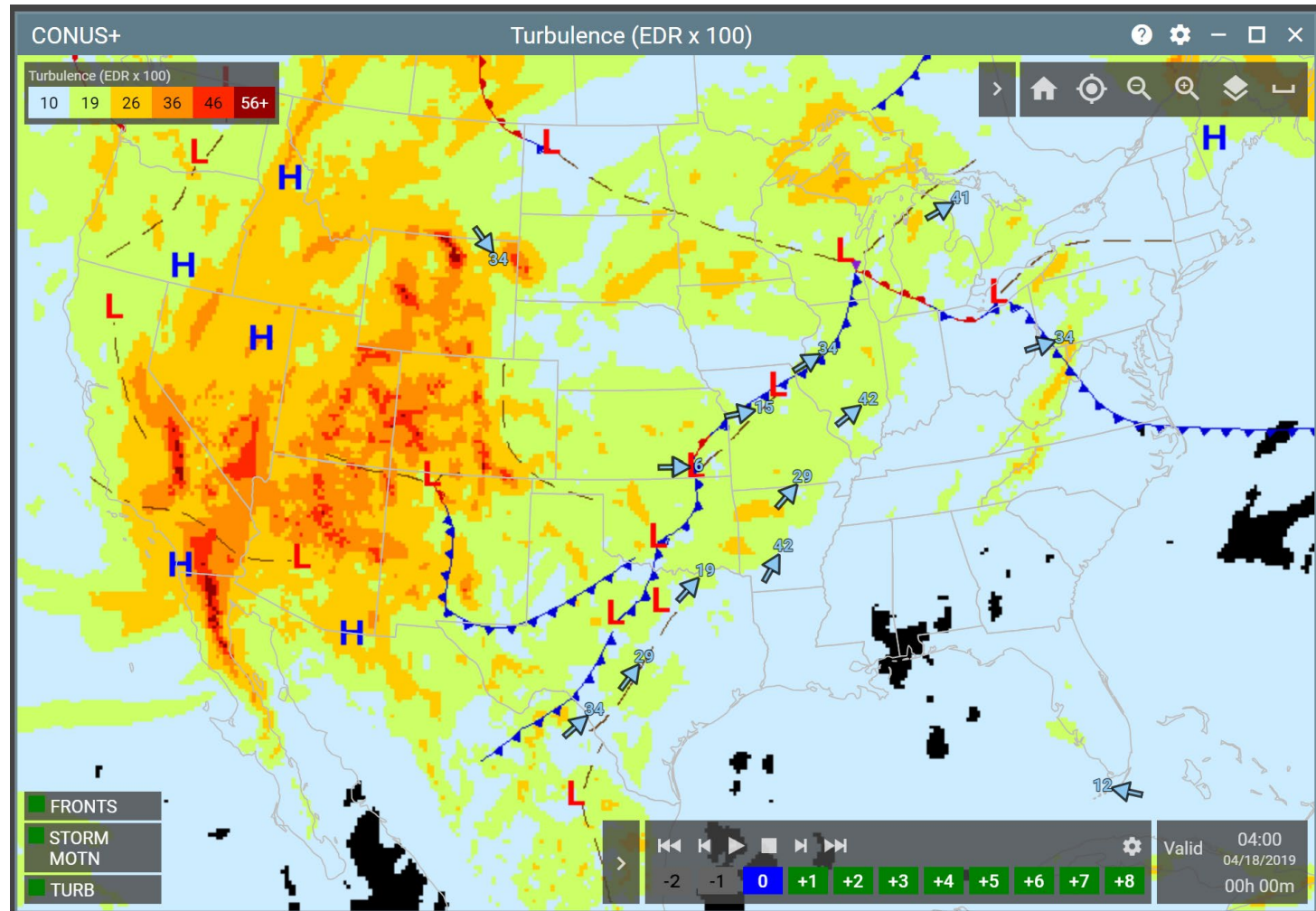


Initial product: 8-hr predictions  
Future system release: 12-hr predictions





# NWS Turbulence w/ NextGen Weather



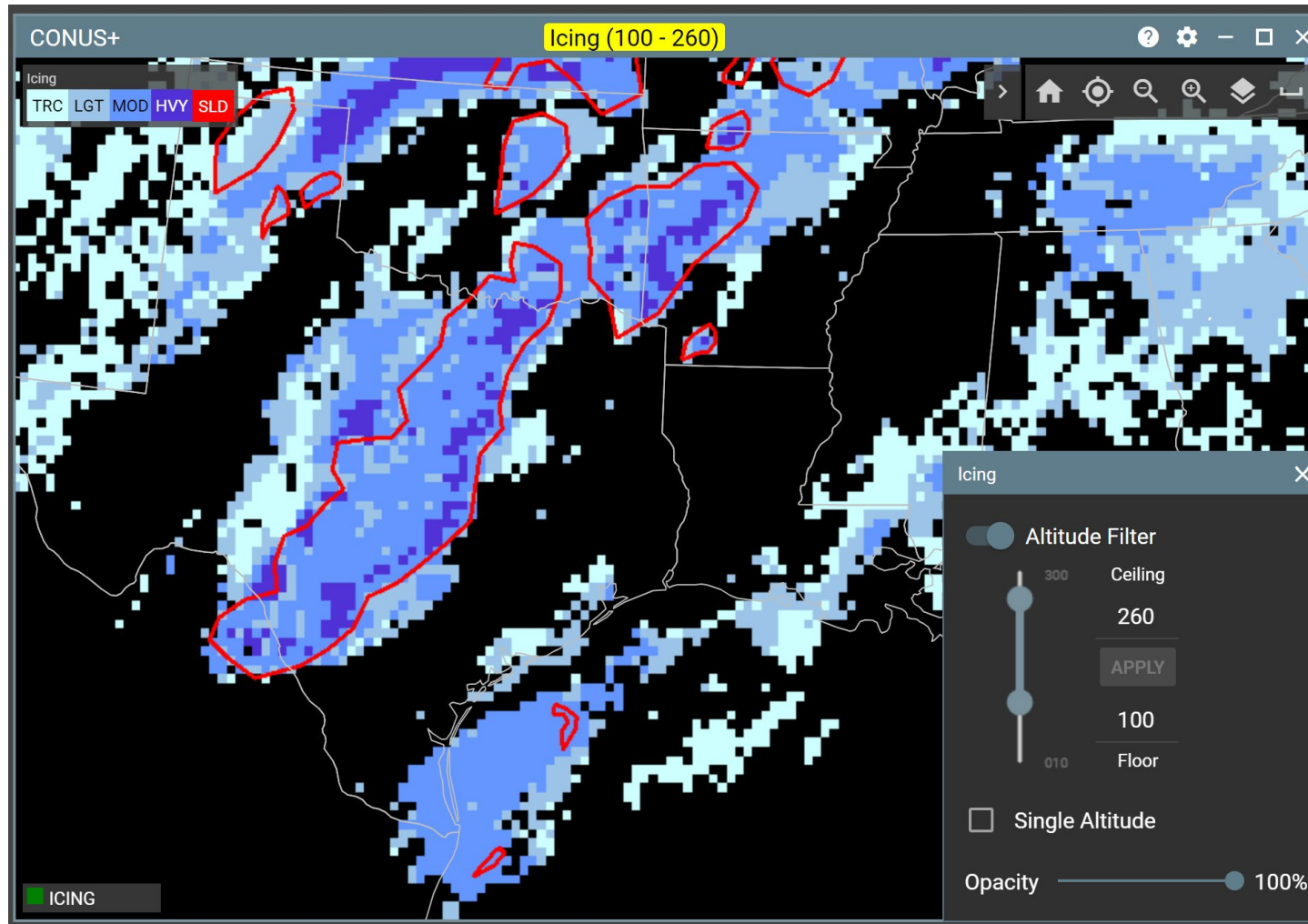
NextGen Weather integrates NWS Turbulence on the Aviation Weather Display

Shown here are NextGen Weather 0-2 hr Fronts and Storm Motion Vecs overlaid on NWS Turbulence map





# NWS Icing w/ NextGen Weather



NextGen Weather integrates NWS Icing and provides Layer selection option (floor/ceiling) for:

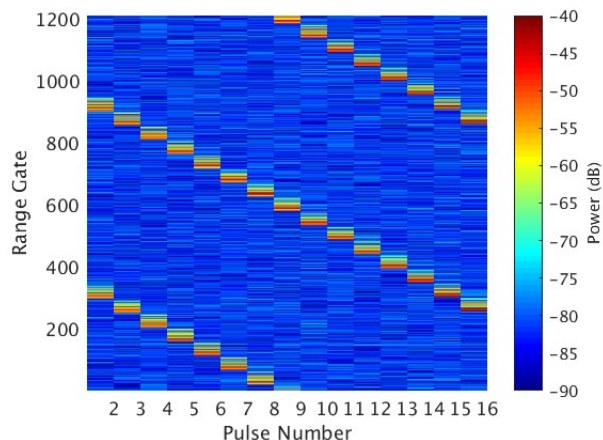
- NWS Icing (shown here)
- NWS Turbulence
- NextGen Weather Composite Reflectivity

Red contour indicates regions of super-cooled large droplets, known to cause aircraft icing

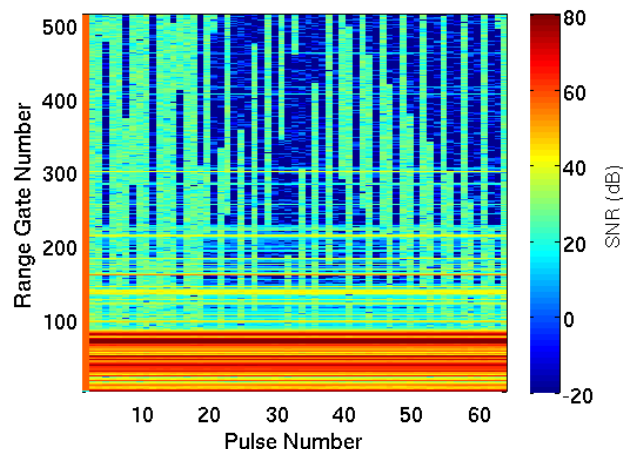


# An emerging Radio Frequency Interference (RFI) Threat

**RFI from a Pulsed Radar**



**RFI from a U-NII Device**



- TDWR is equipped with time-domain single-pulse RFI detector and filter
  - Performs well against RFI from pulsed radars
- At the time of TDWR development and initial deployment (1990s) 5.6-5.65 GHz band was restricted to certain radar systems
- In 2003 unlicensed national information infrastructure (U-NII) devices were allowed into this band
  - Dynamic frequency selection (DFS) function to sense and avoid radar channel is required
- U-NII (wireless communication) RFI is difficult to filter out
  - High transmit duty cycle
  - White noise in Doppler spectrum domain

**Despite DFS requirement U-NIIs became an RFI challenge for TDWRs**



# U-NII-to-TDWR RFI Timeline

5.47-5.725 GHz (including TDWR band, 5.6-5.65 GHz) opened for sharing with U-NII devices with DFS as requirement

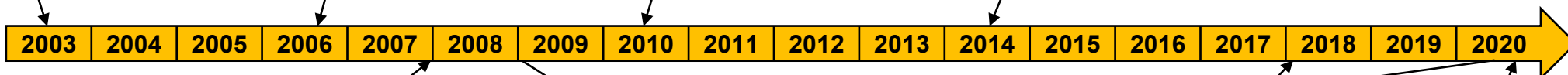
Interim exclusion of 5.6-5.65 GHz band in certifying new U-NIIs

FCC finalizes DFS certification requirements; first products become available on market

- TDWR waveforms not represented in certification test

U-NII certification in TDWR band allowed again

- Wider DFS detection bandwidth (80% → 100%)
- Certification procedure modified to be more robust and include TDWR-like waveforms
- Require country code locked so operator cannot change it



FCC takes over 50 enforcement actions against U-NII operators due to RFI into TDWRs\*

RFI strobes begin appearing at TDWR sites

National deployment of new adaptive multi-PRI waveforms deployed on TDWRs

Now: Half of all sites still experience RFI from U-NIIs



# Why DFS “Sense and Avoid” is not Working as Intended\*

- **Willfully improper installation and operation of U-NIIs**
  - Disabling DFS function—made more difficult by 2014 requirement of locked country codes
  - Connection to non-compliant high-gain antennas
  - Illicit retuning of non-DFS-equipped wireless devices into TDWR band
  - Illegal import of non-US-authorized devices
- **Failure of certified DFS to detect TDWR**
  - Original test did not include waveforms representative of TDWR; there may be other issues
  - Waveform set and procedure revised in 2014; but TDWR has new waveforms since then
- **Post-certification firmware updates unintentionally disabling DFS function**
- **Only the master device in U-NII local network is required to have DFS**
  - If master device is more blocked from radar view than clients, DFS may not detect radar and clients transmissions could cause interference to radar
  - Not documented so far, but physically possible

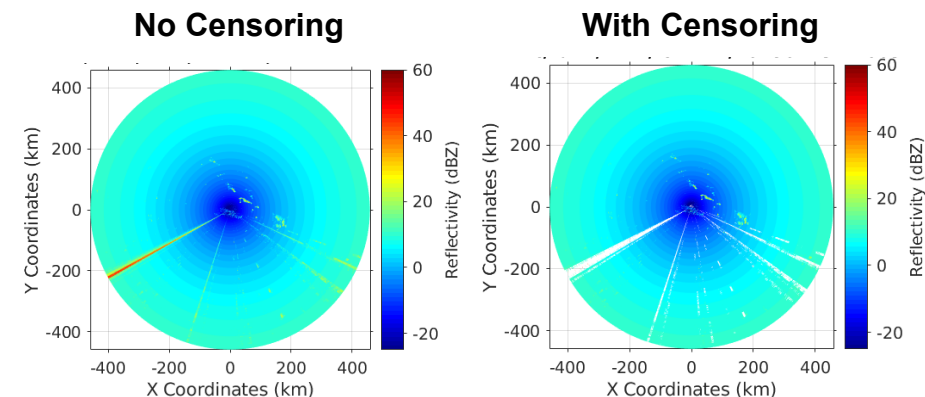
**Problem cannot be solved by technical approach alone**





# Mitigation Approaches

- **Regulatory enforcement:** Track down offenders, levy fines, shut them down
  - Like game of “Whack-a-mole”: New and repeat offenders keep popping up
- **Technical measures**
  - Dynamic “noise” floor estimation and subtraction: Effective if INR not big relative to weather SNR
  - Automated detection and censoring
    - Would help avoid false alerts on wind-shear detection
    - Would not help with missed detections due to obscuration by RFI\*
- **Institute exclusion zones around TDWRs?**
  - Could affect significant fraction of U.S. population
  - Illicit operation still a problem



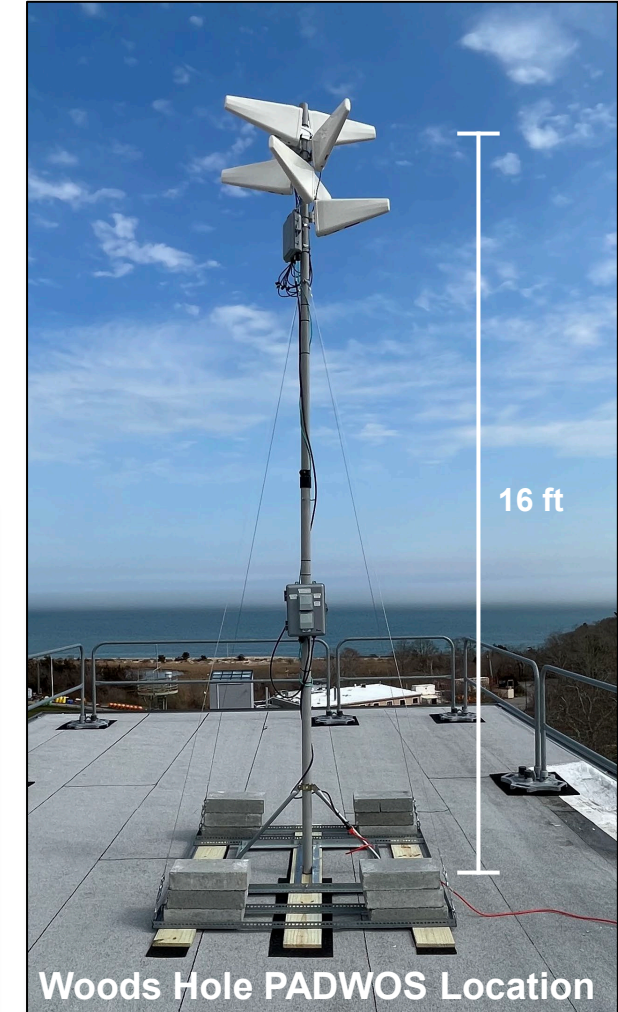
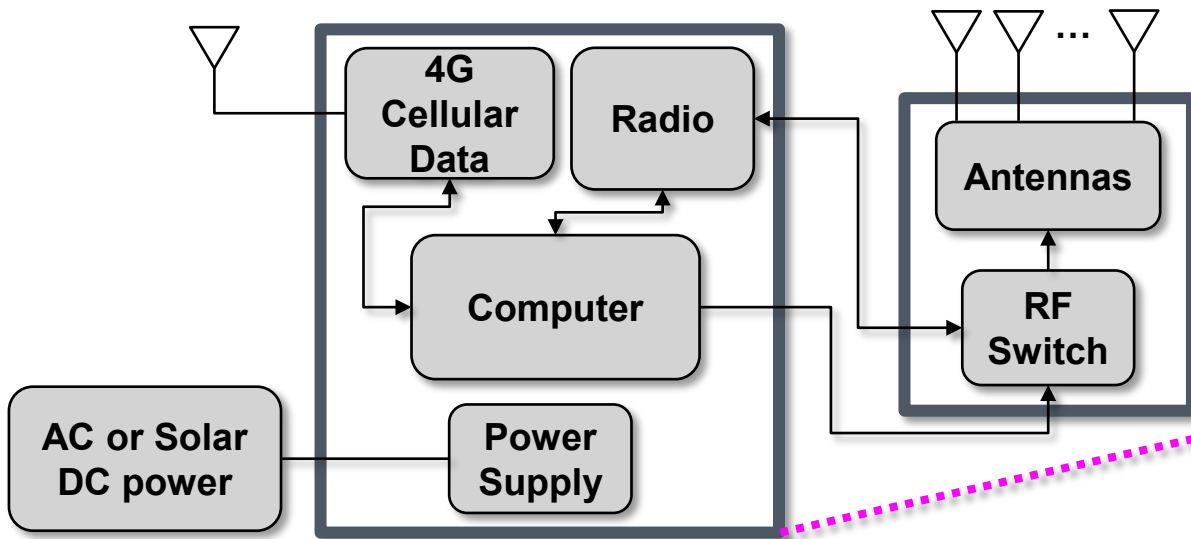
**U-NII RFI is an ongoing issue**

\*No documented case of missed detection or false alert due to RFI yet



# Portable Aircraft Derived Weather Observation System (PADWOS)

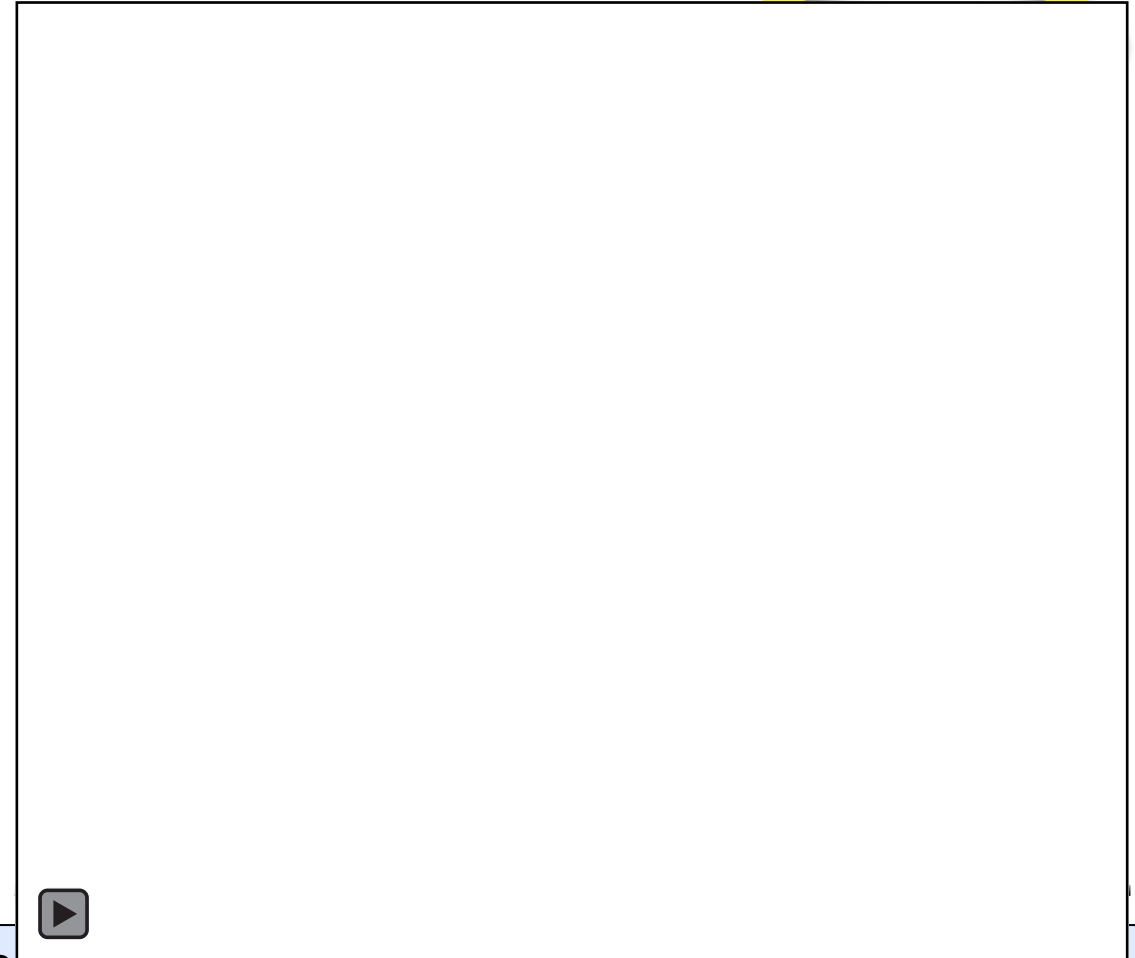
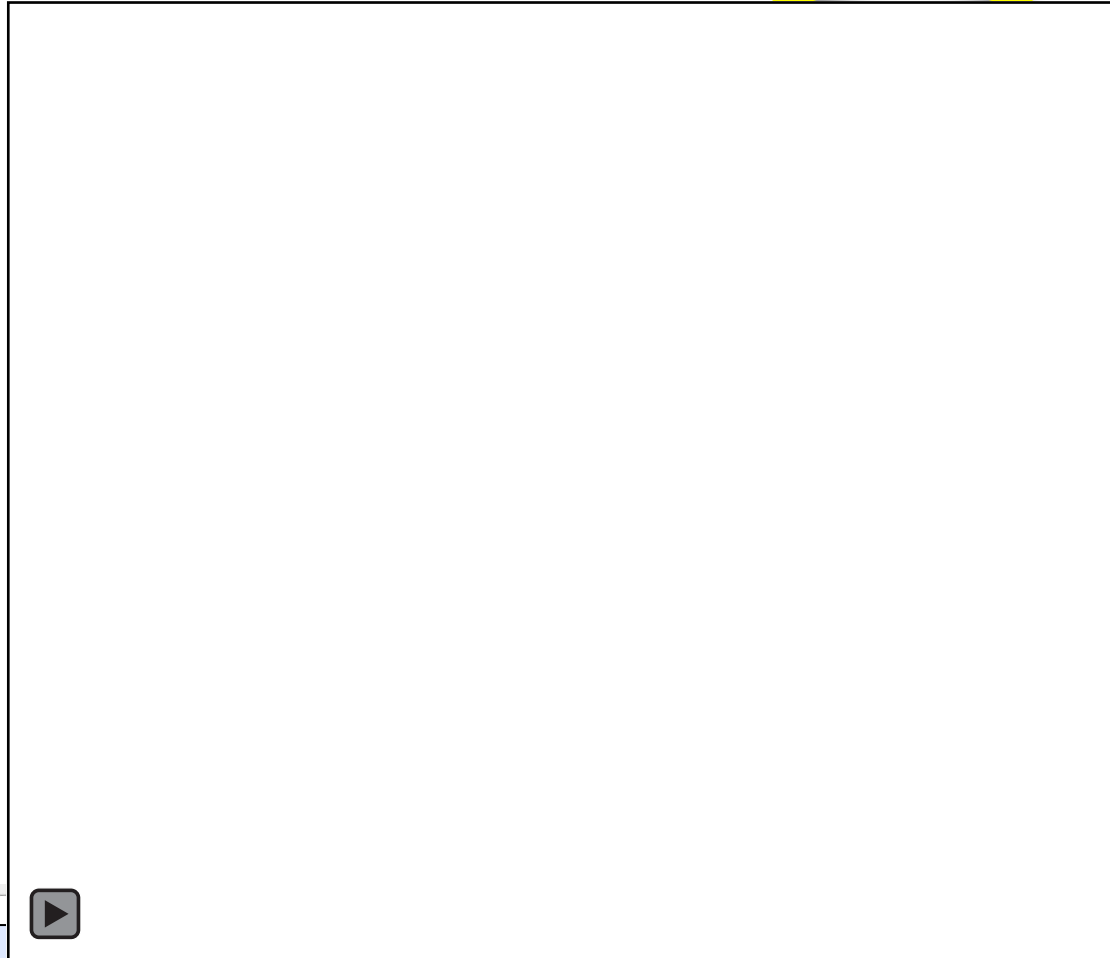
|                      |                                |
|----------------------|--------------------------------|
| Range                | 60 NM (per agreement with FAA) |
| Observation Period   | e.g., 10 - 60 s (programmable) |
| Observation Delay    | $\ll 1$ s                      |
| Network Connectivity | 4G                             |
| Power Requirement    | ~ 28 Watts                     |
| Prototype Cost       | < \$US 12k                     |





# Comparing Current System

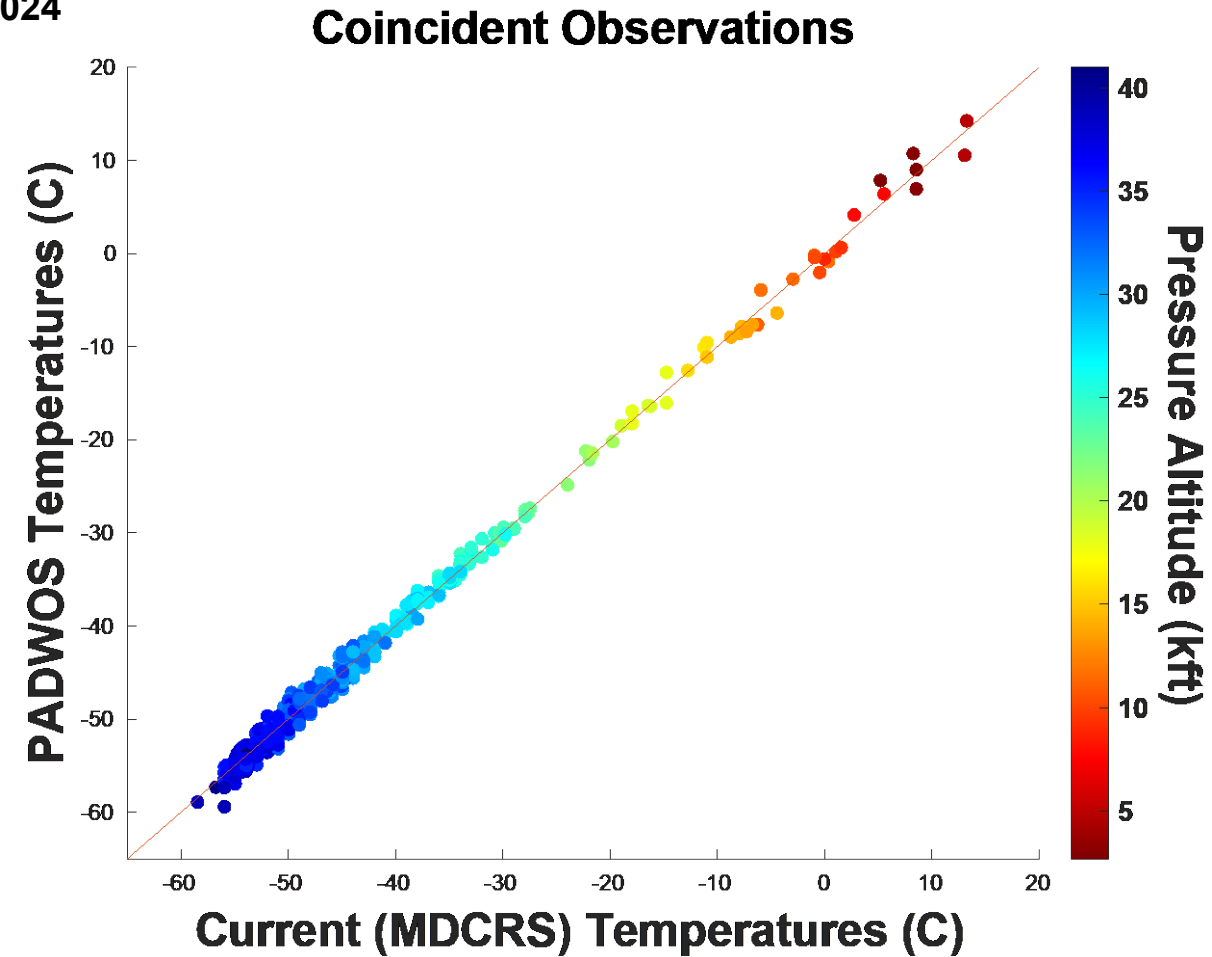
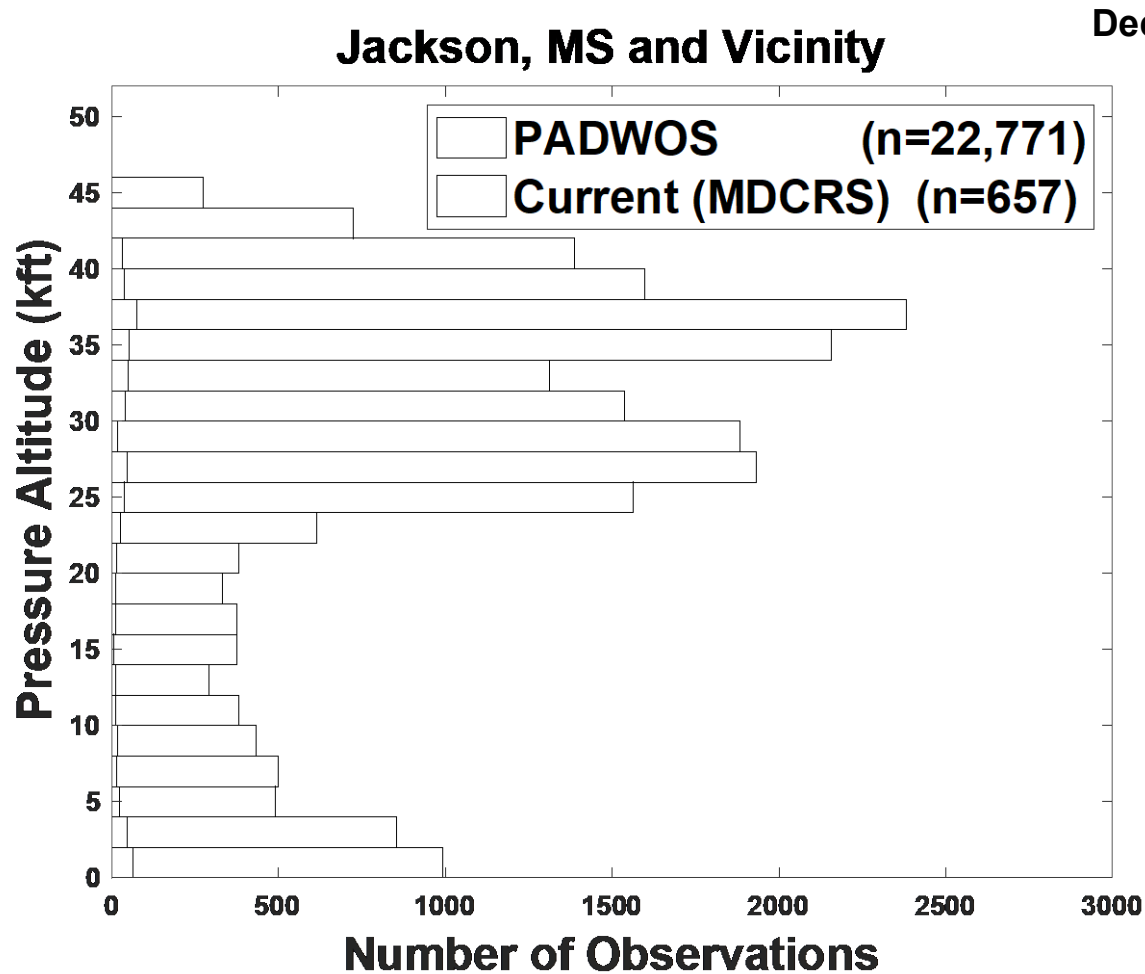
1-hour timelapse, Jackson, MS



two order of magnitude increase in number observations & available with much less latency



# PADWOS Single Day, Single Site Comparison to MDCRS



**Accuracy of estimates from PADWOS are on par with current MDCRS measurements**