Contrail Avoidance Decision Support and Evaluation Project 78

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Massachusetts Institute of Technology

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Alexandria, VA

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Introduction

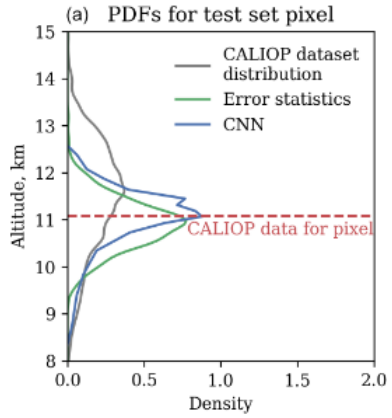
- Contrails are consistently found to be **an important contributor** to aviation climate impacts

- **Large uncertainties** regarding the impact of contrails remain, making it an active research area

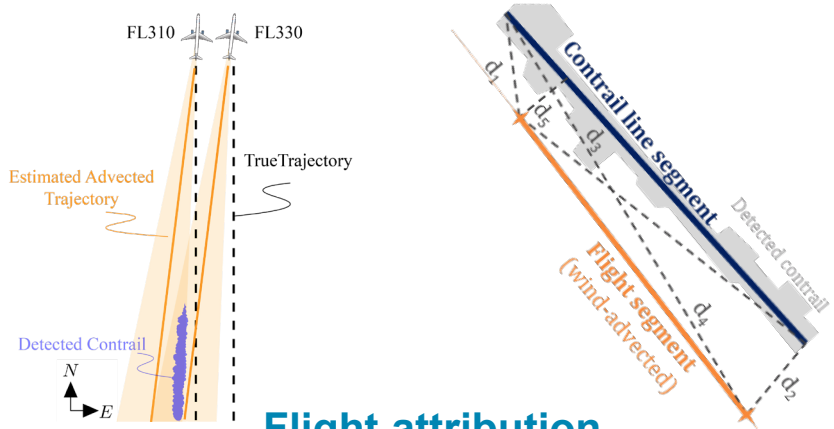
- Observation-based contrail avoidance (amongst other operational techniques) may be a **near-term option** to reduce this impact substantially

Schedule and Status

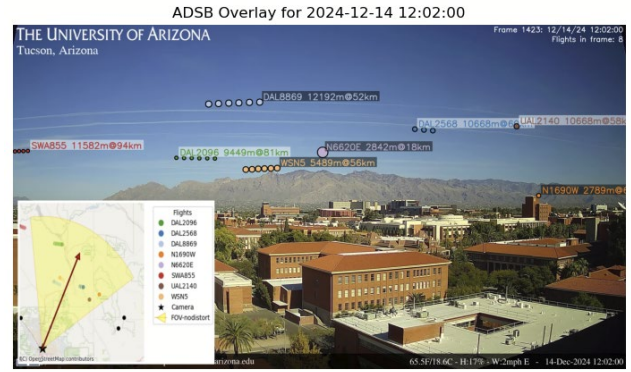
TOOLS & METHODS



Height estimation

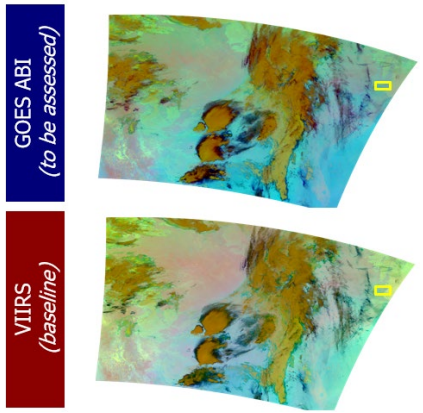


Flight attribution

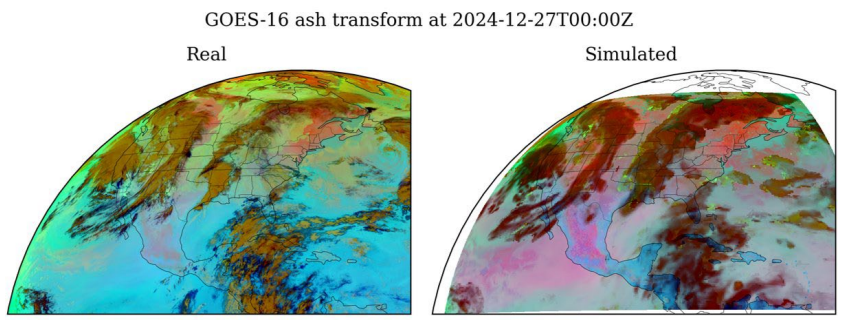


Multi-sensor contrail tracking

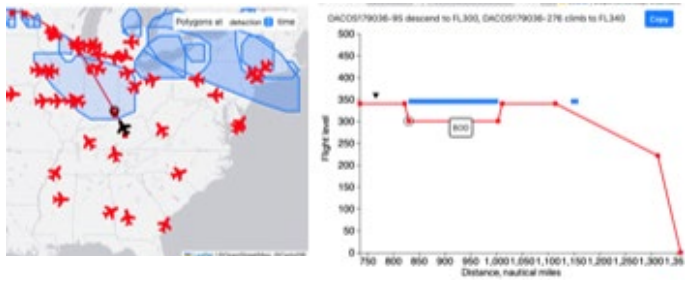
ANALYSIS & VALIDATION



Satellite observability



Synthetic contrails & radiative transfer



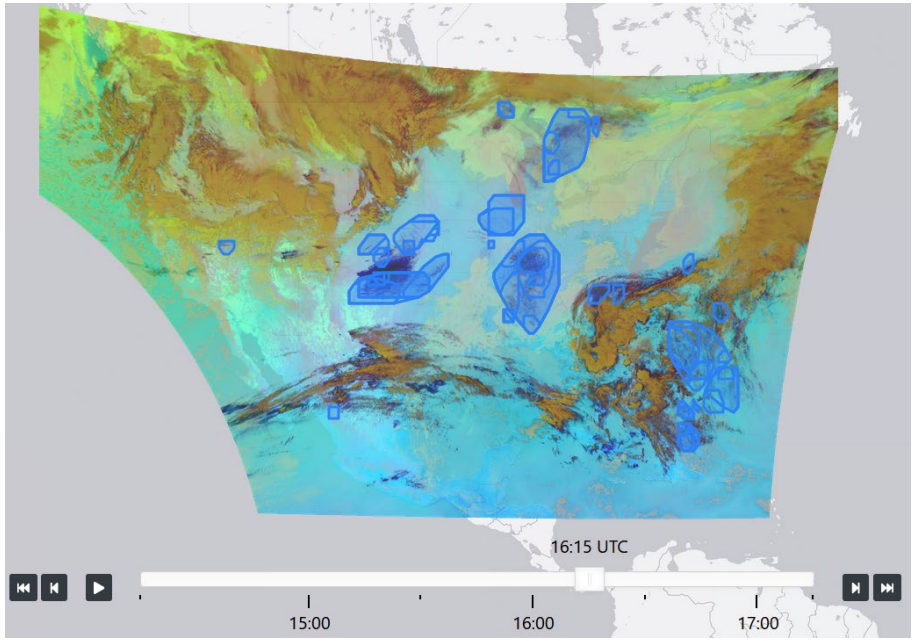
Historical analysis *(beyond POP)*

Completed work | Ongoing progress | Next steps

Recent Accomplishments and Contributions

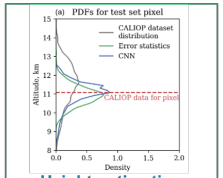
Continued development on **MCAST** (MIT Contrail Avoidance Support Tool)

- Contrail detection through real-time processing of satellite imagery
- Nowcasting pipeline to identify avoidance opportunities via vertical flight rerouting



Publications

- Meijer, V.R., Eastham, S.D., Waitz, I.A., & Barrett, S.R.H. 2024. *Contrail altitude estimation using GOES-16 ABI data and deep learning*. Atmospheric Measurement Techniques.
- Euchenhofer, M.V., Prashanth, P., Parke, S.A., Eastham, S.D., Waitz, I.A. 2025. *Contrail observation limitations using geostationary satellites*. Geophysical Research Letters. Under Review.



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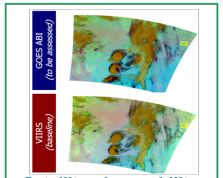


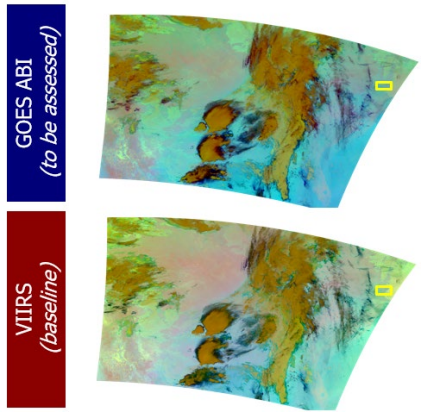
Satellite observability

Schedule and Status

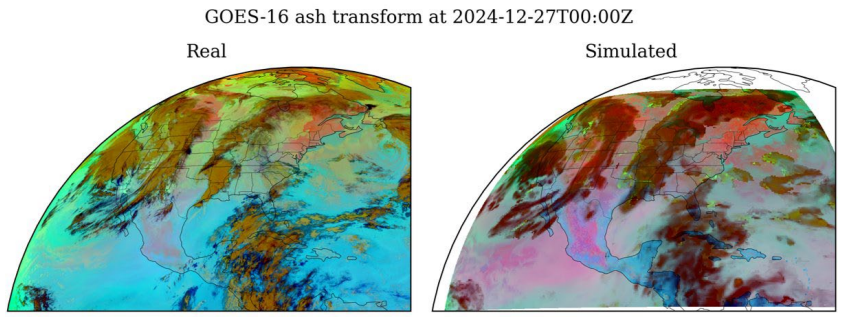
Height estimation

Flight attribution

Multi-sensor contrail tracking



Satellite observability



Synthetic contrails & radiative transfer

Historical analysis *(beyond POP)*

Completed work | Ongoing progress | Next steps

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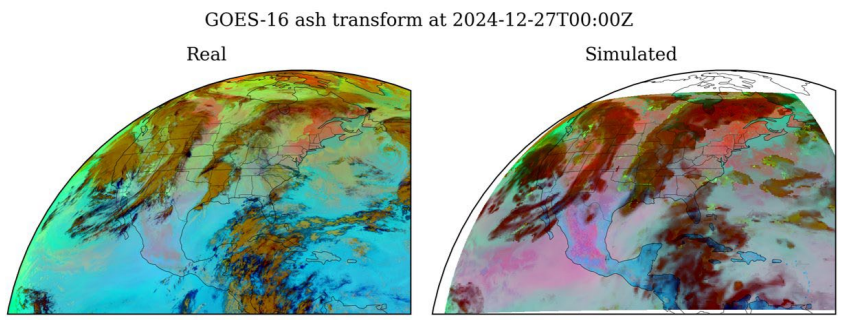

Synthetic contrails & radiative transfer

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Contrail process models need new validation approaches

Motivation

Modeling and simulations for **contrail impact estimates**:

→ Need validation against observation

→ Complex to compare current model outputs against satellite instruments.

Identification of assumed contrail regions for **operational contrail avoidance**:

→ Often based on GEO observations.

→ Trade-off of limited spatial resolution, thus potentially missing contrail regions.

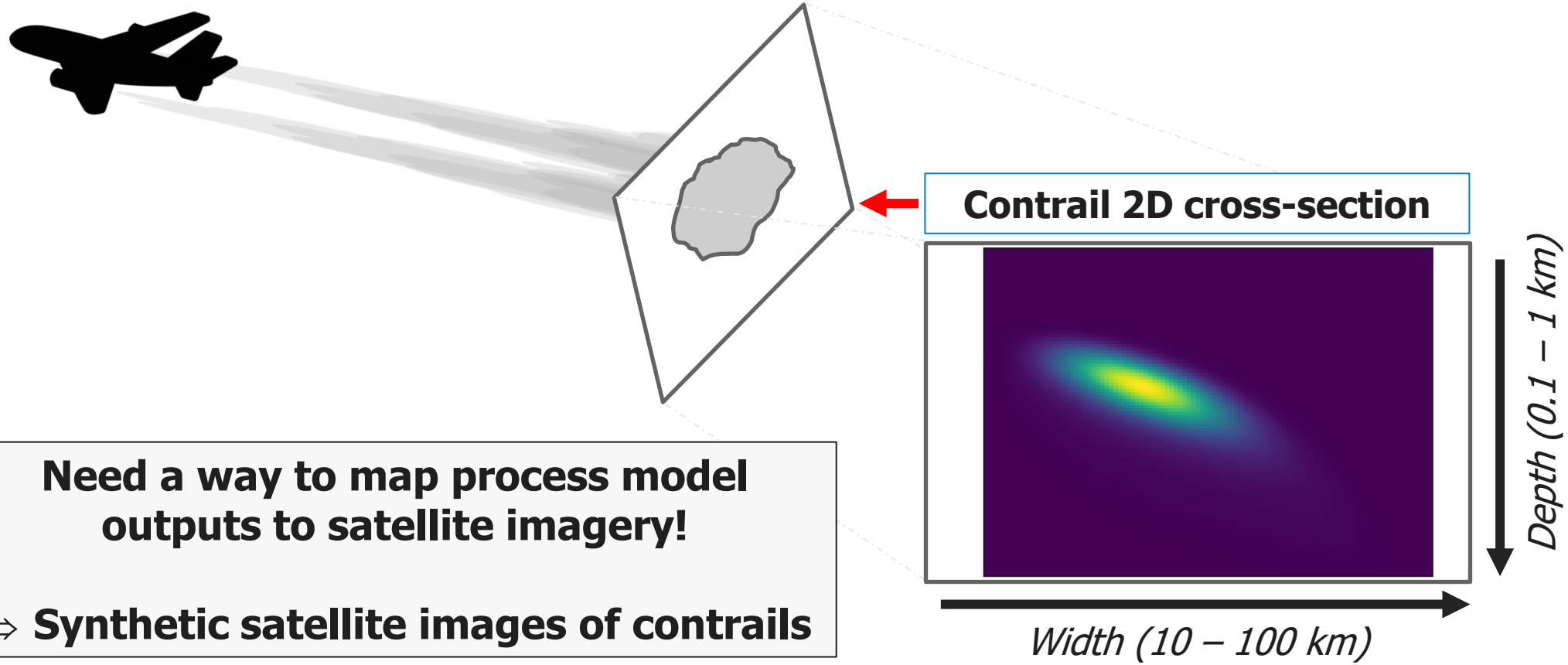
→ Existing approaches focused on bulk statistics, visual inspection or have a few samples

→ Satellites improved in spatial resolution and provide large temporal and spatial coverage

→ But comparing model outputs to satellite imagery is not trivial

What do contrail plume scale models model?

Motivation



Need a way to map process model outputs to satellite imagery!

⇒ **Synthetic satellite images of contrails**

Goals

- Can models reproduce observed properties of contrails?
  - Current models are expected to have correct estimates "on average" but not at the scale of individual contrails
    - Can analyze this at 3 levels:
      - Individual contrails: flight by flight analysis
      - Contrail cluster: ISSR analysis
      - US annual: regional analysis

→ **Verifying that current models mirror average contrail radiative properties in visible / mid-IR bands will inform the accuracy of their RF estimates**

Generating physics-based synthetic contrail imagery

Approach

ADS-B

Aircraft performance model

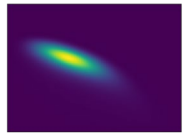
Ambient weather

NWP

Contrail model

CoCiP / APCEMM

Simulated properties



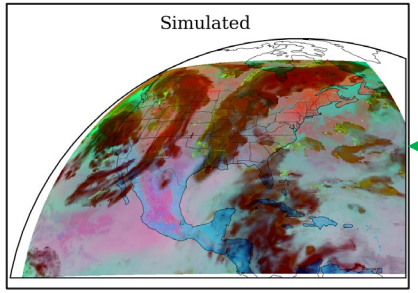
Contrail cross-section

Background met.

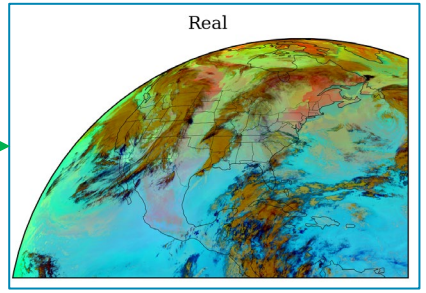
Radiative transfer model

CRTM

Simulated contrail image



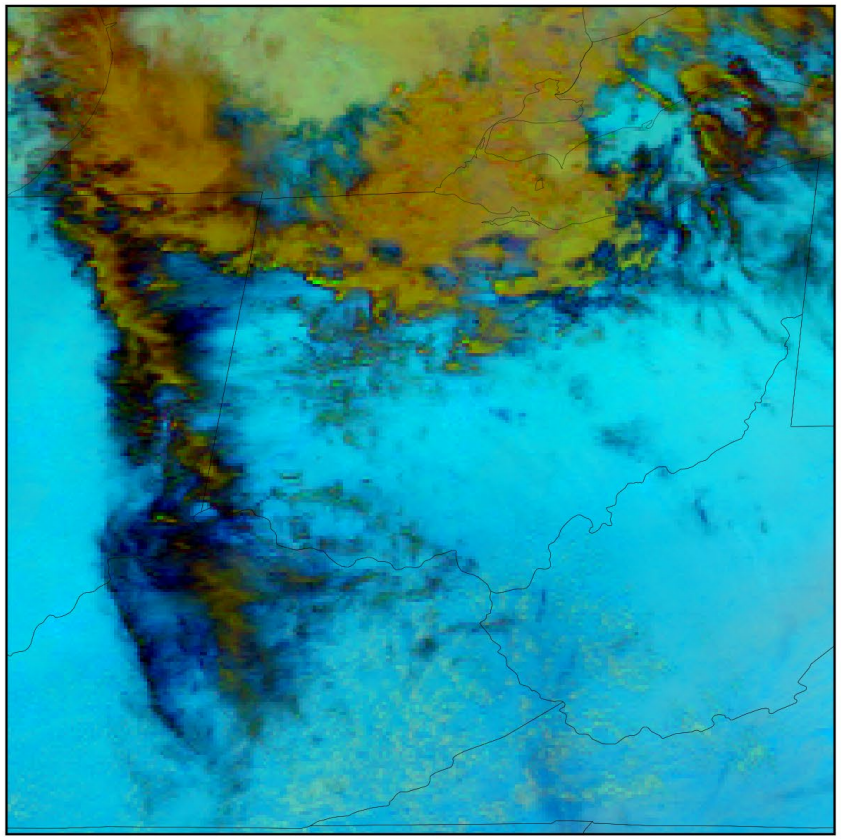
Geostationary satellite imagery



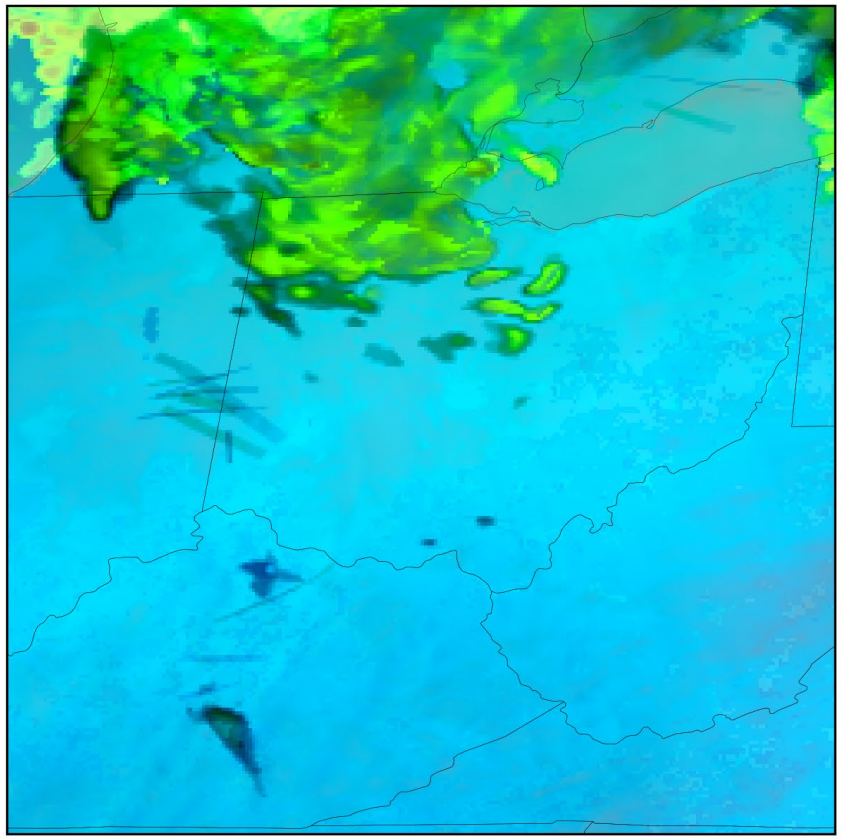
Preliminary simulations

Results

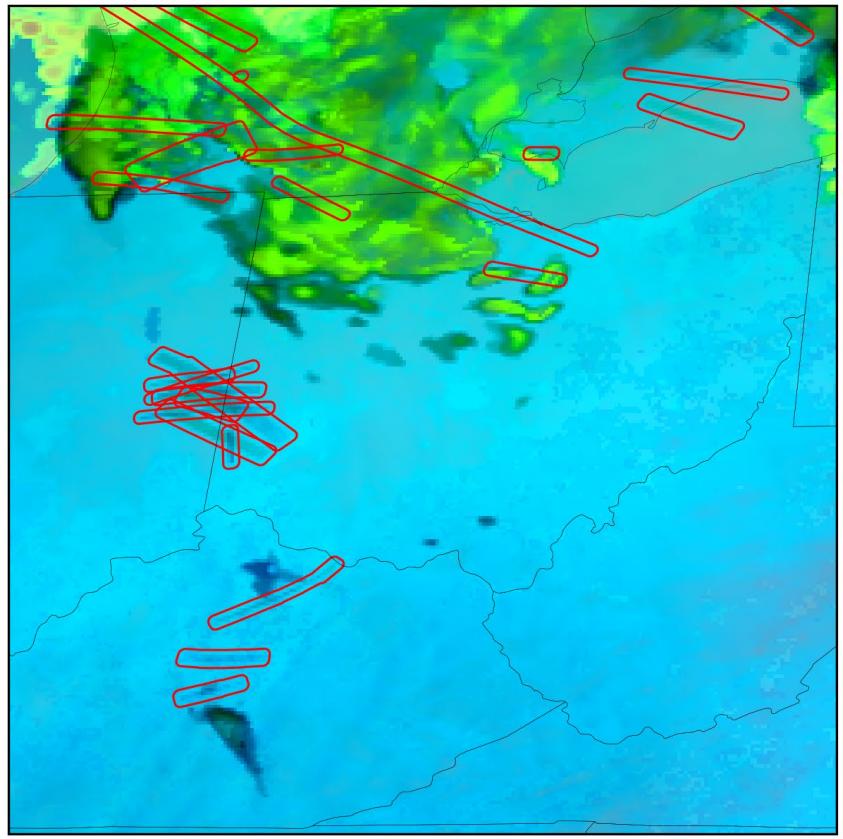
GOES-16 2024-07-02 21:00Z



HRRR + ERA5 Contrails



HRRR + ERA5 Contrails highlighted



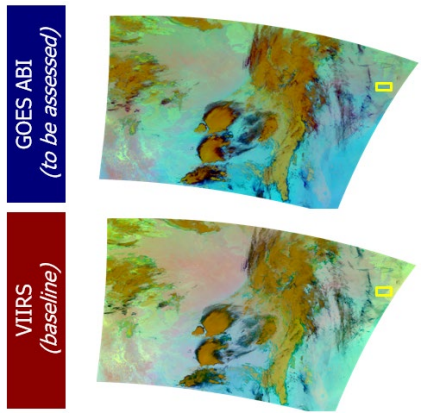
→ Background cloudiness representation needs work
→ Contrails are clearly visible and can be evaluated for observability / brightness temperatures…

Schedule and Status

Height estimation

Flight attribution

Multi-sensor contrail tracking



Satellite observability

Synthetic contrails & radiative transfer

Historical analysis *(beyond POP)*

Completed work | Ongoing progress | Next steps

Observability limits of contrails from geostationary orbit

Motivation

Modeling and simulations for **contrail impact estimates**:

→ Need validation against observation

→ Complex to compare current model outputs against satellite instruments.

Identification of assumed contrail regions for **operational contrail avoidance**:

→ Often based on GEO observations.

→ Trade-off of limited spatial resolution, thus potentially missing contrail regions.

→ Reliance on accuracy of observational input data.

→ Integrity of observations needs to be assessed to bound validity of actions and derived quantities!

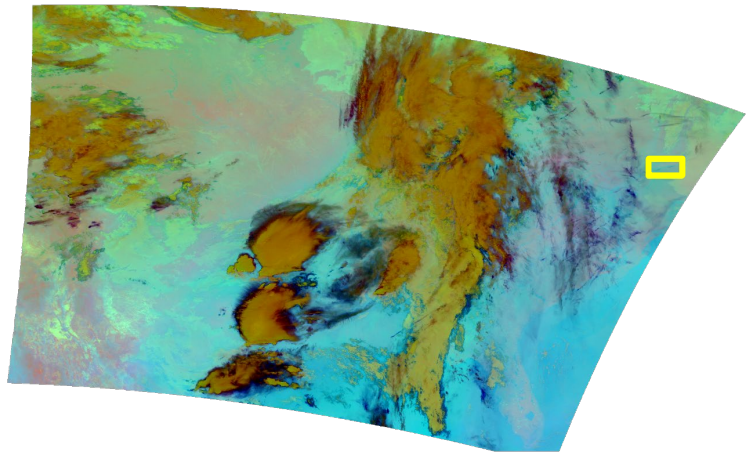
Data generation

Approach

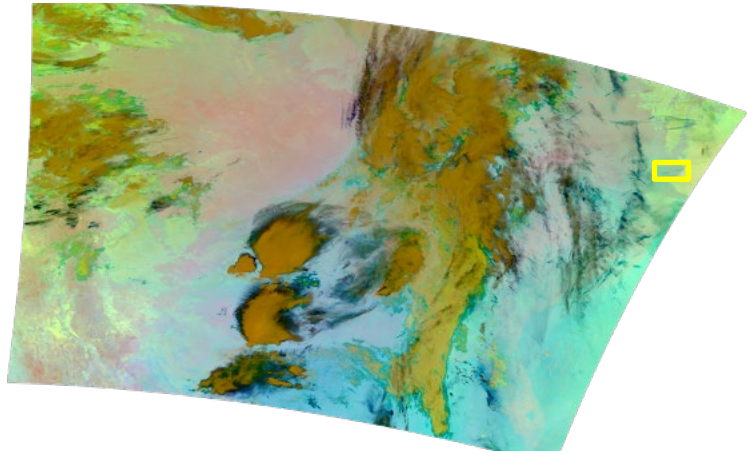
False color images

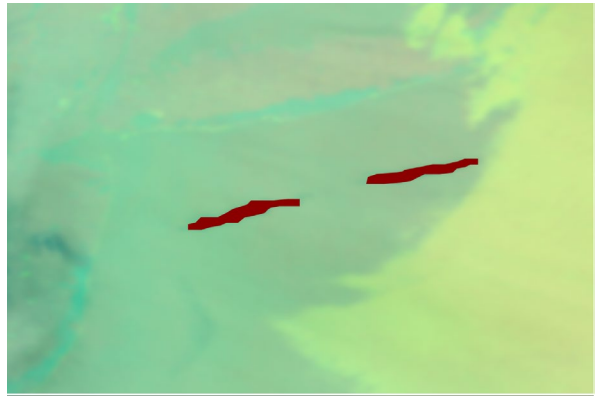
Visually identified contrails

GOES ABI *(to be assessed)*



VIIRS *(baseline)*



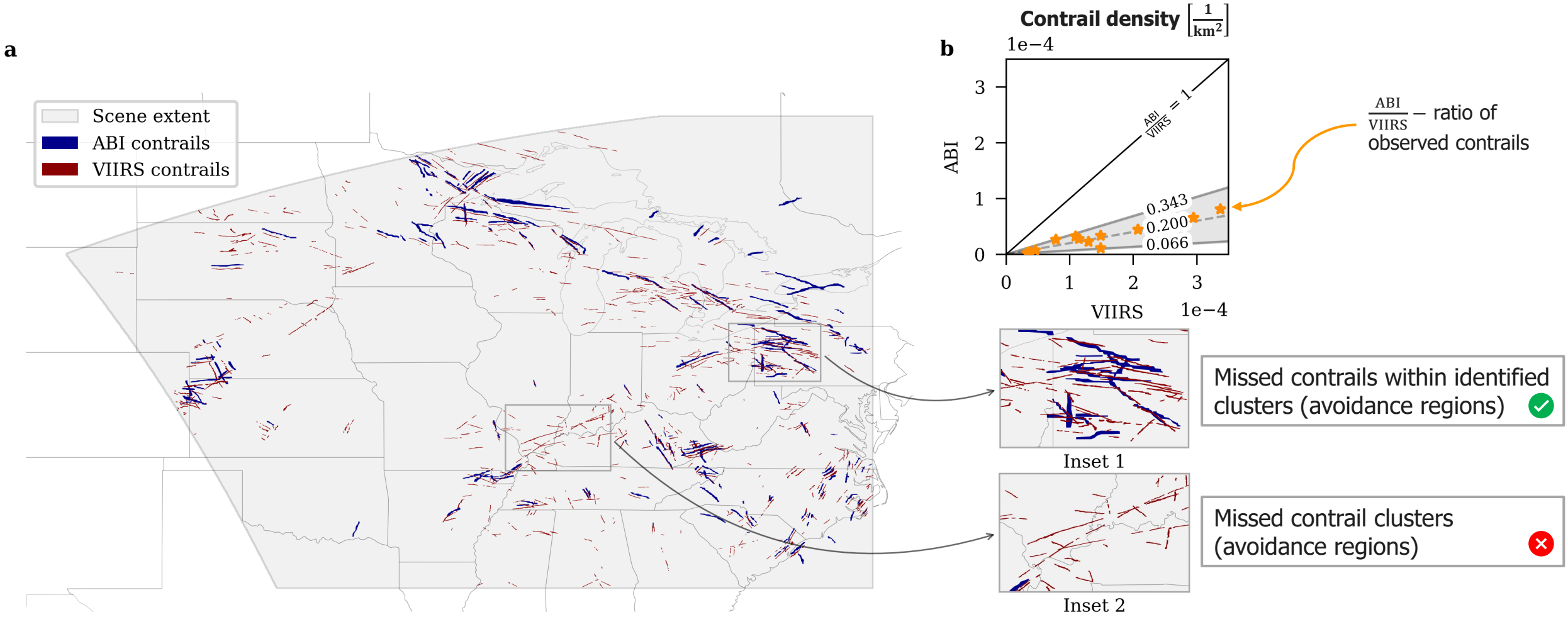


Dataset:

- Twelve scenes over CONUS (varying in extent and location) between Dec 2023 – Nov 2024
- Scenes cover a range of conditions regarding clouds and contrail cover
- Analysis of static scenes (no temporal evolution considered)
- Total number of contrail labels:
  - 1,667 (ABI)
  - 7,731 (VIIRS)

Big picture – number of observed contrails

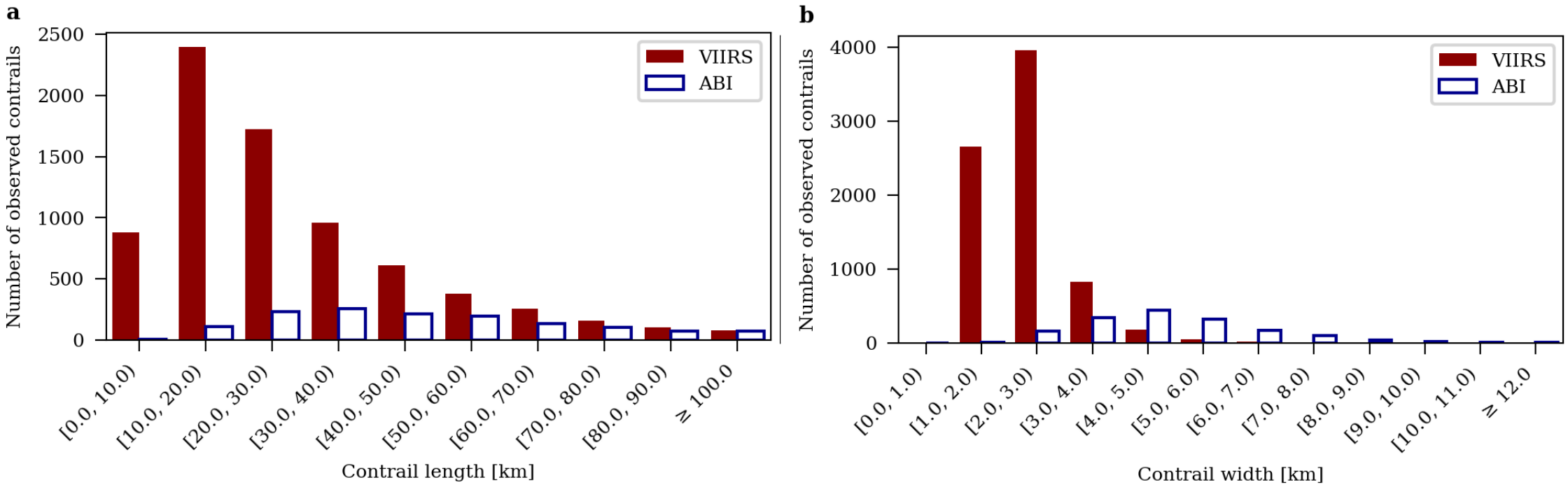
Results



a Exemplary scene: 2024-01-05T18:30Z

Characteristics of (un-)observed contrails

Results



Significantly more shorter contrails observed with VIIRS
- → earlier observation
- → non-persistent contrails

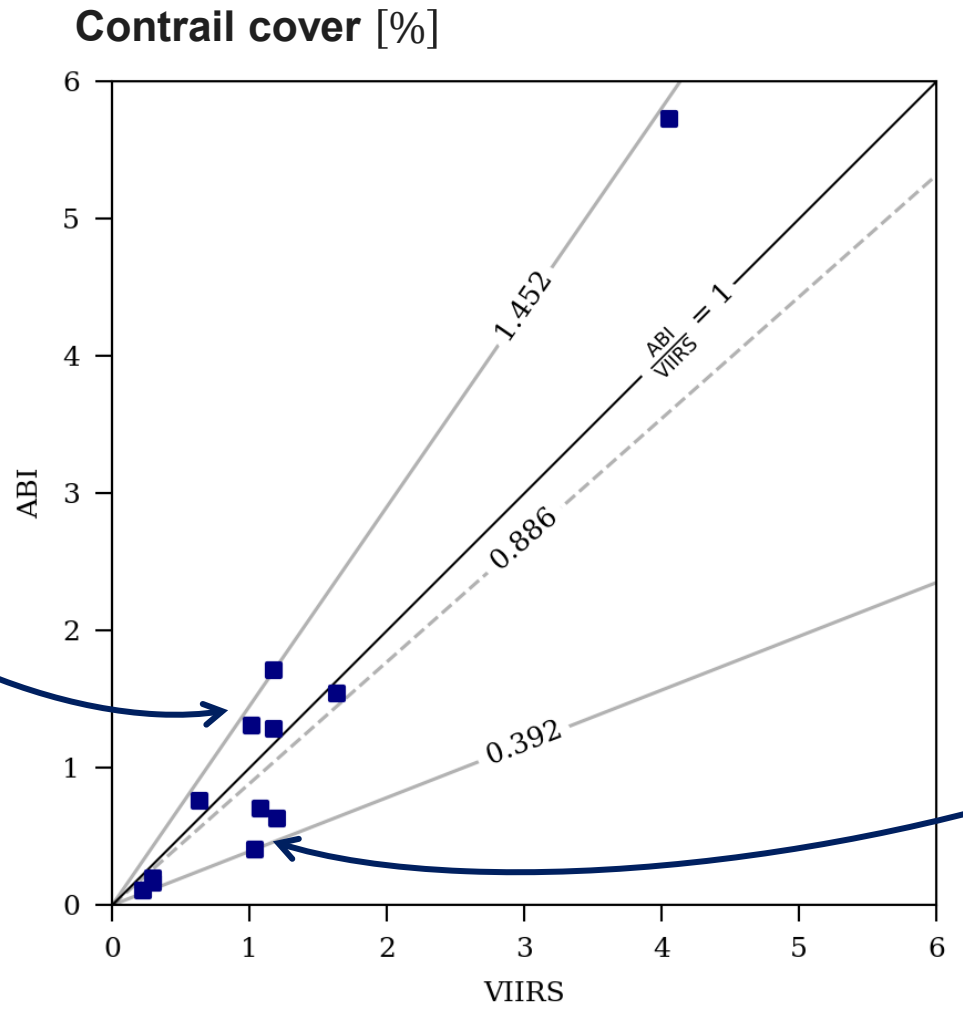
Narrower range of contrail widths observed with VIIRS, and same contrails appear wider when observed with ABI
- → individual widths overestimated

Effect of instrument resolution on observed contrail cover

Results

Blurring of observed contrails

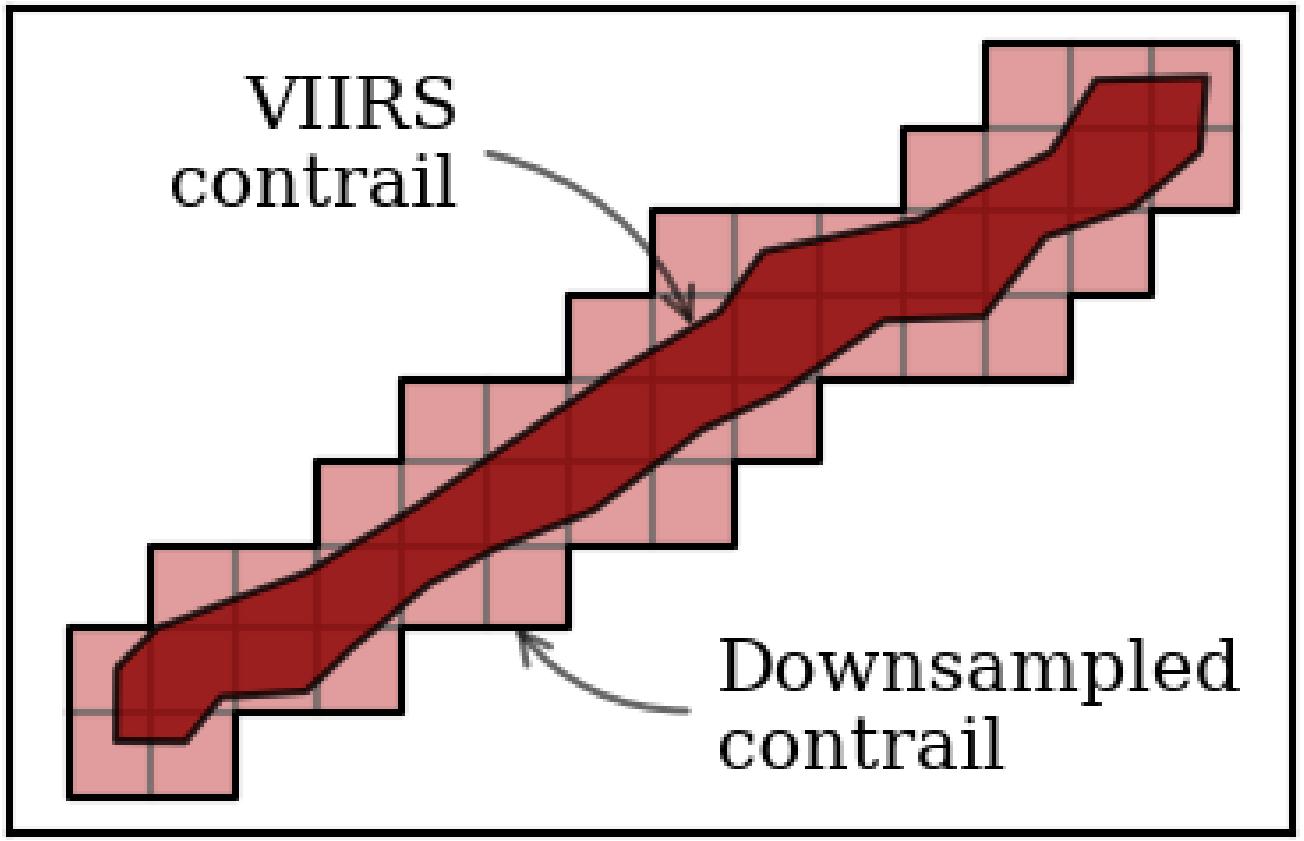
Contrail cover **overestimated**



Fewer contrail observations

Contrail cover **underestimated**

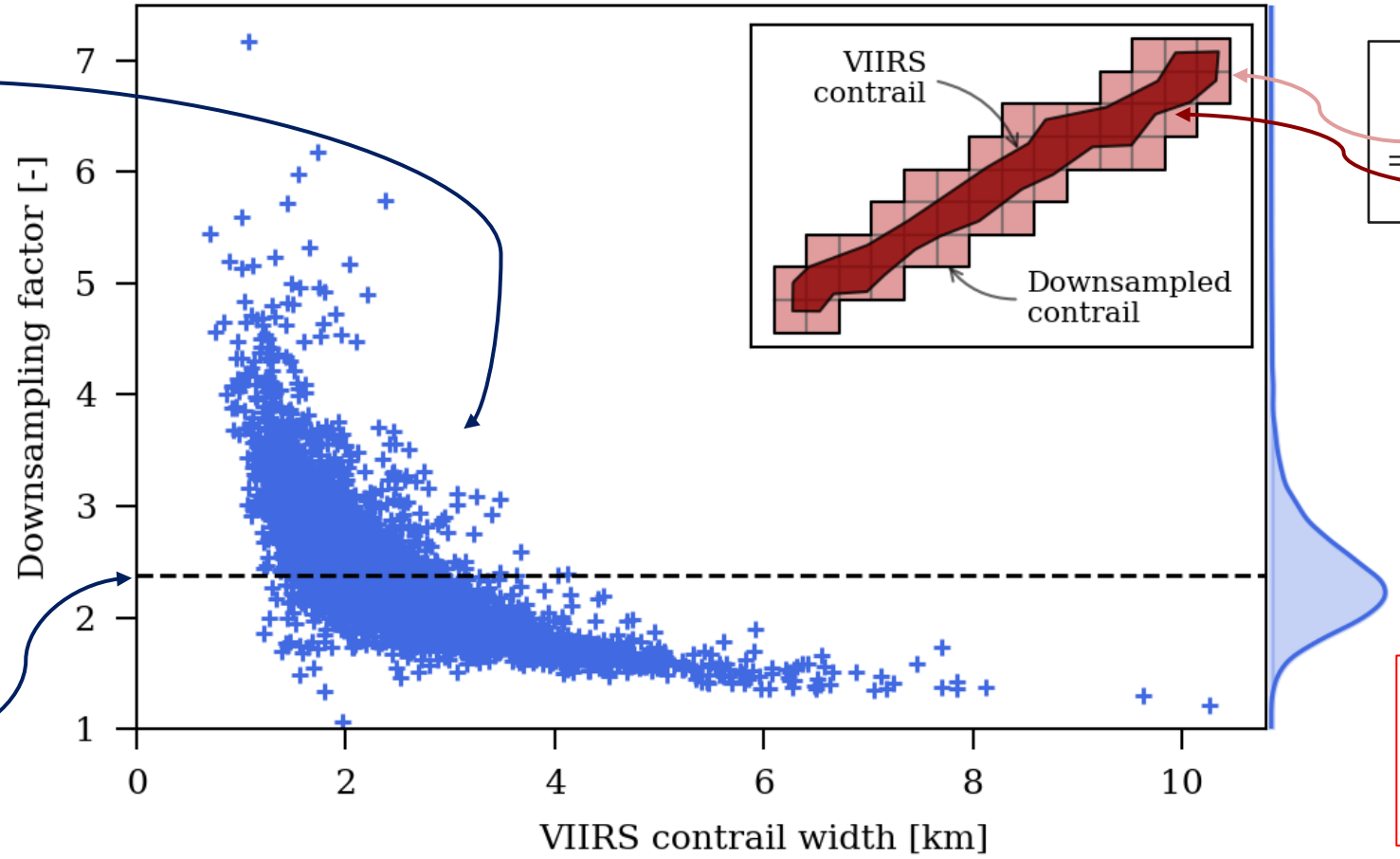
Downsampling of VIIRS contrails



Downsampling of VIIRS contrails

Results

Inverse relationship between downsampling factor and input contrail width:
Narrower contrails (closer to ABI resolution) expected to experience **stronger blurring**



Downsampling factor

$$= \frac{A_{\text{VIIRS contrail, dowmnsampled}}}{A_{\text{VIIRS contrail}}}$$

Average downsampling factor 2.27:
Overestimate of the width (area) of an individual contrail by factor of 127%.

Caveat:
Downsampling factor largest for contrails un-observed by ABI.

* Conservative upper limit.

Summary – Satellite observabiliy

Takeaway

ABI misses 80% of all contrails observable with VIIRS.
The lower resolution results in a **non-systematic error for the derived contrail cover**.

This results in **implications for** both

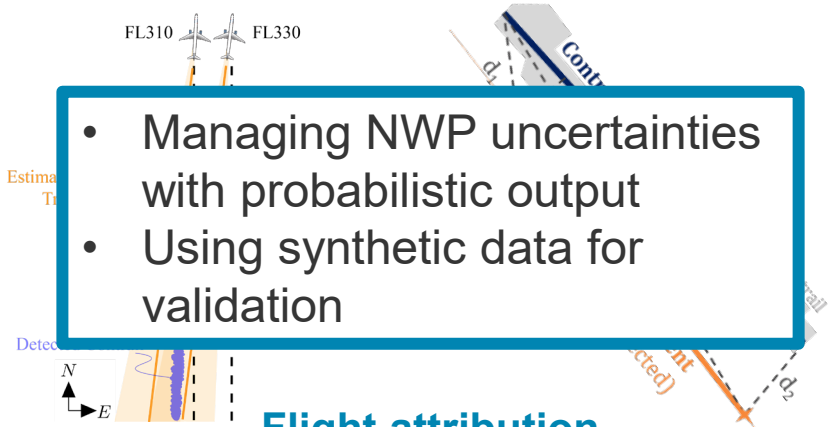
- **operational contrail avoidance** (early and comprehensive identification of ISSRs, ability to verify contrail avoidance trials), and
- **contrail climate modeling** (impact assessment, model calibration and validation of individual contrail behavior, assessment of model predictions of RH).

However, contrail observations from GEO imagers **provide important and continuously sampled information** for navigational avoidance.
Limitations can be addressed by consolidating data from **multiple sensors into single pipeline**.

Next steps

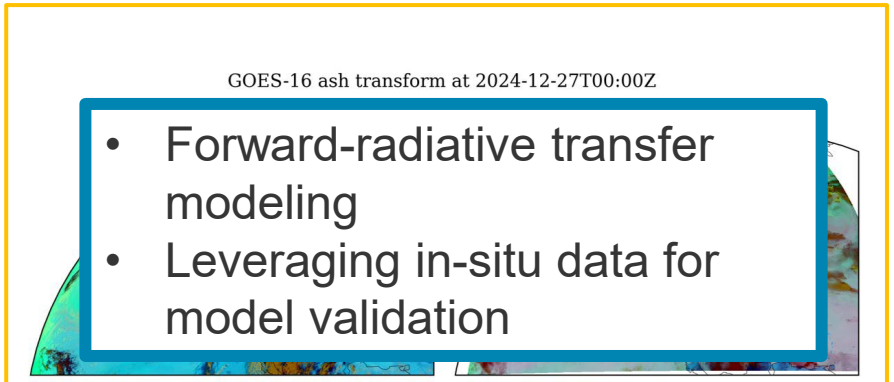
Height estimation

Satellite observability



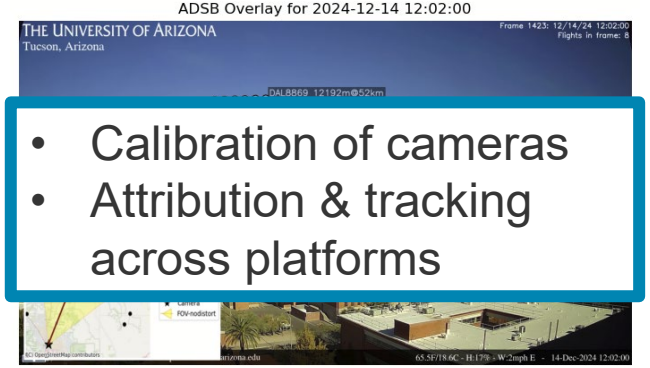
- Managing NWP uncertainties with probabilistic output
- Using synthetic data for validation

Flight attribution



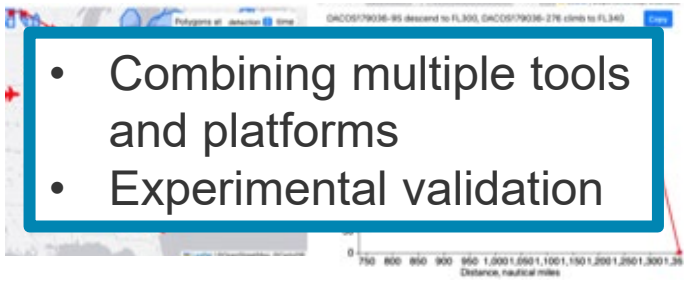
- Forward-radiative transfer modeling
- Leveraging in-situ data for model validation

Synthetic contrails & radiative transfer



- Calibration of cameras
- Attribution & tracking across platforms

Multi-sensor contrail tracking



- Combining multiple tools and platforms
- Experimental validation

Historical analysis *(beyond POP)*

Completed work | Ongoing progress | Next steps

Project 78

Contrail Avoidance Decision Support and Evaluation

Massachusetts Institute of Technology

PI: Ian A. Waitz

Co-PI: Prakash Prashanth

Team: Marlene Euchenhofer, Louis Robion, Olivier Kigotho, Florian Allroggen

PM: Kenisha V. Ford

Cost Share Partner(s): Earth Force Technologies Inc.

Objective:

- **Decision support tool** for aircraft routing to avoid formation of warming contrails by evaluating the **likely costs and benefits** of a contrail avoidance action.
- Evaluate the decision support tool under real-world conditions.

Project Benefits:

- **Rapid evaluation** of contrail formation and impacts for different strategies
- Demonstration of **benefits, cost, and practicality of contrail avoidance** to relevant stakeholders
- Advancement of US-built tools and leveraging US leadership in in-situ measurement campaigns to maintain **global competitiveness**

Research Approach:

- Develop **software modules** as follows:
- **Contrail forecasting** to predict contrail-forming conditions prior to and during flight
- Real-time **contrail identification** in satellite images based on existing deep learning approaches
- Contrail **radiative forcing estimation** based on recent work at MIT
- **Trajectory planning** and forecast fuel burn and emissions for a spectrum of flight paths

Major Accomplishments (to date):

- Instantaneous contrail identification module completed
- ML technique to estimate contrail heights
- Preliminary attribution algorithm developed to match flights to contrails and to derive probabilistic contrail height estimation
- Computer vision-based technique to simultaneously attribute and localize contrails
- Quantification of observability limits of geostationary satellites

Future Work / Schedule:

- Ongoing tool development and continuous integration
- Improve contrail identification module and models for forecasting and radiative forcing assessments
- Rigorous historical analysis

This research was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 78 through FAA Award Number 13-C-AFJE-MIT under the supervision of Kenisha V. Ford.
Any opinions, findings, conclusions or recommendations expressed in this this material are those of the authors and do not necessarily reflect the views of the FAA.