



Intelligent Long Endurance Observing System (ILEOS)

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Intelligent Long Endurance Observing System

PI: Meghan Chandarana (NASA Ames Research Center)

Objective

Intelligent Long Endurance Observing System (ILEOS):

A *Science activity planning* system to enable NOS consisting of satellites and *HALE UAS-mounted instruments*.

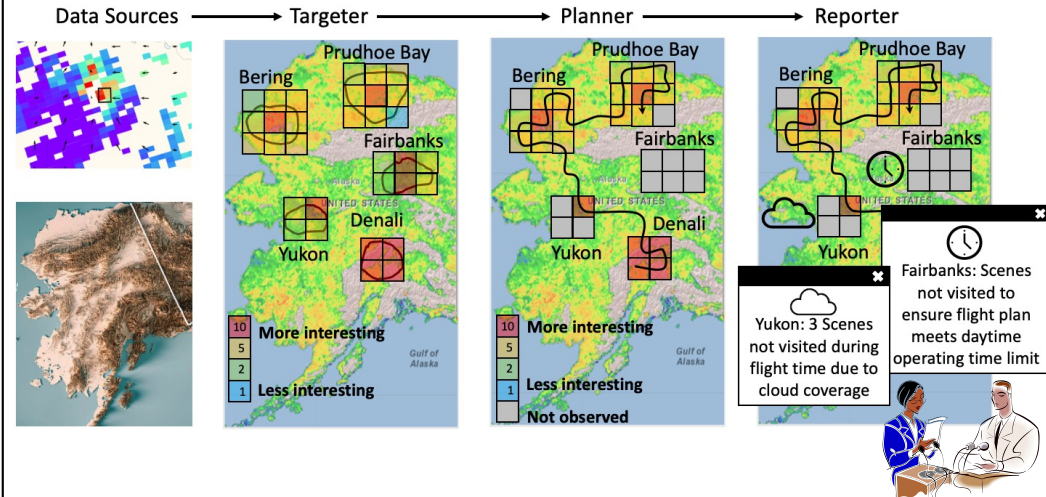
Optimize *fine-grained spatio-temporal resolution data collection* of Earth observations, such as *GHG-relevant gases*, using HALE UAS.

Incorporates *coarse-grained satellite data* and near real-time environmental (e.g., wind, weather, airspace constraints) data to generate high-value fine-grained resolution data collection plans.

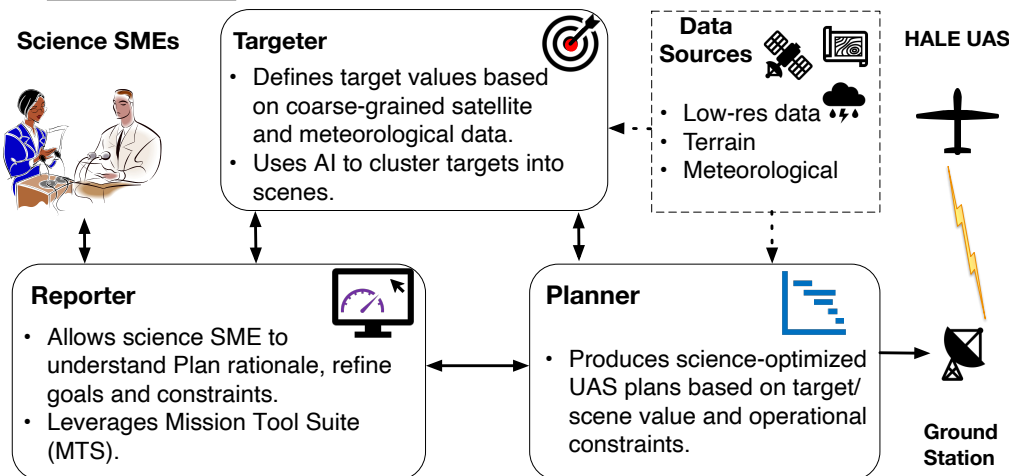
Designed for human operators; *plan explanation and data provenance features* will ensure science mission planners understand all key choices made while generating targets and plans.

IMPACT: Reduced cost for Earth observations in environments ranging from arctic to urban to offshore (some previously inaccessible), continuous observations not possible for current field/in-situ campaigns, improved science outcomes

ILEOS Functional Flow



Approach



Key Milestones

- | | |
|--|-----------|
| • Complete ILEOS requirements / design | Jan 2023 |
| • Prototype ILEOS for NO ₂ science use case | Oct 2023 |
| • Prototype ILEOS for CH ₄ science use case | Jan 2024 |
| • 3rd year proposal to AIST program | Jan 2024 |
| • User testing and evaluation of ILEOS | July 2024 |
| • Airborne Science Program integration reqts/design | Oct 2024 |
| • Infusion into Airborne Sciences Program | July 2025 |
| • Final Report / Project Closeout | July 2025 |

TRL_{in} = 3
TRL_{out} = 5

Co-Is/Partners: NASA GSFC, USGS, JHU/APL



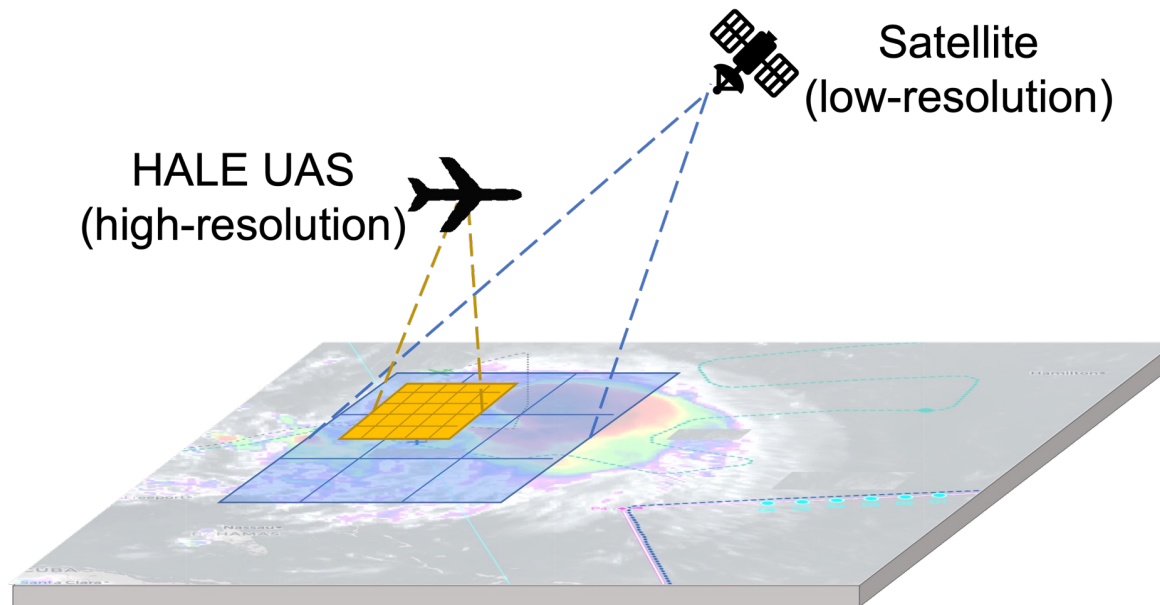


Presentation Contents

- Background and Objectives
- Technical and Science Advancements
- Summary of Accomplishments and Future Plans
- Actual or Potential Infusions and Collaborations
- Publications - List of Acronyms



Concept of Operations



- Current satellites and fine-pointing aircraft do not provide sufficient spatio-temporal resolution to observe stochastic, ephemeral events between observations
- HALE UAS provide mechanism for collecting higher spatio-temporal data
 - Operate for months and loiter over targets

ILEOS will provide a science activity planning system to enable NOS

- Fuse coarse-grained sensor data to target and plan HALE UAS flights



Relevance to Earth Science

- ILEOS will focus on use cases related to NO_2 and CH_4 , which both high relevance to the science and application priorities presented in the 2019 Decadal Survey:
 - NO_2 , here a proxy for combustion emissions (e.g., CO_2), and CH_4 over oil and natural gas extraction areas of the Gulf of Mexico.
 - Estimation of these emission sources(e.g., point - large rigs, line - shipping lanes, and area - small wells and support ships).
 - NO_2 down to the city block level in urban environments
 - Human health (unhealthy to breathe) and environmental justice
 - NO_2 generated from lightening (collected from above storm clouds)
 - Important ingredient in formation of upper tropospheric ozone, expensive to collect with crewed aircraft
 - CH_4 over Artic-Boreal zone
 - Characterize how the water table and air temperature affect the rate of emission
 - CH_4 from various anthropogenic sources such as industrial processes and leaky natural gas distribution pipelines, in complex urban environments
 - Pinpoint sources needing migration for safety reasons or to reduce the GHG footprint of urban areas



Objectives

- Optimize fine-grained spatio-temporal resolution data collection of Earth observations, such as GHG-relevant gases

Novel automated target generation technology

- Incorporates *coarse-grained satellite data* and near real-time environmental (e.g., wind, weather, airspace constraints) data to generate high-value fine-grained resolution data collection plans.

State-of-the-art automated planning and scheduling algorithms

- Designed for human operators; *plan explanation and data provenance features* will ensure science mission planners understand all key choices made while generating targets and plans.

Innovative techniques for user control and review of decision making

IMPACT: Reduced cost for Earth observations in environments ranging from arctic to urban to offshore (some previously inaccessible), continuous observations not possible for current field/in-situ campaigns, improved science outcomes

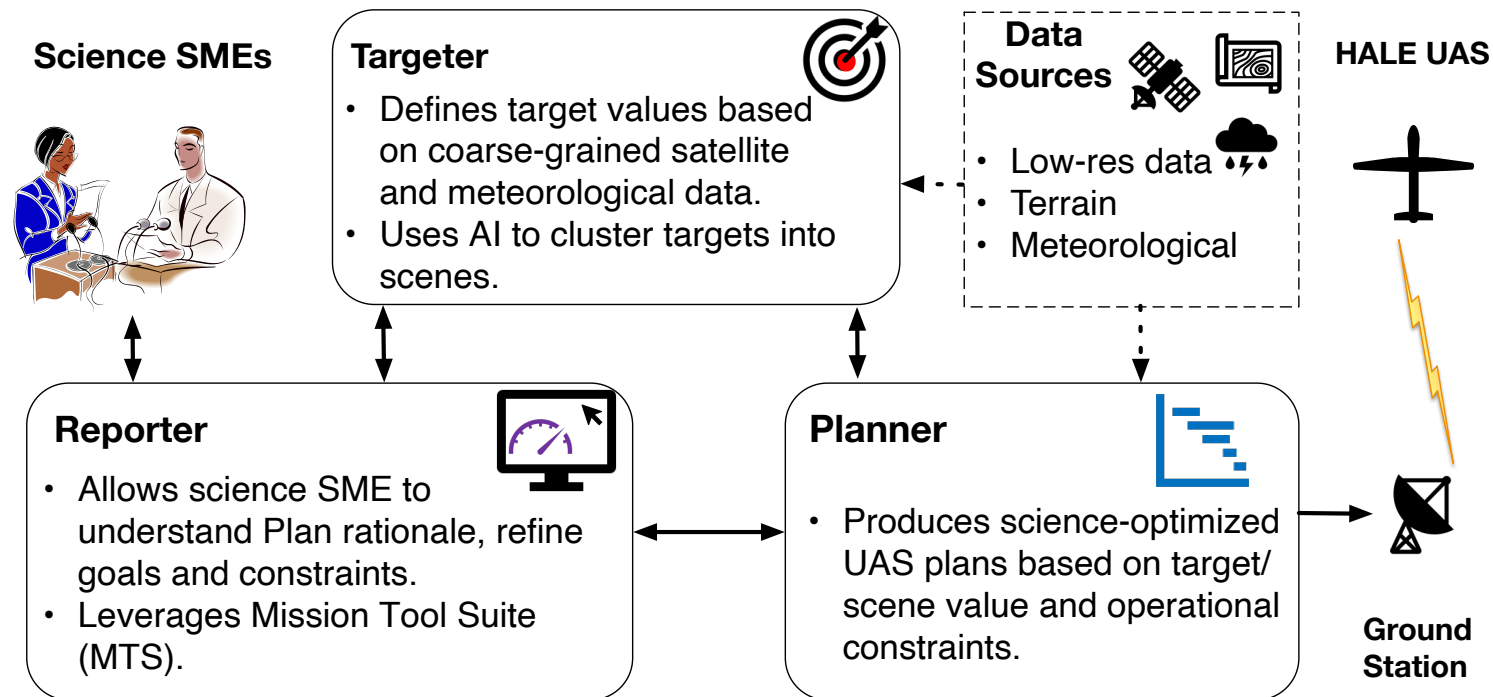


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ILEOS Architecture

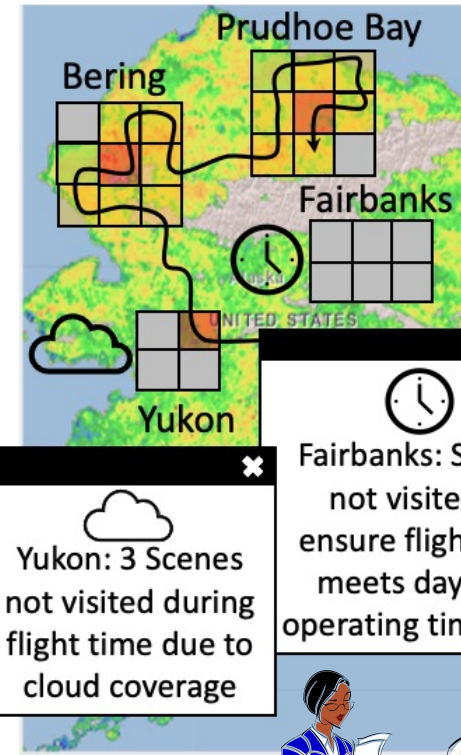
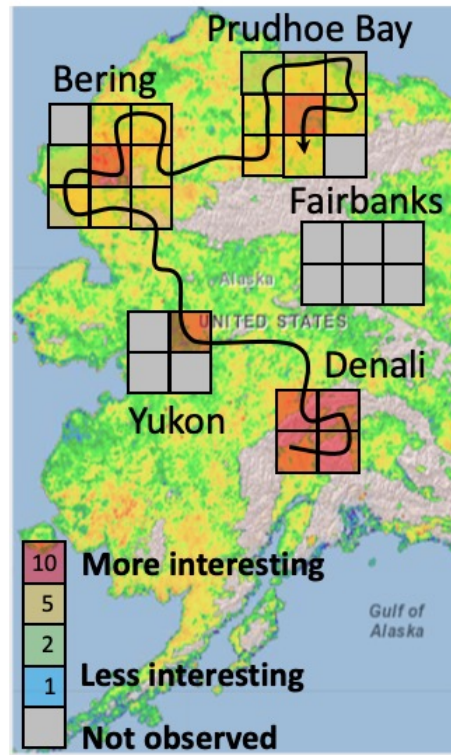
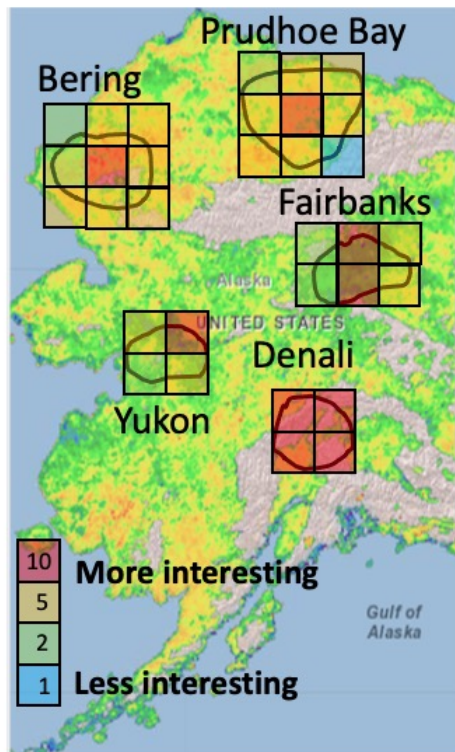
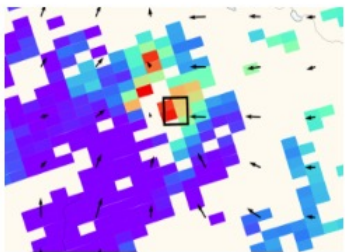


- **Targeter** – leverages Science SME domain knowledge to fuse available coarse-grained data into pixel value maps to generate target scenes
- **Planner** – generate flight plan to observe best identified target scenes while enforcing HALE UAS operating constraints
- **Reporter** – allow users to configure Targeter and Planner, visualize all data and outputs, and request explanations



Full ILEOS Pipeline

Data Sources → Targeter → Planner → Reporter



Yukon: 3 Scenes not visited during flight time due to cloud coverage

Fairbanks: Scenes not visited to ensure flight plan meets daytime operating time limit





Technical Advancements

- Developed the ILEOS planning pipeline architecture design leveraging Science SME domain knowledge
- Identified key coarse-grained data sources
- Identified regions of interest and constraints (general, use case specific, and vehicle) for use cases
- Developed logic structure for interpreting coarse-grained data sources for NOx and Methane use cases
- Identified pertinent clustering and segmentation algorithms for use in scene generation
- Developed Targeter module and produced high interest science targets
- Developed Planner module to optimize HALE flight path by leveraging target interest values, vehicle constraints, and environmental constraints
- Provided user feedback on key factors used to generate targets and plans via the Reporter interface



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Summary

Milestone	Month after task start
ILEOS Architecture requirements/design	6
NO ₂ Targeter	9
CH ₄ Targeter	12
NO ₂ Planner	12
CH ₄ Planner	15
NO ₂ Reporter	15
CH ₄ Reporter	18
3 rd year proposal	18
Integration Testing	21
Human-in-the-loop user testing	24
MTS/ETM migration/integration architecture requirements/design	27
MTS migration	30
ETM integration	33
MTS/ETM integration testing	36



Example NO₂ Use Case

Gulf of Mexico Outer Continental Shelf

8 am-noon

1-5 pm

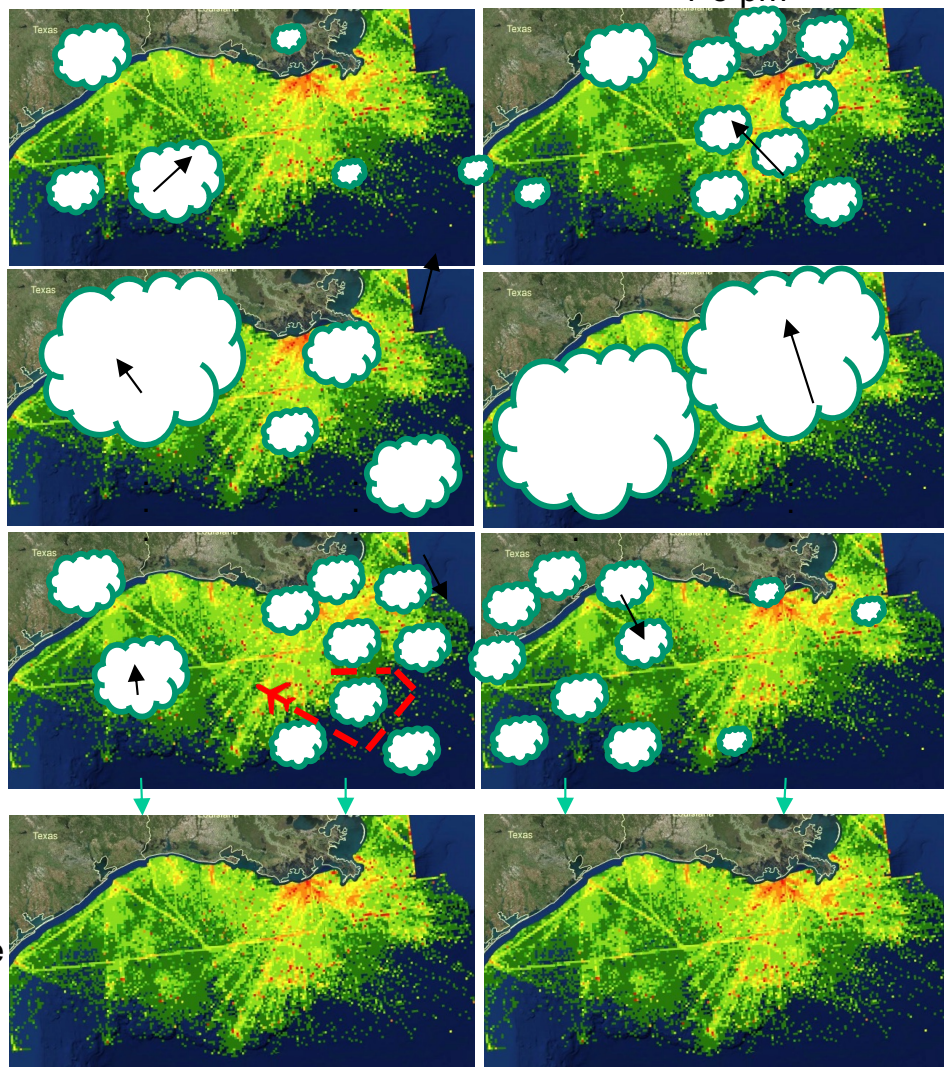
→ Wind direction

Day 1

Day 2

Day 30

30-Day
Average



Intelligent Long Endurance Observing System (ILEOS)

ILEOS is a data collection planning system that generates optimal flight tracks based on mission parameters and various input datasets. It may be applied to numerous aircraft platform-instrument configurations, including in the use case study presented next.

ILEOS Use Case Study Example – Offshore Oil & Natural Gas Operations

The Outer Continental Shelf Lands Act (OCSLA) requires the US Dept. of Interior Bureau of Ocean Energy Management (BOEM) to ensure compliance with the National Ambient Air Quality Standard (NAAQS) so that Outer Continental Shelf (OCS) oil and gas exploration, development, and production do not significantly impact the air quality (AQ) of any state. BOEM has partnered with NASA to explore the use of satellite data to meet this goal.

One air pollutant, nitrogen dioxide (NO₂), is emitted during fossil fuel combustion, including during oil and natural gas extraction activities (e.g., from ships, platforms, flaring), and is readily detected from instruments on satellites. Therefore, it is an excellent tracer of anthropogenic activities.

ILEOS would use data of offshore and onshore NO₂ sources (in figure at left) with weather data to efficiently generate optimal flight plans, such as for a HALE UAS fitted with a NO₂ sensor. The NO₂ sensor, with its small pixel size (30x30 m²; 4.5 km swath), can easily collect data at the platform-scale, including between broken clouds that stymie coarsely-resolved satellite instruments (e.g., TROPOMI; 3.5x7 km² pixel size). Therefore, in this configuration, ILEOS would enable the efficient collection of data for BOEM's applications, including spatio-temporal emission quantification.

Duncan BN. 2020. NASA resources to monitor offshore and coastal air quality. Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2020-046. 32 p. https://espis.boem.gov/final%20reports/BOEM_2020-046.pdf



Targeter

Interest values:

- Unique for each use case
- Based on available coarse-grained data (satellite measurements, meteorological, etc.)
- Leverage Science SME domain knowledge to provide priority

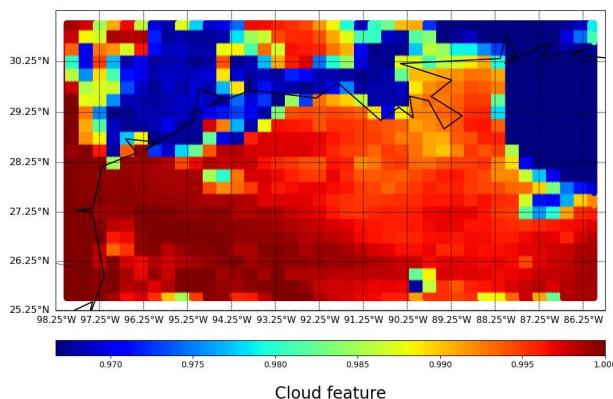
NO₂ Use Case Coarse Grained Data:

- Land cover (target water)
- Measured satellite NO₂
- Cloud cover
- Aerosol optical thickness

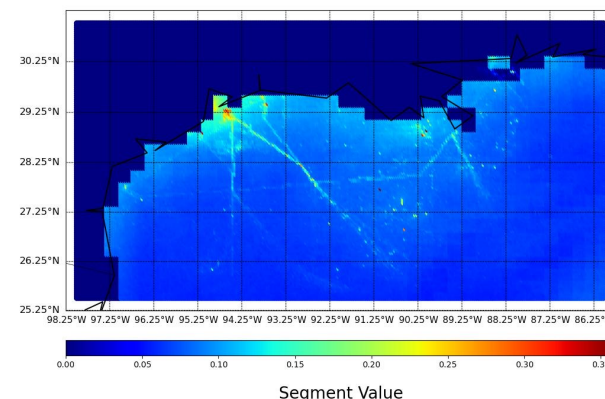
Methane Use Case Coarse Grained Data:

- Land cover (target wetlands)
- Cloud cover
- Inundation
- Measured Methane

Sample Value Map for NO₂ BOEM Inventory Use Case



Cloud Feature



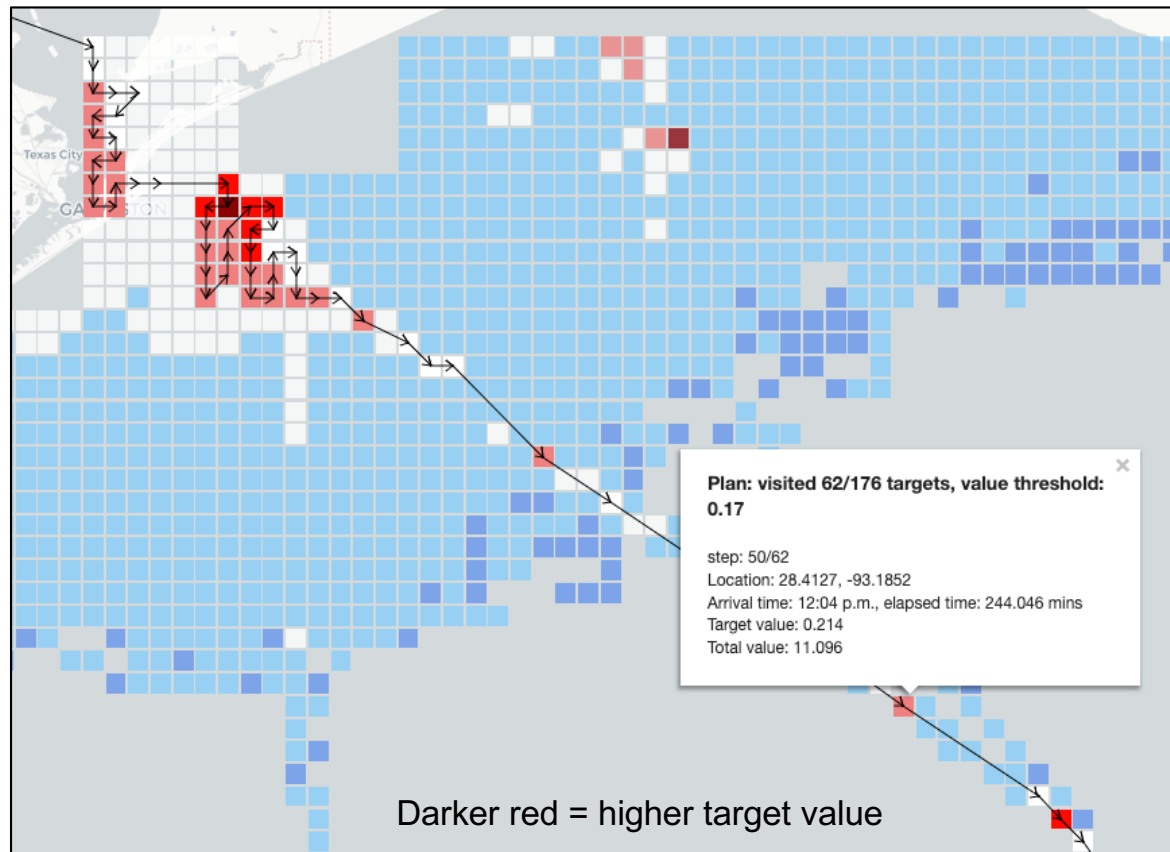
Interest Values



Planner

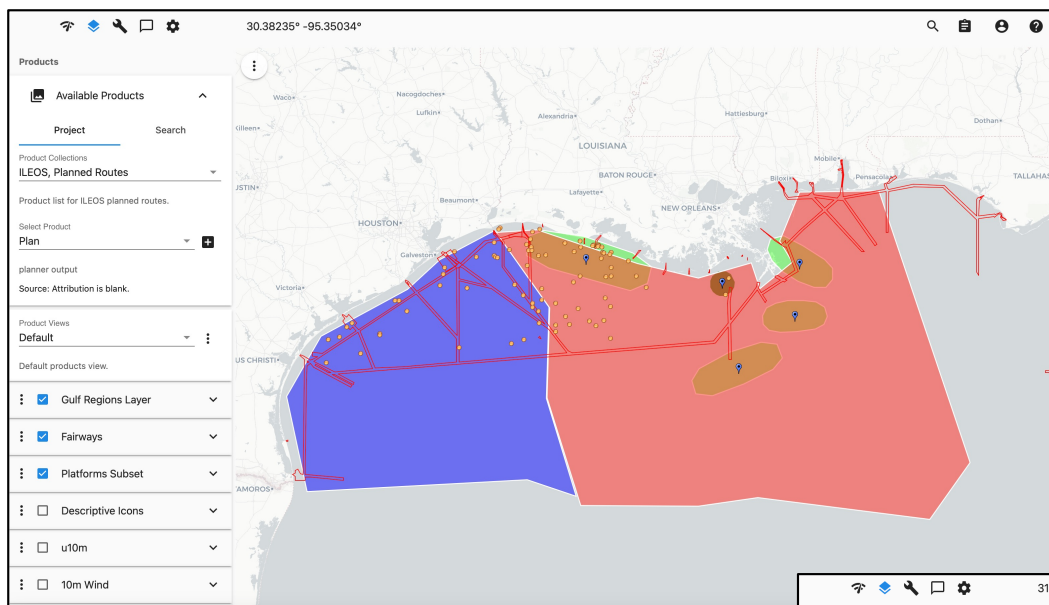
Task: Decide which locations to visit and when

- Modeled as a Multi-Profit Orienteering Problem (MPOP)
- Solution optimizes plan based on rewards at different times for each potential target

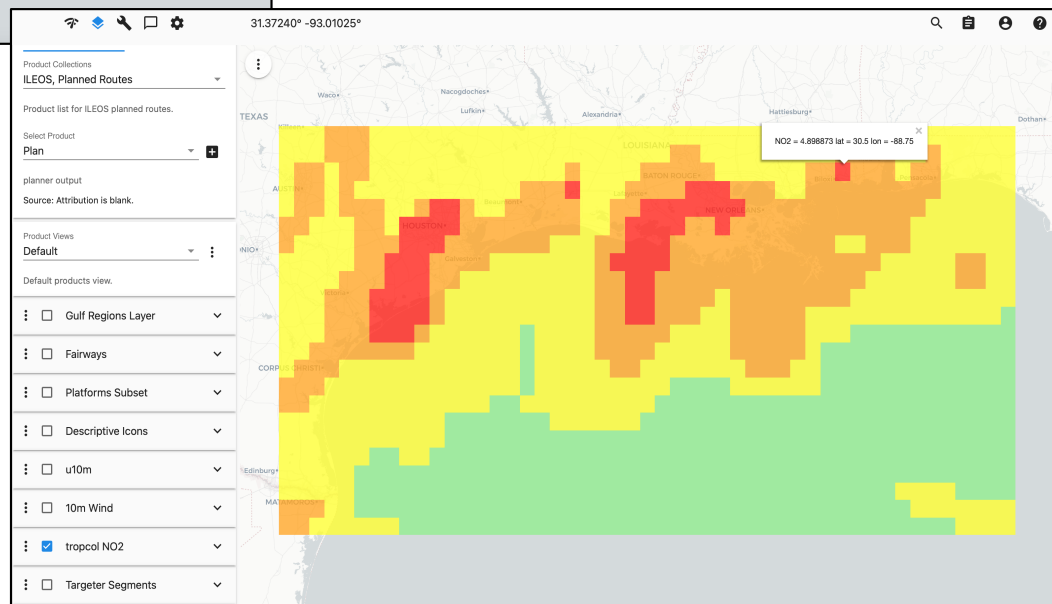




Reporter: Input Data Sources

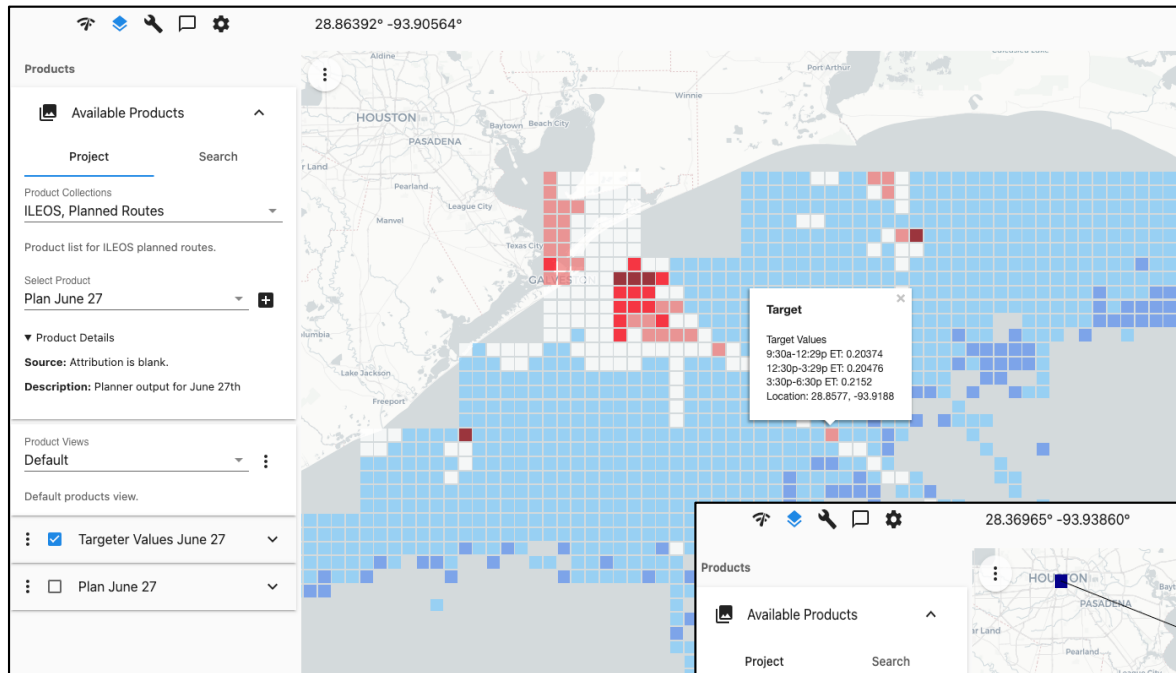


Tropospheric column density of NO₂



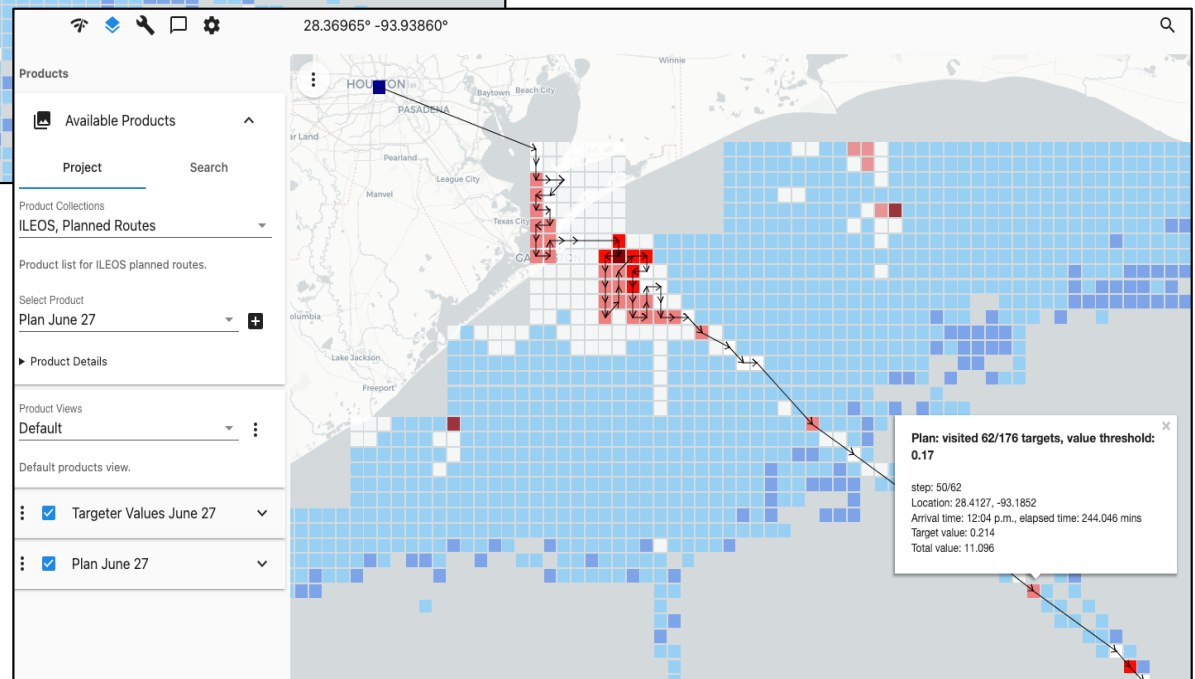


Reporter: Targets and Plans



Targets

Plan





System Evaluation

- ILEOS' first 2 years will culminate with a capstone demo featuring simulated observing campaigns overseen by SMEs
 - Evaluated on at least 2, ideally 4 climate-relevant gas sensing science use cases

Sensing Domain	Use Case Type	
	Nominal	Stressing
Methane	Urban emissions	Arctic permafrost thaw
Nitrogen Dioxide	Urban emissions	Upper atmospheric lightening

- Assess users' ability to generate desired plans and understand relationship between scenes, priority, constraints, and their impact on plan
 - Human-in-the-loop evaluation



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Technology Infusions and Collaborations

Tentative 3rd Year Infusions and Collaborations

- Technology infusion into NASA Airborne Sciences Program (ASP) via integration with:
 - Heritage Mission Tool Suite (MTS) application
 - Upper-E Traffic Management (ETM) Project
- Collaborate to integrate with NOS-T platform to evaluate mission concepts using ILEOS planning architecture



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Acronyms

List of Acronyms

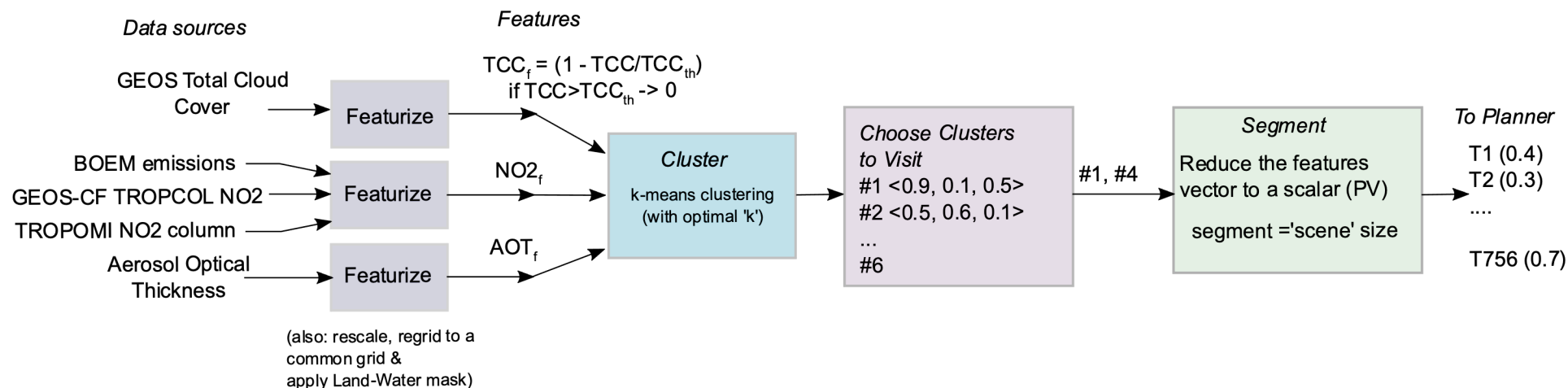
- NOS New Observing Strategy
- GHG Greenhouse gas
- NO₂ Nitrogen Dioxide
- CO₂ Carbon Dioxide
- CH₄ Methane
- HALE UAS High Altitude Long Endurance Uncrewed Aerial System
- MTS Mission Tool Suite



BACKUP



Targeter Pipeline



- Data sources selected based on science case

- Build the 'features' of a 'pixel'
- Pixel resolution ~1km

- Cluster regions with similar feature spaces

- Choose Clusters based on their mean values of the features

- Segment Clusters of interest
- Assign Segment Value based on formulation by SMEs



Features(1/3)

Cloud feature

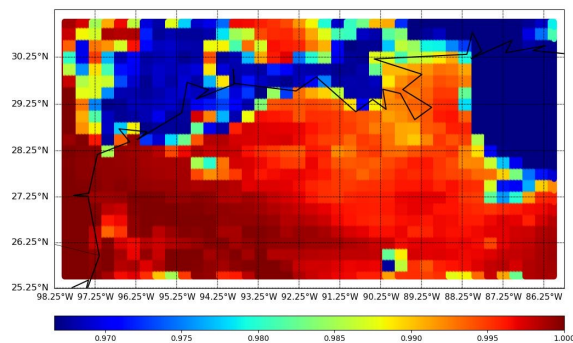
$$cld = cld_{tot_{GEOSFP}}$$

$$x = 1/cld_{thresh} * (cld_{thresh} - cld)$$

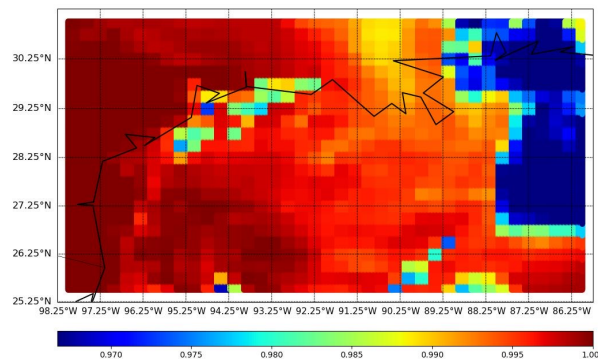
$$if \ cld > cld_{thresh} \rightarrow x = 0$$

$$f_{cloud} = x$$

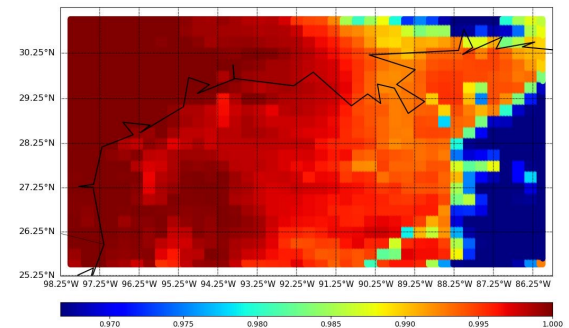
- Less clouds => good observation possible
- If clouds are above a threshold, then the area is completely deprioritized.



Cloud feature
(9:30 ET)



Cloud feature
(12:30 ET)



Cloud feature
(15:30 ET)



Features (2/3)

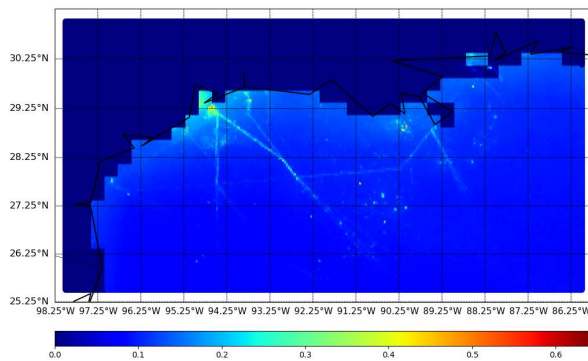
$$tropomiNO2 = mask_{water} * tropomiNO2$$

$$f_{NO2} = a \overline{PlatformEmis} + b \overline{nonPlatformEmis} + c \frac{tropomiNO2}{tropomiNO2_{max}}$$

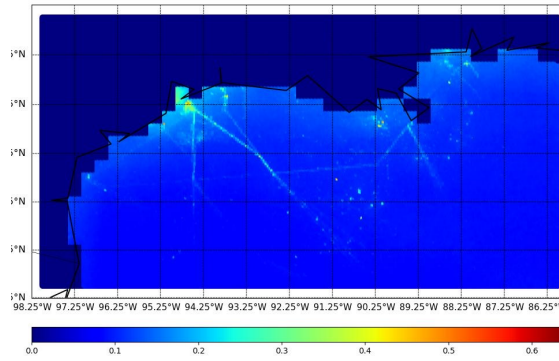
NO2 feature

The weights 'a', 'b', 'c' depend upon the GEOS-CF TROPOL-NO2 which is a measure of continental influence. If the GEOS-CF TROPOL-NO2 is above a threshold, the Tropomi NO2 reading is deemphasized.

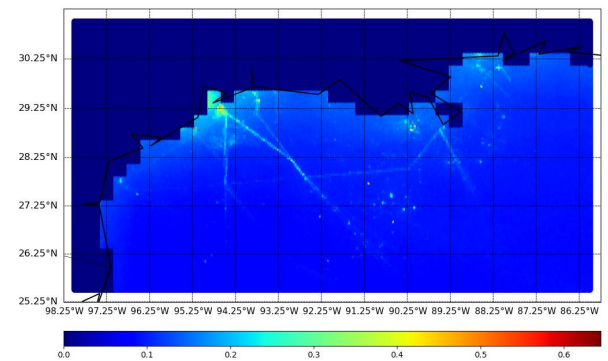
(Land-water mask has been applied prior to normalization of the Tropomi NO2 data)



NO2 feature
(9:30 ET)



NO2 feature
(12:30 ET)



NO2 feature
(15:30 ET)



Features (3/3)

AOT feature

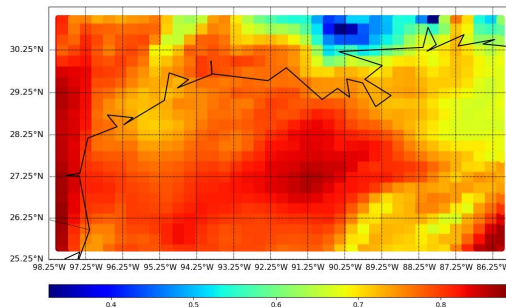
- Less AOT means a better observation.
- Like in the case of clouds, when the Aerosol Optical Thickness is greater than a threshold, the area is completely devalued.

$$AOT = AOT_{GEOSFP}$$

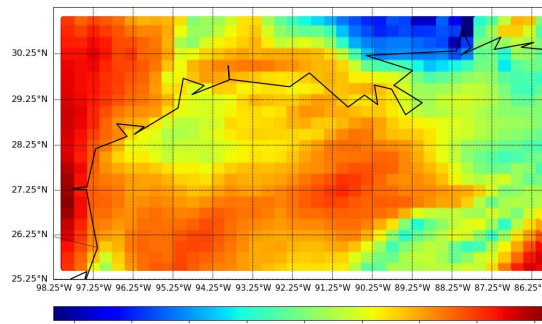
$$x = 1/AOT_{thresh} * (AOT_{thresh} - AOT)$$

$$if \ AOT > AOT_{thresh} \rightarrow x = 0$$

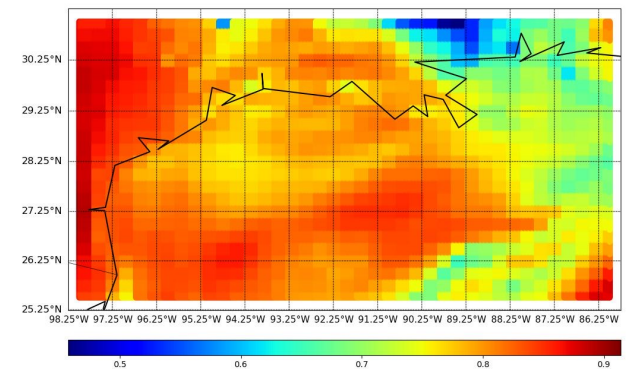
$$f_{AOT} = x$$



(9:30 ET)



(12:30 ET)



(15:30 ET)



Clustering

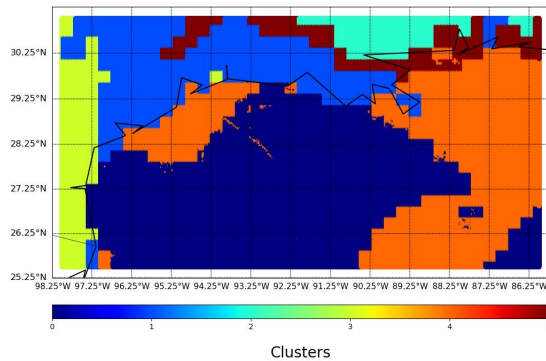
- Clustering was applied with <cloud feature, NO2 feature, AOT feature>
- Looking at the centroid values (of the features), clusters could be selected.

TIME	Clusters to be devalued to 0 (fall on Land)	Clusters to be considered (tradeoff b/w good visibility & NO2)
9:30 ET	#1, #2, #3, #5	#0, #4
12:30 ET	#1, #3, #4	#0, #2, #5
15:30 ET	#1, #3, #5	#0, #2, #4

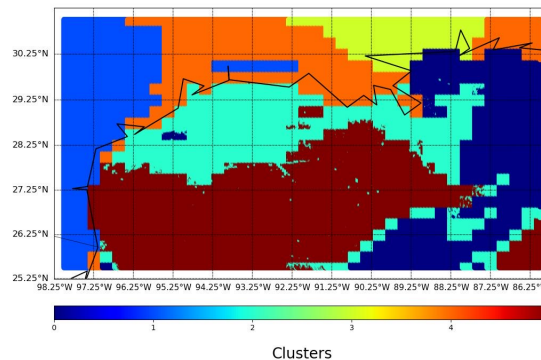
```
Centroid 0:[0.99689402 0.09428842 0.80126798]  
Centroid 1:[9.77492551e-01 6.94805408e-05 7.56075764e-01]  
Centroid 2:[ 9.75385516e-01 -5.59274849e-15 4.91762706e-01]  
Centroid 3:[9.95863201e-01 2.73699363e-06 8.36105321e-01]  
Centroid 4:[0.98449536 0.10991961 0.71720205]  
Centroid 5:[9.77639960e-01 5.45534421e-04 6.47565975e-01]
```

```
Centroid 0:[0.9773663 0.10152901 0.69901884]  
Centroid 1:[9.99729780e-01 1.36929560e-06 8.49629249e-01]  
Centroid 2:[0.99368389 0.11960303 0.76286309]  
Centroid 3:[9.85745194e-01 2.14804811e-06 5.90253910e-01]  
Centroid 4:[9.92937477e-01 8.41505628e-05 7.62709311e-01]  
Centroid 5:[0.99705372 0.08887723 0.81468544]
```

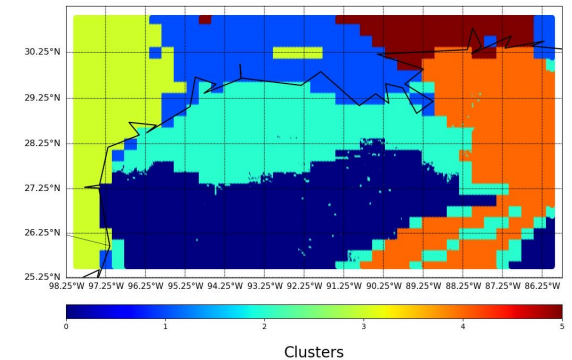
```
Centroid 0:[0.99613391 0.08649785 0.82443154]  
Centroid 1:[9.97362464e-01 8.27451833e-05 7.82542125e-01]  
Centroid 2:[0.99433646 0.11778618 0.78066517]  
Centroid 3:[9.99926501e-01 1.40020914e-06 8.53498595e-01]  
Centroid 4:[0.98125586 0.10213357 0.71393262]  
Centroid 5:[9.84502542e-01 2.12215187e-06 6.30308979e-01]
```



(9:30 ET)



(12:30 ET)



(15:30 ET)

Warning: Do not compare the colors across the cluster maps over time.

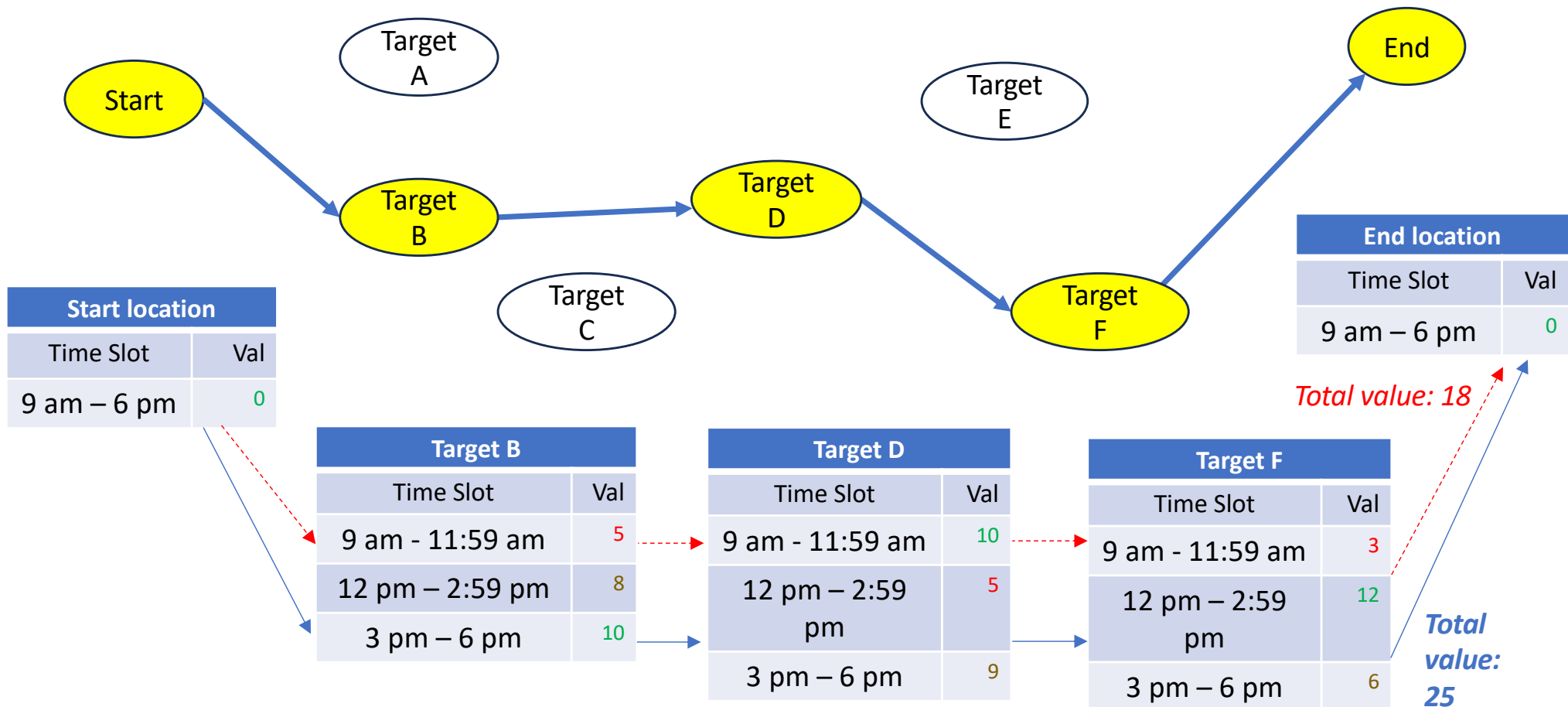
Next time: Remove the land pixels completely from analysis upstream. Why bother to cluster it at all?

Algorithm: The Multi-Profit Orienteering Problem (MPOP)*

- The Orienteering Problem (OP) is like a scavenger hunt game with a time limit
- Multi-Profit means the reward (profit) for visiting each location depends on the time of the visit
- MPOP has many applications, including travel and city tour planning
(Plan a tour of multiple places of interest with different rewards at different times)
- Planning problem: *Decide which locations to visit, and when to visit them*
- MPOP is a formal *math model* (equations) for optimizing a sequence of location visits, within a given time limit
 - Targets are modeled as vertices in a graph
 - Model is constructed in Python then solved by Gurobi Optimization software (fastest optimization engine available)

*[Kim et al., *Hybrid dynamic programming with bounding algorithm for the multi-profit orienteering problem*, European Journal of Operational Research 303 (2022)]

MPOP Example



Blue route is selected for total value 25, Delayed arrival at B until 3 pm to collect B's max value of 10

MPOP Model

Decision Variables (planner must choose values)

$$x_{ij}, y_{kd} \in \{0, 1\}, s_i \geq 0$$

$$x_{ij} = \begin{cases} 1 & \text{if the vehicle visits vertex } v_j \text{ right after vertex } v_i \\ 0 & \text{otherwise} \end{cases}$$

$$y_{id} = \begin{cases} 1 & \text{if vertex } v_i \text{ is visited at } d\text{th time slot} \\ 0 & \text{otherwise} \end{cases}$$

s_i = start time of the visit of the vehicle at vertex v_i

Objective: Maximize sum of profit collected for all visited targets

$$\text{Max} \sum_{i=1}^n \sum_{d=1}^{D_i} P_{id} y_{id} \quad \text{where } P_{id} = \text{profit for visiting vertex } i \text{ during timeslot } d$$