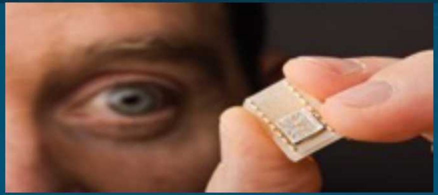
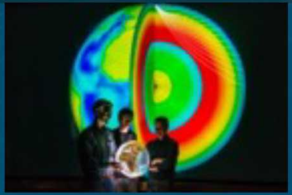
SAND2019-4452PE

Sandia Research Seminar:

Trajectory Analysis & Constellation Optimization





PRESENTED BY

Christopher G. Valicka, PhD

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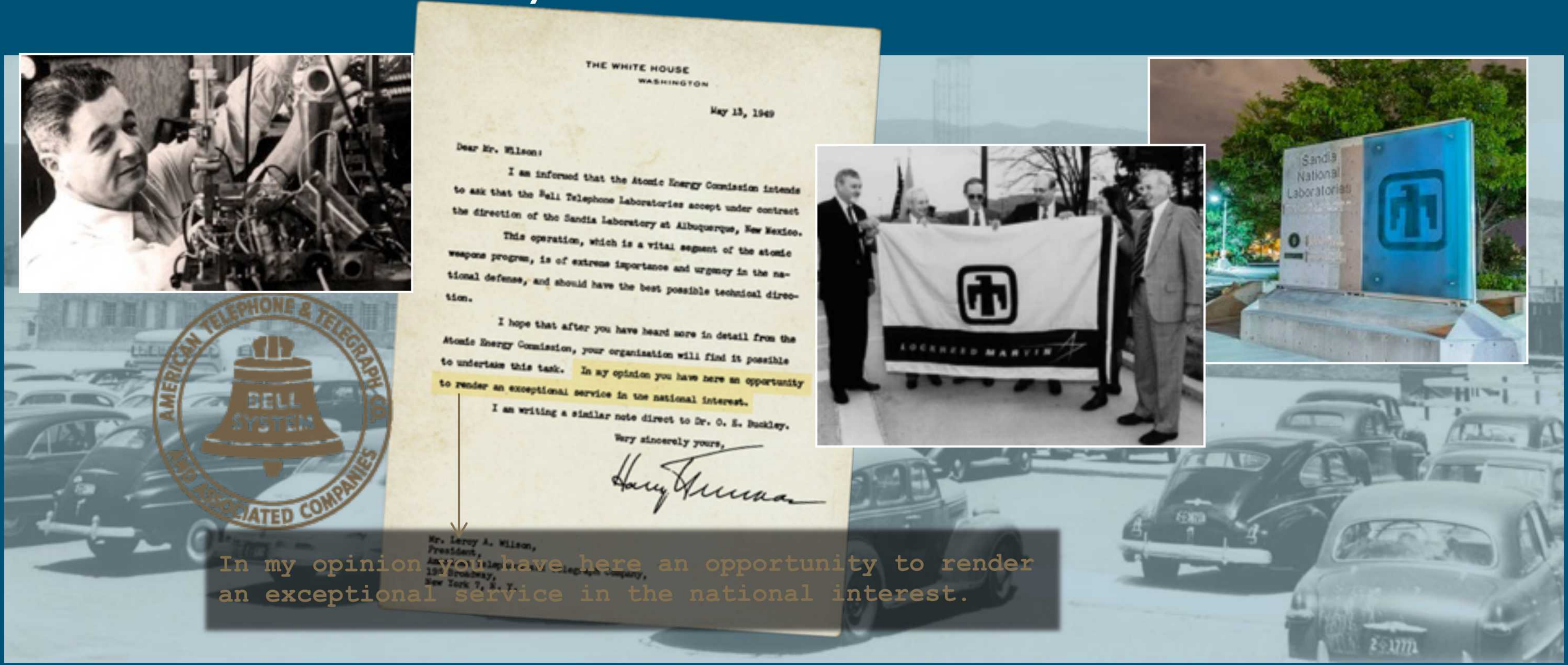
Overview

- PART 0: Brief Sandia National Laboratories overview

- PART I: Clustering analysis of aircraft trajectory data
  - Motivations and applications
  - Algorithm implementation details
    - **Tracktable** open source software
  - Related problems and future topics

- PART II: Mosaic imaging by sampling and optimization
  - Motivations and applications
  - Model formulations and solution details
    - **Pyomo** and **GeoPlace** open source software
  - Related problems and future topics

Sandia: An FFRDC for nearly seven decades

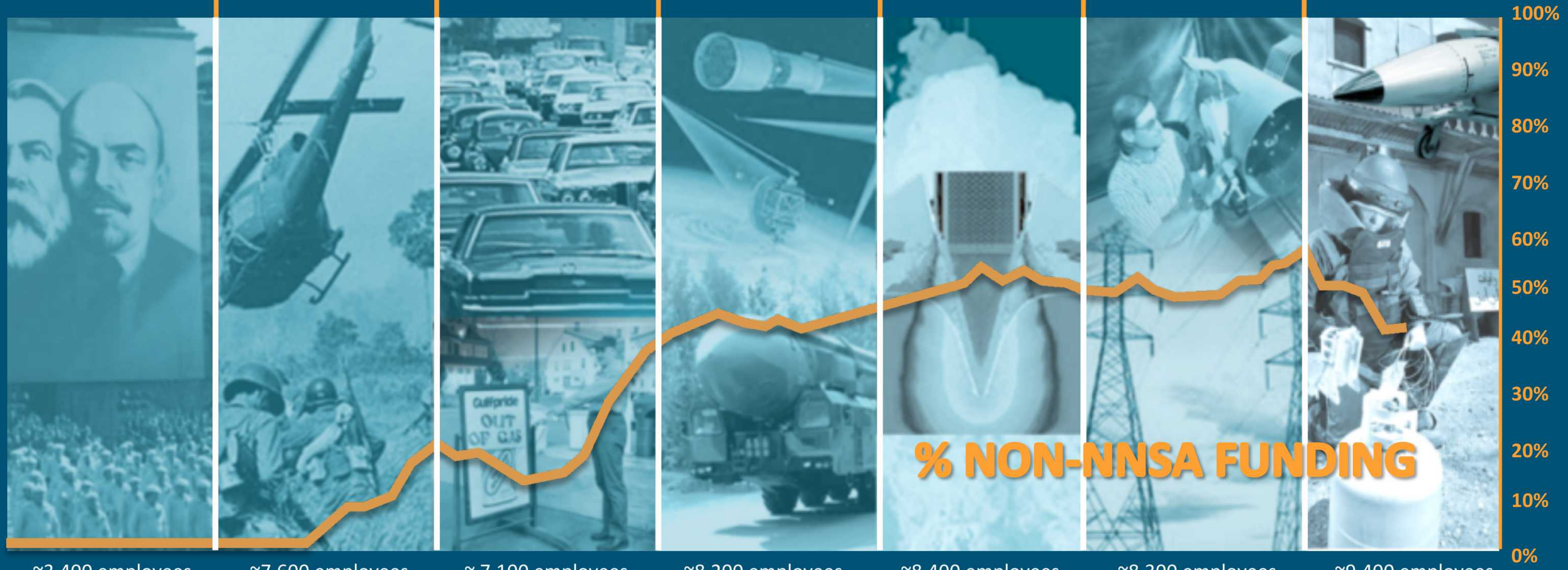


Significant dates

- **July 1945:** Los Alamos creates Z Division at Sandia Base
- **November 1, 1949:** Sandia Laboratory is established and managed by AT&T
- **March 8, 1956:** Sandia's California site is established
- **July 26, 1993:** Martin Marietta wins first Sandia Corporation contract competition
- **April 30, 2017:** Lockheed Martin contract
- **May 1, 2017 – present:** NTESS contract

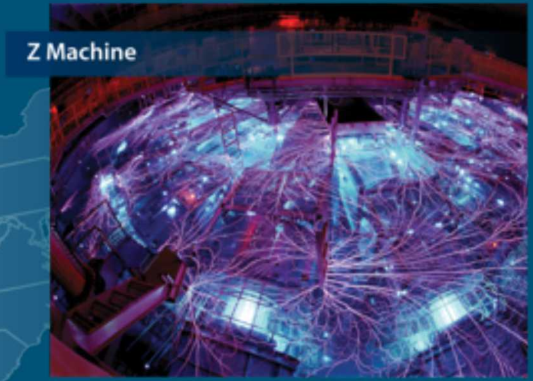
Sandia: A multimission lab

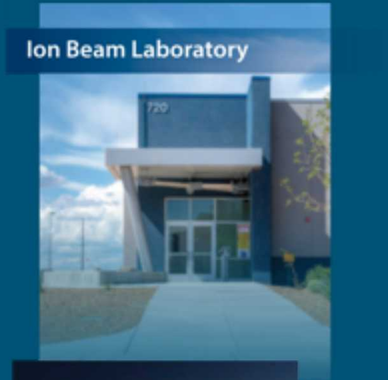
1950s	1960s	1970s	1980s	1990s	2000s	2010s
NW engineering and test	NW stockpile diversity and build-up	NW + energy: Multiprogram laboratory	DOE Multiprogram + missile defense and other DOD work	DOE Multiprogram + DoD, economic competitiveness	Expanded national security role post 9/11	LEPs Cyber, bio, space, terrorism
Arms Race	Cuban missile crisis Vietnam conflict	Energy crisis	Cold war	Stockpile stewardship	Broader national security	Evolving national security challenges



1950s	1960s	1970s	1980s	1990s	2000s	2010s
~3,400 employees	~7,600 employees	~ 7,100 employees Layoffs in late 1970s	~8,200 employees	~8,400 employees 96-97, 2 rounds of voluntary separation	~8,300 employees	~9,400 employees Today, ~10,600 employees

Sites and key facilities: A few examples

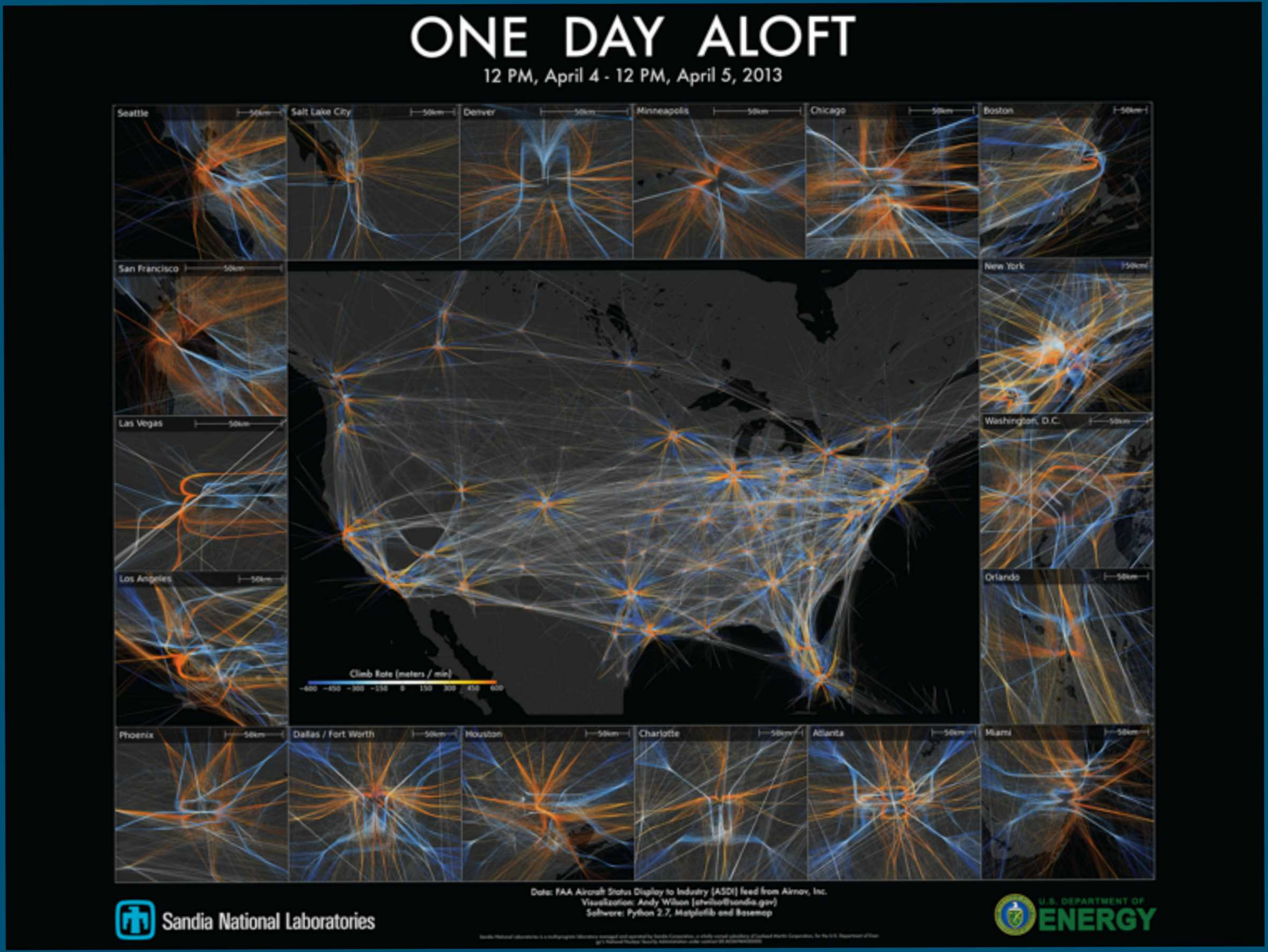




Clustering Analysis of Aircraft Trajectory Data

Motivations and Applications

Nature and Scale of Trajectory Data



Nature and Scale of Trajectory data

Thanks to GPS and new geolocation technologies, enormous corpuses of position/time data exist:

- Collision avoidance data for aircraft (**ASDI**, ADS-B) and ships (AIS)
- Transponder data from ground vehicles, other moving objects

But…often very little additional information and/or some metadata is untrustworthy

Questions then arise related to comparing trajectories:

- What patterns exist in this dataset?
- Have we seen this pattern before?
- Have we seen a pattern related to this known behavior of interest?
- **Can we group together similar patterns, and…**
- **…can we identify patterns that are unique or unusual (outliers)?**
- Can we forecast where a current trajectory will go based on historical observations?
- Can we identify different types of collective behavior among many trajectories?

Clustering Analysis of Aircraft Trajectory Data

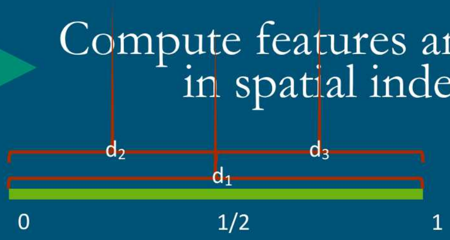
Algorithm Implementation Details

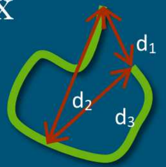
What Does **Tracktable** Do?

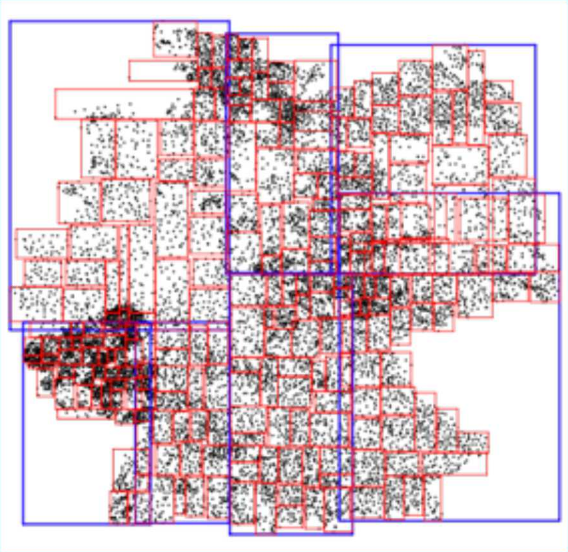
Given a large corpus of trajectory points…

Assemble points into trajectories

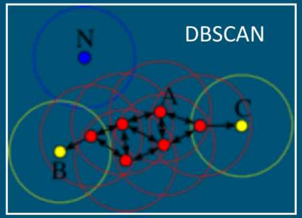
Compute features and store in spatial index

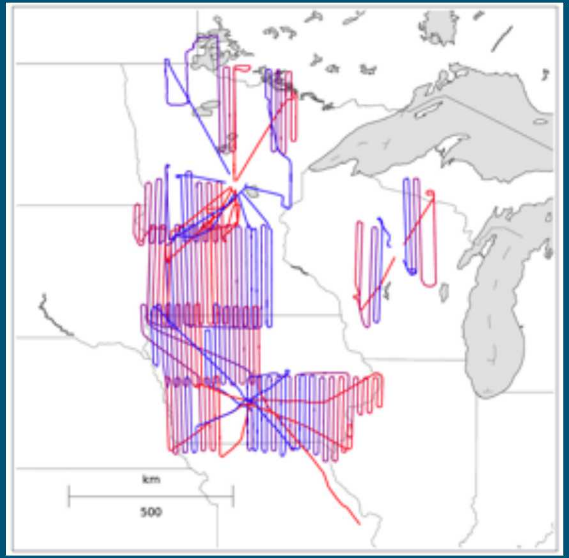






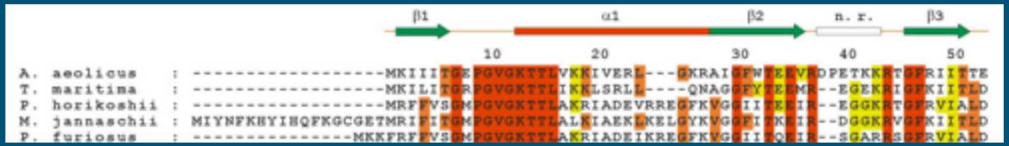
Discover, compare, and forecast patterns





How Does **Tracktable** Compare?

Previous analyses use computationally expensive, unintuitive curve alignment techniques.



Using intuitive combinations of numerical descriptions, trajectories can be analyzed and compared efficiently:

- End-to-end distance traveled
- Total distance traveled
- Ratio of end-to-end distance traveled to total distance traveled
- Total curvature
- Total amount of turning
- Average heading change
- Area covered by flight (convex hull of points)
- Eccentricity of the convex hull
- Perimeter of convex hull
- Centroid of points
- Centroid of convex hull
- Start/Stop point
- Nearest distance to a given point
- “Distance” from a given specified track
- “Distance” from a given specified shape
- Start/Stop time
- Time nearest to a given point
- Average speed
- Range of speeds
- Max altitude
- Fluctuations of altitude/shape of altitude/time curve
- Difference from historical data
- Most common speed/altitude (cruise)
- Place, time and heading where first seen / last seen (might not be start/stop points)
- Other…

FEATURE LIST

Clustering: DBSCAN

Many different types of clustering algorithms exist (k-means, EM, etc.) but DBSCAN has two nice properties:

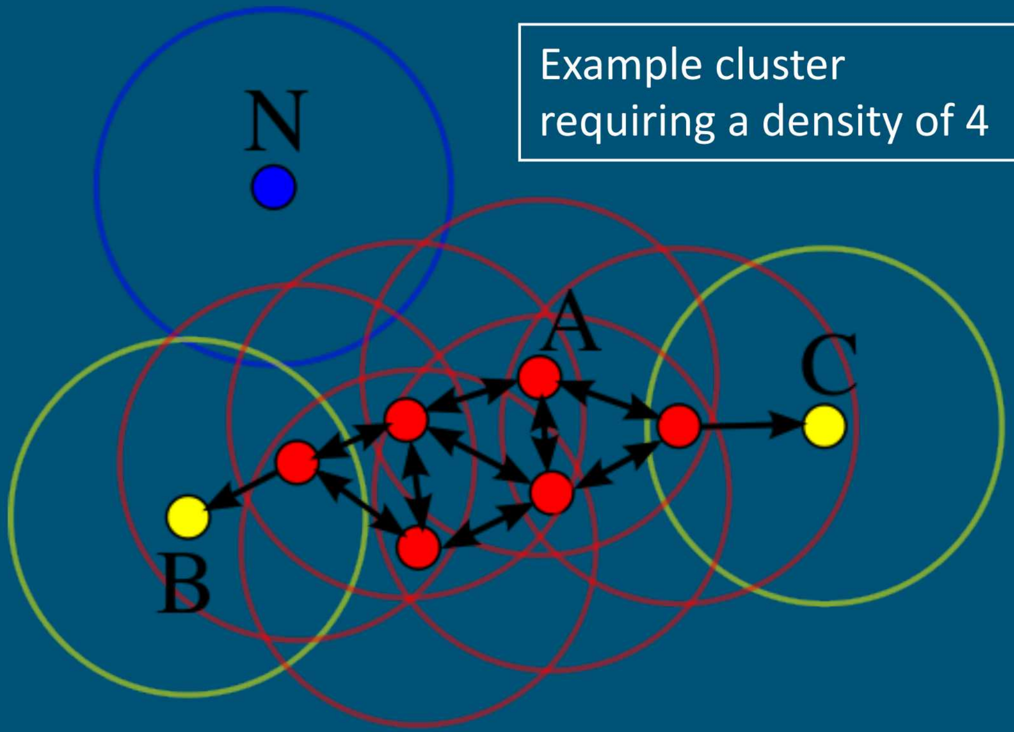
- Doesn't require a pre-defined number of clusters
- Has the notion of noise (outliers)

DBSCAN requires

- A neighborhood density
- A neighborhood radius

Tracktable implements a variation of DBSCAN

- sklearn.cluster Python package includes an implementation



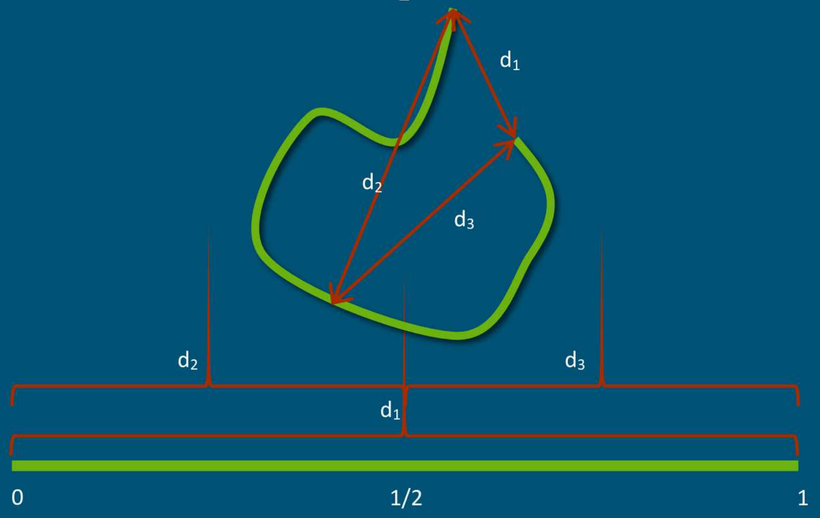
Example cluster requiring a density of 4

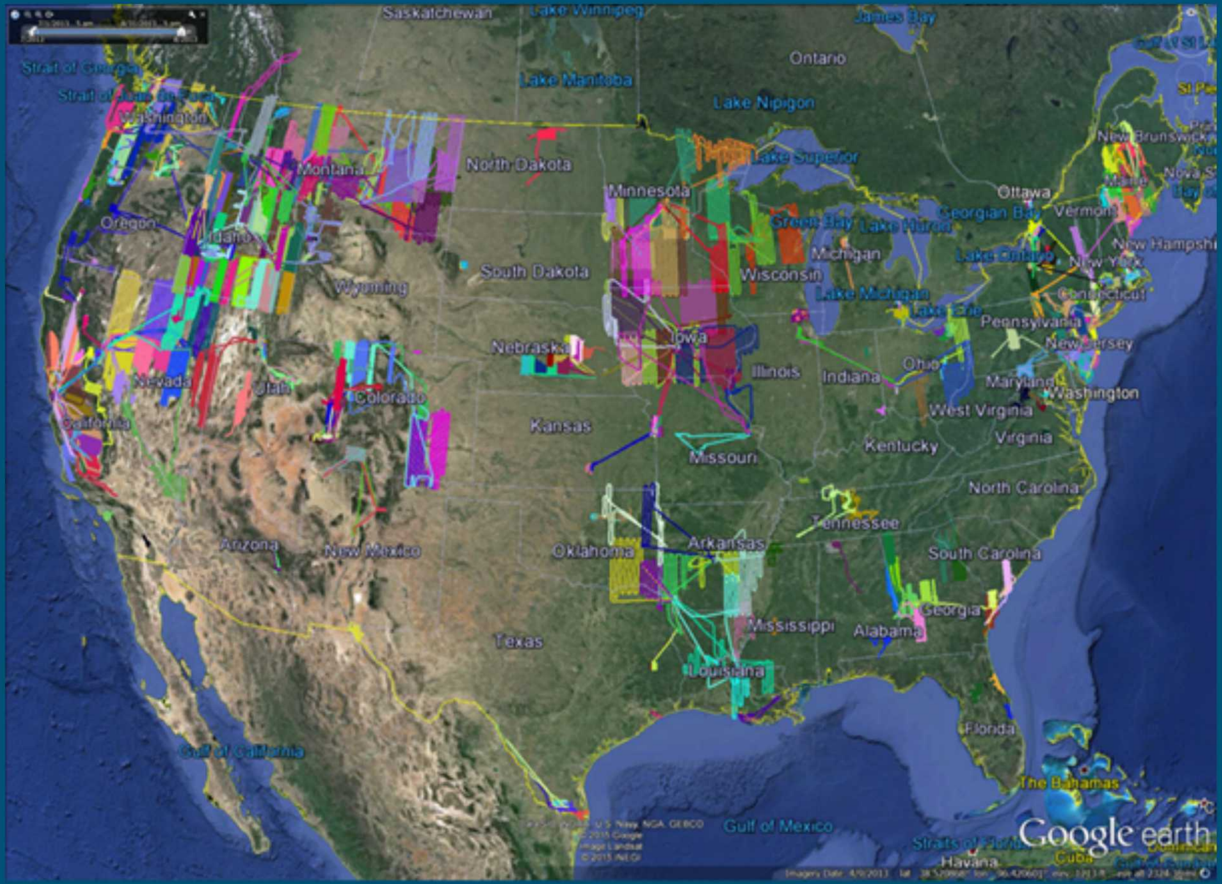
Clustering Pattern Discovery: Mapping flights

Clustered 1 month of ASDI data from July of 2013 according to shape features

Discovered a large cluster of mapping flights across the US

- Mapping/aerial surveillance flights are regularly used to produce commercial and scientific maps





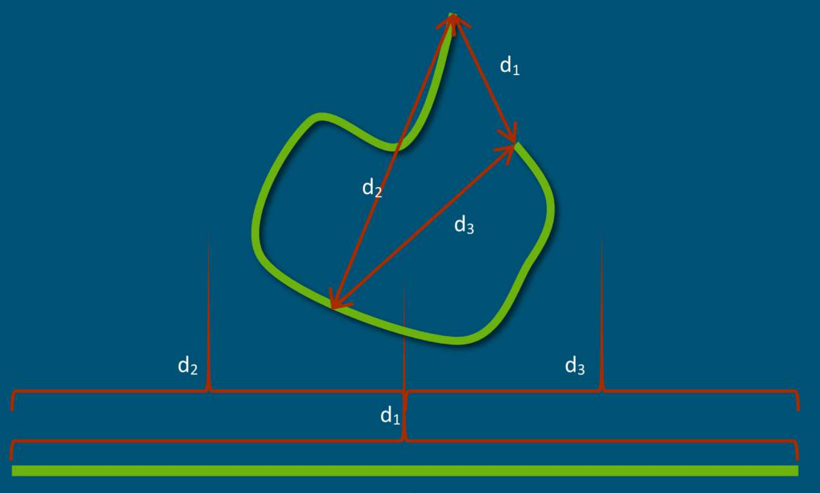
Clustering Pattern Discovery: Oil Rig Helicopters

5 helicopter flights from July 2013

All helicopters belong to the same petrochemical company

- They fly people/equipment out to oil rigs

Spatial proximity was coincidental

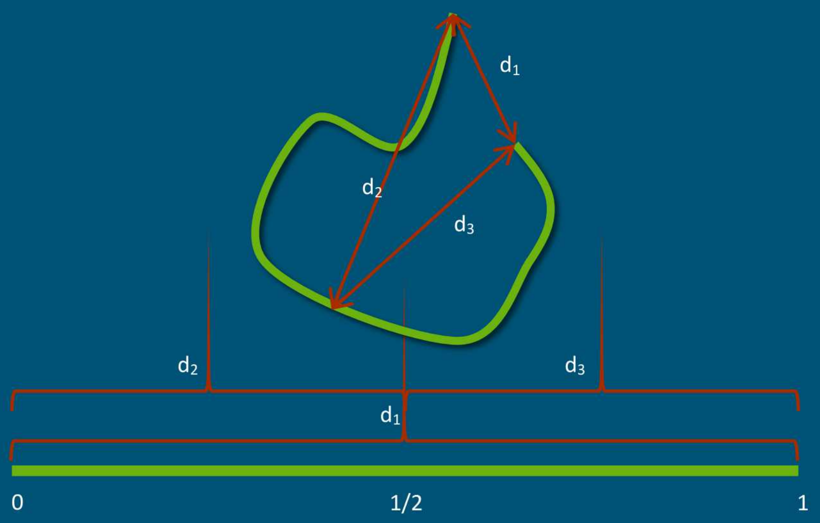


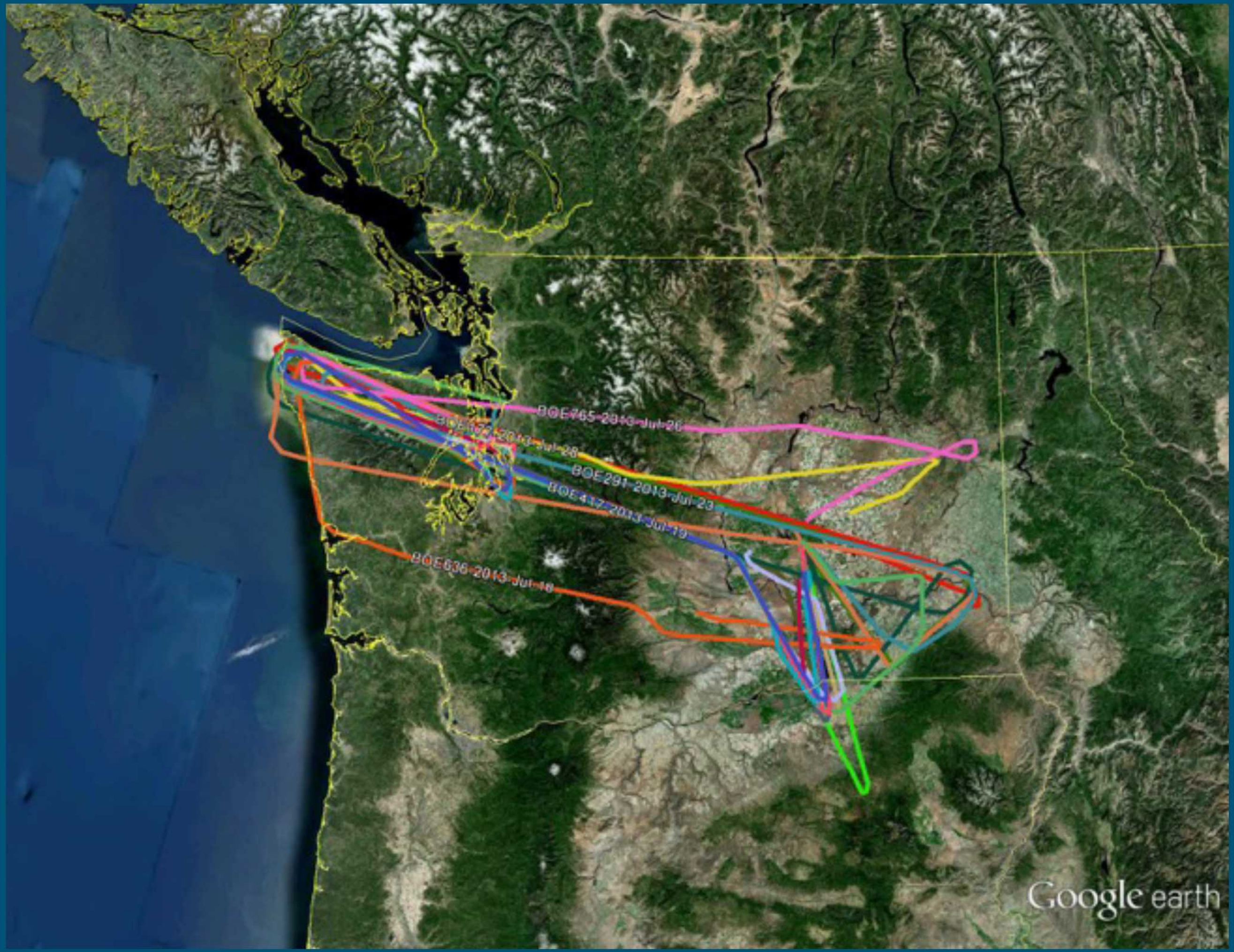
Clustering Pattern Discovery: Boeing Test Flights

Boeing test flights from its factory to a test field near Moses Lake in eastern Washington

Flights occurred over the month of July in 2013

Slightly different routes all with very similar 2-D shapes

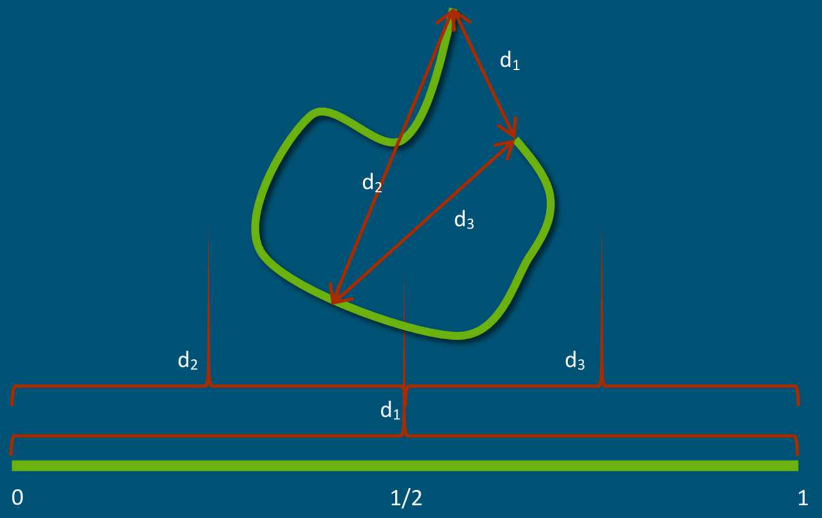


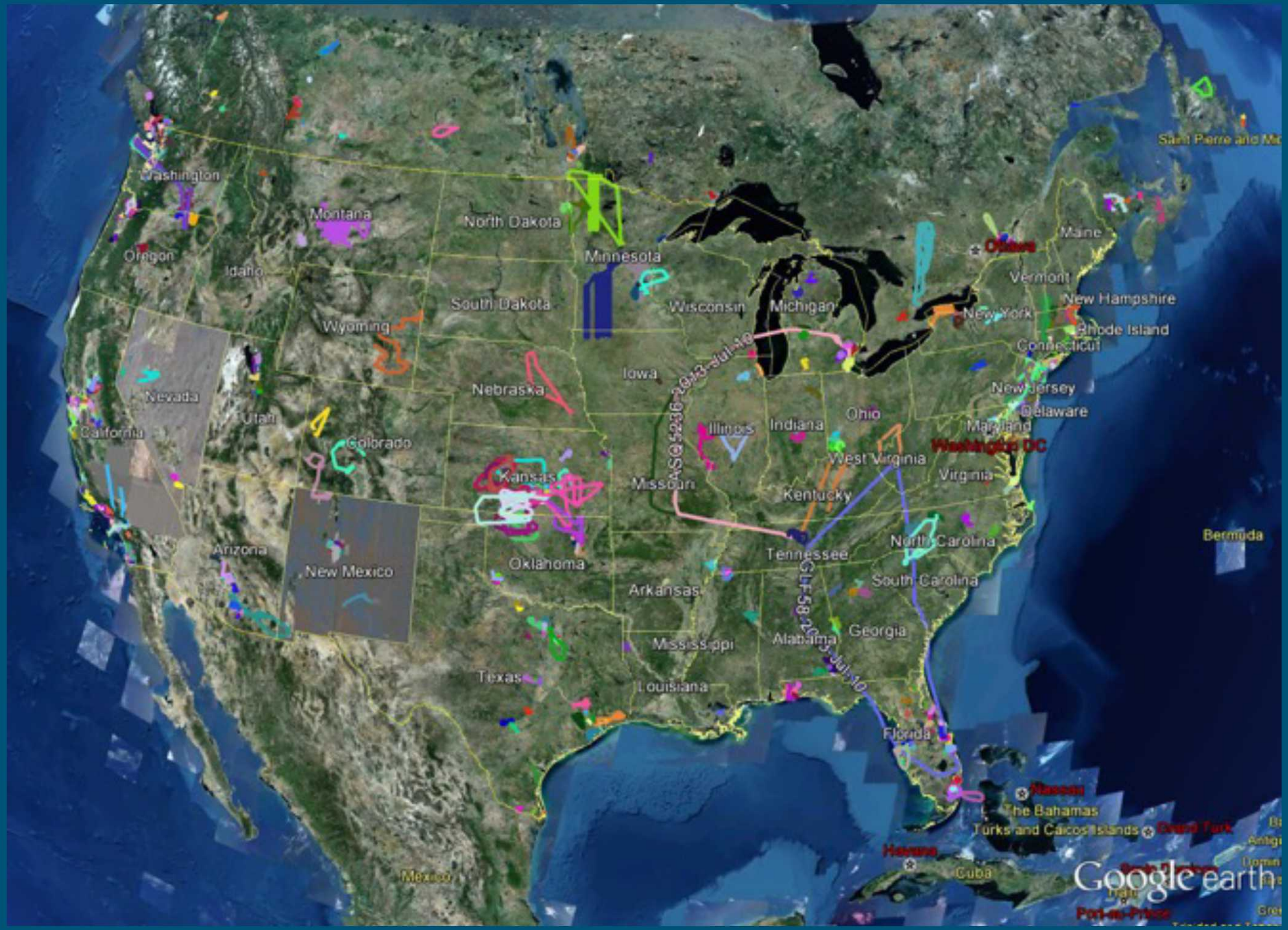


Clustering Pattern Discovery: Outliers

If we use the same feature vector and cluster over one day of flights, we also get a noise cluster

This graphic represents around 700 outliers out of a total of 50,000 flights from July 10th, 2013





Clustering Analysis of Aircraft Trajectory Data

Related Problems and Future Topics

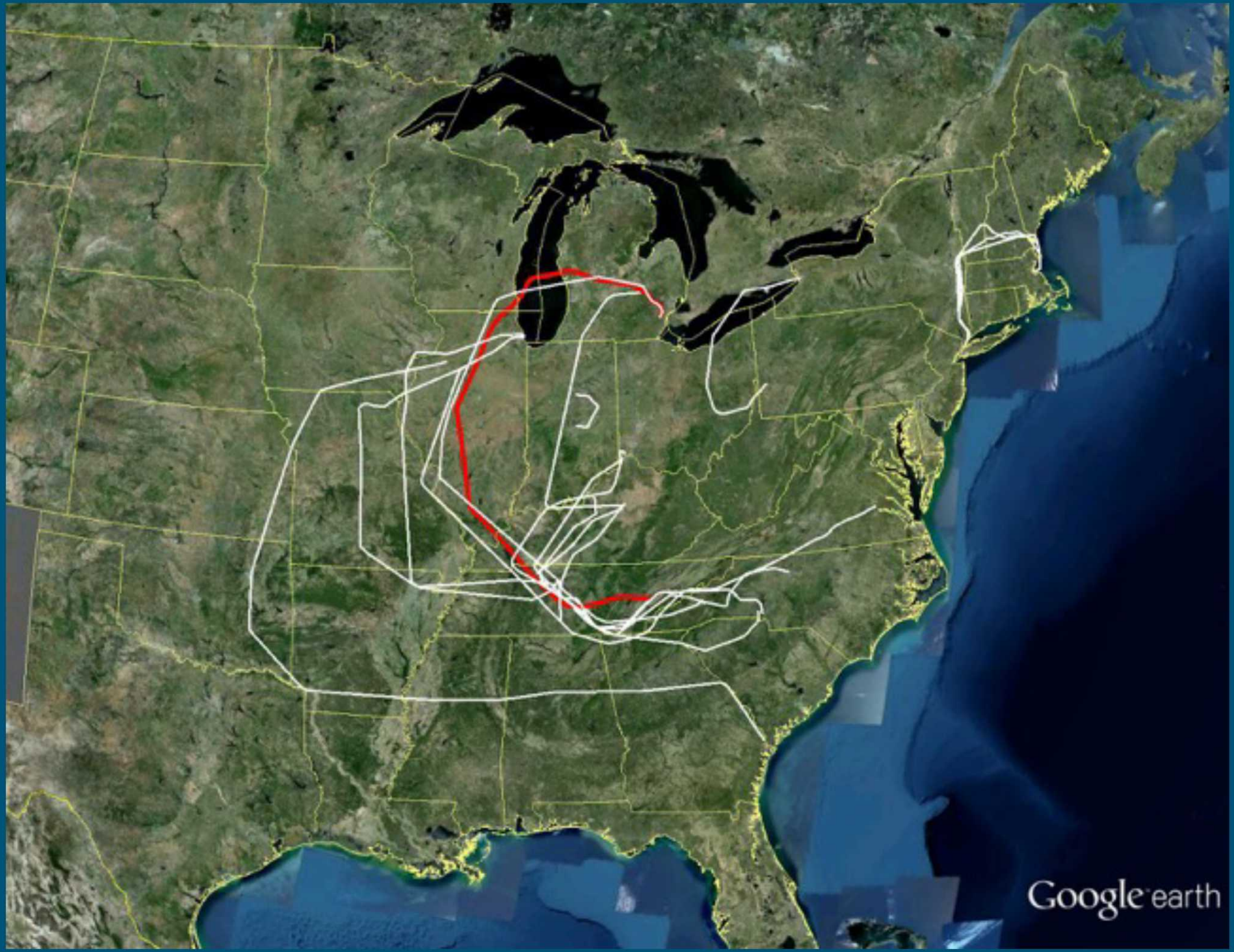
Related Problems: Find a Similar Flight

Consider the red flight, and look at just two features:

- Ratio of length to end-to-end distance
- Aspect ratio of convex hull

A search for flights with similar values gives the white flights

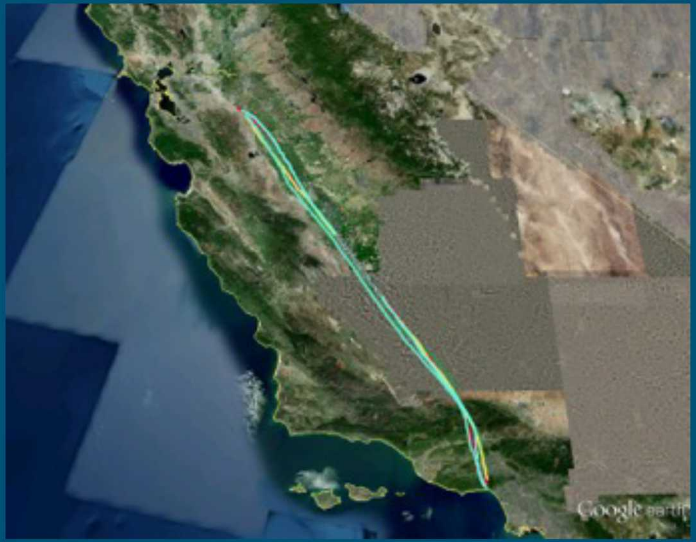
This is an example of a fast, shape-invariant search



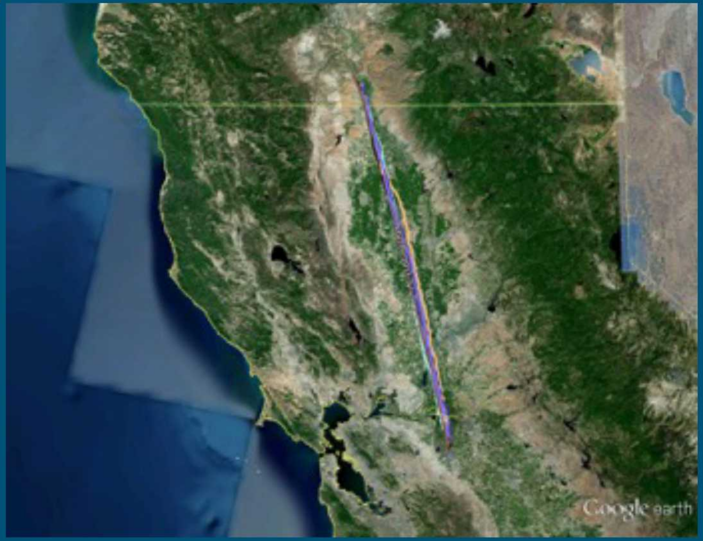
Related Problems: Collective Behavior

Find flights that followed the same path around the same time

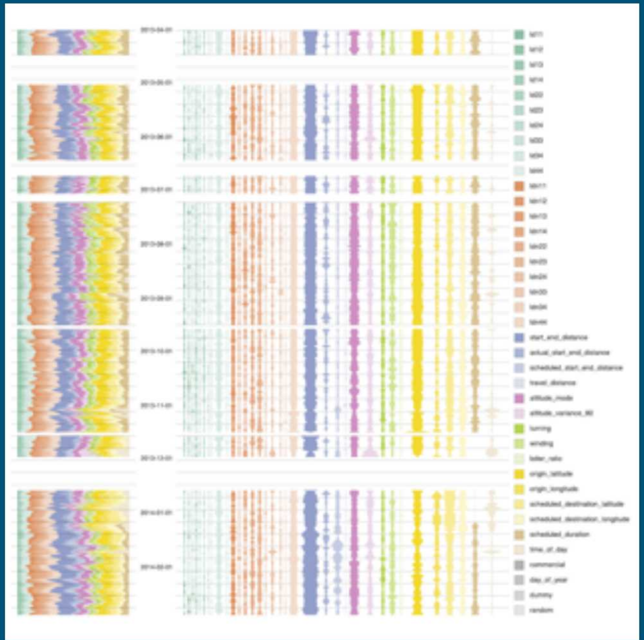
A group of 6 Cessna's all flew from Los Angeles to Tracy on the morning of July 10th.



… and then from Tracy to Redding around noon on July 10th.



Future Topics



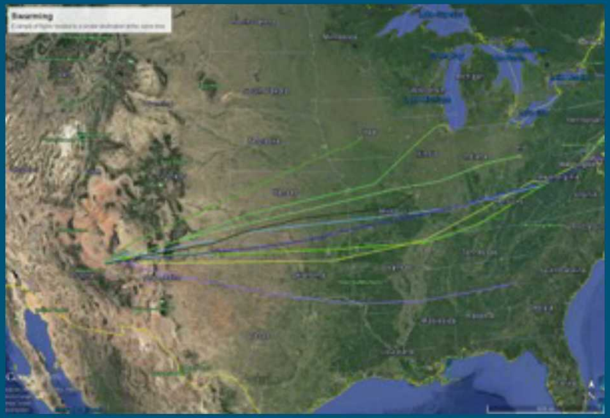
Automated parameter selection for clustering analysis

Automated feature selection for clustering, forecasting, and trajectory comparison
- Dimensionality reduction techniques
- Suitability of specific features across different trajectory data sets

Forecasting and prediction of various trajectory features
- To date, we have explored destination/source/location forecasting

Sub-trajectory lexicon for behaviors

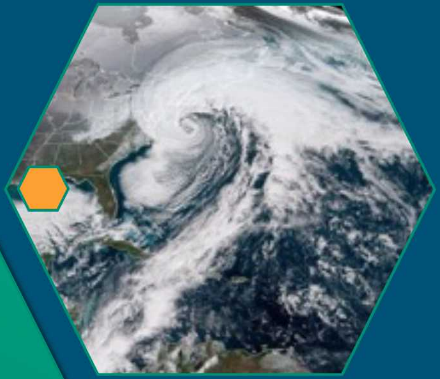
Additional topics in coordinated behavior of trajectories



Mosaic Imaging by Sampling and Optimization

Motivations and Applications

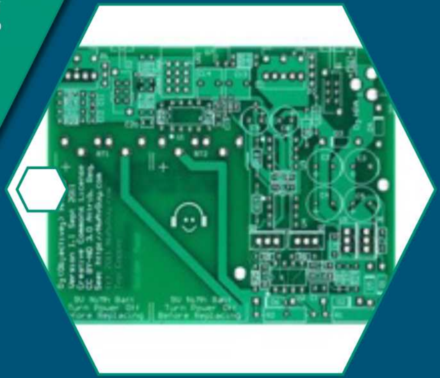
Optimization of Spatial Coverage



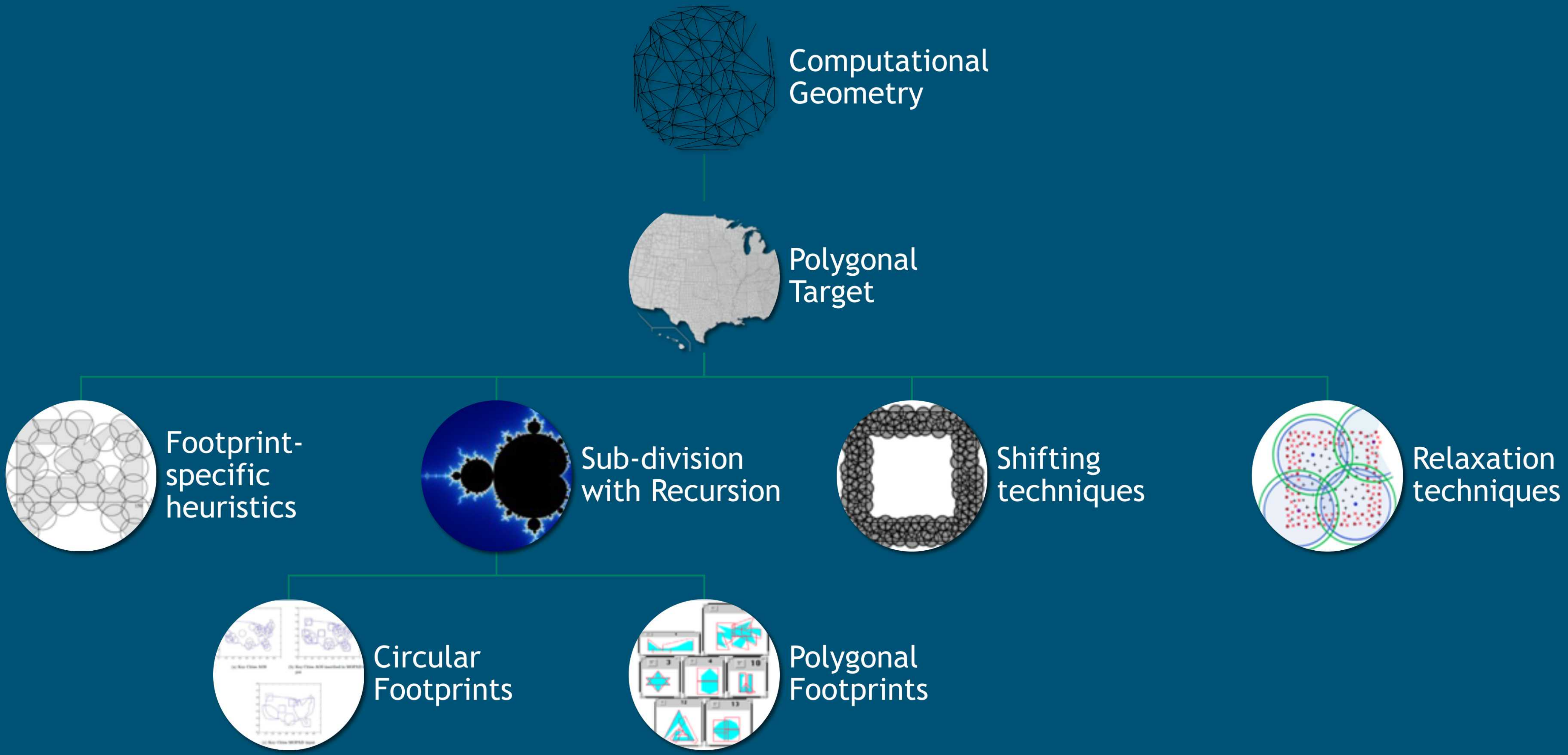
Earth-observing sensors

Logistics and manufacturing

Path planning & monitoring



Applied Coverage Techniques



Model Formulations and Solution Details

Pyomo and **GeoPlace** open source software

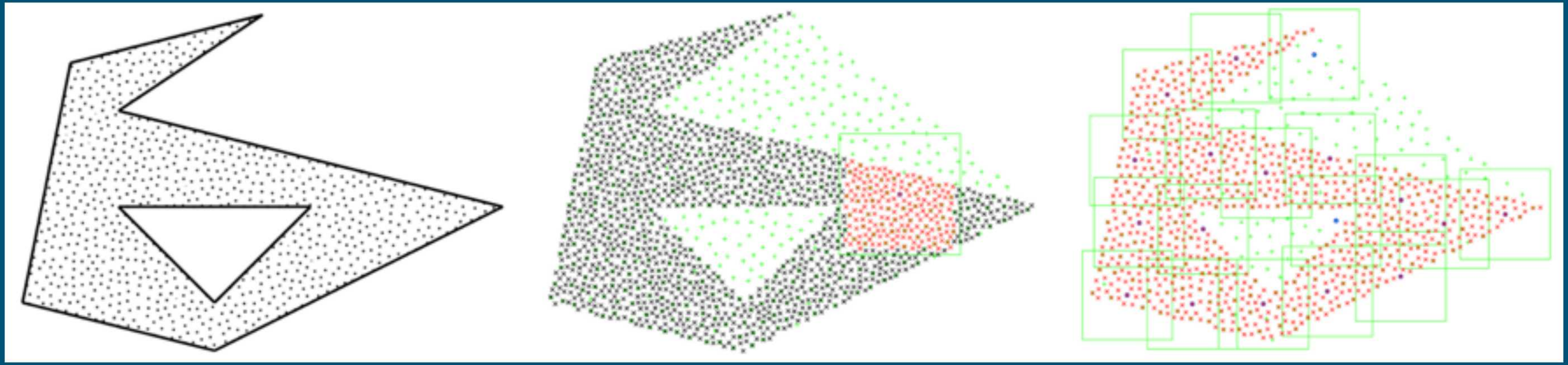
Details of Our Spatial Coverage Problem

- A small number (~10-100) of footprints (images) are required to:
  - Cover a region of interest (ROI) on the earth.
    - No gaps are allowed, some overlap between footprints is desirable.

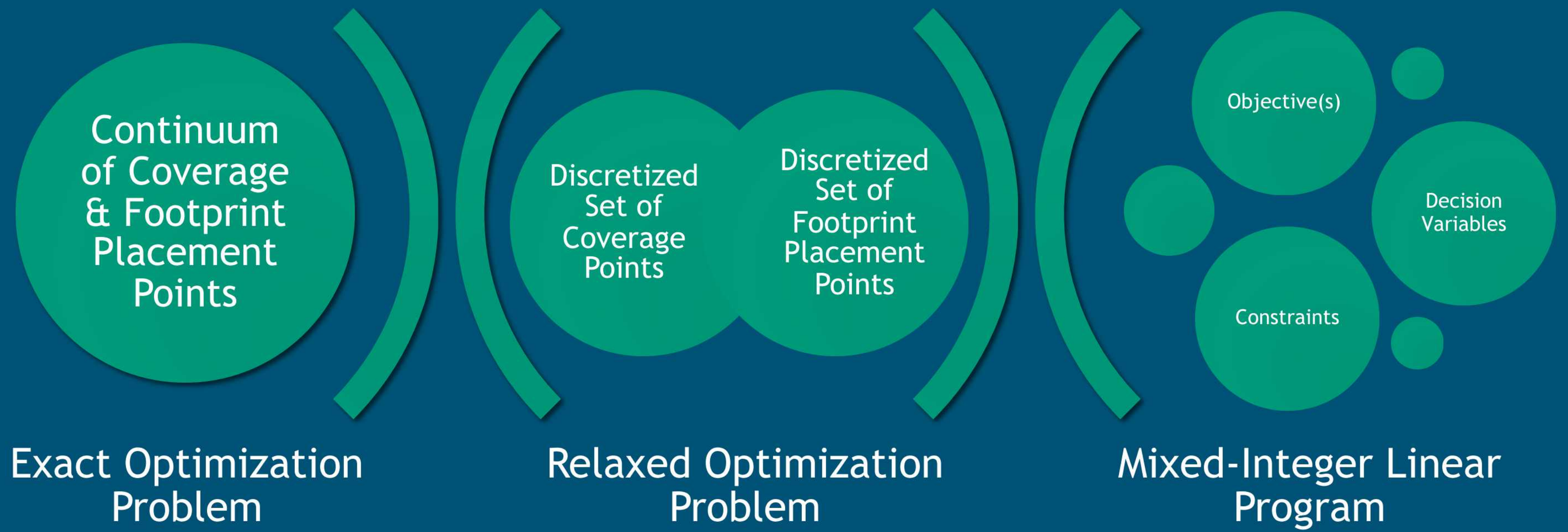
- The ROI is modeled as a polygon, sometimes with holes.

- Footprints are nearly convex and have good aspect ratios when projected on Earth.

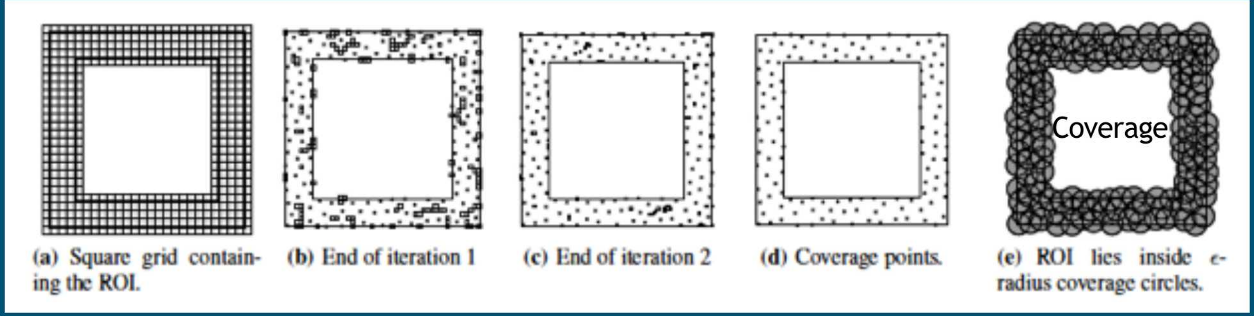
ROI | ROI + Footprint | Solution



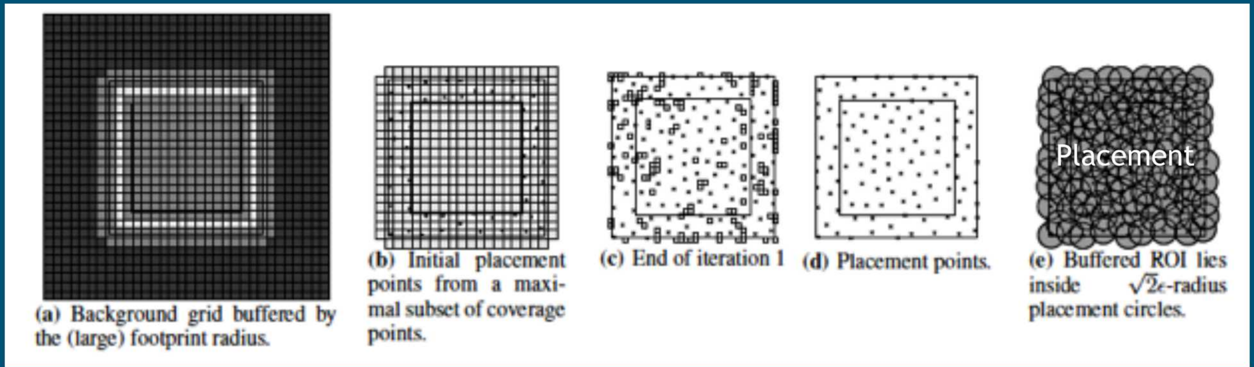
Algorithm


Continuum of Coverage & Footprint Placement Points
Discretized Set of Coverage Points
Discretized Set of Footprint Placement Points
Objective(s)
Decision Variables
Constraints
Exact Optimization Problem
Relaxed Optimization Problem
Mixed-Integer Linear Program

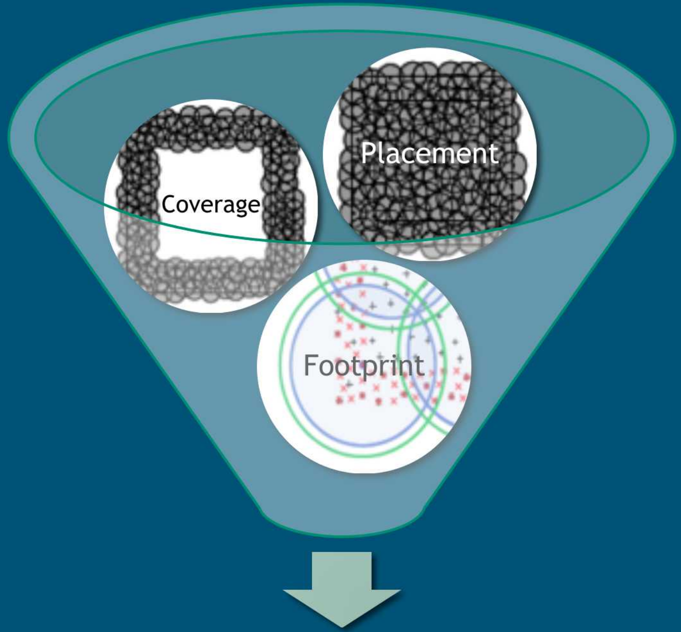
Algorithm (continued)



(a) Square grid containing the ROI. (b) End of iteration 1 (c) End of iteration 2 (d) Coverage points. (e) ROI lies inside ϵ-radius coverage circles.



(a) Background grid buffered by the (large) footprint radius. (b) Initial placement points from a maximal subset of coverage points. (c) End of iteration 1 (d) Placement points. (e) Buffered ROI lies inside $\sqrt{2}\epsilon$-radius placement circles.



Mixed-integer linear program

Mixed-Integer Programs

Formulation and Solution Descriptions

Mixed-Integer Programs

$$\begin{aligned} &\min \sum_{t}^{T} \delta_t \\ &\text{s.t.} \sum_{j}^{J(c)} \delta_j \geq 1 && \forall c \in C, \\ &\delta_t \in \{0,1\} && \forall t \in T. \end{aligned}$$

Equation 1: Basic coverage

$$\begin{aligned} &\min \sum_{t}^{T} \delta_t + \sigma \sum_{(i,j)}^{D} f(i,j)\phi_{i,j}, \\ &\text{s.t.} \sum_{j}^{J(c)} \delta_j \geq 1 && \forall c \in C, \\ &\delta_t \leq 1 && \forall t \in T, \\ &\delta_t \in \{0,1\} && \forall t \in T, \\ &\phi_{i,j} \geq \delta_i + \delta_j - 1, && \forall (i,j) \in D, \\ &\phi_{i,j} \leq \delta_i, && \forall (i,j) \in D, \\ &\phi_{i,j} \leq \delta_j, && \forall (i,j) \in D, \end{aligned}$$

Equation 2: Coverage penalizing overlap

$$\sum_{t}^{T} \delta_t (1 - \sigma_1 h(t)) + \sigma_2 \sum_{(i,j)}^{D} f(i,j)\phi_{i,j}$$

Equation 3: Coverage penalizing overlap, rewarding efficiency

Notation:

- Let T denote the set of (potential) footprint placement points,
- C is the set of required coverage points,
- $J(c)$ are the set of placements $j \in J$ that would cover $c \in C$,
- $\phi_{ij} \in \{0,1\}$ denotes whether or not placement pair (i,j) has footprints placed at both points,
- $h(t)$ is the number of coverage points covered by placing a footprint at placement point t.

Mixed-Integer Programs

$$\min \sum_{t}^{T} \delta_t$$
$$\text{s.t.} \sum_{j}^{J(c)} \delta_j \geq 1 \qquad \forall c \in C,$$
$$\delta_t \in \{0,1\} \qquad \forall t \in T.$$

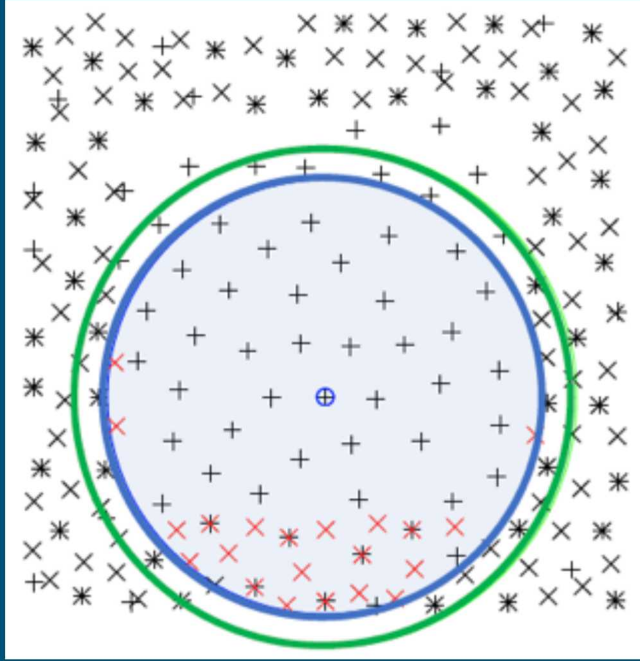
Equation 1: Basic coverage

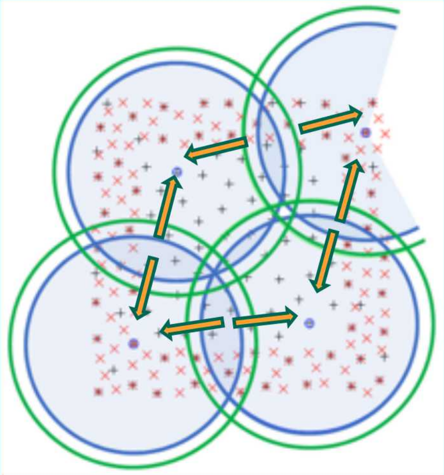
$$\min \sum_{t}^{T} \delta_t + \sigma \sum_{(i,j)}^{D} f(i,j)\phi_{i,j},$$
$$\text{s.t.} \sum_{j}^{J(c)} \delta_j \geq 1 \qquad \forall c \in C,$$
$$\delta_t \leq 1 \qquad \forall t \in T,$$
$$\delta_t \in \{0,1\} \qquad \forall t \in T,$$
$$\phi_{i,j} \geq \delta_i + \delta_j - 1, \qquad \forall (i,\, j) \in D,$$
$$\phi_{i,j} \leq \delta_i, \qquad \forall (i,\, j) \in D,$$
$$\phi_{i,j} \leq \delta_j, \qquad \forall (i,\, j) \in D,$$

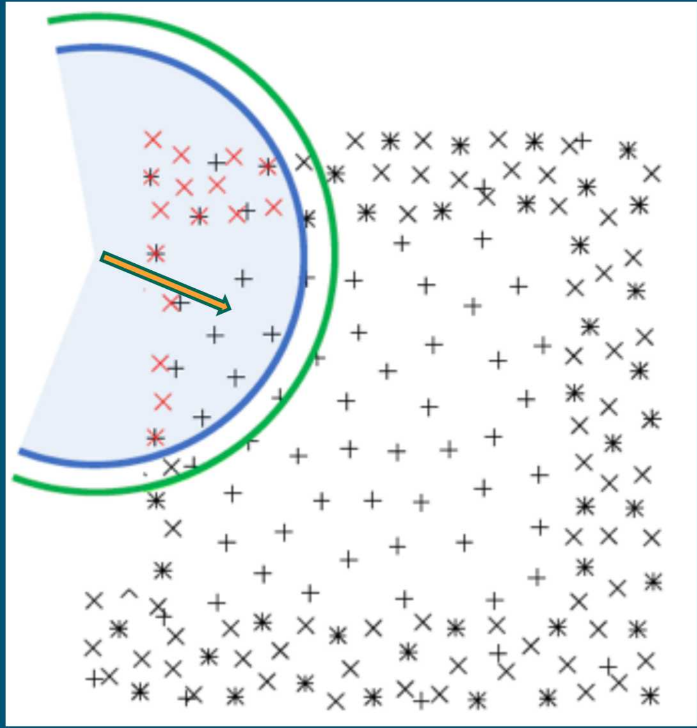
Equation 2: Coverage penalizing overlap

$$\sum_{t}^{T} \delta_t (1 - \sigma_1 h(t)) + \sigma_2 \sum_{(i,j)}^{D} f(i,j)\phi_{i,j}$$

Equation 3: Coverage penalizing overlap, rewarding efficiency



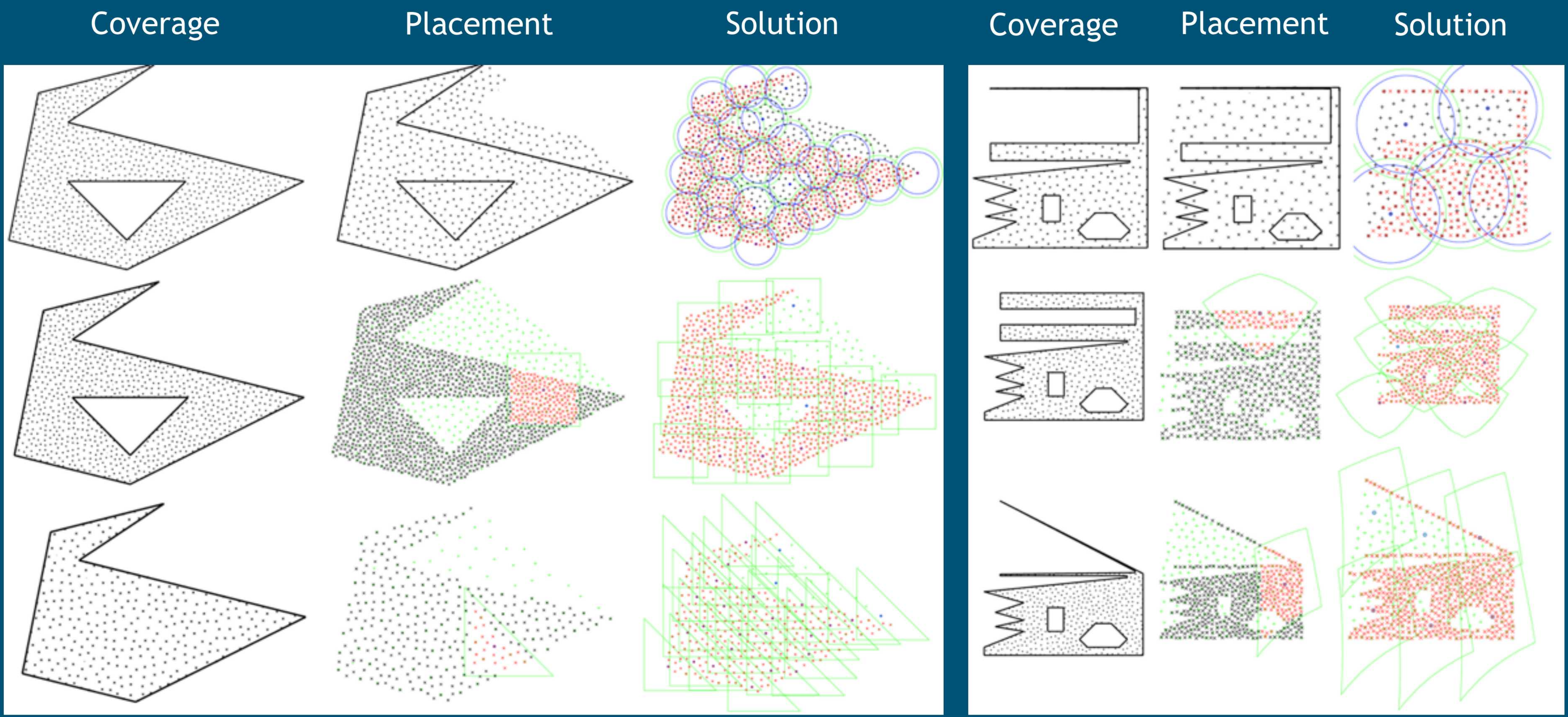




Examples

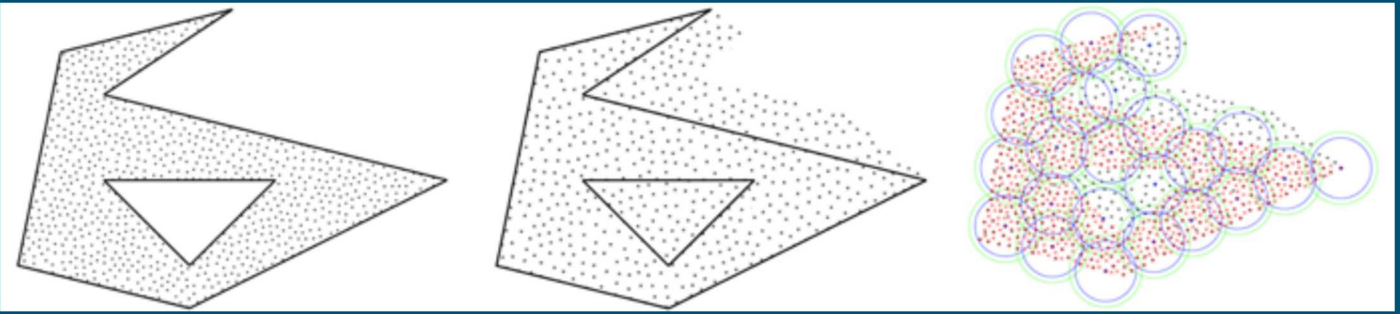
Problem Instances and Solutions with *GeoPlace*

Examples

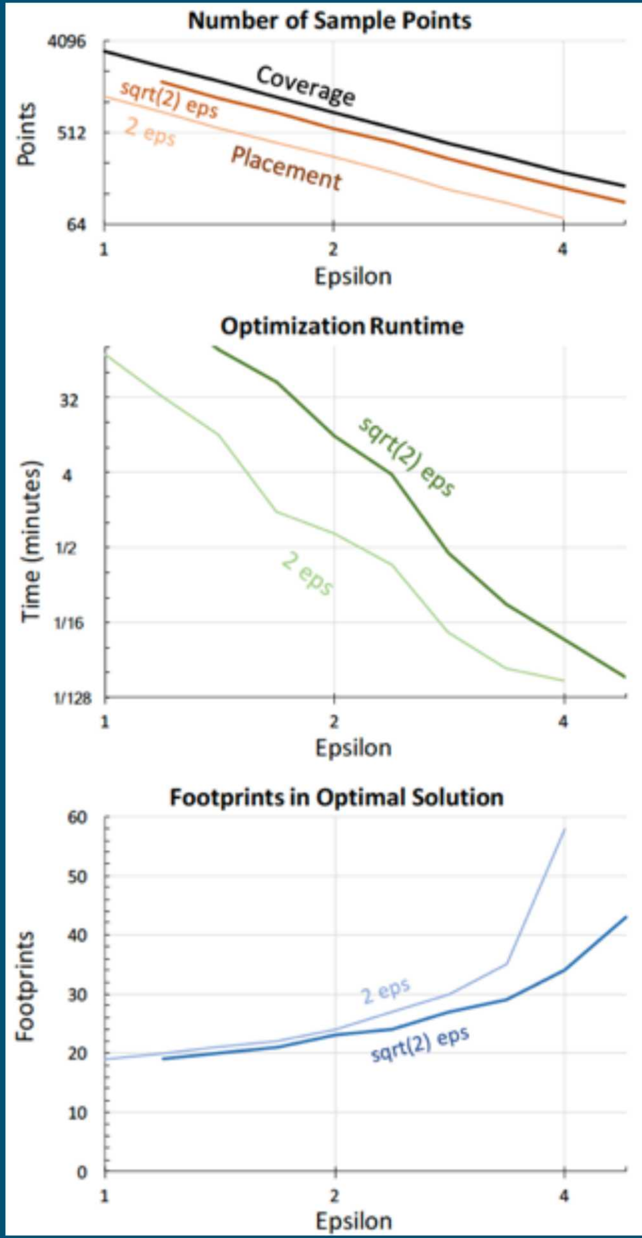


Note: Placements are optimal given fixed coverage and placement points and footprints.

Examples (continued)



- Problem instances were solved using both CPLEX (commercial license) and Gurobi (free academic use license)
  - Optimality gap tolerance was set to 0.01%
  - Solved on a 64-core workstation with 2.4GHz AMD processors and 512GB RAM
- Source code:
  - Available at https://github.com/cgvalic/GeoPlace
  - C++
    - Coverage and placement point generation
    - Visualization
  - Python
    - Mixed-integer linear program models (www.pyomo.org)
    - Solver interface

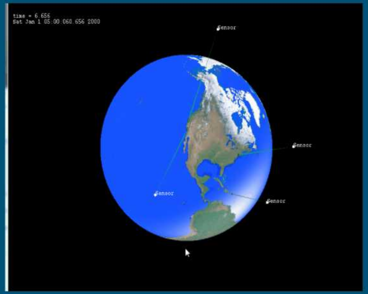


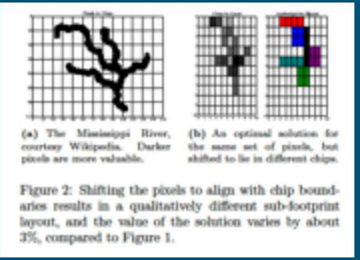
Extensions

Ideas for Future Research

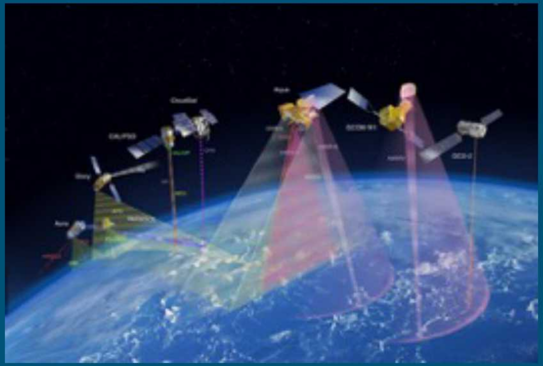
Related Problems and Future Topics

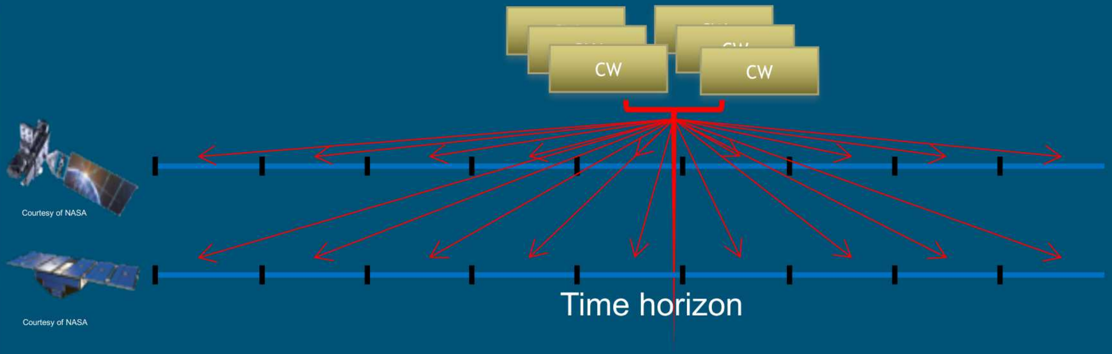
- Alternative mosaics
  - Multiple intra-mosaic footprint shapes
    - Accommodate relative motion of satellite
    - Accommodate cooperative sensing of disparate satellites
  - Placement with priorities and uncertainty





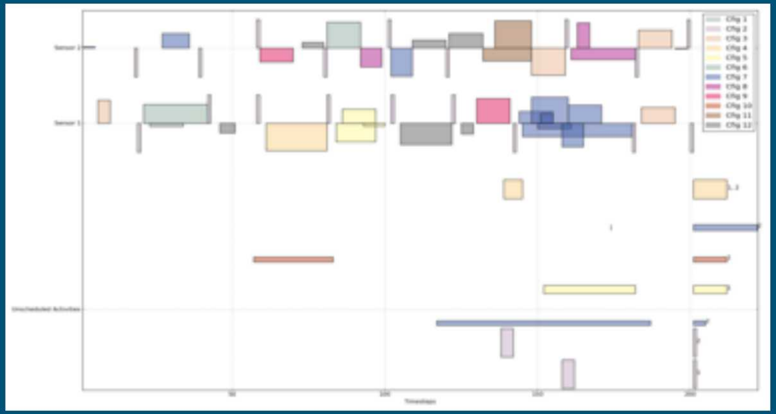
- Constellation job scheduling problems





Research and Development Themes

- Adaptive models: objectives, states and constraints
- Scalable online solutions



Example schedule with model that allows certain collection windows to run concurrently.

Thank You!

Questions?