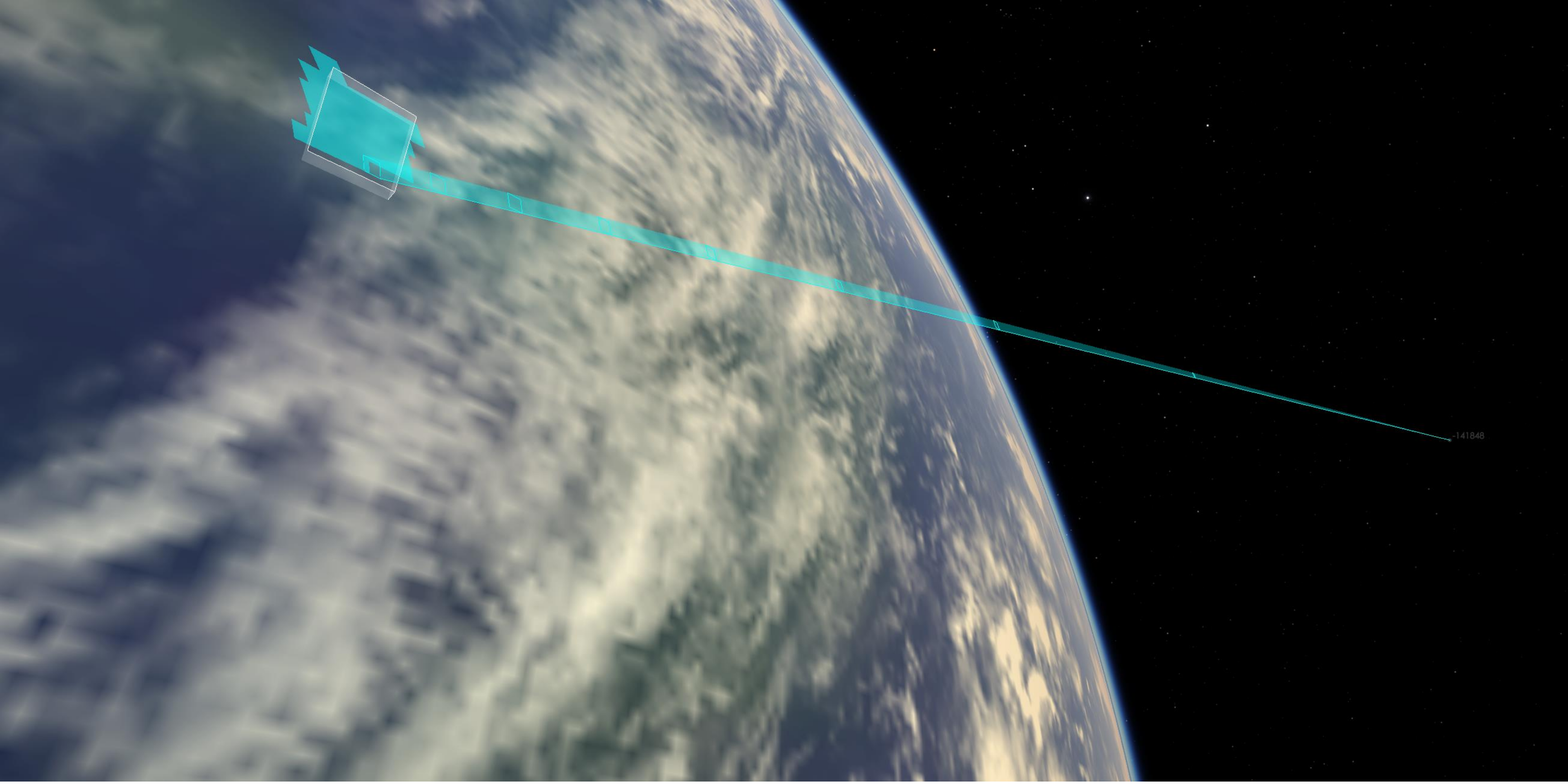


Algorithms for Area Coverage Planning with 3-axis Steerable, 2D Framing Sensors

Elly Shao, Amos Byon, Michael Trowbridge, Russell Knight,
Christopher Davies, Garrett Lewellen
Jet Propulsion Laboratory, California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Motivation

- Earth Observation traditionally uses pushbroom sensors
  - Body-fixed line sensor. Scan by slewing the bus.
  - Examples: PLEIADES (CNES 2014), WorldView (MDA DigitalGlobe 2017), IKONOS (Satellite Imaging Corp. 2017).
  - GOES-R ABI: single line sensor with 2 scanning mirrors (Griffith et al. 2011)
- 2D framing instruments have already replaced pushbroom sensors in the low-cost segment
  - ISERV: ISS telescope w/digital camera (Howell 2011)
  - ALL-STAR/THEIA: 3U CubeSat (Ellison et al. 2013)
  - Goliat/CICLOP: 1U CubeSat (Balan and Piso 2008)
  - Planet Labs Flock: 149x 3U CubeSat constellation
- Many 2D framing instruments don't have path planning problems
  - Proposed GEOCAPE Filter Radiometer: from Geostationary orbit, the scene is relatively static (Frank, Do and Tran 2016), angular distances are small
  - MRO MARCI camera: body-fixed, does not drive bus pointing (Bell, J.F. et al. 2009).
  - Exception: space telescopes

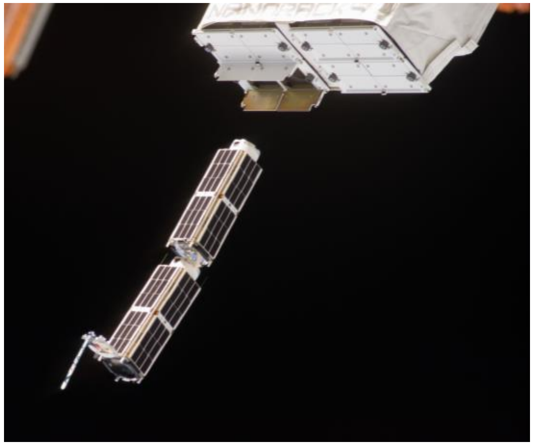


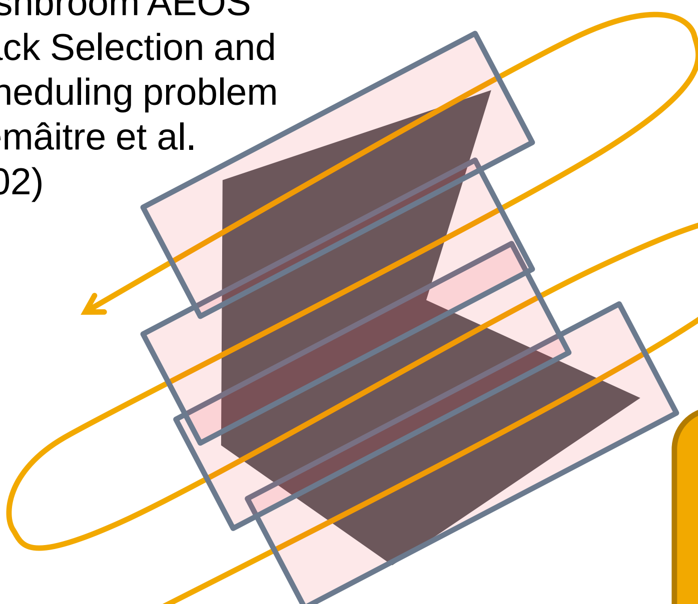
Image credit: NASA

Can I use a pushbroom algorithm for a framer? Yes, but…

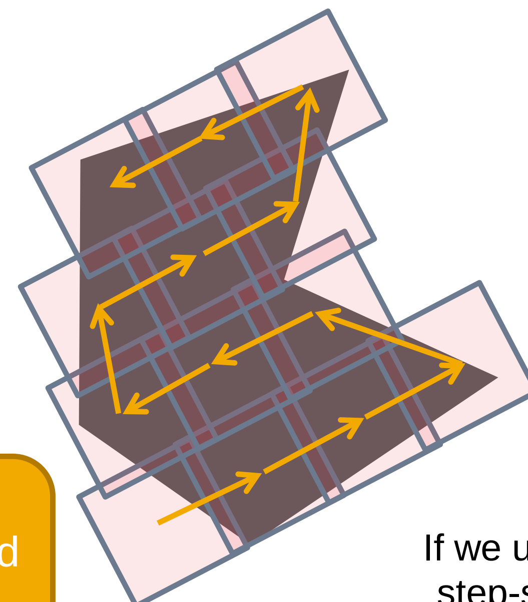
How are framing instruments different?

	Pushbroom (1D)	Framer (2D)
Smear	Cross-boresight smear is part of the sensor, algorithm	Cross-boresight smear reduces image quality
Pixels to read	p: fast read→fast scan	p^2: slow read→slow scan

Pushbroom AEOS Track Selection and Scheduling problem (Lemâitre et al. 2002)



Sub-optimality: pushbrooms need turnarounds; framers don't

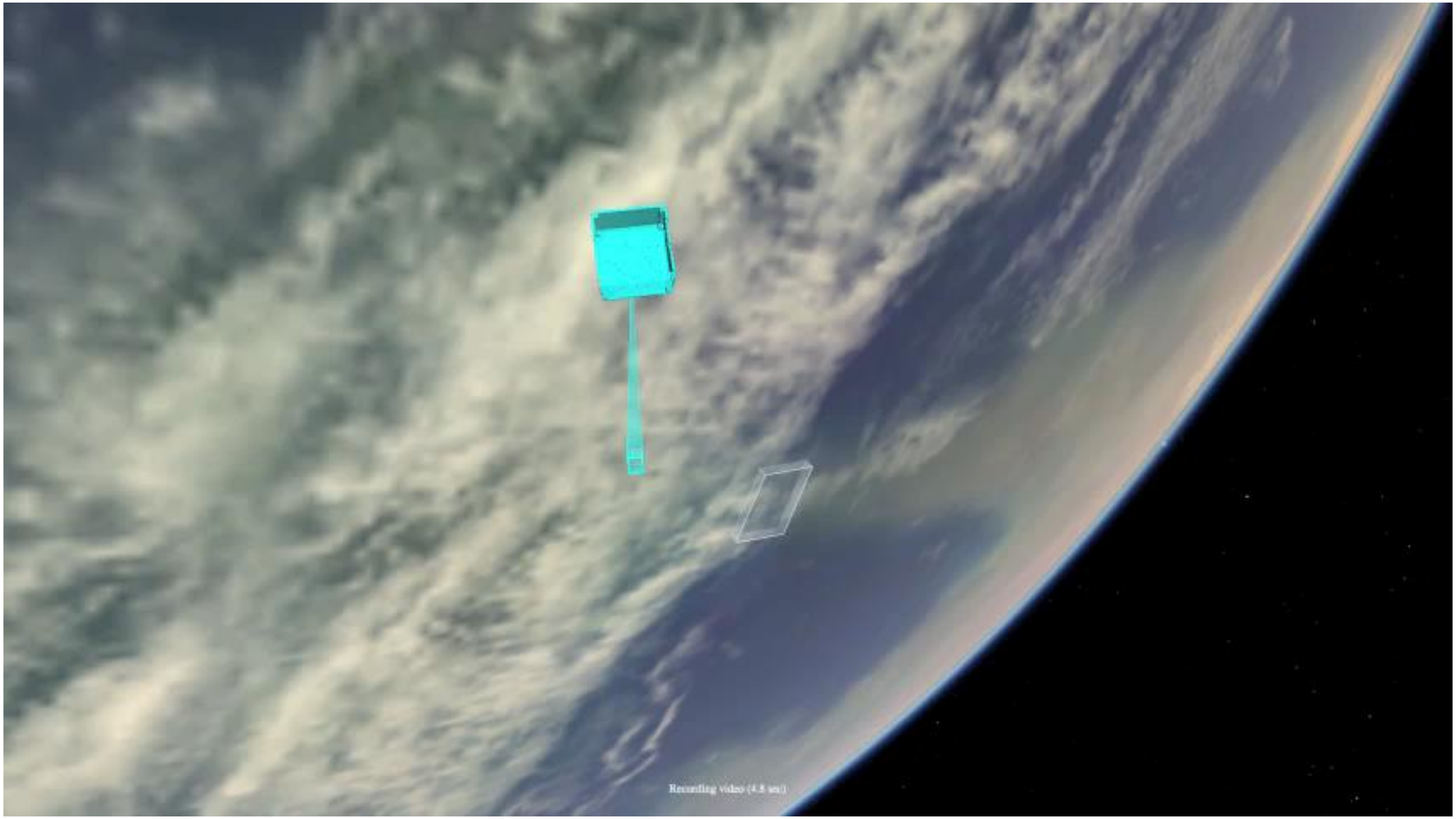


If we use a step-stare tiling concept

Problem overview

- Given
  - Space-based, 3-axis steerable framing sensor
  - Target polygons on the body being orbited
  - Agility model
  - Orbit/ephemeris data of the body, observer
  - Target, visibility, and spacecraft constraints
- Find a sequence of staring targets that covers the entire target area in the shortest time, subject to constraints.

Naïve Approach



State of the Art

Prior work	Planning Approach
Agile Earth Observing Satellite (PLEIADES) scheduling (Lemâitre et al. 2002)	Strip-based Boustrophedon decomposition (Choset and Pignon 1998). Continuously slewing pushbroom sensor.
ISERV (Howell 2011)	Ground-commanded, human-in-the-loop with computer visibility computations. Opportunistic responses to SERVIR tasking hubs.
Proposed: Eagle Eye ISS Telescope (Knight, Donellan and Green 2013)	Points only. No area algorithms published.
Planet Labs Flock (Boshuizen et. al 2014)	Don't. Launch many CubeSats and image continuously at nadir, 1 Hz.
Proposed: Mission to Understand Ice Retreat (Knight, 2014)	Polygons rasterized using flood-fill, then subdivided into even grid-graphs. Concentric ring tours inspired by lawn mower and milling approximation algorithms.

Assumptions

- Agile enough to track point
- Treat target visibility as atomic
  - Don’t need to think in terms of swaths
  - Target can be discretized into multiple tiles
- Overflight long enough to image multiple tiles

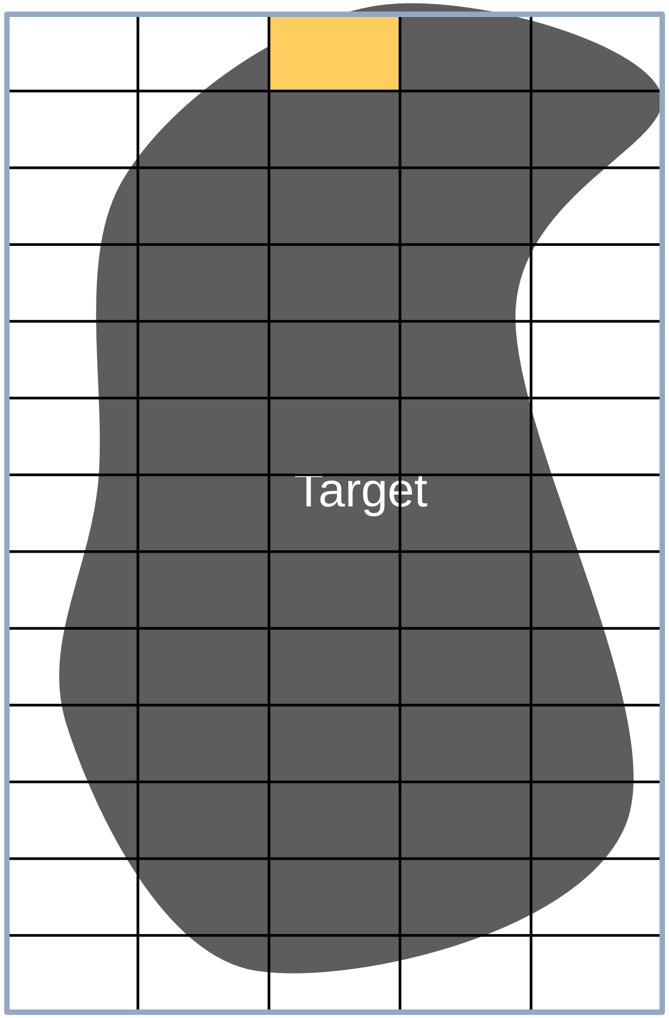
Higher level scheduling concerns

- Exact cost is a function of many things
  - Quality of the path planned
  - Geometry at schedule time
- How to define “visible?”
  - **Any part of the target visible? (optimistic)**
    - Uncertainty: where to start?
  - All parts of the target visible? (pessimistic)
    - Missed opportunities at schedule time
  - Only the unsatisfied parts? (slow to compute)

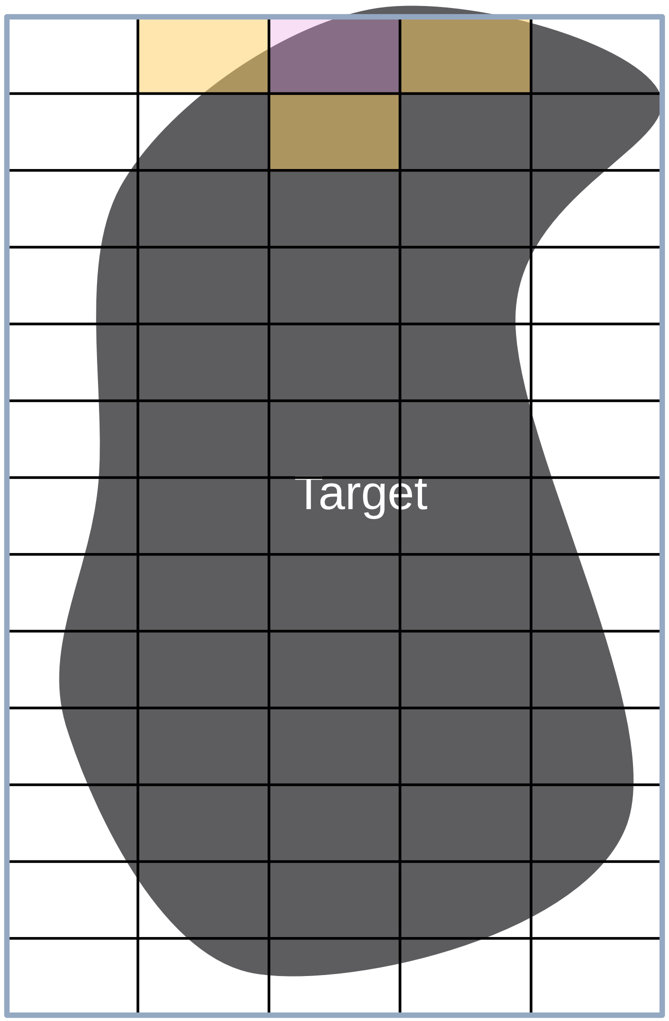
Common terms and approaches

- Freeze time
- Flood Fill
  - Choose instrument space grid origin
  - Add origin to open list
  - For each grid point p in the open list:
    - If p covers some target area, is within bounds and isn't already in a closed list:
      - Add p to closed contained list
      - Add each neighbor that isn't in a closed list to open list
    - Else: add p to closed outside list

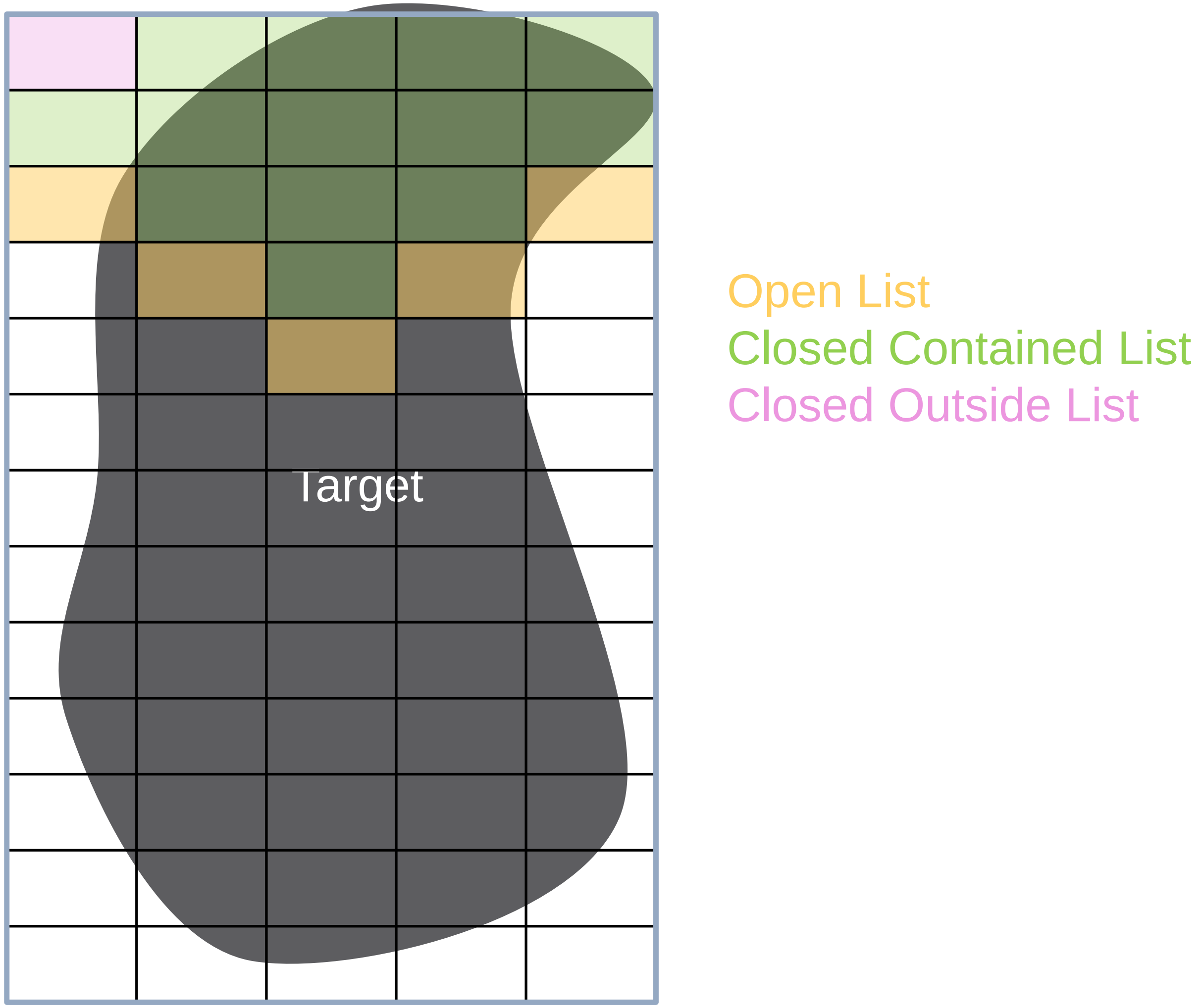
Shani, U. 1980. Filling regions in binary raster images: A graph-theoretic approach. 14:321–327.

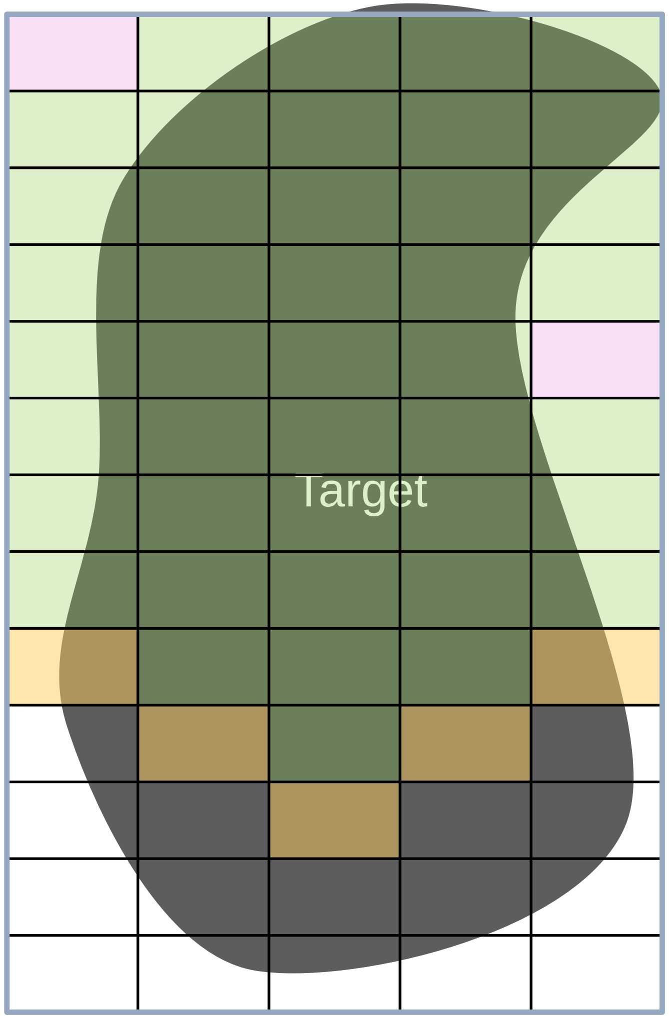


Open List
Closed Contained List
Closed Outside List



Open List
Closed Contained List
Closed Outside List


Target
Open List
Closed Contained List
Closed Outside List



Open List
Closed Contained List
Closed Outside List

Higher level scheduling concerns

- Early: plan gets stale as you execute it
  - Gaps between tiles (slivers)
  - Insufficient overlap between tiles (can't stitch)
- Late: global planning is harder

Table 1: Planning Algorithm Summary. Local scopes are (s)mall or (m)edium.

Algorithm	**TFOVs**	**Scope**
Regular Grid	Early	Global
Sidewinder	Early	Global
Nearest Neighbor	Late	Local (s)
Grid Nibbler (area)	Late	Local (s)
Perimeter Grid Nibbler (dist)	Late	Local (s)
Perimeter Tour	Late	Local (m,s)
Online Frontier Repair	Late	Global

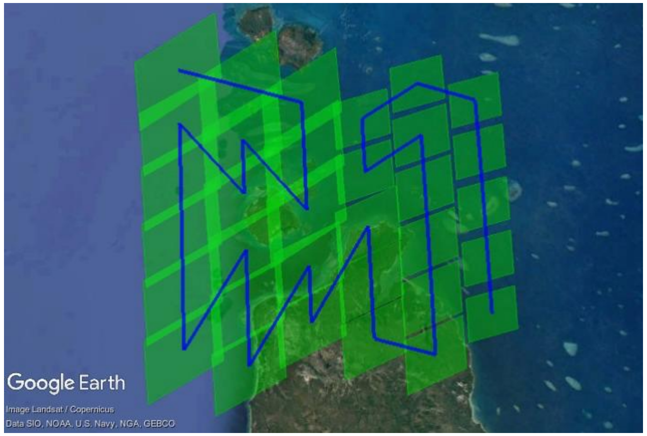
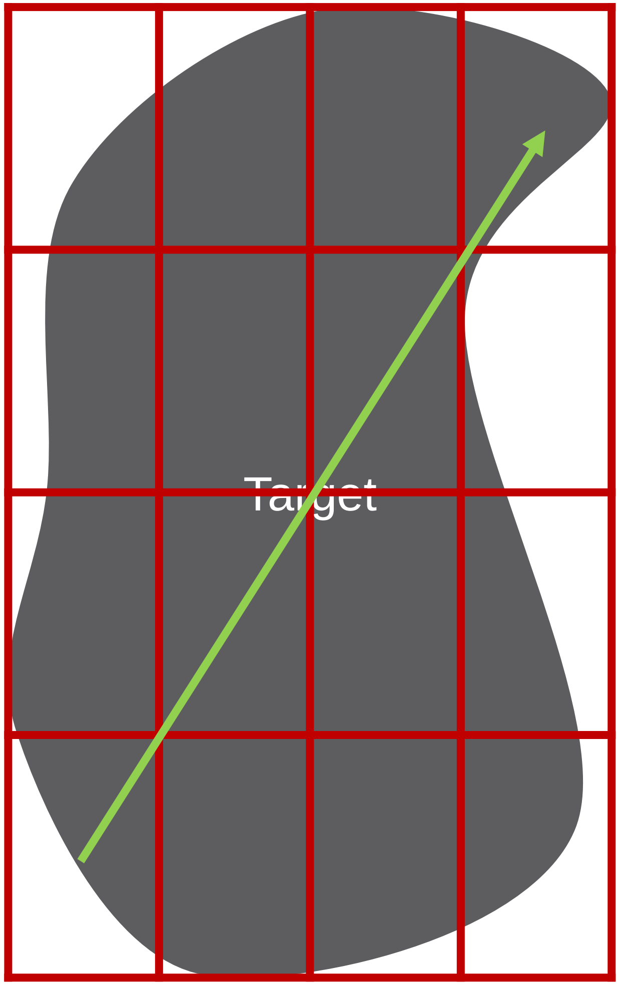


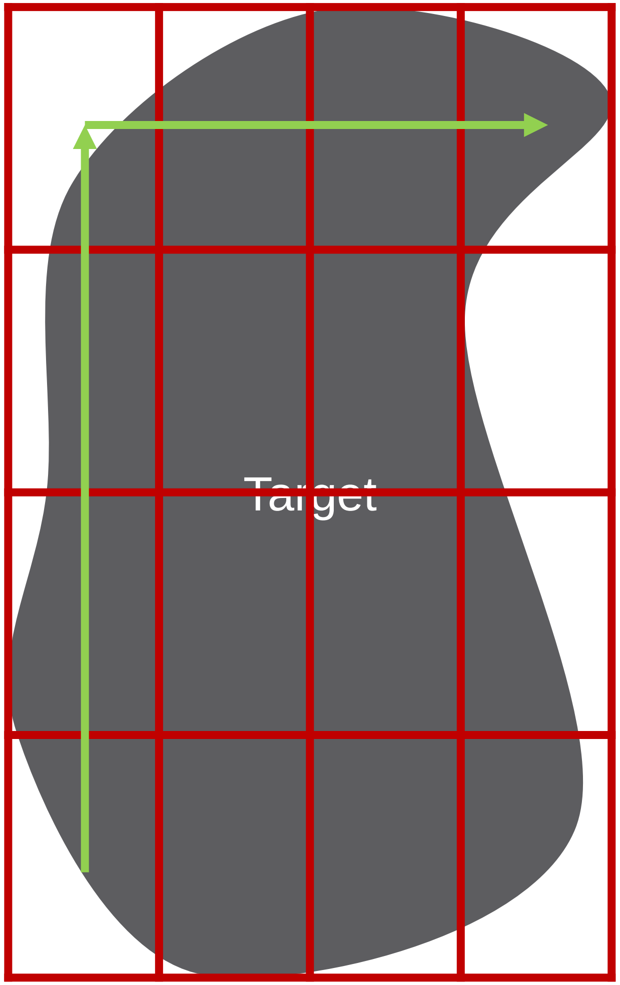
Figure 10: Gaps between tiles in regular grid strategy

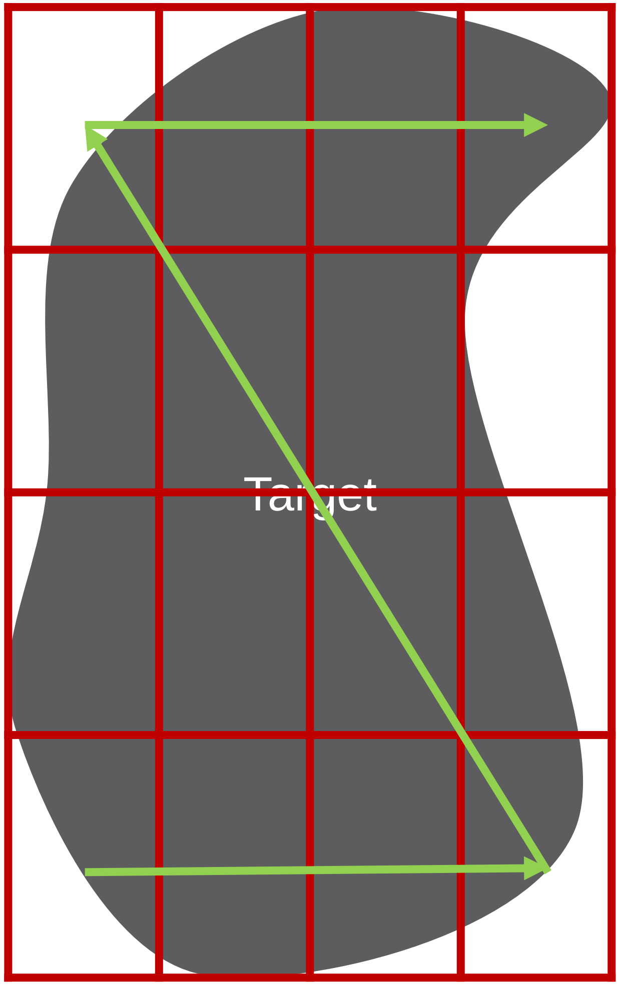
Regular Grid Insert-Furthest

- Flood-fill to discover telescope tiles
  - Freeze at proposed schedule time
- Choose a path through telescope tiles
  - Insert-furthest TSP approximation (Rosenkrantz, Stearns and Lewis 1977)
  - Instantaneous angular separation at observer
- For each telescope tour stop:
  - Schedule tile
  - Subtract satisfied area from target area

Rosenkrantz, D. J.; Stearns, R. E.; and Lewis, II, P. M. 1977. An analysis of several heuristics for the traveling salesman problem. SIAM journal on computing 6(3):563–581.


Target

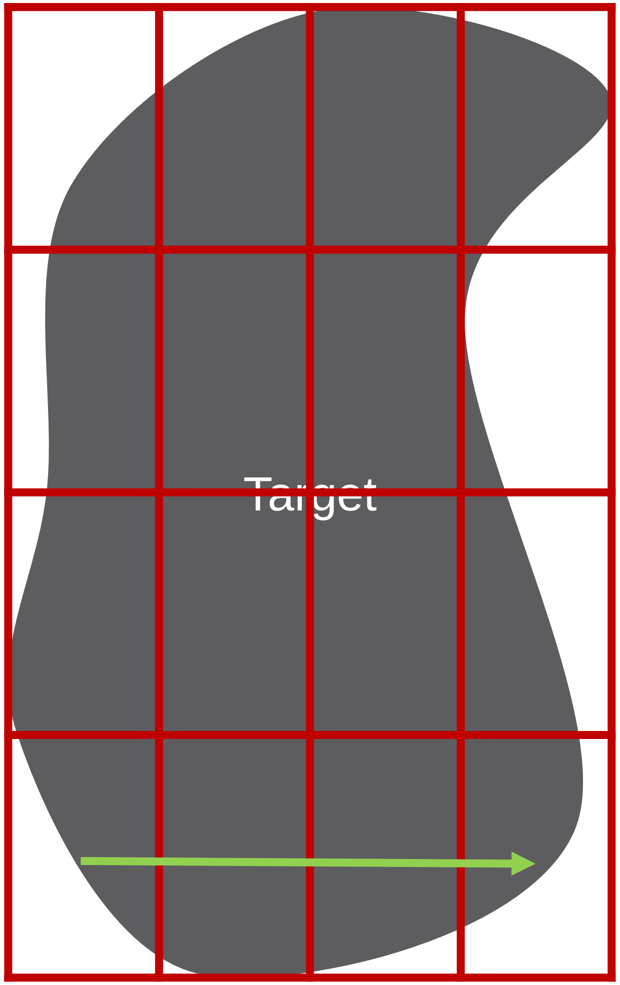

Target

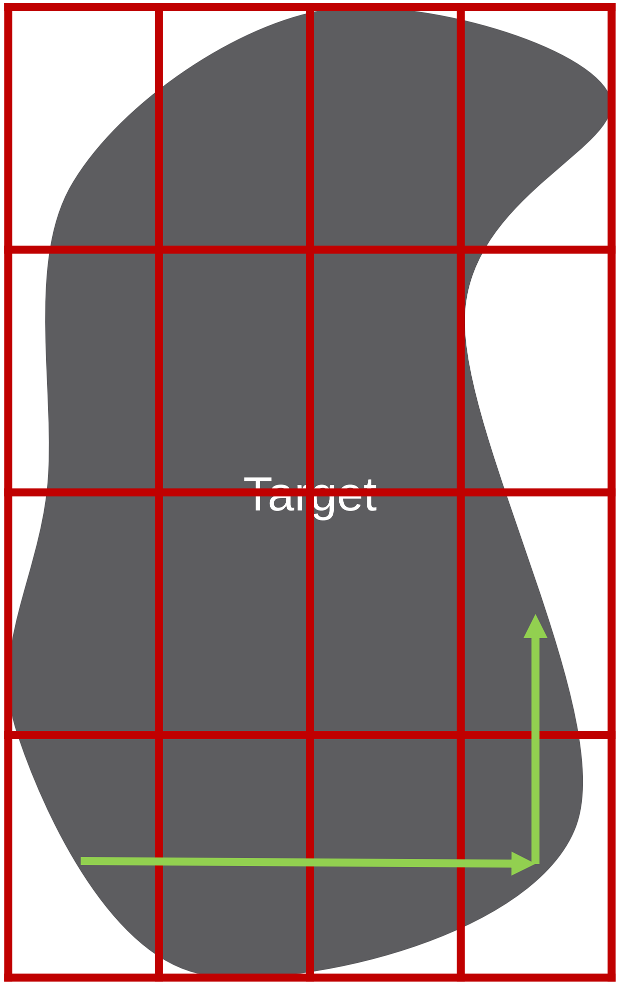

Target

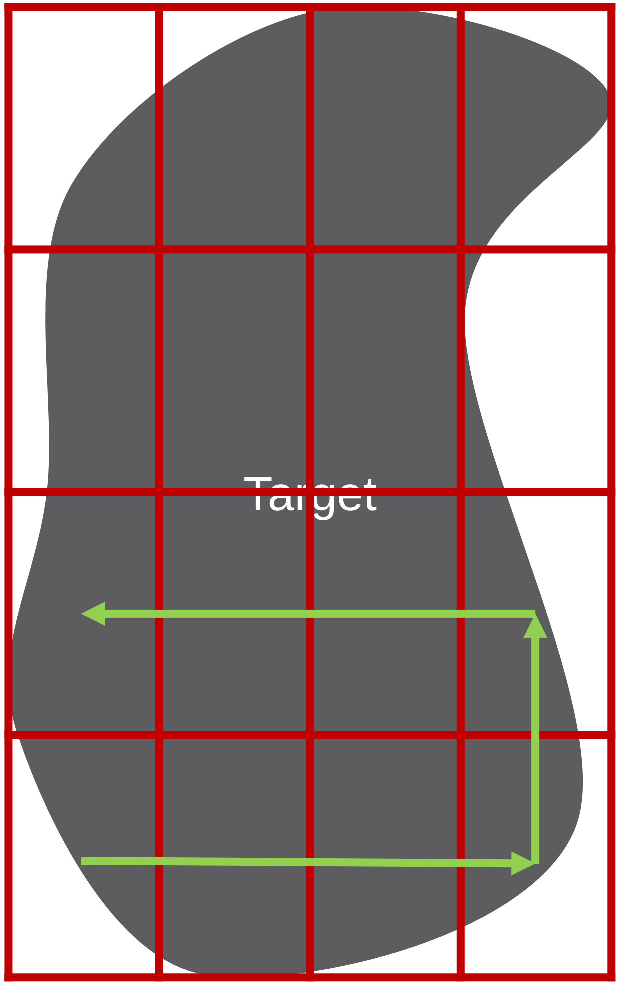
Sidewinder

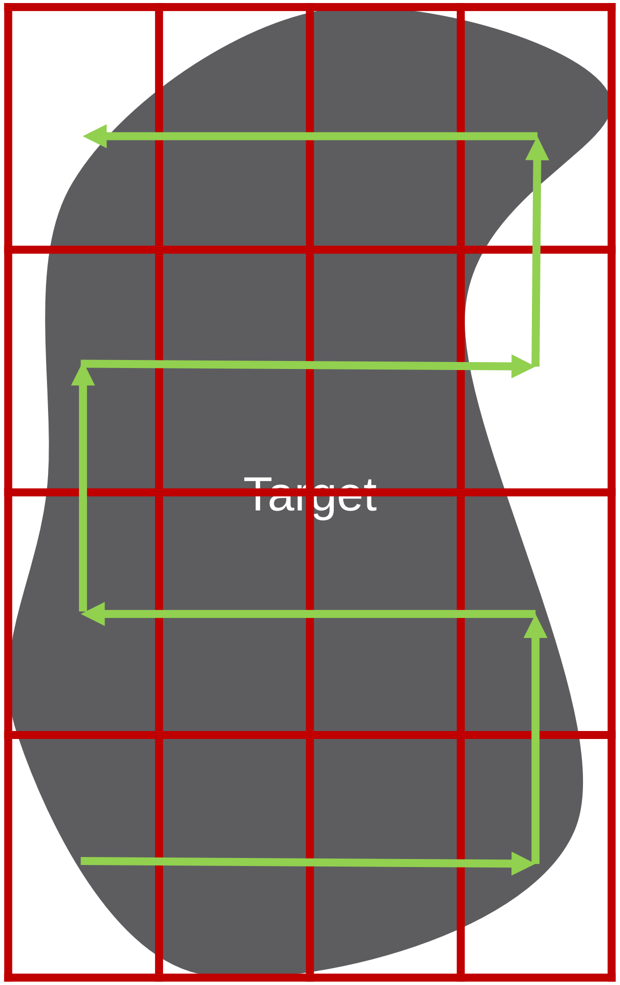
- Pick an initial starting point
  - Closest target point to ground track point or last orientation if available
- Global Grid Planning
  - Freeze time, rasterize entire target area into TFOV tiles
  - Left-to-right alternating rows using ground-based bearings and distances from TFOV tiles
- For each telescope tour stop:
  - Schedule tiles
  - Subtract satisfied area from target area

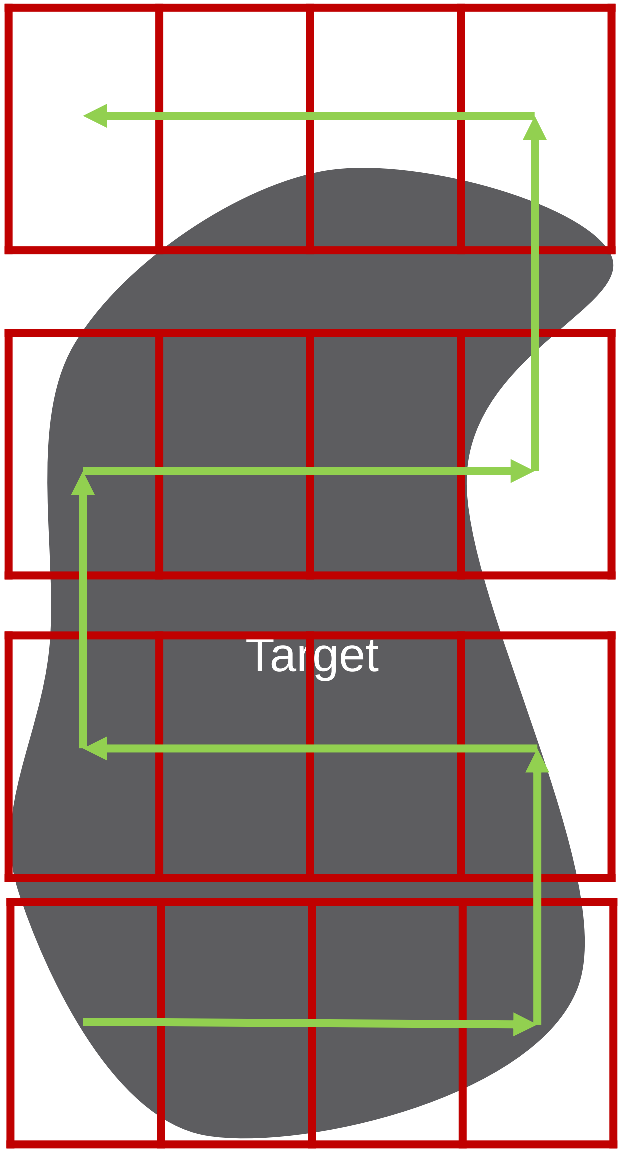
Choset, H., and Pignon, P. 1998. Coverage path planning: the boustrophedon cellular decomposition. In Field and Service Robotics, 203–209. Springer.

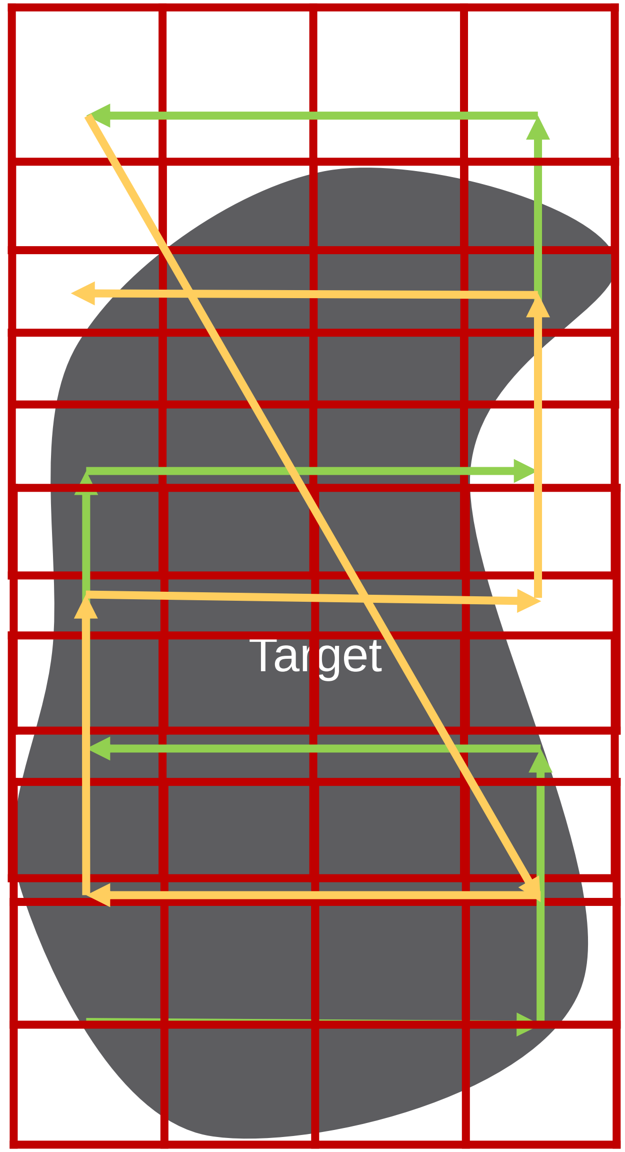

Target


Target


Target


Target

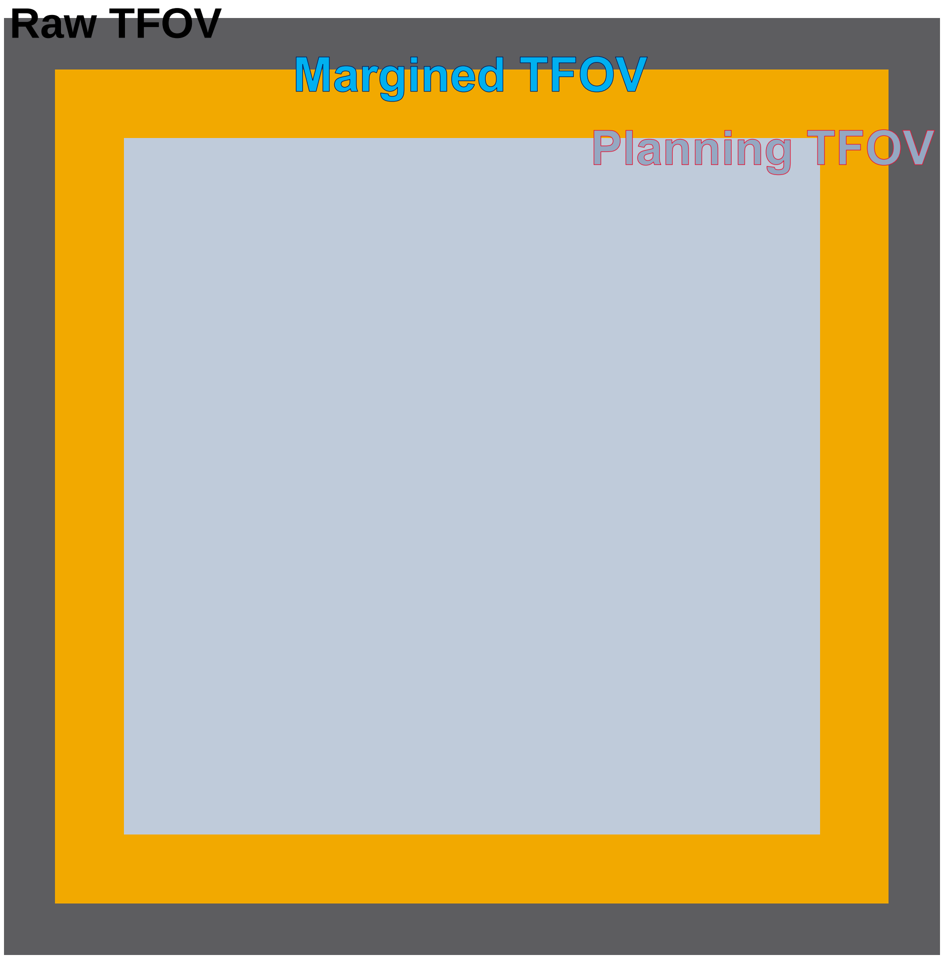

Target


Target

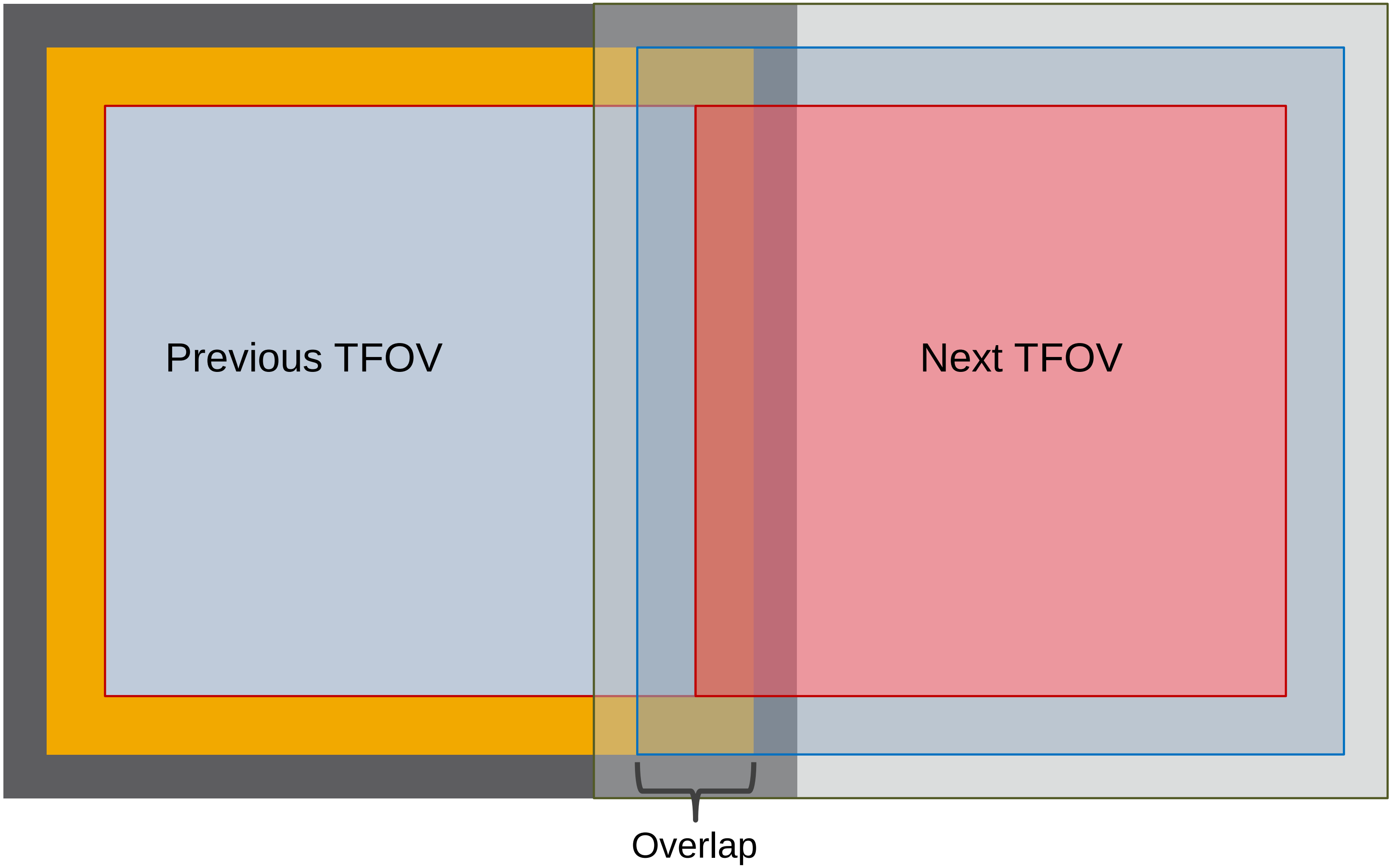
Late Planners

- To prevent slivers between adjacent TFOVs, calculate a planning TFOV based on the margined TFOV
  - Consecutive TFOV centers should be no more than 1 planning TFOV apart

Late Planners



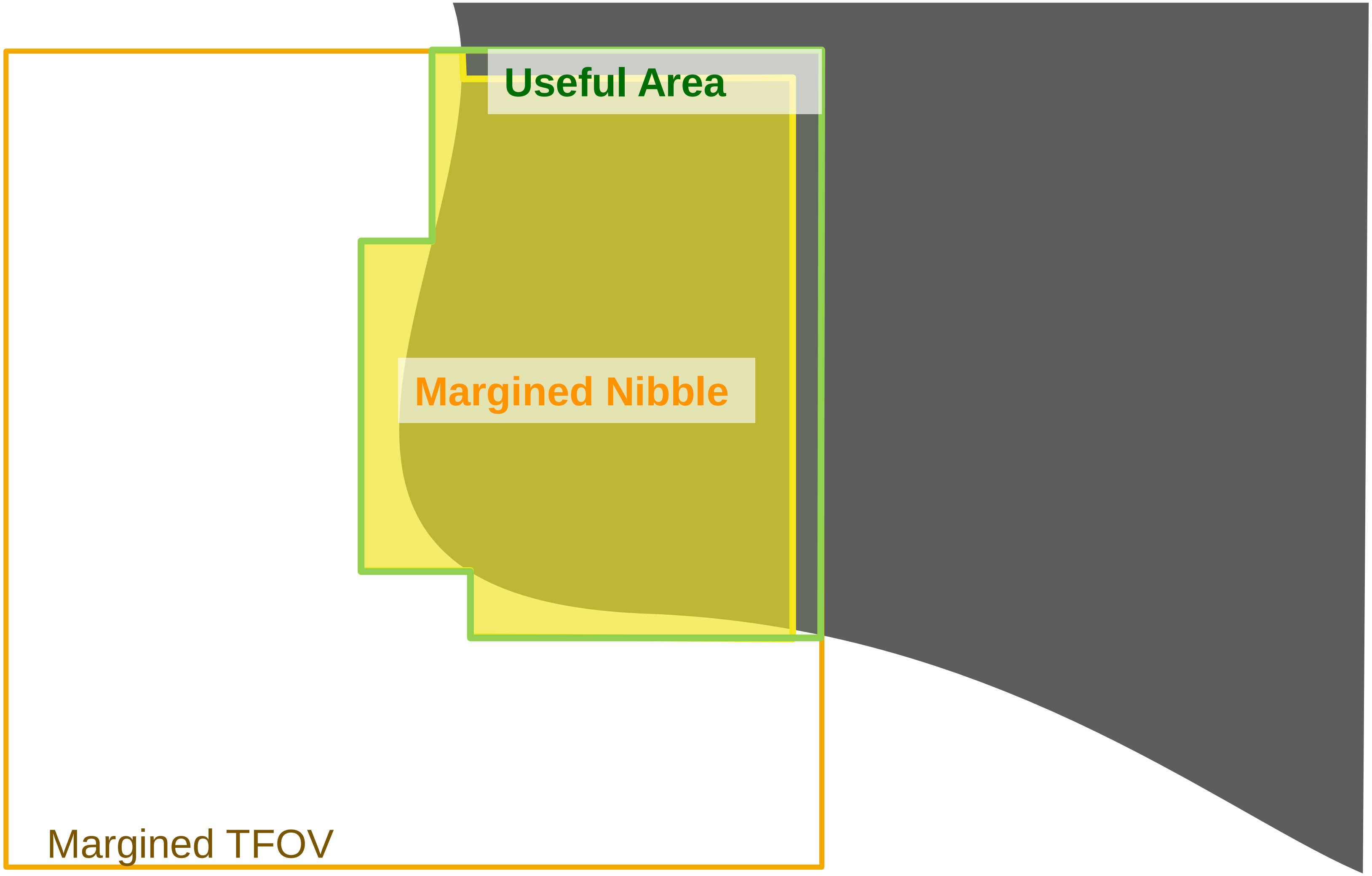
Static TFOV Algorithms



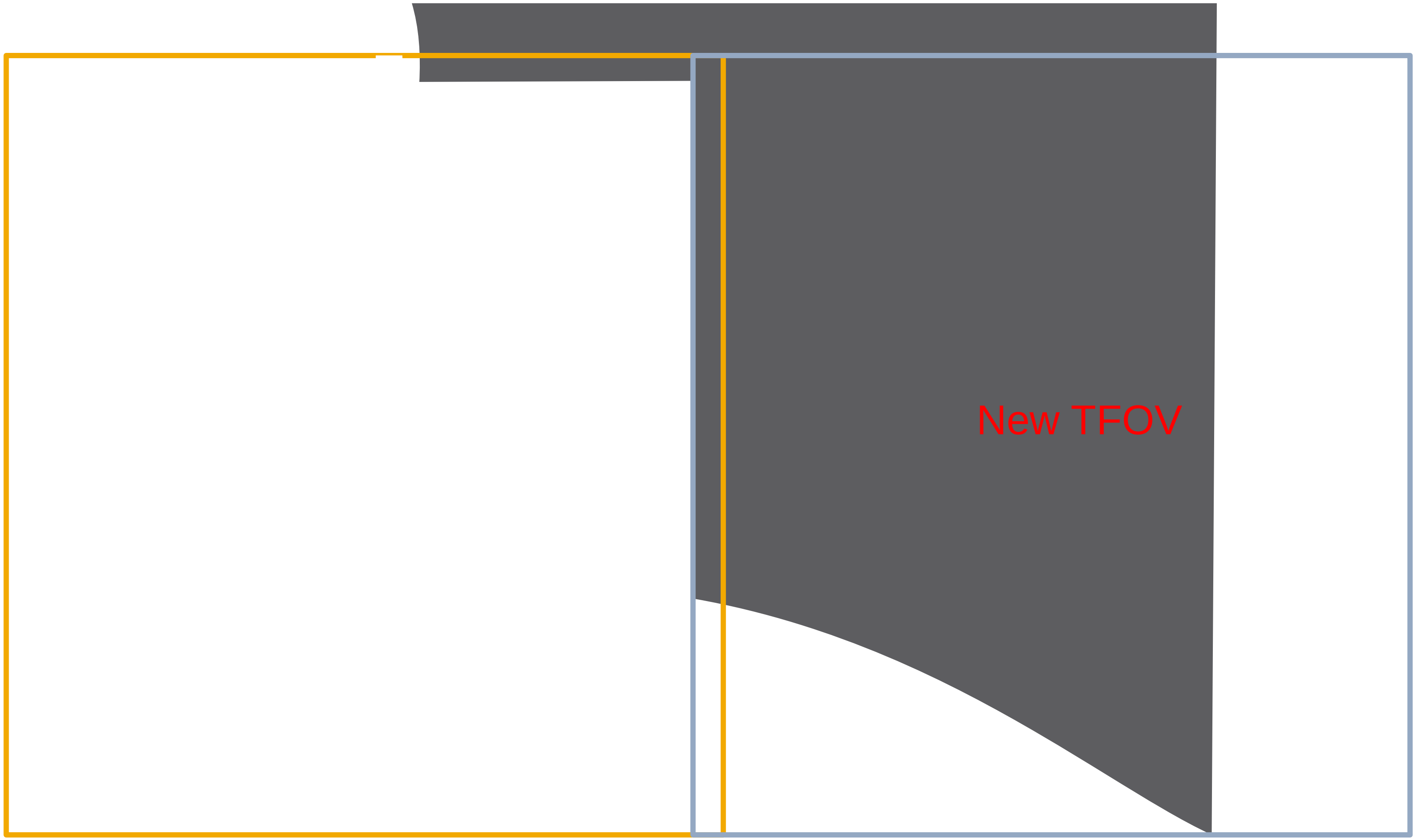
Margined Nibble

- Adjacent tiles must meet some user-specified overlap percentage
  - When nibbling tiles, do not subtract the entire tile coverage area
  - Leave a margin for future tiles to cover

Static TFOV Algorithms



Margined nibble



Nearest Neighbor

- Pick an initial starting point
  - Closest target point to ground track point or last gimbal mount frame vector pointing ground point if available
- Gridless Planning
  - Deduct a TFOV tile from the target set until the set is empty.
  - Use gradient descent to find TFOVs that maximize area and edge length of covered area, with an initial guess of the nearest corner
- For each telescope tour stop:
  - Discover instrument tiles
  - Choose a tour through instrument tiles
  - Schedule instrument tiles
  - Subtract satisfied area from target area

Nearest Neighbor

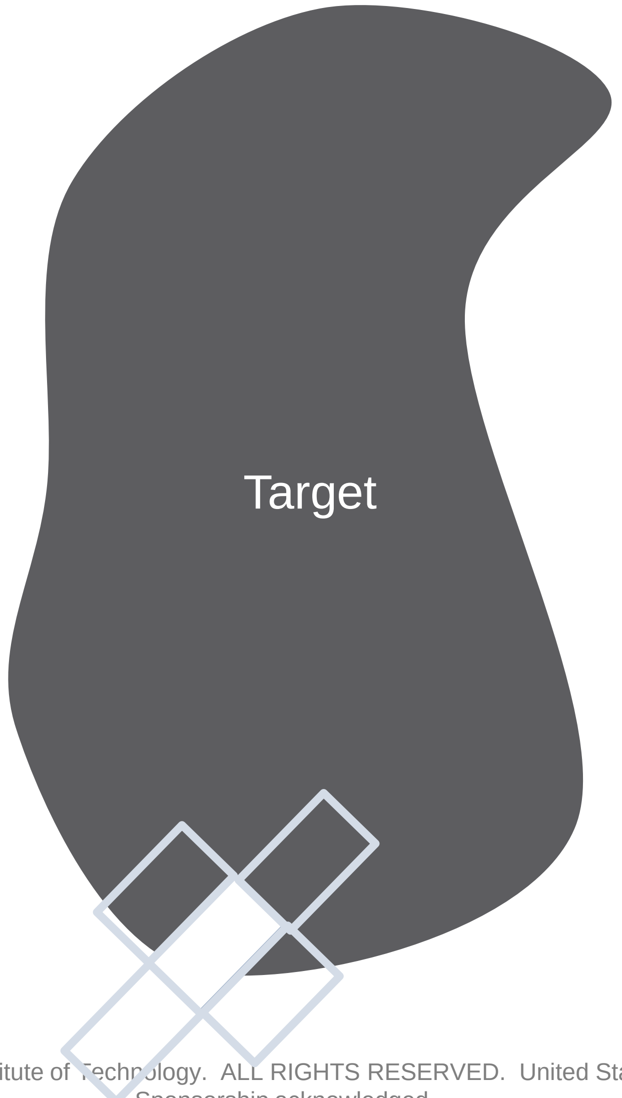
Nearest Neighbor

Nearest Neighbor

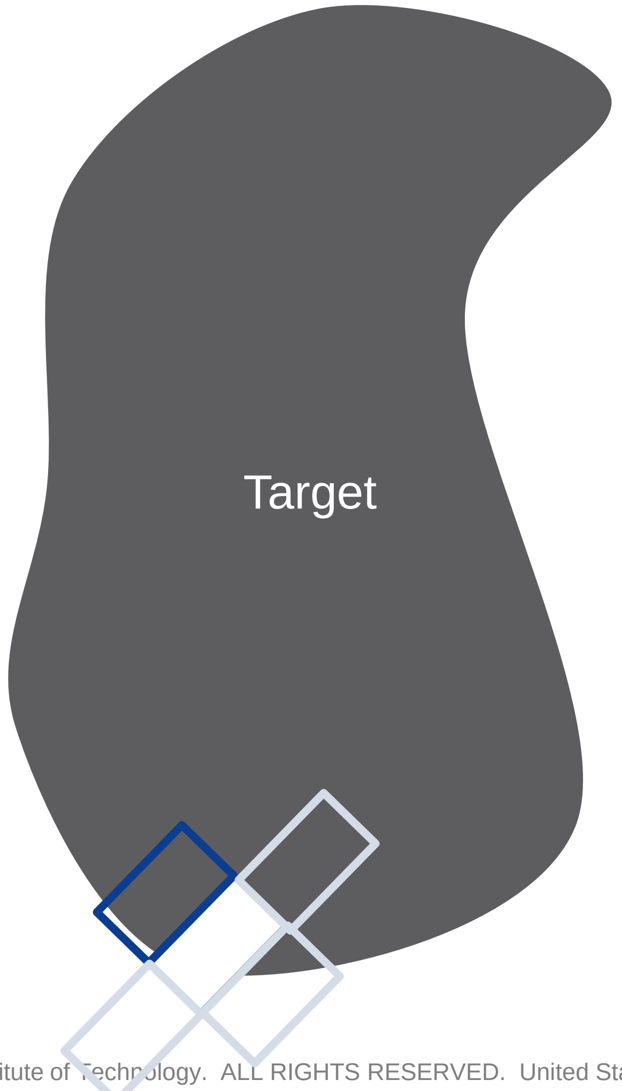
Grid Nibblers

- Local grid planning
  - Like Nearest Neighbor, deduct one tfov at a time
  - Unlike Nearest Neighbor, only consider points one tfov width up, down, left, and right in imager space
    - Score these tfovs, and choose the one with the highest score
    - Remember the direction chosen, to prevent backtracking
  - If none of these candidate tfovs intersect the target area, look at a 3x3 grid of tfovs centered on a nearby corner
- Grid Nibbler: same scoring function as Nearest Neighbor
- Perimeter Grid Nibbler: maximize distance from center of target

Grid Nibblers



Grid Nibblers

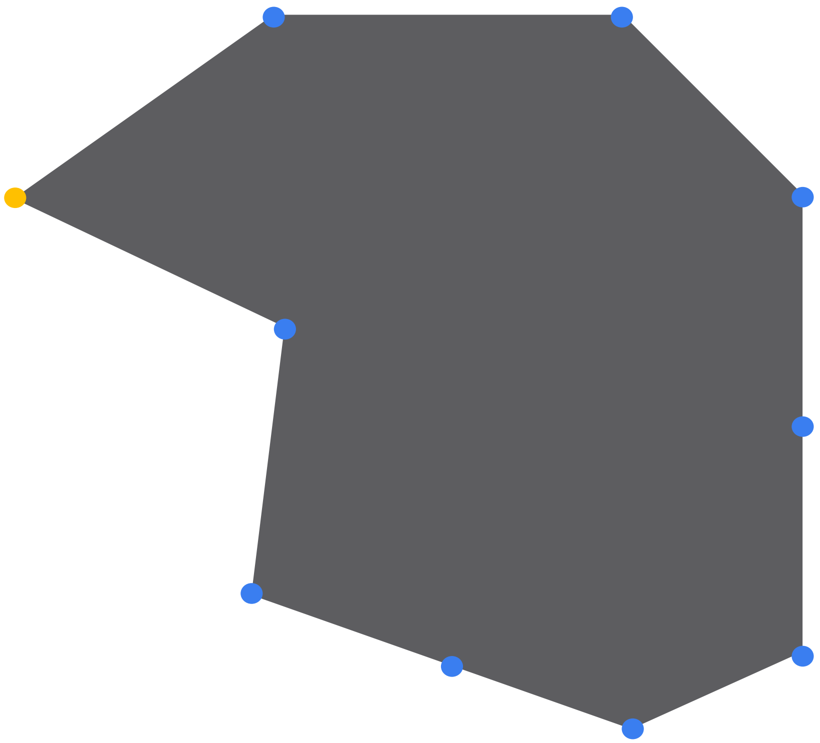


Grid Nibblers

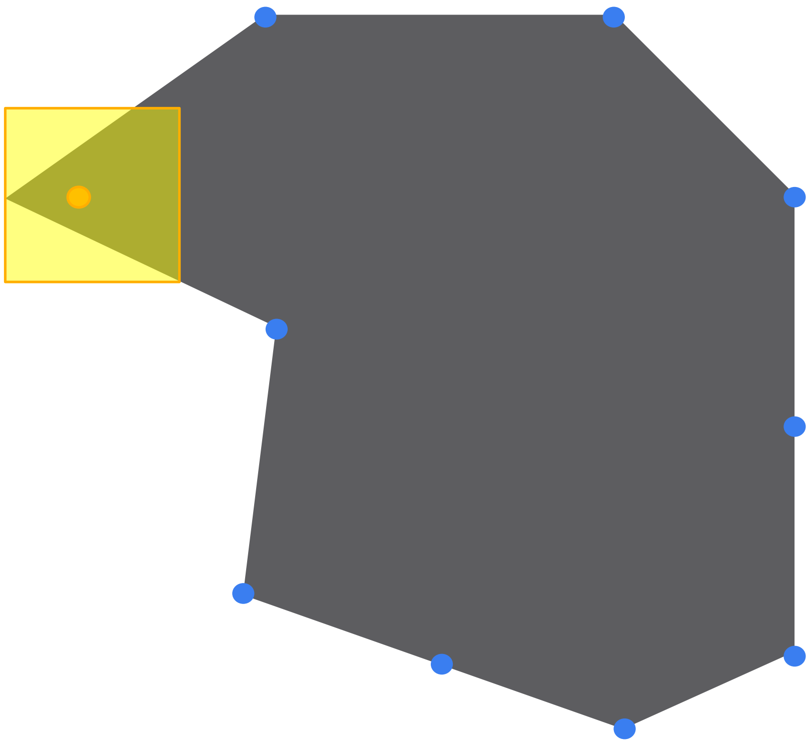
Perimeter Tour

- Place tour points on the target perimeter, starting from the corner closest to the previous pointing
- When the higher-level planner requests the next TFOV center, pop the next point on the precomputed tour, and optimize area coverage using gradient descent
- Once the tour is empty, generate a new tour on the perimeter on the remaining target area

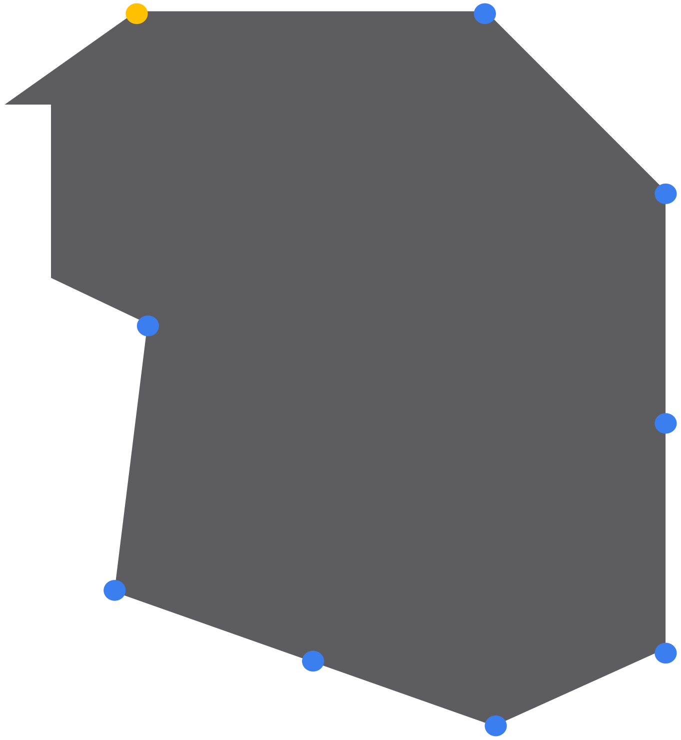
Perimeter Tour



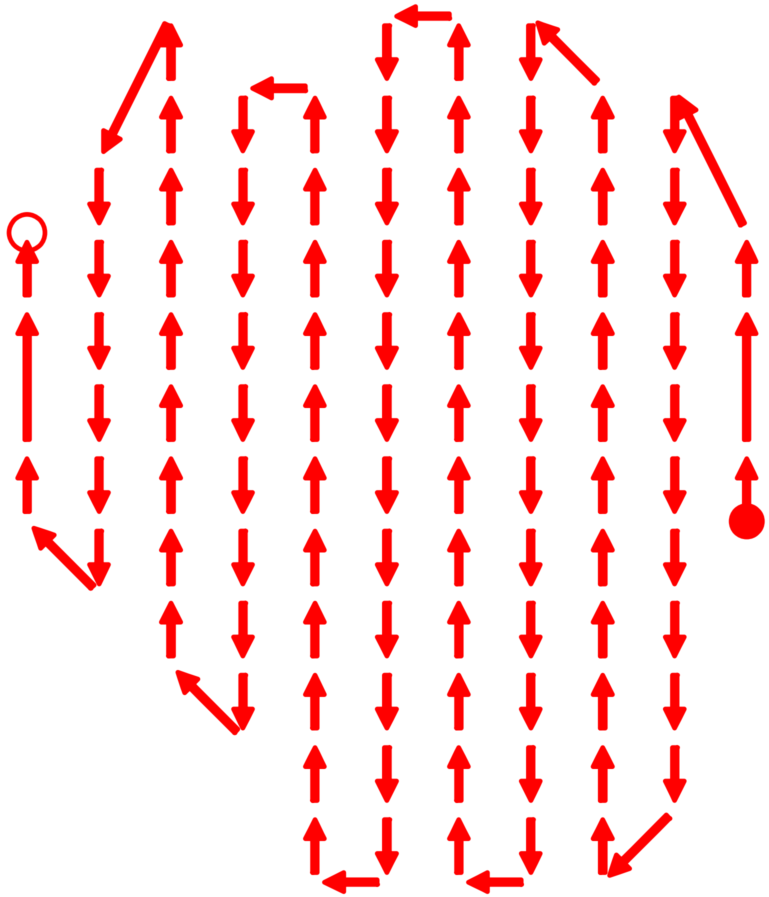
Perimeter Tour



Perimeter Tour

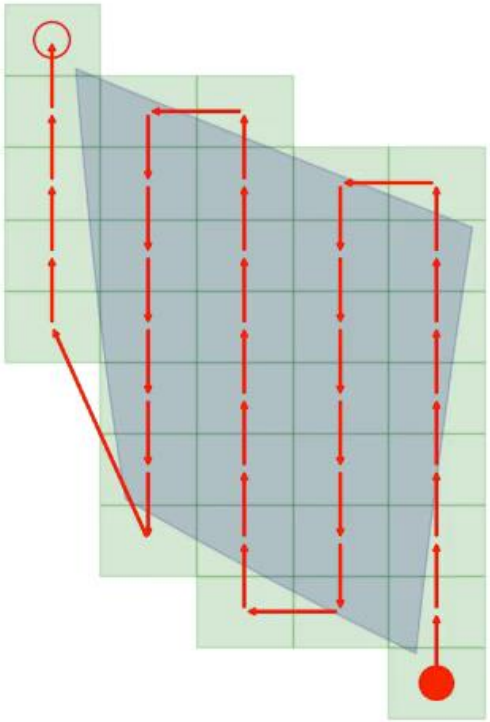


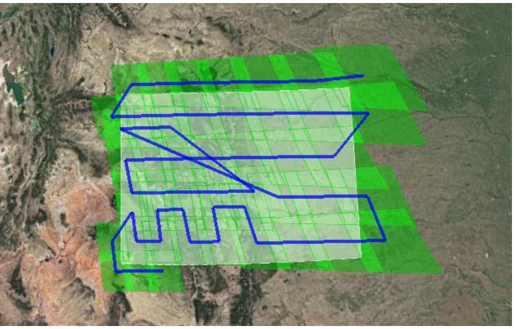
Online Frontier Repair



- Freeze-time flood-fill in telescope space
- Plan (Boustrophedon Choset & Pignon 1998) in telescope space
- While we have tiles:
  - Update tour
    - Reflood frontier
    - Repair tour
  - Pop next tile from tour
    - Convert from telescope space to lat,lon
  - Schedule 1 tile

Online Frontier planning space video



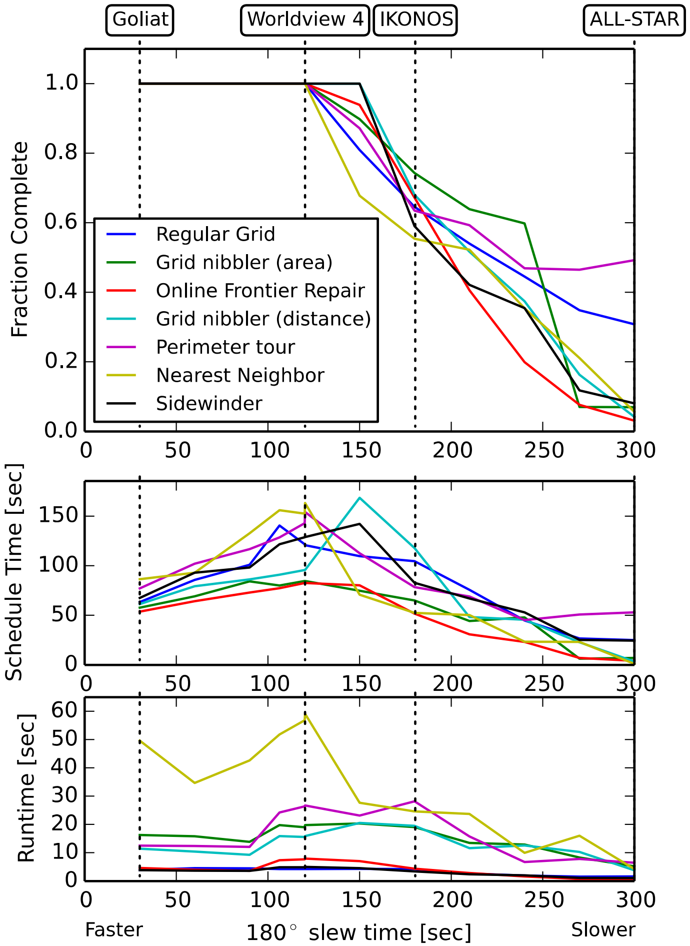


Experiment

- Find out what impact agility has on problem difficulty
  - Fast: Goliat cubesat
  - In between: Worldview-4
  - Slow: ALL-STAR 3U CubeSat
- Fix all orbits at Worldview-4 orbit
  - TLE obtained from Heavens-Above website http://www.heavens-above.com/orbit.aspx?satid=41848
- Use THEIA imagery payload for all cases

Results

Regions of difficulty: Agility Parameter Study



- Phase transition (Cheeseman, Kanefsky and Taylor, 1991) near Worldview 4
- Easy regions:
  - More agile=less constrained
  - Less agile=more constrained

Cheeseman, P. C.; Kanefsky, B.; and Taylor, W. M. 1991. Where the really hard problems are. In IJCAI, volume 1, 331–337.

Agility model sources appear in backup slides.

Experiment

Table 2: Hard and easy case experiment configuration

	Easy	Hard
Agility	Goliat	Worldview-4
Imager	CICLOP	THEIA
Orbit Altitude (km)	354 → 1450	615

Table 3: Imaging Instruments

	CICLOP	**THEIA**
Shape	Rectangular	Rectangular
Horizonatal FOV	5.73°	1°
Vertical FOV	4.26°	1°
Image duration	0.17 s	1.0 s

Figure 6: Target Polygon for Easy Problem Instance

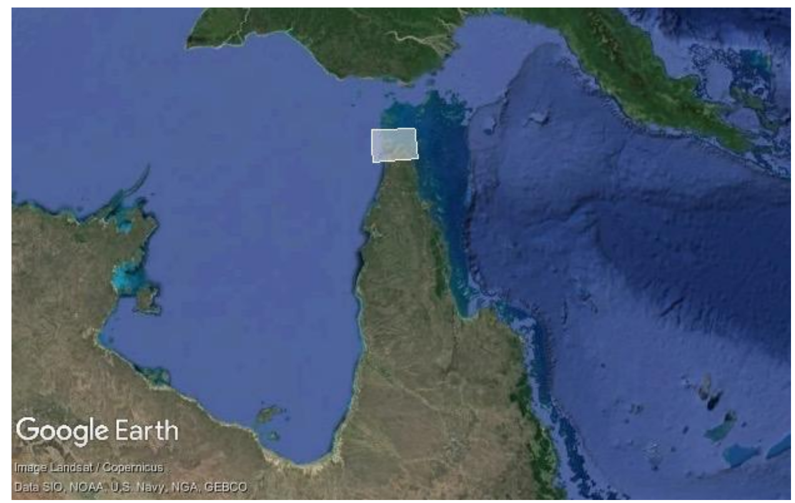


Figure 7: Target Polygon for Hard Problem Instance

Goliat orbit/TLE: Goliat website: http://www.goliat.ro
Worldview-4 orbit: Heavens Above GmbH

CICLOP: Balan and Piso, 2008. THEIA: Ellison et al. 2013. THEIA 1s duration is arbitrary (variable).

Results

Easy and Hard Instances

Table 4: Run and Schedule Times: Goliat (easy)

Algorithm	Run (s)	Schedule (s)
Grid Nibbler (area)	20	76
Sidewinder	3	76
Online Frontier Repair	8	90
Regular Grid	3	91
Perimeter Grid Nibbler (distance)	17	94
Perimeter Tour	22	104
Nearest Neighbor	57	116

Table 5: Run and Schedule Times: WV-4 (hard)

Algorithm	Run (s)	Schedule (s)
Online Frontier Repair	8	83
Grid Nibbler (area)	20	85
Perimeter Grid Nibbler (distance)	16	95
Regular Grid	4	121
Sidewinder	5	129
Perimeter Tour	27	154
Nearest Neighbor	59	163

- Early committers are competitive

- Late committers clearly faster
- Wider span of solution quality

Recommendations for Future Work

- Neighborhood-based planning (Alatartsev, Augustine and Ortmeier 2013) to handle targets that are not all visible within constraints at the same time
- Update milling algorithm implementation, compare to these results
- Investigate impact of backtracking on the local planning algorithms

Conclusions

- In the easy regions (very agile and very slow) of the problem, algorithm choice is less important
- In the hard region, algorithm choice matters
  - Late commitment and global planning strategies performed well
- Recommended algorithms: Online Frontier Repair, Perimeter Grid Nibbler

Acknowledgements

- The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

Sources for agility models

Vehicle	Agility	Source
WorldView-4	200km ground slew in 10.6 sec from 617 km orbit	MDA DigitalGlobe. 2017. WorldView-4 Data Sheet. Web. https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/196/DG2017_WorldView-4_DS.pdf
IKONOS	200km ground slew in 18 sec from 681 km orbit	Hutin, C. 2009. Pleaides meeting with FFG. Web. https://www.ffg.at/getdownload.php?id=3608 Satellite Imaging Corporation. 2017. IKONO Satellite Sensor. Web. https://www.satimagingcorp.com/satellite-sensors/ikonos/
PLEIADES	200km ground slew in 11 sec from 694 km orbit “Roll pitch: 5° in 8 secondes 10° in 10 secondes 60° in 25 secondes”	Hutin, C. 2009. Pleaides meeting with FFG. Web. https://www.ffg.at/getdownload.php?id=3608 Centre National d’Etudes Spatiales (CNES). 2014. Pleaides: In depth: System. Web. https://pleiades.cnes.fr/en/PLEIADES/GP_systeme.htm#orbite

Sources for agility models

Vehicle	Agility	Source
Goliat	180 deg in 30 sec	Balan, M., and Piso, M. 2008. Goliat project overview. In 5th Annual CubeSat Developers' Summer Workshop at the 22nd Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, Utah.
ALL-STAR	180 deg in 300 sec	Ellison, J.; Massone, G.; Ela, N.; Goh, A.; Smith, L.; Sobtzak, J.; Muralidharan, V.; Hayden, I.; Spetzler, B.; Vente, G.; Lopez-Dayer, A.; Montoya, R.; McGehan, Q.; Jeffries, T.; Cook, C.; and Campuzano, B. 2013. All-star system integration review. Web.