RS-EO: The Redstone Project – Earth Observation

Earth Observation Satellite Constellation Mission Design

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SHAPING THE FUTURE OF AEROSPACE

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Contents

I. Mission Design Objective

Object 1: Earth Observation

- Maximize Observability for certain Area for surveillance (Ex: forest fire detection in California Area)
- Observability for two dimensions: Revisit Time Optimization or Ground Area Coverage Time Minimization

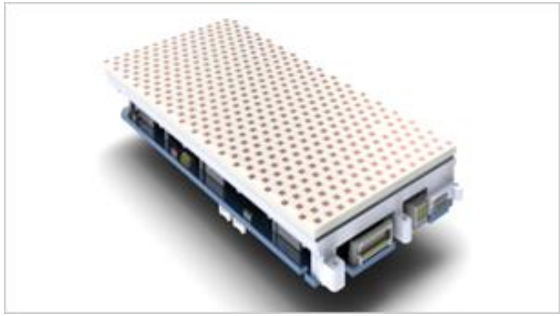
Object 2: Data Transmission

- Minimize Data Transmission Time duration from Imagery Data Acquisition to Ground Station
- Inter-Satellite Link Technology and Data Routing Process Demonstration

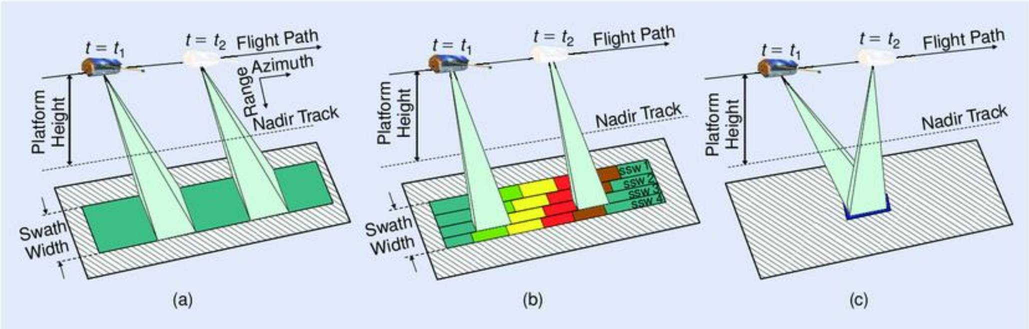
Object 3: Design Autonomous Decision Process for Satellites

- Maximize imagery data generation and minimize the time duration for data transmission

II. Earth Observation Concept Design



Electronically Steerable Antenna



Observation Modes for beam steering by Steerable Phase Array Antenna
(a) Standard – Stripmap (b) Wide Scan mode (C) Video imaging mode

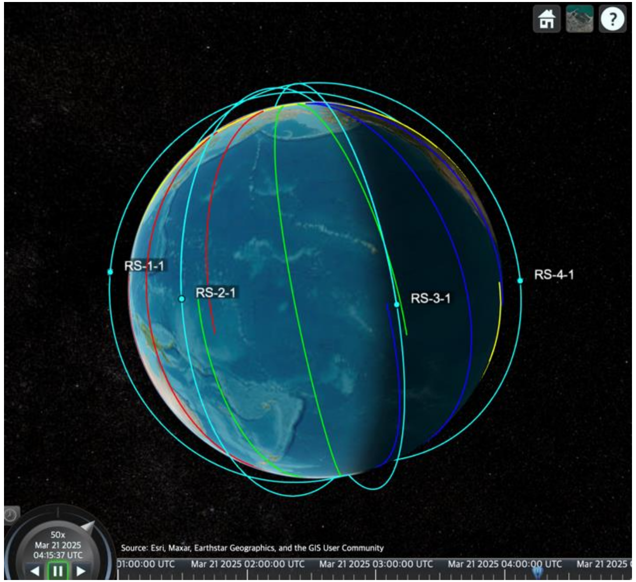
[Characteristic of Earth Observation Payload]

1. The SAR satellite is equipped with electronically beam steerable antenna, which can modify the view angle instead of tilting satellite body.
2. Also, satellite can operate in 3 imaging modes, (a) constant beam tilt angle, (b) moving tilt angle for wide area coverage, and (c) constant area pointing mode for video acquisition.
3. We will concentrate on operation mode (a).

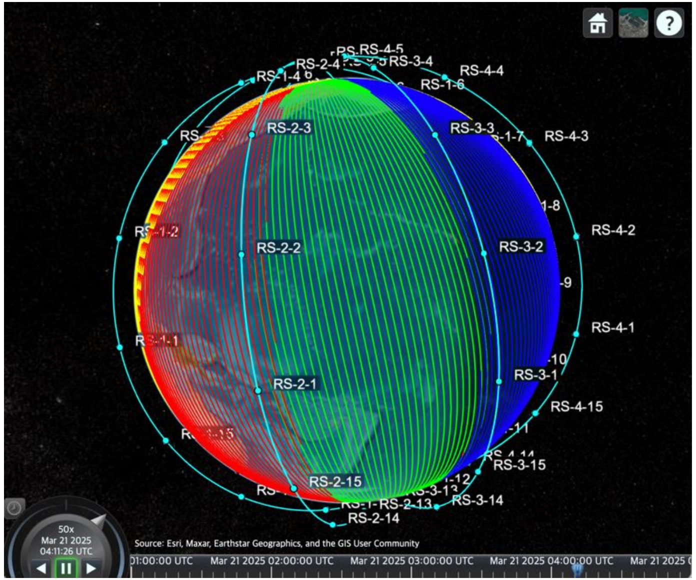
II.1 Why Constellation?

Simulation time: 4 Hours, 4 Orbit Planes: RAAN = {0, 45, 90, 135}

1 Satellite Per Orbit



15 Satellites Per Orbit



[Epoch/Orbit Setting]

```
%Initial Epoch Definition
Year = 2025;
Month = 3;
Day = 21;
Hour = 1;
Minute = 0;
Seconds = 0;

% Duration and Steptime
duration = hours(4);
steptime = 15;
```

```
% Initial Orbit Settings
Altitude = 600;
SMA = Altitude * 1000 + 6378000;
ecc= 1e-5;
inc = 98;
AOP = 0;
number_of_SATs = 15;
TA = 0:360/number_of_SATs:360-360/number_of_SATs;
Orbit_propagator = 'SGP4';
```

- Satellite constellation can achieve ‘Global Coverage’ Observation in shorter time
- In this simulation, theoretically we can observe whole globe every 4 hours revisit time

II.2 Process of Observation

Input:
Ground Target Location
[Latitude/Longitude/Altitude]

Given:
- Satellite Constellation Scenario (60 SATs)
- Elevation Angle Condition (Elevation > 45 deg)
- Satellites Field of View (FOV = 10 deg)

Generated Access Information – Capture Schedule:

Source	Target	StartTime	EndTime	Duration
"RS-3-7"	"Paradise CA"	2025-03-21 02:08:15	2025-03-21 02:09:00	45
"RS-3-8"	"Paradise CA"	2025-03-21 02:01:15	2025-03-21 02:03:00	105
"RS-3-9"	"Paradise CA"	2025-03-21 01:54:45	2025-03-21 01:57:00	135
"RS-3-10"	"Paradise CA"	2025-03-21 01:48:15	2025-03-21 01:50:30	135
"RS-3-11"	"Paradise CA"	2025-03-21 01:42:00	2025-03-21 01:44:15	135
"RS-3-12"	"Paradise CA"	2025-03-21 01:35:45	2025-03-21 01:37:45	120
"RS-3-13"	"Paradise CA"	2025-03-21 01:29:30	2025-03-21 01:31:15	105
"RS-3-14"	"Paradise CA"	2025-03-21 01:23:30	2025-03-21 01:24:30	60

Observation Mode 1:
Wide Area Capture

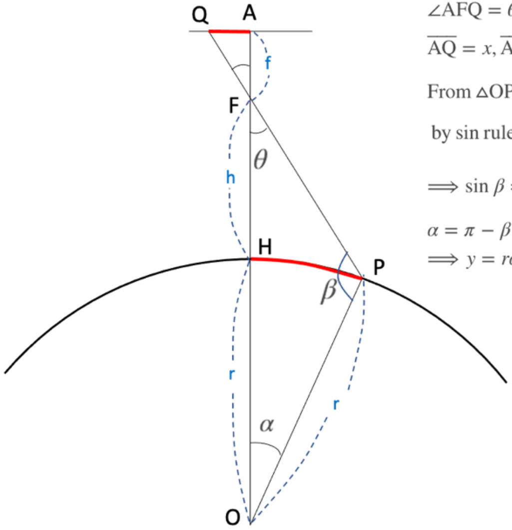
Nadir Pointing:
Roll Angle = 0 deg

Observation Mode 2:
Constant Area Capture

Off Point Tilt Angle:
Roll Angle Modification

II.3 Observation Mode 1: Wide Area Capture [1/2]

- Nadir Pointing
- Calculate Ground Coverage Length for given field of view (FOV) of Satellite



$\angle AFQ = \theta,\ \angle HOP = \alpha,\ \angle OPA = \beta$

$\overline{AQ} = x, \overline{AF} = f,\ \overline{HP} = y = r\alpha,\ \tan\theta = \frac{x}{f}$

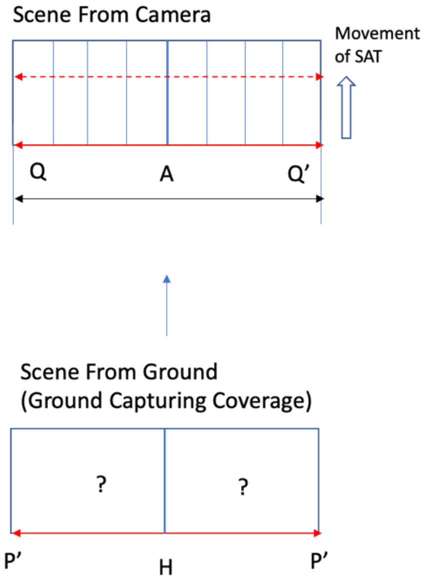
From $\triangle OPH$

by sin rule, $\frac{\overline{OF}}{\sin\beta} = \frac{\overline{OP}}{\sin\theta} \iff \frac{h+r}{\sin\beta} = \frac{r}{\sin\theta}$

$\implies \sin\beta = \frac{h+r}{r}\sin\theta \rightarrow \beta = \sin^{-1}\left(\frac{h+r}{r}\sin\theta\right)$

$\alpha = \pi - \beta - \theta$

$\implies y = r\alpha = r(\pi - \beta - \theta)$



Input

θ : Half of FOV

h : altitude of the satellite

r : radius of Earth

$\vec{r}$, $\vec{v}$ of satellite

$\Rightarrow$ we use $\vec{v}$ for determine direction of $\overrightarrow{HP}$

Assumption : Earth is perfect sphere

Output

Location of H, P, P'

Length of $\overline{P'H} = \overline{PH}, \overline{P'P}$

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and Engineering Mechanics
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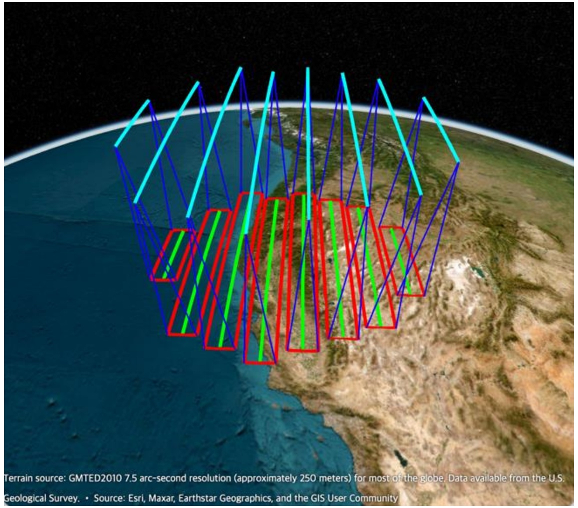
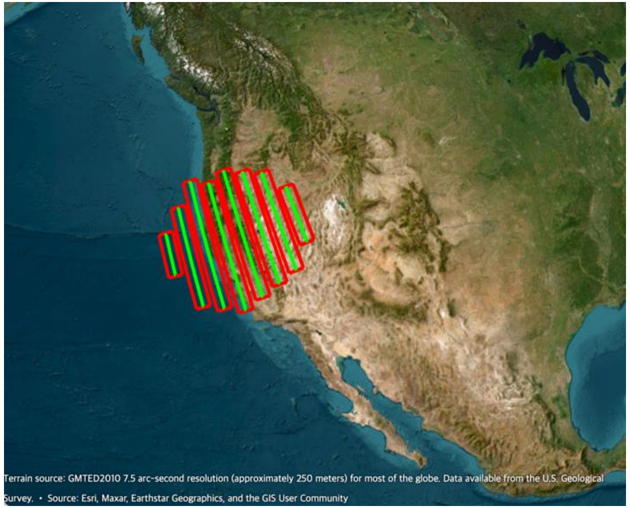
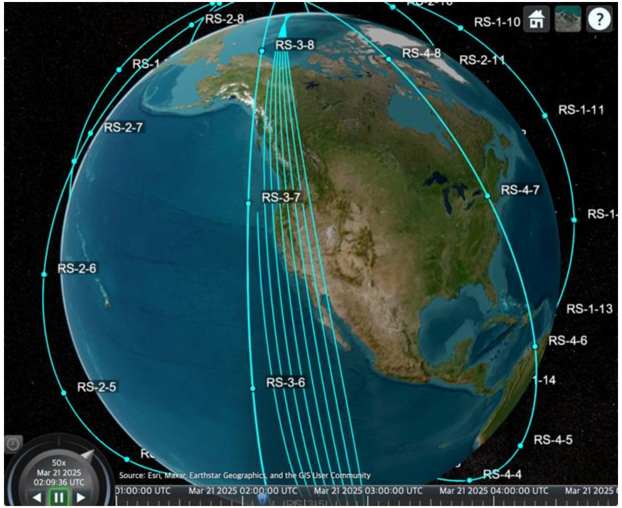
II.3 Observation Mode 1: Wide Area Capture [2/2]








```
ground_target = ["Paradise CA", 39.7596, -121.6219, 542]
elevation_angle_condition = 45;
```

Field of View = 10 degrees

Ground Track of RS-3-7~14

Source	Target	StartTime	EndTime	Duration
"RS-3-7"	"Paradise CA"	2025-03-21 02:08:15	2025-03-21 02:09:00	45
"RS-3-8"	"Paradise CA"	2025-03-21 02:01:15	2025-03-21 02:03:00	105
"RS-3-9"	"Paradise CA"	2025-03-21 01:54:45	2025-03-21 01:57:00	135
"RS-3-10"	"Paradise CA"	2025-03-21 01:48:15	2025-03-21 01:50:30	135
"RS-3-11"	"Paradise CA"	2025-03-21 01:42:00	2025-03-21 01:44:15	135
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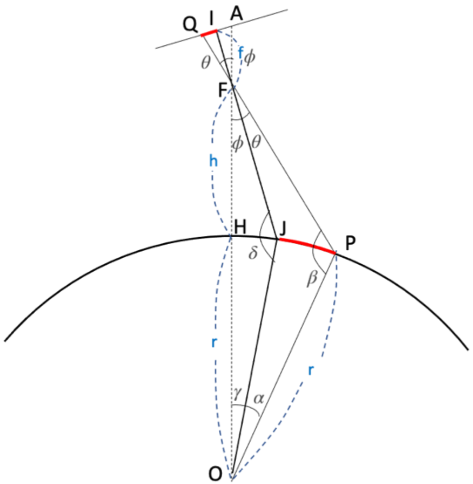
"RS-3-14"	"Paradise CA"	2025-03-21 01:23:30	2025-03-21 01:24:30	60

II.4 Observation Mode 2: Constant Area Capture [1/2]

- Roll Angle Tilt Pointing
- Calculate Ground Coverage Length for given field of view (FOV) of Satellite



$\angle \mathrm{AFI} = \phi$ (Tilted Angle), $\angle \mathrm{IFQ} = \theta$, $\angle \mathrm{POJ} = \alpha$, $\angle \mathrm{OPF} = \beta$, $\angle \mathrm{HOJ} = \gamma$, $\angle \mathrm{OJF} = \delta$

$\overline{\mathrm{FI}} = f$, $\overline{\mathrm{FH}} = h$, $\tan\theta = \frac{x}{f}$, $\overline{\mathrm{AF}} = \frac{\overline{\mathrm{IF}}}{\cos\phi}$ $\overline{\mathrm{PJ}} = y$

1) $\overline{\mathrm{PH}}$

From $\Delta\mathrm{FOP} \Rightarrow \angle \mathrm{HFP} = \theta + \phi$, $\overline{\mathrm{FO}} = h + r$, $\overline{\mathrm{PO}} = r$

$$\frac{r}{\sin(\theta+\phi)} = \frac{h+r}{\sin\beta} \Rightarrow \sin\beta = \frac{h+r}{r}\sin(\theta+\phi)$$

$$\beta = \sin^{-1}\left\{\frac{h+r}{r}\sin(\theta+\phi)\right\},\ \gamma + \alpha = \pi - \beta - \theta - \phi$$

2) $\overline{\mathrm{HJ}}$

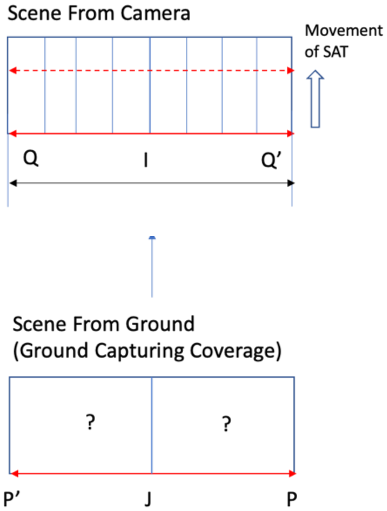
From $\Delta\mathrm{FOJ} \Rightarrow \angle \mathrm{HFJ} = \phi$, $\overline{\mathrm{FO}} = h + r$, $\overline{\mathrm{JO}} = r$

$$\frac{r}{\sin\phi} = \frac{h+r}{\sin\delta} \Rightarrow \sin\delta = \frac{h+r}{r}\sin\phi$$

$$\delta = \sin^{-1}\left\{\frac{h+r}{r}\sin\phi\right\},\ \gamma = \pi - \phi - \delta$$

$$\Longrightarrow \alpha = (\pi - \beta - \theta - \phi) - (\pi - \phi - \delta) = \delta - \beta - \theta$$

$$\overline{\mathrm{PJ}} = r\alpha = r(\delta - \beta - \theta)$$



Input

θ : Half of FOV

ϕ : Satellite off point Roll Angle

h : altitude of the satellite

r : radius of Earth

$\vec{r}$, $\vec{v}$ of satellite

$\Rightarrow$ we use $\vec{v}$ for determine direction of $\overrightarrow{JP}$

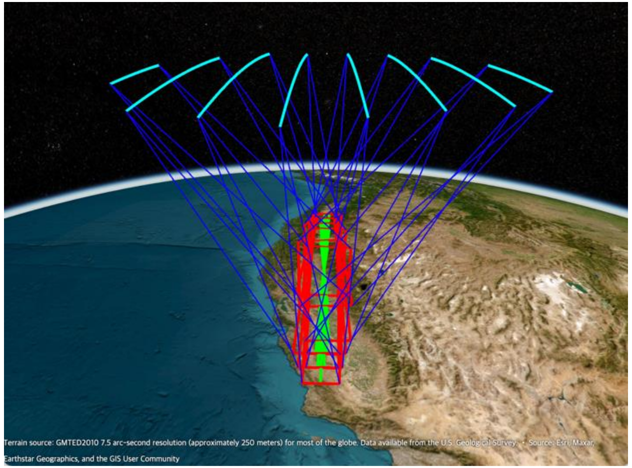
Assumption : Earth is perfect sphere

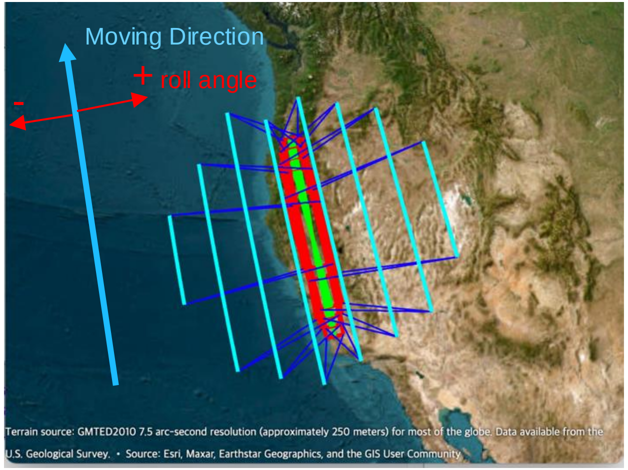
Output

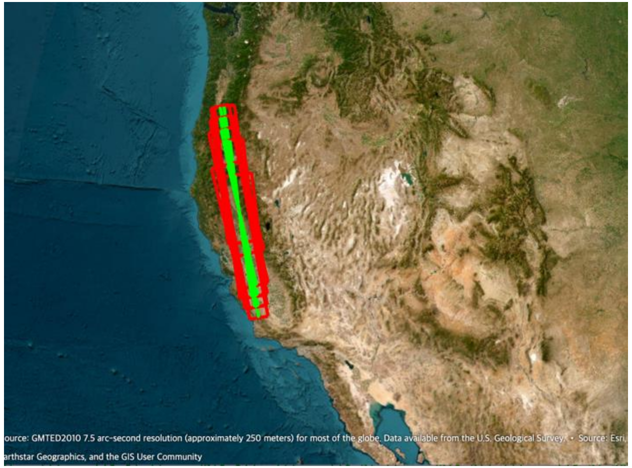
Location of J, P, P'

Length of $\overline{P'J}, \overline{PJ}, \overline{P'P}$

II.4 Observation Mode 2: Constant Area Capture [2/2]



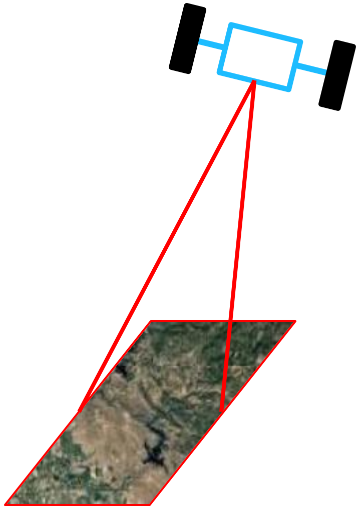




		RS-3-7	RS-3-8	RS-3-9	RS-3-10	RS-3-11	RS-3-12	RS-3-13	RS-3-14
1	Time of Minimum Range	'02:08:37'	'02:02:14'	'01:55:50'	'01:49:28'	'01:43:05'	'01:36:43'	'01:30:21'	'01:24:00'
2	SAT Latitude (deg)	38.9176	39.1360	39.3676	39.6237	39.8985	40.1914	40.5086	40.8444
3	SAT Longitude(deg)	-127.0072	-125.4593	-123.9160	-122.3804	-120.8511	-119.3278	-117.8126	-116.3041
4	SAT Altitude(km)	602.4325	602.4437	602.4567	602.4714	602.4869	602.5042	602.5236	602.5459
5	Minimum Range (km)	779.4538	697.7765	637.8891	605.9707	606.1053	637.8868	696.6011	775.7521
6	SAT Roll Angle(deg)	37.3335	28.8720	18.4102	6.2905	-6.4607	-18.4757	-28.7823	-37.0905

III. Data Transmission Concept Design

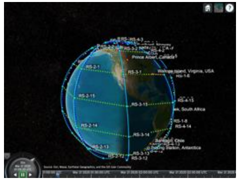
SAT #1



Data Acquisition
by Observation

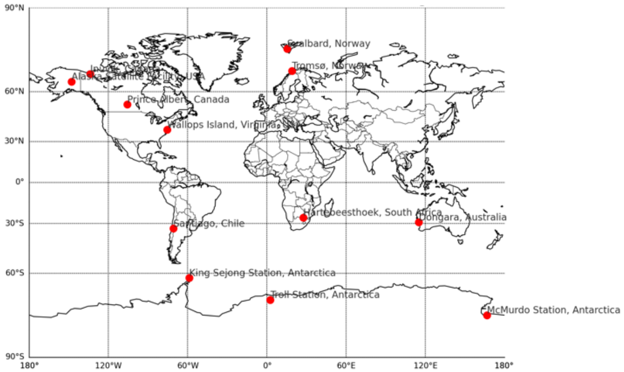
SAT #2 SAT #n-1

Data Handover
by Inter-Satellite Link



SAT #n

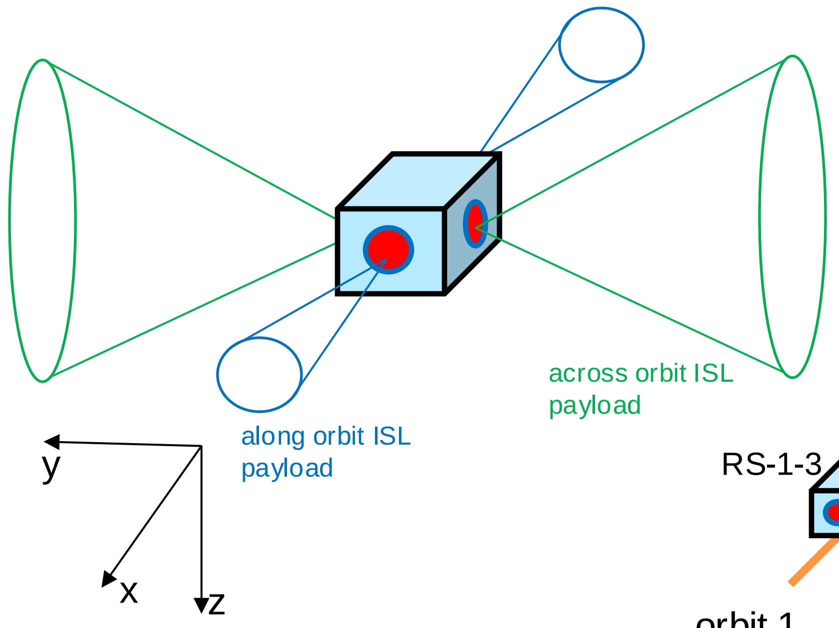
Data Downlink
to Ground Station

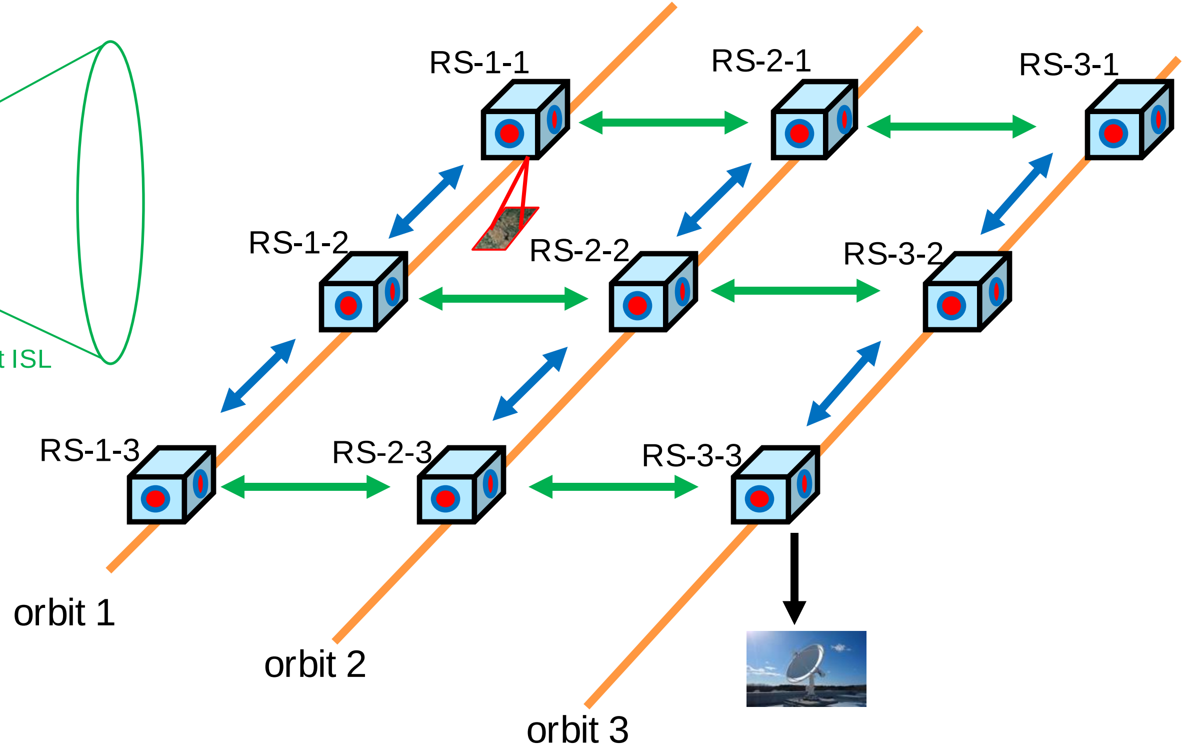


Main Task

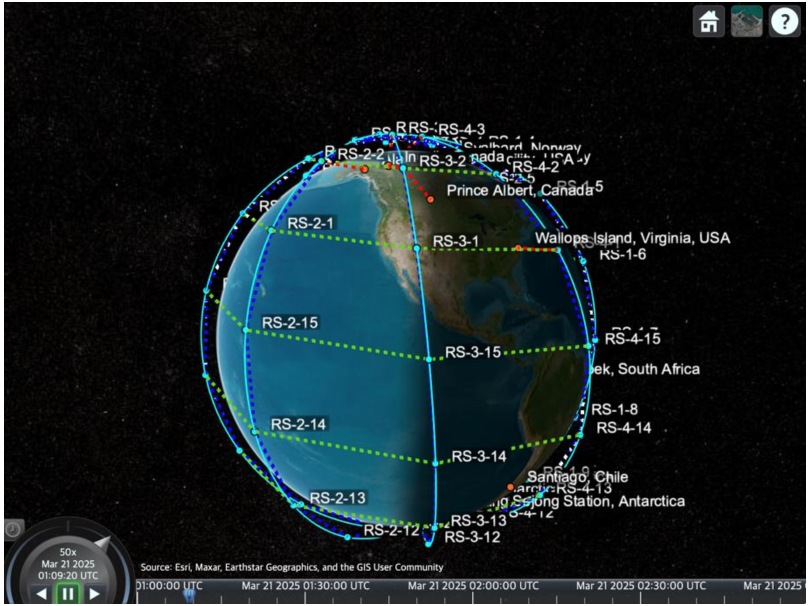
- Select Ground Station which takes minimum time (cost) to transmit data
- Proceed Routing Process to Ground Station

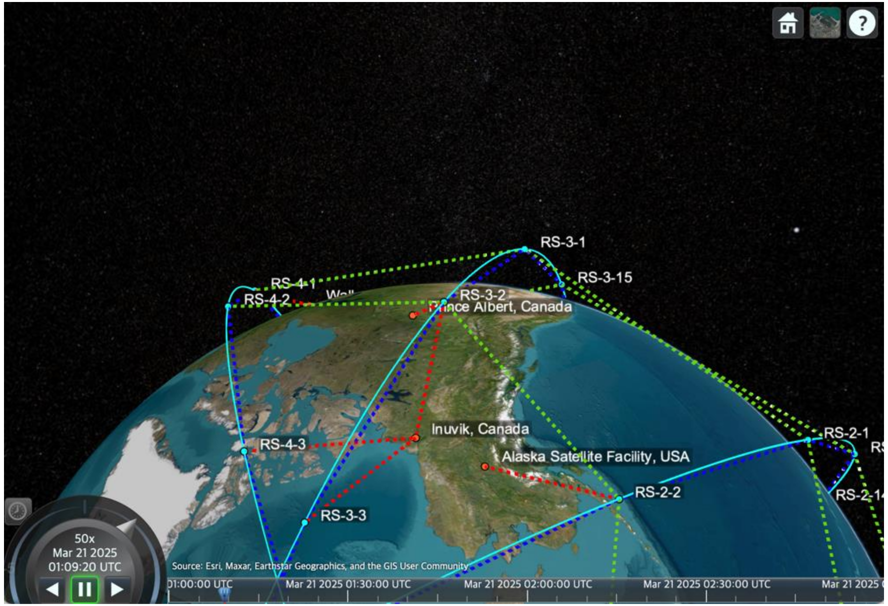
III.1 Communication Payload for Inter Satellite Link



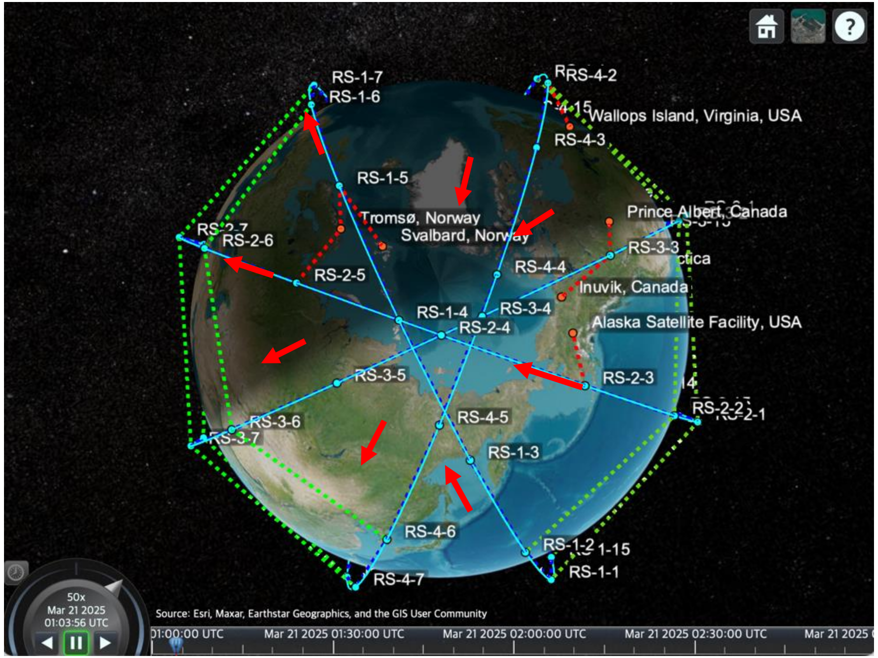


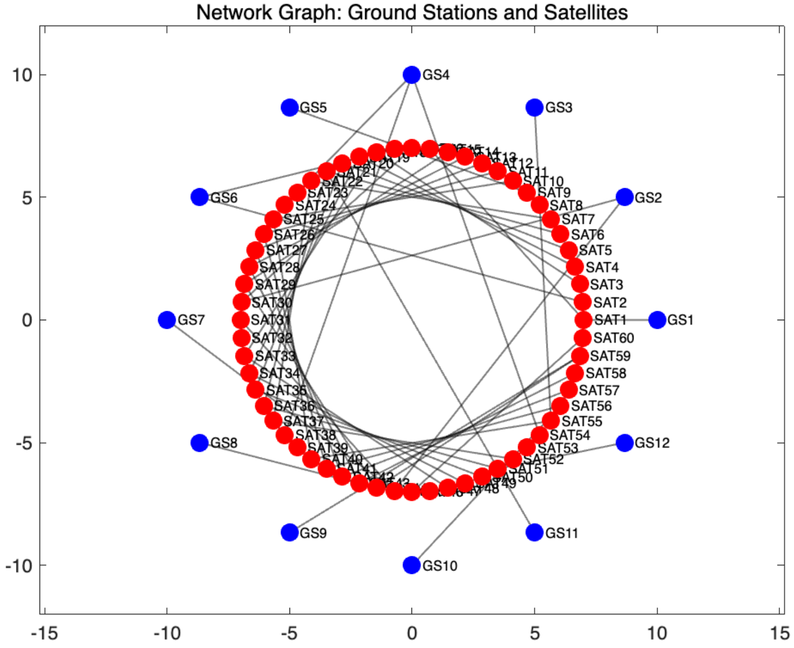
III.2 Orbital Visualization of Inter-Satellite Links



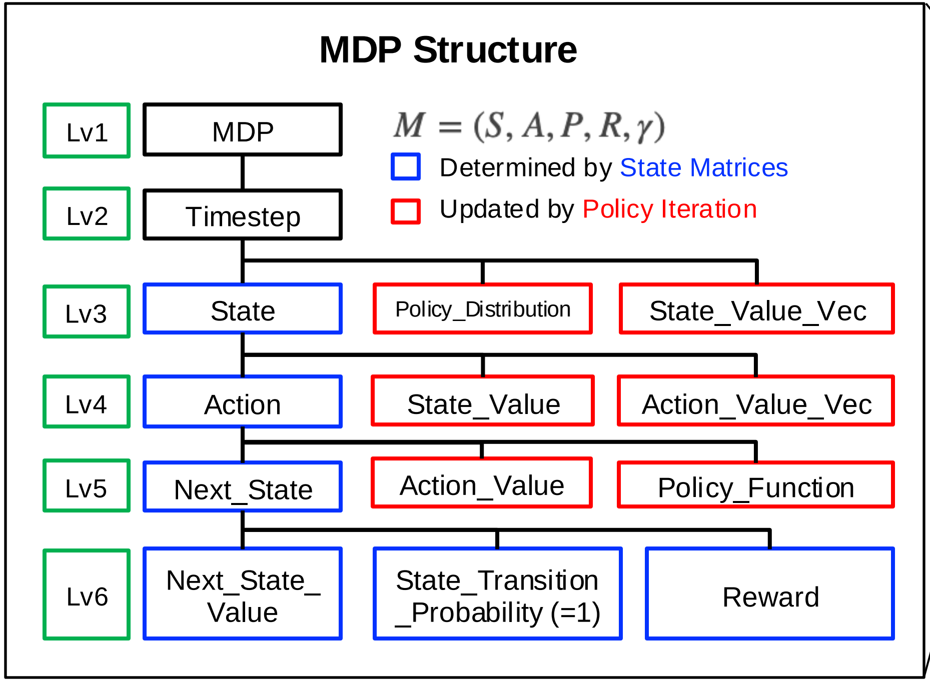


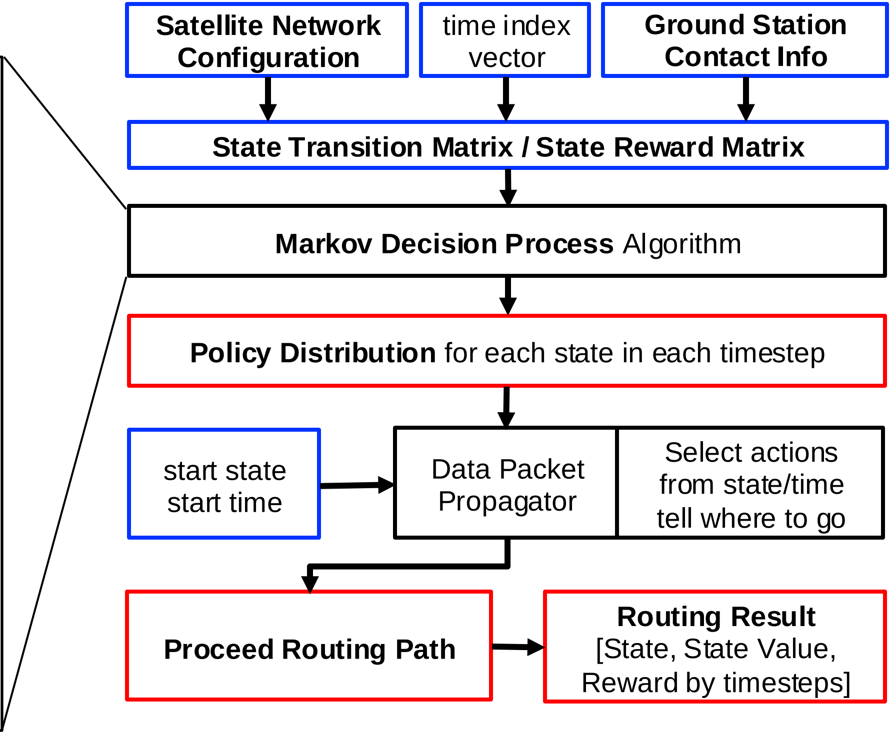
III.3 Generation of Network Chart





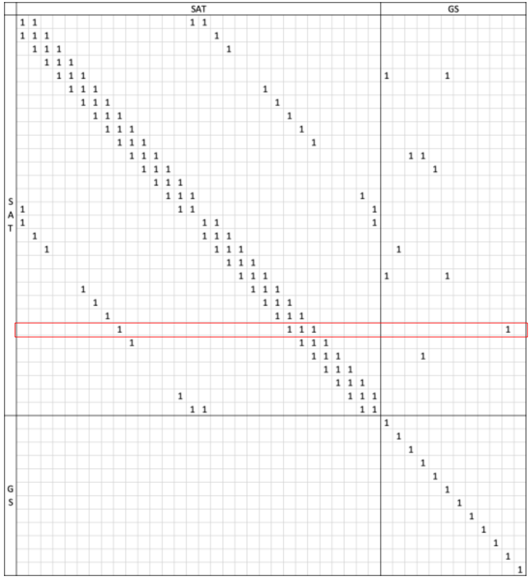
III.4 MDP Structure Design



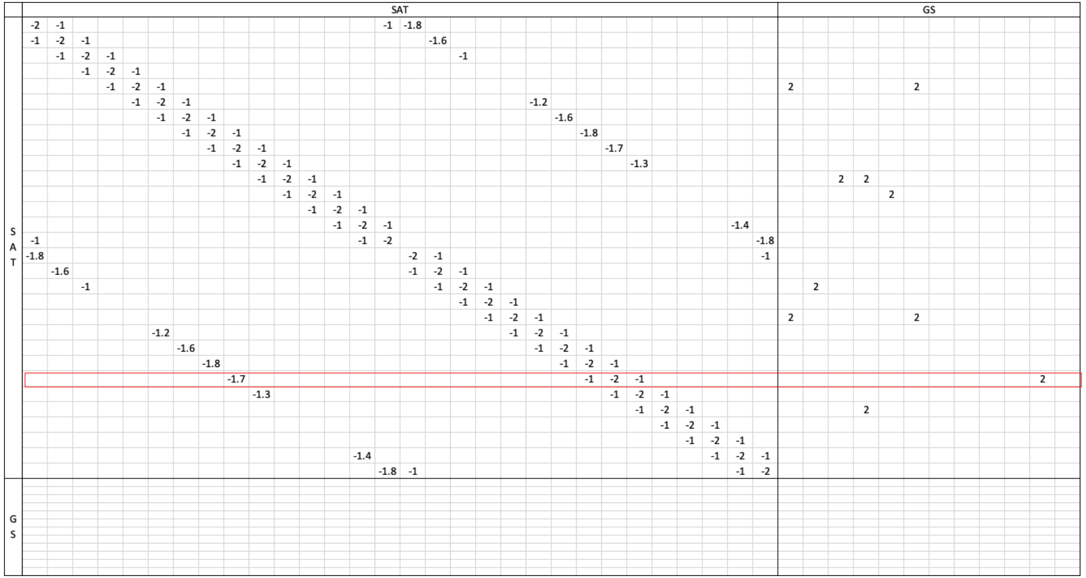


III.5 State Transition and Reward Matrix

State Transition Matrix



State Reward Matrix



Transition Structure

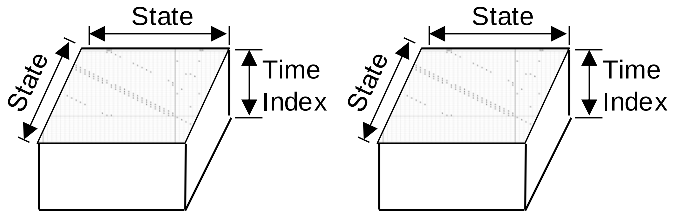
- Row: Transmit State (Define Starting States)
- Column: Receive State (Define Available Actions)
- SAT-to-SAT / SAT-to-GS: From Orbit Config
- GS – to – SAT: Deactivate
- GS – to - GS: Stay Current State

Reward Structure

- SAT – to – SAT inside orbit: -1
- SAT – to – SAT inter-orbit: - normalized distance
- Staying in Current SAT: -2
- SAT – to – GS: +2
- GS –to GS: 0

III.6 Policy Iteration and Backward Induction

Dataset: State Transition / Reward Matrix



State Transition matrix

State Reward matrix

Take Last Timestep's Information

Policy Iteration for Last Timestep

1. Initialization: Initial Policy and State Value

   $V(s) \in R$ and $\pi(s) \in A(s)$ arbitrarily for all $s \in S$

2. Policy Evaluation: Continue until state value converges

   $$\text{State Value}: \quad V(s) \leftarrow \sum_{s',r} p(s', r | s, \pi(s))[r + \gamma V(s')]$$

3. Policy Improvement: Continue until policy function converges

   $$\text{Action Value}: \quad q(s,a) = \sum_{s',r} p(s', r | s, a)[r(s,a,s') + \gamma V(s')]$$

   $$\text{Policy Function}: \quad \pi(s|a) = \arg\max_a q(s,a,t)$$

Converged State Value and Policy for Last Timestep

Backward Induction for the Other Timesteps

Process: Get state value information of t (V(s)) from t+1 (V(s'))

$$\text{Action Value}: \quad q(s,a) = \sum_{s',r} p(s', r | s, a)[r(s,a,s') + \gamma V(s')]$$

$$\text{State Value}: \quad V(s) = \max_a q(s,a)$$

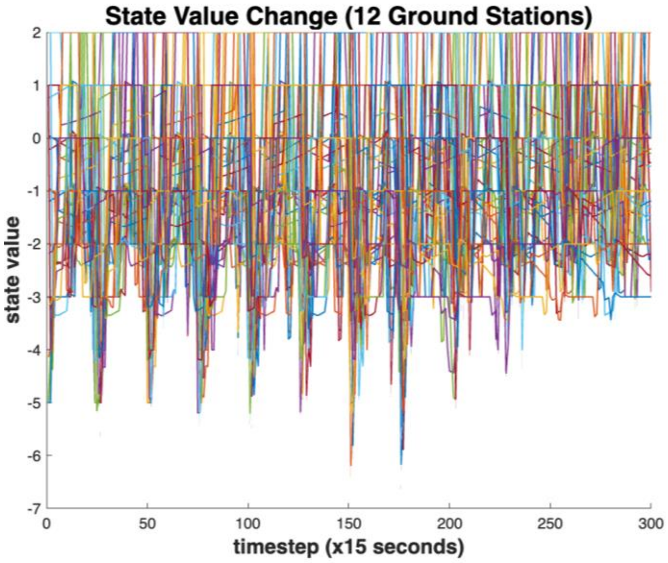
$$\text{Policy Function}: \quad \pi(s|a) = \arg\max_a q(s,a,t)$$

Take the other Timestep's Information

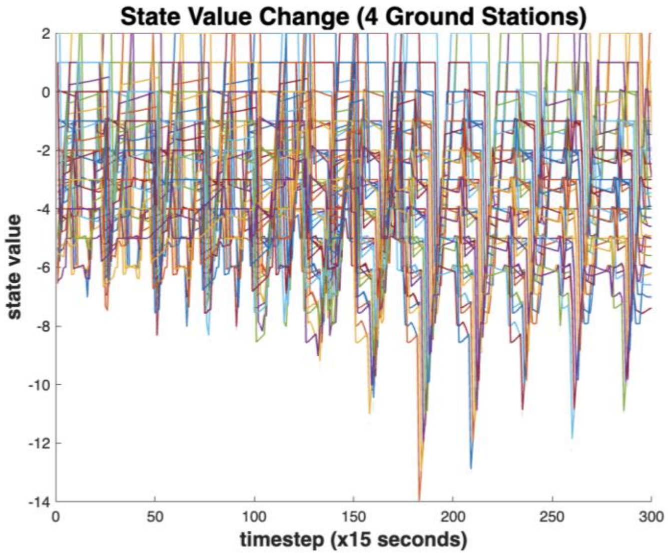
Output:

State Value, Action Value, and Policy Function for each timestep

III.7 State Value Change for Different no. of GS




```
Policy: 1 -> Value Iteration: 216
Policy: 2 -> Value Iteration: 7
Policy: 3 -> Value Iteration: 3
Policy: 4 -> Value Iteration: 3
```



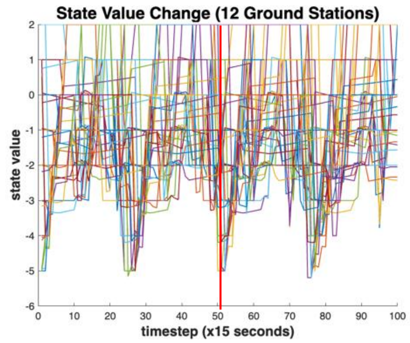

```
Policy: 1 -> Value Iteration: 1691
Policy: 2 -> Value Iteration: 11
Policy: 3 -> Value Iteration: 5
Policy: 4 -> Value Iteration: 3
```

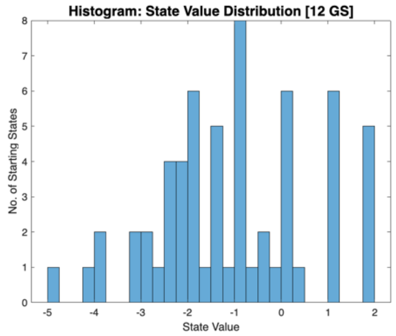
```
elevation_angle_condition = 30;

receiving_gs_info = ...
    ["Svalbard, Norway", 78.2300, 15.4100, 120;
    "Alaska Satellite Facility, USA", 64.8581, -147.8494, 133;
    "King Sejong Station, Antarctica", -62.2233, -58.7855, 11;
    "Troll Station, Antarctica", -72.0167, 2.5333, 1275;
    "McMurdo Station, Antarctica", -77.8419, 166.6863, 24;
    "Tromsø, Norway", 69.6492, 18.9560, 10;
    "Inuvik, Canada", 68.3600, -133.7236, 65;
    "Prince Albert, Canada", 53.2022, -105.7453, 428;
    "Wallops Island, Virginia, USA", 37.9402, -75.4661, 14;
    "Santiago, Chile", -33.4489, -70.6693, 520;
    "Hartebeesthoek, South Africa", -25.8870, 27.7044, 1415;
    "Dongara, Australia", -29.2049, 114.9389, 20
    ];
```

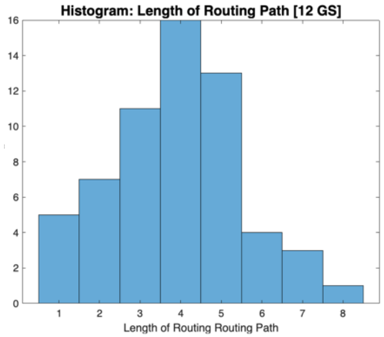
: Selected 4 Ground Stations

- More GS makes less no. of Value Iteration (Calculation Time) and higher State Value Distribution
- Change of GS contact Status makes rapid change of State Value Distribution
- From timestep 1 ~ 300 we can show ever start state (satellite) can reach to the ground station for both GS settings!

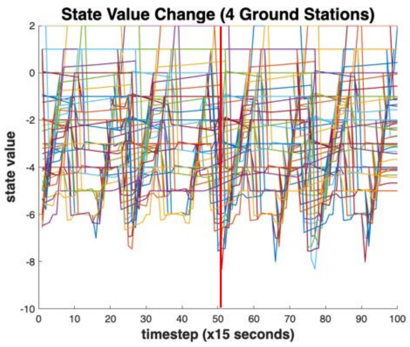
III.8 State Value Distribution and Routing Result

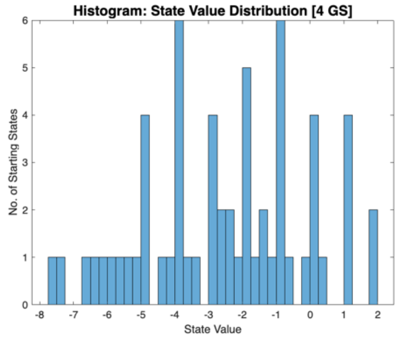


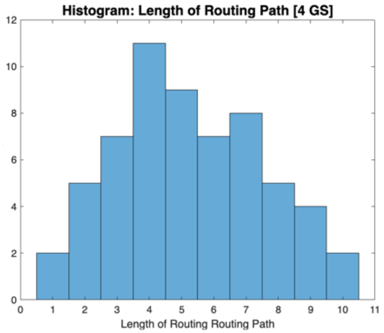





```
mean_state_value = -1.0593
std_state_value = 1.6562
mean_length = 3.9000
std_length = 1.6229
```








```
mean_state_value = -2.5304
std_state_value = 2.3738
mean_length = 5.2667
std_length = 2.2912
```

- More Ground Stations Makes higher state value distribution and shorter length of routing path

IV. Future Research Plan

Object 3: Design Autonomous Decision Process for Satellites

- Maximize imagery data generation and minimize the time duration for data transmission

- We will combine the concept of Earth Observation and Data Transmission into one system, design autonomous decision system from given multiple ground target points.
- Given ground target points, satellite constellation system will decide when to capture, how long to capture, and the strategy to transmit the data autonomously

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