THE AEROSPACE CORPORATION

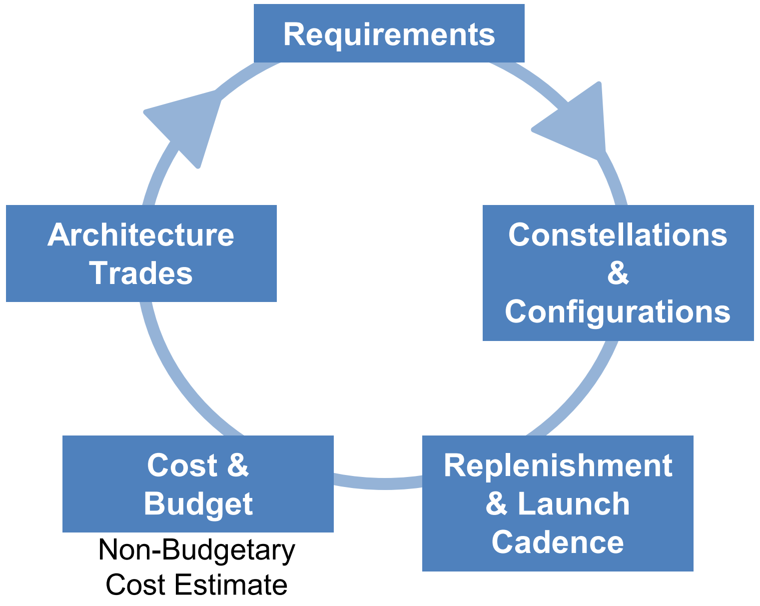
Refresh/Revisit Rate Definitions and Application to NOAA Constellations

SAE Flight Architecture Study Team

December 2023

Overview

- Goals:
  - Support LEO refresh/revisit rate* requirement development
    - Leverages constellation-level analysis to understand implications of revisit rate definitions
  - LEO/GEO trades
    - Performed to determine cost effective options (contributions from both LEO & GEO) to meet well-defined refresh/revisit rate requirements
- Methodology



* "Related to the coverage is the refresh rate, sometimes referred to as "Refresh", "Refresh Rate," or "Revisit Rate" parameters. These terms are defined as the time interval between successive collections of measurements of the same parameter from the same geographical point. Each observation has a threshold and objective refresh rate that expresses a user need and serves to guide sense and constellation design." - NESDIS-REQ-4400.1, Near Earth Orbit Network Program Observational Objectives, Effective Date: July 22, 2023

Carry out constellation-level analyses to determine cost effective options and refine requirement definition

Refresh/Revisit Rate Definition

Use constellation-level analysis to understand implications of how refresh/revisit rate is defined

Purpose

- Goal: Support LEO refresh/revisit rate requirement development
- Methodology
  - Model simple case of three sun-synchronous (SS) satellites (3xSS) and obtain attributes related to revisit rate over the globe
  - Identify potential definitions of revisit rate and compare how they would be expressed in 3xSS situation
  - Identify most understandable expressions for threshold/objective revisit rate requirements based upon typical user needs and make recommendations

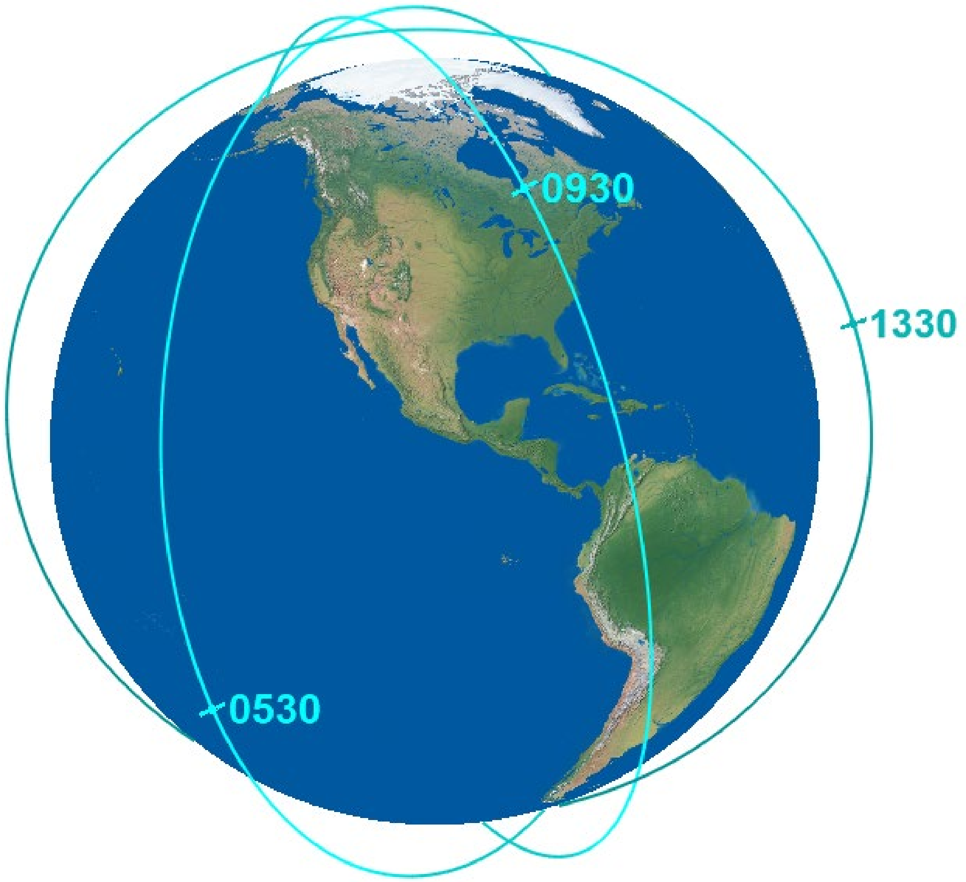
- Bottom Line Up Front
  - Recommendation 1: Write requirements that make it clear whether high refresh/revisit rate at the poles can be averaged with low refresh/revisit rate at the equator to satisfy a global update rate requirement
  - Recommendation 2: Write requirements that make it clear whether refresh/revisit rate is a time-averaged quantity, a worst-case quantity, or somewhere in between
  - Recommendation 3: Frequently will need more than one revisit rate requirement to capture user needs

Exemplar Constellation

3-satellite sun synchronous constellation

- Methodology: Use a familiar constellation to show performance relative to different refresh/revisit rate definitions
- The baseline constellation consists of 3xSS satellites at 833km
  - Three different orbit planes with Local Times of the Ascending Node (LTANs) of 1330, 0930, and 0530
  - Mean anomaly phasing* between satellites in adjacent planes is not specified, so best/worst case performance is characterized
- Collect statistics on the time between observations of each point on the globe (i.e., the gap times**)

Baseline Constellation



* Mean anomaly is the fraction of an elliptical orbit's period that has elapsed since the orbiting body passed periapsis

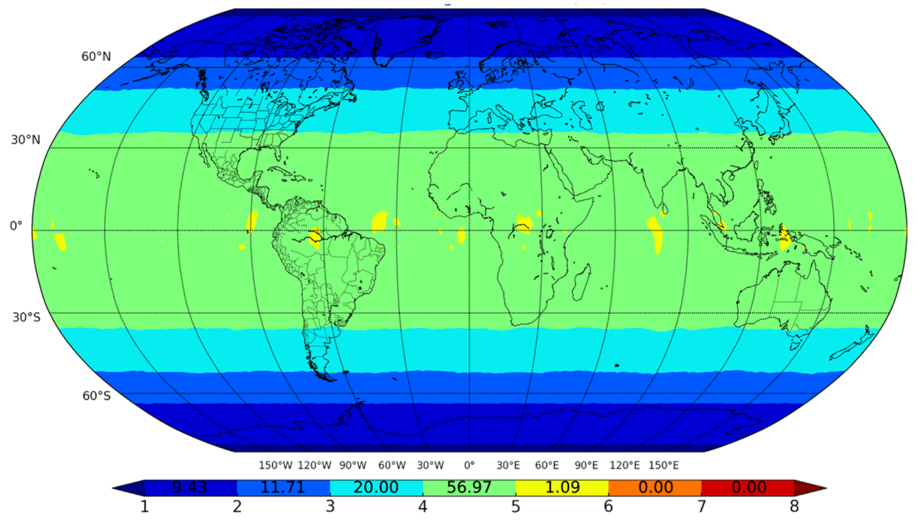
**Time between observations

Exemplar Constellation Performance

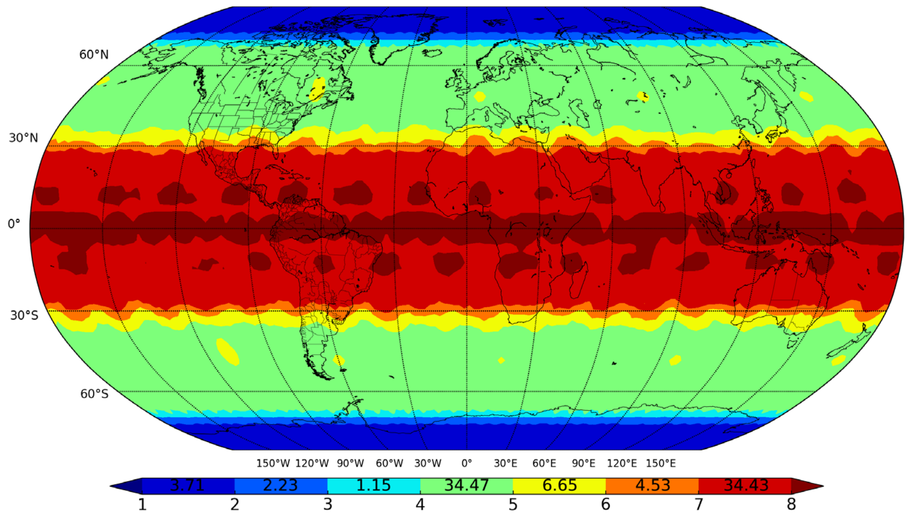
3 Satellites with LTANs of 1330, 0930, and 0530

Metric	Global Average (hours)	Global Worst Case (hours)
Average gap time	3.9	5.1
95th percentile gap time	6.1	8.1
Maximum gap time	7.4	11.1

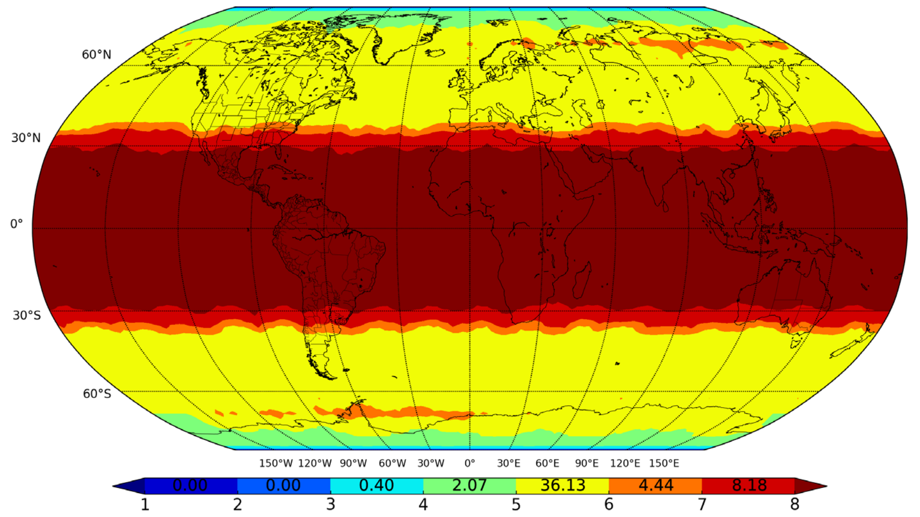
Average Gap Time (Best Phasing)



95th Percentile Gap Time
(Best Phasing)



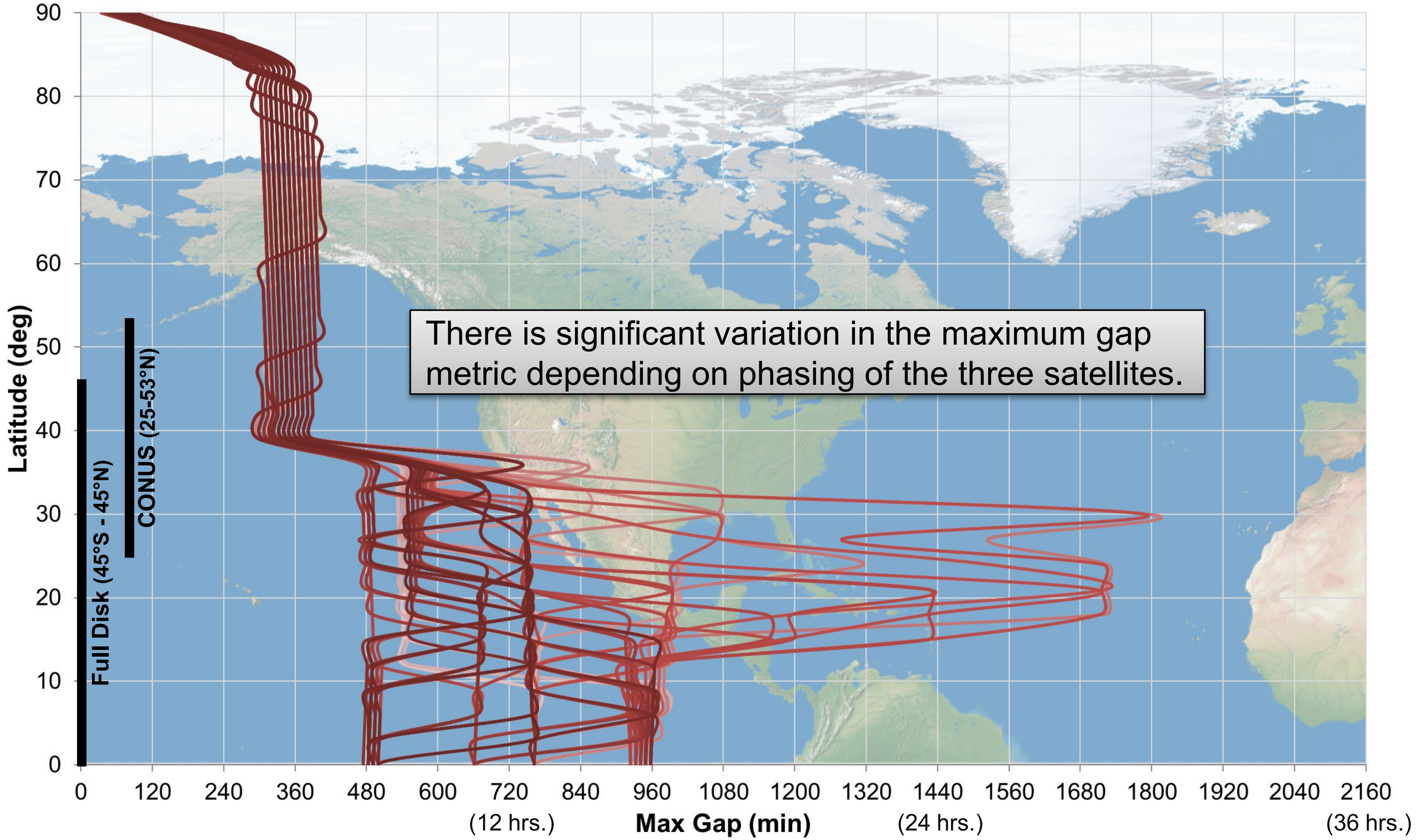
Maximum Gap Time (Best Phasing)



Wide range of reported performance, depending on metric definition

Performance By Latitude: Maximum Gap Time

Across Potential Satellite Phasing Options



Better Performance

Comparison of Constellation Options

"Best" is relative to the metric(s) considered

- The following slides depict the performance of constellations optimized for several revisit performance metrics of interest

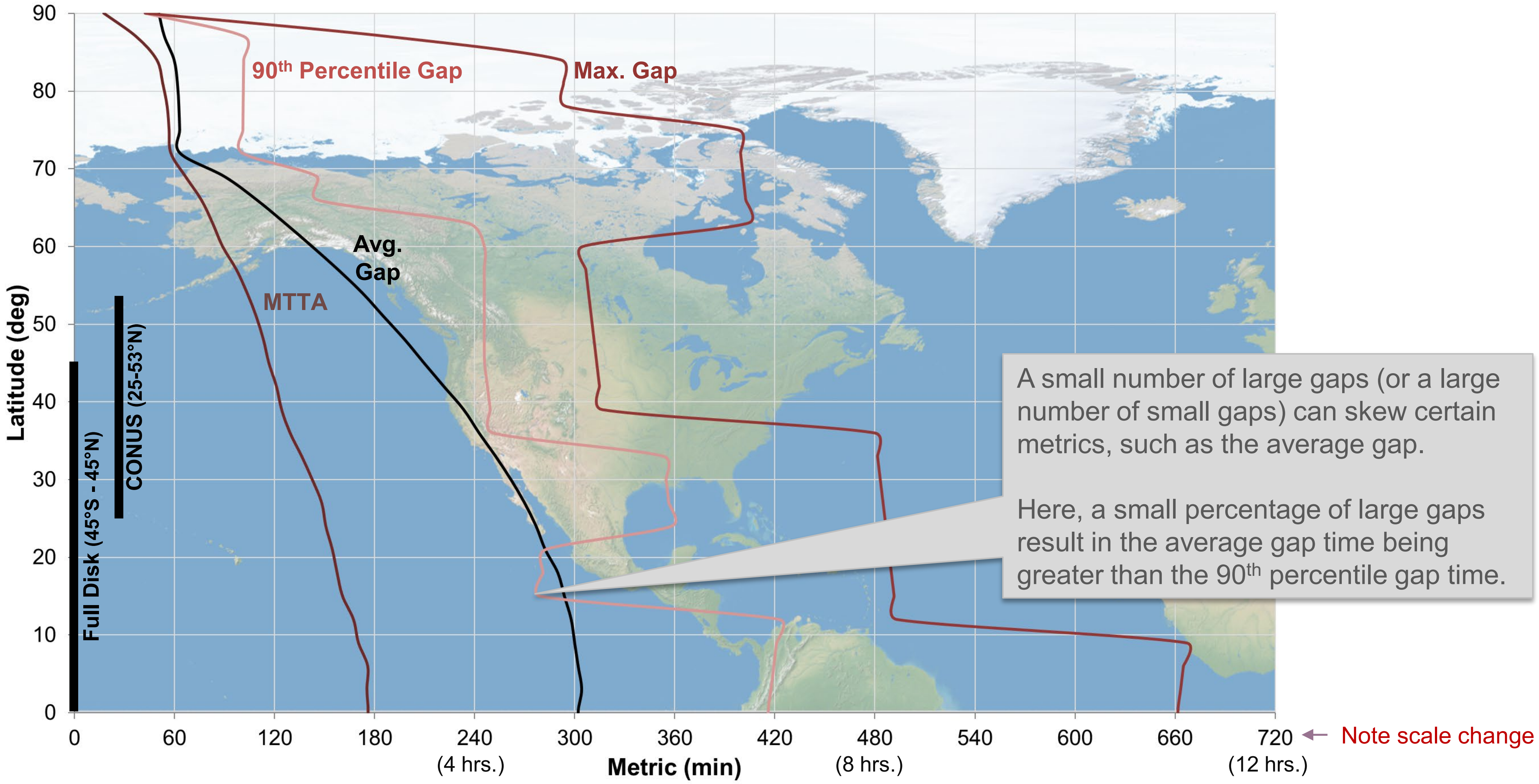
- Revisit performance metrics
  1. **"Best Avg. Gap"**: constellation optimized to minimize avg. gap performance globally and across CONUS
  2. **"Best MTTA*"**: constellation optimized to minimize MTTA performance globally and across CONUS
  3. **"Best 90P Gap"**: constellation optimized to minimize 90th percentile gap performance globally and across CONUS
  4. **"Best Max. Gap"**: constellation optimized to minimize maximum gap performance globally and across CONUS
  5. **"Balanced MTTA and 90P Gap"**: constellation optimized to simultaneously minimize and balance MTTA and 90th percentile gap performance globally and across CONUS

- Tradeoffs exist between these constellations in terms of the various performance metrics considered that subsequently impacts users
  - The "best" constellation for one metric is likely not the best for other metrics
  - Compromises exist when considering multiple performance metrics simultaneously

* MTTA definition: given a random point in time, what is the average expected wait time until the next measurement?

Metric Comparison

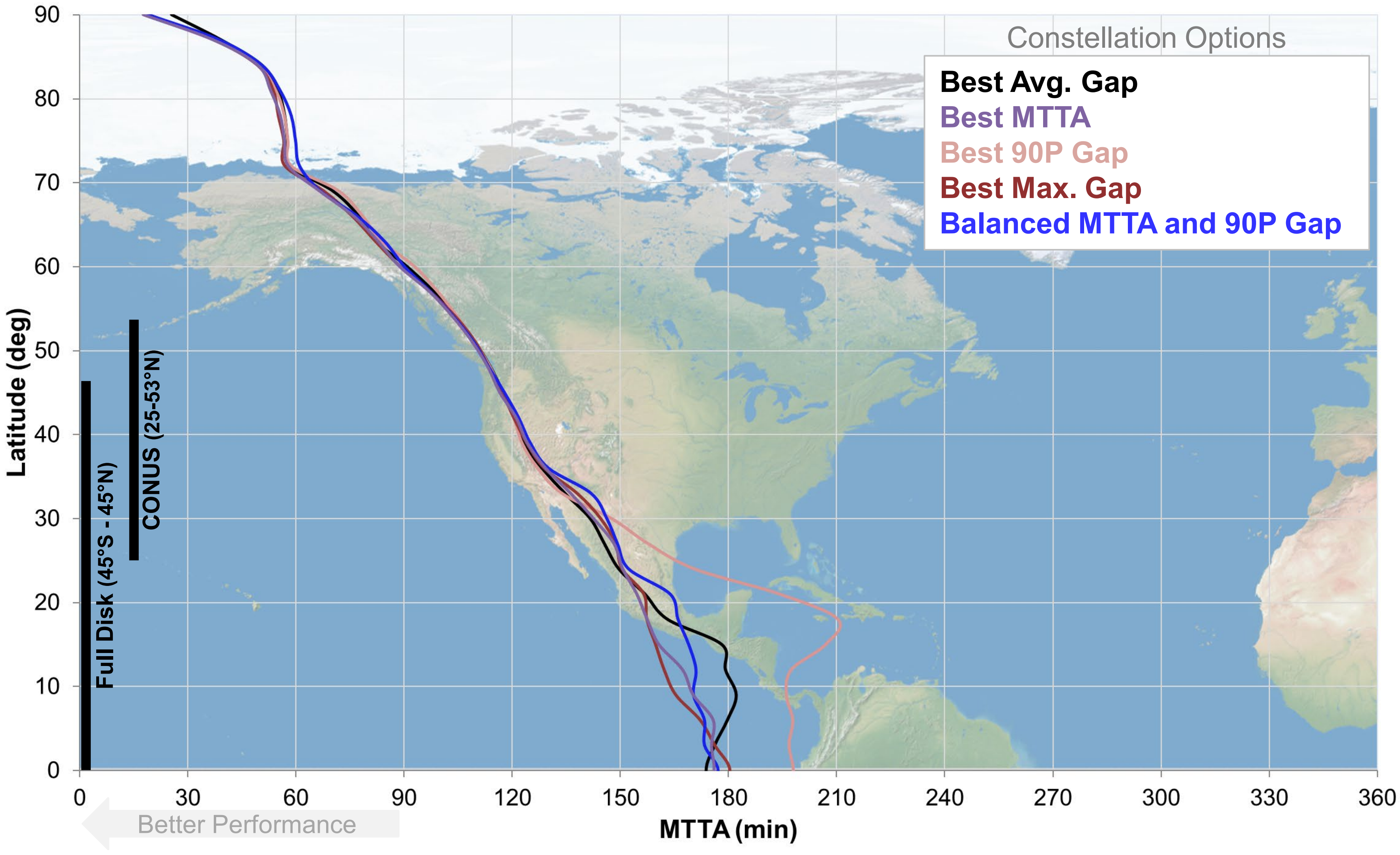
Best Constellation for Each Metric



Note scale change

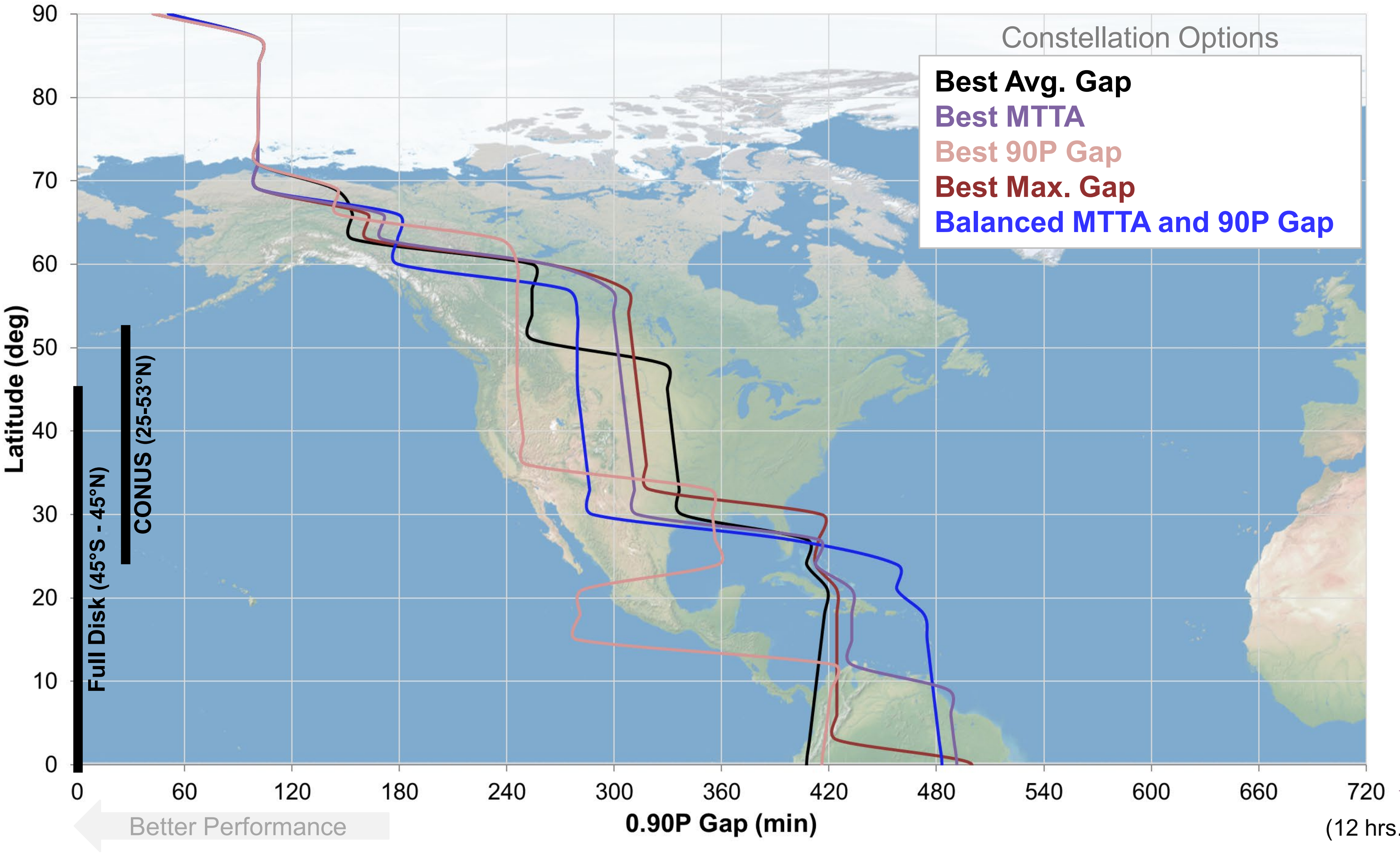
Performance By Latitude: Mean Time to Access (MTTA)

Five Phasings of the 3xSS Constellation



Performance By Latitude: 90th Percentile Gap Time

Five Phasings of the 3xSS Constellation

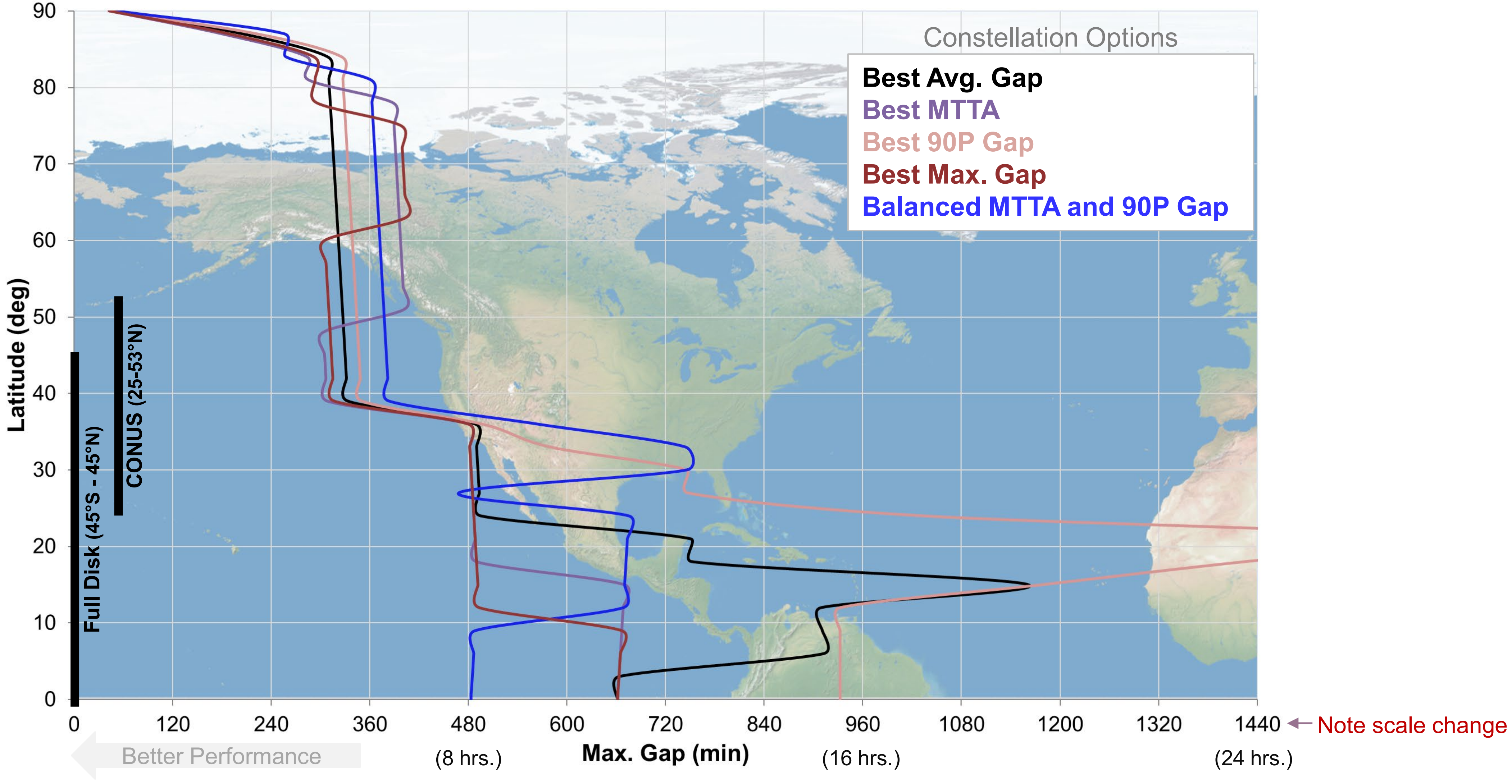


Note scale change

(12 hrs.)

Performance By Latitude: Max. Gap Time

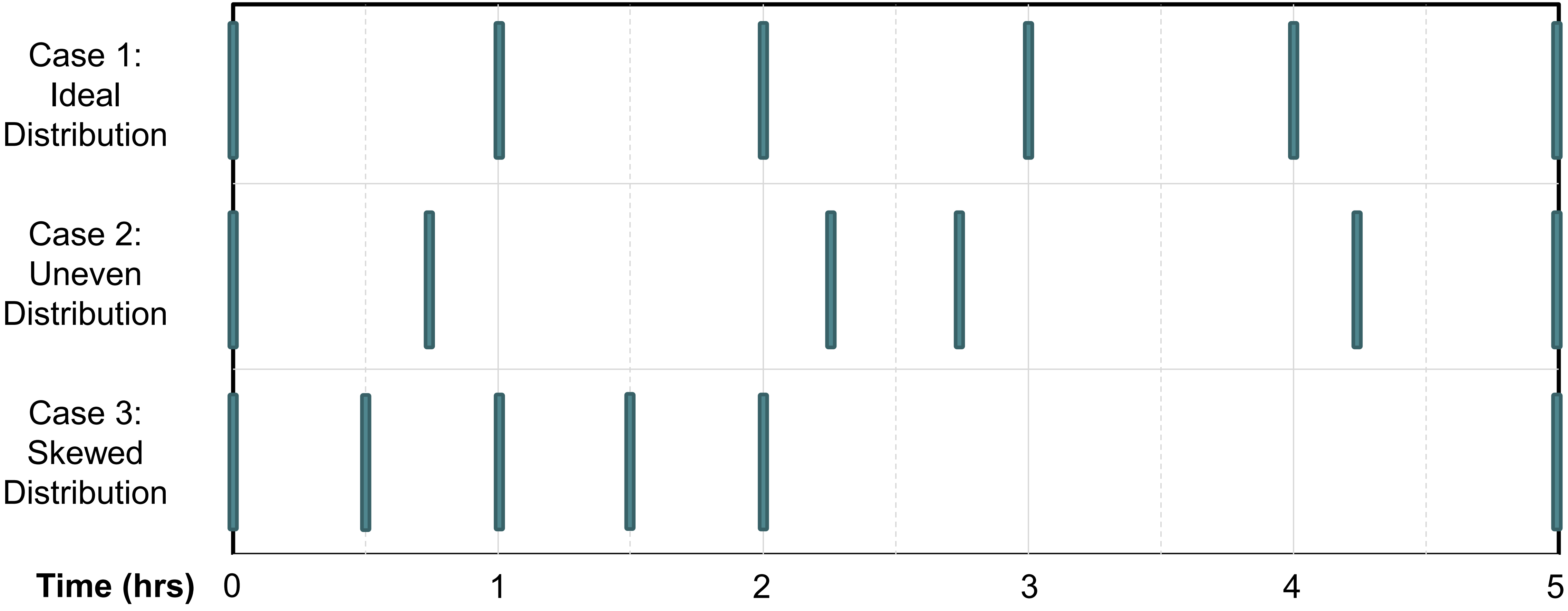
Five Phasings of the 3xSS Constellation



Time Between Observations

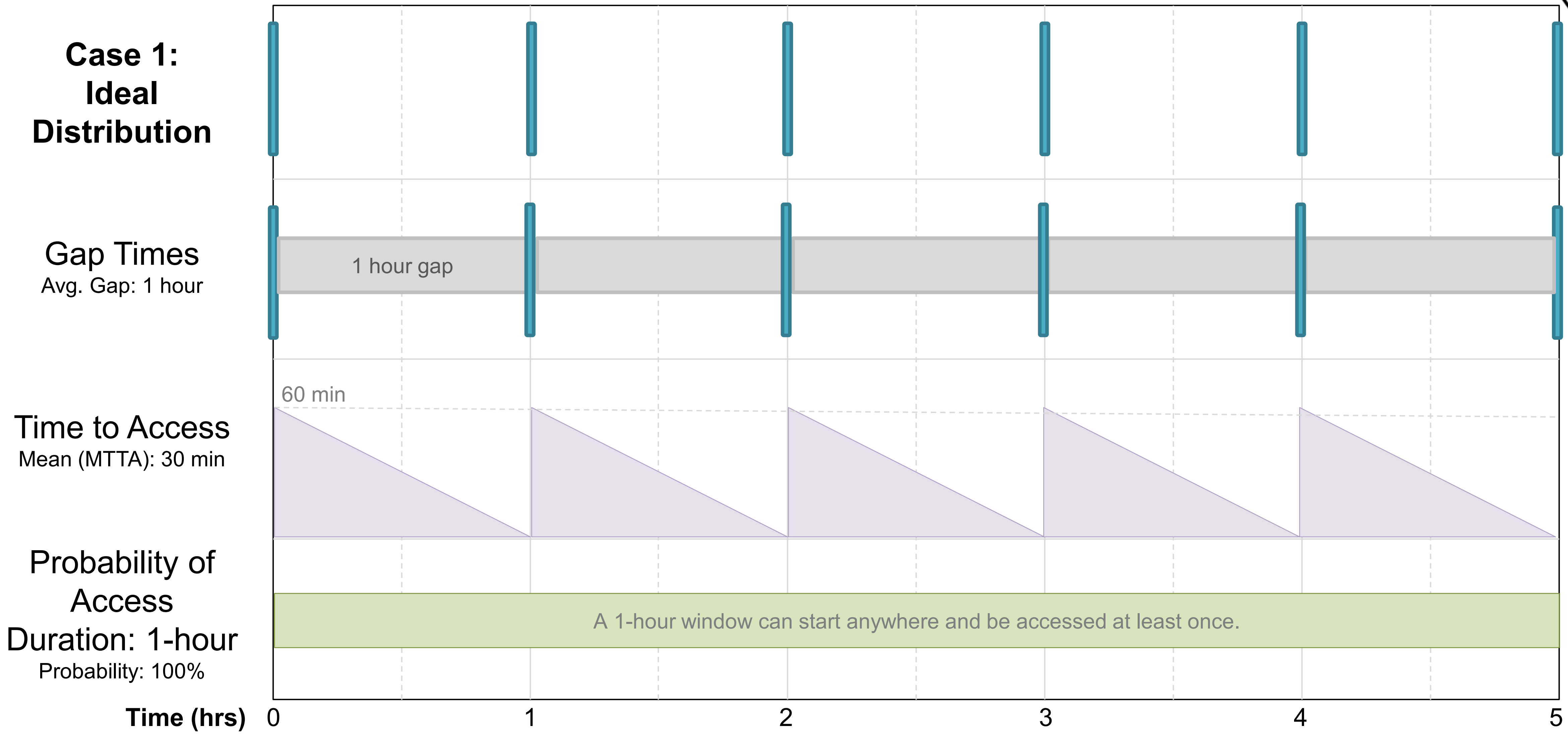
"Evenness" of Temporal Distribution of Observations

- For some users, the evenness / regularity of time between observations may be important



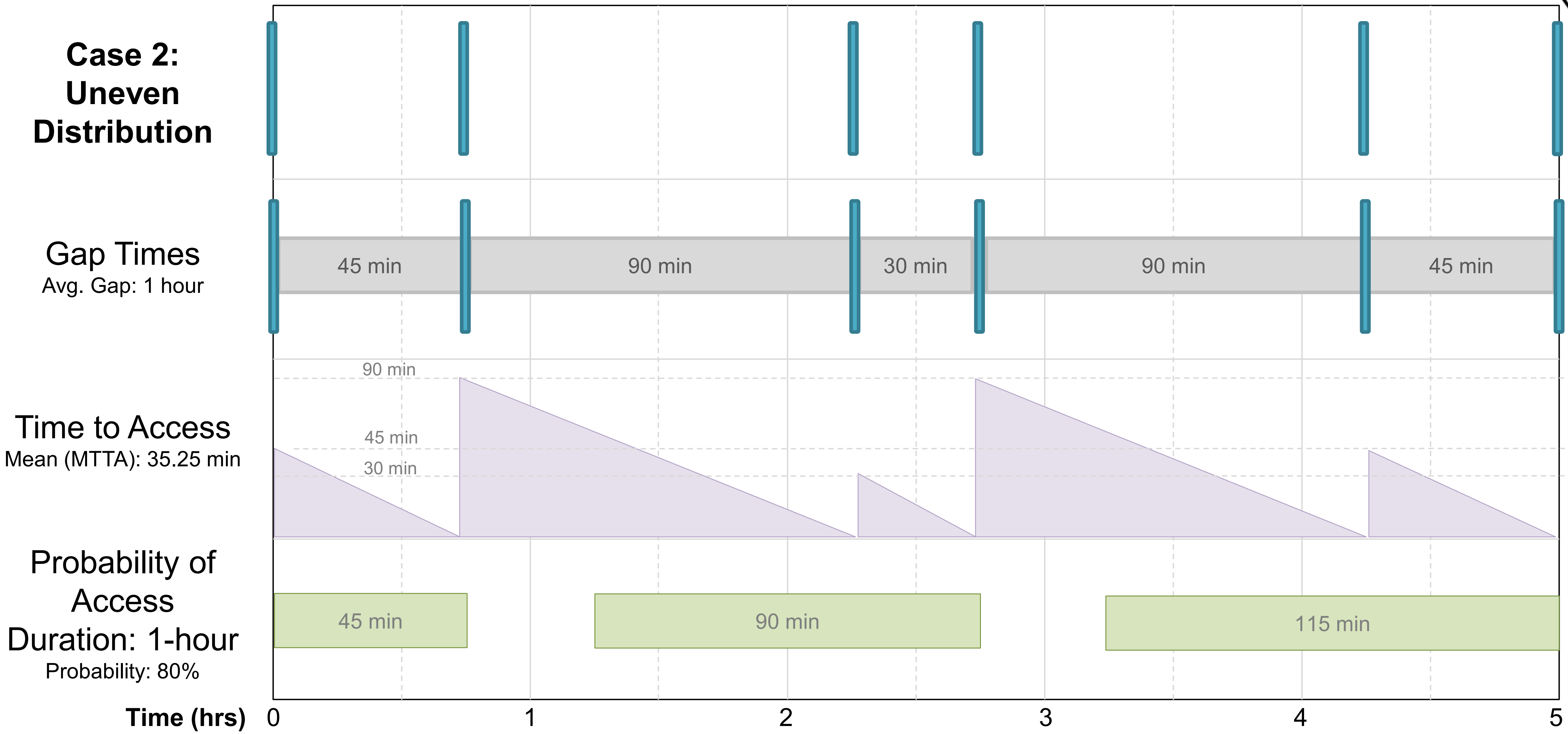
Metric Comparison for Notional Case 1

Desired Refresh/Revisit Rate: 1 hour



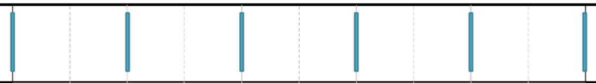
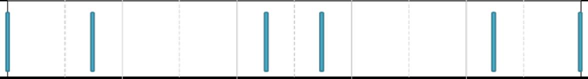
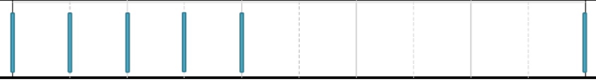
Metric Comparison for Notional Case 2

Desired Refresh/Revisit Rate: 1 hour



Summary of Metric Comparison for Notional Cases

Desired Refresh/Revisit Rate: 1 hour

Notional Case	Avg. Gap Time	Mean Time to Access (MTTA)	Probability of Access Duration: 1-hour
1: Ideal Distribution 	60 min	30 min	100%
2: Uneven Distribution 	60 min	35.25 min	80%
3: Skewed Distribution 	60 min	60 min	60%

Observations

- Unlike average gap time, MTTA and the probability metric will be affected by the number <u>and</u> distribution of gaps
  - Avg. gap time is primarily dependent on the number of accesses vice their distribution
- However, using an average gap time while also setting constraints on additional gap statistics (e.g., maximum gap) can drive distributions towards the ideal
- Goals of setting refresh/revisit rate metrics
  - Meet the needs of users who have well-defined requirements
  - Make requirements that are broadly understood

Exemplar Constellation Performance

Results and Recommendations

Recommendations

- Recommendation 1: Write requirements that make it clear whether high refresh/revisit rate at the poles can be averaged with low refresh/revisit rate at the equator to satisfy a global refresh/revisit rate requirement
- Recommendation 2: Write requirements that make it clear whether refresh/revisit rate is a time-averaged quantity, a worst-case quantity, or somewhere in between
- Recommendation 3: Write more than one refresh/revisit rate requirement to capture user needs, e.g.,
  - An average metric to set the bulk of the refresh/revisits at the right level
  - A maximum gap metric to minimize the tail of the distribution

These recommendations are carried out in the next-generation LEO (NEON) requirements

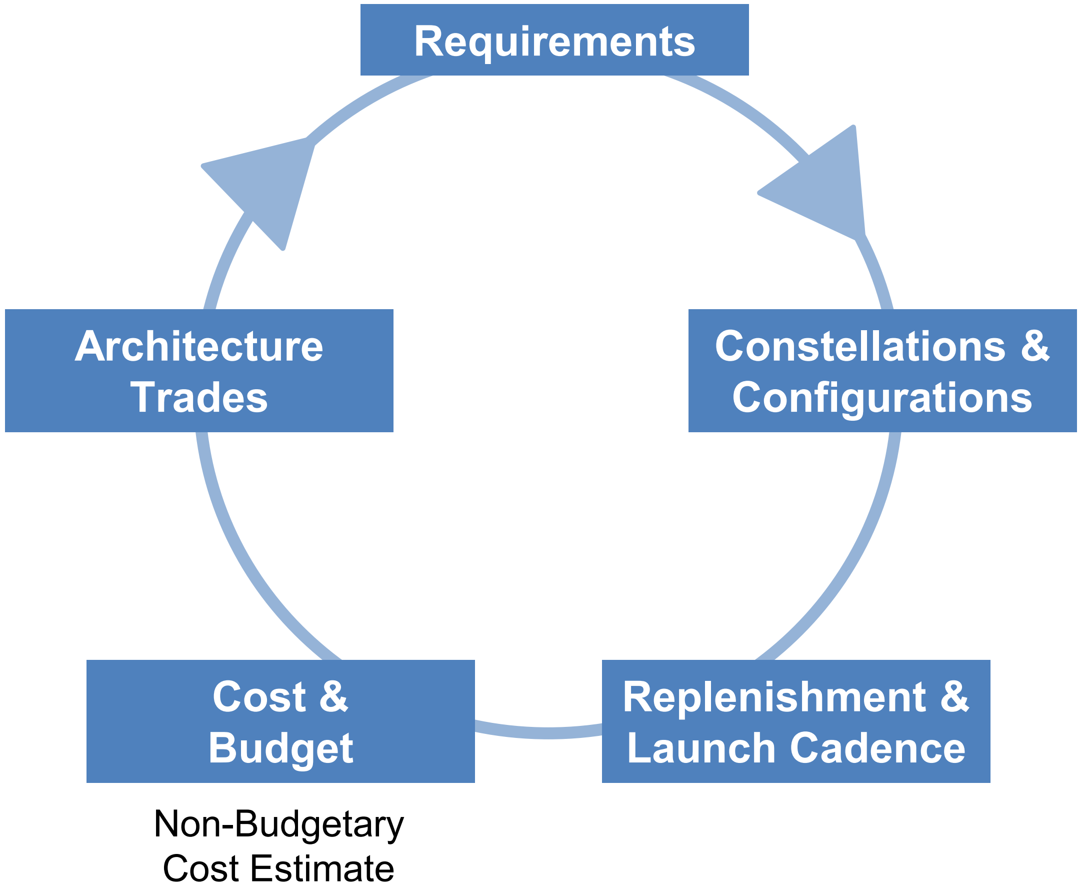
- Example for NEON infrared sounding requirements
  - NEON Program shall provide hyperspectral infrared radiance sensor data with a refresh rate between 6 hr (Threshold) and 1 hour Objective)
    - E.g., global average gap
  - NEON Program shall provide hyperspectral infrared radiance sensor data with a Global Coverage within between 24 hr (Threshold) and 6 hr (Objective).
    - E.g., global maximum gap

LEO / GEO Trades

Determine cost effective options to meet well-defined refresh/revisit rate requirements

LEO / GEO Trade Study Methodology

- Pair requirements with instruments/satellites
- Determine constellation size
- Calculate replenishment rate to maintain the constellation's functional availability
- Find approximate satellite configuration (bus, launch, software, etc.) from NSOSA
- Calculate lifecycle cost of 15-year mission
- Identify impacts of architecture decisions and assumptions on cost



Determine cost effective options to meet well-defined refresh/revisit rate requirements

LEO / GEO Trade Study Objectives

- NESDIS Office of Systems Architecture and Engineering (SAE) has explored the plausibility of meeting regional requirements (e.g., for hyperspectral infrared sounding) with a constellation of satellites in low Earth orbit (LEO)
- In general
  - GEO constellations are associated with regional, high refresh/revisit rate observations
  - LEO constellations are associated with global observations and relatively longer intervals between observations of the same point on the Earth

- Study requirements for hyperspectral infrared sounding
  - Global average refresh rate: 2 hours
  - Global coverage: 100% coverage in 24 hours
  - Regional: 1 hour
  - Availability: 90% for global requirements, 50% for regional requirement

Constellation Design to Life Cycle Cost

Hyperspectral Infrared Sounding

- Start with constellation sized to meet refresh/revisit rate requirements
- Calculate replenishment rate to meet global and regional availability requirements
- Determine number of satellites/instruments needed over mission duration
- Calculate lifecycle cost
  - Note: Lifecycle costs are included in study but not presented here

Observation	NOAA GEO Contributors	NOAA LEO Contributors	LEO Satellite Design Life	Availability Requirement Global / Regional		# Instruments (15-year Mission) GEO / LEO	
IR Sounding	1	1	5 years	90%	50%	1	4
IR Sounding	0	6	5 years	90%	50%	0	15

Mixed LEO / GEO constellation has many fewer satellites and lower lifecycle cost than an all-LEO constellation

Constellation Design

Hyperspectral Infrared Sounding

Optimized orbits to minimize the number of NOAA satellites needed to meet study requirements

- Assume contribution from EUMETSAT: Meteosat 3rd Gen, Sounder Sat
- Driving requirement for mixed GEO/LEO constellation: global coverage
- Driving requirement for all-LEO constellation: regional refresh
  - 6 NOAA LEO satellites can provide a 1-hour average regional refresh
    - 4 NOAA LEO satellites can provide a 2-hour average regional refresh
    - 2 satellites can provide a 3.5-hour average regional refresh and still meet 2-hour global refresh

Metric	Requirement	Constellation: 1xGEO + 1xLEO	Constellation: 6xLEO
Global Refresh	120	51	52
Global Coverage	1440	837	838
Regional Refresh	60	0	59

Mixed LEO / GEO constellation has many fewer satellites than an all-LEO constellation

LEO / GEO Trade Study Results

- Meeting 1-hour regional refresh study requirement with an all-LEO constellation would take 6-7 NOAA satellites
  - Some satellites are placed in low-inclination, non-sun-synchronous orbits to optimize for regional coverage
- Meeting 1-hour regional refresh study requirements from GEO and polar/global requirements from LEO would take 1-2 NOAA satellites
- There are a few drivers for number of satellites over mission duration
  - All-LEO constellations are 2-3 times larger than mixed GEO/LEO constellations
  - Availability requirements for global observations are stricter than for regional observations (90% vs. 50%)
  - All-LEO constellations require 1.5-3 times more satellites over the 15-year mission duration

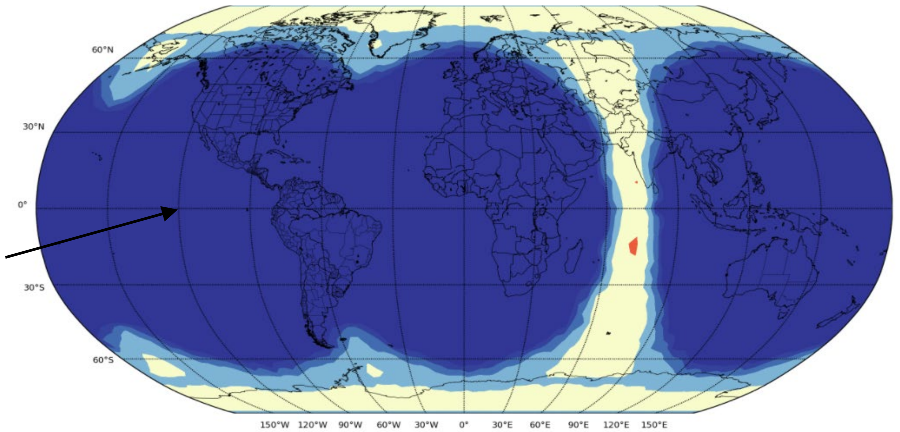
- All-LEO constellations designed to meet regional high refresh/revisit rate requirements are more expensive than mixed GEO/LEO constellations
- Cost results are generally insensitive to LEO satellite design life
  - E.g., similar costs for LEO constellation with 3-year and 7-year satellite design lives

Decision Considerations

- If cost to meet study refresh and availability requirements is the only consideration, then the choice to use a mix of GEO and LEO satellites would be simple, however
- Some observations may be difficult/infeasible to make from GEO
- All-LEO constellations sized to meet 1-hour regional refresh requirements provide better global performance than mixed GEO/LEO constellations
- All-LEO constellations provide graceful degradation
  - The loss of a single satellite in a 6-satellite LEO constellation is much less impactful than the loss of single satellite in a 1xGEO + 1xLEO constellation
- GEO satellites provide regular timing between regional observations while LEO constellations will provide gaps between observations that vary significantly over time and over the globe

GEO + LEO NOAA Architecture

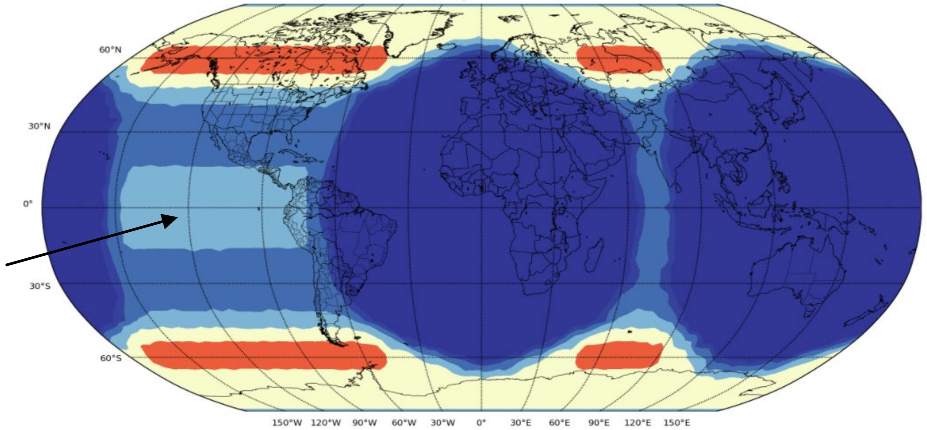
+ LEO + GEO non-NOAA POR



NOAA GEO coverage over CONUS

All-LEO NOAA Architecture

+ LEO + GEO non-NOAA POR



LEO-only coverage over CONUS

Thank you