Autonomous Scheduling for Rapid Responsive Launch of Constellations

Proposal Defense

Proposer/Presenter: Christopher R. Simpson

Agenda

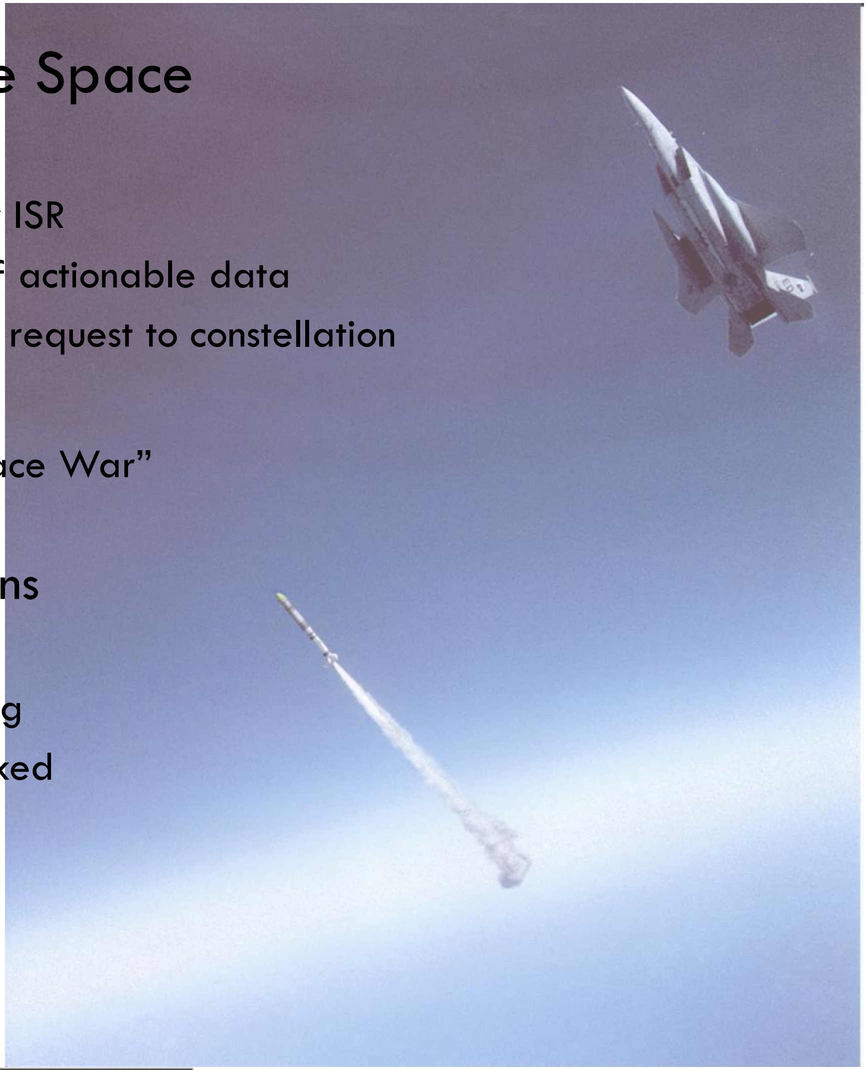
- Motivation for rapid launch
  - Support rapid ISR collection and dissemination
- Objectives
  - Optimized scheduling of airborne launch vehicles
- Quantification
  - Response time and quality coverage
- Plan of attack
  - Incorporate quality metrics into software package
- Schedule

Support rapid ISR collection and dissemination

MOTIVATION

Motivation (1/5)

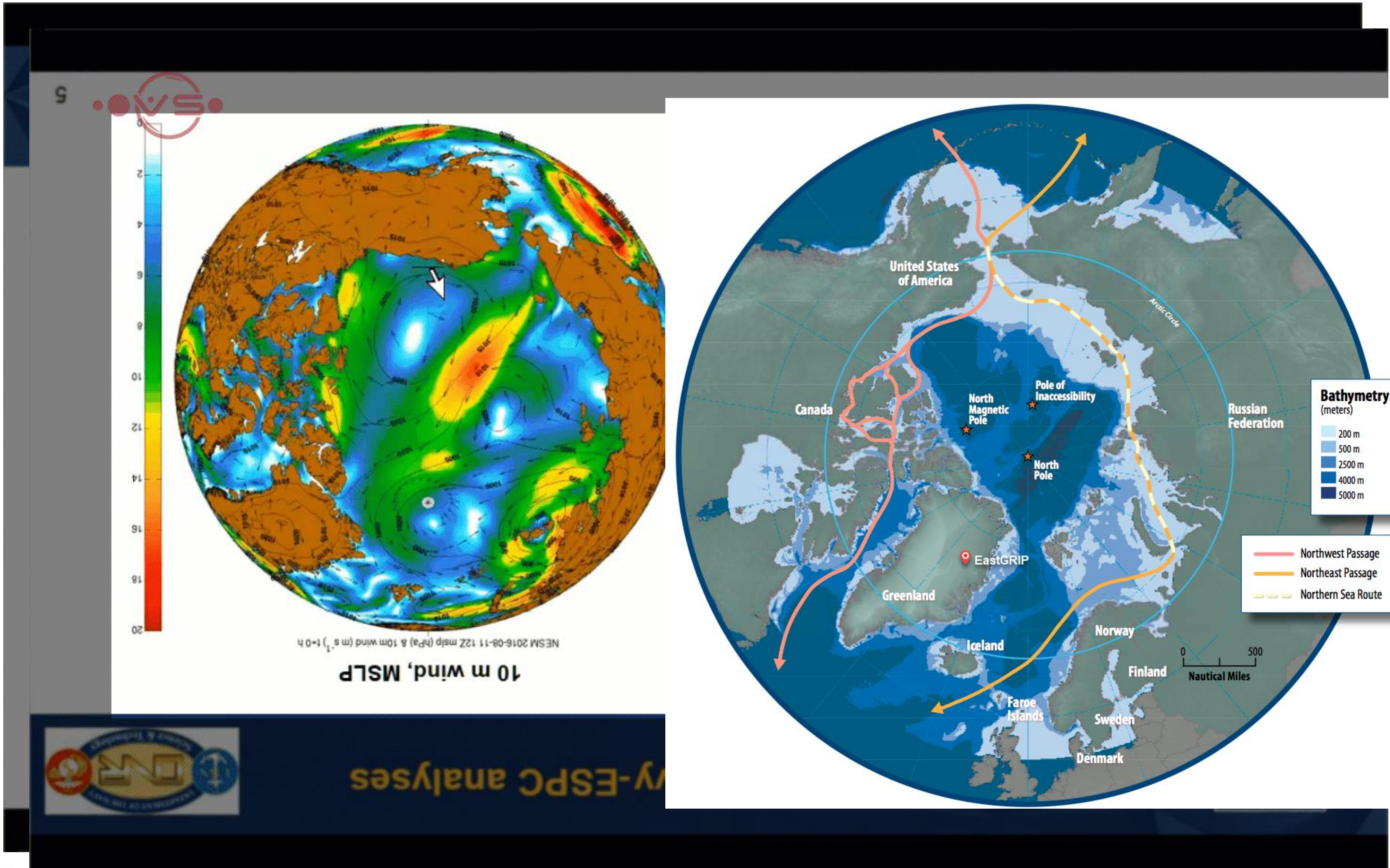
- Government/Military Responsive Space
  - USSOCOM 19.3 SBIR 2019
    - Nanosatellite, 1-10 kg, payloads for ISR
    - Rapid collection and dissemination of actionable data
    - CONOPS of user in theatre issue ISR request to constellation
  - Dependency on space domain
    - Operation Desert Storm or “First Space War”
      - GPS/PNT reliance
  - Problems facing large constellations
    - Launch services demands
    - Constellation replenishment scheduling
    - Fixed terrestrial launches easily tracked
    - Denial of space-based resources
      - EW, Cyber, ASAT



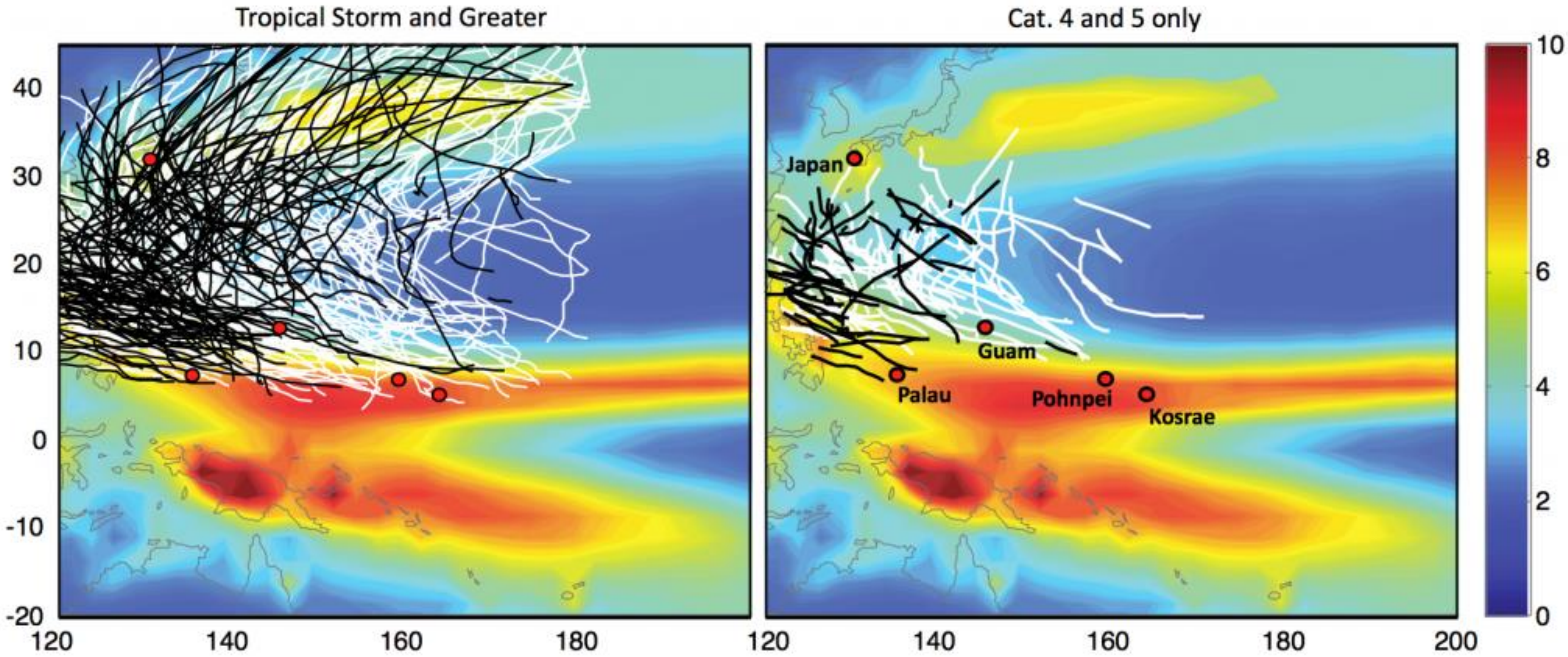
Motivation (2/5)

- Physically remote/extreme science return
  - Support science return from ice sheet, snow pack, and soil moisture measurements
  - Hazardous conditions can pose threats to scientific and remote missions
  - Also poses threat to Navy maritime operations and national security
- Arctic Cyclones
  - Two Great Arctic Cyclones (2012 & 2016)
  - Each only *predicted 72 hours beforehand*
  - Co-located with rapid sea ice loss events
    - Pose hazardous weather, sea, and ice conditions
- Tropical Cyclones in NW Pacific Ocean
  - Most active cyclone basin on planet
  - Affected include China, Hong Kong, Japan, Korea, Phillipines, Taiwan, Guam, American Samoa, Singapore, and other Oceanian islands

Motivation (3/5)

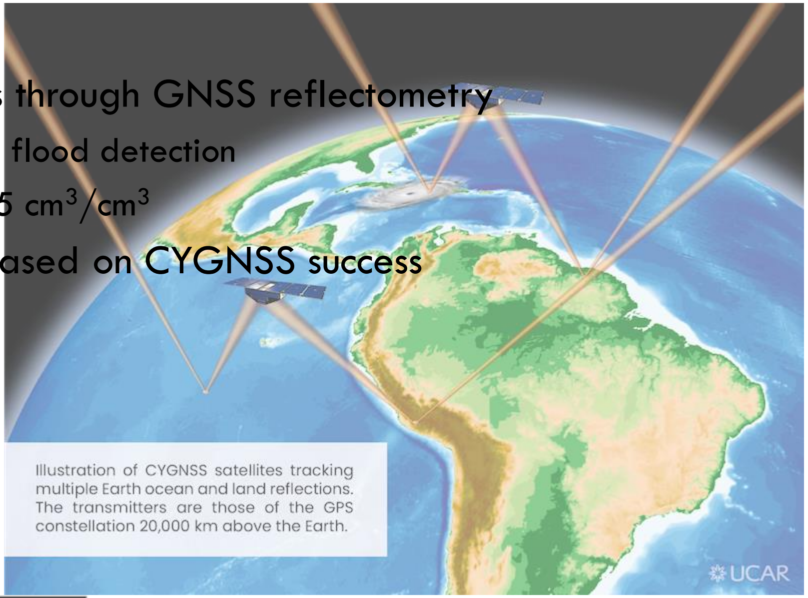


Motivation (4/5)



Motivation (5/5)

- Disaster response
  - Puerto Rico Earthquakes
    - Culminates on 7 Jan 2020 with 6.4 magnitude
      - Small quakes starting 28 Dec 2019
    - C-band SAR and optical used for mapping, imagery, and analysis
      - Identifying damaged structures, surface displacement, and possible landslides
      - Sentinel-1, Maxar Technologies, and Planet
  - Hurricanes/Flood monitoring
    - CYGNSS measures wind speeds in cyclones through GNSS reflectometry
      - Can also monitor soil moisture and provide flood detection
      - RMS between CYGNSS and SMAP is 0.045 cm^3/cm^3
    - Spire Global launched two 3U CubeSats based on CYGNSS success
      - Operational as of 2 Jan 2020



Optimized scheduling of airborne launch vehicles

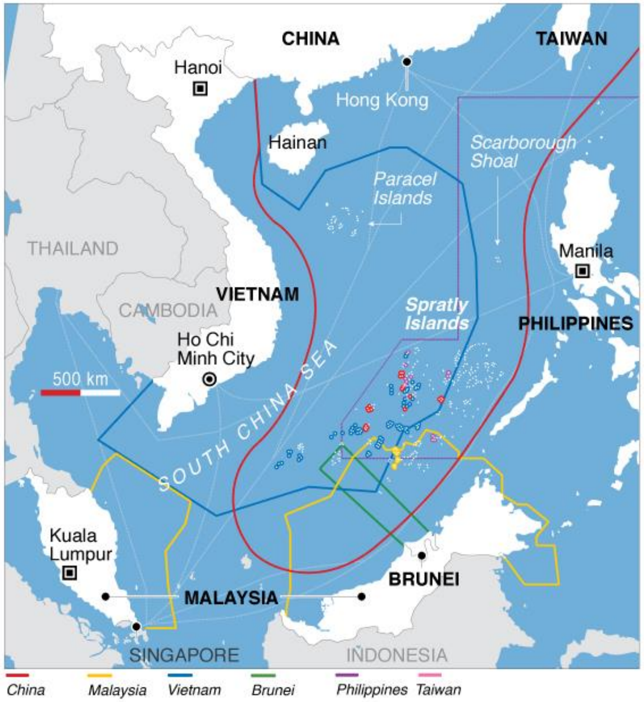
OBJECTIVES

Objectives – Use the motivation

- Taiping Island coverage requested
  - $t_{RT} < 2$ hr, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right] = 0$, $\max(G_t) = 0$, $C_{per} = 1.00$
  - 8 available satellites
    - Maxwell AFB/ HMS Queen Elizabeth/ Pearl Harbor/ Ørland Air Base
- Northern Sea Route coverage requested
  - $t_{RT} < 8$ hr, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right] = 1$ hr, $\max(G_t) = 3$ hr, $C_{per} = 0.80$
  - 4 available satellites
    - MCAS Iwakuni/ HMS Queen Elizabeth
- Tropical cyclone near Marshall Islands
  - $t_{RT} < 4$ hr, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right] = 3$ hr, $\max(G_t) = 6$ hr, $C_{per} = 1.00$
  - 6 available satellites
    - Maxwell AFB/NAWCWD Point Mugu/ Pearl Harbor

Objectives – Case #1

- Taiping Island coverage requested
  - $t_{RT} < 2$ hr, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right] = 0$, $\max(G_t) = 0$, $C_{per} = 1.00$
  - 8 available satellites
    - Maxwell AFB/ HMS Queen Elizabeth/ Pearl Harbor/ Ørland Air Base

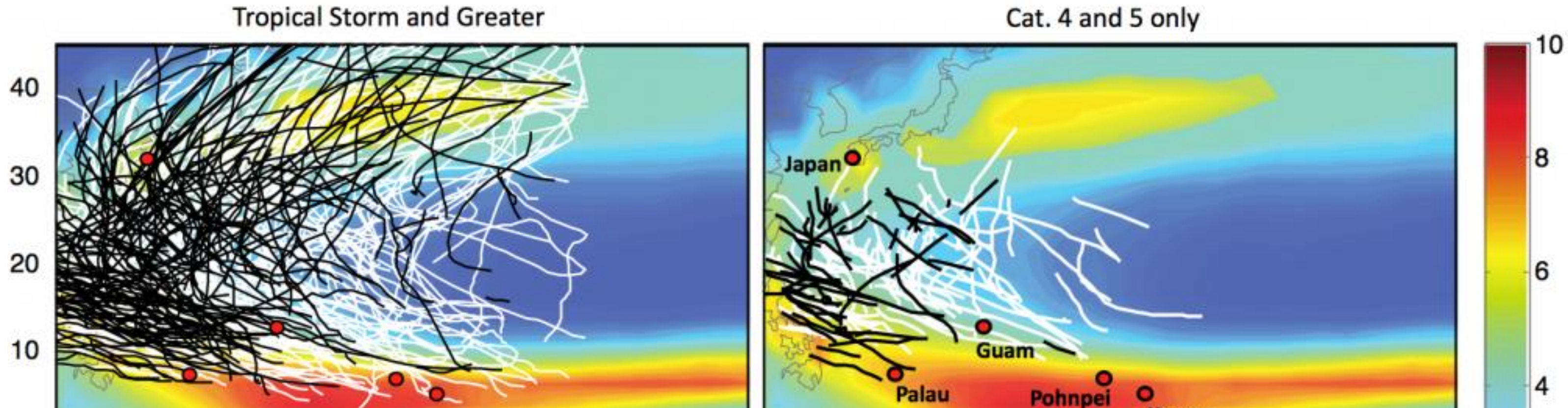


Objectives – Case #2

- Northern Sea Route coverage requested
  - $t_{RT} < 8$ hr, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right] = 1$ hr, $\max(G_t) = 3$ hr, $C_{per} = 0.80$
  - 4 available satellites
    - MCAS Iwakuni/ HMS Queen Elizabeth

Objectives – Case #3

- Tropical cyclone near Marshall Islands
  - $t_{RT} < 4$ hr, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right] = 3$ hr, $\max(G_t) = 6$ hr, $C_{per} = 1.00$
  - 6 available satellites
    - Maxwell AFB/NAWCWD Point Mugu/ Pearl Harbor



Response time and quality coverage

QUANTIFICATION

Quantification – Response Time (1/3)

- Minimize response time

$$E[t_{RT}] = E\left[t_{tasking} + t_{a/c} + t_{LV} + t_{sat} + t_{downlink}\right]$$

$$\min(E[t_{RT}]) = E\left[t_{a/c} + t_{LV}\right] + \min(E[t_{sat} + t_{downlink}])$$

- Assumptions
  - Tasking time, $t_{tasking}$, is fixed
    - An ATO has been received
    - Execution planning and force execution stage (30 min)
  - Loadout and flight time to drop point, $t_{a/c}$, is fixed for each site
    - No holds on launch
    - Flight profile dependent on a/c launch point
  - Airborne launch vehicle flight time, t_{LV}, varies from 3-5 min
    - Dependent upon orbit injection altitude (200-300 km apogee)
    - Improving on 3-5 min of LV flight time is a design problem (out of scope)
  - Nanosatellite has no thrust capability

Quantification – Response Time (2/3)

- Assumptions for launch vehicle
  - Airborne launch vehicle flight time, t_{LV}, varies from 3-5 min
    - Dependent upon orbit injection altitude (200-300 km apogee)
    - Improving on 3-5 min of LV flight time is a design problem (out of scope)
    - TOF to 200 km using Pegasus XL flight data
    - Some inaccuracy because still performing g-turn
  - Using AIM-120 dimensions
    - Payload of 1-10 kg (nanosatellite)
  - ΔV cost met using two stage SP-1a/LOX

Stage	Motor	Length (m)	Case Dia (m)	Segments	Nozzle Dia (m) Throat	Nozzle Dia (m) Exit	Prop (kg)	Ins (kg)	Case (kg)	Nozzle (kg)	Igniter (kg)	Misc. (kg)	Total (kg)	f_{prop}	f_{inert}	f_{pay}
Stage 1	SP-1a/LOX	1.8288	0.18	1	0.0889	0.18	38.371	0.8368	1.7289	0.7428	0.0287	0.0663	41.77413	0.918526	0.081474	0.239383
Stage 2	SP-1a/LOX	0.8950	0.18	1	0.0889	0.18	18.777	0.4694	0.8283	0.7371	0.0329	0.0615	20.90661	0.898156	0.101844	0.478318

Stage	Motor	Pc (Mpa)	Pc (max) (Mpa)	ε_0	tb (s)	F_v (Avg) (kN)	$I_{sp,v}$ (s)	I (N-s)	ΔV_{amraam} (m/s)	ΔV_{req} (m/s) (Ideal)	Feasible	Value Check	Feasibility condition for motor
Stage 1	SP-1a/LOX	5.84	7.38	35.2	72.4	488.9	372	140026.714	4931.60	5110.0036	TRUE	0.6695206	$1 - f_{inert} e^{\frac{\Delta V}{I_{sp} g_0}} \le 0$
Stage 2	SP-1a/LOX	5.83	6.76	50.3	73.3	118.4	372.0	68524.6993	3413.40	3235.1731	TRUE	0.5868923	
									8345.00	8345.18			

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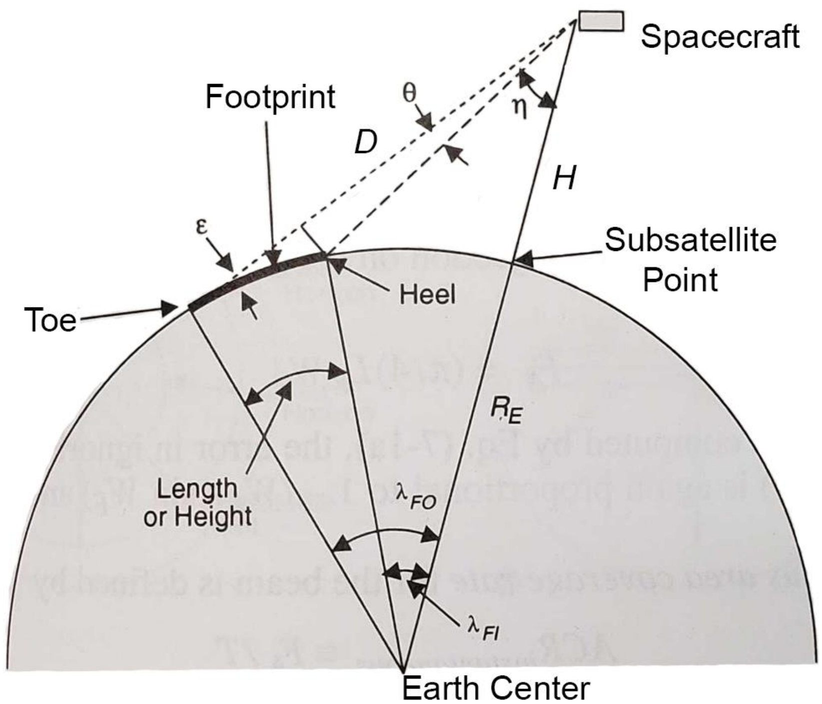
Quantification – Response Time (3/3)

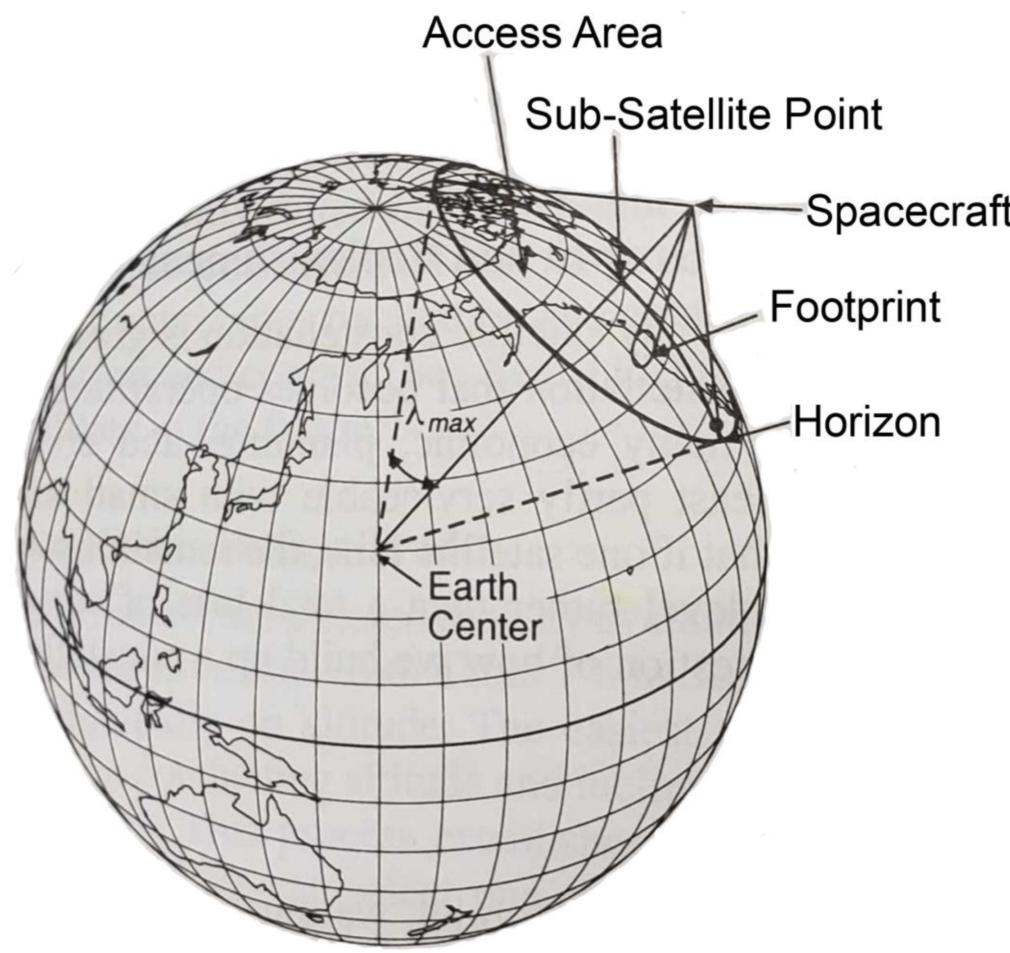
- Minimize response time

$$\min(E[t_{sat} + t_{downlink}])$$

- Orbital mechanics and field of regard (access area)
  - Time from satellite injection until first light (view) of target, t_{sat}
    - Launching directly towards target will be shortest TOF
    - Works great for targets with ground station at target
  - Time from view/data collection until downlink, $t_{downlink}$
    - If ground station collocated with target, $t_{downlink} = 0$
  - Earliest Arrival Time at Destination (EATD)
    - Used if ground station not collocated with target
    - Only certain orbits would be admissible

Quantification – Quality of Coverage (1/3)





Quantification – Quality of Coverage (2/3)

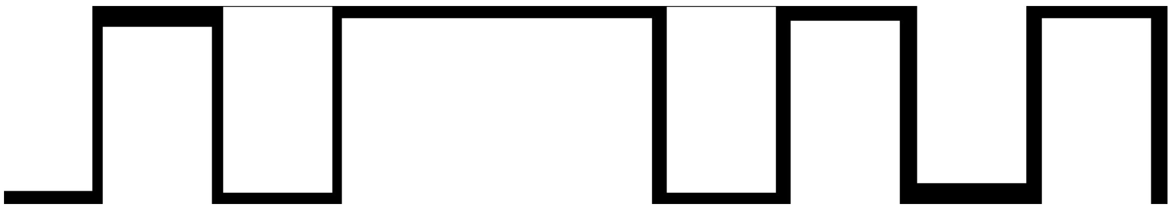
- Quality of coverage constraint

$$Q = \left[-\eta_0 E\left[\frac{\Sigma G_t^2}{\Delta t}\right] - \eta_1 \max(G_t) + \eta_2 C_{per} \right] - E[t_{RT}]$$

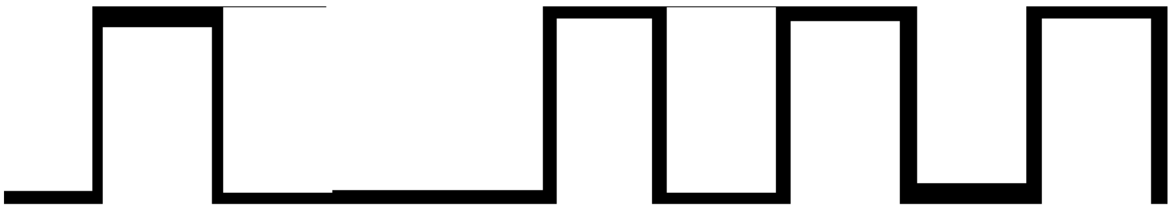
- Time-Averaged Gap (TAG)
  - TAG, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right]$, is the mean gap duration averaged over time
  - Best measurement of quality besides MRT
- Maximum gap duration
  - Maximum gap, $\max(G_t)$, is the longest gap duration in the window
- Percent coverage, C_{per}
  - Number of times a point is covered divided by number of time steps

Quantification – Quality of Coverage (3/3)

- Example calculation (10 time steps, GS collocated)
  - A



  - B



	Percent Coverage	Max Gap	Mean Gap	TAG	MRT	RT
A	60%	1	1	0.4	0.4	1
B	40%	3	1.5	1.2	0.6	1

Incorporate quality metrics into software package

PLAN OF ATTACK

SIMPSON AEROSPACE

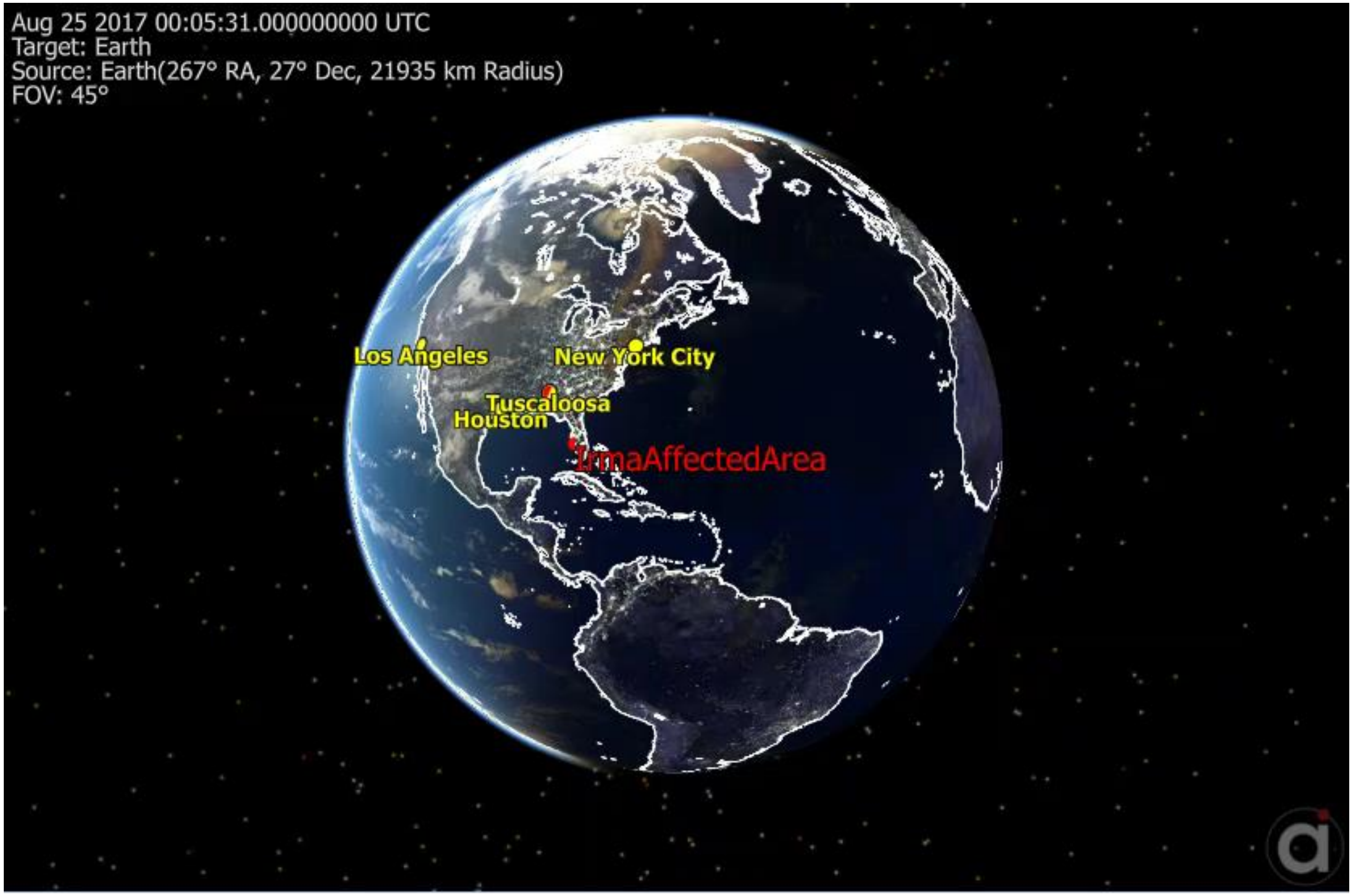
THE UNIVERSITY OF ALABAMA | College of Engineering

Plan of Attack – Incorporate metrics (1/4)

- Software packages
  - Combine a high-fidelity flight dynamics package with an available optimization package
    - FreeFlyer, flight dynamics from a.i. solutions, Inc.
    - CPLEX Optimization Studio from IBM
  - Provide constrained solutions to FreeFlyer
- FreeFlyer supports spacecraft operations
  - Used in modeling and real operations
    - ISS at Johnson Space Center
    - James Webb Flight Dynamics Team
    - MMS
    - Restore-L mission
  - APIs for Python, C#, C++ scripting
    - Often scripting done in program
  - Connects to MATLAB

Plan of Attack – Incorporate metrics (2/4)

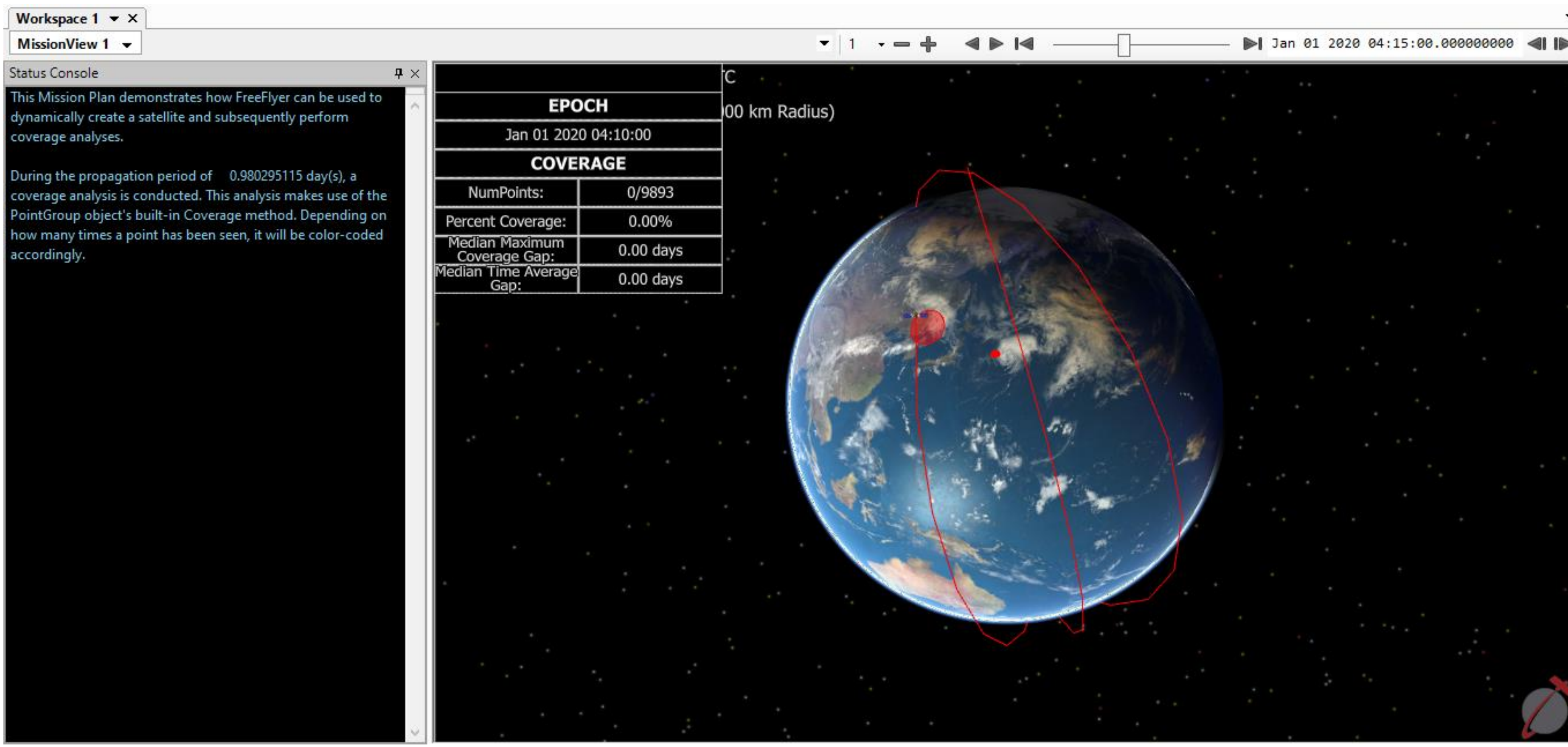
- Demonstration of time-limited solution



Plan of Attack – Incorporate metrics (3/4)

- CPLEX Optimization Studio from IBM
  - Integer programming
    - Very large linear problems
  - Convex and non-convex quadratic programming
  - Convex quadratically constrained problems
  - APIs for Python, C#, C++
    - Connectors to MATLAB and Excel

Plan of Attack – Incorporate metrics (4/4)



Estimated time to complete and defend

SCHEDULE

Schedule – Orbits and Constellations

- Orbital Mechanics
  - Develop or procure software that will incorporate satellite dynamics with a high degree of fidelity
    - **16 Jan 2020 – COMPLETED**
- Satellite Coverage Figures of Merit
  - Percent Coverage – COMPLETED
  - Maximum Gap Duration – COMPLETED
  - Time-Averaged Gap
    - **13 Feb 2020 – BEHIND SCHEDULE**
- Satellite Lifetime (i.e. Mission Lifetime)
  - Perturbation effects at injection altitude
    - Directly dependent upon launch vehicle flight profile
    - The lower the altitude of the orbit the sooner the satellites will deorbit
    - **12 Mar 2020 – BEHIND SCHEDULE**

Schedule – Airborne Launch Vehicles (1/2)

- Flight profile of current airborne launch vehicles
  - Determine the ΔV cost of Pegasus XL and LauncherOne for LEO injections
    - **30 Jan 2020 – COMPLETED**
- Carrier aircraft flight profile
  - Use the L-1011 flight plan during a Pegasus XL launch to develop a flight plan for an F-35C
  - Release conditions of drop
    - Use the max speed of the F-35C
    - At similar altitude of L-1011
    - **2 Apr 2020 – ON SCHEDULE**

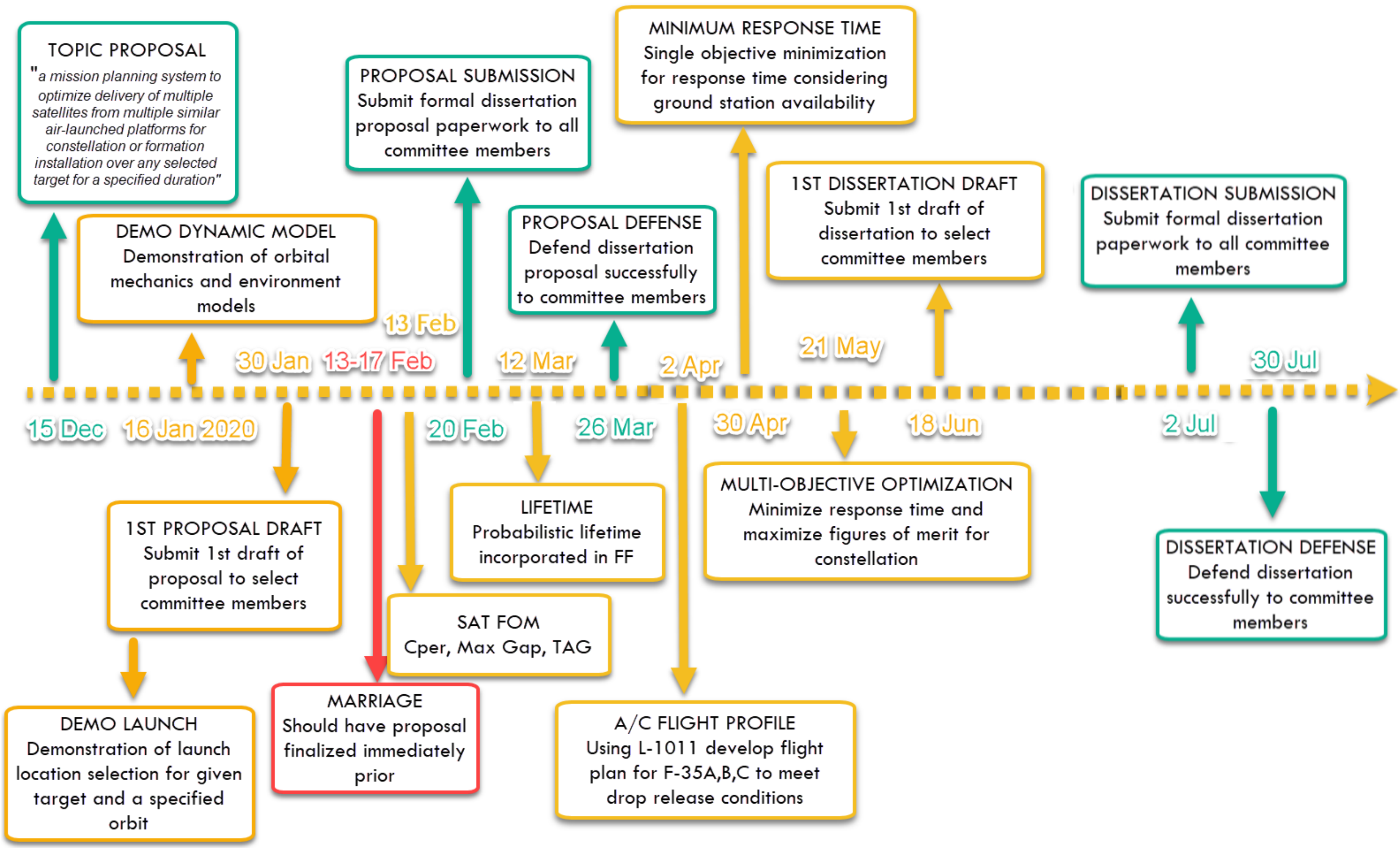
Schedule – Airborne Launch Vehicles (2/2)

- Lambert targeting
  - Write a script to determine the ΔV cost of an AMRAAM to direct injection
    - Dropped at max speed of F-35C
    - Similar altitude of L-1011
    - **30 Jan 2020 – COMPLETED**
- Estimated flight profile for AMRAAM type
  - Use flight profile of Pegasus XL and LauncherOne
    - Use estimated propellant stored to determine capabilities
    - Find max altitude capable
  - Compare ΔV from estimated profile and Lambert Targeting
    - **30 Jan 2020 – COMPLETED**

Schedule – Agile Launch

- Considering $\min(t_{RT})$
  - Single objective optimization for $\min(t_{RT})$
    - Consider communications at point or at another target location
    - Show EATD has or does not have applications formulated as MILP
    - **2 Apr 2020 – ON SCHEDULE**
- Multi-objective optimization
  - Minimize response time and maximize FOM
    - $Q = \left[-\eta_0 E\left[\frac{\Sigma G_t^2}{\Delta t}\right] - \eta_1 \max(G_t) + \eta_2 C_{per}\right] - E[t_{RT}]$
    - Show whether EATD/TSP with prizes have applications as MILP
    - **30 Apr 2020 – ON SCHEDULE**

Schedule


TOPIC PROPOSAL
"a mission planning system to optimize delivery of multiple satellites from multiple similar air-launched platforms for constellation or formation installation over any selected target for a specified duration"
DEMO DYNAMIC MODEL
Demonstration of orbital mechanics and environment models
PROPOSAL SUBMISSION
Submit formal dissertation proposal paperwork to all committee members
PROPOSAL DEFENSE
Defend dissertation proposal successfully to committee members
MINIMUM RESPONSE TIME
Single objective minimization for response time considering ground station availability
1ST DISSERTATION DRAFT
Submit 1st draft of dissertation to select committee members
DISSERTATION SUBMISSION
Submit formal dissertation paperwork to all committee members
13 Feb
30 Jan
13-17 Feb
12 Mar
2 Apr
21 May
30 Jul
15 Dec
16 Jan 2020
20 Feb
26 Mar
30 Apr
18 Jun
2 Jul
1ST PROPOSAL DRAFT
Submit 1st draft of proposal to select committee members
LIFETIME
Probabilistic lifetime incorporated in FF
MULTI-OBJECTIVE OPTIMIZATION
Minimize response time and maximize figures of merit for constellation
DISSERTATION DEFENSE
Defend dissertation successfully to committee members
SAT FOM
Cper, Max Gap, TAG
DEMO LAUNCH
Demonstration of launch location selection for given target and a specified orbit
MARRIAGE
Should have proposal finalized immediately prior
A/C FLIGHT PROFILE
Using L-1011 develop flight plan for F-35A,B,C to meet drop release conditions

Autonomous scheduling for rapid responsive launch

SUMMARY

Summary – Technical Approach (1/4)

- Minimize response time

$$E[t_{RT}] = E\left[t_{tasking} + t_{a/c} + t_{LV} + t_{sat} + t_{downlink}\right]$$

$$\min(E[t_{RT}]) = E\left[t_{tasking} + t_{a/c} + t_{LV}\right] + \min(E[t_{sat} + t_{downlink}])$$

- Minimize response time with quality of coverage constraints

$$Q = \left[-\eta_0 E\left[\frac{\Sigma G_t^2}{\Delta t}\right] - \eta_1 \max(G_t) + \eta_2 C_{per}\right] - E[t_{RT}]$$

- Software packages
  - Combine a high-fidelity flight dynamics package with an available optimization package
    - FreeFlyer, flight dynamics from a.i. solutions, Inc.
    - CPLEX Optimization Studio from IBM

Summary – Objective (2/4)

- Minimize response time to under an hour
  - This includes tasking to downlink of the request
- Maximize quality of coverage
  - Minimize TAG, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right]$, max gap, $\max(G_t)$, and response time, $E[t_{RT}]$
  - Maximize percent coverage, C_{per}

Summary – Objective (3/4)

- Taiping Island coverage requested
  - $t_{RT} < 2$ hr, $E\left[\frac{\Sigma G_t^2}{\Delta t}\right] = 0$, $\max(G_t) = 0$, $C_{per} = 1.00$
  - 8 available satellites
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Summary – Schedule (4/4)