A CubeSat Mission for Locating and Mapping Spot Beams of GEO Comm-Satellites

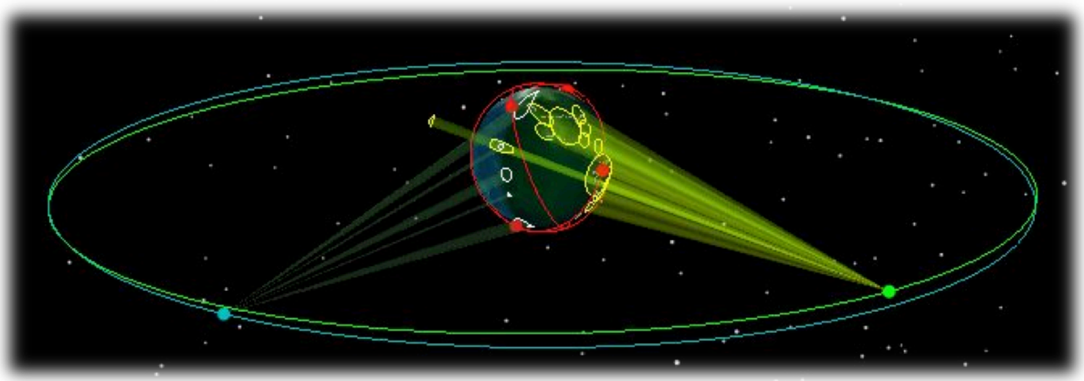
Lt. Jake LaSarge

<u>PI:</u>
Dr. Jonathan Black
Dr. Brad King
Dr. Gary Duke

August 9, 2015

Outline

- Background & Motivation
- Spot Beam Mapping Mission + OV-1
- Design of Mission Model
- Software Tools
- Developed Simulations & Results
- Features of Operation
- Conclusion / Future Work



Background

Radio Frequency domain verification from GEO… tied with small satellite mission development concepts

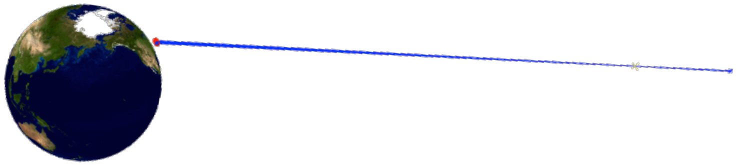
-- Future space environment

- Increased congestion
- Increasingly contested
- Increasingly competitive

Especially at GEO!

-- GEO Spot beam mapping

- Analogous constellation-based RF collection missions
- Enhance RF domain knowledge
- Identify coverage areas



-- Small Satellites (i.e. disaggregation)

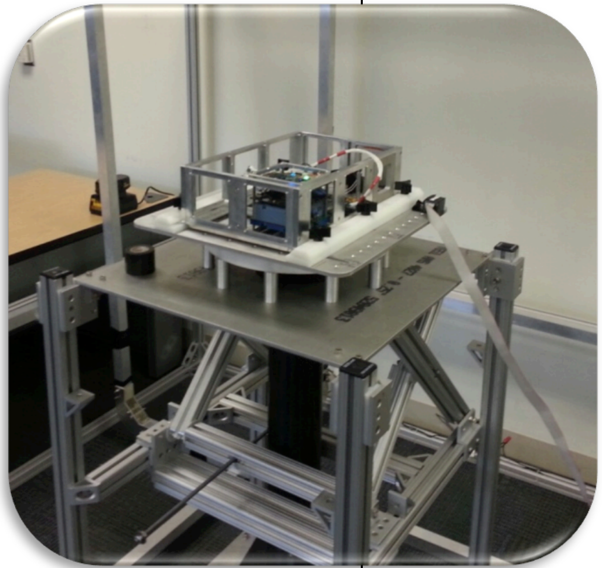
- May reduce costs vs. larger space missions
- Maturing technology increases viability
- Missions include common features / architectures

-- AFIT CubeSat Research

- Mission Analysis and Payload/Bus Design
- Satellite Design and Test Sequence (6U CubeSat)
  1) Systems Engineering
  2) Spacecraft Analysis & Design
  3) Spacecraft Build & Test

-- RF Domain Verification / Analysis

- Identify spot beam locations (space-ground links)
- Manage frequency allocations (avoid interference)
- Improve ground trace knowledge
  - Increase link efficiency
  - Identify areas of poor signal coverage

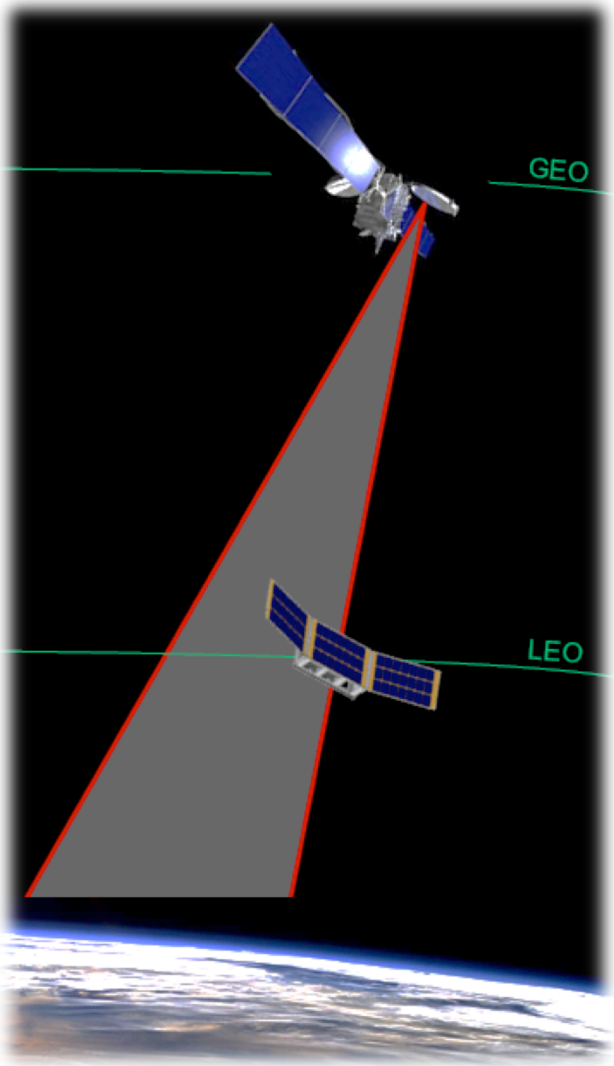


AFIT 6U CubeSat Testbed

Key Focus: **Is it possible to effectively map spot beams coming from GEO Comm-Satellites using a CubeSat constellation?**

The Mission

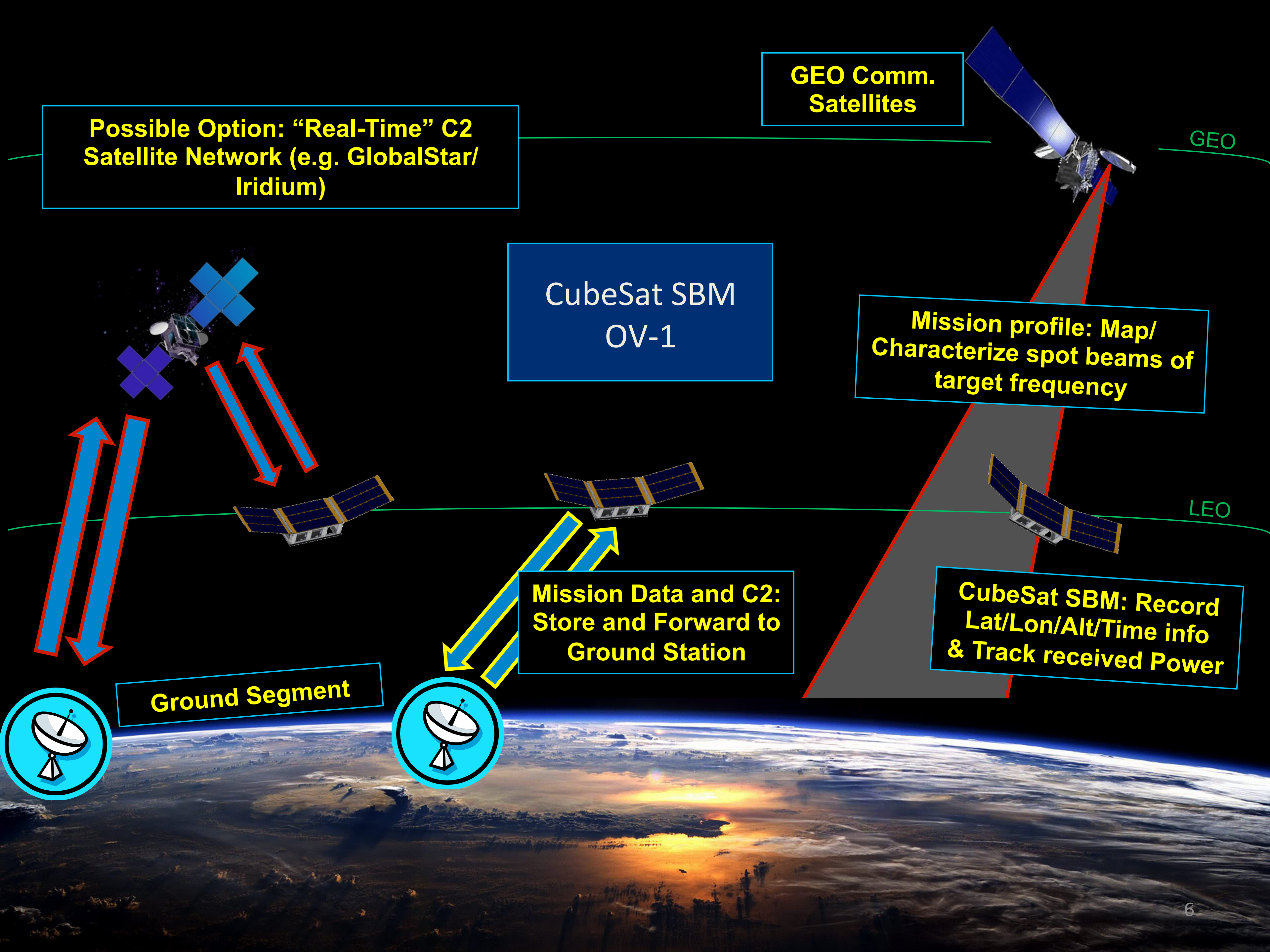
The AFIT of Today is the Air Force of Tomorrow.



Mission Statement: "Detect and map the boundaries of geostationary (GEO) communications satellites spot beams by flying a CubeSat(s) through the spot beams at a low earth orbit (LEO) altitude."

-- Map Spot Beams from GEO
- Frequency targets up to Ka-Band
- Sizes: "Continent" size down to "Island" size

-- CubeSat Bus / Payload
- Small/Simple form factor ==> Easy to integrate
- "Cheap," possibly even expendable
- 6U version assumed
- Smaller Hardware Emerging
  - RF Payloads
  - "Miniaturized" Bus Subsystems

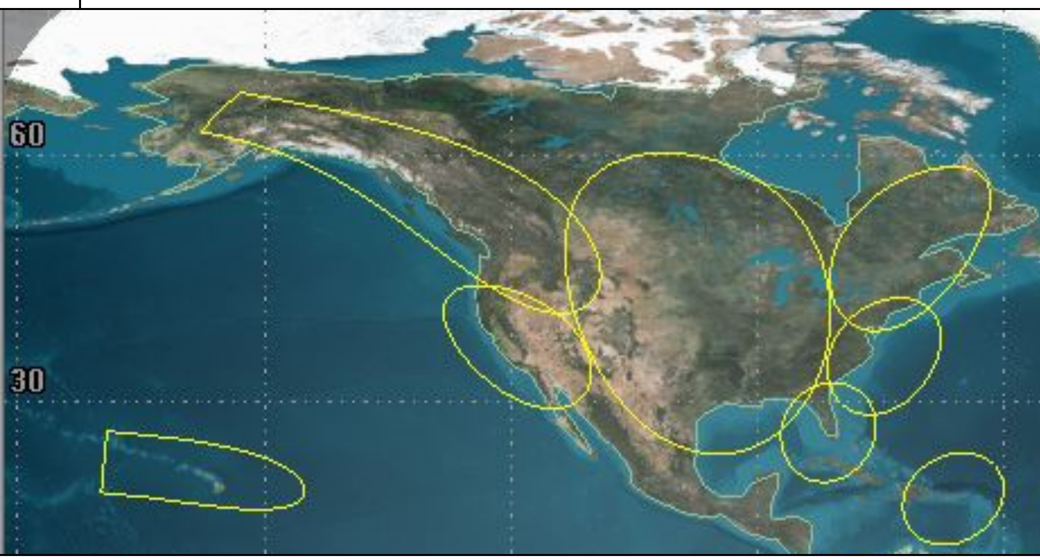

CubeSat SBM
OV-1
GEO Comm. Satellites
Possible Option: "Real-Time" C2 Satellite Network (e.g. GlobalStar/ Iridium)
GEO
LEO
Mission profile: Map/ Characterize spot beams of target frequency
Mission Data and C2: Store and Forward to Ground Station
CubeSat SBM: Record Lat/Lon/Alt/Time info & Track received Power
Ground Segment

Mission Model: Spot Beams

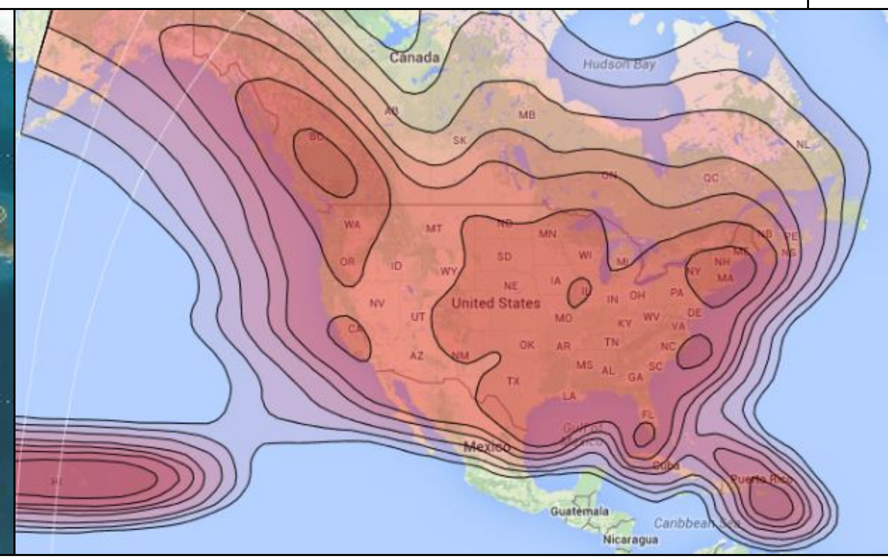
-- Objective: Simulate collections

-- Model beam patterns of "realistic" spot beams

- Chose Intelsat Galaxy 28 (G28) as a test case
- Ku-Band beams -- North and South America (~12 GHz), HPBW
- C-Band beams ignored (K-Band beams "harder" to find)



Model: North American Region
Intelsat Galaxy 28, Ku-Band Beams

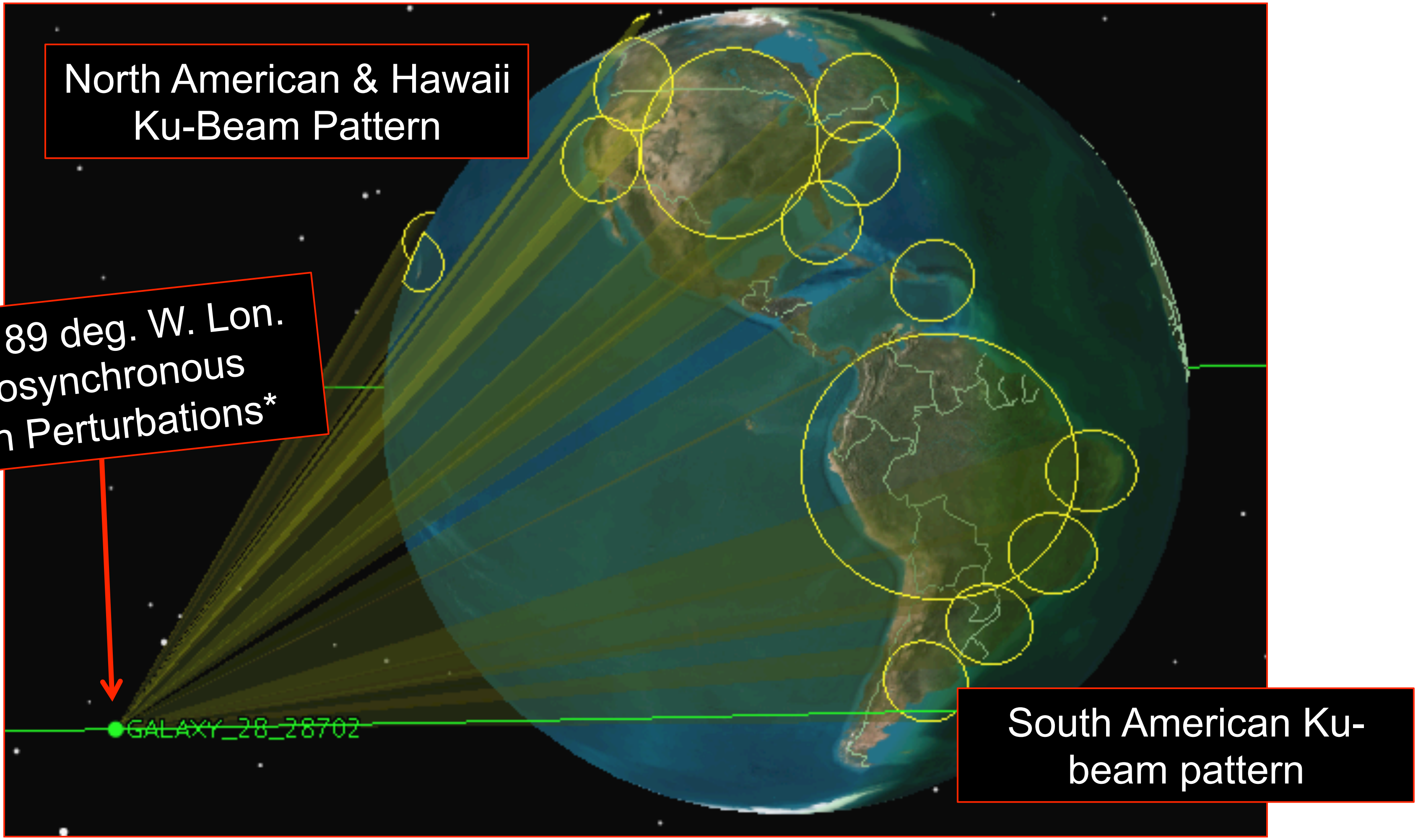


Reference Shape: Satbeams
Intelsat Galaxy 28, Ku-Band Beams

Note: Left is a spherical map projection, right is a Mercator (cylindrical) map projection!

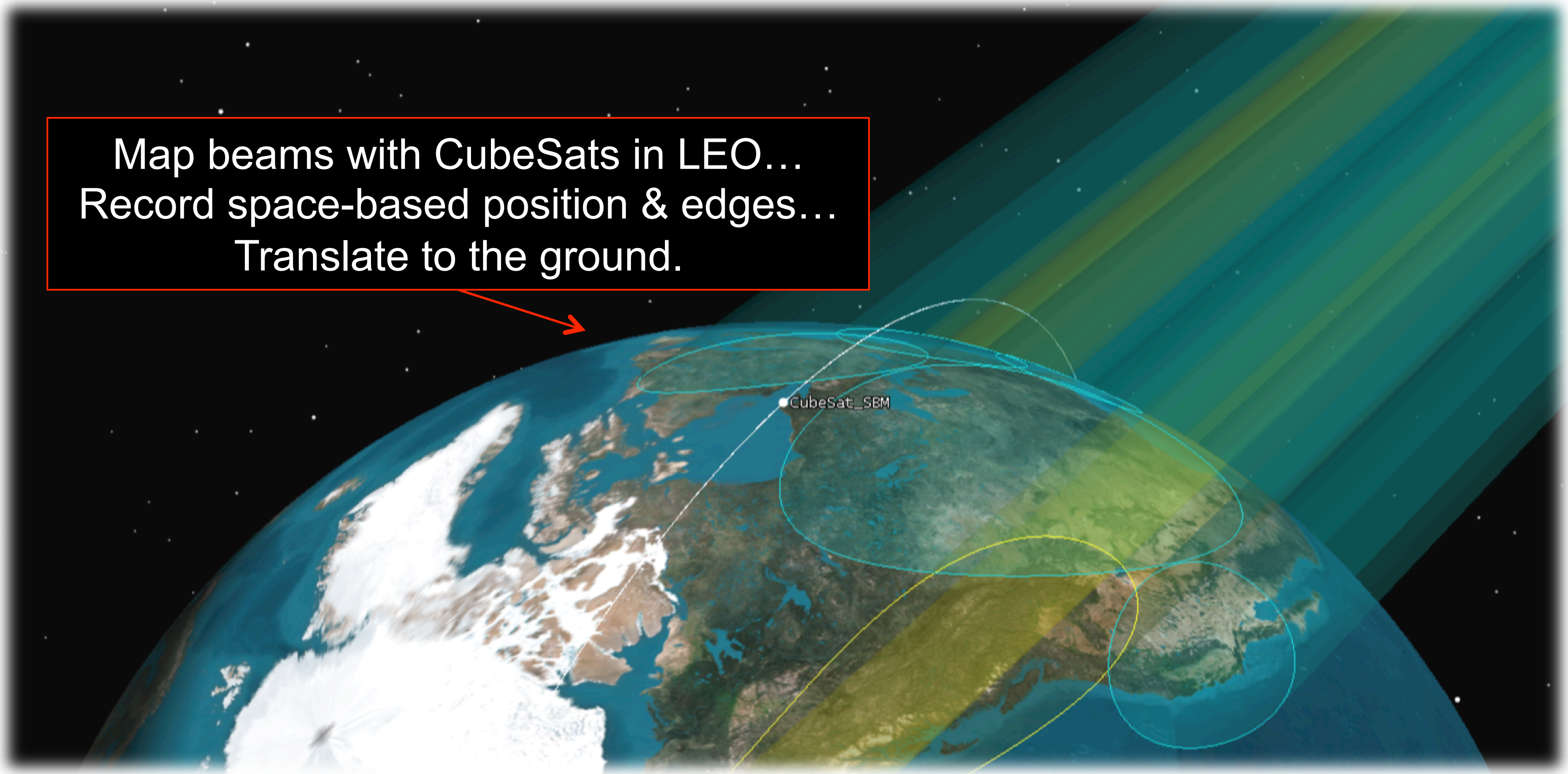
Model: Galaxy 28 Beams

The AFIT of Today is the Air Force of Tomorrow.



Full Version – Shows G-28 Position and South America Beams

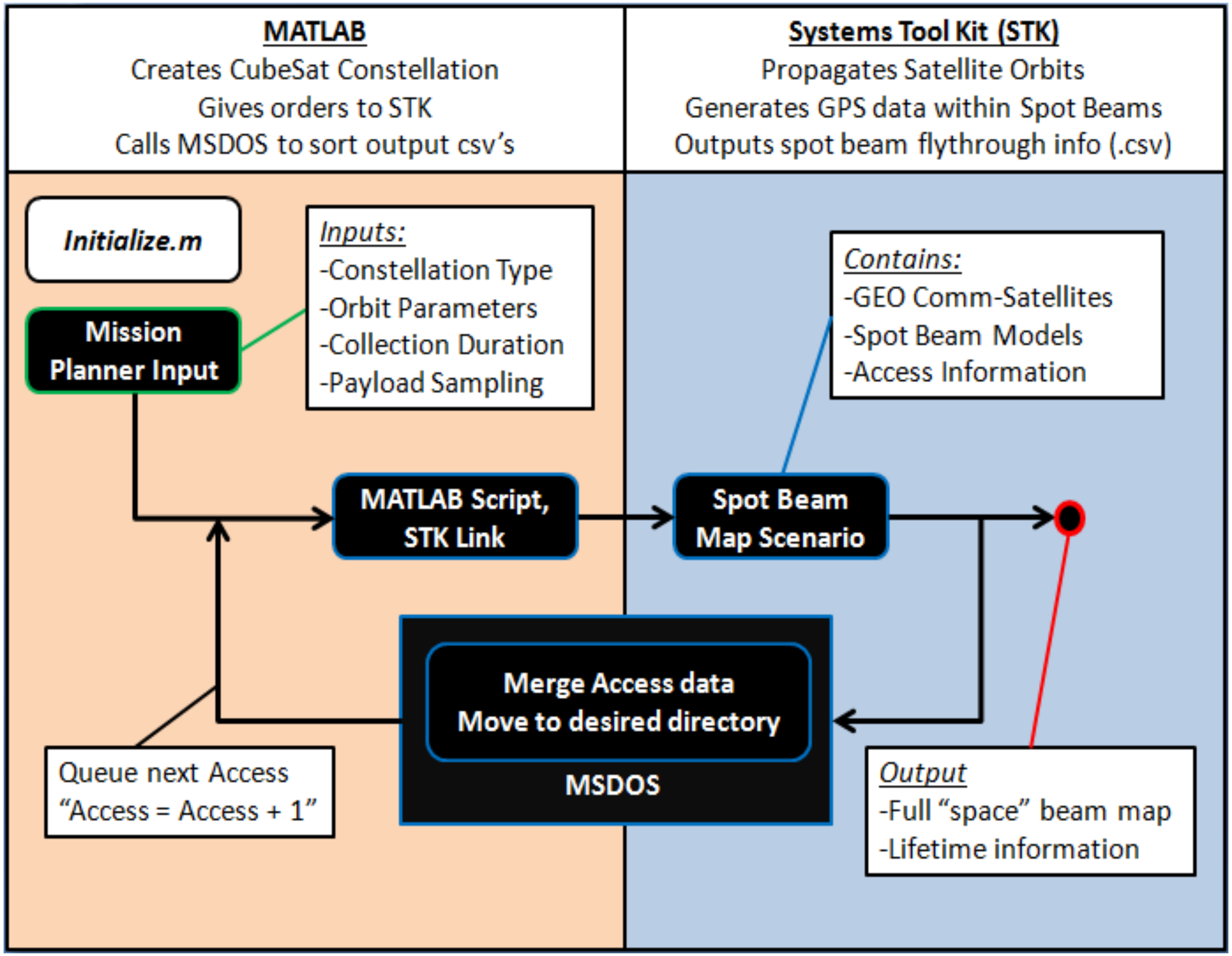
Mission Model: Map Concept



3D Beam Pattern – Spot beam mapper in LEO

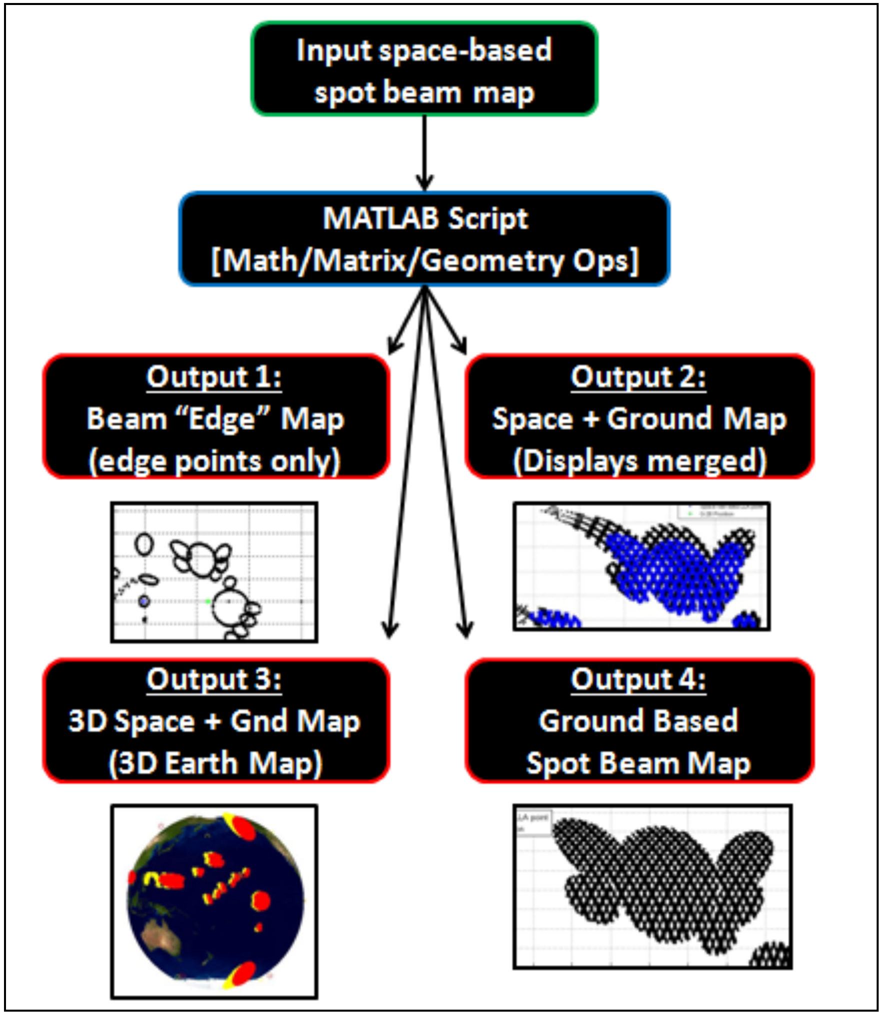
Simulation: Data Collection Tool

The AFIT of Today is the Air Force of Tomorrow.



Simulation: Map Generation Tool

The AFIT of Today is the Air Force of Tomorrow.



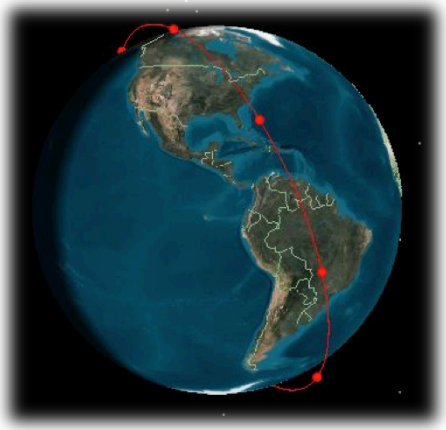
Input: Mission "space" data
- Payload collection (GPS)
- Gain information

Outputs:
- Beam edge locations
- "Full" space beam maps
- "Full" ground beam maps

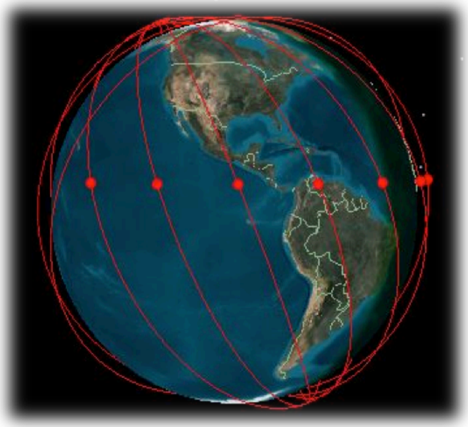
Can observe / analyze:
- Beam Patterns
- Size, position, spread of gaps
- Ground accuracy vs. STK
- Scenario change with time
- Gain patterns within beams

Simulation: Parameters

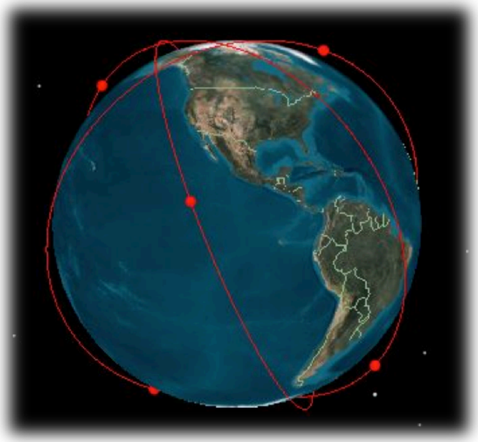
- **-- Constellation Types**
  - - Single Plane
  - - Multi-Plane
  - - Walker Delta
  - - "Formations"
- **-- Mission Altitudes**
  - 200 to 500 km
- **-- Mission Inclination**
  - 68,75,82,90,98
- **-- Payload Data Collection Rate**
  - 1, 5,10 seconds per data point
- **-- Number of CubeSats per Plane**
  - 1-6,8
- **-- Number of Orbital Planes**
  - 1 – 6 planes
- **-- CubeSat Spacing / Plane Spacing**
  - Even spacing vs. set sep. angle
- **-- Collection Duration**
  - 1 to 3 days



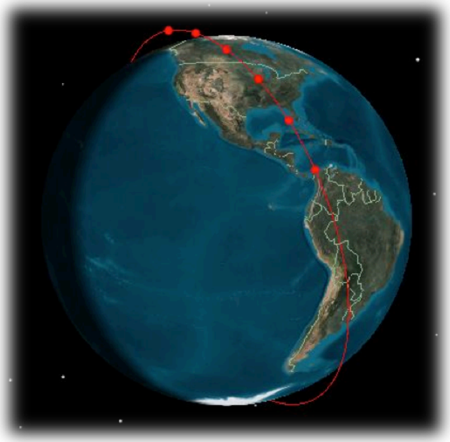
Single Plane



Multiple Plane



Walker Delta



Fixed separation angle "Formation"

Simulation: Altitude Considerations

Assumption: Fully loaded 6U CubeSat!

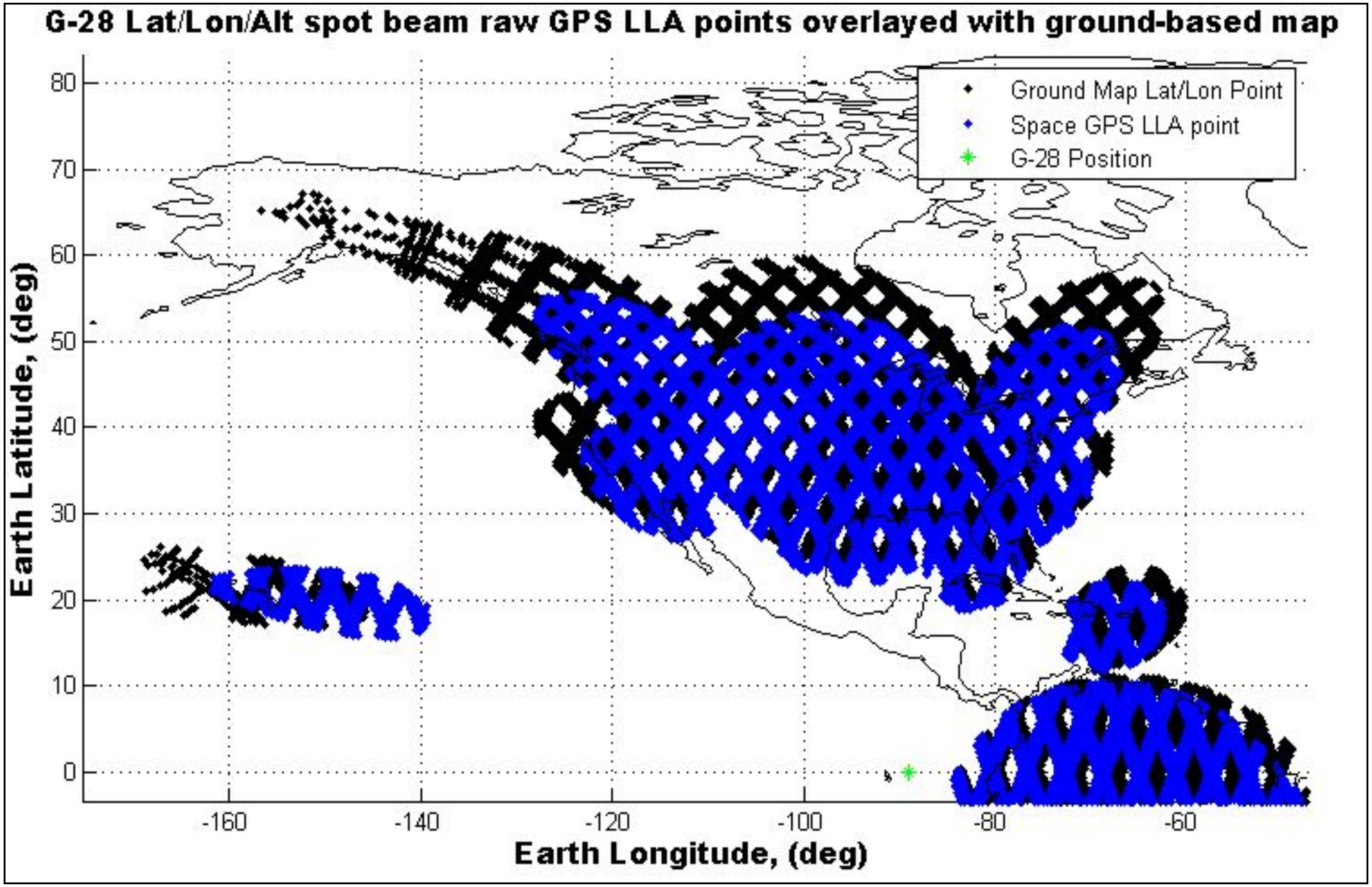
Orbit Altitude	Long Case Lifetime (days / years)	Intermediate Case Lifetime (days / years)	Short Case Lifetime (days / years)	Meets Mission Requirements?
200 km	9d / 0.025y	6d / 0.016y	3d / 0.008y	No
300km	167d / 0.45y	108d / 0.29y	51d / .14y	No
350km	584d / 1.6y	365d / 1y	177d / .48y	Possible
400km	2519d / 6.9y	1351d / 3.7y	548d / 1.5y	Yes
450km	5402d / 14.8y	4088d / 11.2y	2263d / 6.2y	Yes
500km	>9125d / 25y	8870d / 24.3y	4672d / 12.8y	Possible

Constant or Variable	Set Value
Drag Coefficient	2.2, models a "flat plate"
Solar Reflection Coefficient	1.0
Drag Area	0.06 square meters (short case) 0.03 square meters (intermed. case) 0.02 square meters (long case)
Satellite mass	12 kg (Fully loaded 6U) – long case 6 kg ("Light" 6U) – short case
Atmospheric Density Model	NRLMSIS-00 (Mass Spectrometer Incoherent Scatter) [37]

- 200 km: Too low
- 300 km: Too low
- 350km: Workable
- 400 km: Good
- 450 km: Good
- 500 km: Workable

Simulation: G-28 NA Beams Sample

The AFIT of Today is the Air Force of Tomorrow.

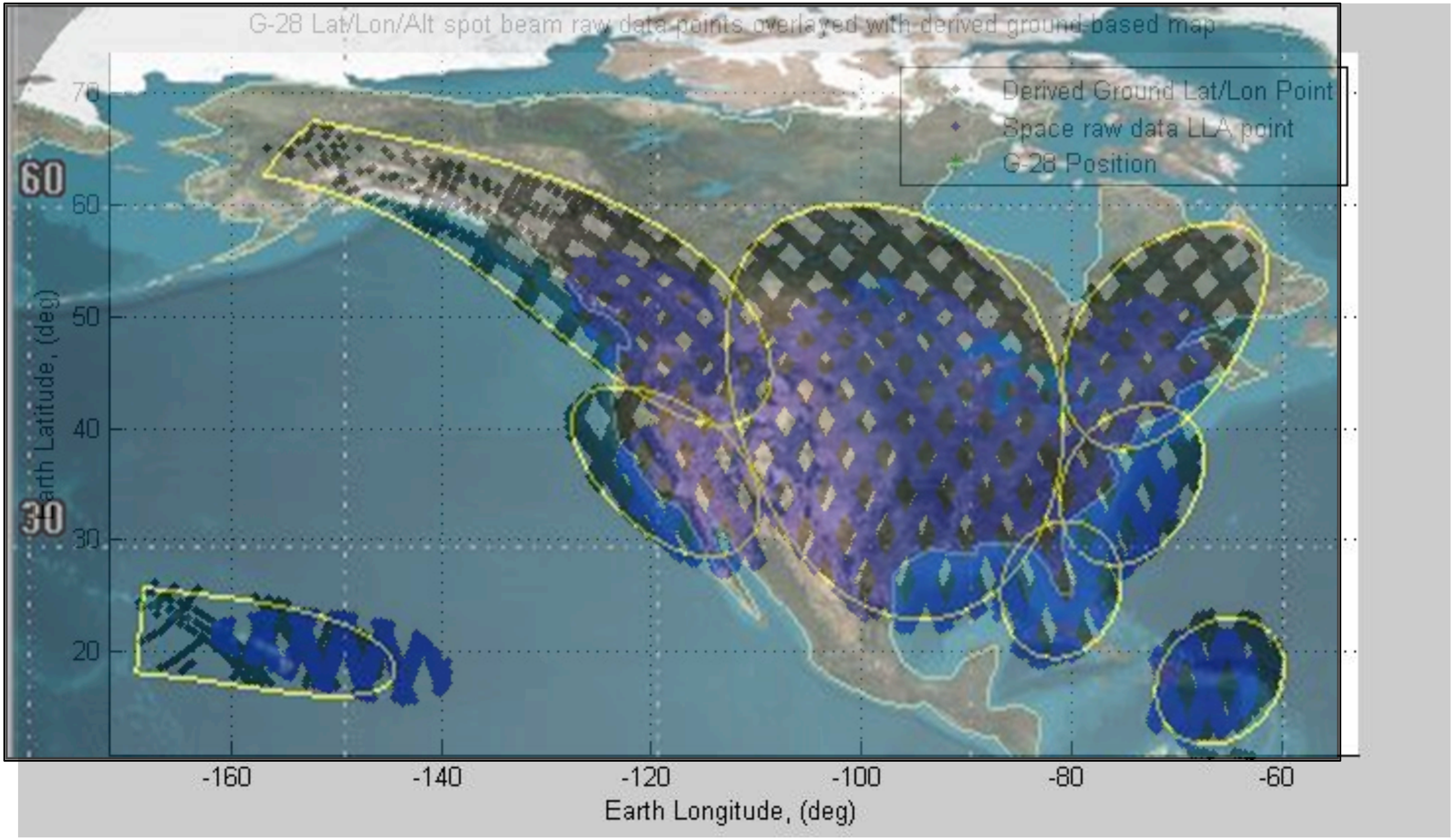


Space-based GPS collects mapped to Ground-based points.

68 deg / 350 km / 0.2 Hz / 1 Plane / 6 Satellites / 72 Hour Collection

Simulation: G-28 NA Beams Sample

The AFIT of Today is the Air Force of Tomorrow.

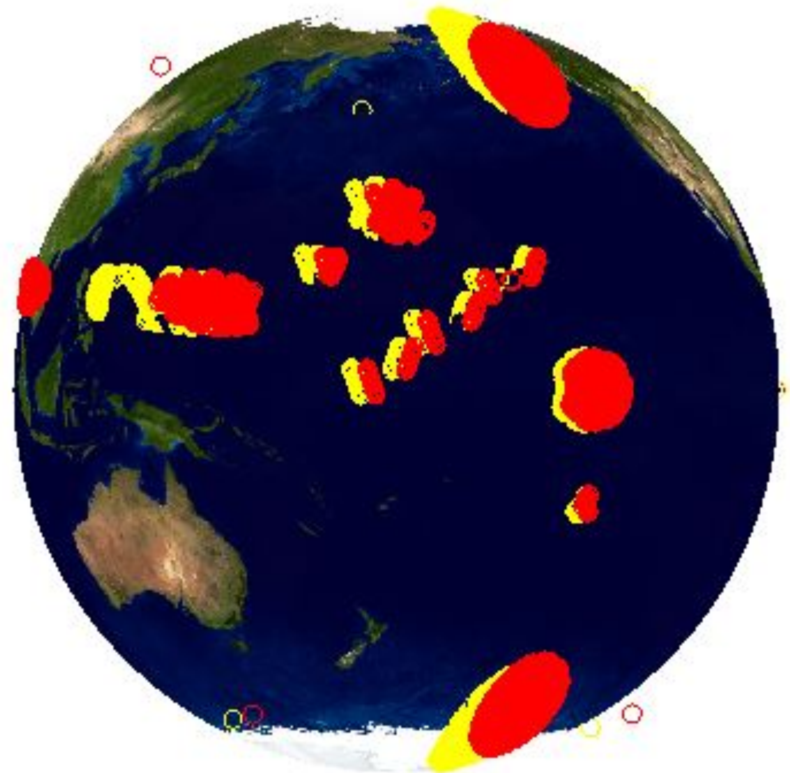


Space-based GPS collects mapped to Ground-based points.

68 deg / 350 km / 0.2 Hz / 1 Plane / 6 Satellites / 72 Hour Collection

Simulation: Applied in 3-D

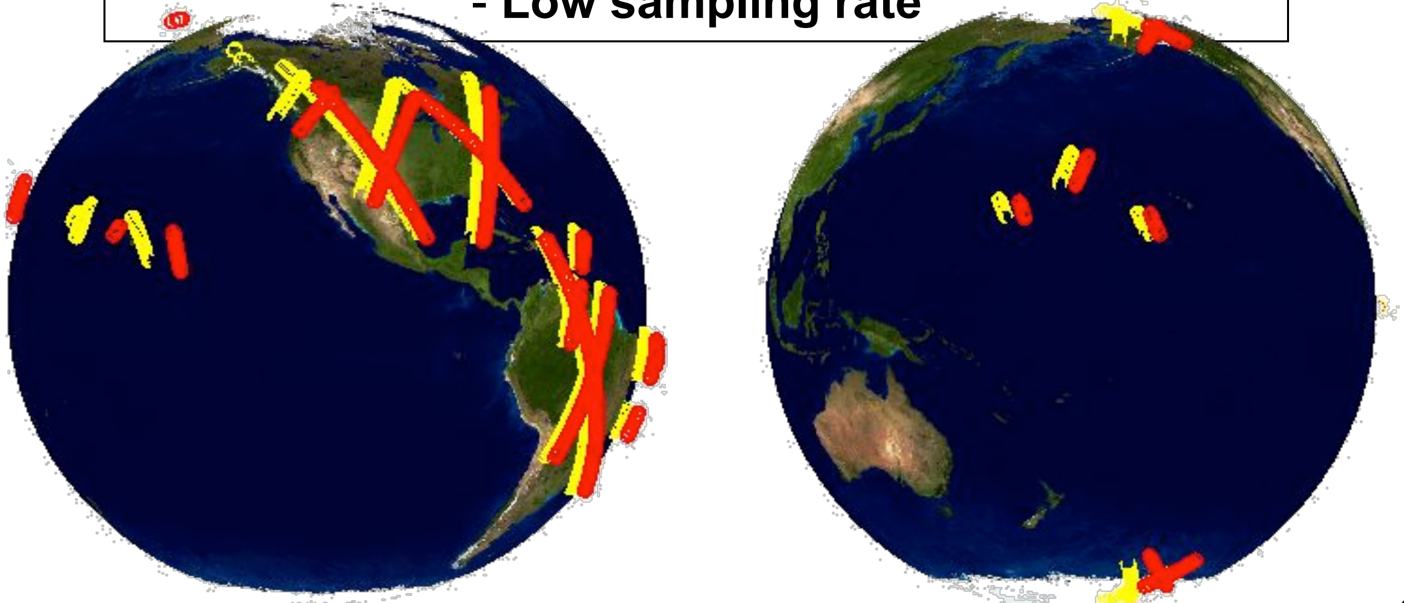
In 3D: Galaxy 28 Space-based GPS collects (Red) with ground trace map (Yellow)



In 3D: G-II Space-based GPS collects (Red) with ground trace map (Yellow)

Simulation: Less desirable…

<u>Characteristics of a “Bad” collection:</u>
-Not enough spacecraft
-Not enough collection duration (i.e. time)
-Directly repeating / harmonic ground traces
- Low sampling rate



<u>Specs:</u>

68 deg

350 km

0.2 Hz

1 Plane

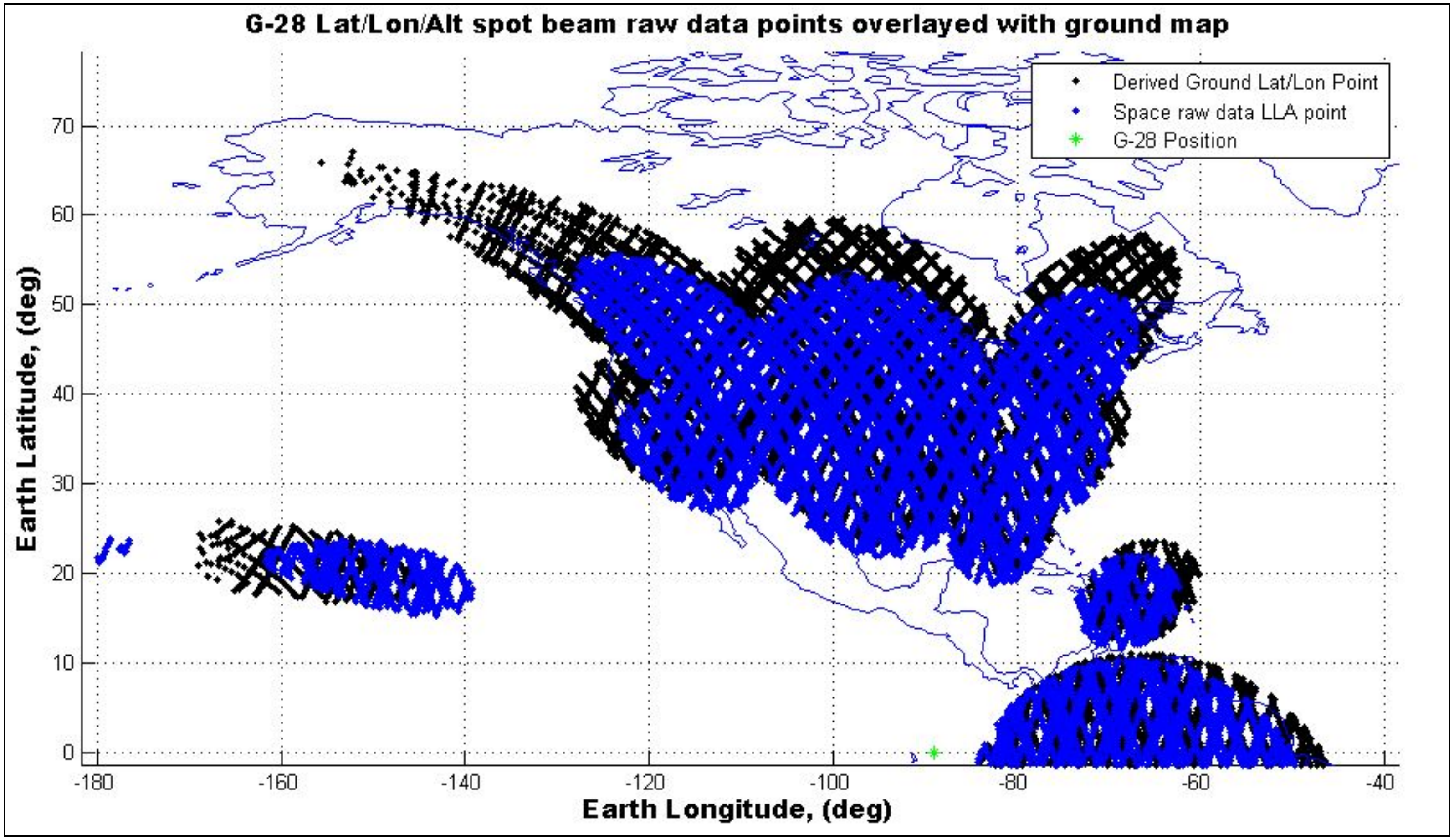
1 Sat.

24 Hour Collection

“Can’t Characterize Beam Shapes”
“Massive Gaps”
“Missing Beams”

Simulation: More desirable

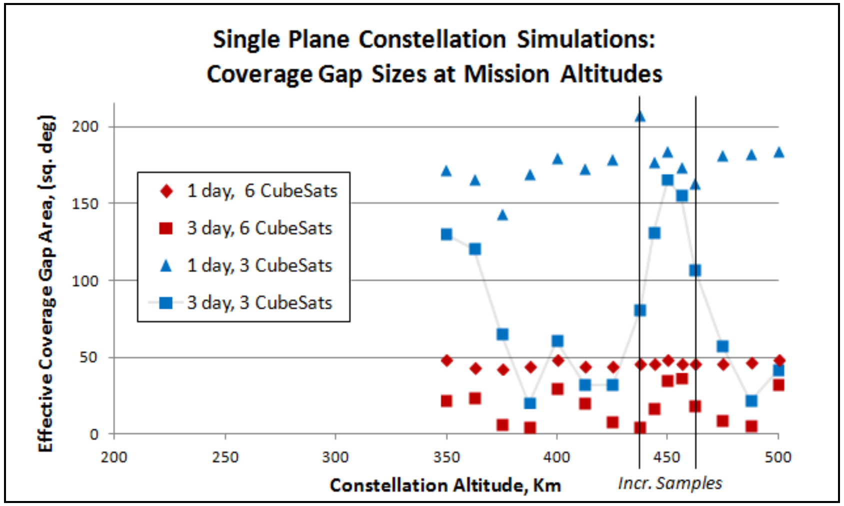
The AFIT of Today is the Air Force of Tomorrow.

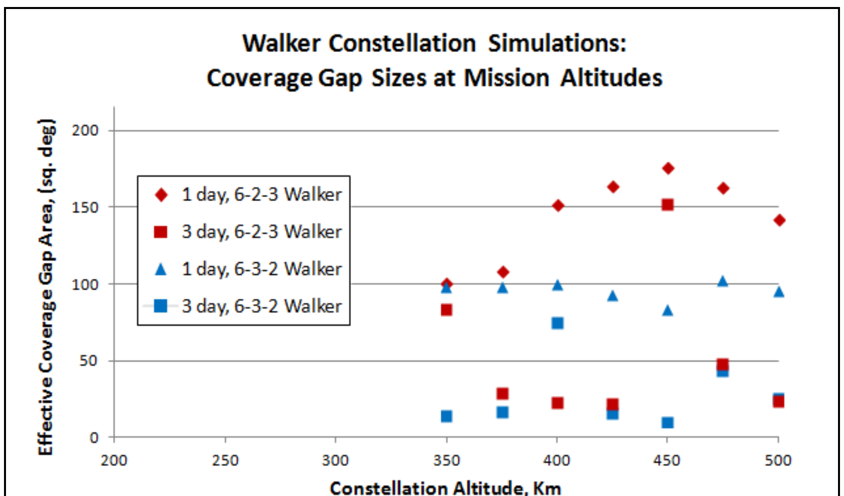


Shown: 350km / 68 deg / 6-3-2 Walker Delta / 3 Day Collection

Simulation: Altitude Effects

The AFIT of Today is the Air Force of Tomorrow.





<u>Goal:</u> Check gap size at mission altitudes

<u>Observations / Main points:</u>

- Altitude selection impacts capability

-Performance can be tailored…

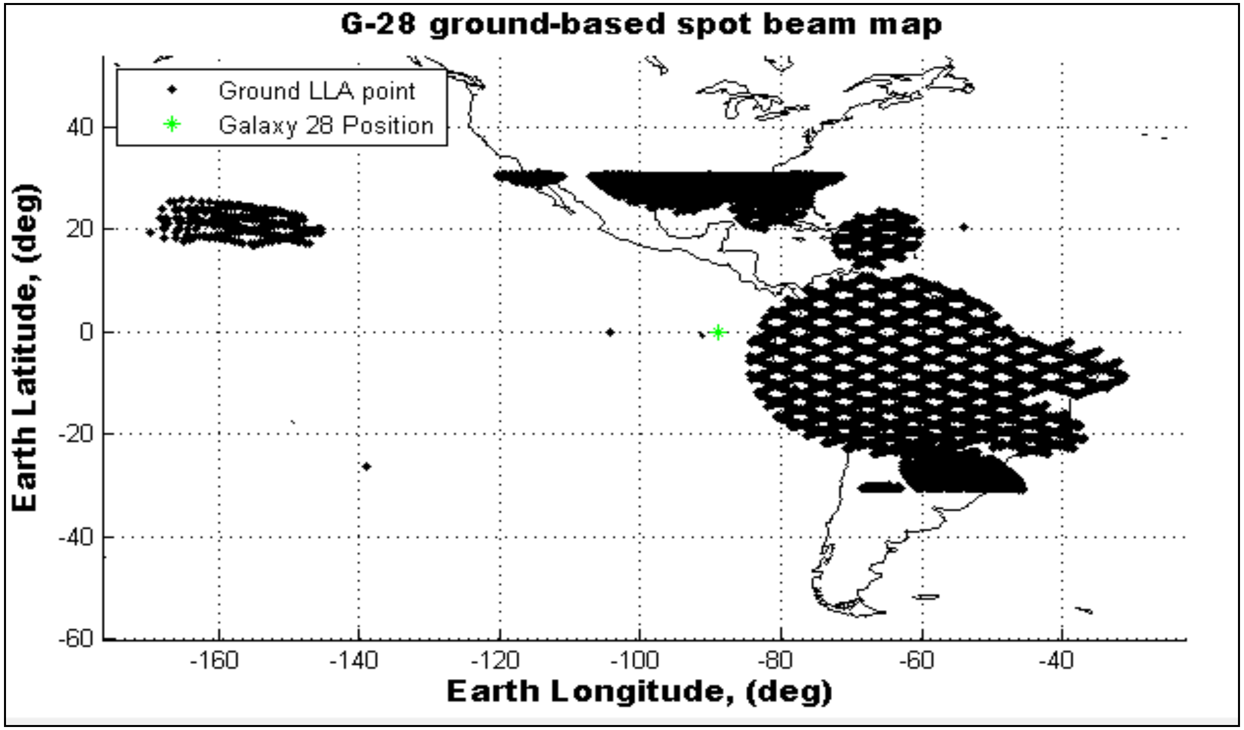
- Some constellations more stable

- More satellites = generally better

- Caveat: Less sats => Need more time

- Repeating ground track…
Bad for spot beam mapping

Simulation: Inclination Changes

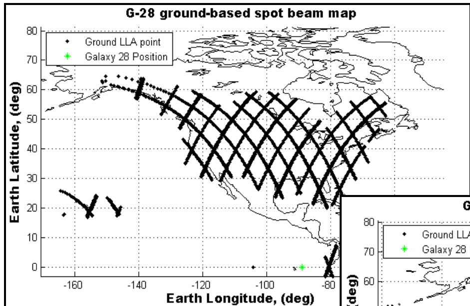


Spot beam mapping at lower inclinations

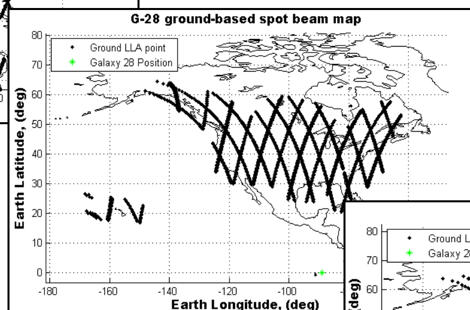
-Very good coverage for orbit region
-Shorter collection durations possible
- Cannot find beams at higher latitudes

Simulation: Inclination Changes

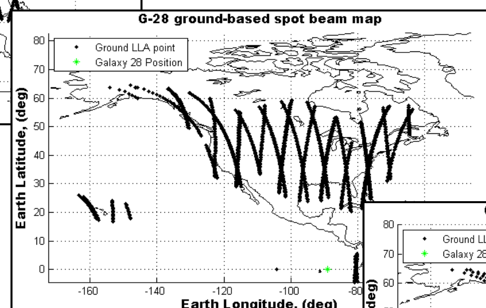
The AFIT of Today is the Air Force of Tomorrow.



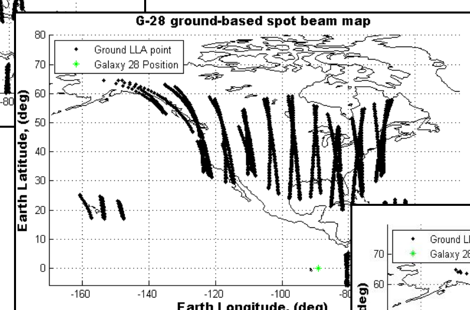
68 degrees



75 degrees

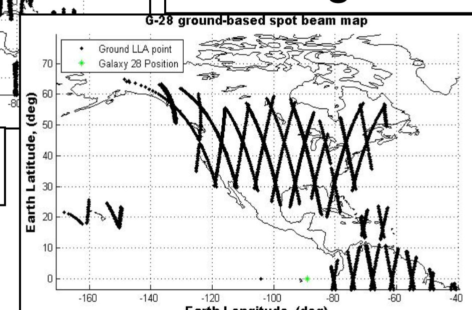


82 degrees



Polar

98 degrees



Increasing inclination (up to polar):

- Increases size of latitude gaps
- Can tailor longitude gaps
- Reduces overall "time in beam"

Inclinations for beam mapping:

- Lowest possible inclination
- Covers all desired latitudes

Simulation: Xmitter Position Knowledge

-- Position knowledge of the GEO transmitters

- Mandatory to generate accurate ground beam map
- Increased GEO position accuracy = increased ground accuracy

-- Option 1: *(Best)* Obtain GEO position information from other sources.

- Easy; No extra hardware required.
- Ground beam map derived from known transmitter location

-- Option 2: *(Complex)* Perform GEO-location on board the CubeSat

- Difficult; adds *stringent* attitude knowledge requirements
- Extra dedicated hardware likely needed
- Requires more data flow, increases demand for data storage

Simulation: Xmitter Position Knowledge

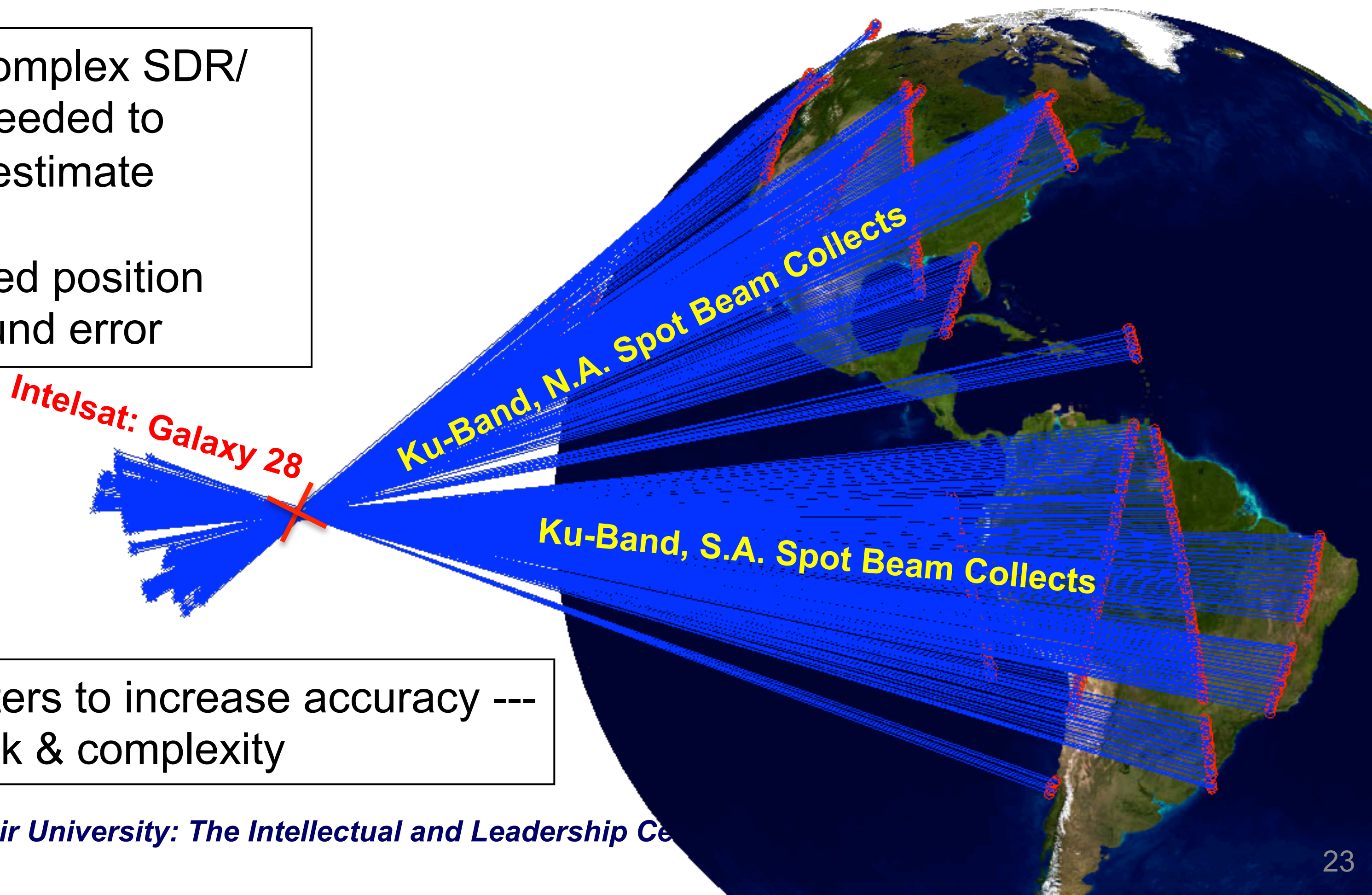
The AFIT of Today is the Air Force of Tomorrow.

Option 2: Simulation of on-board GEO-location

i.e. If the CubeSat can draw Lines of Bearing to the Transmitter…

Parameters: 1 Sat / 450km alt / 0.2 hz sensor collect / minor sensor noise / 10m pos. error

- More difficult, complex SDR/ antennas likely needed to perform bearing estimate
- Error in estimated position correlates to ground error



- Could fly in clusters to increase accuracy --- adds too much risk & complexity

Simulation: GEO-Location

The AFIT of Today is the Air Force of Tomorrow.

Attitude Knowledge “noise” reduces GEO-location capability. (i.e. large error)

Ground trace mapping becomes inaccurate when transmitter position knowledge is poorly known

Kalman-filtering attitude data reduces this error, …even further w/SOA CubeSat sensors

Spot Beam Mapping: On the whole

-- Workable mission for CubeSat Platform

- Simulation tools developed – can generate maps for any constellation
- Best altitudes for established 6U configuration: 350 – 500 km
- Best case: Transmitter position known accurately
- Worst case: Generate angular estimate on board CubeSat

-- Constellation needed for "best" results

- 6+ evenly spaced CubeSats with my assumptions
- 6-3-2 Walker pattern was best from my data sets @ 450km / 68 deg
- Numerous configurations "work" – performance can be tailored.

-- Things to watch out for:

- Directly repeating ground tracks are undesirable
- Accuracy of Ground map at extreme latitudes / longitudes
- Transmitter position knowledge (i.e. the importance of)

Future Work

-- Optimization

- Incorporate tools developed to find best solution
- (Manual approach would take centuries)
- Requires more assumptions with no sponsor (i.e. cost)

-- CubeSat hardware / Subsystem Design & Dev.

- COTS sources vs. new
- Payload selection & supporting hardware
- Form factor trade-offs
- GEO position determination hardware "black-box"

-- Mission Design/Build/Test/Fly

- Would be interesting to compare orbit tests w/findings
- One issue with this "future work" is probably funding

Conclusion

- Background & Motivation
- Spot Beam Mapping Mission + OV-1
- Design of Mission Model
- Software Tools
- Developed Simulations & Results
- Features of Operation
- Conclusion / Future Work

Questions?

Backup Slides

- Mission Requirements
- Tracking Received Power
- Vehicle Profile Transition
- More Duration Information
- Results Format
- Simulation 3D
- Transmitter Position Knowledge
- Simulated Payload Sampling Rate
- More ADCS Information
- Geometry
- Ref. Equations
- References / Sources

References / Sources

The AFIT of Today is the Air Force of Tomorrow.

Bibliography

[1] US. Government, "National Security Space Strategy Unclassified Summary," US Policy, January 2011.

[2] J. Garamone, "Shelton Discusses Importance of Space Defense," *Defense News*, 7 January 2014.

[3] US. Government, "FCC Online Table of Frequency Allocations," Federal Communications Commission Office of Engineering and Technology Policy and Rules Division, 2014.

[4] H. H. et al., "CubeSat: A new generation of picosatellite for education and industry low-cost space experimentation," in *14th Annual AIAA/USU Small Satellite Conference*, Logan, UT, 2000.

[5] E. A. Abbate, "Disaggregated Imaging Spacecraft Constellation Optimization with a Genetic Algorithm," MS Thesis, AFIT-ENY-M-14, Graduate School of Engineering and Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 2014.

[6] D. a. K. D. Selva, "A Survey and Assessment of the Capabilities of CubeSats for Earth Observation," *Acta Astronautica*, vol. 74, 2012.

[7] "2013 AFIT 6U EDU CubeSat Bus Interface Control Document (ICD)," Air Force Institute of Technology, WPAFB, OH, 2013.

[8] M. Blackstun, E. Swenson, S. Hart, J. Black and R. Cobb, "Design, Build, and Test of Engineering Development Unit CubeSats for Satellite Design Courses," in *ASEE International Forum, American Society for Engineering Education*, 2012.

[9] E. Glennon, J. Gauthier, M. Choudhury, K. Parkinson and A. Dempster, "Project Biarri amd the Namuru V3.2 Spaceborne GPS Receiver," in *International Global Navigation Satellite Systems Society (IGNSS) Symposium*, Outrigger Gold Coast, Australia, July 2013.

[10] P. Gurfil and J. Herscovitz, "The SAMSON Project - Cluster Flight and Geolocation with Three Autonomous Nano-satellites," Technion-Israel Institute of Technology, Haifa, Israel, 2012.

[11] D. C. Montgomery, Design and Analysis of Experiments, Hoboken, NJ: John Wiley & Sons, 2009.

[12] "Satbeams," IPC BonAnza LLC., 2014. [Online]. Available: http://www.satbeams.com. [Accessed 1 October 2014].

[13] R. Horak, Telecommunications and Data Communications Handbook, Hoboken, NJ: John Wiley & Sons, 2012.

[14] D. Roddy, Satellite Communications, 4th ed., New York, NY: McGraw-Hill Companies, 2006.

[15] SiRF Technology, Inc., "NMEA Reference Manual," SiRF Technology, Inc., San Jose, CA, January 2005.

[16] Puig-Suari, et al., "Development of the Standard CubeSat Deployer and a CubeSat-Class PicoSatellite.," *Proc. 2001 Aerospace Conference*, vol. 1, pp. 347-353, 2001.

[17] "Canisterized Satellite Dispenser (CSD) Data Sheet, 2002337 Rev B.," Planetary Systems Corp., Silver Spring, MD, 2014.

[18] M. Swartwout, "The First One Hundred CubeSats: A Statistical Look," *Journal of Small Satellites*, vol. 2, no. 2, pp. 213-233, 2013.

[19] University of New Mexico, "ORS Squared," Cosmiac, 2014. [Online]. Available: http://cosmiac.org/space-missions/ors-squared/. [Accessed 18 February 2015].

[20] A. J. Small, "Radio Frequency Emitter Geolocation Using CubeSats," MS Thesis, AFIT-ENG-14-M-68. Department of Electrical and Computer Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 2014.

[21] Fish, et al., "DICE Mission Design, Development, and Implementation: Success and Challenges," in *26th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, 2012.

[22] P. O. Hayne, B. A. Cohen, R. G. Sellar, R. Staehle, N. Toomarian and D. A. Paige, "Lunar Flashlight: Mapping Lunar Surface Volatiles Using a CubeSat," in *USRA Annual Meeting of the Lunar Exploration Analysis Group*, Laurel, MD, 2013.

[23] J. R. Claybrook, "Feasibility Analysis on the Utilization of the Iridium Satellite Communications Network for Resident Space Objects in Low Earth Orbit," MS Thesis, AFIT-ENY-13-M-04. Graduate School of Engineering and Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, March 2013.

[24] S. P. Ingraham, "Dynamic Constellation Tasking and Management," MS Thesis, AFIT-ENY-13-M-18. Graduate School of Engineering and Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 2013.

[25] J. W. Sales, "Trajectory Optimization for Spacecraft Collision Avoidance.," MS Thesis, AFIT-ENY-13-S-01. Graduate School of Engineering and Managment, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 2013.

[26] R. E. Thompson, J. M. Colombi, J. T. Black and B. Ayers, "Disaggregated Defense Weather System Follow-on (WSF) Conceptual Architecture Optimization," in *AIAA SPACE 2014 Conference and Exposition*, San Diego, CA, August 2014.

[27] A. Hatch, "Electrospray Propulsion Interface and Mission Modeling for CubeSats," MS Thesis, AFIT-GA-ENY-12-S47. Graduate School of Engineering and Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 2012.

[28] B. A. Andrews, "A Colony-II CubeSat Mission Modeling Tool," MS Thesis, AFIT-GA-ENY-12-M01. Graduate School of Engineering and Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 2012.

[29] B. W. Spanbauer and J. M. Yates, "Geostationary Orbit Development and Evaluation for Space Situational Awareness," MS Thesis, AFIT-GSE-ENV-09-05DL. Graduate School of Engineering and Management, Department of Systems and Engineering Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, December 2009.

[30] R. T. Bentley, "Experimental investigation of radio frequency (RF) signal geolocation concepts using geostationary satellites," in *AIAA Space Programs and Technologies Conference*, Huntsville, AL, September 1996.

[31] J. E. D. P. J. Wertz, Space Mission Engineering, The New SMAD, Hawthorne, CA: Microcosm Press, 2011.

[32] Honeywell Aerospace, "Ku vs. Ka, Content Brief Pt. I," *Avionics Magazine*, August 2013.

[33] K. Singarajah, "Overview of Ka-band Satellite System Development & Key Regulatory Issues," in *ITU Conference on Prospects for use of the Ka-band by Satellite Communication Systems*, Almaty, Kazakhstan, 2012.

[34] M. W. Tobias, "Cruise Ship Communications for Passengers is About to Change," *Forbes*, 8 March 2013.

[35] USA Today, "Coming to a cruise ship near you: Fast Internet," *USA Today*, 19 November 2012.

[36] D. Welch, "Is Ka-Band the Ku- Killer?," *SatMagazine*, February 2013.

References / Sources

The AFIT of Today is the Air Force of Tomorrow.

[37] D. Vallado, Fundamentals of Astrodynamics and Applications, 3rd ed., New York, NY and Hawthorne, CA: Springer and Microcosm Press, 2007.

[38] W. E. Wiesel, Spaceflight Dynamics, Third Edition, Dayton, OH: CreateSpace Independent Publishing Platform, 2010.

[39] NASA Ames Research Center, "Small Spacecraft Technology State of the Art," NASA/TP-2014-216648/REV1. National Aeronautics and Space Administration, Washington, DC, 2014.

[40] R. Ersoy and G. H. Schennum, "INTELSAT VII Spacecraft Antennas," Ford Aerospace, Palo Alto, CA, 1989.

[41] G. H. Schennum and L. Ersoy, "Antenna Subsytem for the INTELSAT VII Spacecraft," Ford Aerospace, Space Systems Division, Palo Alto, CA, 1989.

[42] B. R. Castello, "CubeSat Mission Planning Toolbox," MS Thesis. California Polytechnic State University, San Luis Obispo, CA, June 2012.

[43] L. Qiao, C. Rizos and A. G. Dempster, "Analysis and Comparison of CubeSat Lifetime," Australian Centre for Space Engineering Research, School of Surveying and Geospatial Engineering, University of New South Wales, Sydney, NSW, Australia, 2013.

[44] H. Voss, "EyeStar: A Paradigm Shift," in *11th Annual CubeSat Developers Workshop*, San Luis Obispo, CA, April 2014.

[45] L. B. Bastow, "Modeling the Impact of the Payload Alert Communications System (PACS) on the Accuracy of Conjunction Analysis," MS Thesis, AFIT-ENV-13-M-01. Graduate School of Engineering and Management, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, 2013.

[46] R. Votel and D. Sinclair, "Comparison of Control Moment Gyroscopes and Reaction Wheels for Small Earth-Observing Satellites," in *26th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, 2012.

[47] T. E. O'Brien, "Space Situational Awareness CubeSat Concept of Operations," MS Thesis, Naval Postgraduate School, Monterey, CA, 2011.

[48] National Science Foundation (NSF), "Annual CubeSat Report, CubeSat Based Science Mission for Geospace and Atmospheric Research," National Aeronautics and Space Administration, Washington, DC, 2013.

[49] E. R. Dannemeyer, "Design and Analysis of an Attitude Determination and Control Subsystem for AFIT's 6U Standard Bus," Air Force Institute of Technology, WPAFB, OH, 2014.

[50] S. K. N. S. B. J. D. D. J. L. D. V. D. Eric Bailey, "Anubis ASYS 631 Final Report," Air Force Institute of Technology, WPAFB, OH, 2014.

[51] C. Le Gaux III, "STARE CubeSat Communications Testing, Simulation, and Analysis," Naval Postgraduate School, Monterey, CA, 2012.

[52] D. Koks, "Numerical Calculations for Passive Geolocation Scenarios," Electronic Warfare and Radar Division, Defense Science and Technology Organization, Australian Government, Edinburgh, SA, Australia, 2007.

[53] B. Weeden, "Radio Frequency Spectrum, Interference and Satellites Fact Sheet," Secure World Foundation (SWF), 2013.

[54] F. Roßberg, "Simulation of the deployment and orbit operations of the NPS-SCAT CubeSat," NPS-SP-08-002. Naval Postgraduate School, Monterey, CA, 2008.

[55] R. Hodges, B. Shah, D. Muthulingham and T. Freeman, "ISARA - Integrated Solar Array and Reflectarray Mission Overview," in *AIAA/USU Conference on Small Satellites*, Logan, UT, 2013.

[56] M. Boghosian, "Cost Estimating Methodology for Very Small Satellites, A-PICOMO (Aerospace Picosatellite Cost Model)," in *1st Interplanetary CubeSat Workshop*, Cambridge, MA, 2012.

[57] K. N. Hale, "Expanding the Use of Time/Frequency Difference of Arrival Geolocation in the Department of Defense," PhD Dissertation. The RAND Corporation, Santa Monica, CA, 2012.

[58] L. Qiao, "Garada: SAR Formation Flying, Annex 7. Orbit Modelling and Analysis, Simulated Mission Planning," Australian Centre for Space Engineering Research (ACSER), University of New South Wales, Sydney, Australia, June 2013.

[59] M. Wade, "Encyclopedia Astronautica, FS-1300 Bus," [Online]. Available: http://www.astronautix.com/craft/fs1300.htm. [Accessed September 2014].

[60] Tachyon, Inc, *Taychon Airborne Satellite Terminal - Power Spectral Analysis Document*, San Diego, CA: Taychon, Inc., [No Date] est. 2012.

[61] R. P. Welle and D. Hinkley, "The Aerospace Nano/PicoSatellite Program," in *In-Space Non-Destructive Inspection Technology Workshop*, Houston TX, July 2014.

[62] K. O. Michael, Satellite Communication Engineering, 2nd ed, CRC Press, 2013.

[63] California Polytechnic State University, "CubeSat," California Polytechnic State University, 2014. [Online]. Available: http://wsw.cubesat.org. [Accessed October 2014].

[64] W. A. Imbriale, S. Gao and L. Boccia, Space Antenna Handbook, Hoboken, NJ: John Wiley & Sons, June 2012.