Ground Communications for Satellite Operations

ASTE 566, Spring 2021

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Outline

Ground Communications for Satellite Operations

- Course Goals
- Organization of Class
- Content
- Schedule
- Course Notes
- Supporting Materials
- Homework
- Project
- Introduction to Satellite and Ground RF Systems

Course Goal(s)

- Provide complete understanding of the operation of a ground communications systems and architecture for satellite operations.
- Provide “hands on” training through combination of early theory, practical training on typical hardware for ground communications setup and actual operations of a mesh dish/yagii ground antenna tracking satellites.
- This is a graduate level course with hardware that relies upon external satellite operations
  - Be flexible during the operational portion of course, schedules change, its part of the training
  - You are expected to learn hands on hardware ops and practice to complete the course

New for Spring 2021

- ASTE 566 is now a DEN based course.
- WebEx will be used for the first 10 weeks of the course
  - Zoom will be used for the last 5 weeks
- The Course is still “hands on”, but the training will take place between on-campus and off-campus.
- Hardware for the course will be shipped to off-campus students.
  - WE EXPECT IT BACK AT END OF SEMESTER!
- Expect snafu’s in first course run remotely!
  - While we are doing everything to streamline the hardware shipment, and setup and training, be patient
  - Through WebEx/Zoom we will be training everyone online to use the hardware
- Spring 2021 has a satellite build activity concurrent at SERC
  - Use of GS with Satellite team will be shared
  - It is possible to introduce some of the operations planned with ASTE 566 class!

Organization of Course instruction

- Course is broken into three separate focused training/teaching activities:
  - First 4 weeks is top level theory, systems architecture, details on orbits and how to track satellites, and basic RF antenna design, noise and link budget determinations, as well as rudimentary encoding practices.
  - Second 6 weeks will be practical lab learning about RF hardware and specification sheet identification, spectrum analyzer training, introduction to transmission protocols and commutation, introduction to tracking software, introduction to software designed radios (SDR), introduction to az and el motor controllers, and calibration and safe operation of the antenna.
  - The last 5 weeks will be hands on antenna operations. This will be instantiated through target satellite sets provided for the class to pair up and track, along with each team of 2 students to complete a project and present for the final.
- Lectures and training to be provided by Prof Barnhart / Rahul Rughani (TA)
  - Industry experts will provide guest lectures/practicals throughout the entire semester

Logistics

- All “classes” will be both Remote and in OHE 336, except the last 5 weeks training will be on the SERC antennas remotely operating on the roof of ACH
- Class starts at 12:00 pm Tuesdays and Thursdays
  - Please be on time. There are no breaks in class.
- Teaching assistant = Rahul Rughani
- Grader/Support = Claire Carlton
- Additional Support:
  - LaJument Staff/Students as possible, as we have a live Cubesat project this semester.
- Questions and complaints about grading
  - Directed toward the TA
  - Only if arbitration is necessary, contact the primary instructor
- Communication with instructor and TA
  - REMOTE Office Hours (Zoom)
  - Telephone and e-mail
    - Email to TA or instructor; add a copy to the other, only if necessary
  - Do not hesitate to contact or call TA with question about class material, homework etc.

Logistics (cont)

- Given USC Covid restrictions we are limiting total of 6 in persons in the Lab at any one time
  - MANDATORY Masks and Faceshields required. Please bring you own mask, and faceshield if you have it, if you don’t we will provide.
- TrojanCheck is MANDATORY for Campus attendance!
  - This is USC requirement. You have to have taken the Health Training Course, gotten a Flu Shot, and a Covid test.
  - Covid Tests are REQUIRED every 7 days, so please plan ahead to get the test every week if you plan to come to campus.
- Remote DEN student hardware will be shipped end of January
  - There will be training for all students on the hardware in early February
- USC VPN Required for any access for the remote hardware.
  - If you don’t have it installed you need to get it installed and checked out prior to hardware testing

Logistics (cont.)

- Class Attendance: Free to walk/dial in / walk/dial out
  - Please do not sleep.
  - No Food or Open Container Drink – Class is given in an active lab with sensitive equipment.
  - Cell phones need to be silenced during lecture for courtesy
  - Cell phones may need to be turned off during practical lab operations for interference in RF ops.
  - **PPE IS MANDATORY**

- Religious or Holy Days
  - Please discuss with instructor in advance for conflicting schedules

- Questions?
  - Questions are welcomed. This is an interactive course thus expect lots of interaction and flexible discussion and practical changes to maximize the experience.

- Academic Integrity
  - Familiarize yourself with Academic Integrity guidelines in USC Student Handbook
  - Homework and practical efforts are individual efforts
  - Project is shared with a partner, but EACH INDIVIDUAL GETS A GRADE

Office Hours

- Teaching Assistant/Graders office hours – ZOOM ONLY
  - Rahul Rughani: TBD
  - Claire Carlton: TBD

- Instructor's office hours – ZOOM ONLY
  - Thursdays 10:00 – 11:30 am

Grading

- Basic grading breakdown is shown

Assignment	Points	% of Grade
Participation in Class and Lab		10
Homework (HW1-HW4)		20
Practical Assignments (PA1-PA8)		20
Satellite Tracking, Final Report and power point presentation		50
Total		100

- The course will entail weekly homework assignments, practical assignments, a set of satellites to track and a final project. The instructor will pair students for lab activities and the final project, and will assign the project to each student pair.
  - 3 homework assignments will be handed out (HW1-HW3) during lectures.
  - Up to 8 weekly practical assignments (PA1-PA8) to be completed during time in the laboratory, with ~2-page report due at the next class meeting. (Template provided)
  - 1 Final comprehensive project during the final 5 weeks of the course, with a 10-page report and 15 minute powerpoint presentation delivered on the last class meeting.
    - A minimum set of 10 satellites are to be tracked independent of your project satellite and documented, and turned in as part of your Final Report.

Assignments

- A typical Homework Assignment may include detailing and calculating a ground based link budget given a specific set of parameters of both a sample satellite and ground antenna details e.g.
- A typical Practical Assignment may include measuring specific sample components provided in the lab/at home after instruction on the sensors for validation of actual to predicted loss e.g.
- A typical Satellite Track will include scheduling passes in advance, then signing up for the control room and physically tracking and recording the SNR of the satellite.
- The Final project report will be 10 pages and should describe in detail the methodology used to determine a satellite's ephemeris from an initial incomplete set of parameters (the "lost in space" problem), and validate the tracking and signals through the antenna to receiver. Each student team will give a powerpoint presentation in class which describes a summary of the report.
    - The projects are done in pairs thus the two students together have a total of 15 minutes including questions to present.

Assignment Logistics

- First HW Assignments due on **2 February**
- There are ~3 lecture based homework assignments, and up to 8 practical homework assignments. (See Contents and Schedule in this package for details)
- **Late homework** may be submitted (to the TA) within two weeks after due date, but not later than 4 weeks after due date
  - Late homework will be graded; the grade will be **reduced by 50%.**
  - No late homework submissions after 4 weeks. (This is firm.)
  - No "make up" homework is possible. No special favors on homework submission, regardless of cause.
  - NOTE: Given the unique nature of "remote hardware practicals", we may have to amend this during course
- Homework assignments/solutions will be posted on D2L, usually a few days after due date.
- All students submit homework in D2L directly. You can scan in and submit paper solutions

Students keep records of their HW assignment scores and check with TA several times during semester for the accuracy of scores in our records.

Assignment Logistics (cont.)

- On all homework pages, please put your name and Course Number ASTE-566

DO NOT submit homework to instructors e-mail address (unless specifically directed by instructor)

- All homework is submitted in D2L on the day its due; all homework graded will be returned in D2L for you to access.
- **Final exam consists of two items:**
  - **Submittal of a 10 page research report on the Lost in Space project, and shows your 10 tracked satellites**
  - **15 minute powerpoint presentation of you and your partners results**
- If you absolutely have to be on a trip during the final – contact the instructor in advance.

Contents and Schedule

Please refer to the Weekly Course Breakdown separate agenda for details

Course Notes and Reading

- Course notes will be provided prior to each week's lecture or practical
  - Some lectures/practicals will work out of a reference manual, or online database or program
- Supplementary materials that provide deeper reference information include:
  - The Satellite Communication Ground Segment and Earth Station Handbook (Artech House Space Technology and Applications) 2nd ed. Edition, Bruce Elbert, ISBN-13: 978-1608076734
  - ARRL Ham radio License Manual, 3rd Edition May 15, 2014
  - Space Mission Engineering: The New SMAD. Ed. James Wertz, ISBN-13: 978-1881883159
  - Fundamentals of Astrodynamics, Bate/Mueller/White, ISBN-13: 978-0486600611
  - http://www.mike-willis.com/Tutorial/PF1.htm
  - http://www.uhf-satcom.com/sband/
  - Noise in Antenna's, http://web.stanford.edu/class/ee252/handouts/antenna_noise.pdf
- Additional information to be provided during the course (examples)
  - Parabolic Dish Antennas, Paul Wade (pdf file to be provided by the instructor)
  - Antenna Noise Temperature and System Signal-to-Noise Ratio, EE Nikolova (pdf file to be provided by the instructor)

Relevant Software Programs

- Several relevant software programs will be used for both training and operations
  - These can be downloaded individually, free of charge for study ahead of time
  - Several of these are available on the ground operations computers in the GS
- Examples of software programs we will use and understand in the course include (but are not limited to):
  - Satellite ToolKit (free version)
  - Gpredict
  - Orbitron
  - AirSpy Translator
  - HackRFOne Software (https://greatscottgadgets.com/sdr/) HIGHLY RECOMMENDED VIDEOS
  - GNURadio Software (Linux)
- GNURadio video's will really help you understand how it works, HIGHLY RECOMMEND
  - https://www.youtube.com/watch?v=ufxBX_uNCa0
  - https://wiki.gnuradio.org/index.php/Tutorials
  - https://wiki.gnuradio.org/index.php/Guided_Tutorial_GRC
  - https://www.csun.edu/~skatz/katzpage/sdr_project/sdr/grc_tutorial1.pdf

Course summary

- This course will provide a broad brush at the top level on spacecraft and related ground systems and communications required

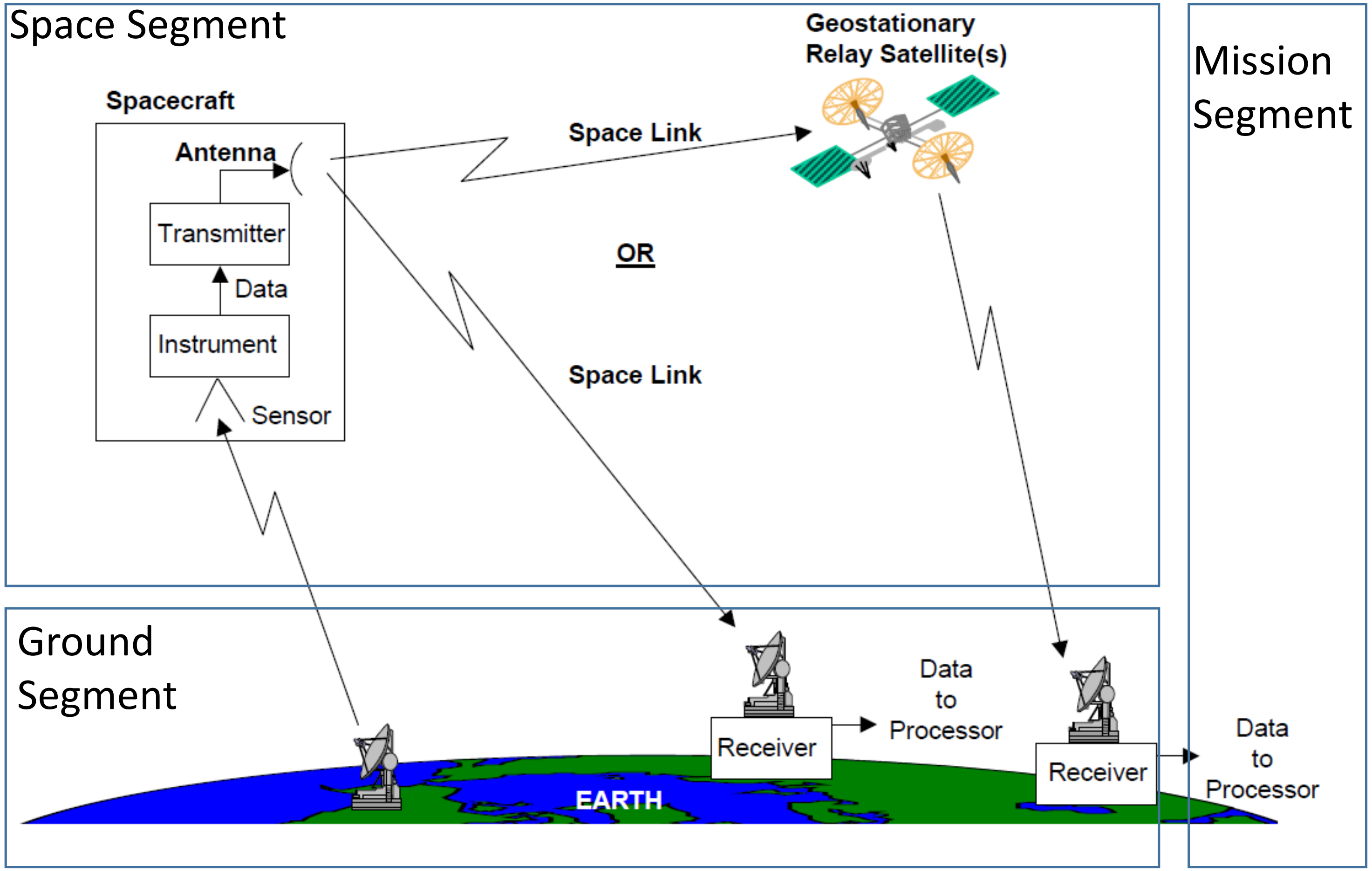
- But the focus will be on breaking down the technical details to actually create and develop a link budget, understand SDR's and modulation intro, the basisc architecture and operation of a ground station for satellite tracking

- By the end of the course you will be adept at LEO based satellite tracking using a dish based/yagii antenna at specific frequencies, and understand the fundamentals to support most commercial or government entities that are executing satellite tracking in the future.

Introduction to RF systems for satellite and ground

- Typical Satellite architectures include
  - Space Segment
  - Ground Segment
  - Customer/Mission User Segment

- Ground Segment supports
  - Space Segment
    - Via "Command and Control"
    - Monitors Spacecraft health
    - Tracks the Spacecraft
  - Relays Mission data to users



Nomenclature for architectures in RF Systems

- Telemetry, Tracking and Control (“TT&C”)
  - Ranging of altitude, location in orbit, tracking, commanding bus or payload operations, schedule or new code upload etc
- Remote Imaging Satellite (or Earth observation satellite)
  - Payload drives the type of communication system, and thus the ground systems
  - High performance optical or higher wavelength sensors generate large amounts of data
    - Can be processed onboard, but most is sent down
- Communications Satellite (“CommSat”)
  - Communications payloads drive the design of systems
    - Examples TDRS, Comstar, Teledesic, Iridium, etc.
- Long Range Data Relay Spacecraft
  - For interplanetary missions that require high power and large gain due to distance from Earth and nature of data
    - Examples Cassini, Galileo, Dawn, Mars Voyager, etc.

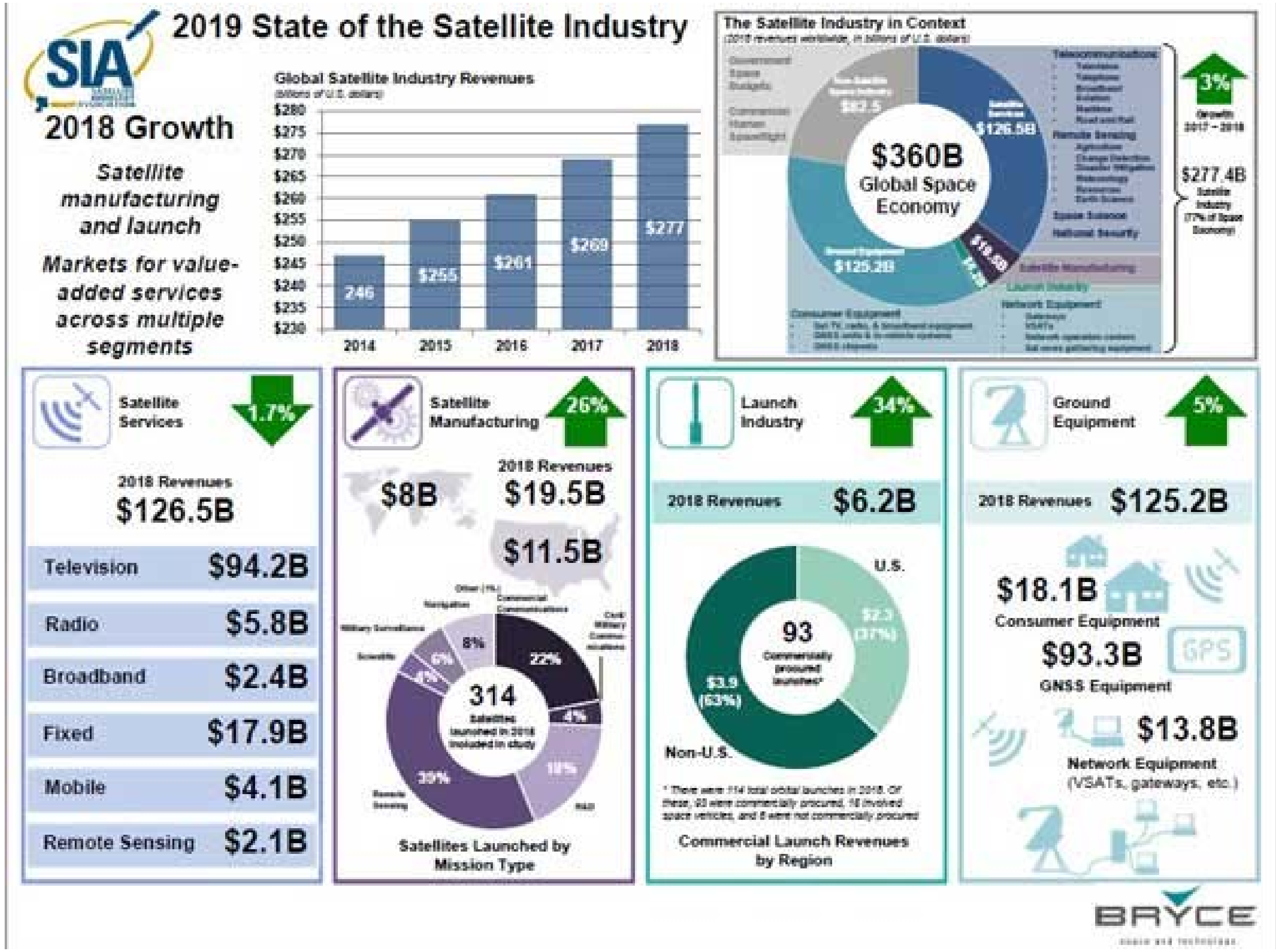
Satellite Communications is Big Business …

- Traditional GEO satellite communications services are strong and expected to grow
- Internet connectivity and multi-media demand is driving huge push to "connect" planet
- "Connecting" the Earth is big business

Past and Future Satellite Communication Revenues ($ billions)

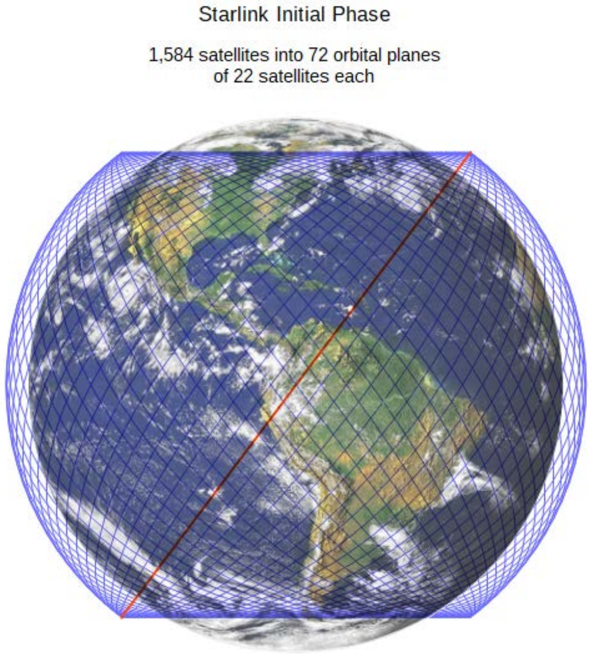
SATELLITE SERVICE	1992	2002 – Original Study	2002 - Adjusted	2005 Projected
Conventional Fixed Sat Service				
INTELSAT*	$4.5	$8.5	$9.0	$11.0
Other Intern'l Systems**	$0.9	$1.9	$2.5	$3.5
U.S./Canadian Systems	$2.3	$4.5	$4.2	$5.0
Other National Systems	$1.4	$3.4	$4.5	$6.0
All Fixed Sat Systems	$10.0	$20.0	$22.1	$29.5
New Ka-Band Broadband Sat Systems				
Broadband Multimedia (GEO)	N.A.	N.A.	$1.0	$6.5
Broadband Multimedia (LEO)	N.A.	N.A.	$0.5	$6.5
All Broadband Multimedia Systems	N.A.	N.A.	$1.5	$13
Mobile Satellite Systems				
Mobile Sats (Aero/Maritime)***	$0.8	$2.0	$2.2	$2.5
Mobile Sats (Land/Geo)	$0.01	$1.0	$2.1	$3.0
Mobile Sats (Land/Meo/Leo)	N.A.	$6.0	$5.5	$7.0
All Mobile Sats	$0.81	$9.0	$9.8	$12.5
Broadcast Satellite Systems	$0.5	$8.0	$12.0	$17.0
Military Satellite Systems	N.A.	N.A.	N.A.	N.A.
Other (Data Relay/GPS)	$0.1	$0.3	$1.5	$2.5
TOTAL SAT SERVICES	$11.4	$38.3	$45.4	$74.5

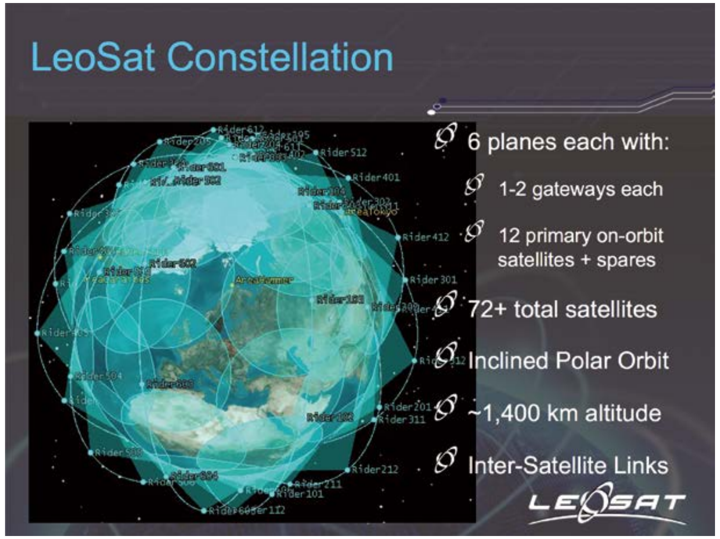
"Global Satellite Communications Technology and Systems", Pelton et al, Dec 1998, International Technology Research Institute



New “mega constellations” will strain all RF … push to optical

Artist’s rendition of the OneWeb constellation. Photo: OneWeb screen capture.





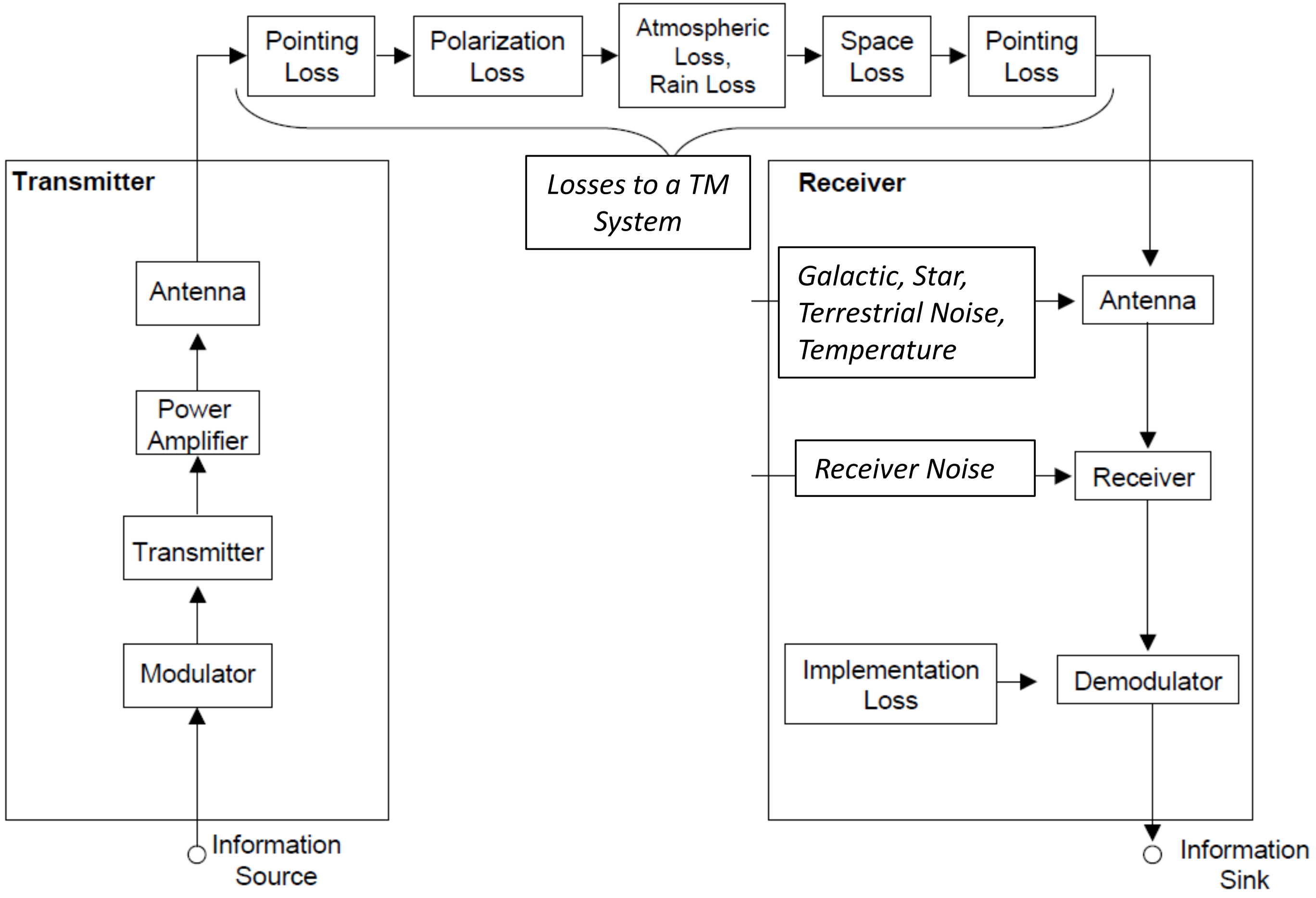
Fast, Secure Broadband Connectivity Via “Fiber In The Sky” By Vern Fotheringham, CEO and Chairman, LeoSat, Inc.

- NSR Forecasts $175 Billion in Non-GEO Revenue
- Mega constellations will push boundaries of RF spectrum capabilities 24/7

Subsystems that drive Satellite RF Communications

- Space Segment
  - Payload
    - Sensors or Communications (broadcast, relay etc)
  - Bus
    - Typical Sat Systems (plus Telemetry)
    - Sometimes includes another Communications system for uplink/downlink
- Telemetry Systems
  - Bus and Payload Commanding, Diagnostics, Health and Status etc.
  - Functions include
    - Filtering, switching, translating, amplifying, etc.

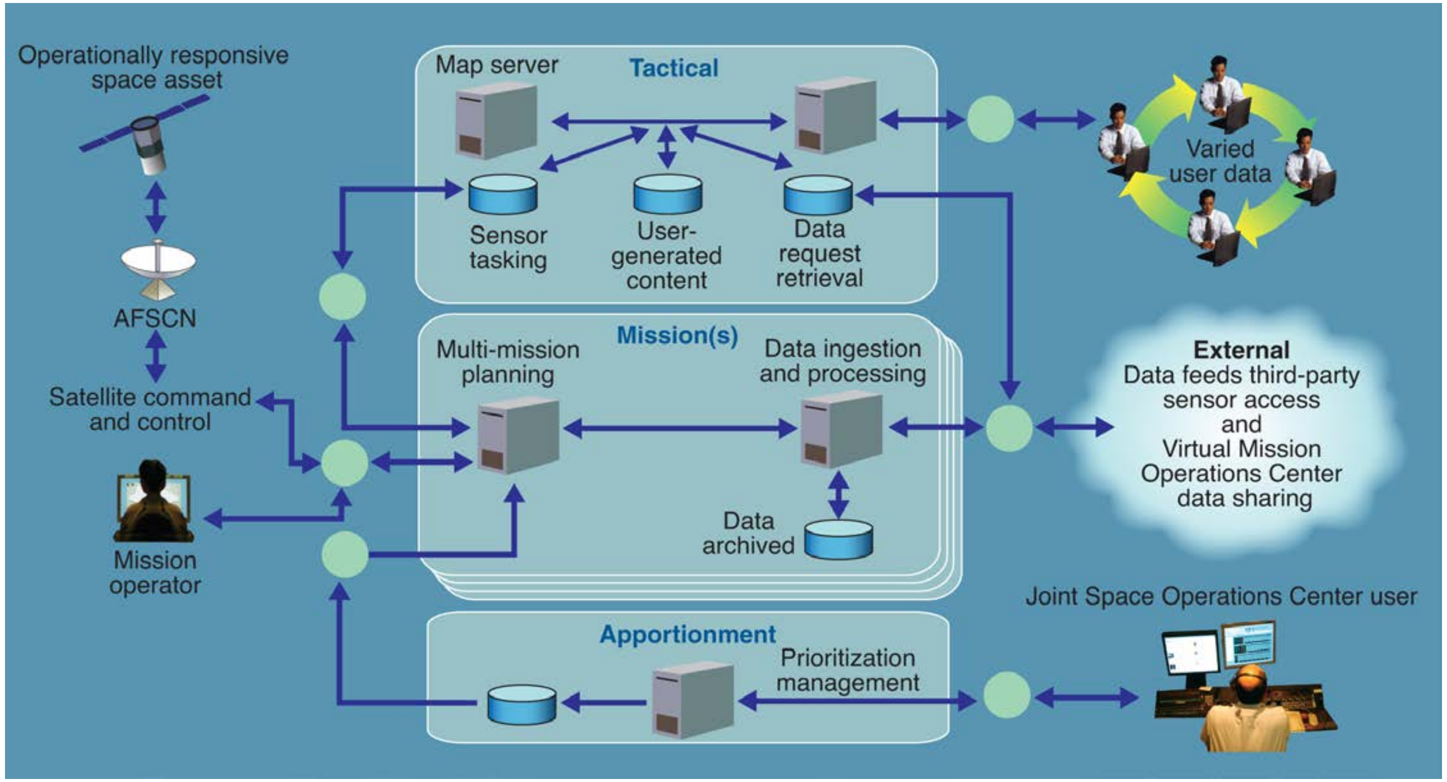
Most basic breakdown of "Telemetry" System



"Uplink" and "Downlink" all see same losses

Ground System (Segment) Design

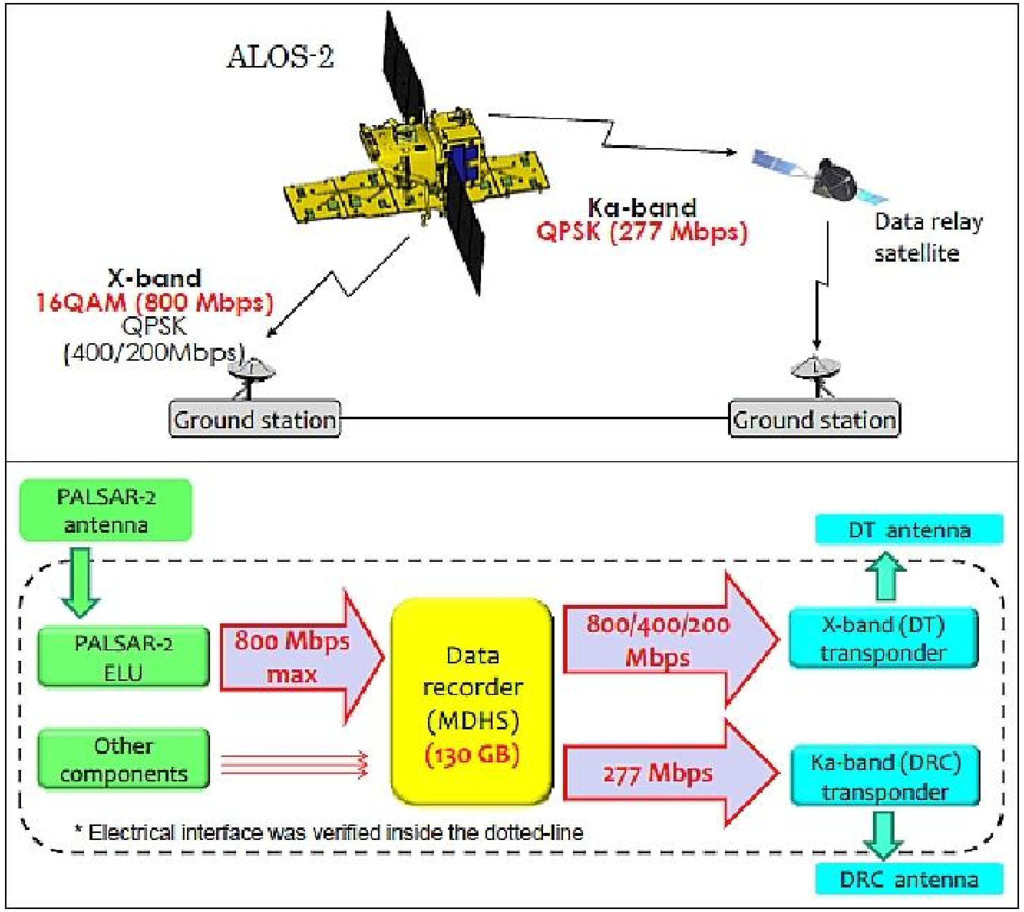
- Ground System
  - Antenna/Aperture and Equipment
  - RF Equipment
  - Mission Operations Center
  - Payload Operations Center
  - Customer Liason or Interface
  - Data Archiving

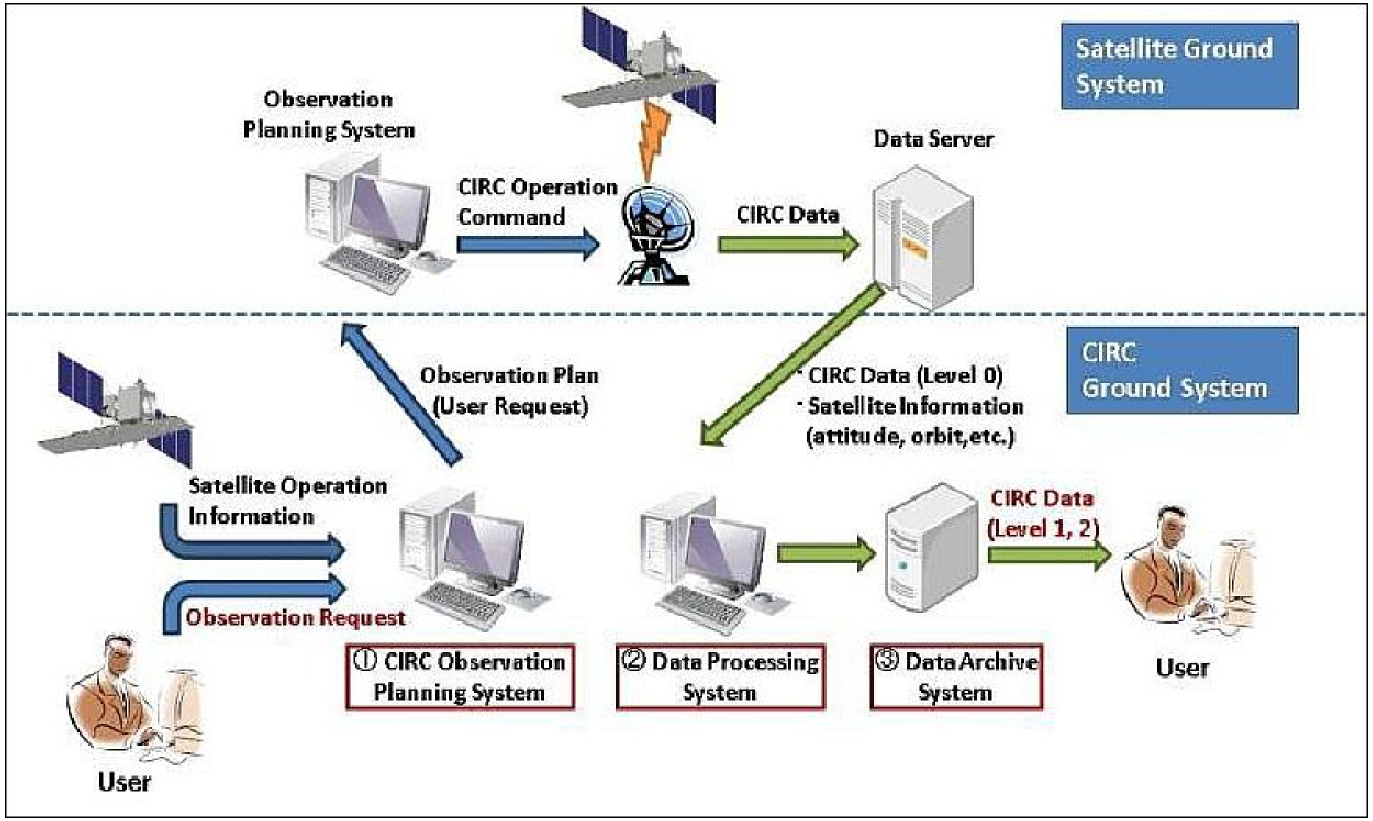


- GROUND DATA FLOW IS A BIG DEAL…!
  - Just as important and in many cases more complicated than onboard data flow

Examples

- ALOS-2

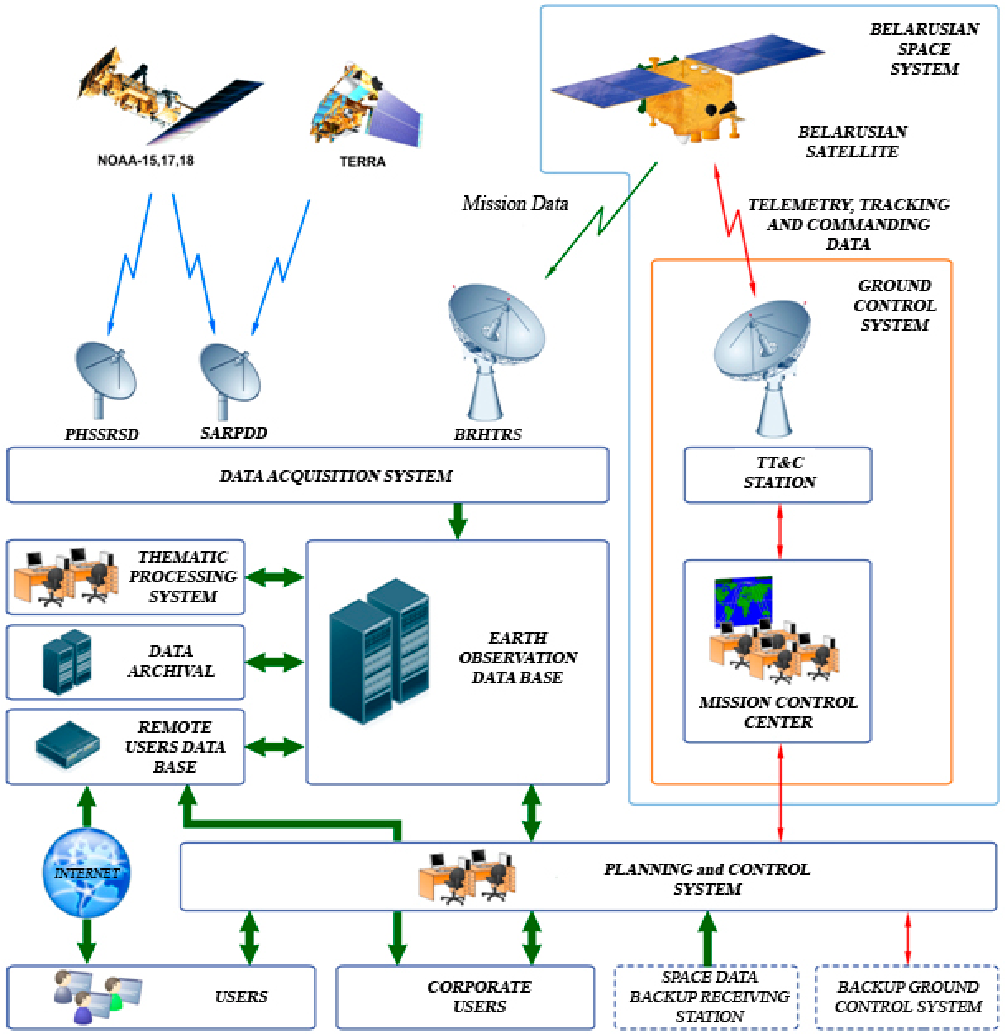




https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/alos-2-1

Examples

- Belarussian space System for Earth Remote Sensing (BSSERS)
  - Belarussian Ground control system
  - Mission Control Center
  - Telemetry, Tracking and Command Station
  - Belarussian Ground Acquisition, Processing and Satellite Data Dissemination System
  - Data Acquisition System
  - BSSERS Planning and Control System
  - Data Repository of Digital Terrain Elevation Data
  - BSSERS Corporate Local Area Network

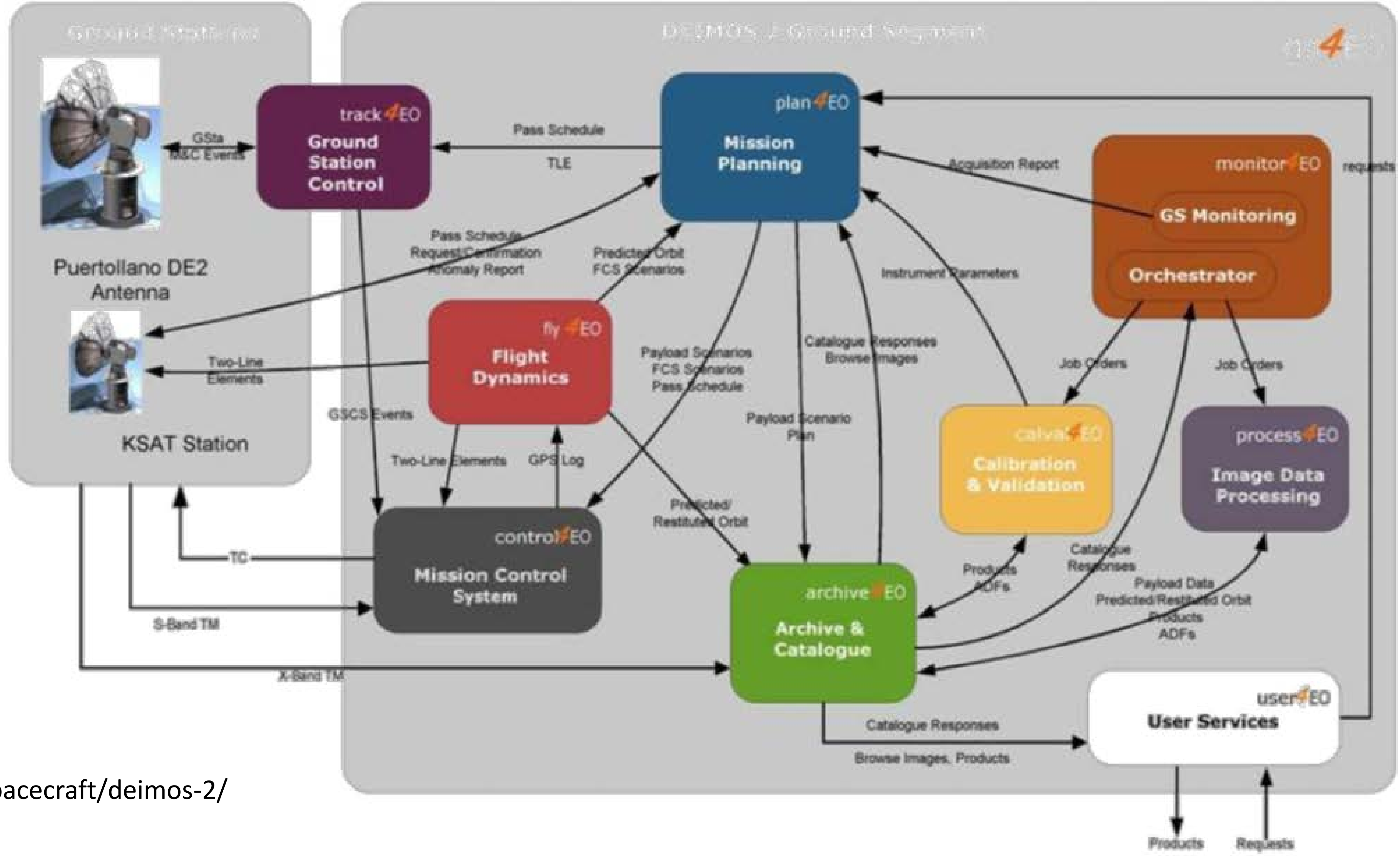


SARPDD - System for Acquisition, Registration and Processing of Digital Data
PHSSRSD - Propietary H/W and S/W System for Reception of Space Data
BRHTRS - Belarusian and Russian High-Throughput Reception System

http://gis.by/en/tech/index

Examples

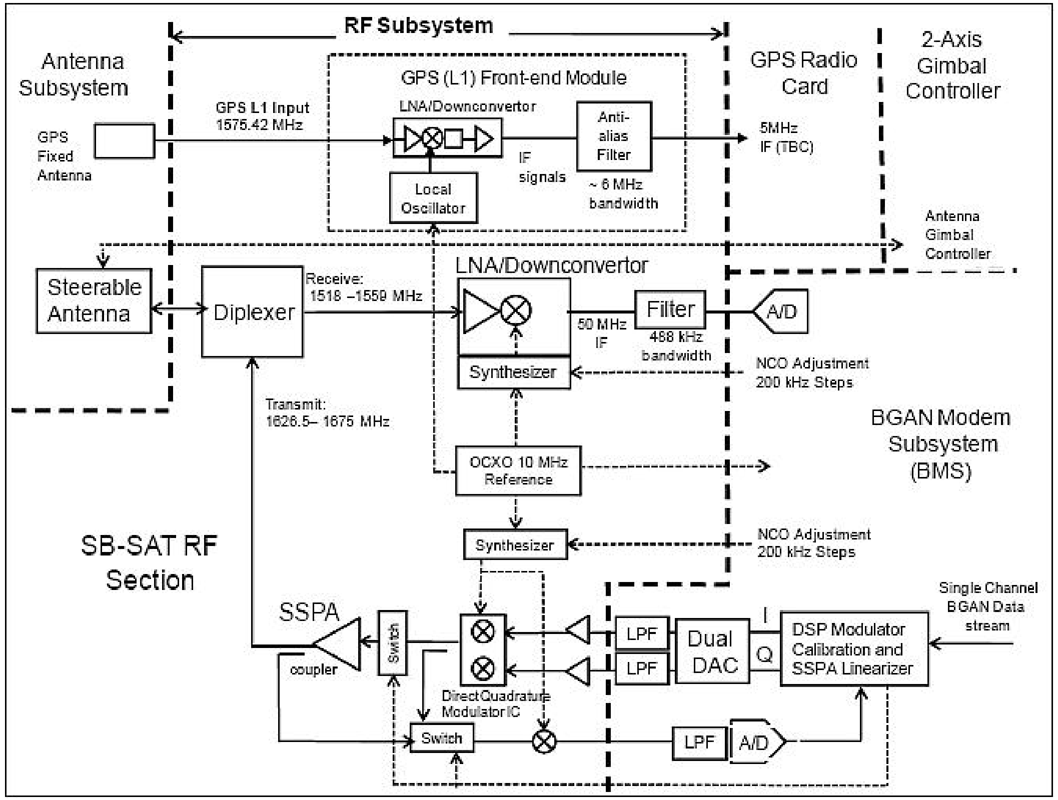
DEIMOS-2

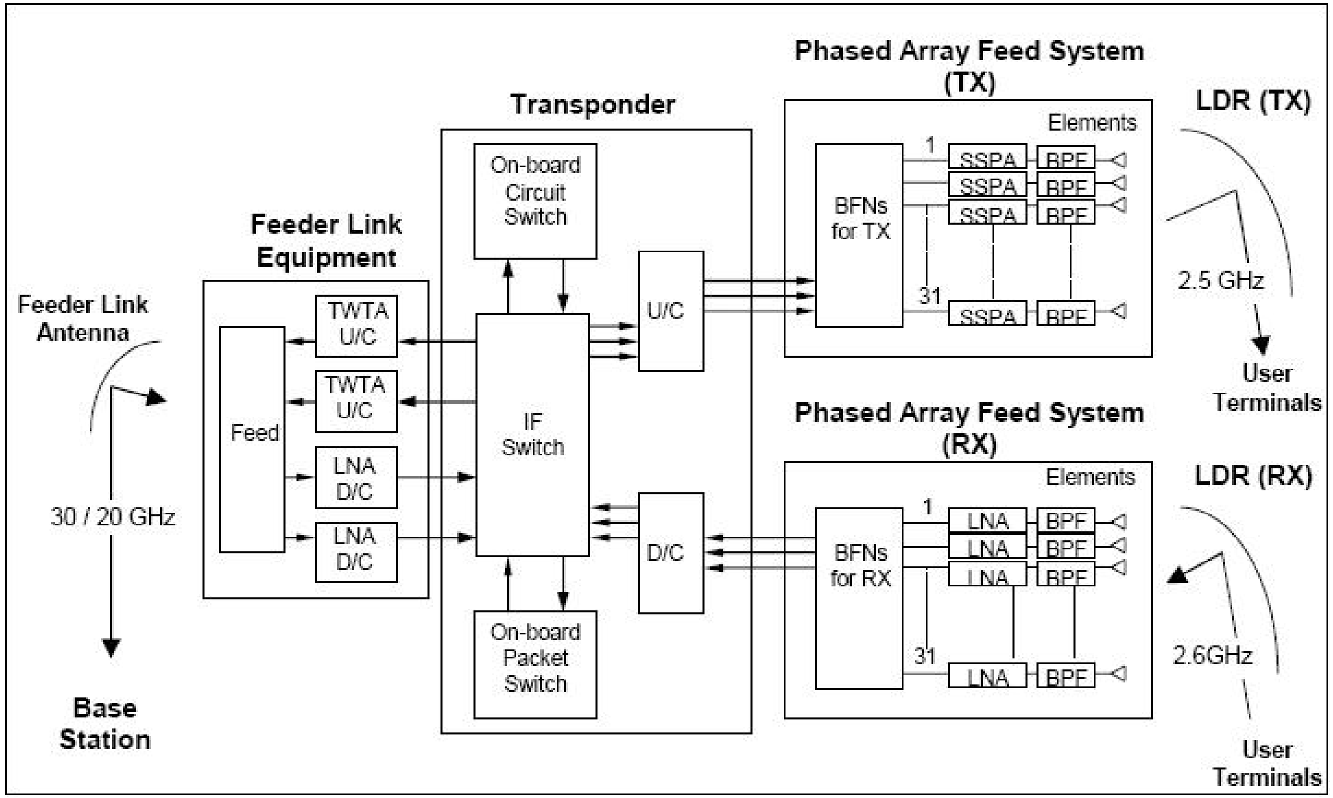


http://spaceflight101.com/spacecraft/deimos-2/

But a "ground station" is more complicated…

SB-SAT/BGAN & ETS VIII





https://directory.eoportal.org/web/eoportal/satellite-missions/e/ets-viii
& SB-SAT/BGAN

Overview of Ground Architecture and Current Systems

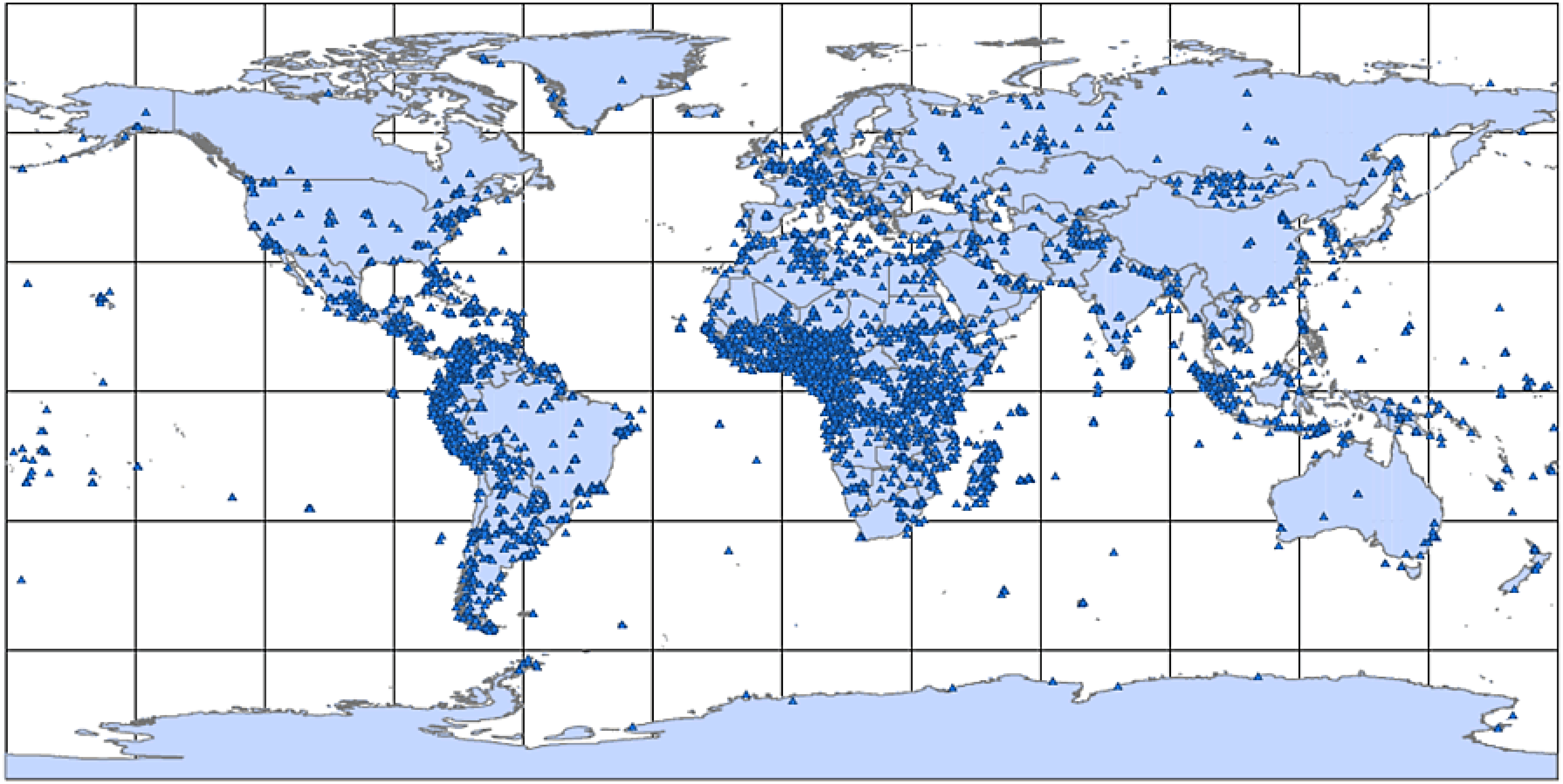
Outline

Overview of Ground Architectures and Current Systems

- What is global coverage?
  - How do elevation angle and placement affect coverage?
- How do connection protocols affect coverage?
  - Intelsat connections
- Current commercial companies
- US Government ground stations and architectures
- Space Situational Awareness-Introduction
- Second homework introduction

Global Coverage…or how many antennas are there?

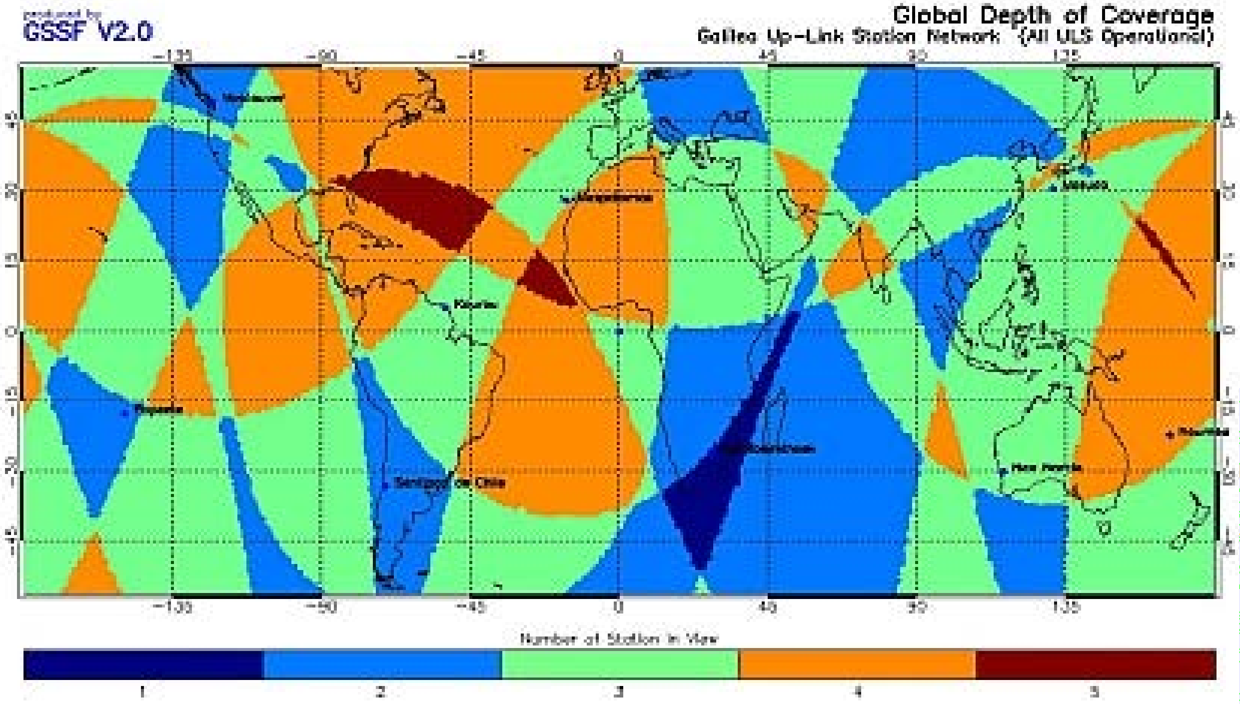
- *Location of ONLY Intelsat registered FSS Receive Earth Stations in the 3700 – 4200MHz band*

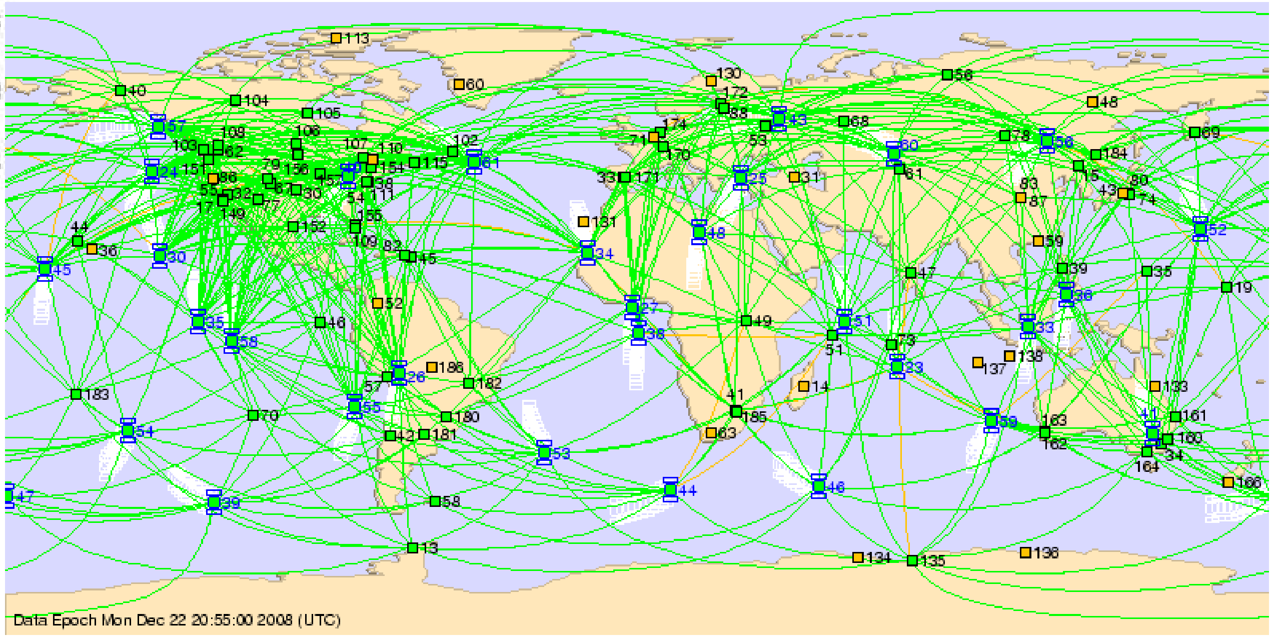


▲ Denotes a site that may include one or more stations

Navigation is global…

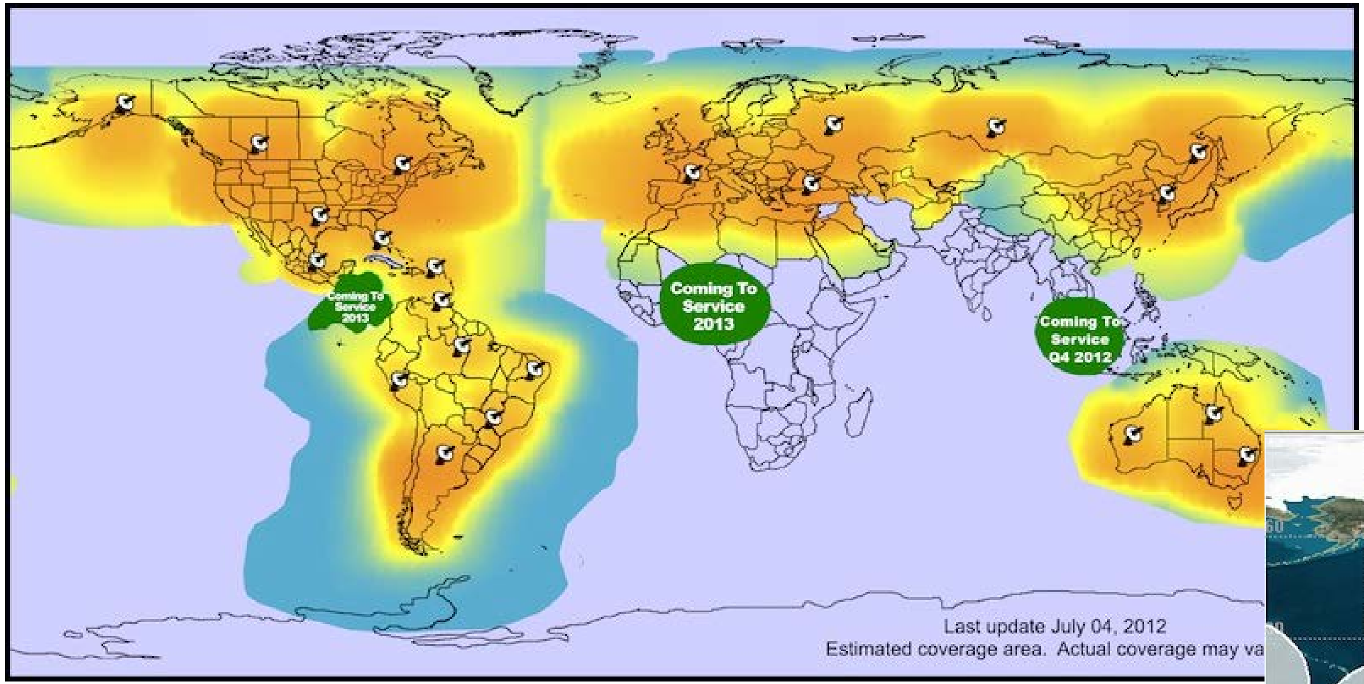
- *ESA Galileo system site coverage and GPS Integrity Map from JPL*

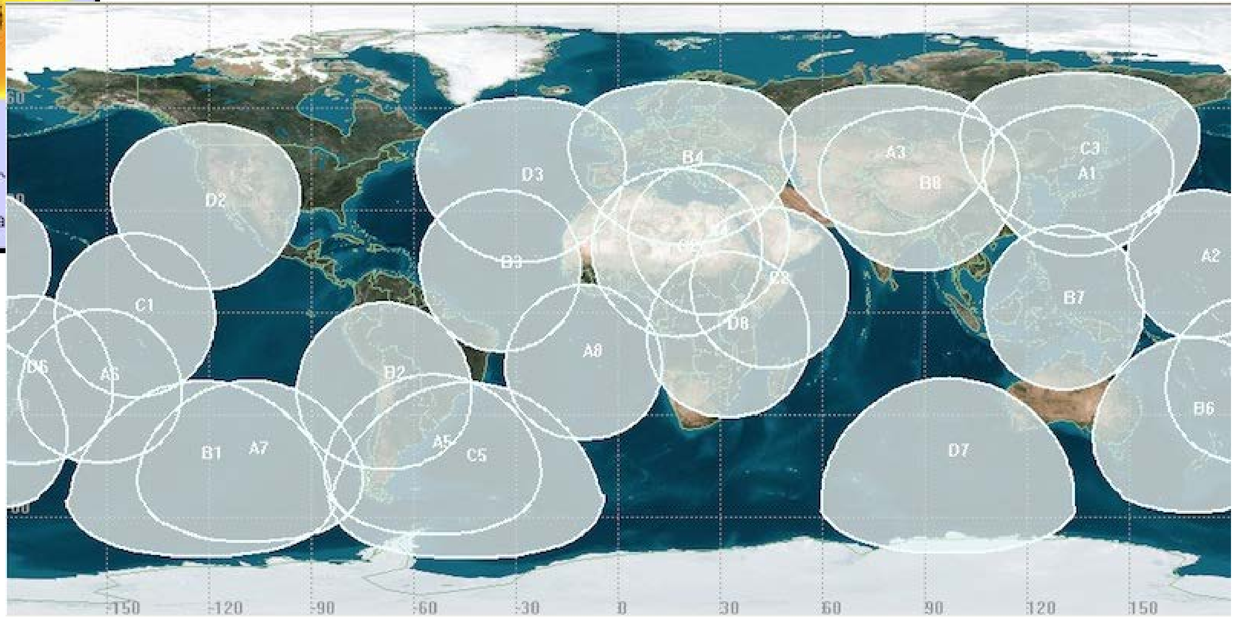




And if your backpacking…

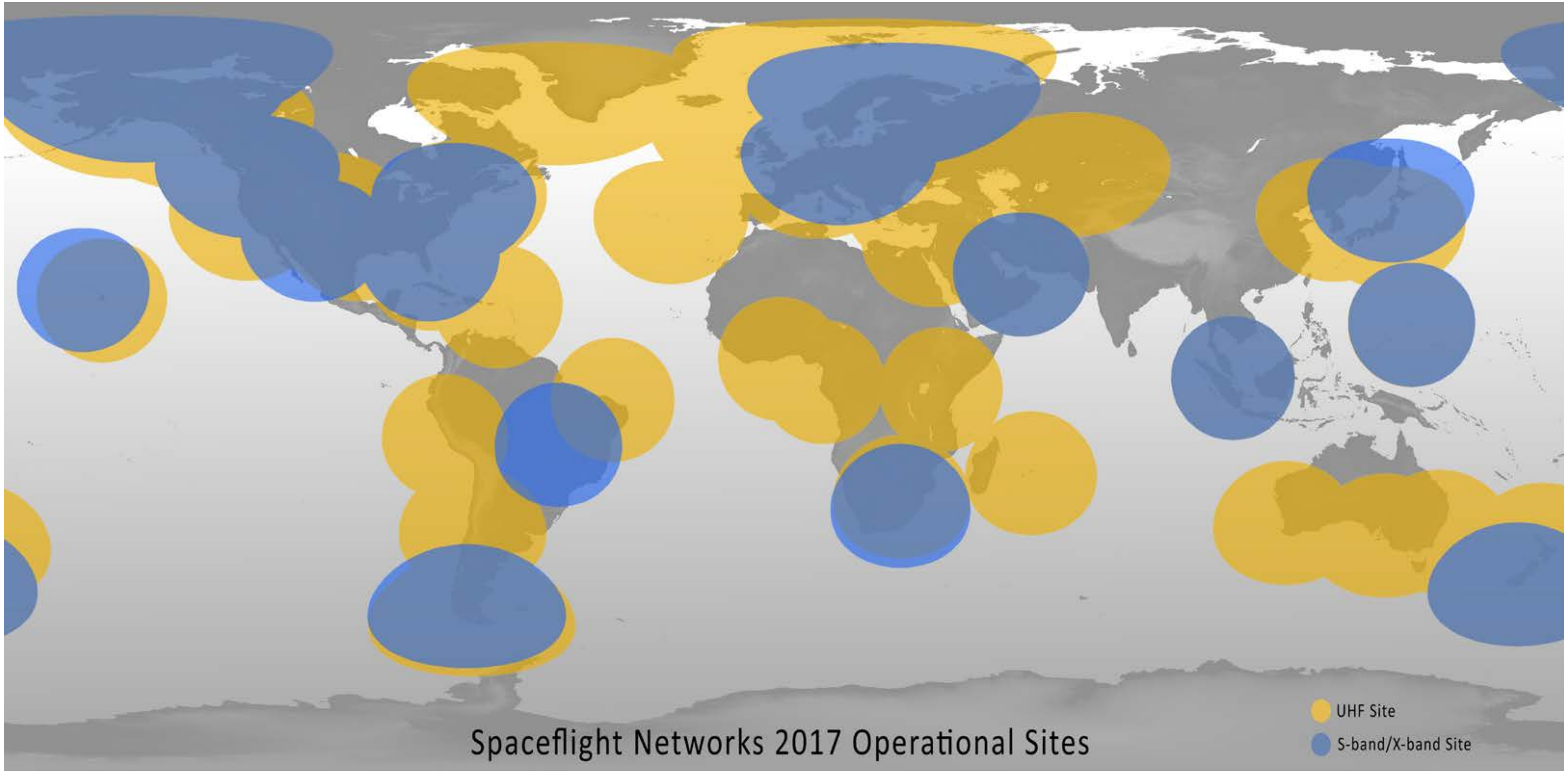
- *Globalstar and OrbComm can hook you up with voice and internet…*



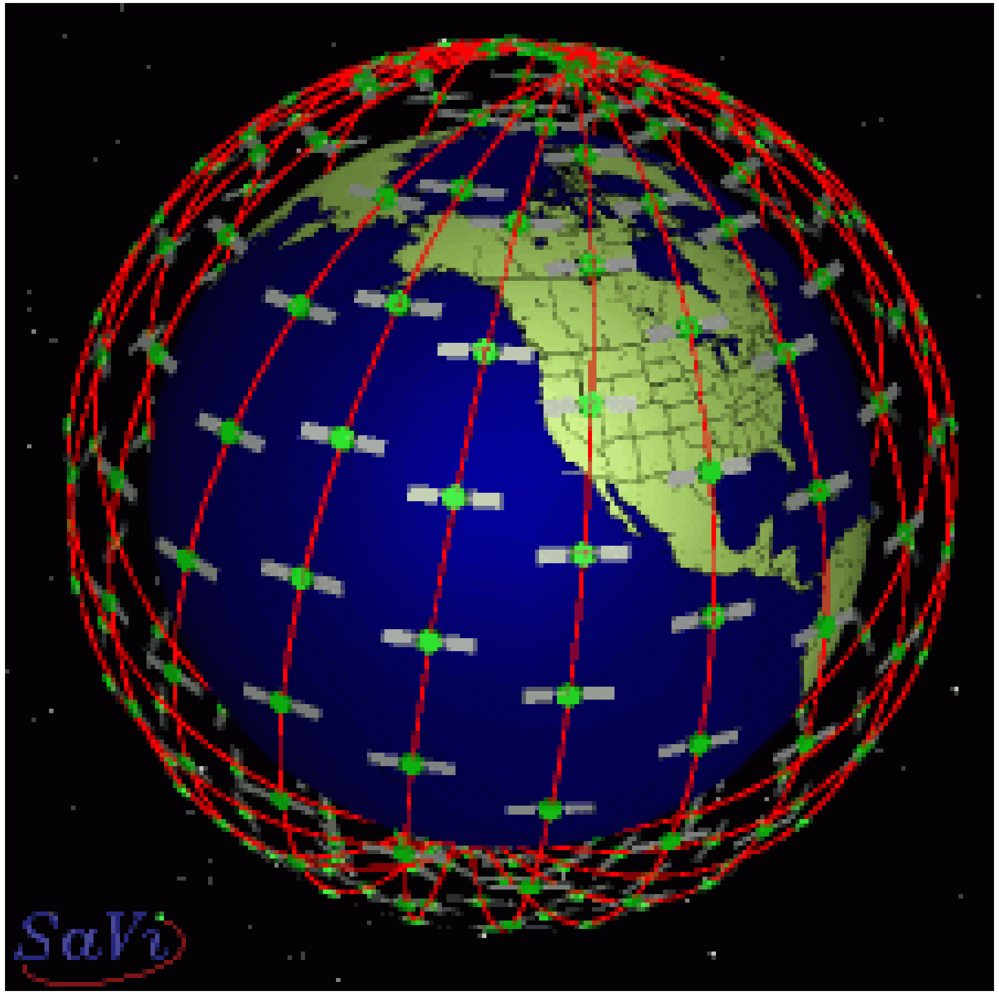


Relatively new phenomena…small sat ground stations

- *Projection of SpaceFlight Networks ground station map in 2017*

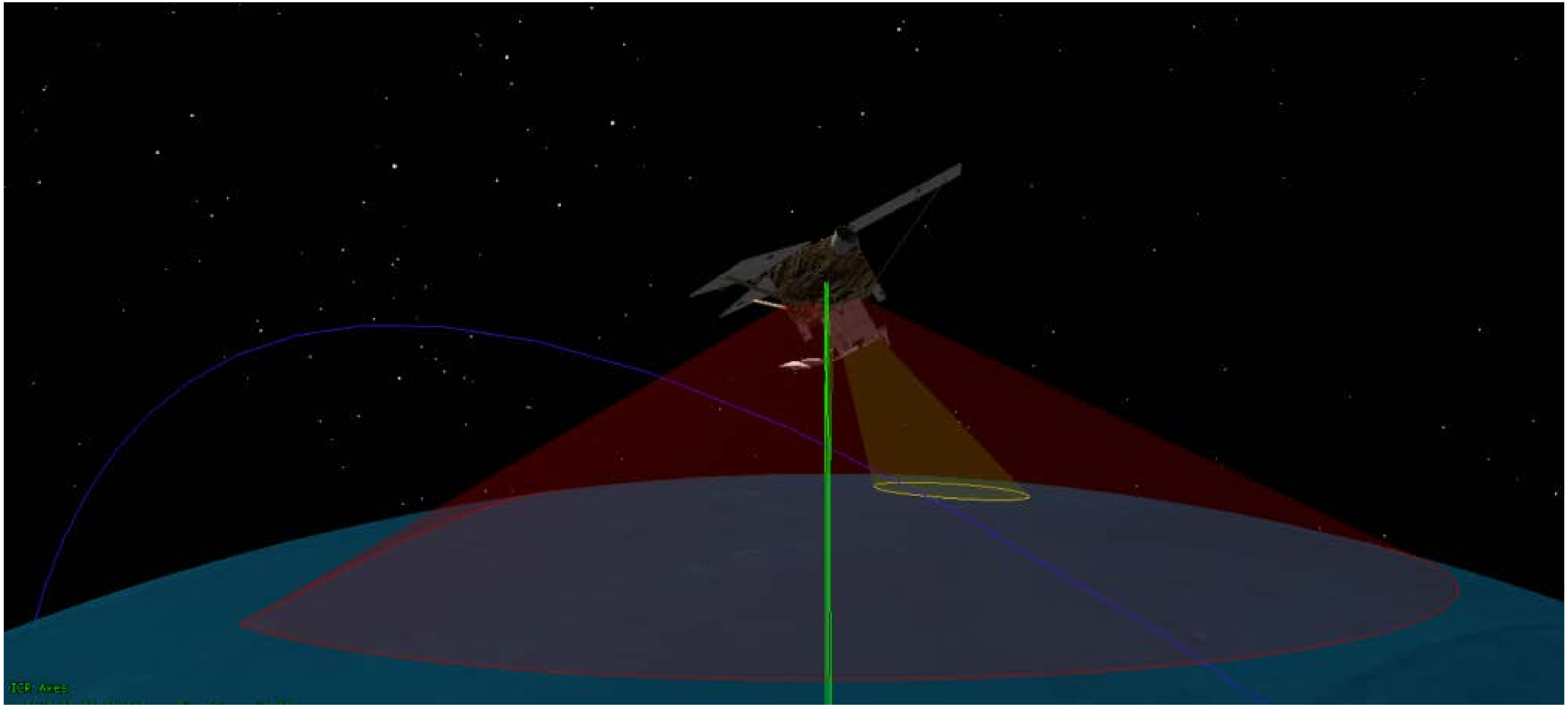


But Google, SpaceX or O3B will link the world….



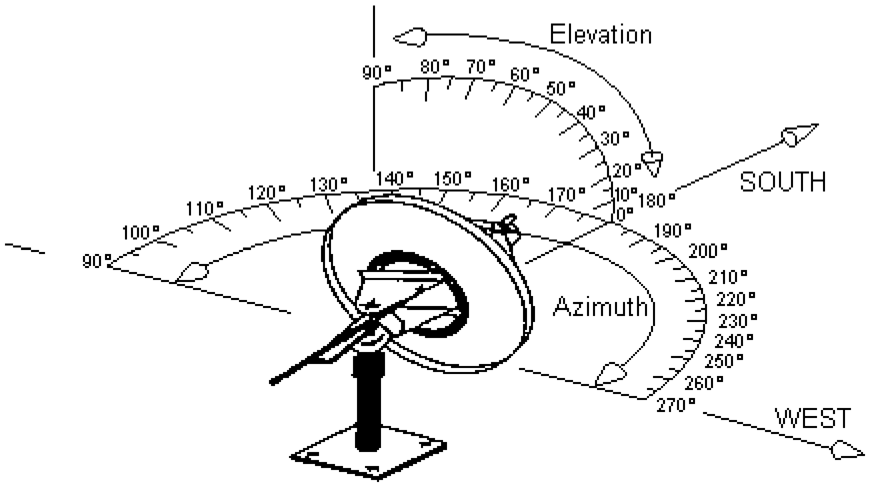
Look angles, geometry and interference

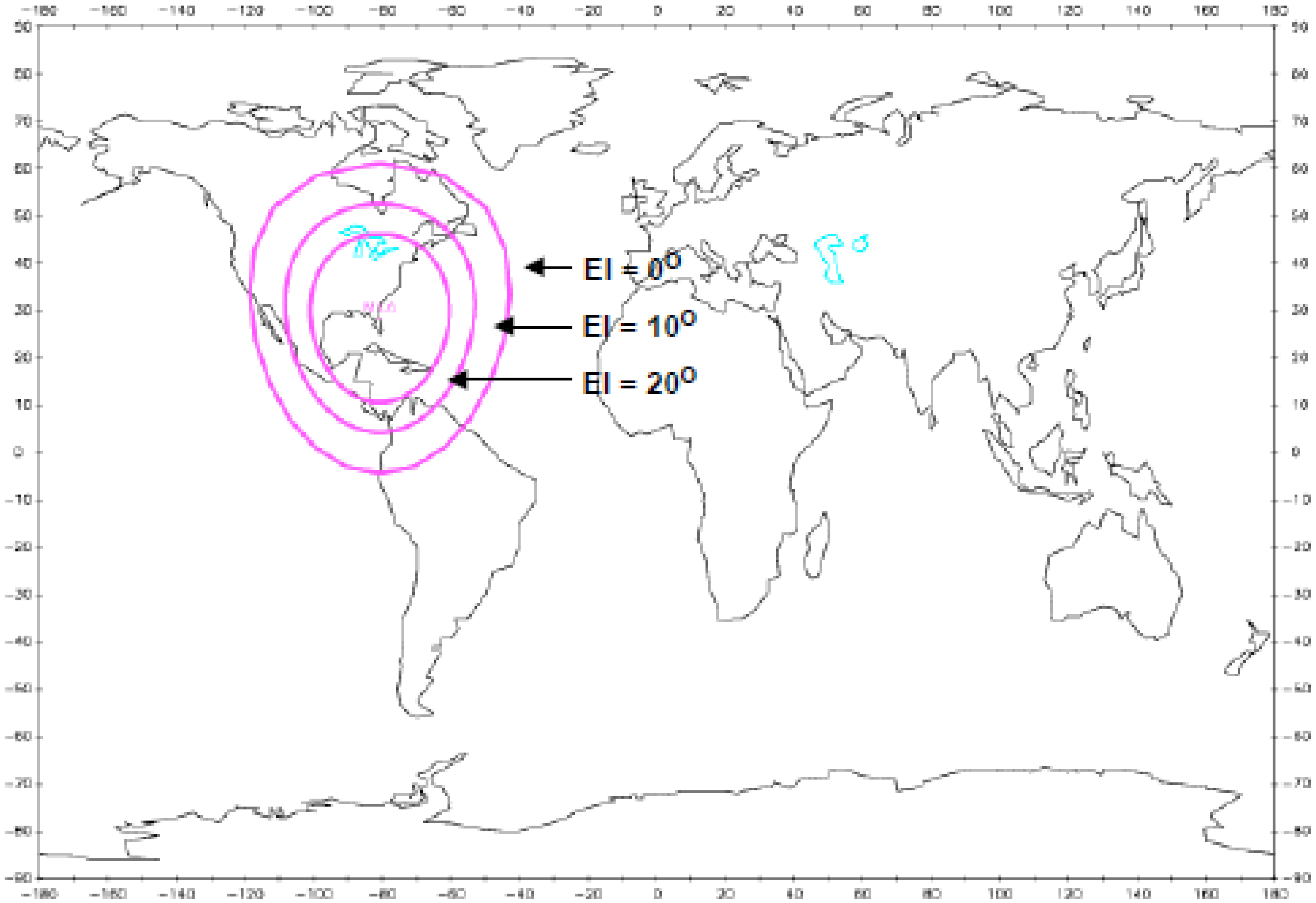
- *Onboard spacecraft the antenna swath is generally referred to in ½ angle, that sweeps out a cone on the ground*



Ground access to orbit is a similar cone, looking up

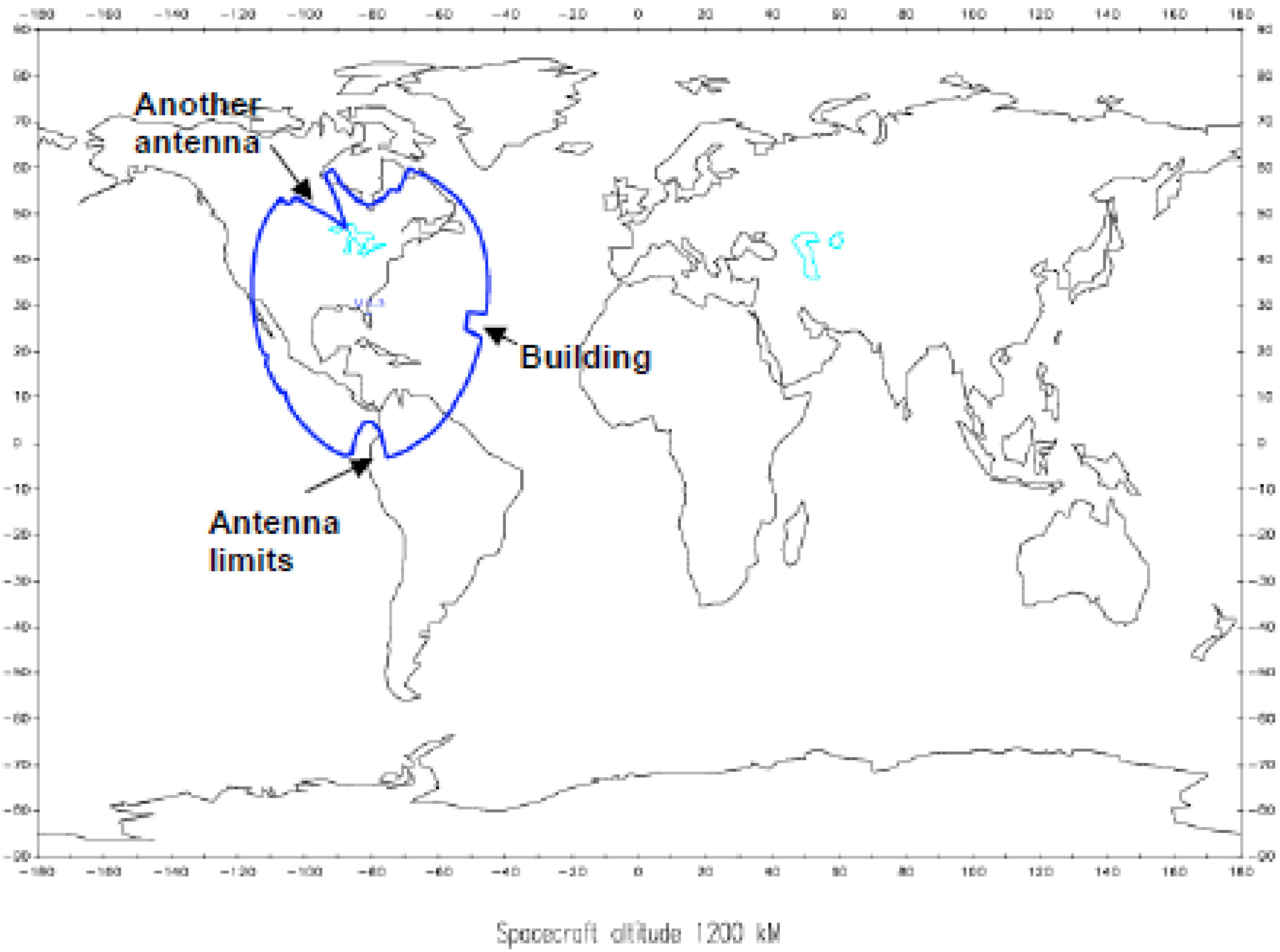
- *Example of a ground site in Florida, with a satellite at 1200km*





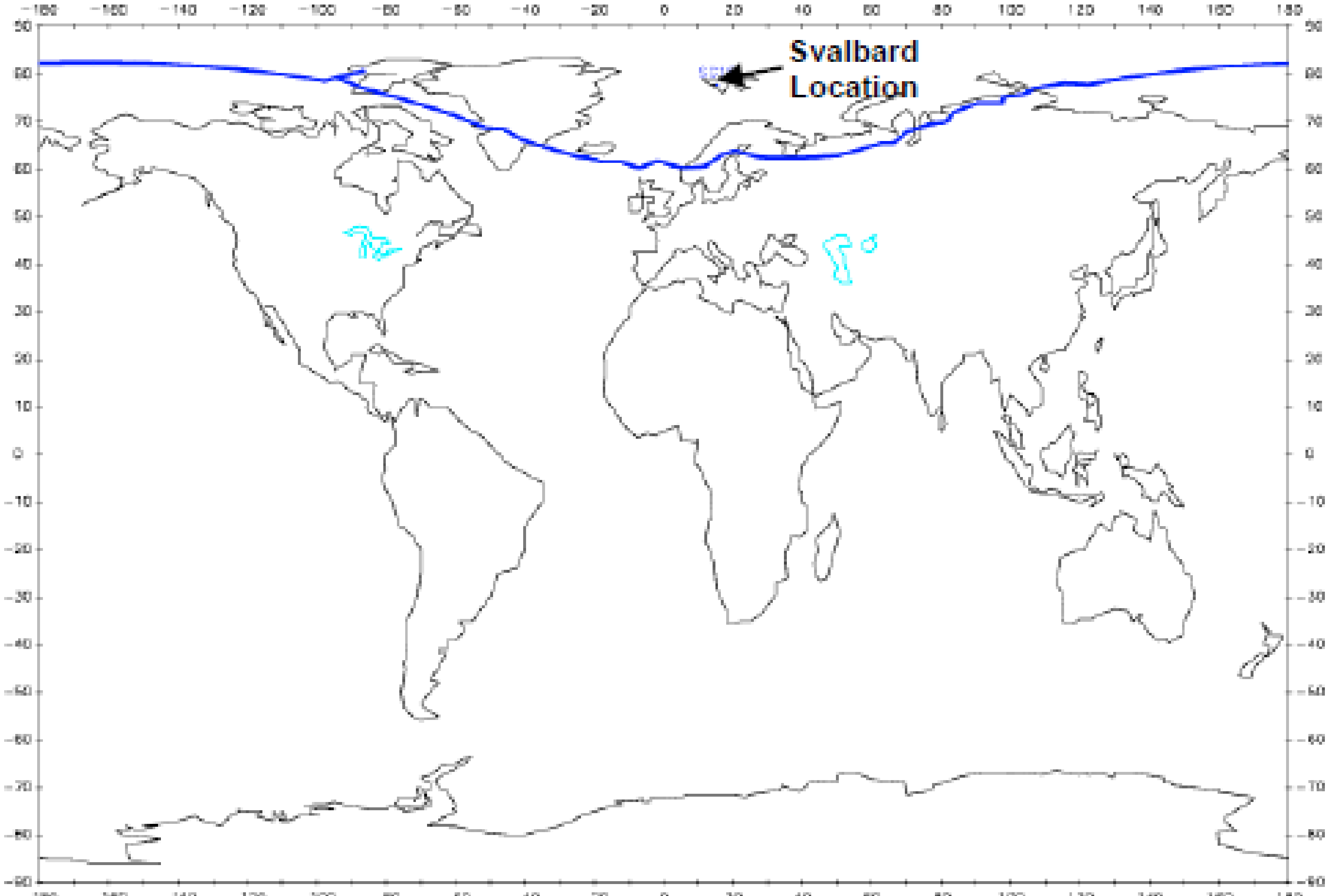
Ground interference

- *Elevation angle 0deg, at 1200km from same ground site*
- *Interference narrows the beams*



Benefits of being at the Poles

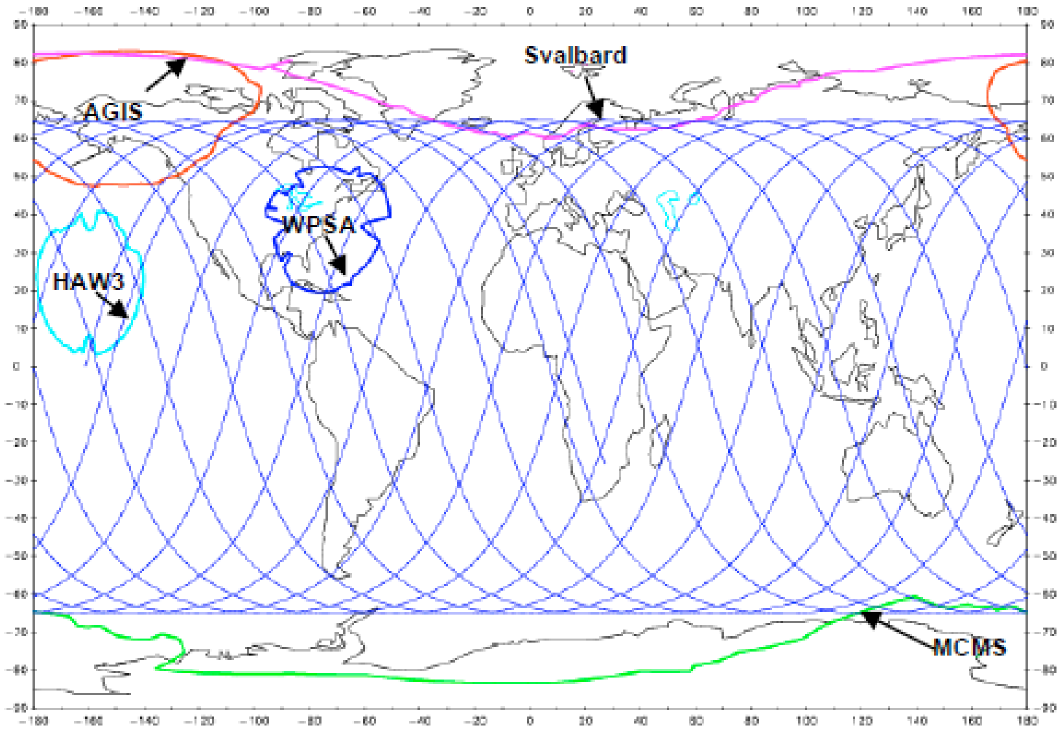
- *Svalbard Station has very high coverage across latitudes*



Inclination of satellite also increases amount of coverage

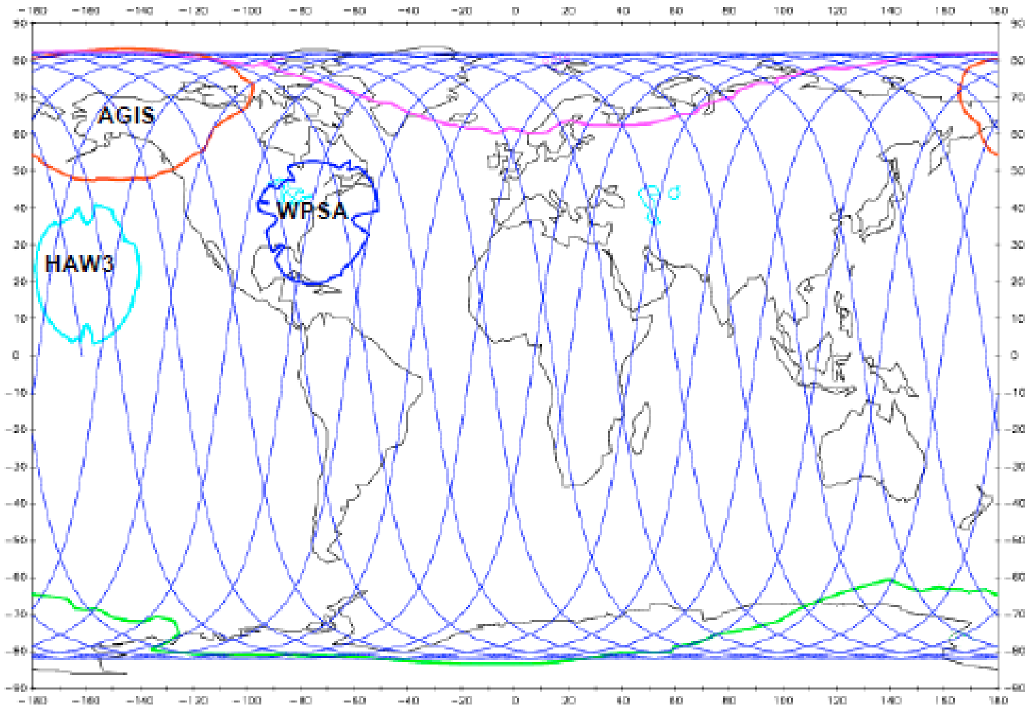
Spacecraft Orbit of 400 KM, 65 deg inc circular

Hawaii (HAW3), Alaska (AGIS), Wallops Island (WPSA), Svalbard (SGIS), McMurdo (MCMS)



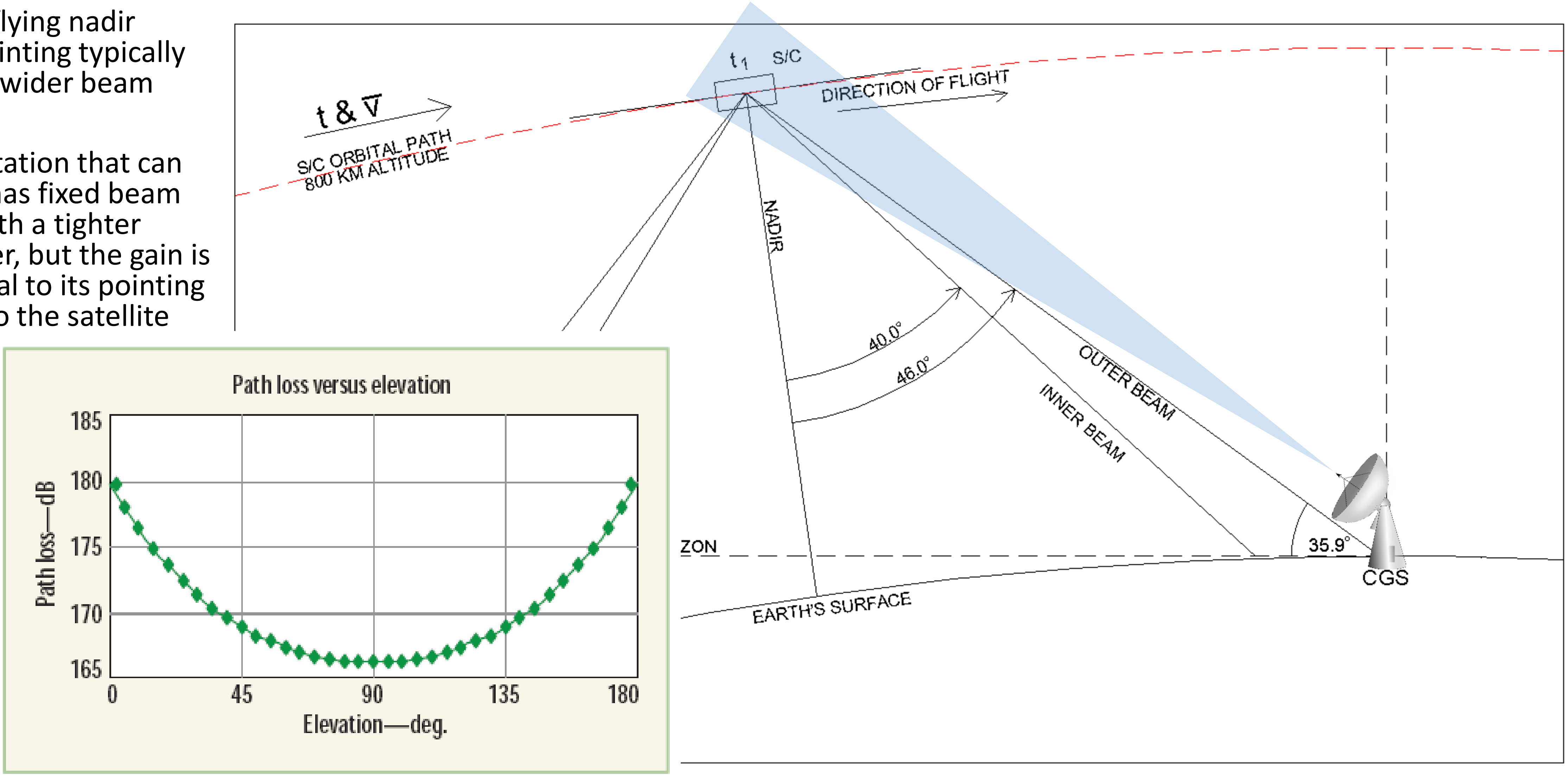
Spacecraft Orbit of 400 KM, 98 deg inc circular

Hawaii (HAW3), Alaska (AGIS), Wallops Island (WPSA), Svalbard (SGIS), McMurdo (MCMS)

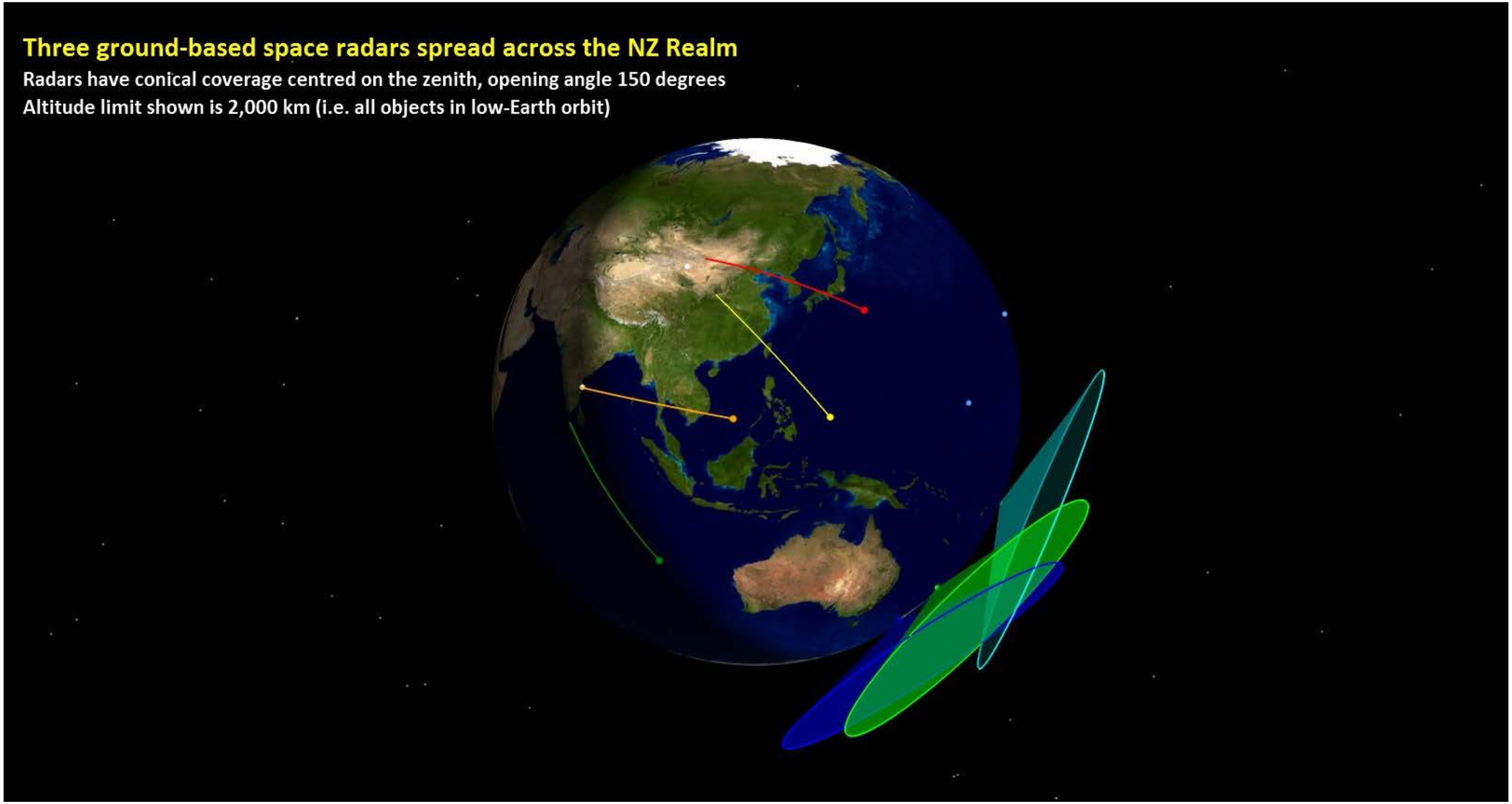


Coordinating antenna pattern maximizes signal reception

- A satellite flying nadir without pointing typically has a fixed wider beam pattern
- A ground station that can track also has fixed beam pattern, with a tighter beam patter, but the gain is proportional to its pointing elevation to the satellite

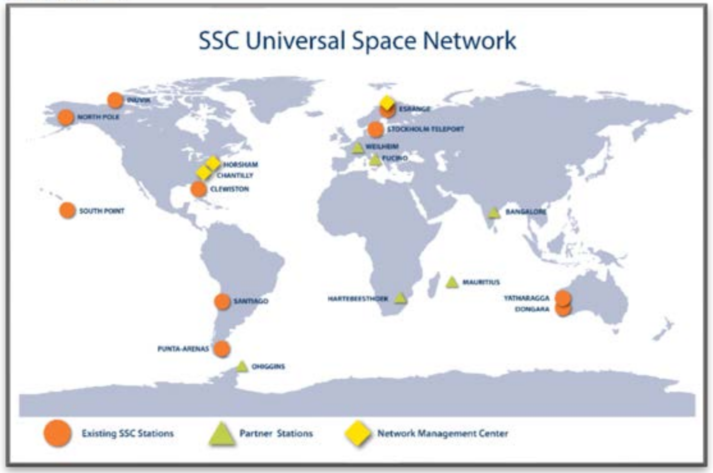


Example of ground beam widths that are very large

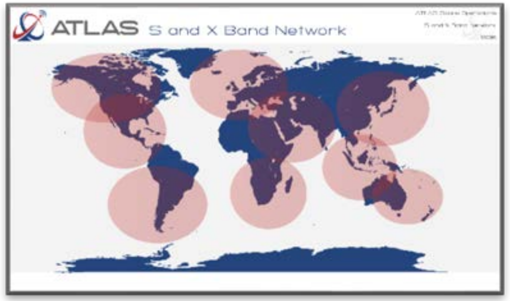


Commercial Ground Network Providers

- SSC Universal Space Network (USN)



- Kongsberg Satellite Services (KSAT)
- Atlas Ground



- Other Comm Providers have their own Space-Ground networks
  - Iridium, Globalstar
  - Viasat, Inmarsat, Intelsat

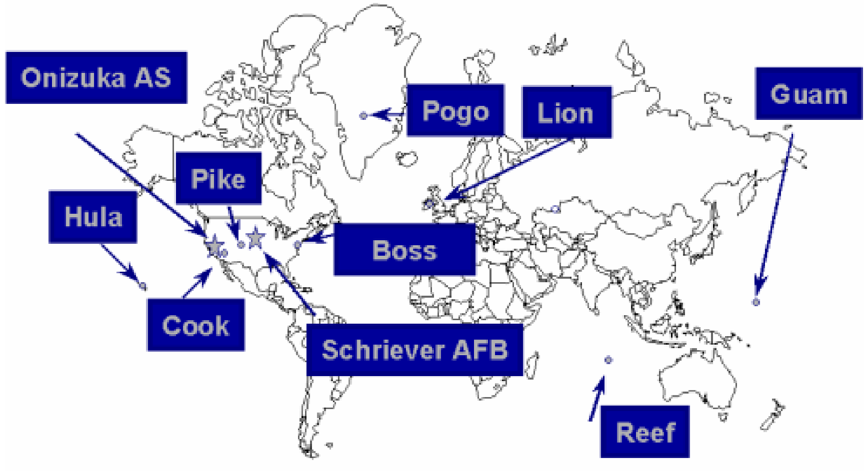
Commercial Ground Network Providers with commercial products available

Provider/Manufacturer	Product available	Supported Bands
RBC Signals	“uber” of ground station services	S, L, X, UHF, VHF
Surrey Satellite Technology Ltd	Surrey Ground Segment	S-Band for U/L and D/L, and X-band for D/L
ISIS B.V.	ISIS Small Satellite Ground Station	Amatuer and non-amateur protocols for VHF, UHF and S-Band
Tyvak Inc.	Endeavour TT&C	VHF, UHF and 2.2-2.29 GHz (S-Band)
Espace Inc.	Open System ofAgile Ground Systems (OSAGS)	S-band for U/L and D/L. HR/VHF/UHF receive.
GAMALINK	GAMALINK Ground Station Network	VHF/UHF and S-Band packets. Ranging and GPS support.
Clyde Space Inc.	Satellite Tracking and Control Station	VHF, UHF, L-Band and 2.4 GHz

https://sst-soa.arc.nasa.gov/11-ground-data-systems-and-mission-operations

US Government Space-Ground Networks

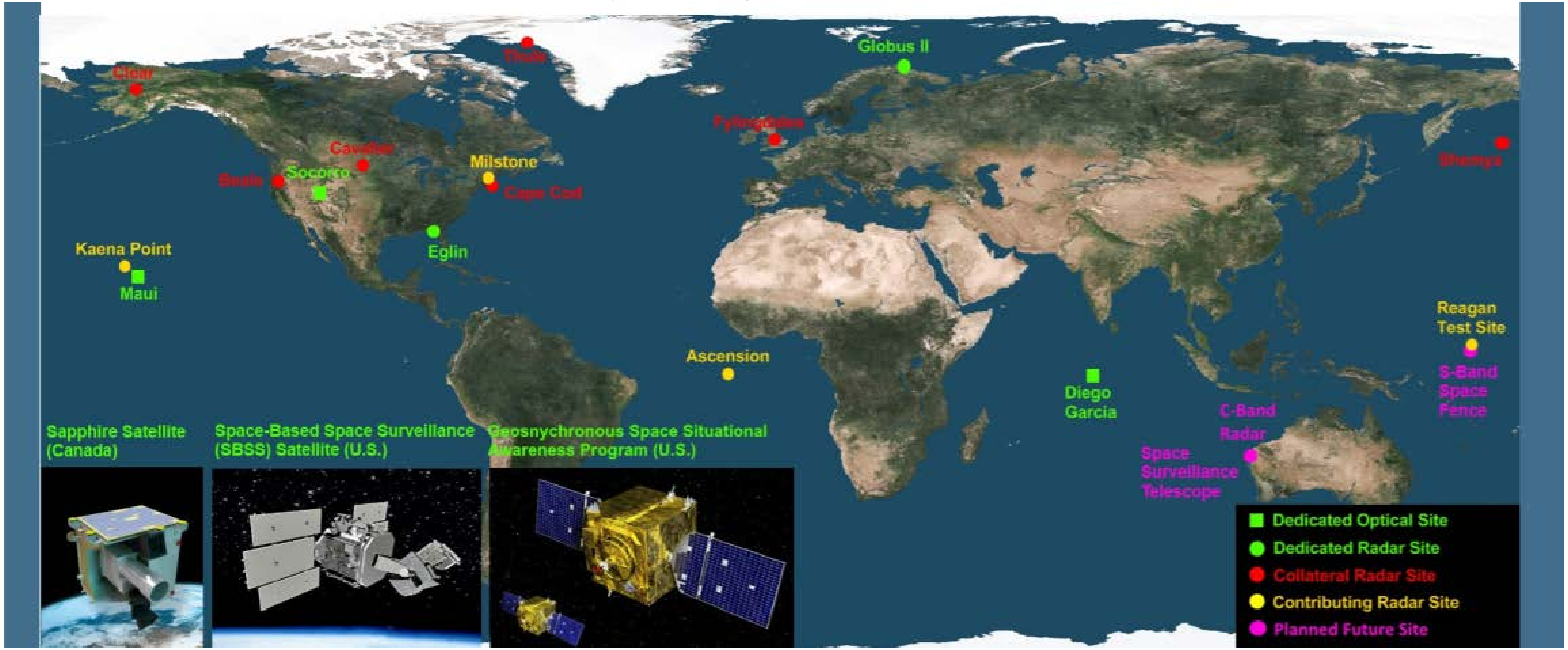
- Air Force Space Control Network (AFSCN)
  - Air-Force Space Control Network
- NASA Space Communication & Navigation (SCaN) Network
  - Combined DSN and Near Earth Network
- Others:
  - Blossom Point Tracking Facility
  - Mission Specific Terminals
    - NOAA Direct Readout



NASA's SCAN…uses govt and commercial systems

SSA: Space Situational Awareness

- SSA is the ability to accurately characterize space environment and activities in space. Civil SSA combines positional information on the trajectory of objects in orbit (mainly using optical telescopes and radars) with information on space weather, and identification/self reporting from satellites themselves.*

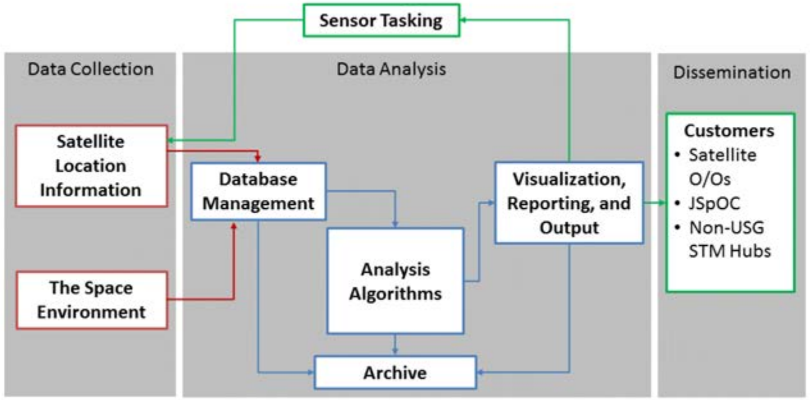


*https://swfound.org/media/1800/swf_ssa_fact_sheet_sept2014.pdf

Space Situational Awareness includes…

*

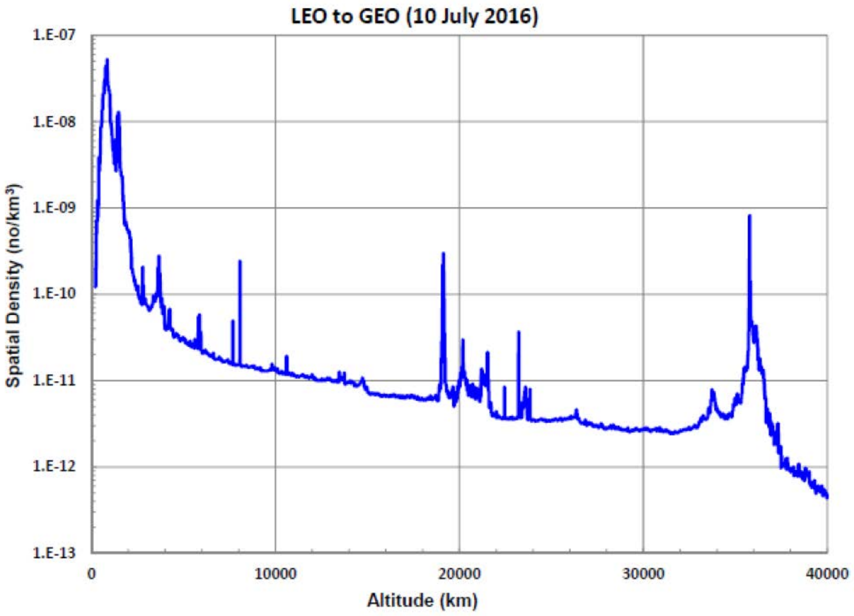
1. Tracking and Characterizing Space Objects: Monitoring space objects with ground- and space-based sensors; identifying the observation(s) with an established list of known objects; updating the list of space objects as needed; determining the size and shape of space objects.
2. Launch and Early Orbit Collision Avoidance (COLA): Comparing the planned launch trajectory above 150 kilometers from time of launch through the first several hours post-launch (currently, 3 hours, with a commonly stated goal of 48 hours) against all other orbital space objects to determine potential on-orbit conjunctions.
3. On-Orbit Conjunction Assessment (CA): Comparing the orbital trajectory of all active satellites against all other orbital space objects to determine potential on-orbit conjunctions that meet a pre-determined close-approach threshold distance.
4. On-Orbit Collision Risk Assessment and Maneuver Planning: Determining the probability of collision resulting from a close approach between an active satellite and another space object, and assessing options for maneuvers to minimize or eliminate the probability of collision.
5. End-of-Life (EOL) Verification: Monitoring an active satellite's end-of-life procedures and verifying compliance with a pre-determined orbital debris mitigation plan specified in the operator's license.
6. Controlled De-Orbit COLA: Comparing operator-generated planned de-orbit trajectories against all other orbital space objects and air traffic flight corridors.
7. Reentry Risk Analysis: Predicting the atmospheric decay of space objects, estimating the potential threat they may pose to aircraft in flight or people and
8. Archive and Analysis: Capture and long-term storage of events for historical analysis and archival purposes.
9. Space Weather Warnings: Monitoring solar activity, and providing notification of a space weather event that poses potential risk to spacecraft or the Earth.
10. Radio Frequency Interference Notifications: Assisting satellite operators in detecting and resolving radio frequency interference impact on satellite command and control or payloads.
11. National Security Activities: Characterizing adversary space object capabilities and intentions, and detecting and addressing hostile threats to satellites



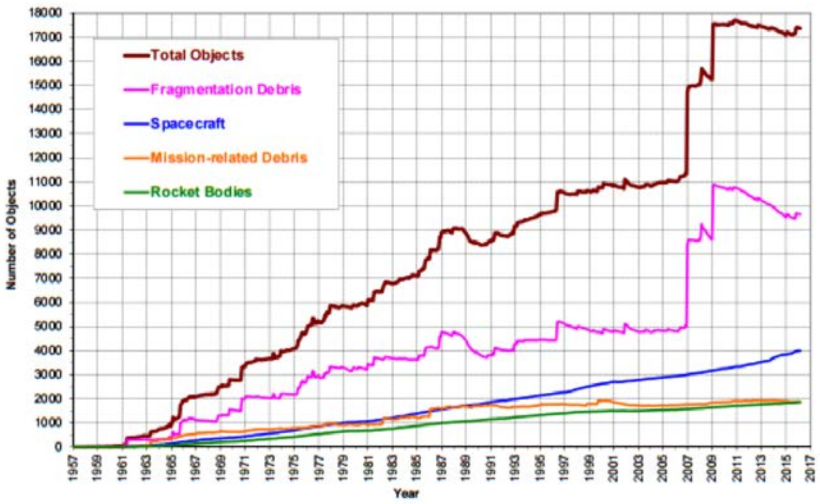
* Figure ES-1. Elements of a Conceptual SSA System

*** "Evaluating Options for Civil Space Situational Awareness (SSA)" - IDA Paper NS P-8038, August 2016***

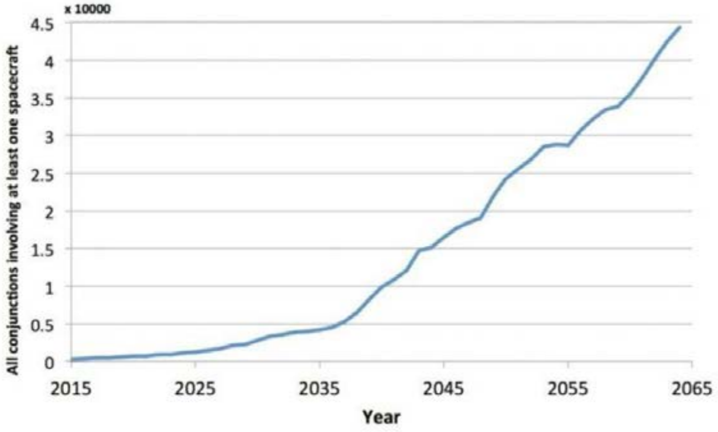
Why is SSA Important?



* *Source*: Liou (2016).



Source: NASA Orbital Debris Program Office (2016, 14).



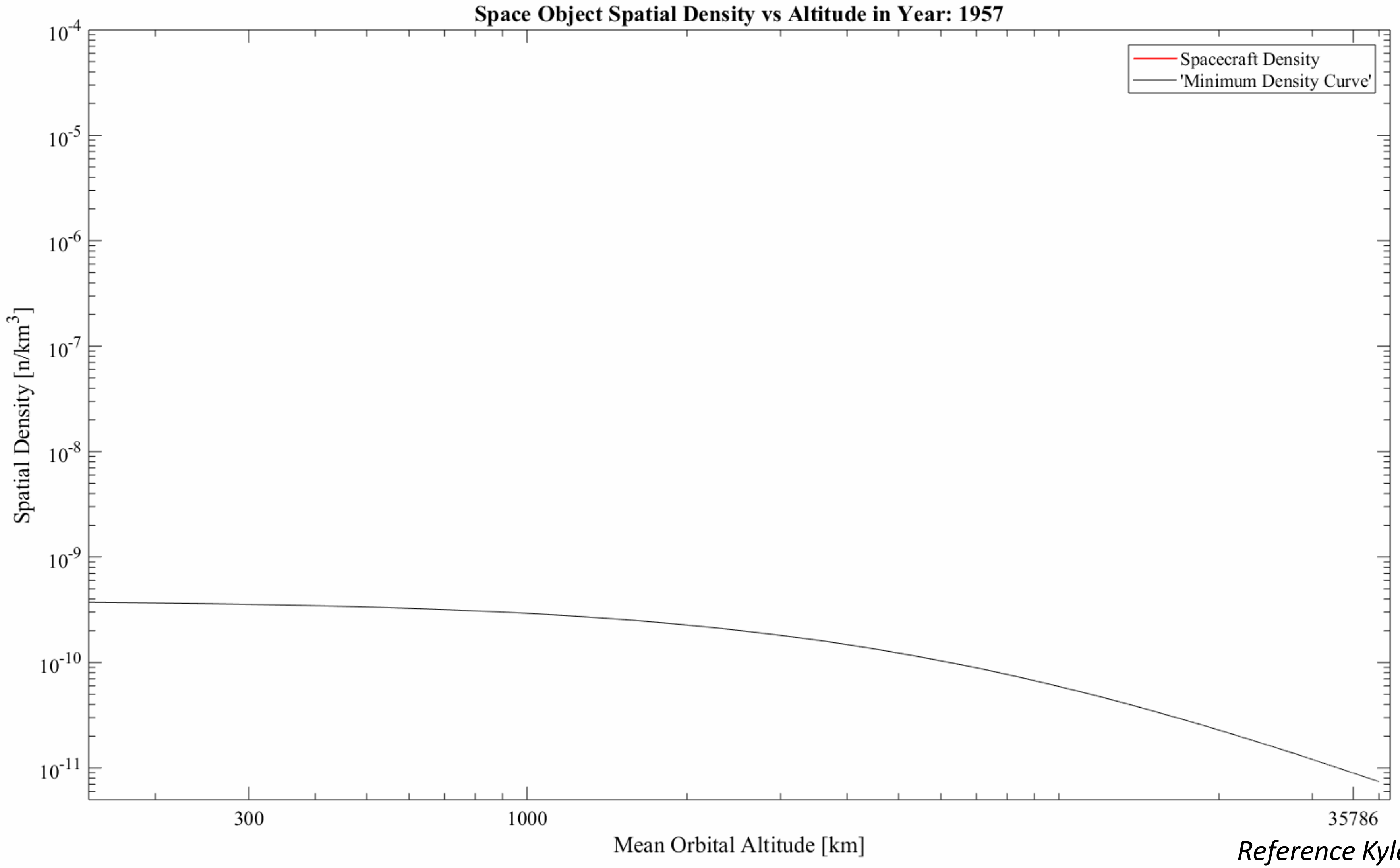
Source: Karacalıoğlu (2016).

Figure 4. Predicted Number of Conjunctions Involving at Least One Spacecraft

- Spatial Density is focused at certain altitudes causing congestion
- Total number of objects includes debris…is rising
- Predicated number of “conjunctions” (sat interaction with other objects) is expected to increase dramatically

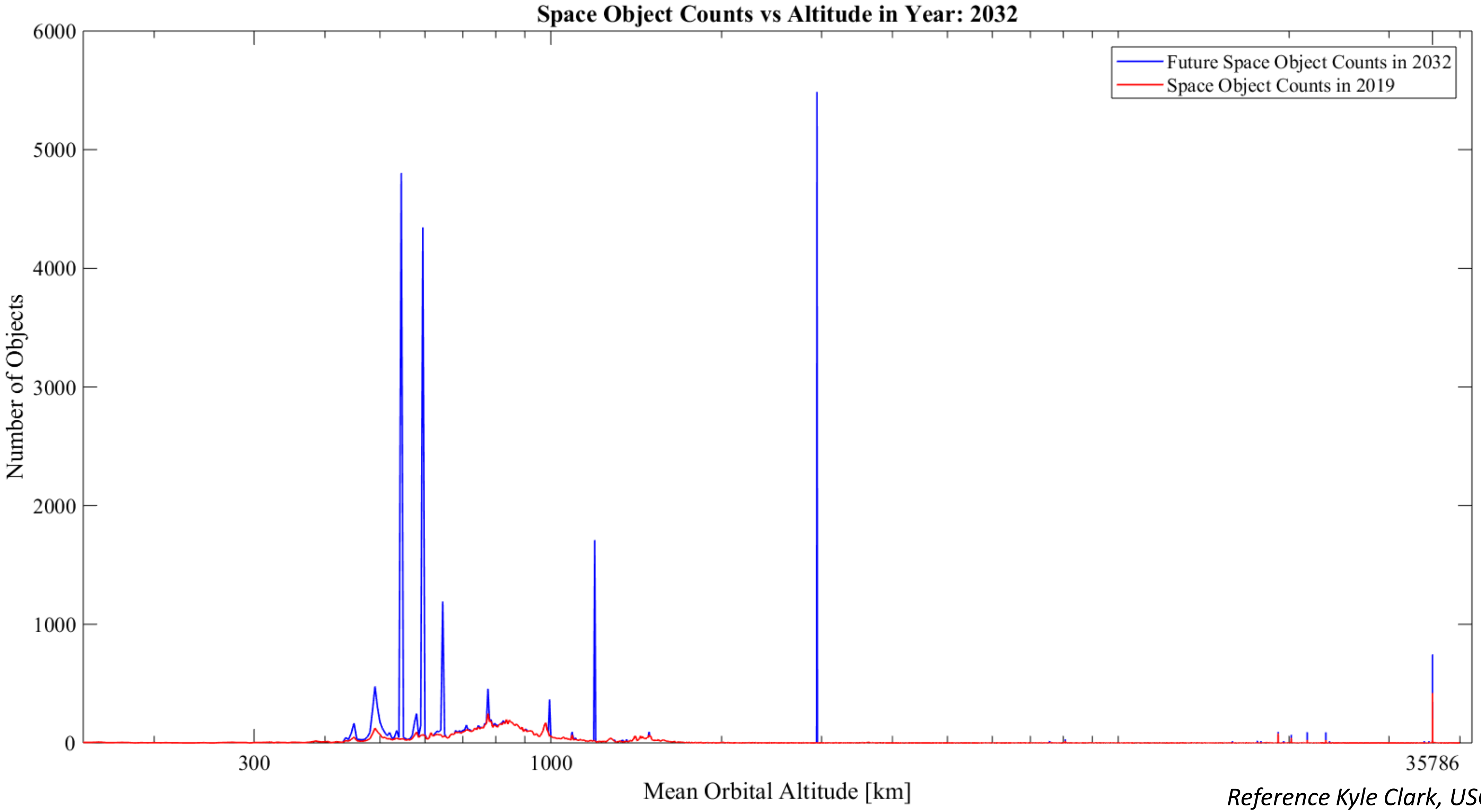
**** “Evaluating Options for Civil Space Situational Awareness (SSA)” - IDA Paper NS P-8038, August 2016***

Why does it matter? there are a lot of objects around Earth!



Reference Kyle Clark, USC

Historical/Projected Spacecraft numbers will only go up…



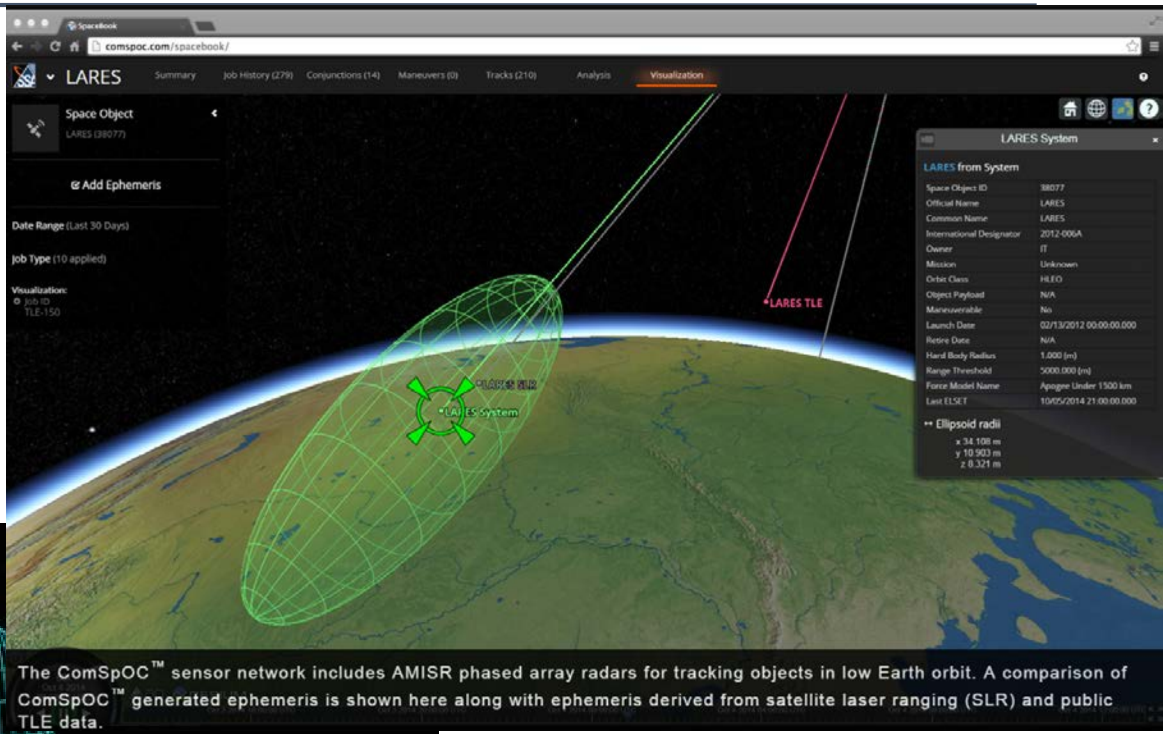
Reference Kyle Clark, USC

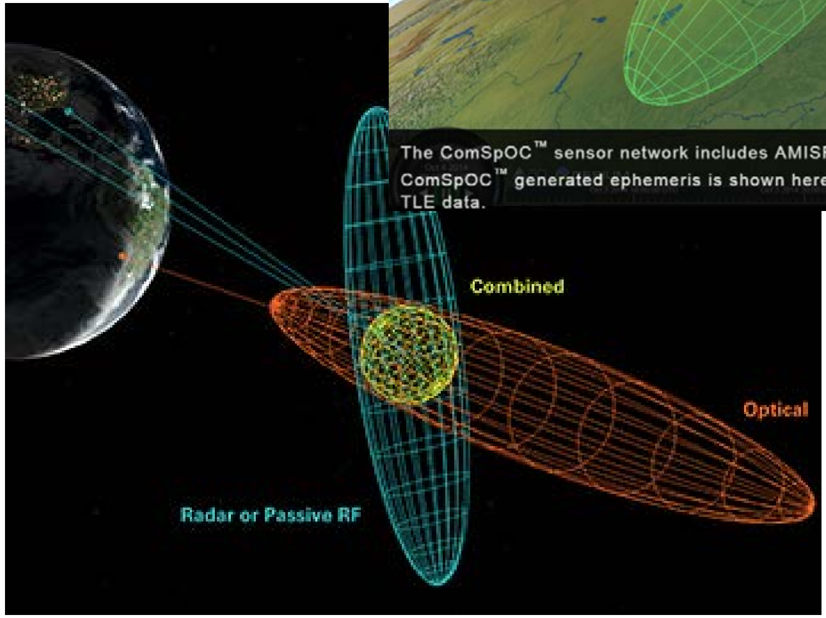
SSA Organizations

- Joint Interagency Combined Space Operations Center (JICSpOC)
  - US led Multi-Military Agency group with three international participants that provides to US (primarily) and International information on satellite/space object orbits.
  - Supports “Space-Track.org” which is public website for all JICSpOC SSA services and supports worldwide space catalog.
  - Provides “notices to satellites” for possible conjunctions
- Commercial Space Operations Center (CSOC)
  - Run from AGI
  - Has access to worldwide commercial/govt sensors, provides data analytics
- ExoAnalytic Solutions Space Operations Center (ESpOC)
  - Supports Commercial SSA analytics, and independent catalog of space objects.
- Schafer Corporation Commercial SSA Unit
  - Supports commercial SSA analytics, and observations from commercial sensors.

The impact of accurate observations

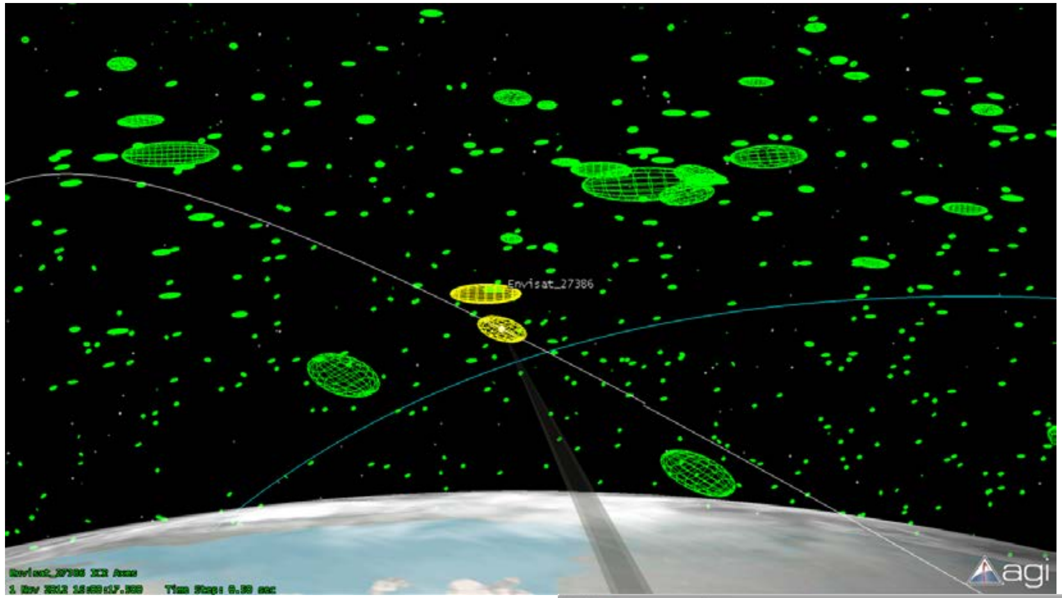
- Accuracy of observations is critical for
  - Conjunction analysis and warnings
  - Understanding accuracy of maneuvers
  - Ground based tracking
- LEO/GEO objects typically have an "error ellipsoid" assigned to them based on their velocity vector
  - From aggregation of errors from the observation station, the accuracy of resolution of the observation, the specific place in the orbital plane at a particular time, etc
- For ground tracking, the specific TLE designation is estimated to be in the "middle" of the ellipsoid
  - But the Ground station itself introduces its own errors on attempting to track the exact object at the exact time

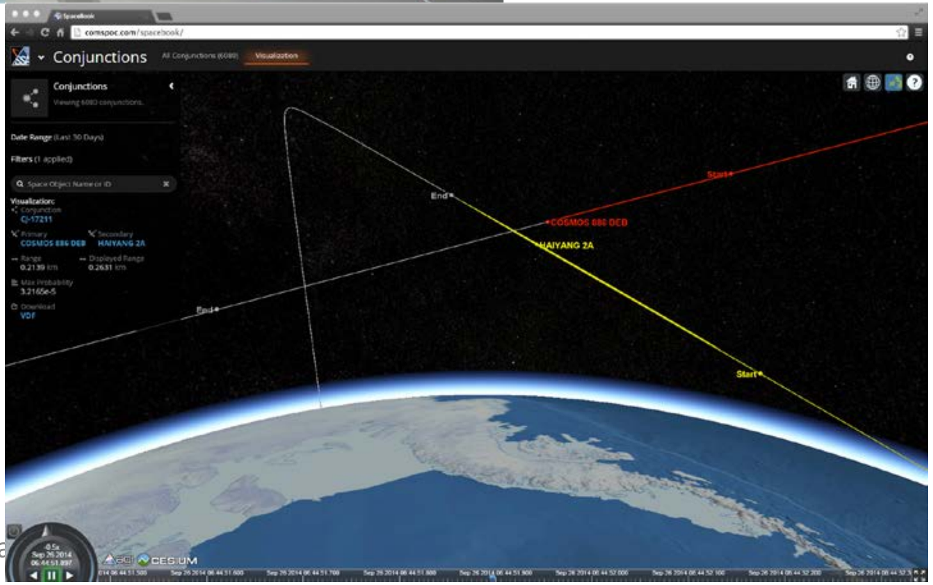




Conjunction analysis: “Get us out of here Scotty”

- “Conjunction analysis” is the determination of close approach or collision potential between two objects in space
  - Satellite to satellite
  - Satellite to debris
  - Debris to debris
- CA is critical for large space constellations in high debris orbits
  - Depending upon “probability of close approach” and how close of an approach, satellite operators have to decide about maneuvering out of the way
  - This has an economic impact, either way
    - i.e. Move or don’t move





Further References for SSA

- ***http://www.agi.com/resources/white-papers***
- ***http://www.agi.com/resources/case-studies***
- ***http://www.agi.com/comspoc***