EXTREMELY LARGE SWARM ARRAY OF PICOSATS FOR MICROWAVE / RF EARTH SENSING, RADIOMETRY, AND MAPPING

Progress report

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UTITLITY AND APPLICATIONS

Principal aim: support NASA's Earth Science activities

"….improve the measurement and prediction of water-related phenomena"

Sense and measure:

- Soil moisture content
- Freeze-thaw cycles
- Snow accumulation levels
- Flooding extent and precise geographical location
- Emergency management after hurricanes and floods
- Water content and temperature profile in atmosphere
- Ocean salinity
- Coastal salinity and river effluents
- Other water-related Earth Science applications

Principal requirement:

- Observe in the low microwave frequencies because they interact best with water

OBJECTIVES
SOIL MOISTURE / OCEAN SALINITY REMOTE SENSING

- High resolution on the ground
- High sensitivity
- Rapid / frequent revisit
- Flexible scan area and pattern, or continuous dwell
- Coverage of nearly a hemisphere from one space system
- Affordable

These objectives cannot be met by any current, programmed, or even planned systems

CAPABILITIES AND DESIREMENTS-HYDROLOGY

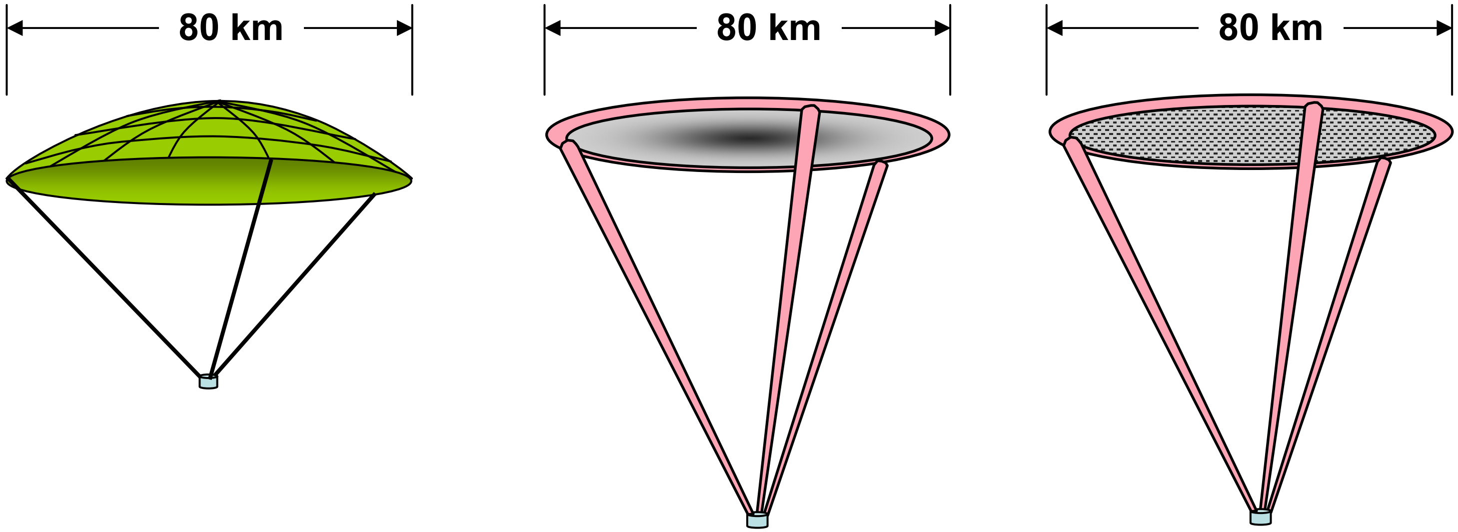
	Soil moisture				Ocean salinity			
	Earth science		Trafficability		Deep sea		Coastal	
	SMOS	Desired	SMOS	Desired	SMOS/ Aquarius	Desired	SMOS/ Aquarius	Desired
Sensitivity	0.8-2.2˚K	<1˚K	0.8-2.2˚K	<1˚K	0.05˚K	0.05˚K	0.05˚K	<0.1˚K
Resolution/spot	35 km	100-300 m	35 km	< 100 m	62 km	> 1 km	62 km	100 m
Revisit time	3 days	2-5 days	3 days	<1 day	3-8 days	Weeks	3-8 days	Hours
Frequency	1.4 GHz	1.4 GHz	1.4 GHz	1.4 GHz	1.4 GHz	1.4 GHz	1.4 GHz	1.4 GHz

- SMOS = Soil Moisture and Ocean Salinity mission. ESA. 2007. LEO
- Aquarius = Sea Surface Salinity mission. NASA. 2008. LEO

THE RADIOMETRY PROBLEM

- Earth remote sensing at low microwave frequencies is best for water detection (1.4 GHz)
- Current systems have spot sizes of 30-100 kilometers and revisit times of 2-5 days
- It is desirable to be able to resolve features 100-300 m size, and revisit them in hours
- This is not possible with current, programmed, or even planned space systems
- It requires a system in GEO, driven by the coverage and revisit needs
- But from GEO a 100 m spot size requires an antenna size of ≈100 kilometers at 1.4 GHz
- Even with inflatable antenna technologies this would weigh ≈ 10^{10} kilograms
- A new approach is clearly needed, which is the subject of this Phase I study

ACHIEVING 300 m GROUND RESOLUTION AT 1 GHz FROM GEO



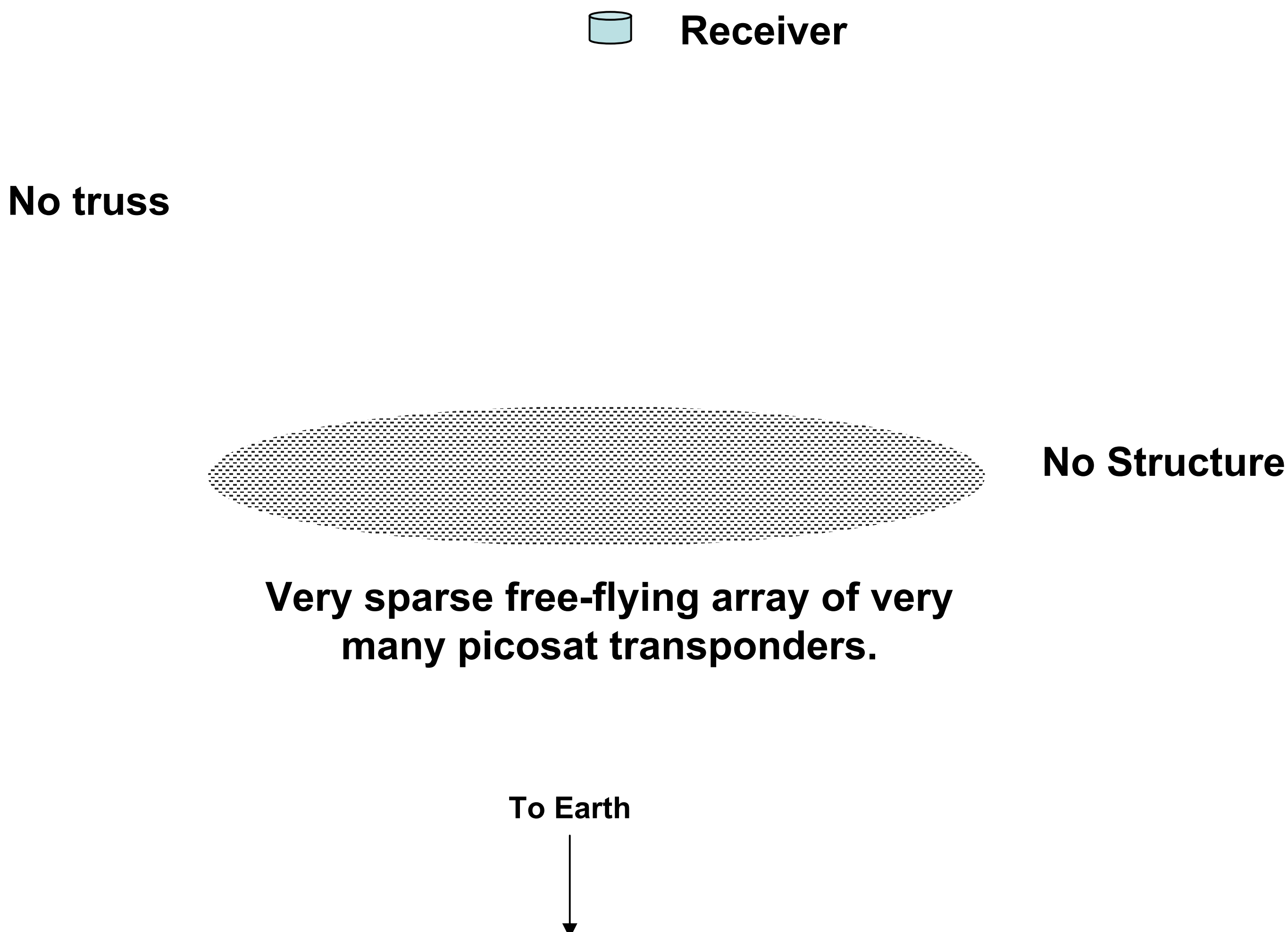
Conventional rib-mesh antenna	Inflatable membrane antenna	10% sparse inflatable membrane antenna
30 kg/sq.m	3 kg/sq.m	0.3 kg/sq.m

Comparative total weight of a hypothetical 80 km diameter antenna

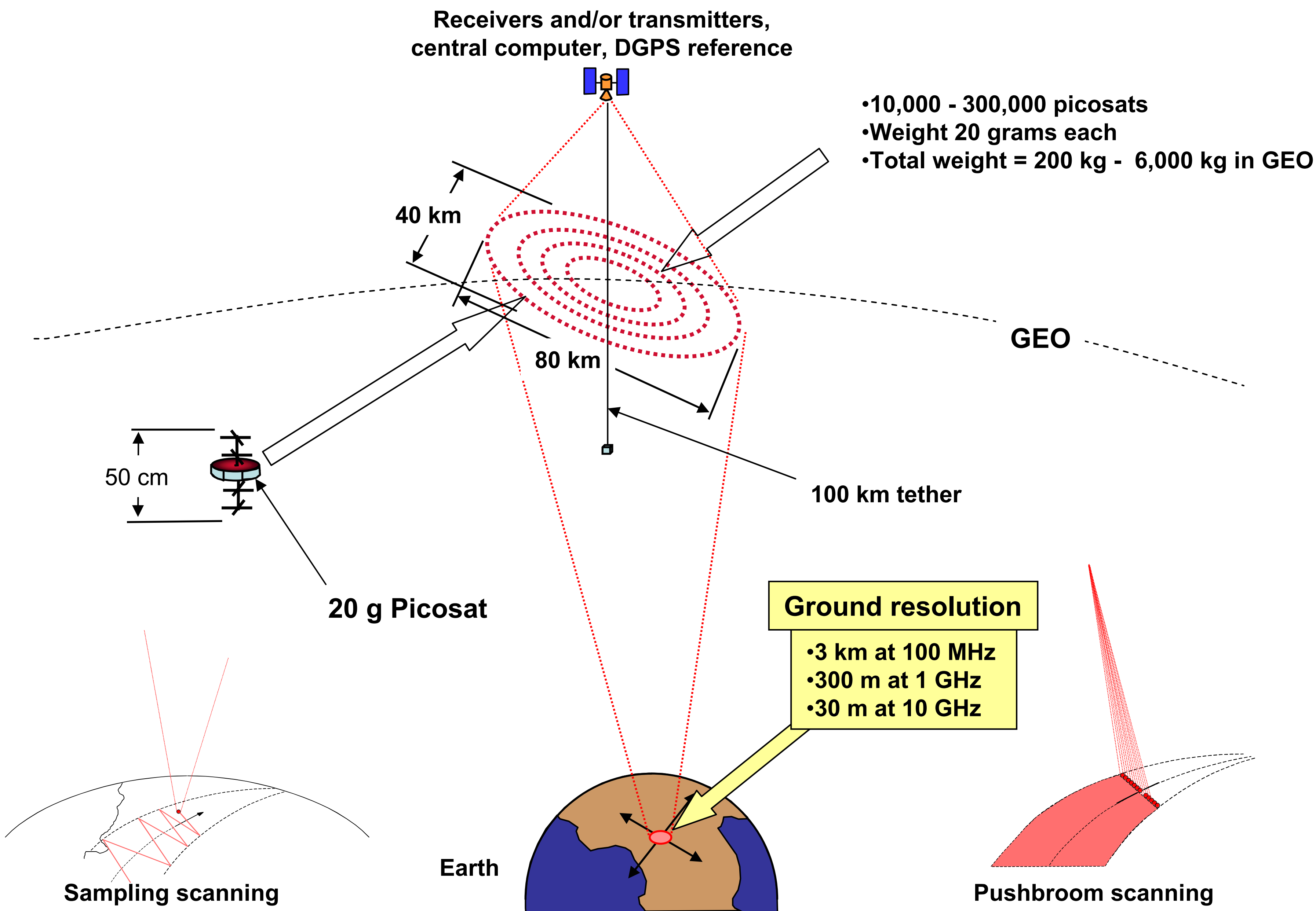
Conventional rib-mesh antenna	Inflatable membrane antenna	10% sparse inflatable membrane antenna
100,000,000,000kg	10,000,000,000 kg	1,000,000,000 kg

THE APPROACH

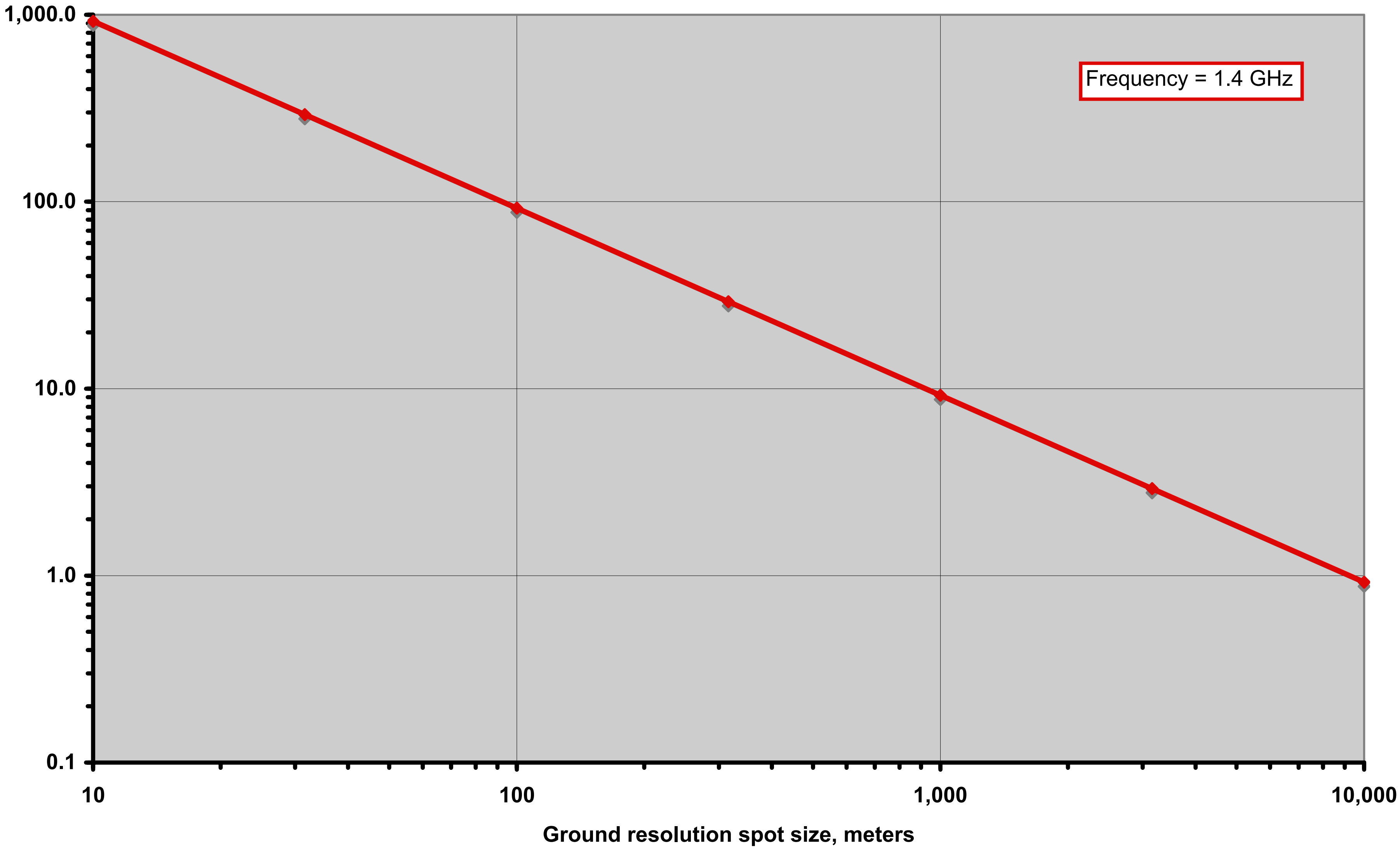
- Use highly sparse space-fed array
- Eliminate all structure and trusses
- Free-flying picosat repeaters



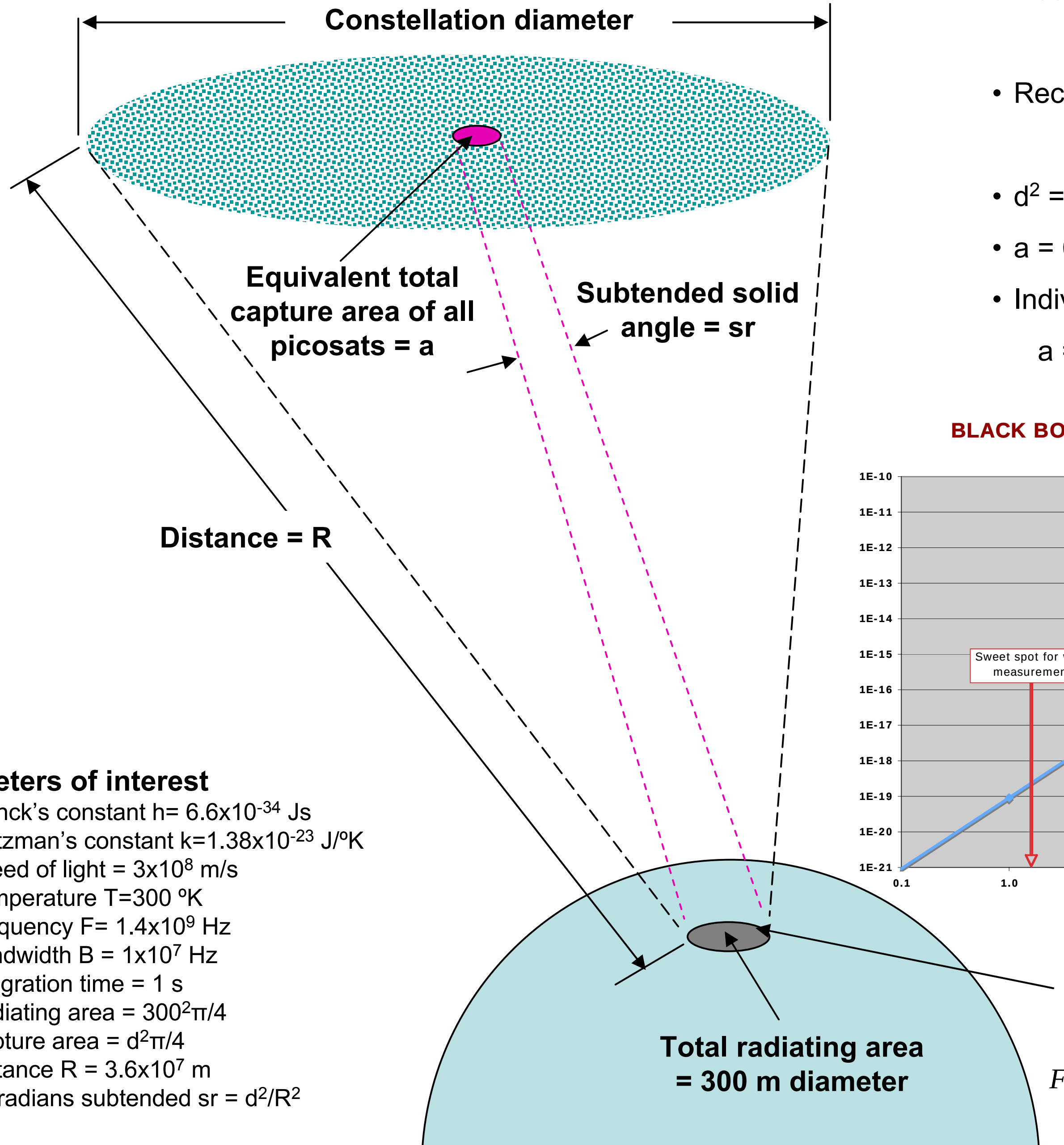
INITIAL CONCEPT: LARGE PICOSAT SWARM ARRAY MICROWAVE PASSIVE RADIOMETER



REQUIRED CONSTELLATION DIAMETER IN GEO

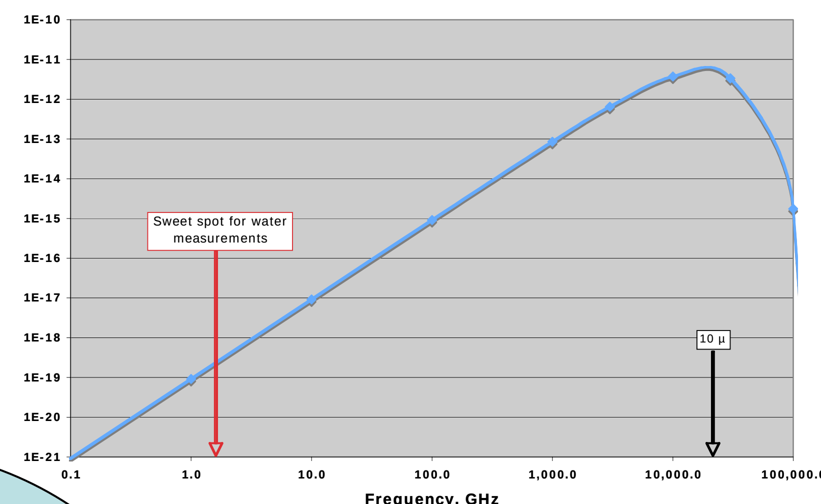


DETERMINING REQUIRED NUMBER OF PICOSATS



- Receiver noise $P_n = kTB$
  $kTB = 6.55 \times 10^{-14}$ Watts
- Received signal $P_r \geq 2P_n$
  $P_r \geq 9.82 \times 10^{-23} d^2$ Watts
- $d^2 = 8.42 \times 10^8$
- $a = 6.6 \times 10^8\ m^2$
- Individual picosat capture area = a
  $a = \lambda^2 / 4\pi = 0.0035\ m^2$

BLACK BODY RADIATION FROM THE EARTH



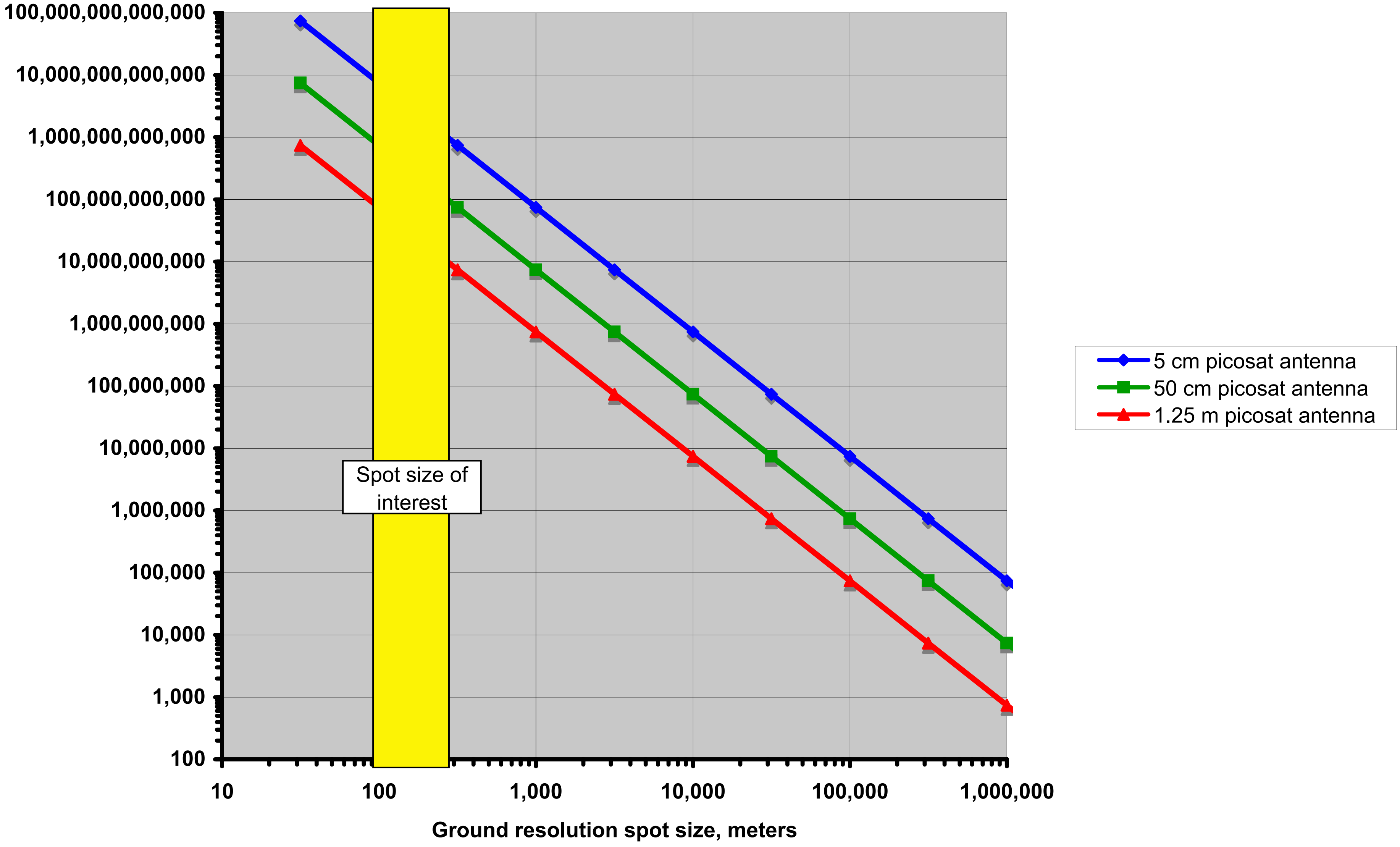
Parameters of interest

- Planck's constant $h = 6.6 \times 10^{-34}$ Js
- Boltzman's constant $k = 1.38 \times 10^{-23}$ J/ºK
- Speed of light = 3×10^8 m/s
- Temperature T=300 ºK
- Frequency $F = 1.4 \times 10^9$ Hz
- Bandwidth $B = 1 \times 10^7$ Hz
- Integration time = 1 s
- Radiating area = $300^2 \pi/4$
- Capture area = $d^2 \pi/4$
- Distance $R = 3.6 \times 10^7$ m
- Steradians subtended $sr = d^2/R^2$

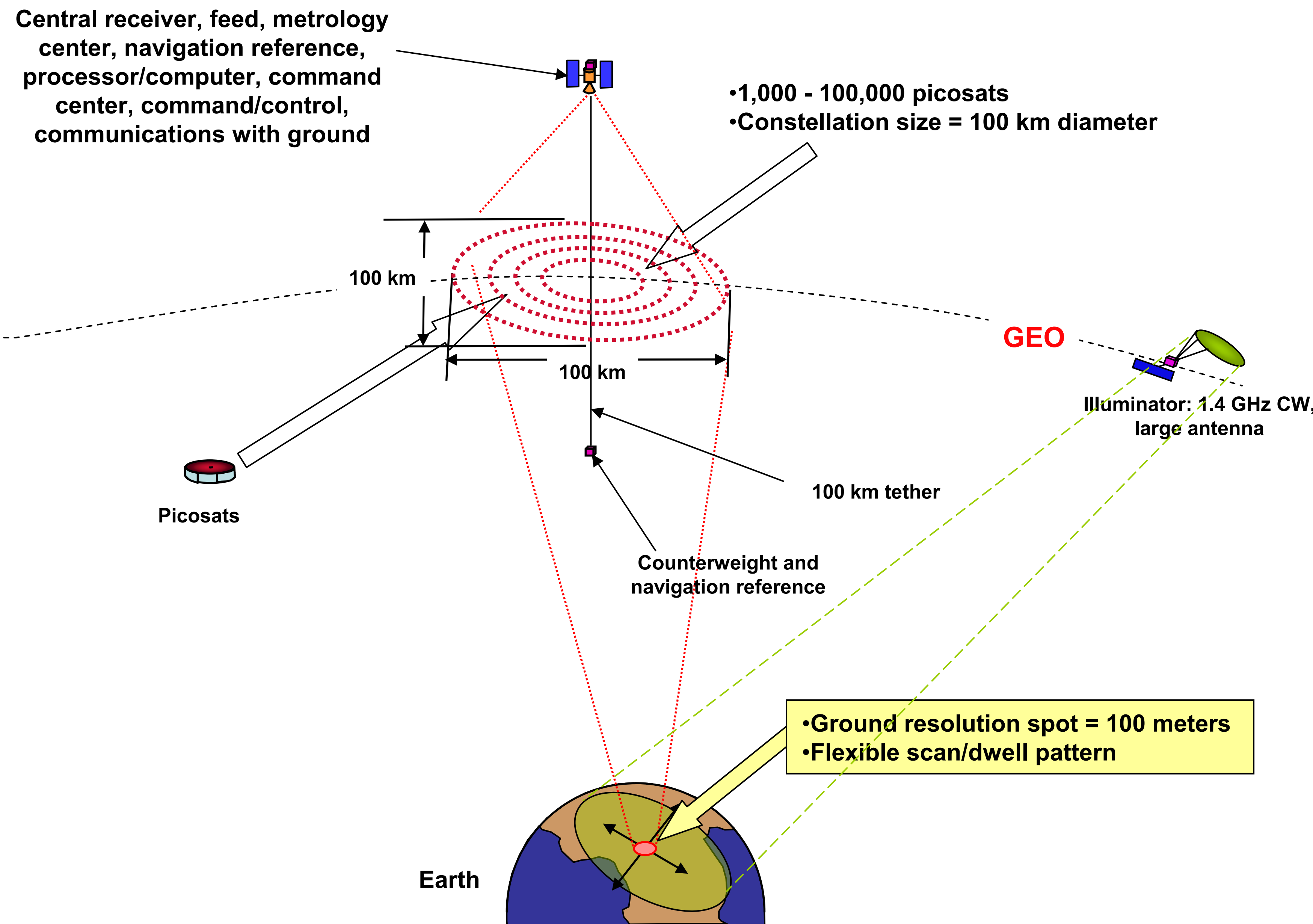
Planck's law for thermal flux

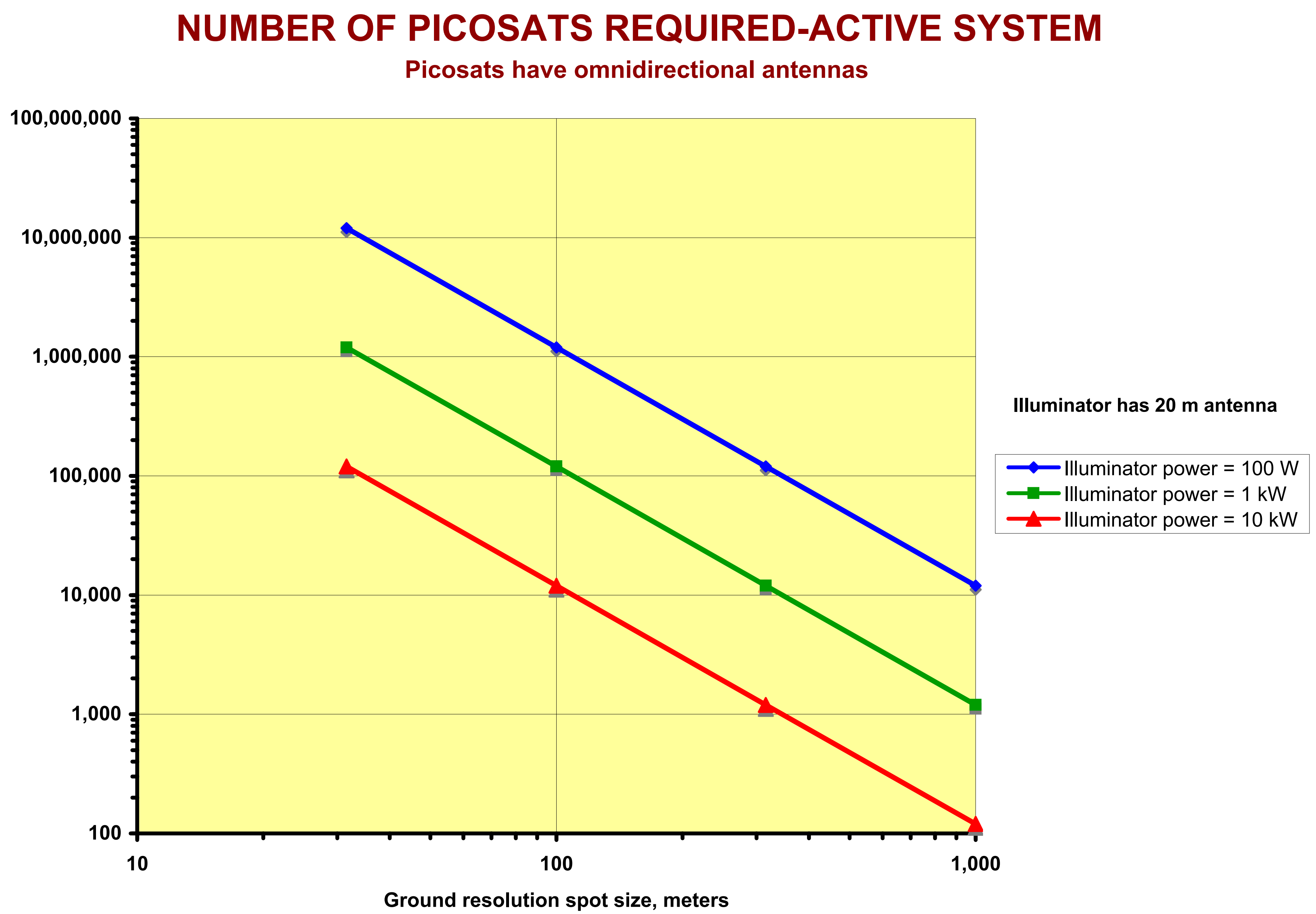
$$F = \frac{2hf^3}{c^2}\left[\frac{1}{e^{\left(\frac{hf}{kT}\right)} - 1}\right] = 1.8 \times 10^{-19} \quad \frac{J}{m^2 \times sr \times Hz}$$

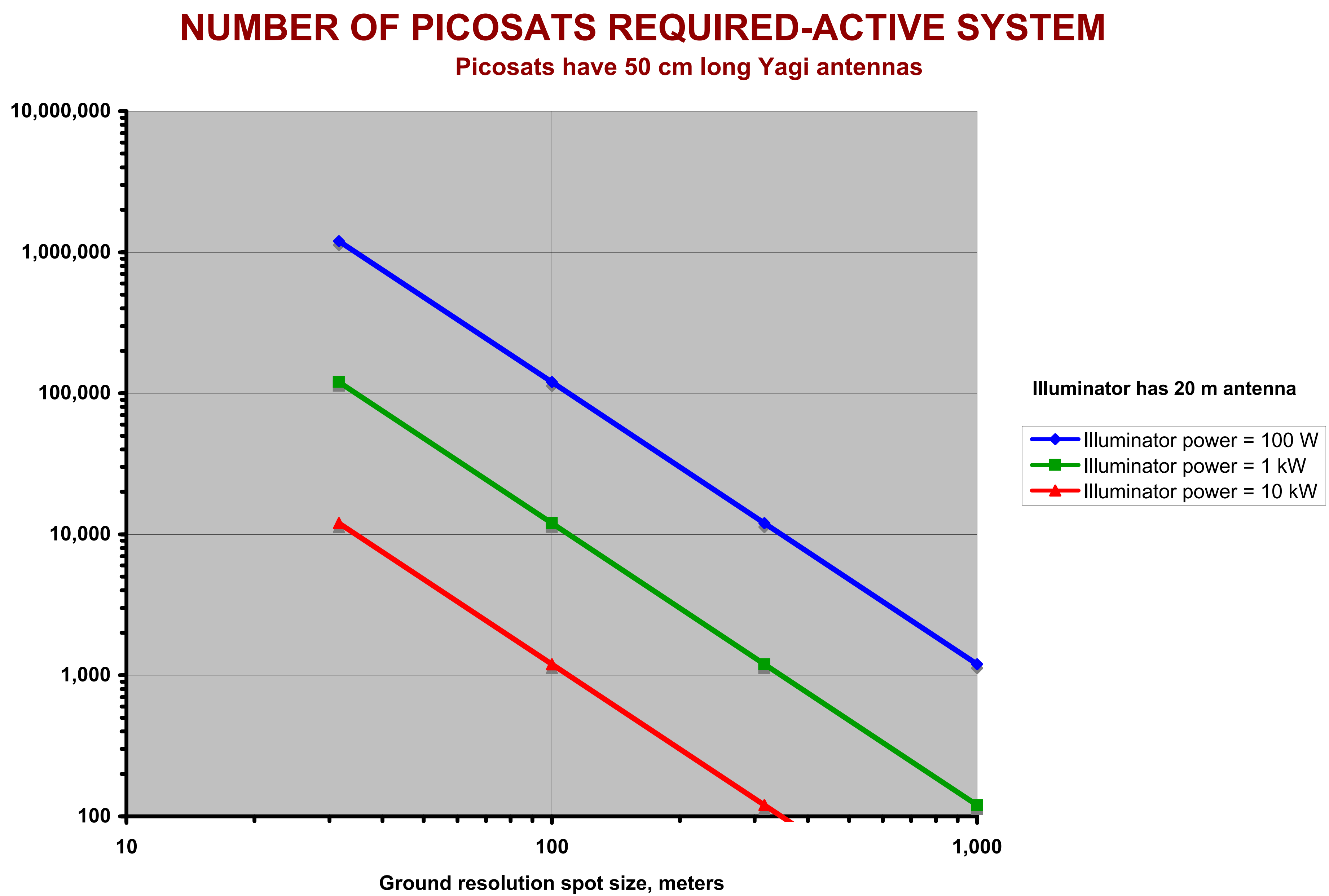
NUMBER OF PICOSATS REQUIRED-PASSIVE SYSTEM



ACTIVE ILLUMINATOR SYSTEM
PICOSAT SWARM ARRAY MICROWAVE EARTHSENSING

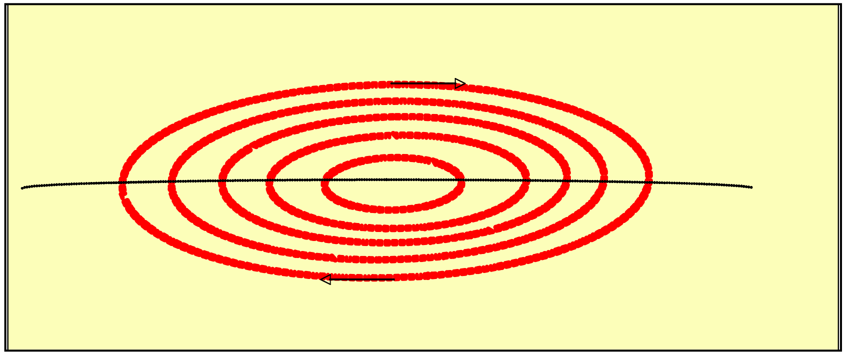



NUMBER OF PICOSATS REQUIRED-ACTIVE SYSTEM
Picosats have omnidirectional antennas
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
100
1,000
Ground resolution spot size, meters
Illuminator has 20 m antenna
Illuminator power = 100 W
Illuminator power = 1 kW
Illuminator power = 10 kW



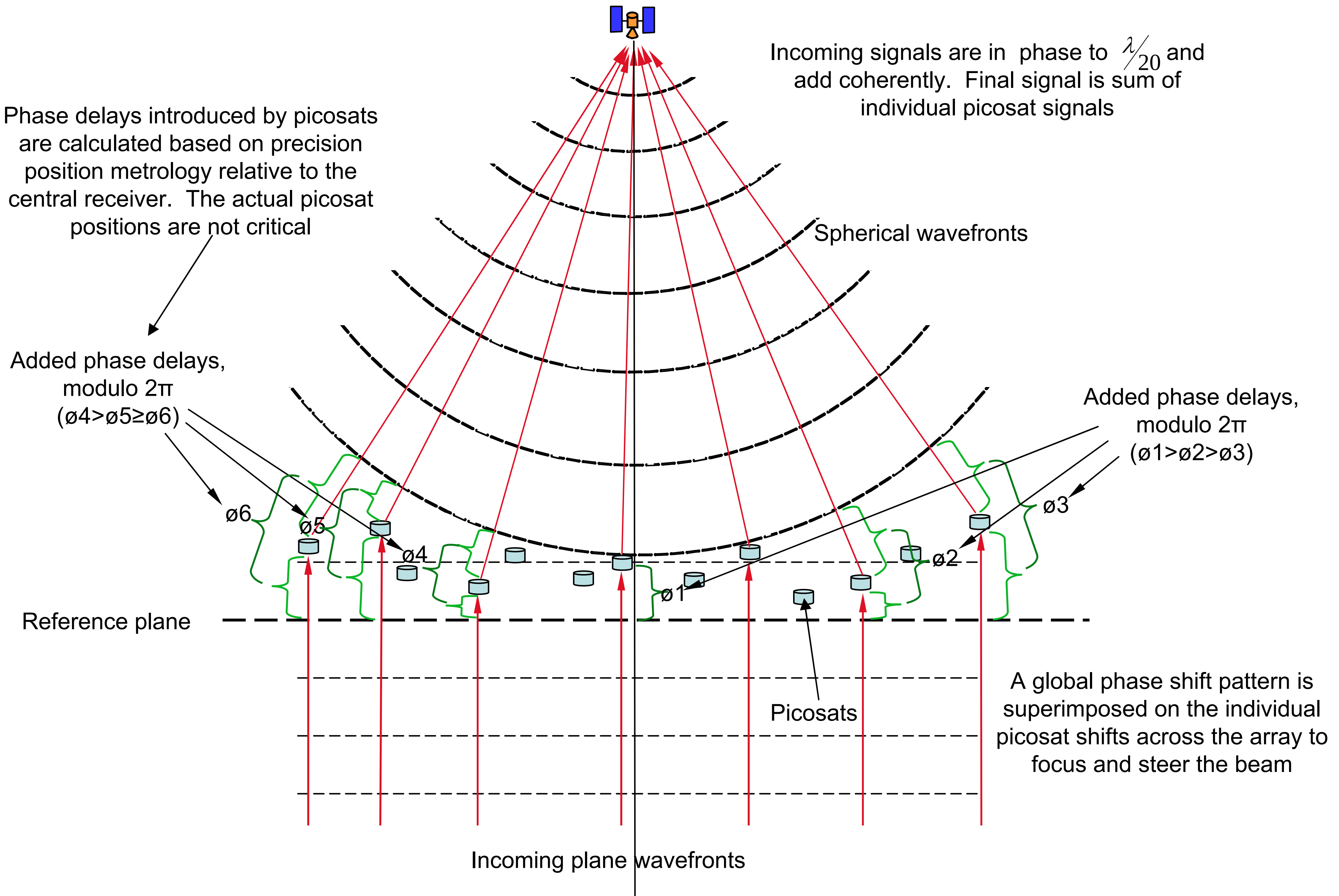
NUMBER OF PICOSATS REQUIRED-ACTIVE SYSTEM
Picosats have 50 cm long Yagi antennas
10,000,000
1,000,000
100,000
10,000
1,000
100
10
100
1,000
Ground resolution spot size, meters
Illuminator has 20 m antenna
Illuminator power = 100 W
Illuminator power = 1 kW
Illuminator power = 10 kW

HALO ORBITS CONSTELLATION DESIGN

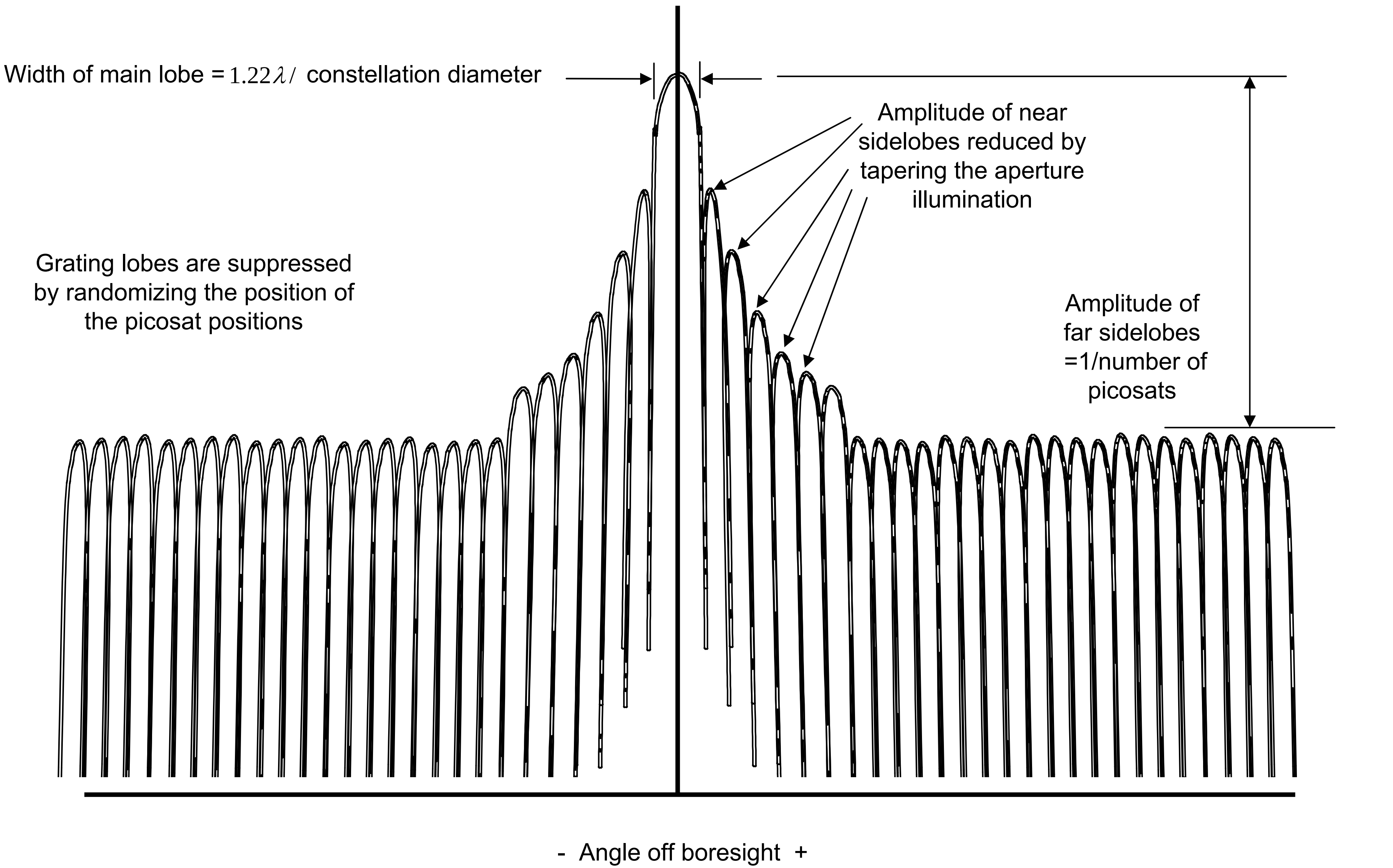


- Halo orbits obeying Hill's equations are set up for picosats
- Picosats deployed into an apparent plane in relative coordinates.
- Picosats rotate around a central point in GEO
- Plane is inclined 30 degrees to local horizontal
- The motions of the picosats are circular around the central point at the 30 degree plane inclination
- The constellation is 100 km in diameter
- Its projection on the ground is an ellipse
- There are 1,000 to 100,000 picosats in the constellation
- Their location in the constellation is made quasi-random during deployment
- The average separation between picosats is 1 km in a 10,000 picosat constellation
- The ΔV required for stationkeeping is an order of magnitude less than if in non-Keplerian orbit

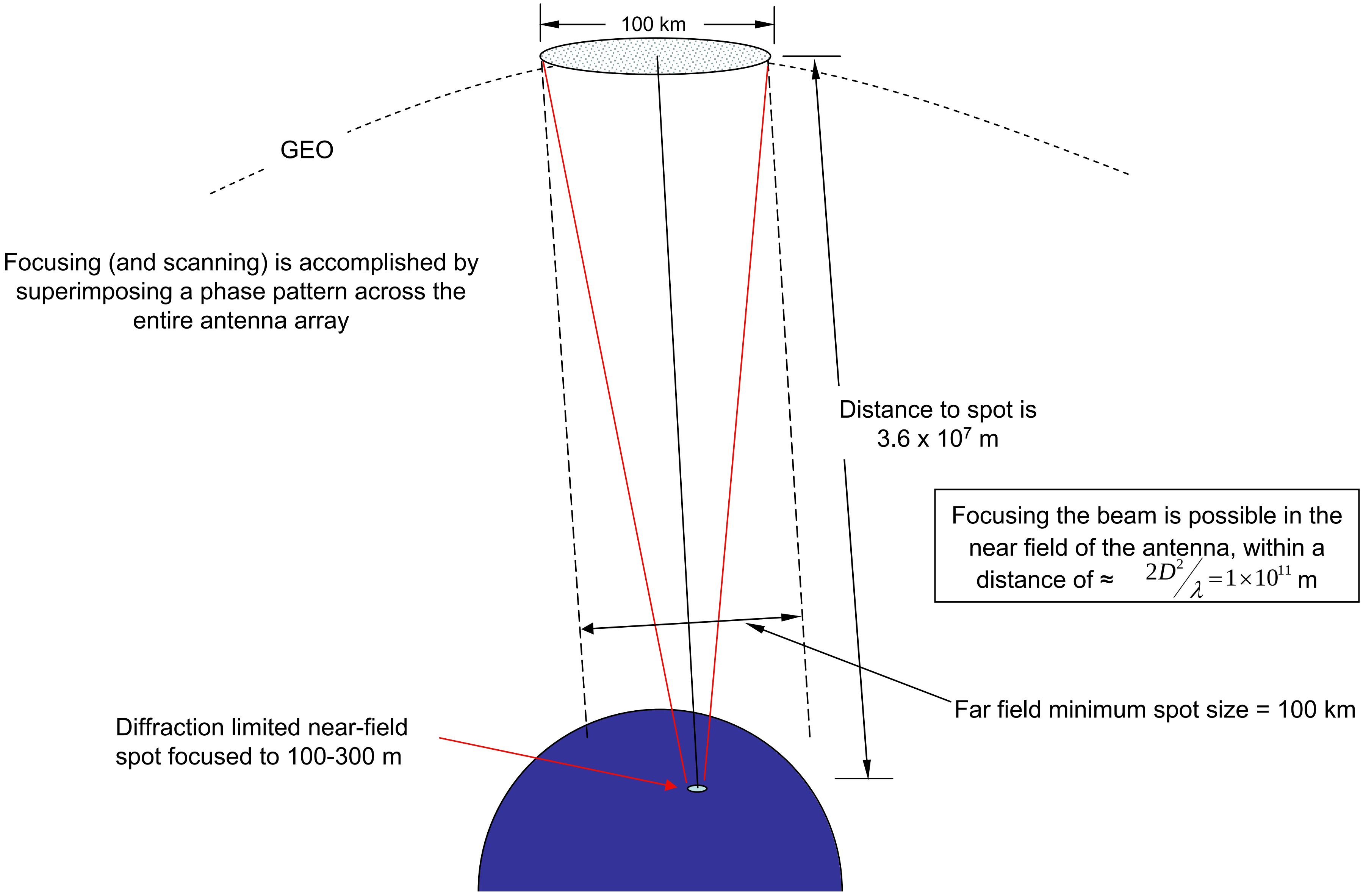
FUNCTIONING OF SPACE-FED PHASED ARRAY



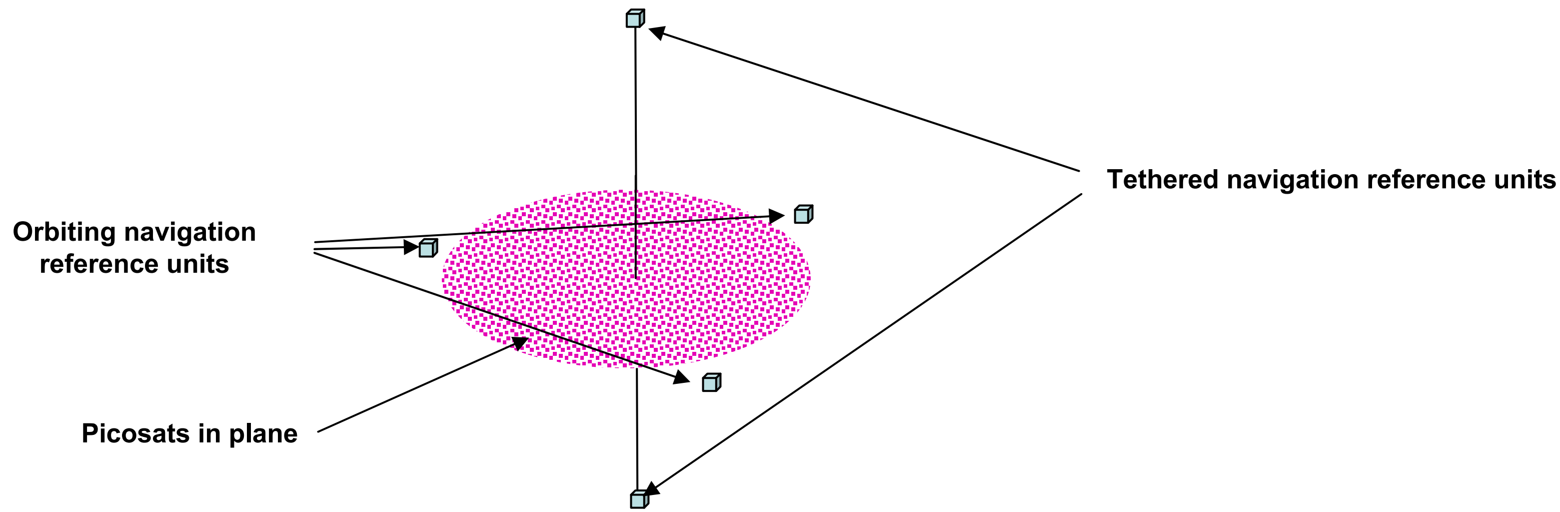
PATTERN OF SPARSE MICROWAVE ANTENNA



FOCUSING THE ANTENNA BEAM SPOT



PICOSAT POSITION METROLOGY



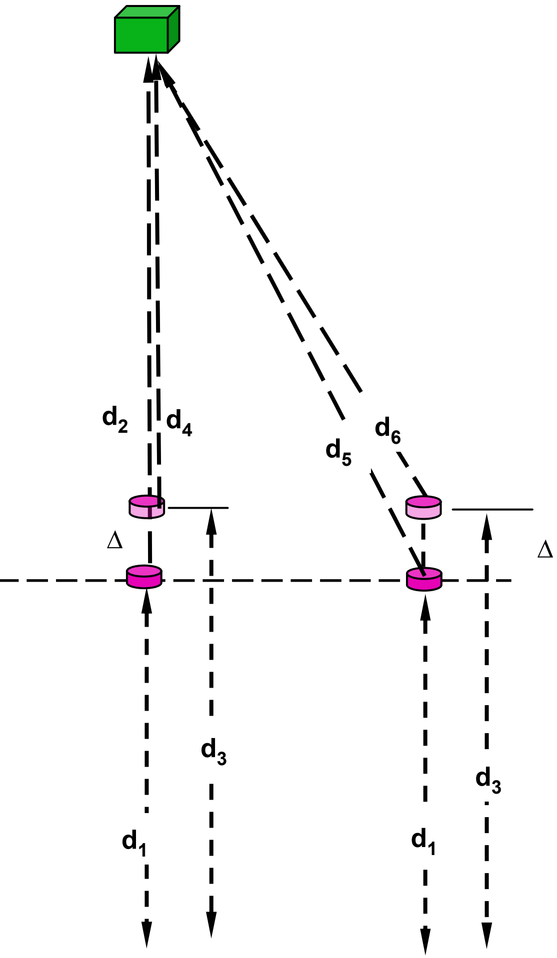
- Set up a GPS-like local navigation environment: a CMS (Constellation Metrology System)
  - 5 reference units have stable oscillators and low power (short range) transmitters
  - Each picosat determines its own position, and then computes its required phase delay
  - Accuracy will be high: no ionosphere, atmosphere, or high relative velocities (highest is 4 m/s)
  - Navigation chips for picosats will be cheap. (Cell phone-mandated GPS chips will cost $10-30 by end of 05)
  - Could use GPS cell phone chips as-is, just add shielding. Total cost will be higher
  - Or make new CMS chips. Will be simpler: no security coding, anti-jam, or spread spectrum needed
  - These new chips might cost $1,000 in lots of 10,000-100,000. But this might still be too expensive

- Alternative # 1
  - Each picosat has a beacon. Navigation units triangulate picosat positions and send to master

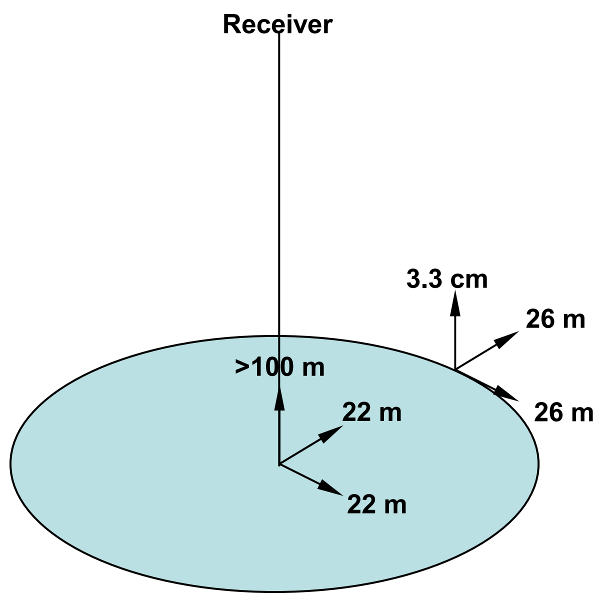
- Alternative # 2
  - Master units transmits ranging tones which are retransmitted by picosats. Master computes range and range rate to each picosat. Three masters compute picosat positions

- Alternative # 3
  - Same as above except that masters send ranging pulses rather than tones

PICOSAT POSITION KNOWLEDGE REQUIREMENTS IN A SPACE-FED ARRAY



	Center picosats		Edge picosats	
	Sensitivity, m/Δ	Δ for 1 cm path delay	Sensitivity, m/Δ	Δ for 1 cm path delay
Normal to plane	0	kilometers	0.3	3.3 cm
In-plane	0.00005 Δ^2	22.4 m	0.000014 Δ^2	26.4 m



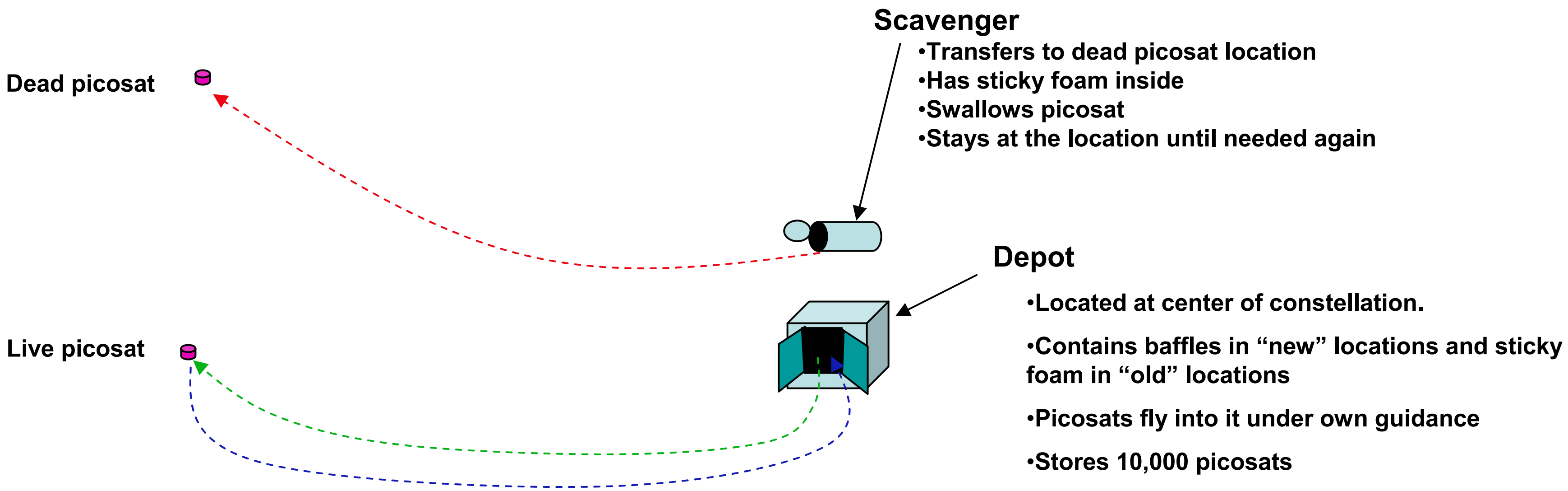
PICOSAT PHASE CONTROL

- Need to control phase to about $\lambda/_{20}$
- Worst case: this is equivalent to about 1 cm at 1.4 GHz
- But space-fed array increases the worst case to 3.3 cm, or $\lambda/_{6}$
- Since can go modulo 2 pi, need only control phase to 6 increments
- This implies a 3 bit phase shifter. These are easy
- Need to determine and set phase frequently due to 3.3 cm tolerance:
  - Velocity around constellation outermost diameter is 3.6 m/s relative to center
  - Thus phase must be adjusted every 10 ms
  - Command to set phase @3 bits 100 times/sec requires 3,300 bps in one channel
  - Set up 100 channels with 100 picosats each and command requires 3.3 kbps per channel

- However the tolerances are much looser than 3.3 cm in most directions of drift
  - So that on average this command link will not be stressed

- Furthermore, if picosats compute their own phase then command is only required to set global phase for beam steering and focusing
  - This requires even lower bit rate because changes are expected very slowly

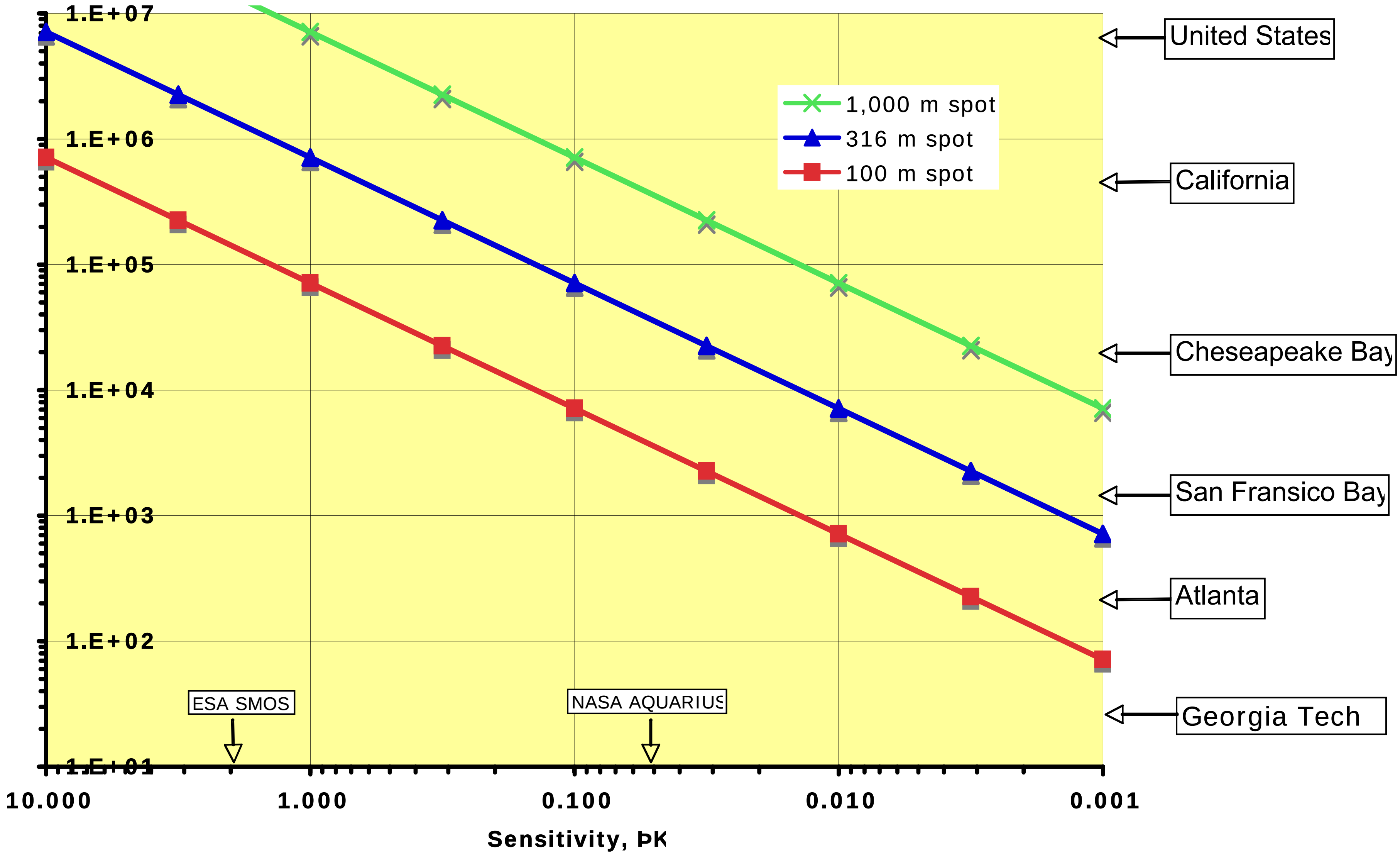
PICOSAT DEPLOYMENT, RETRIEVAL, AND SCAVENGING CONCEPT



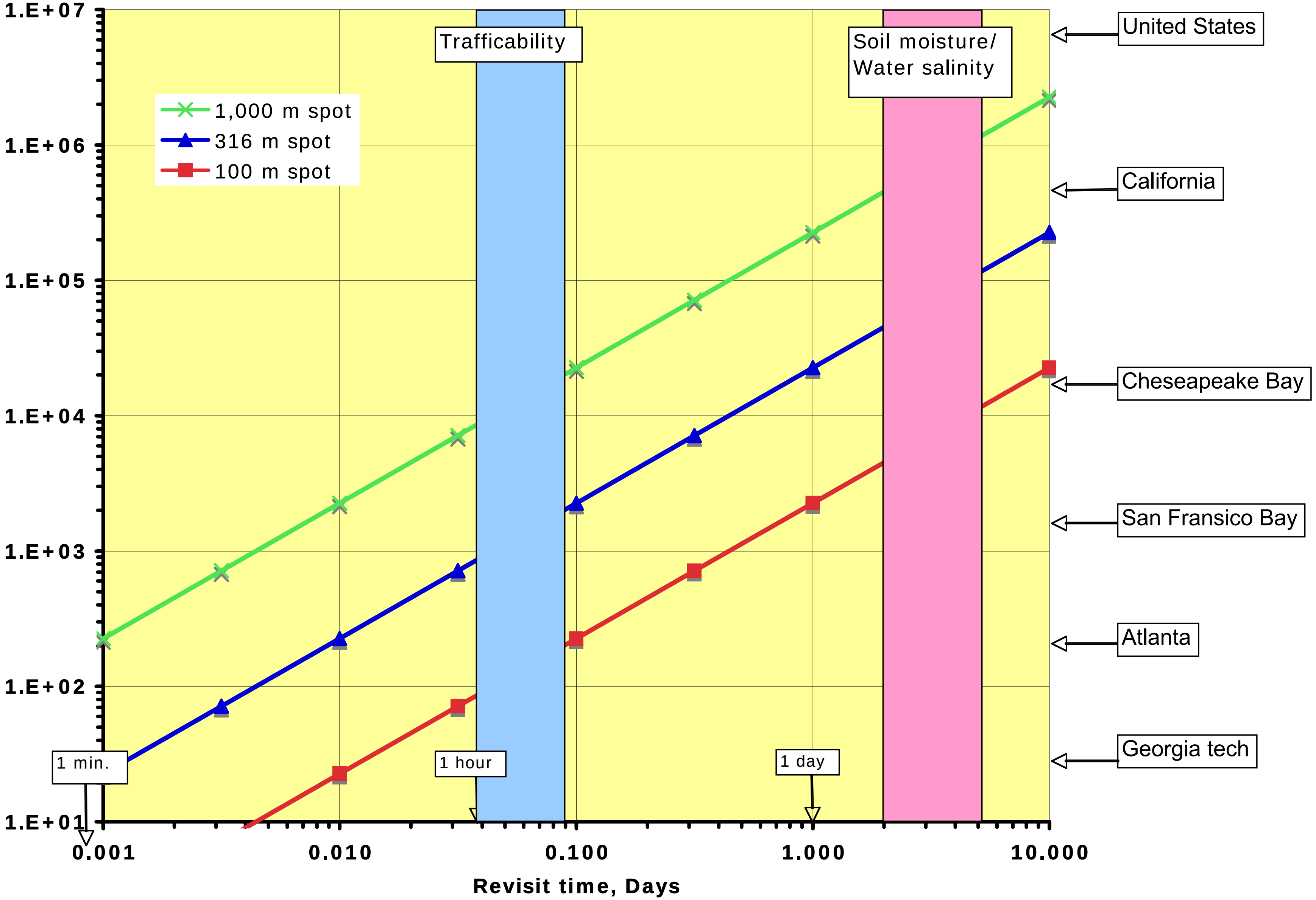
- Picosats will deploy themselves from central unit.
- Each picosat requires 8 micrograms of propellants (100 g picosat) at 3000 Isp for deployment
- Picosats will return to central storage depot when nearing EOL.
- Central depot holds all 10,000 picosats (1,000 kg).
- Depot has doors and sensors, and internal baffles/nets
- Picosats are commanded from master to deploy; and then to return to depot for storage
- If a picosat dies prematurely a scavenger unit is sent to retrieve it and swallow it
- The scavenger stays at the last dead picosat location until it has to go swallow another one
- Returning to central location until needed again would require more propellants
- This requires less propellant than to dispose of dead picosats into above-GEO disposal orbits
- Scavenger can hold 1000 dead picosats (10% picosat failure rate).
- Scavenger needs only about 9 kg of propellants total. Its gross weight is 300 kg

FIRST COVERAGE CALCULATIONS

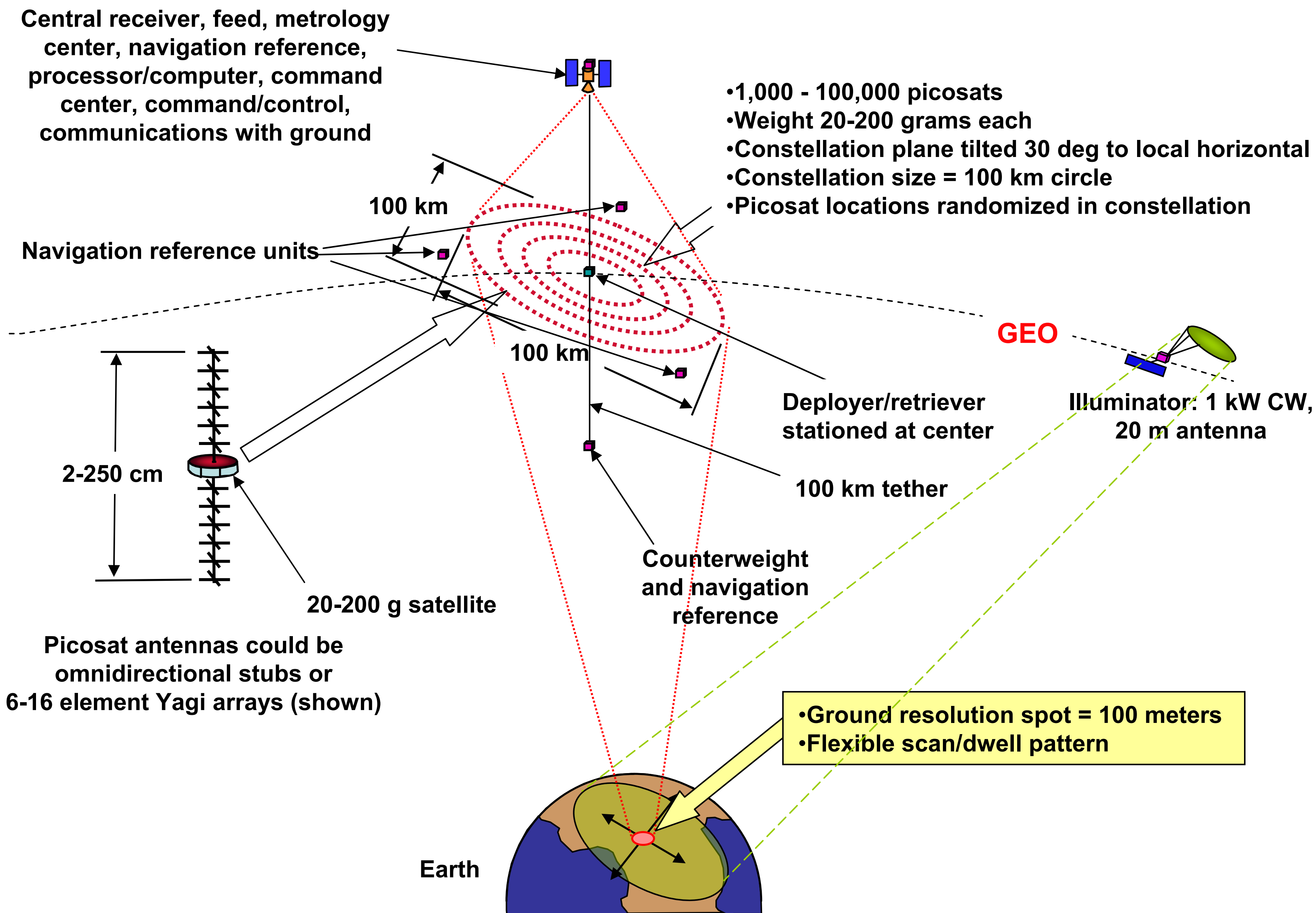
DAILY AREA RATE AS A FUNCTION OF SENSITIVIT
10 BEAM RECEIVER



AREA COVERED AS A FUNCTION OF REVISIT TIME: 10 BEAM RECEIVER



ACTIVE ILLUMINATOR SYSTEM
PICOSAT SWARM ARRAY MICROWAVE EARTHSENSING



STATUS/SUMMARY

- Initial concentration is on Earth Science hydrology missions
- System sizing is nearly complete
- An active illuminator system has been chosen
- The resolution and coverage far exceed anything by SSIS, SMOS, Aquarius, Hydros
- The choice of GEO altitude results in very flexible scanning and coverage
- The concept configuration and its elements still appear viable
- No showstoppers have been found to date
- Its utility will be unprecedented, and likely to be welcomed by the science community
- Phase I will be completed on schedule

END

MISSION/SCIENCE CONTACTS MADE TO DATE

NASA HQ

- Granville Paules
- John LaBreque
- Craig Dobson
- Eric Lindstrom
- Jarred Entin

•NASA GSFC

- Waleed Abdalati
- Edward Kim

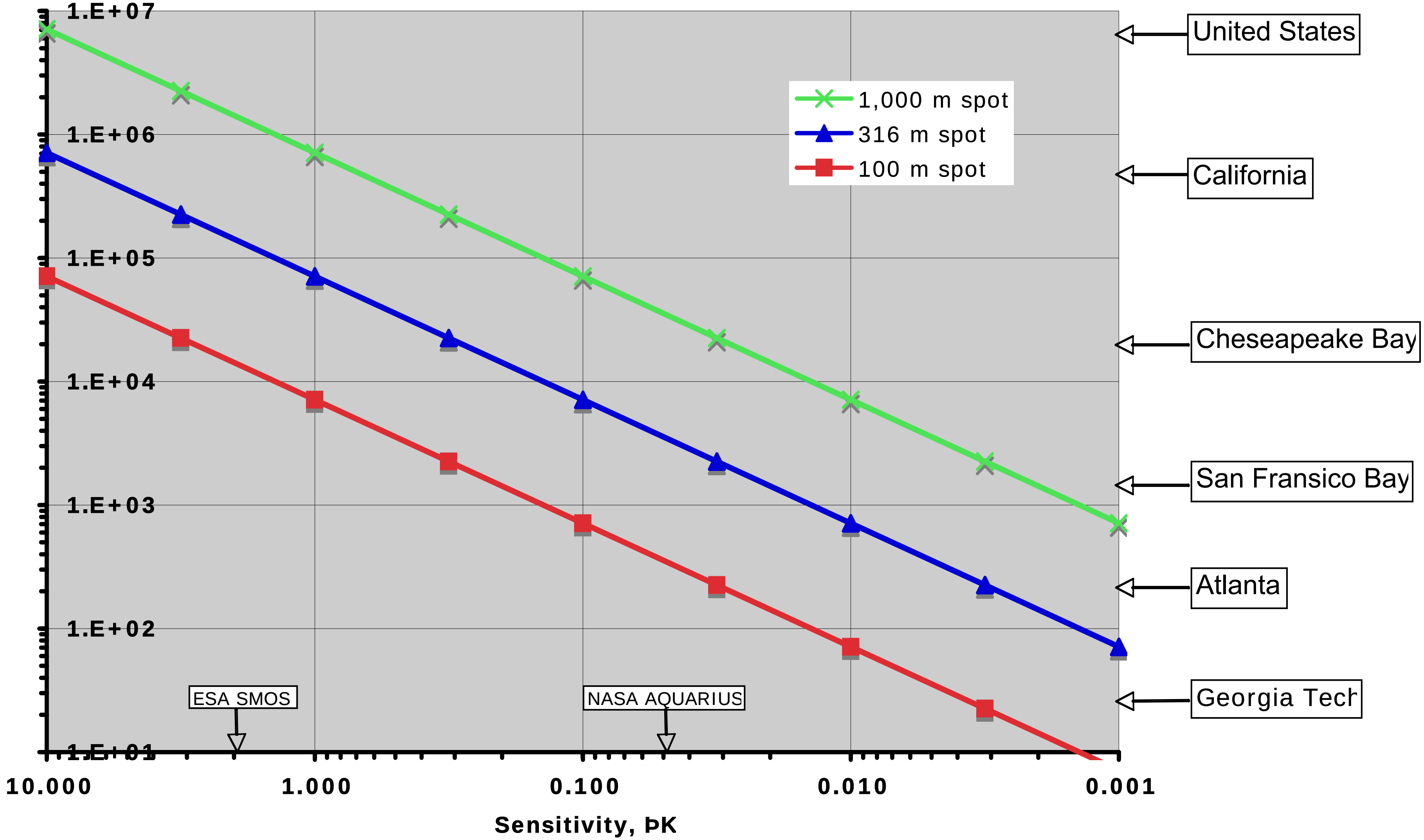
•JPL

- George Hajj
- Cinza Ruffada
- James Zumberge

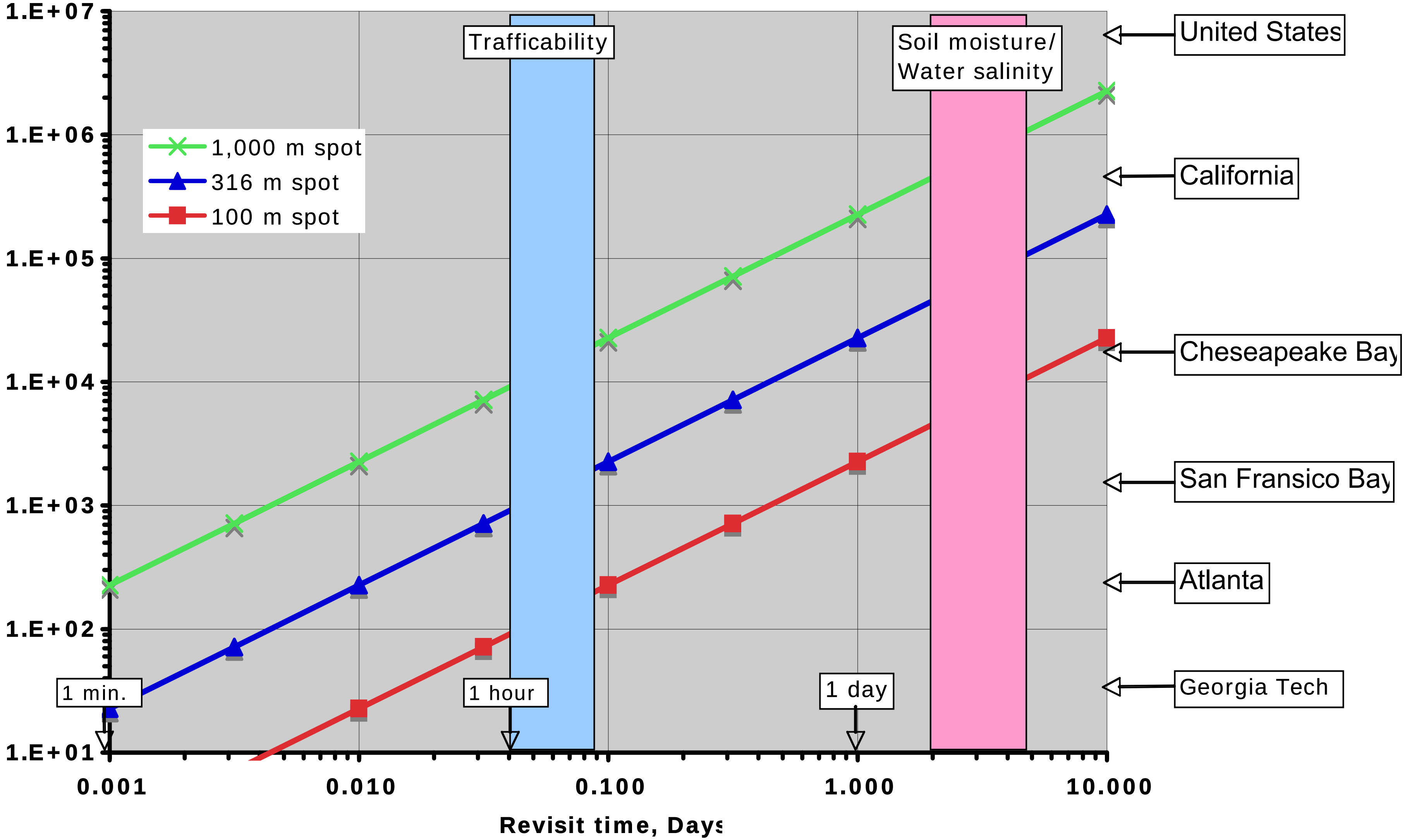
•Other

- Phil Schwartz--Aerospace Corporation
- Numerous web sites for systems: SMOS, Aquarius, Hydros, SSIS, others

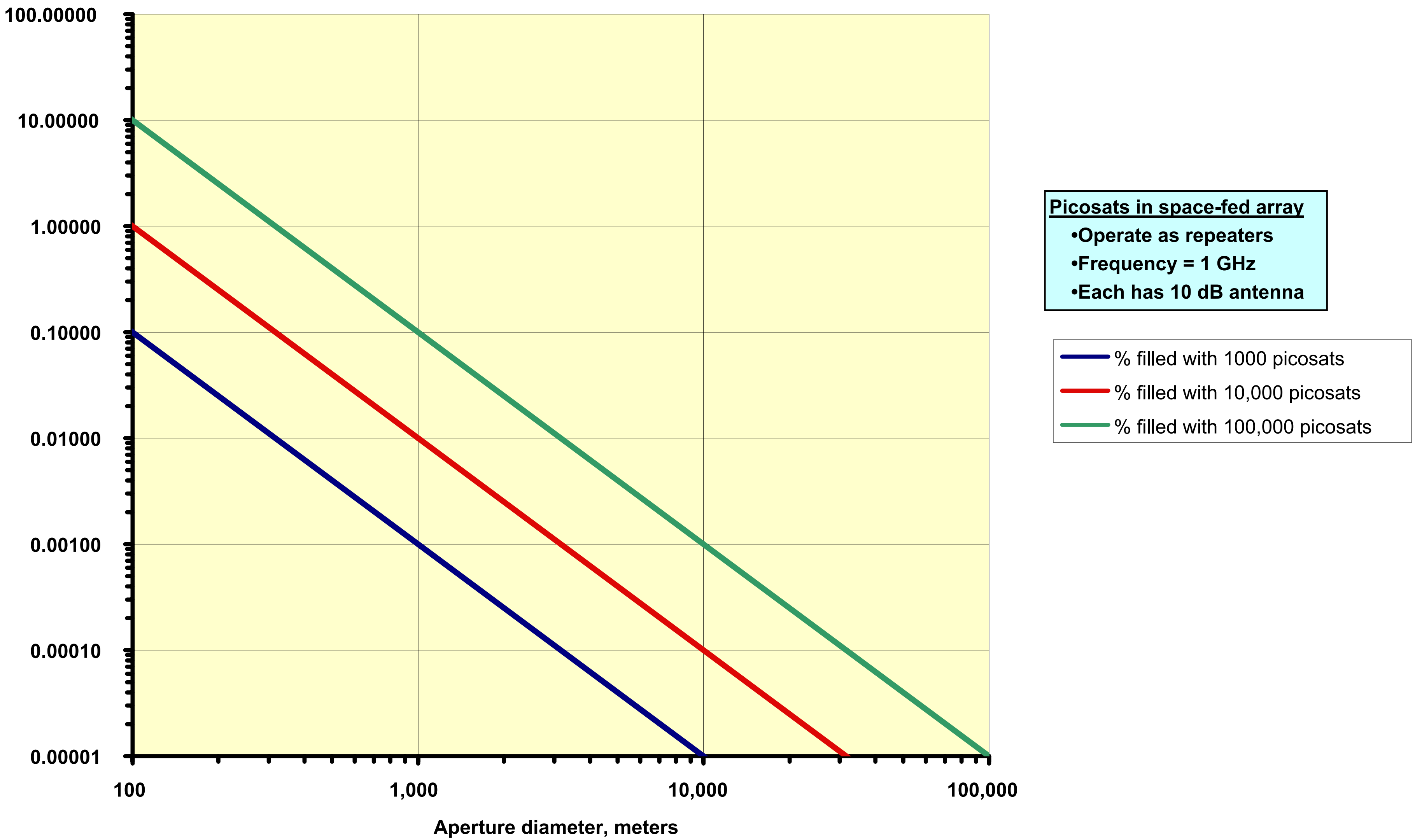
DAILY AREA RATE AS A FUNCTION OF SENSITIVITY
1 BEAM RECEIVER



AREA COVERED AS A FUNCTION OF REVISIT TIM
1 BEAM RECEIVER



SPARSENESS OF SWARMED APERTU



CHOICE OF CONSTELLATION ALTITUDE

	PRO	CON
LEO	•Revisit time OK •Constellation size small--1 km •One constellation suffices--global coverage •Few picosats required in constellation •Passive system OK	•Large ΔV in picosats for stationkeeping •High orbital debris creation problem •High impact probable with other satellites
MEO	•Orbital debris not a problem •Medium size constellation •Medium number of picosats needed	•Very long revisit time •Medium size constellation •Need many constellations •Must use active system
GEO	•Short and flexible revisit time •Flexible scan/dwell patterns/options •Picosats can use omni small antennas •One constellation covers ≈ a hemisphere •Orbital debris problem moderate	•Large constellation size •Active system required •Many picosats required