

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

Progress report

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UTILITY 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

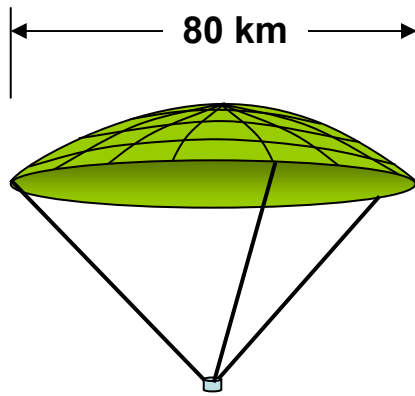
•SMOS = Soil Moisture and Ocean Salinity mission. ESA. 2007. LEO

•Aquarius = Sea Surface Salinity mission. NASA. 2008. LEO

THE RADIOMETRY PROBLEM

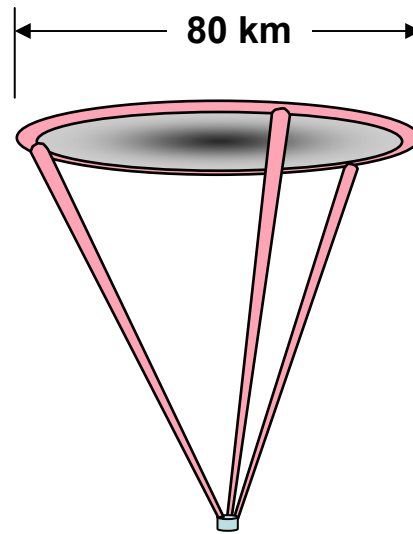
- Earth remote sensing at low microwave frequencies is best for water detection (1.4 GHz)
- Current systems have spot sizes of 30-100 kilometers and revisit times of 2-5 days
- It is desirable to be able to resolve features 100-300 m size, and revisit them in hours
- This is not possible with current, 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 $\approx 10^{10}$ 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



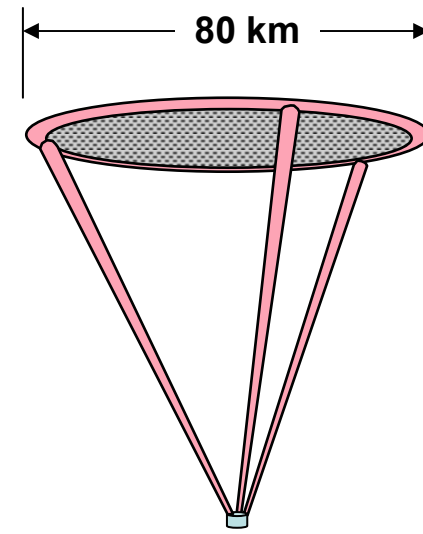
**Conventional
rib-mesh
antenna**

30 kg/sq.m



**Inflatable
membrane
antenna**

3 kg/sq.m



**10% sparse
inflatable
membrane
antenna**

0.3 kg/sq.m

Comparative total weight of a hypothetical 80 km diameter 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

 Receiver

No truss



No Structure

Very sparse free-flying array of very many picosat transponders.

To Earth



INITIAL CONCEPT: LARGE PICOSAT SWARM ARRAY MICROWAVE PASSIVE RADIOMETER

Receivers and/or transmitters,
central computer, DGPS reference



- 10,000 - 300,000 picosats
- Weight 20 grams each
- Total weight = 200 kg - 6,000 kg in GEO

40 km

80 km

GEO

100 km tether

50 cm



20 g Picosat

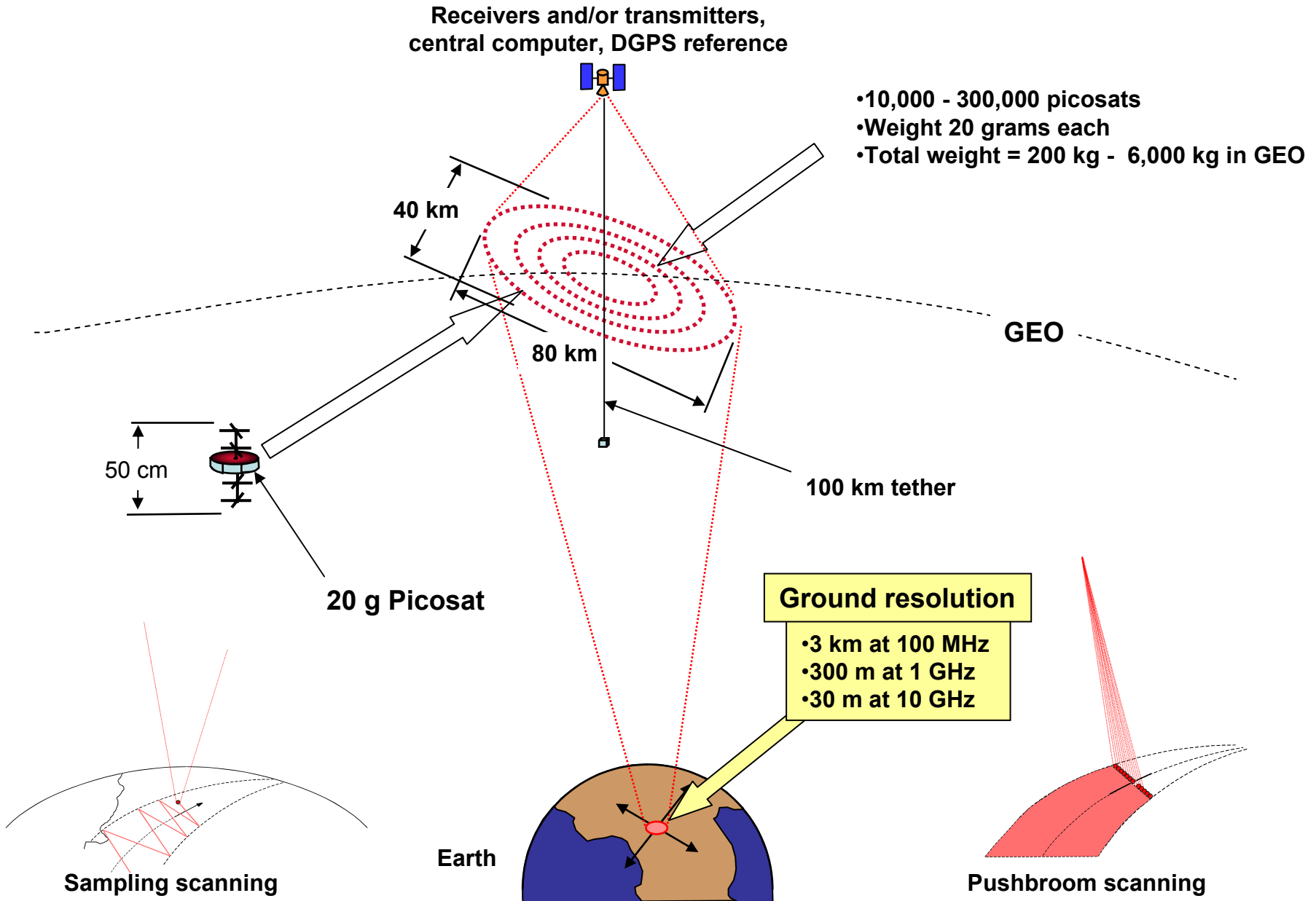
Ground resolution

- 3 km at 100 MHz
- 300 m at 1 GHz
- 30 m at 10 GHz

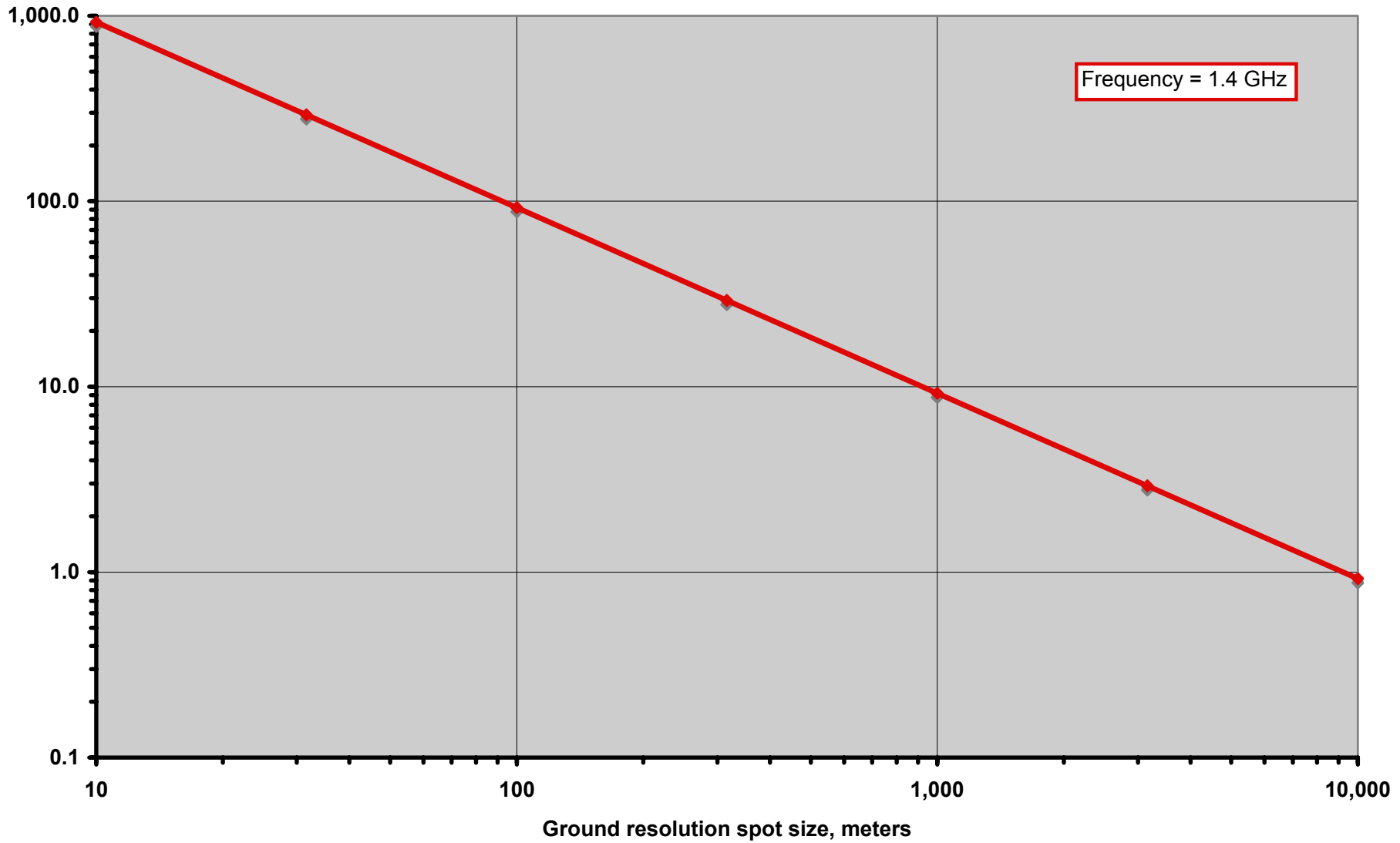
Earth

Pushbroom scanning

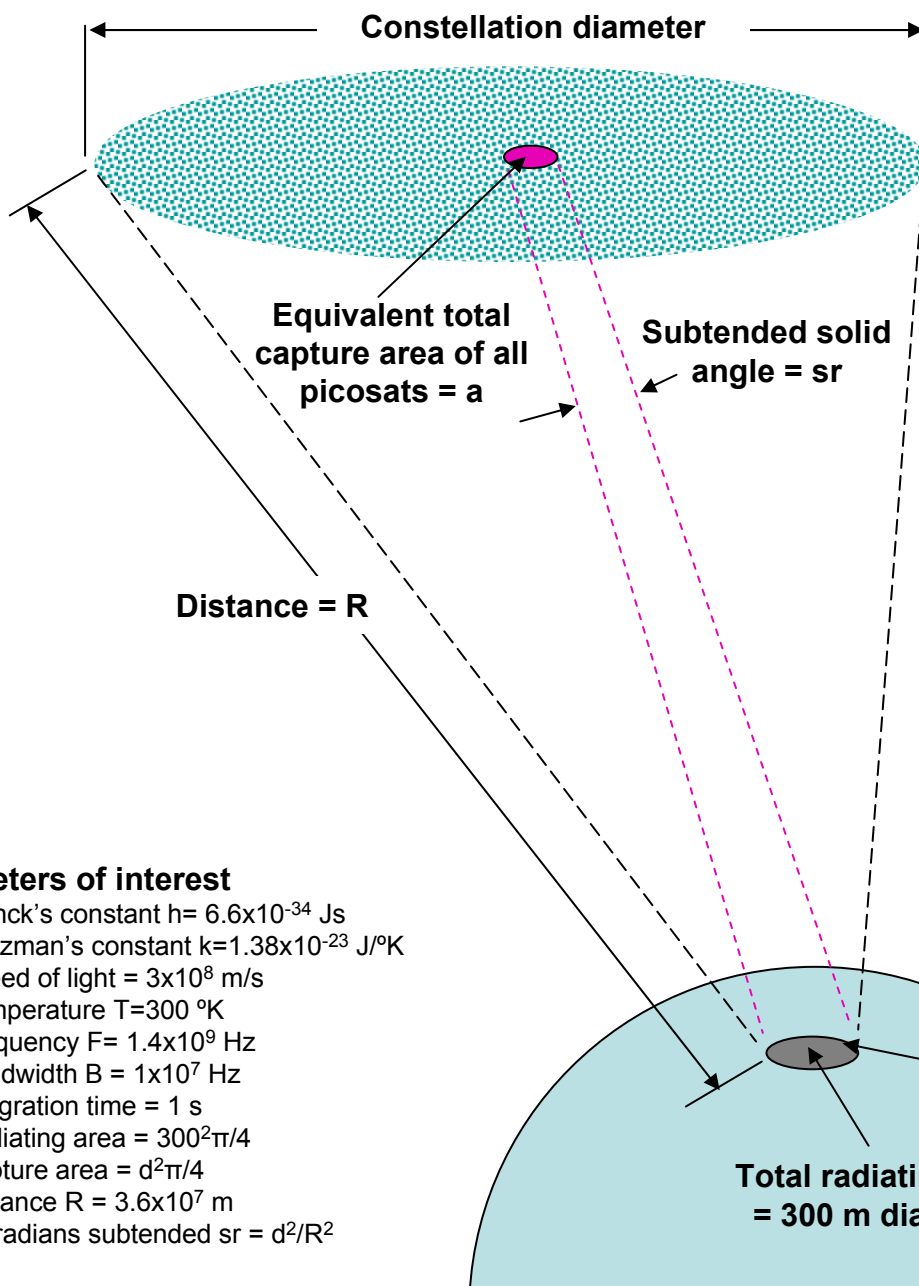
Sampling scanning



REQUIRED CONSTELLATION DIAMETER IN GEO



DETERMINING REQUIRED NUMBER OF PICOSATS



Parameters of interest

- Planck's constant $h = 6.6 \times 10^{-34}$ Js
- Boltzman's constant $k = 1.38 \times 10^{-23}$ J/°K
- Speed of light = 3×10^8 m/s
- Temperature $T = 300$ °K
- 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 $sr = d^2 / R^2$

- Receiver noise $P_n = kTB$
 $kTB = 6.55 \times 10^{-14}$ Watts

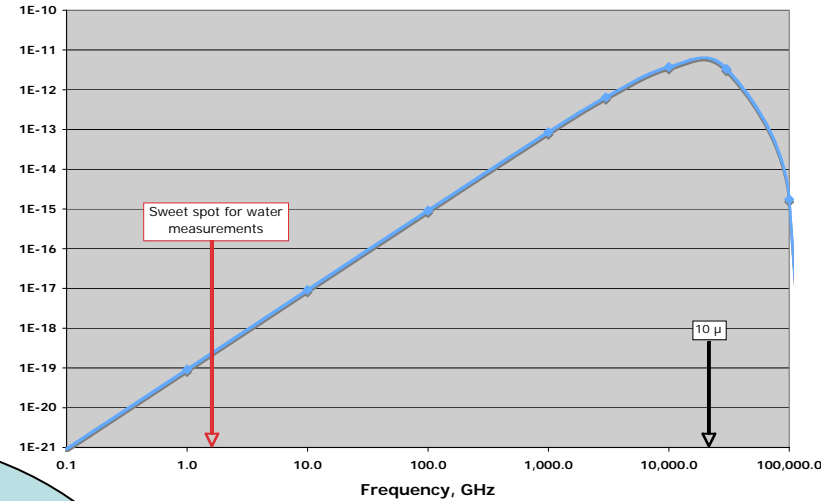
- Received signal $P_r \geq 2P_n$
 $P_r \geq 9.82 \times 10^{-23} d^2$ Watts

- $d^2 = 8.42 \times 10^8$

- $a = 6.6 \times 10^8$ m²

- Individual picosat capture area = a
 $a = \frac{\lambda^2}{4\pi} = 0.0035$ m²

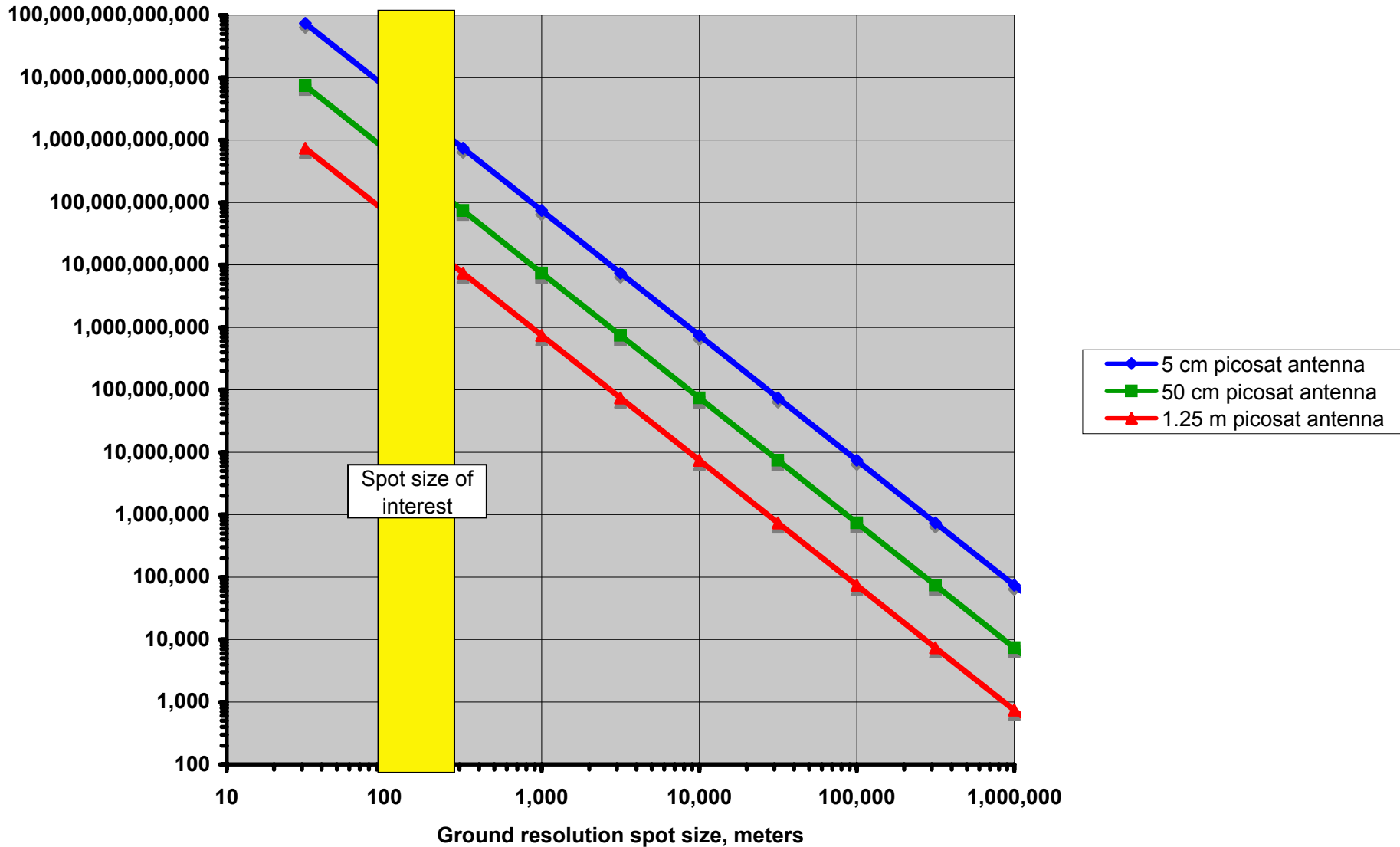
BLACK BODY RADIATION FROM THE EARTH



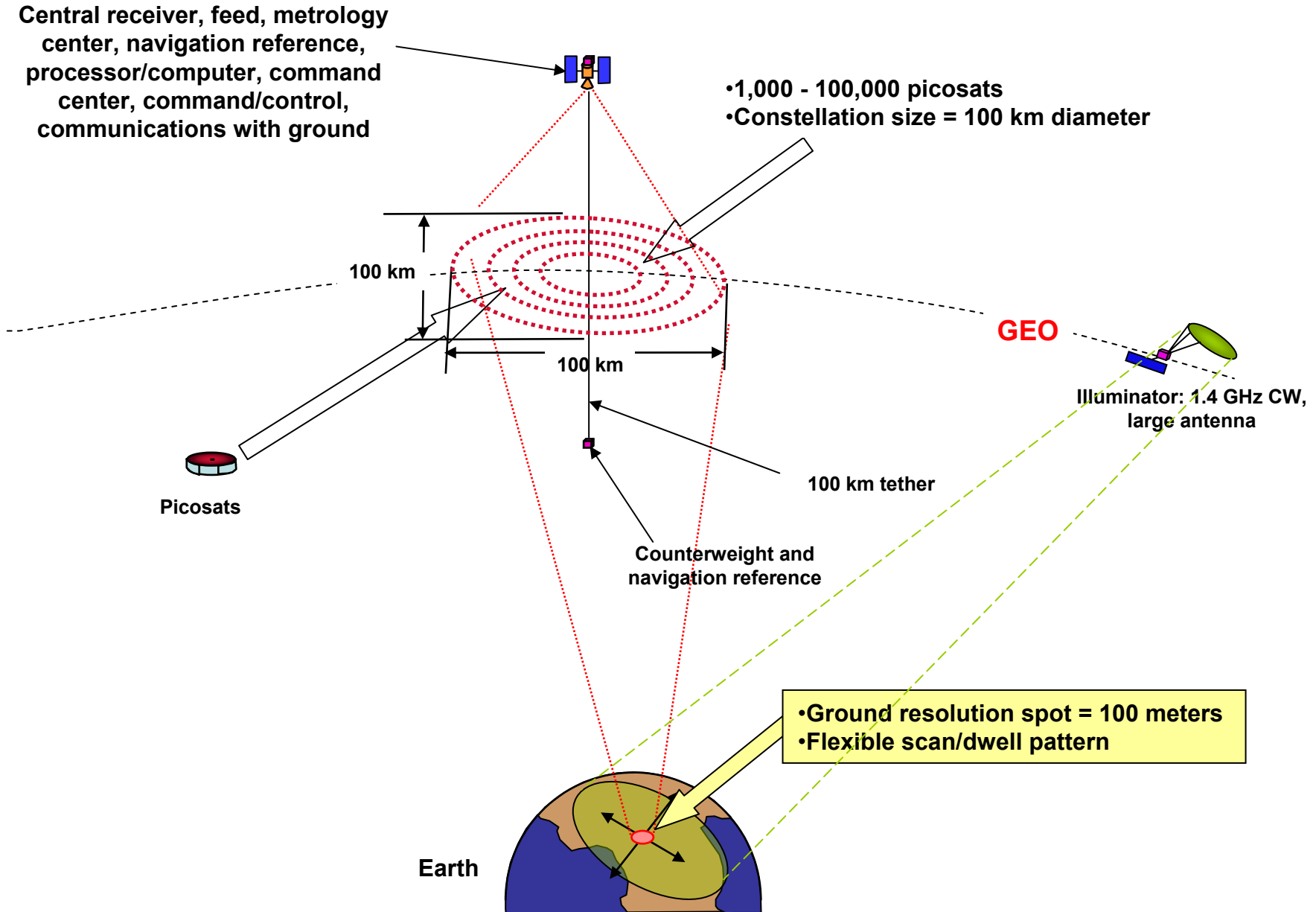
Planck's law for thermal flux

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

NUMBER OF PICOSATS REQUIRED-PASSIVE SYSTEM

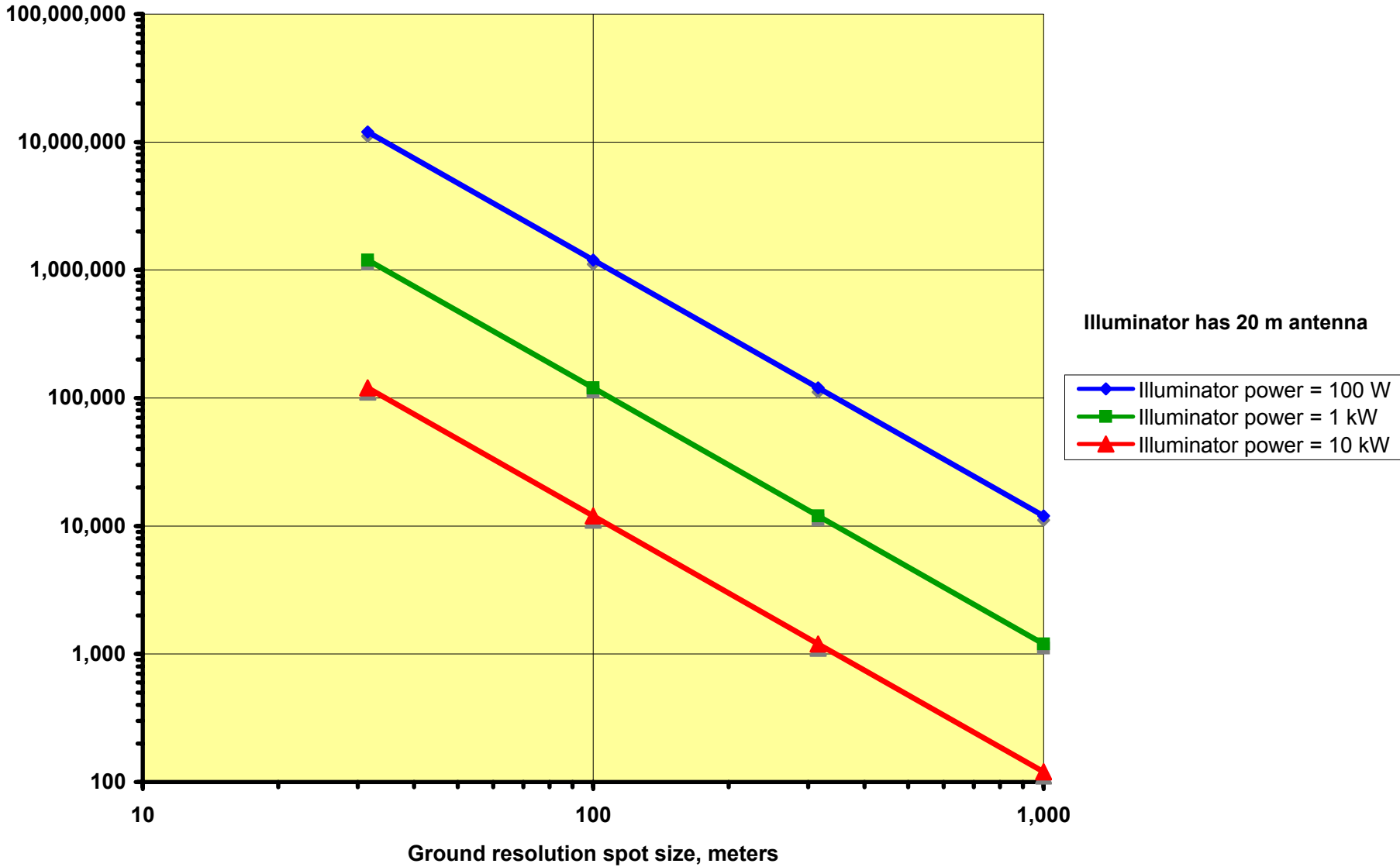


ACTIVE ILLUMINATOR SYSTEM PICOSAT SWARM ARRAY MICROWAVE EARTHSENSING



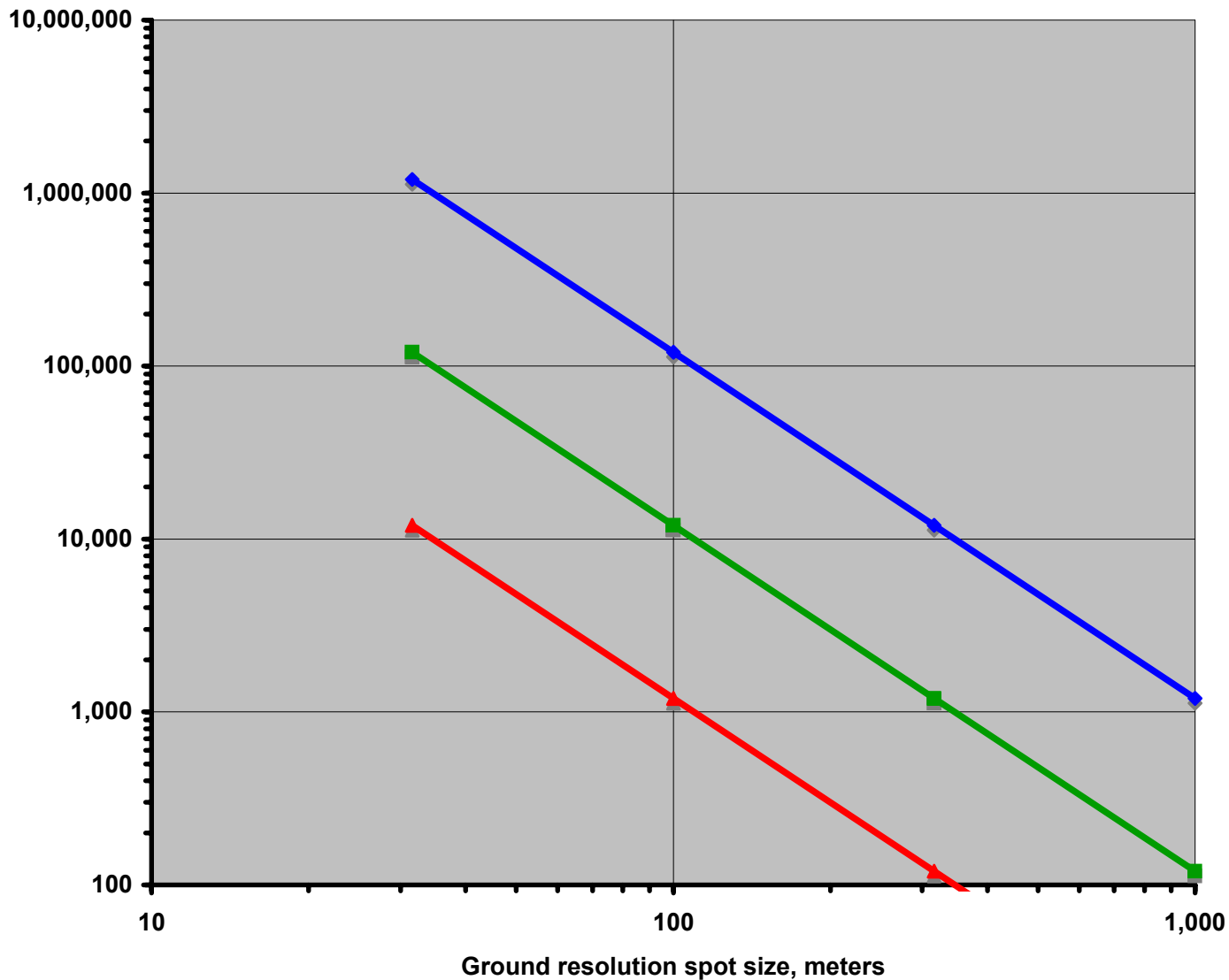
NUMBER OF PICOSATS REQUIRED-ACTIVE SYSTEM

Picosats have omnidirectional antennas



NUMBER OF PICOSATS REQUIRED-ACTIVE SYSTEM

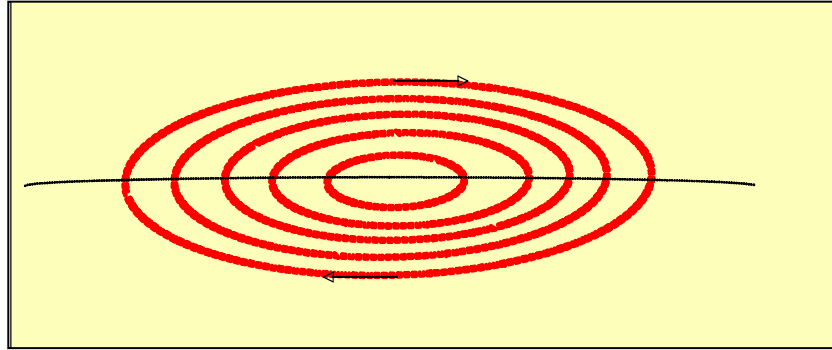
Picosats have 50 cm long Yagi antennas



Illuminator has 20 m antenna

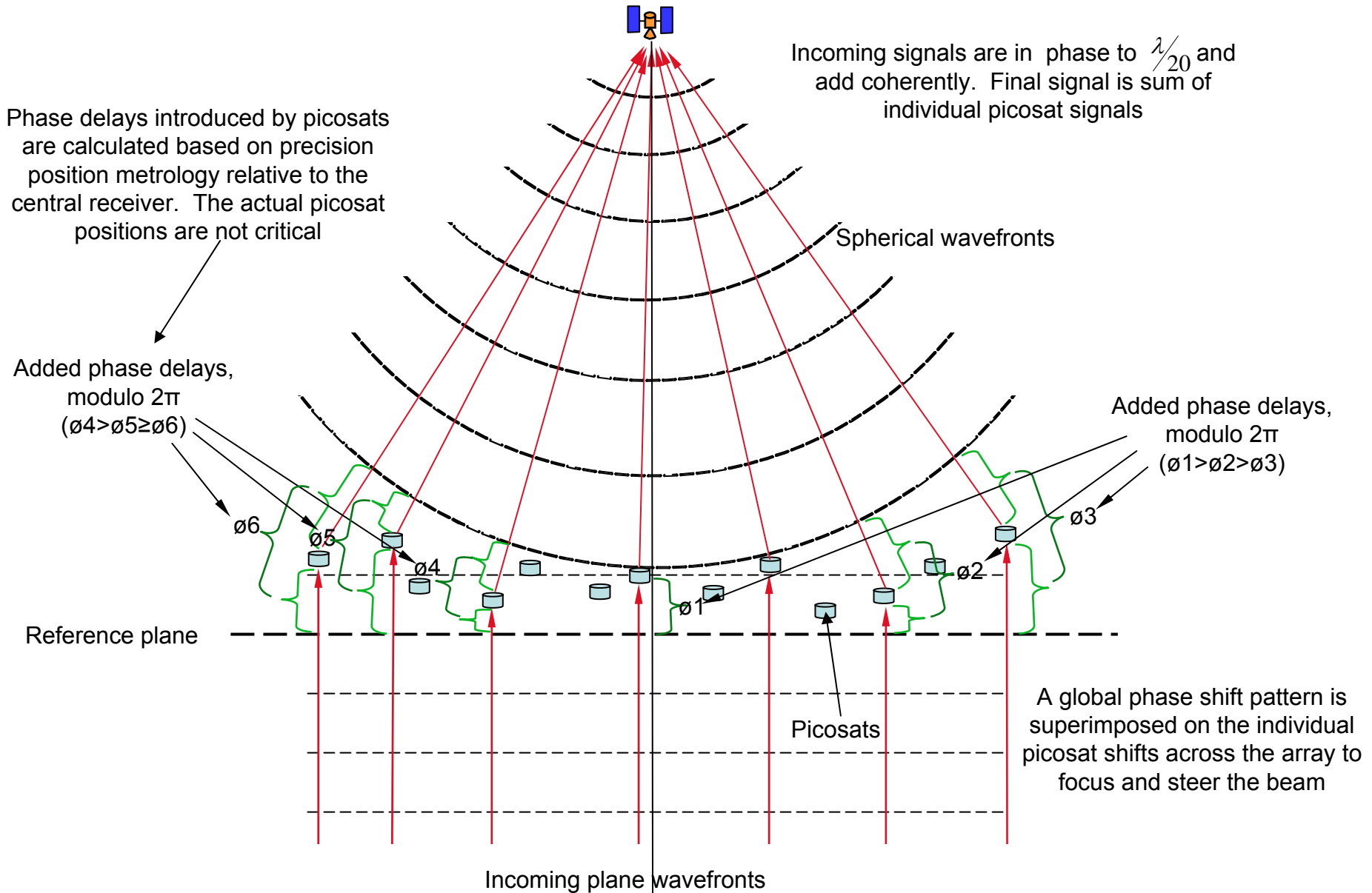
- Illuminator power = 100 W
- Illuminator power = 1 kW
- Illuminator power = 10 kW

HALO ORBITS CONSTELLATION DESIGN

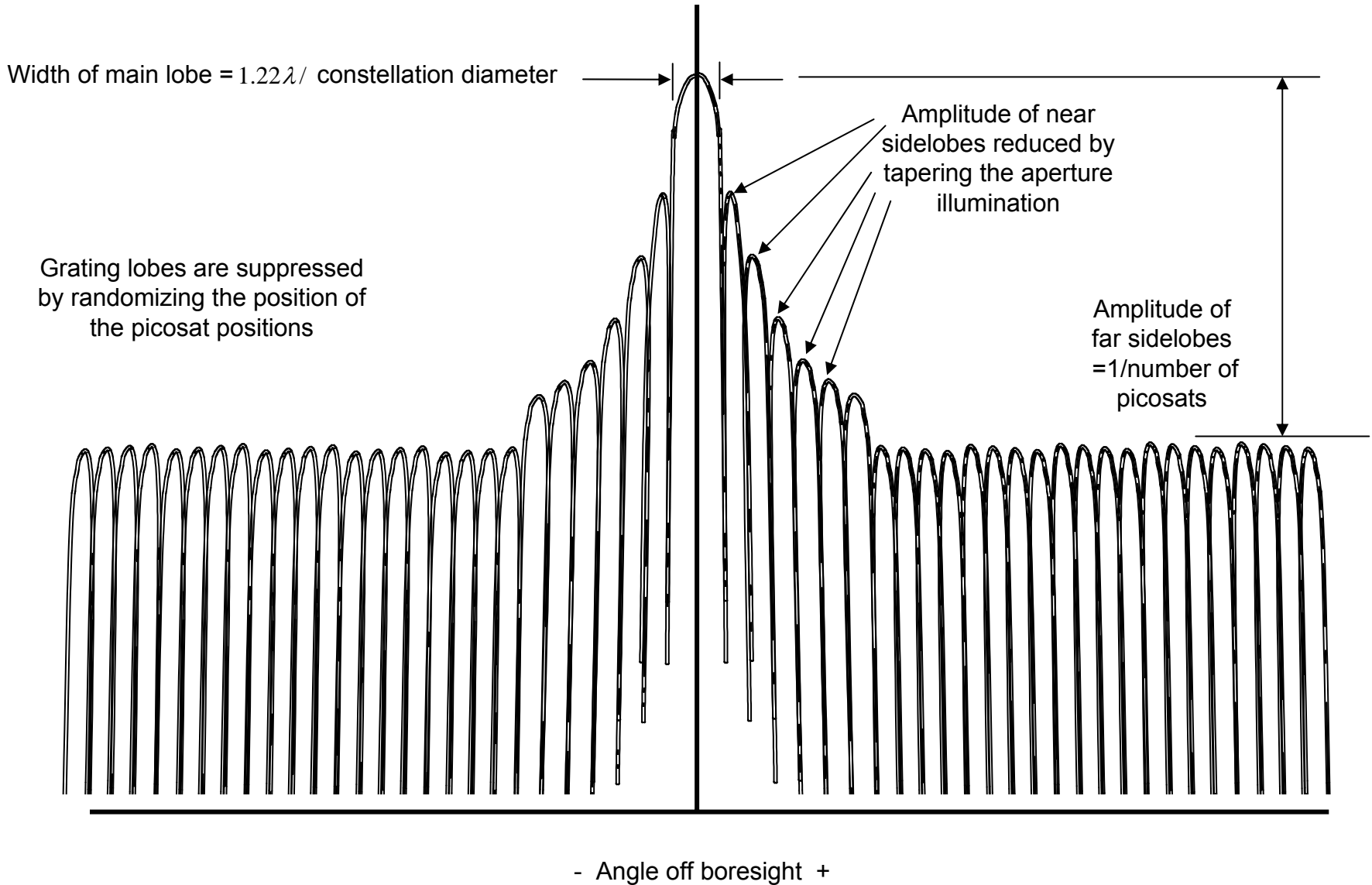


- Halo orbits obeying Hill's equations are set up for picosats
- Picosats deployed into an apparent plane in relative coordinates.
- Picosats rotate around a central point in GEO
- Plane is inclined 30 degrees to local horizontal
- The motions of the picosats are circular around the central point at 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

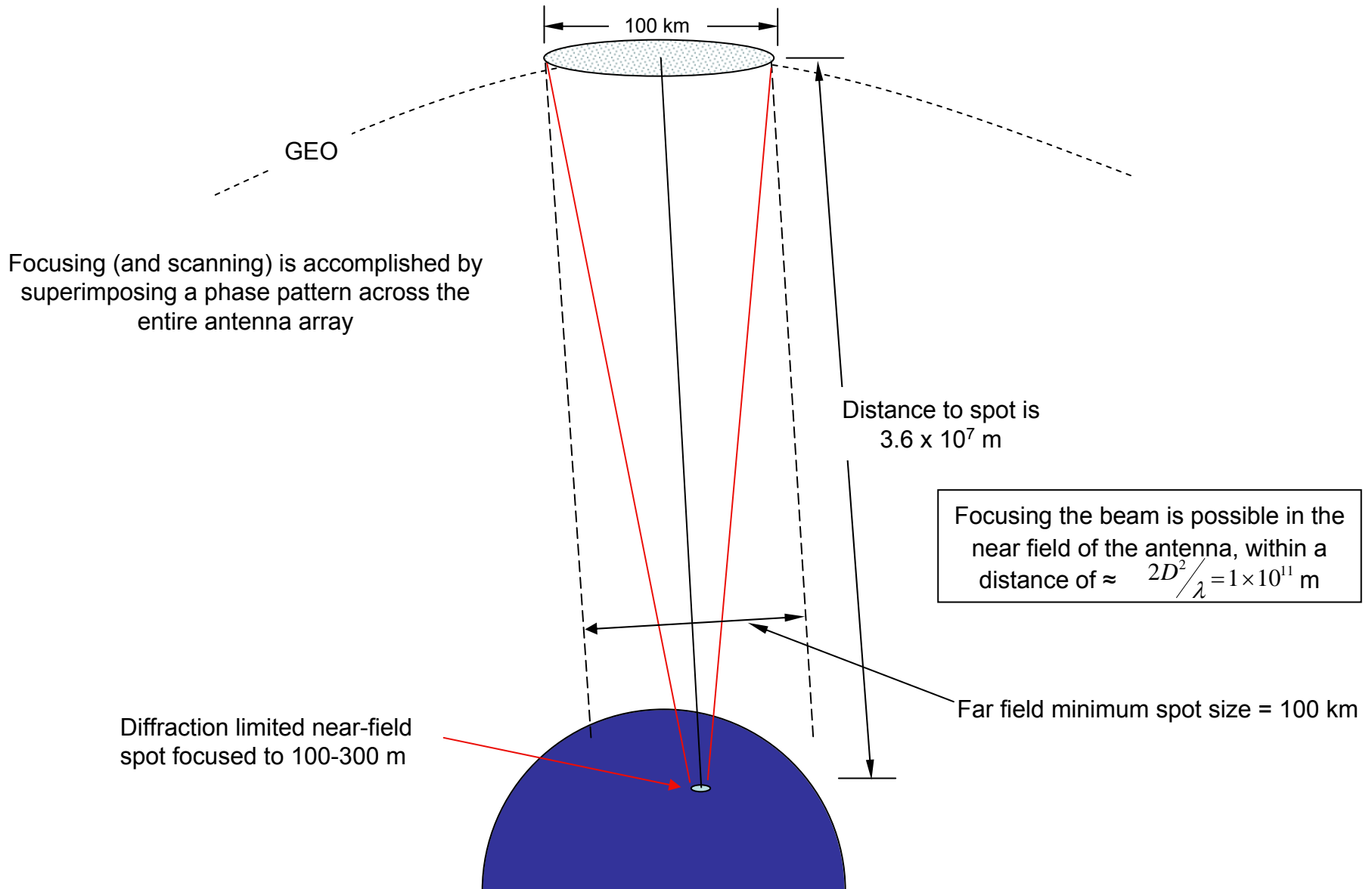
FUNCTIONING OF SPACE-FED PHASED ARRAY



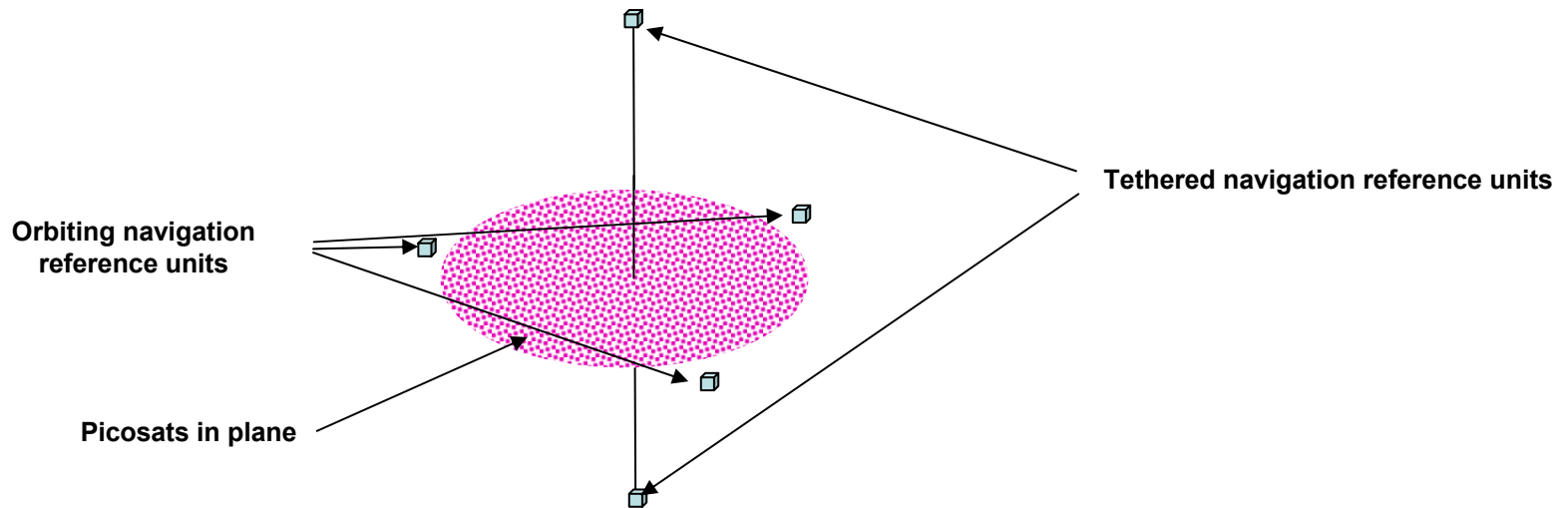
PATTERN OF SPARSE MICROWAVE ANTENNA



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

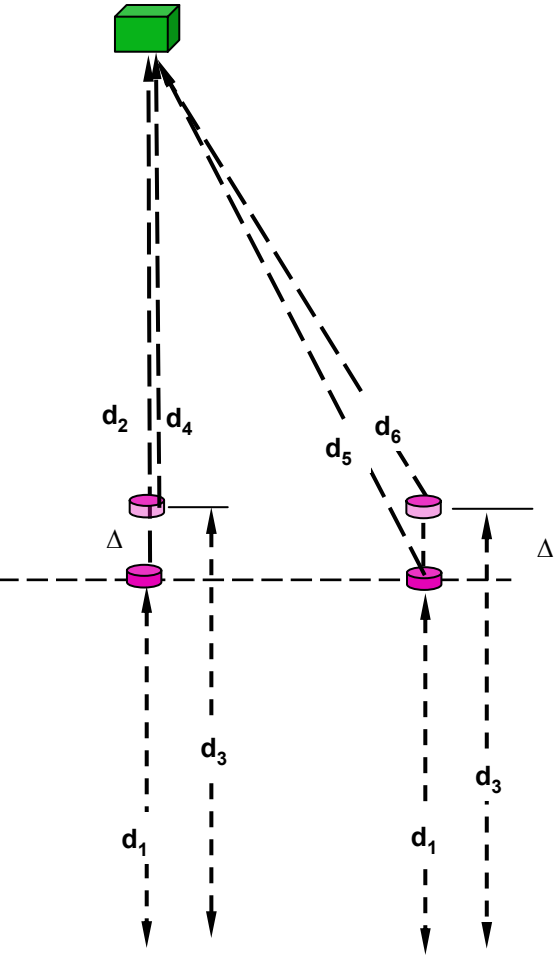
•Alternative # 2

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

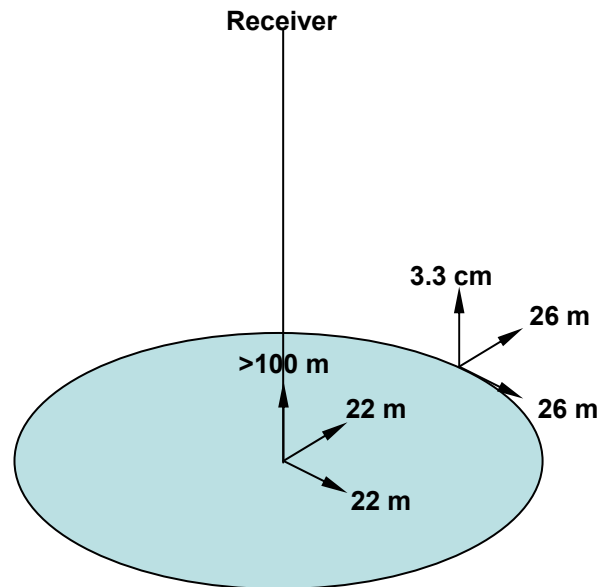
•Alternative # 3

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

PICOSAT POSITION KNOWLEDGE REQUIREMENTS IN A SPACE-FED ARRAY



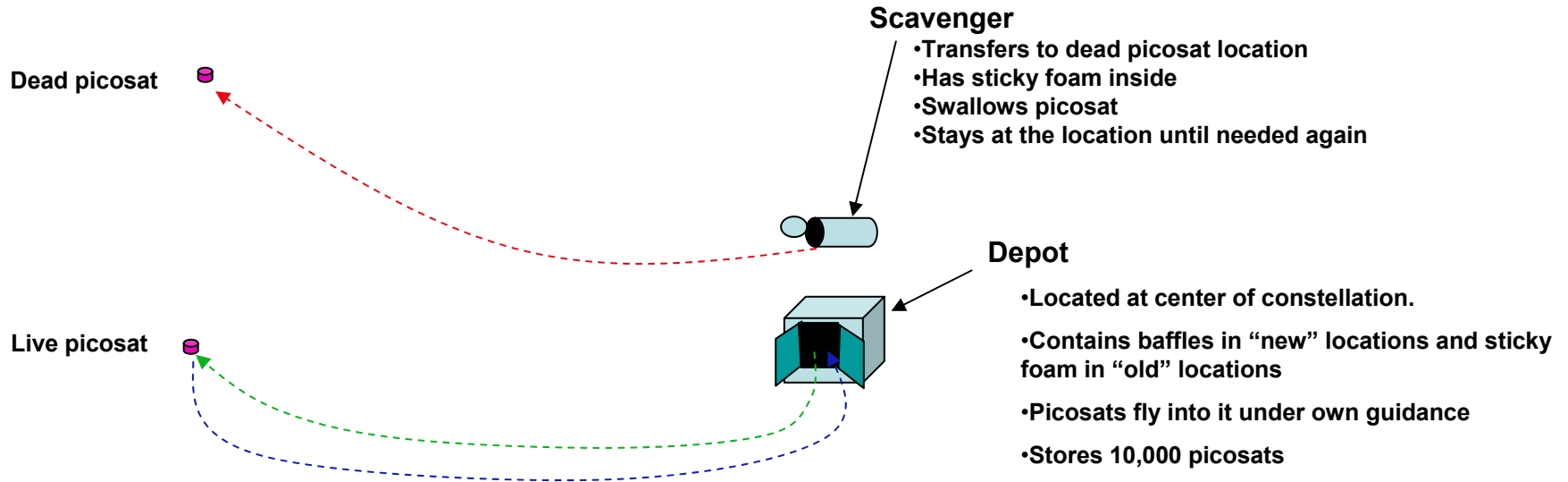
	Center picosats		Edge picosats	
	Sensitivity, m/Δ	Δ for 1 cm path delay	Sensitivity, m/Δ	Δ for 1 cm path delay
Normal to plane	0	kilometers	0.3	3.3 cm
In-plane	$0.00005 \Delta^2$	22.4 m	$0.000014 \Delta^2$	26.4 m



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 2π , 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

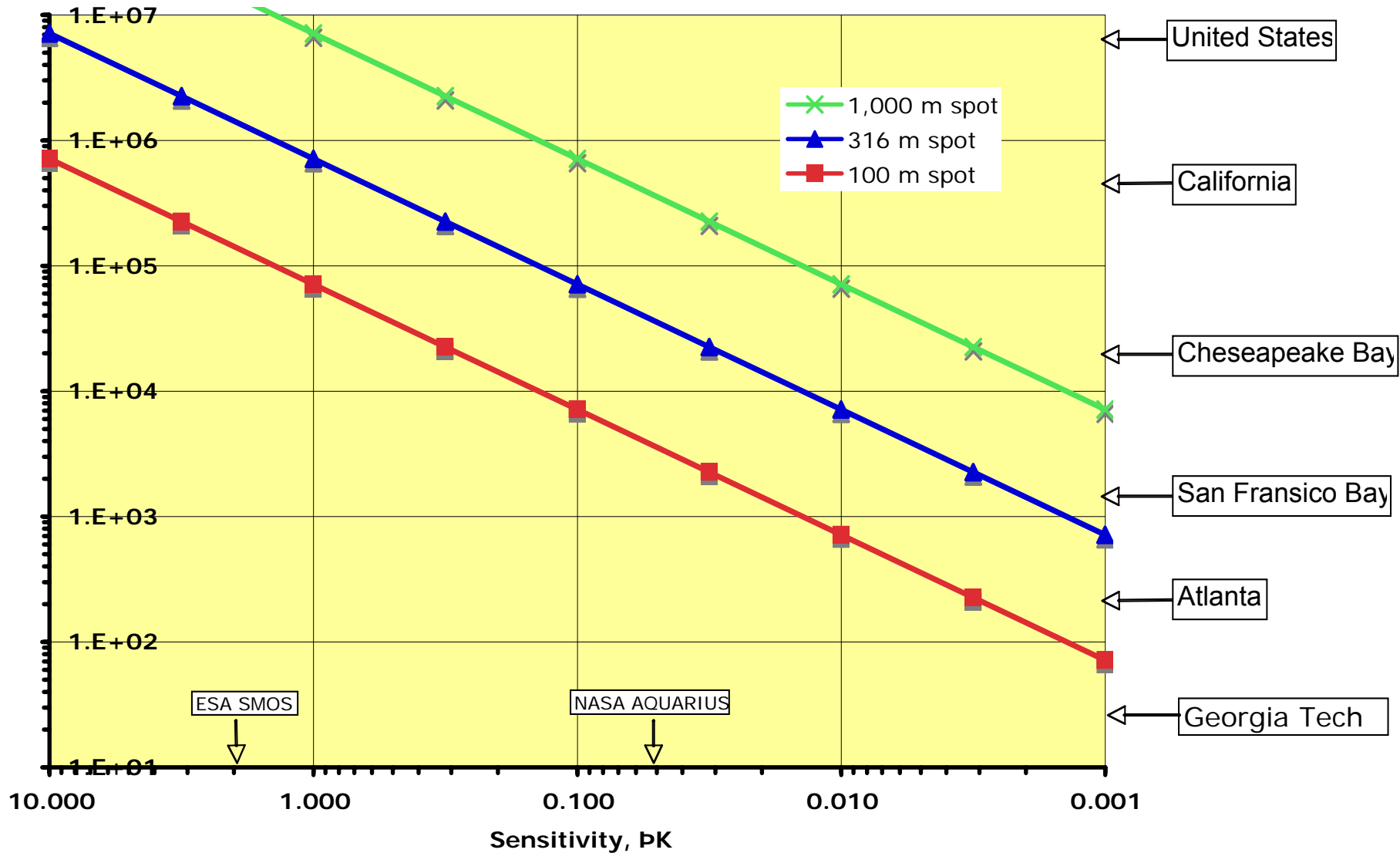
PICOSAT DEPLOYMENT, RETRIEVAL, AND SCAVENGING CONCEPT



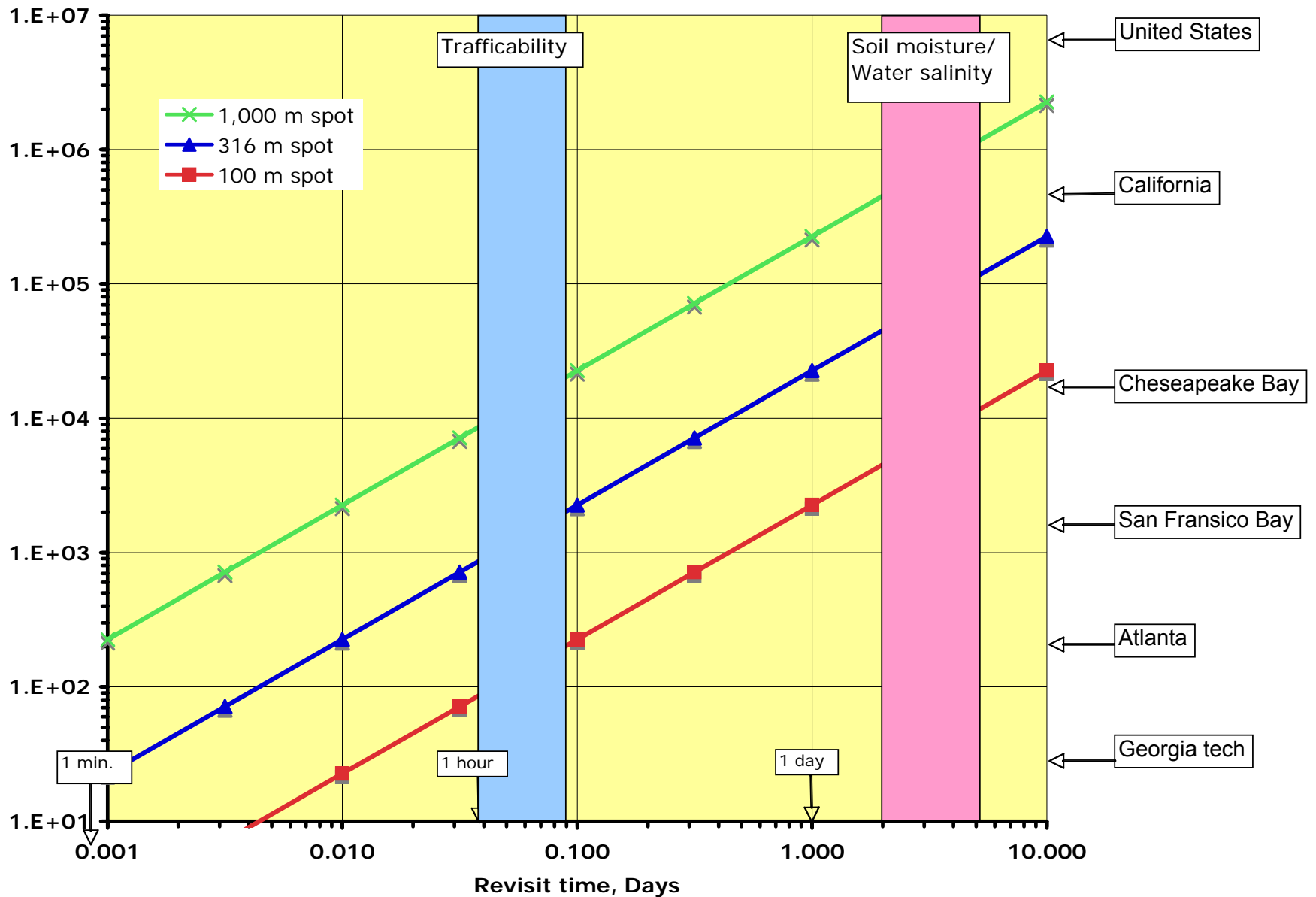
- Picosats will deploy themselves from central unit.
- Each picosat requires 8 micrograms of propellants (100 g picosat) at 3000 lsf for deployment
- Picosats will return to central storage depot when nearing EOL.
- Central depot holds all 10,000 picosats (1,000 kg).
- Depot has doors and sensors, and 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

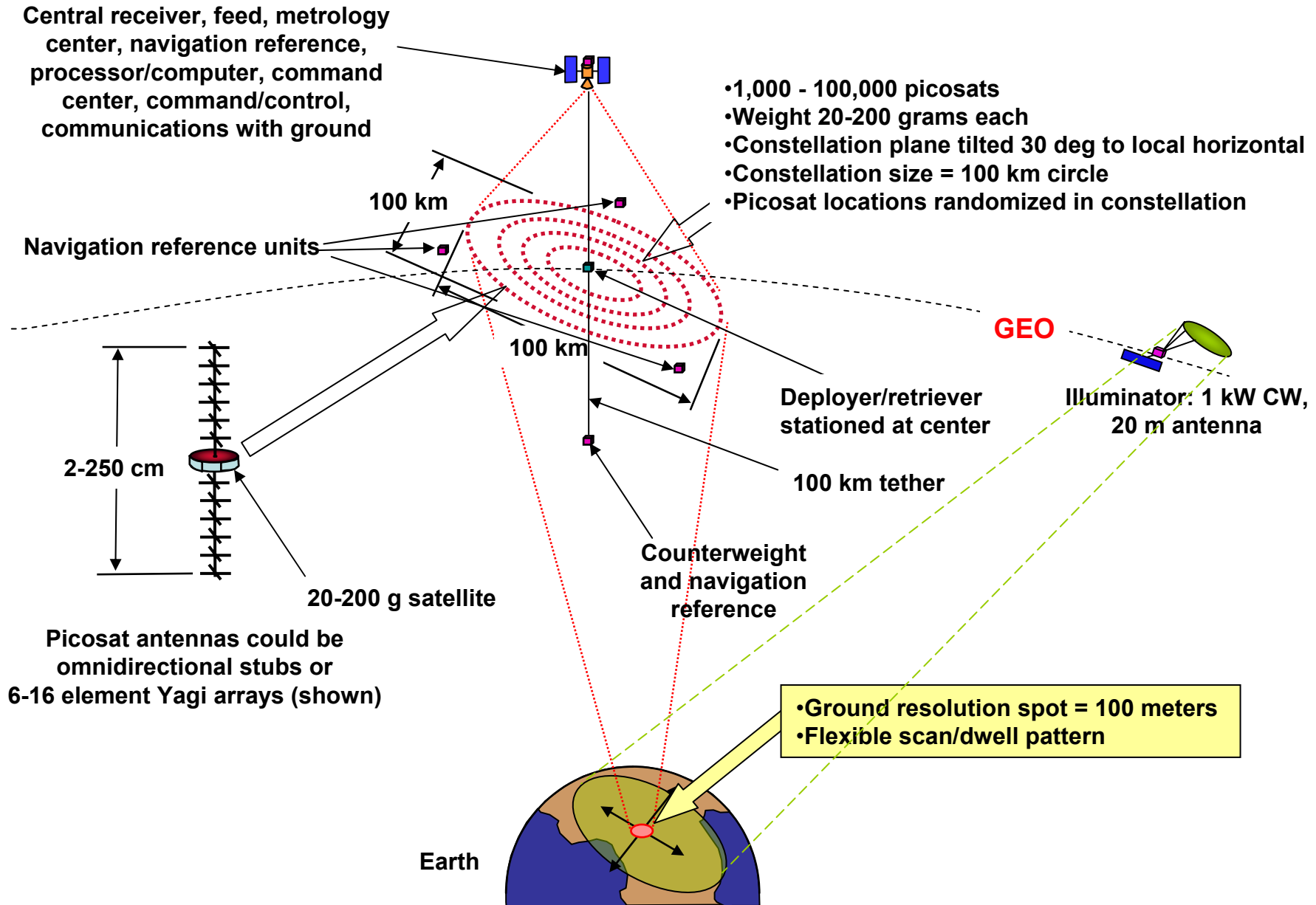
DAILY AREA RATE AS A FUNCTION OF SENSITIVITY 10 BEAM RECEIVER



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

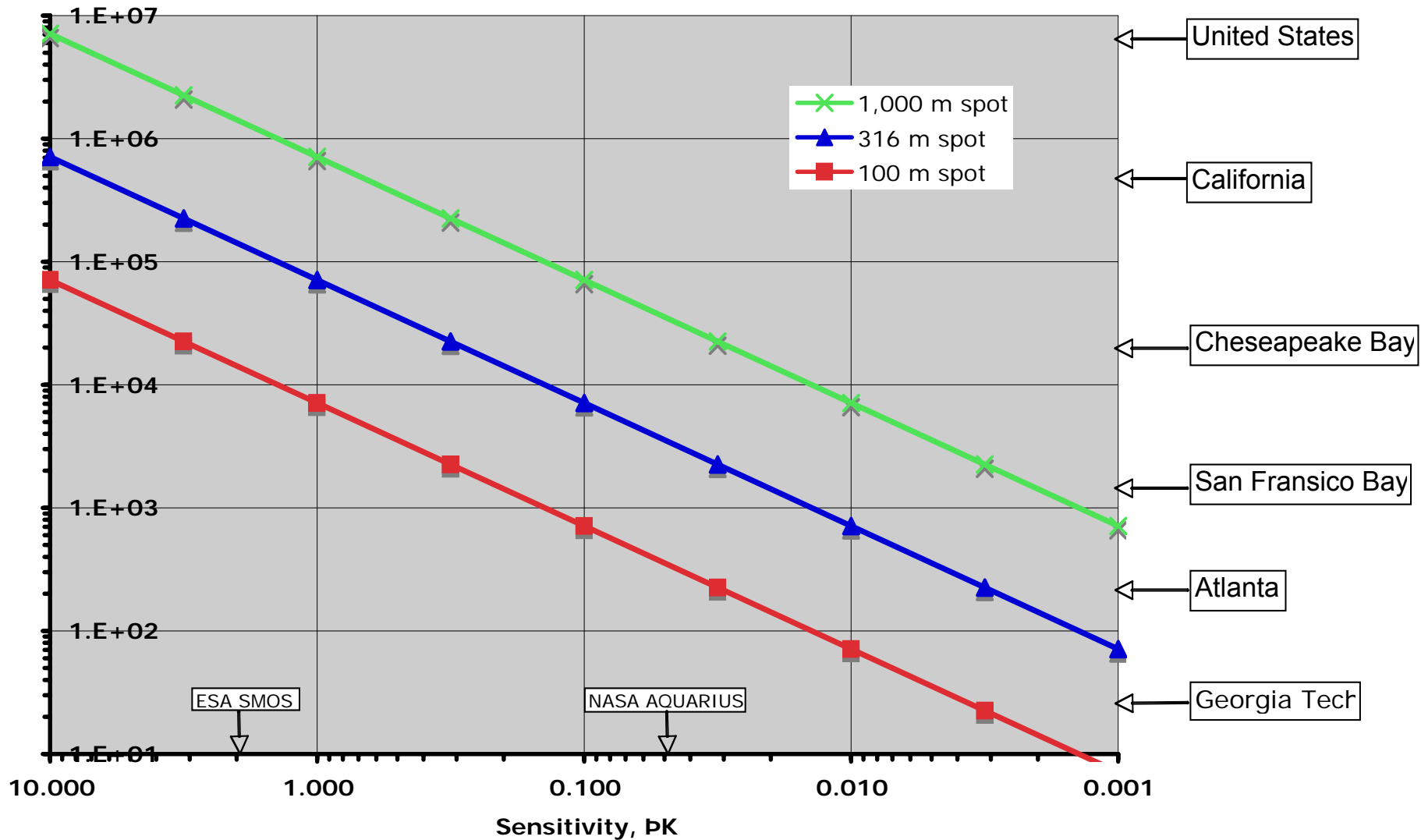
- George Hajj
- Cinza Ruffada
- James Zumberge

•Other

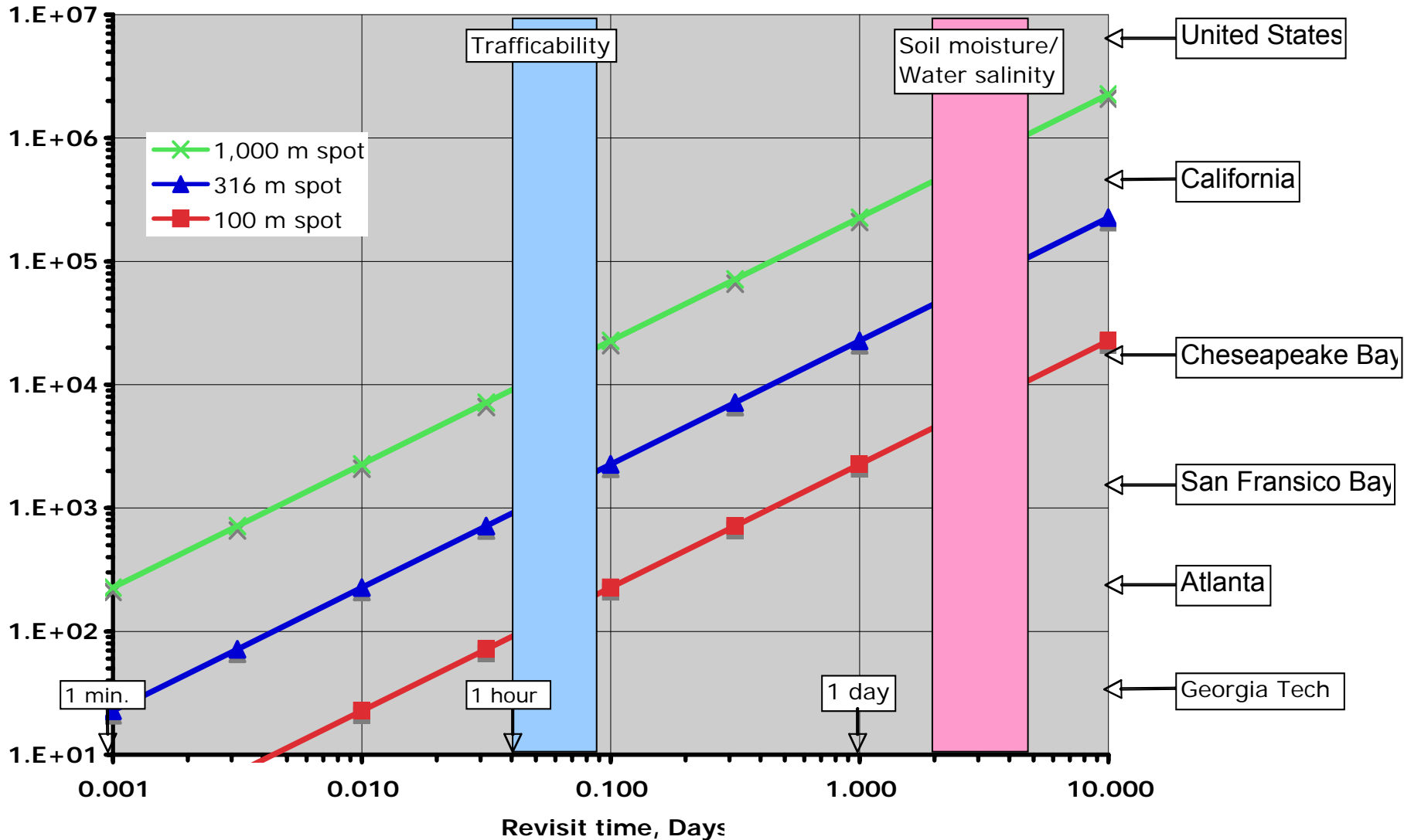
- Phil Schwartz--Aerospace Corporation
- Numerous web sites for systems: SMOS, Aquarius, Hydros, SSIS, others

DAILY AREA RATE AS A FUNCTION OF SENSITIVITY

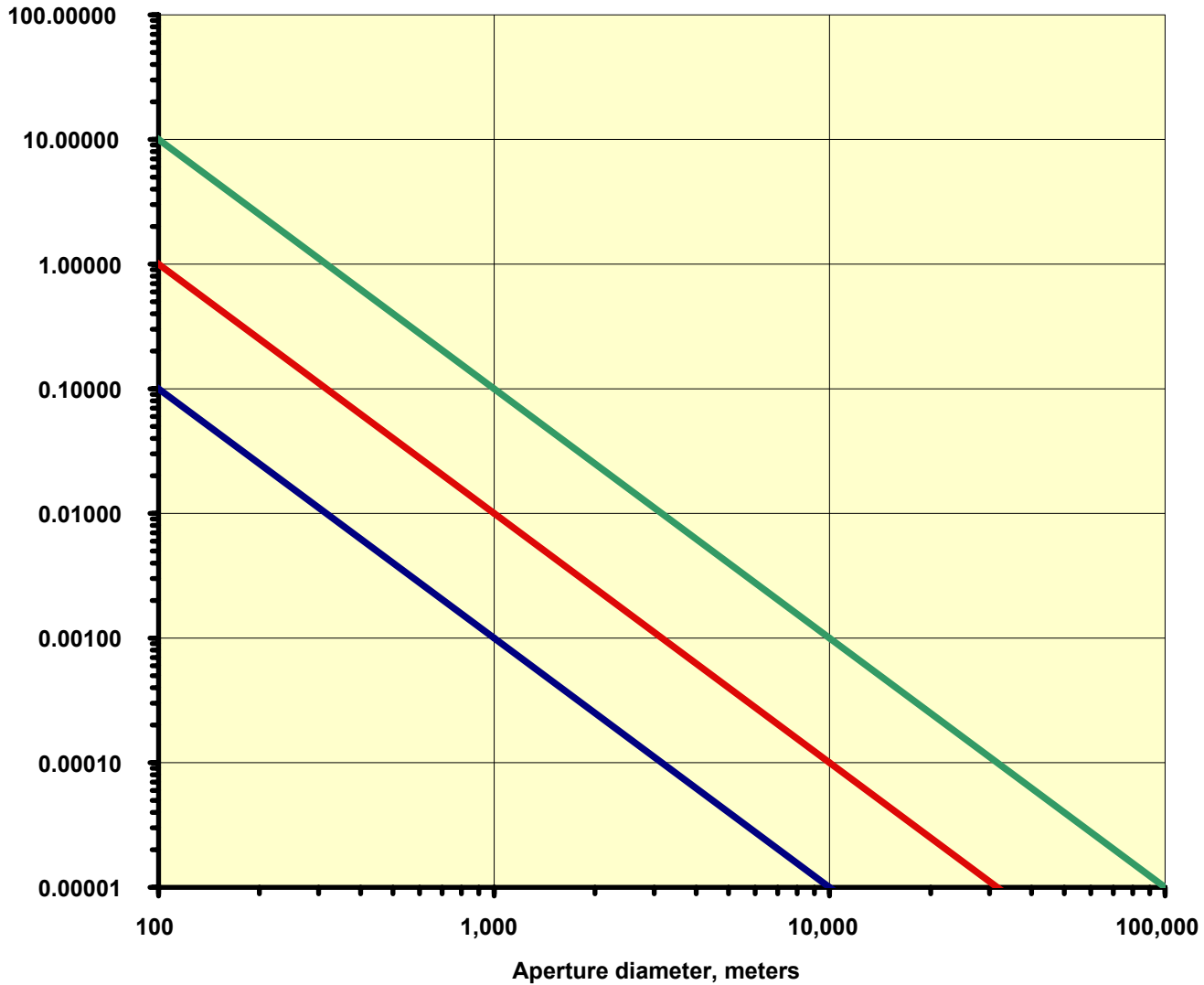
1 BEAM RECEIVER



AREA COVERED AS A FUNCTION OF REVISIT TIME 1 BEAM RECEIVER



SPARSENESS OF SWARMED APERTURE



Picosats in space-fed array

- Operate as repeaters
- Frequency = 1 GHz
- Each has 10 dB antenna

— % filled with 1000 picosats
— % filled with 10,000 picosats
— % filled with 100,000 picosats

CHOICE OF CONSTELLATION ALTITUDE

	PRO	CON
LEO	<ul style="list-style-type: none"> •Revisit time OK •Constellation size small--1 km •One constellation suffices--global coverage •Few picosats required in constellation •Passive system OK 	<ul style="list-style-type: none"> •Large ΔV in picosats for stationkeeping •High orbital debris creation problem •High impact probable with other satellites
MEO	<ul style="list-style-type: none"> •Orbital debris not a problem •Medium size constellation •Medium number of picosats needed 	<ul style="list-style-type: none"> •Very long revisit time •Medium size constellation •Need many constellations •Must use active system
GEO	<ul style="list-style-type: none"> •Short and flexible revisit time •Flexible scan/dwell patterns/options •Picosats can use omni small antennas •One constellation covers \approx a hemisphere •Orbital debris problem moderate 	<ul style="list-style-type: none"> •Large constellation size •Active system required •Many picosats required