Sensing from Space

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Zaw Thett Han, PhD Candidate, EE Department, CCNY/CUNY

Satellite Orbits

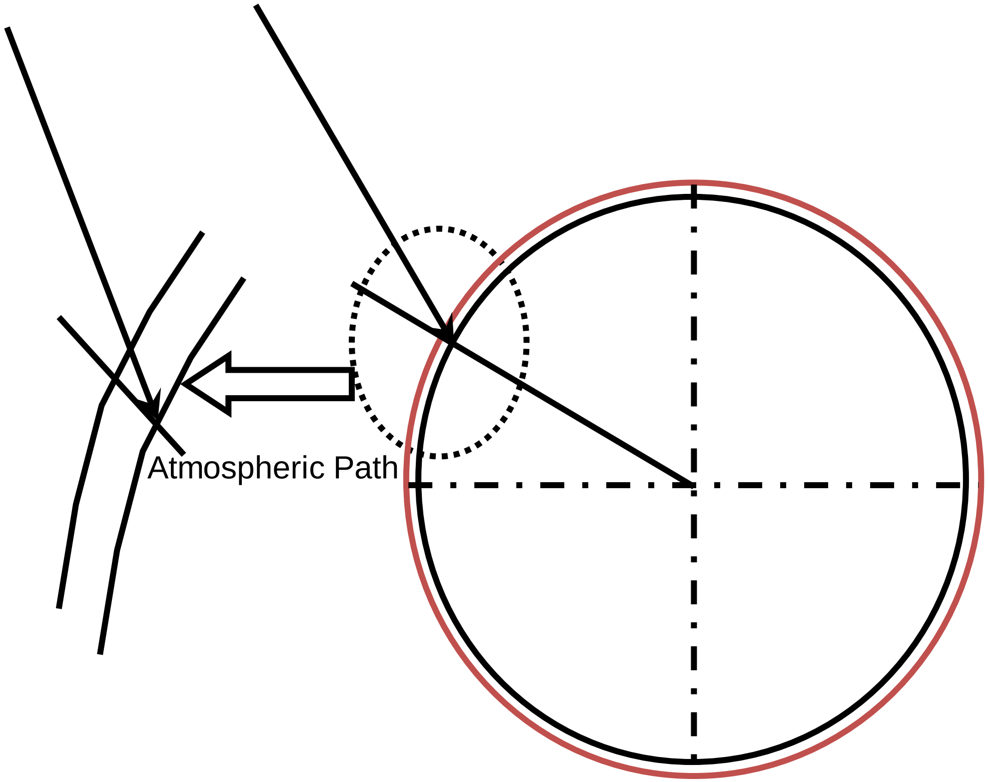
- Satellites can operate in several types of Earth orbit. The most common orbits for environmental satellites are geostationary and polar, but some instruments also fly in inclined orbits. Other types of orbits are possible, such as the Molniya (Better view, but periodic: two orbits per day, ~10 hour duration) orbits commonly used for Soviet spacecraft.

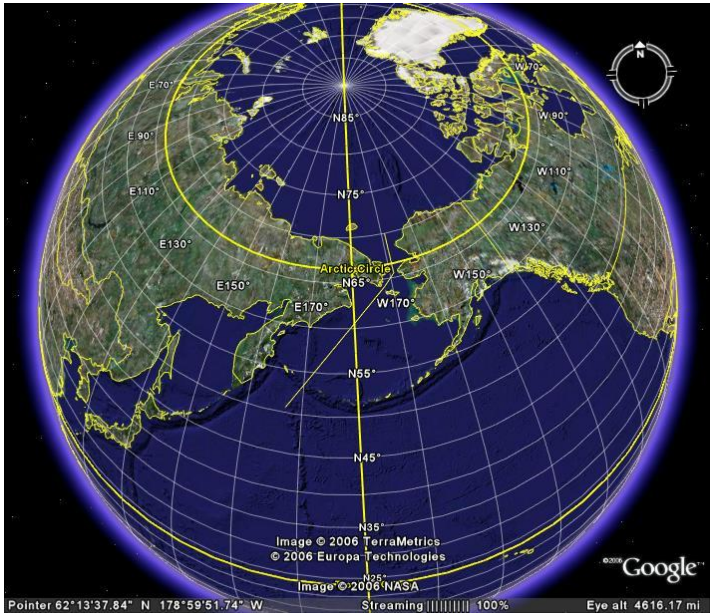
- **Geostationary Orbits**
- **Polar Orbits-**Used for low Earth orbits mostly: builds an Earth image in swaths
- **Inclined Orbits**

Observation Through The Atmosphere

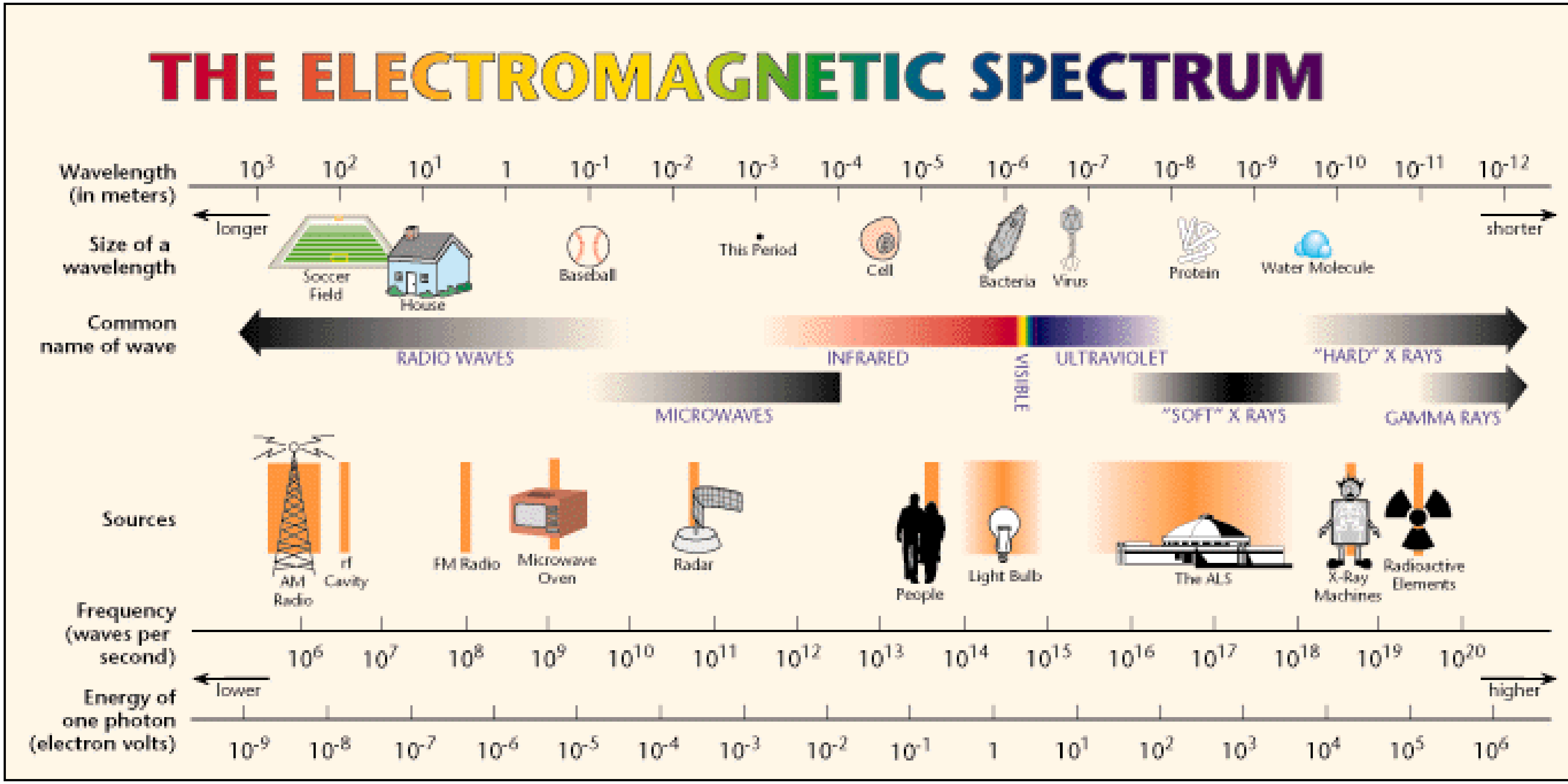
- The hard Earth is surrounded by an atmosphere (50-60 kM thick)

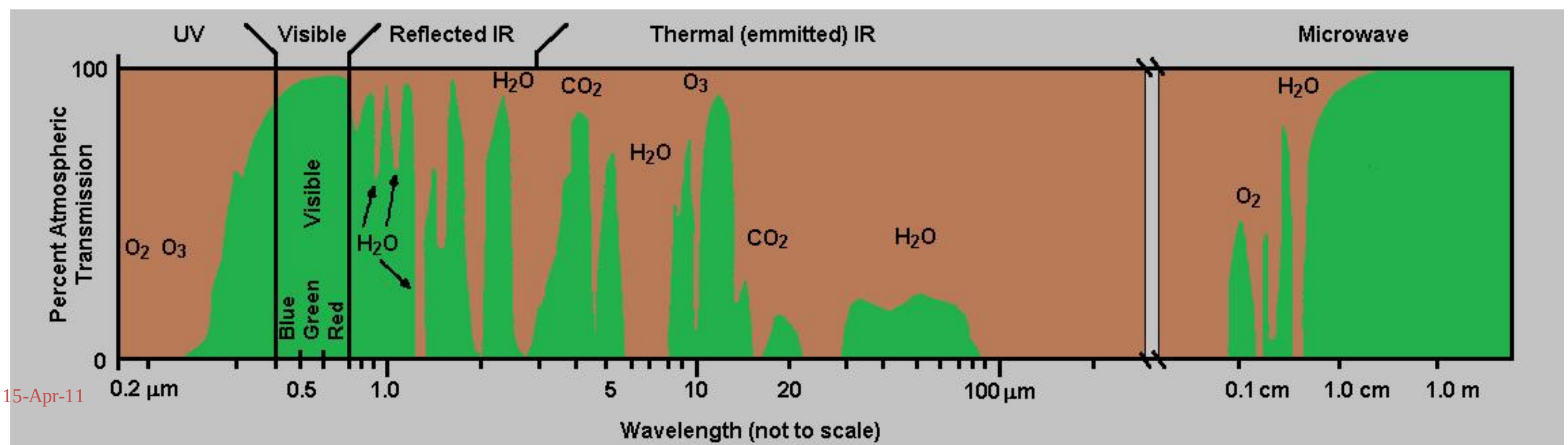
An Earth View Sketch





- **The general problem is to find the target inside of the atmosphere**
  - **Some targets are on the face of the Earth**
  - **Some are at different altitudes**
- **The atmosphere offers both transmission and background radiance of its own**


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}


UV
Visible
Reflected IR
Thermal (emmitted) IR
Microwave
Percent Atmospheric Transmission
100
0
O_2 O_3
Blue
Green
Red
H_2O
CO_2
O_3
H_2O
CO_2
H_2O
H_2O
O_2
H_2O
0.2 µm
0.5
1.0
5
10
20
100 µm
0.1 cm
1.0 cm
1.0 m
Wavelength (not to scale)

Designing Satellite System and Orbits

- Important to convey the system
- More important is making the vision accurate. Develop requirements
  - Number of assets
  - Viewing geometries
  - Coverages
  - Revisit times
  - Thermal environment
  - Access to surveyed areas
  - Ground stations
- Start the thought process “What is your job”
  - Design of a major system is a team action
  - For example the SBIRS constellation has ~1000 requirements that must be satisfied

Mission Needs (Why Build It)

- Understanding of what about the mission and/or its outcome is
  - New
  - Unique
  - Special
  - Why it is needed

- Identification of the users
  - Those that will execute the mission
  - Those that use the data

- Identification of what is critical
  - To the customer
  - And user community

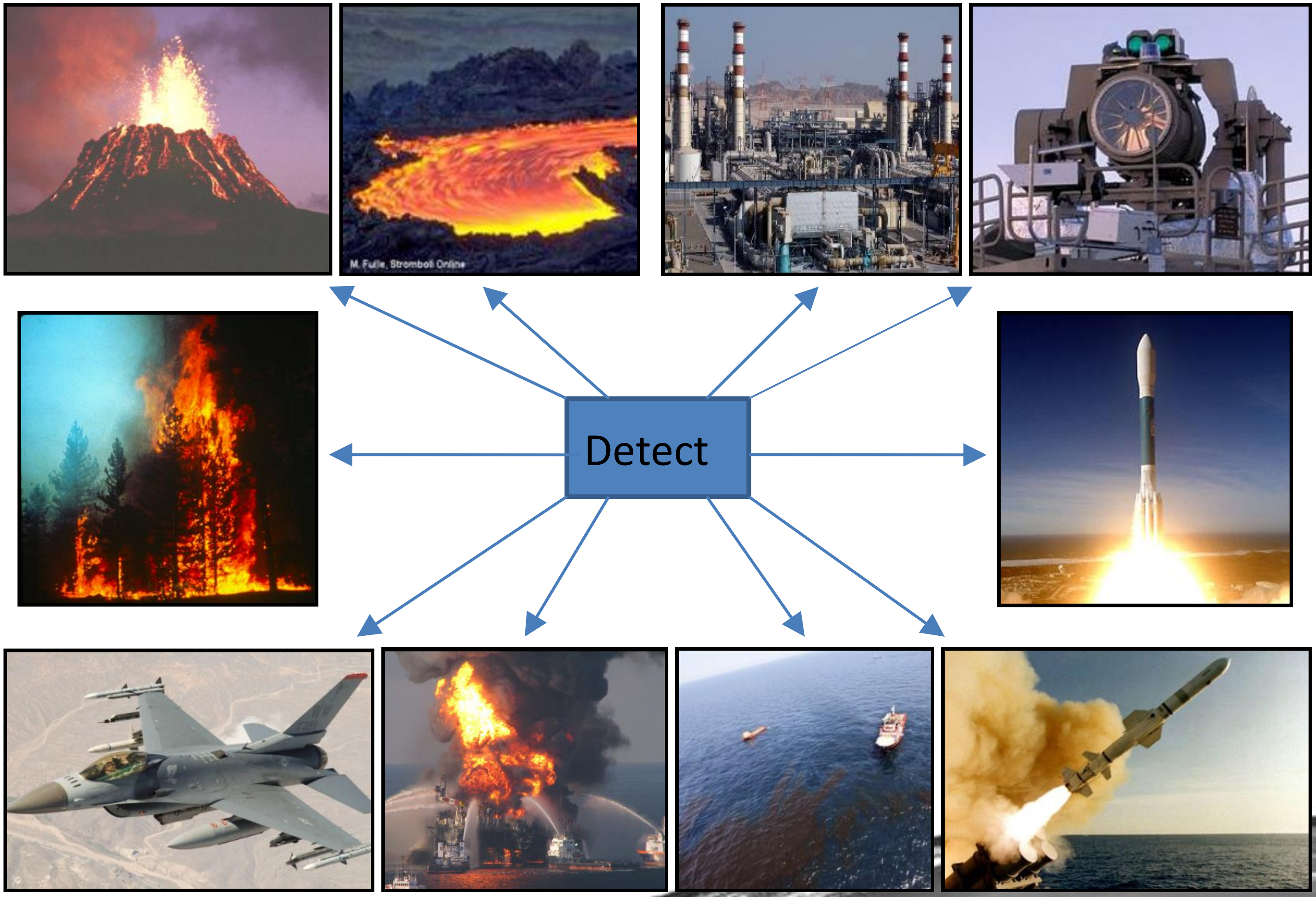
Mission Concept Of Operations: CONOPS

- Who are the players in the mission:
    - Blue assets: on-board systems, off-board systems, other platforms
    - Red assets: Targets and Threats
    - Neutrals
- What is the goal of the mission
    - What are the steps required to achieve that goal.
- Description of battle-space (for a military system)
    - The terrain, time of day, time of year
    - Location of blue and red assets and neutrals
- Mission Timelines
    - The order of the steps
    - What each of the players are doing at each point in time
    - How do each of the players interact

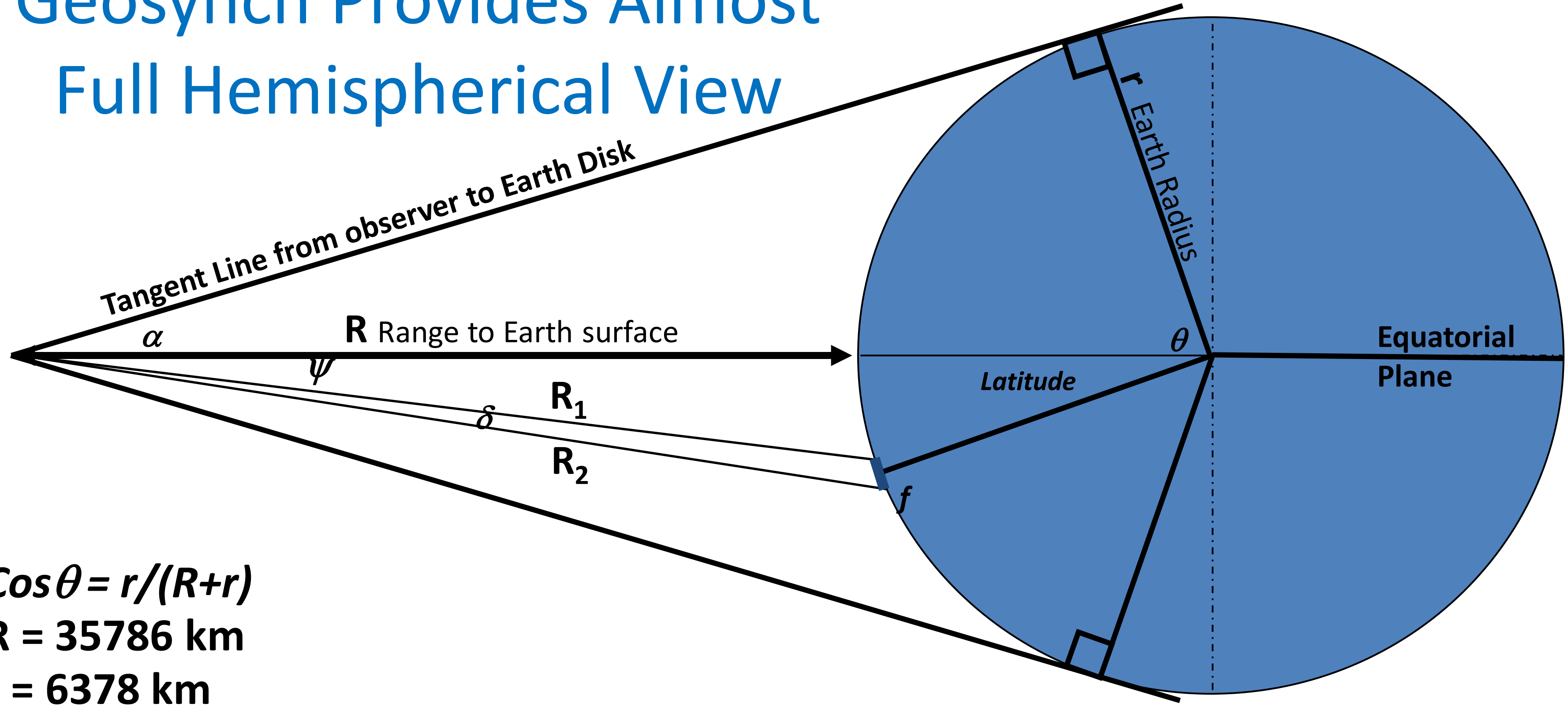
Requirements

- Several Levels of Requirements
  - Operational
    - What the customer/user wants/needs, as derived from the mission needs and CONOPs
  - System
    - Derived from the operational requirements
    - Describes what the system must do
    - Derived based on trade studies
  - Sub-system and component:
    - Derived from the system requirements.
    - By trade studies or budget allocations.
- Traceability is essential
  - Identify source of requirement and supporting documentation
  - Link to the next highest level must be clear

Mission Requirements

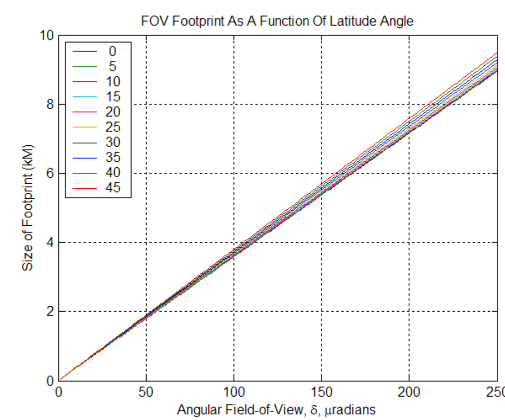


Geosynch Provides Almost Full Hemispherical View



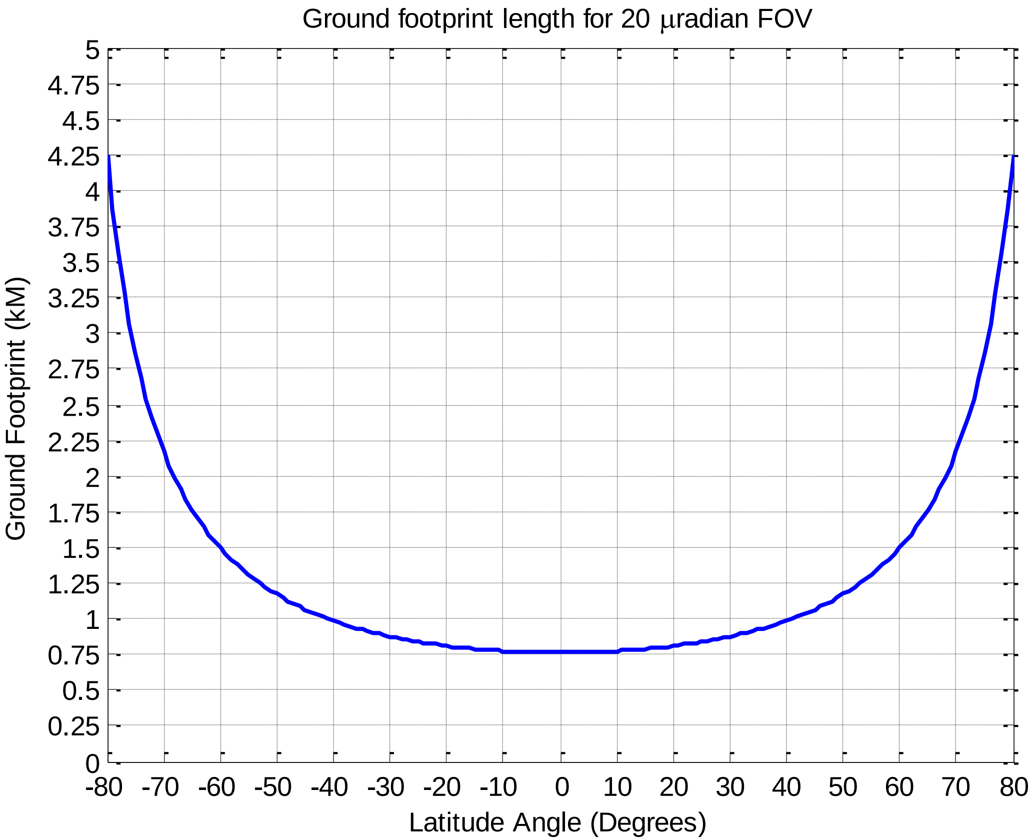
$Cos\,\theta = r/(R+r)$
R = 35786 km
r = 6378 km
We span $2\theta = 2x81.3^o = 162.6^o$
$\alpha = 8.7^o$

- The Earth occupies ~18^o in our vision space
- Angle, δ, much smaller than α, and at ψ from the equatorial plane, projects a footprint, f, onto the Earth surface:
    - $f \approx \delta(R_1+R_2)/2/cos\,\psi$
- Footprint shown on inset



The Surveillance Footprint, *f*, Is A Function Of The Angle α

You ought to do the geometry to prove that:



$$f = \frac{R' \delta \cos \alpha}{\cos \theta}$$

$$R' = \frac{h + R}{\cos \alpha}$$

$$h = r - \sqrt{r^2 - p^2}$$

$$p = r \sin \theta$$

h **and** ***p*** **are parameters of convenience to keep the math expressions concise**

Note that at the equator a 20 radian FOV produces a 800 meter footprint, while near the north or south poles the footprint projects to nearly 4.5 kilometers

Scenes And Their Categorization

- If you have ever observed a cloud filled sky, you note the pseudo-random pattern of clouds. From aircraft and from space clouds provide two impediments to Earth surveillance
  1. They obscure the features below them – consider this as complete obscuration in the IR, and
  2. They provide a irregular reflection of sunlight – consider this as the limiting clutter in the surveyed scene
- We classify clutter by a set of statistics over the FOV, time, and space:
  1. Mean brightness – average intensity, μ
  2. Clutter brightness – standard deviation, σ
  3. Radiance gradient – measure of the raggedness, edge presence, or smoothness of the clutter structure,
  $$F = \sqrt{F_x^2 + F_y^2}, \ where \ F_l = \frac{\partial Scene}{\partial l}$$
  4. Weiner spectra – One or Two dimensional spatial frequency distribution

Get The Correct Phenomenology

- Phenomenology is driven by the targets and backgrounds (Clutter)
- Standard models exist for many targets of interest
  - Rocket plumes – CHARM (Composite High-Altitude Radiation Model)
    - Codes calculate plume source intensities at altitudes >70 km
  - SIRRM (Standardized Infrared Radiation Model) and SPF (Standard Plume Flow Field)
    - Lower altitudes (< 40 kM)
  - Thermal models – Planck
  - Solid body models – Sooty emissivity (emission) of Planck
  - Mixed models – All above
- Earth backgrounds characterized by surface albedo and thermal energy
  - Standard models are available for backgrounds
  - Synthetic Scene Generation Model (SSGM) based collections (bible so far)
- Atmospheric transmission/radiance/scattering
  - MODTRAN – Northrop Grumman uses a MODTRAN derivative: PLEXUS
  - Scattering can be a surprising source of unwanted radiance in the IR
- Other resources for spectra are
  - Google – NASA – JPL – GenSpect, etc

Radiometry Review

Peak radiance shifts to shorter wavelengths with increasing temperature

Temperature contrasts imply differences in blackbody distribution

For 300K, peak is at about 10 µm

Interesting physical constant:

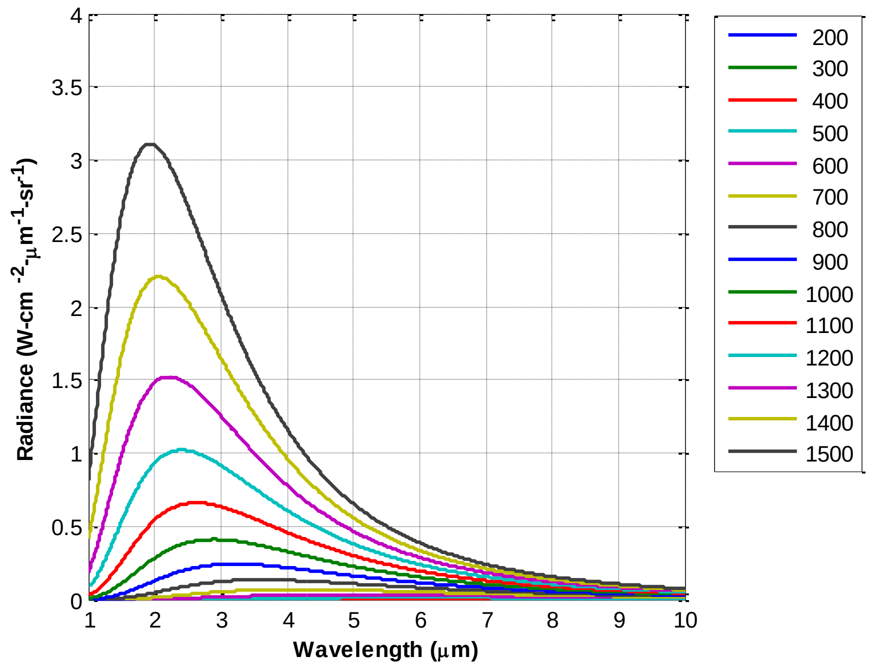
Sun color = yellow

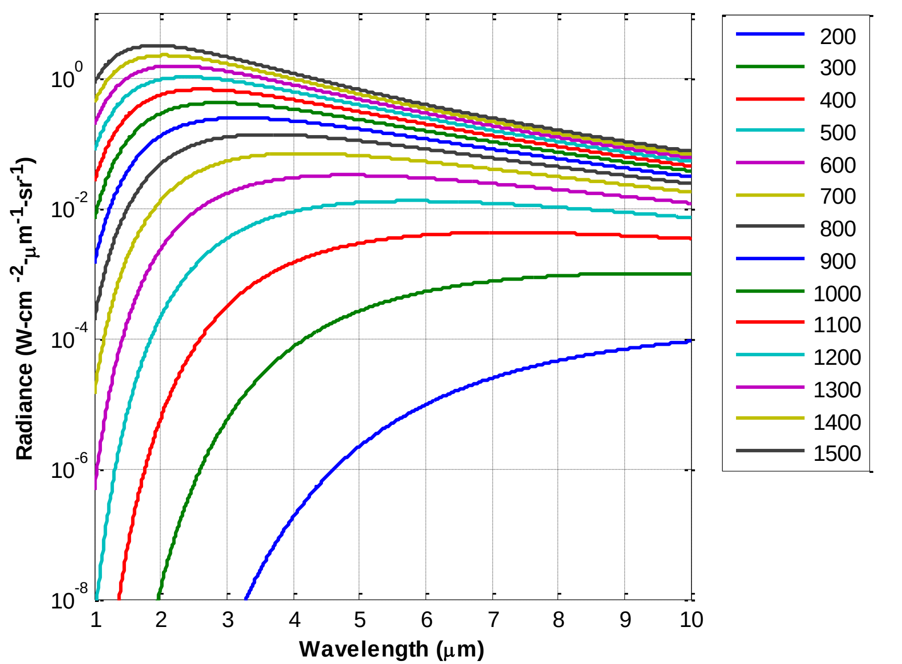
Sun temperature = 5900K

Solar constant = 137 mW/cm^2

$E = \sigma T^4$ (Stefan's Law) applies over the entire spectrum

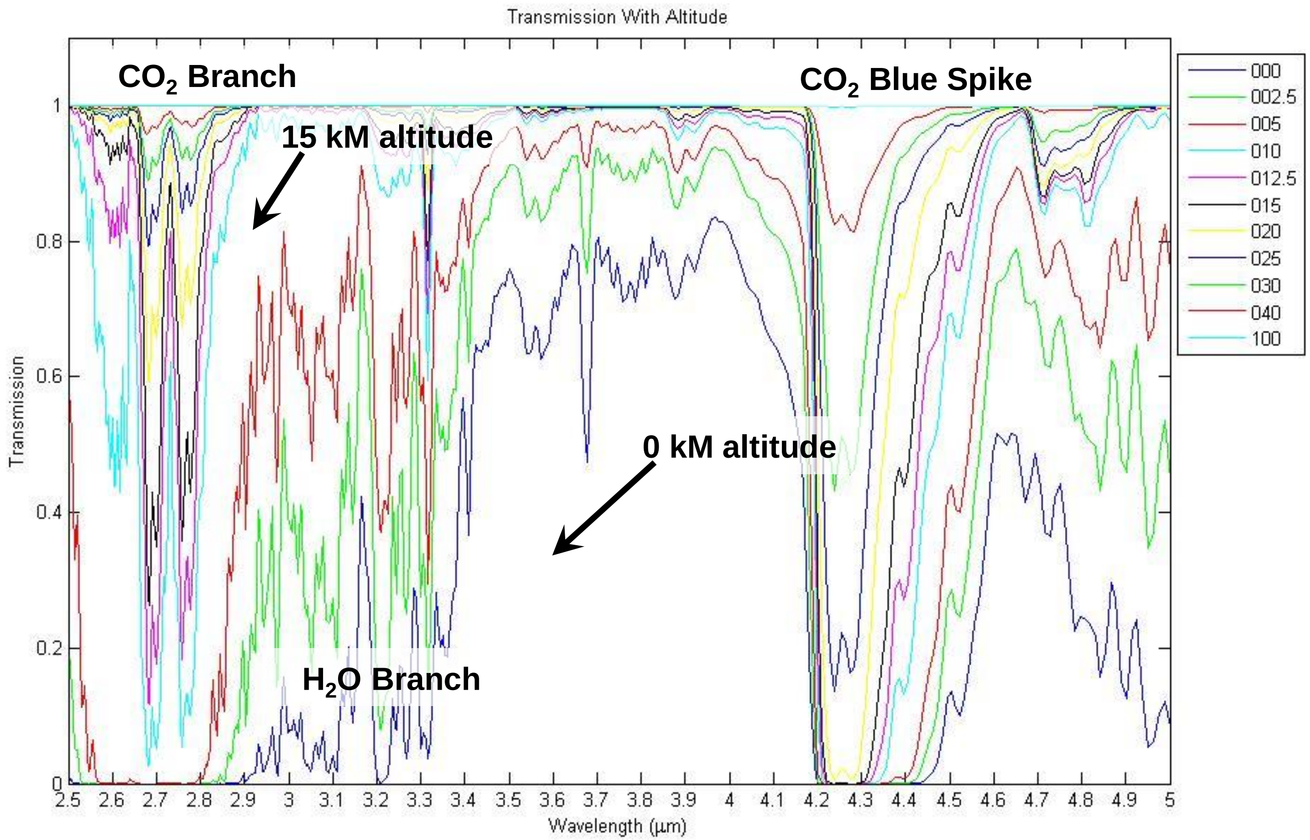
For fun try to derive the solar constant, you'll prove that the Sun is 93 million miles away!





Atmospheric Transmission Varies As A Function Altitude

- Species concentrations are altitude dependent or uniformly mixed
- Gives rise to different transmission as a function of altitude and path length through atmosphere (zenith angle – important for surveillance from space)
- Selecting a band will determine the average transmission in the band



Rules Of Thumb For IR Radiometry

Rules of Thumb:

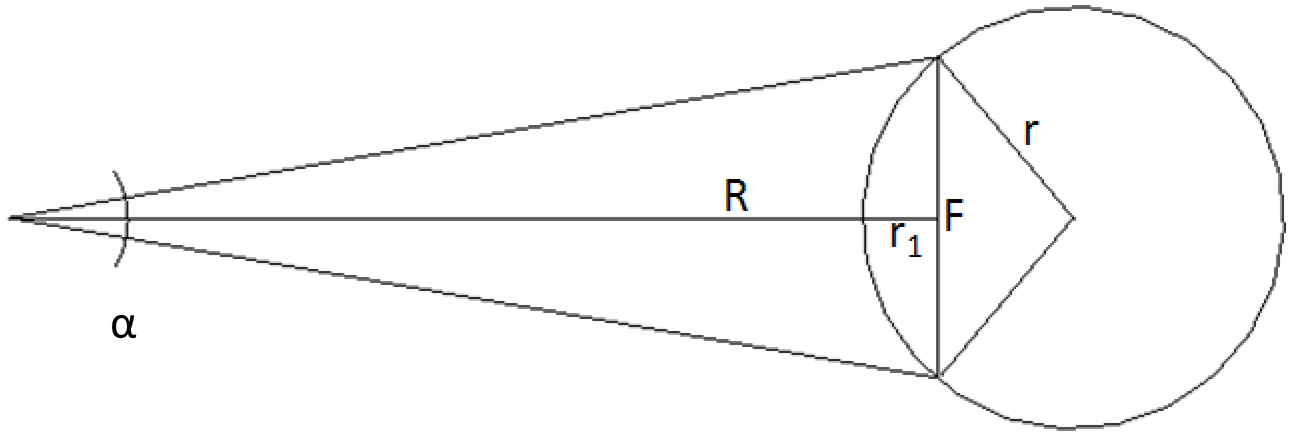
1. ***L**ong**W**ave**I**nfra**R**ed (8 to 12μm) photon flux is about 100X **S**hort**W**ave**I**nfra**R**ed (2 to 3.5μm), and 10X **M**id**W**ave**I**nfra**R**ed (3.5 to 5μm)*
2. **The Earth appears very bright in LWIR**
3. **SWIR is best for observing emissions from hot water vapor**
4. **MWIR deals better with Earth backgrounds**
5. **LWIR operates best against cold (space) backgrounds**
6. **LWIR requires much colder detectors (70K or lower compared to 130K)**
7. **When looking at the Earth, the limiting source of radiance is the atmosphere itself**
8. **Starlight illumination looks like 2856K blackbody – our Sun ~5600K**
9. **For space systems – small angle approximations are excellent – operating orbital ranges are 40,000kM from GEO-sync orbits**
    1. **All of New York State is 1^o from GEO-sync**
    2. **USA is ~7^o**
    3. **The solid angle $\Omega \approx \theta_x \theta_y$**

The Audit Table Collects Sensor Parameters To Build Upon An Example

- Mission level requirements
  - System shall have 0.95 probability of XX W/sr target detection in YY W/cm^2/sr clutter with false alarm probability of 10^{-3}
- Enumerate all the subsystems in the system
  - Allocate performance features
- Model sensor to re-allocate as required
  - Refine allocations as trade studies are completed and performance estimates of various subsystems are improved
- Maintain tables as features mature
- Process is in-exact
  - This is an iterative process that you'll keep doing as system technologies change throughout the years

Task: detect targets	Must achieve 95% efficiency and 1/1000 false alarms	
Subsystem	**Allocation 1**	**Allocation 2**
Aperture	50 cm	25
Pointing System	2-axis Gimbal	2-axis mirror
F#	2	4
Throughput	0.6	0.8
Operating temp	OTA 170K FPA 120K	OTA 150K FPA 100K
Detector pitch	20 µm	30 µm
Detector Noise	800 µv	600 µv
LSB level (quantization)	400 µv	400 µv
Processor Throughput	4 MPixels/s	9 MPixels/s
Comm Bandwidth	2.5Mbit/s	2.5Mbit/s

Field of Regard to Focal Plane

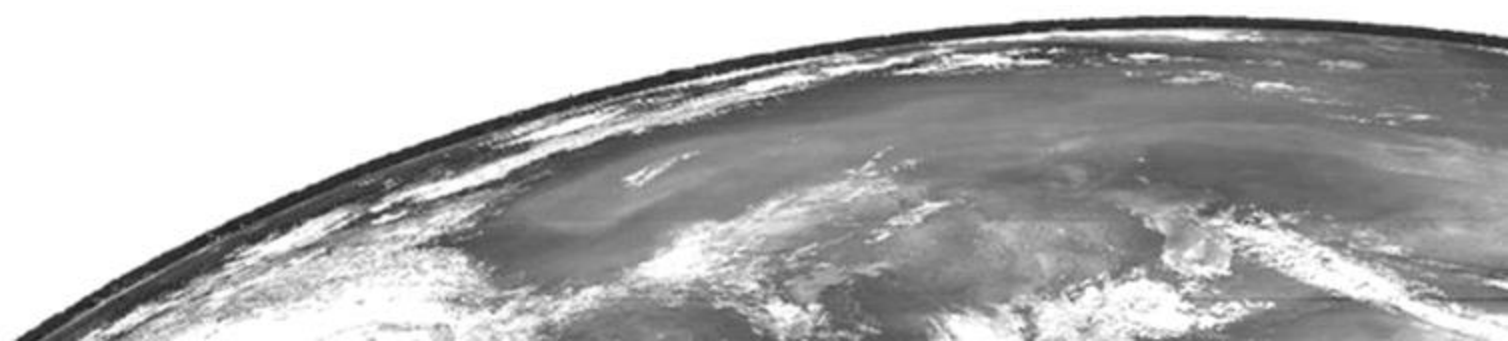


Longitude

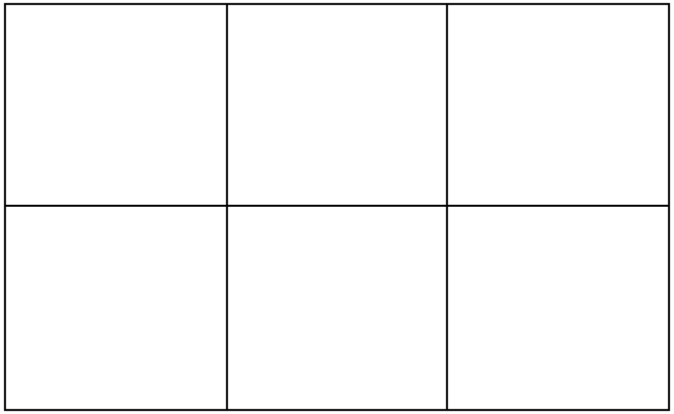
- 100°
- F = 9,771,662.9m
- α = 13.18 = 230mrad

Latitude

- 70°
- F = 5,993,359.5m
- α = 7.72



Primary Focal Plane Array



Starer

- 6 SCAs
- 4096x4096
- 20µm pitch

$\mathrm{IFOV} = (0.230)/(3\mathrm{x}4096)$

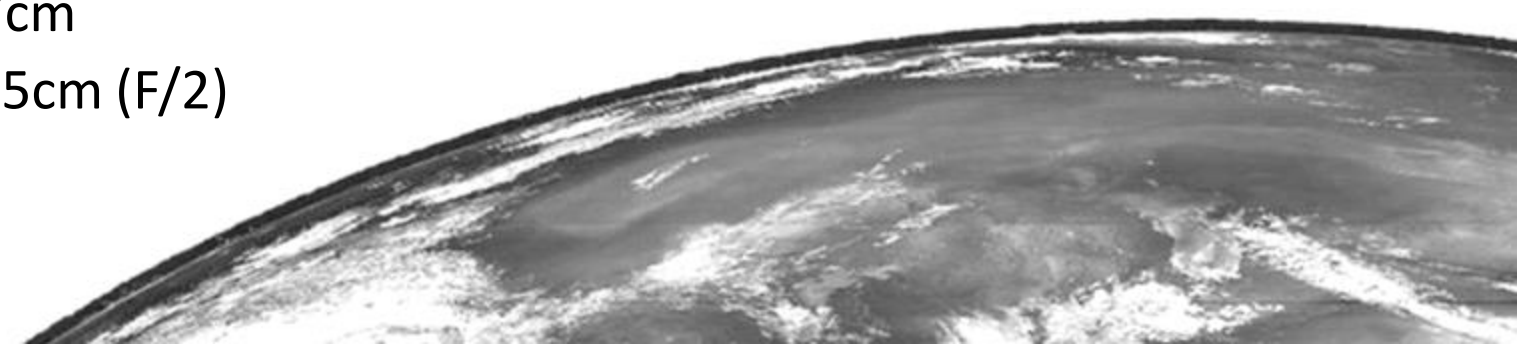
$\mathrm{IFOV} = 18.72\mu\mathrm{rad}$

Footprint =749m

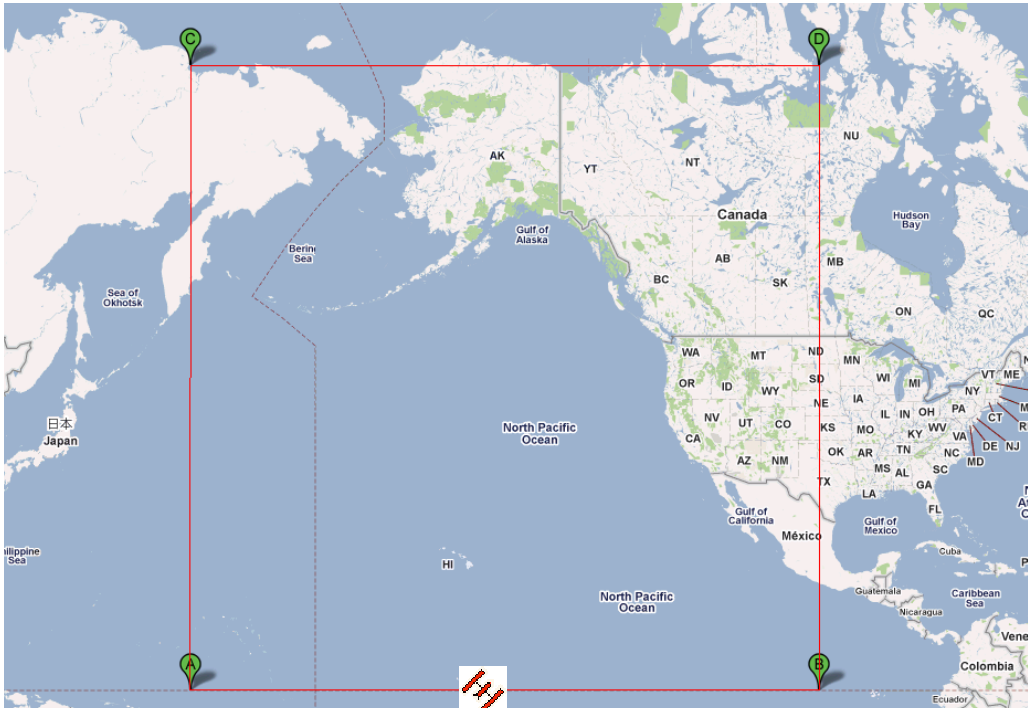
$f = (20\mu\mathrm{m})/(18.72\mu\mathrm{rad})$

$f = 107\mathrm{cm}$

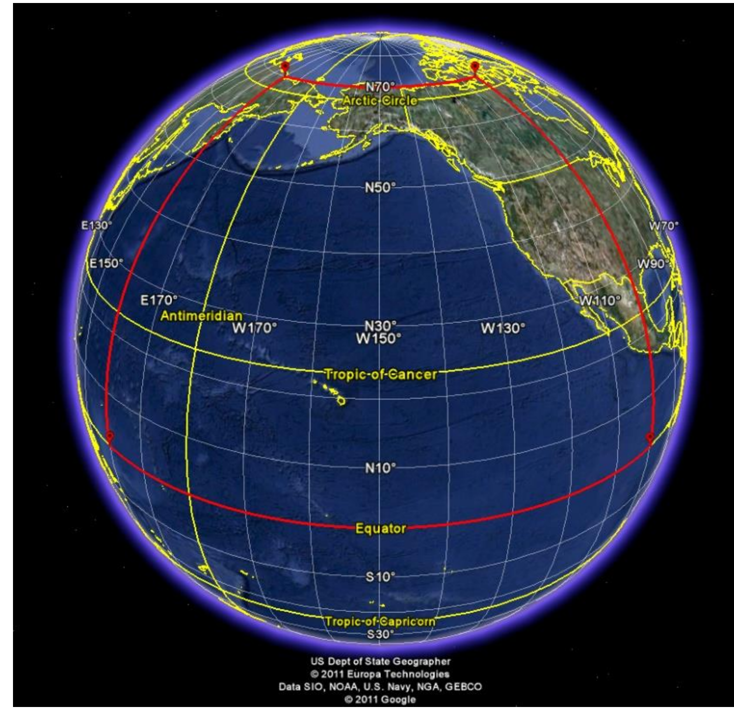
$d = 53.5\mathrm{cm}$ (F/2)

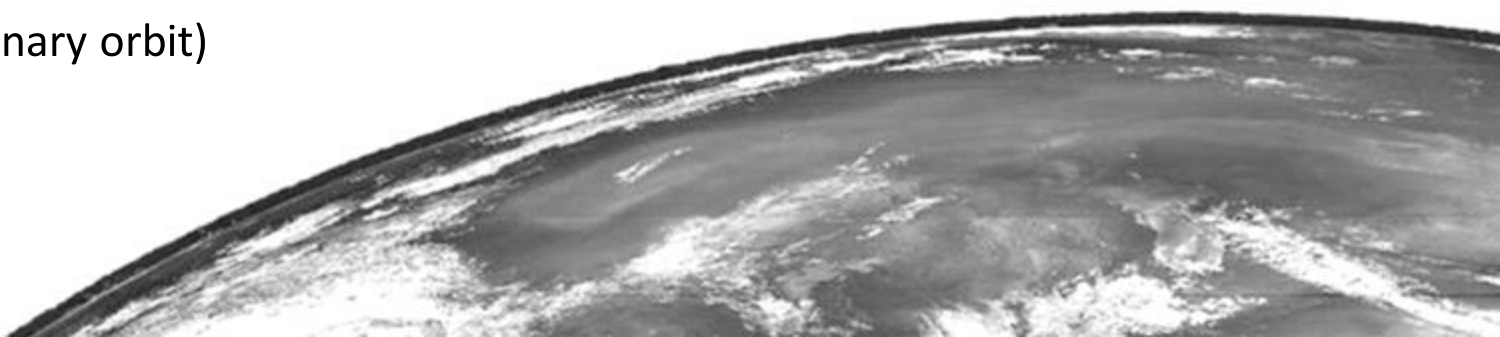


Field of Regard

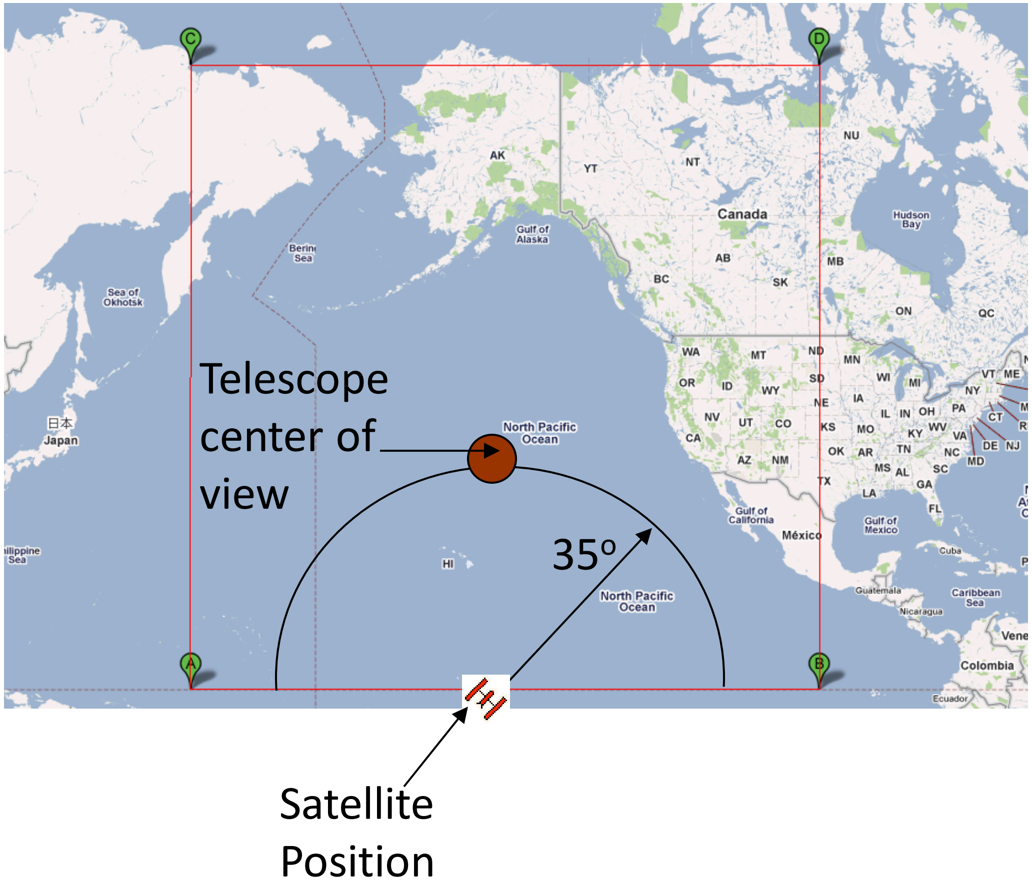


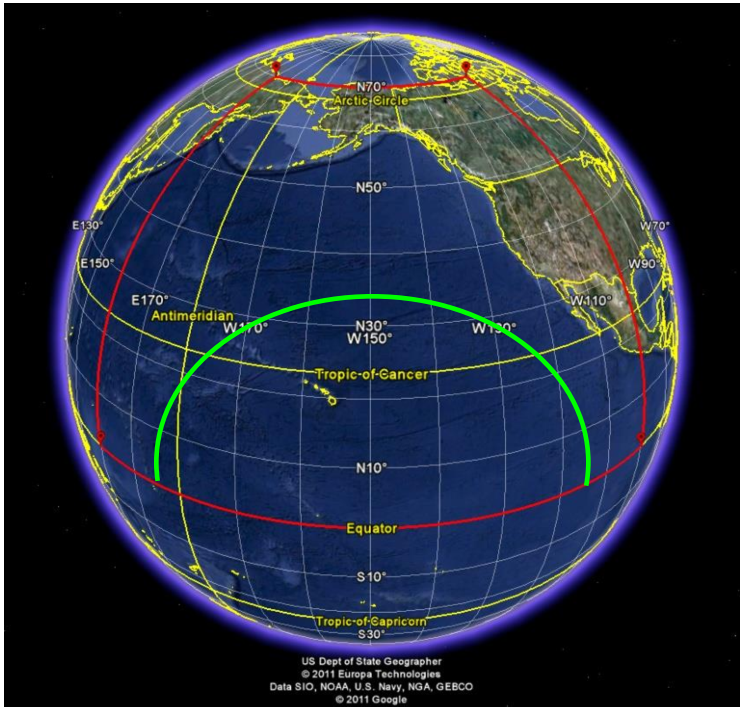
Satellite Position (Geostationary orbit)

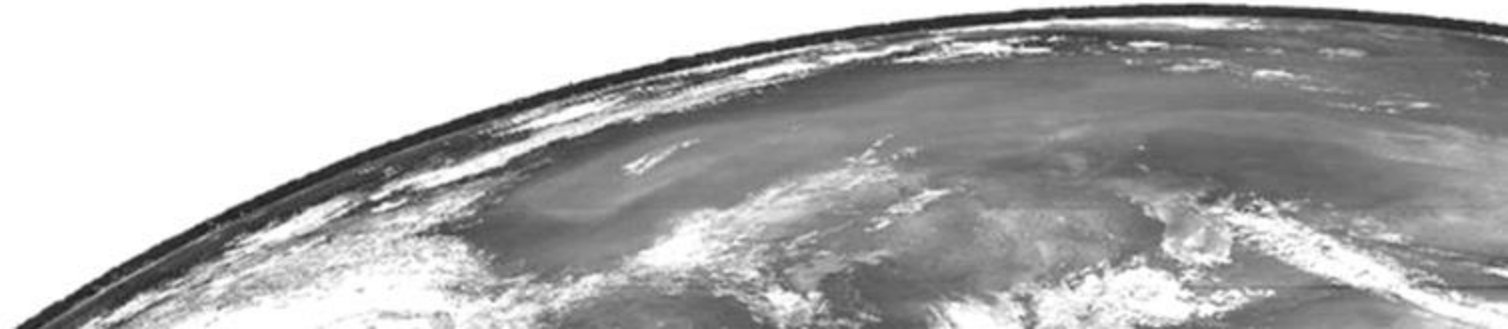




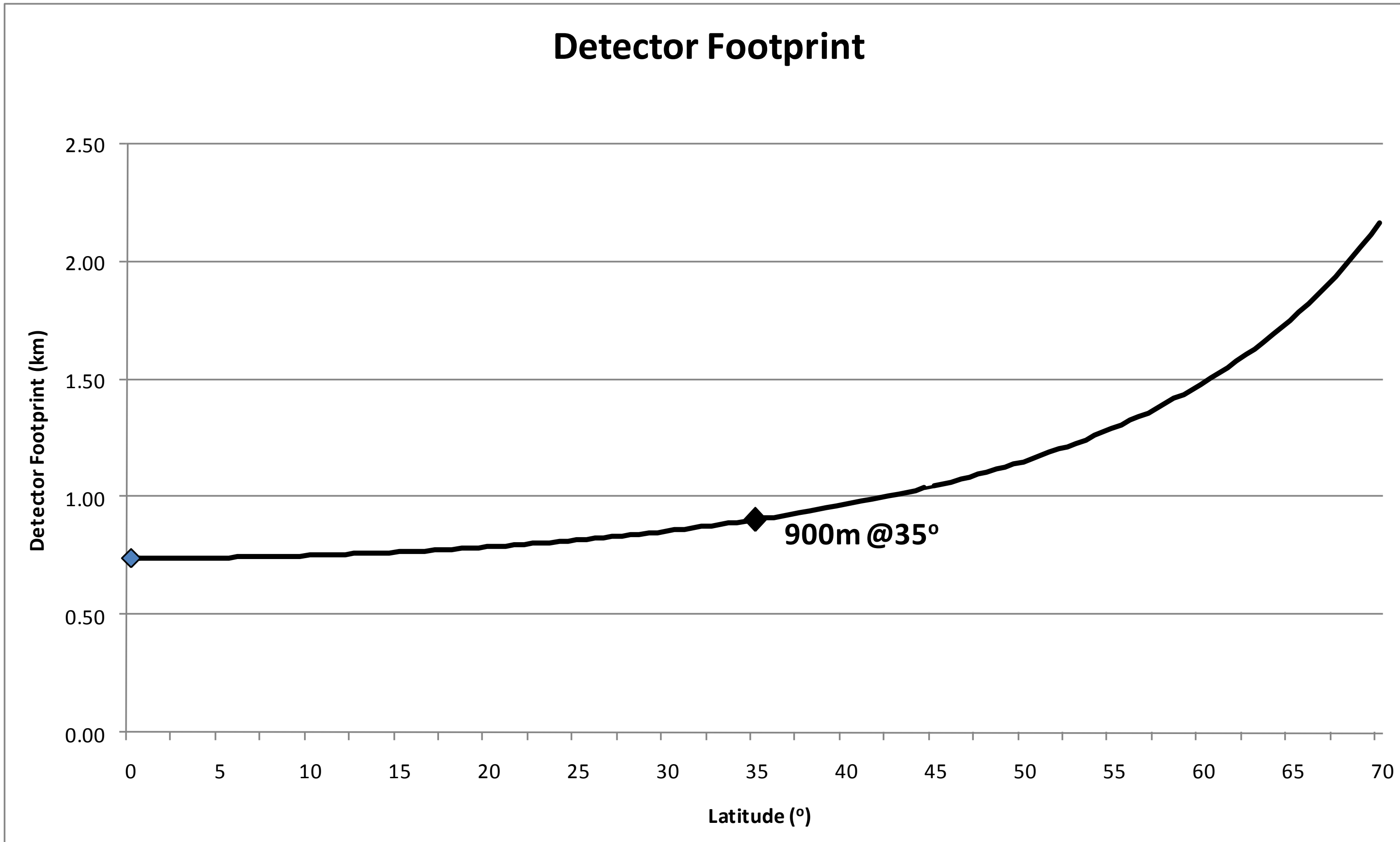
Reference Area

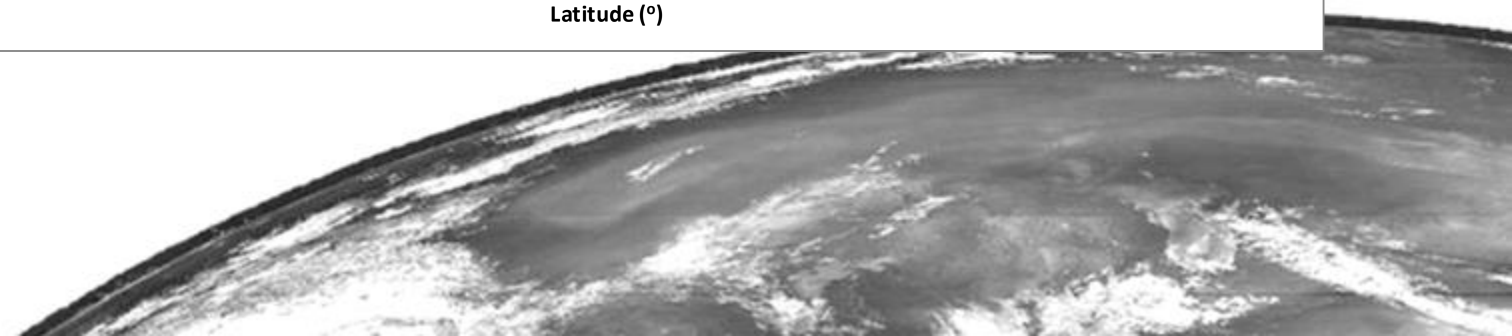




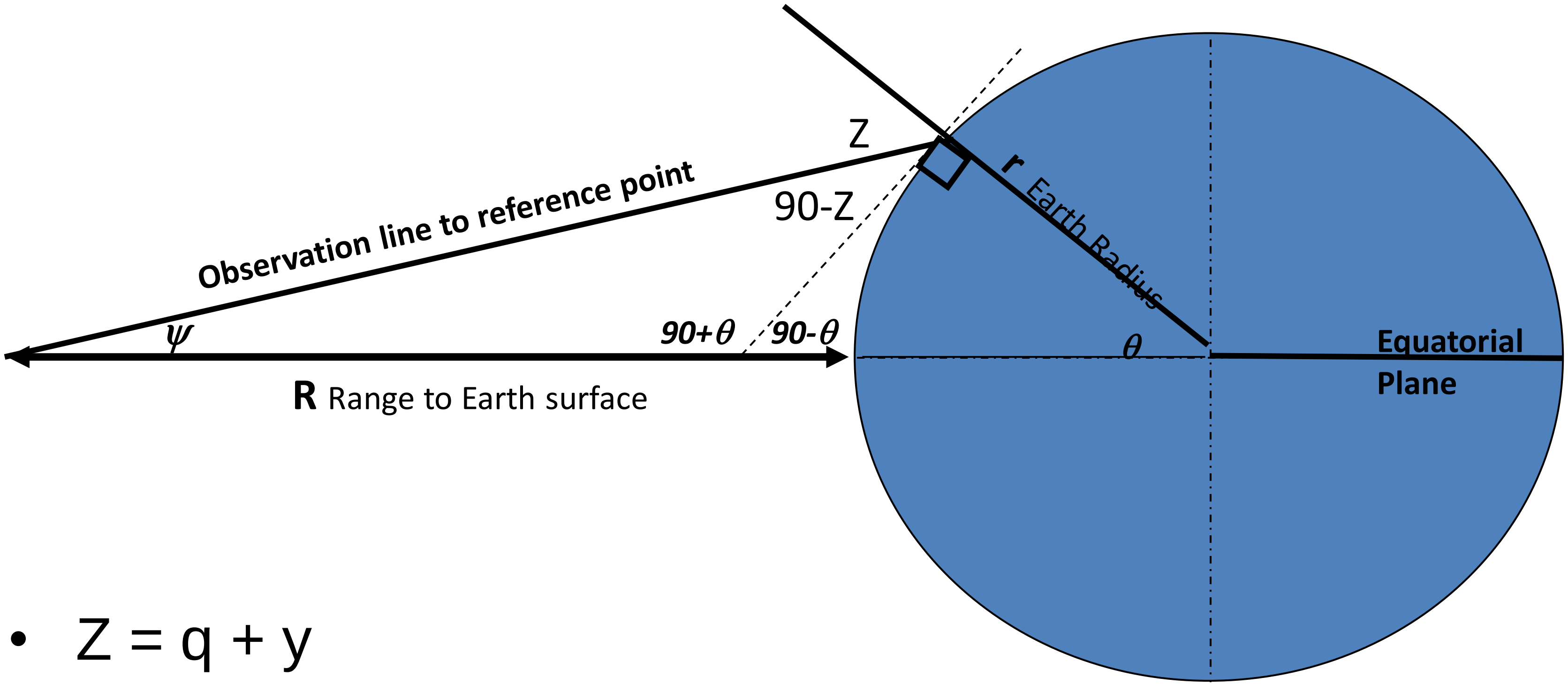


Detector Footprint

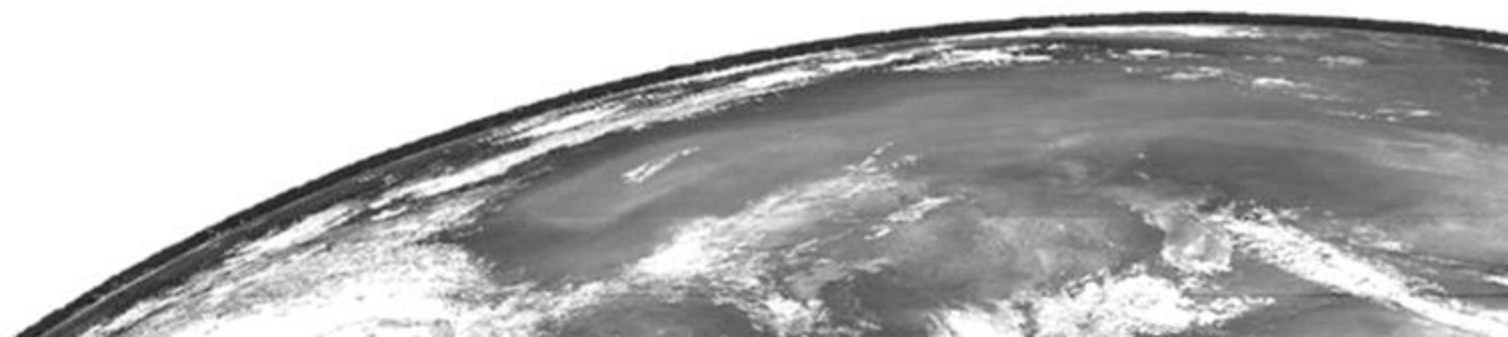




Zenith Angle



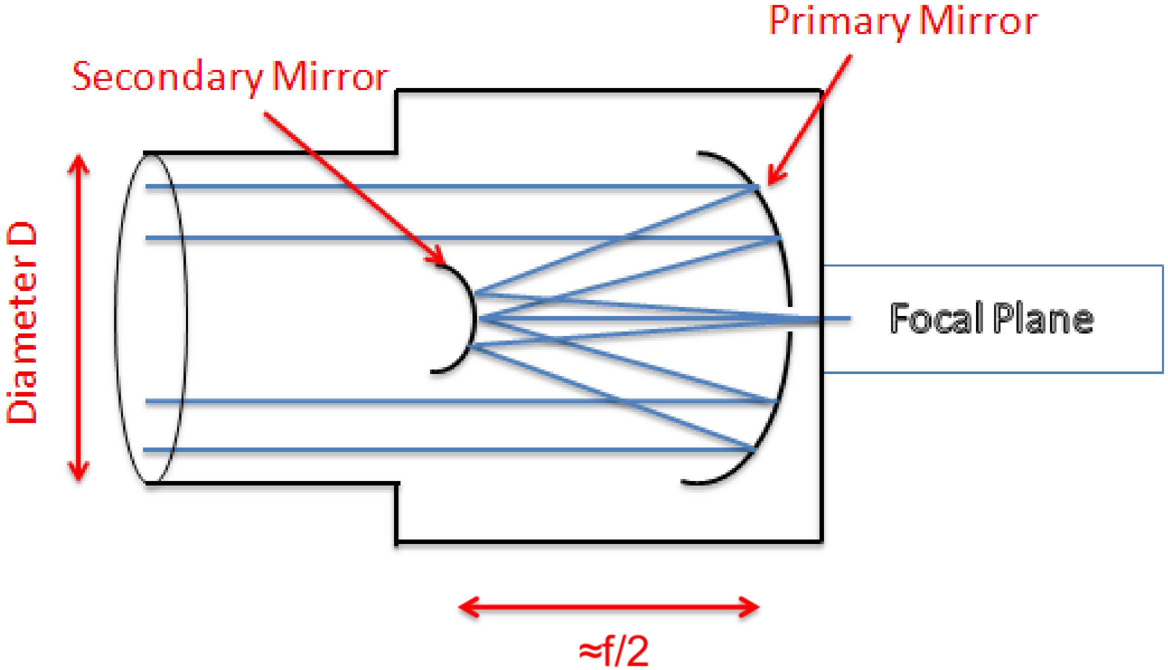
- Z = q + y
- $Z = 35^o + 5.22^o = 40.22^o \approx 40^o$



Telescope

Ritchey-Chretien Cassegrain

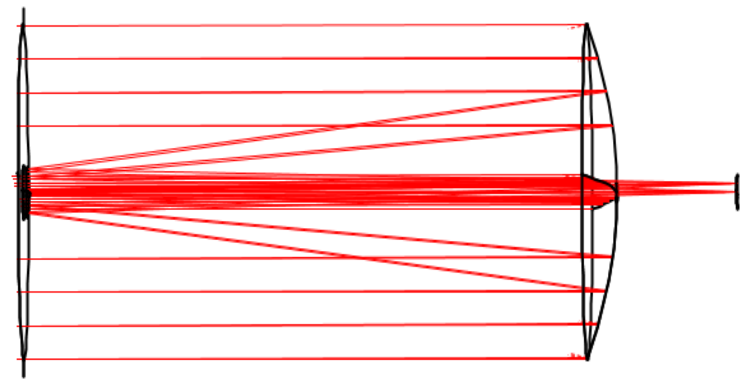
- Ad = 53.5cm
- f = 107cm
- F/2

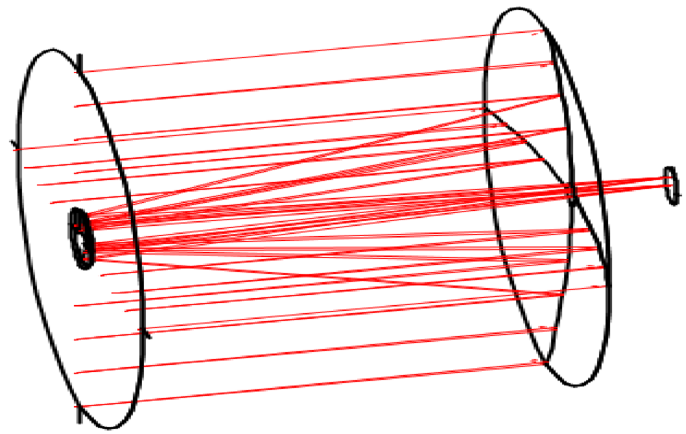


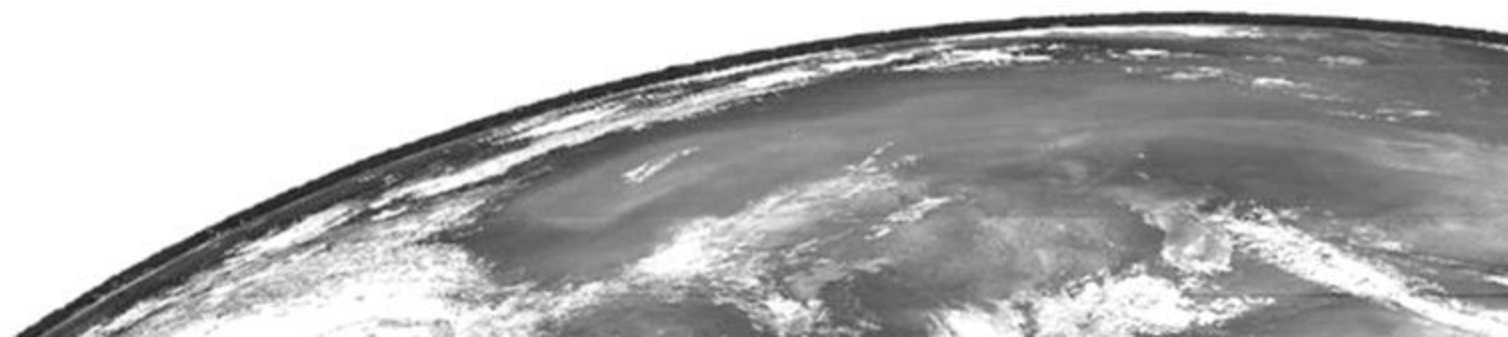
Telescope Ray Tracing

Software: BEAM FOUR

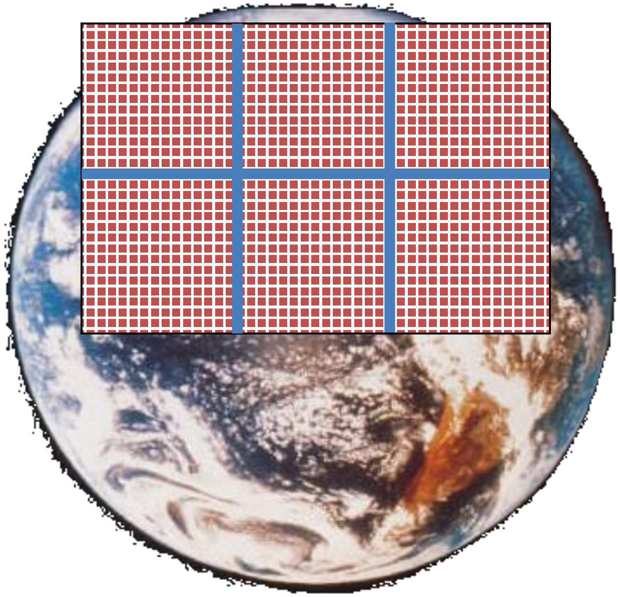
- Primary mirror
  - Curvature: -0.04
  - Diameter 50cm
- Secondary mirror
  - Curvature: -0.1428
  - Diameter 15cm





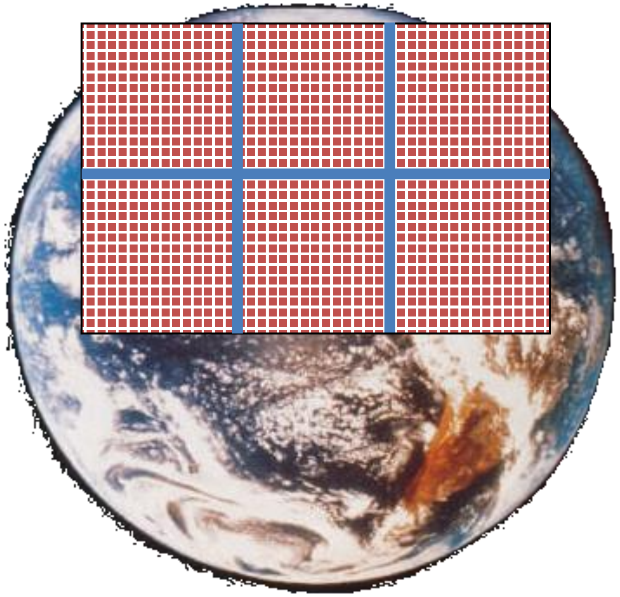


Starer CONOPS

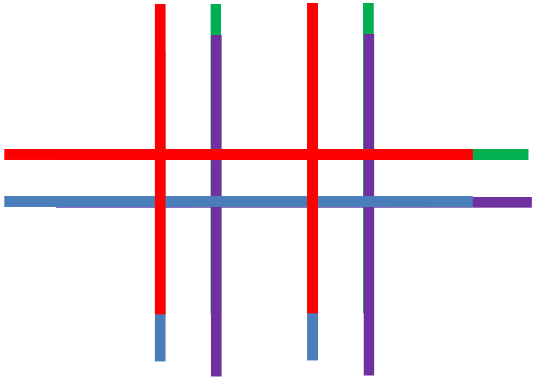


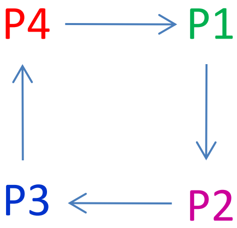
- Challenges
  - Mullion effect
  - Bandwidth
    - ~100 Mega pixels
    - 1.5Gbits/frame
- Solutions
  - Step stare
  - Frame rate of 2Hz
  - On-board processing
  - Image sampling

Step-Stare CONOPS

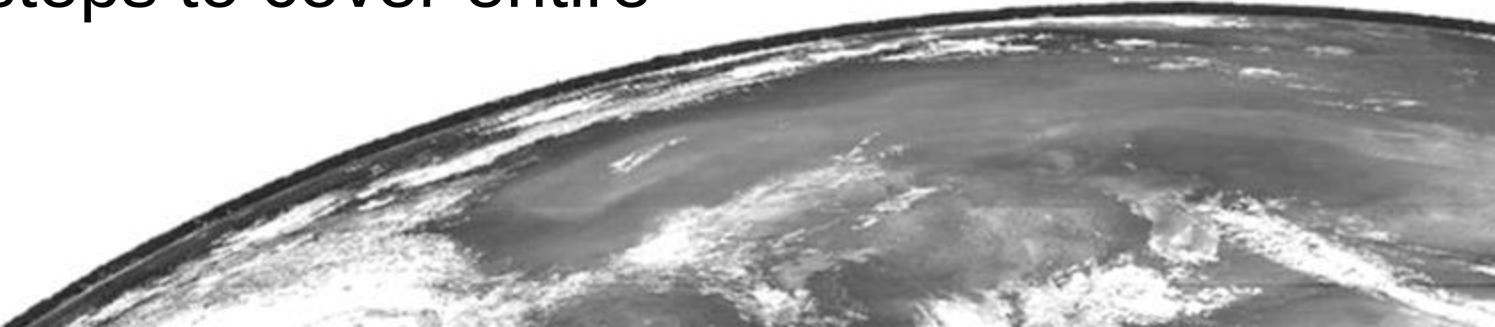


- Inherent Blind Spot
  - 1mm gap
  - 2% FOR Area
- Blind Spot coverage



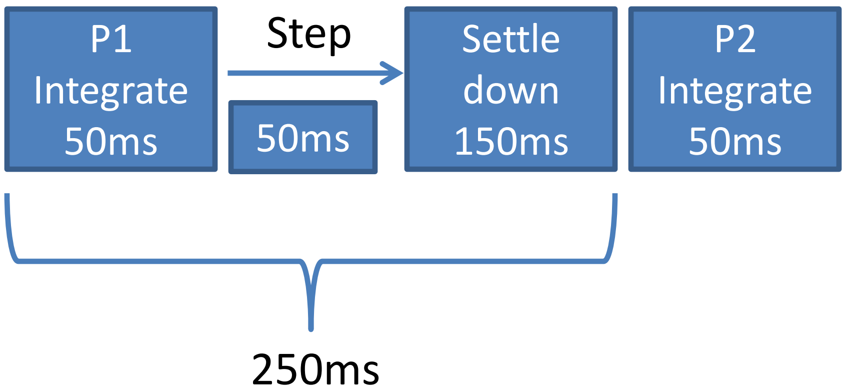


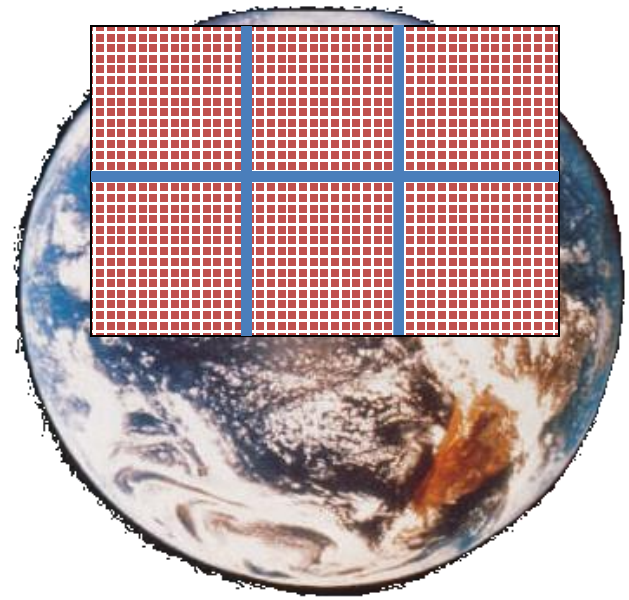
- Three steps to cover entire FOR



Step-Stare CONOPS

- Time Management





- Revisit time*
- Frame rate

500ms

*Effective Revisit Time = 750ms

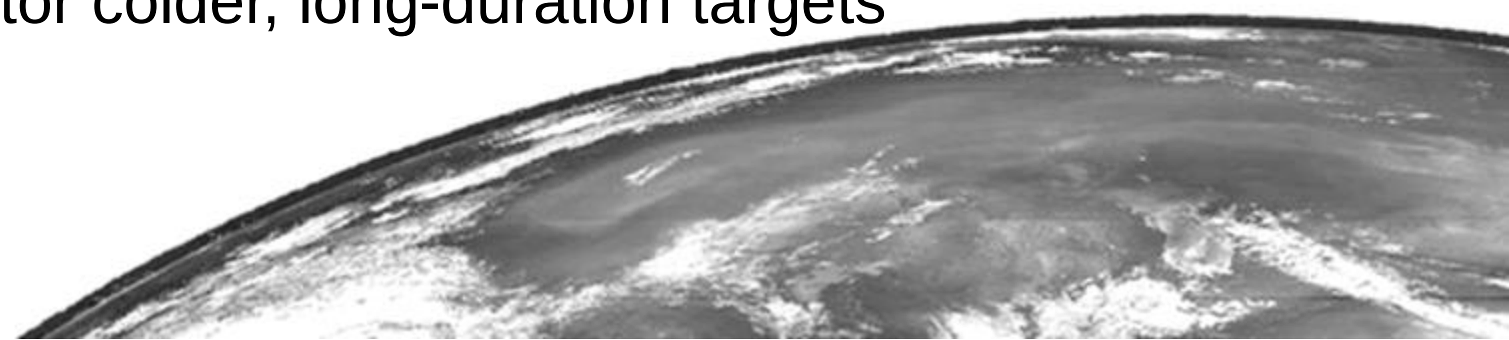
- Four points have a time delay from the rest of the image

Primary Array Deficiencies

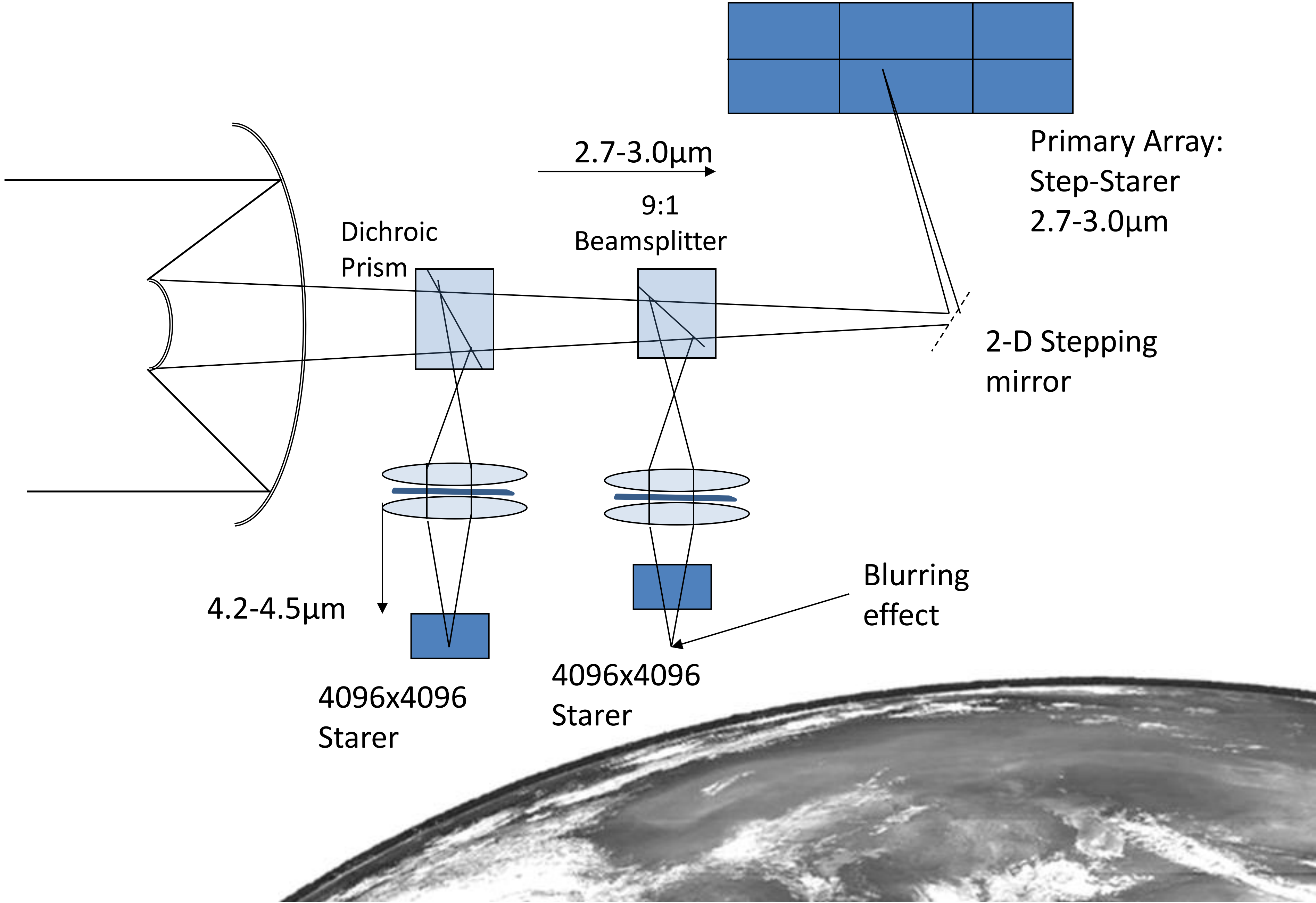
- 192 MB per frame requires lower frame rate
  - Laser would be missed
- 2.7-3.0μm band not receptive to colder targets
  - Oil Spill would be missed

Solution: Design secondary arrays

- "Passive" array
  - Watch for quick, bright targets
  - Transmit only if target is found
- 4.2-4.5μm array
  - Monitor colder, long-duration targets



Final Setup



2.7-3.0µm
Primary Array:
Step-Starer
2.7-3.0µm
9:1
Beamsplitter
Dichroic
Prism
2-D Stepping
mirror
Blurring
effect
4.2-4.5µm
4096x4096
Starer
4096x4096
Starer

Questions and Answers