Evaluation of Hyperspectral Snapshot Imagers onboard Nanosatellite Clusters for Multi-Angular Remote Sensing

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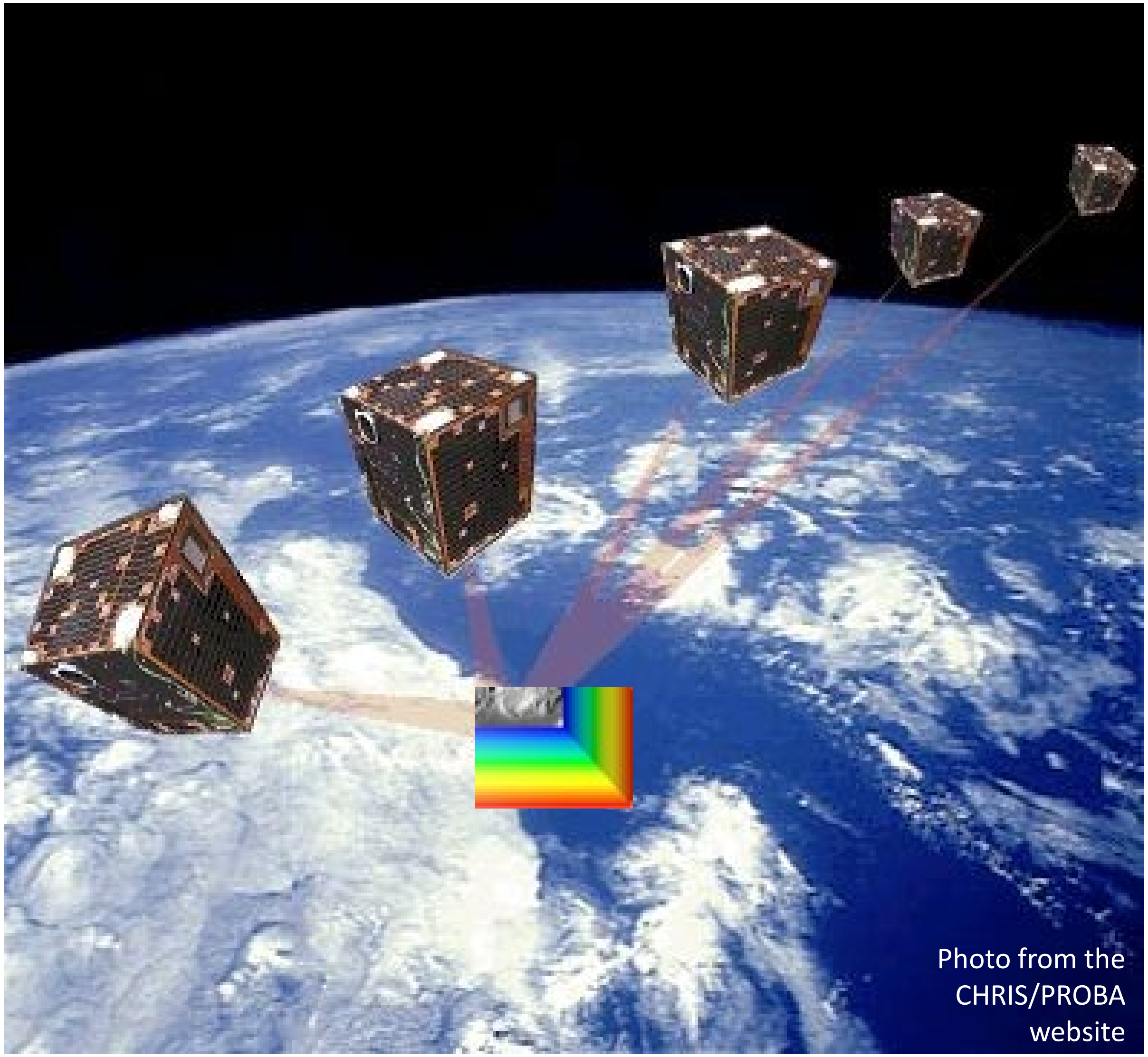
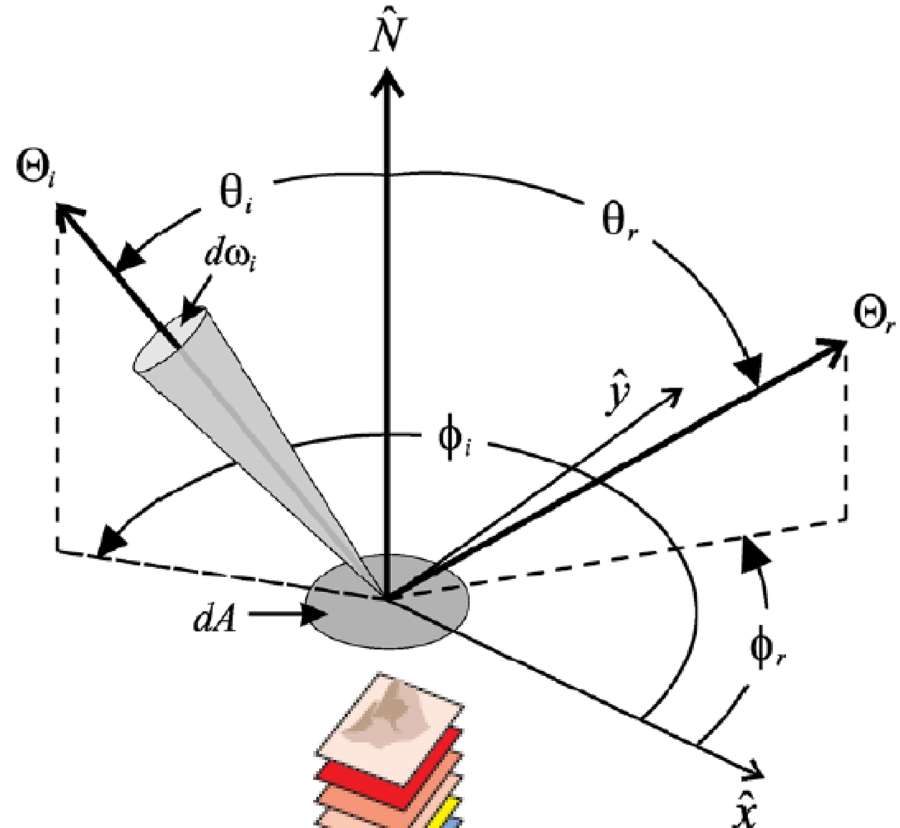
Introduction

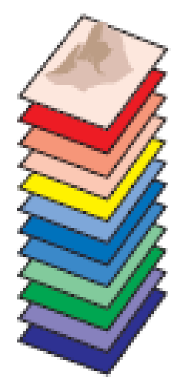
Multi-Angular, Multi-Spectral Remote Sensing of the Earth



Why Multi-Angular?

- Because reflectance values depend on the direction of solar illumination and direction of measured reflection
- Angular performance metric: Bi-directional reflectance distribution function (BRDF)
- Anisotropic (angle-dependent) and multispectral (near-solar spectrum) reflectance of clouds and ground surface
- $R\ (\Theta i, \Theta r, \phi i, \phi r, \lambda)$
- Angular sampling is inadequate using monolithic spacecrafts presenting an angular challenge





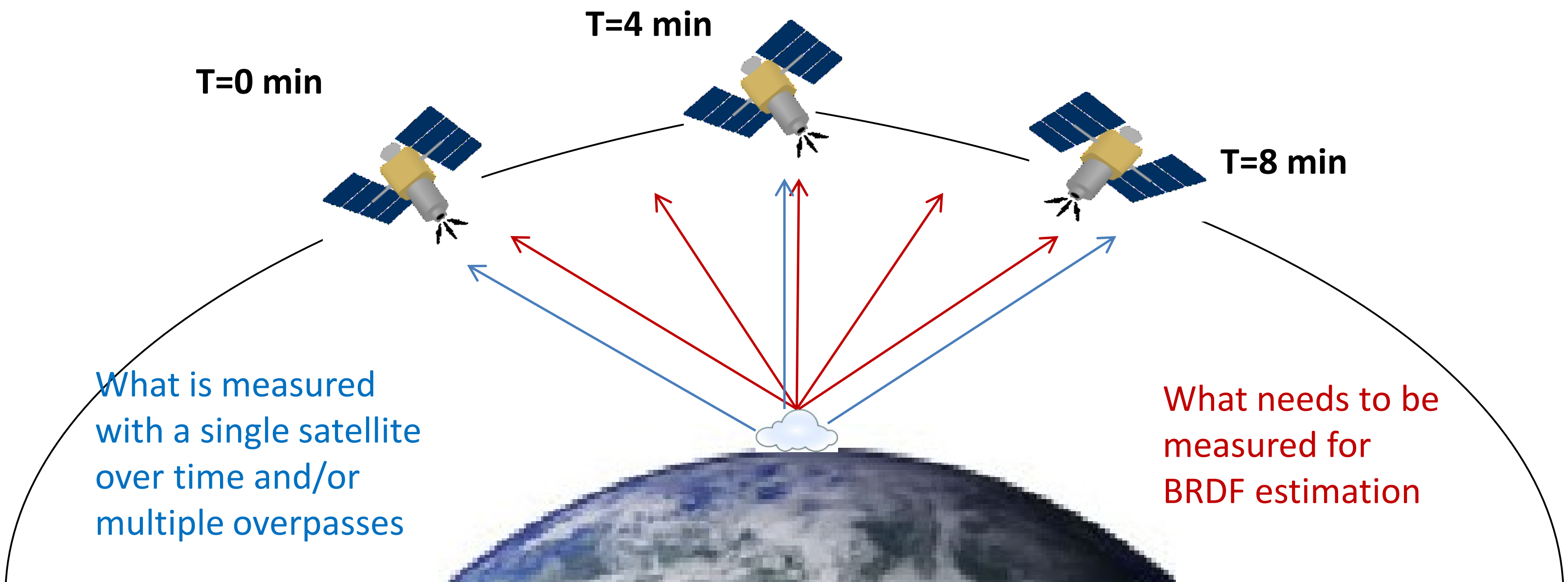
BRDF Ground Spot spectrum

Angular Challenge

BRDF Estimation by combining the consecutive measurements

Problem: 1. Restrictive plane with respect to the sun

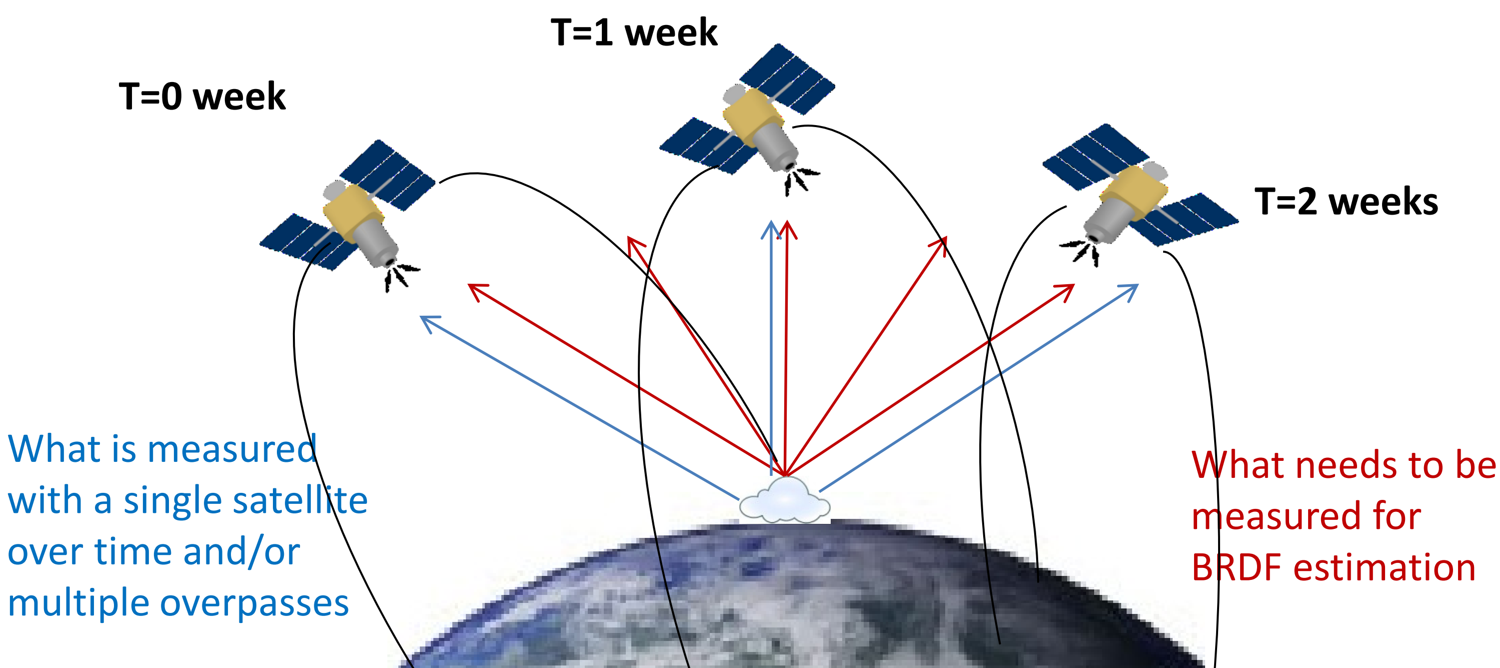
2. Up to 10 minutes between measurements



Angular Challenge

BRDF Estimation by combining measurements over consecutive overpasses

Problem: 1. Restrictive plane with respect to the sun
2. Up 2 weeks between measurements



BRDF Importance

BRDF effects on important applications such as **albedo** radiative forcing, gross primary productivity is stark

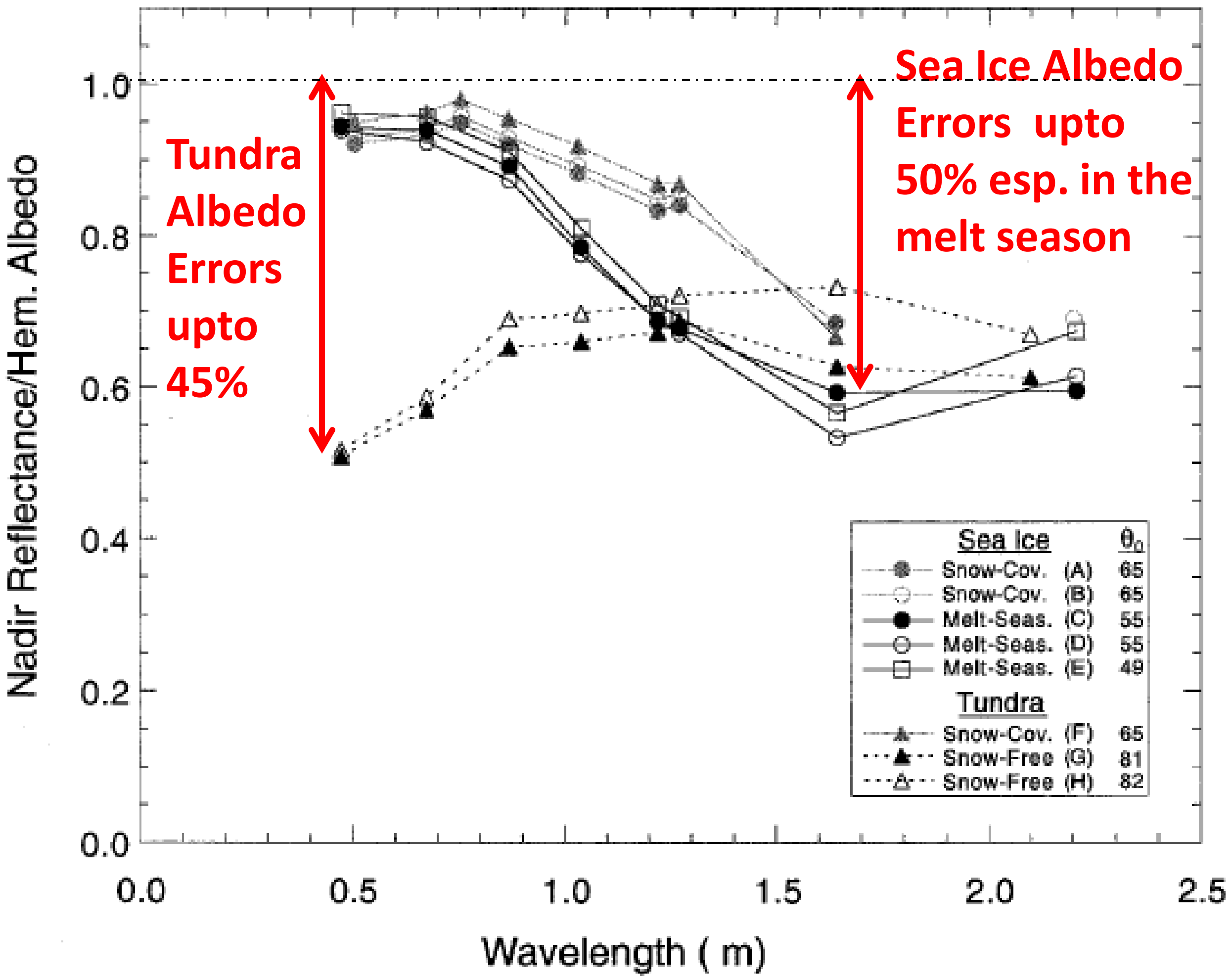


Image Credits: Arnold et. al, 2002

Figure uses thousands of angular measurement data from the airborne Cloud Absorption Radiometer taken during the ARMCAS campaign in 1998.

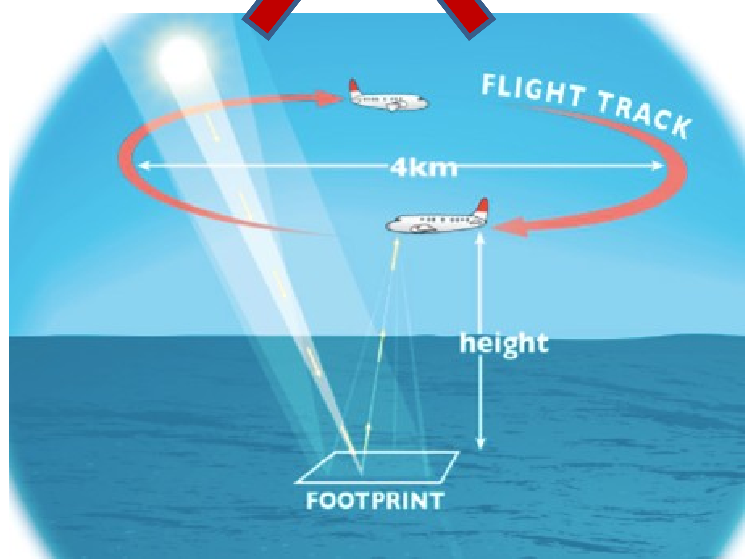
Monolithic Measurement Gaps

Airborne: Very accurate for local BRDF estimation
e.g. Cloud Absorption Radiometer (CAR)

BUT no global or continuous coverage, expensive to scale up area and time

Geometrical Requirements | **Spectral Requirements**

BRDF-Science Metrics →	Number of angles	Ground Pixel Size in km X km	Revisit [illegible]e (any view [illegible]ays	Spectral Range	# of spectral bands



Monolithic Measurement Gaps

Spaceborne: Angular coverage through Large swath or FOV[1], Fwd-Aft sensors[2], autonomous maneuverability[3]

BUT fall short in terms of science metric/s + nearing EOL

Geometrical Requirements | **Spectral Requirements**

BRDF-Science Metrics → / Current Instruments ↓	Number of angles	Ground Pixel Size in km X km	Revisit Time (any view) in days	Spectral Range	# of spectral bands
[1]MODIS	1	0.25 to 1	~2(16day RGT)	0.4-14.4 μm	36
[1]POLDER	14	6 X 7	~2(16day RGT)	0.42-0.9 μm	9
[1]CERES	1	10 to 20	~2(16day RGT)	0.3-12 μm	3
[2]MISR	9	0.275 to 1.1	9(16 day RGT)	0.44-0.87 μm	4
[2]ATSR	2	1 to 2	3-4	0.55–12 μm	7
[2]ASTER	2	0.015 to 0.09	~2(16day RGT)	0.52–11.65 μm	14
[3]CHRIS	5-15	0.017 to 0.5	As per command	0.415-1.05 μm	18-63

Filling in the Monolithic Gaps

Major Gap: Angular undersampling (θs,θr,ϕ)

Potential Solution: Clusters (NFOV) or constellations (WFOV) of nano-satellites

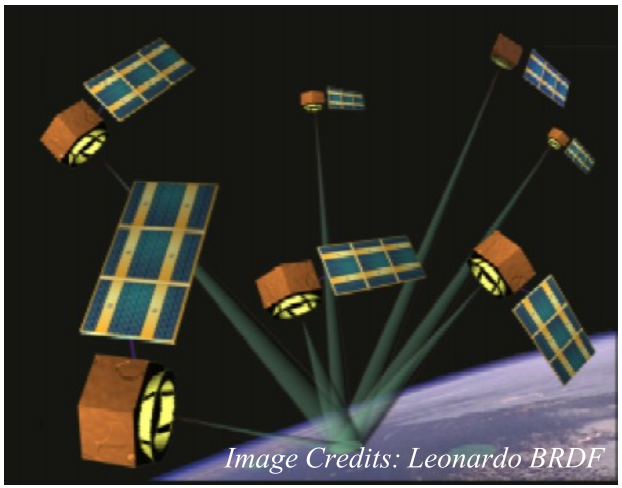


Image Credits: Leonardo BRDF

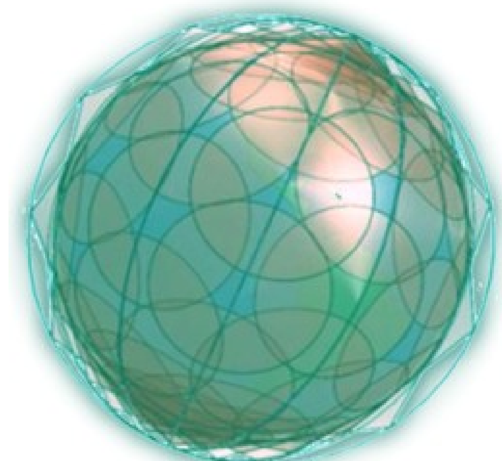
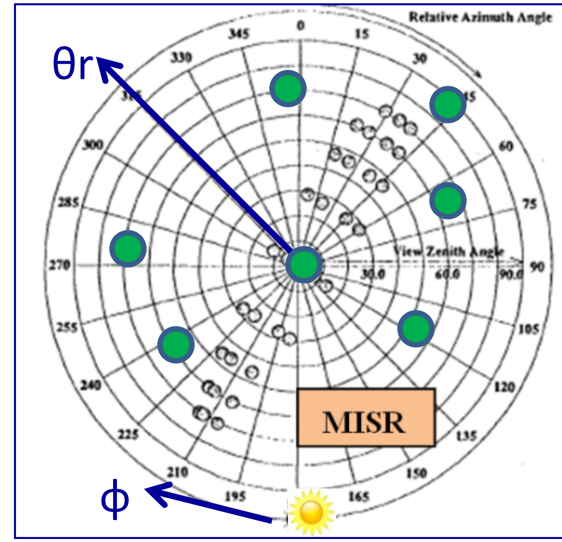
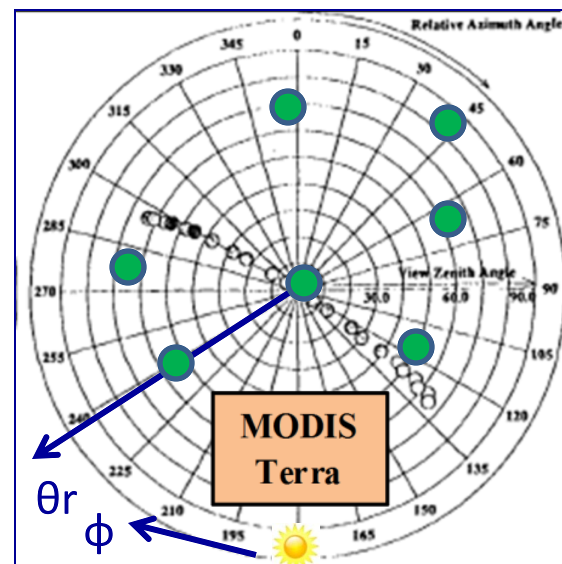


Image Credits: GEOScan





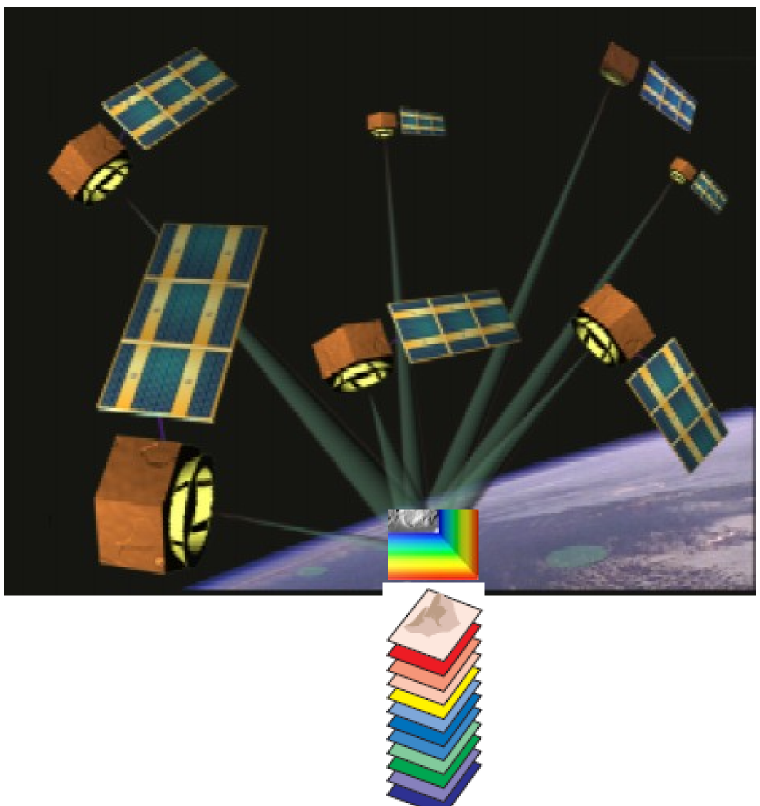
Additional advantages:- Small sats, 6U cubesats under development, Standard bus, Secondary payload launches, Cubesat GS network

Disadvantages:- Restrictive h-i combinations, mass/volume constraints

Filling in the Monolithic Gaps

Minor Gap: Spatial, spectral and temporal undersampling in some missions

Potential Solution: A mini VNIR spectrometer for the satellites that satisfies the spatial resolution, spectral range & resolution, RGT



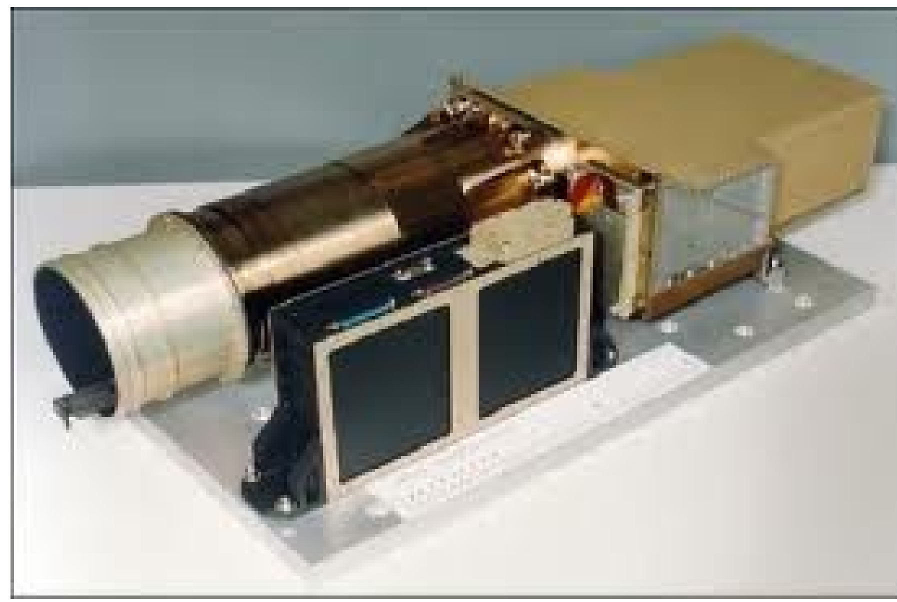


Image Credits: CHRIS on PROBA

Why Snapshot Imaging?

- Because of attitude determination and control challenges. Spectral requirement makes it 3D 92D spatial+1D spectral imaging)
- Pushbroom sensors in FF would miss the common ground spot if they have a zenith attitude error > sensor' iFOV

Pushbroom

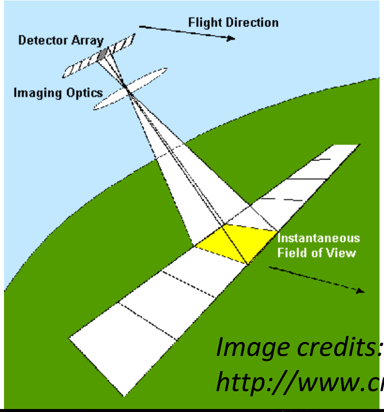


Image credits: http://www.crisp.nus.edu.sg/

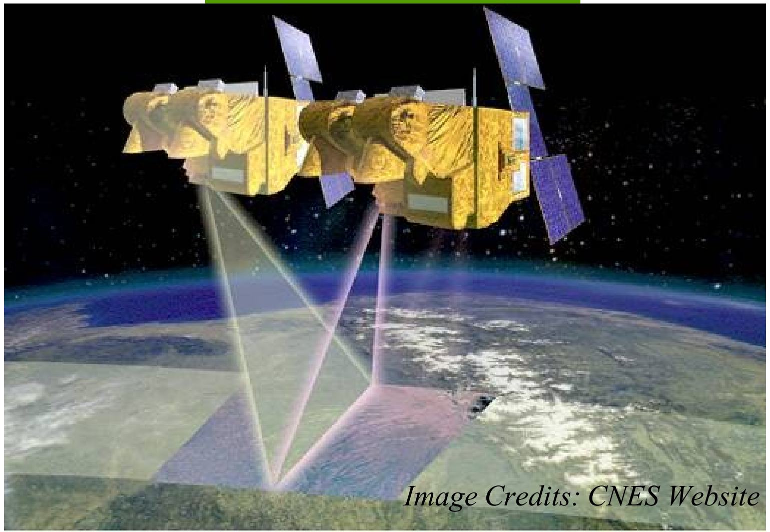


Image Credits: CNES Website

HSI

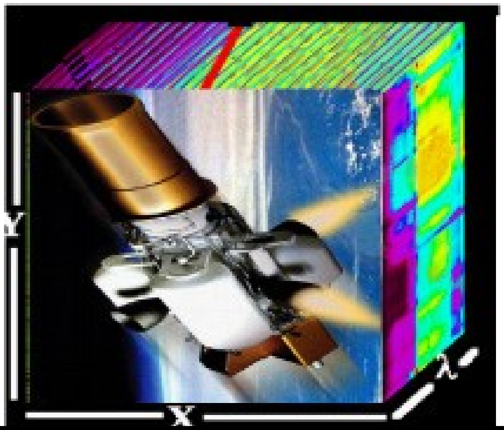


Image credits: http://computing.ornl.gov/

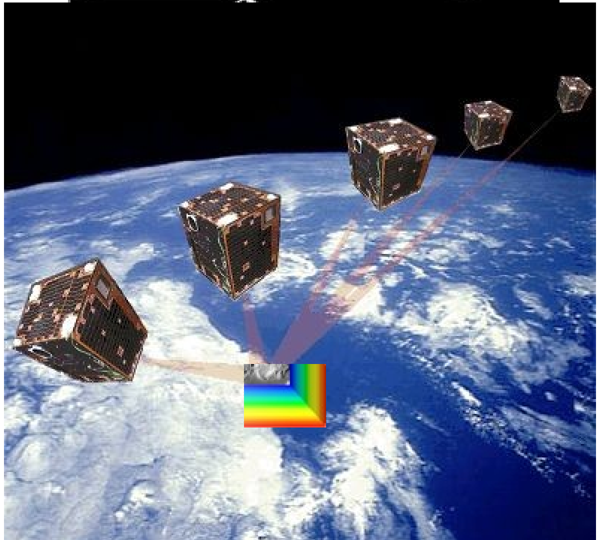
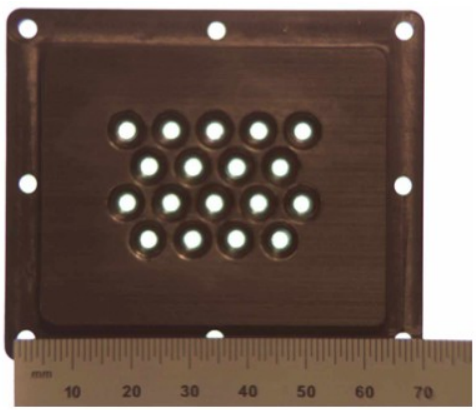
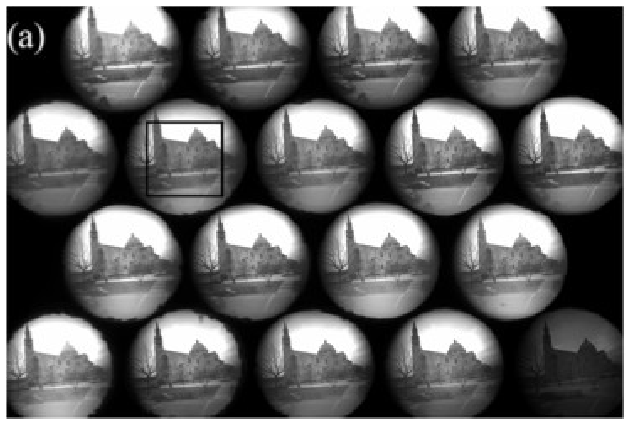


Photo from the CHRIS/PROBA website

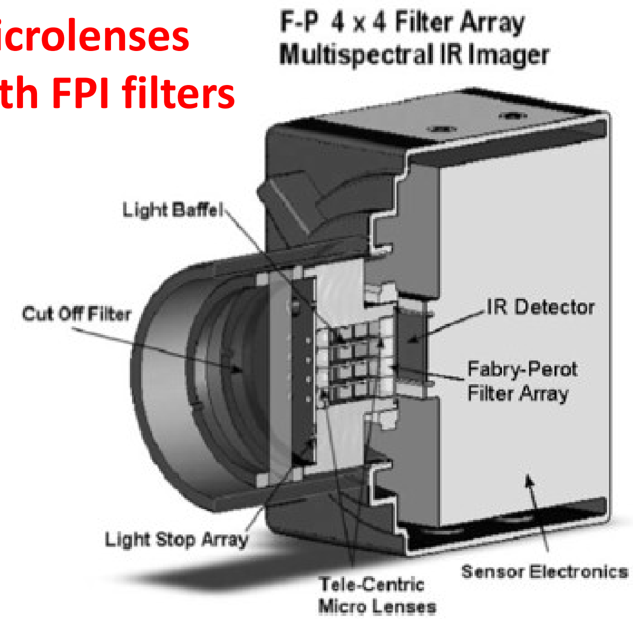
Existing HSI

Multiple Aperture Imaging

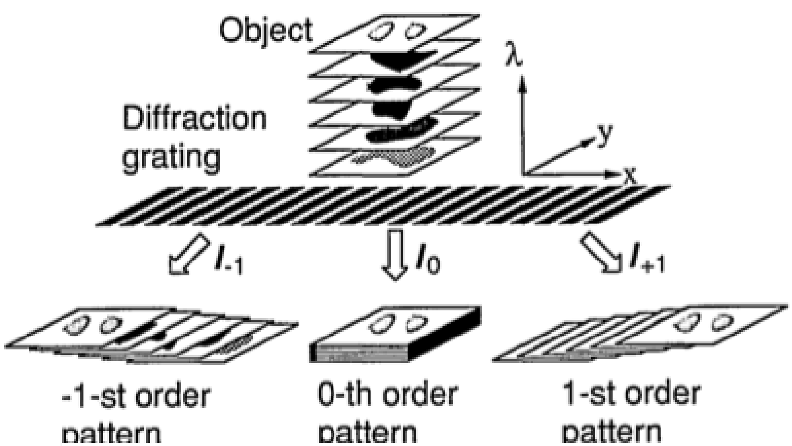




Microlenses with FPI filters

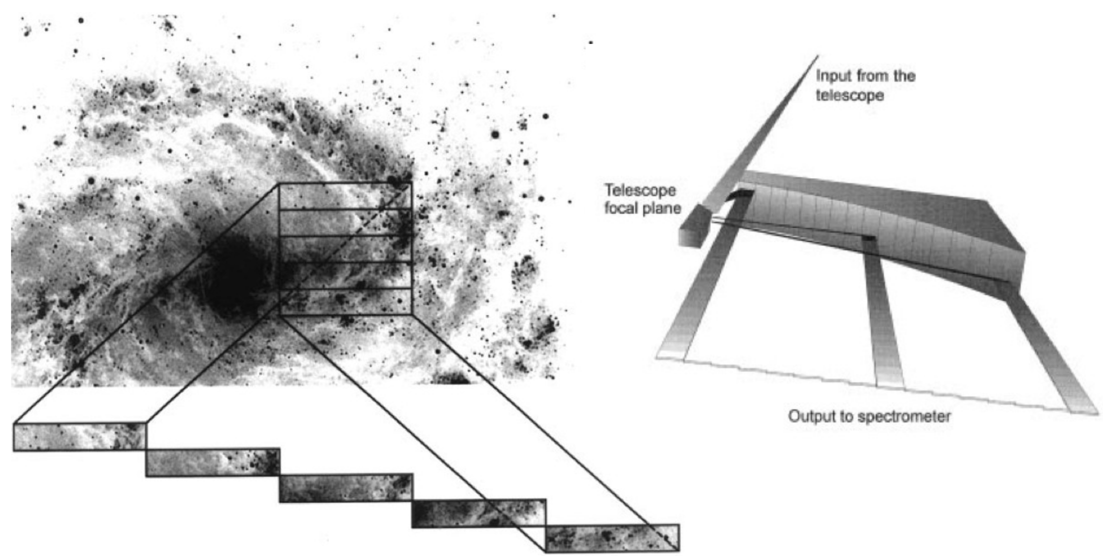


Tomographic Imaging



$$i(x, y) = \int_0^\infty b(\lambda)[o(x, y, \lambda) * g(x, \lambda)]\mathrm{d}\lambda .$$

3D Image Slicers using Grisms



Approach

Build a Systems engineering (SE) model integrated with traditional BRDF Estimation models to finalize the ideal cluster architecture, satellite design, subsystem design and primary instrument

BRDF Systems Engineering -SE- Model
(dependent on satellite subsystems)

Simulated measurements/ sampling of the BRDF function

agi
Software for Space, Defense & Intelligence

GCC

Errors in BRDF Estimation + other application specific metrics

BRDF Science Evaluation Model
(dependent on application)

Measurement Requirements from Science Traceability Matrix Goals Layer

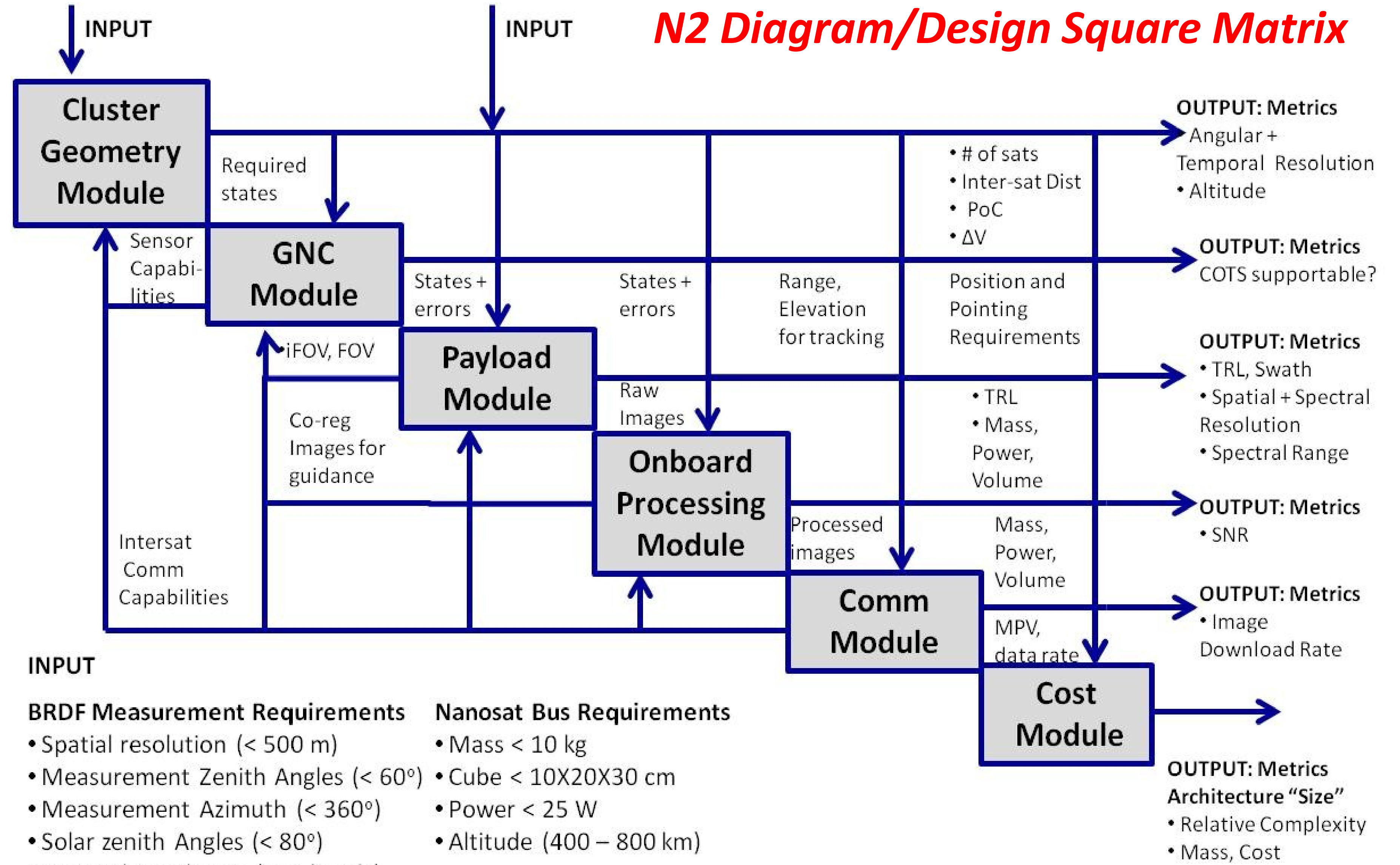
INPUT

Estimated BRDF + errors; other application specific metrics

OUTPUT

System Trades

N2 Diagram/Design Square Matrix



INPUT

BRDF Measurement Requirements
- Spatial resolution (< 500 m)
- Measurement Zenith Angles (< 60°)
- Measurement Azimuth (< 360°)
- Solar zenith Angles (< 80°)
- Spectral Resolution (>14 bands)
- Spectral Range (350-2300 nm)

Nanosat Bus Requirements
- Mass < 10 kg
- Cube < 10X20X30 cm
- Power < 25 W
- Altitude (400 – 800 km)

Payload Summary

Preliminary design of a VNIR Imaging spectrometer for a nanosatellite to fit the BRDF spectral and spatial requirements

I. External System Requirements

Ground Pixel Length
Boresight angles
Altitude
Wavelengths
Number of detector pixels
F-Stop Number (F#)
Number of bands
Attitude Pointing Errors
Solar zenith angles

System Trades

II. Payload System Requirements

Waveband ranges
Aperture diameter
Focal length
Pixel sizes, FPA size
Radiometric resolution
Well depths
Noise allowed
Integration Time

System Trades

IV. Spectral Element Customization

4 competent instruments identified
Compared by resource and performance metrics
Calibration summarized and Risks Assessed

System Trades

III. Payload System Performance Metrics

Number of Wavebands
Swath
Signal-to-Noise Ratio (SNR)

System Trades

External System Requirements

1. *Ground Pixel Length (<500m)*
2. *Boresight angles (<60°)*
3. *Solar zenith angles (<80°)*
4. *Altitude (500 to 800 km)*
5. *ADCS Pointing Errors*
6. Wavelength (<4 ranges: .35-2.3um)
7. Number of bands (>14)
8. Number of detector pixels (<4m pix)
9. F-Stop Number (F# 0.5 to 4)
10. Other Nanosat bus requirements from N2 diagram

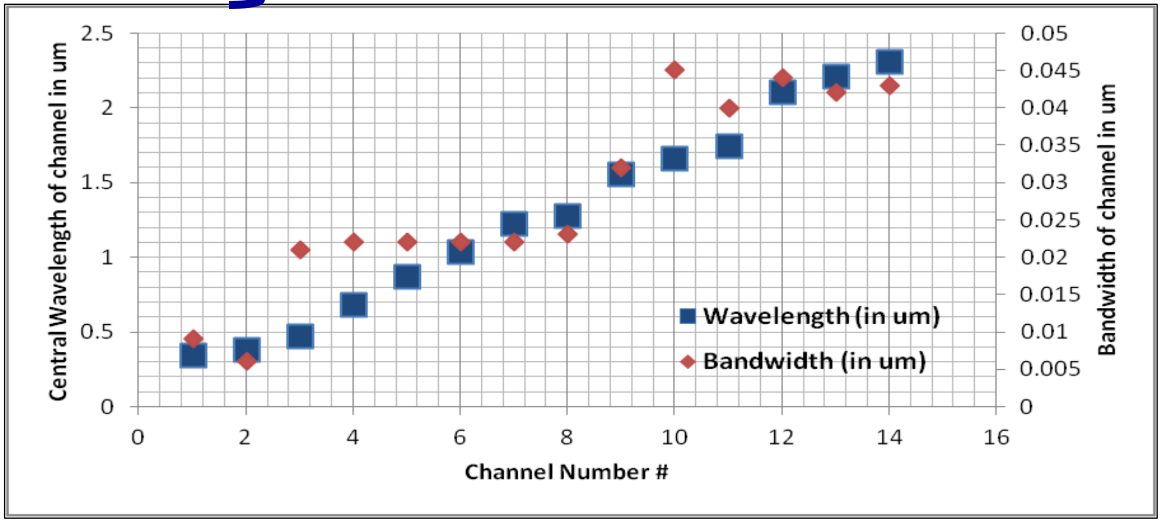
Outputs from the Cluster Geometry Module optimized from BRDF science requirements

Output from the ADCS Model

BRDF science requirement

Typical Nanosatellite capabilities

Spectral characteristics of the airborne Cloud Absorption Radiometer:



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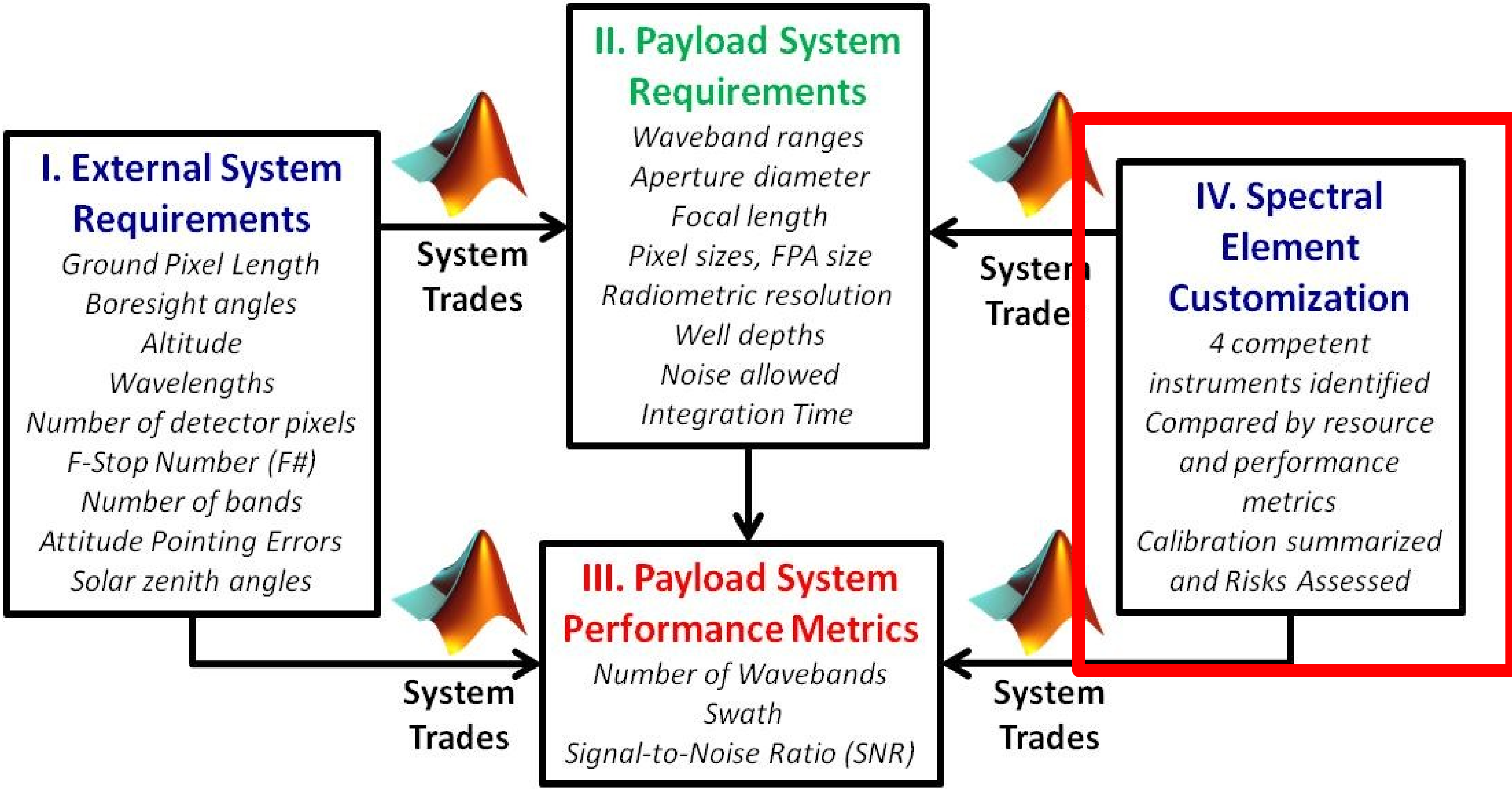
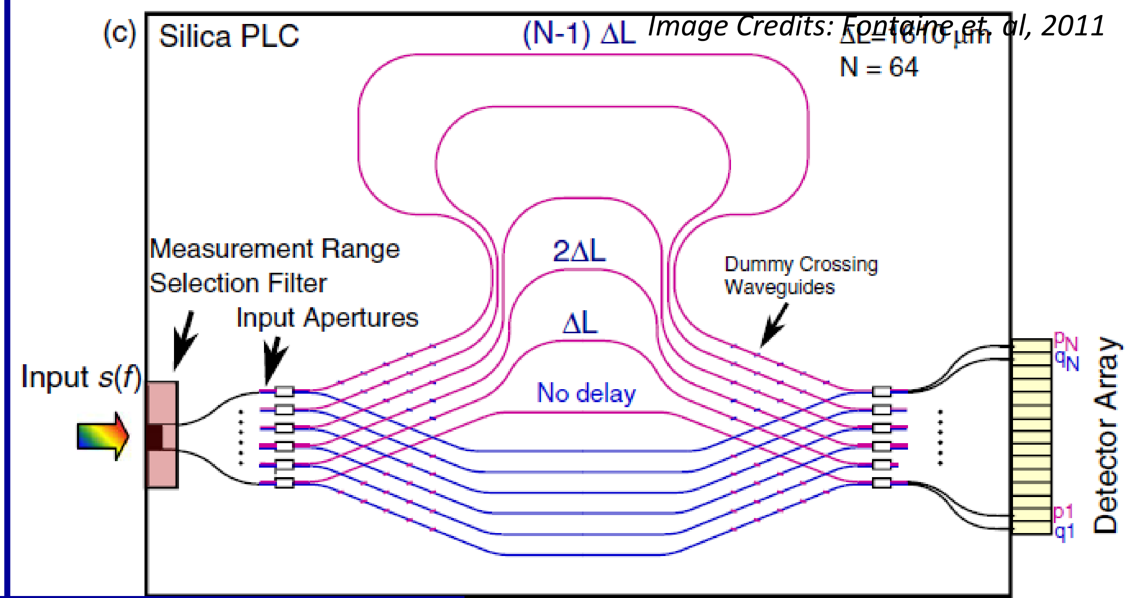


Spectral Element Customization

Proposed Designs based on:

1. Payload subsystem requirements from modeling external inputs
2. Literature Review of matrix (3D) dispersers
3. Nanosatellite Bus Requirements

Image Credits: Fontaine et. al, 2011



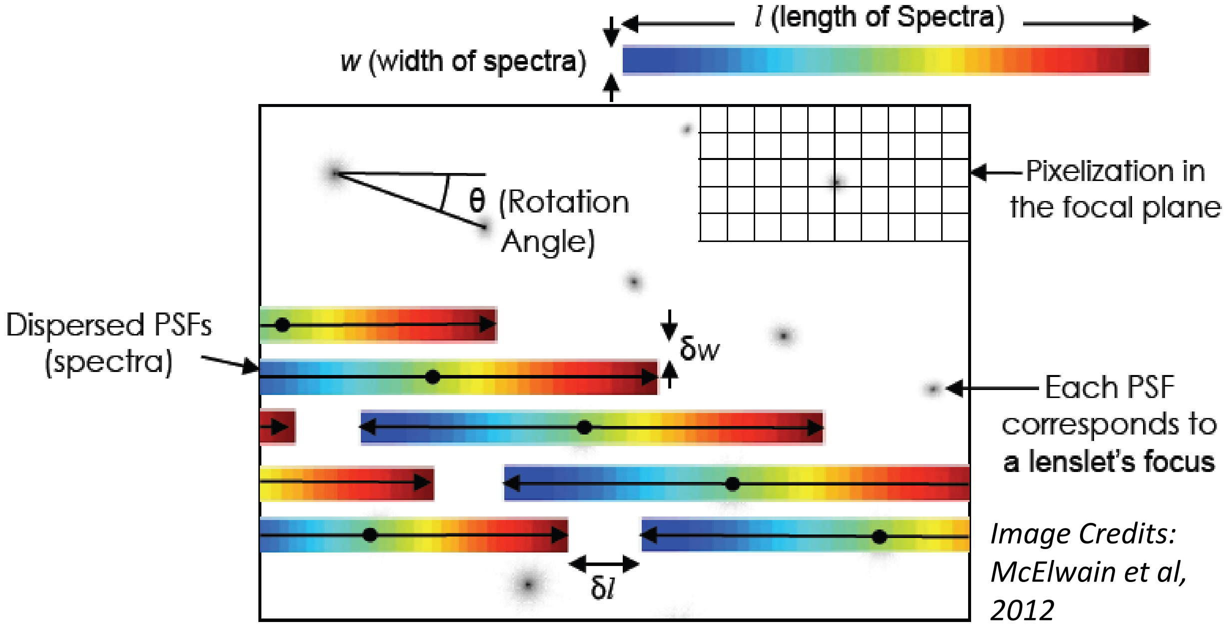


Image Credits: McElwain et al, 2012

Waveguide Spectrometers (WG FTS)

172 waveguides, A chip of 12 mm X [18.75 mm, 15 mm, 47.95 mm, 33.3 mm] X 1 mm per pixel << 1 cube per wavelength range, Electronics < 0.7 kg

Integral Field Spectrograph (IFS)

Spatial pixel => 35 X 6 detector pixels

Spectral Element Customization

Proposed Designs based on:

1. Payload subsystem requirements from modeling external inputs
2. Literature Review of matrix (3D) dispersers
3. Nanosatellite Bus Requirements

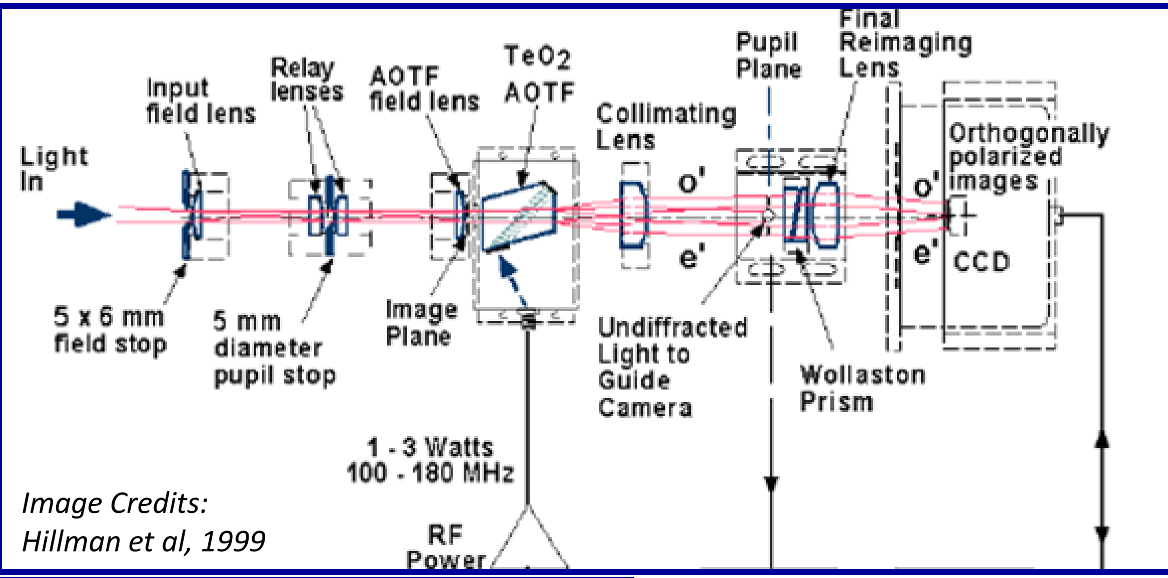
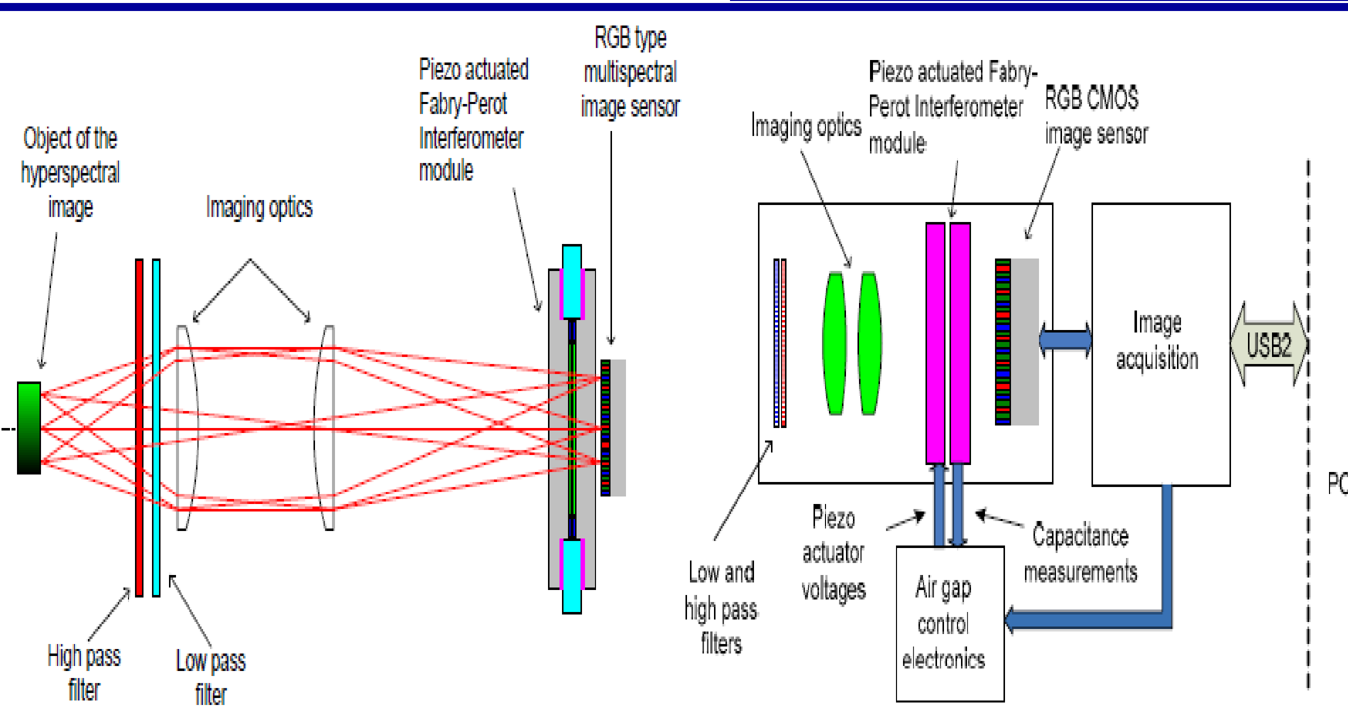


Image Credits: Hillman et al, 1999



Acousto-Optic Tunable Filters (AOTF)

Transducer Power < 1 W for TeO2, Time per image < 12 m of movement, Optical unit ~ 1.2 kg X 2 + 0.7 kg of electronics < 5 kg

Electronically actuated Fabry Perot Inferometers (FPI)

Range=400 – 1100 nm @ <1 nm. Tuning time<2 ms, FOV upto 20^{o}, fits within 110 mmX75 mmX55 mm, < 350 g, <3W.

Spectral Element Customization

Qualitative comparison between the dispersive elements chosen:-

- Relative weights assigned: score of [1, 0.5, 0] for every [green, yellow, red] box, all metrics equally weighted and summed
- AOTFs at 65%, waveguides at 60% , FPIs at 55% and IFS at 35%.

Spectrometer Types in terms of Dispersive Elements:	**Waveguide Spectrometers** [47]	**Acousto-Optic Tuning Filters** [27]	**Integral Field Spectrographs** [54]	**Tunable Fabry-Perot Inteferometers** [29]
Dispersive Element Resource Metrics:				
Mass	Medium	Low	High	Low
Volume	High	Medium	Medium	Medium
Power	Low	High	Low	High
TRL	Low	High	Medium	Medium
Dispersive Element Performance Metrics:				
Required Num of pixels	Medium	Low	High	Low
Susceptible to aberrations	Medium	Low	High	Low
Resolution per aperture	High	Medium	Low	Medium
Optical Throughput	High	Medium	High	Medium
Polarization Measurement	Medium	High	Low	Low
Spectral Range	High	Low	Medium	Medium

System Trades

Design Variables:

1. *Ground Pixel Length*
2. *Boresight angles*
3. *Altitude*
4. Wavelength
5. **Detector pixels #**
6. **F-Stop Number (F#)**
7. **Spectral Element + Detectors**
8. **Number of wavebands**
9. Attitude Pointing Errors
10. *Solar zenith angles*

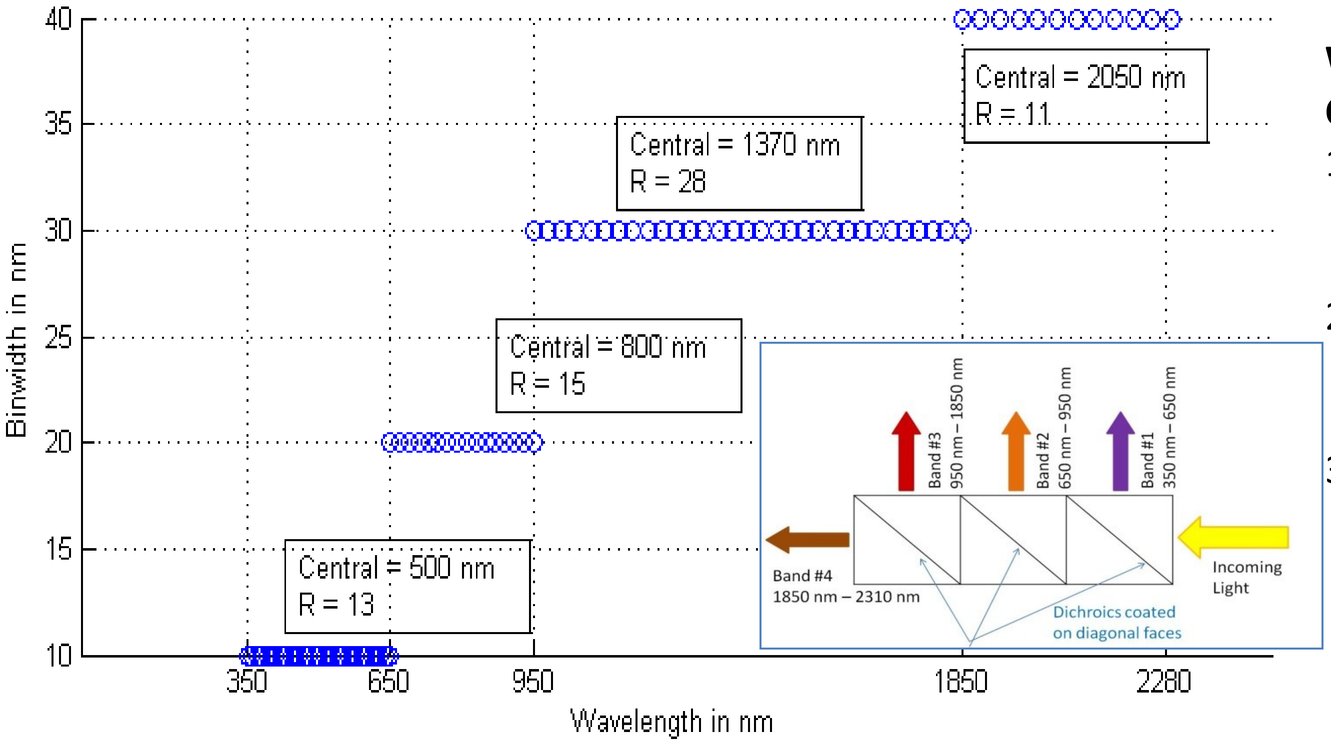
- Payload System Performance Metrics in Red

- Optical System Requirements in green

System Trades: Wavebands

Wavelength Bands:

Band #	Wavelength lower bound (nm)	Wavelength upper bound (nm)	Central Wavelength (nm)	Binwidth (nm)	Number of Bins
1	350	650	500	10	30
2	650	950	800	20	15
3	950	1850	1370	30	28
4	1850	2310	2050	40	13



Waveband Selection Constraints:

1. Free spectral Ranges of consecutive bands should not overlap
2. Same detector type should be able to read one entire bad
3. Radiometric Range of photons received over each waveband should be detectable

System Trades

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1. *Ground Pixel Length*
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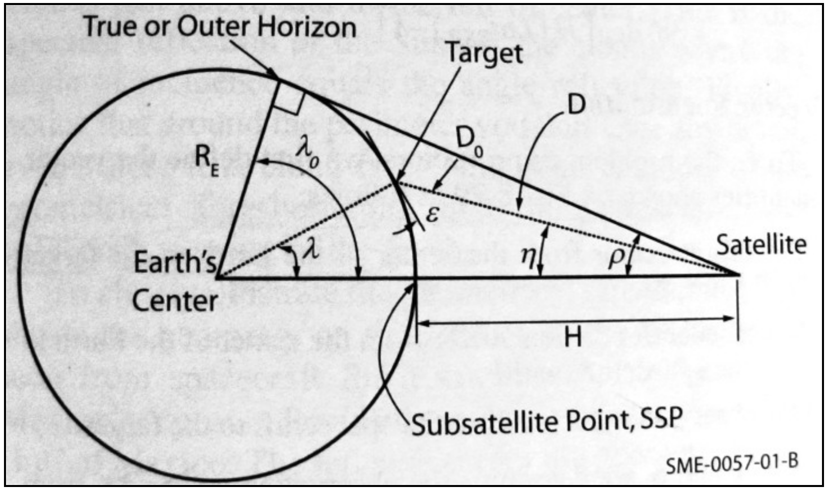
Ground Pixel Length → Instantaneous Field of View

Boresight angles, Altitude → Slant height → Instantaneous Field of View



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Instantaneous Field of View

Slant height

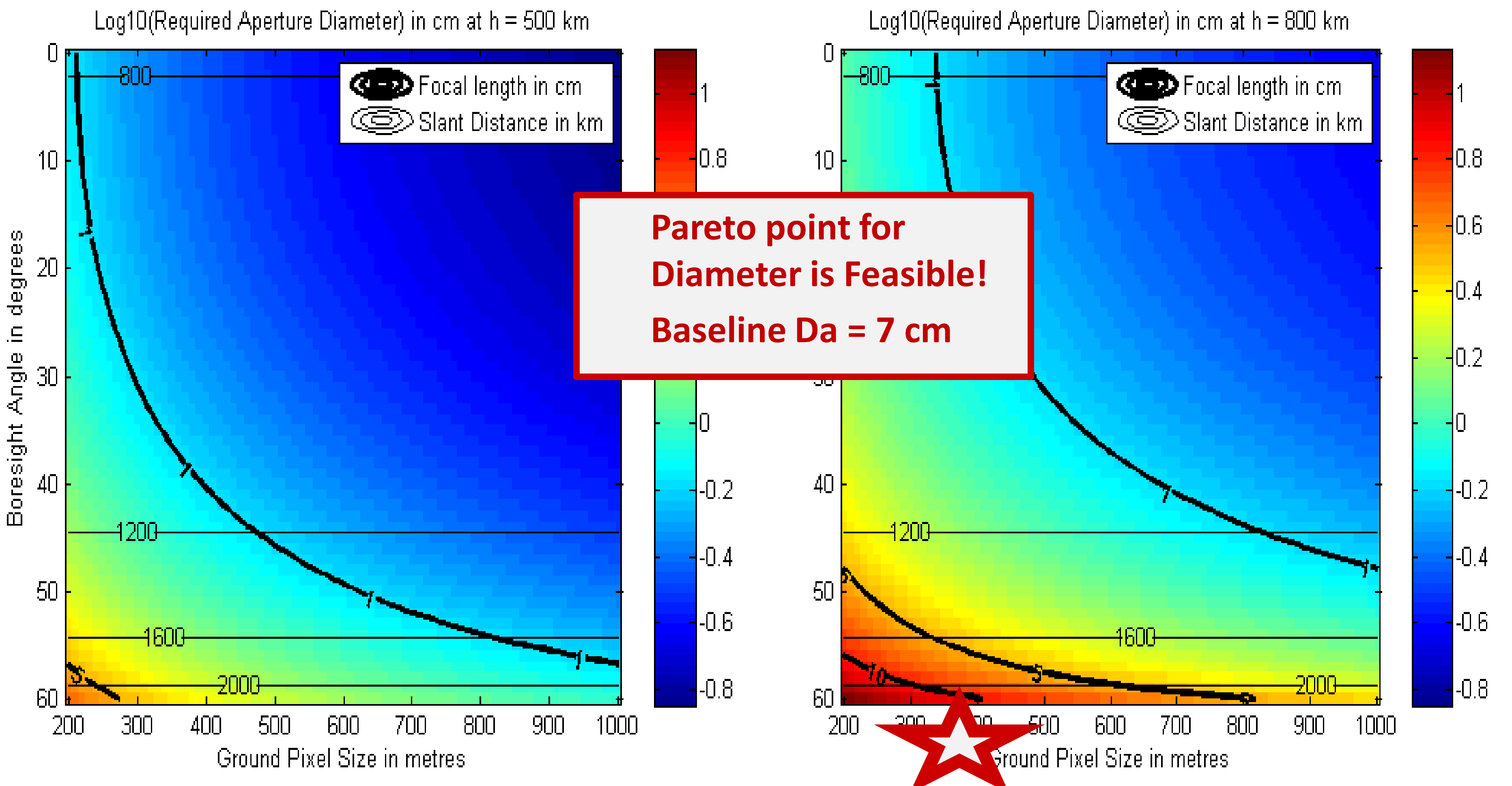
Aperture Diameter

- Payload System Performance Metrics in Red

- Optical System Requirements in green

System Trades: Optics

Dependence of optical front end requirements (aperture diameter, focal length) **on cluster geometrical parameters** (altitude + look angle => slant height, ground resolution). **Constant F#** = 1.5 and **max λ** = 2300nm **assumed**



System Trades

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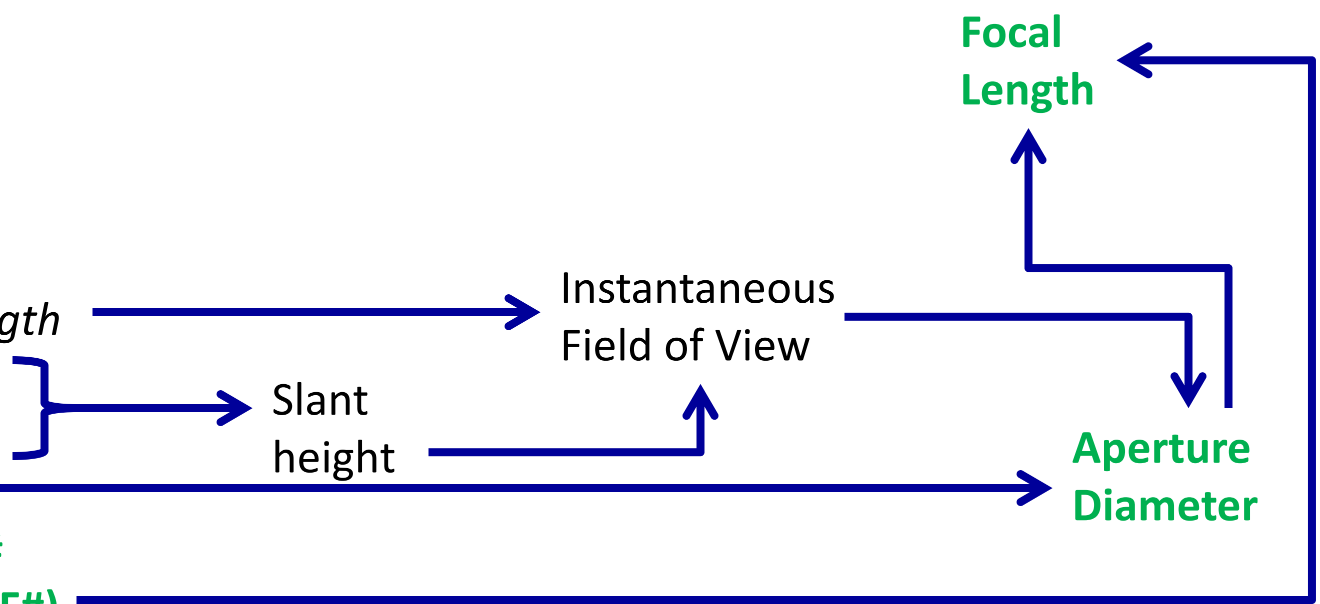

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System Trades

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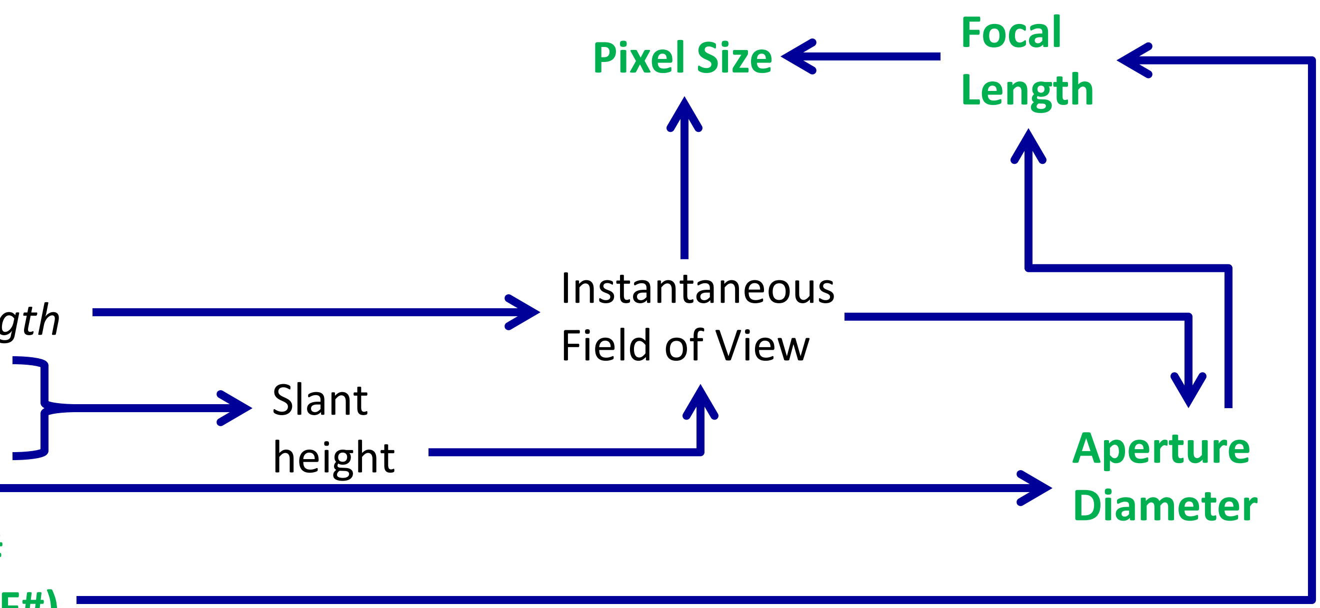

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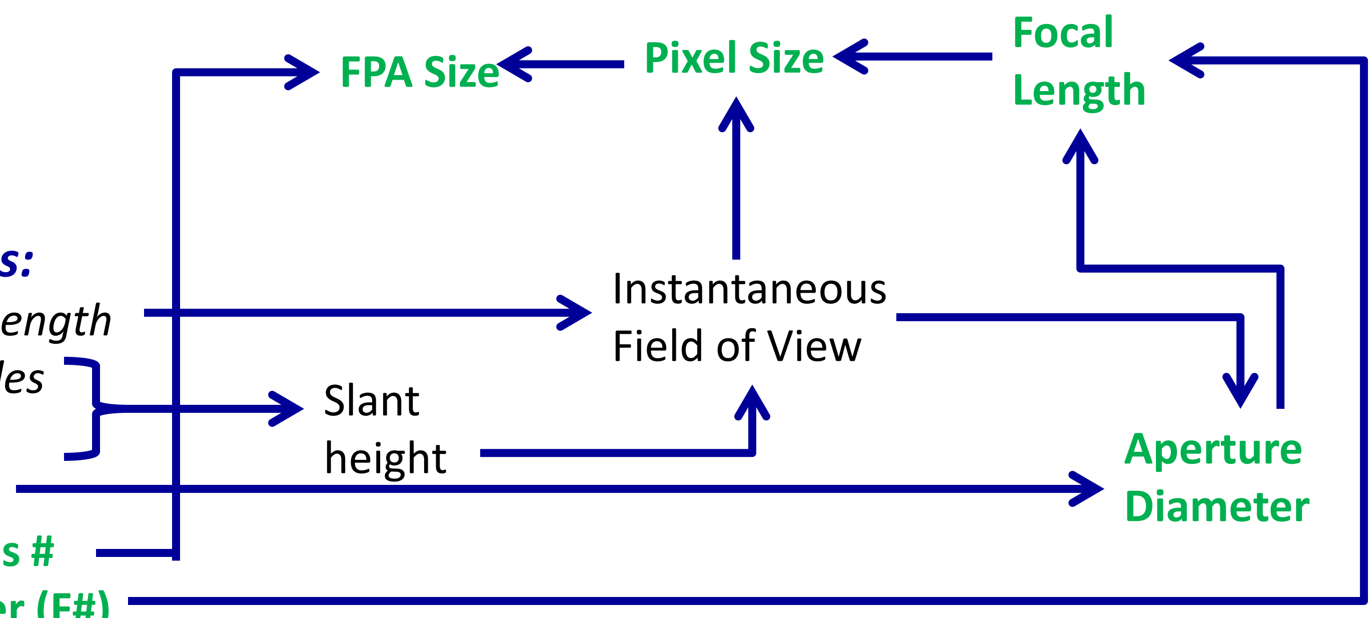

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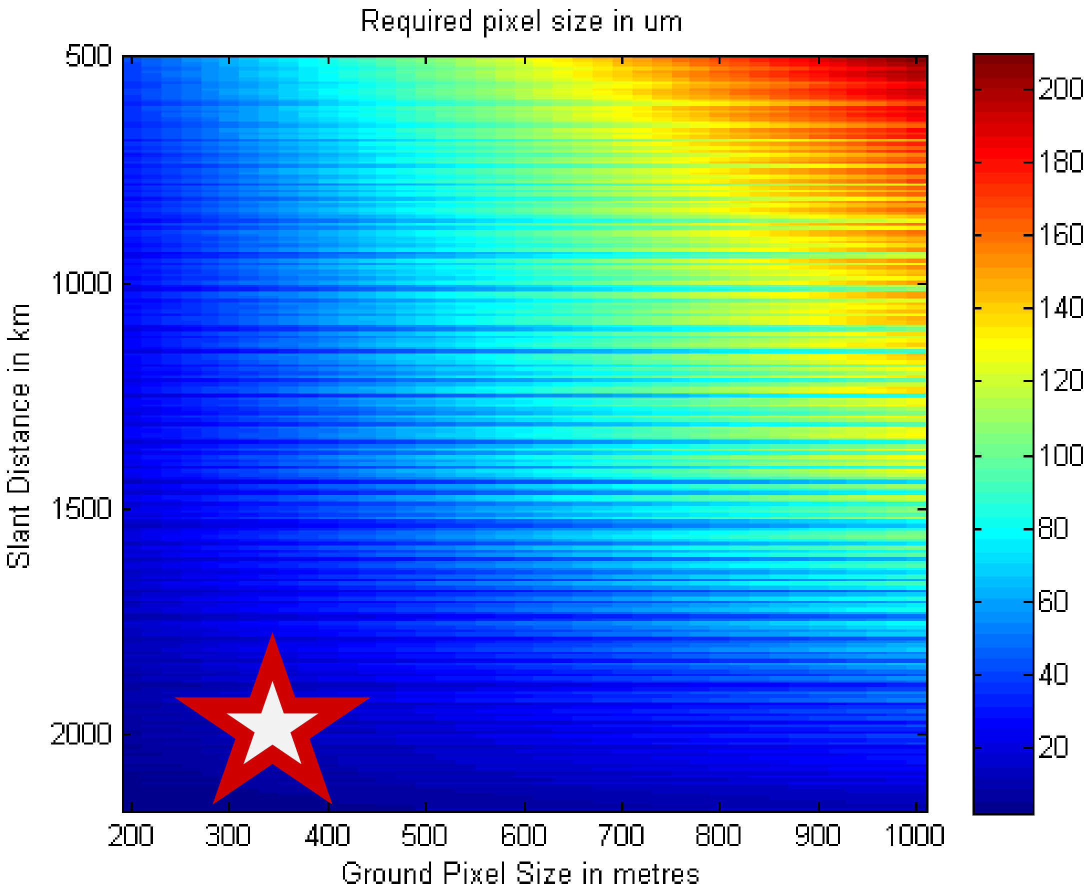
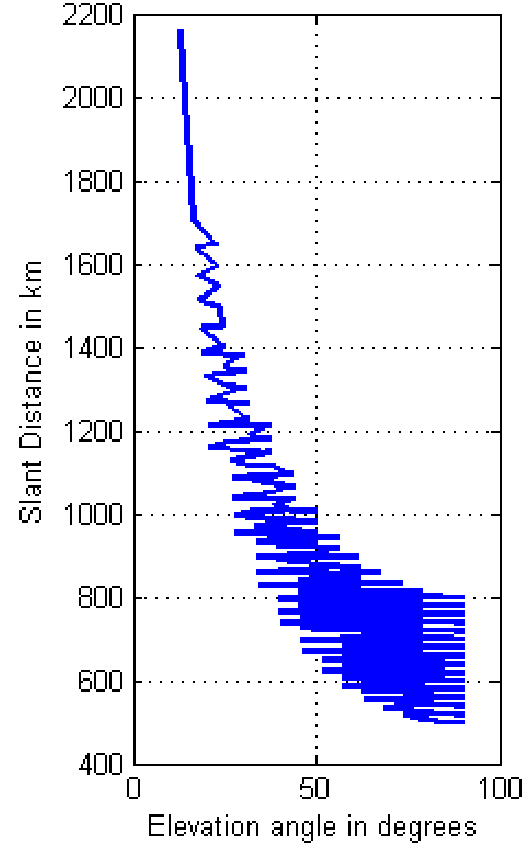
System Trades: Pixels

At **Da = 7cm, f = 10.5 cm** => Tradespace of slant distance (function of altitude h, measurement angle θ) and ground resolution gives detector pixel size.
Constant pixel/GRE = 1 assumed

Pareto point for required pixel size is Feasible!

Baseline dp = 20 µm





System Trades: Pixels

- Pixel delimited imaging requires smaller pixels for shorter wavelengths

$$dp = 1.22 * \lambda * F\#$$

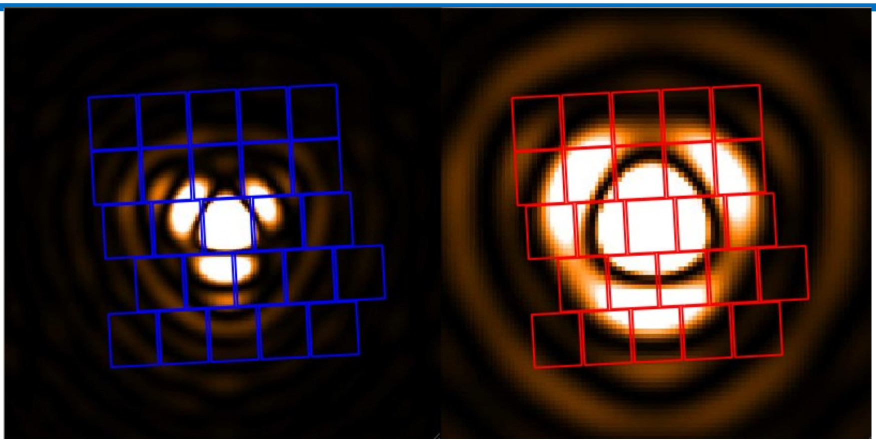
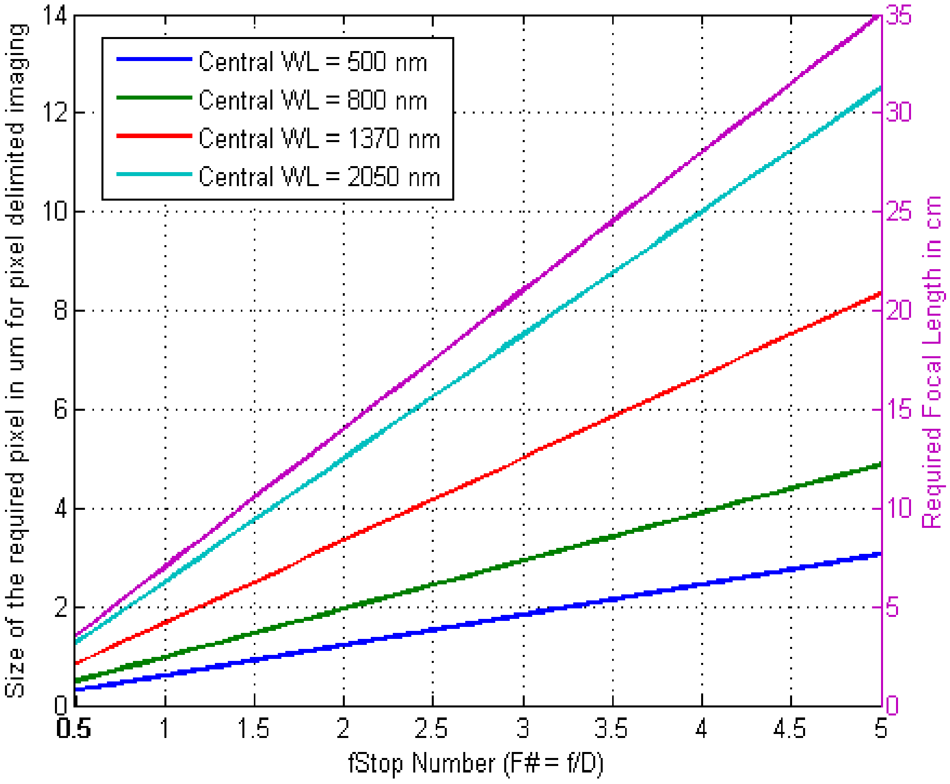
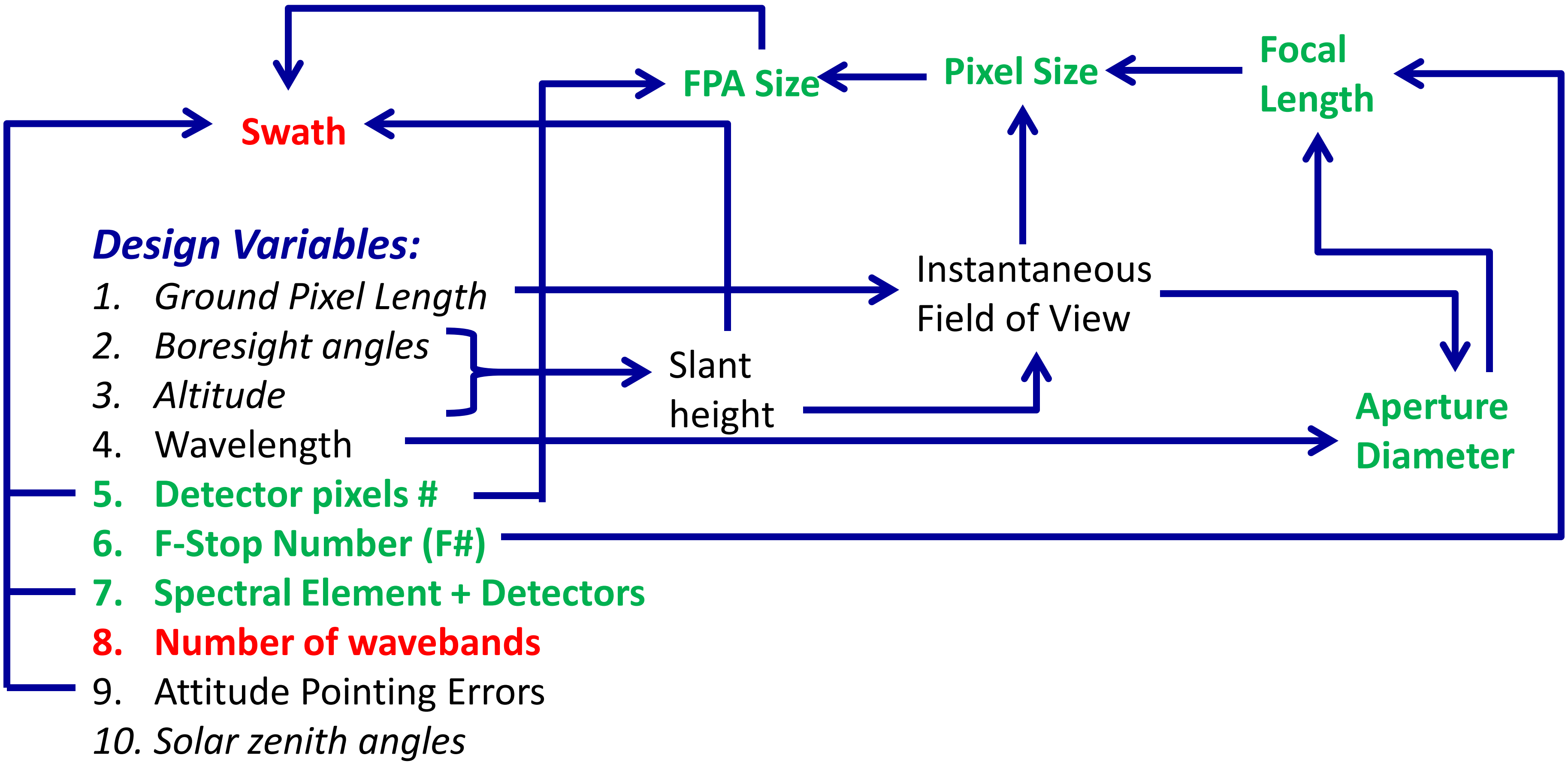


Image Credits: PACS spectrometer detector sampling of the telescope PSF at 75 µm (left) and 150 µm (right). Color scaling of the PSF is chosen to enhance the lobes and wings of the psf

- Variation of the F#



System Trades



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- Optical System Requirements in green

System Trades: Pixels

WGs image the spectral bands spatially.

AOTFs and FPIs image the spectral bands temporally.

Total pixels on the FPA are distributed accordingly.

$$spatialPixelsWG = floor\left[\sqrt{\frac{totalPixels}{nbands}}\right]$$

$$intTime + nbands * \ 10^{-6}[spatialPixelsAOTF + 10] < \frac{gps}{V_g}$$

AOTF and FPI spatial pixels *and* integration time are limited by total time available and wavebands required.

AOTF spatial pixels are limited by wavebands required BUT have #flexibility

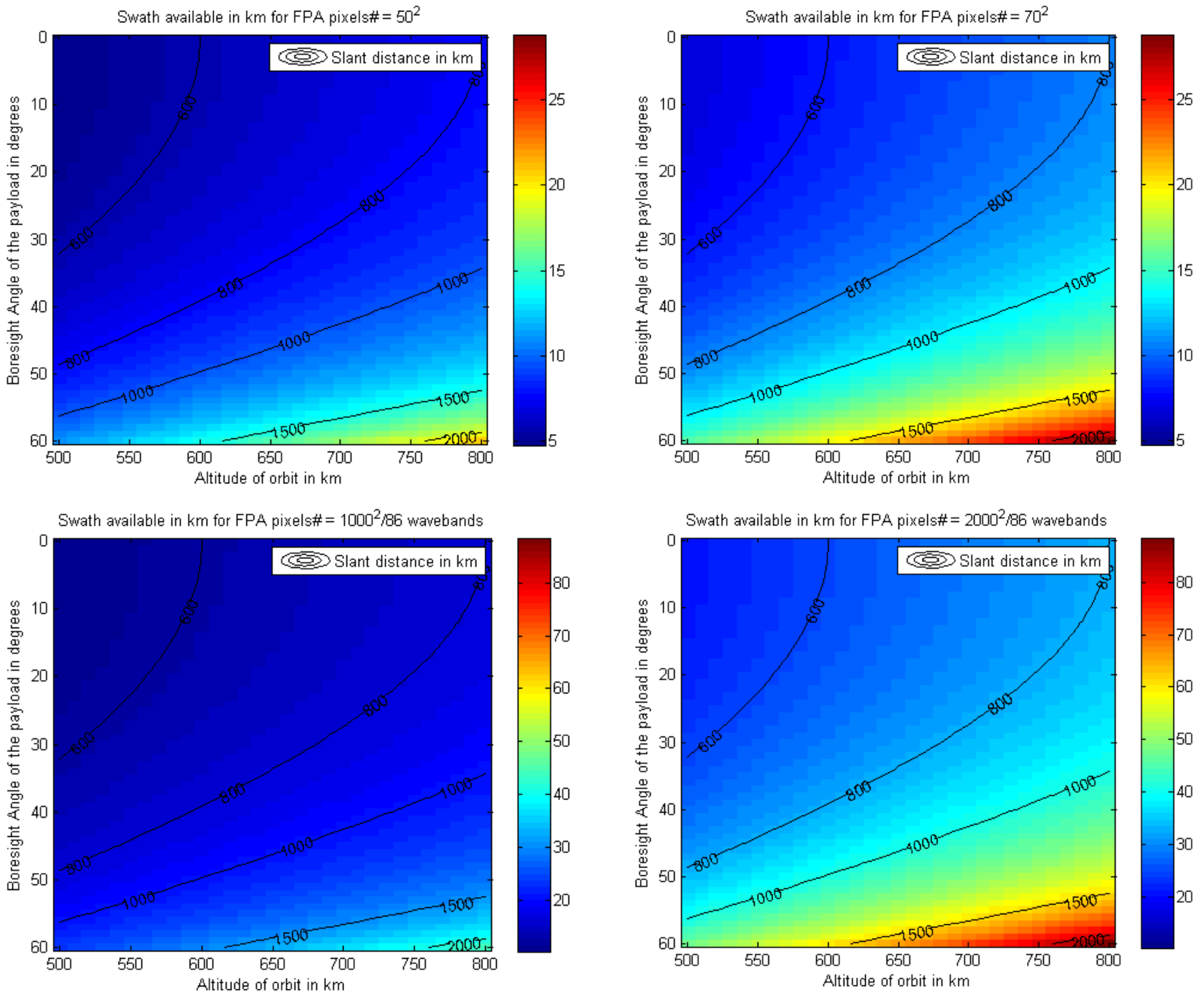
AOTF/FPI swath *and* SNR are affected more than WG.

$$P(\lambda,\eta,h,SZA) = \ L(\lambda,\eta,SZA) * BW(\lambda) * \left(\pi * Da * \sin\left(\frac{FOV}{4}\right)\right)^2$$

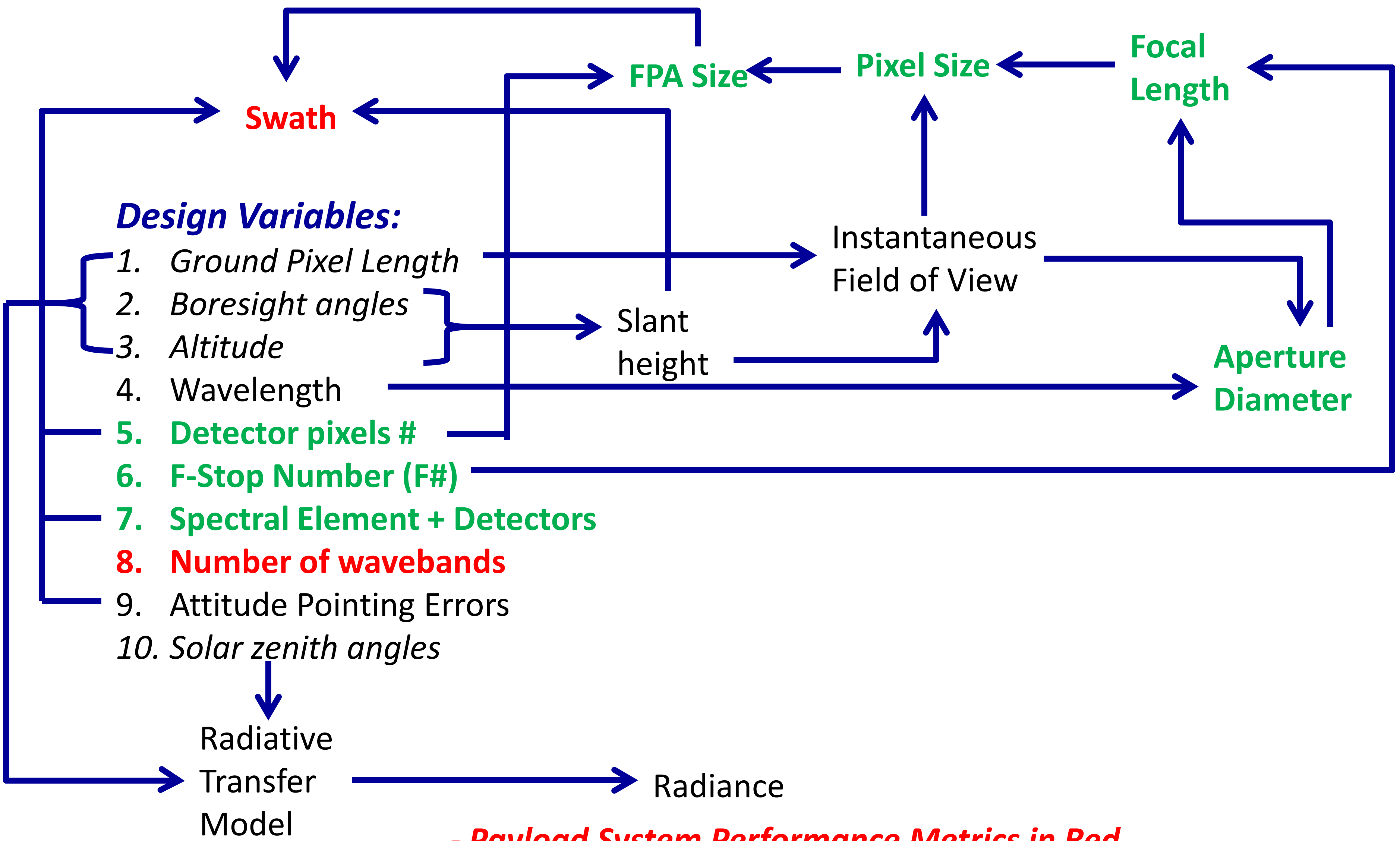
$$E(\lambda,\eta,h,SZA) = \ P(\lambda,\eta,h,SZA) * IT(disp.Type)$$

System Trades: Swath

- At **Da = 7cm, f = 10.5** cm, number of pixels per image set to 1600
- WGs imaging 86 wavebands on FPA. AOTFs imaging 14 wavebands on FPA
- Nanosat clusters have **lower pixels so lower swath**. They make up using clustellations



System Trades

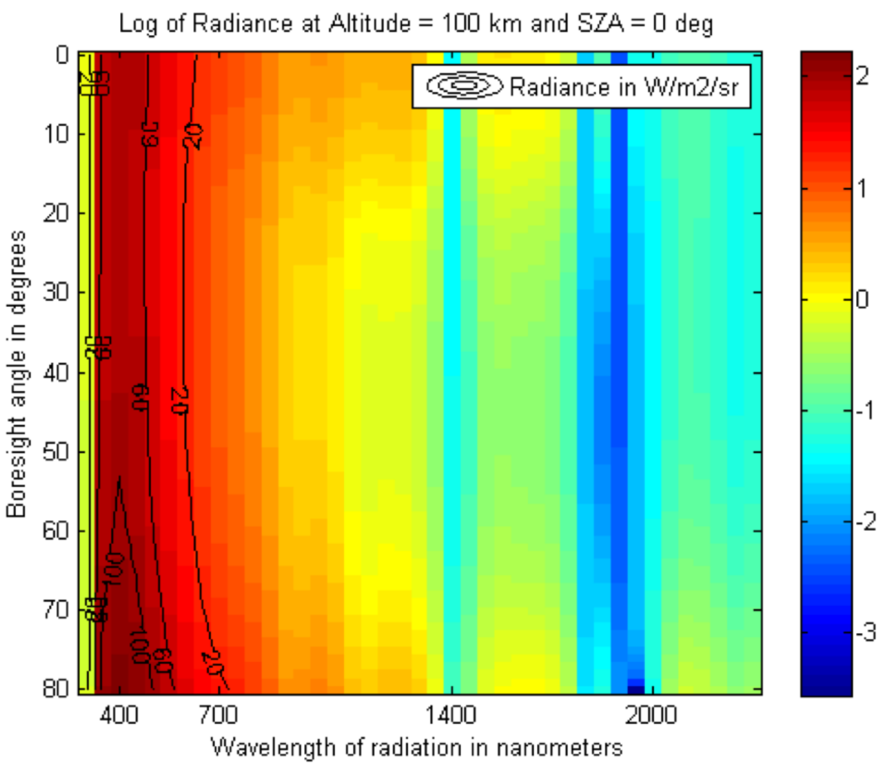


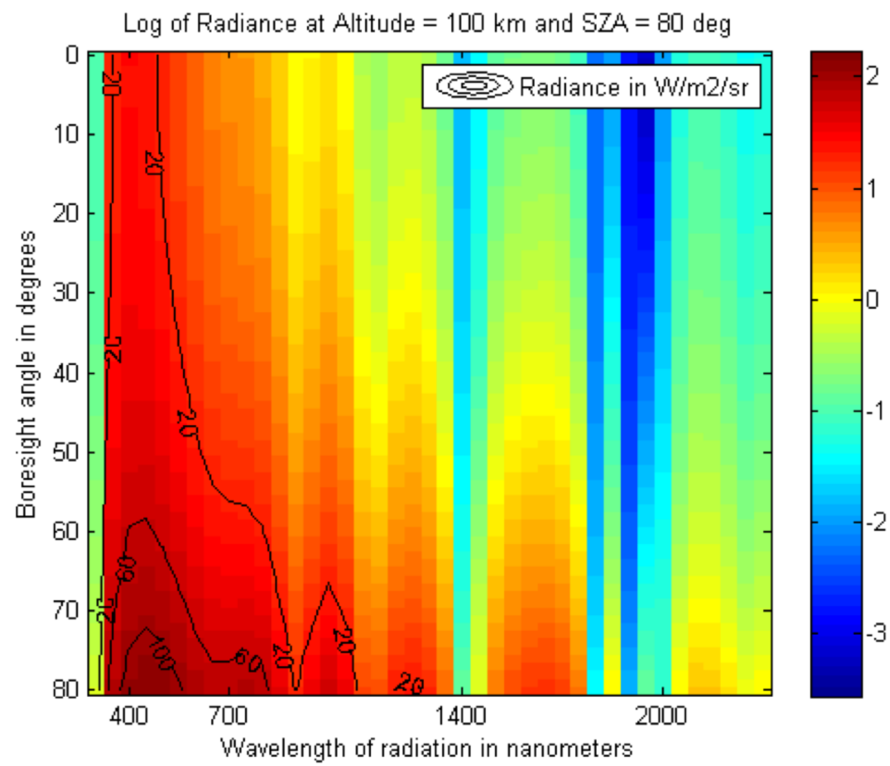
- Payload System Performance Metrics in Red

- Optical System Requirements in green

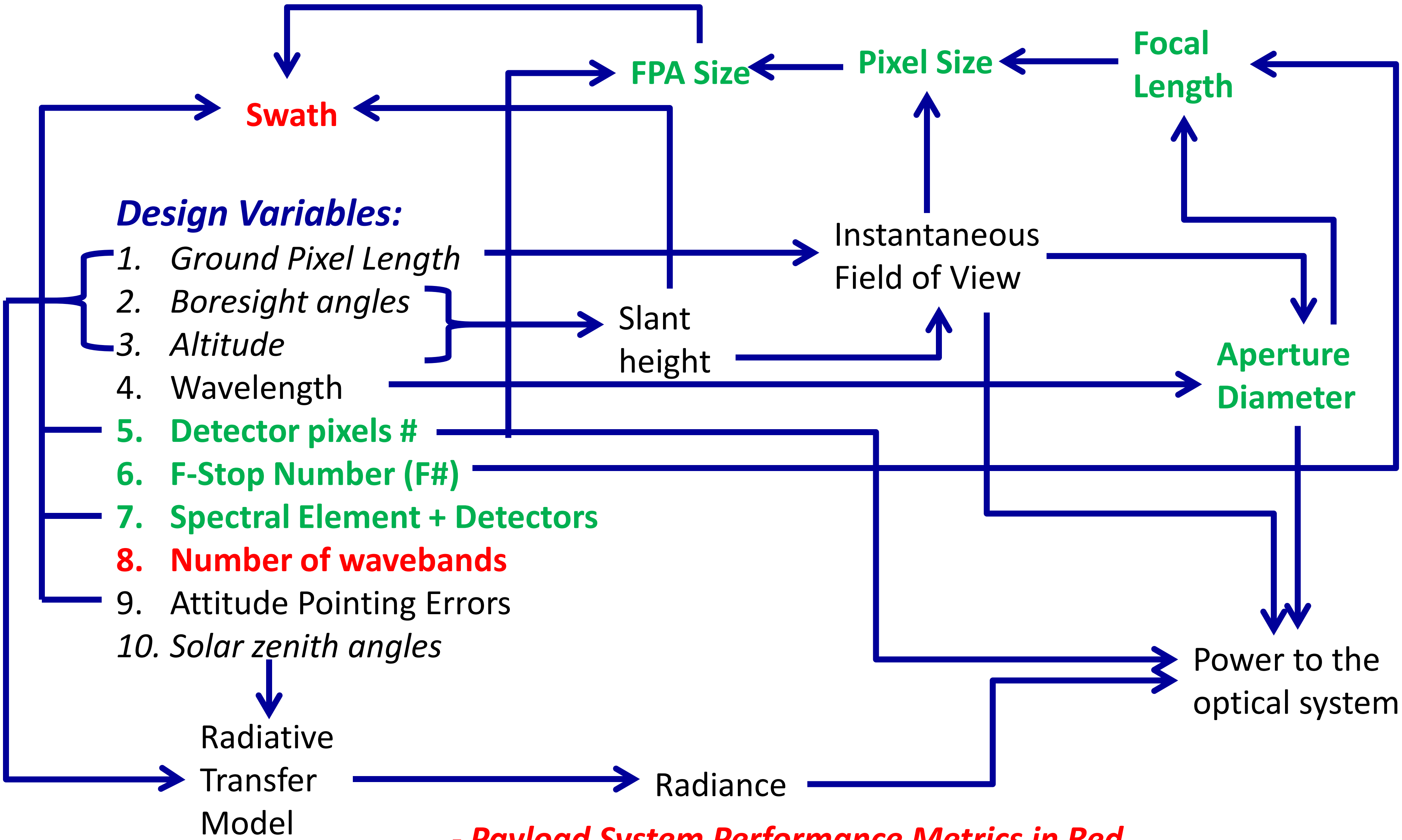
System Trades: Radiance

- Used **NASA Langley's COART model** to estimate radiance at h=100 km as a function of λ, measurement angle θ, φ and SZA
- Default conditions of wind speed and ground reflectance
- Alternatives: MODTRAN (free for government contracts)





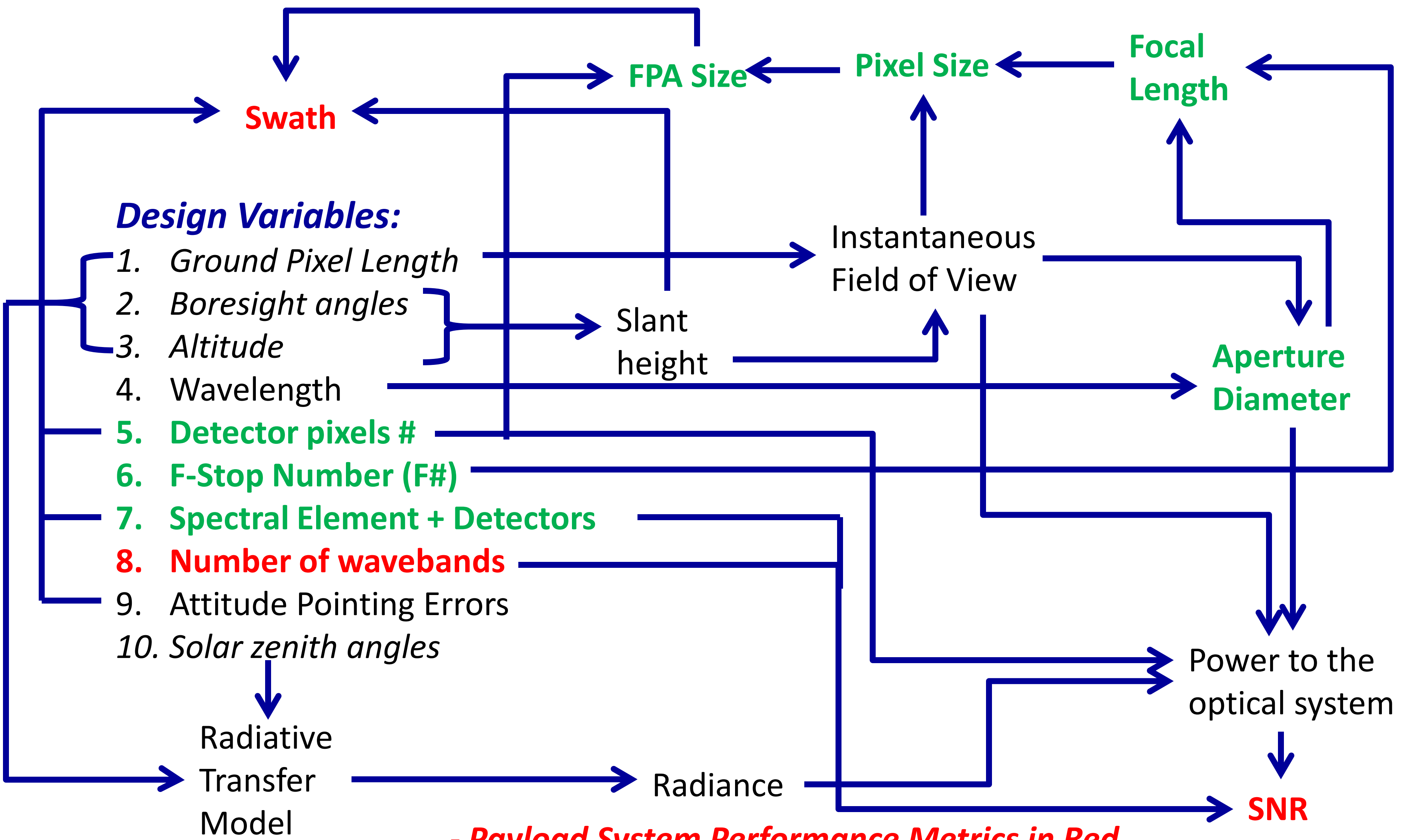
System Trades



- Payload System Performance Metrics in Red

- Optical System Requirements in green

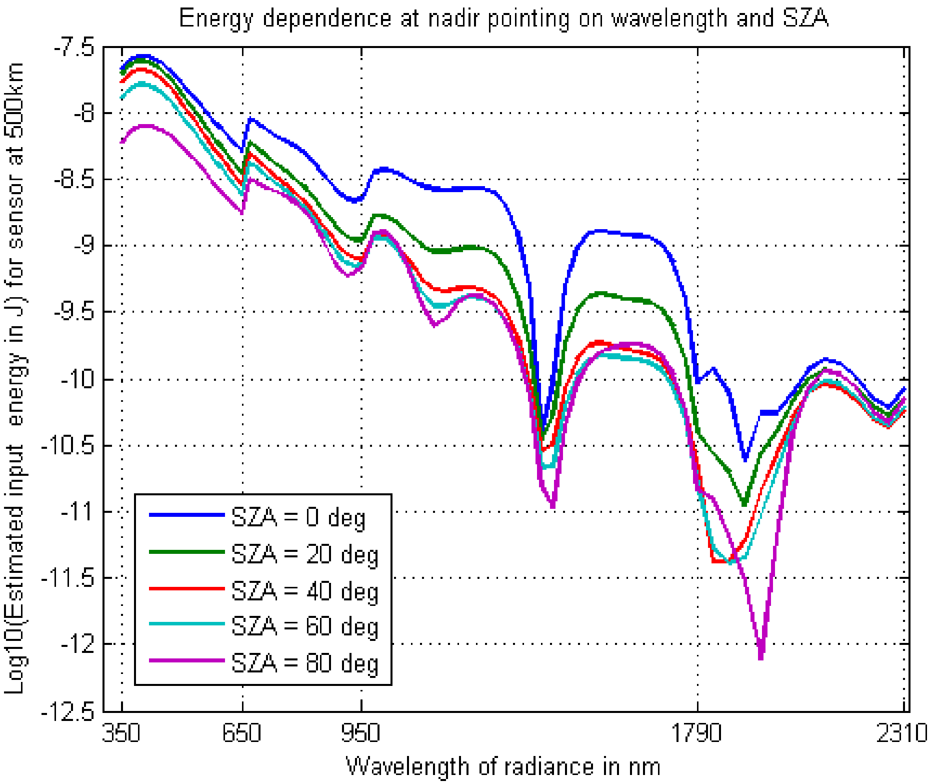
System Trades

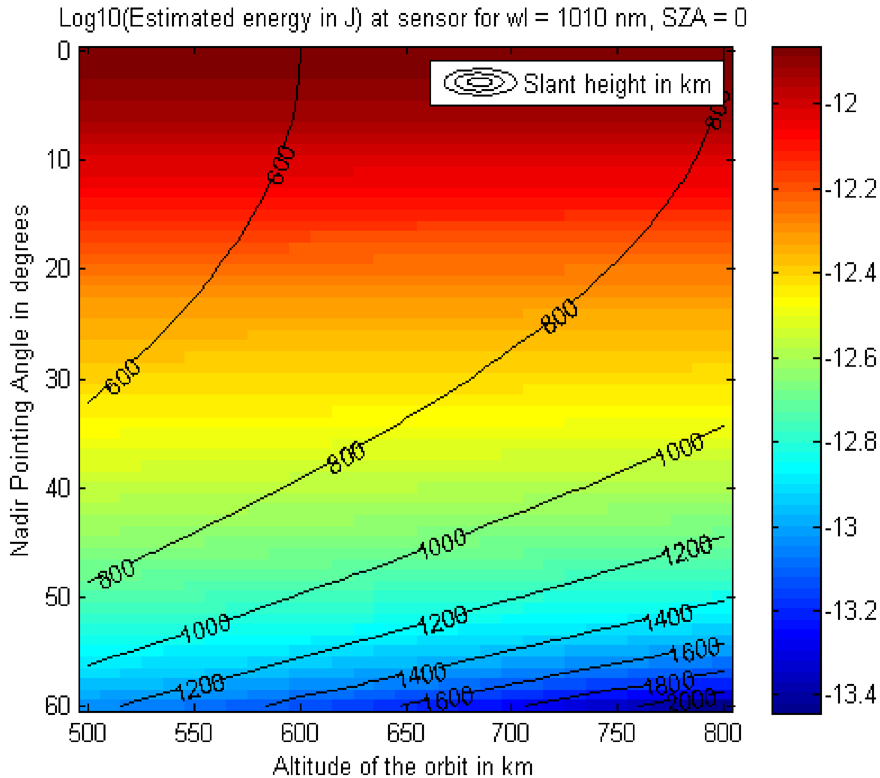


- *Payload System Performance Metrics in Red*
- *Optical System Requirements in green*

System Trades: Signal

- For aperture diameter of 7 cm, BW defined, FOV = f(h, θ, 10k pixels), calculate the power received by the optical sensor
- Power received depends on the spectral elements through spatial pixels #
- Energy [*E(λ,η,h,SZA)]* is power over integration time (spectral element dependent). Plotted below for **AOTFs only** for 60X60 pixels on the FPA





System Trades: Signal to Noise Ratio

E(λ,η,h,SZA) => Signal Photons(**λ**,η,h,SZA) => Noise Photons

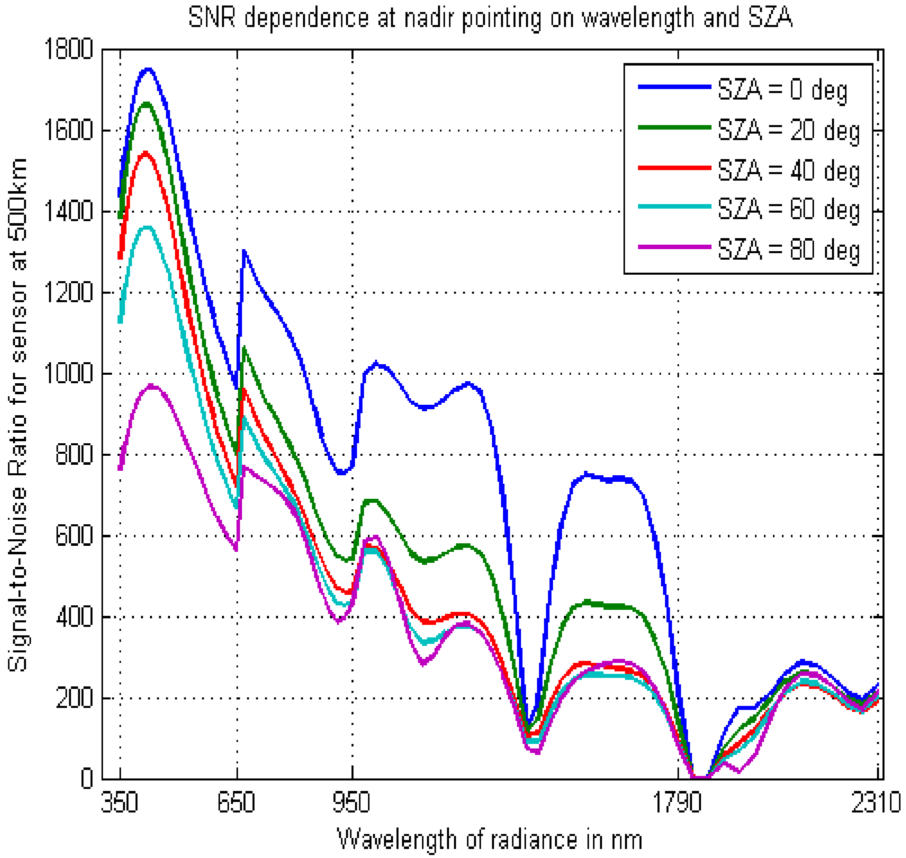
$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix}\left(N_S + N_D + {N_R}^2\right)}}$$

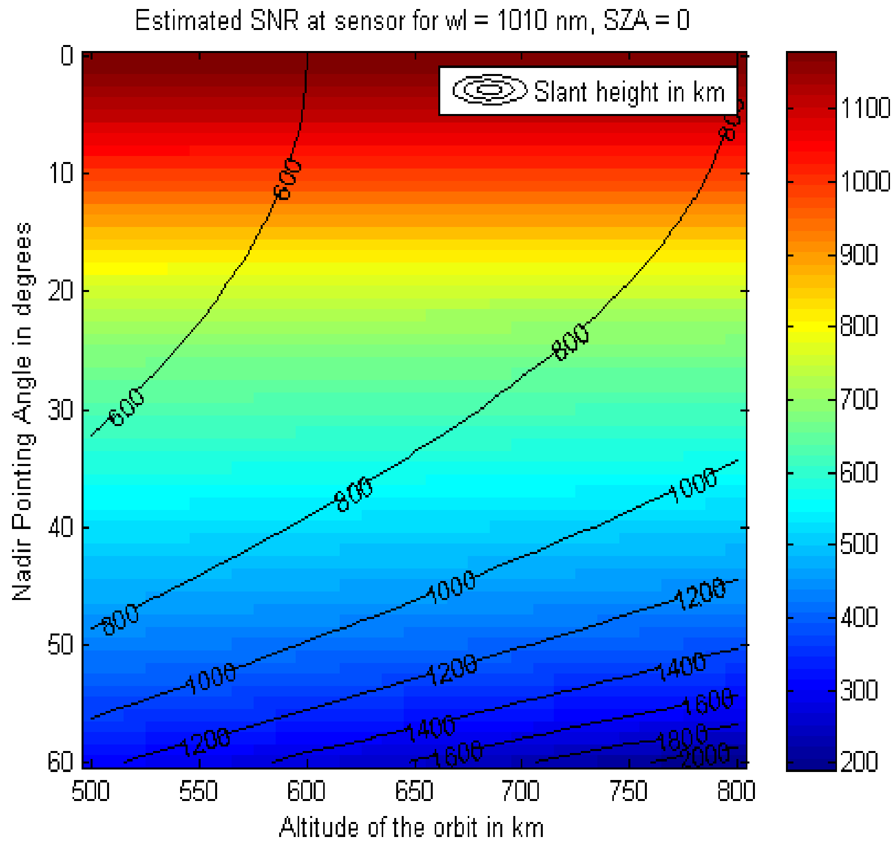
Other determinants of sensitivity:

- Quantum efficiency (QE) = ratio of incoming photons to those photons actually detected by the CCD (0.5-0.9 for CCD).
- System gain = number of electrons which cannot be resolved by ADC's bits (16 bits)
- Charge transfer efficiency (CTE) = level of accuracy that the charge stored in each pixel can be transferred to another during readout process (0.8).
- Well depth = total amount of charge that can be stored in the pixels before the charge overflows into adjoining pixels (200 ke^- for 3U cubesats).

System Trades: Signal to Noise Ratio

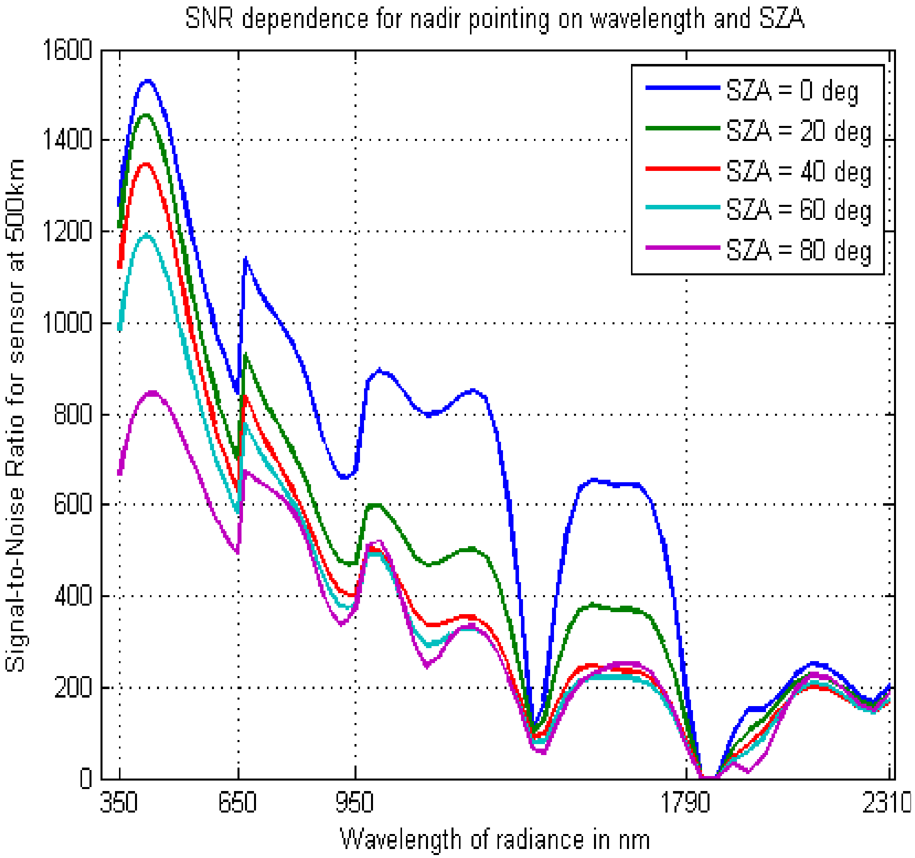
SNR for **AOTFs with 60X60 FPA pixels** (calculated with IT restrictions) for a wavelength of 1010 nm at noontime (right) and nadir viewing at a 500 km altitude (left) to image a total of 14 wavebands

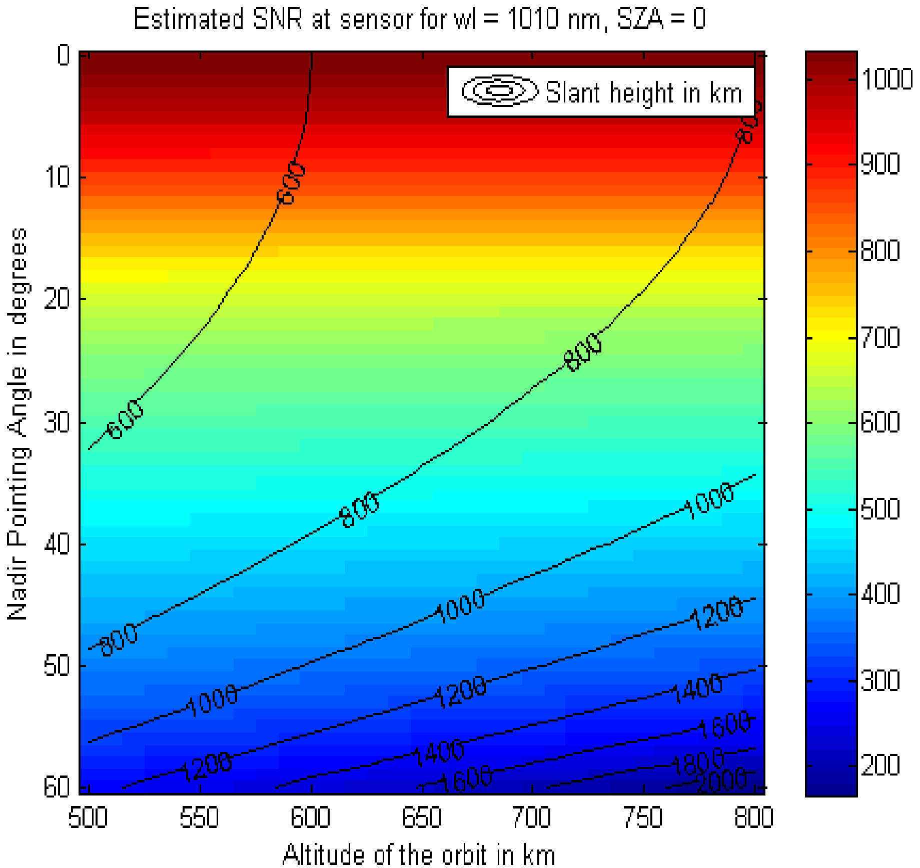




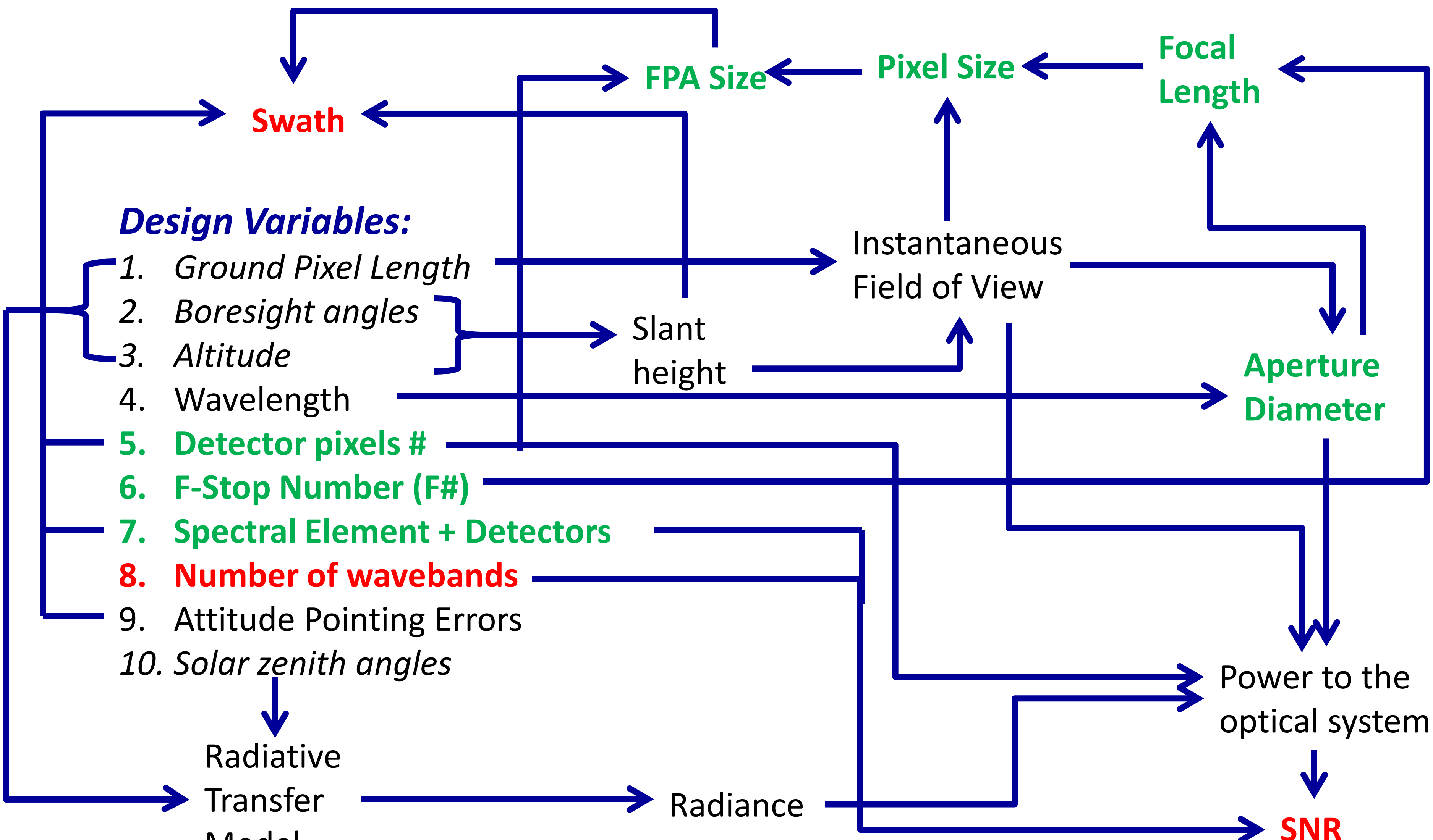
System Trades: Signal to Noise Ratio

SNR for **Waveguide Spectrometers with 1000X1000 FPA pixels** (spatial pixels calculated after) for a wavelength of 1010 nm at noontime (right) and nadir viewing at a 500 km altitude (left) to image a total of 86 wavebands





System Trades



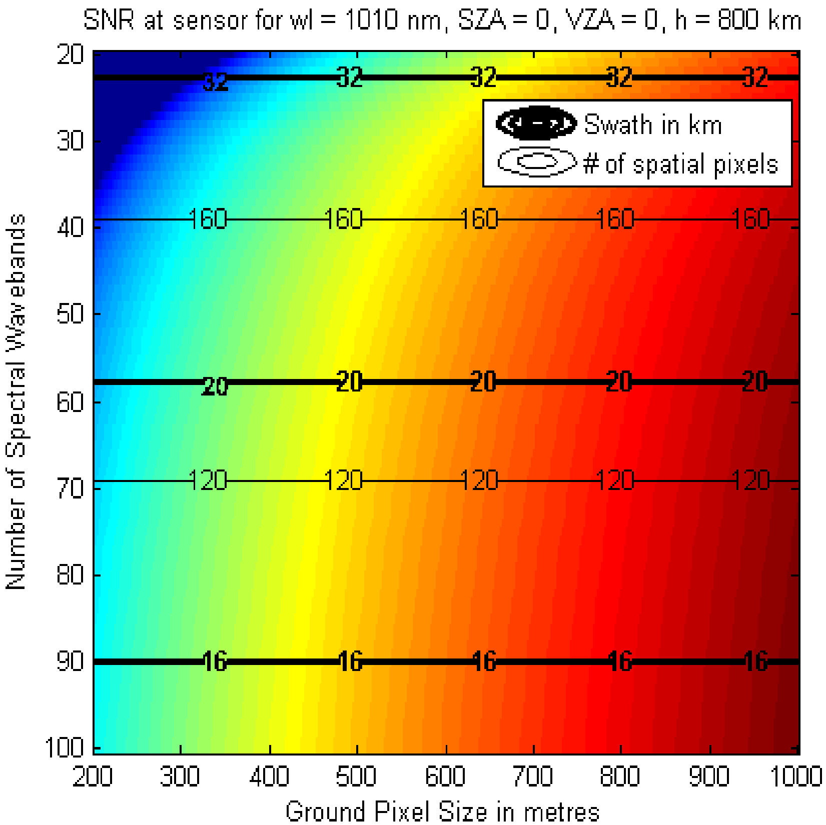
- Payload System Performance Metrics in Red

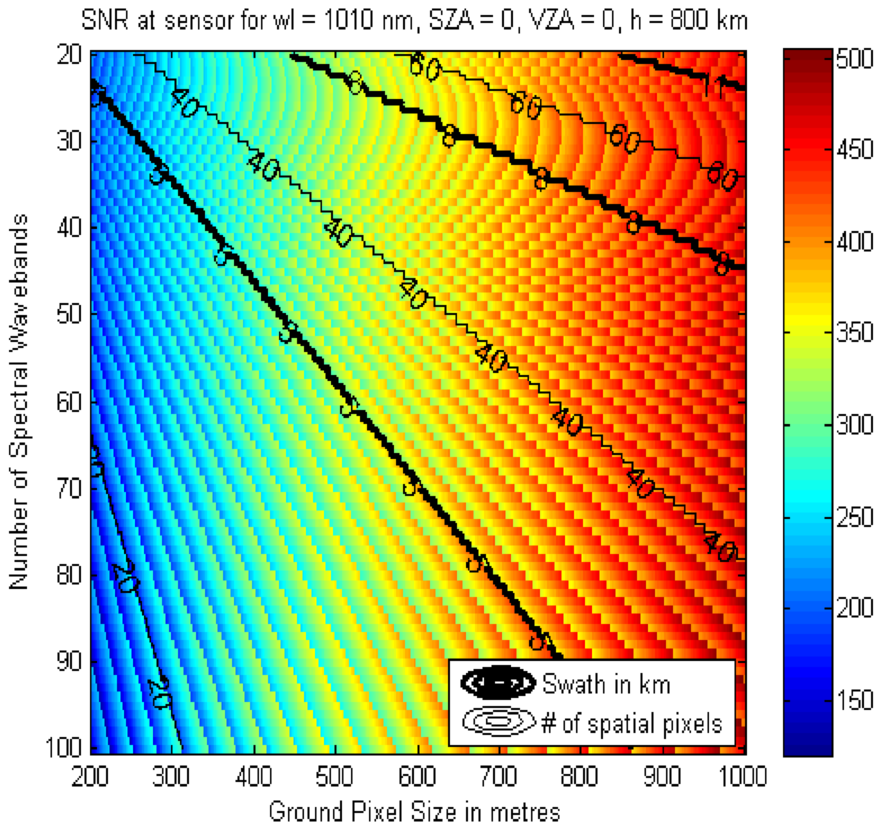
- Optical System Requirements in green

System Trades: All Metrics

Results from modeling and simulations:

- As wavebands increases for WGs, the spatial pixels allowed decreases therefore less readout time and more time available for integration.
- For any number of wavebands, AOTFs try to maximize the spatial pixels available + keeping >5% time for integration, therefore the quantum jumps when the next level of pixels is reached.





Payload Tradespace Baselines

Payload External Requirements:

1. *Ground Pixel Length (<500m)*
2. *Boresight angles (<60°)*
3. *Solar zenith angles (<80°)*
4. *Altitude (500 to 800 km)*
5. *ADCS Pointing Errors*
6. Wavelength (<4 ranges: .35-2.3um)
7. Number of detector pixels (<4m pix) **[BL = 10k (1024X1024)]**
8. F-Stop Number (F# 0.5 to 3) **[BL = 1.5]**
9. Number of bands (>14) **[BL = 86]**

Payload Optical Requirements:

1. Aperture Diameter **[BL = 7 cm]**
2. Focal Length **[BL = 10.5 cm]**
3. Pixel Size **[BL = 20 um, all bands]**
4. Matrix Imaging Spectrometer **[WG]**
5. FPA Size **[BL = 800 um, all bands]**

Payload Optics Evaluation Metrics:

1. FOV **[BL = 4 to 10 deg]**
2. Swath **[BL = 15-90 km]**
3. SNR **[100-1000]**

Many architectures are possible by varying the design requirements within acceptable bounds and recalculating system requirements

BL = Baseline selected for ~best science after trades

Conclusions

- Identified a critical Earth remote sensing application for hyperspectral snapshot imaging
- Performed a feasibility study of nanosatellite HSI for BRDF using a unique, systems-based approach to designing, customizing and evaluating a hyperspectral imager for nanosats
- Presents an MBSE-style tradespace analysis and optimization tool for payload design, customization and evaluation for any DSM
- Baseline optical parameters for NFOV payloads are possible using state-of-art COTS
- Spectral elements shortlisted: WG Spectrometers, AOTFs, Electronically actuated FPIs and IFS.
- WGs perform better in terms of achievable swath (10-90 km) and SNR (>100) for the same number of imaged wavebands but AOTFs and FPIs have programming flexibility to improve SNR.
- Future work: Detailed customization of the instrument in itself + in relation to other limiting systems in the nanosatellite + random processes.

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Questions?