A review on sensor spatial resolution & a discussion on geometric specifications

JACIE Workshop Session:
Standards/Specs/Format

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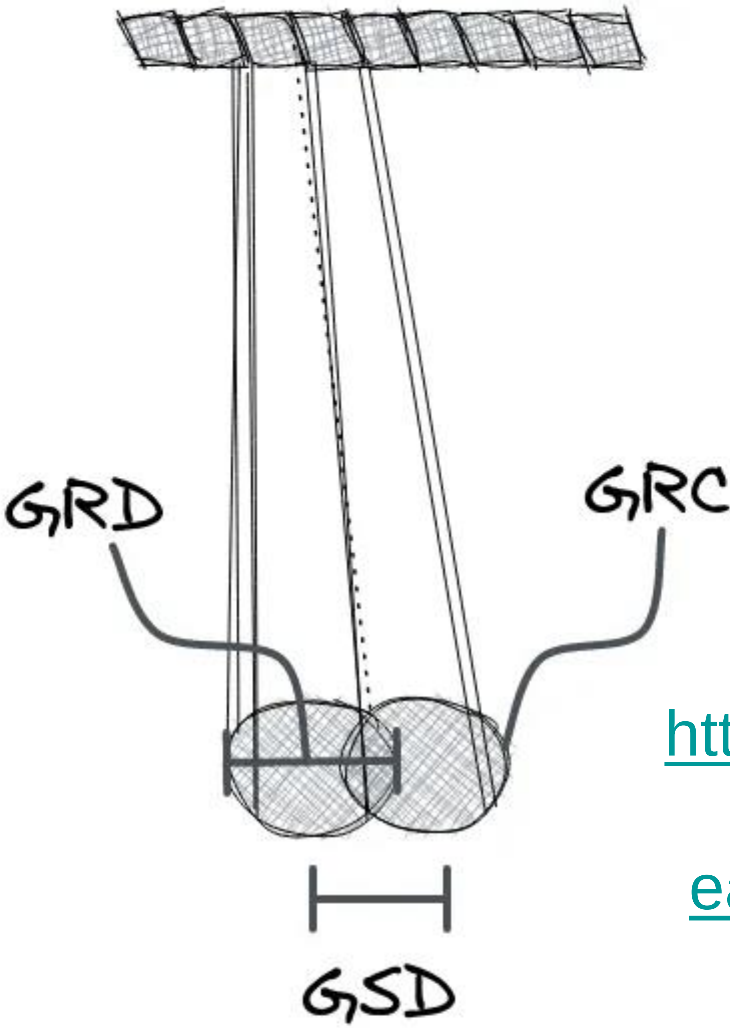
Question to be addressed

- What is the proper gridded image pixel size?

The most misunderstood words in Earth Observation

"Spatial resolution"



Ground Resolved Cell

https://medium.com/sentinel-hub/the-most-misunderstood-words-in-earth-observation-d0106adbe4b0

by Devis Peressutti and Matej Batič.

Definitions of spatial resolution

1. Based on electronics-mechanical operations

- Ground sampling distance (GSD), separation between centers of two adjacent samples on the ground.

2. Based on optical property

- Sensor Spatial Resolution (SSR): full-width at half-maximum (FWHM) of sensor line spread function (LSF) projected on the ground

  = "Footprint size".
- Ground resolved distance (GRD):   "effective" sensor resolution = half wavelength on the ground where modulation transfer function (MTF) of LSF drops to ½ .

  = "Horizontal spatial resolution (HSR)" , used in VIIRS specifications.

3. Based on convenience in mapping and usage, and some physics

- Gridded image pixel resolution: evenly distributed grid cells in a map projection. Hopefully, it is vetted in physics.

Sizes of spatial resolution

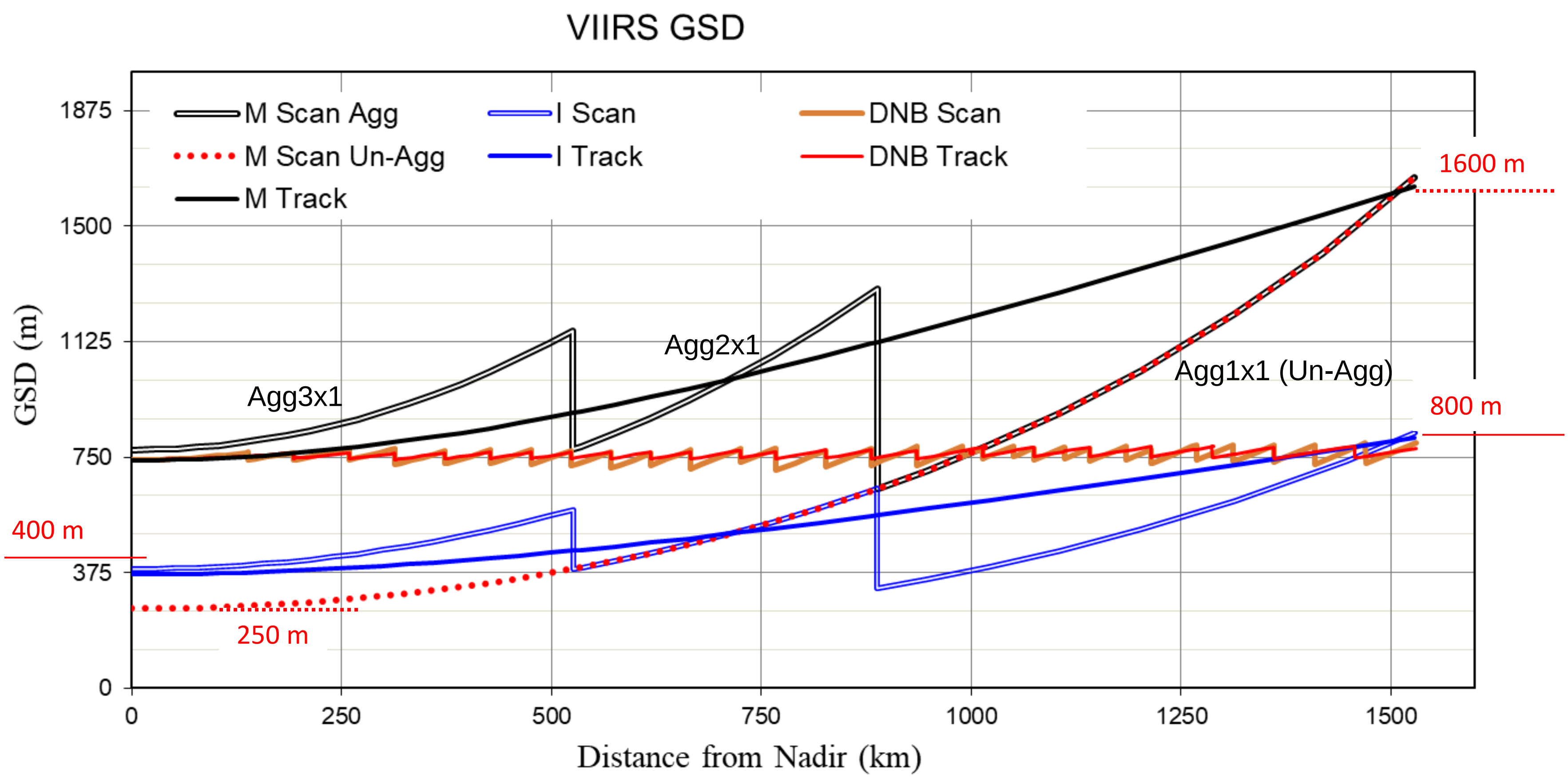
LR	Low Resolution,	coarser than	300 m
MR	Medium Resolution,		30 to 300 m
HR	High Resolution,		5 to 30 m
VHR	Very High Resolution,	finer than	5 m

The above definitions are from Guidelines below.

DRAFT

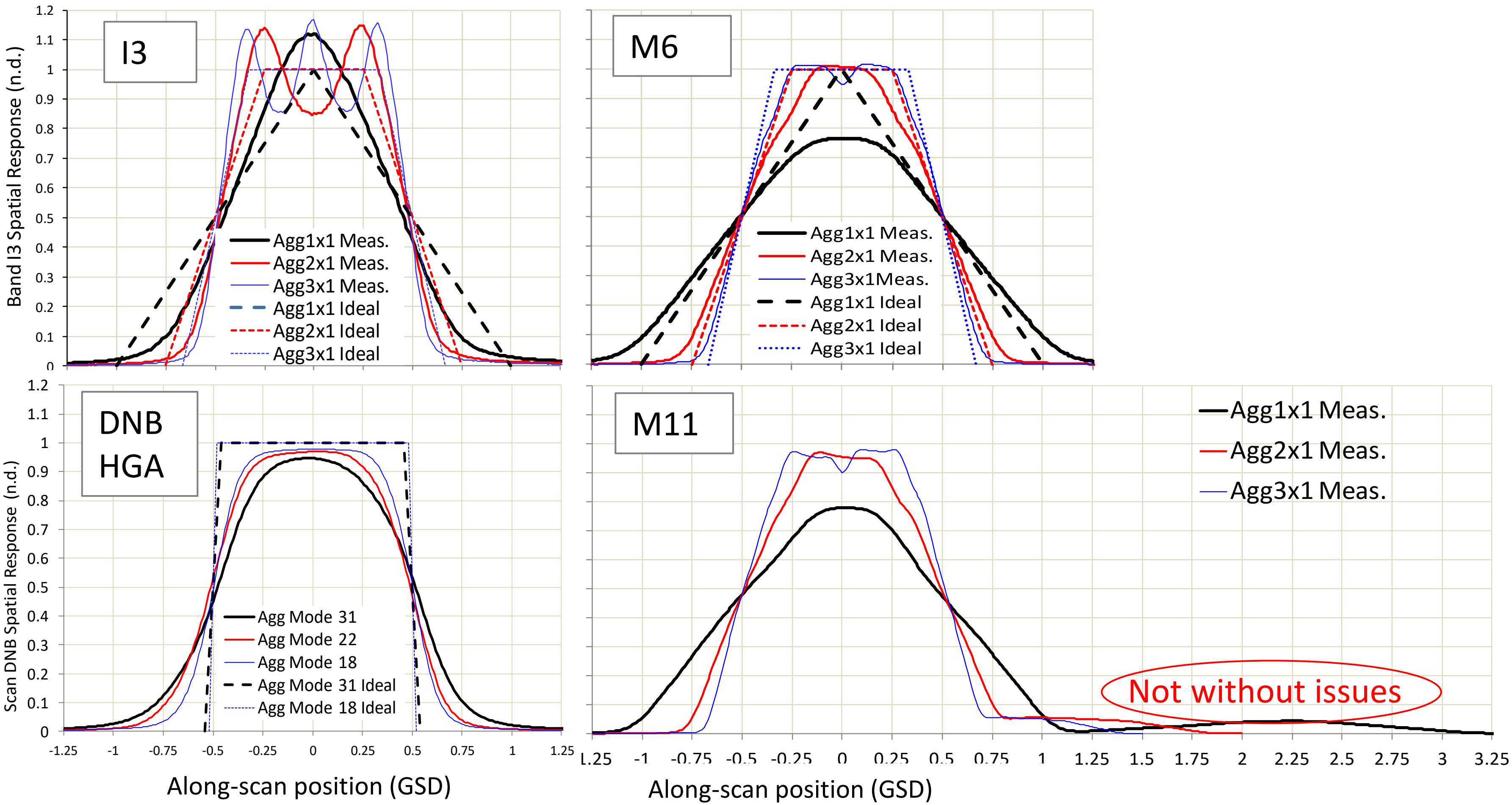
Earth Observation Mission Quality
Assessment Framework - Optical Guidelines

VIIRS ground sampling distance (GSD)



- 375 m for 5 Imagery bands, 750 m for 16 Moderate resolution bands, at nadir.
- 750 m for 1 Day-night (DNB) in 32 aggregation modes, throughout scan.
- Sample aggregation limits the growth of GSD and increases SNR.

Typical SNPP VIIRS scan direction LSFs



- Aggregation makes LSFs more square
- DNB LSFs are nearly square
- LSFs in the track direction are mostly squares (not shown here)

Definition of MTF and GRD

- Modulation transfer function (MTF)

$$MTF(\omega) = \frac{\left|FourierTansform(LSF)\right|}{\left|FourierTansform(LSF)\right|_{|\omega=0}}$$

where spatial frequency ω is expressed in fraction of Nyquist frequency

$$NF = \frac{1}{2\,GSD}$$

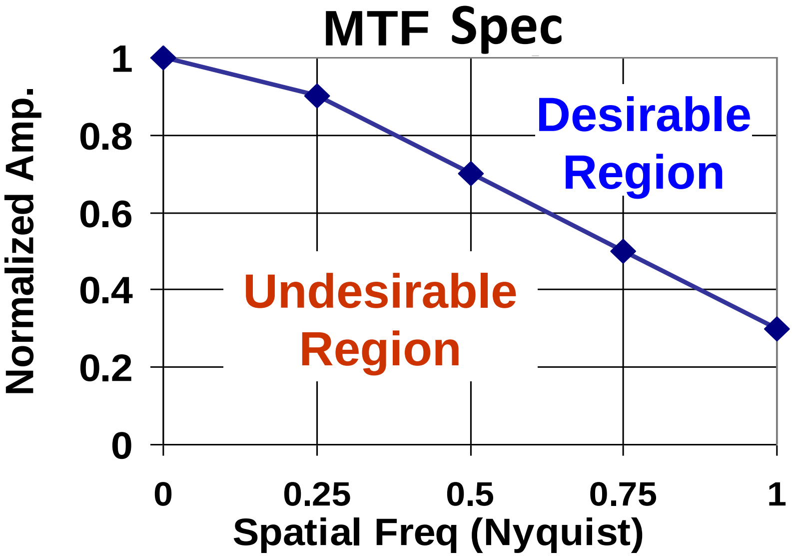
- Ground resolved resolution (GRD)

$$MTF\left(\frac{1}{2\,GRD}\right) = \frac{1}{2}$$

VIIRS MTF, GRD requirements

- The MTF of the moderate bands shall equal or exceed the values specified at fractional Nyquist frequency (NF).

Nyquist Freq. Fraction	MTF
0.00	1.0
0.25	0.9
0.50	0.7
0.75	0.5
1.00	0.3



- The VIIRS instrument imaging bands shall achieve a GRD ≤ 400 m at nadir and ≤ 800 m worst case throughout the scan.
- The VIIRS instrument DNB shall achieve a GRD =< 800 m throughout the scan.

GOES-R ABI MTF requirements

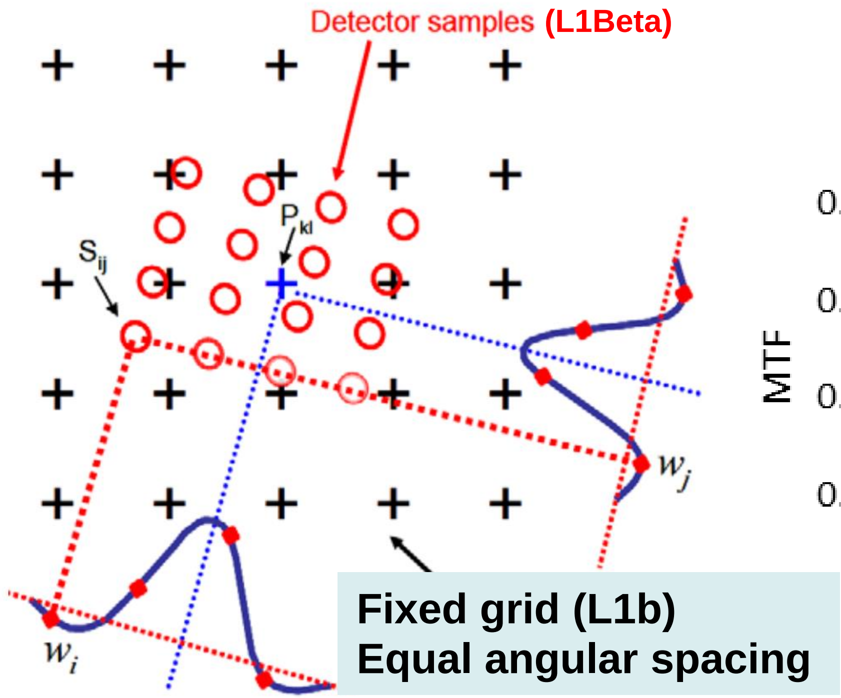
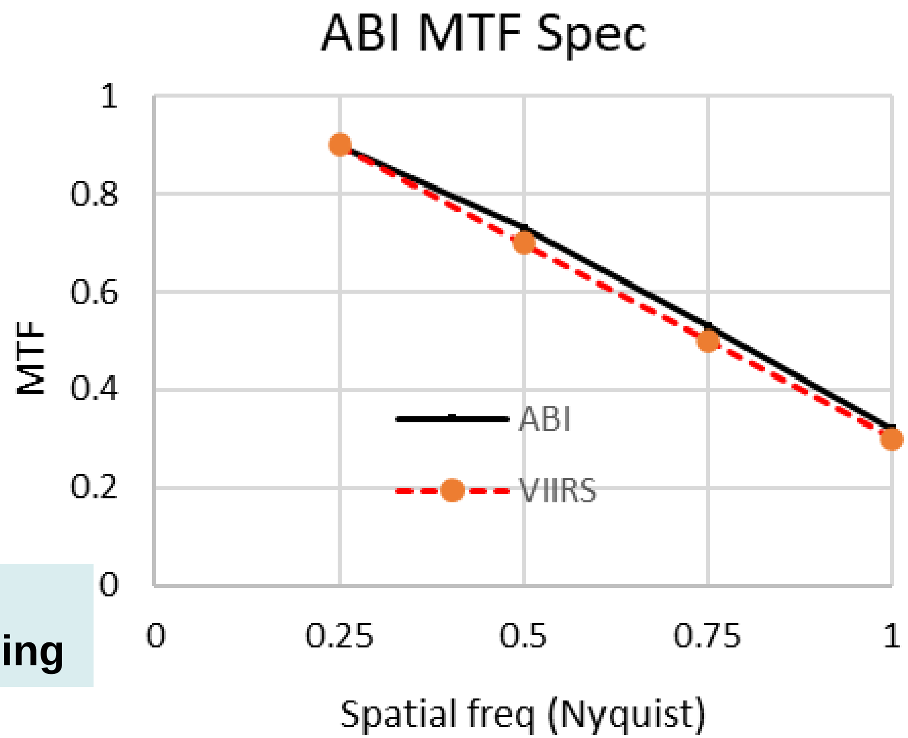


Figure 5.1.3.5 ABI Level 1b Resampling Process

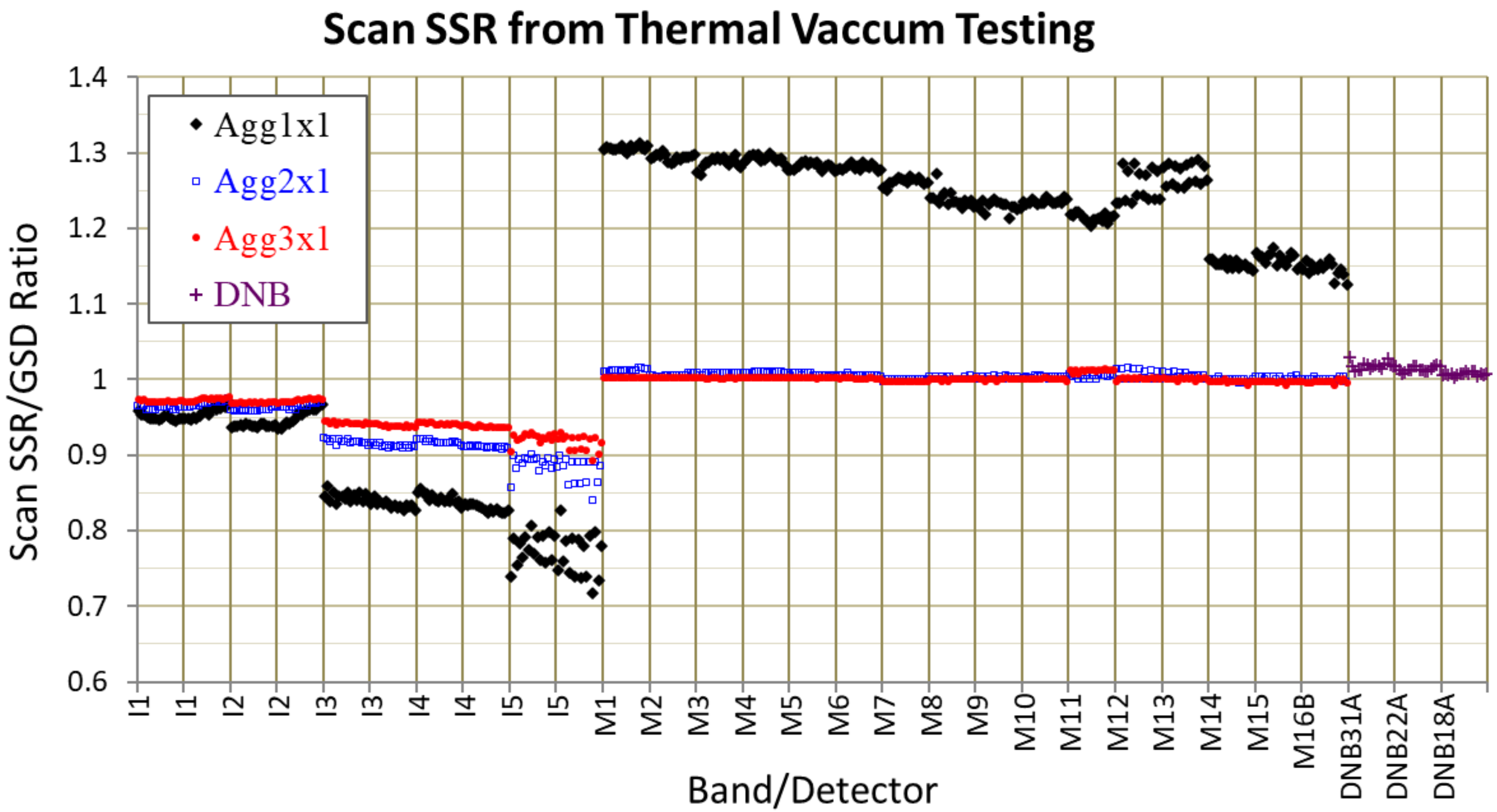
https://www.goes-r.gov/users/docs/PUG-L1b-vol3.pdf

Truncated sinc function $\frac{sin(x)}{x}$ in [-2π, +2π] is used as kernels



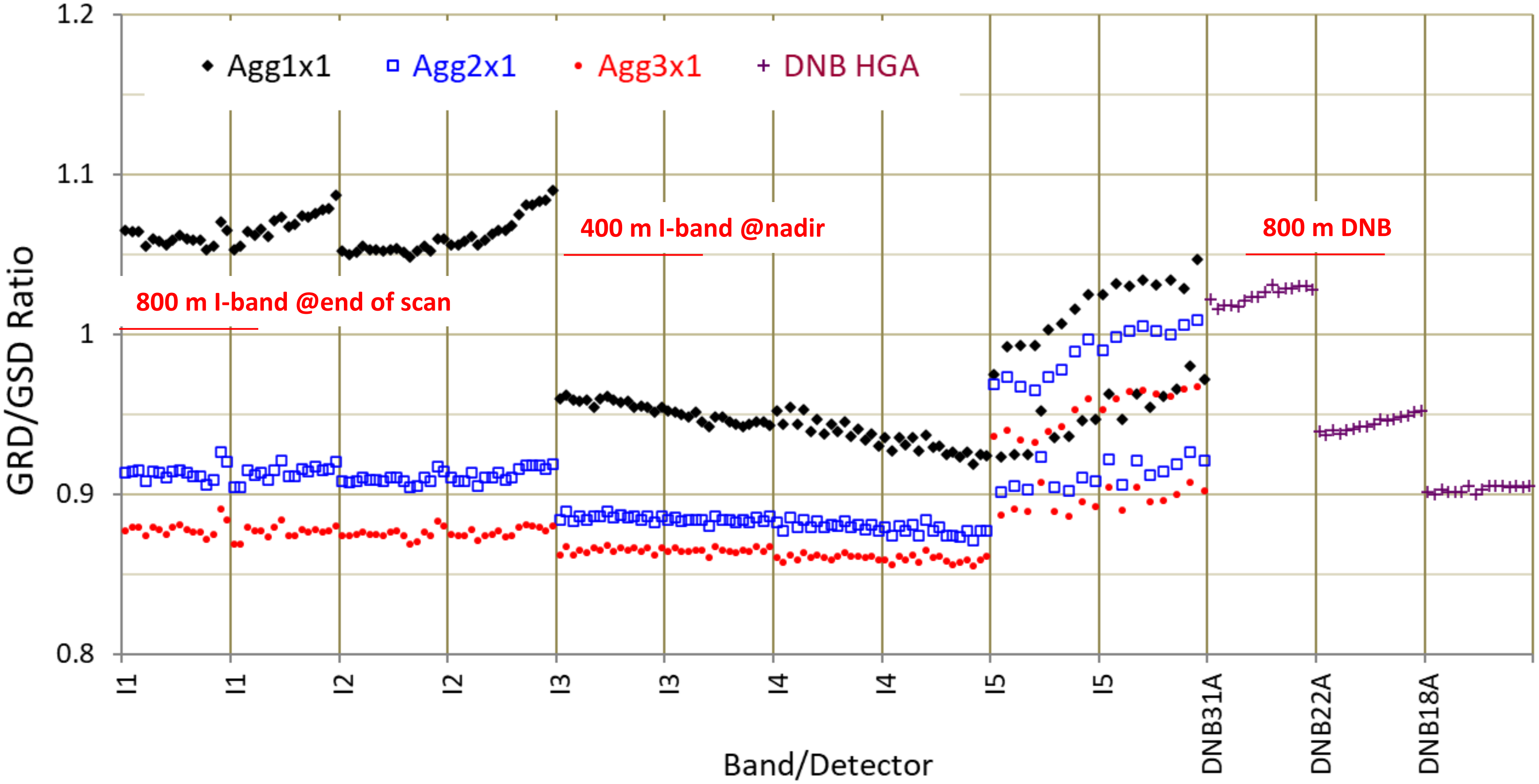
M. Cook et al, “A Pathway to Optimize GOES-R ABI Hot Spot Detection and Fire Monitoring using ABI L1Beta Imagery”, AMS Annual Meeting, 1/28 - 2/2, 2024, Baltimore, MD

SNPP VIIRS SSR in scan direction



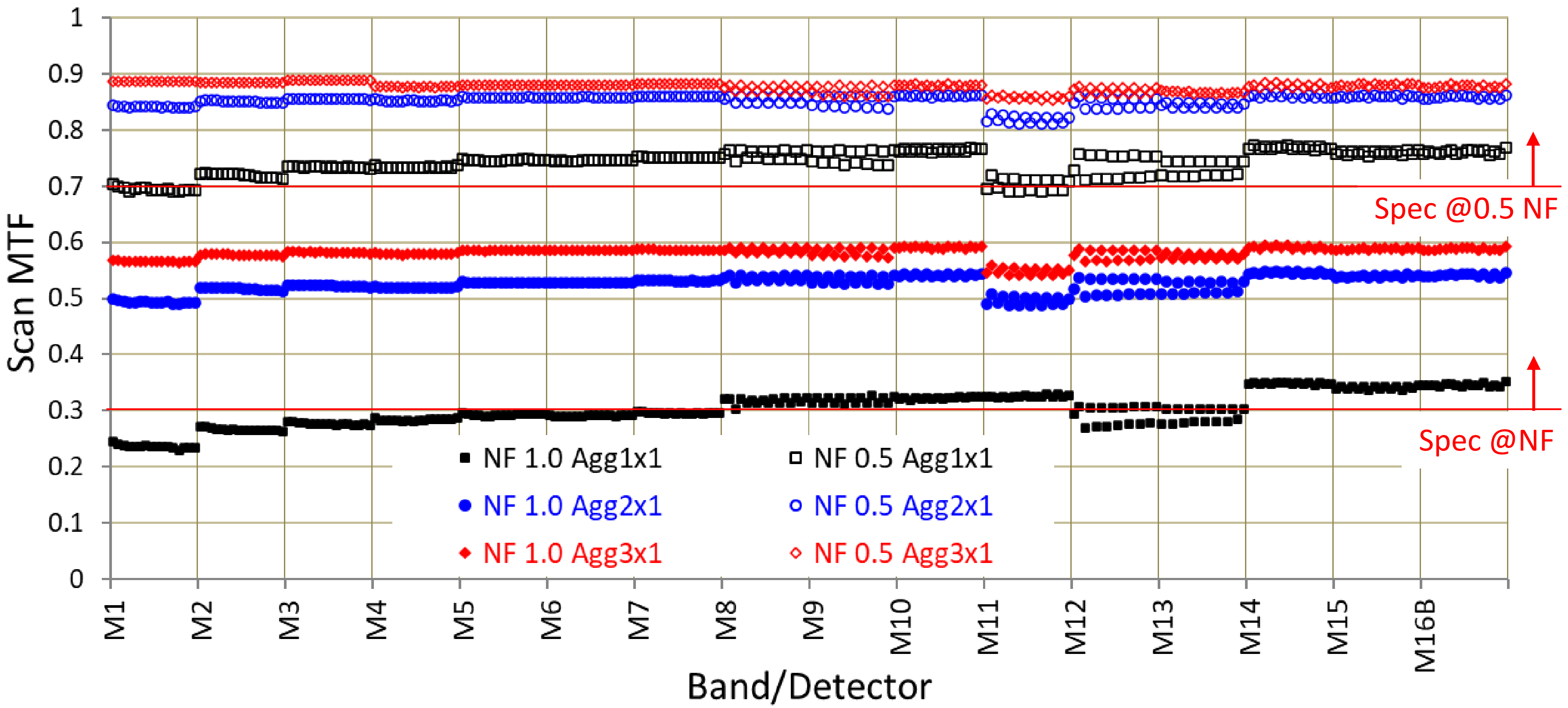
- I-bands under-sample in all aggregation zones
- M-bands oversample in Agg1x1 zones
- DNB and M-bands in Agg2x1 & 3x1 zones sample at “Nyquist”

SNPP VIIRS GRD in scan direction



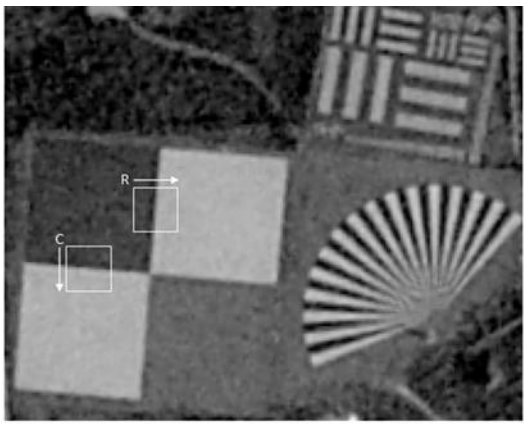
- GRD as an "effective" resolution (where MTF drops to ½) affected by system blur
- Waivers were approved for spec non-compliance for bands I1, I2 at the end of scan

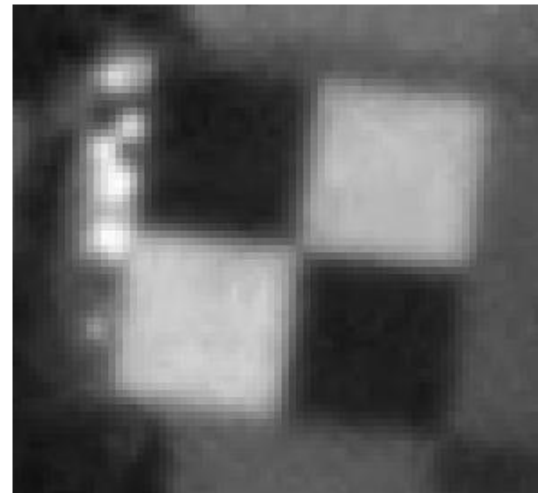
SNPP VIIRS MTF in scan direction



- MTF improves as more samples are aggregated
- Waivers were approved for spec non-compliance in some bands

Validation sites for VHR images





https://calval.cr.usgs.gov/apps/spatialsites_catalog

China site, 40.854^{o}N, 109.628^{o}E.

4 48 m x 48 m slanted squares.

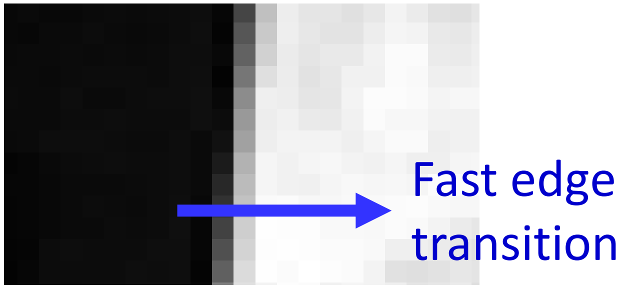
India site, 17.034^{o}N, 78.183^{o}E.

4 70 m x 70 m slanted squares.

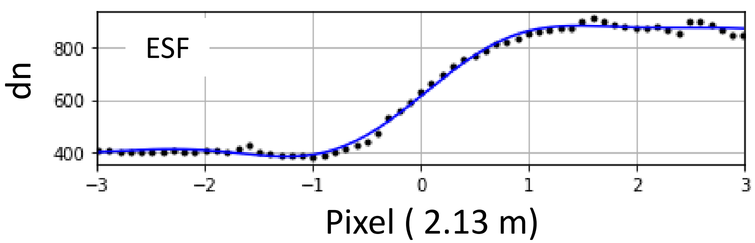
- Construct edge spread function (ESF)
- Derive line spread function (LSF)

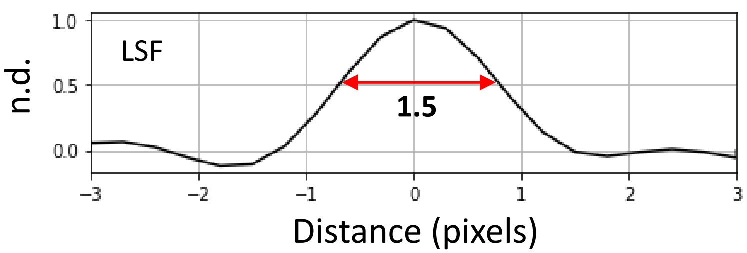
WorldView-2 and Planet Images

over China site

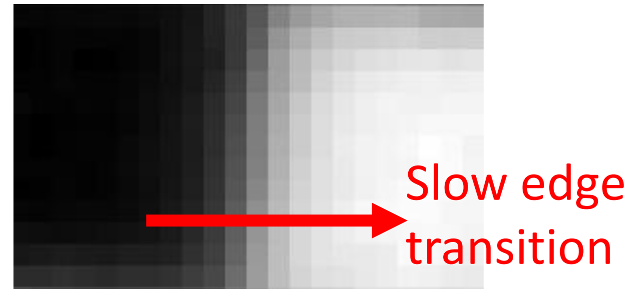


Worldview-2 image, red band
raw pixels: along row

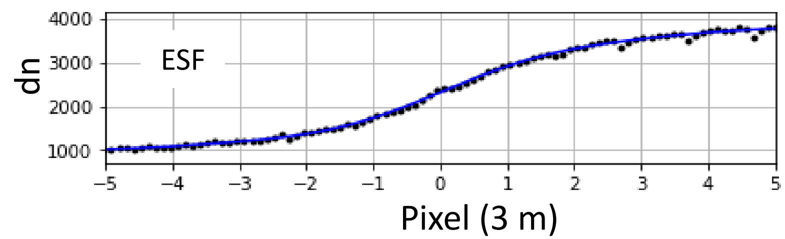


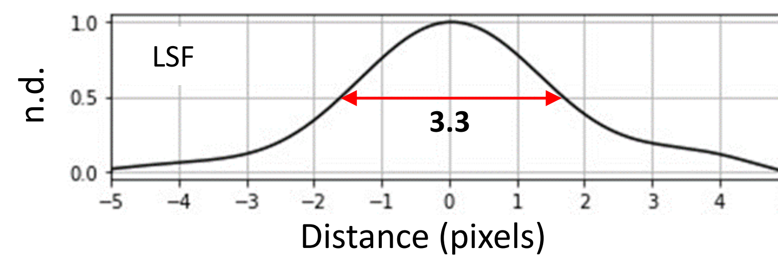


FWHM = 1.5 pixels = 3.2 m



Planet Image, red band
raw pixels: along row





FWHM = 3.3 pixels = 9.9 m

- Slower edge transition blurs the edge. It has larger SSR/pixel ratio.
- The Planet image is over-sampled > 3 times.

Grid aggregation of Planet Image

over China site

Original, 3m pixels

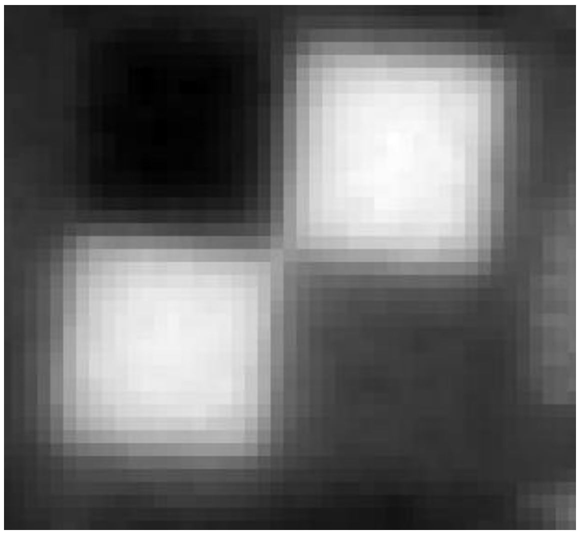
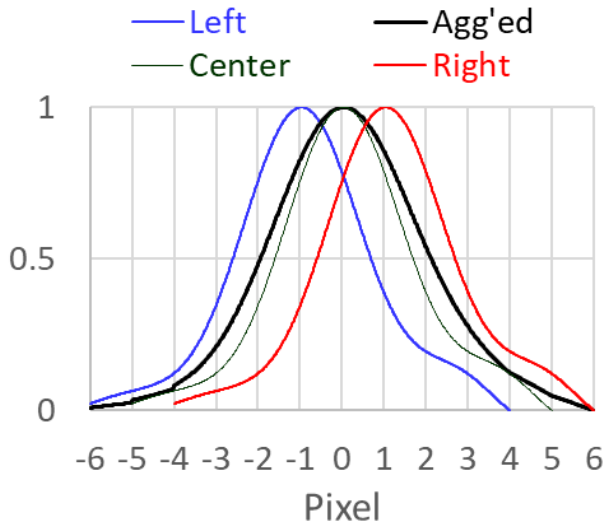


Image ID: 20221005_031939_43_2254

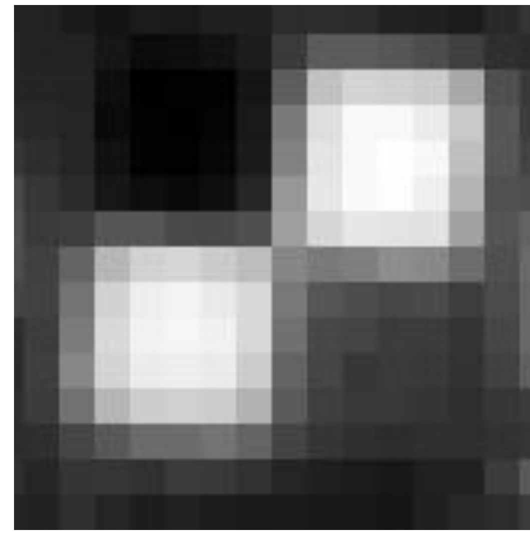
SSR/pixel-size ratio = 3.3

3-to-1 LSF aggregation



Agg’ed FWHM = 4.1 pixels
= 1.4 agg’ed pixels

3x3-pixel Agg to 9m pixels



SSR/pixel-size ratio = 1.4

- The aggregated image has sharper edges, SSR/pixel-size ratio 3.3 → 1.4
- Data volume down ~90% (1.11 GB → 114.5 MB) and SNR up 200%.

Planet image over India site

4 70 x 70 m squares

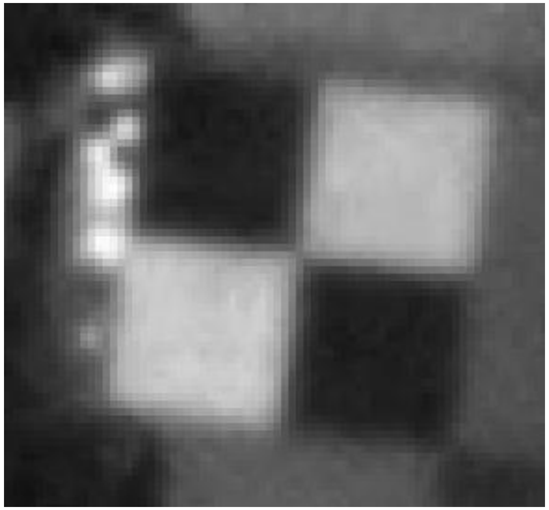
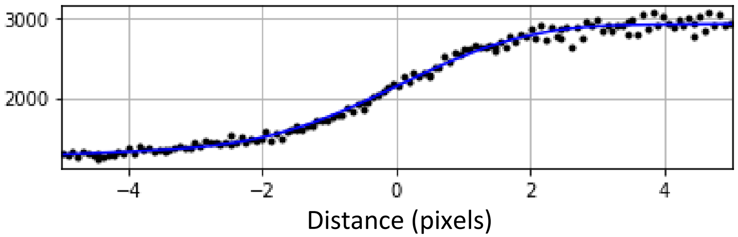


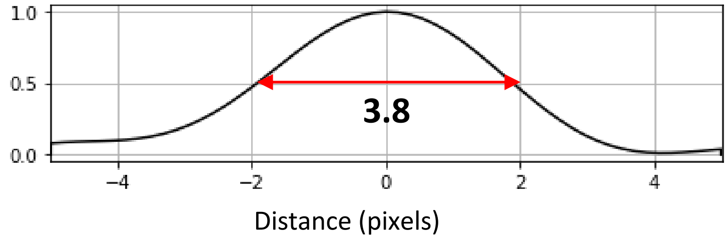
Image ID: 20230310_042633_64_24a1
Band: Red

Edge used in evaluation

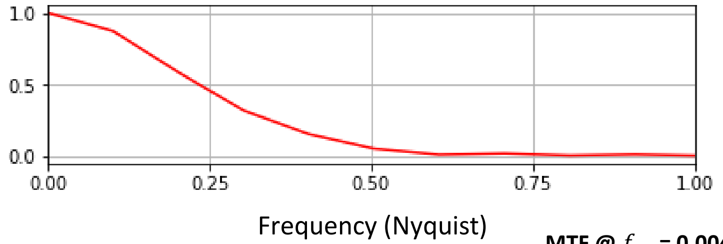
Red Edge Spread Function (ESF)



Red Line Spread Function (LSF)



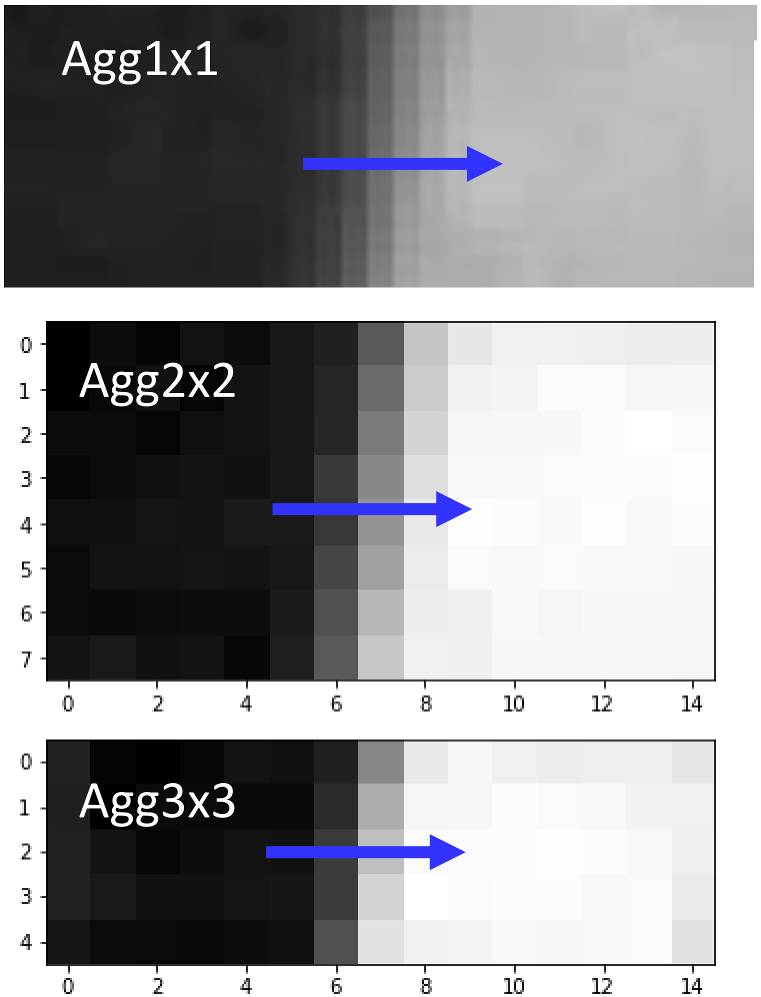
Red Modulation Transfer Function (MTF)



MTF @ f_{ny} = 0.004

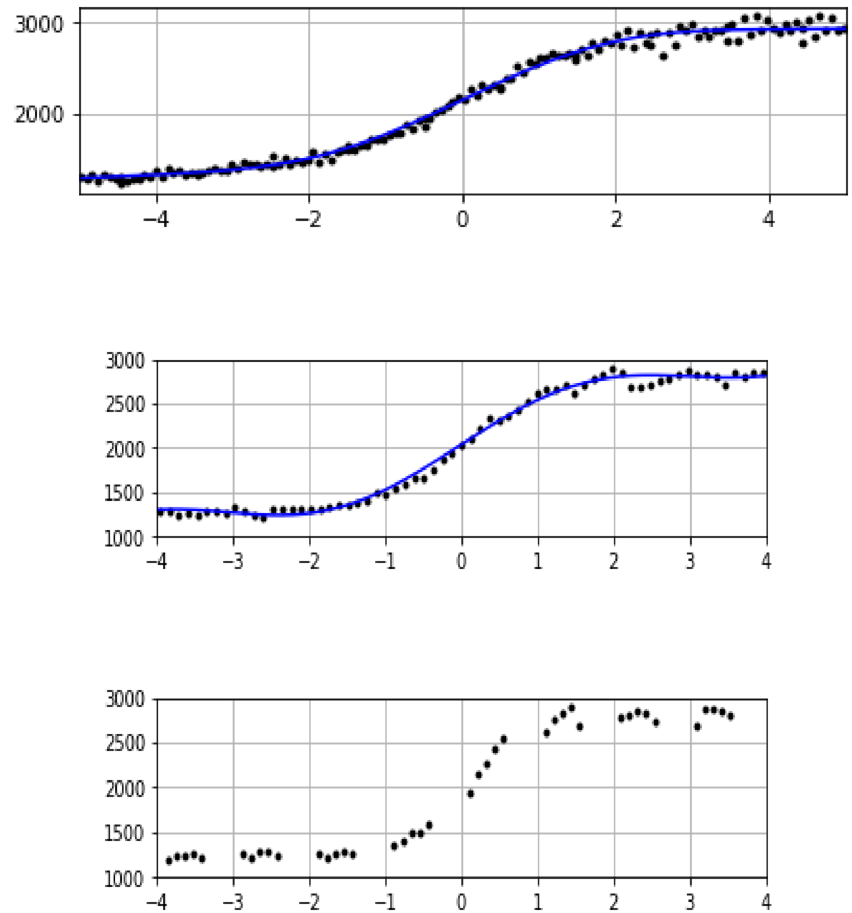
Effects of aggregation for Planet images

over India site



Changes in edge transition

Red Edge Spread Function (ESF)



Distance (Agg'ed pixels)

BlackSky images & aggregation

over China site

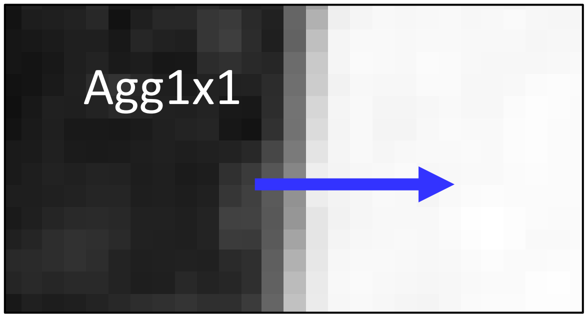
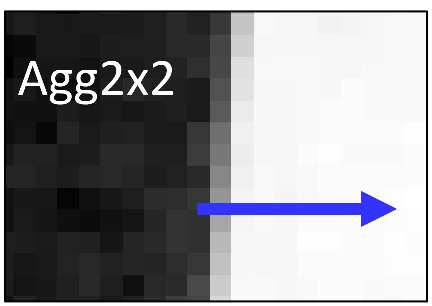
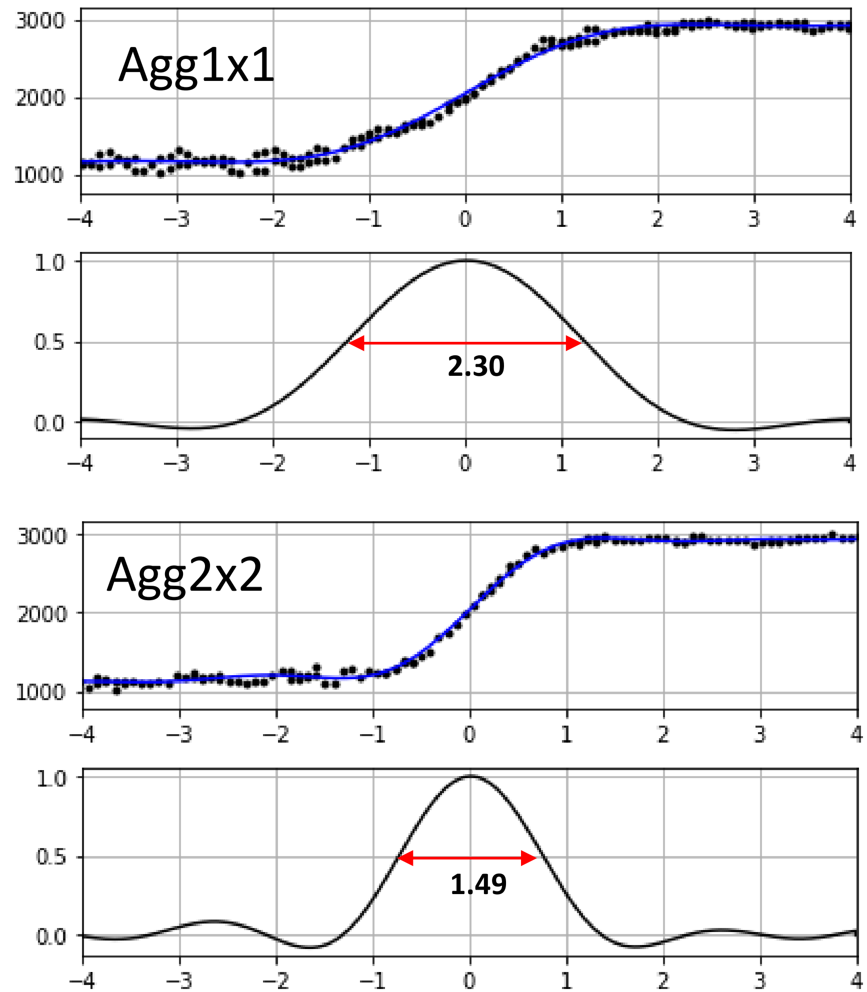


Image ID: BSG-115-20220220-001023-19247291
Band: Red
Pixel size: 0.93 m (original)



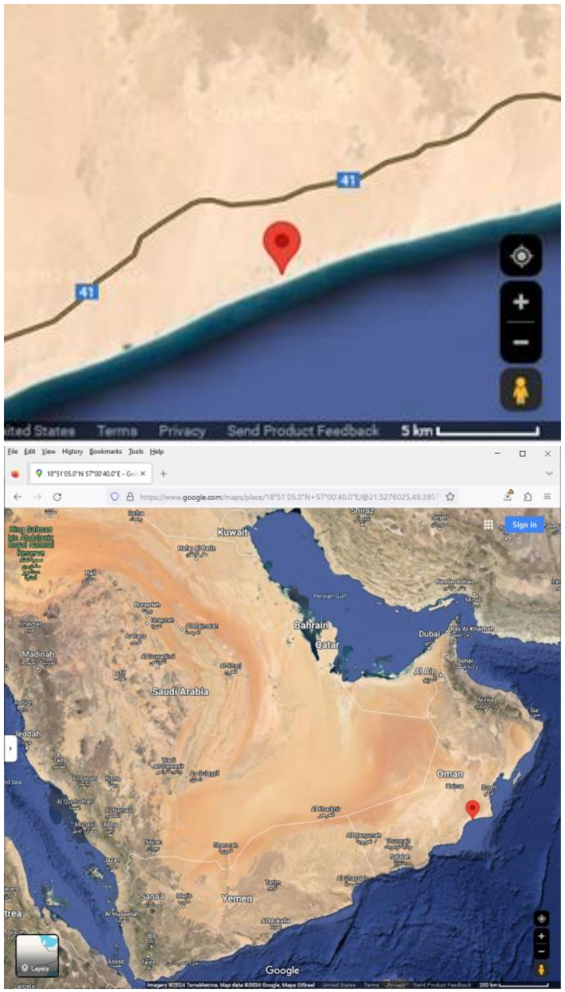
Change in edge transition

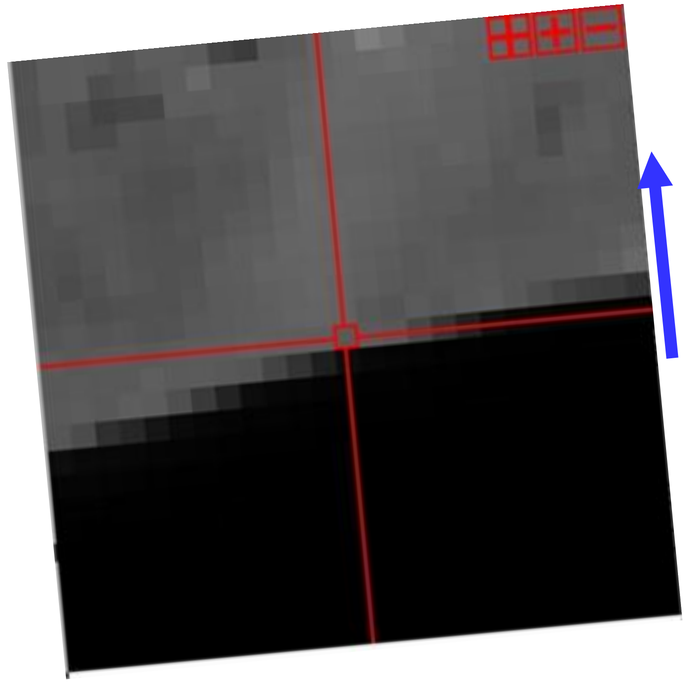
Red Edge Spread Function (ESF)



Distance (Agg'ed pixels)

VIIRS DNB edge sampling

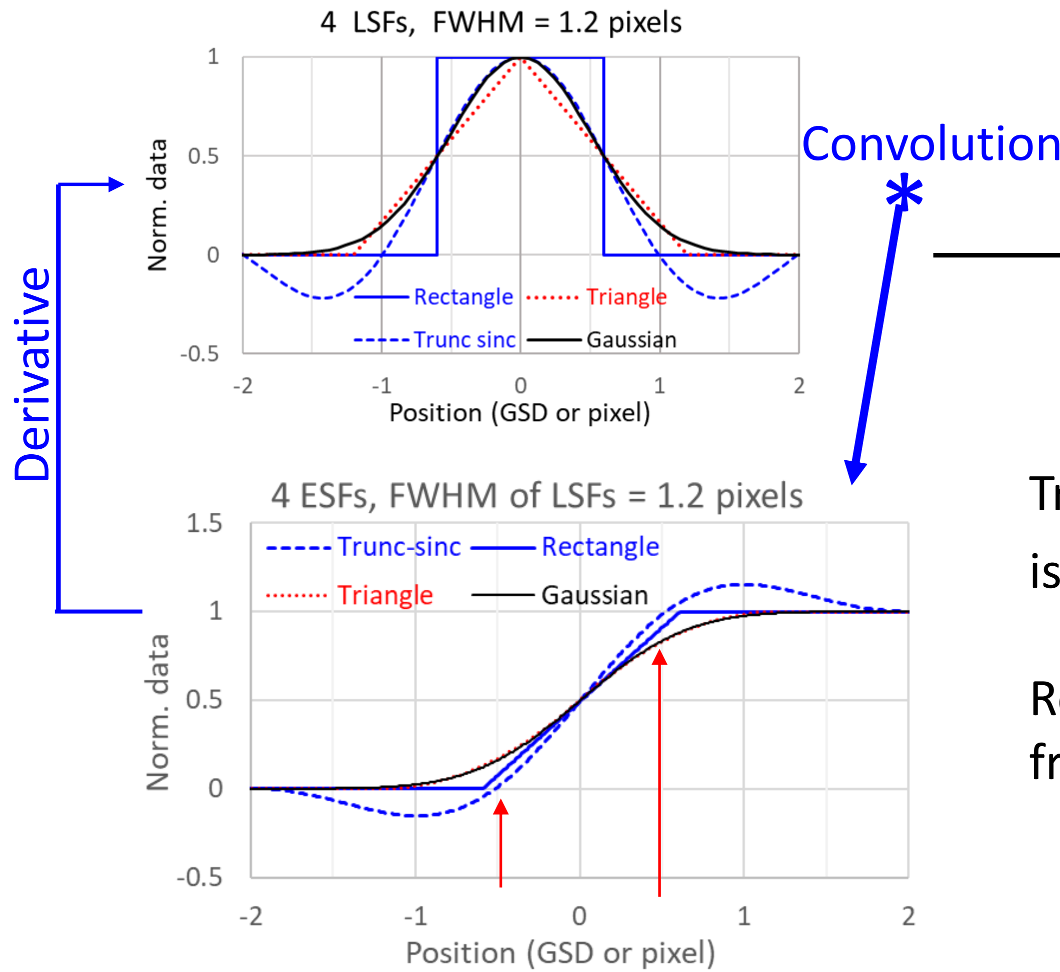


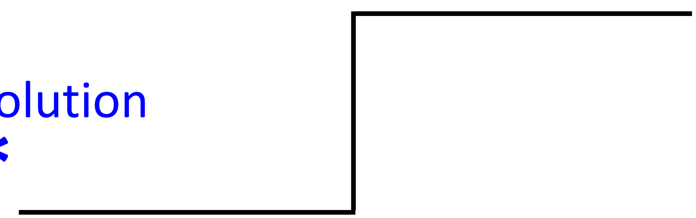


- Nyquist sampling
- Fast edge transition

Sample in Oman, Arabian peninsula
J2 VIIRS DNB Level-1B swath data
Day: 2022340 Granule: 0912
Lat, Long: 18.8514N, 57.0111E
Sample, Line:2312, 2977 (granule size 4064x3232)

Simulation:
LSF, ESF, FWHM





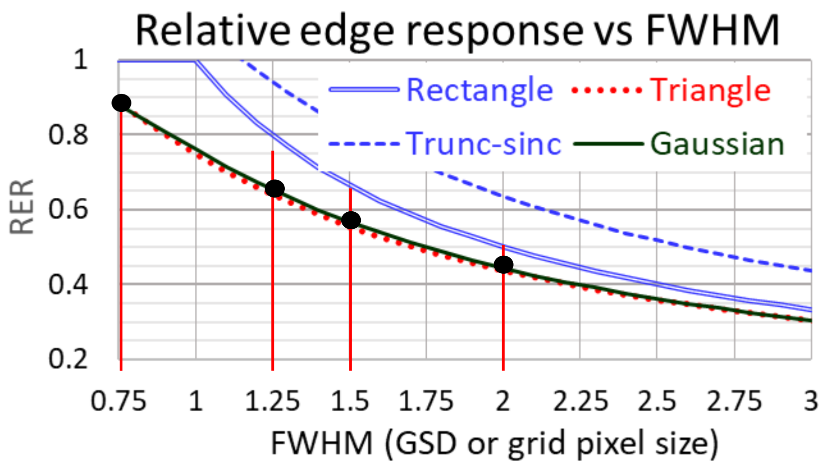
Step (edge) function

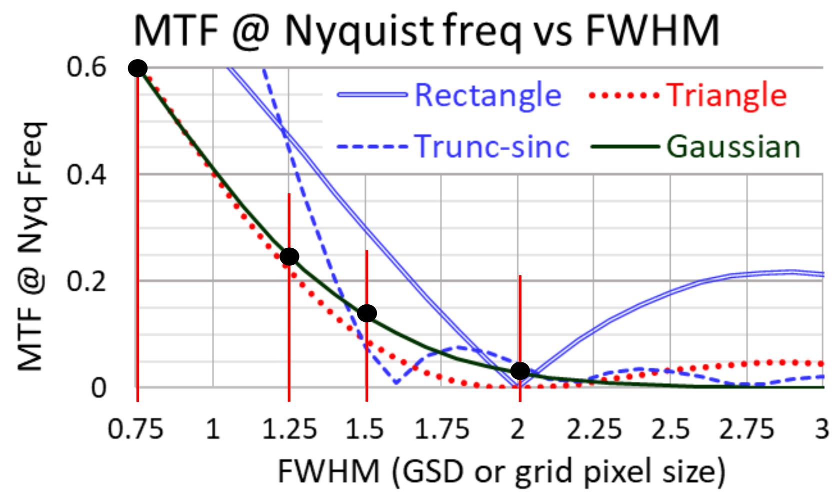
Truncated sinc function $\frac{sin(x)}{x}$ is defined in [-2π, +2π]

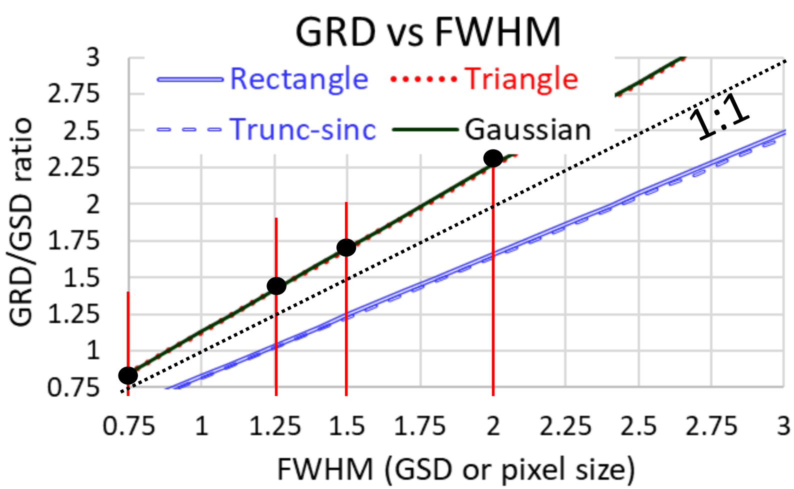
Relative edge response (RER) from edge spread function (ESF)

$$RER = \frac{ESF(0.5) - ESF(-0.5)}{ESF(\infty) - ESF(-\infty)}$$

Simulation:
RER, MTF, GRD







Gaussian function is used to set grading criteria (next chart)

Spec/Grading discussion: SSR, RER, MTF, GRD?

- Primary parameter: SSR to GSD or pixel-size ratio?

	Ideal?	Excellent?	Good?	Basic?
SSR/pixel ratio	(0.75, 1.25]	(1.25, 1.5]	(1.5, 2.0]	> 2.0

- Secondary parameters: RER, MTF and GRD based on Gaussian LSF?

	Ideal?	Excellent?	Good?	Basic?
RER	[0.65, 0.9)	[0.55, 0.65)	[0.44, 0.55)	< 0.44
MTF@NF	[0.25, 0.6)	[0.13, 0.25)	[0.03, 0.13)	< 0.03
GRD/pixel ratio?	(0.8, 1.4]	(1.4, 1.7]	(1.7, 2.25]	> 2.25

DRAFT

Acronyms:
SSR: Sensor Spatial Resolution = FWHM
FWHM: full-width at half-maximum of LSF
LSF: sensor system line spread function
GSD: ground sampling distance
RER: relative edge response
MTF: modulation transfer function
NF: Nyquist frequency
GRD: ground resolved distance

Earth Observation Mission Quality Assessment Framework - Optical Guidelines

Backup slides

References

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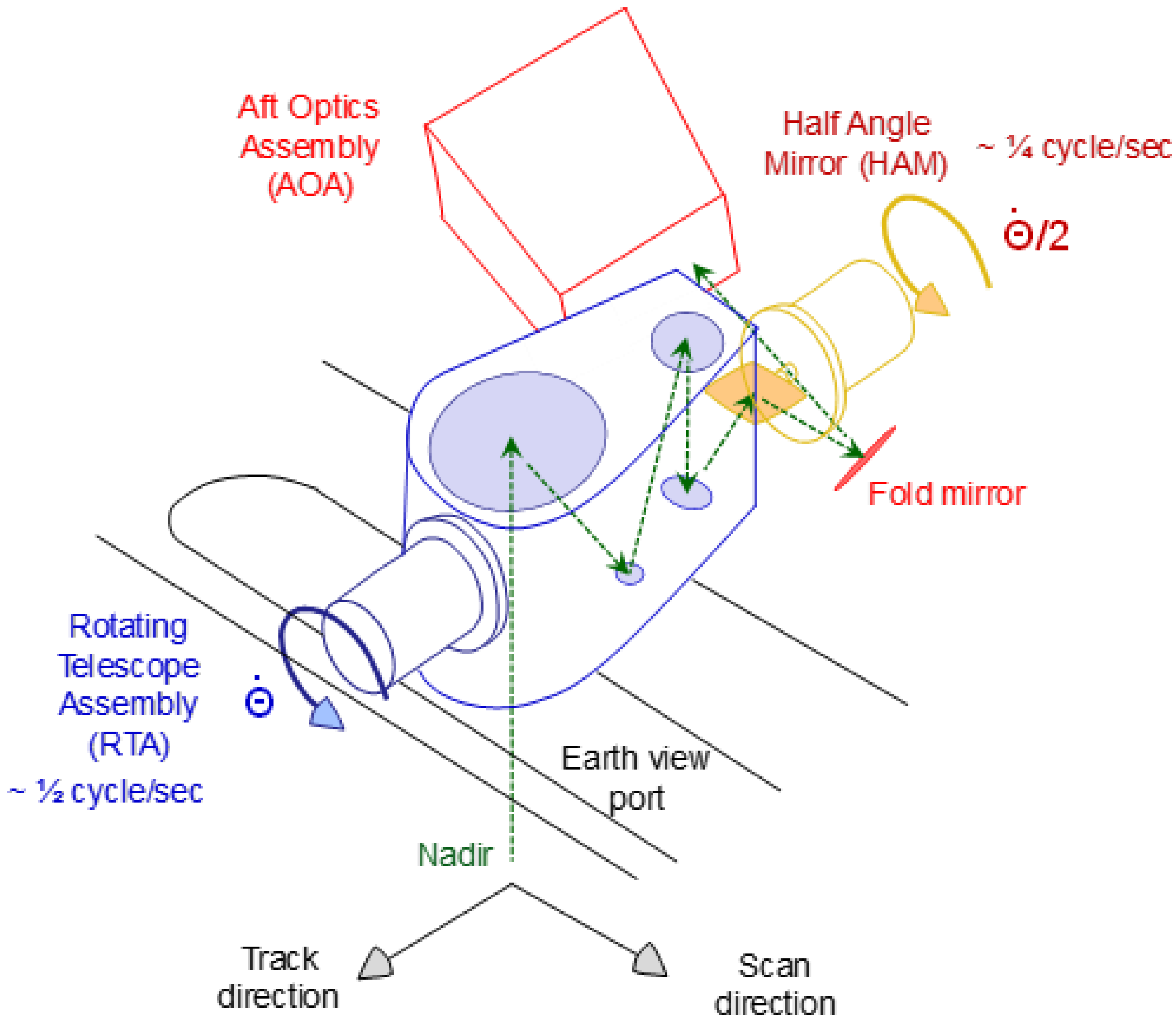
Acronyms of example sensor, satellites

- AVHRR: Advanced Very-High-Resolution Radiometer
- OLS: Operational Linescan System
- VIIRS: Visible Infrared Imaging Radiometer Suite
- ABI: Advanced Baseline Imager
- NPOESS: National Polar-Orbiting Operational Environmental Satellite System
- NPP: NPOESS Preparatory Project
- SNPP: Suomi National Polar-orbiting Partnership (Suomi NPP) = NPP renamed after launch
- JPSS: Joint Polar Satellite System (J1 = NOAA-20, J2 = N21 after launch, J3 & J4 to be launched ~ 2032, 2027)
- GOES-R: Geostationary Operational Environmental Satellites-R series (-R/16/East, -S/17/Storage, -T/18/West, -T to be launched mid-2024)

VIIRS instrument characteristics

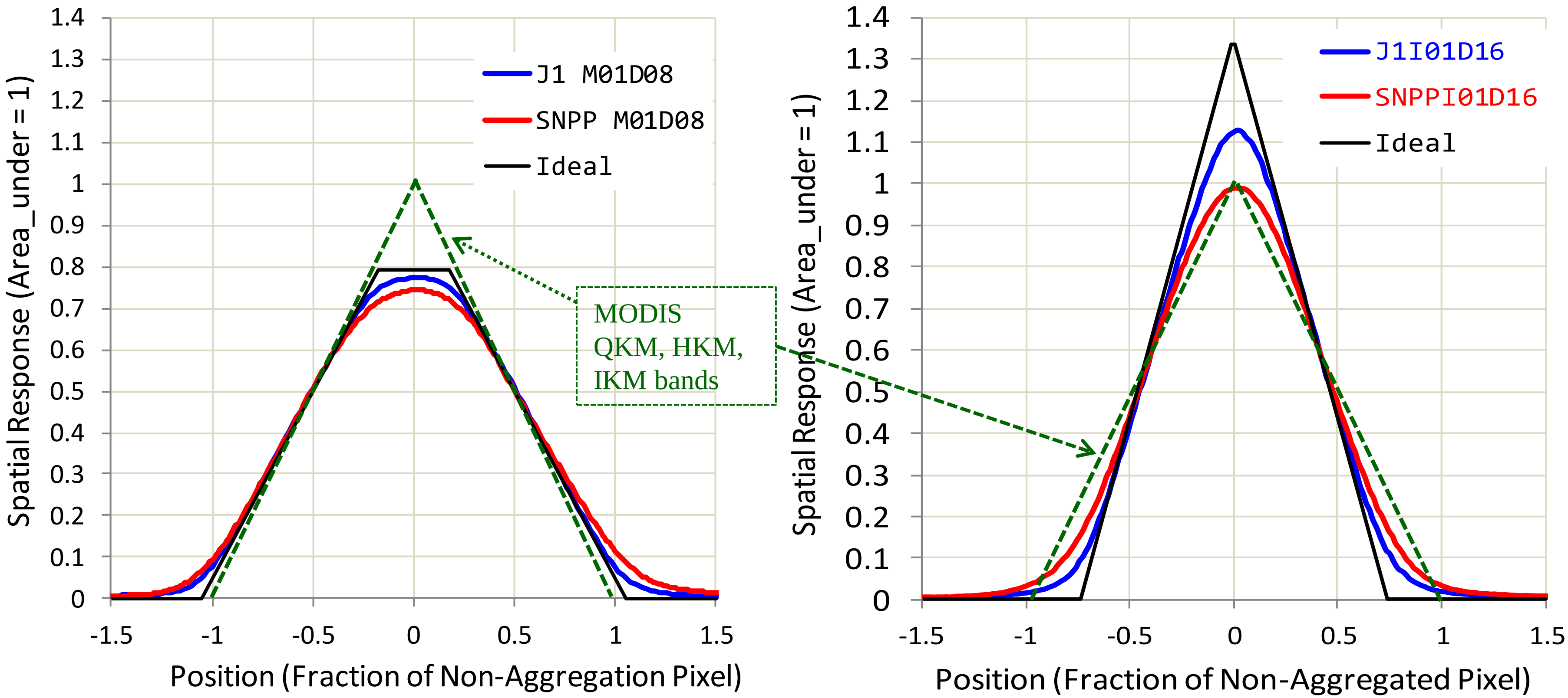


VIIRS 22 Bands:
16 M-Band, 5 I-Band and 1 DNB

VIIRS Band	Spectral Range (um)	Nadi GSD (m)
DNB	0.500 - 0.900	750
○ M1	0.402 - 0.422	750
○ M2	0.436 - 0.454	750
○ M3	0.478 - 0.498	750
○ M4	0.545 - 0.565	750
I1	0.600 - 0.680	375
○ M5	0.662 - 0.682	750
M6	0.739 - 0.754	750
I2	0.846 - 0.885	375
○ M7	0.846 - 0.885	750
M8	1.230 - 1.250	750
M9	1.371 - 1.386	750
I3	1.580 - 1.640	375
M10	1.580 - 1.640	750
M11	2.225 - 2.275	750
I4	3.550 - 3.930	375
M12	3.660 - 3.840	750
○ M13	3.973 - 4.128	750
M14	8.400 - 8.700	750
M15	10.263 - 11.263	750
I5	10.500 - 12.400	375
M16	11.538 - 12.488	750

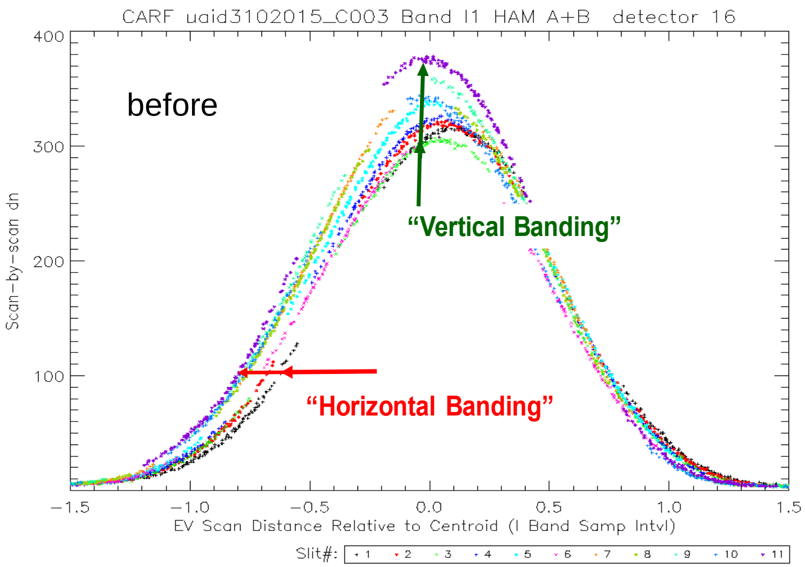
○ **Dual gain band**

Optical calibration



- J1 VIIRS has improved optical system over SNPP
- J2, J3, J4 ~= J1

LSF “banding” issue in VIIRS ground testing



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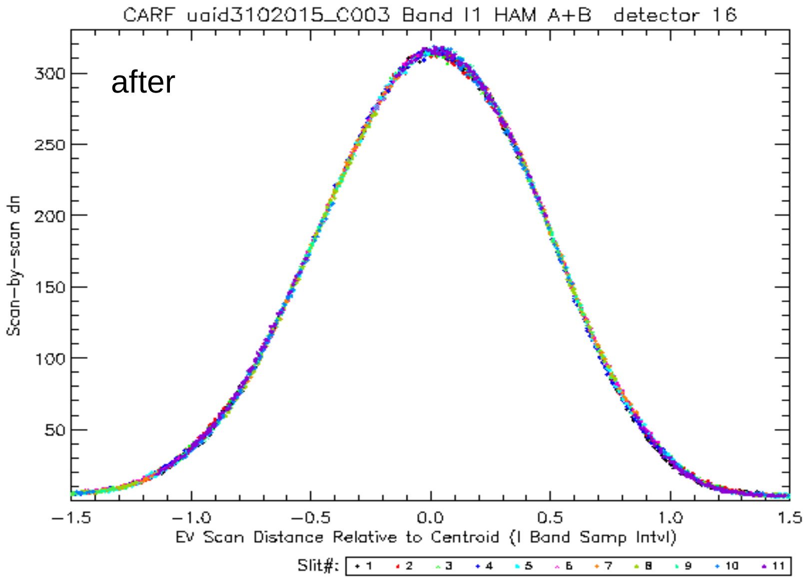

- “Horizontal banding” was caused by test reticle slits phase (spacing) non-uniformity
- “Vertical banding” was caused by test reticle slits throughput (opening) non-uniformity
- Resolved by using the calibratee (instrument) to calibrate the calibrator (test equipment)

For more details of the issue, c.f.: Fang, D.T and Puschell, J. (2010), “Imagery spatial performance throughput correction methodology,” Remote Sensing System Engineering III, SPIE 7813, doi: 10.1117/12.860740.