Spatial Performance Analysis of Satellite Images using Causeways

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Minsu Kim
KBR / Chief Scientist
minsukim@contractor.usgs.gov

KBR, contractor to the U.S. Geological Survey (USGS)
U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD 57198, USA.
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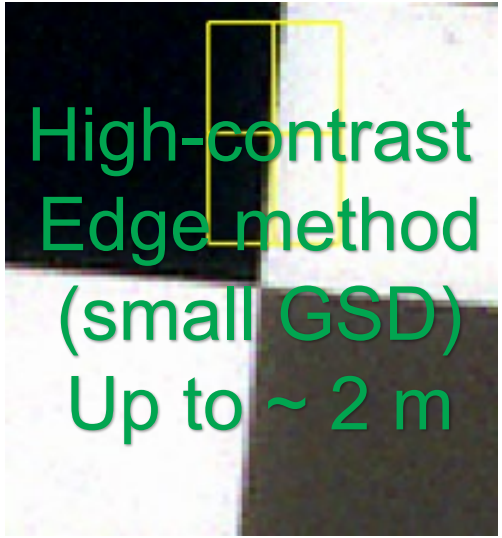
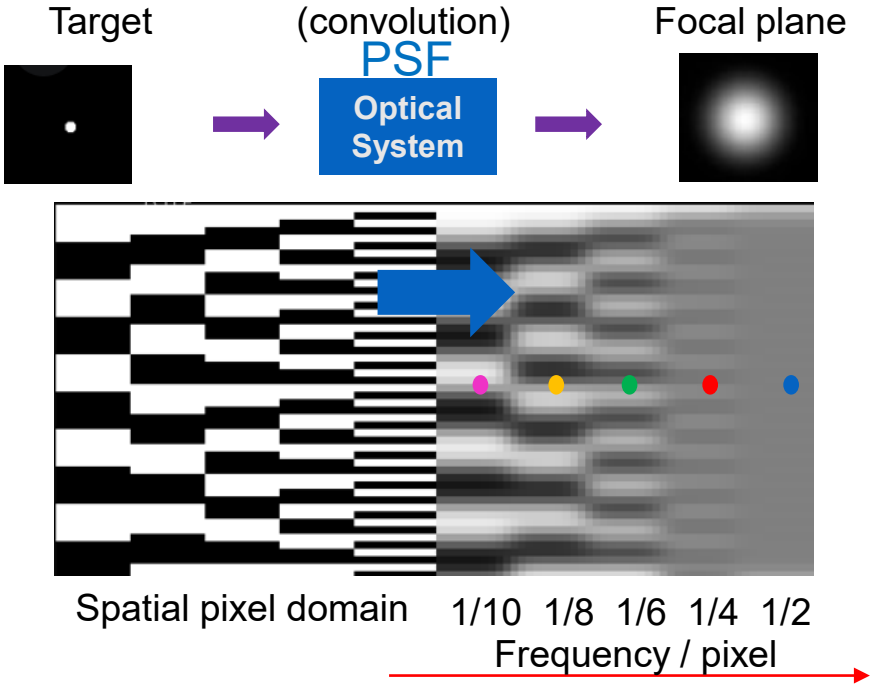
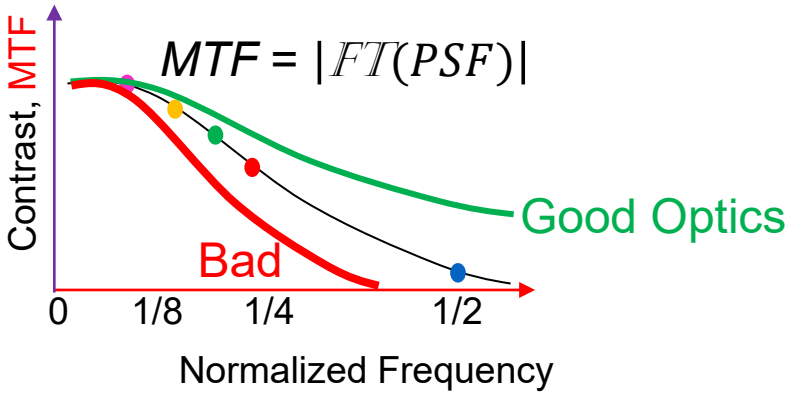
Spatial Performance Analysis of Satellite Image



PSF (impulse response)

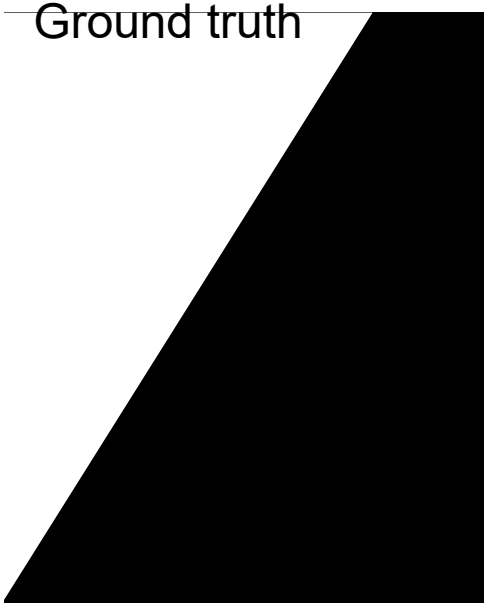


Contrast (normalized difference) at frequency domain

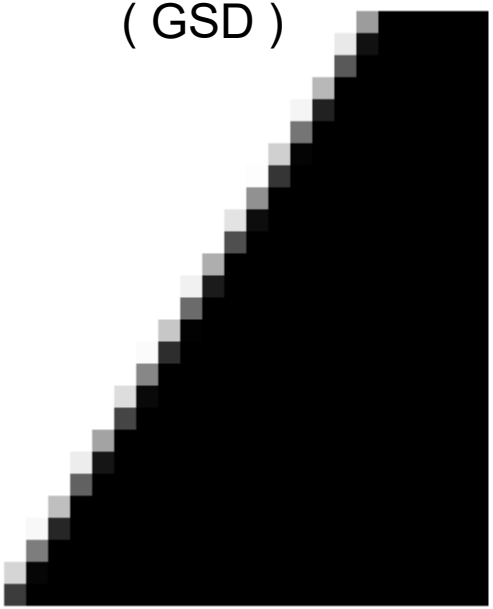


Spatial Analysis using High Contrast Edge

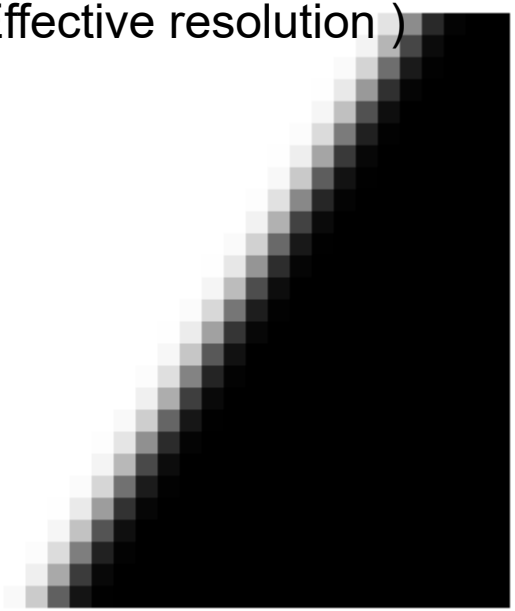
Analog
Ground truth

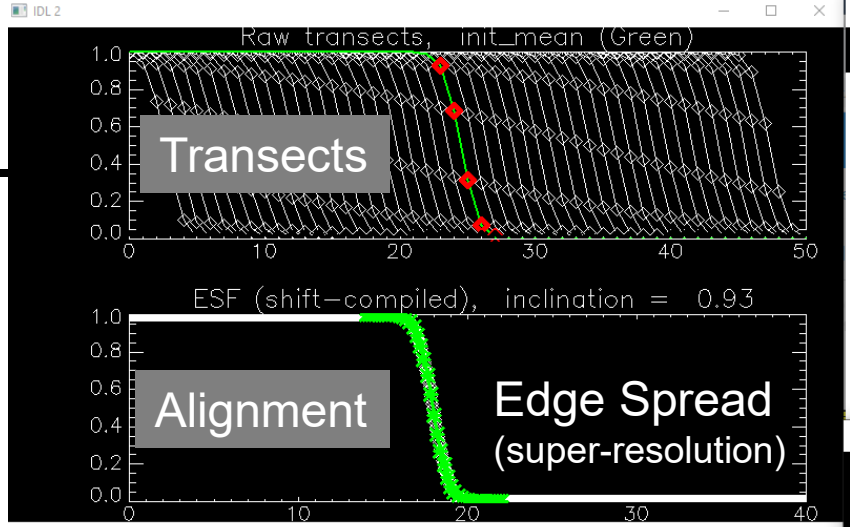


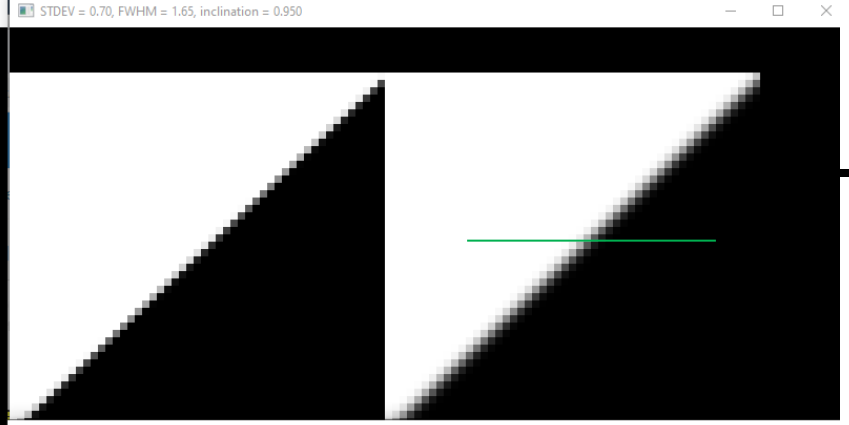
Discrete Resampling
(GSD)

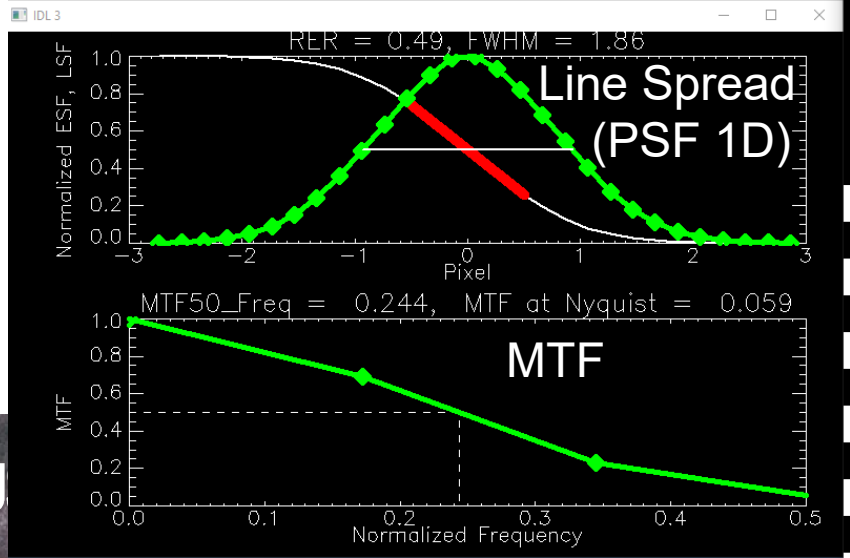


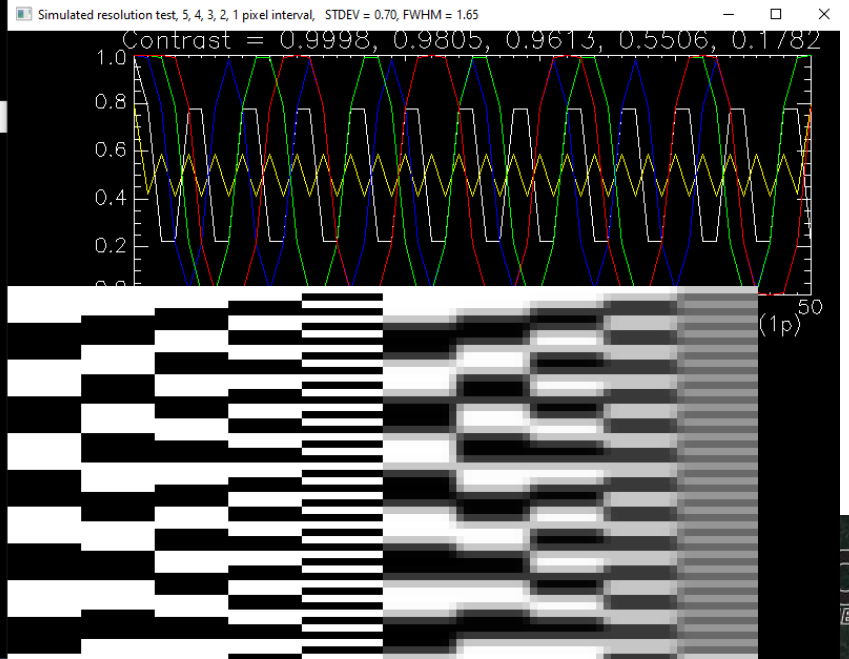
Convolution w/ PSF
(Effective resolution)



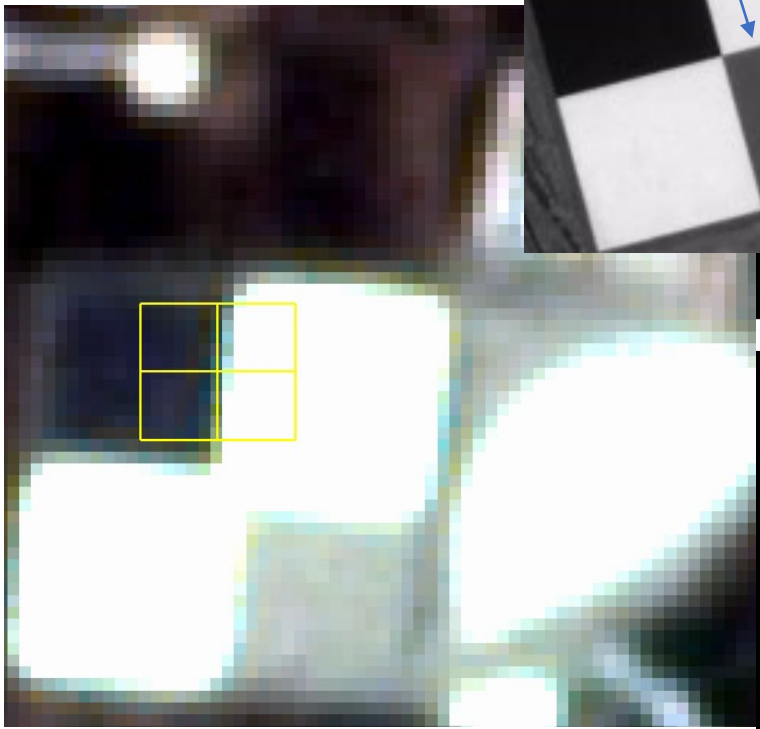

IDL 2
Raw transects, init_mean (Green)
Transects
ESF (shift-compiled), inclination = 0.93
Alignment
Edge Spread
(super-resolution)

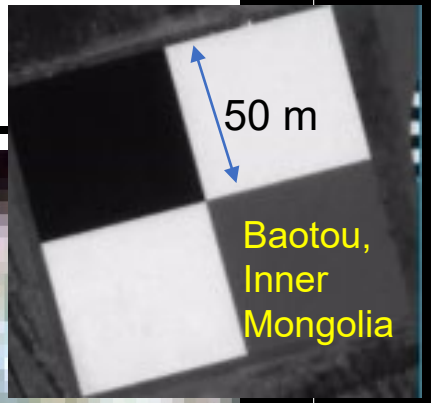

STDEV = 0.70, FWHM = 1.65, inclination = 0.950

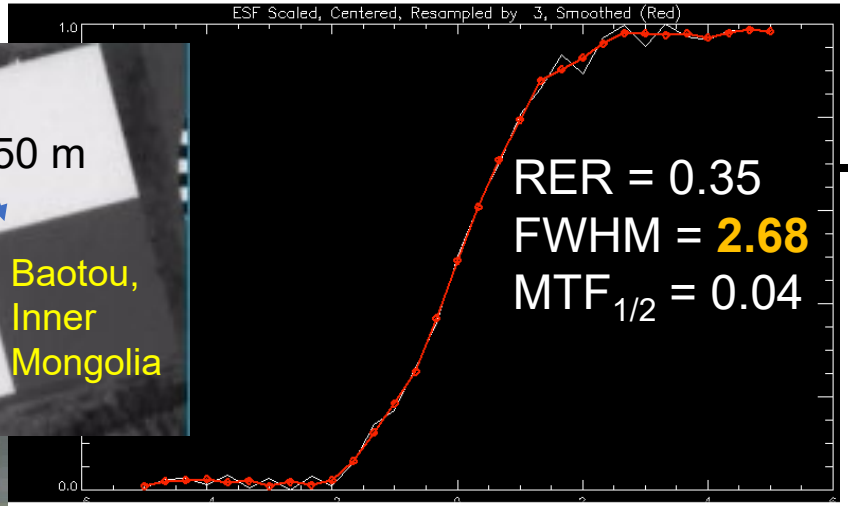

IDL 3
RER = 0.49, FWHM = 1.86
Normalized ESF, LSF
Pixel
Line Spread
(PSF 1D)
MTF50_Freq = 0.244, MTF at Nyquist = 0.059
MTF
Normalized Frequency

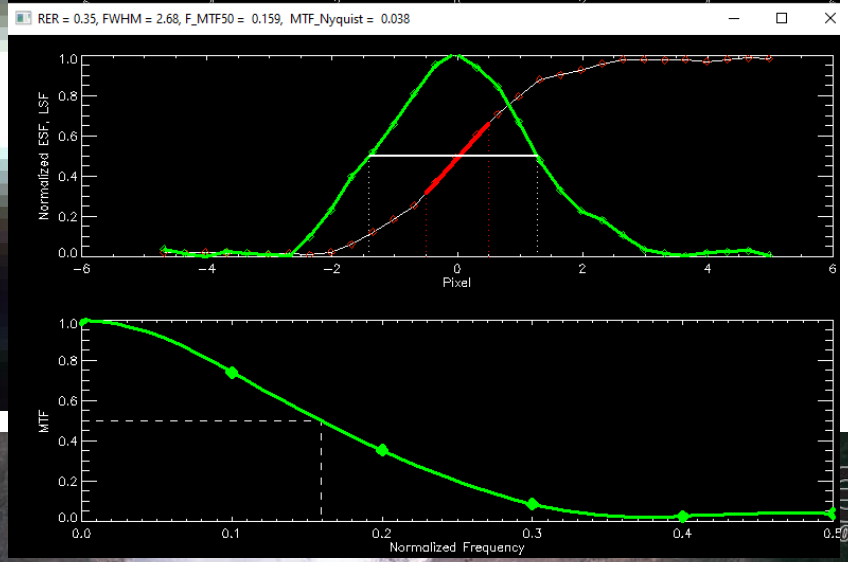

Simulated resolution test, 5, 4, 3, 2, 1 pixel interval, STDEV = 0.70, FWHM = 1.65
Contrast = 0.9998, 0.9805, 0.9613, 0.5506, 0.1782
(1p)

Blurry sensor

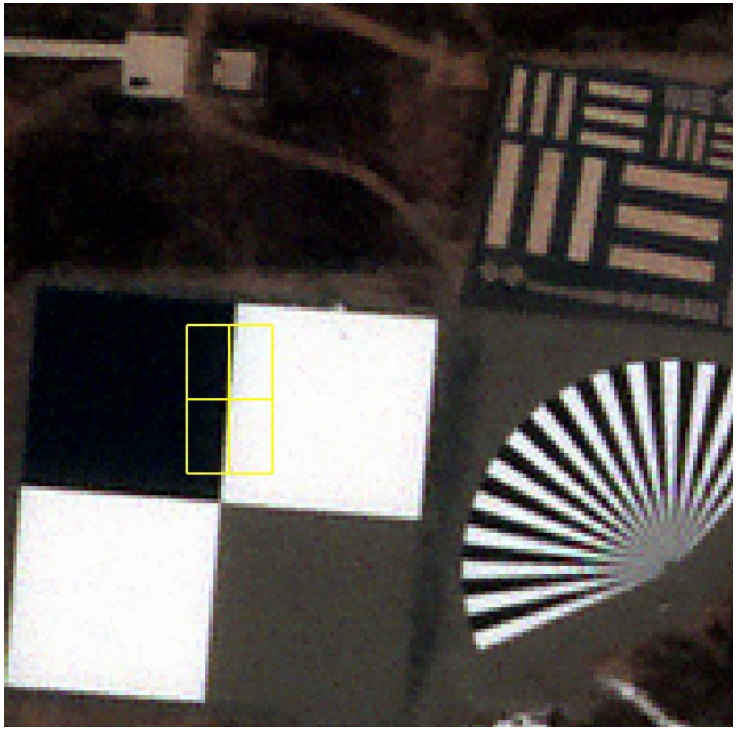


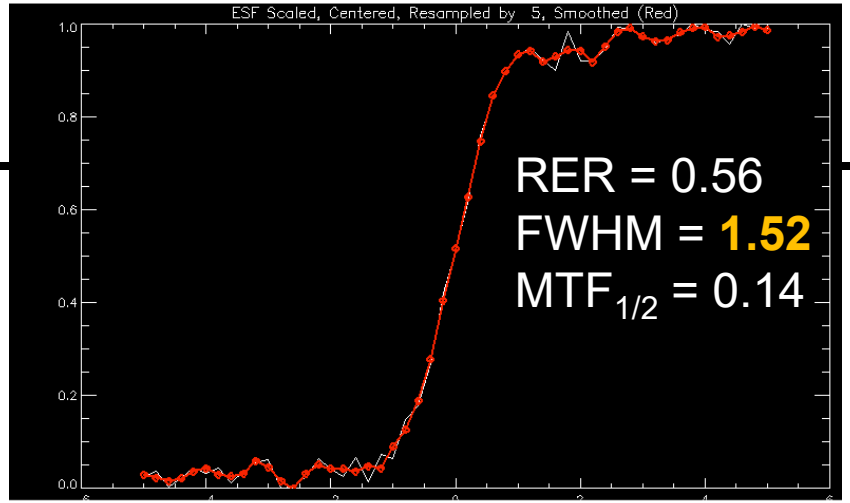


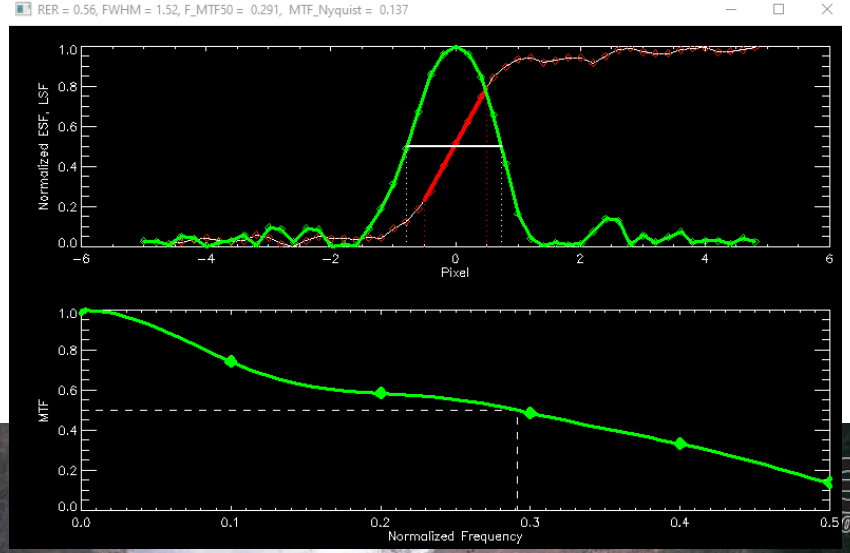




Sharper sensor







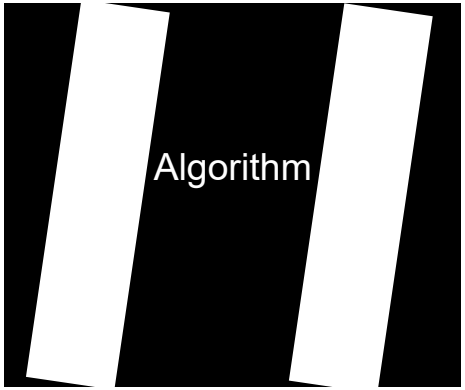
Ukraine
Russia
Farmland

Hedgerow (x)
Road (x)

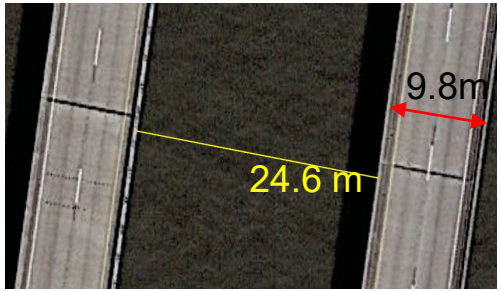
High contrast
(crop types)

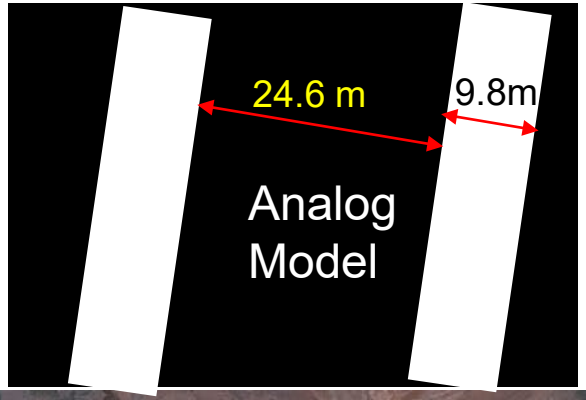
USGS

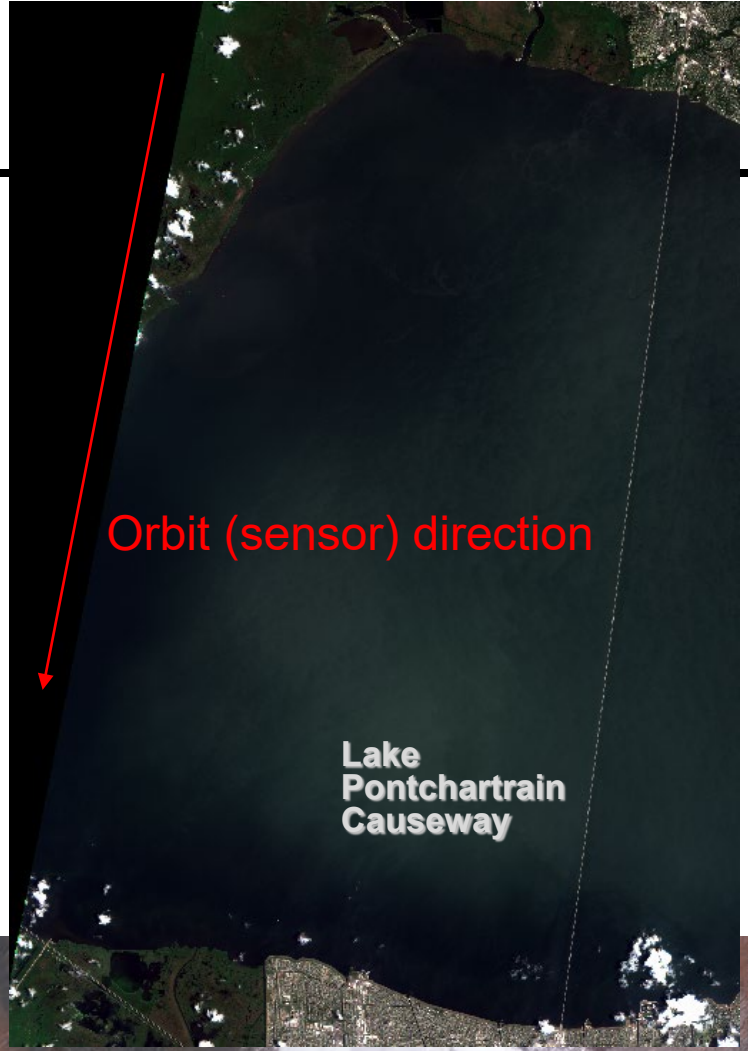
Bridge Method



Analog Bridge Modeling





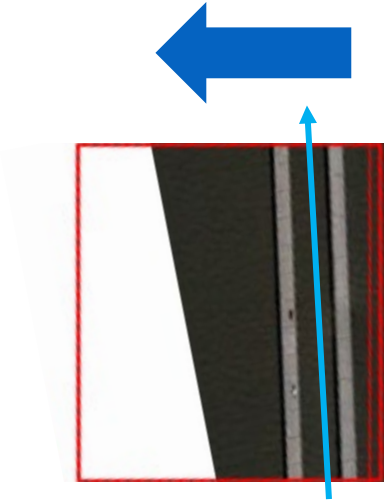


USGS

Imaging at Satellite Coordinate

Causeway
Tilted to eastward

Imaging at Sat. Coord.
Causeway tilted to westward



Bridge Modellig
Sat. Coord.

Analog Modelling

↓

Discrete Sampling (GSD)

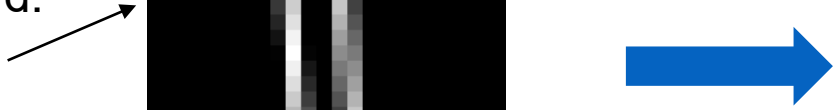
PSF Convolution

Gaussian
(FWHM)

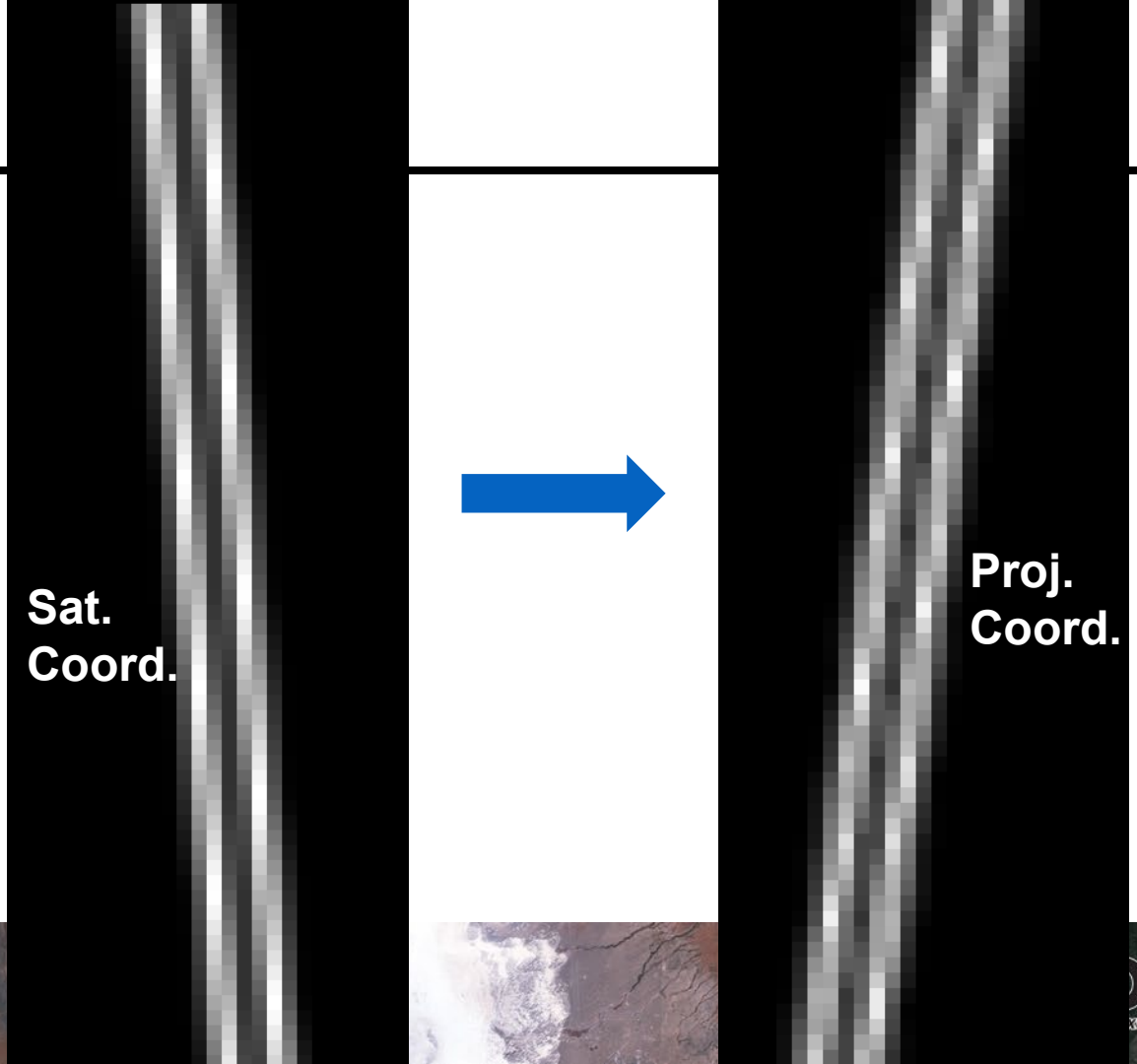
* **PSF =**

Convoluted
Image
(blurred)

Analog bridge
in Sat. Coord.
Discretized
using GSD



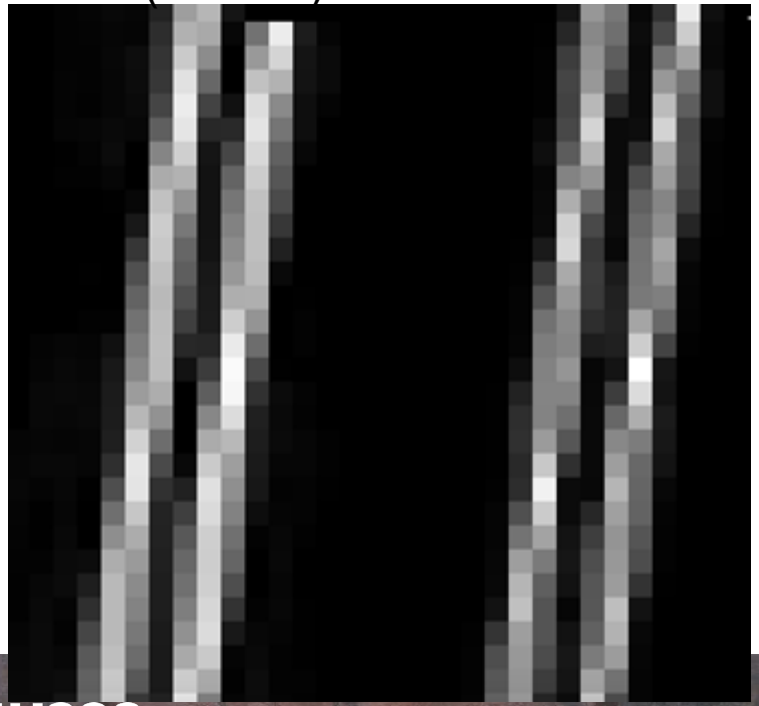
Resampling to Projection Coord (UTM)



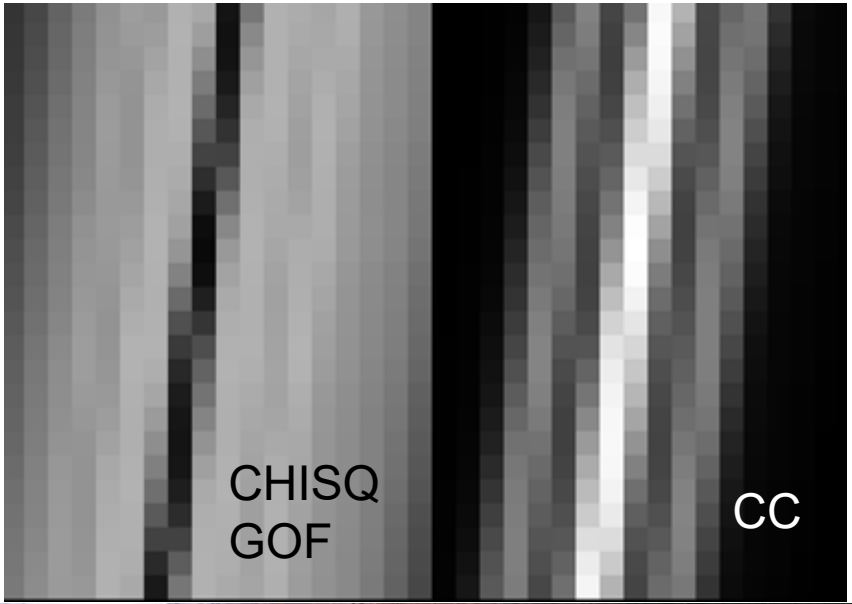
To estimate unknown PSF (FWHM)
Quantify the Similarity between Model & Image

Model
= f (FWHM)

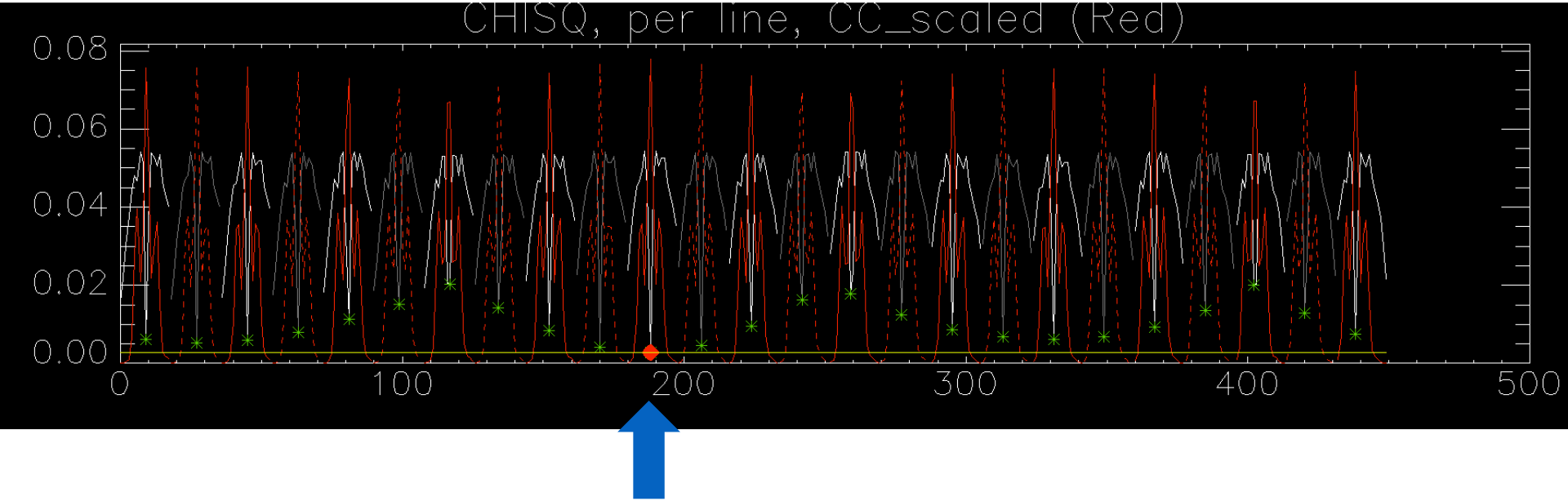
Image (S2 MSI)



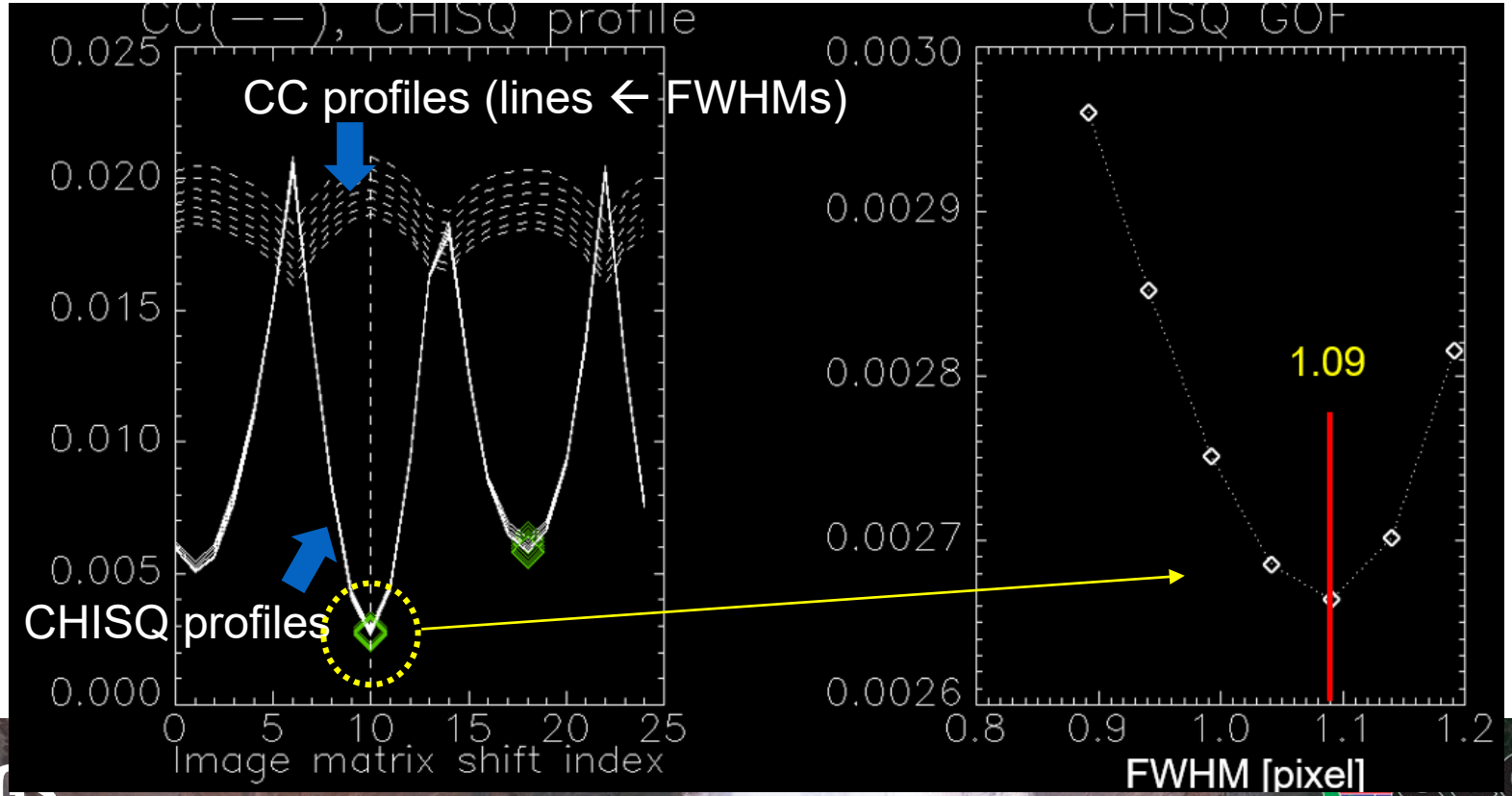
Similarity : using (1) Cross-correlation
(2) RMSD (3) CHISQ GOF



Find Best Similarity between Model & Image

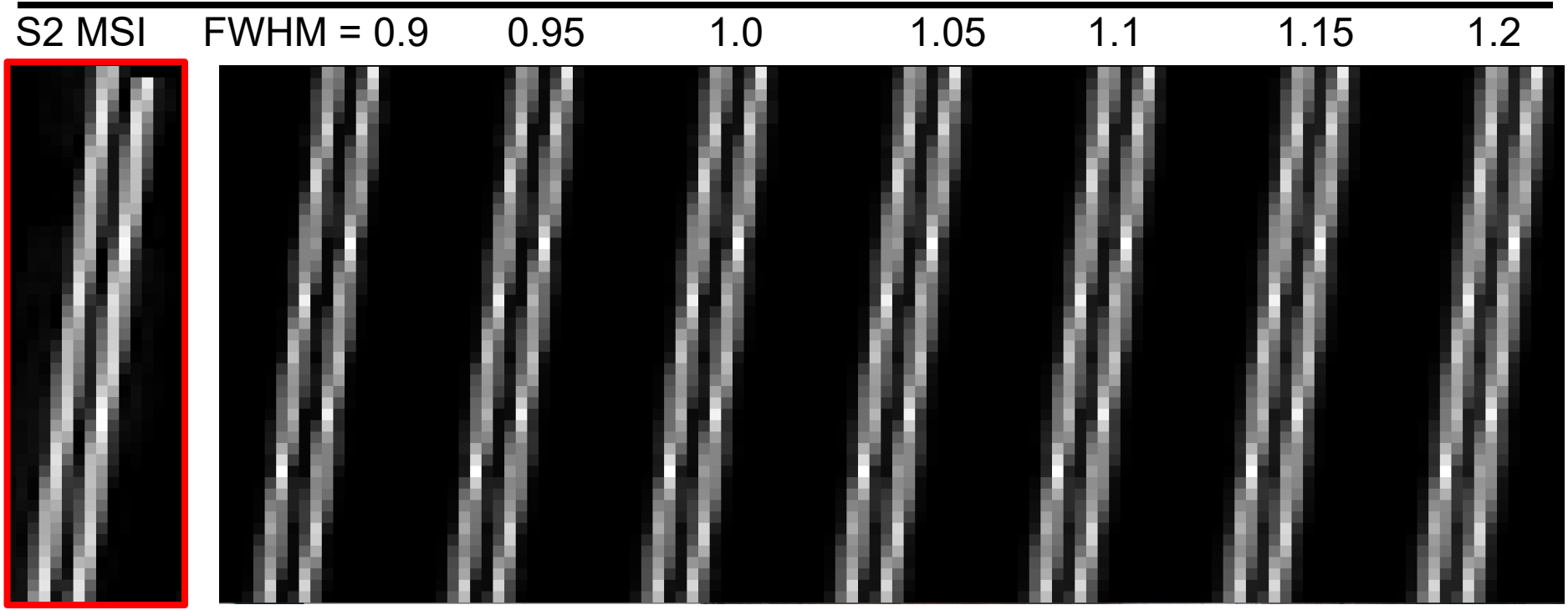


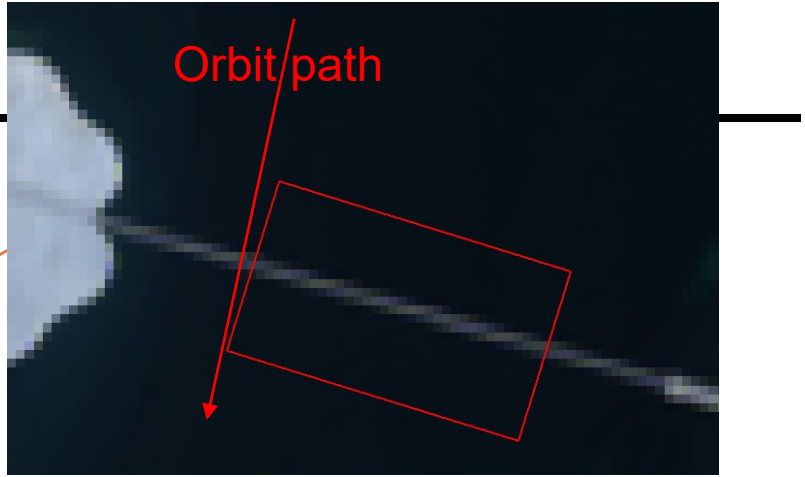
Determine best-matching FWHM (from a range of FWHMs)

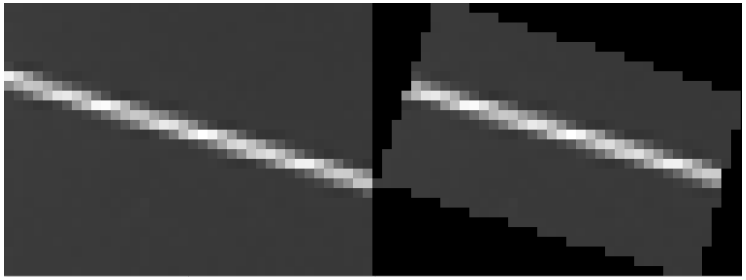


Best-matching FWHM

(1.09)

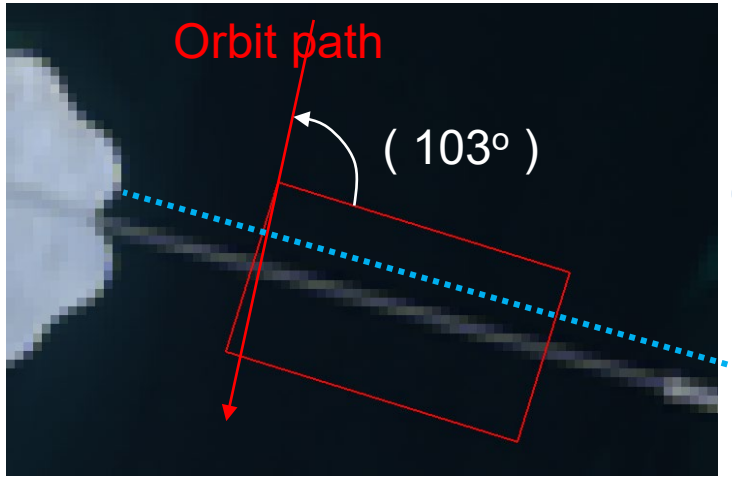






Pushbroom scanner slope ~ 4.5 (77^{o})
(due to orbit inclination angle)

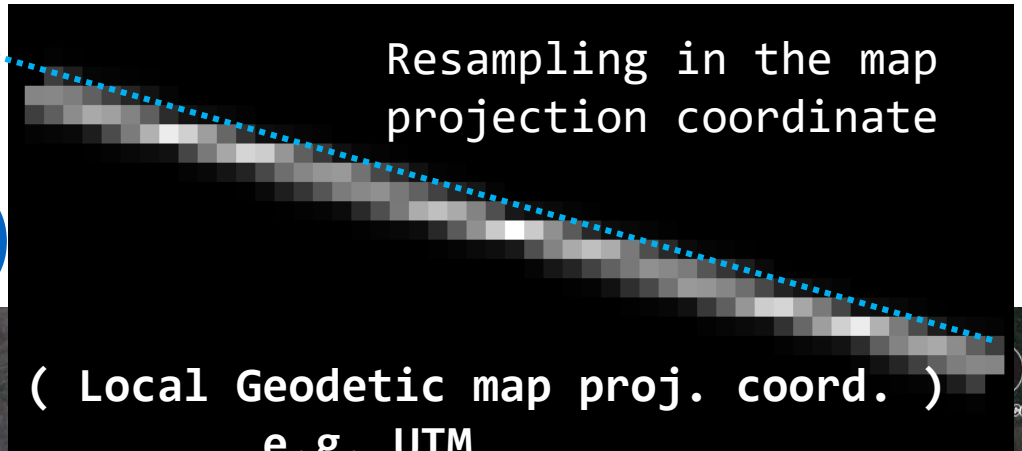
Analog Model Example
King Fhad Causeway



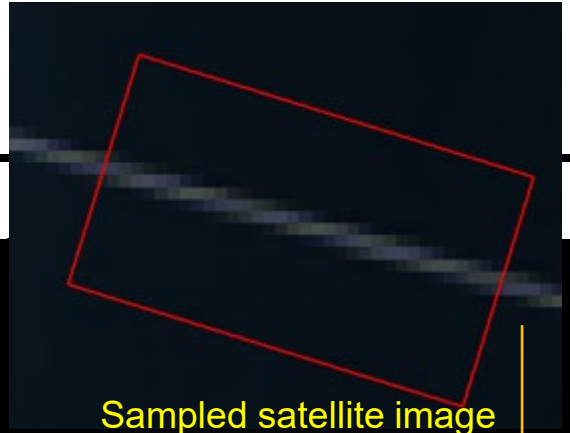
1

2

3

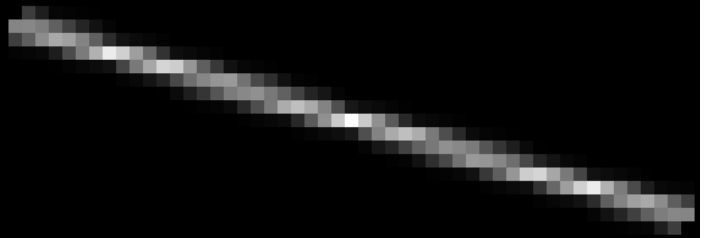


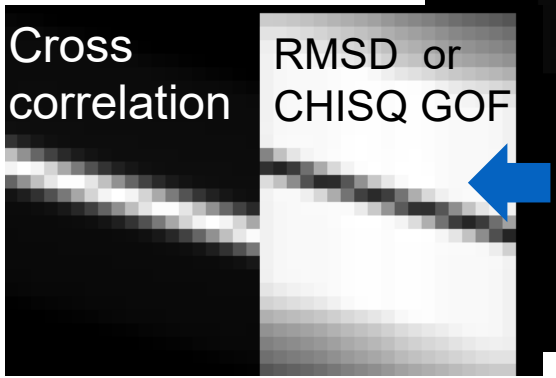
USGS



Sampled satellite image

Simulated image from Analog modeling





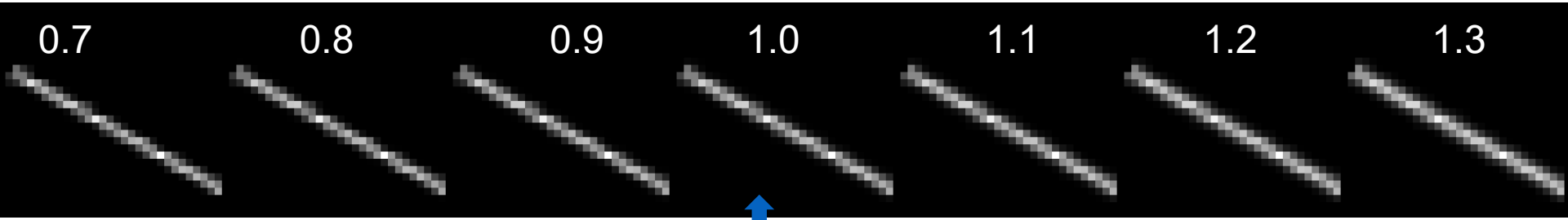
This is used as a **kernel** over larger simulated image to compute CC or RMSD

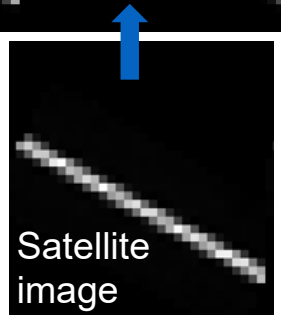
This should be long enough to capture the best alignment to compensate the randomness of discrete sampling of satellite image.

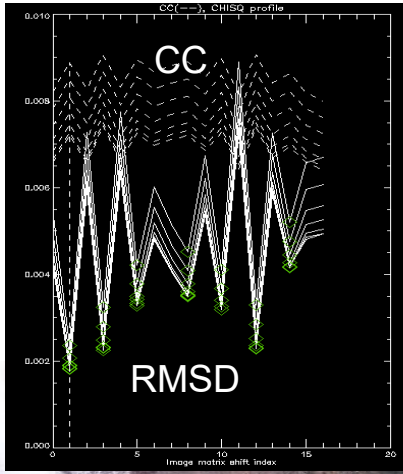
Best-matching FWHM

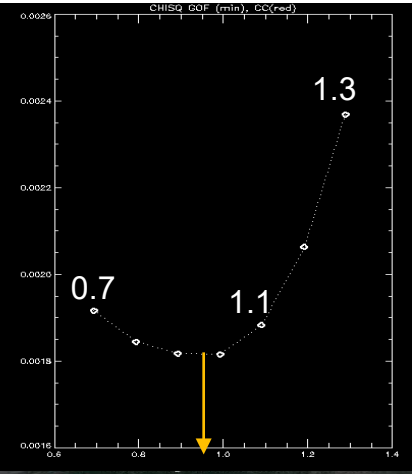
(0.97)

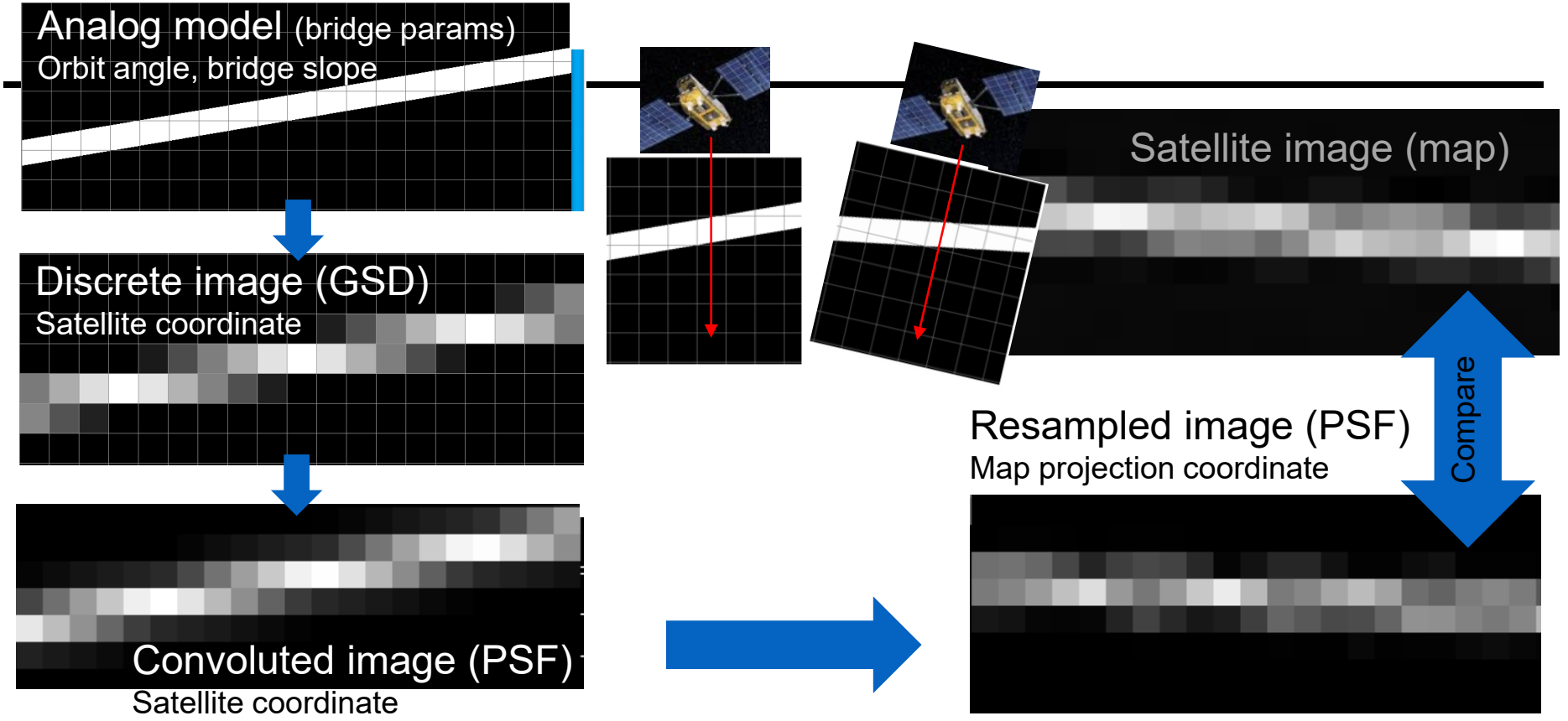
Simulated images





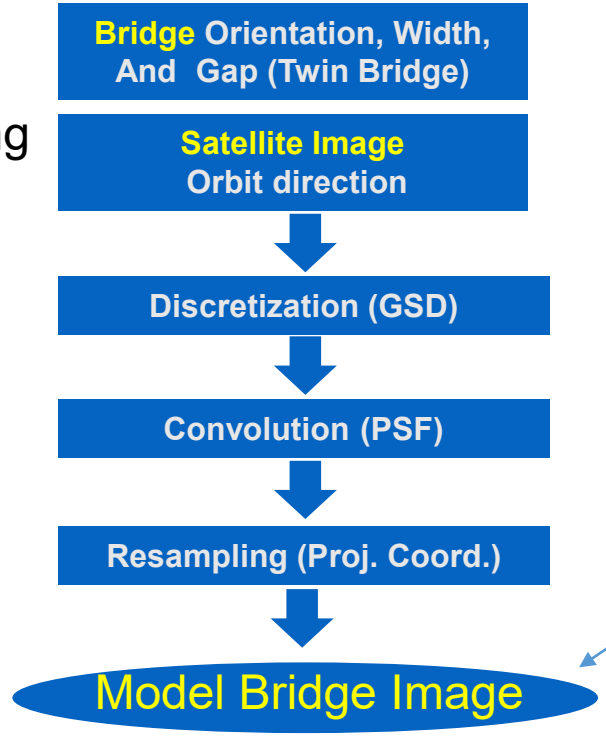





Analog model (bridge params)
Orbit angle, bridge slope
Discrete image (GSD)
Satellite coordinate
Convoluted image (PSF)
Satellite coordinate
Satellite image (map)
Compare
Resampled image (PSF)
Map projection coordinate

Method Summary

Analog Modelling

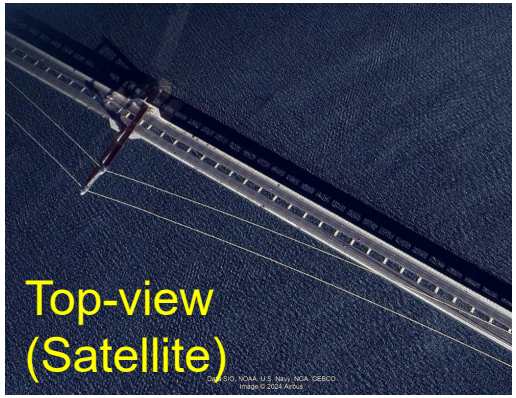


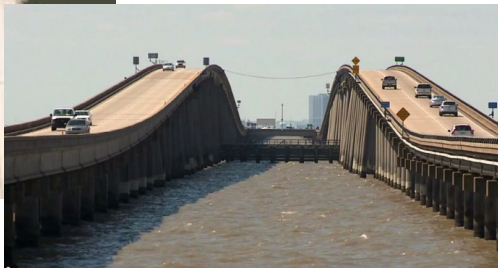
Sampled Bridge Image Segment From a Satellite Scene

Sat. Bridge Image

Determine best-matching FWHM

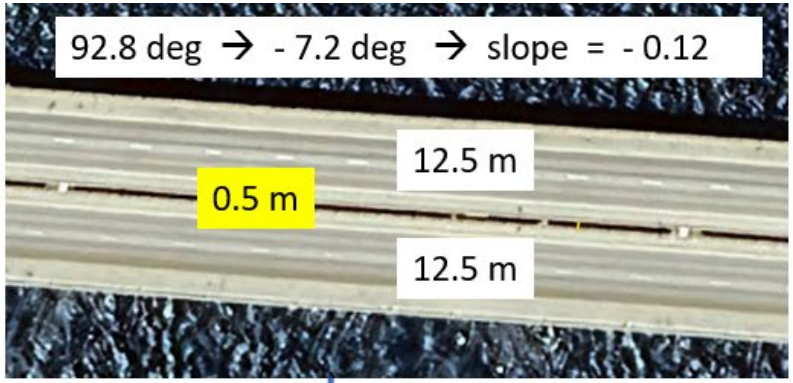
Use Causeway, Avoid Suspension Bridge

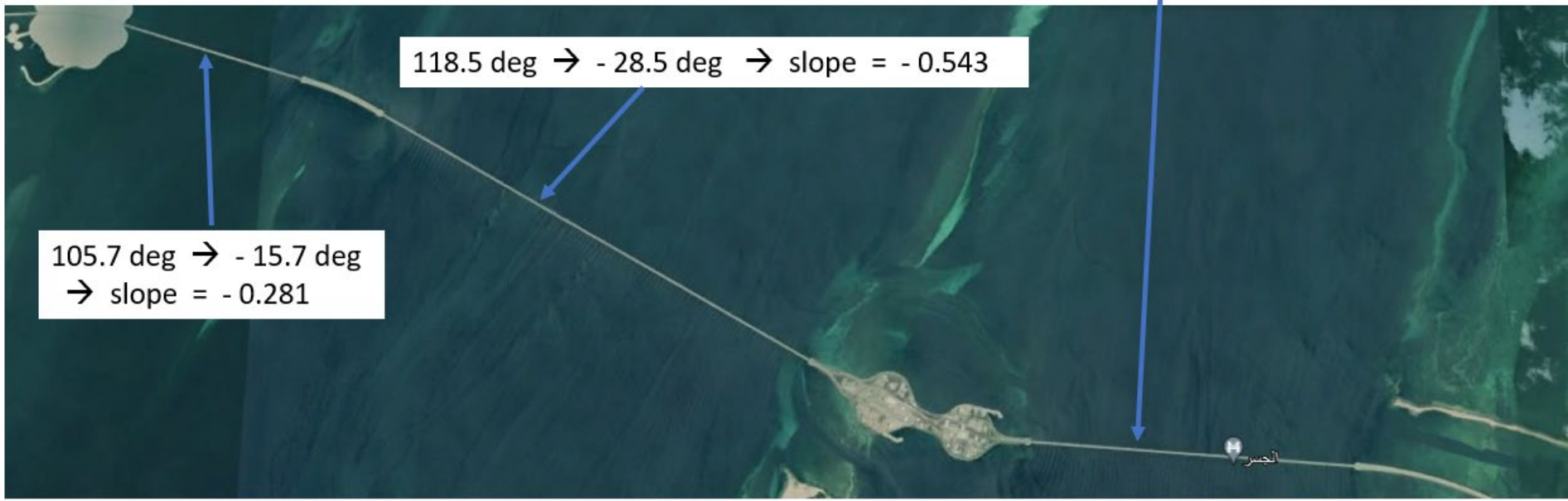


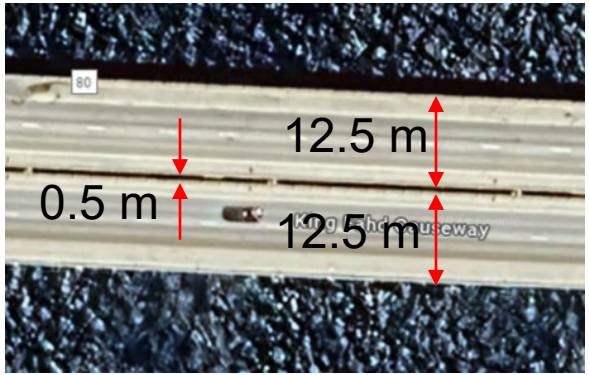


Simple radiometric model :
Linear feature over
water background

King Fahd Causeway



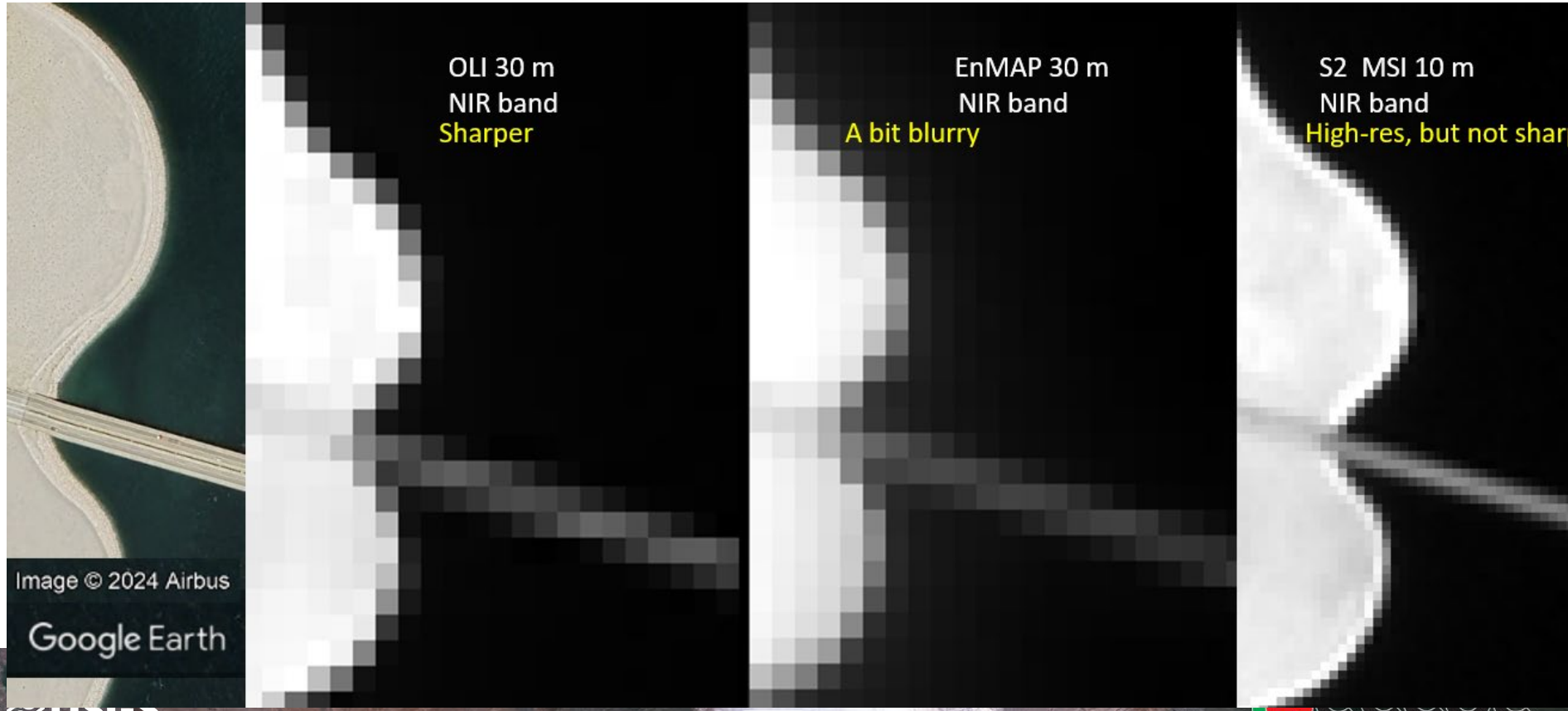


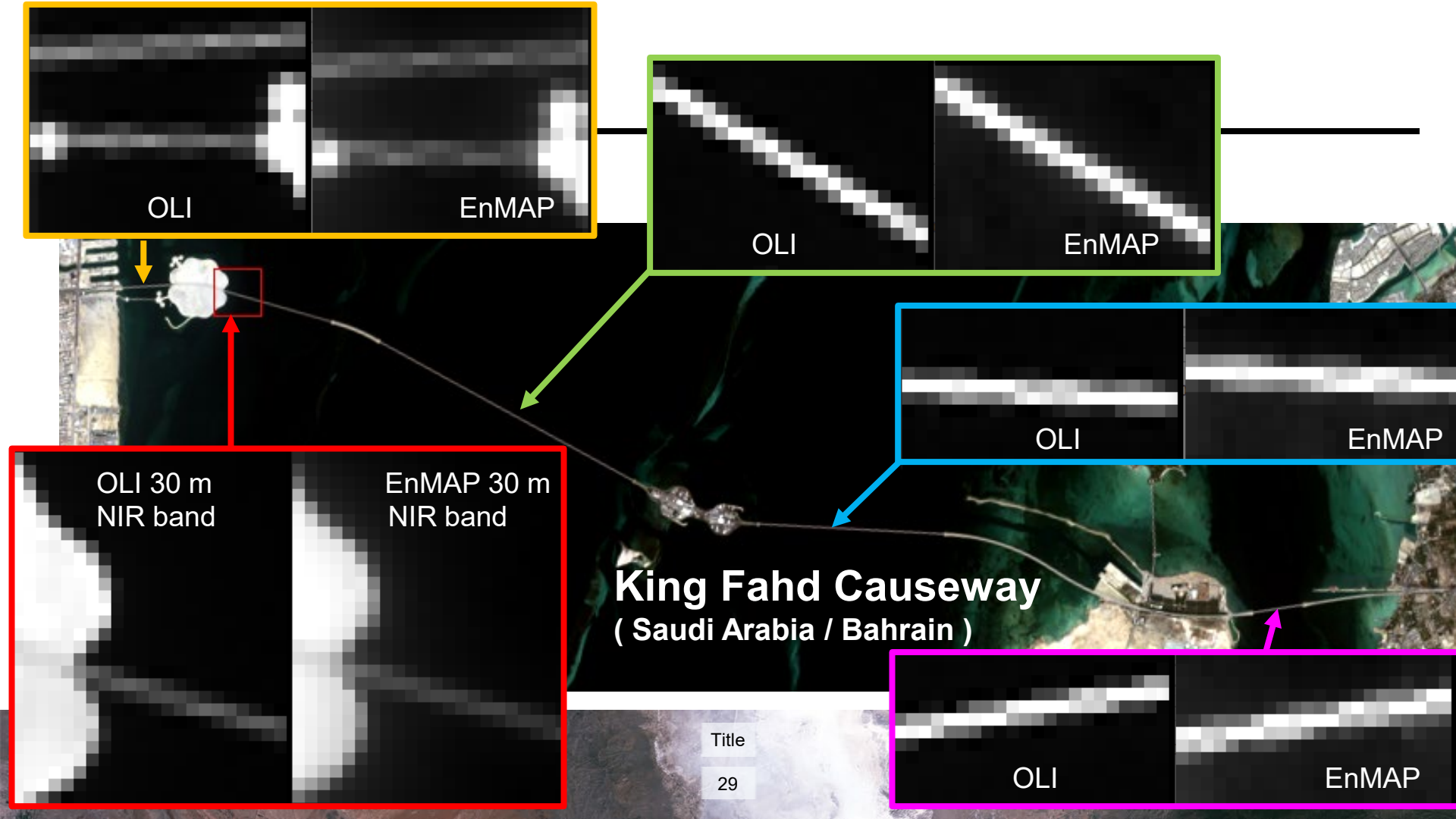

80
12.5 m
0.5 m
12.5 m

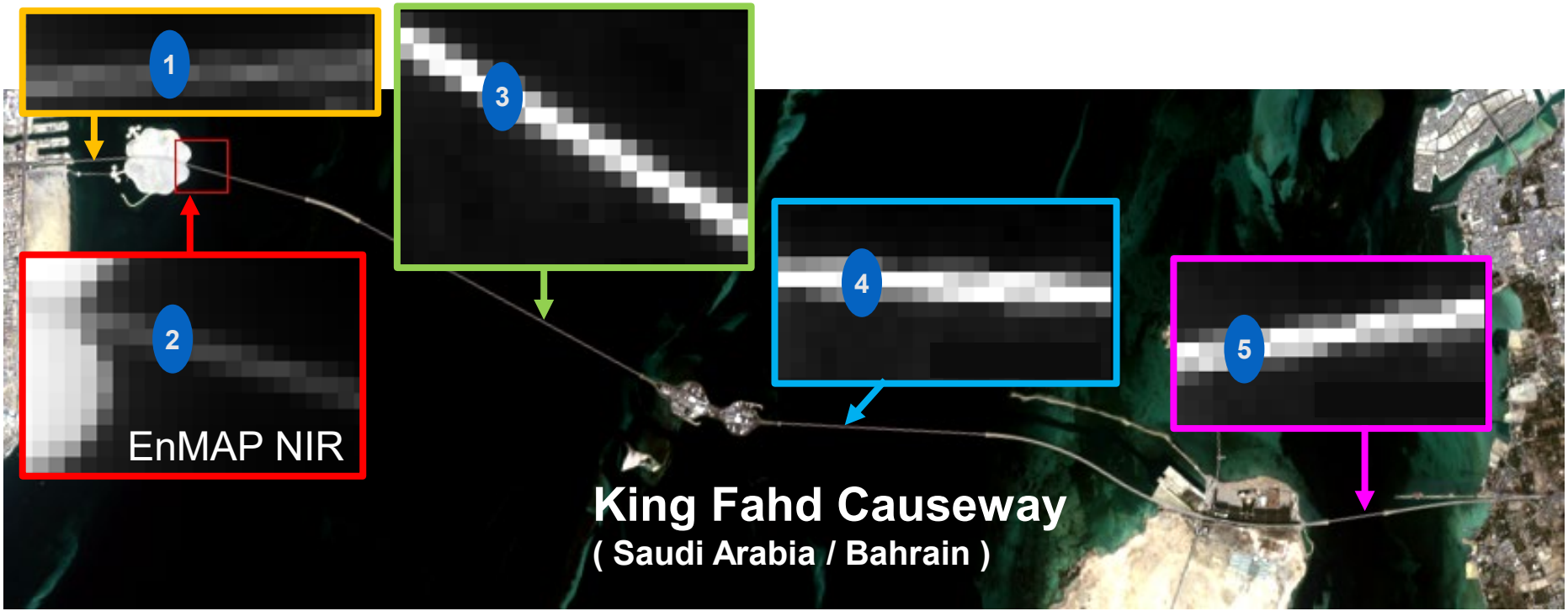

80
King Fahd Causeway

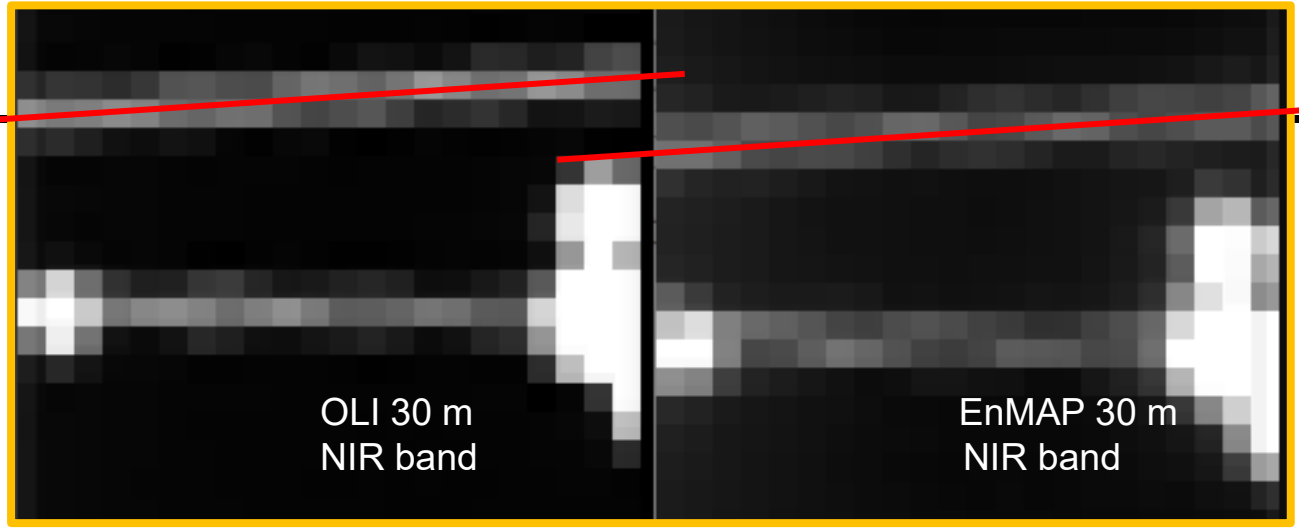

King Fahd Causeway

OLI (30m), EnMAP (30m), MSI (10m)

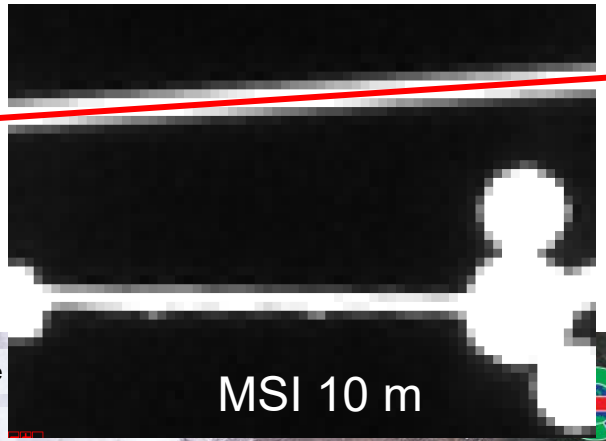


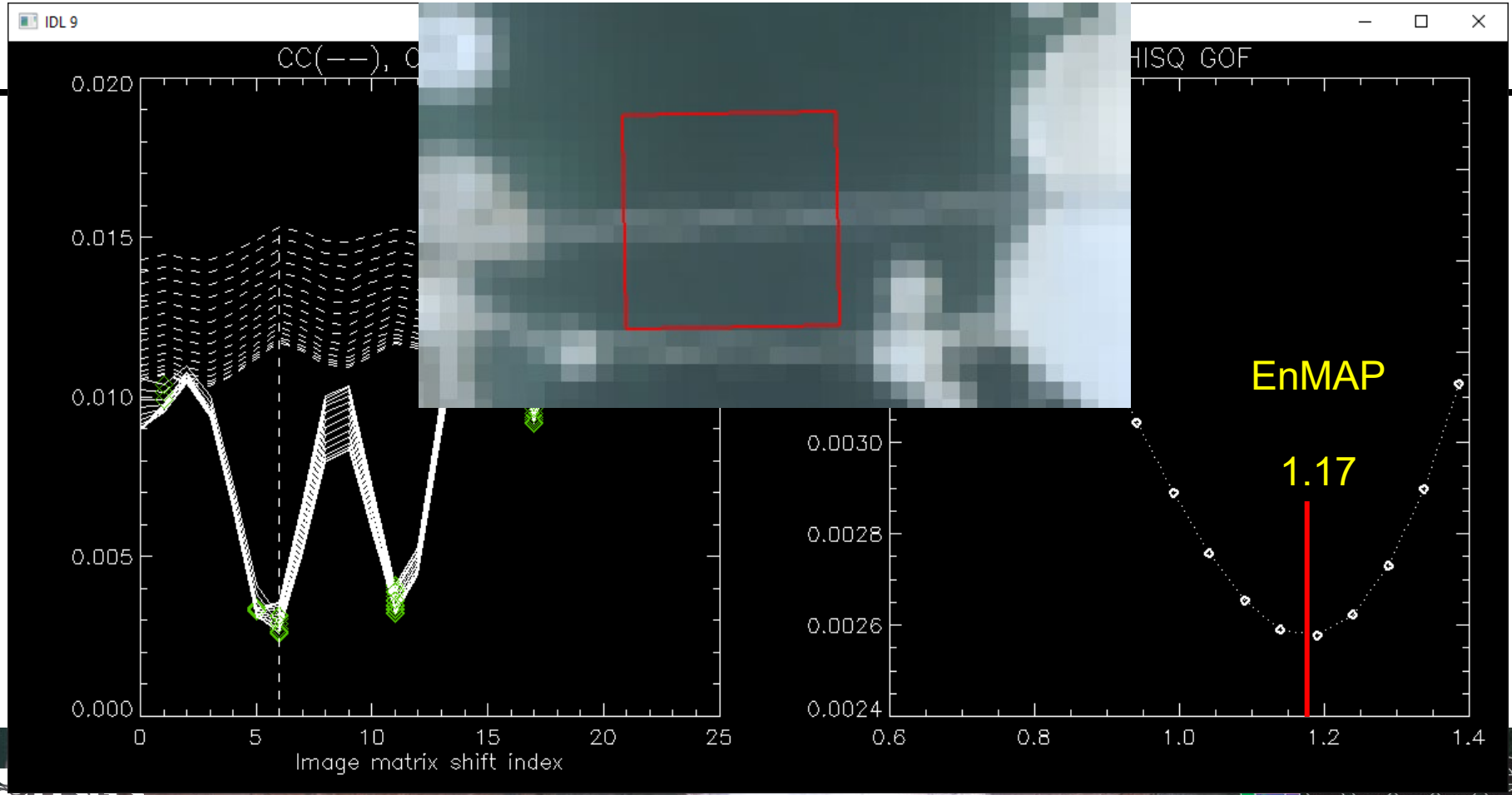

OLI
EnMAP
OLI
EnMAP
OLI
EnMAP
OLI 30 m
NIR band
EnMAP 30 m
NIR band
King Fahd Causeway
(Saudi Arabia / Bahrain)
OLI
EnMAP

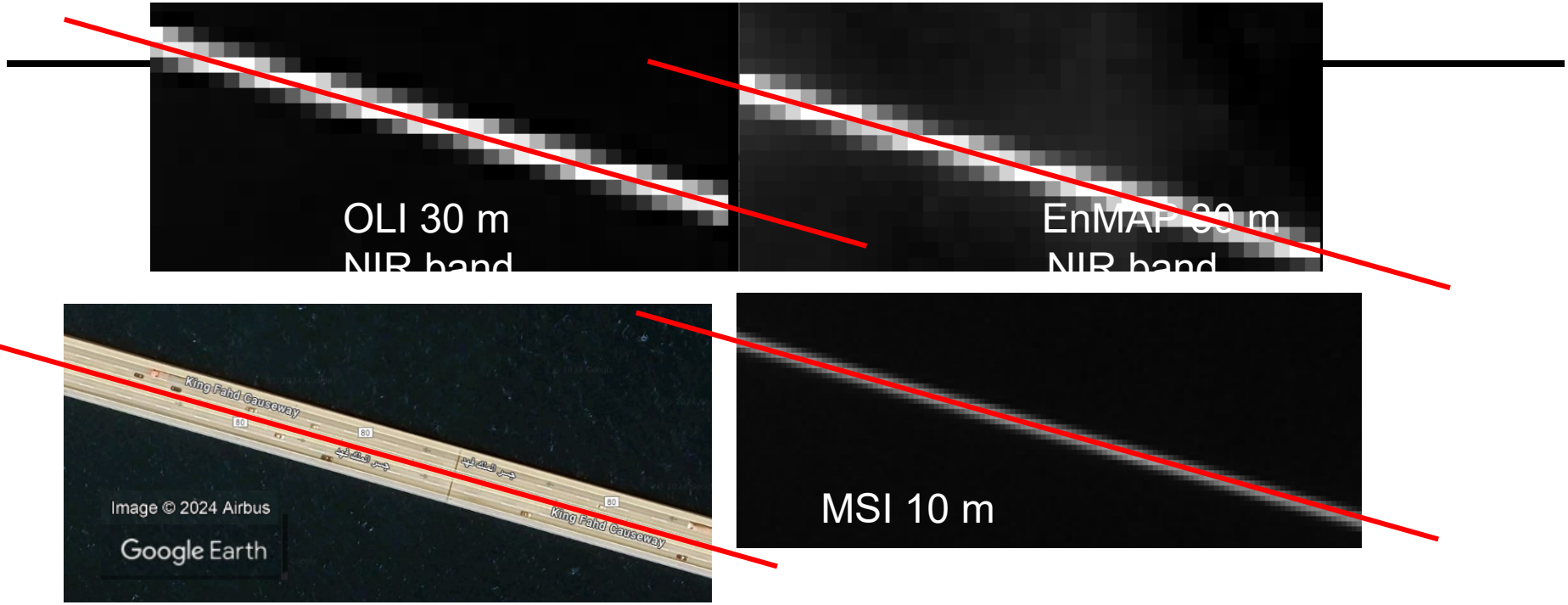

1
2
3
4
5
EnMAP NIR
King Fahd Causeway
(Saudi Arabia / Bahrain)

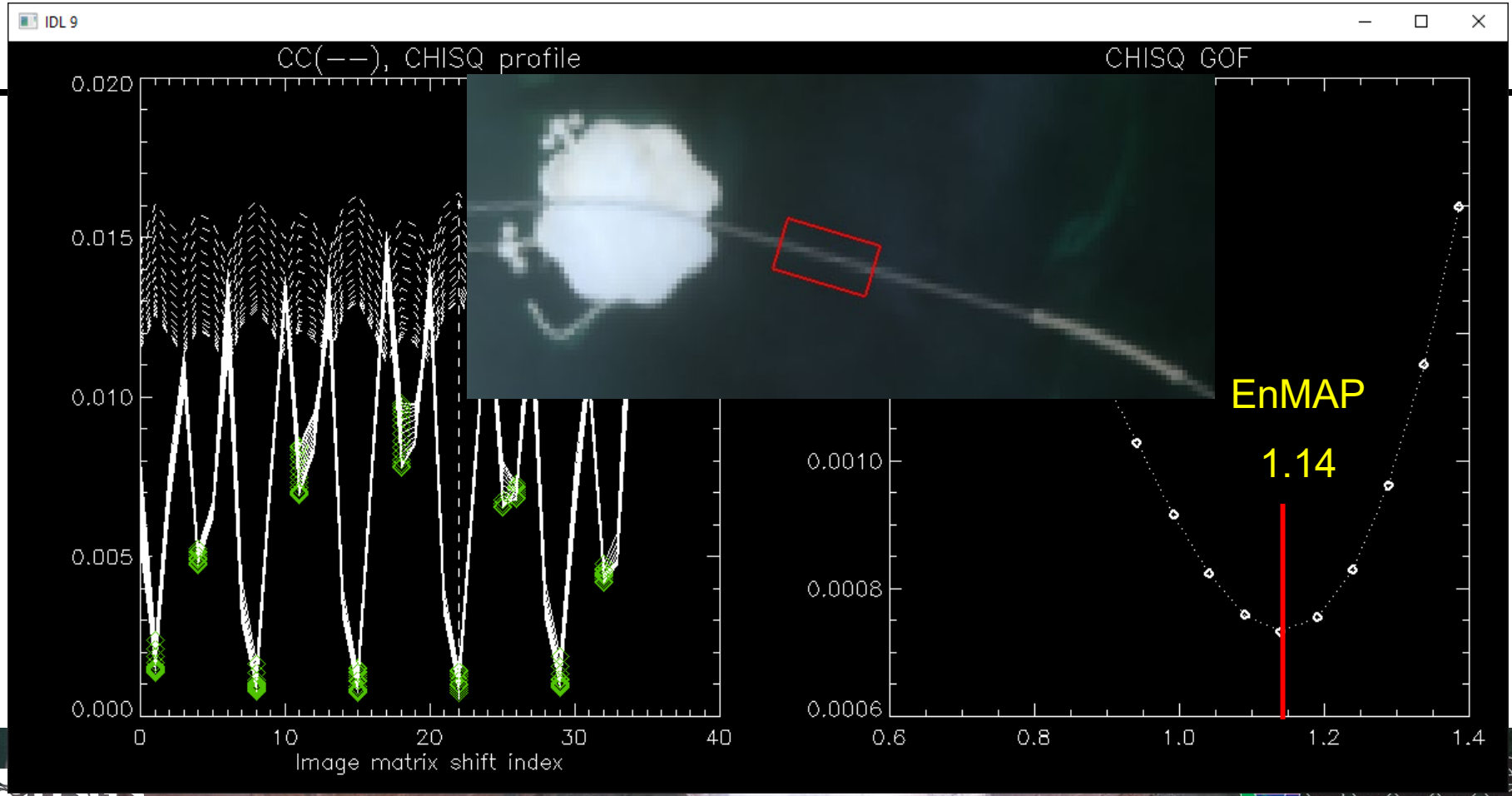

OLI 30 m
NIR band
EnMAP 30 m
NIR band

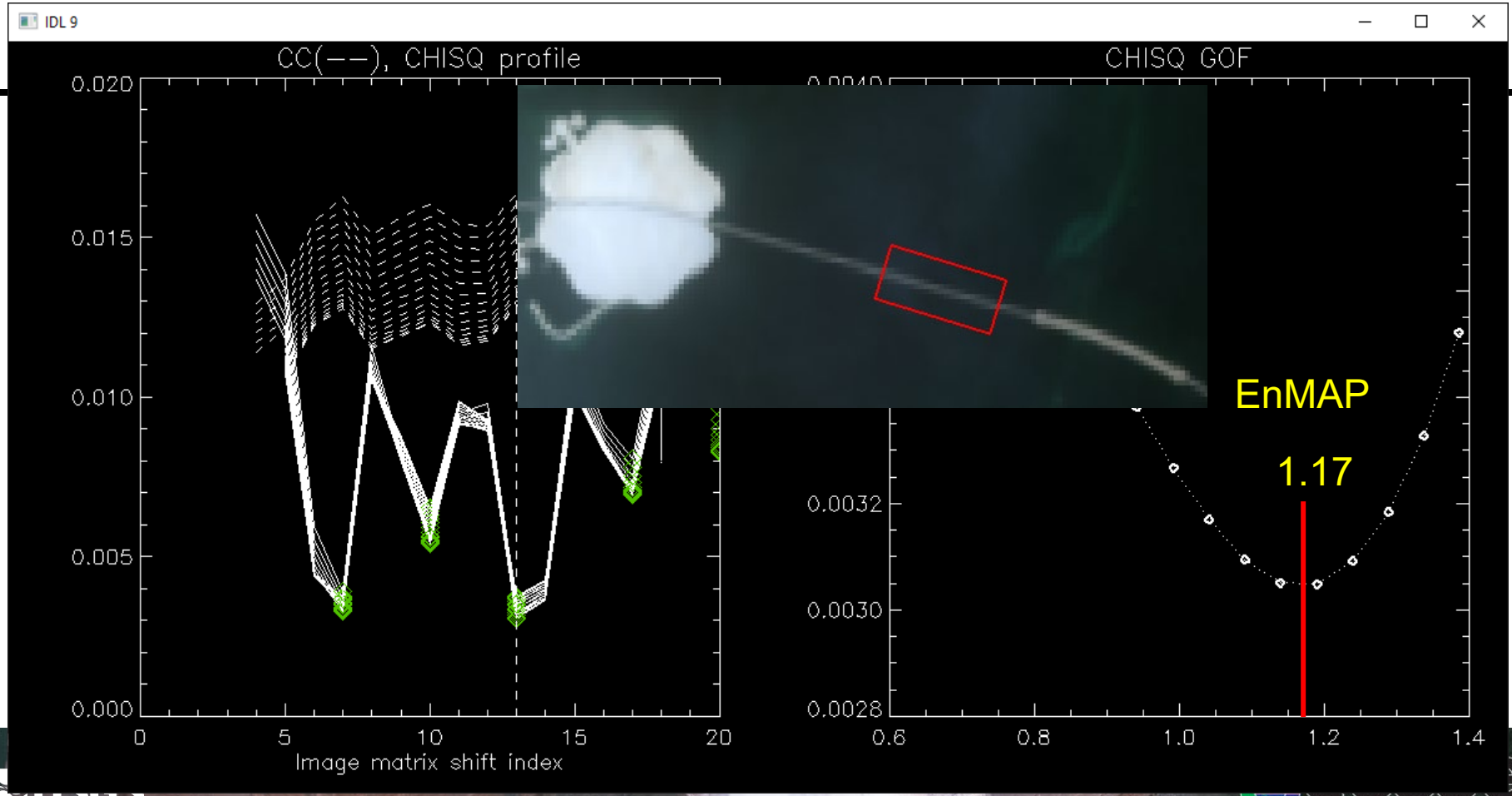

Saudi Arabia Customs
Image © 2024 Airbus
Google Earth

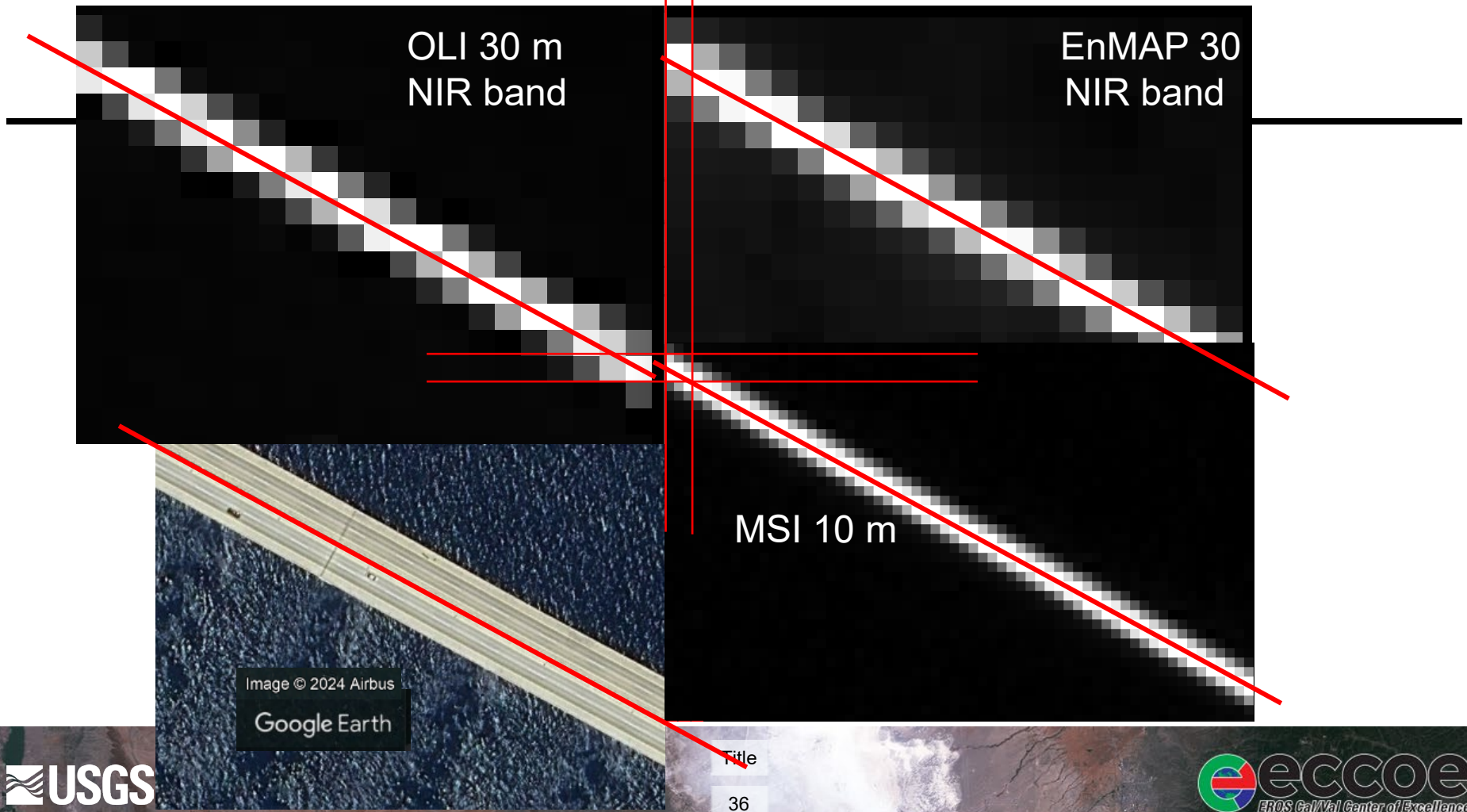

MSI 10 m

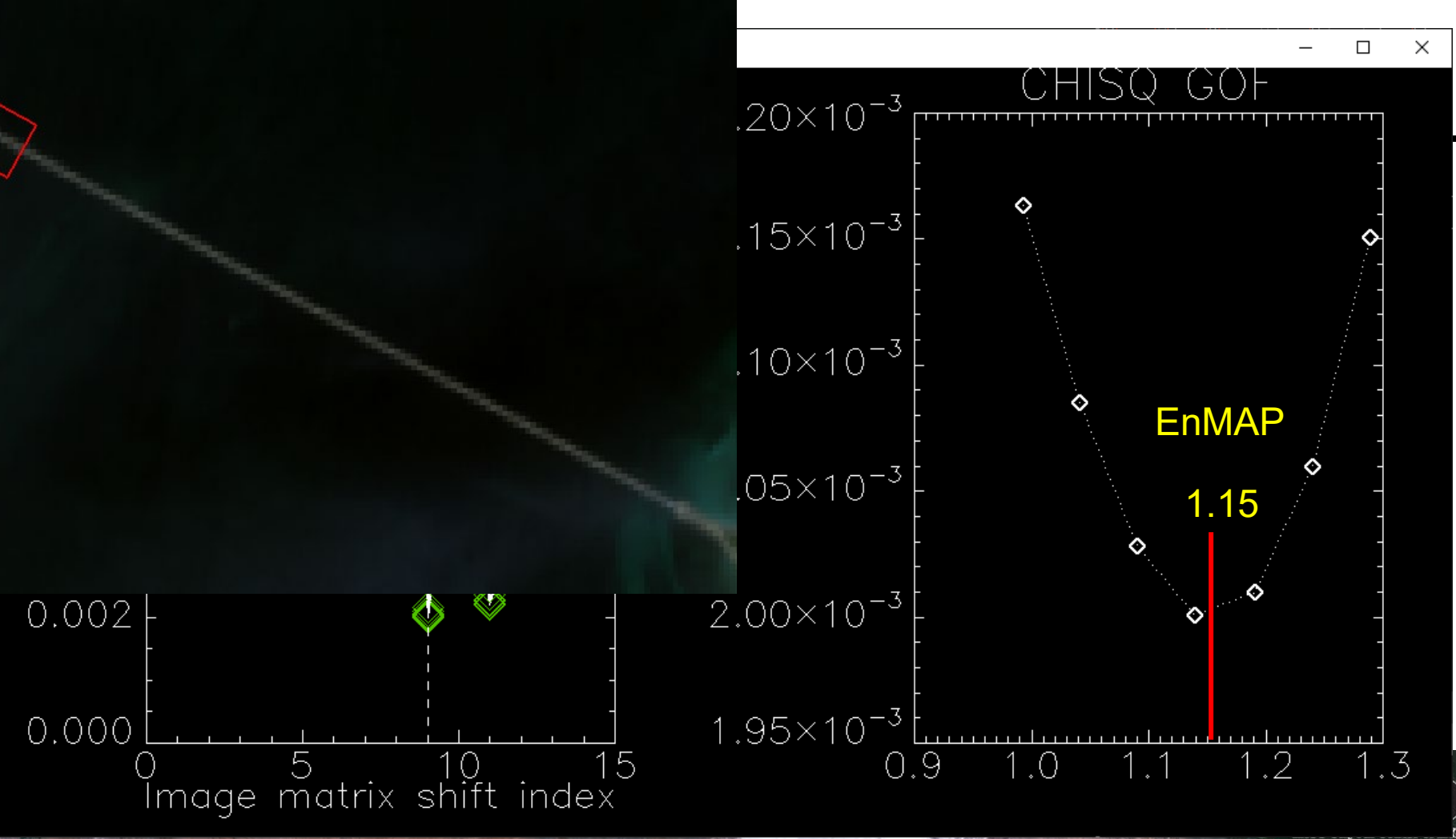


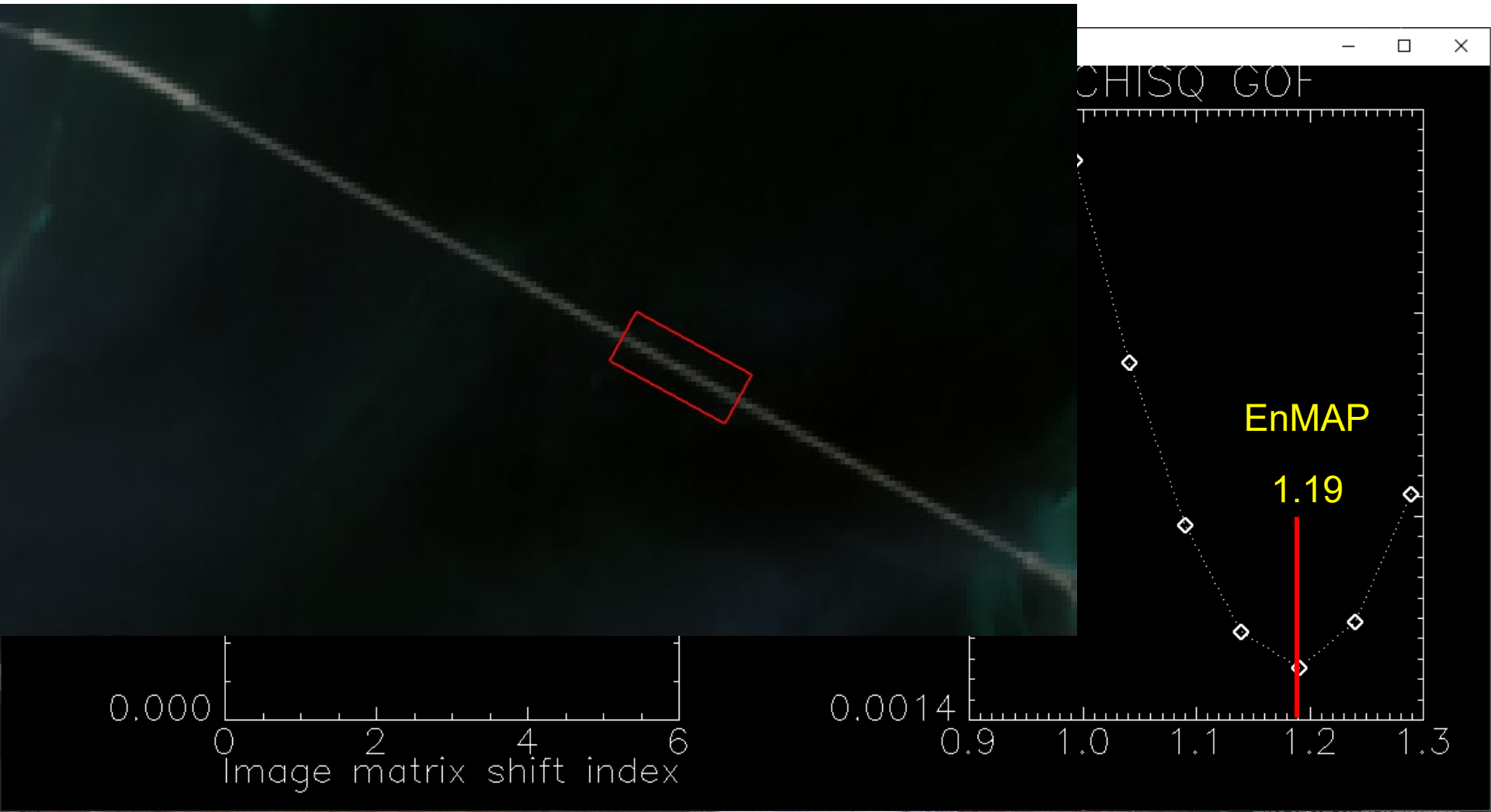

OLI 30 m
NIR band
EnMAP 30 m
NIR band
King Fahd Causeway
Image © 2024 Airbus
Google Earth
MSI 10 m

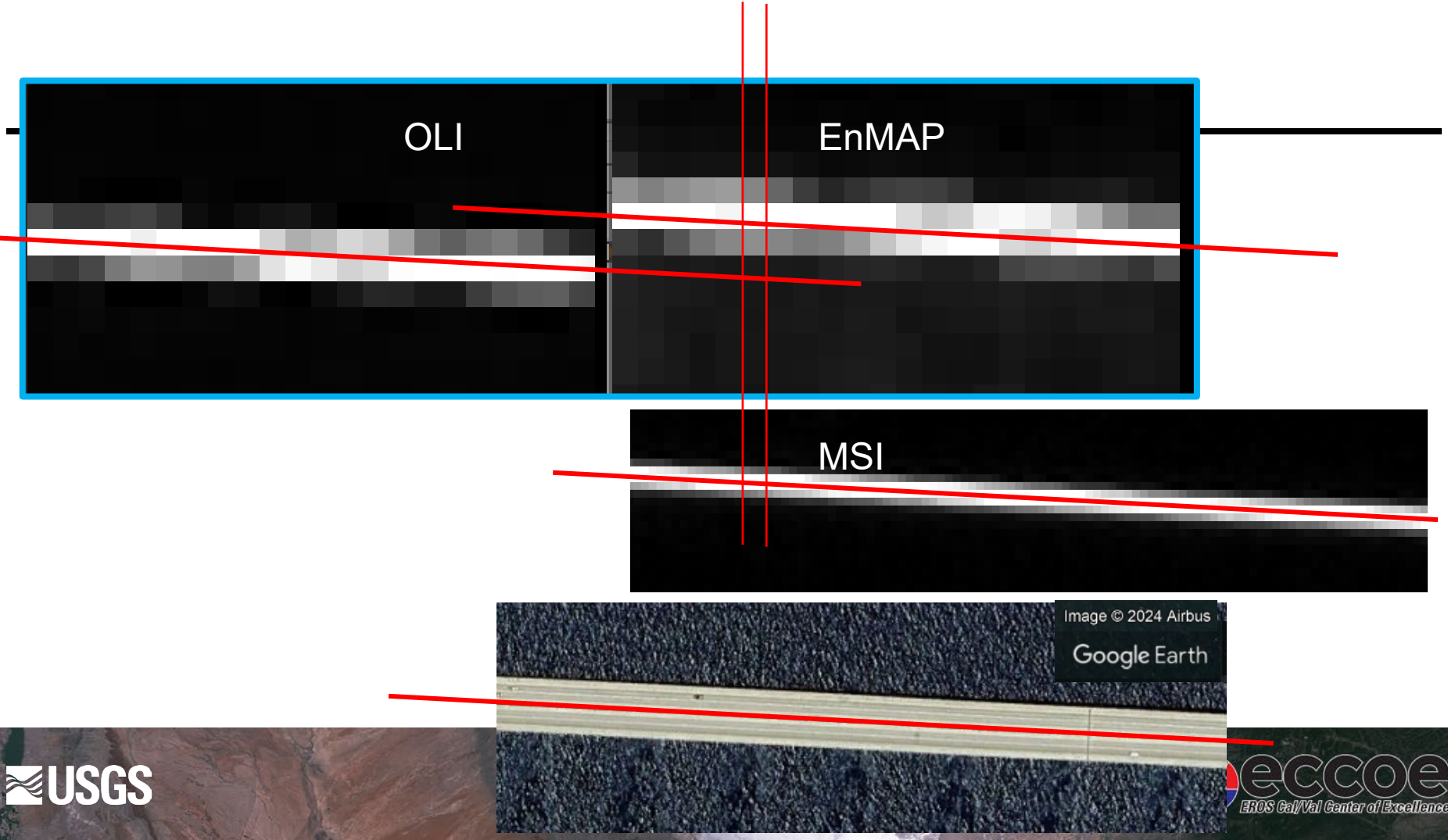


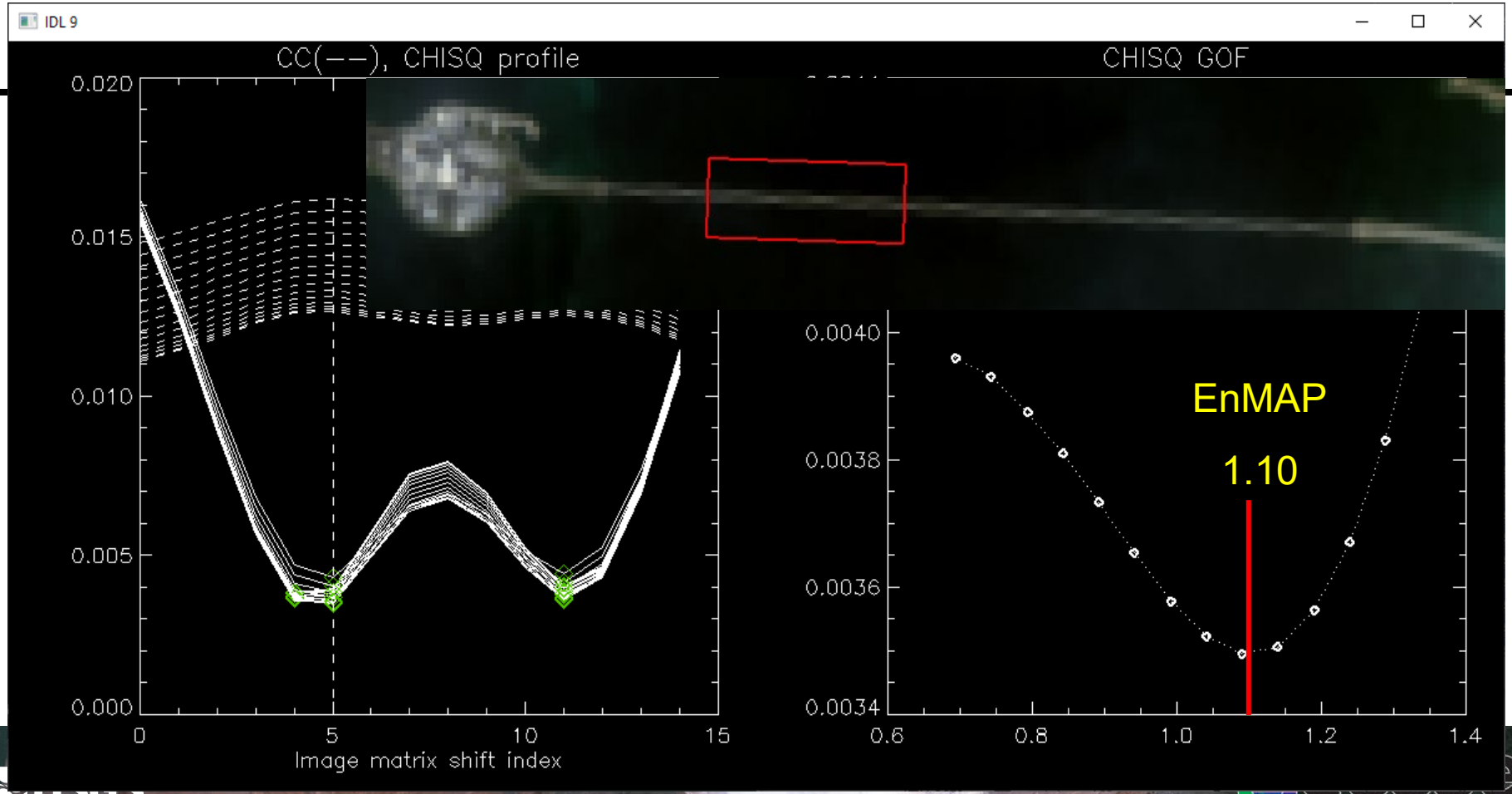


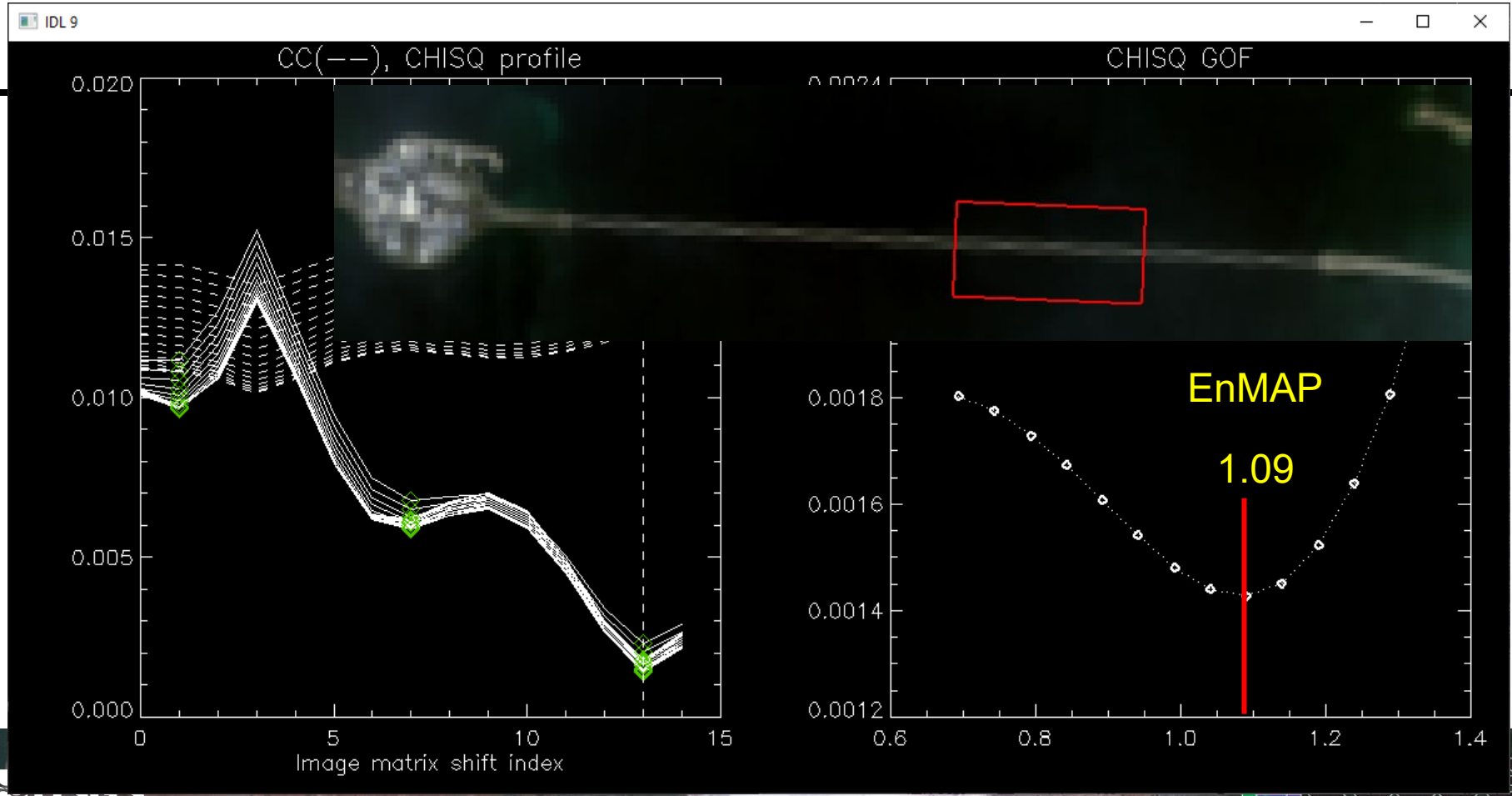

OLI 30 m
NIR band
EnMAP 30
NIR band
MSI 10 m
Image © 2024 Airbus
Google Earth

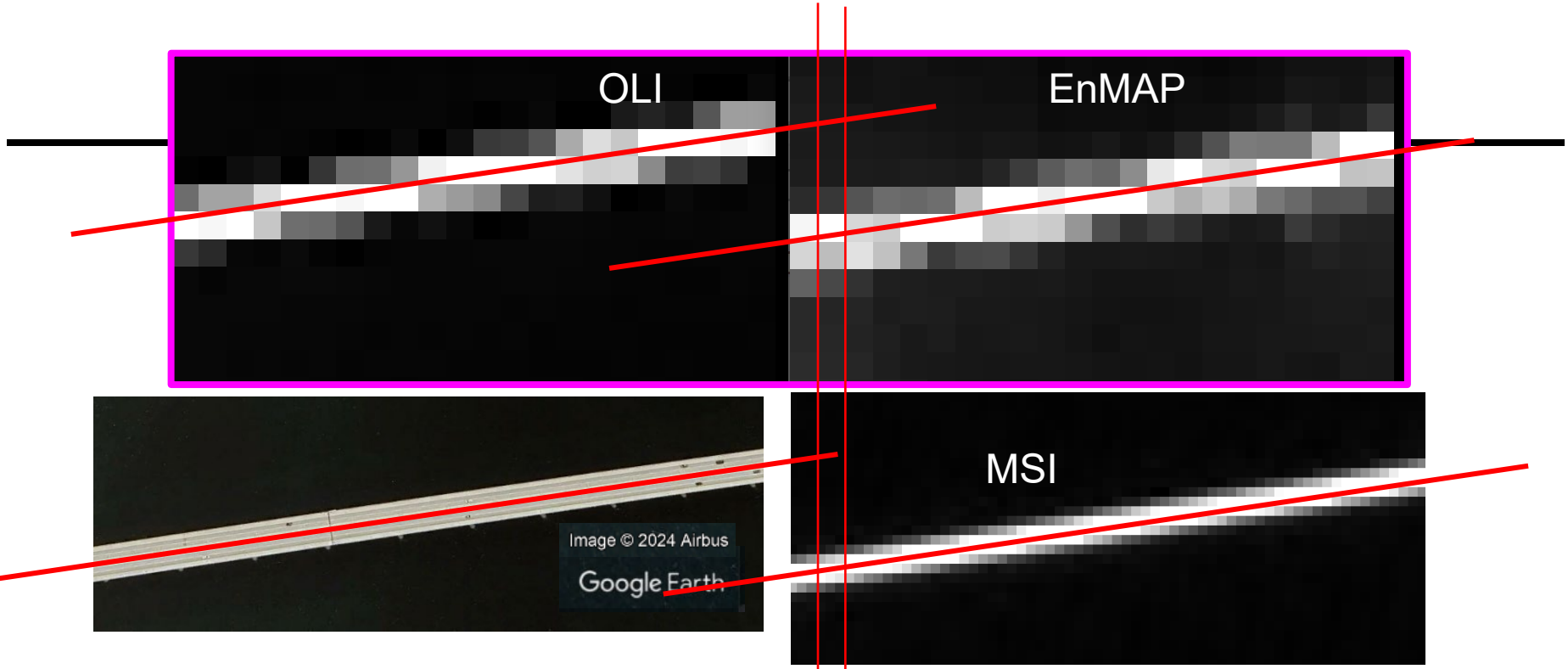

0.002
0.000
0
5
10
15
Image matrix shift index
CHISQ GOF
.20×10⁻³
.15×10⁻³
.10×10⁻³
.05×10⁻³
2.00×10⁻³
1.95×10⁻³
0.9
1.0
1.1
1.2
1.3
EnMAP
1.15

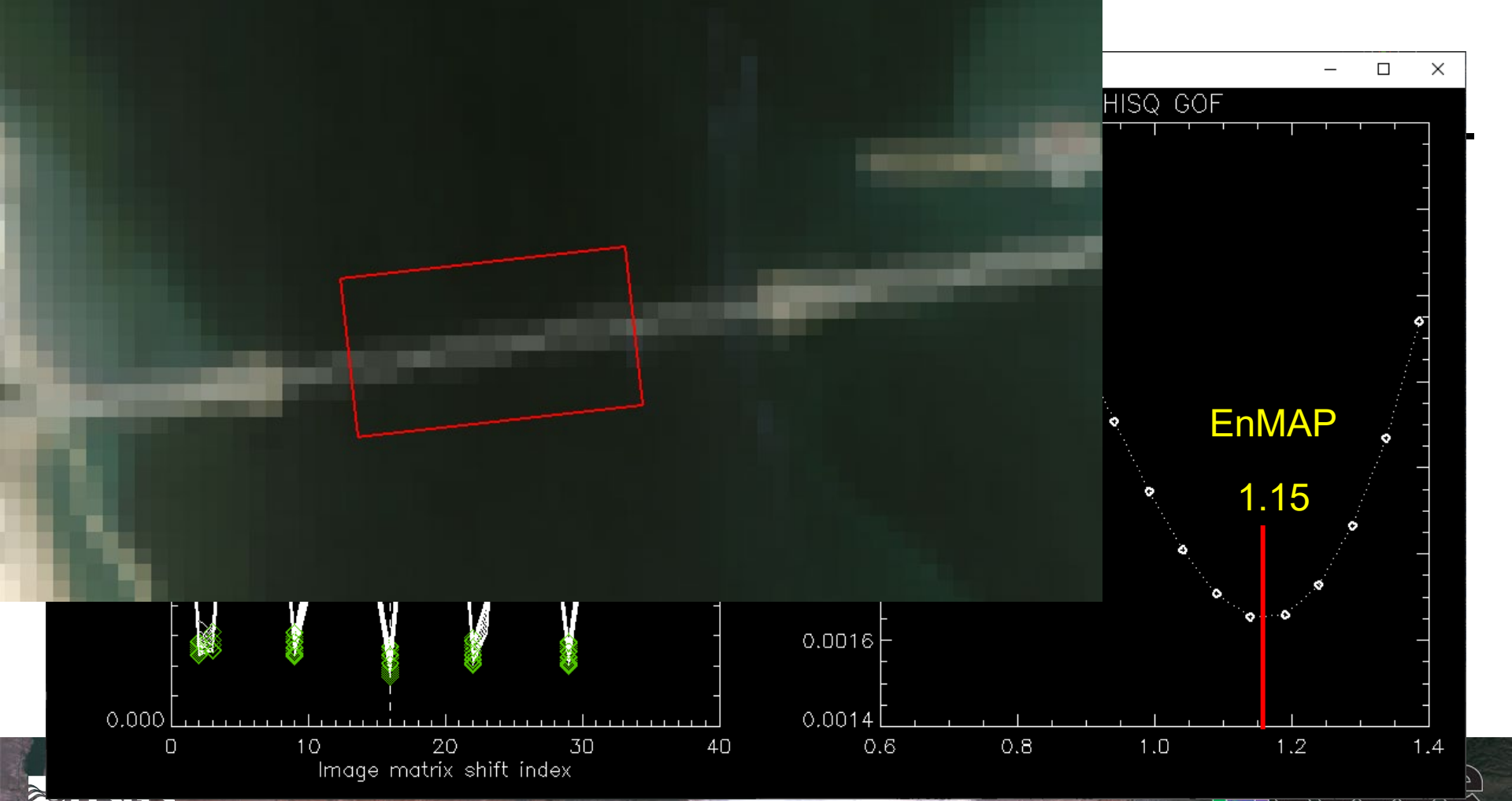

CHISQ GOF
EnMAP
1.19
0.0014
0.9
1.0
1.1
1.2
1.3
0.000
0
2
4
6
Image matrix shift index


OLI
EnMAP
MSI
Image © 2024 Airbus
Google Earth
USGS
eccoe
EROS Cal/Val Center of Excellence

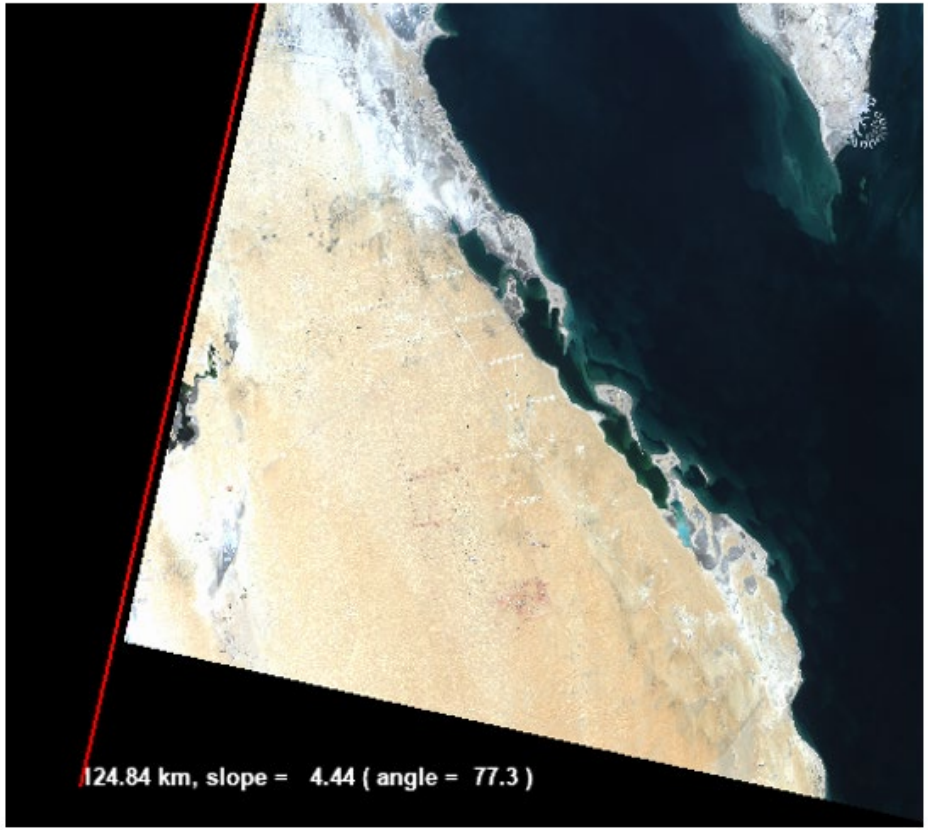

IDL 9
CC(−−), CHISQ profile
CHISQ GOF
0.020
0.015
0.010
0.005
0.000
0
5
10
15
Image matrix shift index
0.0040
0.0038
0.0036
0.0034
0.6
0.8
1.0
1.2
1.4
EnMAP
1.10




OLI
EnMAP
Image © 2024 Airbus
Google Earth
MSI


HISQ GOF
EnMAP
1.15
0.000
0
10
20
30
40
Image matrix shift index
0.0016
0.0014
0.6
0.8
1.0
1.2
1.4

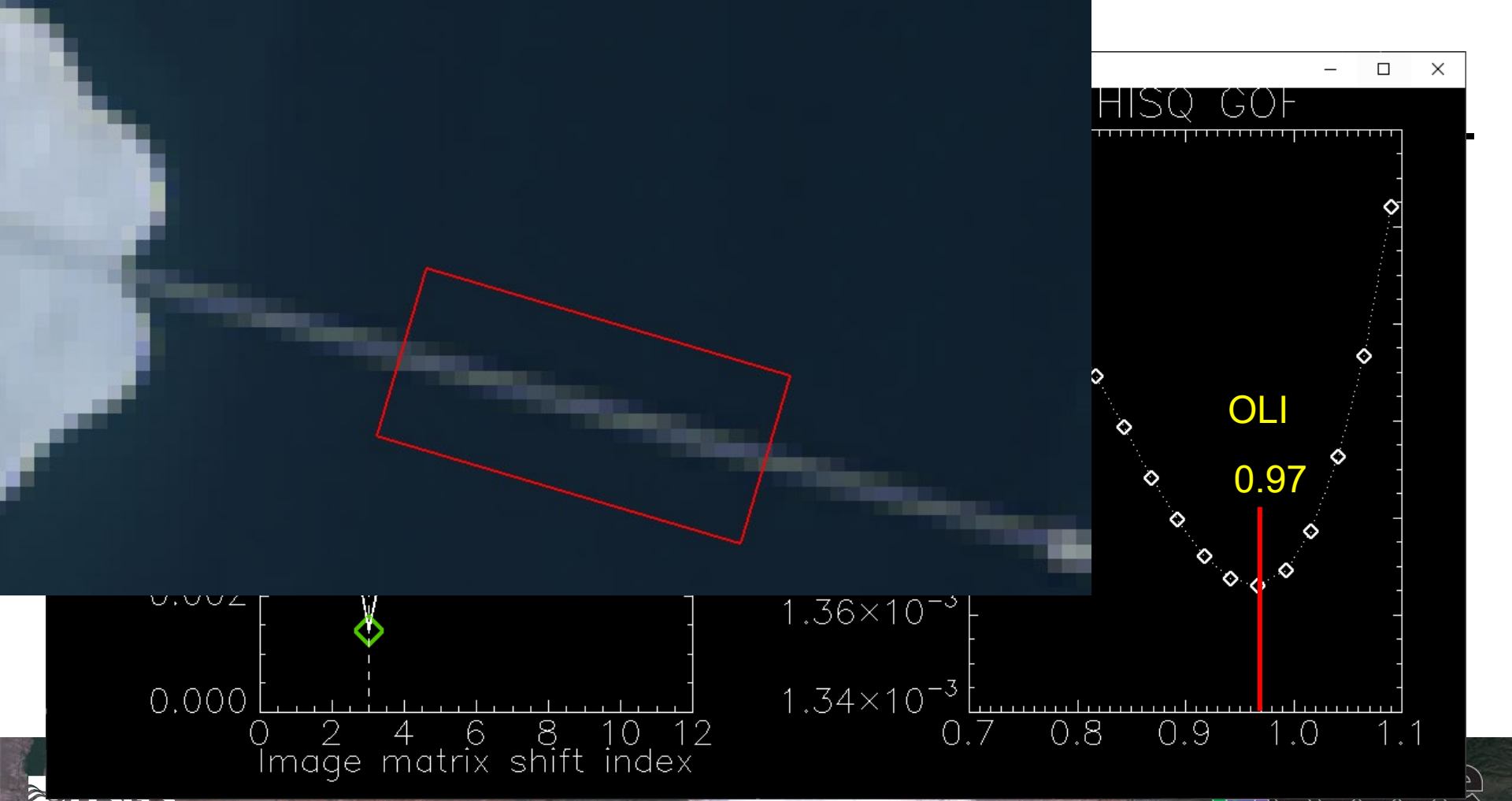
Landsat OLI : King Fahd Causeway

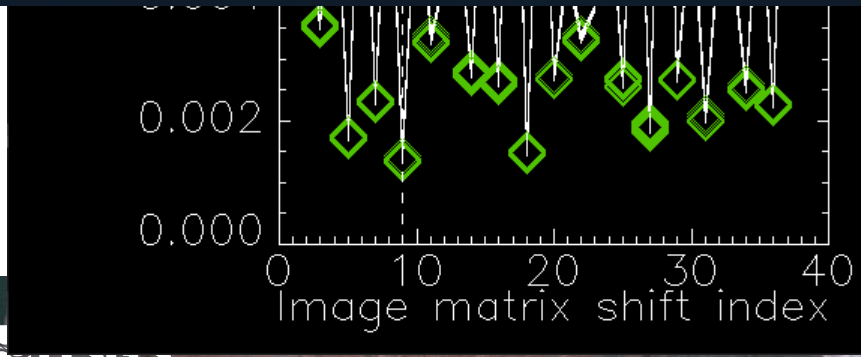


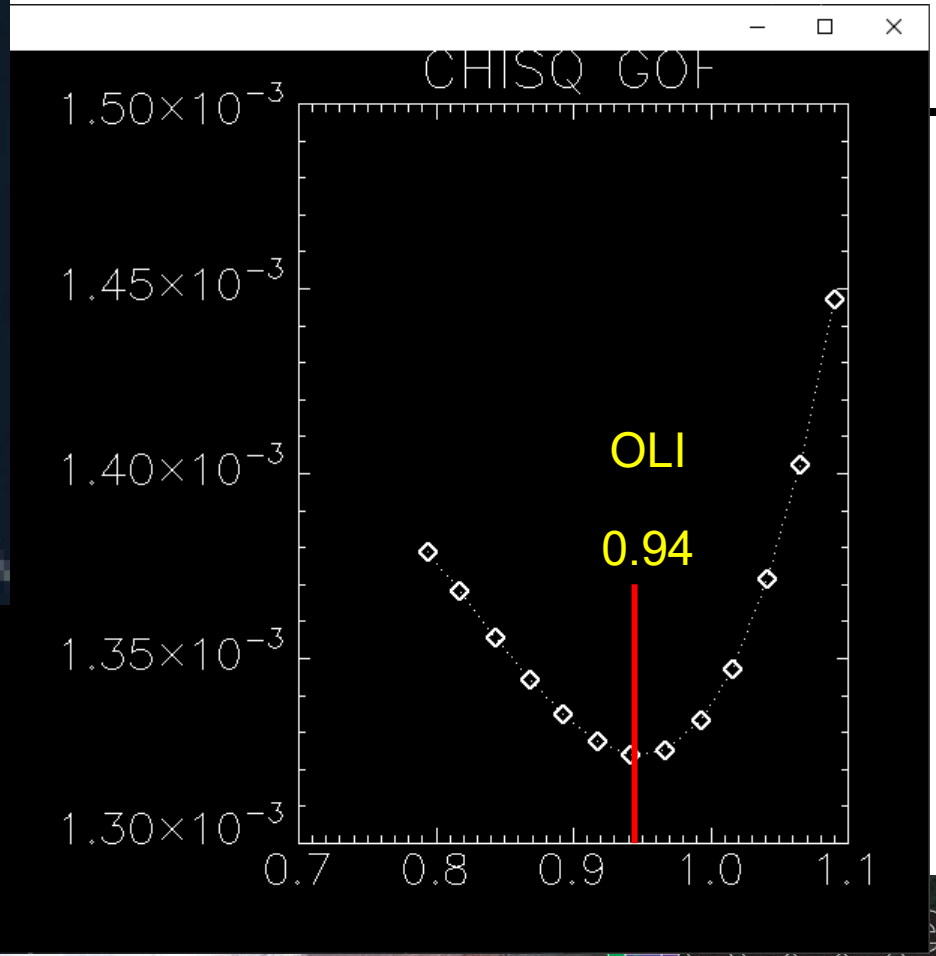
USGS

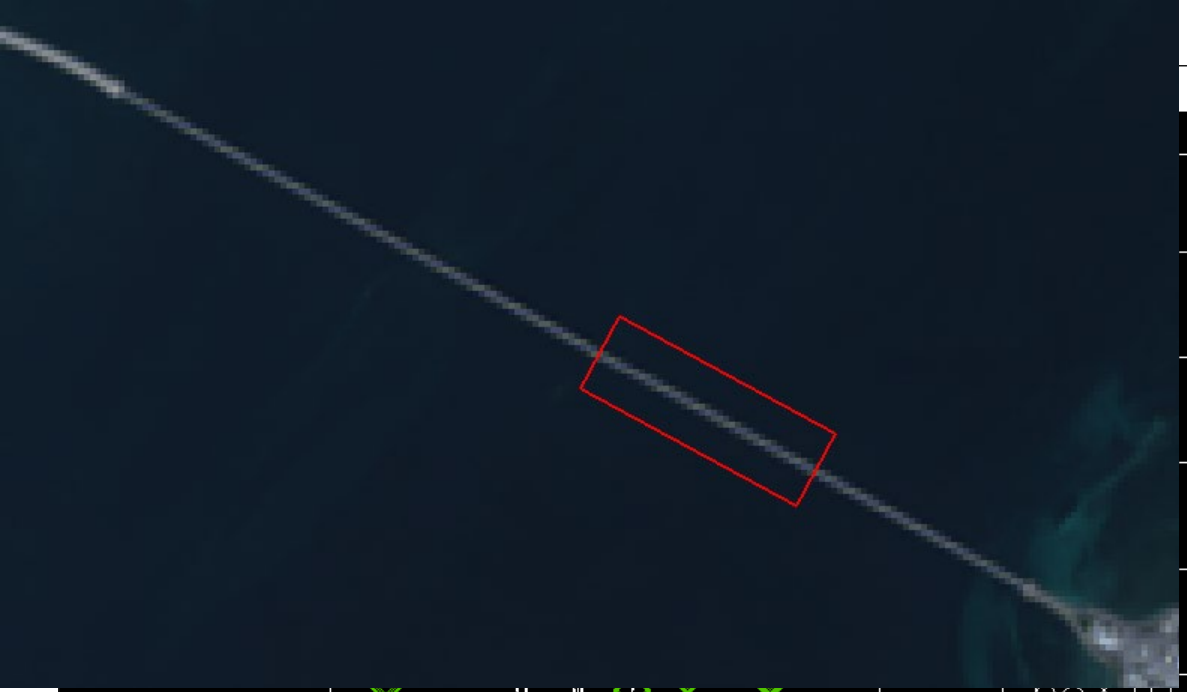
eccoe
EROS Cal/Val Center of Excellence

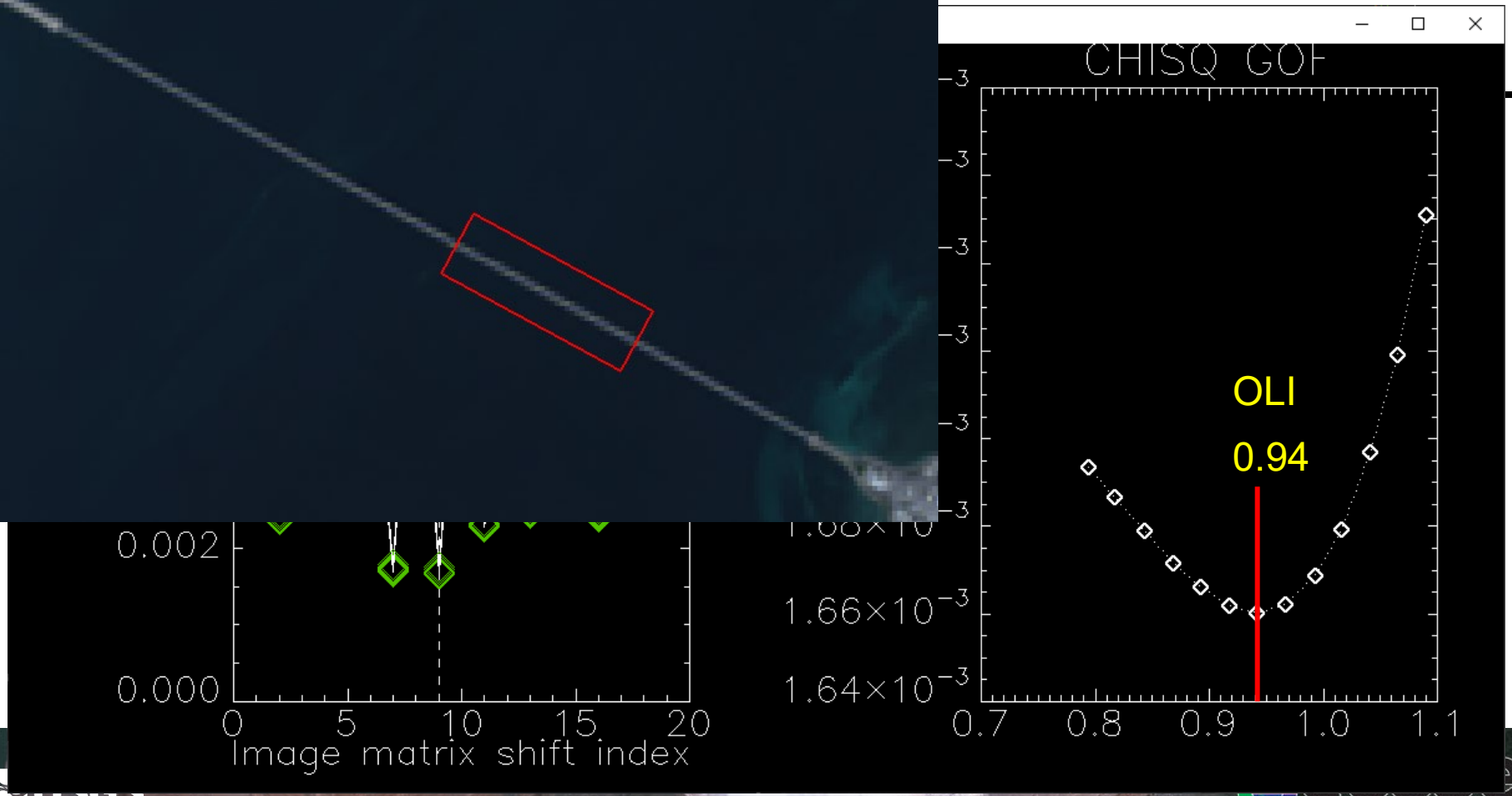

SQ GOF
OLI
0.96
0.000
0
10
20
30
40
Image matrix shift index
1.62×10⁻³
0.7
0.8
0.9
1.0
1.1

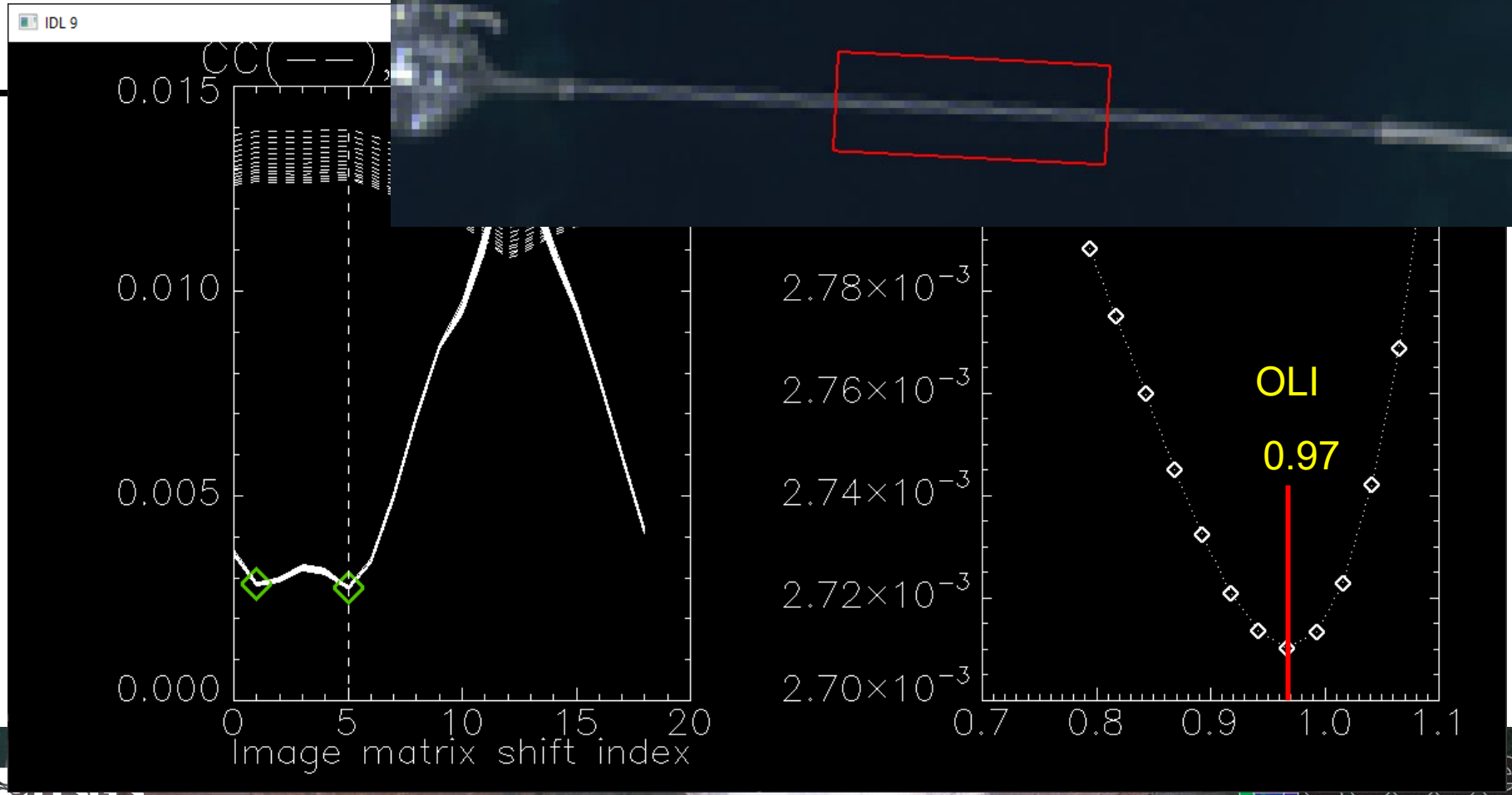


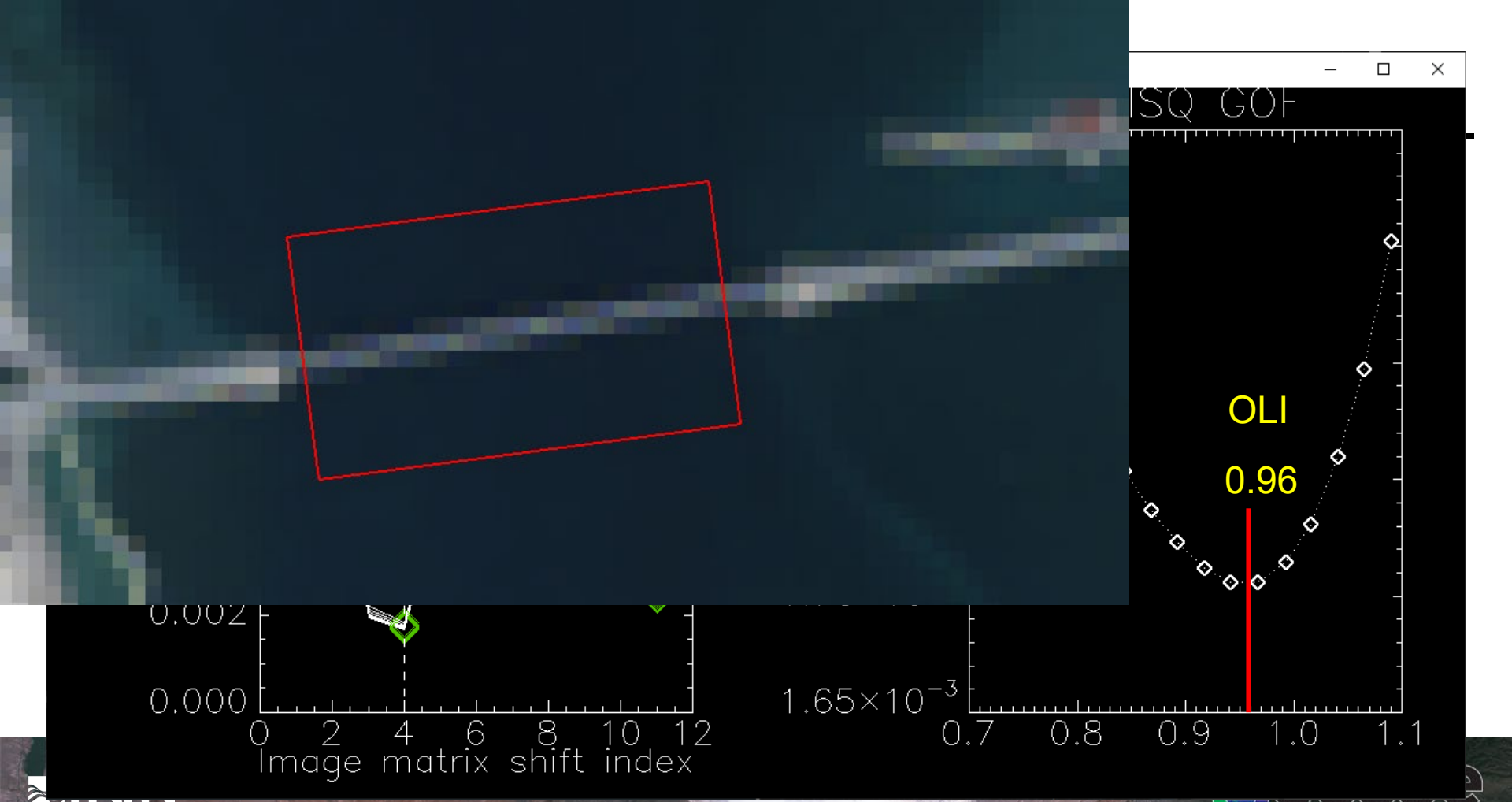




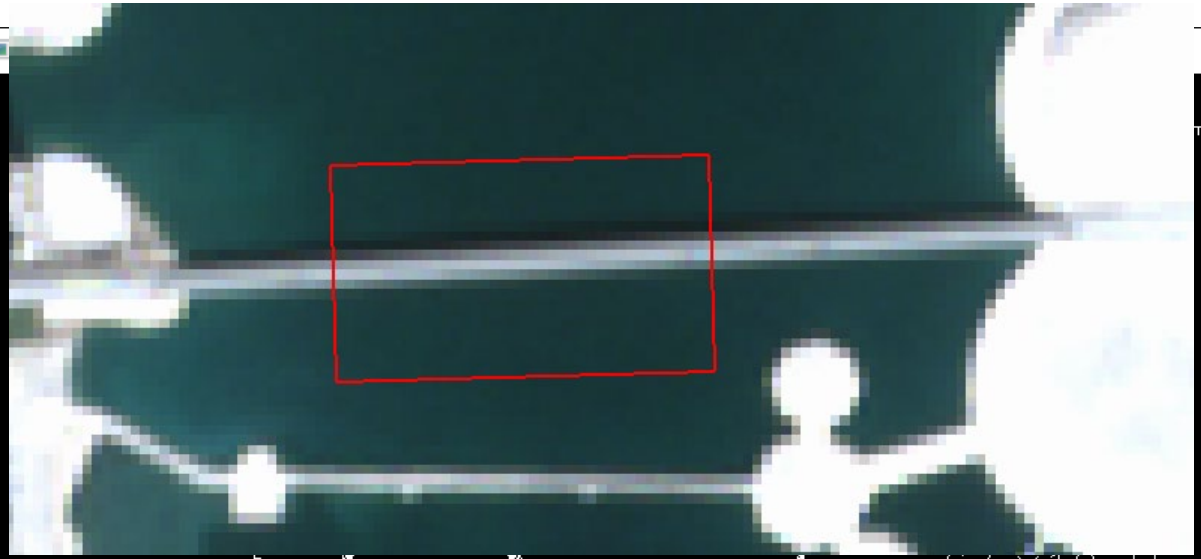


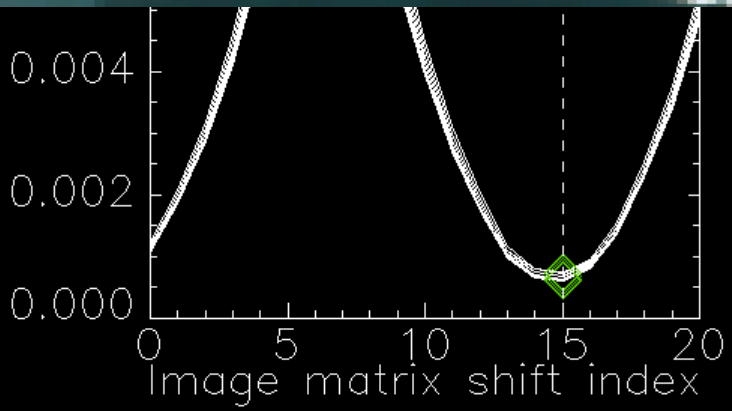

CHISQ GOF
OLI
0.94
0.002
0.000
0
5
10
15
20
Image matrix shift index
1.66×10⁻³
1.64×10⁻³
0.7
0.8
0.9
1.0
1.1

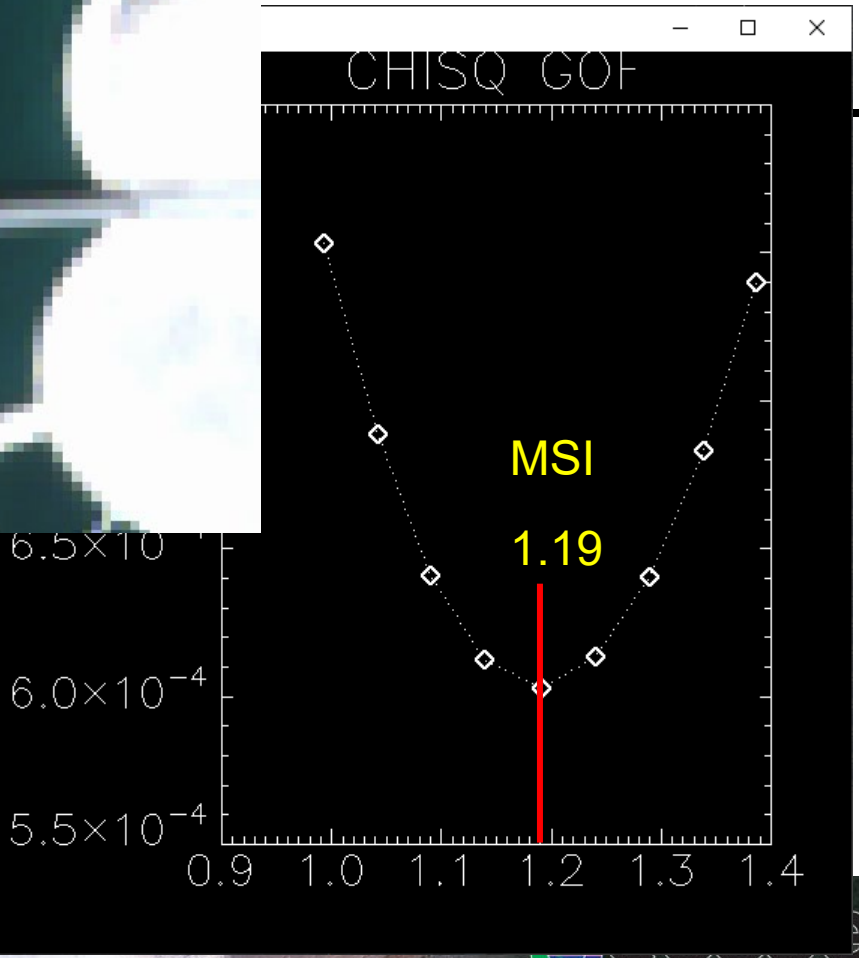


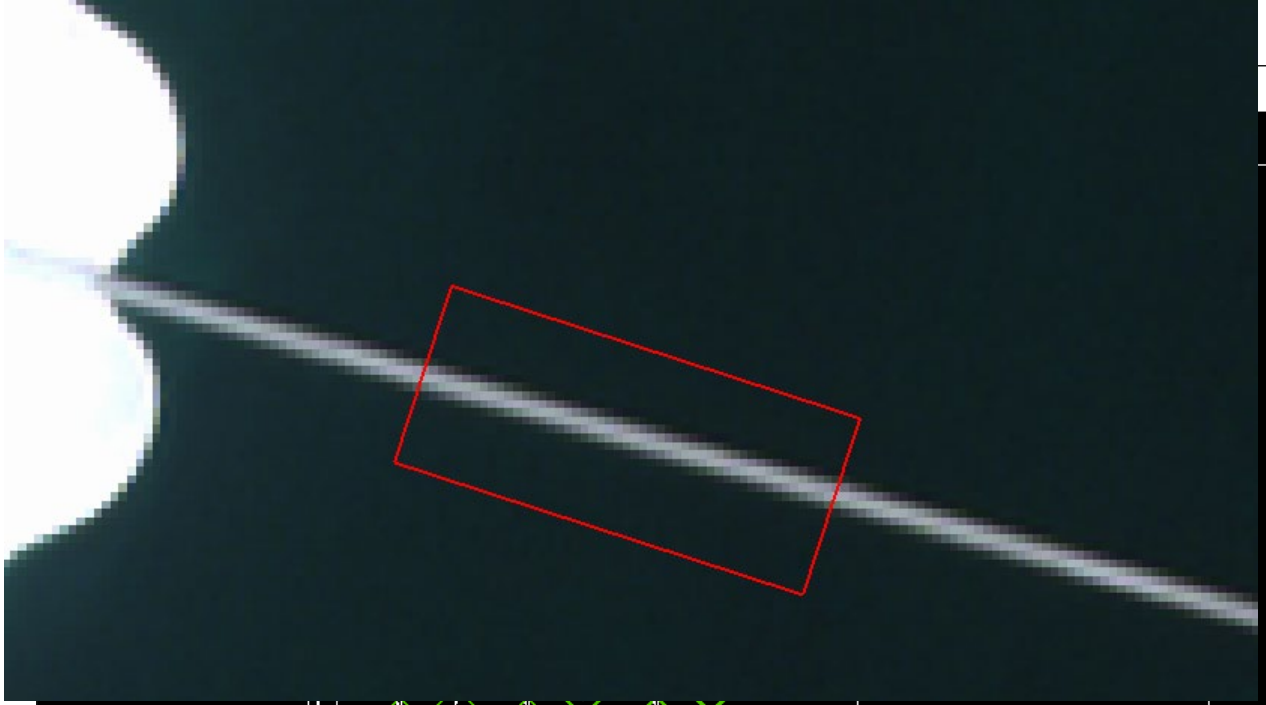

SQ GOF
OLI
0.96
0.002
0.000
0 2 4 6 8 10 12
Image matrix shift index
1.65×10⁻³
0.7 0.8 0.9 1.0 1.1

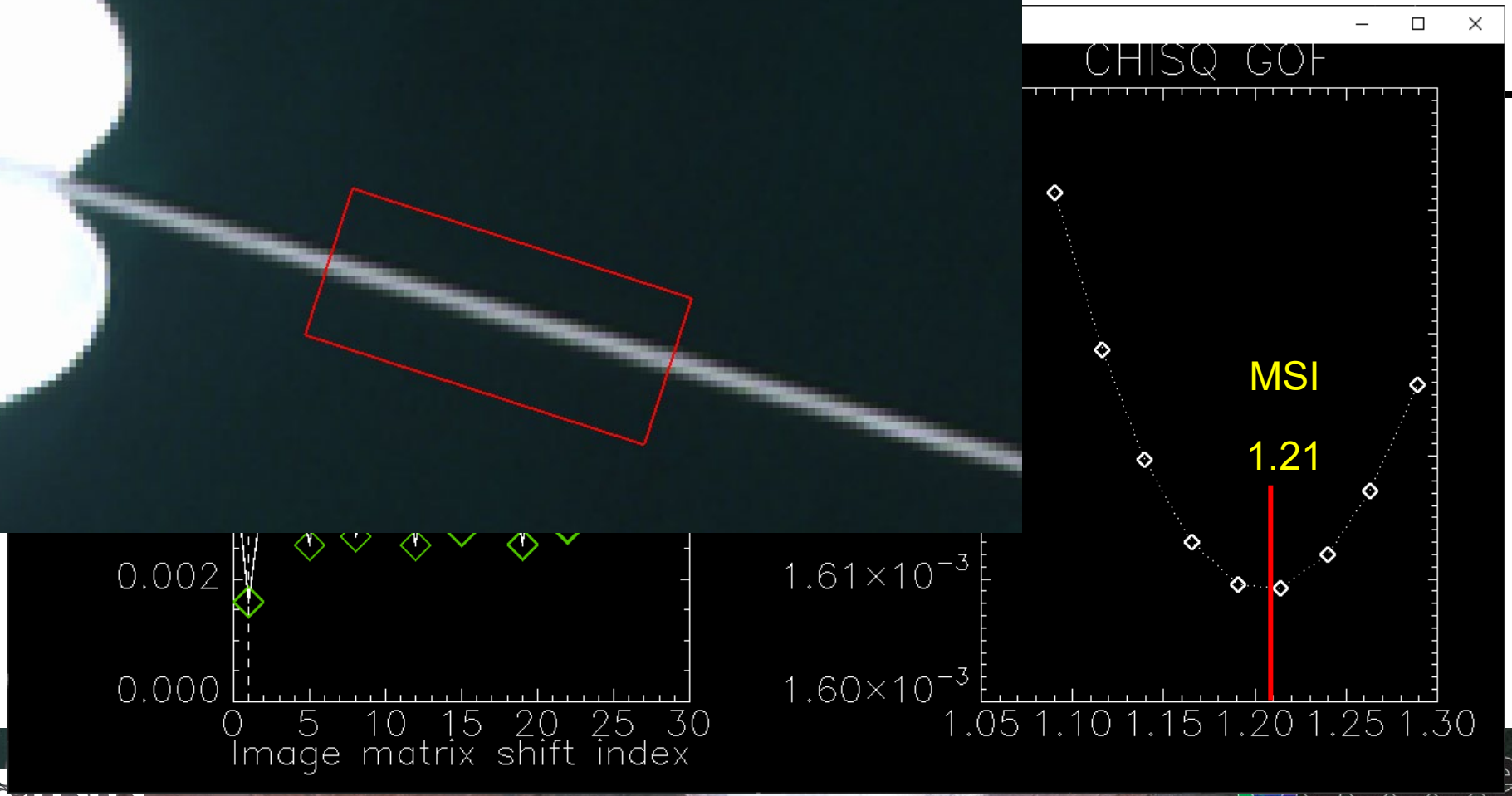
S2 MSI : King Fahd Causeway

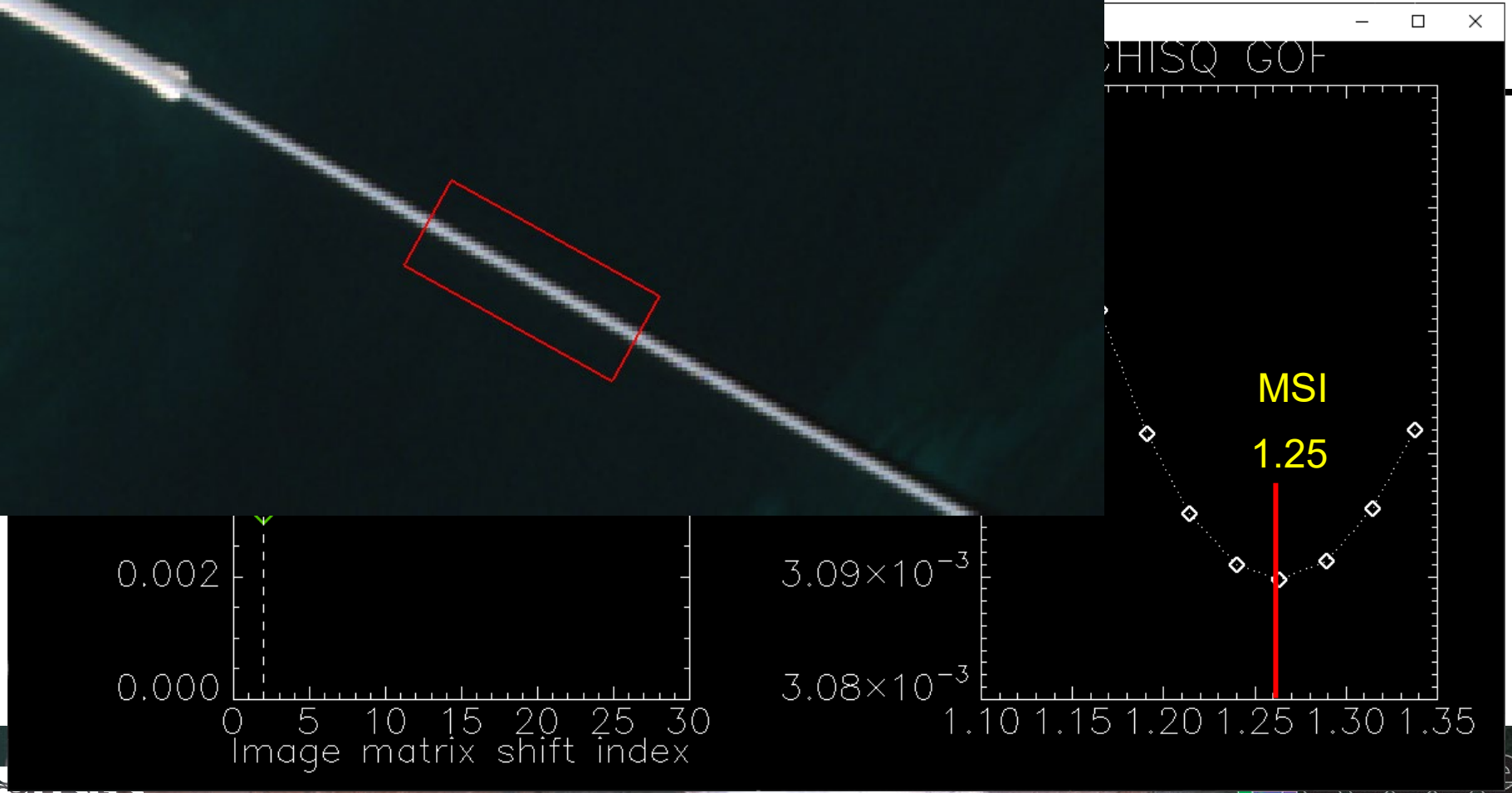


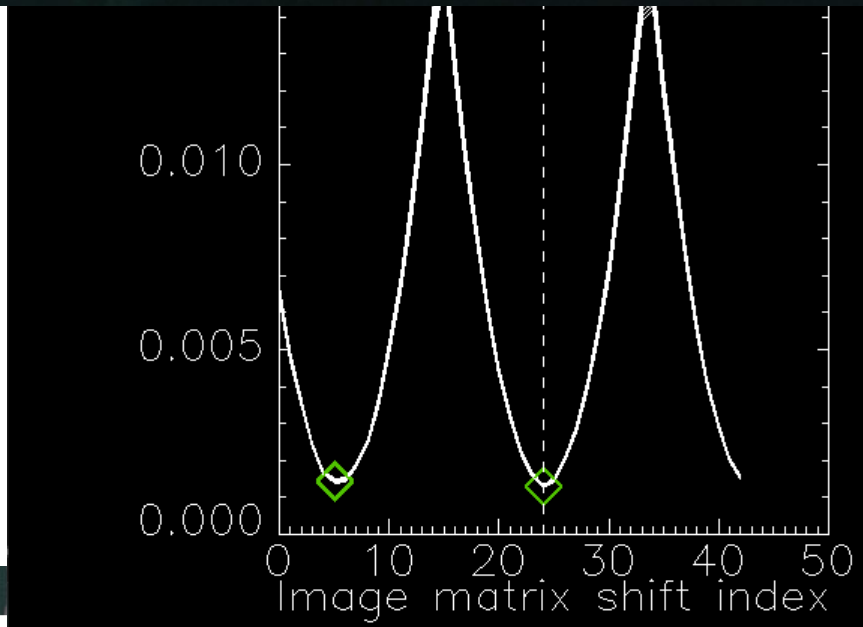

0.004
0.002
0.000
0
5
10
15
20
Image matrix shift index

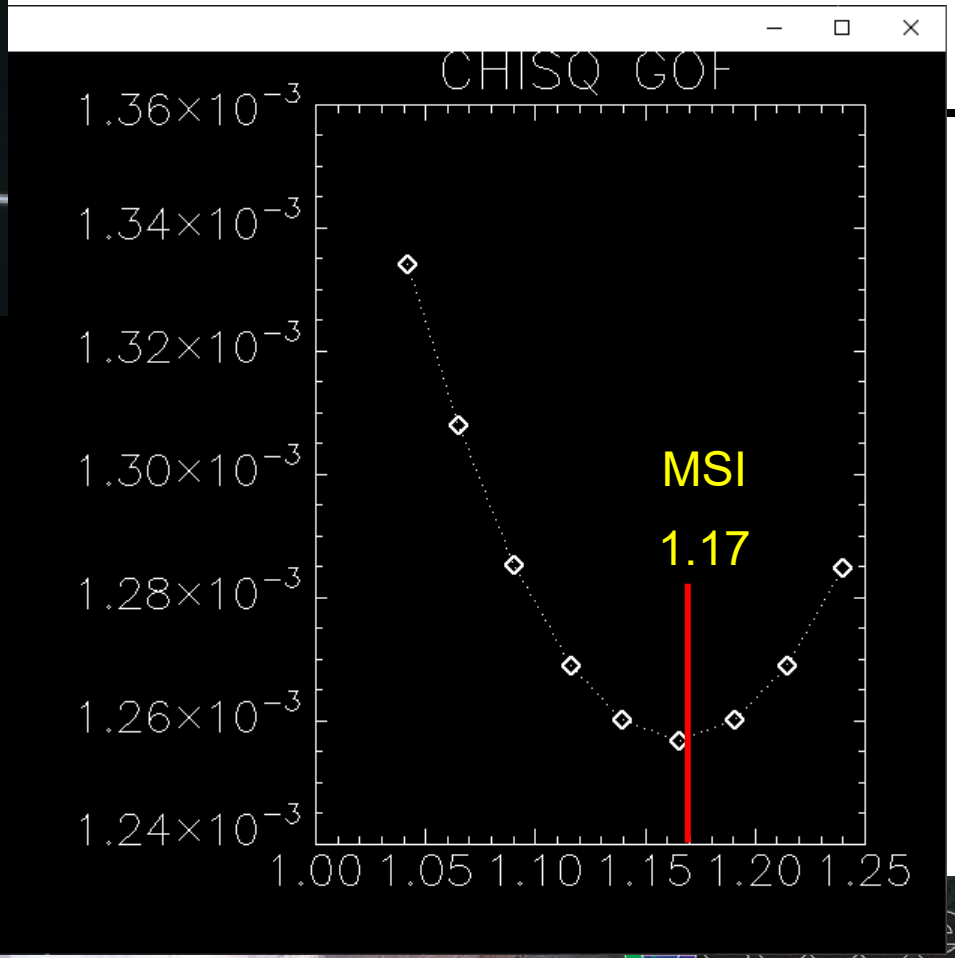

CHISQ GOF
MSI
1.19
6.5×10
6.0×10⁻⁴
5.5×10⁻⁴
0.9
1.0
1.1
1.2
1.3
1.4

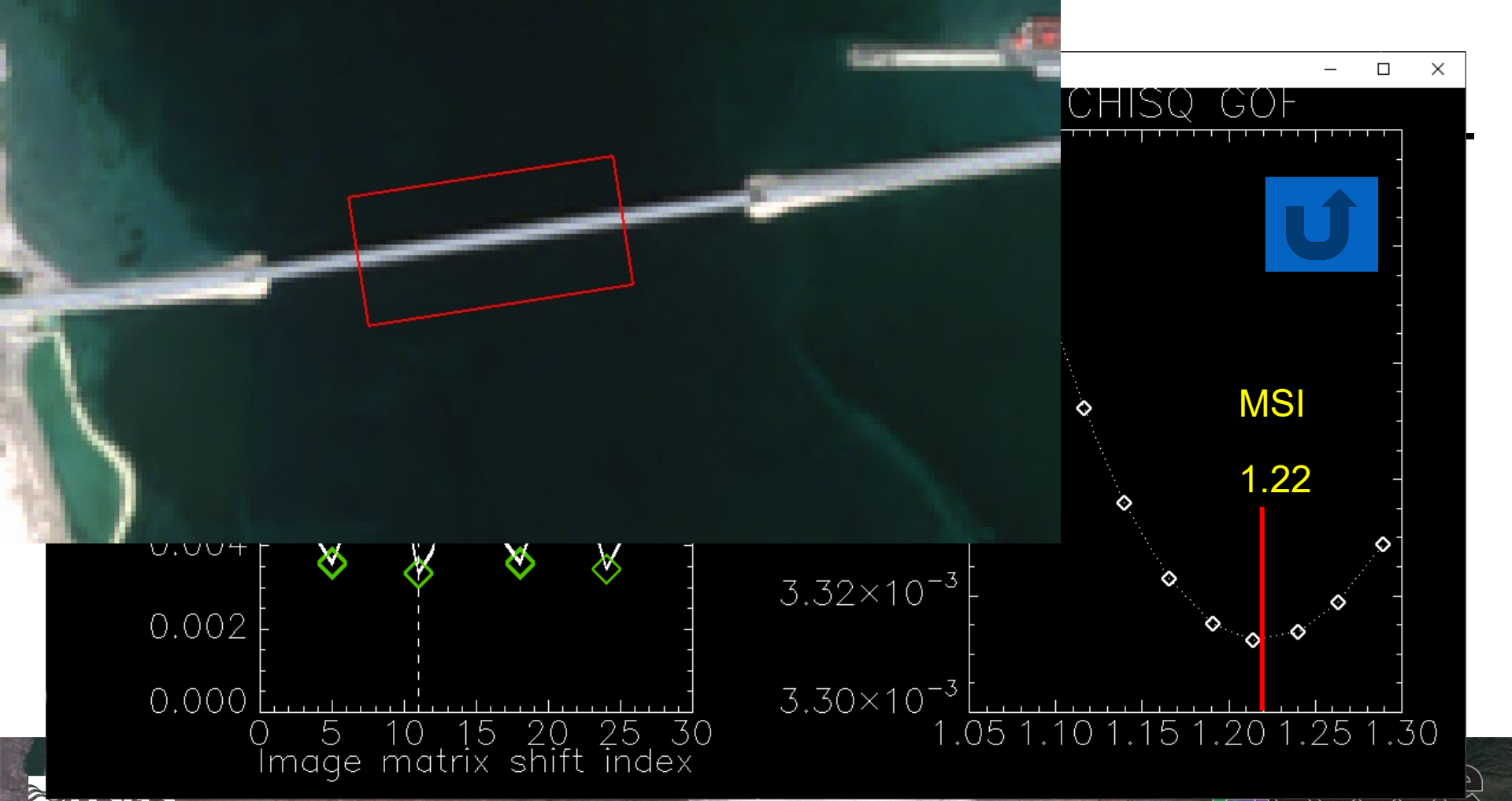




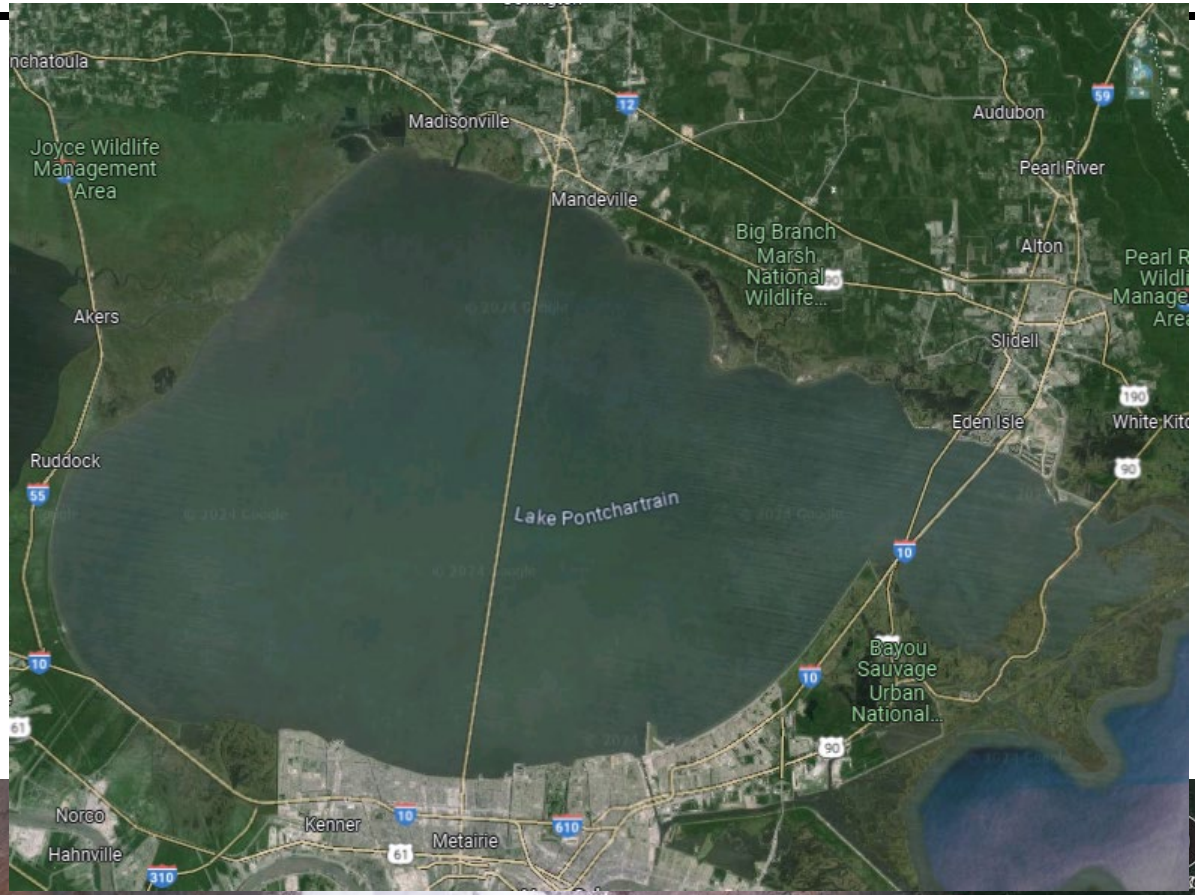

CHISQ GOF
MSI
1.25
0.002
0.000
0 5 10 15 20 25 30
Image matrix shift index
3.09×10⁻³
3.08×10⁻³
1.10 1.15 1.20 1.25 1.30 1.35



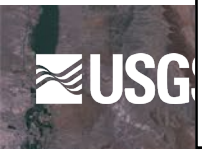


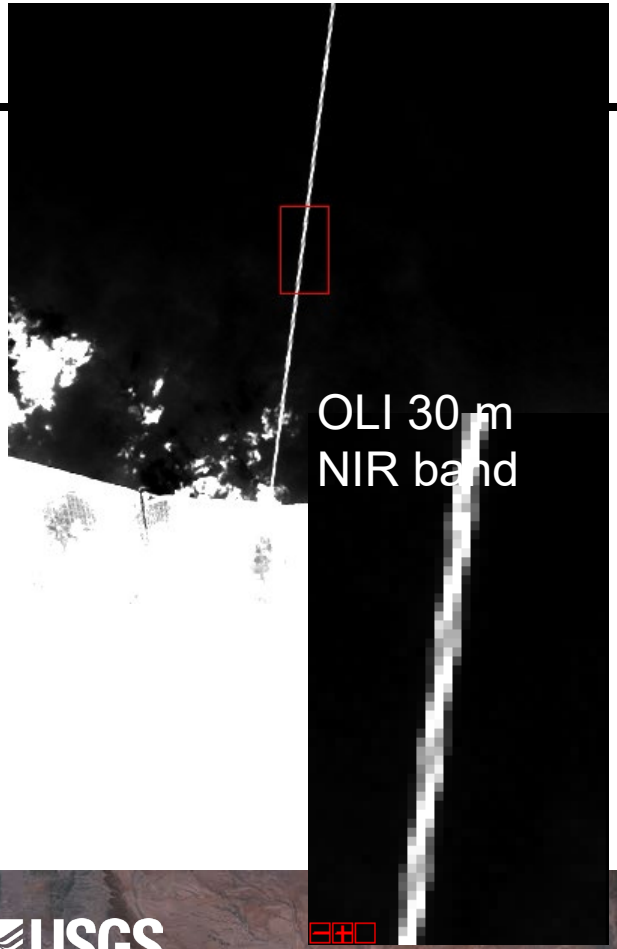


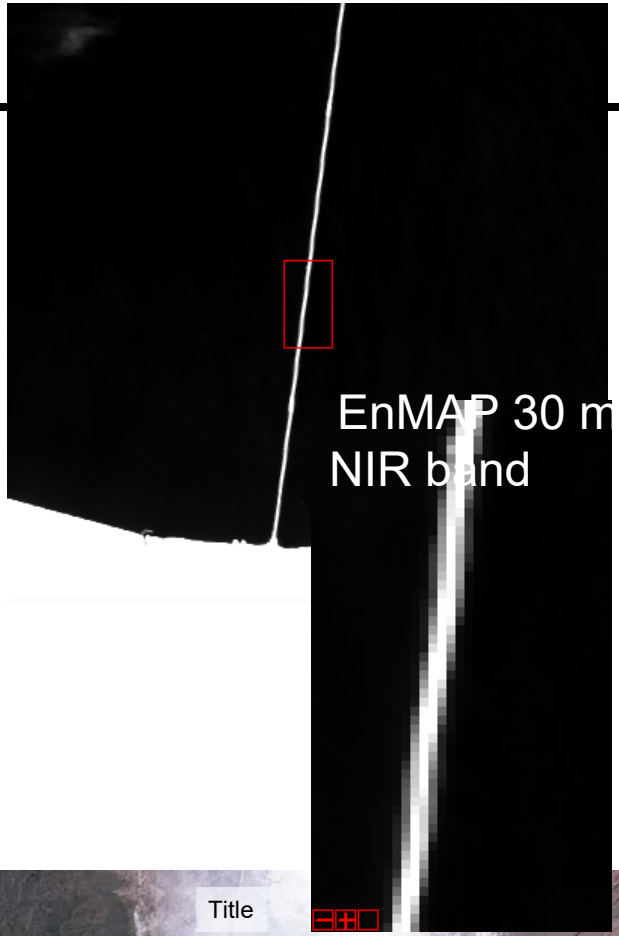
Lake Pontchartrain Causeway, LA, USA

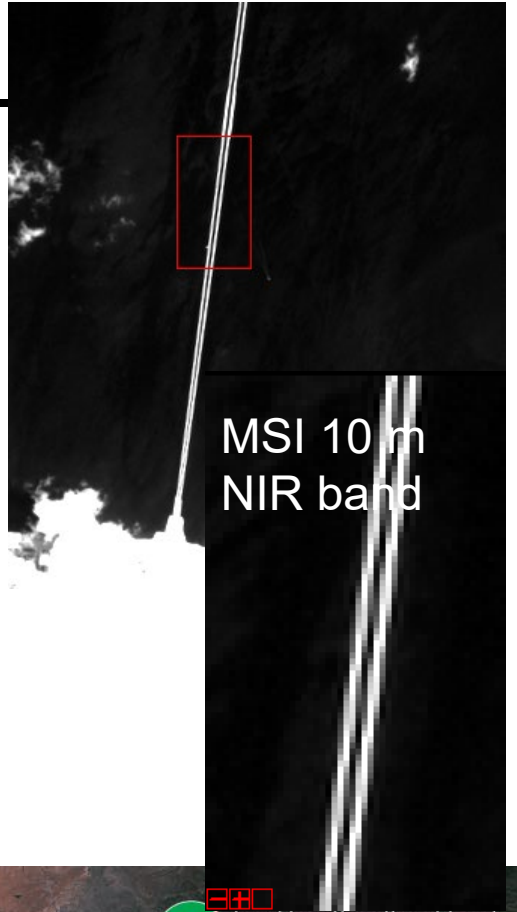


USGS

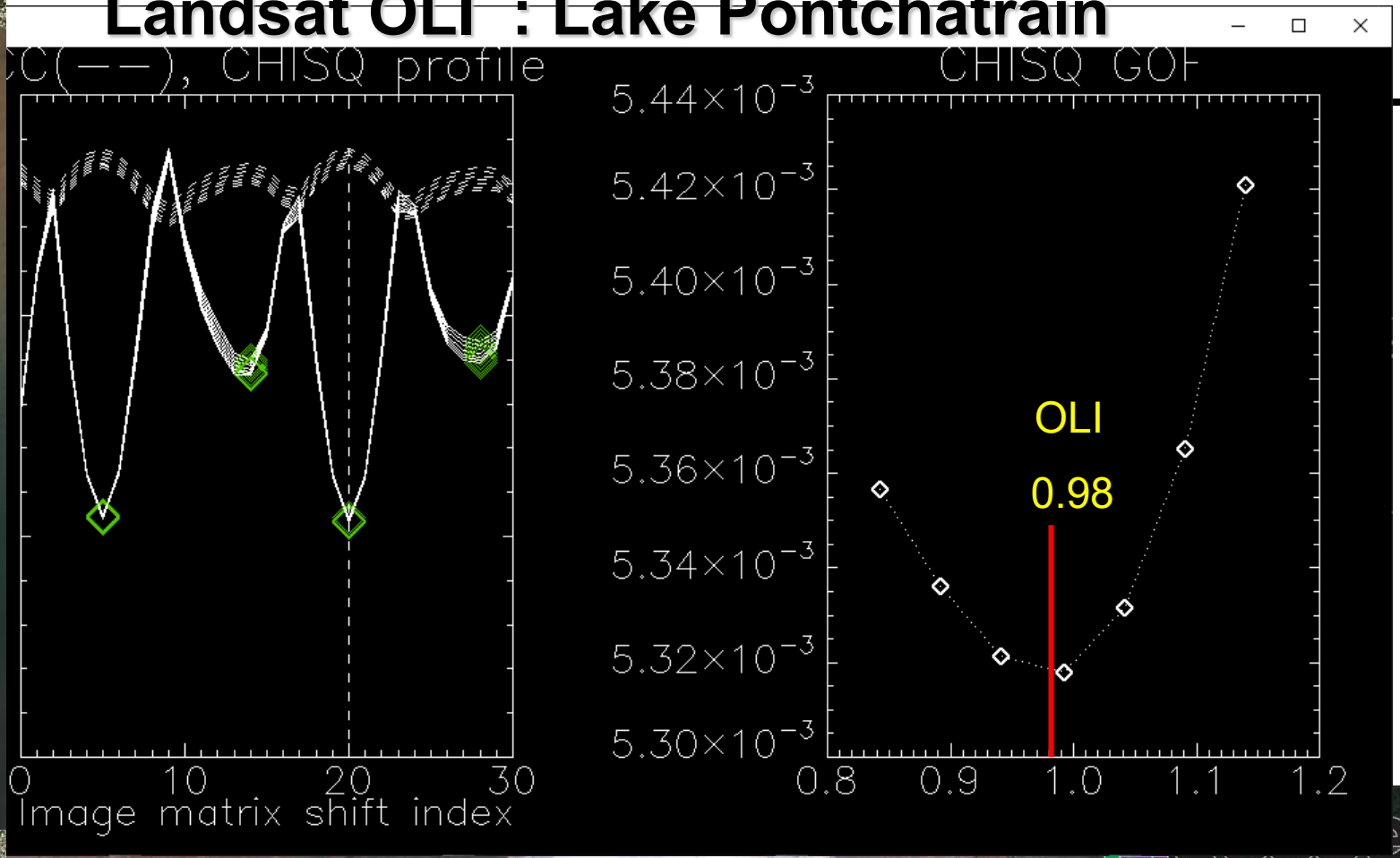

USG

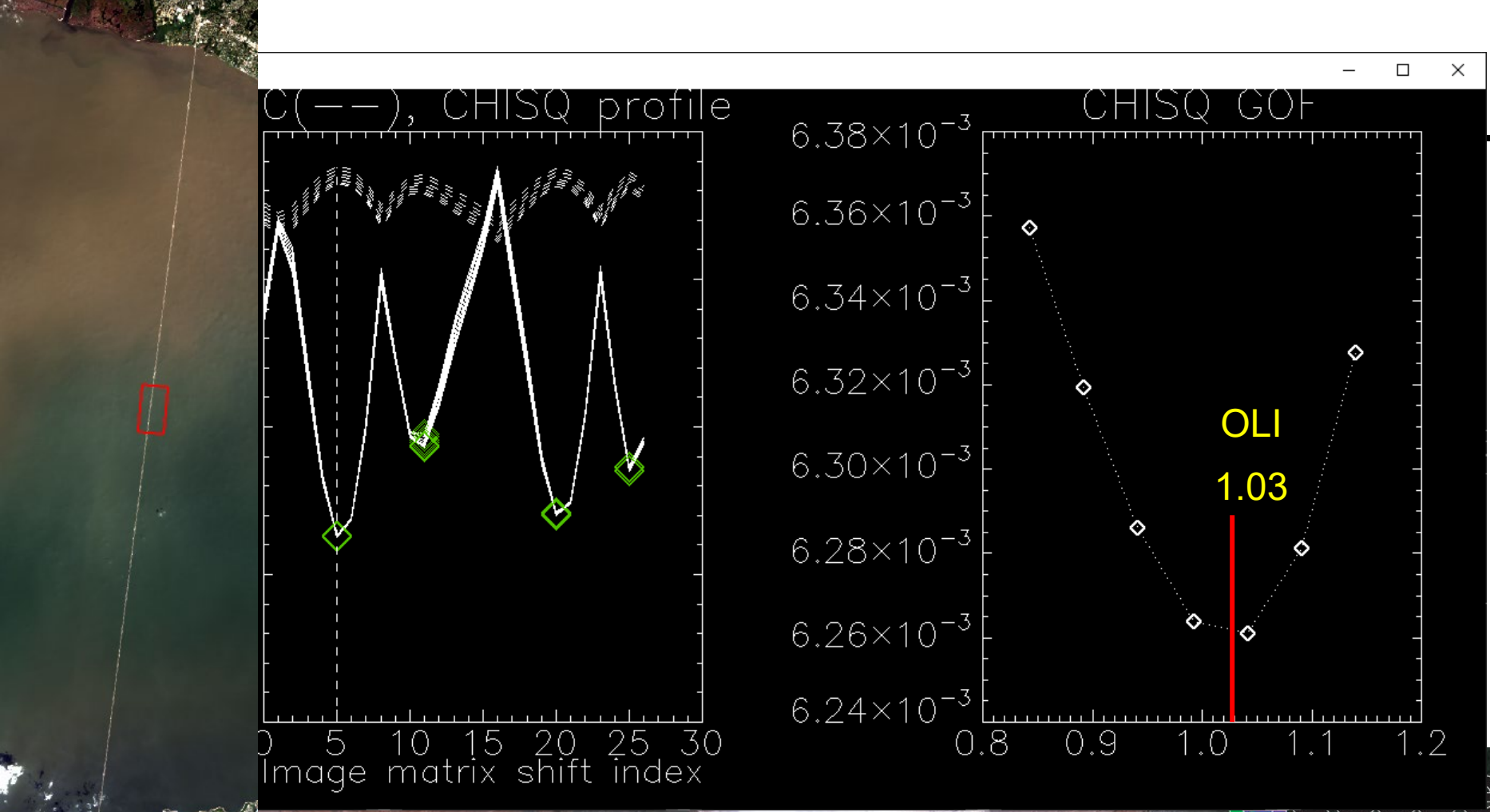

OLI 30 m
NIR band

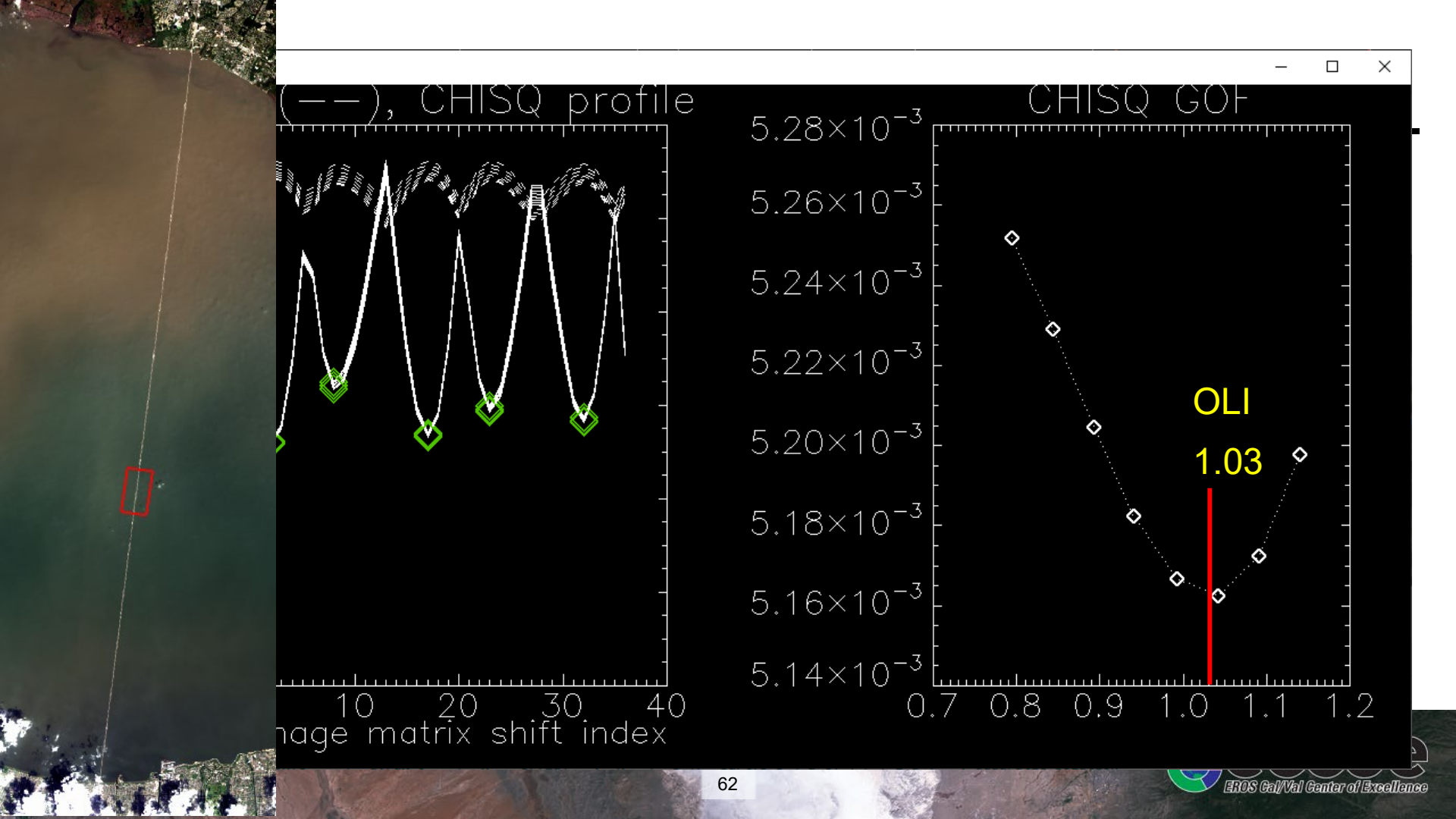

EnMAP 30 m
NIR band


MSI 10 m
NIR band

Landsat OLI : Lake Pontchatrain




C(——), CHISQ profile
0 5 10 15 20 25 30
Image matrix shift index
CHISQ GOF
6.38×10⁻³
6.36×10⁻³
6.34×10⁻³
6.32×10⁻³
6.30×10⁻³
6.28×10⁻³
6.26×10⁻³
6.24×10⁻³
0.8 0.9 1.0 1.1 1.2
OLI
1.03



S2 MSI : Lake Pontchatrain

USGS

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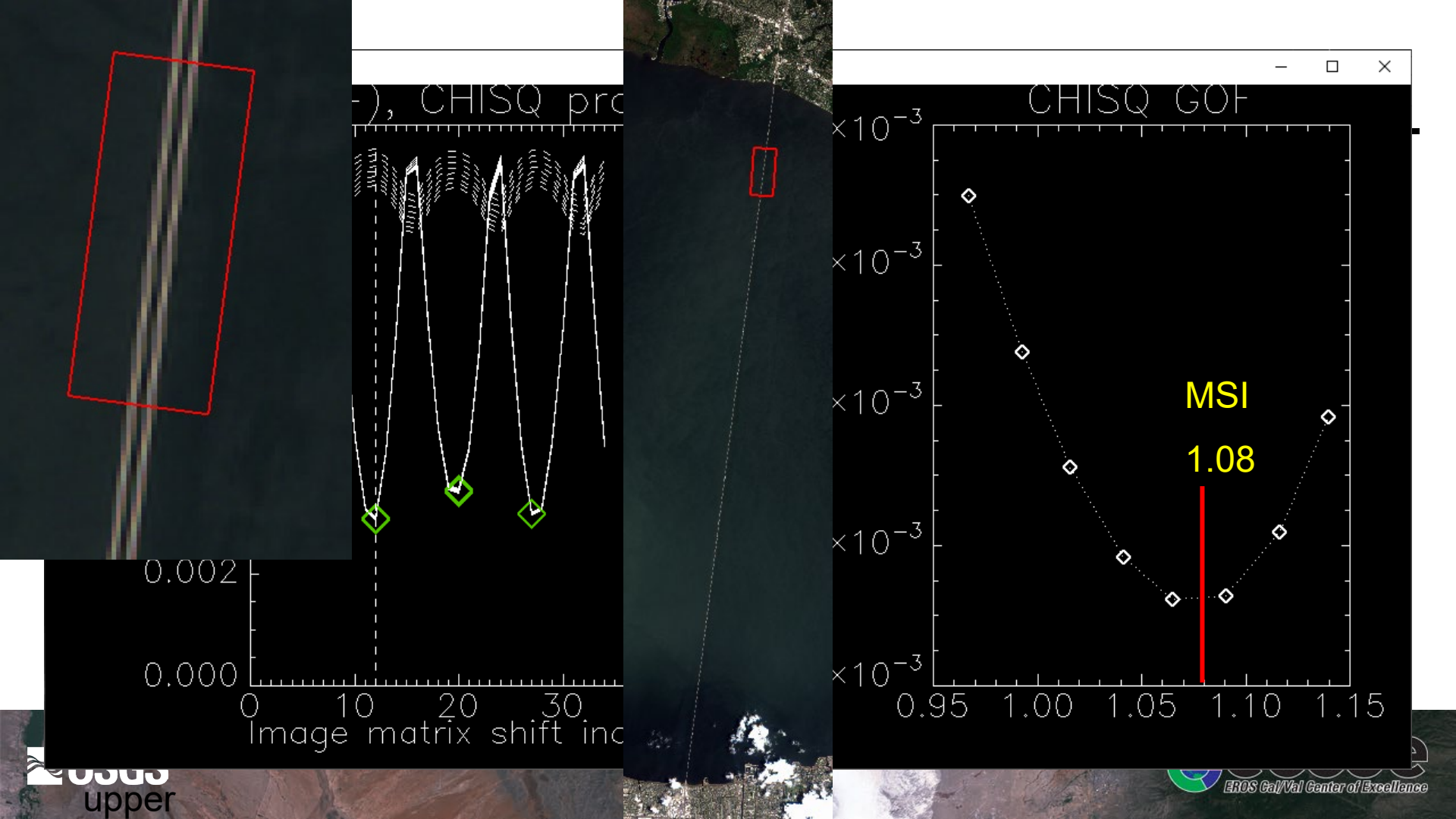
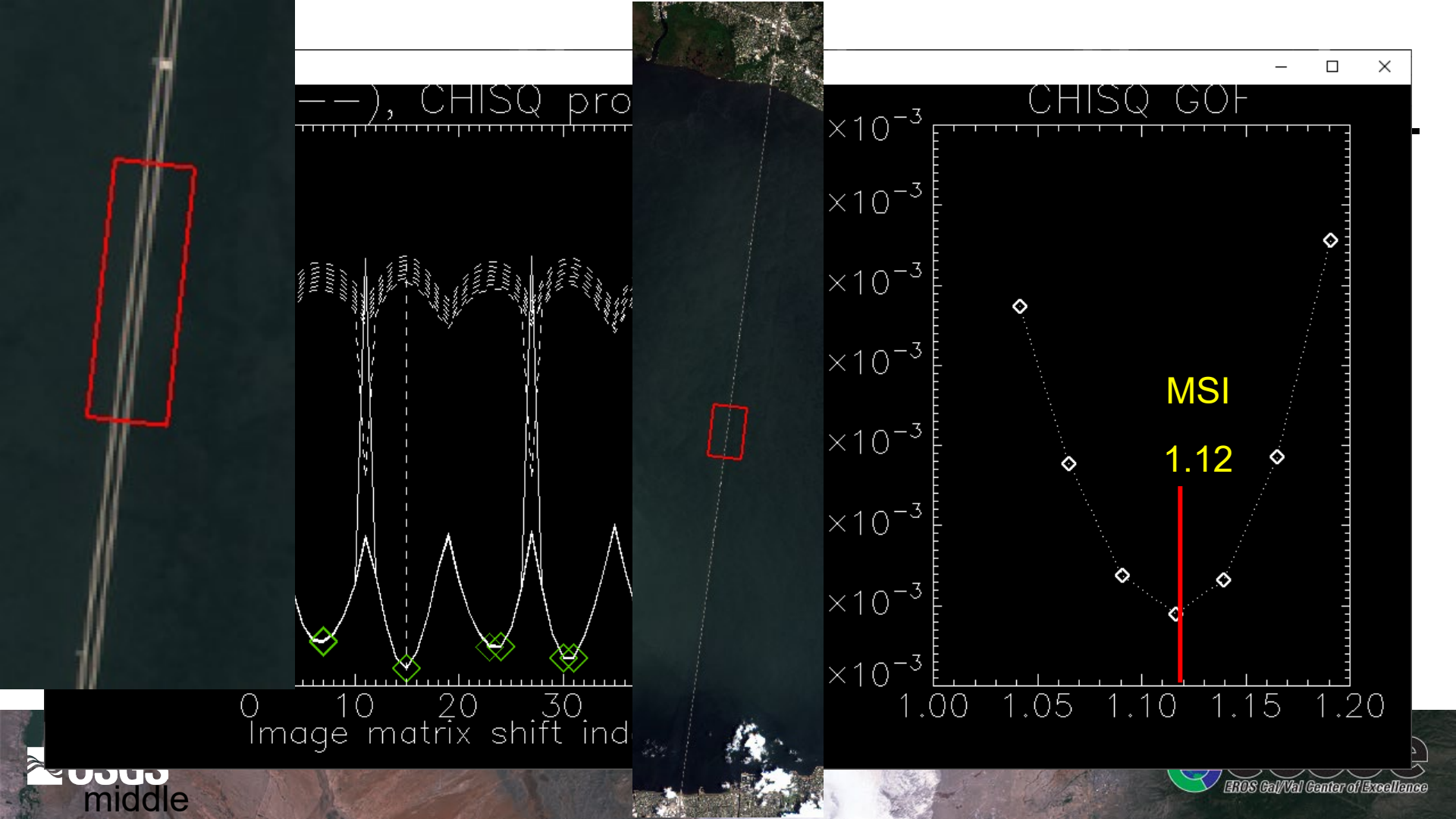
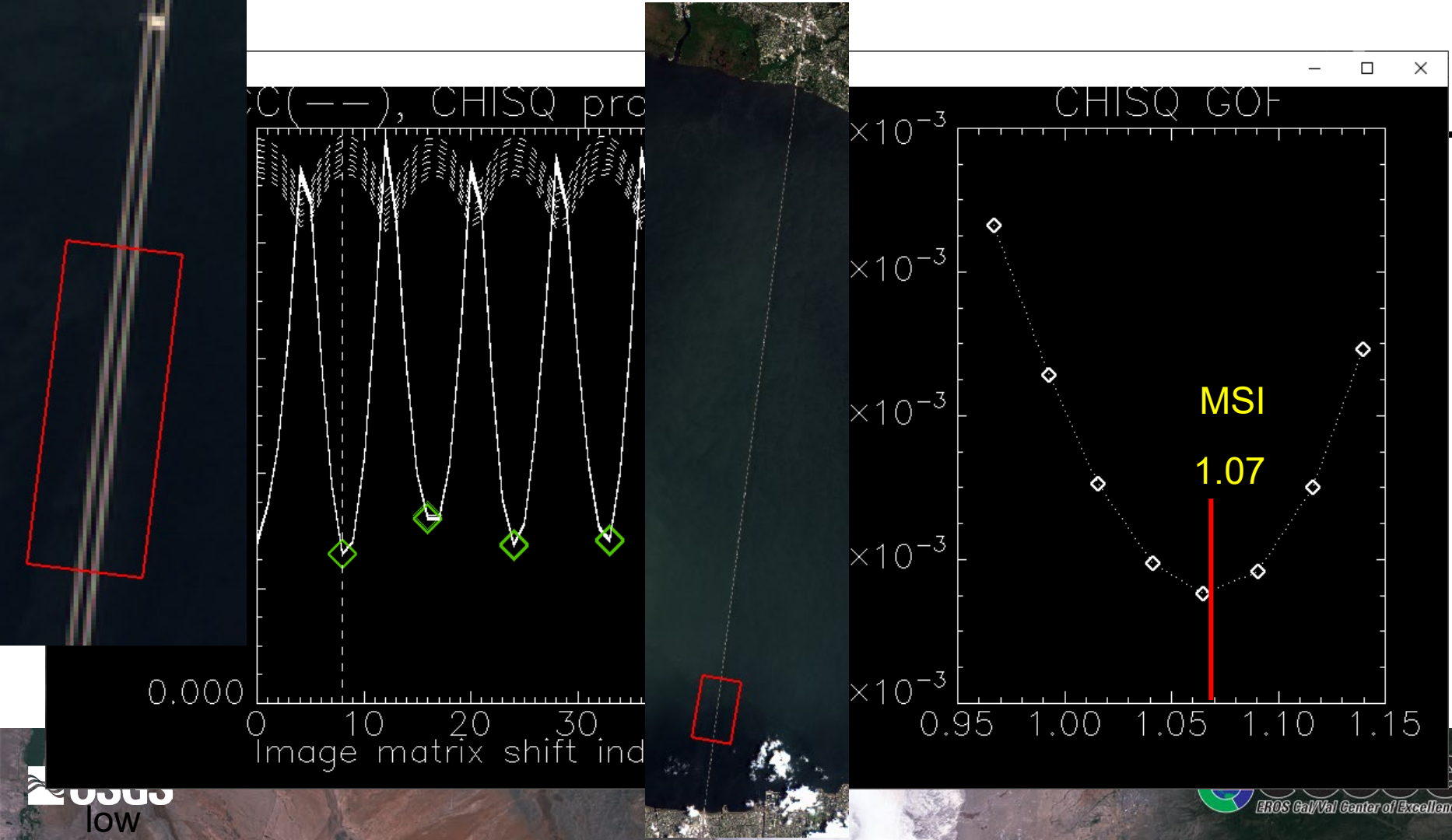
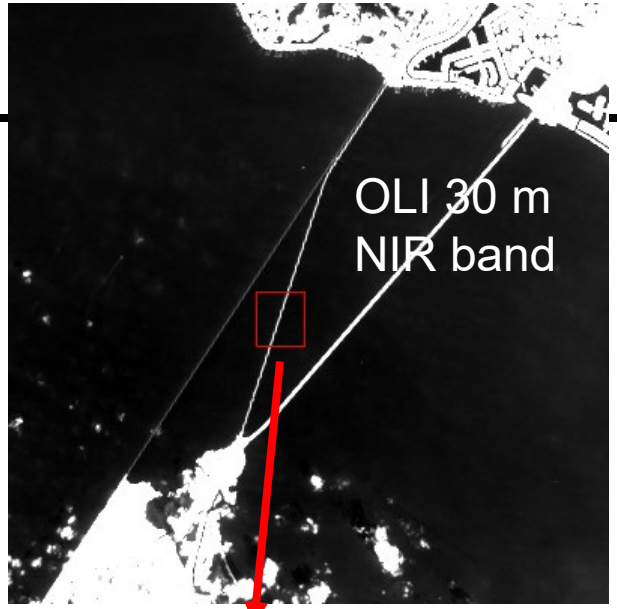
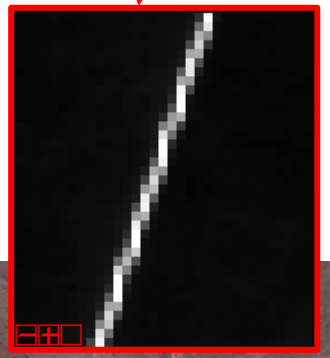
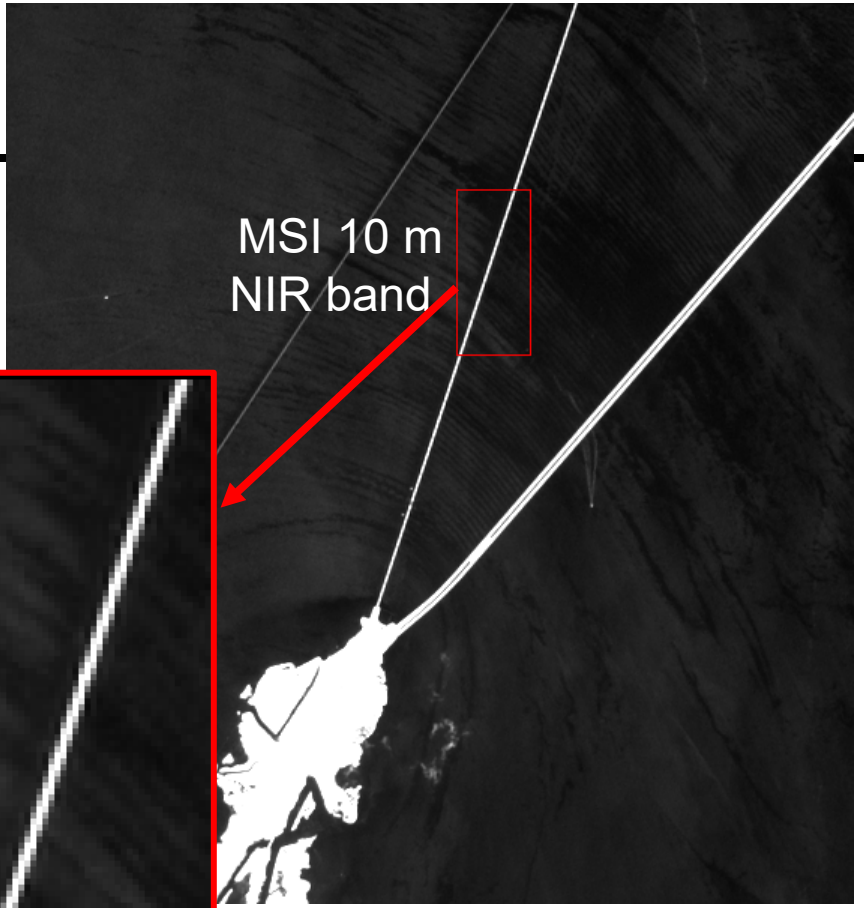

CHISQ GOF
×10⁻³
×10⁻³
×10⁻³
×10⁻³
×10⁻³
MSI
1.08
0.95 1.00 1.05 1.10 1.15
0.002
0.000
0 10 20 30
Image matrix shift inc
upper
EROS Cal/Val Center of Excellence

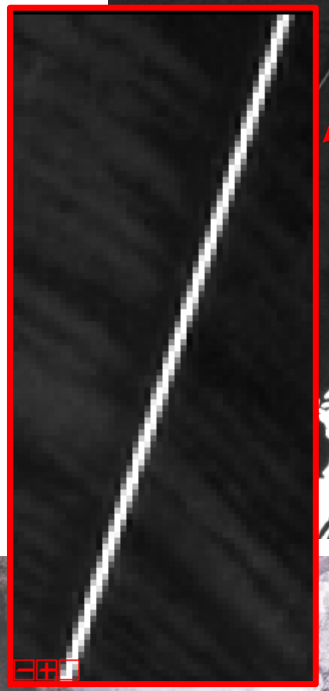

), CHISQ pro
0
10
20
30
Image matrix shift ind
CHISQ GOF
×10⁻³
×10⁻³
×10⁻³
×10⁻³
×10⁻³
×10⁻³
×10⁻³
MSI
1.12
1.00
1.05
1.10
1.15
1.20
middle
EROS Cal/Val Center of Excellence

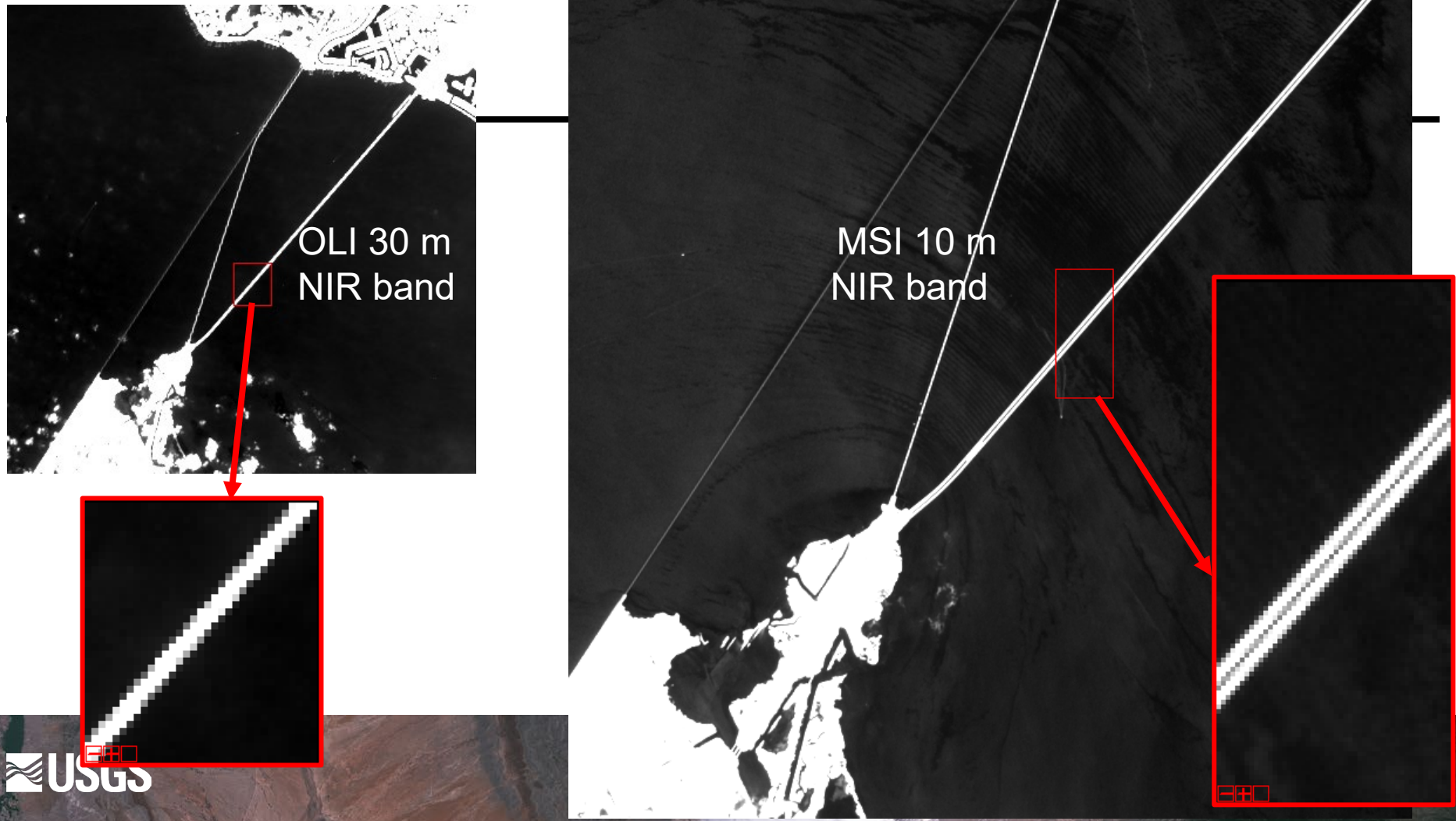

CHISQ GOF
×10⁻³
×10⁻³
×10⁻³
×10⁻³
×10⁻³
MSI
1.07
0.95 1.00 1.05 1.10 1.15
0.000
0 10 20 30
Image matrix shift ind
low
EROS Cal/Val Center of Excellence

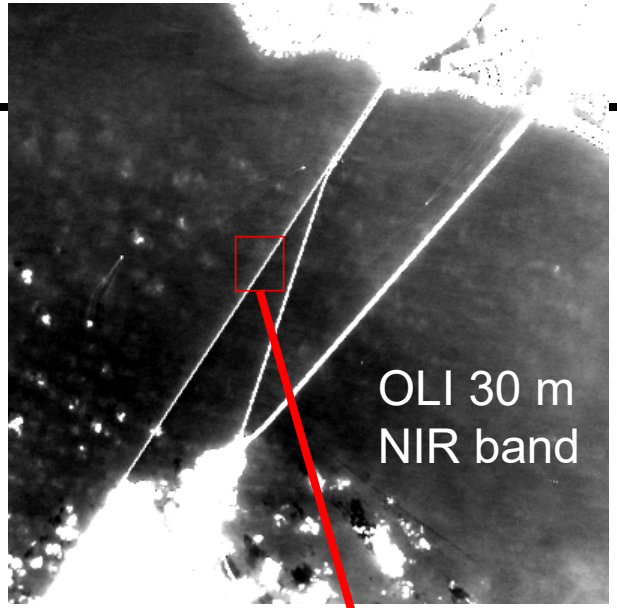

OLI 30 m
NIR band

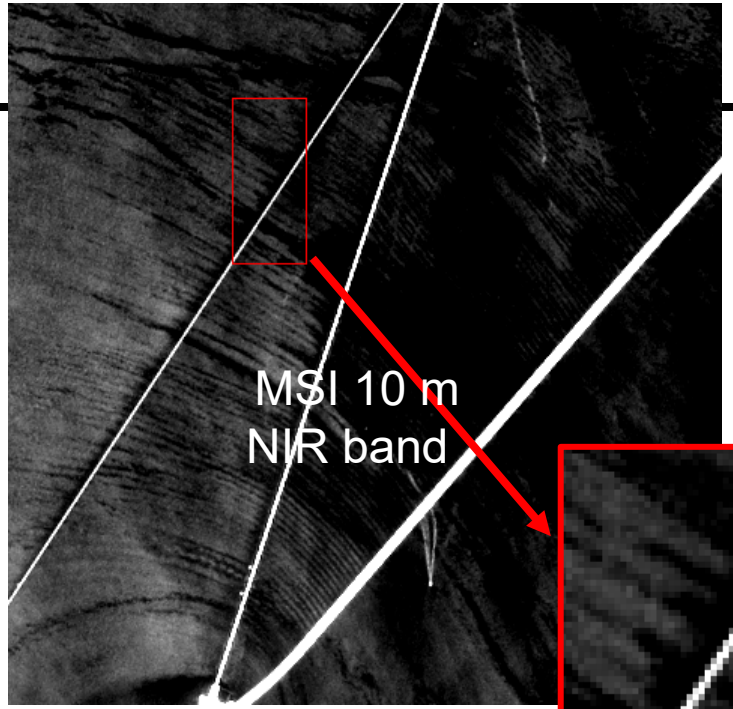



MSI 10 m
NIR band

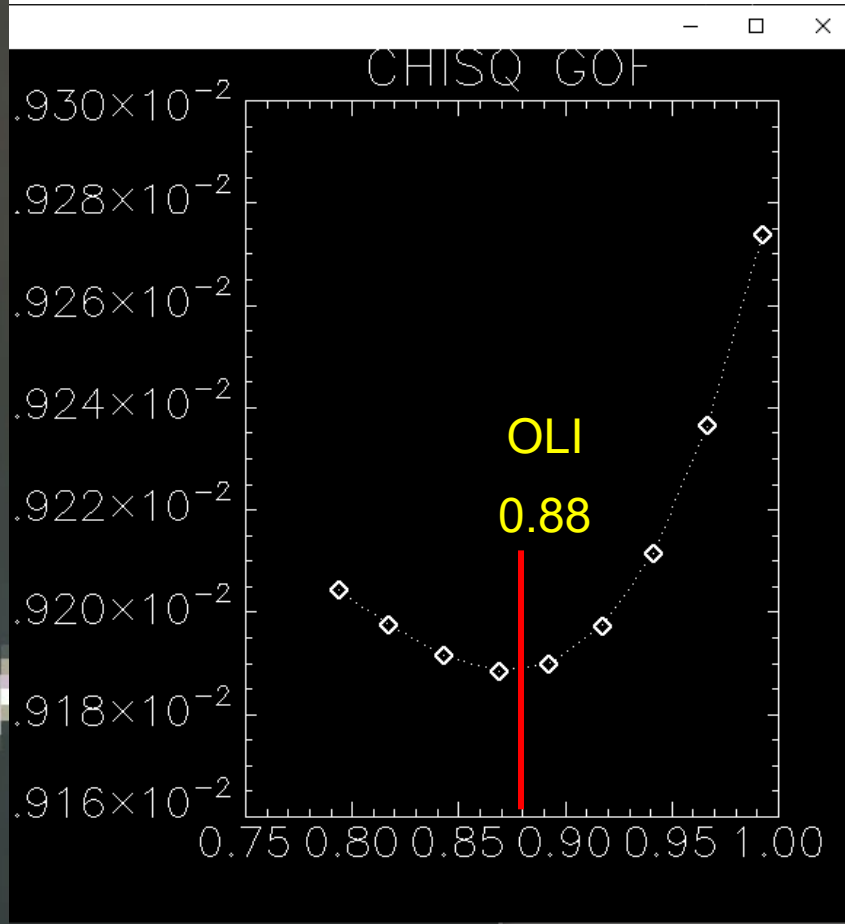


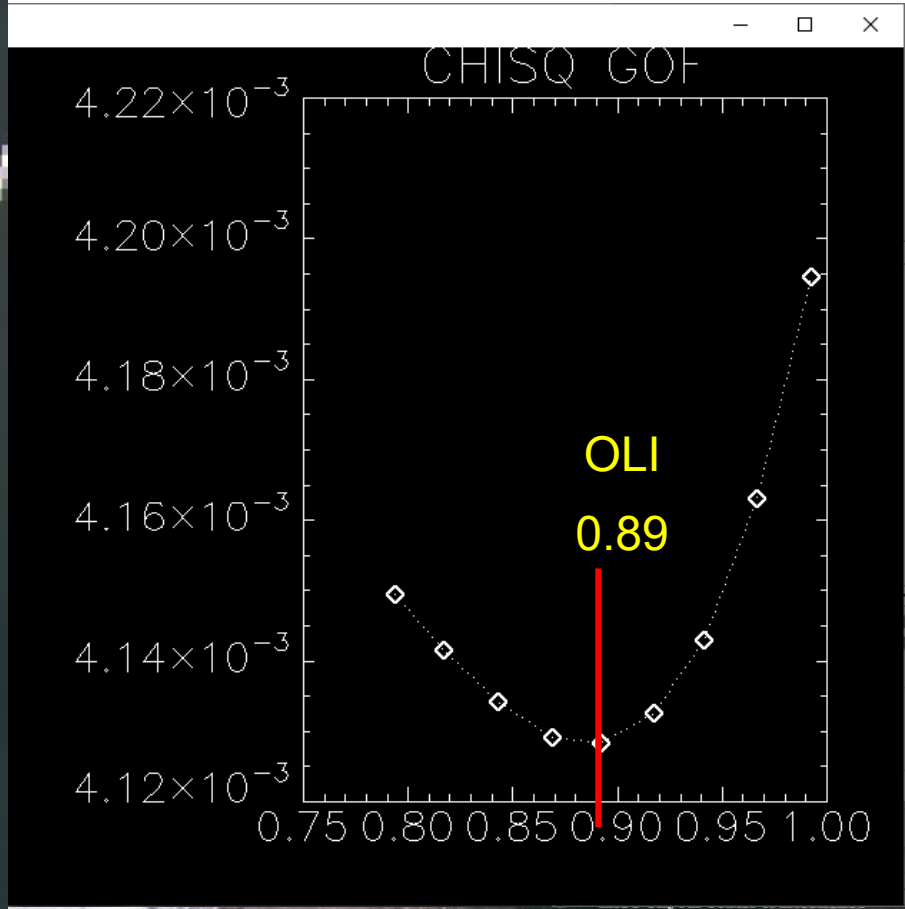

OLI 30 m
NIR band
MSI 10 m
NIR band


OLI 30 m
NIR band

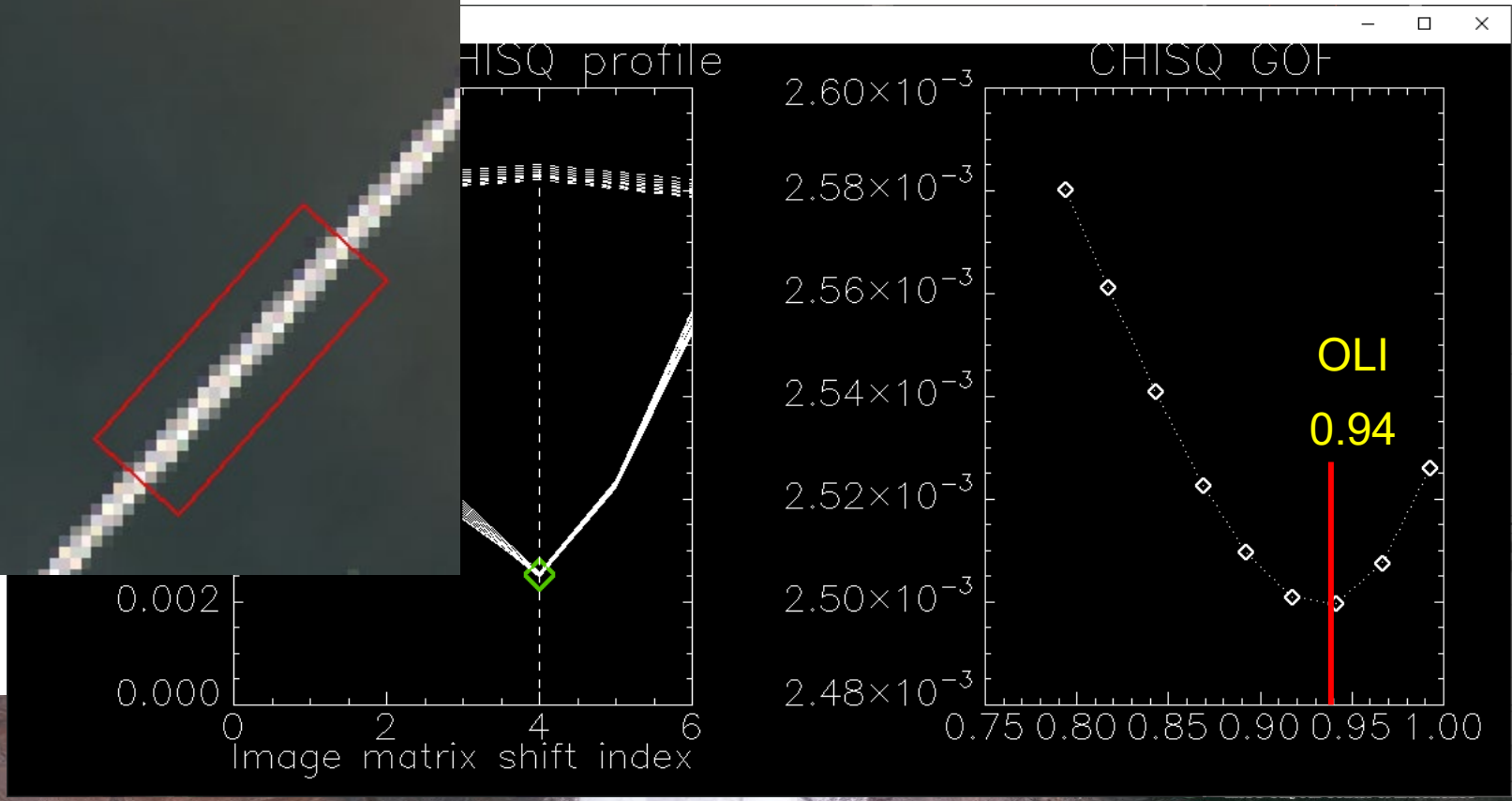

MSI 10 m
NIR band

Landsat OLI : US-11 (10m single bridge)

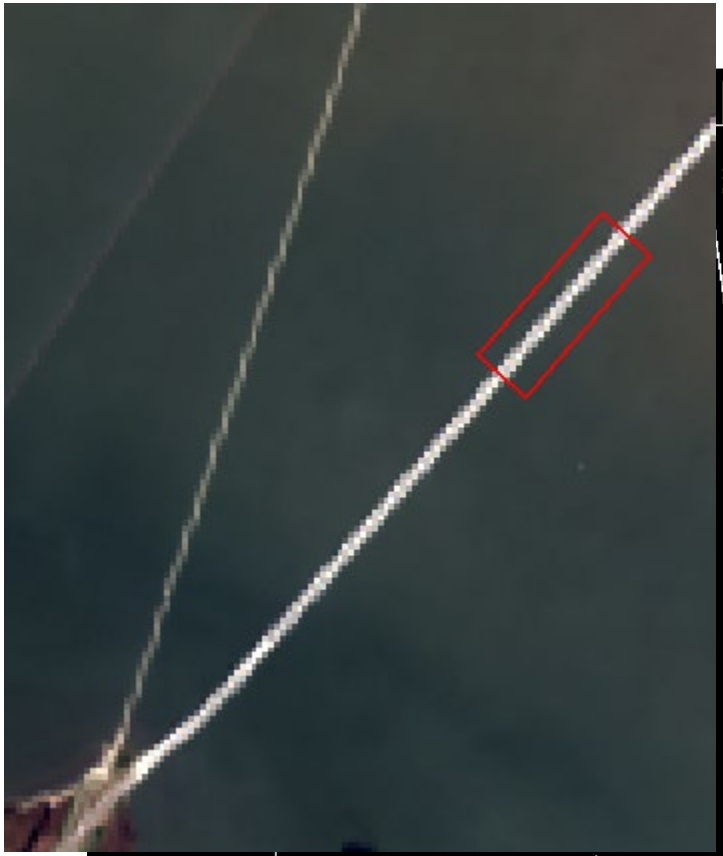



CHISQ GOF
4.22×10⁻³
4.20×10⁻³
4.18×10⁻³
4.16×10⁻³
4.14×10⁻³
4.12×10⁻³
OLI
0.89
0.75 0.80 0.85 0.90 0.95 1.00

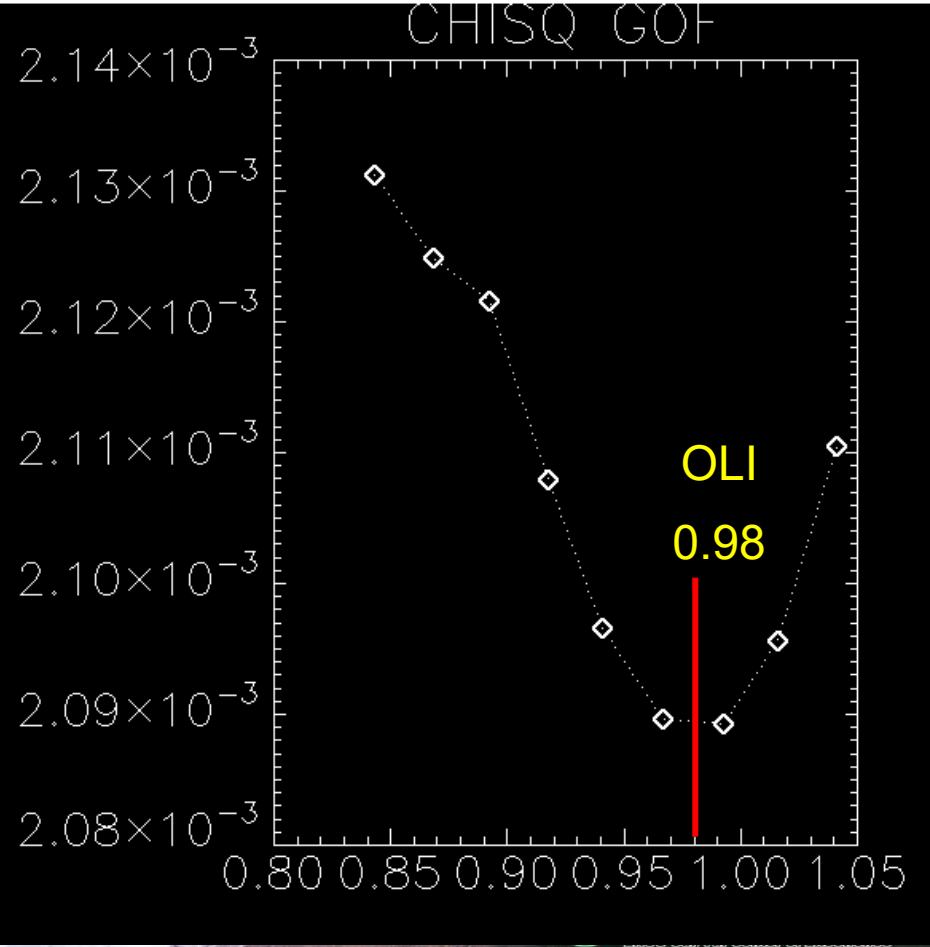
Landsat OLI : I-90 (19-15-19 m Twin bridge)



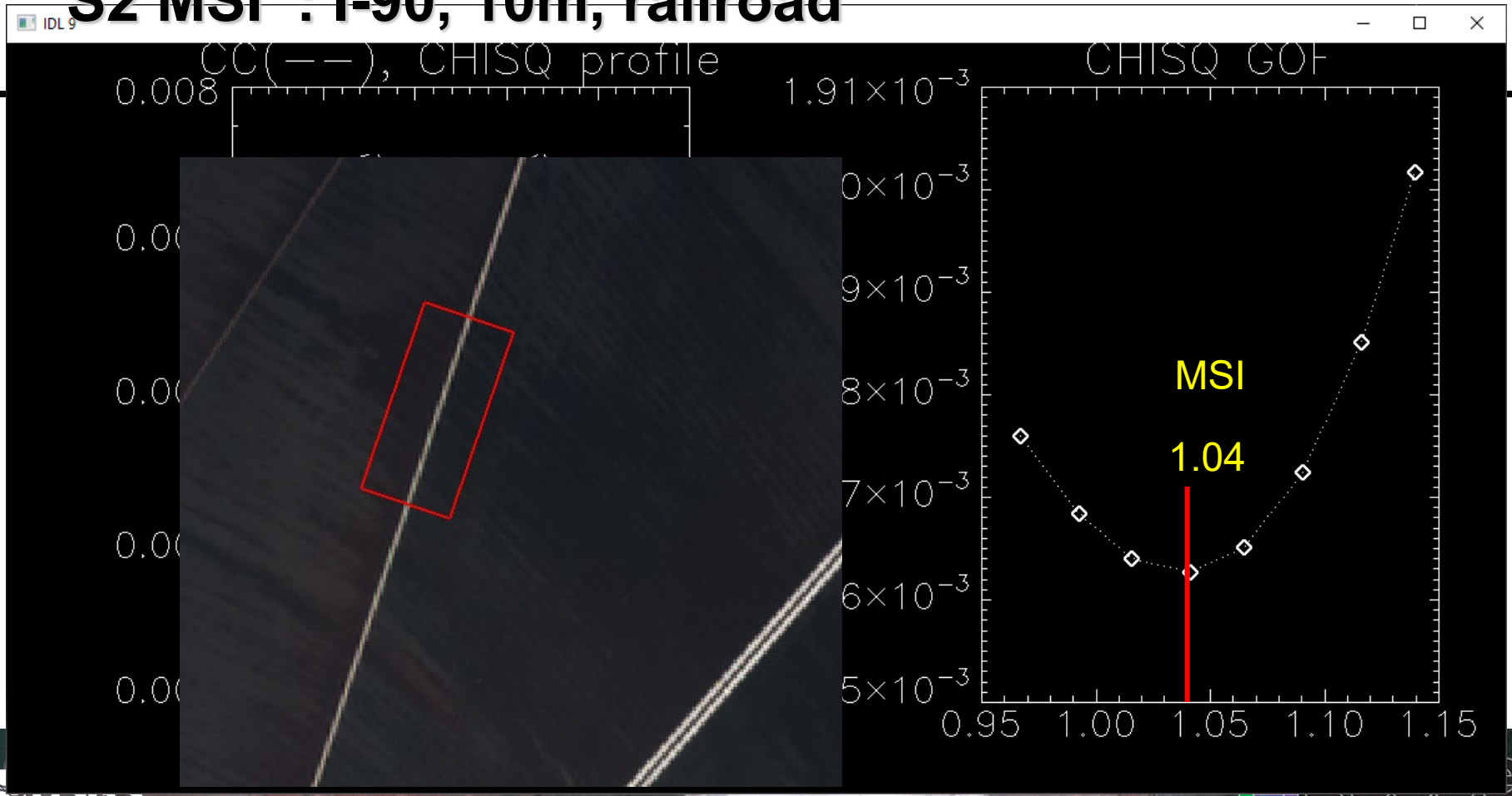
USGS



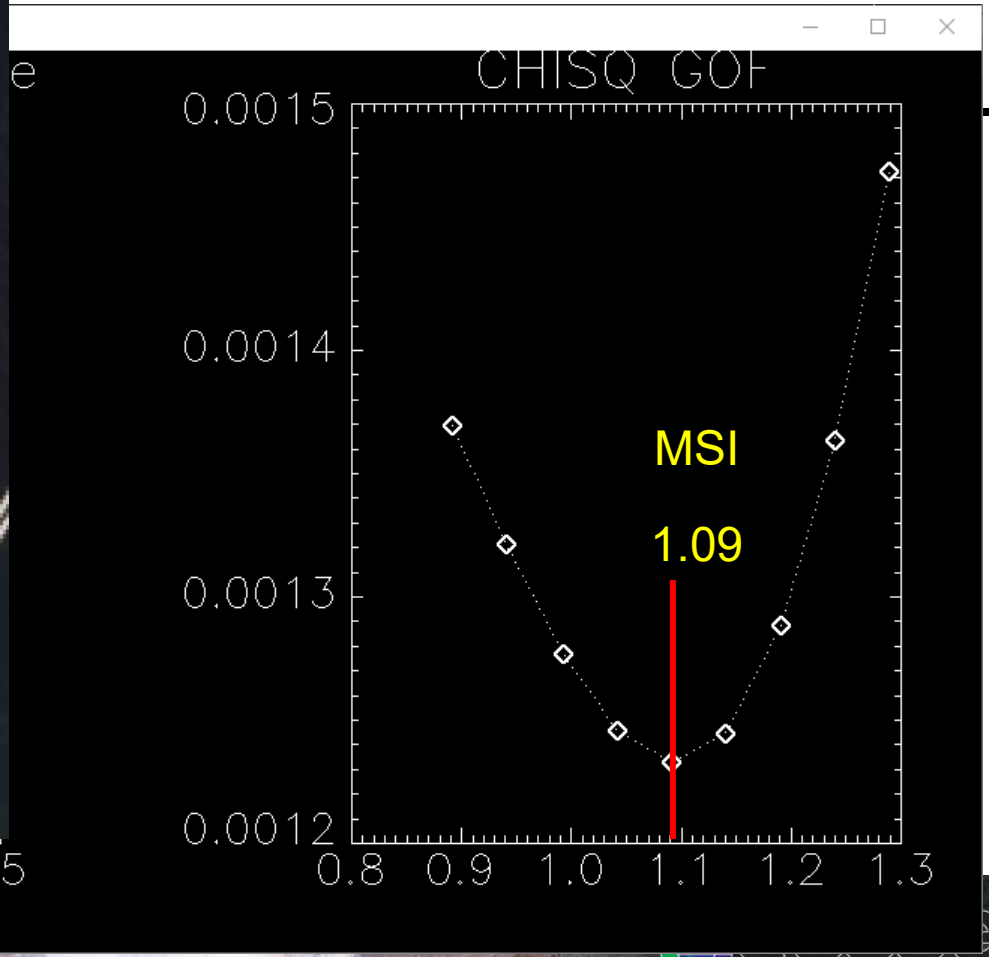
profile
0.000
0
5
10
15
20
Image matrix shift index

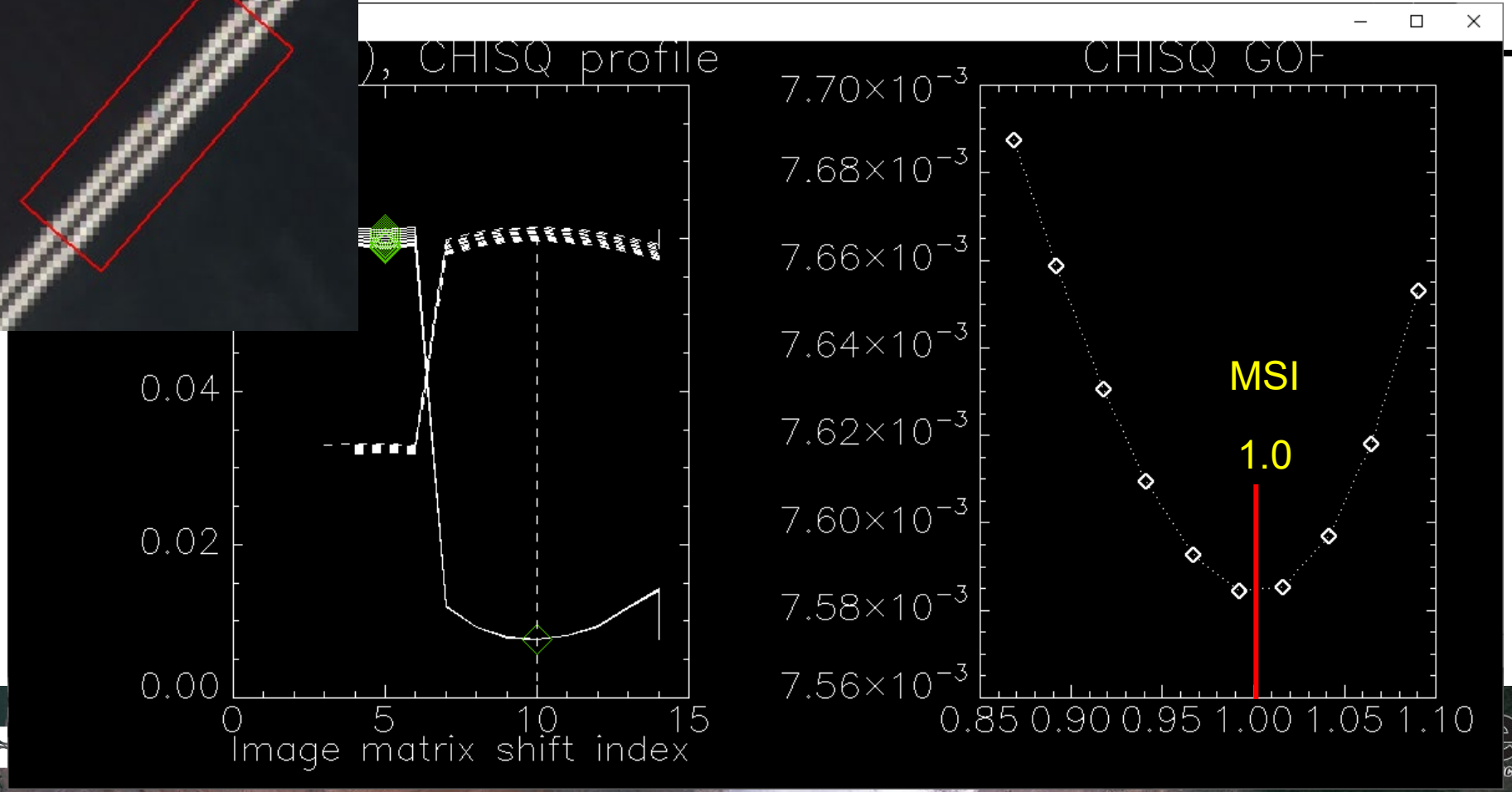

CHISQ GOF
2.14×10⁻³
2.13×10⁻³
2.12×10⁻³
2.11×10⁻³
2.10×10⁻³
2.09×10⁻³
2.08×10⁻³
OLI
0.98
0.80 0.85 0.90 0.95 1.00 1.05

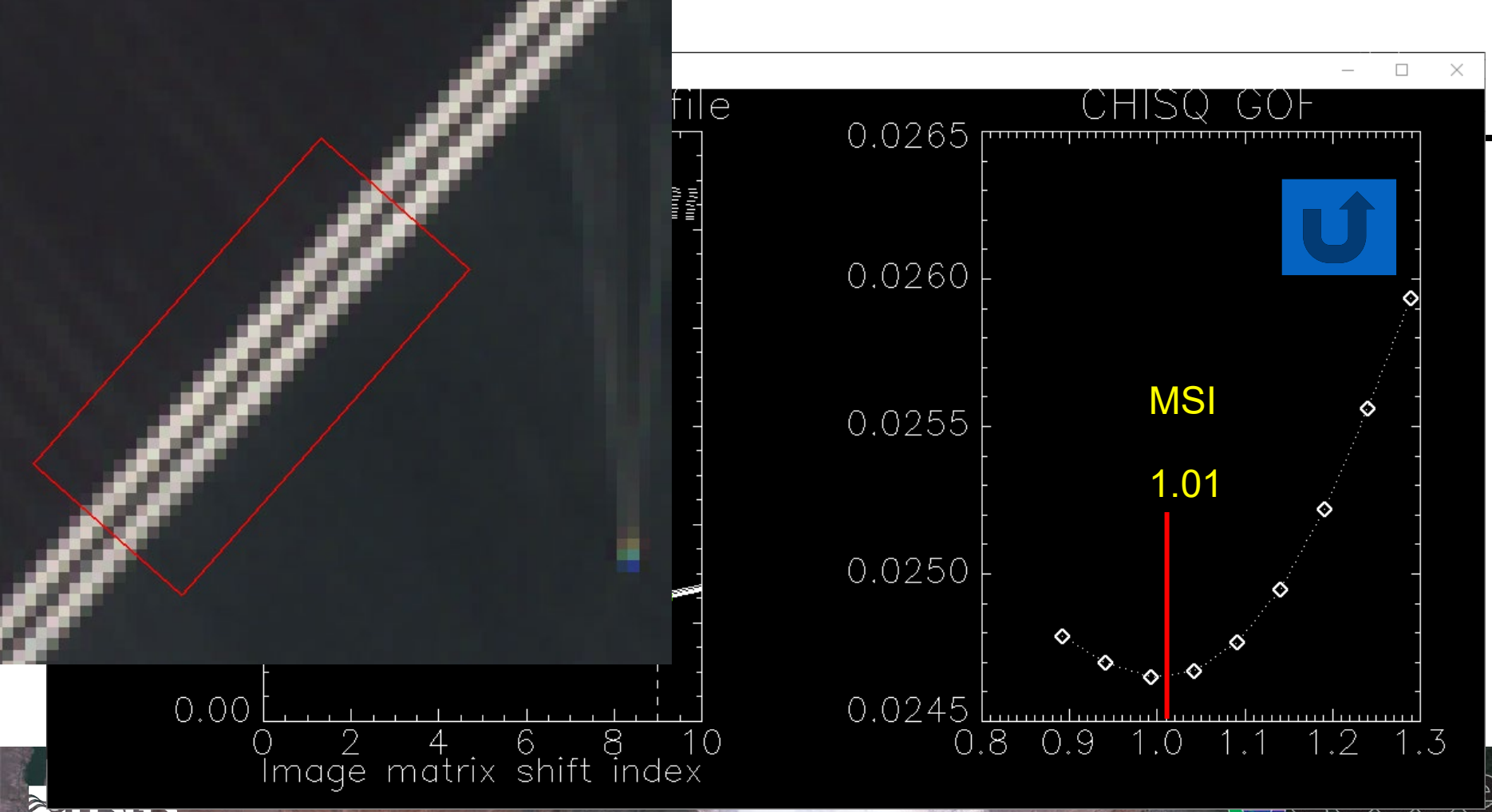
S2 MSI : I-90, 10m, railroad




0
5
10
15
Image matrix shift index


CHISQ GOF
0.0015
0.0014
0.0013
0.0012
MSI
1.09
0.8
0.9
1.0
1.1
1.2
1.3


), CHISQ profile
0.04
0.02
0.00
0
5
10
15
Image matrix shift index
CHISQ GOF
7.70×10⁻³
7.68×10⁻³
7.66×10⁻³
7.64×10⁻³
7.62×10⁻³
7.60×10⁻³
7.58×10⁻³
7.56×10⁻³
MSI
1.0
0.85 0.90 0.95 1.00 1.05 1.10


file
CHISQ GOF
0.0265
0.0260
0.0255
0.0250
0.0245
MSI
1.01
0.8 0.9 1.0 1.1 1.2 1.3
0.00
0 2 4 6 8 10
Image matrix shift index

Result : FWHMs

King (25 m) **EnMAP 1.17 1.14 1.17 1.15 1.15, 1.19, 1.11 1.10, 1.09**
King (25 m) **OLI 0.96 0.97 0.94 0.94 0.97 0.96**
King (25 m) **MSI 1.19 1.21 1.25 1.17 (horizontal) 1.22**

Lake Pon Causeway (10-24-10 m) **EnMAP: orbit & bridge virtually identical direction**
Lake Pon Causeway (10-24-10 m) **OLI 0.98 1.03 1.03**
Lake Pon Causeway (10-24-10 m) **MSI 1.08 1.12 1.07**

OLI shows more stable results from a range of bridge widths, location.

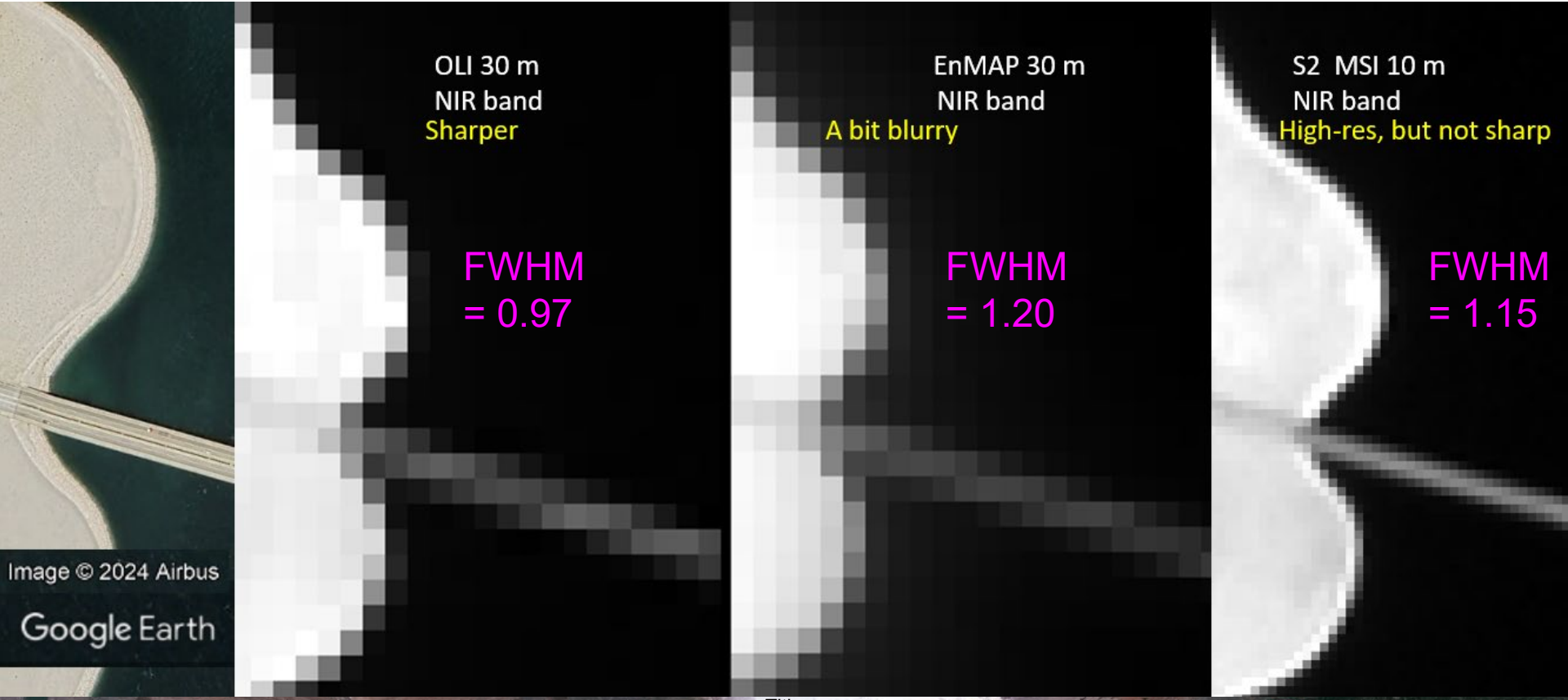
I-90 (19-15-19) **OLI : 0.98 0.94**
I-90 (19-15-19) **MSI : 1.1 1.01**

OLI FWHM is better than EnMAP, MSI (0.1 ~ 0.2)

US-11 (10 m) **OLI : 0.88 0.89**
US-11 (10 m) **MSI : 1.04 1.09 1.1**

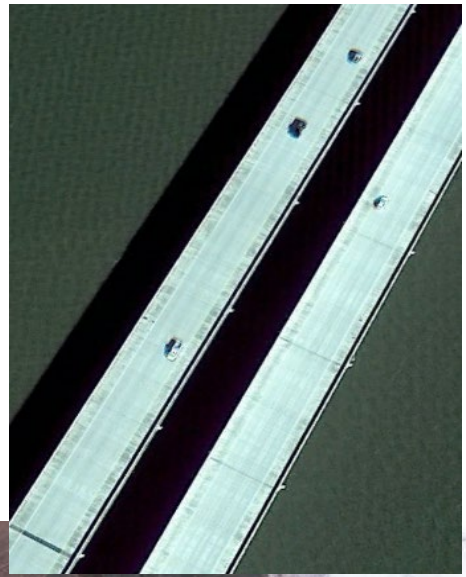
Less consistency of EnMAP, MSI needs further study.

OLI (30m), EnMAP (30m), MSI (10m)



Radiometric Noise

Random vehicle placement (distribution)
Varying vehicle reflectances (colors)
Blemish on the surface



Bridge shadow especially visible wavelength bands.

Numerical Challenge :

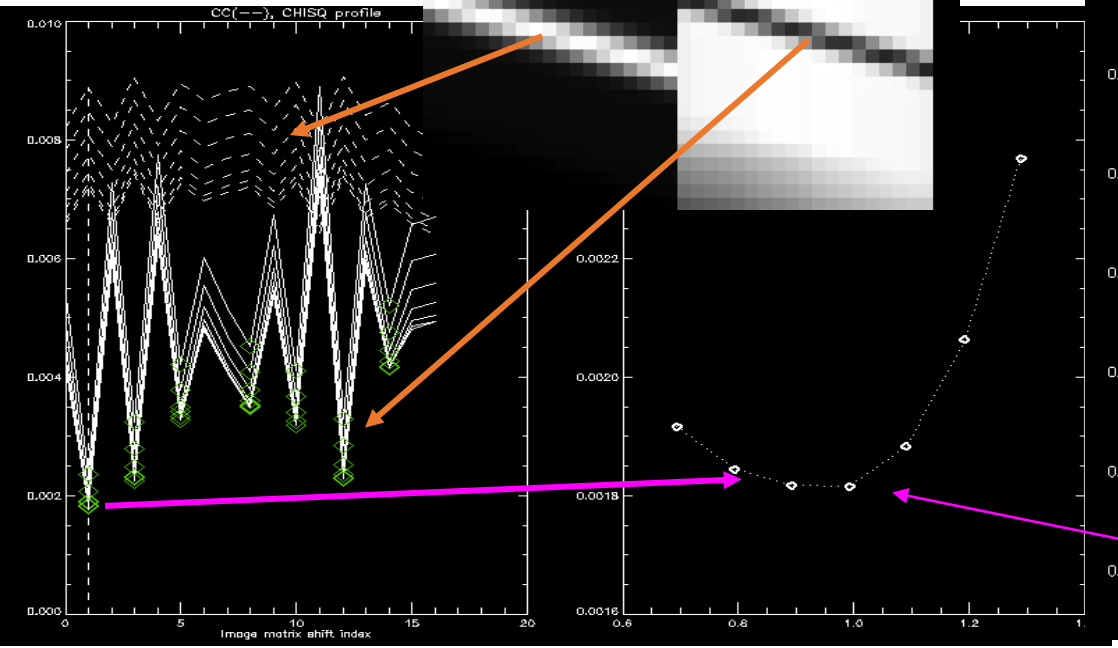
High sensitivity in CC, RMSD

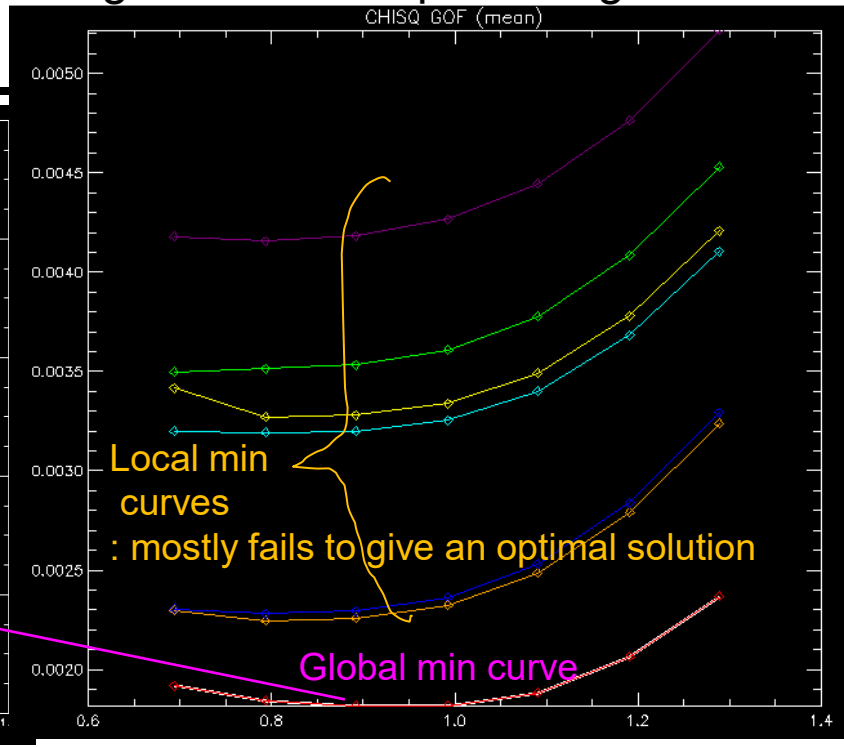
Due to any potential deviation from a simple analog model

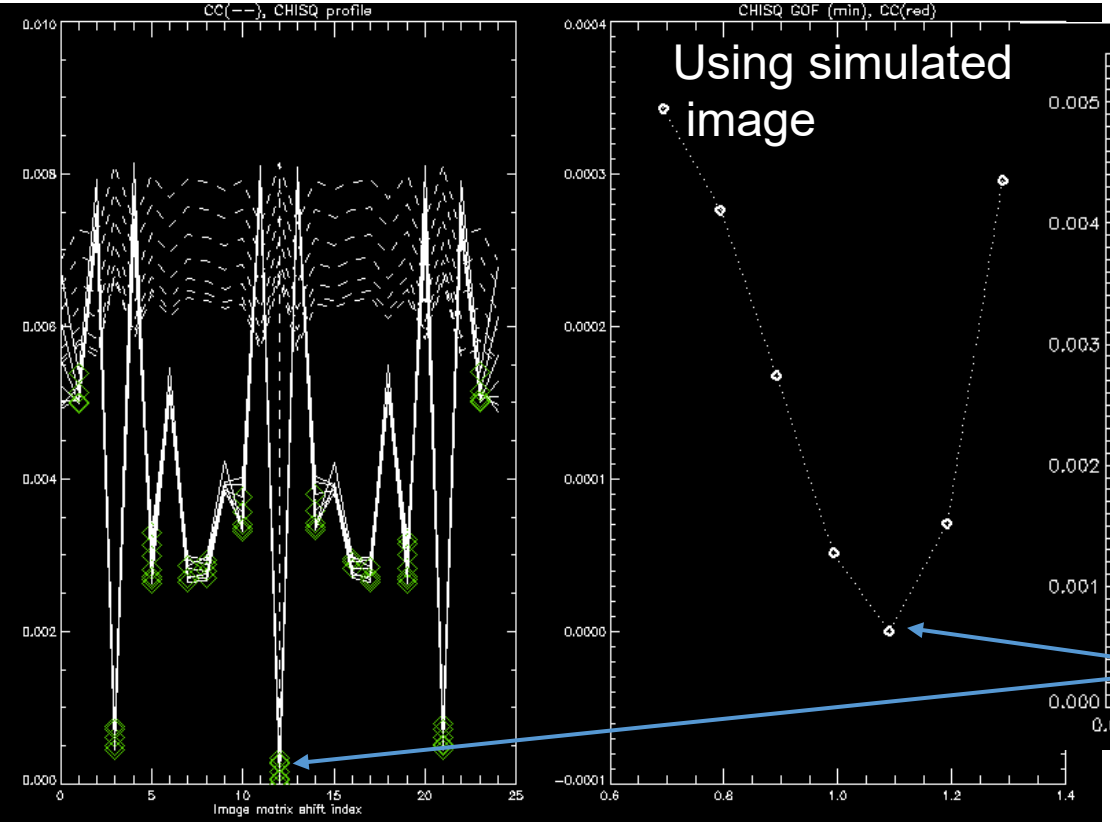
Cross correlation

RMSD or CHISQ GOF

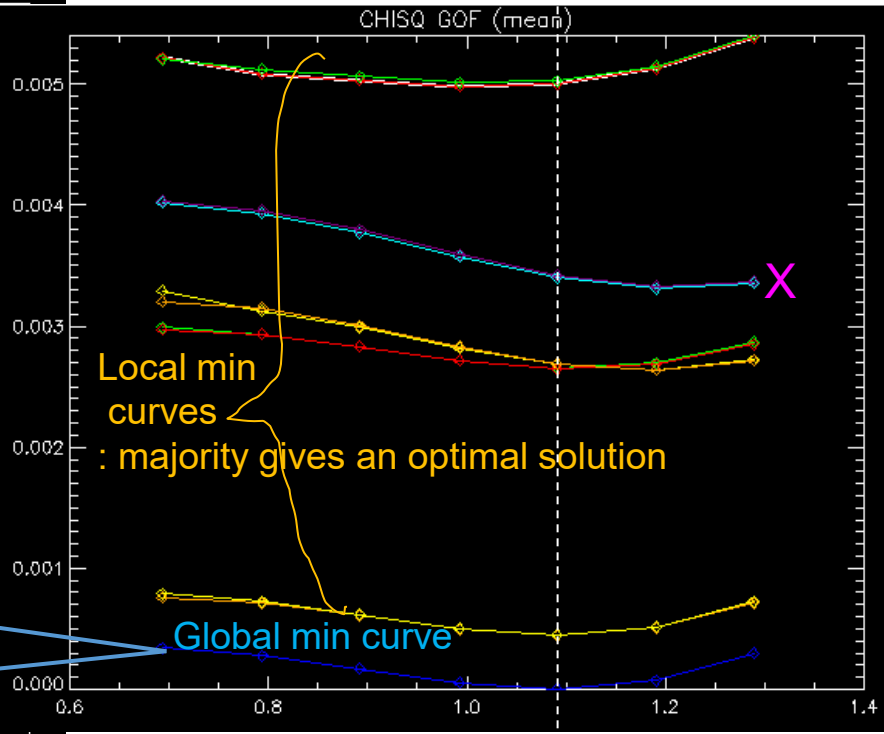
Using Satellite sampled image







Using simulated image



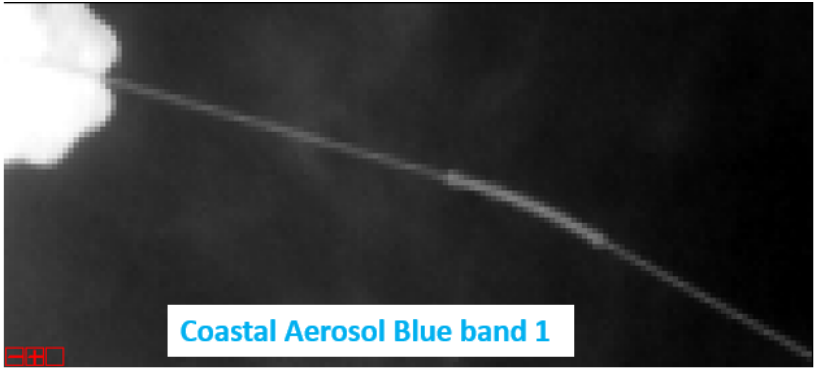
High Sensitivity to Dark background Quality

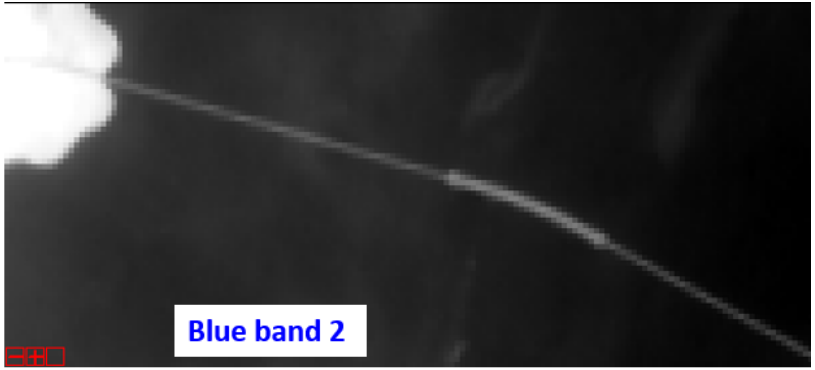
S2 MSI NIR band
: NIR supresses water volume backscattering

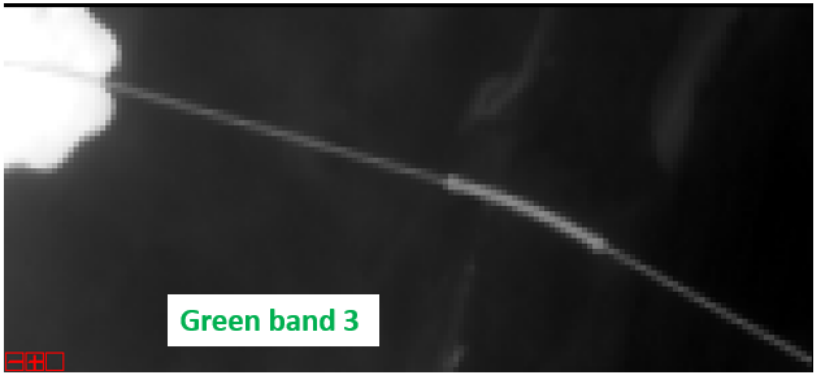
However, reflected sky Radiance and Glint due to Surface wave survives at NIR

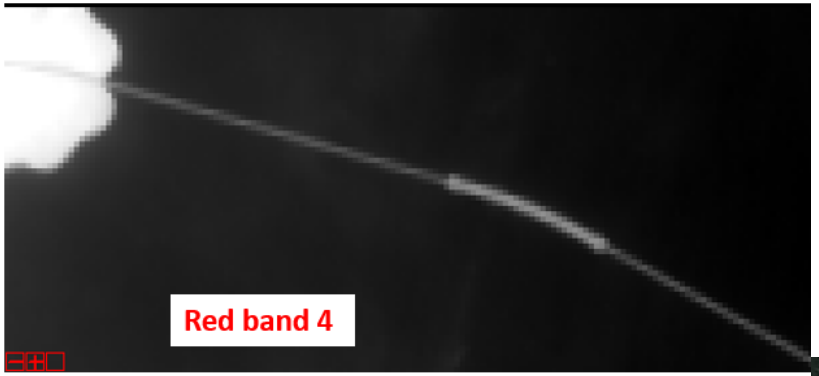
USGS

Wavelength Sensitivity



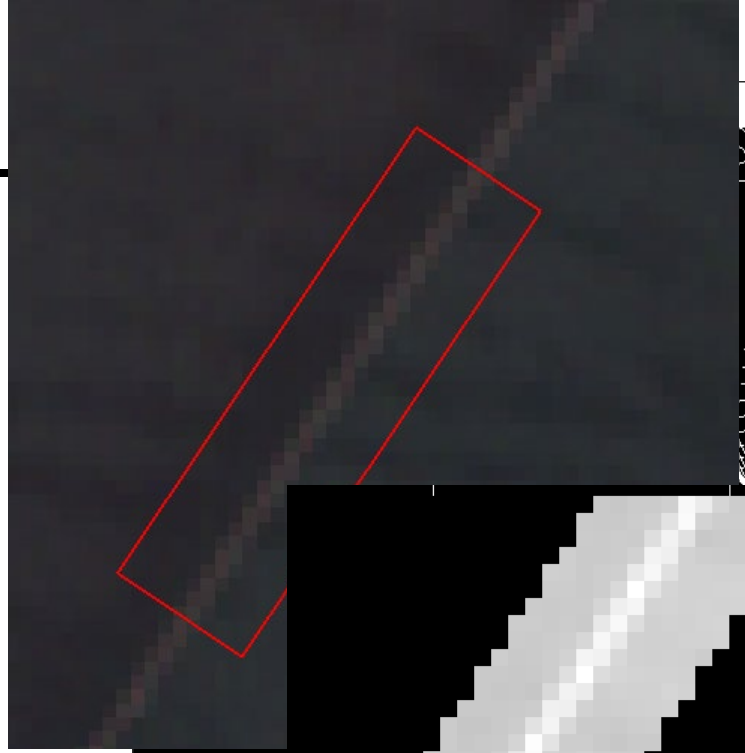


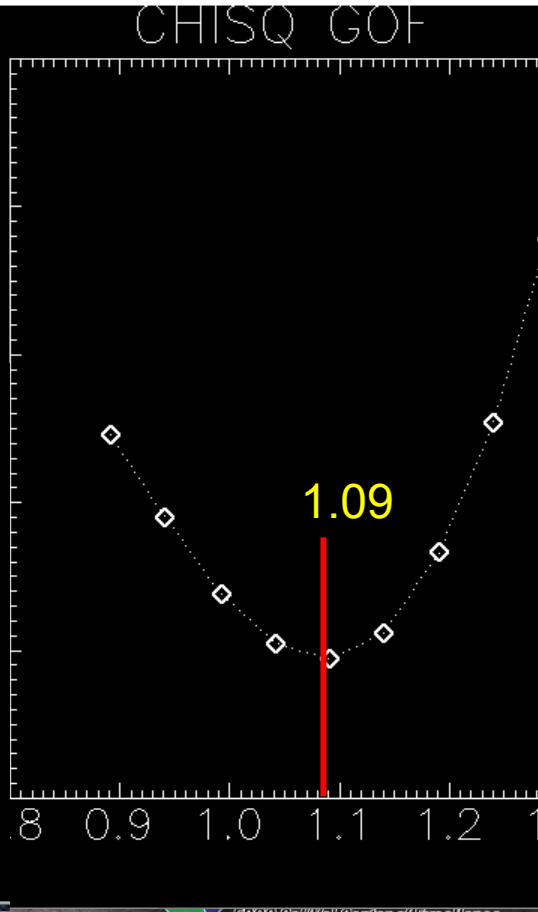




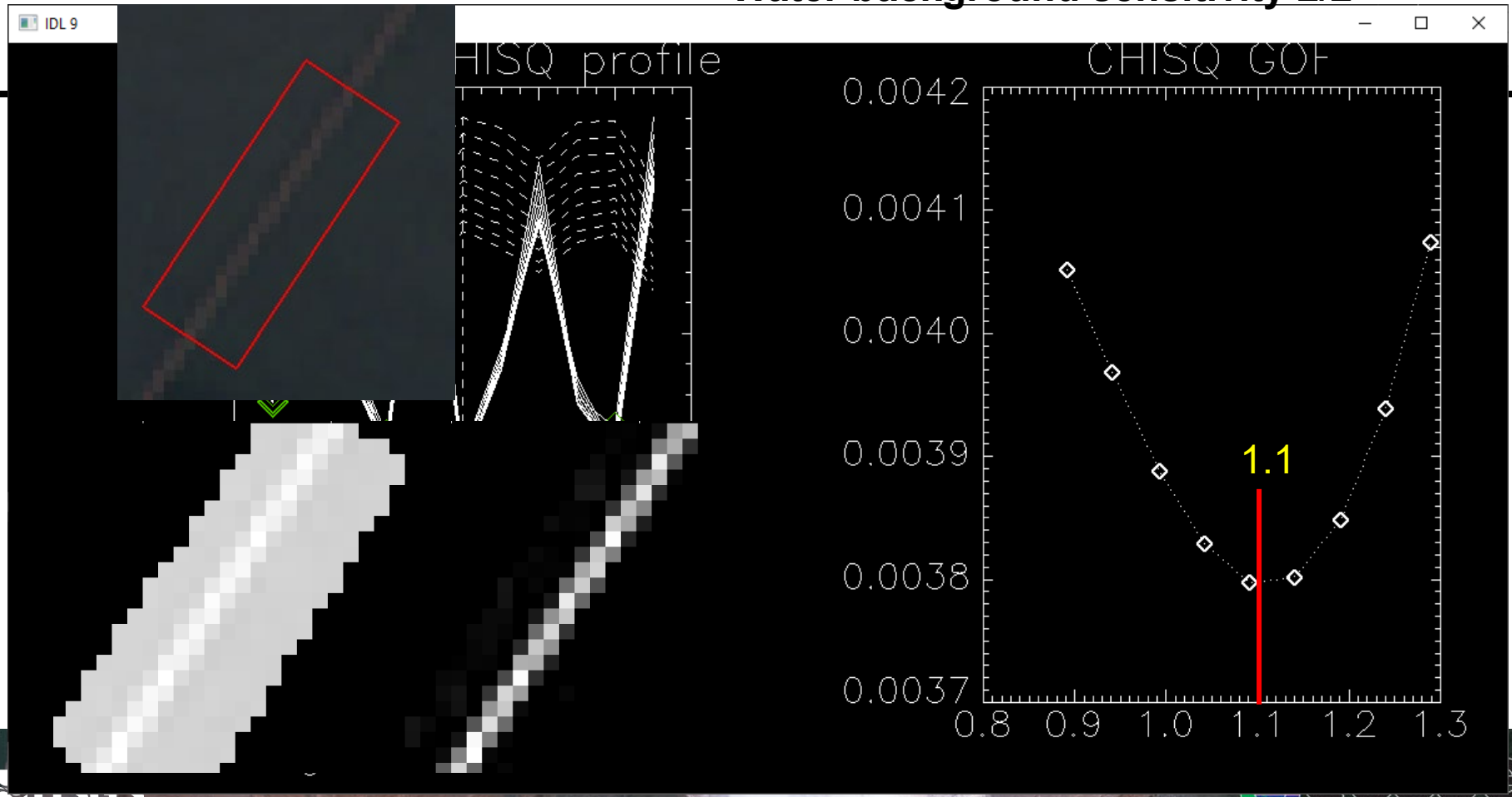
NIR (5), SWIR (6, 7) band images have **pitch black** background
→ most ideal for spatial performance analysis

Water background sensitivity 1/2





Water background sensitivity 2/2



Sensitive to the Image Quality

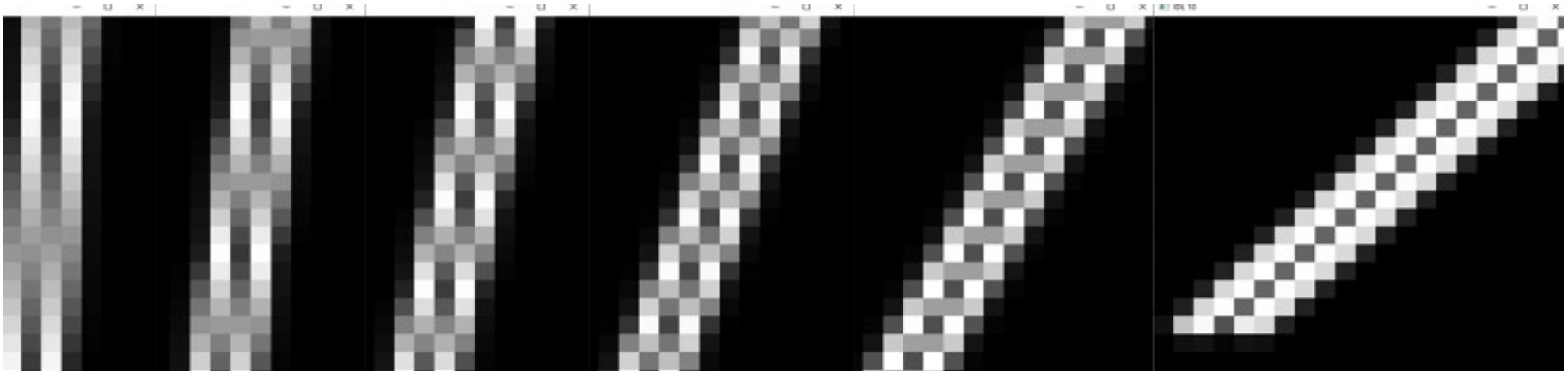
EnMAP over King Fahd Causeway : total ~ 10 scenes available over last 2+ years.
Relatively cloud-free scenes : only two below

Difficulty of obtaining ideal image using causeway! → cloud-free, negligible aerosol, clear water, glint-free

ENMAP01-____L1C-DT0000001670_20220713

ENMAP01-____L1C-DT0000001263_20220628

Effect of Line Orientation on Image Segment Sampling



Low Frequency ⟷ High Frequency

Longer segment needed.

Higher precision

image segment

FWHM estimation
Uncertainty

Short segment would do well.

Lower precision