CRSRA SAR Benchmarking

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3 November 2021

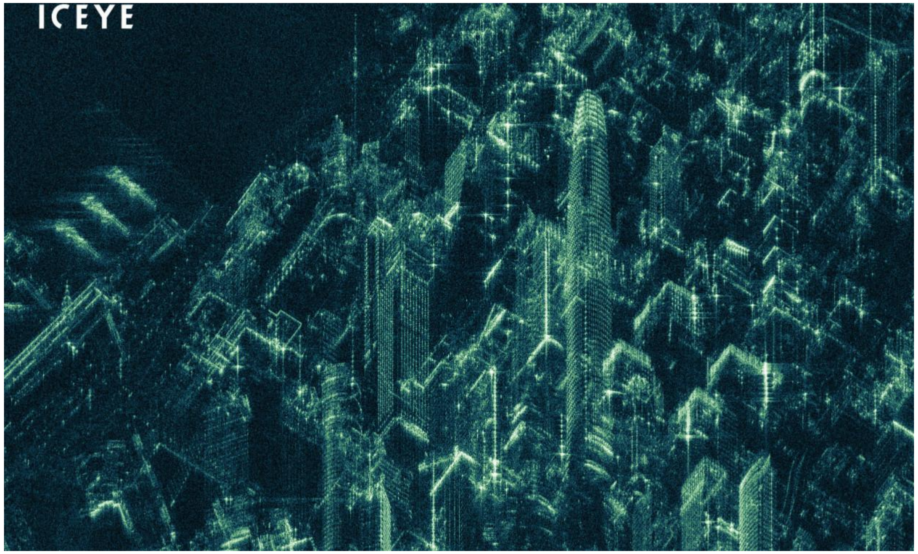
Purpose

- **Provide technology background**
- **Review Benchmarking requirements**
- **Describe new metric for SAR Benchmarking**
- **Describe process for selection**

Agenda

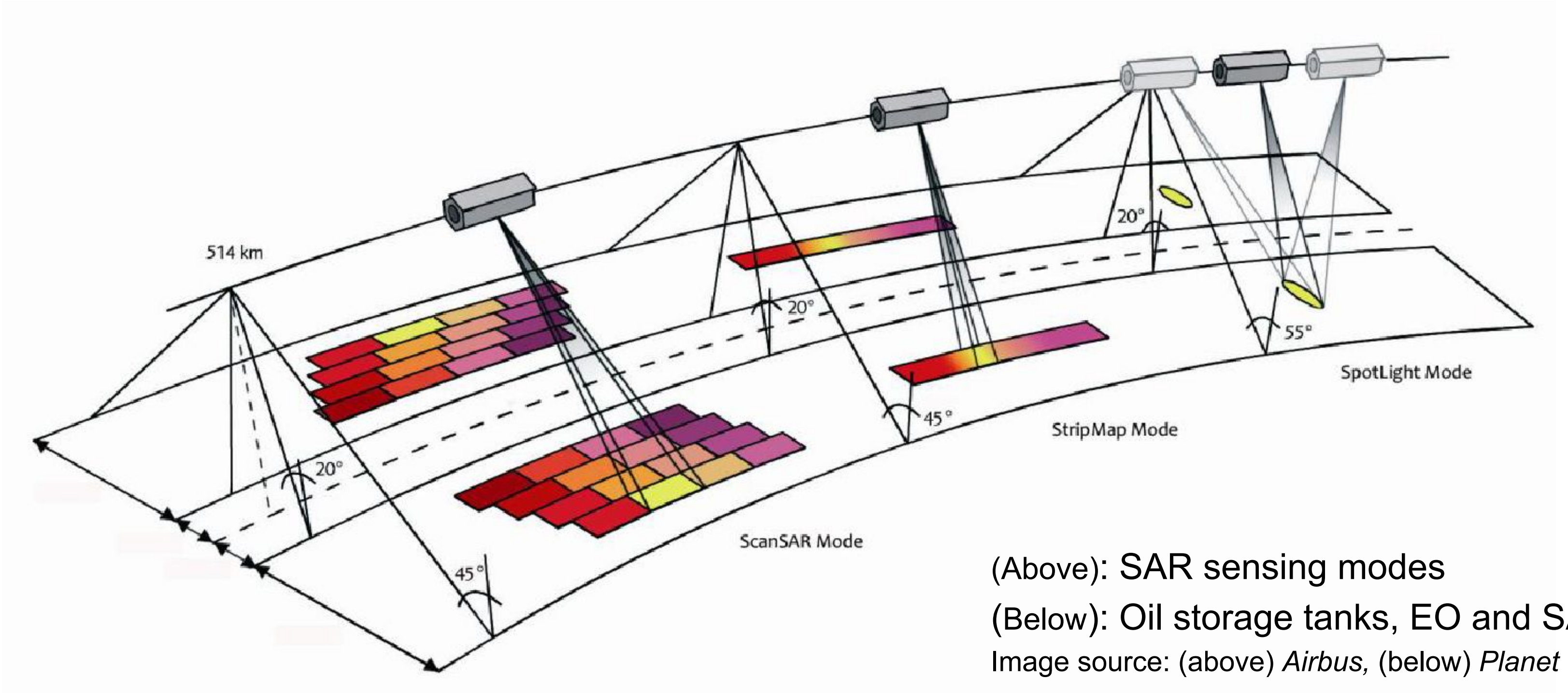
- SAR background
- Resolution vs image quality
- Problem background
- Approach
- RGIQE
- Results for four possible metrics
- Impact of persistence
- Q3 Benchmarks
- Current Status
- Other Factors - Spectrum

SAR Images
Sources: ICEYE (upper), Capella (lower)



Synthetic Aperture Radar (SAR) Remote Sensing

SAR imaging modes



(Above): SAR sensing modes

(Below): Oil storage tanks, EO and SAR

Image source: (above) *Airbus,* (below) *Planet Lab, ICEYE*

Electronically Steered Array (ESA) SAR

COSMO-SkyMED Second Generation (CSG)

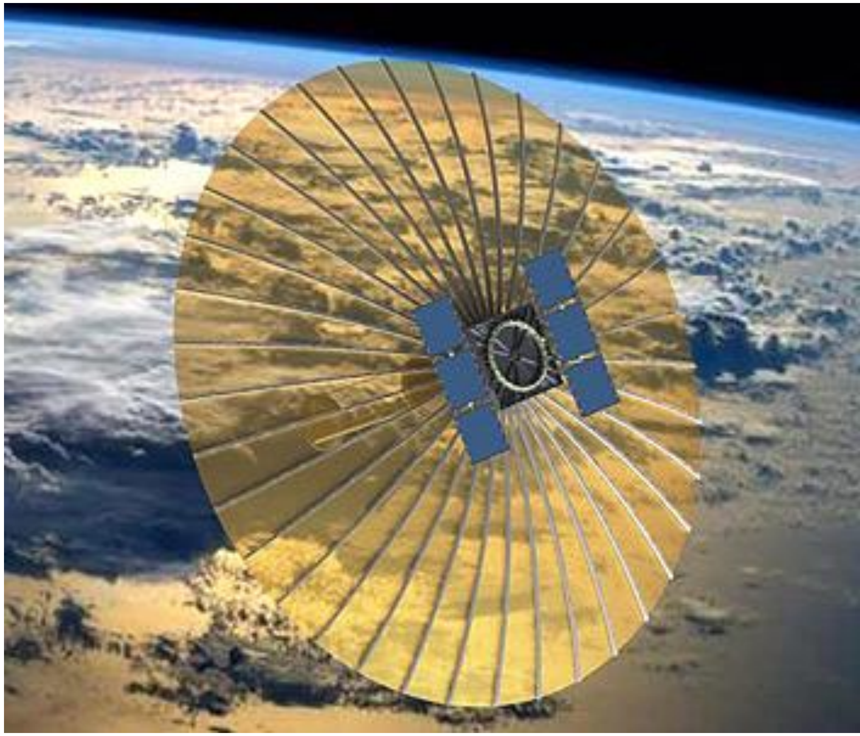
SAR parameter	CSG	ICEYE
Antenna size	5.7 m x 1.4 m (~7.5 m^2)	3.2 m x 0.4 m (1.28 m^2)
RF peak power	9 kW	3.2 kW
Max bandwidth	(1200) MHz	300 MHz
NESZ (noise floor)	-23.5 to -20	-18 to -15 dB
Grazing angle range	30-70º	55-70º
Spacecraft mass	810 kg	85 kg
Polarization	Double, quad	Single
Downlink	560 Mbps	140 Mbps

Large and small SAR Systems
Image sources:
ESA (upper), ICEYE (lower)

ICEYE-X3

Conventional Mechanical Element (Dish) SAR

Capella



Umbra

SAR Systems
Sources:
Capella Space, Umbra Space

What defines or differentiates SAR performance?

Need to be universal and apply to all sensor types

- Spatial Resolution
  - *Ability to distinguish two closely spaced objects*
  - *Range direction*
    - Radar (CHIRP) bandwidth
    - The width of the radar “pulse” defines the spatial resolution in the range direction
    - Varying the frequency during the pulse allows it to be compressed via processing
    - CHIRP bandwidth determines how much pulse compression c
  - *Azimuth or cross-range direction*
    - Dwell time
    - Determines azimuth spatial resolution potential
- SNR ratio (Signal-to-Noise Ratio)
  - *Affects image quality, interpretability*
  - *Transmitter & receiver design*
- Collection capacity, revisit rate
  - *Single satellite vs. constellation*
- Processing, calibration, etc.

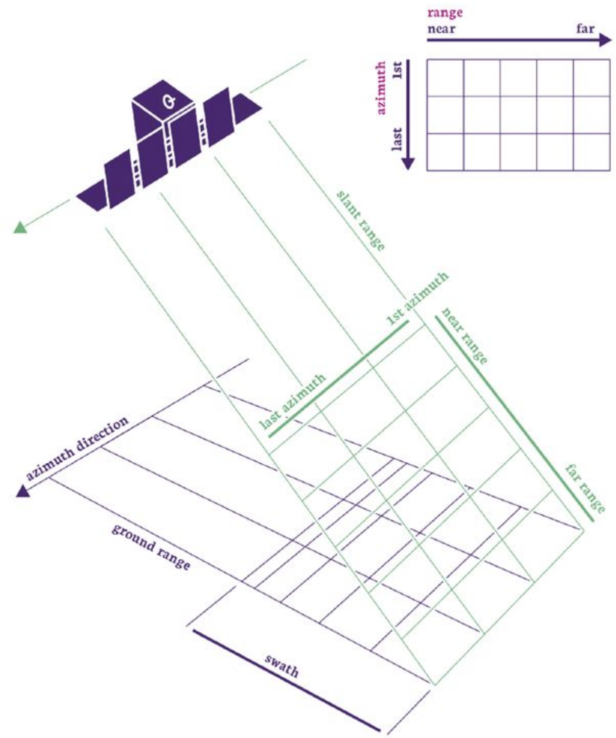
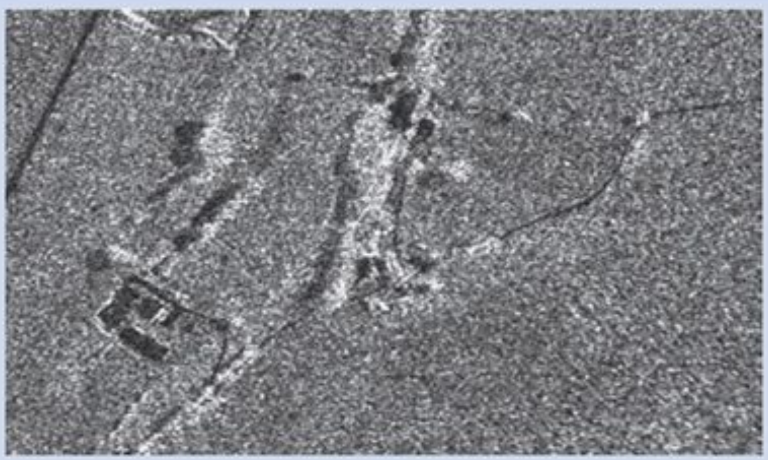


Figure 4.1: Slant range and ground range image geometry.

SAR Resolution vs. Image Quality (1/2)

- Resolution is the ability to distinguish two closely spaced objects
- Image quality includes the effect of Signal-to-Noise (SNR)
  - *Closely related to Noise Equivalent Sigma Zero (NESZ) – the sensitivity of the radar*
- Resolution example
  - *The image on the left is 1 m resolution. The image on the right is 0.25 m resolution.*
  - *The salt-and-pepper appearance of the image on the left is due to “speckle”, which is an inherent part of SAR phenomenology. <u>Speckle is reduced when the resolution increases.</u>*
  - *Some features clearly visible in image (b) cannot be seen in image (a), shown by the two*



(a)

(b)

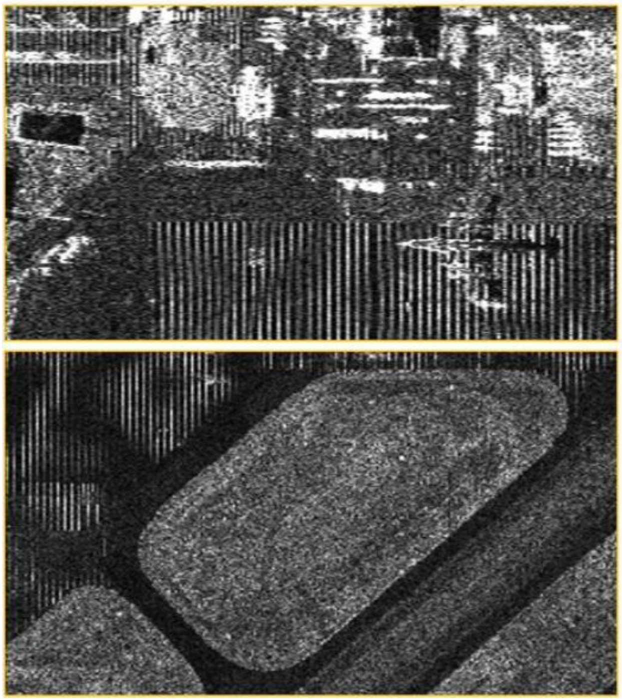
Both images are X-band SAR. Image (b) was acquired by the F-SAR sensor of DLR.

Image source: *“A Tutorial on Synthetic Aperture Radar”, A. Moreira, P. Prats-Iraola, M. Younis, G. Krieger, I. Hajnsek and K. P. Papathanassiou, IEEE Geoscience and Remote Sensing Magazine, March 2013, pp.6-43*.

Resolution vs. Quality, (2/2)

- A long dwell can be used to improve resolution <u>or</u> SNR (and quality/readability)
- Both products below are 0.5 m resolution

Single look product



Multi-look product

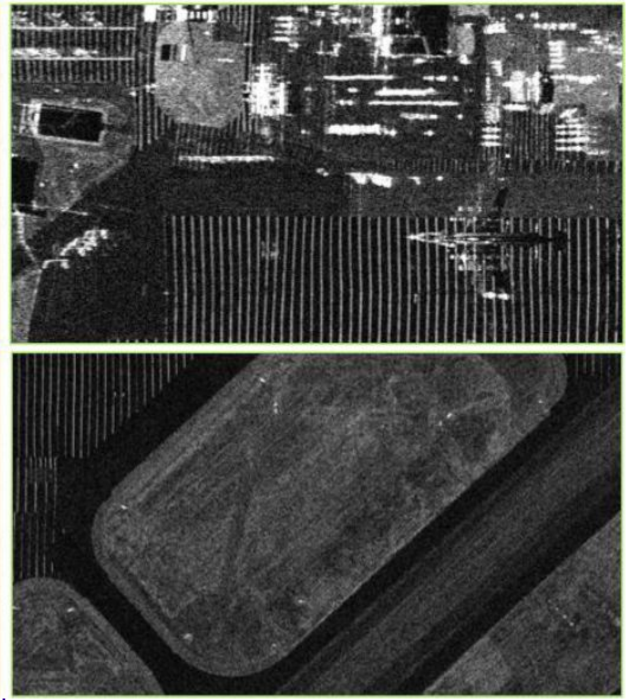


Image source: *Capella Space SAR Imagery Products Guide*, 2020

- Approximately **2.5 seconds** to collect
- Higher (worse) NESZ
- Lower image quality.

Count Number of Airplanes

- Approximately **30 seconds** to collect
- Significantly lower (better) NESZ
- Higher image quality

Discern Types of Airplanes

Benchmarking Problem Background – 1/2

CRSRA needs a more effective Benchmark to compare SAR providers

- Current SAR Benchmark metric easily understood but not effective
  - *Ground Range Detected (GRD) square pixel resolution*
  - *Readily advertised by foreign providers*
  - *Easy to relate GRD imagery and measurement to optical equivalent*
  - *Does not capture best SAR system performance*
    - Less processed data may have higher spatial resolution
    - Does not incorporate other SAR performance attributes
  - *May put U.S. firms at disadvantage*

Imaging mode	Polarization	Access region	Swath [Az. X Rg]	Resolution [Az. X Rg]
Spotlight-2A	Single/Dual	20-25° 25-50° 50-60°	3.1 x 7.3 Km 3.2 x 7.3 Km 4.4 x 7.3 Km	0.3 x 0.6 m 0.3 x 0.5 m 0.3 x 0.5 m
Spotlight-2B	Single/Dual	20-60°	10 x 10 Km	0.6 x 0.6 m
Spotlight-2C	Single/Dual	20-60°	5 x 10 Km	0.8 x 0.8 m

Table 5 - Standard Spotlight 2 imaging modes

COSMO SkyMED advertised SAR Products
Source: Cosmo SkyMed Seconda Generazione: System and Products Description
Doc. No: CE-UOT-2021-002
Rev.: A
Date: 08/02/2021
Page: 20 of 217
File: CSG

Benchmarking Problem Background – 2/2

CRSRA needs a more effective Benchmark to compare SAR providers

- New Benchmark metric should
  - *Bridge instrument capability (U.S. licensees) and data quality (foreign providers)*
  - *Capture multiple SAR performance attributes*
  - *Capture highest resolution*

Table 1 Possible Benchmark metrics

Approach (Metric)	Priority
Bandwidth Only	Sensor Capability
Slant Range Resolution	Sensor Capability
Geometric Mean Resolution	Sensor Capability
RGIQE	Produced Imagery, scene independence, sensor capability

Approach

- CRSRA asked U.S. Government and industry subject matter experts (SME's) how to best compare SAR systems
  - *NGA SAR SME's*
  - *ACCRES SAR WG*
  - *Aerospace SAR SME's*
- No immediate consensus
  - *SAR is more complex than EO*
    - Spatial resolution may not be consistent in range/cross range dimensions and is variable
  - *SAR industry & NGA have not standardized a methodology to compare systems and image quality*
- Lots of good ideas and input
  - *ACCRES suggested bandwidth / slant range IPR*
    - Industry did not want Azimuth resolution regulated
    - Concerns about accuracy of input parameters, complexity of calculations
  - *NGA suggested bandwidth / slant range IPR, or RGIQE*
    - Split on the importance of Azimuth resolution
  - *Aerospace evaluated 6 possible metrics*

RGIQE

A single metric that factors in performance attributes to quantitatively measure or estimate information contained in an image

- RGIQE=**Radar General Image Quality Equation**
  - *Builds on EO general imagery equation concept*
  - *Adapted from communication theory*
- **C= information Density = bits/square meter = β * $\mathbf{\log_2(1 + \mathit{SNR})}$**
  - *Direct dependence on bandwidth/resolution for both range and azimuth*
  - *Log (base 2) dependence on SNR*
    - SNR calculation includes EIRP, system noise figure, and scene factors
    - For our purposes, scene contribution would be set to zero
    - Any losses from transmitter/receiver imperfections are also zeroed out
    - <u>Results: calculation is simplified to SNR=1/NESZ, but C will be slightly inflated for some systems</u>
  - *Applies to a single look collect at lowest grazing angle*
- RGIQE translates between sensor performance and data quality

Results for Four Possible Metrics

Slant range, geometric mean, RGIQE yield somewhat similar results

System	BW (Hz)	Best Slant Range (SR)	Best Gnd Range	Best Azimuth	Geometric mean (SR) (Slant Plane)	RGIQE
ICEYE	300	.5	.87 (55-70)	.25	.35	23
CSK	373	.4	.7 (25-60)	.3	.35	30
TSX	300	.5	.87 (55-70)	.24	.35	39
CSG	523	.29	.5 (25-60)	.3	.30	51

Y=I US=I   Red =Foreign Benchmark,

Impact of "Persistence"

- Temporal aspect of data availability
  - *Can drive certain US SAR providers to Tier 3*
  - *Relationship to resolution*

SAR System	#Satellites/ Persistence (Hours)
ICEYE	10/3-6 hours
CSK	4/12
TSX	3/24
CSG	1/24

Current Benchmark

Satellite or Constellation	Country	Resolution (type) Spectral or Other Information	Slant Range Resolution (meters)	Number of Satellites (current advertised revisit rate)
SYNTHETIC APERTURE RADAR (SAR) X-Band				
ICEYE	**Finland**	23 (bits/m^2) (Info. Density: ID)	0.5	≥10 (3-6 hours)
COSMO Sky MED 1st Generation (CSK)	**Italy**	33 (bits/m^2) (ID)	0.4	4 (12 hours)
TerraSAR/TanDEM/ PAZ	**Germany, Spain**	39 (bits/m^2) (ID)	0.5	3 (24 hours)
COSMO Sky MED 2nd Generation (CSG)	**Italy**	51 (bits/m^2) (ID)	0.29	1 (~24 hours)
Best US	**US**	1619 (bits/m^2) (ID)	0.25	44 (3-6 hours)
C-Band				
RADARSAT-2	**Canada**	5.17 (bits/m^2) (ID)	1.6	1 (24 hours)
TY-MiniSAR (Hisea-1)	**China**	4.2 (bits/m^2) (ID)	1.0	1 (6-10 days)
Best US	**US**	TBD	TBD	TBD

Current Status

RGIQE implemented, with caveats, and work remains

- Using RGIQE can address the slight SNR advantage of foreign SARs
- Care advised in handling of azimuth resolution factor
  - *Use of best theoretical Azimuth resolution will put US providers at significant disadvantage*
  - *Foreign <u>best</u> azimuth resolution unknown*
  - *Azimuth resolution is not infinite*
    - squint capability of spacecraft is limited
    - smearing in the scene occurs with too large of a change in aspect angle as SAR moves over target
  - *Address disparity in future update of regulations*
- Give guidance to licensees on calculating resolution, SNR

Other Factors - Spectrum

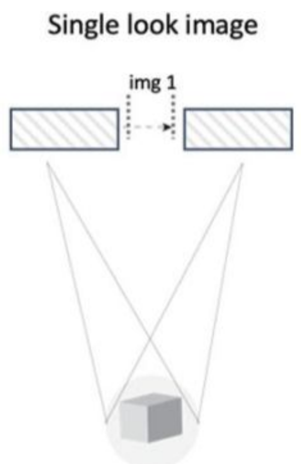
- Space radar (ITU) spectrum allocation already regulates/limits SAR performance
  - *ITU regulations (only) allocate 1200 MHz, not likely to change*
  - *Practically speaking, 1200 MHz enables slant range IPR of 0.125 m, ground range IPR of* ***0.22 m*** *(at 55° Grazing angle)*
  - *US has only allocated 600 MHz (per current US table)*
    - US acceptance of treaty means we have accepted imaging of the US by foreign SARS at ~0.22 meters

Questions?

Resolution vs. Quality

- Image Quality depends on both <u>resolution</u> and <u>noise</u> (NESZ).
- Incoherently adding together multiple images reduces (improves) the NESZ.
  - *This is referred to as multi-look processing*
  - *<u>Multi-look processing is another way to reduce speckle, but in the process, resolution is lost</u>*
  - *<u>Amplitude images are typically multi-looked in azimuth using two to 12 sub-apertures (ICEYE)</u>*

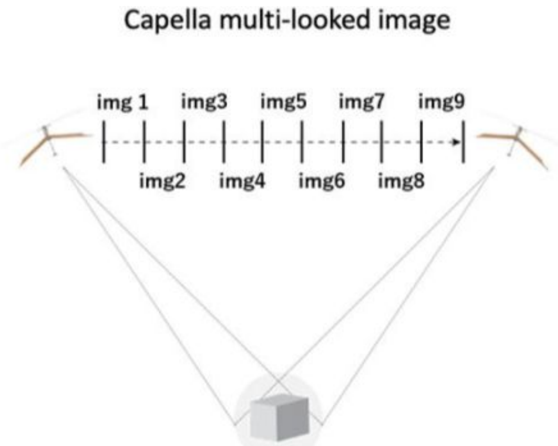
An image with 0.5 m azimuth resolution collected at broadside requires about **2.5 sec** of dwell time but will have inherently poor NESZ.



Allows for increased **quantity** of images

9 individual 0.5 m resolution images multi-looked together takes about **30 sec** of dwell time and yields an RNIIRS 5.5 image.

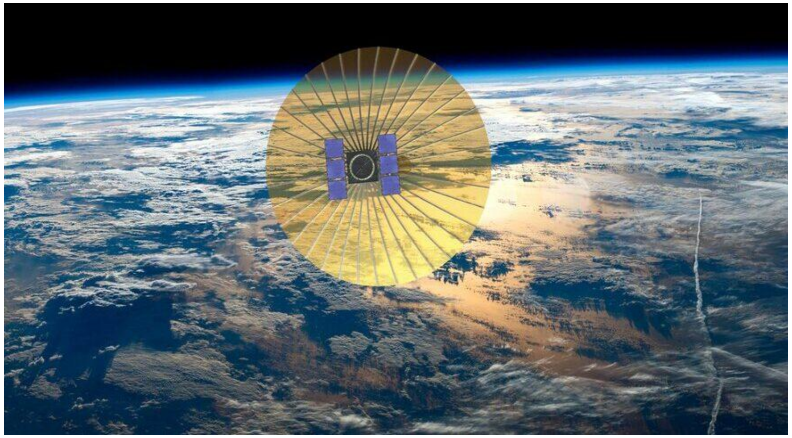
- *By collecting 9 individual images, they can be multi-looked without losing resolution.*



Allows for increased **quality** of images

Figures borrowed from *Capella Space SAR Imagery Products Guide*, 2020

NESZ - Noise Equivalent Sigma Zero, a common measure of image noise in SAR systems.



Umbra advertises SAR imagery with 15-centimeter resolution

Umbra has a patent for an antenna designed to stow compactly for launch and expand in orbit with a series of ribs attached to a central hub. The antenna is covered in a flexible reflective material. *Credit: Umbra*

by Debra Werner — March 12, 2021 [SpaceNews]

SAN FRANCISCO – Radar satellite startup Umbra plans to capture imagery with a resolution as high as 15 centimeters per pixel thanks to a Federal Communications Commission license.

The FCC granted Umbra, a Santa Barbara, California, startup preparing to launch its first X-band synthetic aperture radar (SAR) microsatellite this year, an experimental license in February to operate high-bandwidth SAR using the 1,200 MHz band centered on 9.8 GHz and low-bandwidth SAR with the 600 MHz band centered on 9.6 GHz.

Gabe Dominocielo, Umbra co-founder and president, referred to the FCC license as "hitting the regulatory jackpot."

"Bandwidth is the limiting factor in determining slant range resolution, and ultimately ground plane resolution in the cross-track direction," Dominocielo said by email. "Improvement in resolution is proportional to the amount of bandwidth available for use by the sensor."

The company plans to provide customers with inexpensive SAR data rather than geospatial analytics. The National Oceanic and Atmospheric Administration granted Umbra a license in 2018 to offer 25-centimeter resolution from satellites in 515-kilometer sun synchronous orbit.

With the new FCC license "better resolution will be available to some customers," Umbra said in a March 11 news release. "Umbra anticipates being the sole commercial provider of these high-resolution radar products in the United States and will be selling imagery commercially to customers based in the United States and to allies abroad." Dominocielo declined to say whether U.S. defense and intelligence agencies were the customers likely to obtain access to Umbra's highest-resolution …

The Commerce Department revised regulations for commercial remote sensing satellite systems in 2020, streamlining the licensing process with the goal of making U.S. companies more competitive globally. The revised rules compare remote sensing systems with similar systems that are not subject to NOAA's jurisdiction, including those licensed by other nations. Anything with similar capabilities to what is already available is now subject to minimal regulation compared with systems that offer improved capabilities.

Table of Frequency Allocations

International Table			United States Table	
Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table
9.2-9.3 EARTH EXPLORATION-SATELLITE (active) 5.474A 5.474B 5.474C RADIOLOCATION MARITIME RADIONAVIGATION 5.472 5.473 5.474 5.474D			9.2-9.3 MARITIME RADIONAVIGATION 5.472 Radiolocation US110 G59 5.474	9.2-9.3 MARITIME RADIONAVIGATION 5.472 Radiolocation US110 5.474
9.3-9.5 EARTH EXPLORATION-SATELLITE (EESS) (active) RADIOLOCATION RADIONAVIGATION 5.475 SPACE RESEARCH (active) 5.427 5.474 5.475A 5.475B 5.476A			9.3-9.5 EESS (active) RADIOLOCATION G56 RADIONAVIGATION US475 SPACE RESEARCH (active) Meteorological aids 5.427 5.474 5.475A 5.475B US67 US71 US476A	9.3-9.5 RADIONAVIGATION US475 Meteorological aids Earth exploration-satellite (active) Radiolocation Space research (active) 5.427 5.474 US67 US71 US476A
9.5-9.8 EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION RADIONAVIGATION SPACE RESEARCH (active) 5.476A			9.5-9.8 EARTH EXPLORATION-SATELLITE (active) RADIOLOCATION SPACE RESEARCH (active)	9.5-9.9 Earth exploration-satellite (active) Radiolocation Space research (active) Private Land Mobile (90)
9.8-9.9 RADIOLOCATION Earth exploration-satellite (active) Fixed Space research (active) 5.477 5.478 5.478A 5.478B			9.8-9.9 RADIOLOCATION Earth exploration-satellite (active) Space research (active)	
9.9-10 EARTH EXPLORATION-SATELLITE (active) 5.474A 5.474B 5.474C RADIOLOCATION Fixed 5.474D 5.477 5.478 5.479			9.9-10 RADIOLOCATION 5.479	9.9-10 Radiolocation 5.479
10-10.4 EESS (active) 5.474A 5.474B 5.474C FIXED MOBILE RADIOLOCATION Amateur 5.474D 5.479	10-10.4 EESS (active) 5.474A 5.474B 5.474C RADIOLOCATION Amateur 5.474D 5.479 5.480	10-10.4 EESS (active) 5.474A 5.474B 5.474C FIXED MOBILE RADIOLOCATION Amateur 5.474D 5.47	10-10.5 RADIOLOCATION US108 G32 5.479 US128	10-10.45 Amateur Radiolocation US108 5.479 US128 NG50

Table of Frequency Allocation footnotes

5.474A The use of the frequency bands 9200-9300 MHz and 9900-10 400 MHz by the Earth exploration-satellite service (active) is limited to systems requiring necessary bandwidth greater than 600 MHz that cannot be fully accommodated within the frequency band 9300-9900 MHz. Such use is subject to agreement to be obtained under No. 9.21 from Algeria, Saudi Arabia, Bahrain, Egypt, Indonesia, Iran (Islamic Republic of), Lebanon and Tunisia. An administration that has not replied under No. 9.52 is considered as not having agreed to the coordination request. In this case, the notifying administration of the satellite system operating in the Earth exploration-satellite service (active) may request the assistance of the Bureau under Sub-Section IID of Article 9. (WRC-15)

5.474B Stations operating in the Earth exploration-satellite (active) service shall comply with Recommendation ITU-R RS.2066-0. (WRC-15)

5.474C Stations operating in the Earth exploration-satellite (active) service shall comply with Recommendation ITU-R RS.2065-0. (WRC-15)

5.474D Stations in the Earth exploration-satellite service (active) shall not cause harmful interference to, or claim protection from, stations of the maritime radionavigation and radiolocation services in the frequency band 9200-9300 MHz, the radionavigation and radiolocation services in the frequency band 9900-10 000 MHz and the radiolocation service in the frequency band 10.0-10.4 GHz. (WRC-15)

NESZ Values for Selected Missions

System	NESZ	Source
• Sentinel	-25dB	ESA Portal
• CSK	-21 to -22	eGeos
• CSG	-20 to -23.5	eGeos (30 vs 70º Grazing Angle)
• TSX	-19 (worst) -23 typ.	ESA Portal
• ICEYE	-15 to -18	ICEYE
• Capella	-10 to -14	Capella
• Umbra	-18	Umbra

SAR Design and Operating Tradeoffs

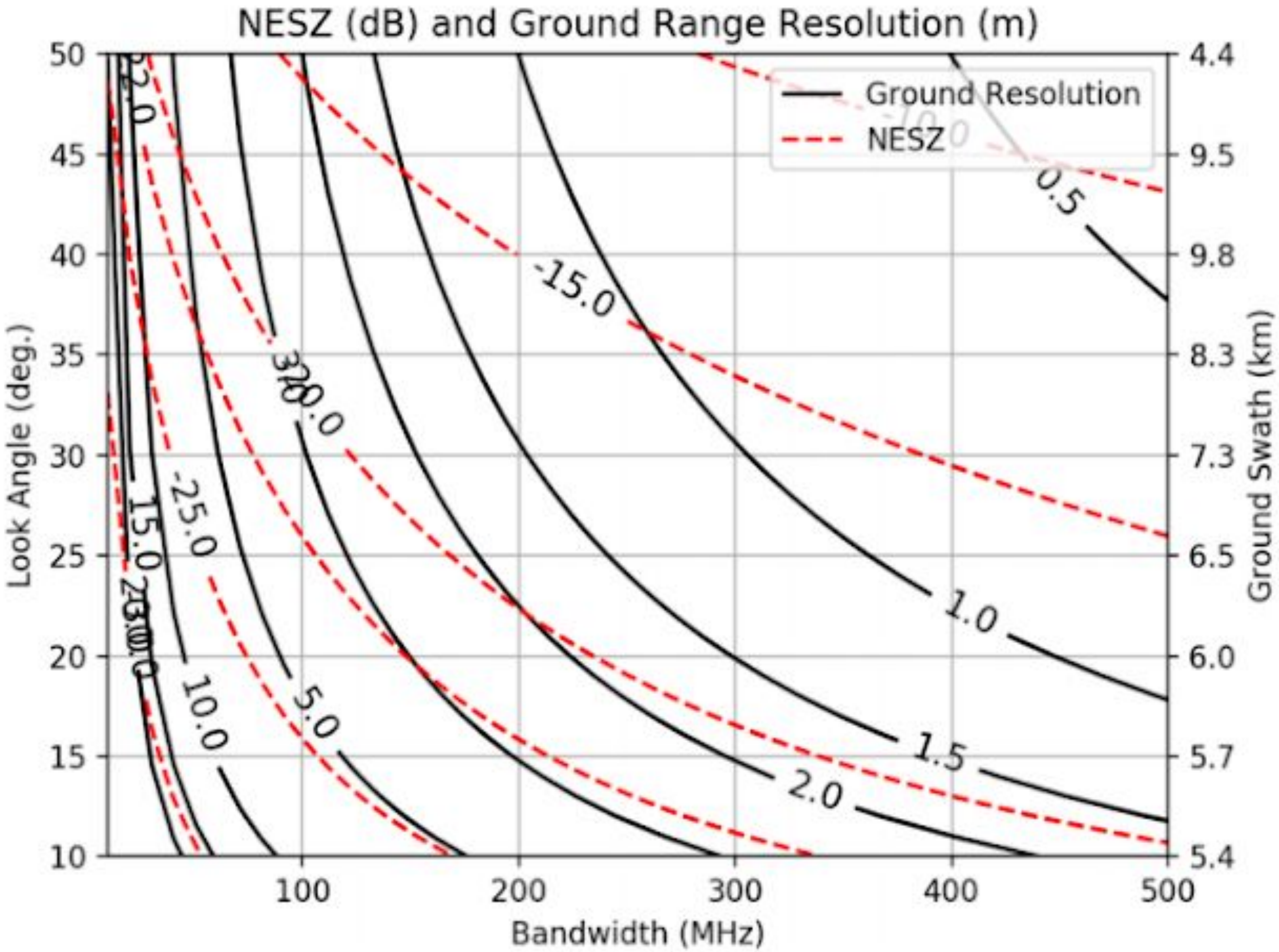
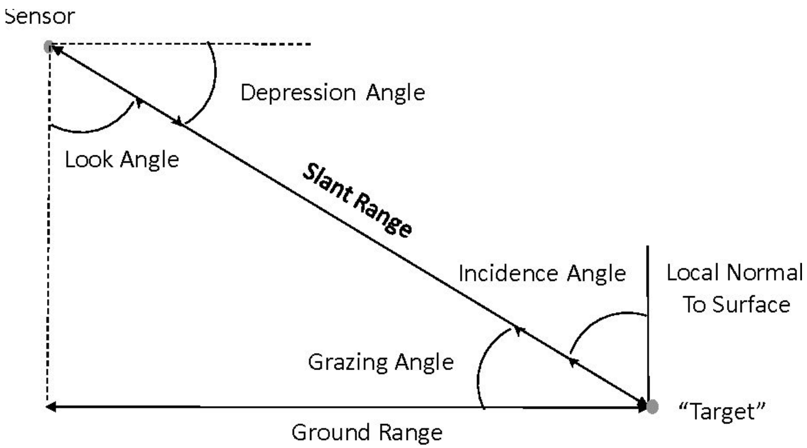


Diagram Source: Capella

SAR Terminology

Grazing vs Incidence angles, Slant Plane vs Ground plane



SAR Geometry

(Source: Chapter 1 Synthetic Aperture Radars (SAR) Imaging Basics, Descanso, JPL, Semantic Scholar.org. https://descanso.jpl.nasa.gov/SciTechBook/series2/02Chap1_110106_amf.pdf)

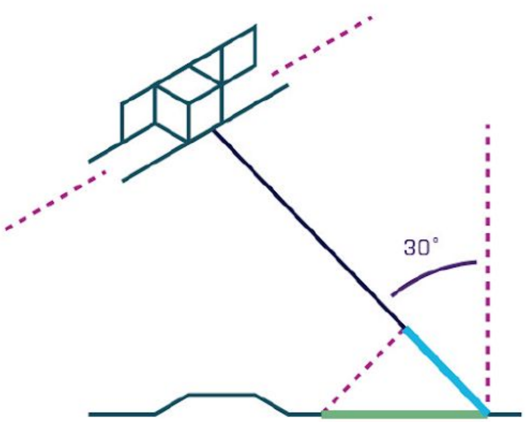


Figure A.14: Ground Range Resolution.

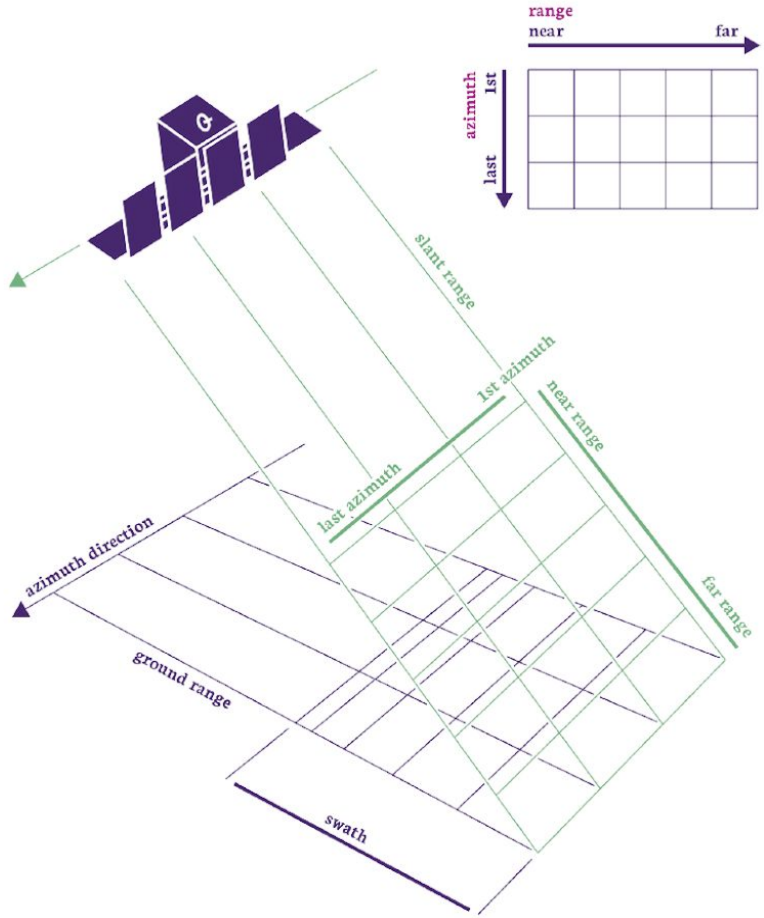


Figure 4.1: Slant range and ground range image geometry.

Aerospace Assessment

Approach (Metric)	Priority
Bandwidth Only	Sensor Capability
Geometric Mean Resolution	Sensor Capability
Ellipticity Constrained Resolution	Sensor Capability
Best RNIIRS Calculation	Produced Imagery
Resolution and Power Aperture Combo	Produced Imagery
PTCR Calculation*	Produced Imagery

*Point Target Contrast Ratio (PTCR). A contrast ratio that … compares scene backscatter to a known target backscatter. Single image quality metric. Includes hardware effects, resolution, ambiguities scene backscatter effects.

The preferred metric (RPAC) is based on the Information Density metric (RGIQE), but generalized to examine hardware capability, not individual image quality. Requires knowledge of system noise figure and imaging time per orbit.

Backup

SAR Resolution

- Resolution is the ability to distinguish two closely spaced objects.
  - *The image on the left is 1 m resolution. The image on the right is 0.25 m resolution.*
  - *The salt-and-pepper appearance of the image on the left is due to "speckle", which is an inherent part of SAR phenomenology. Speckle is reduced when the resolution increases.*
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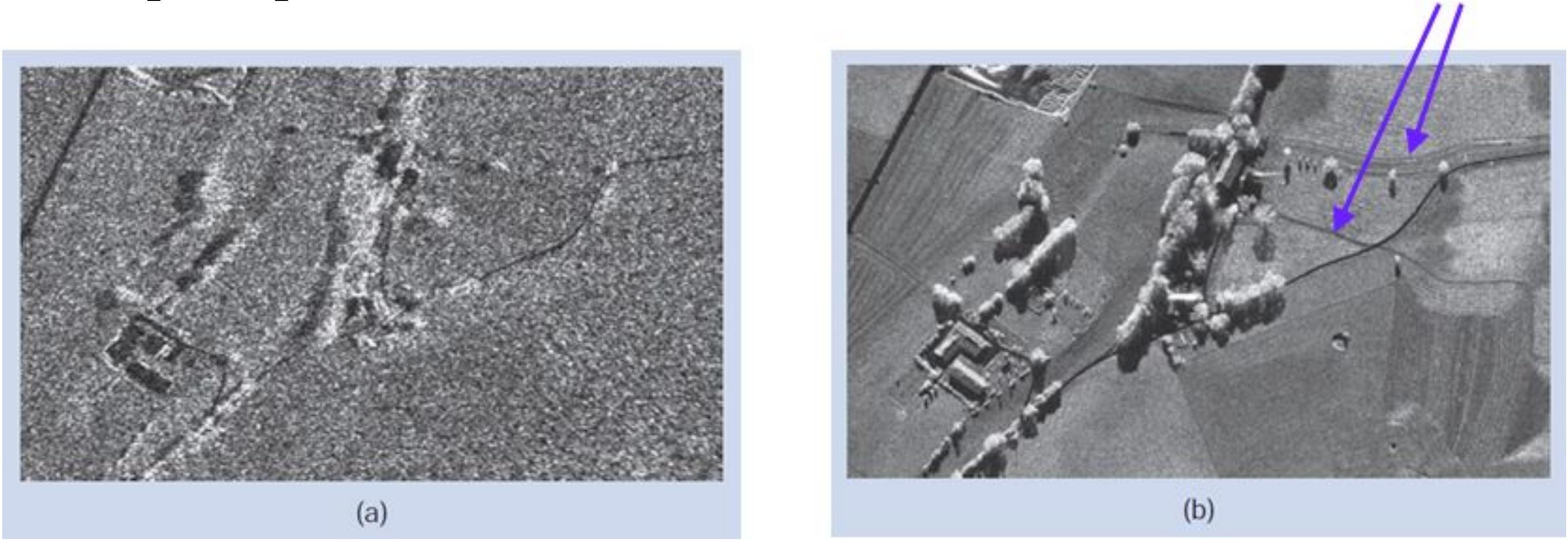


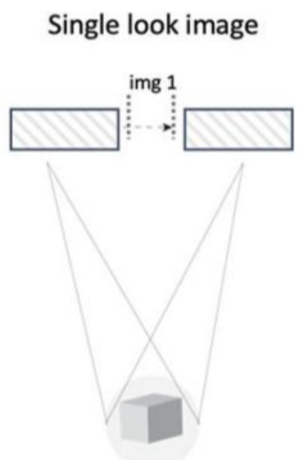
Both images are X-band SAR. Image (b) was acquired by the F-SAR sensor of DLR.

Images taken from: *"A Tutorial on Synthetic Aperture Radar",* A. Moreira, P. Prats-Iraola, M. Younis, G. Krieger, I. Hajnsek and K. P. Papathanassiou, *IEEE Geoscience and Remote Sensing Magazine*, March 2013, pp.6-43.

Resolution vs. Quality

- Image Quality depends on both resolution and noise (NESZ).
- Incoherently adding together multiple images reduces (improves) the NESZ.
  - *This is referred to as multi-look processing.*
  - *<u>Multi-look processing is another way to reduce speckle.</u>*

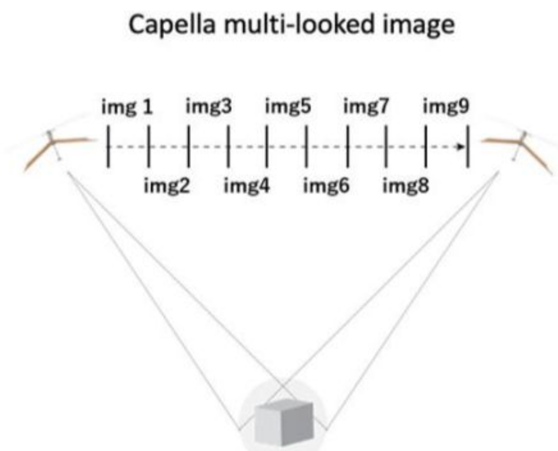
An image with 0.5 m azimuth resolution collected at broadside requires about **2.5 sec** of dwell time but will have inherently poor NESZ.



Allows for increased **quantity** of images

9 individual 0.5 m resolution images multi-looked together takes about **30 sec** of dwell time and yields an RNIIRS 5.5 image.

- *By collecting 9 individual images, they can be multi-looked without losing resolution.*



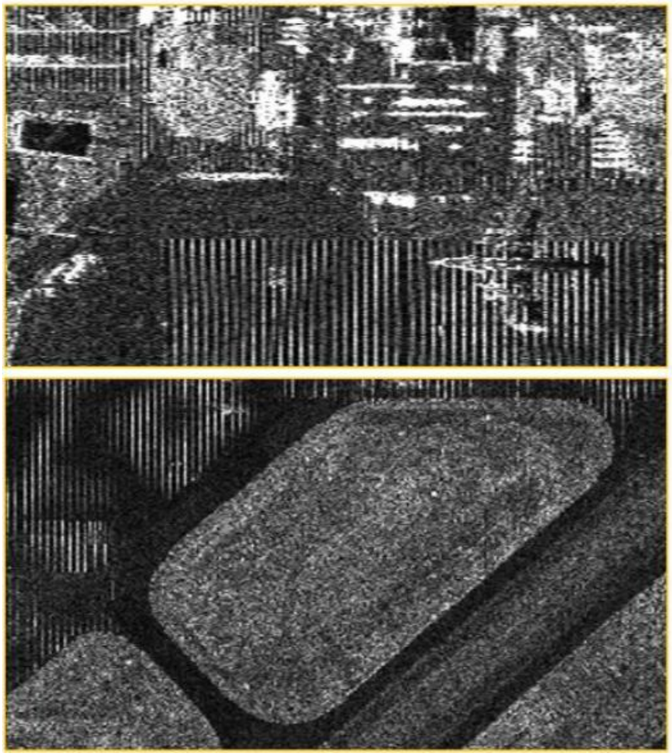
Allows for increased **quality** of images

NESZ - Noise Equivalent Sigma Zero, a common measure of image noise in SAR systems.

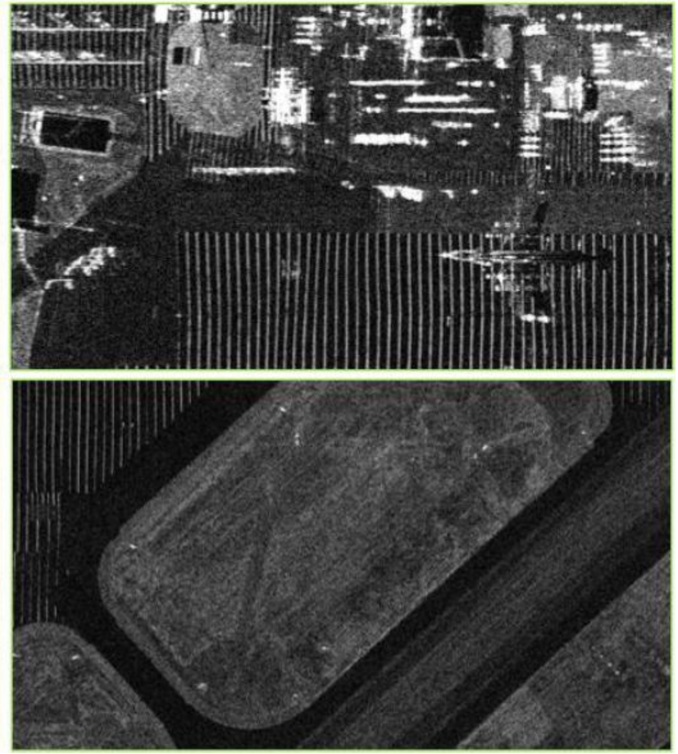
Figures borrowed from *Capella Space SAR Imagery Products Guide*, 2020

Resolution vs. Quality, cont.

Single look product



Multi-look product



Images borrowed from *Capella Space SAR Imagery Products Guide*, 2020

Both products are 0.5 m resolution

- Single look image takes approx. **2.5 sec** to collect
- At the expense of having higher (worse) NESZ.

Count Number of Planes

- Multi-look image has significantly lower (better) NESZ
- At the expense of taking approx. **30 sec** to collect

Discern Types of Planes

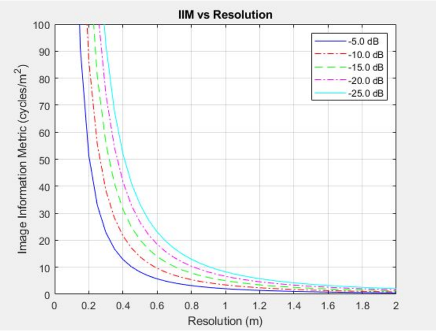
Best RNIIRS (Information Density)

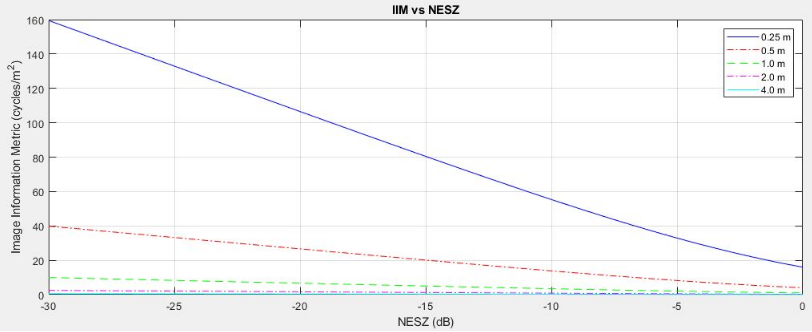
Commentary

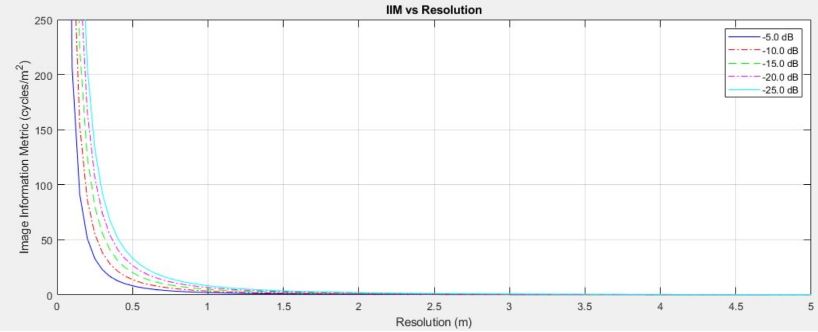
idm Information Density metric: RGIQE

$$idm = \frac{1}{\rho_{Gaz} \cdot \rho_{Grg}} \cdot \log_2\left(1 + \frac{1}{NESZ}\right) = \frac{1}{\rho_{Gaz} \cdot \rho_{Grg}} \cdot \log_2(1 + SNR)$$

IDM increases linearly with improving NESZ, when NESZ is measured in dB.
IDM increases exponentially with improving resolution, when resolution is in meters.
Resolution is a much stronger driver than NESZ.



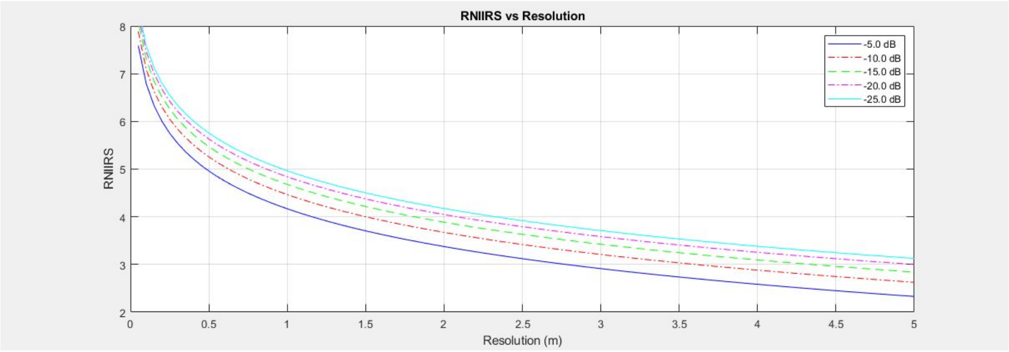




rniirs Radar National Imagery Interpretability Rating Scale

$$rniirs \cong p_1 \cdot \log_2(idm) + p_0$$

RNIIRS is a logarithmic scale. Improving the resolution by a factor of ~2.4x increases RNIIRS by 1.



For NESZ = -15 dB:

	Resolution (m)	RNIIRS
2.4x	0.125	7.078
2.5x	0.30	6.054
2.4x	0.75	5.007
2.39x	1.80	4.007
	4.30	3.012

Resolution and Power Aperture Combo

Commentary

S Radar System Sensitivity

$$S = \frac{P_{Tavg} \cdot G_T \cdot G_R}{NF \cdot L}$$

This is a common radar system metric. The Power Aperture (PA) portion, M_2, of the rpac metric replaces the Average power above with Peak power to eliminate the dependency on tasking.

The M_2 portion of the rpac metric also removes the System Losses term since it is comprised primarily of atmospheric loss, which would be common to most systems.

P_{Tavg}	Average transmit power, in Watts
G_T	Peak transmit antenna gain
G_R	Peak receive antenna gain
NF	System composite Noise Figure
L	System Losses

$$P_{Tavg} = \frac{P_{Tpeak} \cdot PRF \cdot \tau_p}{L_T}$$

P_{Tpeak}	Peak transmit power, in Watts
PRF	Pulse Repetition Frequency
τ_p	Pulse duration
L_T	Transmit Losses

$NESZ$ Noise Equivalent Sigma Zero

$$NESZ = \frac{4 \cdot v \cdot \sin(DCA) \cdot \cos(Slope) \cdot k \cdot T_0}{c} \cdot \frac{B_{RF}}{\boldsymbol{S}} \cdot \left(\frac{4\pi R}{\lambda}\right)^3$$

The NESZ equation includes Radar System Sensitivity, S, as a term.

Note that it is desirable for NESZ to be as small as possible, so the larger the value of S the better.

k, $T_0 = 290\ K$, and c are constants, v depends on the satellite altitude, and λ depends on the center frequency. DCA, $Slope$, and R are geometry dependent. The proposed metric eliminates all these terms, leaving only those terms directly dependent on the hardware.