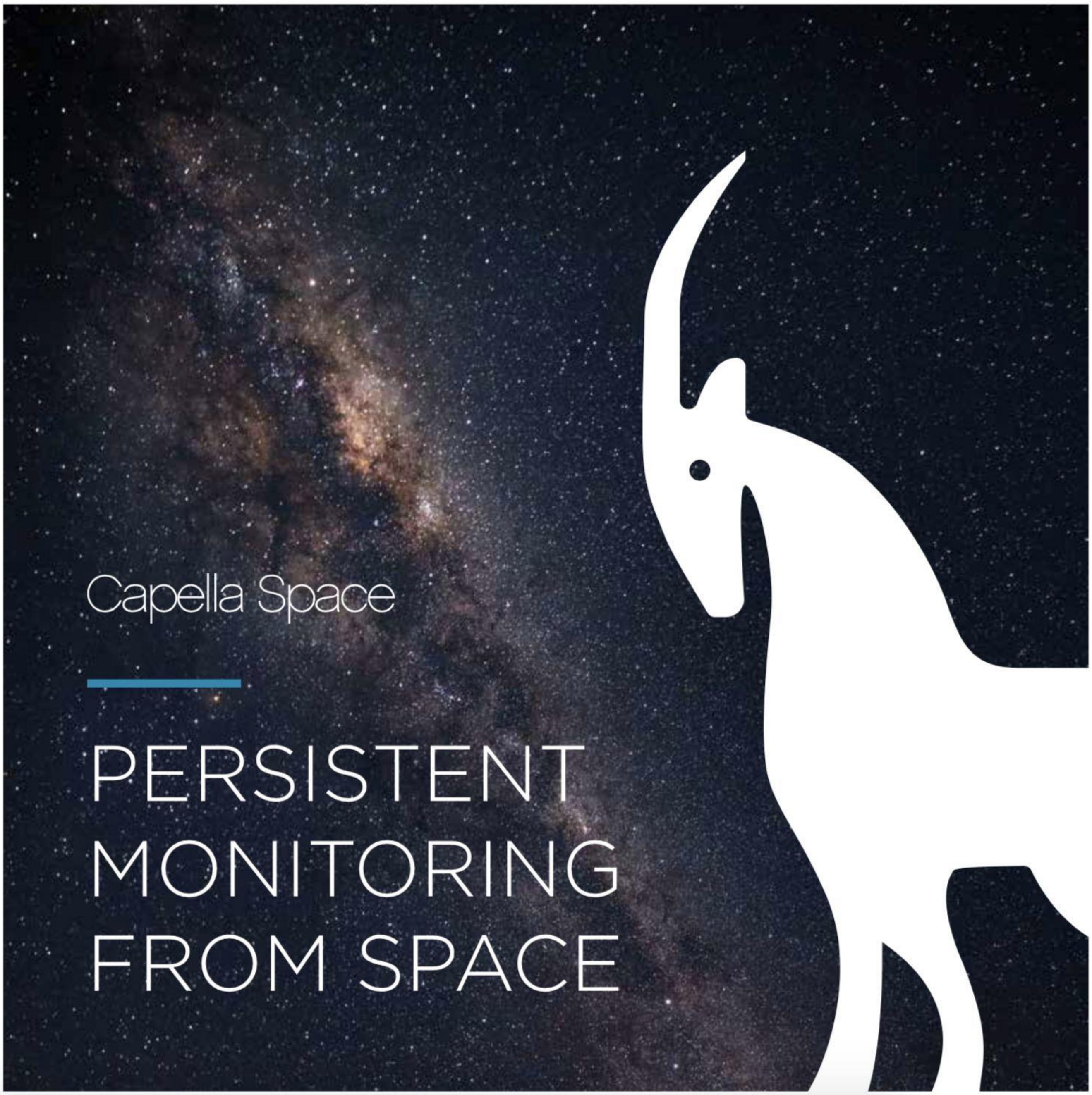
CAPELLA SPACE

SAR SYSTEM PERFORMANCE



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DOCUMENT CHANGE LOG

Version	Date	Change Description
1.0	8 July 2020	Initial document version
2.0	11 September 2020	Added specifications for Extended and Custom products

INTRODUCTION: SEQUOIA SYSTEM

This document describes the Capella Synthetic Aperture Radar (SAR) system and Capella SAR products. We provide an overview of the main technical characteristics of the radar (Table 1), then introduce the product performance metrics used in the document, and describe the Standard, Extended, and Custom SAR imagery products.

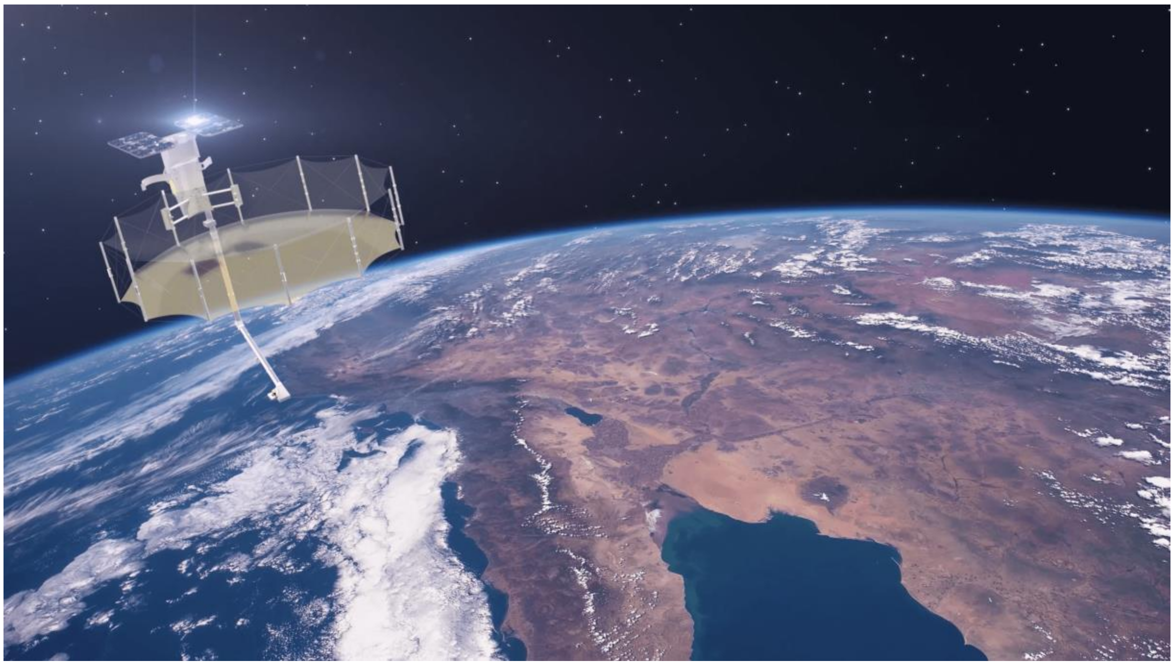


Figure 1: Sequoia artistic representation.

Frequency Band	X-band (9.4 – 9.9 GHz)
Peak Transmit Power	600 Watt @ 20% duty cycle
Polarizations	Single-pol HH
Imaging Bandwidth	Up to 500 MHz
Look Angle Range	25° - 40° (Standard Products) Up to 15° - 45° (Extended Products) Up to 5° - 45° (Custom Products)
Imaging Modes	Spotlight, Sliding Spotlight, Stripmap
Acquisition Direction	Left and Right sides
Nominal Orbit Altitude	535 km
Orbit Inclination	45° (accessible imaging latitude from -48.9°S to +48.9°N)
Imaging Time Per Orbit	Up to 9 minutes during peak usage orbits

Table 1: Sequoia main system parameters. All the numbers are estimated pre-commissioning.

DEFINITION OF PERFORMANCE METRICS

SAR ACQUISITION GEOMETRY

There are two key dimensions in a synthetic aperture radar image – the ranging (or range) dimension and the along-track dimension. These dimensions arise from the way in which SAR data is collected and processed.

Synthetic aperture radar data is collected by a coherent radar that is carried by a moving platform. The platform advances the radar in the "along-track" dimension of the scene, and synthetic aperture processing is used to place objects according to their position along the track. In contrast, the ranging ability of radar is used to place objects in the image according to the distance of the objects away from the radar. A SAR image is formed from the reflected signals in both dimensions – the along-track dimension and the "range" (ranging) dimension. The figure below visually illustrates the dimensions described above.

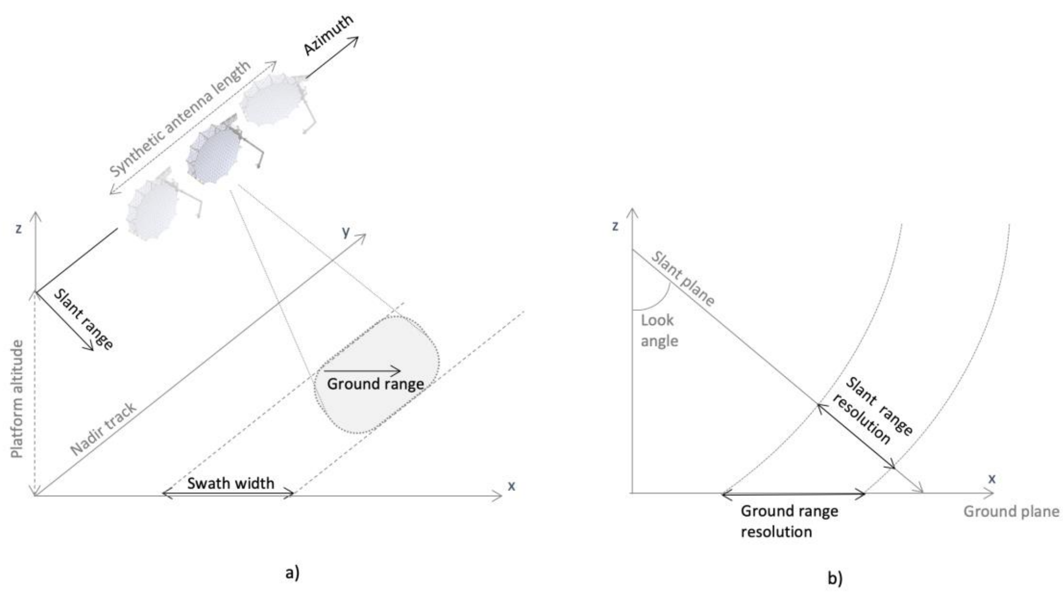


Figure 2: Capella SAR acquisition geometry.

The figure also illustrates the difference between the slant-range plane (the plane in which distance from the radar to the object) is measured, and the ground-range plane. In SAR images, distances measured in the slant-range plane are transformed to distances in the ground range plane using knowledge of the position of the satellite and the topography of the ground. Users of SAR data have the option of selecting ground plane surfaces (ellipsoid, DEM, etc.) that suit their application when transforming SAR data from the slant plane to the ground plane.

RANGE AND AZIMUTH RESOLUTION

The spatial resolution of SAR data is defined by the impulse response (IPR). The IPR of a SAR system is the response of the sensor and processing to a theoretical spatial impulse target, i.e., a target that is infinitesimally small in all dimensions. IPR is two-dimensional and is characterized by the range-dimension width (the width of the IPR in the ranging dimension) and the cross-range (or azimuth) dimension width. The generally accepted definition of radar resolution is the width of the IPR at points at 3 dB below the peak of the IPR. In the range dimension, a larger transmitted bandwidth corresponds to improved range resolution. In the cross-range dimension, a larger Doppler bandwidth corresponds to better azimuth resolution. IPR is also affected by the processing used to form the image, e.g., windowing, and distortions in the signals due to hardware limitations or uncompensated platform motion.

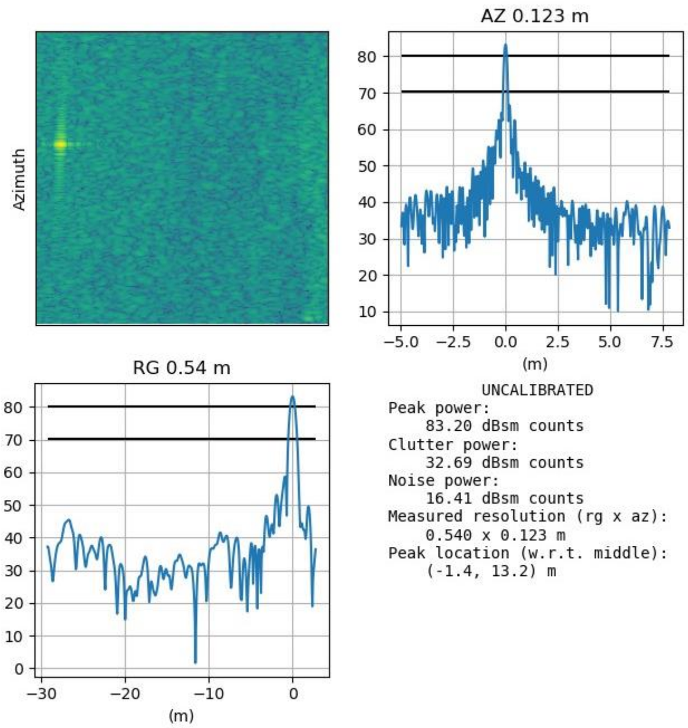


Figure 3: Example of two-dimensional impulse response function (top-left), and ground-range (bottom-left) and azimuth (top-right) dimension impulse response functions measured from a corner reflector during an airborne test of the Capella radar hardware.

Unless specified, IPR, and thus inherent SAR sensor resolution, is defined in the slant-range plane. When the SAR image is translated to the ground plane, the mapping from slant range to ground range causes the IPR to broaden (Figure 2). Therefore, the IPR-defined range resolution in the ground plane is always worse than that in the slant plane. Resolution in the cross-range direction does not change in the slant plane to ground plane mapping.

The ground-range resolution (resolution in the ranging direction projected onto the ground plane) depends on the bandwidth of the transmitted signal and the angle from which the ground is imaged. Larger bandwidth enables a better range resolution. For instance, the theoretical resolution with a 300 MHz bandwidth is 0.5 m in the slant plane and 0.91 m in the ground plane at a look angle of 30 degrees. With a bandwidth of 500 MHz, the slant range resolution is 0.3 m and the ground-range resolution is 0.55 m for the same look angle.

As mentioned, the azimuth resolution depends on the Doppler bandwidth. A larger Doppler bandwidth can be obtained by pointing the antenna beam at a target for a longer time.

Many existing SAR satellites use phased array antennas to steer the beam to dwell on objects. As these phased array antennas are designed to scan over a few degrees, the azimuth resolution achieved is on the order of tens of centimeters.

Capella SAR satellites have a transmitter bandwidth of 500 MHz, so can achieve 0.3 m resolution in the slant plane. The satellites have also been designed to point to a spot on the ground for tens of seconds, which would allow to achieve theoretical centimeter-scale azimuth resolution. This fine resolution is used to reduce speckle in the images and provide high-quality multi-looked SAR imagery. The figure below shows the measured impulse response from an airborne test of the Capella radar hardware.

NOISE EQUIVALENT SIGMA ZERO (NESZ)

In addition to spatial resolution, other metrics are important in overall interpretability of a SAR image. The radar measures the intensity of the reflected signal at each resolution cell in the image. The intensity depends on the transmitted power, antenna gain, distance between the scatterer and the radar, and geometry, roughness, and material properties of the object being imaged. For interpreting intensity in a radar image, two features are important: the ability to make out objects against the inherent noise generated by the sensor, and the ability to discriminate two objects that have similar intensities. The first is captured by the noise equivalent sigma zero (NESZ) of a SAR image. The second is captured by the concept of radiometric resolution.[1]

A target is detectable in a SAR image when, for a certain pixel resolution, the received power and therefore the intensity at the pixel level overcome the thermal noise. In SAR, NESZ is the most commonly used metric that captures the effect of system noise on image quality. It can be analytically predicted during the design of the radar and can be empirically measured over "dark" targets in the SAR image. For instance, calm lakes are highly reflective targets in the side-looking geometry and allow the characterization of the noise level of the sensor.

The effect of NESZ on image interpretability is demonstrated with the images in Figure 4. The SAR data were processed to 0.5 m ground range resolution and 0.5 m azimuth resolution. In both cases, bright scatterers, e.g., buildings, are clearly detectable. The difference between the two is the NESZ (–10 dB versus –20 dB). The aircraft and the roads are far more discernable in the image that has an NESZ of –20 dB. In particular, the aircraft shadows are much clearer in the –20 dB NESZ image. This shows that lower NESZ values are preferable when targets with low-backscattering intensity need to be detected.

NESZ varies also with transmitted bandwidth (range resolution). A SAR image generated with a 300 MHz transmitted bandwidth (0.5 m slant-range resolution) will have more noise than one generated with 150 MHz (1 m slant-range resolution). A wider bandwidth enables better resolution but causes more noise in imagery (higher NESZ).

[1] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/radiometric-resolution

Figure 4: NESZ is a metric that informs about the system noise level in a SAR image. NESZ is usually provided as a log-scale quantity in dB, and more negative values indicate better image quality. For SAR users, the required NESZ depends on the application. Hard target detection and vegetation analysis have very different NESZ and resolution requirements.

RADIOMETRIC RESOLUTION

Speckle is caused by the reflection of the radar signal from multiple objects (scatterers) that are distributed within a resolution cell. The branches and leaves of a tree, grass and rocks in a field, and bricks that make up the walls of a building are examples of objects that have distributed scatterers. The sum of the contribution from all the scatterers results in variation in the intensity of the measured signal in adjacent resolution cells. This variability in image intensity, called speckle, limits the radiometric resolution of a SAR sensor.

Speckle in images looks like the snowy noise found on old analog television sets. Speckle makes it harder to distinguish features in SAR images because it corrupts the outline of objects. Radiometric resolution is a metric that describes the ability of a sensor to discriminate between two objects that have similar radar cross sections (i.e., that are radiometrically similar). Radiometric resolution depends on the measured signal to noise ratio and the number of independent looks from which the pixel was formed. Overcoming speckle and improving radiometric resolution is only possible by averaging multiple SAR images or averaging pixels in a SAR image. This averaging process is commonly referred to as “multi-looking”.

Multi-looking in single SAR images is most typically done by averaging adjacent pixels. Sometimes this averaging is achieved using sophisticated techniques, but the result is always a loss of resolution compared to the original image. For example, a 4-look 1 m (slant range resolution) × 1 m (azimuth resolution) spotlight image could be created from a SAR acquisition that has a slant range-resolution of 1 m and an azimuth resolution of 0.25 m, by averaging 4 adjacent 0.25 m resolution cells to form a 1 m cell in the azimuth direction.

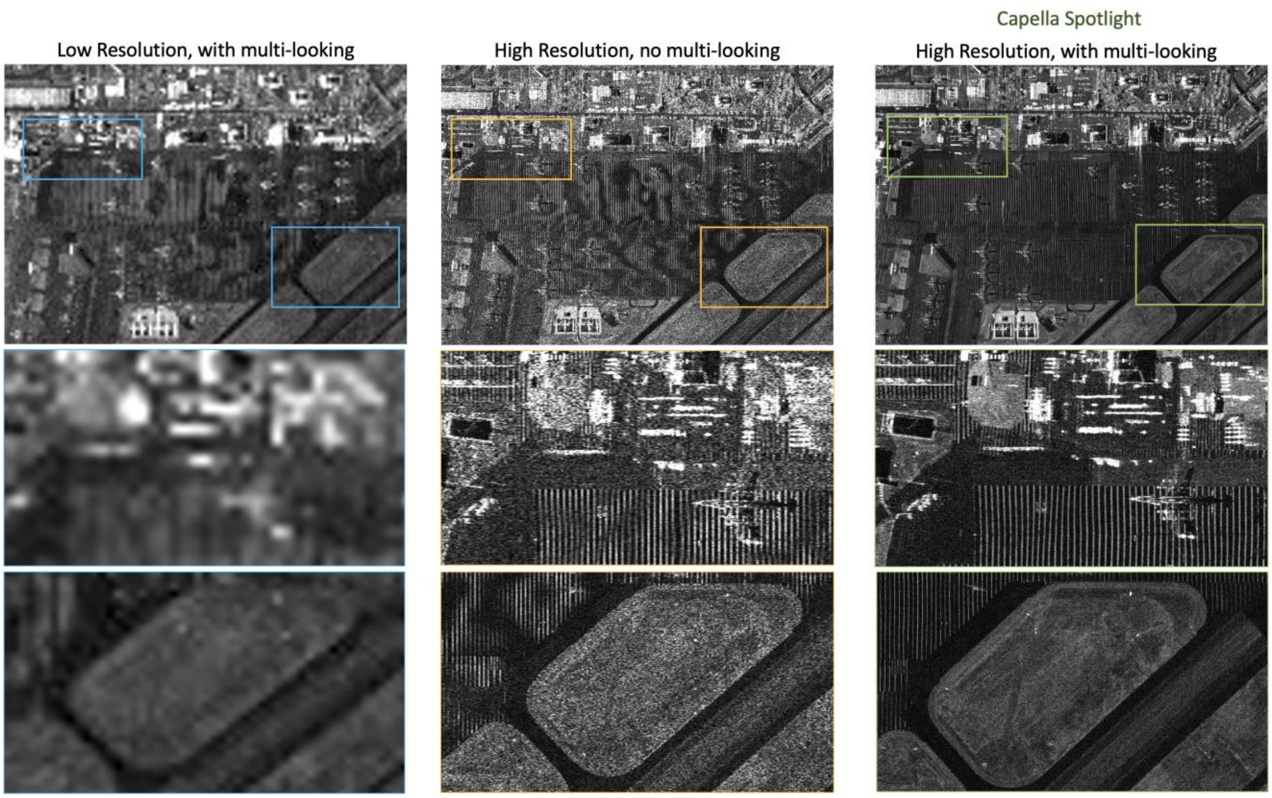


Figure 5: Low-resolution multi-looked image (left column), high-resolution single-look image (middle column), and high-resolution multi-looked image (right column). These images highlight that both resolution and speckle affect interpretation of the image.

Multi-looking is a common pre-processing step for SAR users interested in change detection or in target detection or classification. We demonstrate the image quality improvement using multi-looking with Capella data (Figure 5). The images in the left column of are from a low-resolution SAR imaging mode that has been multi-looked to reduce speckle and improve radiometric resolution. The boxed sections of the image have been reproduced below to show that the loss of spatial resolution significantly hinders identification of objects in the scene. The images in the middle column are single-look 0.5 m resolution images (both azimuth and ground range) where the speckle in the image hinders the identification of small targets. The image in the third column is a multi-looked

0.5 m resolution image. The shadow of the aircraft is significantly improved, and the features on the grassy areas are clearly visible.

CAPELLA SAR IMAGERY PRODUCTS

In this section, we present the Capella SAR Image products. We show basic performance metrics, such as resolution and NESZ. We provide the formulation used to estimate NESZ in Annex 1.

STANDARD SAR IMAGERY PRODUCTS

Standard imagery products are characterized in Table 2 and Table 3. Standard imagery products have been defined using the optimal performance range for the Capella radar. This category of Capella standard imagery products will be acquired with a look angle range between 25˚-40˚. Standard Imagery Products will be cataloged into the Capella Archive, unless the customer has purchased exclusivity.

Product	Imaging Mode	Nominal Scene Size	Azimuth Resolution	Slant Range Resolution	Look Angle Range	NESZ
Site SLC	Sliding Spotlight	5 km x 10 km	1.0 m	0.5 m	25° to 40°	-17 dB to -14 dB
Strip SLC	Stripmap	5 km x 20 km	1.7 m	1.0 m	25° to 40°	-20 dB to -16 dB

Table 2: Specification of the standard single look complex (SLC) imagery products.

Product	Imaging Mode	Nominal Scene Size	# Of Looks	Azimuth Resolution	Ground Range Resolution	Look Angle Range	NESZ
Spot GEO	Spotlight	5 km x 5 km	9	0.5 m	0.5 m to 0.7 m	25° to 40°	-14 dB to -10 dB
Site GEO	Sliding Spotlight	5 km x 10 km	5	1.0 m	0.8 m to 1.2 m	25° to 40°	-17 dB to -14 dB
Strip GEO	Stripmap	5 km x 20 km	1	1.7 m	1.6 m to 2.4 m	25° to 40°	-20 dB to -16 dB

Table 3: Specification of the standard geocoded (GEO) imagery products.

EXTENDED SAR IMAGERY PRODUCTS

Extended SAR imagery products provide increased acquisition opportunities and shorter revisit time periods via imaging acquisitions in broader look angle ranges than the standard products. Other than the look angle, all other imaging acquisition parameters are the same as the standard SAR imagery products. The specification for extended SAR imagery products is delineated in Table 4 and Table 5 below.

Product	Imaging Mode	Nominal Scene Size	Azimuth Resolution	Slant Range Resolution	Look Angle Range	NESZ
Site SLC (Extended)	Sliding Spotlight	5 km x 10 km	1.0 m	0.5 m	15° to 45°	-19 dB to -11 dB
Strip SLC (Extended)	Stripmap	5 km x 20 km	1.7 m	1.0 m	15° to 45°	-21 dB to -14 dB

Table 4: Specification of the standard single look complex (SLC) imagery products.

Product	Imaging Mode	Nominal Scene Size	# Of Looks	Azimuth Resolution	Ground Range Resolution	Look Angle Range	NESZ
Spot GEO (Extended)	Spotlight	5 km x 5 km	9 to 10	0.5 m to 1.0 m	0.5 m to 1.2 m	15° to 40°	-17 dB to -10 dB
Site GEO (Extended)	Sliding Spotlight	5 km x 10 km	5 to 6	1.0 m to 2.0 m	0.7 m to 1.9 m	15° to 45°	-19 dB to -11 dB
Strip GEO (Extended)	Stripmap	5 km x 20 km	1 to 2	1.7 m to 3.4 m	1.5 m to 3.9 m	15° to 45°	-21 dB to -14 dB

Table 5: Specification of the standard geocoded (GEO) imagery products. In geocoded products, number of looks is adaptively selected to bring the azimuth resolution near to the azimuth resolution.

CUSTOM SAR IMAGERY PRODUCTS

Custom SAR imagery products provide advanced control of imaging acquisition parameters. Using the Capella Console or Capella API, expert SAR users can submit tasking requests with very specific SAR imaging parameters in order to collect bespoke image products that satisfy their application requirements. Capella's custom SAR imagery acquisition unlocks the full accessible look angle range of the Capella radar system, 5˚-45˚ (varies slightly by imaging mode).

Table 6 shows the list of custom tasking parameters and the range of values that users can select for Spotlight (Spot), sliding spotlight (Site) and stripmap (Strip).

Imaging Parameter	Description	Minimum	Maximum
Window Open	The earliest user-defined time when acquisition can occur. Image acquisition can begin any time after the Window Open time up to the Window Close time. Units for this parameter is Date Time.	n/a	n/a
Window Close	The latest user-defined time when acquisition can occur. Image acquisition must occur no later than the Window Close time which effectively sets the tasking request expiration date. Units for this parameter is Date Time.	n/a	n/a
Tasking Tier	The new acquisition tasking tier (e.g. 1-Day, 3-Day, 7-Day). Units for this parameter is String.	n/a	n/a

Look Direction	Whether spacecraft is looking left or right with respect to its velocity vector during image acquisition. Units for this parameter is String.	n/a	n/a
Ascending/Descending	Whether the spacecraft is on the ascending (South to North) or descending (North to South) orbit during image acquisition. Units for this parameter is String.	n/a	n/a
Look Angle Minimum	Minimum angle between the sub-satellite point and image center point. Based on the full accessible look angle range of the Capella radar the smallest possible look angle is 5°. Units for this parameter is Degrees.	5	40 for Spot 45 for Site 45 for Strip
Look Angle Maximum	Maximum angle between the sub-satellite point and image center point. Based on the full accessible look angle range of the Capella radar the largest possible look angle is 45°. Units for this parameter is Degrees.	5	40 for Spot 45 for Site 45 for Strip
Imaging Mode	The radar system imaging mode (e.g. spotlight, sliding spotlight, stripmap). Units for this parameter is String.	n/a	n/a
Scene Length	Desired image scene length. This parameter is only customizable for sliding spotlight and stripmap imaging modes. Units for this parameter is Kilometers.	5	5 for Spot 50 for Site 200 for Strip
Ground Range Resolution Minimum	Minimum ground range resolution of the resulting image. Modification of this parameter only impacts the resolution of the GEO product type. Units for this parameter is Meters.	0.5 for Spot 0.7 for Site 1.5 for Strip	3.1 for Spot 5.0 for Site 11.5 for Strip
Ground Range Resolution Maximum	Maximum ground range resolution of the resulting image. Modification of this parameter only impacts the resolution of the GEO product type. Units for this parameter is Meters.	0.5 for Spot 0.7 for Site 1.5 for Strip	3.1 for Spot 5.0 for Site 11.5 for Strip
Azimuth Resolution Minimum	Minimum azimuth resolution of the resulting image. Modification of this parameter impacts the resolution of both the SLC and GEO product type. Units for this parameter is Meters.	0.5 for Spot 1.0 for Site 1.7 for Strip	3.1 for Spot 5.0 for Site 11.5 for Strip
Azimuth Resolution Maximum	Maximum azimuth resolution of the resulting image. Modification of this parameter impacts the resolution of both the SLC and GEO product type. Units for this parameter is Meters.	0.5 for Spot 1.0 for Site 1.7 for Strip	3.1 for Spot 5.0 for Site 11.5 for Strip

Table 6: Imaging acquisition parameters for custom SAR imagery products. In GEO image product type the number of looks in azimuth is fixed to 9, 5 and 1 for Spot, Site and Strip, respectively. When custom collects are requested SLC image product type is recommended in order to optimize multi-looking and geocoding to match user needs.

Figure 6 shows the performance space for the Capella radar. Capella's SAR bandwidth of 500 MHz can achieve a slant range resolution of 0.3 meter. As shown in the figure, the look angle variation affects the performance metrics (ground range resolution and potential image swath). The NESZ degrades as bandwidth increases but the use of smaller incidence angles can help mitigate this effect. For all incidence angles, high-bandwidth images will always show small bright targets. Parameters of the swath are defined by a combination of the look angle, the antenna beam width, and the PRF.

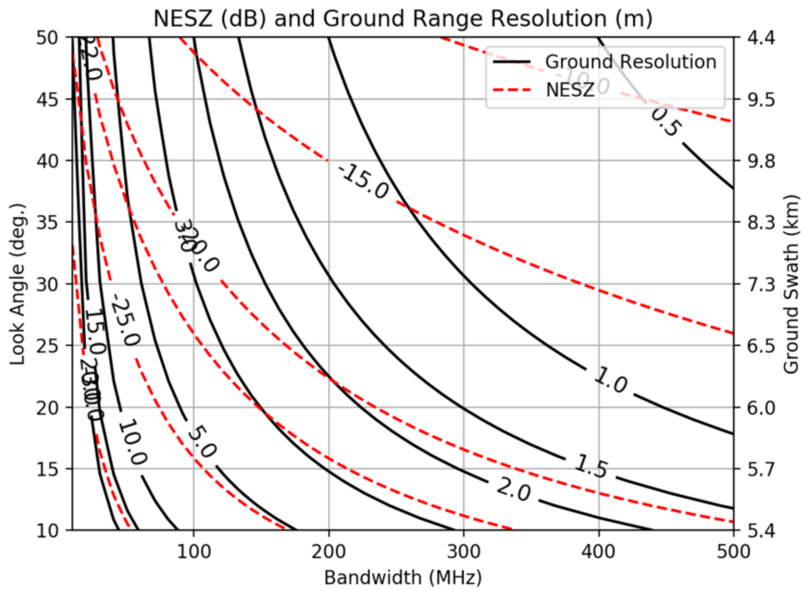


Figure 6: Capella radar ground-range resolution (black contours) and noise equivalent sigma zero (red dashed contours) performance as a function of radar bandwidth and look angle. Note that the ground-range resolution is a function of look angle and will always be a larger value than slant-range resolution.

Figure 7, Figure 8 and Figure 9 show different performance metrics for Strip, Site and Spot. We characterize NESZ, ground range resolution, azimuth ambiguity to signal ratio (AASR) and range ambiguity to signal ratio (RASR) in the 5 to 45 degrees range. The range of NESZ values for each nominal look angle results from the antenna pattern of the radar. We also present the radar pulse repetition frequency (PRF), fixed for stripmap and variable for spotlight and sliding spotlight. The data rate generated from the collection of Spot, Site and Strip is also shown from different look angles. These plots are generated for a minimum PRF of 10 kHz.

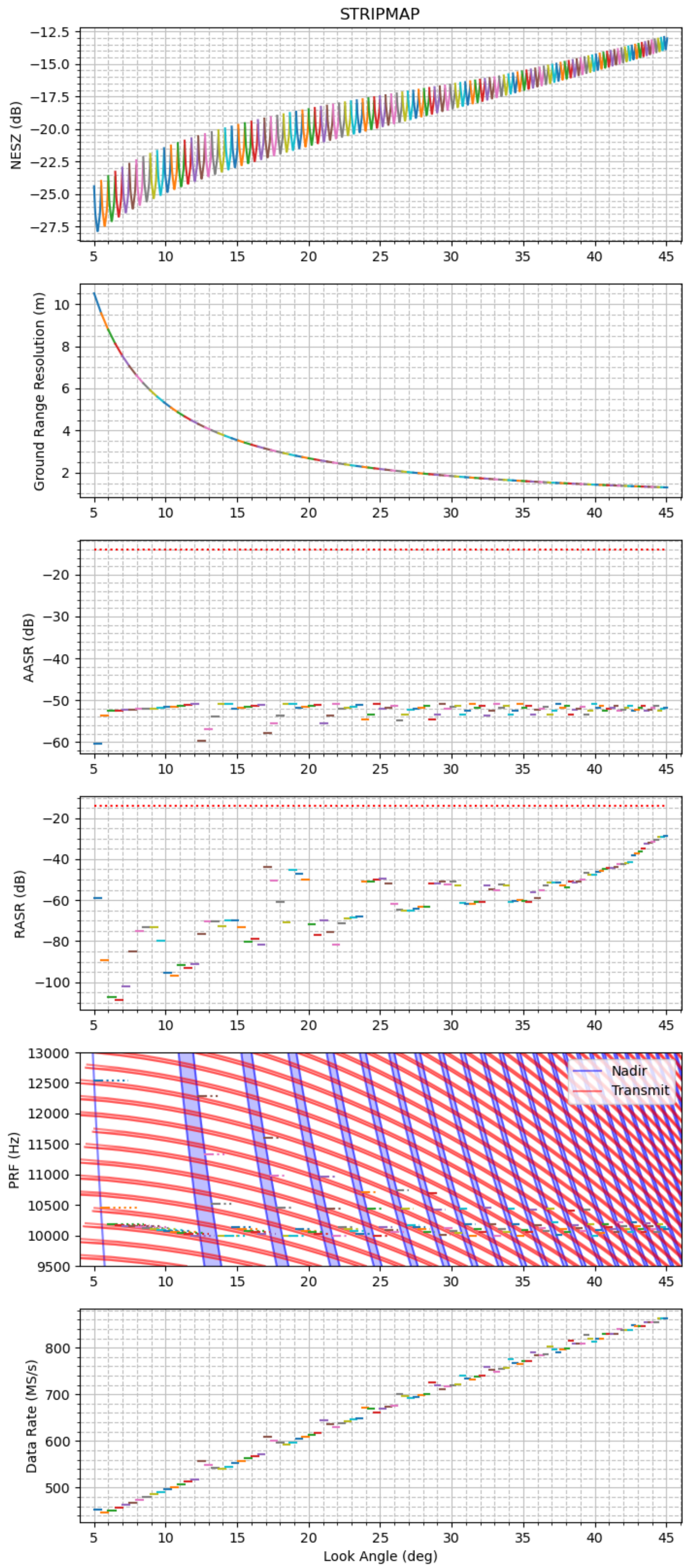


Figure 7: Performance for the Stripmap collects using a bandwidth of 150 MHz.

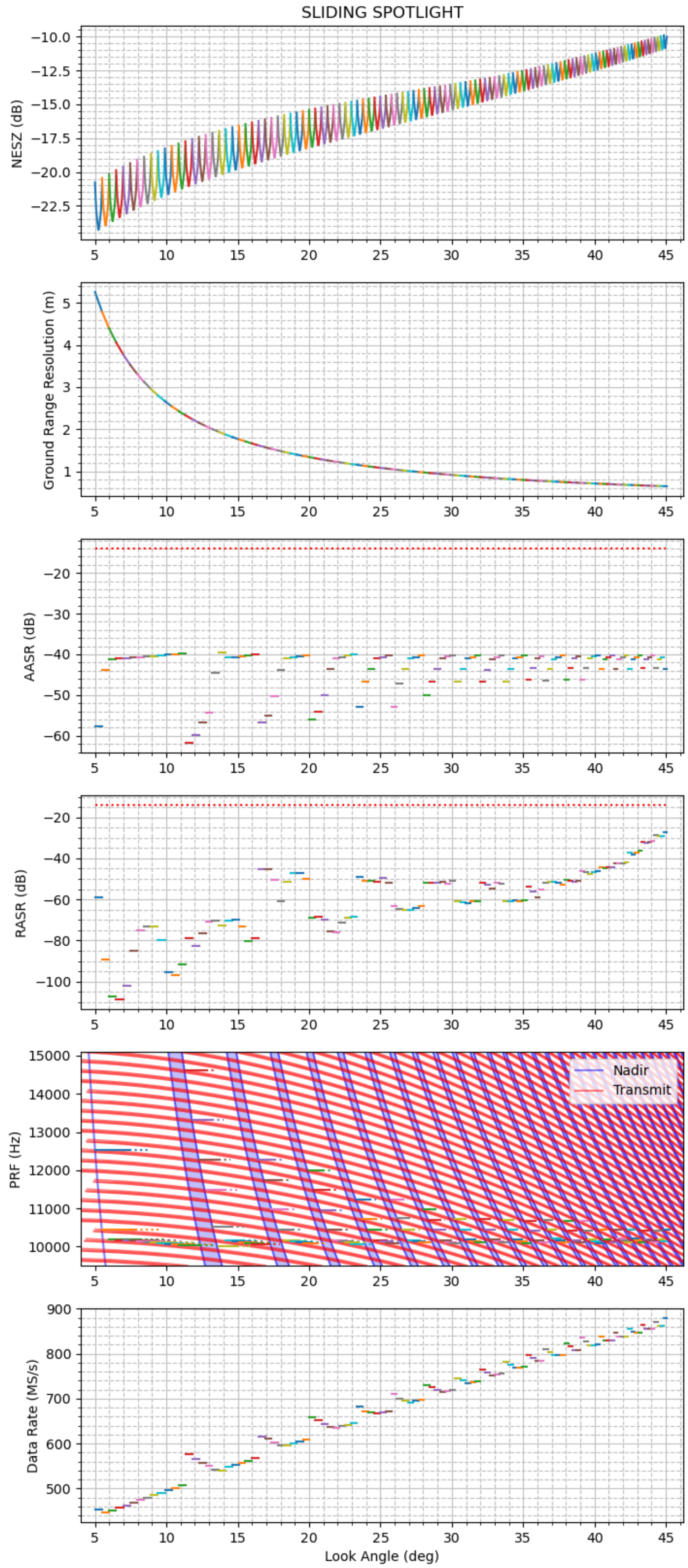


Figure 8: Performance for the Sliding Spotlight collects using a bandwidth of 300 MHz.

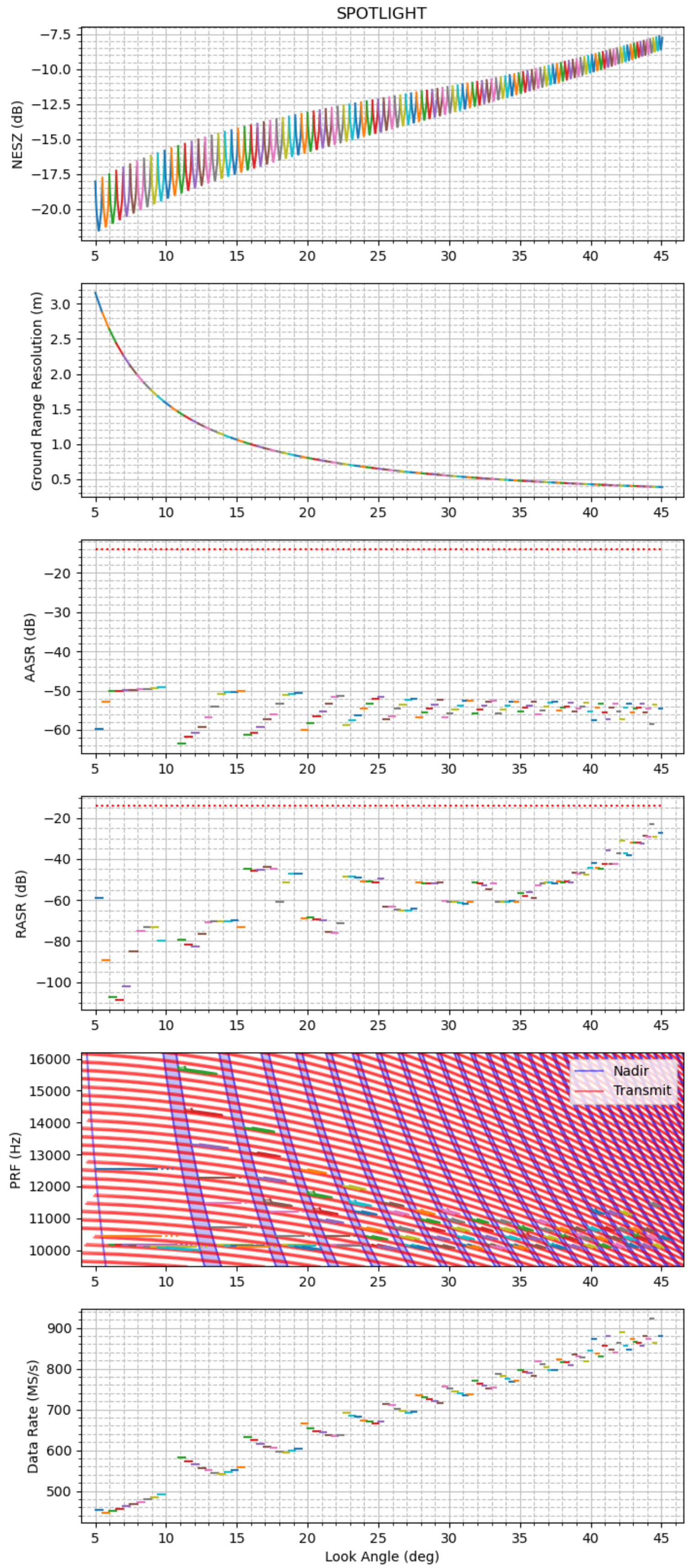


Figure 9: Performance for the Spotlight collects using a bandwidth of 500 MHz.

GEOMETRIC ACCURACY

SAR imagery is dependent on orbit determination and the system measurements that are used to compute Range-Doppler coordinates. Orbit state vectors are downlinked together with the radar imaging collection data. Range values in the SLC product are accurate to within 0.5 m after refraction corrections have been applied, and the zero-Doppler angles are accurate to less than a single pixel. Table 7 shows the expected orbit determination accuracy within the first 6 month after Sequoia launch and after commissioning and orbit operation optimization.

The ground location accuracy for the GEO product largely depends on the accuracy of the Digital Elevation Model (DEM) used for map projection and terrain correction. The geolocation accuracy varies also within the incidence angle range. During the commissioning phase and beyond, we plan to start the characterization of geolocation error based on satellite data to estimate range and azimuth offsets and standard deviation over a statistically relevant number of products acquired in the different imaging modes.

Orbit Determination	Orbit Determination Accuracy (first 6 months from Sequoia launch)	Orbit Determination Accuracy (operationally)
Rapid	< 50 cm	< 10 cm

Table 7: Capella orbit determination.

CONCLUSIONS

This document presents a high-level description of Sequoia system performance and quantitative estimation of image quality metrics of Capella radar SAR imagery. We plan to update the characterization of image performance metrics during Sequoia commissioning phase. Sequoia radar data has been calibrated using both pre-flight measurements. Pre-flight calibration measurements are made of the flight hardware before the launch and they include measurement of the gain and delay through the receive and internal calibration channels (both RF and digital sections), and measurement of the transmit power.

In-flight calibrations measurements will include acquiring data over calibration sites such as corner reflectors and transponders and noise only collects. These acquisitions will be used to check and refine radiometric accuracy, geolocation accuracy, and image, and point target response. A custom-built ground transponder, and acquisitions overs sites such as the Amazon Rain Forest will be used for antenna pattern characterization.

ANNEX 1: PERFORMANCE PARAMETERS

Noise Equivalent Sigma Naught (NESZ)

NESZ describes the strength of the system noise in units of normalized radar cross section (NRCS). NESZ represents the normalized backscatter which is equivalent to the noise observed in a SAR image. Finite NESZ is caused by thermal noise, analog digital converter quantization noise and, to a negligible extent, processing noise. As noise is not dependent on distance from the radar, compensation in the SAR processor for both the range spreading loss $1/R^3$ associated with reflected signals and the antenna pattern, cause a spatial variation of the noise level in the product.

The NESZ at the center of the image can be computed as:

$$\mathrm{NESZ} = \frac{2(4\pi r_0)^3 \sin(\Theta_i) k\, T_n T_{loss} V}{P_{Tx} G^2 \lambda^3 \Delta_R}$$

where r_0 is the range distance, k is the Boltzmann's constant, T_n is the system noise temperature, T_{loss} is the transmit loss, V is the orbit velocity, P_{Tx} is the transmitted power (20% duty cycle), G is the peak antenna gain, λ is the wavelength, A_{cell} is the area of the resolution cell of the image, and T_{int} is the integration time.

Range Ambiguity to Signal Ratio (RASR)

The RASR is the ratio of the range ambiguous signal power to the desired signal power in the range directions.

Azimuth Ambiguity to Signal Ratio (AASR)

The AASR is the ratio of the ambiguous signal to the desired signal within the SAR correlator azimuth processing bandwidth in the Doppler domain.

Peak Sidelobe Ratio (PSLR)

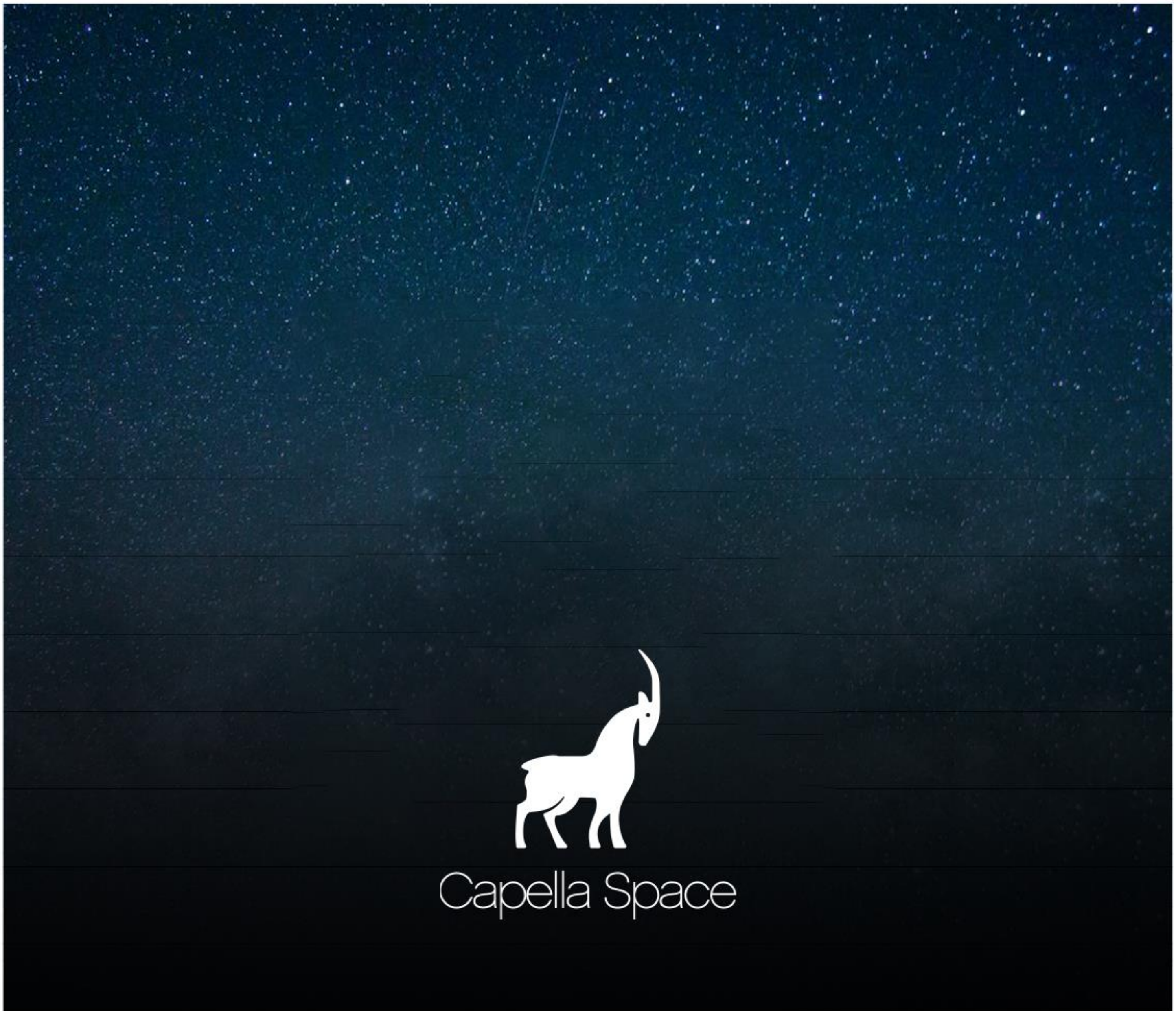
The PSLR measures of the SAR ability to identify a weak target from a nearby strong target. The PSLR is defined as the ratio of the peak intensity in the main lobe of the IRF to the peak intensity of the most intense sidelobe. It is calculated as:

$$\mathrm{PSLR} = 10 \log 10 \left(I_{peak} / I_{side}\right)$$

Integrated Sidelobe Ratio (ISLR)

The integrated sidelobe ratio characterizes the ability to detect weak targets near bright targets. The ISLR is defined as the ratio of energy of the main lobe to that in the sidelobes and is calculated as:

$$\mathrm{ISLR} = 10 \log 10(E_{main}/E_{side})$$



Capella Space

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