ICEYE

COMPLETING THE PICTURE

SAR PRODUCT GUIDE

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www.ICEYE.com

THE ICEYE VISION

▶ THE ICEYE

VISION

YOUR CHOICE FOR PERSISTENT MONITORING

ICEYE empowers commercial and government partners with unmatched persistent monitoring capabilities for any location on Earth. We do this with our continually growing SAR satellite constellation, currently in orbit and delivering SAR data. This product guide reviews our constellation, products, imaging modes and ordering process.

This is a living document because our innovative small SARs are flexible and they welcome our routine upgrades to their resolution, coverage and quality. We'll release new versions of this guide as we improve our sensors, expand our constellation, and streamline our order and delivery systems.

SAR sensors see through clouds and darkness. They measure pulse echoes with a precision much smaller than a single wavelength. Their resolution is independent of distance. They are capable of pristine geolocation, and they are change detection machines.

WE LOOK FORWARD TO SERVING YOU

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1. SMALL SAR REVOLUTION IN EARTH IMAGING

During the Middle Ages, if you wanted to understand the way the world worked you would consult your local religious leader. A Priest or Prophet would interpret the Word of God from beautifully written tomes that were transcribed by hand over many years. These books were ornate and so precious that they could not be widely distributed, and most people did not know how to read. In these years, the thoughts of nations were controlled by various religious and political leaders.

Then everything changed. The Renaissance and Reformation spurred new ways of thinking, and their ideas were recorded in printed books that were produced at low cost and in great volumes. People learned to read for themselves and think for themselves. Information spread across the globe.

Sometimes disruption can be good.

Hundreds of years later, in 2012, a small team of students working in the Nanosatellite Group of Aalto University considered the sequestered world of earth observation. The team was bothered by the limitations of government satellite programs in the same way that Renaissance and Reformation advocates challenged the knowledge control of the Middle Ages.

Satellite imagery has been mostly provided by massive, government-owned or government-sponsored, exquisite systems. Like the tomes of old, these are beautifully implemented and precious. But normal people rarely have access to their images, and even when they are available, they do not have the timeliness to support the quick decisions needed in this rapidly changing world.

The Nanosatellite students thought that timely, always available fine-resolution imagery should become a part of everyday life in the 21st century in the same way that GPS became integrated to nearly all businesses in the last decade of the 20th century. The humanitarian applications of easily-accessible imagery would include earthquakes, floods, volcanoes, glacial flow, and numerous environmental indicators. But if earth-observation imagery were to become as available, reliable and timely as the pace of our modern lives requires, things needed to change.

▶ SMALL SAR
REVOLUTION IN
EARTH IMAGING

Fueled by curiosity, passion, and long, dark Helsinki nights, the students decided that Synthetic Aperture Radar (SAR) would be the most useful way to obtain guaranteed, all-weather, day-night, observations of this cloud-covered planet. They reconsidered the conventional thinking regarding the mass and size needed to build SAR satellites, and then developed experimental sensors to prove and revise their thinking.

In 2015, ICEYE Oy was born. And thanks to several backers who shared our vision, on January 12th, 2018 the world's first micro-SAR satellite was launched. In contrast to the existing SAR systems that each weigh several tons, our ICEYE-X1 weighed only 75kg. It provided beautiful 3-meter resolution imagery, and it allowed our company to evaluate many natural disasters.

The ICEYE fleet is now growing rapidly. We began 2021 with 7 satellites, and we'll expand this to a constellation of 18 by mid-2022. Change is natural to our flexible systems. We upgrade our satellites the way programmers update code. Our resolution and coverage improves with each new version. And our low-cost, low-mass satellites are so highly maneuverable that we can reposition them to optimize revisit rates and support global change detection.

We will bring our users access to highly accurate, highly reliable monitoring, whenever and wherever they need it, at a pace that has never before existed.

WELCOME TO THE EARTH OBSERVATION RENAISSANCE!

2. THE ICEYE FLEET

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FLEET

The ICEYE global imaging service uses an innovative satellite and sensor design based on advancements in small satellite technologies and an adaptable New Space approach. The ICEYE constellation is constantly evolving. We began 2021 with seven operating satellites and we'll finish the year with thirteen systems. There will be more than ten more units added in 2022. The ICEYE constellation is optimized for persistent monitoring: rapidly repeatable access of any location on Earth, with flexible tasking for very high resolution spots as well as wide area scans.

The following describes the current fleet and their orbital configuration.

Figure 2.1: ICEYE generation 2 satellites

2.1 SAR SENSOR PARAMETERS

The ICEYE sensors are X-band radars, each with an active phased array antenna and electronic beam steering. The innate mechanical agility of these low-mass satellites and their electronic steering enable fast and precise pointing of radar pulses to the ground. The satellites can also image to the right or left side of the satellite track. Technical parameters of the current sensors are listed in Table 2.1.

PARAMETER	SPECIFICATIONS
SENSOR PARAMETER	
Carier Frequency	9.65 GHz (X-band)
Look Direction	both LEFT and RIGHT
Antenna Size	3.2 meters (along-track) x 0.4 meters
PRF	2-10 kHz
Range Bandwidth	37.6-299 MHz
Peak Radiated Power	3.2 kW
Polarization	VV
Incidence Angle Range	15-35 (mode dependent)
Mass	85 kg
Communication (radar payload data downlink)	X-band 140 Mbits/s

Table 2.1: ICEYE Generation 2 satellites system parameters

2.2 ORBITS

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Each satellite is in a sun-synchronous orbit with 15 revolutions per day. Their ground track repeat cycles vary between 1 and 22 days, depending on the satellite. Each orbital plane is phased around the Earth with a different local time of the ascending node (LTAN). This means that the overall constellation can observe a location at different times of the day. This has an advantage over dawn-dusk sun-synchronous orbits, in which the local time of collection is always close to sunrise or sunset.

At present, the LTANs of the ICEYE constellation are not uniformly spaced. This means that the time to revisit a location on the equator varies over a period of days. The mean revisit rate at the equator is 20 hours and the mean time to access a location on the equator is 12 hours. At higher and lower latitudes, the rates are more frequent. Table 2 lists the orbital parameters of the current SAR instruments.

PARAMETER	VALUE
ORBIT PARAMETER	
Nominal Altitude	560 to 580 km
Inclination	97.7 ° (sun-synchronous)
Orbits / Day	15
Ground Track Repeat	18-22 days
Constellation Mean Revisit at Equator	20 hours
Constellation Mean Time to Access at Equator	12 hours
Nodal Crossing (LTAN)	22:30, 15:05, 14:04, 21:36
Satellite Catalog Numbers	43800, 44390, 46497, 46496, 47510, 47506
Orbit Maintenance	Ion Propulsion

Table 2.2: Constellation parameters

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Each satellite has the ability to slowly adjust their orbits throughout their operating life. Adjustment is usually performed in the orbital plane by raising or lowering the satellite's altitude. This changes the orbital period, which in turn changes the ground track repeat period. Over the next 12 months, the fleet will gradually be adjusted into one-day repeating coherent ground tracks. This provides novel opportunities to combine data collections of the same area whilst maintaining rapid access times.

The location of each ICEYE satellite is publicly available. The current configuration of the constellation can be found using the satellite catalog numbers in Table 2.2 and one of the excellent online orbital elements tools such as celestrak [1] or n2yo [2], which provides a live view of the current ICEYE constellation.

3. ICEYE PRODUCTS

3.1 PRODUCT TYPES

There are two basic forms of ICEYE images: complex images in the slant plane and amplitude images projected to the ground surface[1]. Details about the formats of these products are provided in Chapter 4.

[1]Appendix A provides a review of the technologies mentioned in here.

3.1.1 COMPLEX IMAGES

SAR complex images contain pixels that have both amplitude and phase values. They are produced at full resolution and are projected in the inclined direction of illumination, called the slant plane. Since complex images retain phase information, they can be used to produce numerous SAR products like coherent change detection images and precise surface motion measurements.

3.1.2 AMPLITUDE IMAGES

These are the familiar SAR gray-scale images with amplitude-only pixels. They are "multi-looked" to reduce the grainy effect of speckle, at the cost of slightly lower resolution. Amplitude images are projected to the ground surface and can be oriented with respect to the sensor or produced on an ellipsoid-based map projection. For historical reasons our amplitude images are associated with the acronym *GRD* which stands for *Ground Range Detected*. This term may change in the future to be something more meaningful.

3.2 TYPES OF SAR COLLECTION

Our first set of satellites operate in one of two primary imaging modes called Strip Mode and Spot Mode. These are available in both right and left-looking configurations. The design flexibility of our satellites allows their imaging modes to be continually evolved. We will be adding more modes, and more flexible illumination patterns, in future versions. A recent addition is the introduction of a wide area imaging capability that utilises electronic beam steering. This is called Scan Mode. A summary of the imaging modes is listed in Appendix B.

▶ ICEYE PRODUCTS

3.2.1 STRIP MODE

In this mode the ground swath is illuminated with a continuous sequence of pulses while the antenna beam is fixed in its orientation. The beam is pointed off to the side of the satellite at an angle broadside to the satellite flight path (see Figure 3.1). This results in a long image strip parallel to the flight direction.

ICEYE standard Strip products have a ground resolution of 3m in range and azimuth and cover an area of 30km (range) by 50km (azimuth). The strip length can be tailored up to a length of 600 km, in increments of 50 km.
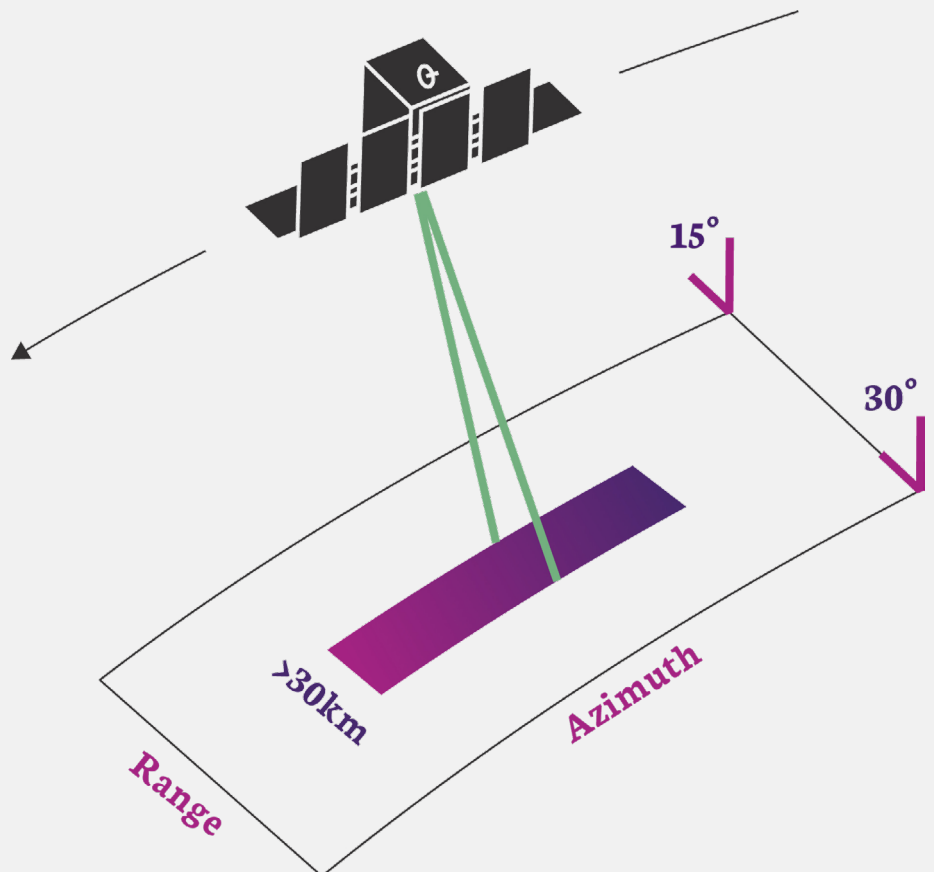
Figure 3.1: Schematic of Strip imaging mode.

► ICEYE PRODUCTS

3.2.2 SPOT MODE

In Spot mode the radar beam is steered to illuminate a fixed point. This increases the illumination time and the length of the synthetic aperture, and it improves azimuth resolution. The standard Spot mode uses the maximum 300 MHz pulse bandwidth and it provides a 0.5m x 0.25m resolution complex image (slant range by azimuth). The final multi-looked amplitude image has 1m x 1m resolution on the ground.

Figure 3.2: Schematics of Spot imaging mode.

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3.2.3 SCAN MODE

This mode uses the phased array antenna to create multiple beams in the elevation direction. This beam steering means that points on the ground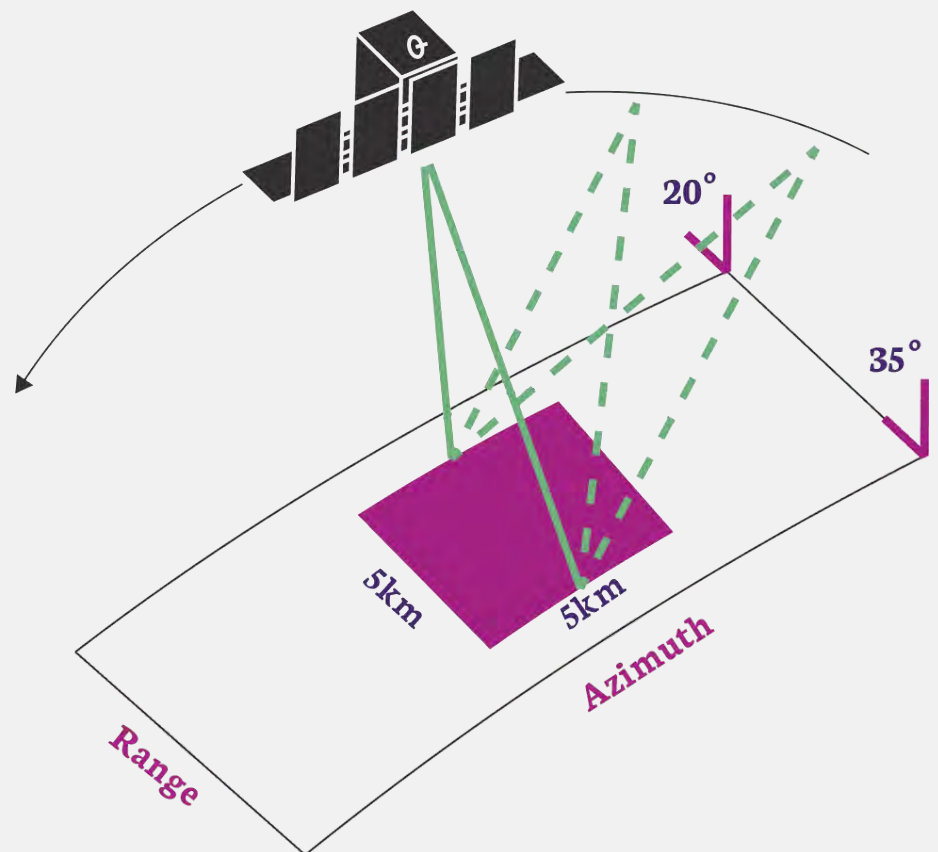 are not illuminated for as long which reduces the resolution of a Scan product compared to Spot or Strip modes. Conventionally, ground points are illuminated by different parts of the radar beam resulting in brighter and darker regions in the image. We compensate for this by also steering the radar beam sideways during each burst of radar pulses resulting in an overall improvement in image quality. This technique is called Terrain Observation by Progressive Scans (TOPS or TOPSAR [3]).

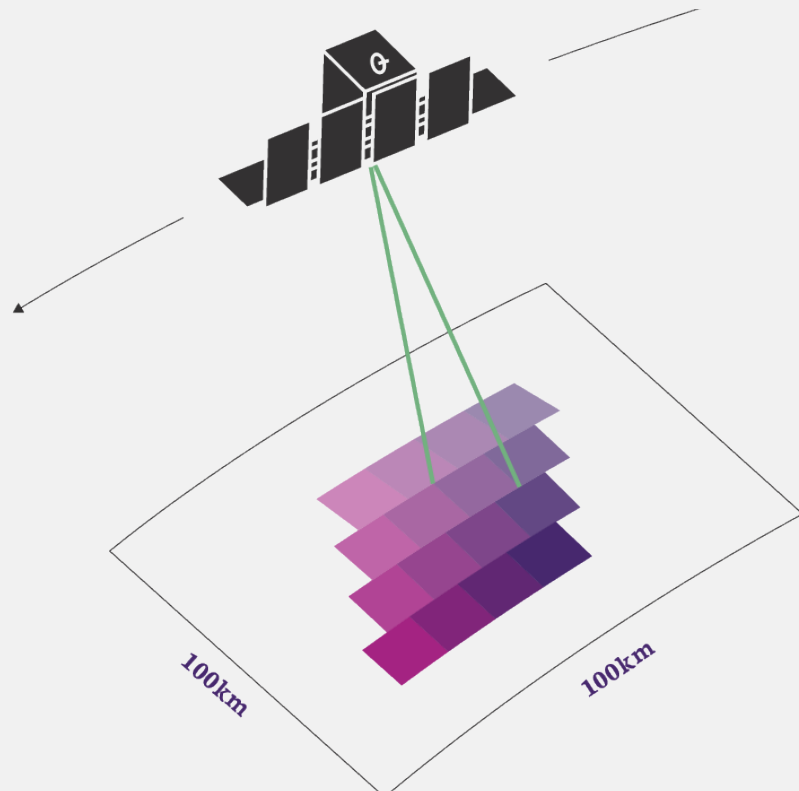Our Scan product produces imagery that covers an area of 100km x 100km with a resolution better than 15m.

Figure 3.3: Schematics of Scan imaging mode.

4. PRODUCT FORMATS

▶ PRODUCT FORMATS

4.1 GEOCODING INFORMATION IN ICEYE IMAGES

To enable easy and fast geolocation, a processed form of the geometry model called rational polynomial coefficients (RPCs) is provided for each image. RPCs link image locations to ground locations via simple equations that enable rapid calculations. In addition to ease and speed, RPC coefficients have the further advantage of being sensor independent. The structure of the RPC equations is always the same. For this reason, RPC exploitation code does not have to change to accommodate different sensors. In fact, both optical and SAR sensors are modeled by the same RPC structure. Exploitation code that performs geolocation for images from optical sensors can actually be used to derive ground locations from the RPC data included with ICEYE complex and amplitude images[2]. This process is now commonplace in most geospatial viewers[3].

4.2 SINGLE LOOK COMPLEX (SLC) PRODUCT

These are full-resolution, single-look images of the focused SAR signals. Scenes are stored in the satellite's native image acquisition geometry, which is the slant-range-by-azimuth imaging plane. As shown in the green surface in Figure 4.1, the pixels are aligned perpendicular to the sensor flight track[4]. They are spaced equidistant in azimuth and in slant range. Each pixel contains both amplitude and phase information as represented by a complex magnitude value with in-phase and quadrature components (I&Q).

SLC products are suitable for applications that rely on phase information or require the full image resolution. Because SLC images are in the native sensor orientation, there are no radiometric artefacts induced by the spatial resampling applied to map projection images. The range-azimuth orientation also enables further geometric manipulation, like orthorectification. Ortho versions can be produced using both commercial and free software tools, such as the European's Space Agency's Sentinel Application Platform (ESA SNAP S1TBX [5]).

The SLC product is particularly useful for those analysts who require multiple collections with matching phase data for applications like Coherent Change Detection (CCD). SLC images are typically used by scientists and organisations with advanced SAR expertise, but complex images will become

[2]Image geolocation of any mono image, optical or SAR, requires that an elevation model be used during exploitation. This is true for the physics-based equations and RPCs.

[3]we recommend using QGIS [4]) and it is freely available for analysts and software developers.

[4]The pixels have zero-Doppler SAR coordinates.

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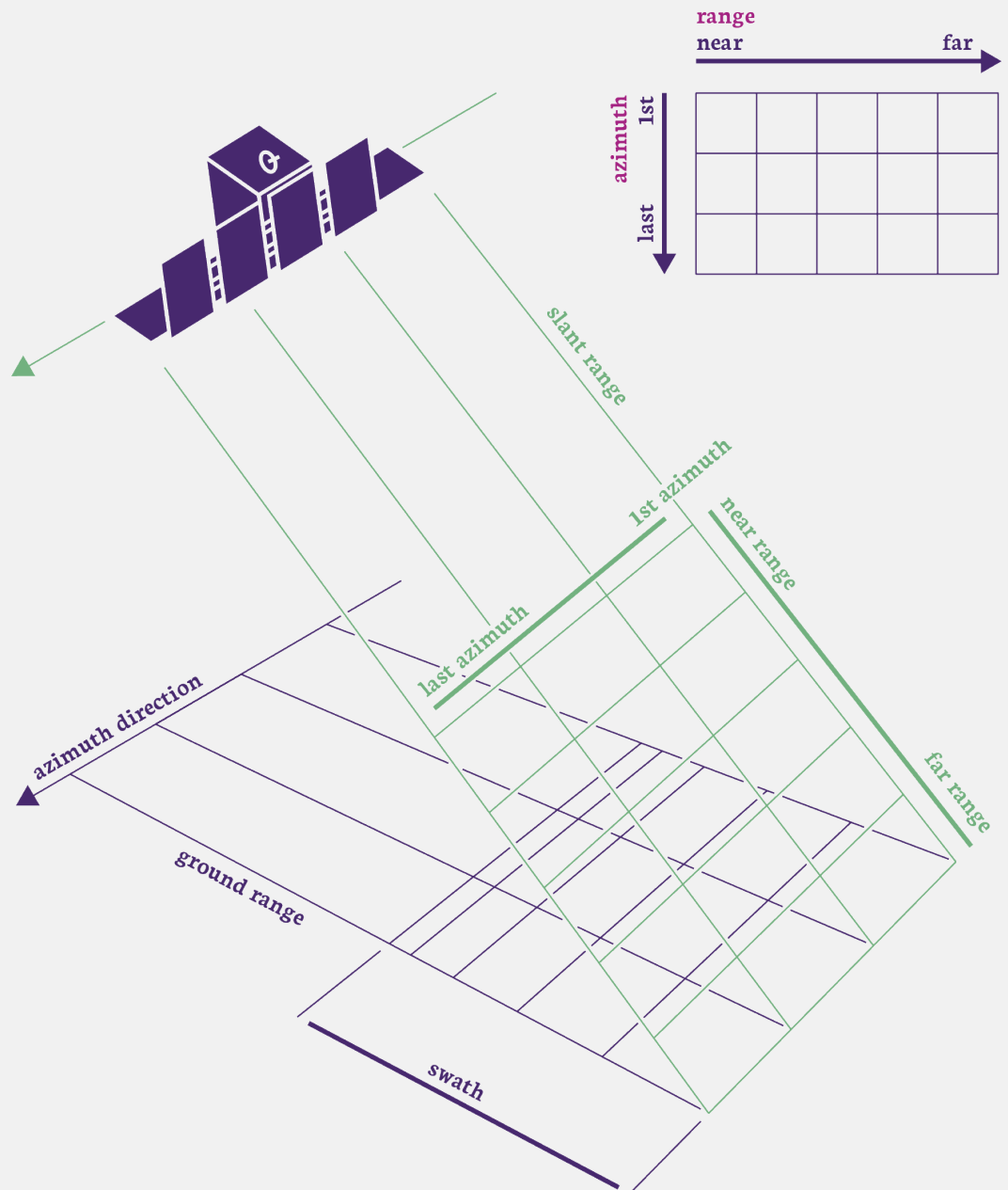core products for numerous users once SAR applications become more user-friendly.

Figure 4.1: Slant range and ground range image geometry.

[5]The average elevation of the scene is applied to the ellipsoid used in the projection

4.3 AMPLITUDE IMAGE

These are viewable forms of SAR data used for analyst exploitation; the pixels have brightness values but no phase data. Amplitude images are multi-looked to reduce the salt-and-pepper effect of speckle. The images are also projected from the slant plane onto an ellipsoid model of the ground surface (See Figure 4.1)[5]. The resulting product has approximately square spatial resolution and equal pixel spacing. It also has reduced speckle, due to the multi-look processing. Figure 4.2 illustrates slant range and ground range projections of amplitude pixels. The pixel's dimensions are equal in range and azimuth in the ground projection on the right.

As with SLC images, sensor-oriented amplitude images maintain the native sensor geometry of range and azimuth and no image rotation to a map coordinate system has been performed. This avoids interpolation artefacts and it supports image stacking for change detection applications and physics-based, rigorous geolocation. ICEYE images can be viewed using open standard GIS readers such as QGIS [4].

We do not orthorectify our amplitude images or project them to an ellipsoid-based map projection, but we do provide information and free software that allows users to quickly apply these to their ICEYE imagery. This lowers the cost to our customers and ensures that they are always aware of the provenance of the elevation data used to project the image pixels to the topographic surface. This software is described in our Imagery Product Format Specification Document [6].
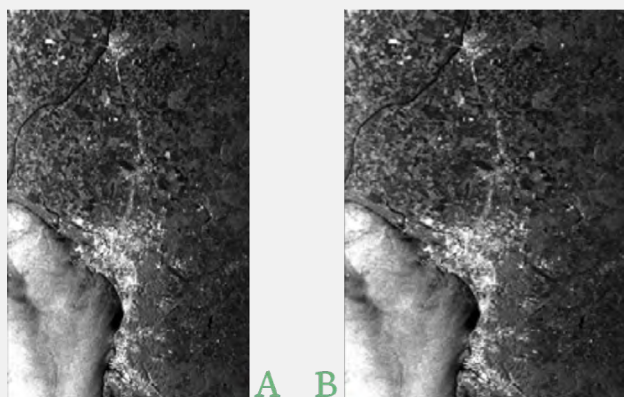
Figure 4.2: Slant range and ground range images.

4.4 ICEYE IMAGE FORMATS

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ICEYE SLC products are stored and delivered in the HDF5 format, which is particularly suitable for storing binary complex SAR data channels and annotated metadata. Amplitude images are produced as GeoTiff files. These are readable by common GIS software tools. Additionally, both SLC and Amplitude products are accompanied by XML metadata files. This enables quick screening of products without the use of specialized software.

A detailed description of the format of SLC data and amplitude images is given in the ICEYE Product Format Specification Document, which is available on the ICEYE website [6].

	COMPLEX	AMPLITUDE	QUICKLOOK
FILE FORMAT			
Strip	HDF5, XML	GeoTiff , XML	PNG, KML
Spot	HDF5, XML	GeoTiff , XML	PNG, KML
Scan	-	GeoTiff , XML	PNG, KML

Table 4.1: Available file formats.

5. SUPPORT

5.1 CUSTOMER OPERATIONS AND SATELLITE PLANNING TEAM

The Customer Operations and Satellite Planning (COSP) team is the department of ICEYE in charge of order processing and customer support. Customer Operations and Satellite Planning staff who interact directly with the customer are called Customer Operations and Satellite Planning Specialists. The responsibilities of the COSP Specialist are:

- ▶ Customer on-boarding and training
- ▶ Customer order management
  - ▶ Receiving orders
  - ▶ Confirming orders
  - ▶ Processing orders
  - ▶ Conducting Quality Control of the products
  - ▶ Delivering orders
- ▶ Customer Communications regarding any issues within the framework of the current contract
- ▶ Customer Satisfaction Surveys
- ▶ Improvement of the overall customer experience

5.1.1 WORKING HOURS
The Customer Operations and Satellite Planning team is available 24 hours per day to answer any collection planning queries or to help you find solutions to technical problems.

5.1.2 CONTACT INFORMATION
The customer can reach out to the Customer Operations and Satellite Planning team via email customer@iceye.com.

6. ORDERING ICEYE PRODUCTS

▶ ORDERING ICEYE

PRODUCTS

ICEYE offers timely and reliable global SAR imaging. This section describes the tasking process for new ICEYE collections and how to order archived imagery from ICEYE's catalog.

6.1 ICEYE TASKING

To make things easier for customers we have a simple tasking process for new images based on standard imaging configurations and simple time windows (**Standard Orders**). This provides the quickest and simplest way to order SAR imagery. More sophisticated requests can be placed using a **Custom Order**.

6.1.1 STANDARD ORDERS

ICEYE Tasking Standard Orders are based on the concept of **acquisition time windows**. When placing an order, the customer specifies a list of timing requirements that define one or more time windows in which the desired images should be acquired. This allows ICEYE to confirm that the images will be acquired during the specified time windows, **without** the need for the customer to review a preliminary feasibility study with exact acquisition times.
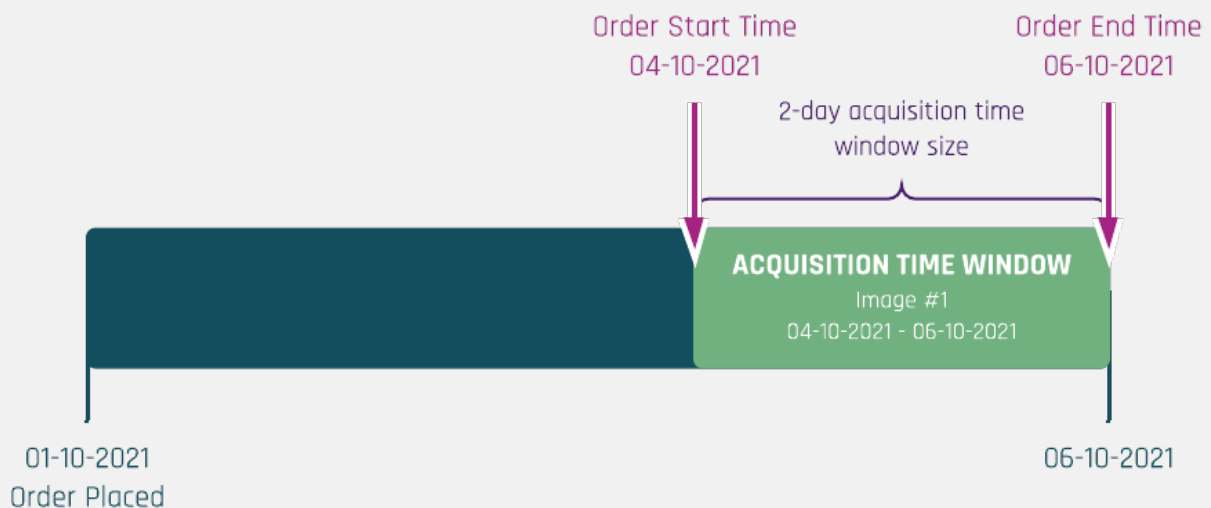

Figure 6.1: Example of a single image order with an acquisition time window of 2 days. This order specifies that the image should be collected anytime between 4-October-2021 00:00 and 6-October-2021 00:00.
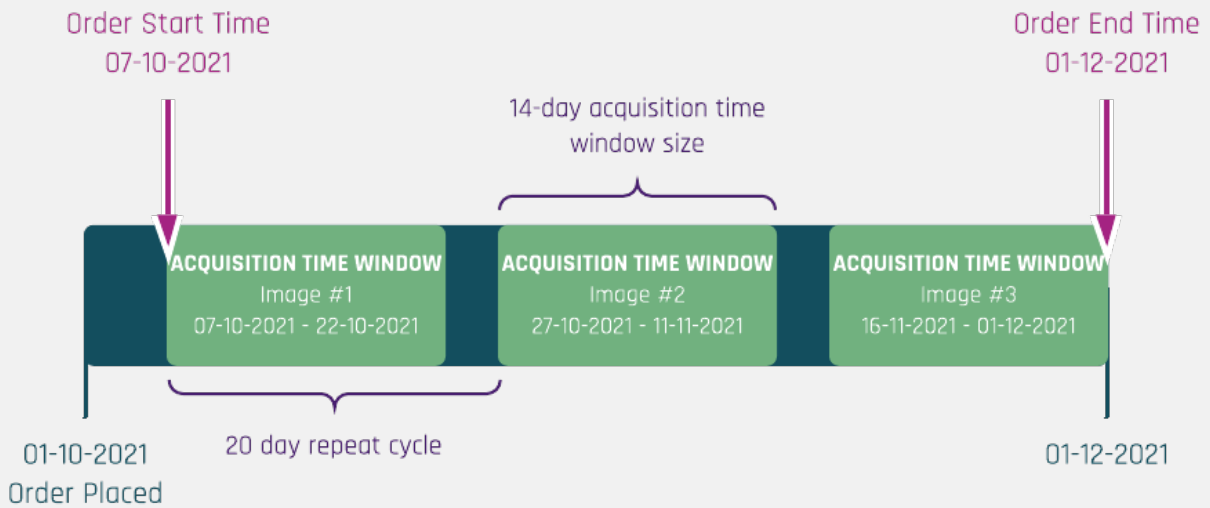
Figure 6.2: Example of an order for a stack of images with a repeat cycle of 20 days and an acquisition time window for each image of 14 days.

[6]The order form will be provided by COSP. If you need a new one please email customer@iceye.com

Standard orders are submitted via email. To order, please fill out the Standard Order Form[6] with your contact information, and be sure to specify all the required tasking options described in the paragraphs below. Once completed, please send your Standard Order Form and the optional AOI file to the email address customer@iceye.com.

Figure 6.3: Standard ICEYE Tasking order flow.

The named recipients for that order will be notified via email once the order is received by the ICEYE Customer Operations and Satellite Planning (COSP) team.

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Once received, your order will be ingested into the ICEYE's planning system which will determine if the order can be confirmed within the AOI, and time windows that you have requested for the AOI. If the order can be fulfilled, you will be notified via email that your order has been accepted and the images will be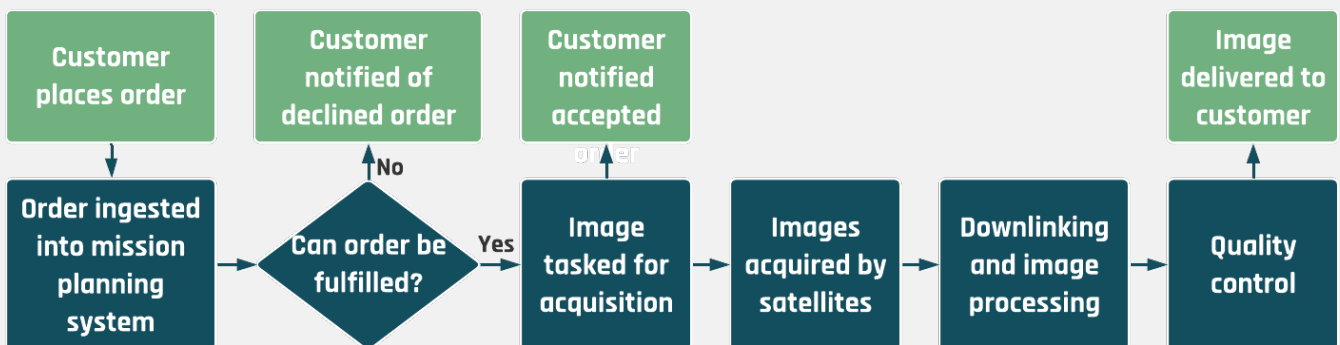 scheduled for acquisition. If the order cannot be fulfilled in time, you will be notified via email that your order cannot be completed.

Please note that **standard** orders require no final confirmation from you. If your order is accepted, the images will be acquired and delivered to you.

After an order is confirmed, ICEYE will make sure that your images are acquired, downlinked, processed, quality controlled and delivered to you. The exact acquisition times are determined by the acquisition time window size that you chose when placing your order.

How to fill in a standard order form
When placing a Standard Order you will need to specify and/or select from the following options available in the Imagery Order Form[6]:

1. AOI: The Area of Interest in the form of a latitude/longitude pair in the WGS 84 coordinate system. Alternatively, you can include a KML/KMZ, or geojson file as an attachment to your order.

2. Timing information:
    ▶ **Start and End time for the order:** This is the time range in which the order is valid.
    ▶ **Acquisition time windows size:** Choose a time window size according to the precision that you require for each of the images that should be acquired.
        ▶ **Basic:** Each image is acquired within a 14-day time window from your specified order start time and repeat cycle. This time window size is ideal for non-time-critical monitoring applications that do not require precise acquisition times.

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> ▶ **Pro:** Each image is acquired within a 2-day time window from your specified order start time and repeat cycle. This is our base level service, commonly used in applications that do not depend on exact acquisition times or geometries.
>
> ▶ **Exact:** Each image is acquired within a 2-hour time window from your specified order start time and repeat cycle. This is our premium service, tailored for time-critical collections that do not depend on the customer requiring a precise imaging geometry. Note that for Exact time window size, you can optionally include an attachment with your desired exact acquisition times. This attachment can be the result of a feasibility study that you had previously requested or it can be generated directly by you using our published satellite ephemerides. Please see the section Optional Feasibility Studies below.
>
> ▶ **Repeat cycle:** This is the time between the start of consecutive acquisition time windows. This information is only required for orders of image stacks (repeat acquisitions).

3. **Acquisition type:** Select whether you want a ...
   ▶ Single acquisition of the specified AOI
   ▶ Stack of images of the same AOI over a time period

4. **Imaging Mode:** Refer to Section 3.2 for more information on these imaging modes
   ▶ Strip
   ▶ Spot
   ▶ Scan

Feasibility Study as Part of a Standard Order

At any time, when considering placing an ICEYE Tasking standard order you can request a feasibility study by emailing customer@iceye.com. You will need to provide an AOI, an imaging mode (or resolution), a time period and any possible additional instructions that you may require. The ICEYE Customer Operations and Satellite Planning Team will respond with a list of acquisition opportunities. Please note that **Feasibility Studies** are for informational purposes and do not reserve constellation capacity for the opportunities reported. The required constellation capacity to fulfill an order

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under the agreed time window size is only reserved after ICEYE confirms an **order**. Please also note that feasibility studies are **not required** to place a standard order. You can eliminate the need for a feasibility study by accurately describing the time windows and other acquisition constraints that match your actual needs as part of your standard order.
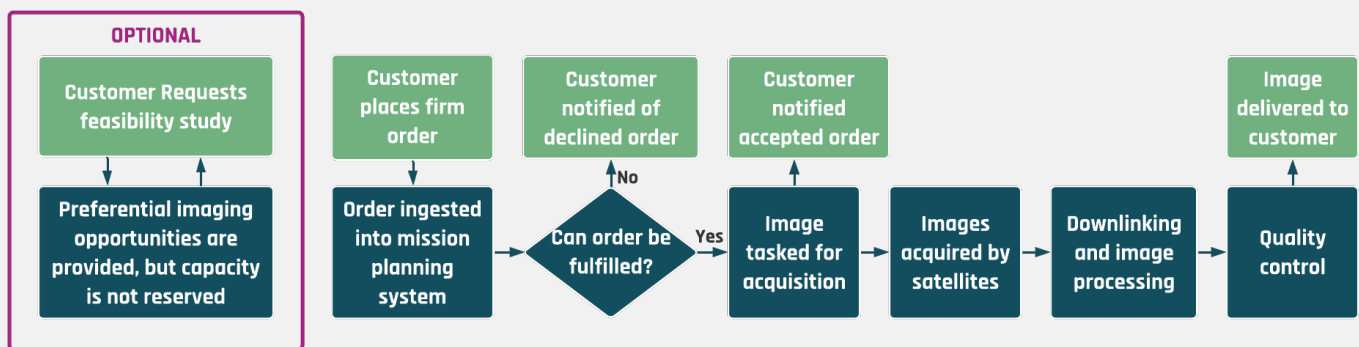
Figure 6.4: Feasibility studies can be requested before placing a standard order.

Sometimes you might like to perform your own feasibility studies and we encourage this. We have made sure our satellite ephemeris information is publicly available at celestrak [1] and n2yo.com [2], and have provided step by step instructions on how to use the Swath Acquisition Viewer Software, SaVoir on the ICEYE website . Let us know how well this works for you.

6.1.2 CUSTOM ORDERS

Custom Tasking orders offer a higher level of flexibility when specifying tasking requirements you desire. In general, any options that are not available as part of standard order can be requested as part of a custom order. Custom orders are initiated by submitting a Custom Order Form via email to customer@iceye.com. Our tasking experts will study the feasibility of your request and will quote an acquisition plan for you to approve.

The following are examples of options that are currently available as part of a custom order:

▶ **Mosaics:** Coverage of large areas by acquiring multiple images

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▶ **Custom AOI coverage requirements:** Each acquired image must cover at least a minimum percentage of the area of interest.

▶ **Local time deviation limits:** Images belonging to a stack or mosaic collection should be acquired within a certain local time range.

▶ **Long image size requirements:** Images that exceed the standard frame size of the requested imaging mode to cover the desired AOI. For example, long Strip acquisitions.

▶ **Azimuth angle deviation limits for stacks or mosaics:** Images belonging to a stack or mosaic collection should be acquired within a certain azimuth angle range.

▶ **Custom acquisition time windows not available as standard tasking options:** For example 72-hour, or 96-hour time windows for each acquisition.

Our tasking experts will be happy to try to accommodate any special tasking request that is required to meet your business needs.

Customer sends request → Request is turned into a customer order → Order details sent to customer for approval → Customer approves order → Image tasked for acquisition → Images acquired by satellites → Downlinking and image processing → Quality control → Image delivered to customer
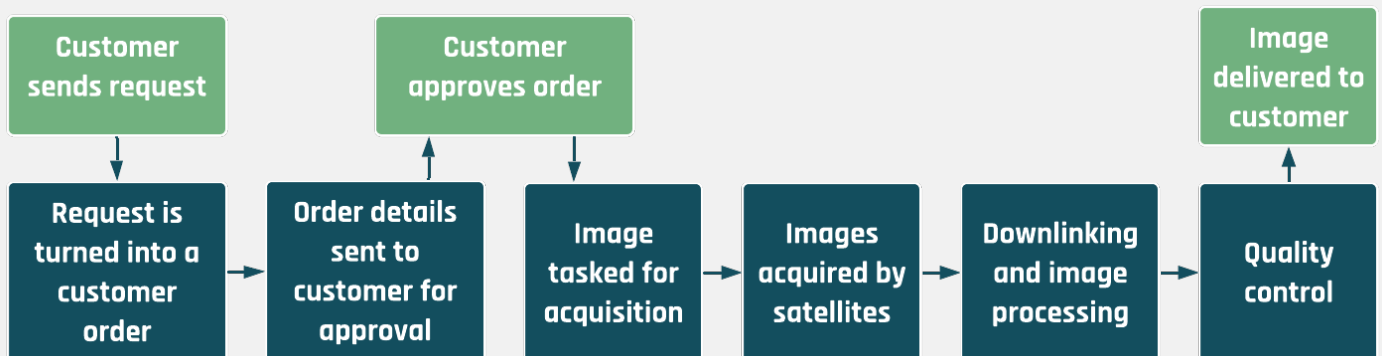
Figure 6.5: Custom ICEYE Tasking order flow.

6.2 QUALITY CONTROL AND IMAGE DELIVERY

The processed data will be assessed during the Quality Control process. An ICEYE image analyst will verify that the frame contains the customer's target location, that it complies to the product specifications and that it does not contain any disqualifying ambiguities.

The standard orders are delivered to customers via a SFTP server, within 12 hours after the data is acquired. ICEYE offers faster delivery times for customers that require near-realtime data. New customers receive instructions from the Customer Operations and Satellite Planning team on how to access your SFTP account. Through the SFTP server, you will have access to download all of your frames. You will receive a notification (via email) every time a new frame has been added to your SFTP account and is ready for you to download[7].

[7]Images are stored in your SFTP account for a period of 30 days

6.3 UNFORESEEN CIRCUMSTANCES

In very rare situations, it might not be possible to acquire an image within the agreed time window. In this case, the Customer Operations and Satellite Planning team will immediately inform the customer and will propose an extended acquisition time window size or allow the customer to cancel the collection.

6.4 ICEYE ARCHIVE IMAGERY

As an ICEYE customer, you have access to a complete catalog of archive imagery that is available for ordering. This catalog is updated on a regular basis on your SFTP account. The catalog is available in kmz and geojson formats and it includes low resolution image thumbnails so you can get a feel for the content of the image. The archive catalog can be viewed in Google Earth, QGIS or your favorite GIS where you can browse image locations, filter by time or different image metadata and perform advanced searches. Please note that imagery is included in the ICEYE Archive Catalog at least seven days after its acquisition time.

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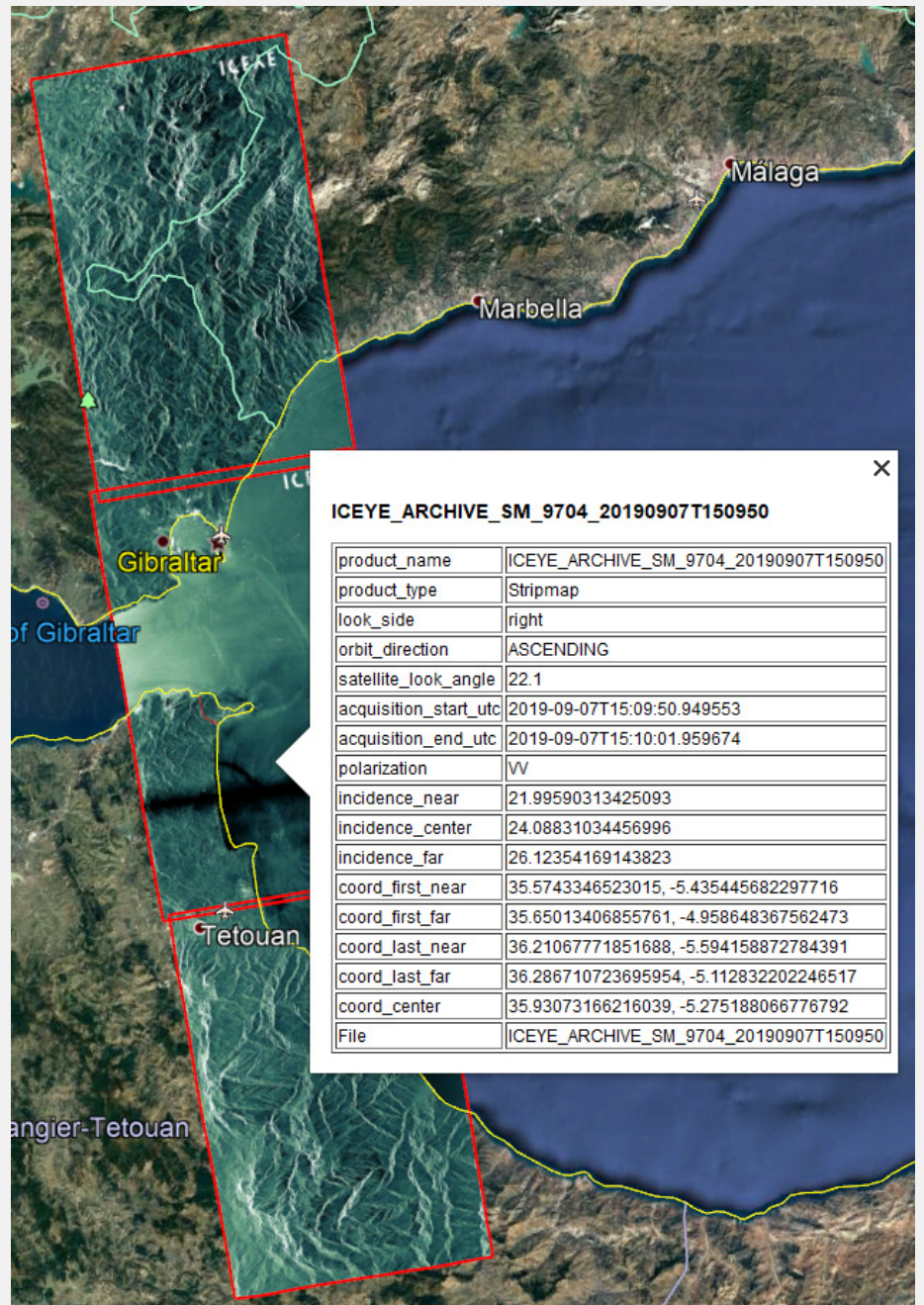
Figure 6.6: Browsing the ICEYE Archive catalog in Google Earth (kmz format).

▶ O R D E R I N G   I C E Y E

   P R O D U C T S

Archive imagery orders can be submitted via email. To place an order, please fill out either the Standard Order Form or the Custom Order Form with your contact information, and include a list of the product names for the scenes that you wish to purchase. An example of a product name that identifies an image scene is:

ICEYE_ARCHIVE_SM_10306_20190918T125047

Figure 6.7: Browsing the ICEYE Archive catalog in QGIS (geojson format).

Once an order is received, the ICEYE Customer Success team will deliver the requested images to you within 12 hours. Please note that all orders for archive imagery require no final confirmation from you. The images that you request in your order will be delivered to you.

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   PRODUCTS
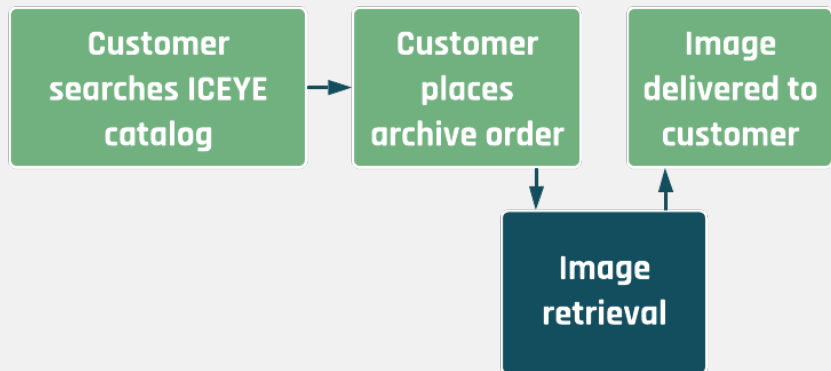
Figure 6.8: Archive imagery order flow.

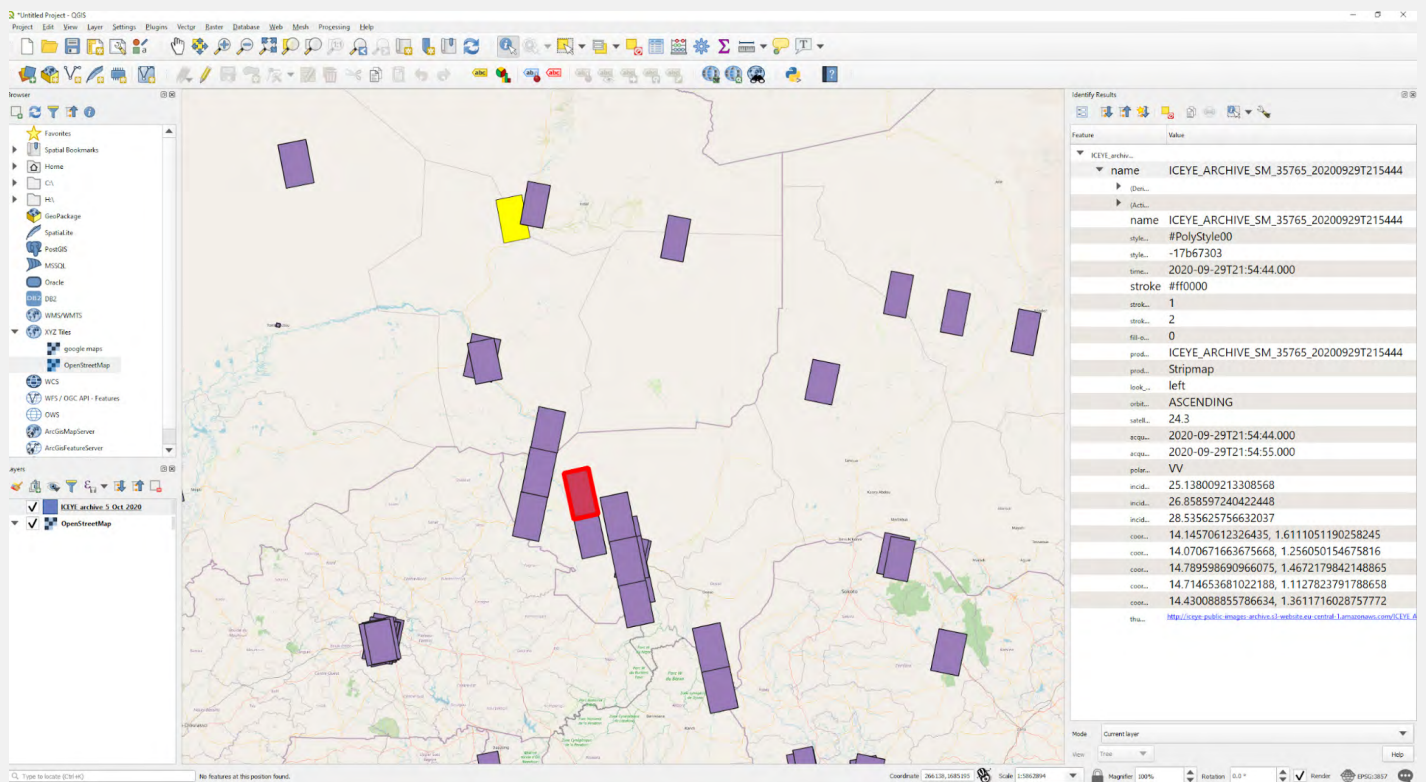Please note that orders for archive imagery do not go through additional quality control. However, if you are not satisfied with the quality of an archive image that you have received, you can make use of our return policy described below.

6.5 ORDER CANCELLATION

In order to support your evolving business requirements, ICEYE supports a user-friendly order cancellation policy.

6.5.1 CANCELLATION OF TASKING ORDERS

Standard Tasking orders confirmed by ICEYE can be cancelled free of charge up to 72 hours prior to the start of the acquisition time window.

Custom Tasking orders may be cancelled or rescheduled within twenty four (24) hours after order confirmation at no cost, as long as the order is submitted at least 27 hours before the proposed data collection time.

Cancellation policy conditions are presented in the table below.

CANCELLATION REQUEST TIME	ADDITIONAL CONDITION	CANCELLATION CHARGE
Within 24h of order confirmation of a Customer Order	Order Submitted >72h before the acquisition time window	Free of charge
More than 72h prior to the start of the acquisition time window	N/A	Free of charge
72-48h prior to the start of the acquisition time window	N/A	10% of the image value
48-24h prior to the start of the acquisition time window	N/A	20% of the image value
Less than 24h prior to the start of the acquisition time window	Order submitted >24h before the start of the acquisition time window	100% of the image value

Table 6.9: Cancellation Requests.

6.6 RETURN POLICY

If you are not satisfied with your purchase, please contact our Customer Operations and Satellite Planning team at customer@iceye.com within 30 days of receiving your order. Your satisfaction is our priority, so we will work quickly to resolve your concerns.

6.7 INVOICING

ICEYE users can pay for imaging in a range of different ways in order to be as flexible as possible:

- ▶ **Prepayment:** In this option a number of images can be paid for up-front. When the prepayment has been paid, you can place orders and receive the amount of data up to your prepaid quota. This is designed for customers that know that they would like to purchase a number of images and offers imagery at a reduced rate.
- ▶ **Net 30:** This is designed for larger or industrial customers wishing to purchase imagery in volume. In this case we will discuss your needs and enter into a contract with you. Images can then be tasked as and when you see fit and we will invoice you monthly. Payment then has to be made within 30 days of sending you the invoice.

ICEYE Finance will send invoices during the first week of the month for all the products delivered to the Customer within the previous month. The monthly invoice will not include the products that have been ordered but have not yet been delivered to the Customer. If no products have been shipped to the Customer during the previous month, invoice will not be extended.

APPENDICES

A. AN OVERVIEW OF SAR IMAGING[8]

A.1 THE VALUE OF SAR IMAGING

Synthetic aperture radar is well known as the imaging technique that can see through clouds and darkness. But SAR provides a number of other capabilities that are simply not available from optical sources. These include:

▶ **High Resolution Independent of Distance:** One of the outstanding characteristics of SAR is that it is capable of detailed resolution regardless of how far away the sensor is from the ground. SAR sensors can provide very high resolution, even from space.

▶ **Variable Resolution and Coverage:** SAR illumination is controlled electronically, and it can be manipulated to vary resolution and coverage. Images can be collected over small areas at fine resolution, over medium-sized areas at medium resolution or over large areas at coarse resolution.

▶ **Precision Geolocation:** SAR measurements are inherently precise. Properly calibrated images can have geolocation accuracy less than the scale of a single pixel for well-defined features.

▶ **Coherent Illumination and Many Products:** The controlled nature of SAR imaging enables the formation of images and many other products. These include sub-aperture image stacks that highlight glinting features and motion, dense elevation models, precise measurements of surface motion, and amplitude and coherent change detection pairs or series.

A.2 RADAR BANDS

There are several radar bands ranging from wavelengths at the millimeter level to a full meter A.1. X-Band has the best combination of cloud-penetration and resolution for space¬borne sensors.

▶ AN OVERVIEW

OF SAR

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In addition to atmospheric gases, there are larger atmospheric particles that scatter visible light but which are transparent to microwaves. In addition to penetrating clouds, X-band radar waves travel through smog, volcanic ash, and sandstorms.

BAND	WAVELENGTH	FREQUENCY [GHZ]	ORIGIN
RADAR BANDS			
UHF	30 to 100	1 to 0.3	Ultra High Frequency
P	60 to 120	0.5 to 0.25	For "previous", as the British used the band for the earliest radars, but later switched to higher frequencies
L	15 to 30	2 to 1	For "long wave"
S	7.5 to 15	4 to 2	For "short wave", not to be confused with the radio band
C	3.75 to 7.5	8 to 4	Originally for "compromise" between S & X band
X	2.5 to 3.75	12 to 8	Used in WWII for fire control, X for cross, as in crosshair
Ku	1.67 to 2.5	18 to 12	For "kurz-under"
K	1.11 to 1.67	27 to 18	German "kurz" means short, another reference to short wavelengths
Ka	0.75 to 1.11	40 to 27	For "kurz-above"
V	0.4 to 0.75	75 to 40	For "very" high frequency - not to be confused with VHF
W	0.27 to 0.4	110 to 75	W follows V in the alphabet
mm	0.1 to 0.27	300 to 110	Milimeter wave

Table A.1: Radar Bands.

A.3 A SIMPLE FORM OF RADAR IMAGING

▶ AN OVERVIEW
 OF SAR
 IMAGING8

As seen in Figure A.1 the radar antenna emits a series of pulses toward the ground where they are scattered in many directions. The sensor records the "backscatter", which is the portion reflected toward the antenna. It measures the strength of the echo and the time it took for the pulse to travel to the ground and back.
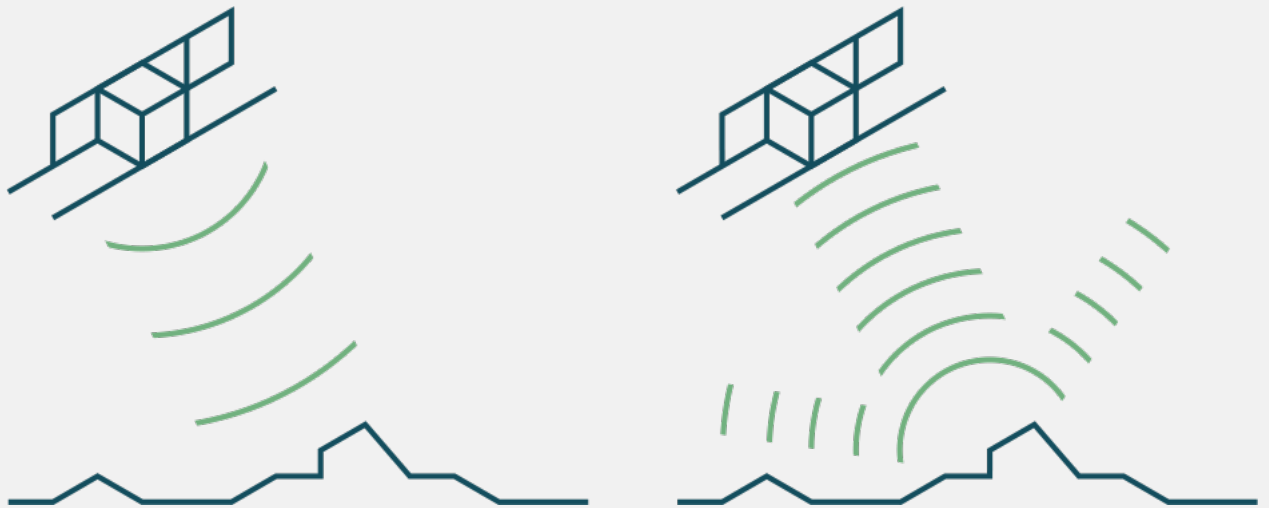
Figure A.1: Pulse Transmission and Backscatter.

Signal strength corresponds to pixel brightness and the timing provides range information. The range is one-half the total travel time. In the equation below, ΔT is the travel time and c is the speed of light:

$$\text{Range} = \frac{\Delta Tc}{2}$$

A.3.1 SIDE-LOOKING ILLUMINATION

Since the pixels of a radar imaging system are placed on the image based partly on their range, the antenna cannot illuminate the ground in a vertical orientation. If it did, features on the same imaging line at equivalent angles off nadir would have identical ranges, like the two purple diamonds in Figure A.2, and they would occupy the same pixel location.

▶ AN OVERVIEW
  OF SAR
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Figure A.2: Vertical Illumination.

Radar imaging must be side-looking so that ground points from the near to far range have different range values (Figure A.3). The illumination is typically broadside, or perpendicular, to the flight direction.
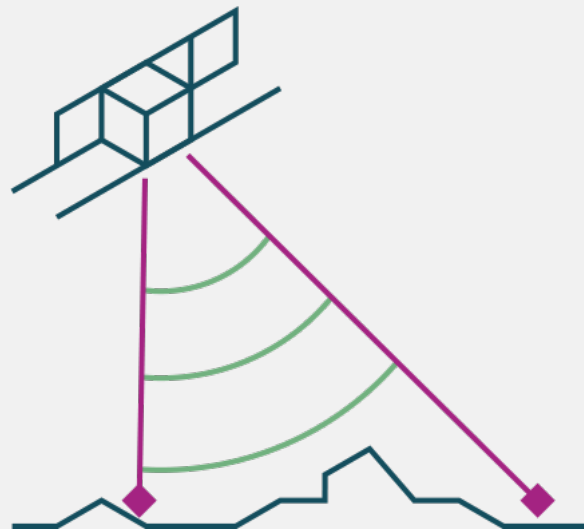
Figure A.3: Side-Looking Illumination.

A.3.2 RADAR ANGLES

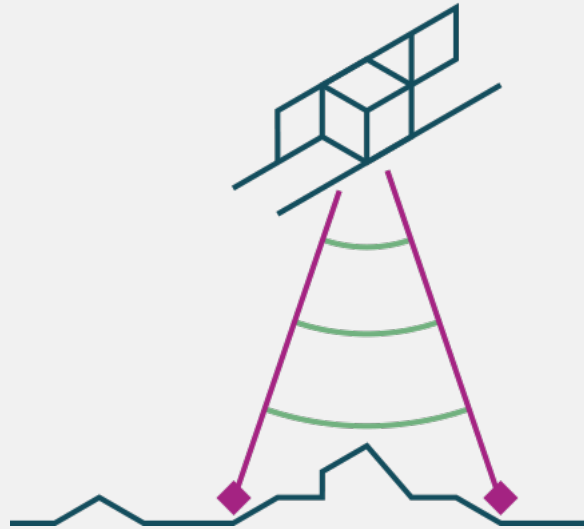The angles associated with radar illumination are shown in Figure A.4, which is based on a spherical earth surface. Most radar imaging is broadside to the flight direction, but some systems can collect off-broadside in a squinted orientation. The angle down from the local level at the sensor is called the depression angle. The angle between the line-of-sight ray and the local vertical is the incidence angle. The angle between the tangent to the surface and the line of sight is the grazing angle. Note that the incidence and grazing angles are complements in that they form a right angle when combined. This means that a 60° incidence angle is the same as a 30° grazing angle.
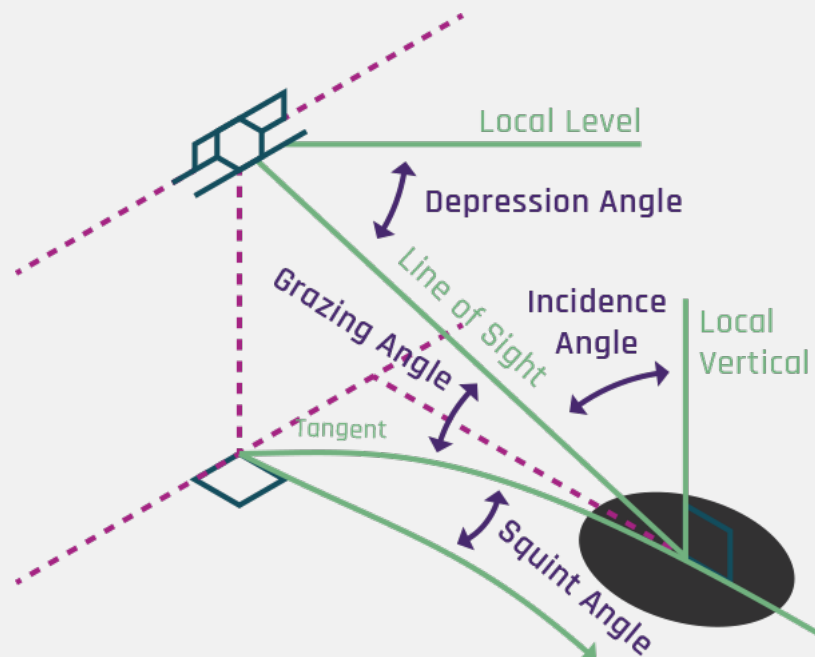
Figure A.4: Radar Imaging Angles.

A.3.3 SIDE LOOKING AIRBORNE RADAR

The first useful radar imaging technique was a form called Side-Looking Airborne Radar (SLAR) (Figure A.5). The image is built up via the forward motion of the antenna, one line at a time. The pulses are emitted at a rate called the pulse repetition frequency (PRF), which can range from a few hundred pulses each second for airborne systems to thousands each second for spacecraft. In the SLAR technique, the individual pulses create each image line.

The angular width of the pulse on the ground along the direction of flight, or azimuth direction, determines one component of resolution. The range measurements are collected in the "slant range" direction, and range variations to different objects form the second dimension of resolution.
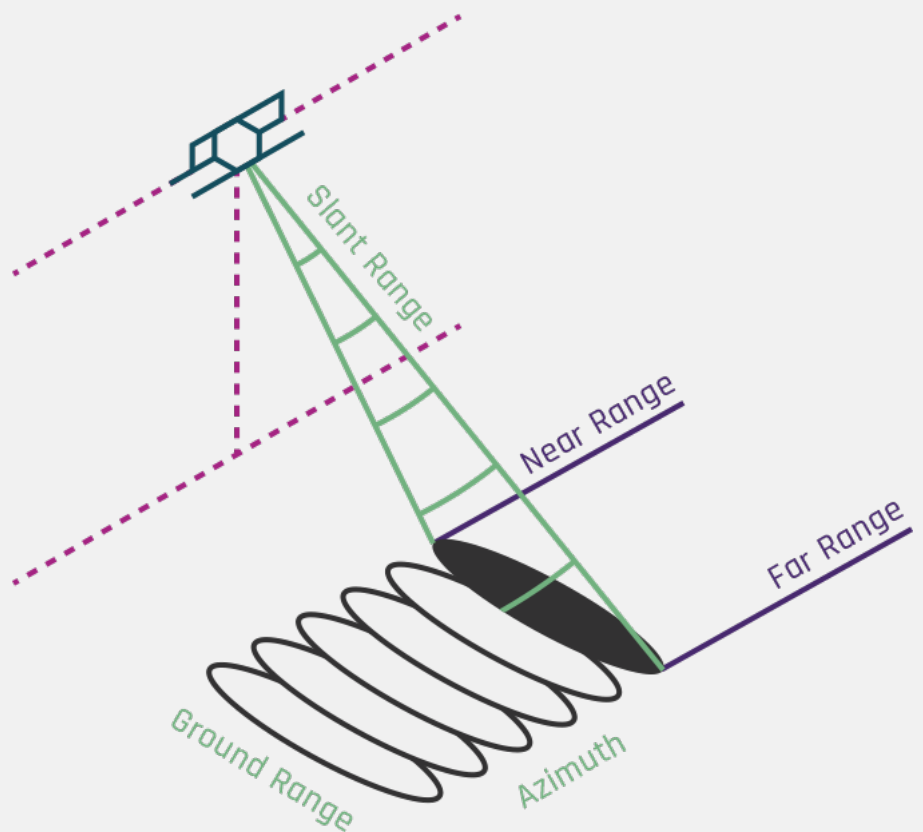
A.5 Side-Looking Airborne Radar

SLAR was used the early days of radar imaging but it had serious limitations. Range resolution was one-half the length of the pulse in the range direction. Since the pulses are emitted at light speed, even a very brief pulse of one-millionth of a second would be 300 meters long and produce range resolution of 150 meters (Figure A.6).

Azimuth resolution was based on the angular width of the pulse in the azimuth direction (β). Long antennas create narrow beams, but the beam spreads out from the antenna to the distant ground surface. Antennas cannot be made long enough to produce good azimuth resolution, and SLAR produced images with resolutions in the hundreds of meters, even from aircraft. This is

why the brilliant concept of synthesizing a long antenna from the actions of a small one was developed. We call this Synthetic Aperture Radar.
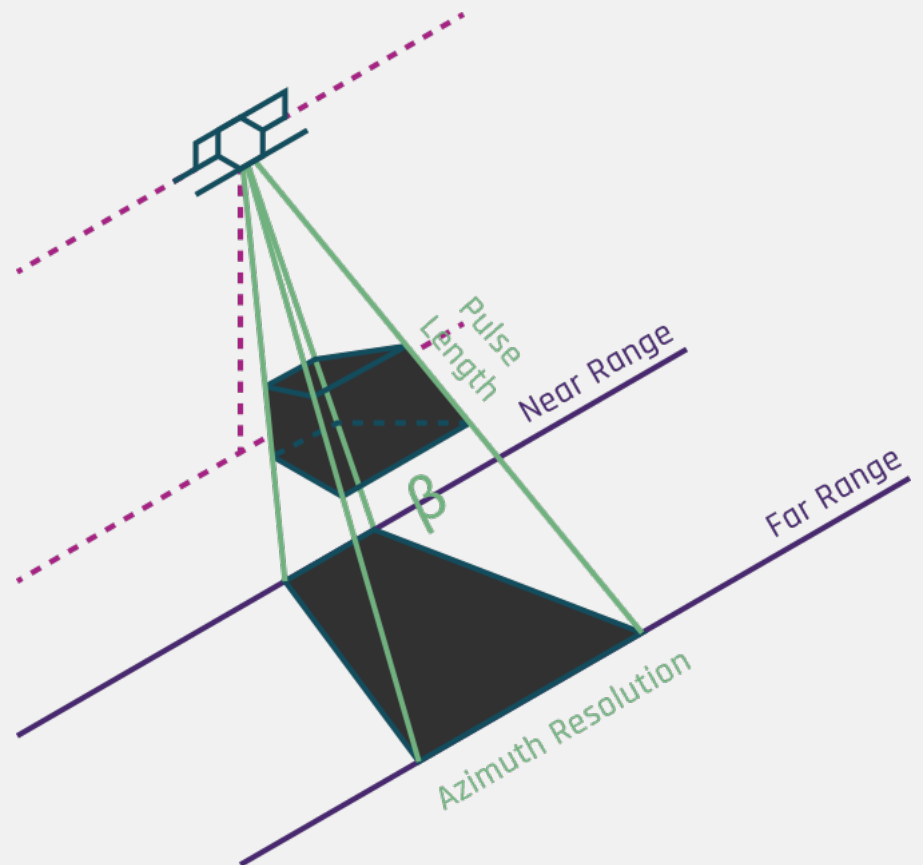
Figure A.6 SLAR Pulse Dimensions.

▶ AN OVERVIEW

OF SAR

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A.4 THE REMARKABLE STORY OF SYNTHETIC APERTURE RADAR

A.4.1 IMPROVING AZIMUTH RESOLUTION BY SYNTHESIZING A LONG ANTENNA

It takes a long antenna to create narrow radar beams, but the aperture itself does not have to be a giant physical antenna. Instead, a "synthetic" aperture can be created from a small antenna and a linear extent of recording locations. Figure A.7 shows a radar antenna sequentially emitting a series of pulses, like a microwave strobe light, and recording the echoes from a string of receive positions.

Figure A.7: Linear Extent of Recording Locations.

In the SAR technique all of the measurements are stored and later processed together. It is as if they were collected from one long antenna equal in length to the extent of the sensor locations that received the echoes. Synthetic Aperture Radar is a post-processing scheme applied to data collected by a standard radar antenna and receiver.

A.4.2 STRIPMAP AND SPOTLIGHT APERTURES

There are a few methods to illuminate the ground in SAR imaging. These collection modes trade off resolution and coverage in different ways. To establish how we can simulate long apertures we'll contrast the two most common forms of SAR imaging: stripmap and spotlight.

▶ AN OVERVIEW
OF SAR
IMAGING8

In stripmap mode the pulses are sent out at a constant angle, usually broadside to the flight direction. In this case, the length of this simulated aperture (L) is the same as the width of the beam on the ground (Figure A.8). Wider beams produced by smaller antennas mean longer apertures and better azimuth resolution. This directly contrasts with the real-aperture radar of SLAR where the beam was kept as narrow as possible to obtain good resolution.
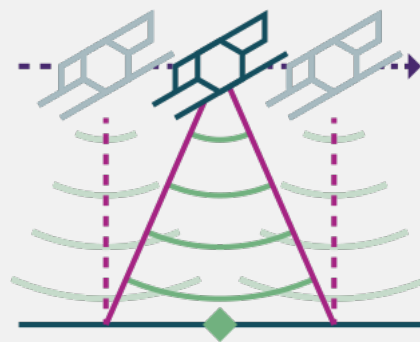
Figure A.8: Stripmap Synthetic Aperture.

The spotlight form of SAR varies the boresight angle in the azimuth direction to illuminate a fixed ground location (Figure A.9). This technique greatly increases the synthetic-aperture length and offers excellent azimuth resolution, at the cost of limited ground coverage. At ICEYE we are capable of illuminating a fixed spot for as long as 30 seconds. Given the velocity of low-earth orbits (7.5 km/sec), this yields a synthetic aperture more than 225 kilometers long!
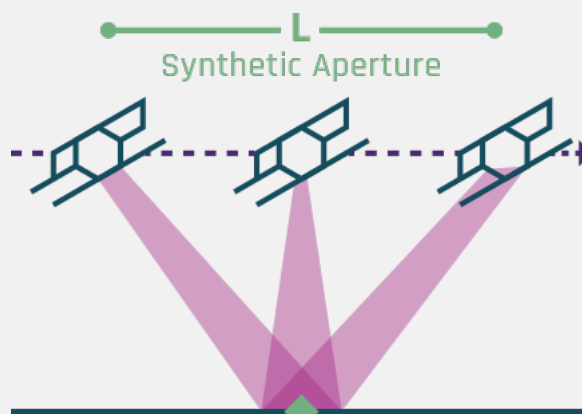
Figure A.9: Spotlight Synthetic Aperture.

A.4.3 PHASE HISTORY DATA AND SAR AZIMUTH RESOLUTION

We can create long "synthetic" apertures because radar illumination is coherent. That is, the sensor controls the structure of the transmitted pulses and they all have the same form. It emits pulses and measures the details of each echo: time, strength and "phase". Phase refers to the position of the wave in its cycle, denoting whether it is at its peak, trough or somewhere in between.

The SAR antenna moves only slightly from pulse to pulse. It turns out that the change in location must be less than one-half the antenna length. But this small change in location causes the successive measurements of the range to some object to change as well. The slight change in position imparts a slight change in range. Since the phase is dependent on the range, the small change in adjacent sensor locations also imparts a slight change in phase. These phase changes form a pattern across the aperture, which changes depending on the azimuth location of a ground feature. The record of all the changing phases for all the scatterers in the scene is called phase history data. For a particular object, this is the "history" of how phase changed from one receive location to the next.

Given carefully measured sensor locations, the phase histories for each location across the scene are predictable. The azimuth position of each scatterer can be calculated by comparing the predicted phase pattern of some location to the measured phase history pattern for that point. This is the essence of azimuth resolution. Phase history data and their reference patterns are compared to discriminate the azimuth position of scatterers in the scene.

Now that we have that huge aperture and the equation for azimuth resolution becomes:

$$\delta az = \frac{\lambda}{2\Delta\theta}$$

where δaz is the SAR azimuth resolution.

This equation is gorgeous. It says that azimuth resolution is based on the wavelength of our radar waves and the change in the integration angle ($\Delta\theta$) while the point was being imaged (Figure A.10). Resolution improves when the wavelength is small and the integration angle change is large.

▶ AN OVERVIEW
   OF SAR
   IMAGING 8
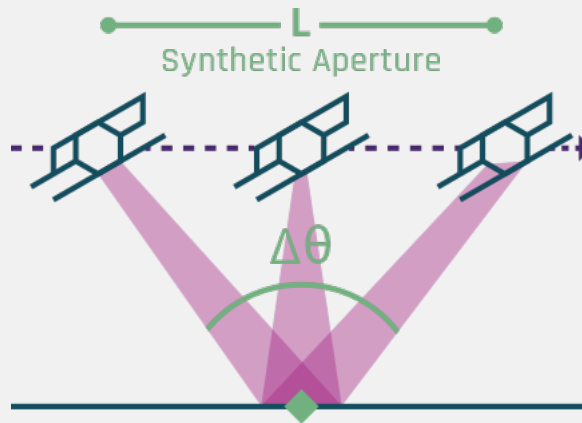
Figure A.10: Spotlight Synthetic Aperture Angle.

Now let's use SAR with an integration angle change of 0.07 radians (4.5°). This is reasonable because the current operational performance of ICEYE's spotlight mode can easily exceed this angle.

$$\delta az = \frac{\lambda}{2\Delta\theta}$$

$$\delta az = \frac{3cm}{2 \times 0.07}$$

$$\delta az = 0.21m$$

For stripmap mode the azimuth resolution equation reduces to a simpler form, where D_A is the length of the antenna in the azimuth direction:

$$\delta az = \frac{D_A}{2}$$

This is just a special stripmap case of the more general equation, but it seems to imply that we could make the antenna really small to achieve good stripmap resolution. While this is literally true, the small size of the antenna would lessen the total power that could be transmitted and also degrade the ability to record the weak backscattered echoes. Noise would increase significantly. It would also require the PRF to get unreasonably large because a pulse is required at least every one-half antenna length.

Stripmap cannot support high-resolution SAR. For that we need to steer the beam during illumination to increase the synthetic aperture, as with a spotlight collection. This mode is capable of fine resolution and it can use a larger, and therefore more powerful and sensitive antenna.

A.4.4 SOMETHING IS MISSING

These elegant equations are an astonishing statement about resolution, but it is even more amazing when we consider what is missing. Notice that the SAR azimuth resolution equations do not include a term for distance. Use it on an aircraft or move it all the way out into space, and azimuth resolution does not change.

Of course, distance does impact signal strength. When the sensor is further away, the signal strength weakens dramatically and this poses serious challenges to the SAR imaging process. We will not discuss this issue in this overview, but we can say here that radar antennas are very sensitive. Spaceborne SARs successfully record very weak backscatters.

A.5 FIXING RANGE RESOLUTION BY SYNTHESIZING A SHORT PULSE

In our discussions about aperture synthesis, we did not say anything about range resolution. This is because the "synthetic aperture" technique itself deals only with azimuth. It does not do anything to address the problem we saw with brute-force range resolution. Recall that this is one-half of the pulse length, which is the speed of light (c) times the pulse duration, T:

$$\delta ra = \frac{cT}{2}$$

where δra is the slant range resolution.

Thus far, we have described our radar pulses as if they have a fixed frequency, like X-band pulses of 10 GHz frequency and a 3 cm wavelength. But most radars actually transmit *chirped* pulses in which the frequency changes (Figure A.11). Notice how the wavelength of the green pulse is manipulated and varies from long to short.

▶ AN OVERVIEW
  OF SAR
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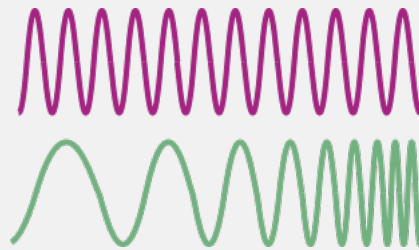
Figure A.11: Chirped Pulse.

When we state the frequency or wavelength of a SAR sensor, those values typically apply at the mid-way time of the pulse. This is known as the radar center frequency or wavelength. The actual transmitted wavelengths are varied quite a bit on either side to form chirped pulses (Figure A.12).
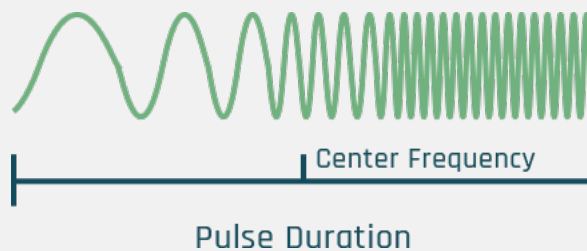
Figure A.12: Centre Frequency.

There are many different pulse modulation techniques, but the chirp with a smoothly varying frequency is most common. A chirped pulse is easy to produce and since the total transmitted energy is a product of amplitude and duration, a long pulse can contain a substantial amount of energy without needing a large peak power.

A chirped pulse enables high range resolution because its form is exactly specified and its echo is a reversed and weakened copy. The reflection has the same shape as the emitted signal, it's just flipped and has a much smaller amplitude. The two are compared in what is called a matched filter process. The known structure of the emitted pulse is compared to the echo at various locations. A calculation is performed, and if they are misaligned the result of this calculation is zero. At the exact location where they match there is a strong signal that indicates the match. A synthetic pulse that is narrow in range replaces the spread-out pulse (Figure A.13).

Compressed Pulse

Figure A.13: Range Compression.

The width of the compressed pulse is based entirely on the bandwidth of the emitted pulse. The slant range resolution equation is transformed:

$$\delta \text{slant range chirp compressed} = \frac{c}{2B}$$

This is a really beautiful equation. It is so simple and powerful. Resolution in range is entirely based on how much bandwidth we impart to chirped pulses, and like its azimuth counterpart it has nothing whatsoever to do with distance to the ground.

A.5.1 SLANT RANGE RESOLUTION EXAMPLES

So how much can we vary pulse frequency? Well, bandwidths can be made really large. Consider an X-band system capable of 300,000,000 cycles per second (300 MHz) of bandwidth. We can calculate resolution in the slant range:

$$\delta ra = \frac{3 \times 10^8 \text{ m/sec}}{2 \times 300 \text{ MHz}}$$

$$\delta ra = \frac{3 \times 10^8 \text{ m/sec}}{2 \times 300 \times 10^8 \text{ Hz}}$$

$$\delta ra = 0.5 \text{ meters}$$

Plans for the next generation of ICEYE satellites include pulse bandwidths of

600 MHz and 1200 MHz. These will yield a slant range resolution cell of 0.25 meters and better from a satellite that is perhaps 750,000 meters away from the imaged area.

A.5.2 GROUND RANGE RESOLUTION

The slant range is the distance between the antenna and the target, and that is the direction where range resolution is measured. To produce images along the ground surface, the pixels have to be projected to the "ground range" from their original slant range orientation (Figure A.14). This has the effect of elongating the pixels in range.
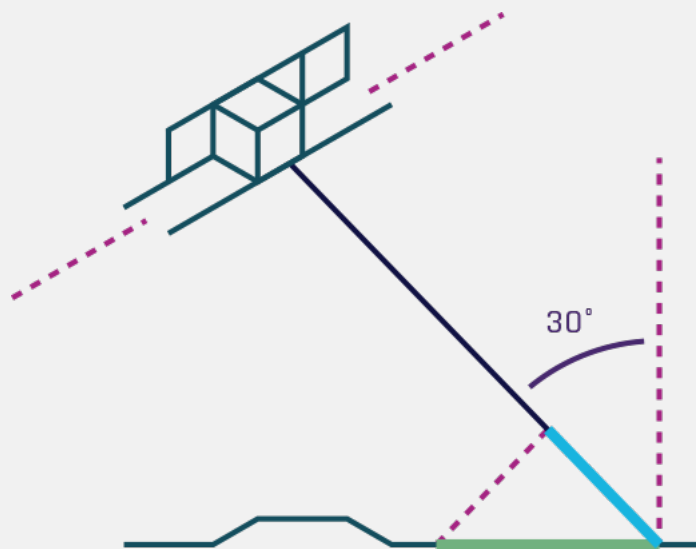
Figure A.14: Ground Range Resolution.

The illustration shows the relationship between slant range resolution, shown in blue, and the length of the equivalent resolution distance along the ground, shown in green. When the illumination is steep, as in this example, the projection to the ground surface results in a much longer ground range cell. You can imagine what would happen as the steepness continued to approach nadir. This is exactly opposite to the situation with optical imaging resolution, which is best at nadir.

Slant range and ground range resolution comparisons for two incidence

angles are shown in Table A.2. Notice the dramatic increase for the steeper illumination.

	INCIDENCE ANGLE 30°	INCIDENCE ANGLE 60°
Slant Range	0.5 m	0.5 m
Ground Range	1 m	0.55 m

Table A.2: Resolution comparison between slant range and ground range.

While slant range resolution seems "better" than ground range resolution, keep in mind that it refers to the sensor's ability to discriminate features along the oblique path of the energy. Most of the features we care about lie along the ground surface, and ground range resolution is a useful way to describe image resolution.

A.6 THE BEAUTIFUL EQUATIONS

The brute force method of real-aperture radar cannot produce high-resolution images. In synthetic-aperture radar we take advantage of the natural coherence of radar illumination to produce structured and consistent pulses. These enable the measurement of slight pulse-to-pulse phase shifts and the use of frequency-modulated chirps. The innovations of aperture synthesis, modulated waveforms and pulse compression produce images capable of a remarkable pixel resolution and which does not degrade as distance to the ground increases.

Even though they are handled differently, the azimuth and range processes have a fundamental similarity:

> *Azimuth resolution is based on phase variations across the collection interval. These are compared to known phase variations across that area to produce a long "synthetic" aperture and a resolution cell narrow in azimuth.*

> *Range resolution is based on frequency variations across the returned pulse. These are compared to known frequency variations in the reference pulse to produce a short "synthetic" pulse and a resolution cell*

narrow in range.

These processes result in two of the most simple and powerful equations in all of remote sensing. They are the equations that describe the spatial resolution of a SAR sensor. They are **The Beautiful Equations**:

$$\delta az = \frac{\lambda}{2\Delta\theta}$$

$$\delta sr = \frac{c}{2B}$$

with δaz and δsr being the azimuth resolution and the slant range resolution respectively.

A.7 THE SAR PROCESSING FLOW AND ITS PRODUCTS

SAR image generation begins with the emission of thousands of coherent pulses and the decomposition of each echo into raw measurements of time, amplitude and phase. The first part of the processing flow is called Phase History Processing because it accounts for the changes over time of the phase values of each scatterer. Phase history data are focused into the azimuth and range components of each resolution cell to produce an image product called a "complex image" (Figure A.15).

▶ AN OVERVIEW
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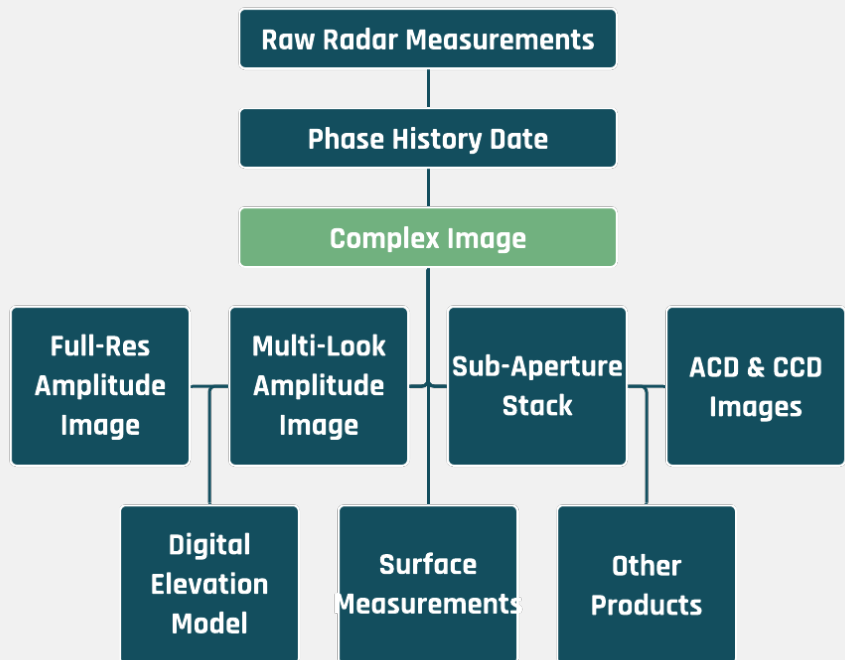
Figure A.15: The SAR Processing Flow and Its Products.

A.7.1 THE COMPLEX IMAGE

The left image in Figure A.16 is a ICEYE amplitude image of agricultural fields. In this image each pixel has a brightness value assigned to it. This is what many people consider to be the base SAR product, but this is really only half of the full image. The SAR processor calculates the average phase value for each pixel as well. The matching "phase image" of that same scene is on the right in the figure. The combination of these two images is called a complex image, in which every pixel has amplitude and phase values[9]. We use the term "complex" because the pixels are described by a mathematical construct called a complex number, where every number has two components.

[9]By the way, you will hear SAR engineers refer to the two parameters of a complex image as "In-Phase" and "Quadrature". These are just another way to describe the complex values.

▶ A N   O V E R V I E W

    O F   S A R

    I M A G I N G 8

Amplitude Pixels   ## Phase Pixels
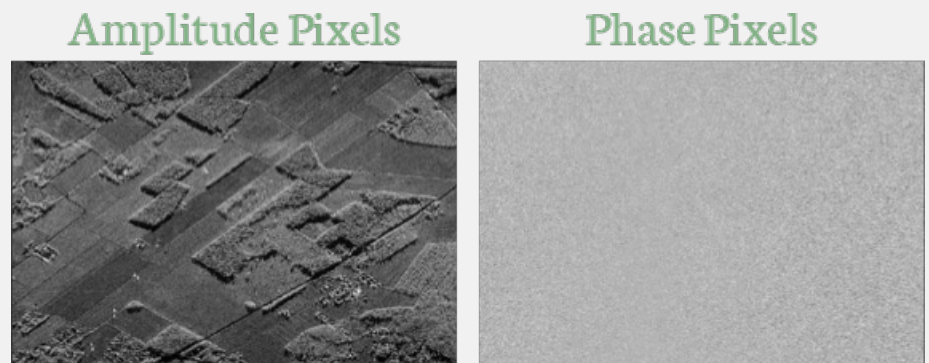
Figure A.16: Amplitude and Phase Structure of a Complex Image.

Of course, phase data are not useful for direct human interpretation. And while they may look like random noise, phase pixels are a unique and valuable aspect of SAR imaging. Phase data can be used to manipulate the synthetic aperture in different ways to extract useful information that is not available from amplitude images. Moreover, changes in the phase measurements of the same object on different images can be used to detect small surface structure characteristics. In the next section we'll discuss how we can use phase data to refine images and create other products.

A.8 SAR PRODUCTS DERIVED FROM COMPLEX DATA

A.8.1 AMPLITUDE IMAGES

An amplitude image is certainly the most common SAR product, but you need to appreciate that this image is produced for human viewing and analysis. It is not the core image product. Amplitude images do not contain any phase information. Furthermore, the version of the amplitude image used for human viewing is not a direct copy of the amplitude values in a complex image. This is because radar sensors record an enormous span of brightness levels for each complex pixel. The maximum intensity of amplitude in a complex image is usually more than 100,000 times (50 dB) the minimum intensity, and for the best-quality images with bright targets, it is much greater. ICEYE images are produced with 16 bits of dynamic range per pixel (65536 gray levels) but even this is not sufficient to record the full dynamic range of SAR.

▶ A N   O V E R V I E W

    O F   S A R

    I M A G I N G 8

[10]You should also be aware that an engineering calculation called "detection" converts in-phase and quadrature values to amplitude values. Engineers often refer to SAR amplitude images as "detected" images.

[11]Speckle is a grainy, noise-like feature of SAR images. It is caused by the coherent nature of SAR illumination. The reflections from small scatterers within a resolution cell combine constructively and destructively to brighten or darken the returns.

As valuable as they are, amplitude images have no phase data and they lose much of the dynamic range of complex pixels[10]. You can imagine the growing potential for computers and algorithms to process those complex pixels in ways the human visual system cannot.

A.8.2 MULTI-LOOK AMPLITUDE IMAGES

One way in which we can use complex data is to produce different versions of the seemingly simple amplitude image. One common form of an amplitude image, for example, is called a multi-look image. Consider that azimuth and range resolution are handled independently. One is based on the length of the synthetic aperture and the other is based on the signal bandwidth, and sometimes these are quite different in magnitude. It is common for azimuth resolution to be collected at a higher fidelity than range resolution. If a full-resolution image were produced from such data it would look compressed in range. To view the image in a more natural aspect we need to "square the pixels" so that the range and azimuth scales are the same. This is done by manipulating the synthetic aperture into smaller sub-apertures and then combining them. The sub-apertures are called "looks" and they each produce an image with lower azimuth resolution. This may sound disappointing, but when these individual sub-aperture images are combined, they form a multi-look image in which the noisy effect of speckle is reduced[11]. Complex images are stored at full-resolution and are called single-look complex (SLC) images. Amplitude images are typically multi-looked in azimuth using two to 12 sub-apertures. If range resolution exceeds azimuth resolution a similar multi-look process can be applied in the range dimension.

A.8.3 SUB-APERTURE STACK OR VIDEO IMAGE

Suppose we take the aperture splitting further and create six or seven segments to produce multiple sub-aperture images. One advantage of this sub-aperture stack is that it can indicate glints that are bright in only a portion of the full aperture. This signature might be washed out on the full-resolution image by the bulk of the aperture in which there was no glinting, but it can be very noticeable in one of the low-resolution sub-apertures. Glints tend to be important signatures because they are usually caused by human-made features. We could even loop the stack like a short movie, or SAR video image, to look for such glints and moving objects. This product works best for long spotlight exposures of ten seconds or more.

A.8.4 AMPLITUDE AND COHERENT CHANGE DETECTION

Perhaps the most useful SAR products are the amplitude and coherent change detection images (ACD, CCD). Two or more images of the same site are collected at different times to detect scene changes. For ACD only the brightness values are compared, while CCD uses phase data.

In order for change detection to work, the images have to be collected from nearly the same location in space with similar illumination geometries. For ACD the two images can be overlaid in the complementary colors (eg red and cyan). In this way, features with similar backscatters will be gray, but features with backscatters that changed during the imaging period will appear in one of the two colors. It is conventional for the first image to be displayed in red and the second in cyan. If something on the ground changes between the two collections you will see whichever color signature is dominant.

A mnemonic is used to help interpret ACD products: "Red is fled. Blue is new". That is, a red signature indicates a feature that was present on the first image but left the scene prior to the second image, and a blue signature indicates a feature that appears only on the second image. This mnemonic is an easy way to help remember the order of the images, but appreciate that the second image is actually cyan, not blue. The intentional sloppiness of the mnemonic is acceptable here because verbal precision would ruin the rhyme.

In contrast to amplitude change detection, CCD compares the phase values of two nearly identical images taken at different times. CCD is far more sensitive to changes because it is based on phase differences rather than pixel brightness differences and, as we know, phase is measured to within a small fraction of a wavelength. The collection constraints to ensure image-to-image coherence are tighter for CCD than ACD.

When the collection parameters are nearly identical, the phase values are also nearly identical, and any changes are due to backscatter differences at a scale of less than one wavelength. It is typical for CCD images to display pixels where phase is consistent in white and the pixels where the phase has changed are dark. These are areas where the two images have "decorrelated", or lost phase consistency, due to some subtle change in the scene.

A.8.5 OTHER MULTI-IMAGE SAR PRODUCTS

The amplitude and phase data of SAR images can be combined to produce other useful products that are too numerous to describe in detail in this overview. These include **digital elevation models** derived from pixel brightness values or phase data, millimeter-level **surface motion measurements** derived phase comparisons of sets of matching images, and **automated detections** of ships, oil spills and other features. Once constellations of small SARs are established it will be possible to monitor any site in the world with large stacks of exactly matching images whose consistent signatures are linked to known ground features. These images could be collected within hours of each other and they will be the basis of **intelligent site monitoring** services that will not only detect changes, but which will also say what has changed and how it has changed.

A.9 SEPARATING SIGNALS FROM NOISE

A.9.1 THE WHISPER

As a radar pulse travels from the antenna to the ground surface its total power remains constant, but as it moves away from the antenna, it spreads out into space and its power density weakens. As shown in Figure A.17, it is as if the "skin" of the pulse becomes thinner with distance. This weakening is dramatic; it decreases with the square of the distance from the antenna.
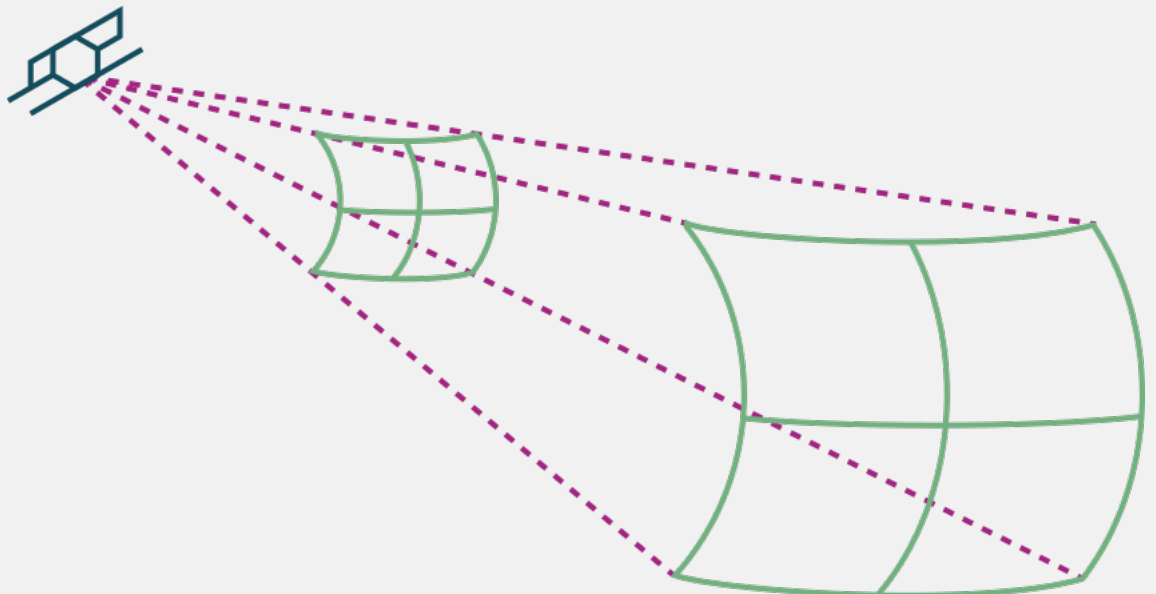

Figure A.17: Expanding Surface Area of a Pulse.

▶ AN OVERVIEW
OF SAR
IMAGING8

Given that the ground might be 750 km from the antenna, the pulse is quite weak by the time it finally reflects from surface objects. This presents even more of a problem because only a portion of the weakened pulse is reflected toward the receive antenna, and then it has to travel all the way back, weakening again with the square of the distance. By the time the microwaves return to the antenna, they are microscopically faint. The antenna and radar receiver manage to detect, amplify, and record these echoes so that they can be processed into SAR resolution cells that span more than 100,000 brightness values. SAR is amazing.

A.9.2 THE CHALLENGE OF NOISE

Those backscattered microwaves are so weak when they arrive at the antenna that they are perturbed by any noise sources that get mixed in with them. Noise is an artifact of random microwave emissions caused mostly by onboard sensor hardware. One of the tenets of remote sensing is that all objects emit electromagnetic energy based on their temperature. The thermal noise of heated receiver hardware spans wide swaths of the spectrum, including the microwave bands, and this competes with those whispering pulse echoes.

As they struggle to capture those fading backscatter whispers, radar receivers also record random, interfering microwaves that they themselves produce. One of the disappointing aspects of the noise level is that it increases as range bandwidth increases. The large signal bandwidth that the receiver has to be capable of recording also lets more noise enter the receiver.

One of the ways that noise is quantified for SAR sensors is called the Noise Equivalent Sigma Zero (NESZ). This parameter describes the noise floor of an image. All received signals have to be stronger than the NESZ value to rise above the noise level, so it is best for NESZ to be as low as possible. Images with high NESZ values look grainy.

Unfortunately, NESZ is mystifying to SAR users who are not familiar with the dB language of engineering. Many users are confused by NESZ values like -20 dB, which actually indicates a fractional level of 1%. That is, an NESZ of -20 dB means the noise level is 1% as strong as a reference reflection from an idealized metal sphere. An NESZ of -17 dB would means the noise level is 2% as strong as the reference.

▶ AN OVERVIEW
OF SAR
IMAGING8

System designers have to consider many competing imaging parameters to balance image quality, resolution and noise. For spacecraft, the best choices are increased average power, larger antennas, the use of high-quality receivers with low noise factors, steeper illumination angles, and lower orbits.

A.10 THE ICEYE INNOVATION

In this overview of SAR, we have discussed several remarkable capabilities beyond its famous ability to penetrate clouds. These include image resolution independent of distance, electronic beam control to vary resolution and coverage, pristine geolocation, and the natural ability to measure phase to within a small fraction of a wavelength. We've seen that SAR pixels have both amplitude and phase, and from these we can produce many useful products.
At ICEYE, we have developed an innovative way to incorporate all of these aspects of SAR in our small and adaptable systems. We are launching a full constellation of small SARs, and we'll upgrade them routinely to better image this ocean planet.

B. IMAGING MODE CHARACTERISTICS

▶ IMAGING MODE

CHARACTERISTICS

The following provides additional technical information on the performance of the current imaging modes used by the ICEYE fleet. Our satellites are constantly being improved with recent satellites usually having better performance. In order to manage expectations we have decided to provide the *worst case* values across the fleet. Some parameters warrant a more detailed explanation which you can read in the Notes (section B).

PARAMETERS	STRIP	SPOT	SCAN	COMMENTS
IMAGING MODES OVERVIEW				
Product Short Name	SM	SLH	SC	Note 1
Radar Beams Used	1	1	4	Note 2
Nominal Swath Width	30 km	5 km	100 km	Note 3
Nominal Product Length (Azimuth Direction)	50 km	5 km	100 km	Note 4
Nominal Collection Duration	10 s	10 s	15 s	
Maximum Collection Duration	35-72 s	N/A	15 s	Note 5
Maximum Scene Length	240-500 km	5 km	100 km	Note 5
Noise Equivalent Sigma-Zero	-21.5 to -20 dBm^2/m^2	-18 to -15 dBm^2/m^2	-22.2 to -21.5 dBm^2/m^2	Note 6
Azimuth Ambiguity Ratio	-15 dB	-15 dB	-15 dB	
Range Ambiguity Ratio	-20 dB	-20 dB	-20 dB	
Geospatial Accuracy (CEP90)	9 m	9 m	15 m	
ESA Copernicus Contributing Mission (CCM) Class	VHR2	VHR1	HR1	See [7]
Polarization	VV	VV	VV	
RNIIRS	3.6	5.5	2.1	Note 8
RGIQE	0.8 bits/m^2	22 bits/m^2	0.1	Note 9
Performant Incidence Range	15-30°	20-35°	21-29°	Note 12
Time Dominant Incidence Range	11-56°	11-56°	N/A	Note 13

Table B.1: ICEYE imaging modes technical summary.

▶ IMAGING MODE

  CHARACTERISTICS

Table B.2 provides parameters associated with ICEYE complex images and Table B.3 provides the technical parameters associated with ICEYE Amplitude Images.

PARAMETERS	STRIP	SPOT	COMMENTS
COMPLEX IMAGE PRODUCT			
Focusing Plane	Slant Plane		
Slant Range Resolution	0.5 to 2.5 m	0.5 m	Note 7
Slant Azimuth Resolution	3 m	0.25 m	
Impulse Response Weighing Function (Peak Side Level)	Uniform (-13.3 dB)		
Slant Range Sample Spacing	0.4 to 2.4 m	0.4 m	Note 7
Slant Azimuth Sample Spacing	1.6 m	0.2 m	
Slant Range Product Format	HDF5 + XML		
SLC Product Size	3.4 to 2.9 GB	0.6 to 0.8 GB	
Dynamic Range	32 bits per pixel		Note 10

Table B.2: Parameters for ICEYE Complex Images.

▶ I M A G I N G   M O D E

C H A R A C T E R I S T I C S

PARAMETERS	STRIP	SPOT	SCAN	COMMENTS
AMPLITUDE IMAGE PRODUCT				
Ground Range Resolution	3 m	1 m	< 15 m	
Ground Azimuth Resolution	3 m	1 m	< 15 m	
Impulse Response Weighing Function (Peak Side Level)	Taylor Weighting (-20dB)			
Ground Range Sample Spacing	2.5 m	0.5 m	6 m	
Ground Azimuth Sample Spacing	2.5 m	0.5 m	6 m	
Range Looks	1	1 to 2	1	
Azimuth Looks	1 to 2	1 to 4	1	
Product Format	GeoTiff + XML			
GRD Product Size	700 MB	250 MB	800 MB	
Dynamic Range	16 bits per pixel			Note 11

Table B.3: Parameters for ICEYE Amplitude Images.

IMAGING MODE CHARACTERISTICS

NOTES

1. **Short Name:** For example, Strip mode has 'SM' : ICEYE_X7_GRD_SM_36535_20201020T175609

2. **Radar Beams:** The current generation of ICEYE satellites use electronically steered elements to control multiple radar beams.

3. **Nominal Swath Width:** The actual image size will be slightly larger than this to guarantee that the tasked area is covered.

4. **Nominal Swath Length:** The actual image length may be slightly larger to guarantee that the tasked area is covered.

5. **Maximum Collection Duration/Length:** Spot images do not have a maximum collection duration as they image for the required amount of time to obtain a tasked azimuth resolution. For Strip mode the maximum collection duration (and therefore the maximum image length) is limited by the amount of on-board memory storage. As different incidence angles have different slant range resolutions in order to provide the same ground range resolution, then the maximum collection duration is also a function of incidence angle.

6. **NESZ:** The noise equivalent sigma zero values are taken at scene center for near and far range extents.

7. **Slant Range Resolution:** For Strip mode the transmitted bandwidth is varied to make sure that the resolution on the ground remains the same. For Spot modes the maximum bandwidth is transmitted at all times.

8. **RNIIRS:** Radar National Imagery Interpretability Rating Scale is a subjective assessment of Radar Image Quality used primarily by military analysts. The scale is from 0 ("interpretability of the imagery is precluded by obscuration, degradation, or very poor resolution") to the highest quality figure of merit, 10 [7].

9. **RGIQE:** This is the Radar General Image Quality Equation. It is an adaptation of the concept of a General Image Quality Equation [8] Developed by NGA. Unlike the RNIIRS scale which is a largely subjective assessment of image quality, the RGIQE uses maximum channel capacity (measured in bits of information) as a figure of merit. From the Shannon-Hartley Theorem [9] the maximum information that can be carried in a signal (conventionally called a channel due to the origins in communications) is given by:

$$C = B \log_2 \left(1 + \frac{S}{N} \right)$$

Where C is measured in bits per second, B is the bandwidth of the system and   is the signal to noise ratio. Recognising that a resolution cell in a SAR image is ultimately defined in range by the transmitted bandwidth and in azimuth by the Doppler bandwidth, a measure of the maximum information content of a resolution cell in bits/m^2 can be formulated :

$$I = Baz \ BR_{ground} \log_2 \left(1 + \frac{S}{N} \right)$$

Where I is the information content measured in bits/m^2, Baz is the Doppler bandwidth used to form the azimuth extent of a pixel and BR_{ground} is the range bandwidth in the ground plane used to form the range extent of a pixel. The noise in this case is made up from all the noise elements that contribute to reduced image quality in the final image (Thermal noise, quantization noise, sidelobes, ambiguities). In this scale the higher the figure then the more 'information' is available for exploitation within the pixel.

10. **Complex Dynamic Range:** A complex number with 16bit I and 16bit Q values

11. **Amplitude Dynamic Range:** Stored as an unsigned 16 bit integer.

12. **Performant Incidence Range:** This is the nominal or standard range of incidence angles that the ICEYE Fleet operates over. The parameters in these tables are correct within this range of angles.

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13. **Time Dominant Incidence Range:** Being quite small and agile, and having an electronically steered antenna, ICEYE satellites can collect radar imagery from a wide range of angles. Outside of the *Performant Incidence Range*, SAR image quality may be degraded. However in some situations it may be more important to obtain a SAR image quickly rather than wait for an opportunity to image the location with the performant range of angles. For this reason ICEYE offers time dominant tasking as either a Tactical or a Custom order.

C. GLOSSARY

▶ GLOSSARY

Acquisition: A Synthetic Aperture RADAR collection or imaging event made by an ICEYE satellite

Altitude: The distance in metres above the Earth's surface

Amplitude Image: The name for a SAR image that has undergone a conversion from pixels that are represented as complex numbers to pixels that represent only the amplitude of that complex number.

Antenna: The part on an ICEYE satellite that radiates electromagnetic energy. Most commonly this refers to the radar payload antenna but it can also refer to one of the satellite's communication antennas.

Archive: ICEYE's imagery holdings.

Azimuth: In Radar terms this is a direction orthogonal to the range direction. In a SAR sensor it refers to the along-track or velocity direction.

Azimuth Ambiguity Ratio: This is a measure, specified in decibels (dBs) of the ratio of unwanted azimuth signatures compared to the wanted signal from an object in the image. The unwanted signatures are usually caused by objects that reflect energy from the side of the radar beam.

Bandwidth: The range of frequencies within an ICEYE transmitted pulse. Usually measured in megaHertz (MHz)

Beam-steering: This refers to the pointing of the payload radar beam. ICEYE satellites can steer their radar beam either mechanically - by rotating the radar antenna, or electronically, by applying phase adjustments across the radar phased-array antenna

Coherent Change Detection: This is a technique that uses two radar collections taken from almost identical imaging geometries relative to a scene's contents. Changes are highlighted by disturbances in the phase information contained in the SAR image.

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Complex Image: The name for a SAR image where each pixel is represented as a complex number. The complex number provides both a measure of radar brightness (amplitude) and the fraction-of-a wavelength component of range (phase).

Constellation: The formation of all ICEYE satellites in orbit around The Earth.

Customer Operations and Satellite Planning (COSP): The ICEYE team responsible for managing customer relations and planning successful acquisitions on their behalf.

Ephemerides: A table or data file giving the calculated positions of ICEYE Satellites.

Feasibility Study: A task performed by COSP on behalf of a customer to estimate how the ICEYE constellation will perform imaging operations for a scenario.

Fleet: Colloquial term often used to describe the ICEYE satellite constellation.

Geolocation: The process or technique of identifying the geographical location of a pixel in a SAR image.

Geospatial Accuracy: A measure of how well a location in a SAR image represents the true location of the object causing the SAR signature. Usually measured in terms of 90% circular error probable (CEP90).

GeoTiff: A tagged image file format that comprises geospatial tags. Used by ICEYE to represent amplitude images.

GIS: Geospatial information system.

Ground Range: Used to define the coordinate vector that represent a SAR image in the range direction, projected from the slant plane onto the Earth's surface.

Ground Range Resolution: The resolution of a SAR image along the ground

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in the direction of the ground range vector.

GRD: Ground Range Detected. This is an older term use to describe amplitude only SAR imagery that is projected onto the ground plane. The term detected refers to the process of converting complex samples into magnitude only samples. ICEYE amplitude images are marked as GRD images in their name.

HDF5: Hierarchical Data Format Version 5. A data storage standard used by ICEYE to store complex imagery.

I & Q: In-phase and Quadrature. These terms refer to the way that radar pulses are captured and recorded by the ICEYE Radar payload. They are used to ensure that the electromagnetic signal is sample is recorded as both amplitude and phase measurements.

ICEYE: Your favourite small SAR satellite company.

Incidence angle: This is the angle measured on the surface of the Earth between the zenith position and the satellite antenna.

Inclination: The angle between the equatorial plane and the plane of a satellite's orbit.

Local Time: The time at a particular place as measured from the sun's transit over the meridian at that place, defined as noon.

Look: Refers to a partitioning of a SAR collection. A SAR image is comprised of one of more independent looks that can be in either the range or azimuth direction, or both. The purpose of looks is to reduce the noisy effect of speckle in an image at the cost of a reduced resolution.

Look Direction: The direction the satellite image is taken relative to the satellite's motion. It can be left-looking or right-looking.

LTAN: Local time of ascending node. This is the local time at the sub-satellite point when the satellite crosses from the southern hemisphere to the north-

▶ GLOSSARY

ern hemisphere. As ICEYE satellites are in sun synchronous orbits, the LTAN is fixed for an orbit.

LTDN: Local time of descending node. See LTAN. This is the local time of the sub-satellite point when it crosses from the northern hemisphere to the southern hemisphere.

Metadata: The term used to describe all the ancillary information related to a SAR dataset. ICEYE satellite images have metadata stored both within the image and as a human-readable XML file that is distributed with the image.

Noise Equivalent Sigma Zero: This is a measure of the thermal noise floor of a SAR system. It provides a useful measure of how sensitive a SAR sensor is to small or low-radar-return objects.

Orbital Elements: These are the six parameters that describe the motion of an orbiting body.

Orthorectification: The process where any layover or foreshortening effects caused by a sensor's imaging geometry is corrected so that an object's top appears in the image above its base. Such an image is said to be orthorectified.

Phase History Data: The description of raw radar data before any image formation corrections are applied. The data is stored as an array of digitised pulse returns as a function of satellite time (hence history), with each pulse storing range information coding as phase and magnitude.

Pixel: An individual image sample. Not to be confused with resolution.

Polarization: A property of electromagnetic waves. The polarization of a wave describes the geometrical orientation of the electric field. For radar systems this is most commonly described with two letters representing the transmitted polarization and the received polarization. The letter V represents a vertical alignment and H represents a horizontal alignment. ICEYE's current generation of satellites have VV polarization.

Peak Power: The maximum (peak) power in a transmitted radar pulse.

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PRF: The Pulse Repetition Frequency (PRF) is measured in Hz and is the number of radar pulses transmitted per second.

Range Ambiguity Ratio: This is a measure, specified in decibels (dBs) of the ratio of unwanted range signatures compared to the wanted signal from an object in the image. The unwanted signatures are usually caused by objects that reflect energy from the far and near edges of the radar beam.

Rational Polynomial Coefficients (RPC): These are a set of polynomial coefficients that precisely describe the mapping of the sensor's imaging geometry to ground pixel coordinates. They provide an easy and fast way for GIS tools to determine the location of a pixel without performing warping or interpolation of the data representation (which often leads to a reduction in image information content).

Repeat Cycle: The amount of time it takes for a satellite to pass over the same location on the ground.

Resolution: A measure of the resolving power of a sensor or image. Not to be confused with sample spacing or pixel size.

RGIQE: Radar Generalized Image Quality Equation. This is a measure of image quality or SAR collection performance. It is a measure of the theoretical maximum information content that can be contained within a pixel and is measured in bits per metre squared. It is derived from Shannon's Information Theory [10] and uses bandwidth as a measure of information. It is particularly applicable to fine resolution imaging systems.

RNIIRS: Radar National Imagery Interpretability Rating Scale. An empirical measure of image quality based on analysts assessments. It was developed by the US government to provide an indication of suitability of a SAR image to be used for certain tasks such as detecting aircraft or ships. RNIIRS is the radar version of the more common NIIRS designed for optical imaging systems.

Sample: A single measurement of data. Usually used to describe an image pixel but also used as a single measurement of received radar energy as a function of range (a range sample).

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SAR: Synthetic Aperture Radar

SaVoir: The name of the mission planning software used by ICEYE when working with customers. It is sold by Taitus Software and was originally developed for the European Space Agency.

Scan Mode: A collection mode where the radar beam is scanned electronically either in the elevation direction, the azimuth direction or both.

SCANSAR: a type of Scan mode collection strategy that uses electronic beam steering in elevation to increase coverage area.

SFTP: Secure File Transfer Protocol.

Slant Range: A measure of range radiating away from the radar payload. Although independent of any direction it is commonly used to describe a direct path from SAR antenna to an image's scene centre.

Slant Range Resolution: This is the resolving power of a collection measured in the slant range direction. It represents the finest range resolution that can be achieved by a radar sensor.

SLAR: Side-looking Radar. A precursor to Synthetic aperture radar, where the antenna radiates energy to one side of the platform track.

SLC: Single-Look Complex. This is a term used to describe the most natural image format of a SAR collection. Samples are complex meaning they have amplitude and phase. The images have one look meaning that image pixels (and resolution) are often asymmetrical. By convention SLC images are in the slant plane.

Speckle: This is an imaging effect caused by adding coherent signals together. In SAR imagery it is seen as a salt-and-pepper effect in areas of homogeneous clutter. The effects of speckle are often undesirable and are reduced by incoherently averaging multiple looks together.

Spot Mode: Sometimes called 'Spotlight mode'. An imaging mode where the

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radar continuously points its beam at a single location. It allows finer azimuth resolution imagery to be obtained at the cost of a reduced area.

Strip Mode: Sometimes called 'Stripmap mode'. An imaging mode where the beam is not steered but remains in a fixed orientation with respect to the satellites motion. It allows long collections with a lower azimuth resolution than a spotlight mode collection.

TOPSAR: Terrain Observation by Progressive Scan (TOPS) SAR. A Scan mode where electronic beam steering is used in elevation and azimuth. The elevation steering increases the area covered (at the cost of dwell time and therefore resolution of ground points). Azimuth steering is performed in bursts and ensures that all ground points are illuminated equally.

XML: Extensible Markup Language. A human and machine readable file format used by ICEYE as auxiliary data distributed with image products to allow a user to more easy obtain information about a collection.

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▶ REFERENCES

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CHANGE LOG

▶ CHANGE LOG

This document revision: Version 4.1

From branch: V4.1

CHANGES SINCE PREVIOUS VERSION

V4.1.0

▶ Included ICEYE-X8 and ICEYE-X9 in constellation.
▶ Added Scan mode and redefined modes as 'Spot', 'Strip' and 'Scan'
  ▶ Added Scan related definitions to glossary
  ▶ Added Scan mode parameters to imaging mode characteristics in Annexe B.
▶ Rearranged Chapters 5 and 6 to introduce COSP team before providing ordering information.

V4.0.0

▶ Major rewrite since Version 3 to make content more accessible to readers.
▶ LaTeX / Github version control- more frequent revisions.
▶ Revised Fleet information.
▶ Revised Sensor information.
▶ Moved reference material to appendices to allow easier access to key information.
▶ Updated customer support process.
▶ Improved ordering process includes workflow for Standard and Custom tasks.
▶ Collection changes:
  ▶ SPOTLIGHT HIGH renamed to SPOTLIGHT and is the default (Quality Improvement).
  ▶ STRIPMAP Modes consolidated providing increased collection capacity.
  ▶ STRIPMAP Maximum length increased to 600km (from 300km).
▶ Product Changes:
  ▶ Improved Geospatial accuracy.
  ▶ Improved Radiometric accuracy.

Table E.1: Change Log.