The ICEYE Constellation - Some New Achievements

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***Abstract*—ICEYE's journey to discover new SAR capabilities with a microsatellite SAR constellation is well documented. The journey continues as the ICEYE fleet grows, opening up opportunities for experimentation in extended dwell imaging and coherence analysis. This paper presents an update of the ICEYE fleet's capabilities as of early 2022. Latest results from two recent innovations will be presented - Daily Coherent Ground Tracks and Extended Dwell imaging.**

***Index Terms*—SAR, X-band, ICEYE, Spotlight, SAR-Video, Coherent Change Detection**

I. Introduction

The ICEYE constellation currently consists of 16 satellites and is constantly growing with between 4 and 8 satellites launched each year. Because of this rapid development rate, each satellite has a baseline configuration and various experimental augmentations designed to pave the way for future production level capabilities. Each satellite therefore has slightly varying parameters with some satellites no longer performing imaging capabilities whilst others have the latest advances. The company manages a minimum **baseline** SAR product capability [1] and as new experimental modes become stable and well characterised they are promoted to be available to users. A summary of the current baseline specification is in Table I

TABLE I
System parameters of the ICEYE baseline constellation

SYSTEM PARAMETER	SPECIFICATION VALUE
carrier frequency	9.65 GHz
look side	both LEFT and RIGHT
antenna size	3.2 m x 0.4 m
PRF	2-10 kHz
range bw	40-300 MHz
peak power	4 kW
polarization	VV
incidence angle (Strip)	10-30 deg
incidence angle (Spot)	20-35 deg
incidence angle (Scan)	21-29 deg
mass	85 kg

Two capabilities that have recently become available are the Extended Dwell collection and the Daily Coherent Ground Track Repeat image stack. Each will now be discussed.

II. Extended Dwell Imaging

ICEYE's normal Spot collection has a 10 s coherent integration period. This provides a comfortable 25 cm azimuth resolution that is multilooked by averaging 4 independent looks to form a 1 m azimuth resolution. The satellite however, being quite small, is highly manoeuvrable and able to point its radar beam at a point on the ground for considerably longer than this. The limitation for imaging therefore is the satellite memory size and buffer fill-rate. During development of this mode a nominal 25 s collection was used. The ICEYE SAR processor was augmented with a new core focusing module that uses a version of the fast factorised back projection algorithm [2]. Collections were obtained over a range of locations including the Rosamond Corner Reflector Array [3] provided by NASA/JPL. When processed as a single look complex image the native slant plane resolution was measured to be between 0.05 and 0.1 m in the azimuth direction although it is important to remember that the slant range resolution is still limited by the 300MHz transmit bandwidth to provide 0.5 m slant range resolution.

Such asymmetric IPR (impulse response) images have limited utility for human exploitation in themselves and so a range of derived 'image products' have been developed.

A. Amplitude Multi-Look

This can almost be considered a 'standard product' for Spotlight Extended Dwell (SLED) Processing. The asymmetric IPR of the collection is circularised on the ground plane by incoherently averaging adjacent looks as a post-processing step after aperture focusing. The result is a 1 m x 1 m resolution image in the ground plane with significantly reduced speckle due to the integration of 10 independent looks.

Figure 1 is a SLED image taken over the Ras Tanura Oil Depot in Saudi Arabia. This is a useful facility for demonstrating the utility of a SLED Multi-Look image. The oil storage tanks in this facility have floating lids that rise and fall as oil is pumped in or removed. The height of the lid (and therefore the amount of oil in the tank) can be estimated from the predictable layover and dihedral returns of the different component parts [4]. A common source of error is the determination of the different parts of the tank and the isolation of the tank elements from speckle. The inset

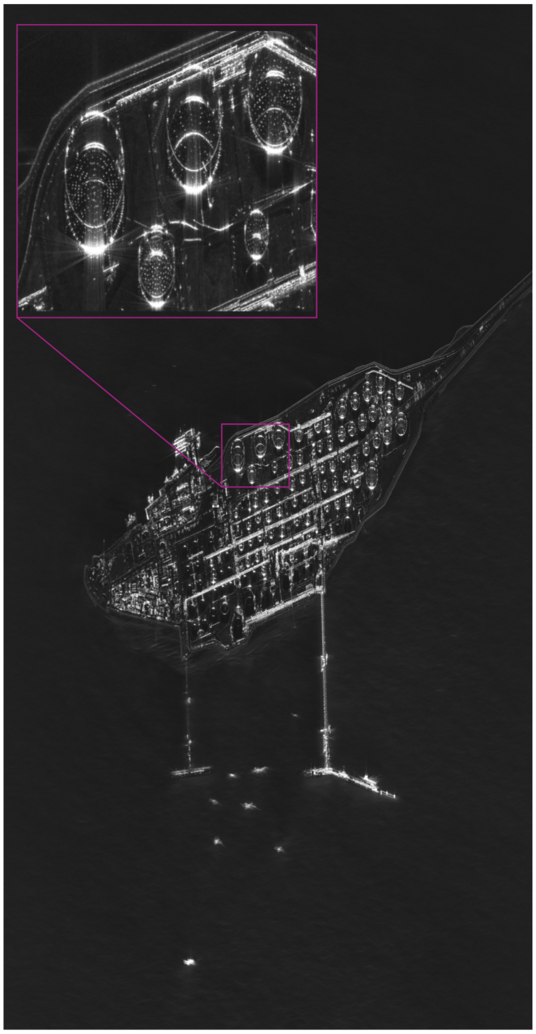

Fig. 1. Amplitude Multi-Looked image from a SLED collection of Ras Tanura, Saudi Arabia showing fine detail of floating top oil-tanks in the oil depot. Original image resolution is 1 m x 1 m with 10 independent azimuth looks.

is an enlarged region of the image showing the significantly reduced speckle and different elements of the tank and its lid.

B. Color Multi-Look

The second exploitable SLED product is a natural evolution of the amplitude multi-look image. In this product each individual look has a color applied to it. The selection of color is carefully chosen from around the *color wheel* so that a single pixel with the same amplitude in each frame retains a grey-scale *color*. This has the effect of highlighting dominant scattering aspect angles for objects. It is also a useful way to highlight non-isotropic scattering objects or moving targets.

Figure 2 is a Color Multi-Look image from a SLED collection taken over Busan Harbor in South Korea. The Busan Harbor Bridge has many suspension cables aligned in a range of angles from one of two main towers. The different aspect angle of each of the 12 looks in the collection is orthogonal to a different suspension cable and so they appear take on the color of the dominant orthogonal look.

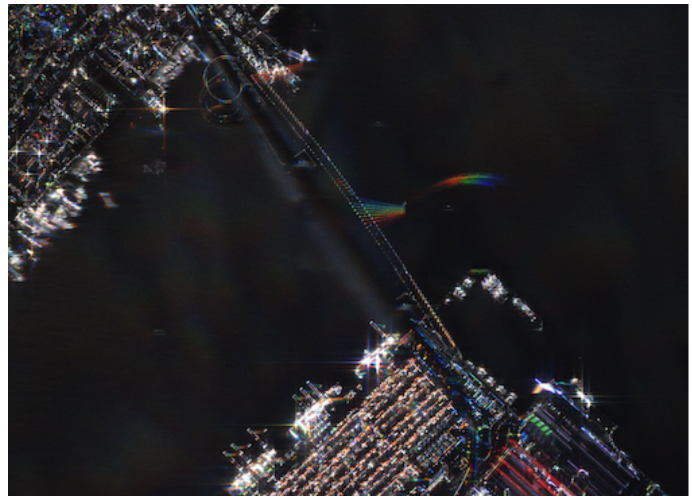

Fig. 2. Color Multi-Look SLED image of the Busan Harbor Bridge in South Korea

C. SAR Video

The final SLED product is the SAR Video. This has been an experimental capability for a year now [5] but it has been challenging to convert the capability into a product that can easily be exploited in a meaningful and scientific way. For this reason the product is available as both a animated movie file format (mp4 and gif) as well as a multiband geotif. The coherent integration period of the SAR collection is broken into 25 overlapping frames each with a resolution of 1 m on the ground. The frames are adjacent and overlap to provide a movie representation as the satellite transits past a target area.

Figure 3 presents an interesting use case of SAR video. In this standard SAR image a vessel is moving during the collection and as a result is defocused and unidentifiable. Playing the SAR video allows the motion to be isolated and the user to select the frame that has the best focusing. The individual sub-apertures are shown as image chips in Figure 4.

As the duration of each of the SAR video frames is considerably reduced, the amount of defocussing that occurs due to the vessel's motion is also reduced. Usually the analyst would play the SAR video from their workstation and select the frame that provides the easiest analysis. This can be different for different vessels. Once the preferred frame has been identified it can be extracted (Figure 5) for further analysis or even additional refocusing.

III. Daily Coherent Ground Tracks

Another useful feature of a small satellite is that it is relatively easy to adjust its altitude through the use of ion propulsion. ICEYE satellites use indium ion propulsion which provides a near limitless supply of fuel. Through precise thrust maneuvers, each satellite can adjust its altitude until its mean motion is exactly 15 orbits per day. This means that each imaged location has a coherent revisit time of 24 hours.

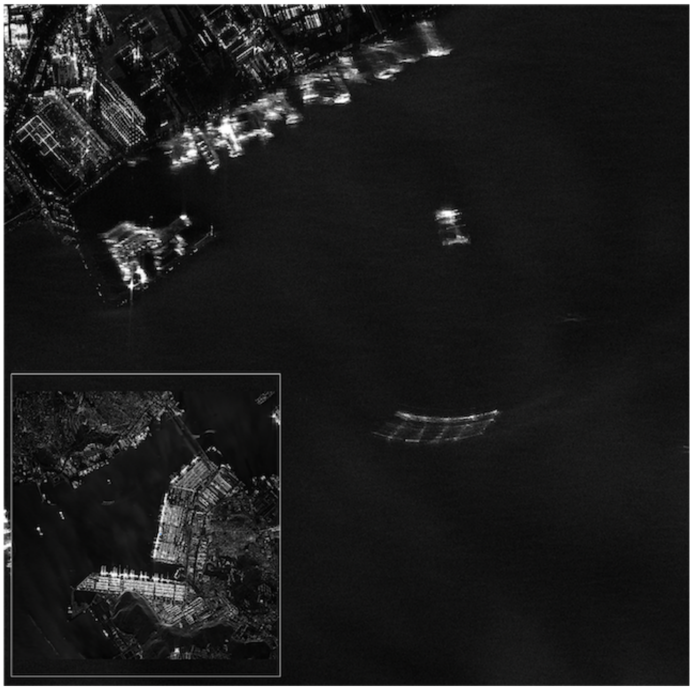

Fig. 3. Inset: Spot Extended Dwell collection at 1m resolution. Main image: A vessel can be seen in the harbour. Due to its motion during the coherent integration period it cannot be identified.

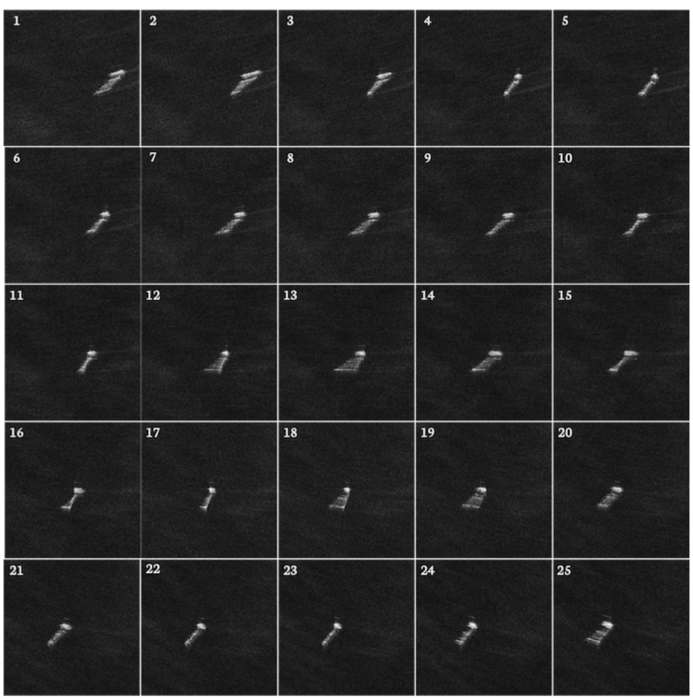

Fig. 4. A SAR video is made from the image in Figure 3. In this image chips around the defocused vessel have been extracted. As the synthetic aperture duration is less for each frame the amount of defocusing is reduced. The frame with the best focus can be selected for further analysis.

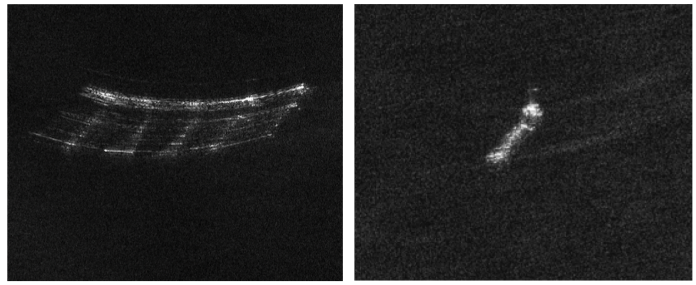

Fig. 5. Defocused vessel from Figure 3 before (left) and after SAR Video frame isolation.

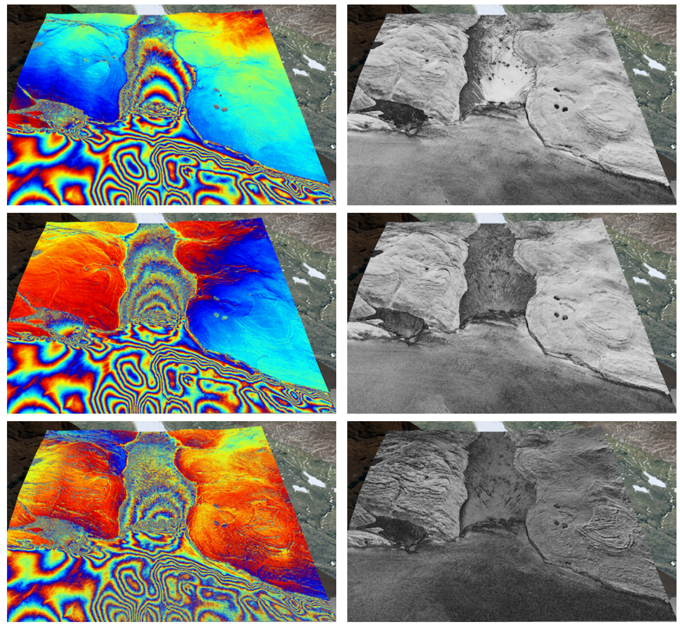

Fig. 6. Interferometric SAR (left) and Coherent Change Detection images of a tributary glacier in Greenland

Due to the earth's oblateness, the orbital eccentricity and argument of perigee varies slightly causing small inaccuracies in the baseline separation from one day to the next. If not managed the baseline will grow to the point that images will no longer be coherent and so periodic 'maintenance manoeuvres' have to be applied.

Over the last year ICEYE has been experimenting with tolerances for daily baseline separation and time between images for a range of locations. Due to variations in weather and unknown propagation effects it is impossible to precisely determine a preferred baseline for each application and location so ICEYE attempts to keep orbital drift to be less than 500m per day and for optimal coherent change detection (CCD) performance a revisit rate of 3 days or less is preferred. Figure 6 shows an example result of a tributary glacier in Greenland taken over three consecutive days (from a 9 day stack) in October 2021. Amplitude imagery alone shows no change whereas the CCD images show which part of the glacier is moving and even the formation of cracks and crevasses as it moves.

IV. The future

The ICEYE Constellation continues to grow and is expected to reach a compliment of 18 fully operational satellites by the end of 2022. This will provide a global field of regard with each satellite being able to maintain a 1-day coherent ground track over an imaged location. Each launched satellite provides valuable lessons and insights into fine resolution SAR earth observation which leads to improvements in reliability and capability on future satellites. The next generation of satellites will see improvements in resolution, power (image sensitivity), geospatial accuracy and timeliness.

Acknowledgment

The ICEYE team would like to acknowledge the enduring advances of the world's RADAR pioneers. We are humbly in your debt. Thank you.

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