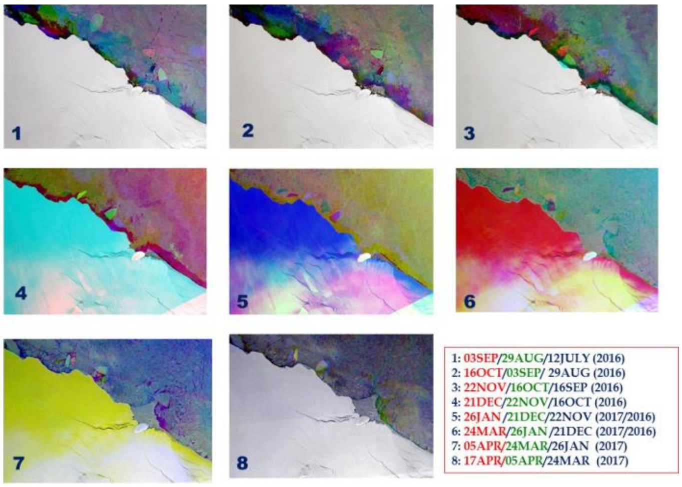
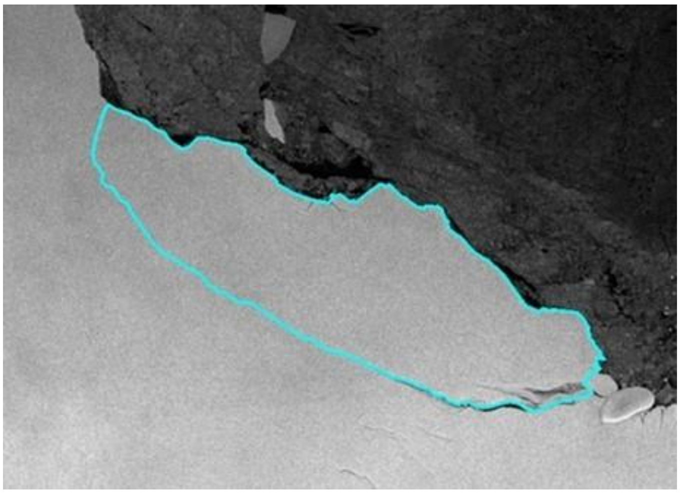
SAC/EPSA/AMHTDG/MTDD/SR-01/ June 2017

Rift Propagation and Ice Calving at Larsen C, Antarctica





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8	Originating Unit	AMHTDG/EPSA, SAC, Ahmedabad, India.
9	Abstract	A temporal image analysis of the Larsen C ice shelf was carried out to study the rift propagation and ice calving in this region. MODIS data from 2000 to 2017 and Sentinel data from Oct 2014 to June 2017 were used. The detailed analysis shows that there is an increasing rate at which the rift propagation is increasing and a large portion to a tune will be calved in the near future. Also a small calving event in 2004 – 2005time frame to the tune of 1100 km^2 was also studied. The events are happening in the summer season. Increased melting period and percolation of the melting water in to crevasses may be attributed as important causes of calving. The Sigma_0 analysis also revealed the drastic dip in backscattering value implicating the melt. A recent ice calving of the order of ~ 6500 km^2 is expected within a time span of days to a few months.
10	Classification	Non Restricted
11	Circulation	General

Content

1.0 Introduction

Antarctic Peninsula is one of the major zones which control the long term climate variation for the entire globe. This region has thus been the focus of many a scientific study, and regular research related observations. India, with its two Indian Antarctic research stations Maitri and Bharati, has also been contributing a major role in routine scientific expeditions and scientific research. The large scale disintegration of ice into ice bergs and rift propagation has focussed limelight on Antarctic Peninsula especially on Larsen ice shelves during the last decade. Larsen C is the fourth largest ice shelf in Antarctica after Filchner-Ronne, Ross and Amery. A rift is a large through fracture that propagates transverse to ice flow direction and acts as a precursor to ice calving. Initially small cracks form due to longitudinal stress which results into crevasses and finally forms the rift. The rift propagation and calving (the disintegration) of ice into ice berg (the floating land ice) are natural phenomena in the Antarctic ice margins. Global warming may be attributed as one of the causative factor for unusual fast rift propagation in the Larsen C in the recent past.

The rift propagation taking a gigantic acceleration from 2014 in Larsen C has drawn the attention of a large number of researchers focussing their study over this region. Availability of cloud free data in the Antarctic environs is very difficult, since cloud free days are bare minimum. Continuous synoptic observations of this area are only possible through satellite remote sensing and availability of cloud free optical data restricts its application. The Synthetic Aperture Radar (SAR) sensors, capable of all weather, day and night imaging at a temporal resolution defined by the sensor, are providing continuous data sets for such studies.

The fast pace of rift propagation is attributed to the global warming in the Antarctic Peninsula and melt percolation. In the summer, due to the increase in atmospheric temperature, ice melts and percolates through the crevasses /rift and reaches the ocean bed. This also fastens the rift propagation and finally collapses the portion of the shelf into the ocean as icebergs. Another process is basal melting. The increase in ocean temperature during summer and the hot water carried by the ocean currents cause the bottom of the shelf to melt. The inverse propagation of crevasse in to a rift will causes the shelf to calve. The disintegration and calving of the ice, leaves the shelf to retreat. This, in turn, increases the velocity of the glaciers as shelf acts as a barrier to the flow. This results in the increased sea ice formation.

More than 28,000 km^2 of floating ice shelves have disintegrated along the Antarctic Peninsula (AP) over the past three decades, punctuated by the catastrophic break-up of Larsen A in 1995 and Larsen B in 2002 (Cook and Vaughan, 2010). Khazender et. al. studied the stability of ice in the Antarctic peninsula and inferred that the northern half of the ice shelf has been accelerating since 2000, speeding up by 15% between 2000 and 2006 alone. The study concluded that, although Larsen C is not facing imminent collapse, it is undergoing significant change in the form of flow acceleration that is spatially related to thinning and fracture. The process of rift formation by crevasse hydrofracture, the process by which water-filled surface crevasses propagate downwards, is considered as the primary mechanism for ice calving (Van der Veen, 1998; Zwally and others, 2002). Scambos et. al. has studied the glacier velocity and thinning of the glacier after collapse of Larsen B. The results concluded seasonal variations in speed preceding the large post-collapse velocity increases suggest that both summer melt percolation and changes in the stress field due to shelf removal play a major role in glacier dynamics. McGrath et. al. (2012) and Mueller et. al. (2011) have attributed the instability of the Larsen C shelf due to the basal crevasses and associated surface crevassing. Basal crevasses are large-scale structural weaknesses that can control melt water ponding and also induce surface crevassing.

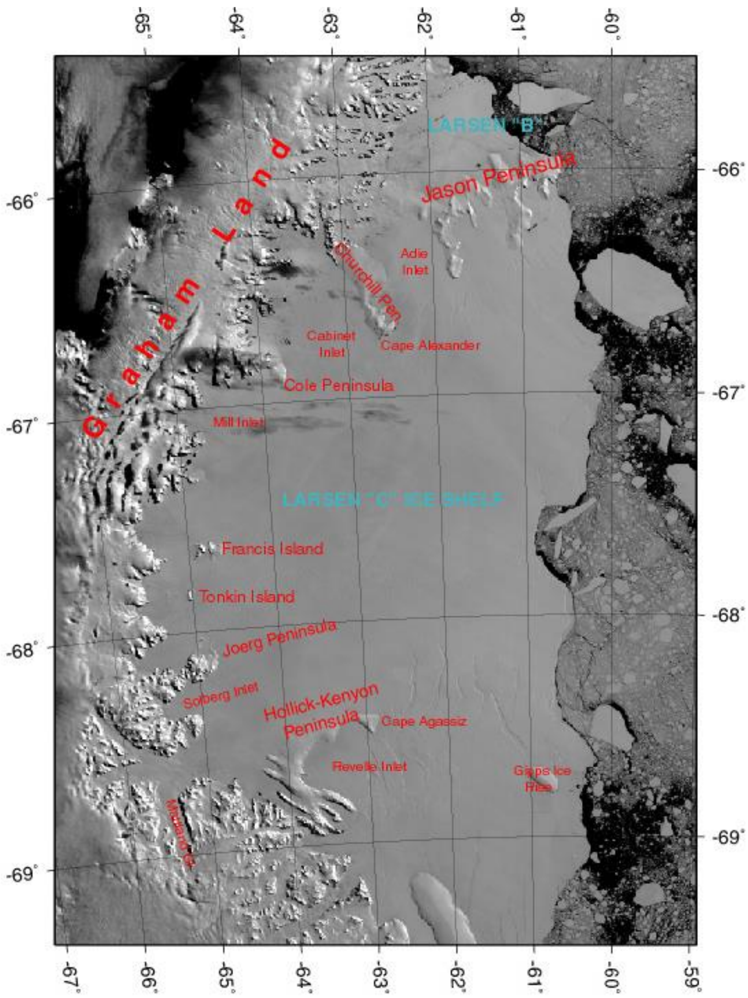
Recent posts in the various scientific sites show the emerging calving event of Larsen C. The report by Nagaraj Adve in the "The Wire" has enthused the Indians by his report on 28 March 2017. "Half a planet away from the immediacy of politics that dominates our headlines, there's a crisis unfolding that can dog us for centuries. In West Antarctica, a huge ice shelf called Larsen C has developed a rift 175 kilometres long and half-a-kilometre wide. A chunk of the shelf is poised to break off soon. When that happens, the 'chunk' will be an iceberg over 5,000 sq. km across and 350m high – more than four times the height of Delhi's Qutub Minar and over an area one-and-a-half times the size of Goa". The project "MIDAS", a UK based Antarctic Research project, is closely watching the event by analysing various datasets. It is based at Swansea University and Aberystwyth University in Whales. They reported that the event may happen any time now. The recent reports from MIDAS suggest that the break is just 13 km away. The post is the recent one on June 28th 2017. All the agencies in India and Abroad working in the field of cryosphere are closely watching the progress.

In this study, an attempt has been made to monitor the rift propagation and coastal deformation happening in the Larsen C shelf. A systematic monitoring was carried out using Moderate Resolution Imaging Spectroradiometer (MODIS) data from MODIS Shelves archive at NSIDC. The data from MODIS was used for monitoring the rift propagation at a coarser scale (250m pixel). Sentinel images were also used for detailed analysis for the accelerated changes from July 2014 to June 2017. Both the images from 2000 onwards show the deformation happening at Larsen C shelf especially the rift propagation taking a momentum from 2014 onwards till April 2017.

2.0 Study Area

Larsen ice-shelf system broadly consists of four major ice-shelves namely Larsen A, Larsen B, Larsen C and Larsen D. Larsen A receded and then collapsed in January 1995, with the loss of 1600 km^2 of ice shelf. Larsen B partially collapsed in February–March 2002, with the loss of 3250 km^2 of ice shelf. There are two major rift propagation happening in both Larsen C and Larsen D which will result into large calving event in the very near future.

The Larsen C Ice Shelf covers an area of approximately 50,000 square kilometres between Jason Peninsula in the North and Hearst Island in the South (Figure-1). The major islands in this area are Francis and Tonkin. Jason, Churchil, Cole, Joerg and Hollick-Kenyon are the peninsula in this region. Both the islands and peninsula are responsible for arresting the ice flow in to the ocean. Hearst Island also spread in East West play an important role to prevent the ice loss. There are about twelve outlet glaciers feeding in to Larsen C. Gipps Ice Rise and Bawden Ice Rise is in the shelf boundary which also make the disintegration happening at a slower pace. Monitoring the changes in Antarctic Peninsular coastal region, specially in Larsen shelves will provide an insight into the nature of activities happening there due to natural processes as well as due to effects of global warming. Recently, Larsen C ice shelf is in news because of the ever progressing cracks that further went ahead by



~17 km by length as monitored by US scientists stationed over there.

Figure-1: Larsen C ice shelf (courtesy: https://nsidc.org/data/iceshelves-images/)

3.0 Data Used

Both optical (MODIS) and Sentinel SAR data (C-band) were used for the study of rift propagation and calving. The lack of cloud free optical data makes opportunistic use and cloud free SAR data make a deterministic use for the present study.

3.1 MODIS Ice Shelves data from NSIDC and MODIS Mosaic from NASA sites

Modis provides a continuous mosaic of Antarctic terrain (https://lance.modaps.eosdis.nasa.gov/imagery/subsets/?subset=Antarctica). The data pertaining all the major ice shelves are kept available at National Snow and Ice data Center (https://nsidc.org/data/iceshelves-images/) from 2000 onwards. This site provides all the cloud free acquisition pertaining to all the ice shelves of Antarctic terrain. The data is at five resolutions: 250 m, 500m, 1 Km, 2Km and 4 Km and in 3 three band combinations namely true colour, 3-6-7 and 7-2-1. Due to heavy clouds and blizzards in this region, getting a cloud free data is very difficult. In most of the months hardly one or two totally cloud free data is available. Mostly data is available in summer months (Dec – Feb). But Sept – Nov and March to May months also have a few clear sky observations. The cloud free data in geotiff format was downloaded from NSIDC from 2000 to 2017 at the spatial resolution of 250 m.

3.2 Sentinel data over Larsen C Ice Shelf

SENTINEL-1 carries a single C-band synthetic aperture radar instrument operating at a centre frequency of 5.405 GHz. It includes a right-looking active phased array antenna providing fast scanning in elevation and azimuth. Sentinel-1A/1B satellite was launched on 3 April 2014/25 April 2016 respectively. The Sentinel data, with its repetivity 12 days, provide a detailed monitoring of this area. With its ascending and descending passes, and 1A and 1B combinations, a systematic acquisition is possible in the Antarctic terrain. The incidence angle range was ~ 18° to 48° near and far range respectively.

The Extra Wide swath imaging mode is intended for ice and polar zone operational services where wide coverage and short revisit times are demanded.

The sentinel 1A / 1B data sets were downloaded from the Copernicus site https://scihub.copernicus.eu/dhus) as well as Alaska facility (https://www.asf.alaska.edu) from October 2014 onwards. The Ground Range Detected (GRD) extra wide (EW) data in the geotiff format were downloaded every month pertaining to the Larsen C focussing the propagation of the rifts till April 2017. We have analysed HH polarisation as it is the only available data configuration in this region. The present study focuses on showcasing the rift propagation in Larsen C. August 2016 to April 2017 data sets has been used for backscatter variation analysis. Efforts are made to download the same frame data to avoid registration errors.

4. 0 MODIS data analysis

Temporal analysis of both optical and SAR data have been carried out. Geotiff data with spatial resolution 250 m was downloaded from MODIS data archive. The cloud free images of MODIS data available from National Snow and Ice Data Center. pertaining to Larsen C were also downloaded from 2000 onwards. The data were projected on to polar stereographic projection and enhanced for clear visibility of rift. Time series monitoring of the data shows changes in every two years from 2000 to 2010 in Figure-2 and yearly changes from 2012 to 2017 in Figure 3. The exact extent of crevasses was not very clear in MODIS data due to its spatial resolution, presence of clouds in the terminating region and due to snow cover over the crevasses. The ice calving event was noticed between Oct 2004 and Jan 2005. The cloud free data were not available during every month to identify the exact time of calving.

A major ice calving to the tune of 1100 sq. km was observed during November 2004 and January 2005. The event is mapped on the MODIS cloud free images between 2004 March to 2006 as shown in Figure-4 and Figure-5.

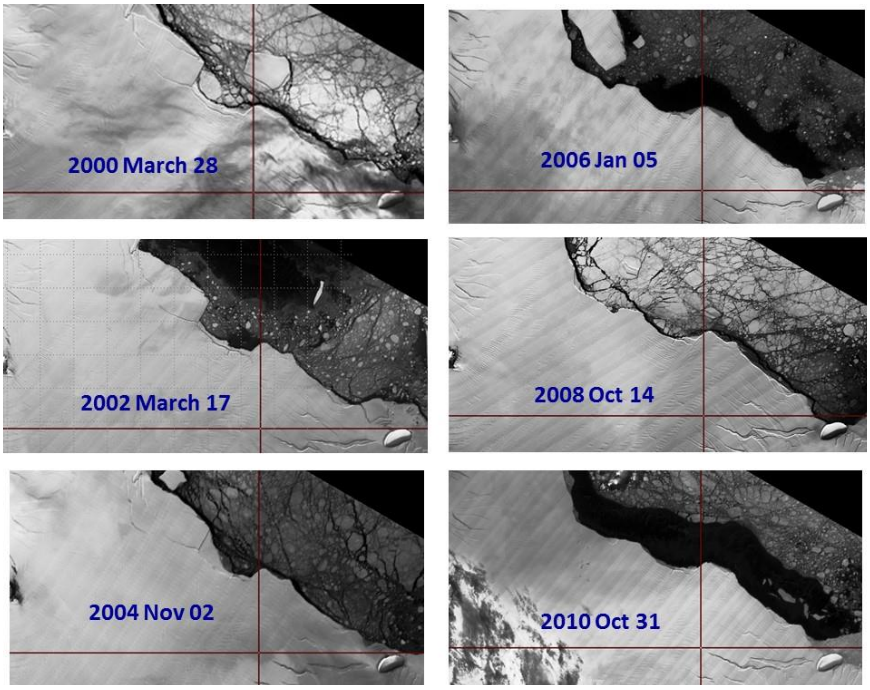


Figure-2: Monitoring the Larsen C rift propagation from 2000 – 2010: The cross mark is at the tip of the rift. See how the rift propagates from 2000 to 2010. Two Year advancement of the rift is shown by the cross mark.

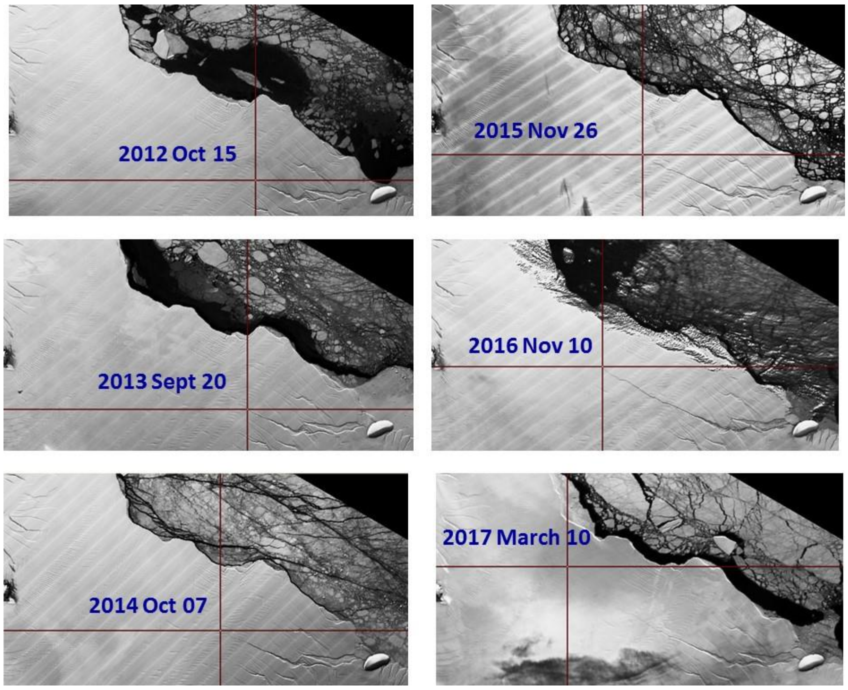


Figure-3: Monitoring the Larsen C rift propagation from 2012 – 2017. Yearly advancement of the rift is shown by the cross mark. Rapid propagation of the rift from 2014 to 2017 is depicted in the figure.

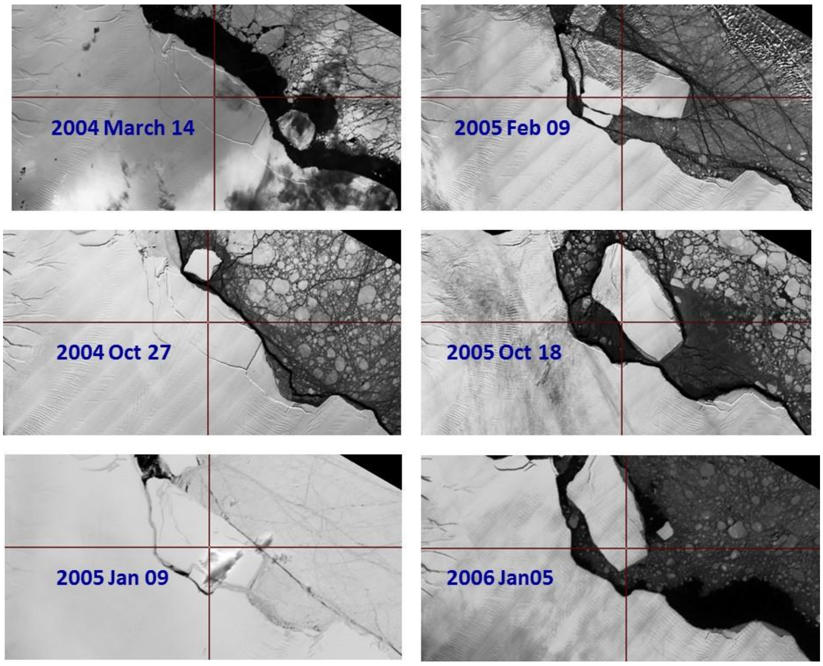


Figure-4: Monitoring the Larsen C Ice Self Calving 2004 - 2006 (from NSIDC SITE-MODIS SHELVES). Ice Calving event from 2004 to 2006 shows the rift propagation and iceberg formation. White portion is ice shelf and right portion is sea ice.

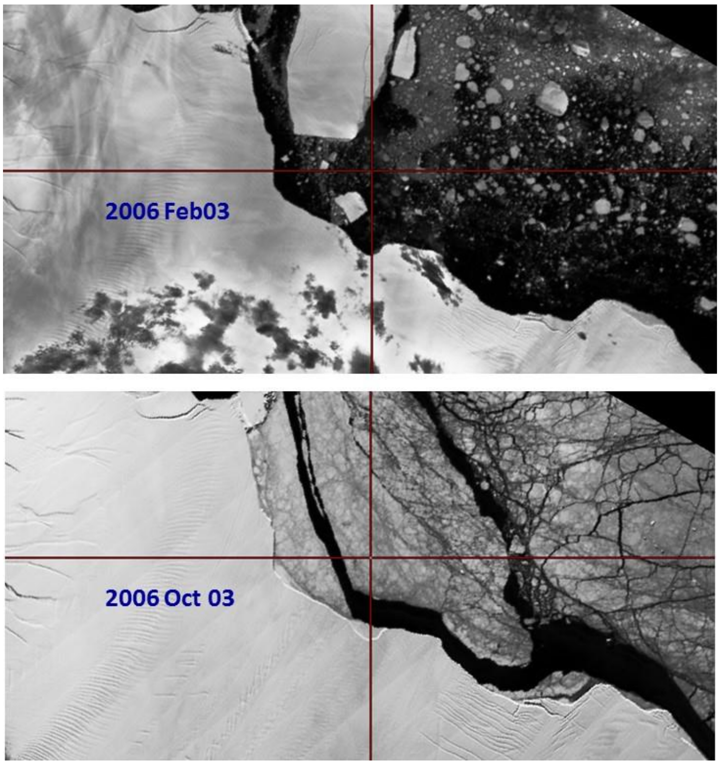


Figure-5: Monitoring the Larsen C Ice Self Calving 2006 Feb – 2005 Oct (from NSIDC SITE- MODIS SHELVES). Drifting of the iceberg (2006 Feb03) and Sea ice formation (2006 Oct03) is shown in the figure.

5. Sentinel Data Analysis

Sentinel data available from 2014 was used for detailed rift propagation and ice calving. The data was downloaded from the site (https://scihub.copernicus.eu/dhus/data) and speckle filtered using GammaMap with a 3X3 window using Commercially Off the Shell (COTS) software and Freeware. A systematic monitoring of the Larsen C shelf was carried out using Sentinel 1A/ 1B data. This data with its resolution of 40 m provides an unhindered dataset during the high blizzard conditions and heavy clouds. During the blizzard conditions, which prevails in the Antarctic region particularly in coastal region in most of time, optical imaging is impossible. Blizzard is a severe snow storm with wind speed greater than 56 km/hr and sustaining over a longer period typically more than three hours to days. The time series analysis of the data was used for detailed study of the rift propagation. Detailed monitoring of the rift propagation in Larsen C is divided into the transition period (summer to winter), shown for three consecutive transition periods. The changes are depicted in Figure-6 (2014-2015 transition period), Figure-7 (2015-2016 transition period) and Figure-8.

The summer data (December to February) shows a gradual melting events and freezing starts from March onwards. The 2014 Dec – Feb 2015 summer data is not showing a drastic reduction in the sigma0 in the Larsen C region. Hence the exact extent of the rift is not clear. 2015 Dec to 2016 Feb and 2016 Dec to 2017 Feb shows a drastic change in the sigma0 which can be interpreted as an increase in the melting over the region. During these summer regions the rift propagation has taken a larger leap.

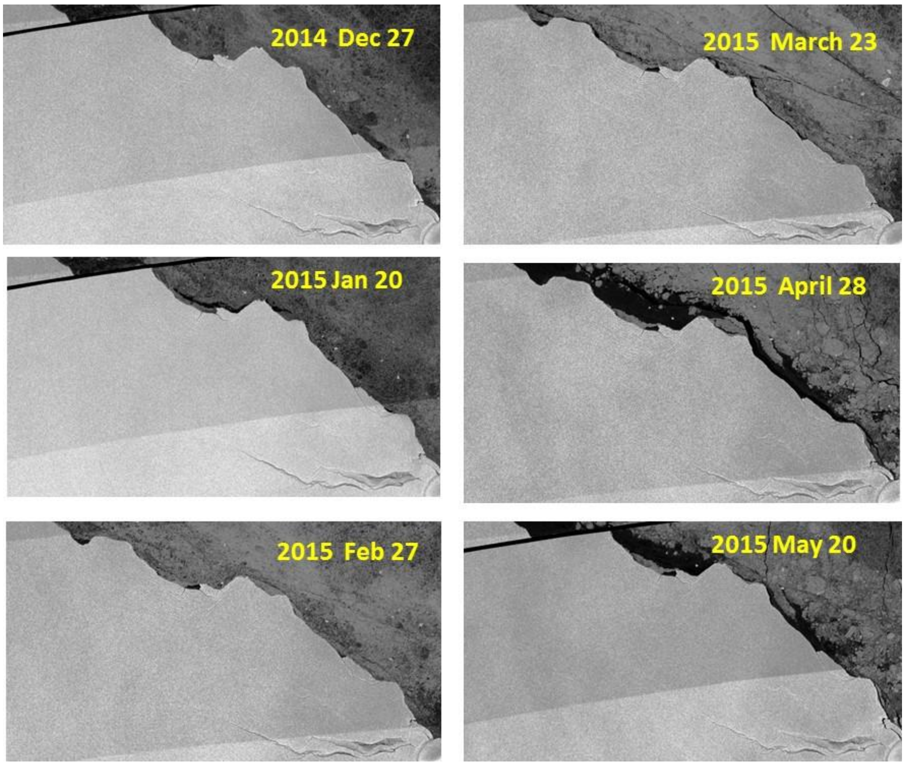


Figure-6: Monitoring the Larsen C Ice Self Rift propagation from 2014 Dec to 2015 May 20 ((Sentinel 1 from Copernicus). Beginning of summer (Dec) and next winter (March) data is shown. Rift propagation is shown from the bottom right corner (2014-2015).

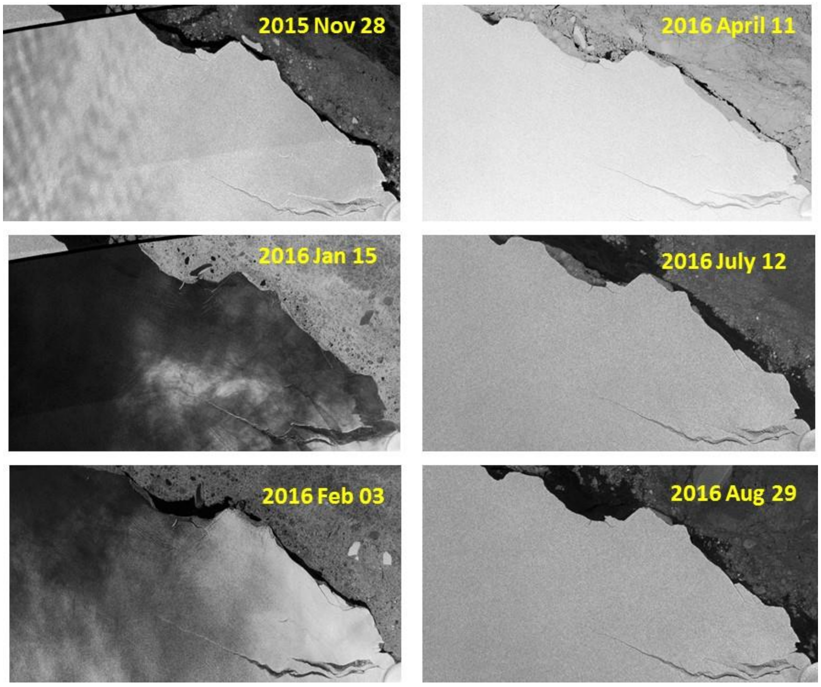


Figure-7: Monitoring the Larsen C Ice Self Rift propagation from 2015 Nov to 2016 Aug (Sentinel 1). 2015 summer to 2016 winter signature variations. January and Feb shows dark patches due to melting. The extend of rift is clearly visible in summer. Snow cover makes it difficult to extract the tip of rift propagation.

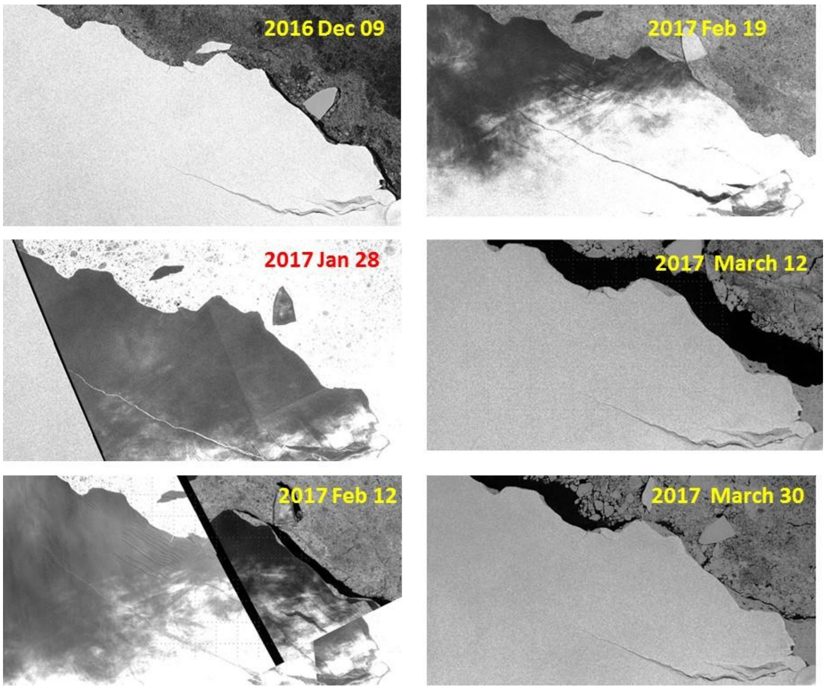


Figure-8: Monitoring the Larsen C Ice Self Rift propagation from 2015 Nov to 2016 Aug (Sentinel 1). Jan 28 and Feb19 show the extend of rift propagation.

6. 0 Change in Backscattering in the transition periods

The backscattering images were generated using the SENTINEL-1 Toolbox (S1TBX) which is a part of the Sentinel Application Platform (SNAP) software package. To re-project the images from geometry of the sensor to the geographic projection, ellipsoid correction was applied with stereographic South Pole projection for Antarctica region and bilinear interpolation has been used as image resampling method. The schematic diagram for the data analysis is shown in Figure-9.

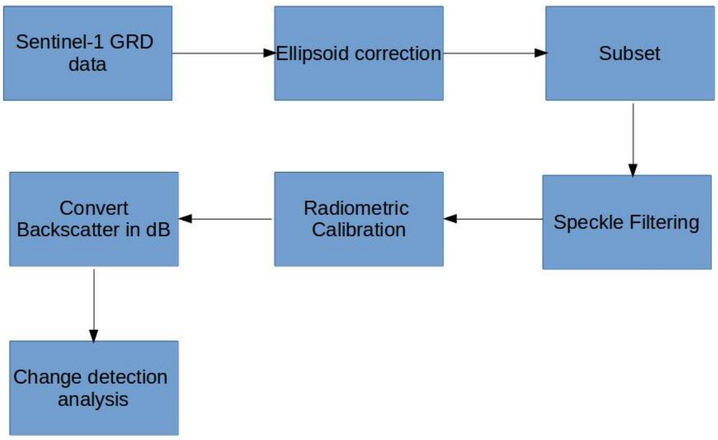


Figure-9: Flowchart for Sentinel-1 data processing

Speckle noise reduction was applied by using Refined Lee Filter (RFF). For converting digital pixel values to radiometrically calibrated backscatter, all the required information is available in the meta data. A calibration vector is included as an annotation in the product allowing simple conversion of image intensity values into Sigma 0 values.

Level-1 products provide four calibration Look Up Tables (LUTs) to produce Sigma nought. The LUTs apply a range-dependent gain including the absolute calibration constant. For GRD products, a constant offset is also applied.
The radiometric calibration is applied by the following equation

$$\sigma^0 = \frac{< DN >^2}{A_\sigma^2}$$

A_σ^2 is radar cross section, and DN is pixel value. Bilinear interpolation is used for any pixels that fall between points in the LUT. This backscattering coefficients can be converted into dB using $10\log_{10}$ (Sigma 0).

A multi-temporal FCC of the image data was generated from the sentinel data by advancing one month from 2016 July to 2017 April. It is plotted in Figure-10. This data clearly shows the changes happening on ice features supported by the backscattering intensity analysis. A study has been carried out to analyse the variation of backscattering intensities using multi-temporal SENTINEL 1 data over transition period of from August 2016 to April 2017 (Winter-Summer-Winter). The profiles are taken at 10 locations as shown in Figure-11. The locations were selected at various ice features which are well discriminated. One data was ensured every month, signatures were averaged over various targets having uniform area and the mean value of backscattering intensity was plotted for different targets. Monthly variation was platted for various targets for 2016-2017 winter–summer-winter variations. The monthly variation of backscattering intensity is shown in Figure 12.

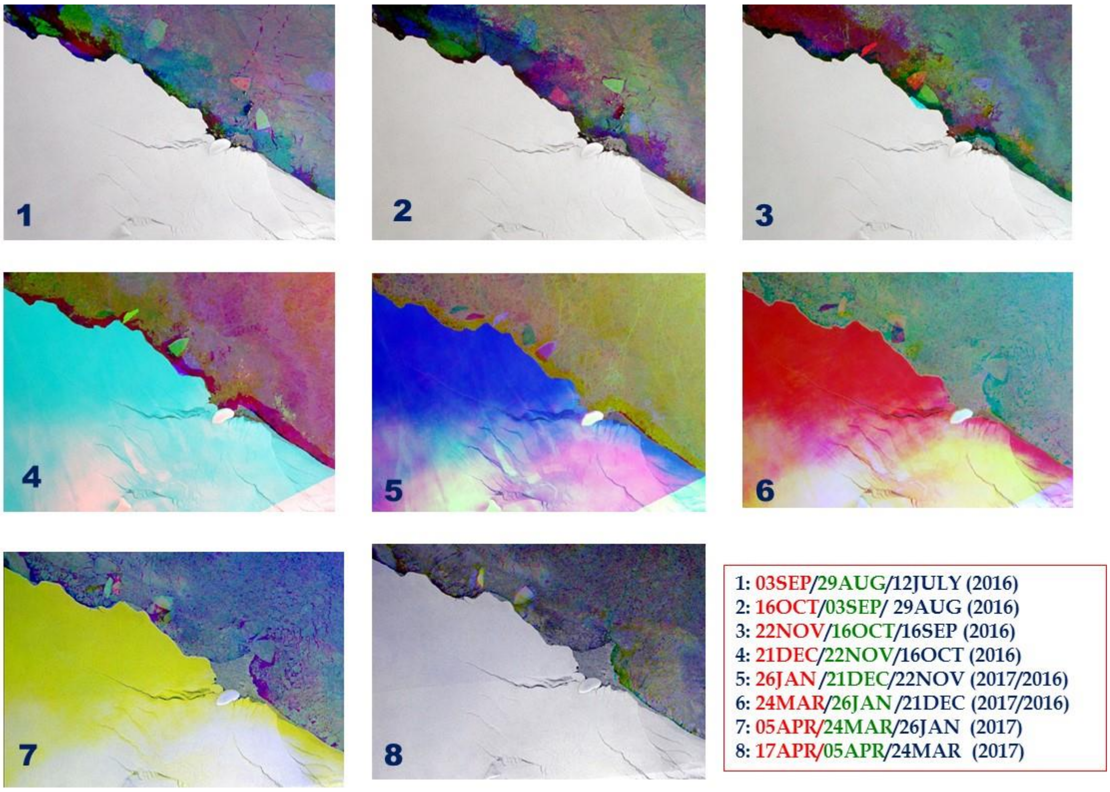


Figure- 10: Sentinel-1 Multi-temporal FCC: July 2016 – April 2017. The FCCs are generated from running monthly data by advancing one month. In Figures 10_1, 10_2, 10_3 and 10_8, ice shelf is white, which shows less variations of the targets. One of the summer data add colour in FCC (10.4 TO 10.7). Implication of melting during this period is clear and is supported by sigma0 analysis.

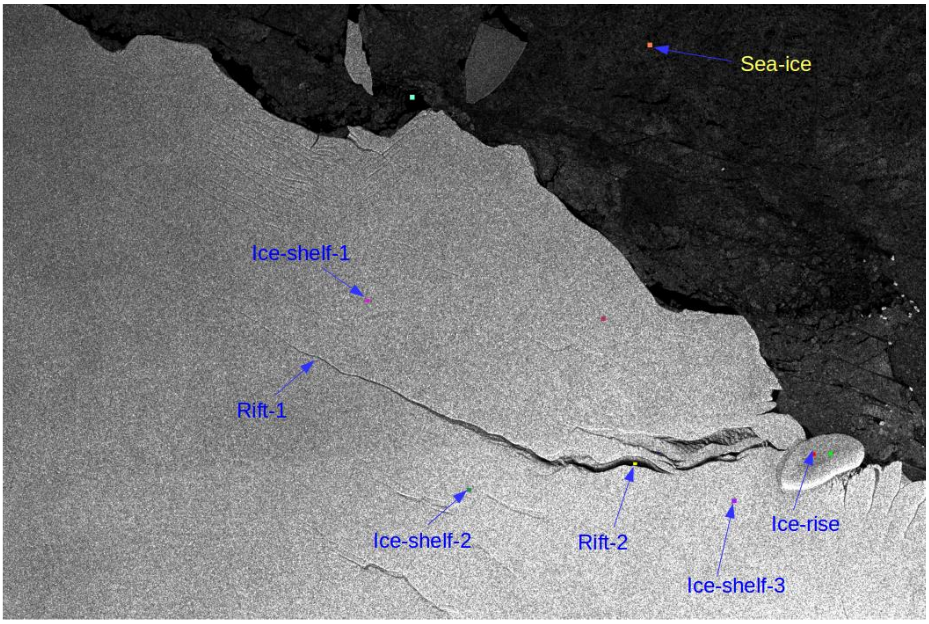


Figure- 11: The locations of Ice Features on Sentinel 1 image

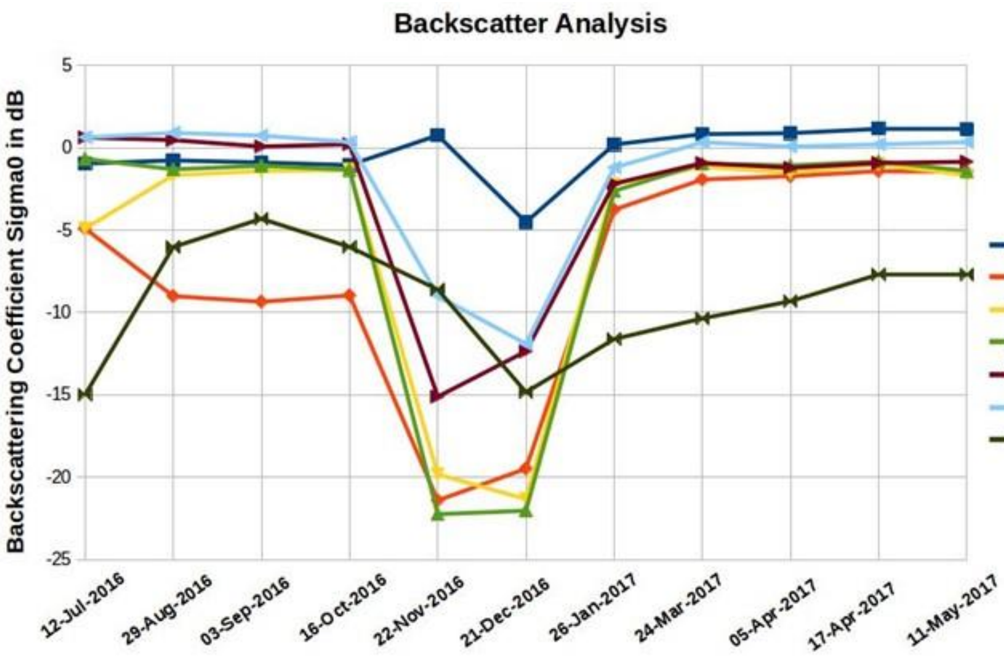


Figure- 12: Variation in the Sigma 0 in the transition periods: Winter (2016 Aug-2016 Nov)–Summer (2016 Dec-2017 Feb)-Winter (2017 Mar- 2017Apr). All targets show a dip in sigma0 values during the summer period. The dip is minimum for ice rise. Rift 1 is signature is taken in the beginning of rift and rift 2 near end. The rift 2 is covered by snow for the winter months and its sigm0 is high in the winter months compared to rift 1. Sea ice signature is as low in July and steadily increasing as sea ice cover increases. Then towards the summer it starts deforming and sigma0 decreases.

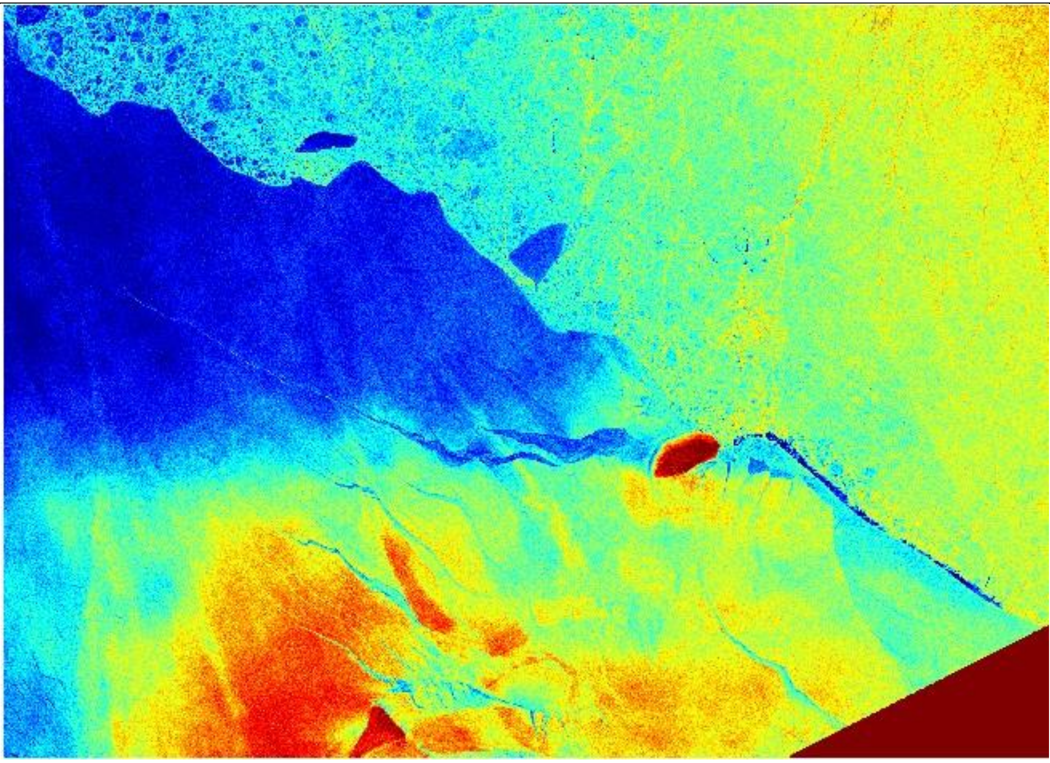
7.0 Automatic Rift Extraction

Texture based analysis has been carried out to automatically extract the rift in Larsen-C ice shelf during Decemeber-2016 to April 2017 and results are shown in Figures 13-15. The top image is the scaled sigm0 and bottom one the texture. In the figures 13-14 top images, blue shade represents very low backscatter due to melting of top shelf layer. Texture based analysis like Grey Level Co-occurrence Matrix (GLCM) has been tried to identify the rift and its progress. Correlation matrix is computed from grey level difference vector (GLDV) with an optimum window size (21 x 21). This texture analysis is done using in-house developed Matlab script. The texture images show rift in red linear features. The coastal boundary as well as ice rise boundary also has seen in this colour. In Figure 14 the rift has come very vividly.

This is the data of 26 January 2017. This time melting has reached its plateau and will continue till February. In Figure 15 the rift is filled with snow and is not picked by automatic feature extraction module. This show that the summer / peak summer images will clearly demarcate the exact extend of the rift as the top surface snow is melted away.

The rifts and crevasses are come out as red colour along with the coastal boundary along with other boundaries such as ice rise boundaries along with leads in the sea ice. A lead is fracture in the sea ice and a linear area of open water that can be used for easy navigation. The rift is clearly seen in the Jan image. The rift is suppressed by snow fall over the rift tip as indicated in January and April images in Figures 14 and 15.

Figure-16 shows the major ice calving event researchers are looking for. The vector layer was digitised through the rift propagation and interpreting its patterns. An area of ~ 6500 km^2 out of ~ 50000 km^2, almost 13 %. The area will be calved in the near future as the aerial survey by international Antarctic research agencies also supports an early event. The shape is carved by along the rift and interpreting the image deformation and further trend in rift propagation on the June 2017 image.



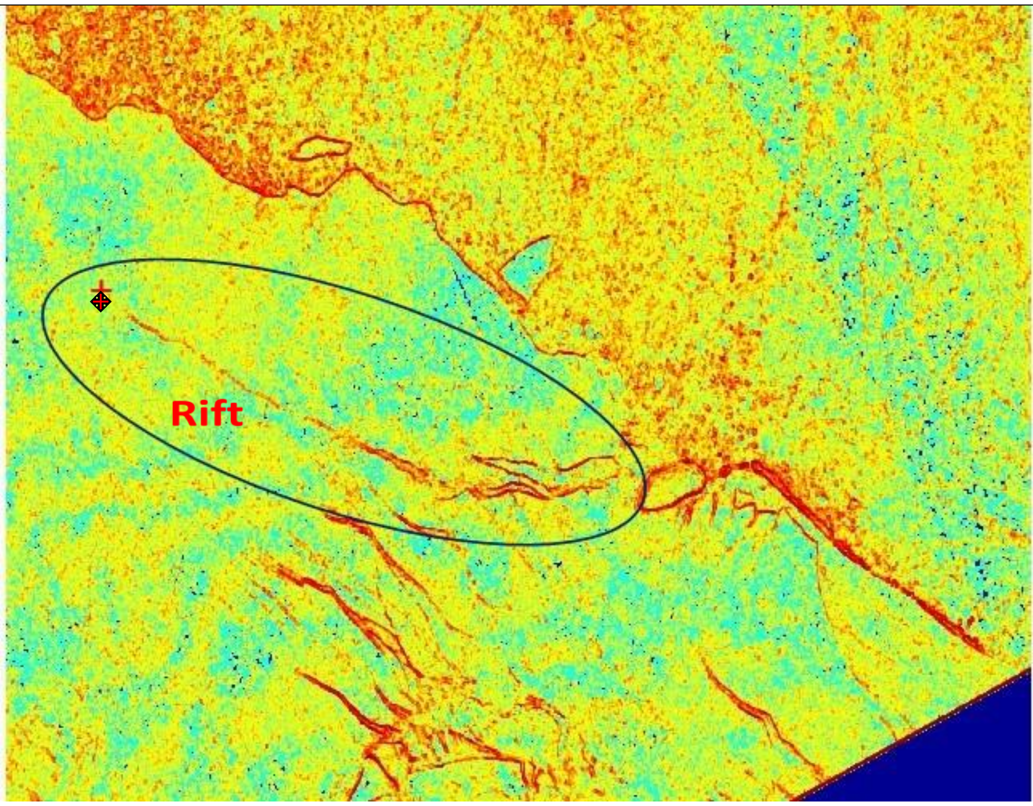


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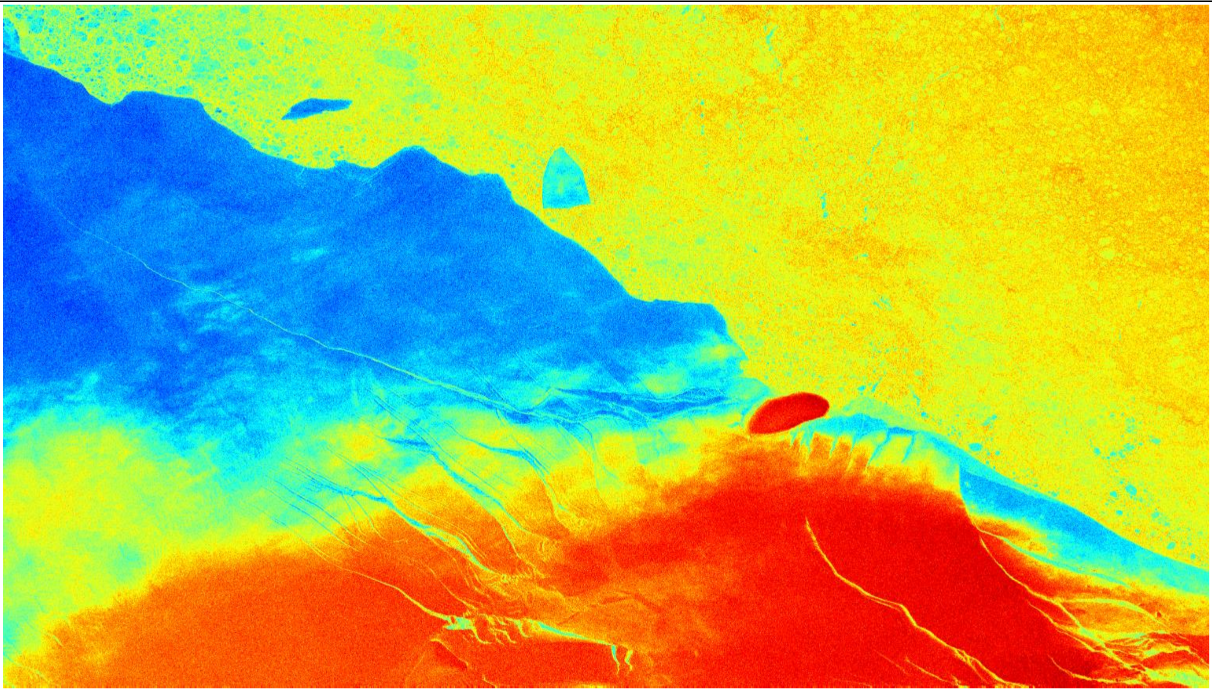
Figure-13: Sentinel image of Larsen-C acquired on 21/12/2016; (Top): Scaled backscatter image; (Bottom): Grey Level Co-occurrence Matrix (GLCM) texture analysis (correlation) of the top image.



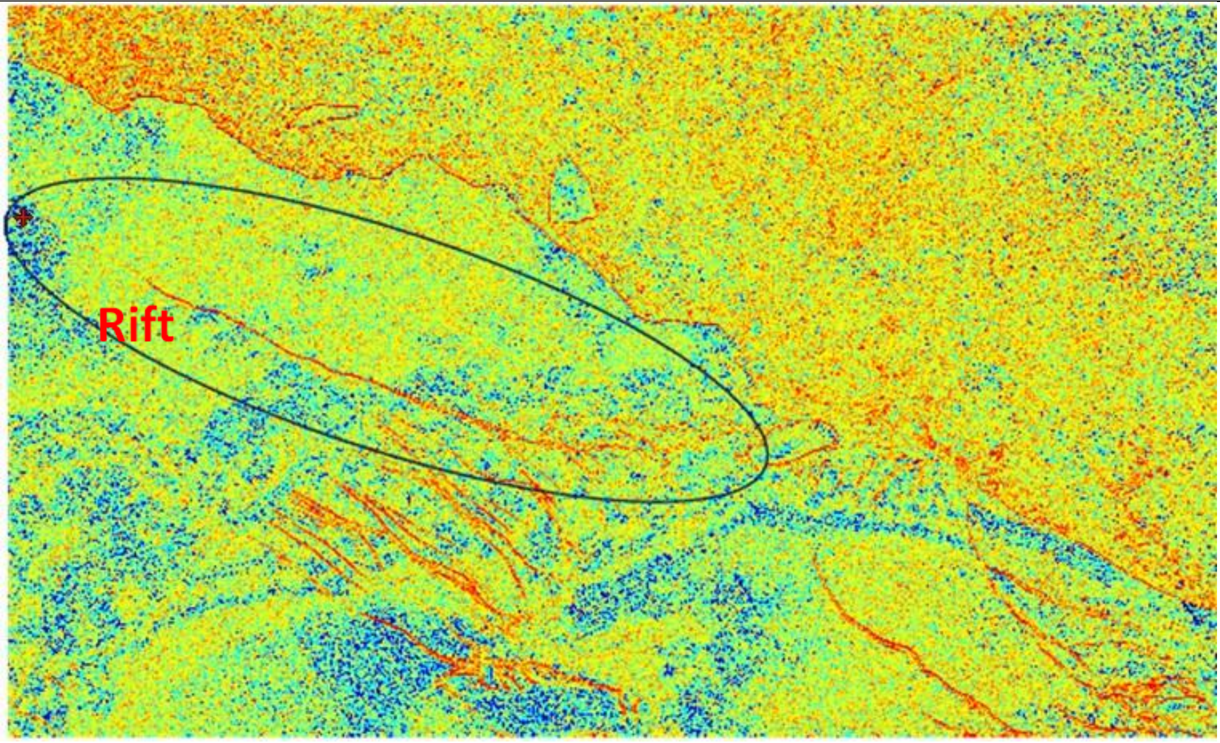
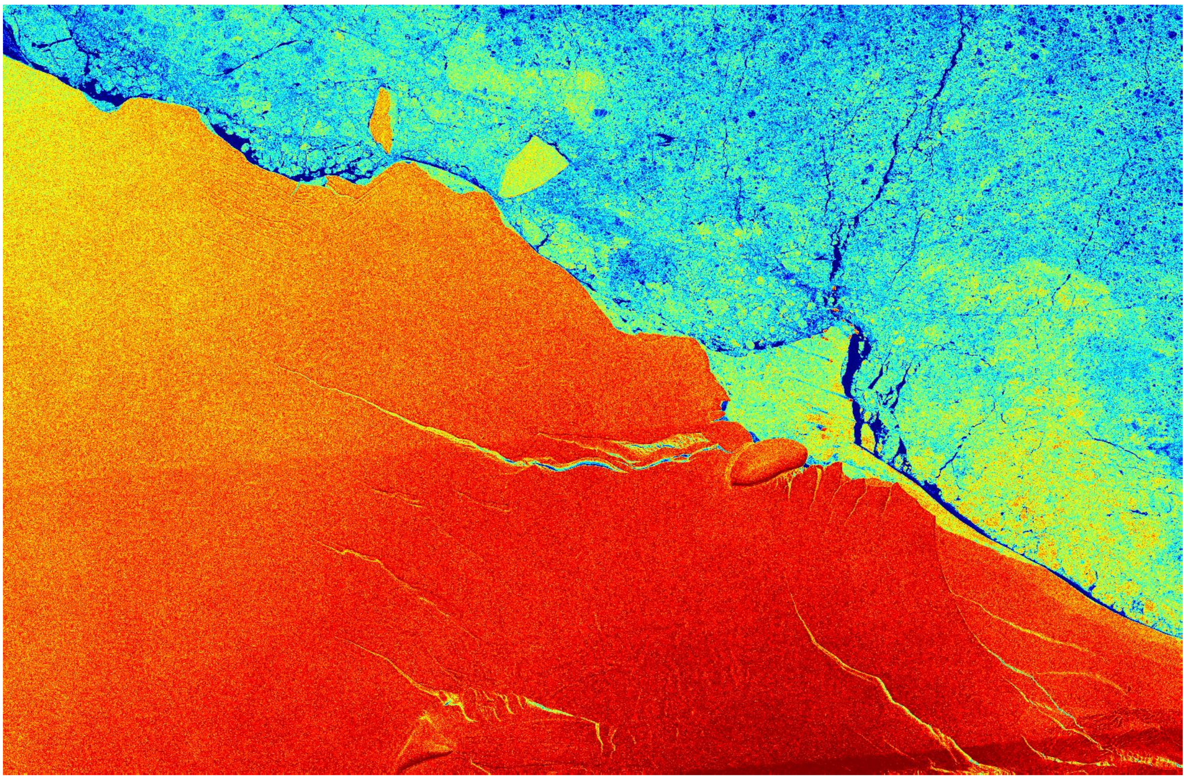


Figure-14: Sentinel image of Larsen-C on acquired 26/01/2017; (Top): Scaled backscatter image; (Bottom): Grey Level Co-occurrence Matrix (GLCM) texture analysis (correlation) of the top image.



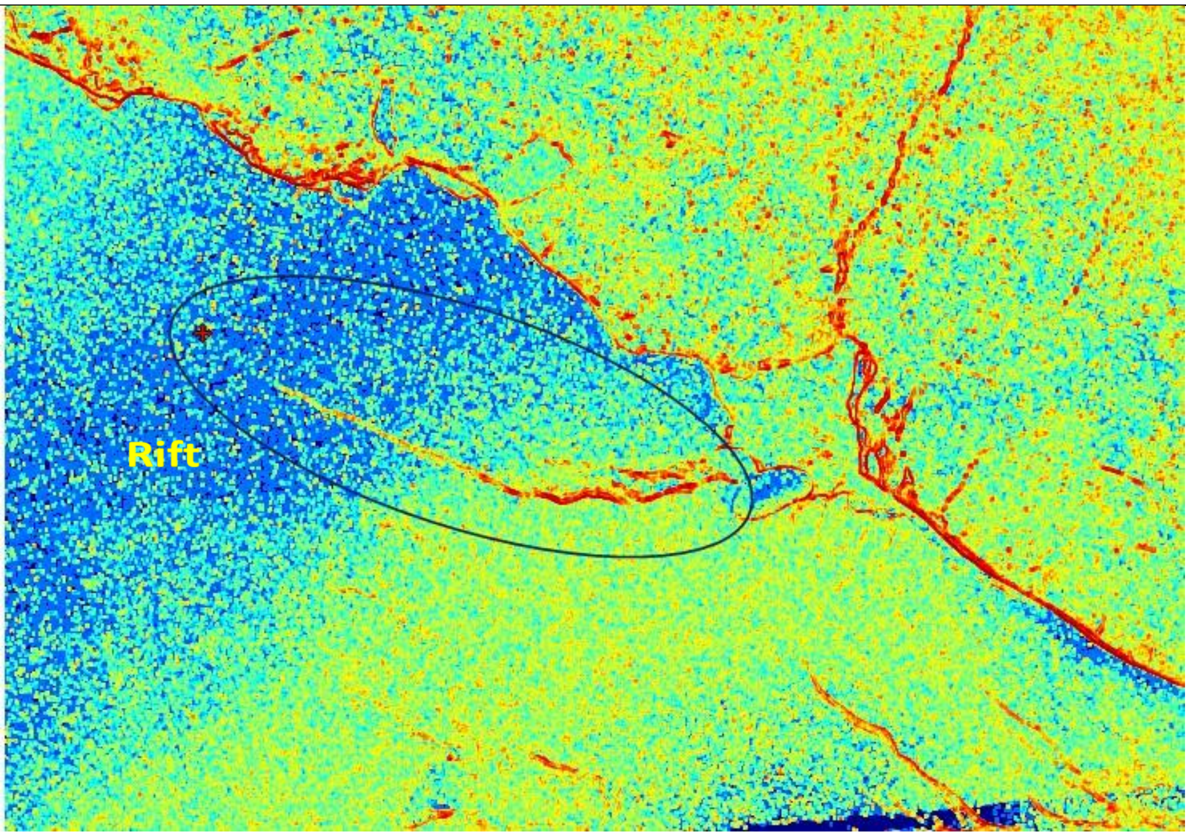
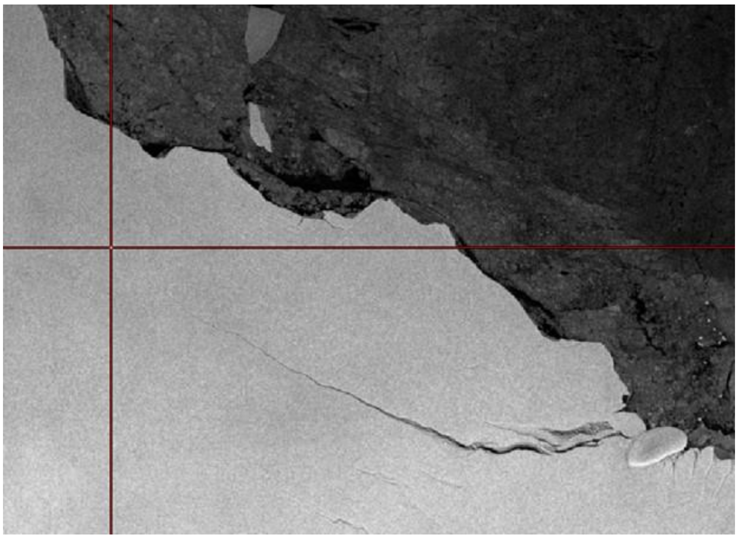


Figure-15: Sentinel image of Larsen-C acquired on 17/04/2017; (Top): Scaled backscatter image; (Bottom): Grey Level Co-occurrence Matrix (GLCM) texture analysis (correlation) of the top image.



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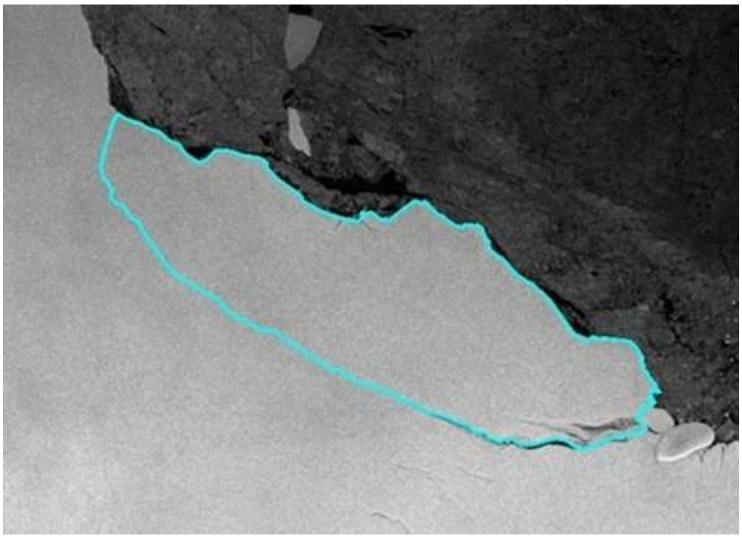

16 b

Figure-16 a; The visible rift tip (Cursor+). b; Projected near future calving event extracted from 28 June 2017 Sentinel image (onscreen digitisation).

7. 0 Results and Discussions:

The calving events in the early 2005 and the rift propagation in the Larsen C ice shelf from 2000 till present day in the Antarctic peninsula over Larsen C has been studied using MODIS and Sentinel-1 data.

Figure 2 and Figure 3 show the MODIS data time series from of the Larsen C depicting the coarser level rift propagation and ice calving events. As it is evident from Figure 2, the rift propagation is taking a low pace during 2000 to 2013. The summer period 2014-2015, 2015-2016 and 2016-2017 witnessed an accelerated rift propagation. During the summer of 2004 2005, there was a calving event in Larsen C ice margins. This is evident from the Figure 4 and Figure 5. The major chunk of ice to the tune of ~ 1100 km^2 during the summer months of Dec 2004 to 2005 Jan followed by a small ice calving event before. The event occurred between October and January. The presence of fast ice created a buttressing effect and the iceberg was fastened to the shelf. Between January and February 2005, the buttressing effect of Sea Ice / Fast Ice was removed due to melting and the iceberg got disintegrated. The deformation happening on the east of Gipps Ice rise is also alarming. The results show that the stability of the ice shelf is affected drastically from 2014 onwards. This is also shown by the international community. Development of the stress after the ice calving event is visible on the MODIS data. This propagation rate growth made many to believe the eventuality of the calving event to happen.

The images from Sentinel-1 data as depicted in the Figures 6 - 8 also confirms the accelerated rift propagation. The images of Jan / Feb 2016 and 2017 clearly shows the extend of rift propagation as compared to other images as the melt water percolation is visible in these images. The strong reflection from the rift is an example of that. As the winter begins, snow fall and freezing of the meltwater is clearly demarking the extend of the rift.

Backscatter intensity changes were studied over two transition period. The multi-temporal FCC clearly brings the metamorphosis of ice features. In Figure-10, images 1,2,3 and 8 show that changes happening in the ice shelf are minimum. In both winter season only drastic changes happening in sea ice. Images 4,5,6 and 7 shows changes in both sea ice and ice shelves. This is attributed to the presence of summer data in the FCC(DEC/JAN). Figure-11 shows the areas of site selection. Figure-12 depicts the mean value of backscatter intensity over the rectangular patches selected as shown in the Figure -12. The study shows that the ice-rise or grounded ice shelf withstands the backscattering variation to a bare minimum. The ice shelf regions and crevasse region shows a sudden dip in the transition period (Nov to Dec: winter to summer) and a sudden rise in the next transition (Jan – March: summer to winter). Feb data for the same path/raw was not available.

The exact extent of rift propagation is clearly visible on January image. The melting has reached a sufficient threshold to pick the signatures as seen in the image. As the winter begins, due to the presence of snowfall and freezing of the melt water make it difficult to demarcate the rift propagation terminus. One can demarcate the rift length at the time of melting accurately than that at the time of freezing and snow covered. Presently the rift propagation is advanced to a state in which there is a small gap of in the East and West to make the shelf to calve. This implies that both Larsen C and Larsen D collapse will be happening in the near future. The previous studies also demonstrated the rift propagation has accelerated from 2014 onwards which is corroborated by MODIS images and Sentinel images. The rift is propagating both in its length and breadth.

Texture based analysis has been carried out to automatically extract the rift in Larsen-C ice shelf during Decemeber-2016 to April 2017 and results are shown in Figures 13-15. We have tried entropy, angular second moment, dissimilarity and GLDV (Grey Level Difference Vector) based analysis with varying window sizes and found correlation based result with window size 21 x 21 is best among all the previous output.

Figure-16 shows the major ice calving event researchers are looking for. The vector layer was digitised through the rift propagation and interpreting its patterns. An area of approximately ~6500 km^2 out of ~ 50000 km^2. The area will be calved in the near future as the aerial survey also supports an early event. The shape is carved by along the rift and interpreting the image deformation and further trend in rift propagation on the 28 June 2017 image.

8.0 Conclusion:

The Larsen C rift propagation is monitored using available MODIS data from 2000-2017 and using Sentinel-1 data from Oct 2014 to May 2017. From both the image sets it is very clear that the rift propagation has taken an accelerated jump from 2014 onwards. The dip in the backscattering values suggested an increased melt conditions which are prevalent on the summer images of 2016 and 2017. The beginning of the winter is also witnessing an increased snow fall, filling the cracks in the advancing portions making difficulty in quantifying the rift propagation. These are evident in the rift as depicted in January and February images vs those observed in the March April images of both 2016 and 2017. The ice calving is evident from the latest datasets of Sentinel on 28 June to a tune of 6500 km^2.

The study lacked the availability of the systematic acquisition of Indian Satellite data over Antarctic peninsula. RISAT-1 future missions and NISAR mission will be utilised for similar studies. Automatic techniques will be developed for detecting and monitoring calving events and rift propagation.

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