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Use of SARAL AltiKa Geophysical Products towards the study of cyclone 'Phailin'

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Abstract*— *The Bay of Bengal Cyclone 'Phailin' has made landfall on 12 October 2013 along the coast of Orissa in the Indian region. The event was studied using the geophysical products from SARAL AltiKa, the Ka band satellite altimeter placed in space orbits by Indian Space research Organization (ISRO). The altimeter data has captured the features of ocean and atmospheric dynamics developed during the cyclonic event. The altimeter based geophysical products like; Significant Wave Height (SWH), Surface Wind Speed (SWS) and Sea Surface Height Anomaly (SSHA) during the cyclonic event were studied to explain the impact of cyclone at the sea. The tropical cyclone 'Phailin' induced features at the sea surface have shown large variations along the path of cyclone covered by the along track SARAL AltiKa data. The products of Jason-2, a contemporary satellite altimeter in Ku band were compared. High amplitude winds corresponding to cyclone was observed with a central low in the along track data. The SWH data have also shown their changes under the impact of the cyclone. The SSHA have reduced indicating diverging field along the cyclone track. The changes are captured better in high resolution altimeter waveform data in 40 Hz of SARAL AltiKa and Jason 2 data in 20 Hz.

***Index Terms*— Tropical cyclone, Phailin, scatterometer, altimeter, Oceansat-2, SARAL.**

I. INTRODUCTION

The tropical depression developed in the Gulf of Thailand on October 4, 2013 passed over the Bay of Bengal and made landfall at the Gopalpur coast, Orissa around 2130 hours on 12 October 2013. The lowest atmospheric pressure recorded as 936 mbar with one minute sustained wind of 260 Km/h (160 mph as reported in Wikipedia on 20 November 2013). The Category 5 cyclone in Saffir-Simson Hurricane Wind Scale (SSHWS) has lasted till 14 October 2013. The event was monitored with ground based radars, while at the sea; the observations were restricted to information acquired through moored buoys deployed in the coastal water or those drifting in offshore region. The satellite sensors provided synoptic view of the event, which restricted their observation to the surface of the sea. The cyclone induced surface roughness used in the estimation of wind was captured by active sensors like, Scatterometer and Altimeter. They provide wind and related geophysical products that helped to assess the state of sea during cyclone. The Oceansat-2 scatterometer (OSCAT) and AltiKa onboard SARAL from Indian Space Research Organization (ISRO) are recent additions. The OSCAT wind products are generated in 50 Km spatial resolution at NRSC. Recently scattterometer winds are prepared in the spatial resolutions of 25 Km and 12.5 Km from PODAAC (Physical Oceanography Distributed Active Archive Center). Whereas the satellite altimeters like, SARAL AltiKa, and Jason-2 provide geophysical products in high spatial resolution along their track. This helped a better view of the cyclone impact on the sea surface. However, such observations of cyclonic events remained an opportunity due to their 35 days repeat coverage for SARAL AltiKa and 10 day for Jason-2. SARAL AltiKa coverage of the cyclone 'Phailin' was an opportunity to study impact of the cyclonic events. Jason-2 and OSCAT products of October 2013 in the Bay of Bengal are used supplement the event study and compare the AltiKa products. Earlier, the low pressure events study with altimeter data was carried out in the North Atlantic Ocean [1]-[4]. Guidelines have also been provided to use of algorithms and develop geophysical products for cyclonic events using satellite altimeter. The present work explores the response of Ka band altimeter [5]-[8]. Onboard SARAL, a Ka band sensor is deployed for the first time from Indian soil.

II. DATA AND METHODS

A. Cyclone 'Phailin'

The cyclonic event has passed through the Bay of Bengal before making landfall along the coast of Orissa at Gopalpur-on-sea on 12 October 2013 around 1800 Hours. A drifting buoy numbering 23598 moved from 86.14^{o}E to 88.95^{o}E along 13^{o}N. This has recorded atmospheric pressure variation in the range of 1004 to 1014 mbar with low values on 11 October 2013 (Figure 1). The water temperature along its path remained between 28.5 and

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29.5°C. The buoy was dragged for about 400 to 500 Km to the west recorded 6 to 8 mb drop in atmospheric pressure. A westerly current of 4 to 5 cm/s has been observed with the drifting buoy. While the satellite altimeters like, SARAL AltiKa along with Jason-2 provide a scope to explore further on the cyclonic event.

India Meteorological Department (IMD) on 9 October 2013 reported on the formation of a deep depression centered at 13°N, 93.5°N with wind of 50 to 60 Kmph gusting at 70 Kmph. IMD predicted its landfall along the coast of northern Andhra Pradesh and Orissa as a very sever cyclonic storm with sustained wind of 175-185 Kmph. As predicted the cyclone Phailin made its landfall in the afternoon at 1800 Hours on 12 October 2013 with wind attaining 200 Km/hr.

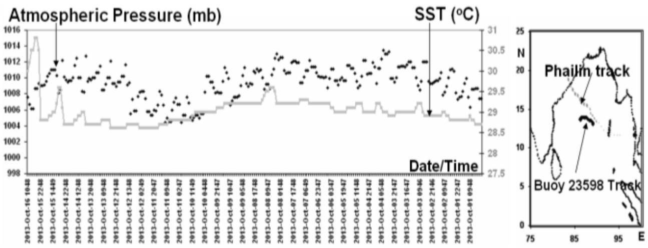

Fig-1: Drifting buoy 23598 from 1 to 16 October 2013 show pressure and water temperature (°C) along with the track in the Bay of Bengal.

Under this circumstance, observations are difficult to make with ground based sensors. These events do not provide enough time to organize experiments to collect enough data. Even collecting quality data is difficult. Whatever the arrangements made, the field based observation remained difficult for the occasion. For such an event, satellite with suitable sensors provides a systematic and unbiased observation. In visible spectrum, satellite sensors provide cloud movements to study cyclone. This however, restricts the view to sea surface changes. Active microwave sensors like, sactterometer and altimeter having the capability to penetrate thick clouds provide sea surface observations to facilitate estimation of the surface wind. While the wind vectors are estimated from scatterometer observations in 50 km grids, the surface wind speed is estimated from nadir viewing altimeters in high spatial resolutions of six kilometers along the satellite track. This helps to track the cyclone impact with high precision and understand the type of changes at the sea around it. However, low temporal resolution of altimeter made such advantages an opportunity based on the coverage of a cyclonic event. The present study on the cyclone 'Phailin' with SARAL AltiKa data help to explore the details.

B. OSCAT Wind

The OSCAT wind is provided since 2010. The vector wind products are generated with the help of a pencil beam rotating parabolic antenna operating in the active microwave range of Ku band (13.515 GHz). The scatterometer collected data in two view angles with the inner beam 48.9 degrees of incident angle and outer beam of 57.6 degrees able to cover a swath of 1400 km and 1840 Km, respectively. The sensors provide 50 x 50 Km vector wind field for the globe in every 2 days[7]. The wind was used in the analysis of global weather and climatic studies including cyclonic events like the present one in the Bay of Bengal.

The OSCAT wind data of the cyclone remained around 20 m/s along the path and mapped for the northern Bay of Bengal (figure-2). The OSCAT winds of 50 km resolution captured the cyclonic event during its passage from the Andaman Islands to the Orissa coast. In the descending pass of OSCAT on 9 October 2013, the event appeared around the Andaman Islands. On 10 October 2010, wind attained a peak speed of about 24 m/s and seen reducing its intensity in the descending pass. The event achieved maximum strength of 28.38 m/s on 11 October 2013 and hit the coast in the afternoon hours on 12 October 2013.

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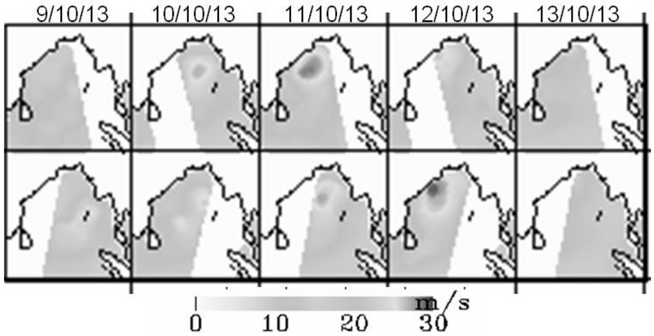

Fig 2: Oceansat-2 Scatterometer wind speed observations between 9 to 13 October 2013 in the Bay of Bengal with ascending passes in the upper row and descending passes in the lower half.

C. Altimeter Data Products

SARAL AltiKa launched on 25 February 2013 is providing altimeter data products 'ready to use' along its track. The nadir looking Ka band altimeter track 14 passes every day in ascending mode and an equivalent number of passes in descending mode. The repeat cycle of 35 days make the task of capturing cyclonic events difficult. However, the cyclone Phailin was viewed with SARAL AltiKa on a number of occasions in October 2013 (table-1).

Table-1: Satellite atimeter along track data used.

Cycle/Path	Date-Time YYYYMMDD_ HHMMSS	Product code*
6/939	20131007_235921 to 20131008_004939	SRL_IPS_2PTP
6/967	20131008_232742 to _20131009_001800	SRL_IPS_2PTP
6/982	20131009_120211 to _20131009_125229	SRL_IPS_2PTP
7/051	20131011_233327 to _20131012_002345	SRL_IPS_2PTP
7/066	20131012_120757 to _20131012_125815	SRL_IPS_2PTP
7/137	20131014_233913 to _20131015_002931	SRL_IPS_2PTP
194/14	20131008_064619 to 20131008_074232	JA2_IPS_2PdP
194/40	20131009_070754 to 20131009_080407	JA2_IPS_2PdP
194/53	20131009_191841 to 20131009_201454	JA2_IPS_2PdP
194/116	20131012_062013 to 20131012_071626	JA2_IPS_2PdP

*(SAL = SARAL; JA2 = Jason-2)

The geophysical parameters like, SSHA, SWH, and SWS along with water vapor and liquid cloud water were extracted to analyse the cyclonic event. The operational and interim data products made available in few hours and 3 to 4 days of satellite pass respectively helped to study the event in near real time. The interim sensor products (native and reduced mode) are used in the present study. High resolution in altimeter data is achieved with interim native data products in 40 Hz waveform observations. While Jason -2 waveform data are available for Ku and C band in 20 Hz resolution mode.

III. GEOPHYSICAL PRODUCTS

The SSHA is derived from the satellite range of the altimeter echo, while SWH is estimated from the slope of the leading edge of the echo. The wind speed is estimated form the intensity of the echo. The well validated

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geophysical data products as GDR available for public use after 40 days. While the OGDR (Operational Geophysical Data Records product in three to four hours of satellite pass) and IGDR (interim products available after three days) products along its track are available for use. The satellite products are available for 1002 passes in every 35 days towards a full cycle of global coverage[8]. The distance between two passes was 80 kilometers at the equator. For the SARAL data sets collected to study the cyclonic event in the Bay of Bengal, path 66 remained close on 12 October 2013. While path 982 on 11 October 2013, path 967 on 8 October 2013 and path 939 on 7 October 2013 passed through the Bay of Bengal used to support the present study. Jason-2, a Ku/C band altimeter similar to SARAL also used in this study for the data sets of paths 53 and 40 on 9 October 2013 and data from path 14 on 8 October 2013 (Figure-3).

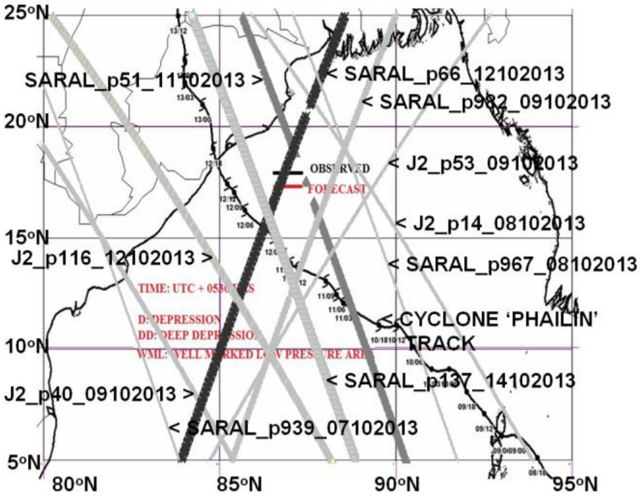

Fig-3: Altimeter tracks in Bay of Bengal from 7 to 12 October 2013.

Along track data in 1 Hz resolutions and waveform data in 40 Hz mode for SARAL AltiKa and 20 Hz mode for Jason-2 are used. Jason-2 products being well validated, they are used to compare corresponding with the SARAL geophysical products. Altimeter products also carried parameters like, inverted Barometer correction, ECMWF wind in latitudinal and longitudinal direction, radiometer wind (available with Jason-2 altimeter), water vapor and cloud liquid water along with mean sea surface, tide and bathymetry information. Altimeter winds available in high spatial resolution are of significance to the cyclonic event study in comparison to scatterometer and radiometers wind products in low spatial resolutions. This help to understand the cyclonic events in better spatial resolution, which otherwise difficult to access data without field campaign. Air borne and automated sensors deployed to get a better view has limited success. In this direction, SARAL AltiKa provide an opportunity to collect key geophysical parameters to study the ocean and atmosphere processes more precisely on the passage of a cyclonic event in the Bay of Bengal.

A. Sea Surface Height Anomaly (SSHA)

AltiKa, the Ka band sensor deployed first time in the history of altimeter operations to accommodate low ionosphere interference to achieve precise and accurate estimations of sea level. However, interference of rainfall in Ka band signals loose 10 percent of tropical area difficult to extract at any point of time. A two band radiometer onboard SARAL in 23.8 and 37 GHz used to improve water vapor corrections. The eight millimeter wave of SARAL AltiKa define sea surface better than those of Ku band signal. High frequency (4 kHz) and large band width (500 MHz) define the signal of the echo better focused and record a high rate of independent observations. Thus, having less interference the SSHA observations made from the range information is expected to improve. However, the echo influenced by intermediate atmosphere and ocean surface variations like, ocean, earth and pole tide, barometric pressure, and water vapor need corrections. The SSHA was estimated subtracting mean sea surface from sea surface height, which is estimated subtracting range information from satellite altitude. SARAL AltiKa SSHA is estimated as follows, SSHA (10^{-3} m) = Altitude –range –gim ionosphere correction – model dry troposphere correction – model wet troposphere correction – Sea state bias correction – solid earth tide – geocentric ocean tide height solution 1 – geocentric pole tide – inverted barotropic height correction – high frequency fluctuations –mean sea surface.

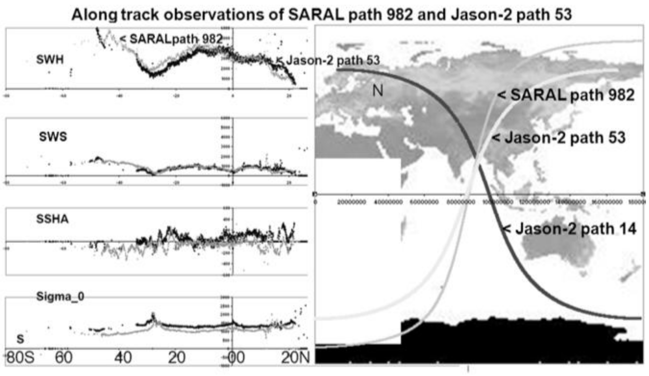

Fig-4: Along track altimeter geophysical parameters of SSHA, SWH, SWS and sigma_0 on 9 October 2013 of SARAL AltiKa path 982 (light grey) and Jason-2 path 53 (deep grey).

The SSHA for the along track observations on path of 982 SARAL and path 53 of Jason-2 on 09 October 2013 remained close to each other in the near equatorial belt and differed significantly in the sub tropical region (Figure 4). The low values in the Bay of Bengal segment can be attributed to diverging flow under the impact of cyclone. The parameters like, wet troposphere, sea surface bias, and inverted barometer height used as a correction parameter in the estimation of SSHA also expected to carry signature of cyclonic event in the along track data.

B. Surface Wind Speed (SWS) Products

The wind speed is estimated from altimeter based on intensity of the altimeter echo, represented as sigma_0 values. The wind speed model function is estimated at 10 meter above the sea surface and is accurate to 2 m/s. The products are used to explain local processes resulted due to the cyclonic event. SARAL AltiKa winds on path 982 have followed closely with Jason-2 path 53 observations, even though they differed by 7 hours and passed in ascending and descending mode, respectively. Both the paths are in close proximity to the track of cyclone path. The wind from both the altimeters followed a good linear relationship with ECMWF wind (r = 0.91 for Jason-2 and r = 0.67 for SARAL AltiKa as shown in Figures 5 and 6). The ECMWF wind was close to Jason-2 wind. The wind was estimated well in the northern Atlantic Ocean accurate to an extent of 2 m/s in magnitude while accuracy remained around 5 m/s in the southern Pacific Ocean. The SARAL winds are underestimated by about 2.2 m/s. For Jason 2 altimeter data, there was radiometer wind estimated from onboard three channel radiometer in 18, 23 and 35 GHz.

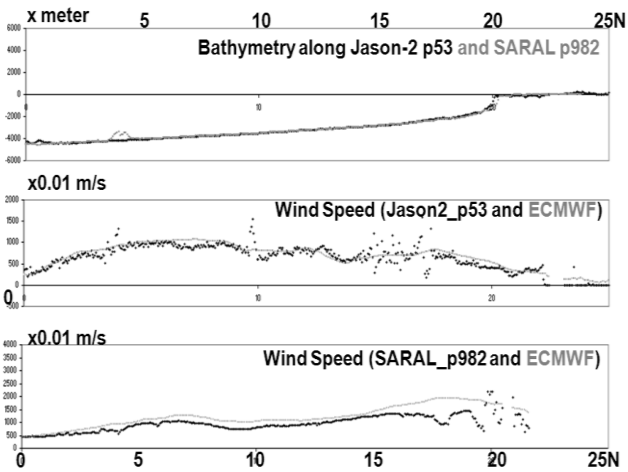

Fig-6: Altimeter wind fields of SARAL (path 982 date 09102013 on left) and Jason-2 (path 53 date 09102013 to right) compared with ECMWF wind.

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C. Significant Wave Height (SWH) Products

Surface wind and waves complement each other. The SWH is estimated based on the empirical relation between slopes of the leading edge of the altimeter echo with sea surface observations of wave height. The SWH from SARAL and Jason-2 are well related (r = 0.9). In the region of cyclonic event, the wave height has shown a wide range of variation.

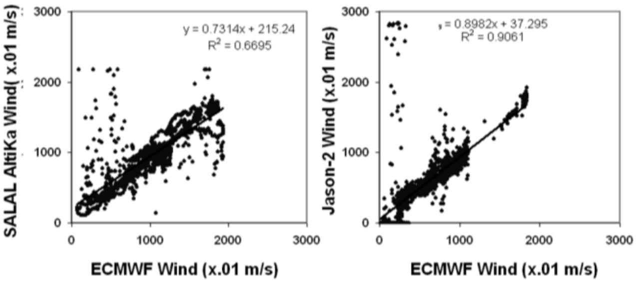

Fig-5: Along track bathymetry and ECMWF wind along with altimeter wind on 9 October 2013 of SARAL AltiKa path 982 and Jason-2 path 53.

IV. IMPACT OF PHAILIN

The cyclonic event was studied with 50 Km spatial resolution OSCAT wind form 9 to 13 October 2013 in ascending and descending passes. Recently, the spatial resolutions have been improved to 25 Km at NRSC and 12.5 Km at Royal Netherlands Meteorological Institute (KNMI) and National Oceanic and Atmospheric Administration (NOAA). The OSCAT wind is available around the globe every alternative day, while altimeter winds are provided for 1Hz foot prints of about six kilometers in ground resolution along the track of satellite pass. SARAL takes thirty five days for a repetitive observation with 1002 passes each separated by about 80 Km at the equator. The altimeter and scatterometer use sigma_0 as the basis of wind estimation. The products however, differ in their utilities as the scatterometer provide wide swath wind vector in low resolution, while altimeters provide along track wind speed in high spatial resolutions. The altimeter winds are used to investigate further details along the track that define the eye of cyclone much better. With SARAL AltiKa and Jason-2 winds, the cyclonic event was studied to investigate details of their distribution along the satellite pass (figures 7 to 9). The OSCAT wind has recorded a high value of about 28 m/s along the Orissa coast on 12 October 2013 (Figure 2). A maximum wind of 21.8 m/s was observed with SARAL on 12 October 2013, while Jason-2 recorded 16 m/s. The observations are made with SARAL products on the paths of 939, 967, 982, 51, 66 and 137 and Jason-2 products on the paths of 14, 40, 53 and 116 covering from 7 to 14 October 2013. SARAL winds are about 2 m/s lower than Jason-2 wind. The OSCAT wind in the region of cyclonic event within 14 to 18^{o}N recorded 9 to 11 m/s, while the ECMWF wind increased from 5 to 8 m/s. Altimeter winds related well with the ECMWF wind except in the region of the cyclonic event. Low winds close to the center of cyclone and high values at the boundaries observed along the track altimeter data. The cyclonic events around 17^{o}N captured well with altimeter wind field. Jason-2 radiometer wind has also shown winds as high as 29 to 30 m/s (Figure 7).

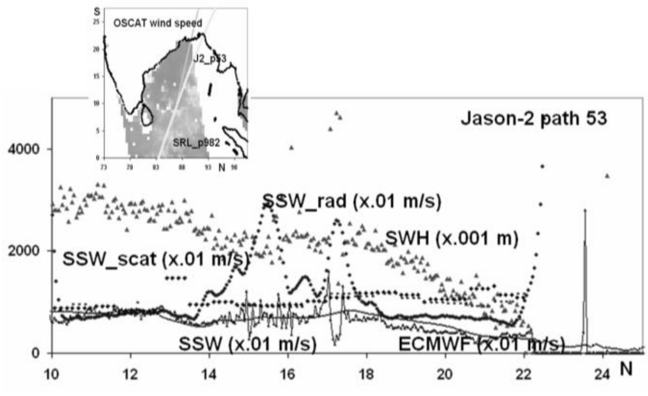

Fig-7: Altimeter wind and Oceansat-2 scatterometer wind field were compared to ECMWF and Radiometer wind field along track of Jason-2 path 53 on 9 October 2013.

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The radiometer winds showing very high values in the region of cyclonic event need corrections. Altimeter wind thus provides an edge over the other wind products (i.e. radiometers and scatterometers) for resolving features of low pressure event. In this regard, SARAL AltiKa recorded a more realistic signature of low pressure event as seen along its path 66 on 12 October 2013.

V. HIGH RESOLUTION ALTIMETRY

A. Coastal Altimeter Waveforms

Altimeter data on 9 and 12 of October 2013 on path 982 and 66 for SARAL and path 53 of Jason-2 analysed in 1 Hz mode (Figures 8 to 10). On 9 October 2013, wave height reached as high as 8 meters on SARAL path of 982 between 12 and 14°N, while wind reached around 21.5 m/s around 12.3°N (Figure-8). A low wind of 1.3 m/s was observed around 14°N and increased gradually northward to 5.5 m/s at 20°N. To the south of 11.7°N, wind was 5.7 m/s. Jason-2 passed on path 53 along the track in six to seven hours afterwards in ascending mode. A low wind was observed around 17.3°N with wind reaching to 3.81 m/s at the center which was about 6 to 7 km with high winds of about 13 to 16 m/s on the southern edge and about 8 m/s to its north (Figure 9). The SWH of 6.5 meters was seen around 15°N and reduced to about 4.6 meters at the center of low pressure event. The wind reduced from 6.6 m/s to 3.2 m/s towards the coast. While the wind field between 14°N and 17°N remained noisy with speed ranged from 4 m/s to 12 m/s. The SSHA indicated a downward slope of about 20 cm towards the coast. On 12 October 2013, SARAL observations made on path 66 while the low pressure event moved towards the coast (Figure 10). Along the path SWH reached maximum value of 9.2 m along the coast which was as low as 3 m in the south. The wind speed reached maximum value of 21.8 m/s around 20°N. A low wind of 6.85 m/s remained around 19.7°N, whereas wind speed of 8 m/s was observed in the south. The negative SSHA of 35 to 45 cm was observed between 15 and 19°N.

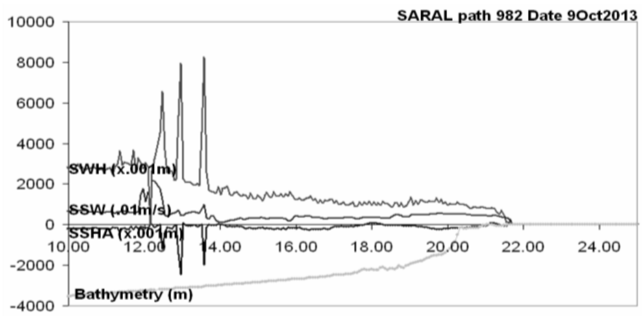

Fig-8: SWH (x0.001 m), SSW (x0.01 m/s) and SSHA (x0.001 cm) of SARAL path 982 on 9 October 2013

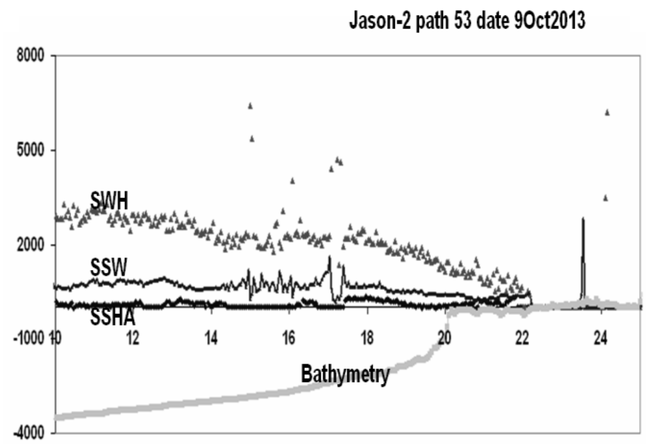

Fig-9: SWH (x0.001 m) , SSW (x0.01 m/s) and SSHA (x0.001 cm) of Jason-2 path 53 on 9 October 2013

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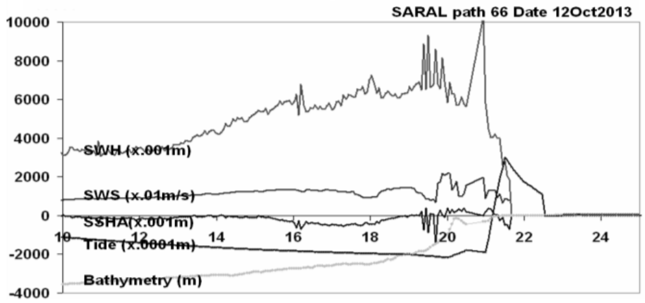

Fig -10 SWH (x0.001 m), SWS (x0.01 m/s) and SSHA (x0.001 cm) of SARAL path 66 on 12 October 2013.

Further high resolution achieved with altimeter waveform data (Figure-11). Jason-2 data is available in 20 Hz mode for Ku and C band, while SARAL provides 40 Hz data in Ka band along the track. Jason-2 waveform data on path 53 on date 9 October 2013 was seen bearing the signature of low pressure event around 17°N. The wave form data available in 104 gates for individual echo represented a detailed view of the change in geophysical product under influence of the cyclonic event. Figure 11 show the waveform data overlaid with 1 Hz geophysical products of SSHA, SWH and SWS. The SWH of about 2.5m height corresponded well with highs and lows of echo structure along the track. SARAL waveform too provided results similar to those of Jason-2. The SWH followed well with the waveform features, whereas wind speed remained less sensitive. Along track SSHA followed well with the echo structure with its intensity fields of waveform data. The echo edge, slope and intensity as in the waveform data indicated existence of enriched signals corresponding to the cyclonic events.

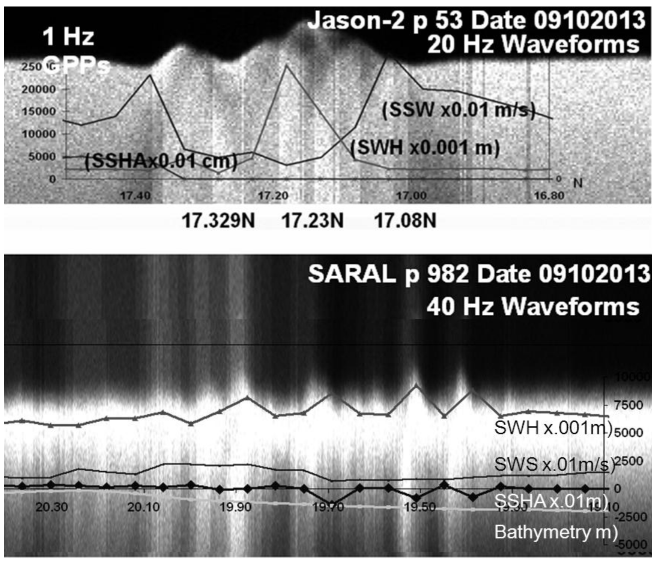

Fig 11 Altimeter waveforms of Jason-2 (top) and SARAL (bottom) with overlaid profiles of 1 Hz geophysical products as SWH, SSW and SSHA profiles.

VI. CONCLUSION

SARAL AltiKa geophysical products exhibited high resolution surface features during the cyclonic event 'Phailin' developed in the Bay of Bengal in October 2013. Along track altimeter data in 1 Hz and waveform data in 40 Hz for SARAL and 20 Hz for Jason-2 acquired between 9 and 13 October 2013 analyzed for their signatures of the cyclone impact depending on their proximity to the cyclone path. The geophysical products like, SWS, SWH and SSHA along with water vapor and cloud liquid water exhibited a wide range of variation in the areas of their coverage. Altimeter winds exhibited low winds corresponding to close proximity with the cyclone center, while high winds are observed on either side in the along track data covering the cyclone track area. The SARAL wind remained lower by about 2 m/s than Jason-2. The SWH varied widely in the area of cyclone impact for along track observations of SARAL and Jason 2 products. The SSHA recorded negative fields indicating impact of cyclone.

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Hence the impact of cyclone is evident in all the geophysical products like, SWH, SWS and SSHA. The associated products on water vapor and cloud liquid water used to correct sea surface height estimations from altimeter data like, inverted Barometer correction, Sea Surface Bias also expected to carry signatures of tropical cyclone need further investigation.

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This work is carried out at NRSC, Hyderabad using SARAL AltiKa and Oceansat-2 geophysical products. Jason-2 geophysical products acquired from AVISO and PODAAC web sites and support from ISRO are also acknowledged. Dr. V. K. Dadhwal, Director, NRSC for all his support and institutional facilities made available during this work are also acknowledged.

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Saurabh Bansal, Scientist, NRSC is born on 20 May 1990 in Haryana, India has completed Central Board of Secondary Examination (CBSE) and under-graduation program in Physical Sciences and subsequently graduated from Indian Institute of Space Science and Technology (IIST) with major subjects in Astronomy & Astrophysics in 2012. Presently, he is working as a scientist in Ocean Sciences Group of Earth and Climatic Sciences Area (ECSA)

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