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Characterization of Nonlinear Internal Waves in the Southwest Sulu Sea: Insights from Satellite and In-Situ Observation

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ABSTRACT

Nonlinear internal waves, also known as solitons, are significant oceanographic phenomena that can influence offshore operations, marine navigation, and environmental stability. The Sulu Sea, shaped by complex bathymetry and tidal forcing, is recognized for the frequent occurrence of solitons; however, detailed characterization of these waves remains limited. This study addresses that gap by investigating the occurrence, structure, and propagation behaviour of nonlinear internal waves in the region. A combination of satellite-based and in-situ observational techniques was employed to provide a comprehensive analysis. Sentinel-1 synthetic aperture radar (SAR) imagery was used to detect surface expressions of internal waves, while a moored Acoustic Doppler Current Profiler (ADCP) recorded subsurface current variations over a three-month period to capture soliton events. The satellite analysis revealed internal wave signatures in 72-77% of the images examined. In-situ measurements identified over 100 soliton events, with individual wave durations ranging from 4 to 12 minutes and wave packets lasting up to 3 hours. Soliton propagation was predominantly shoreward toward the southwest, with some events directed west and south. SAR imagery indicated soliton packet spacing between 15-20km, and inter-soliton spacing of 250-400m, with estimated propagation speeds reaching up to 0.45m/s. The predominance of upward-propagating solitons, which are typically less visible in satellite imagery, highlights the critical role of in-situ measurements. These findings confirm the presence of distinct soliton types and emphasize the value of integrating satellite and in-situ methods to capture the full spectrum of internal wave dynamics, particularly in the Southwest Sulu Sea.

1. Introduction

Nonlinear internal waves, particularly solitons, are a significant oceanographic phenomenon due to their potential impact on offshore structures, subsea operations, and other critical activities in the oil and gas industry. These waves are characterized by their ability to maintain shape and speed

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over long distances, making them a subject of extensive research. Previous studies have documented the occurrence and properties of nonlinear internal waves in various regions, including Sulu Sea[1]. The Sulu Sea, located in the southwestern Philippines, is known for its complex bathymetry and strong tidal currents, which contribute to the generation of nonlinear internal waves. Jackson (2004)[2] provided an early assessment of solitons in the Sulu Archipelago, highlighting their propagation into the Sulu Sea. Subsequent studies have utilized satellite imagery and in-situ measurements to further investigate these waves[3]. For instance, Sentinel-1 synthetic aperture radar (SAR) data has been employed to detect internal wave signatures, offering coverage independent of cloud cover and lighting conditions.

Despite recent advancements, understanding nonlinear internal waves in the Sulu Sea remains limited, particularly in studies that integrate both satellite and in-situ observations. This study addresses that gap by combining Sentinel-1 SAR imagery with Acoustic Doppler Current Profiler (ADCP) measurements to characterize the occurrence, properties, and propagation of solitons in the Southwest Sulu Sea, and to examine their potential impact on the marine environment. Figure 1 below shows the approximate location of interest.

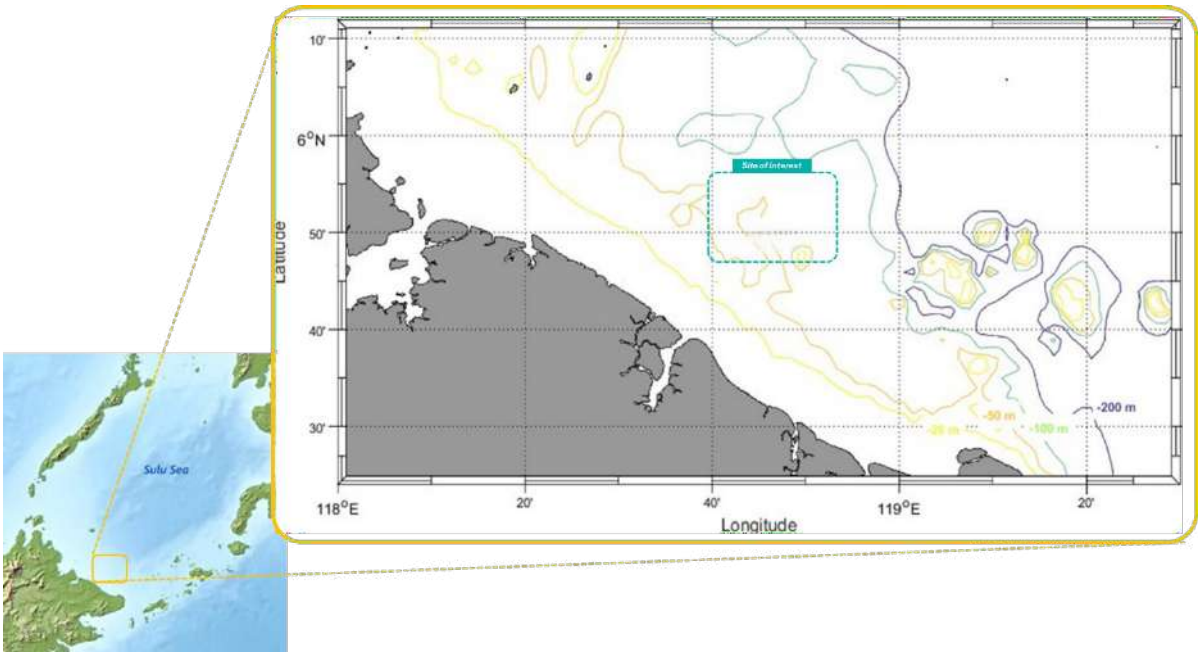


Fig. 1. Approximate location of site of interest

2. Methodology

This study aims to characterize nonlinear internal waves in the Southwest Sulu Sea using a combination of satellite and in-situ observations. Research framework focuses on understanding the occurrence, properties, and propagation patterns of solitons in this region. It involves two primary methods: satellite synthetic aperture radar (SAR) observations and Acoustic Doppler Current Profiler (ADCP) measurements. These methods are chosen for their complementary strengths in detecting and analysing internal wave signatures. By combining satellite and in-situ observations, this study offers valuable insights into the behaviour and characteristics of nonlinear internal waves in the Southwest Sulu Sea, contributing to both theoretical knowledge and practical applications.

2.1 Satellite Observations

Sentinel-1 SAR data were examined to determine the presence of nonlinear internal wave signatures. Satellite SAR was chosen for its ability to provide coverage independent of cloud cover and lighting conditions. Sentinel-1 provided regular coverage over the site with a 12-day revisit frequency. The study acquired SAR imagery on 100 dates between January 2020 and May 2023, covering a portion of the central and southwest Sulu Sea (Figure 2). This coverage allowed for observing the occurrences of both large solitons in the deep basin and finer scale packets on the Borneo Shelf at the site of interest.

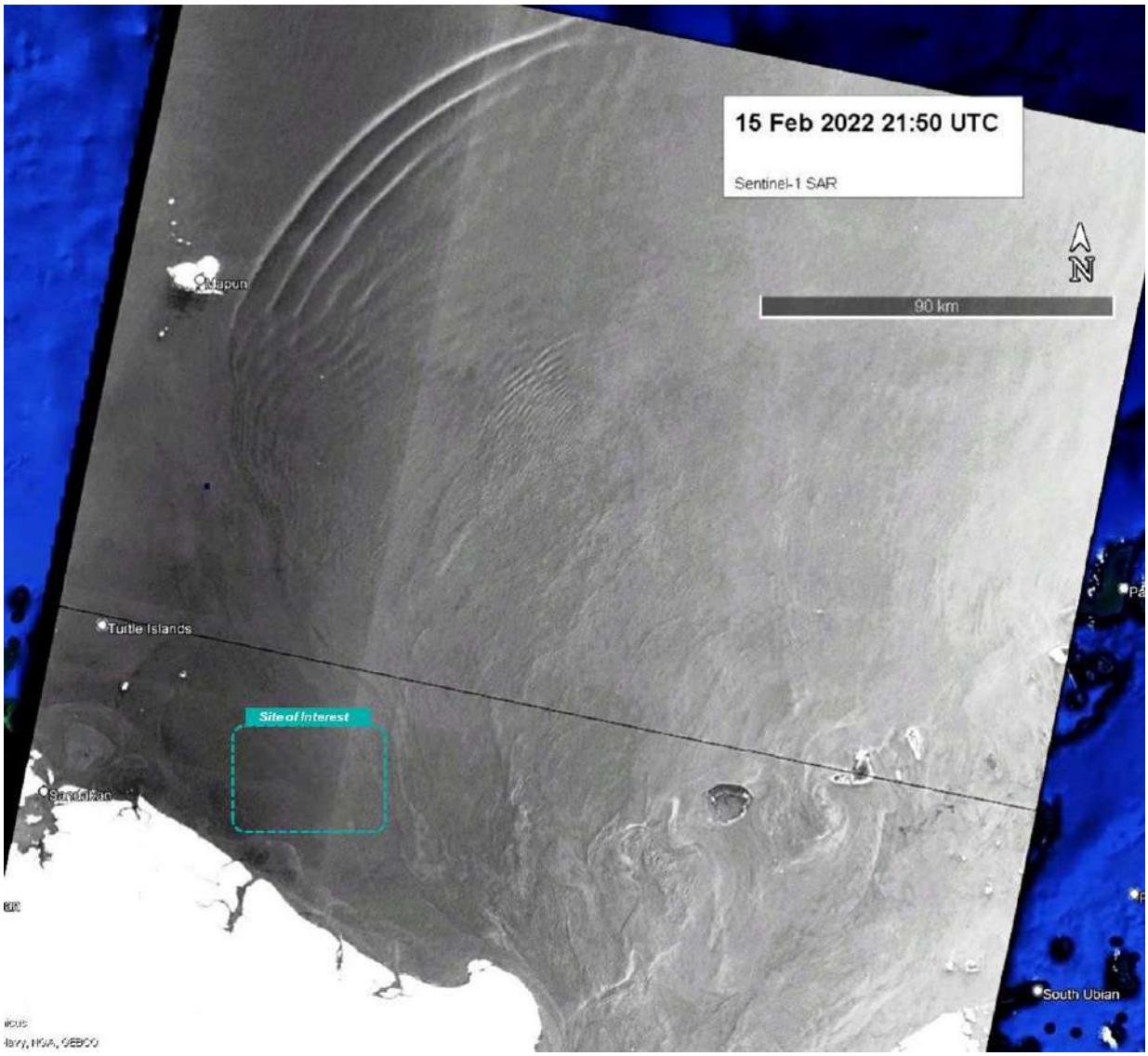


Fig. 2. Sentinel-1 coverage of the region used in the analysis

2.2 In-Situ Observations

The Acoustic Doppler Current Profiler (ADCP) was deployed in approximately 80 meters of water depth below mean sea level, recording current measurements across 29 to 31 vertical bins with a bin size of about 2 meters. Data quality control (QC) was performed using standard parameters such as percentage good, echo amplitude, and error velocity to ensure reliable measurements. In addition to automated QC, the data underwent manual inspection to identify and remove any abnormal values. Overall, the ADCP operated stably throughout the deployment, resulting in a high rate of quality data return. Figure 3 illustrates the configuration of the ADCP mooring system deployed in this study. The setup consists of an anchor weight to secure the system on the seafloor, an acoustic release mechanism to allow for retrieval, and a series of flotation devices to maintain the ADCP in an upright and stable position within the water column. A GPS locator was also attached to assist in surface tracking during recovery. This configuration was designed to ensure accurate positioning, reliable data acquisition, and safe recovery of the equipment after the deployment period.

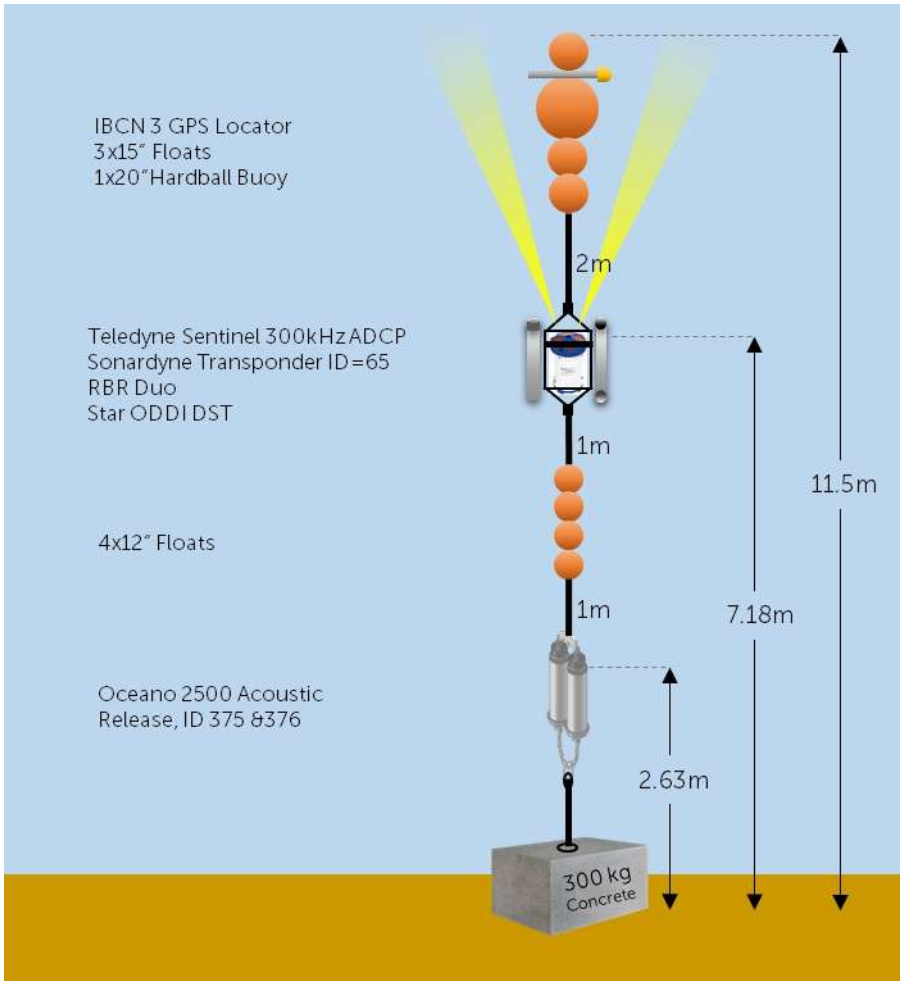


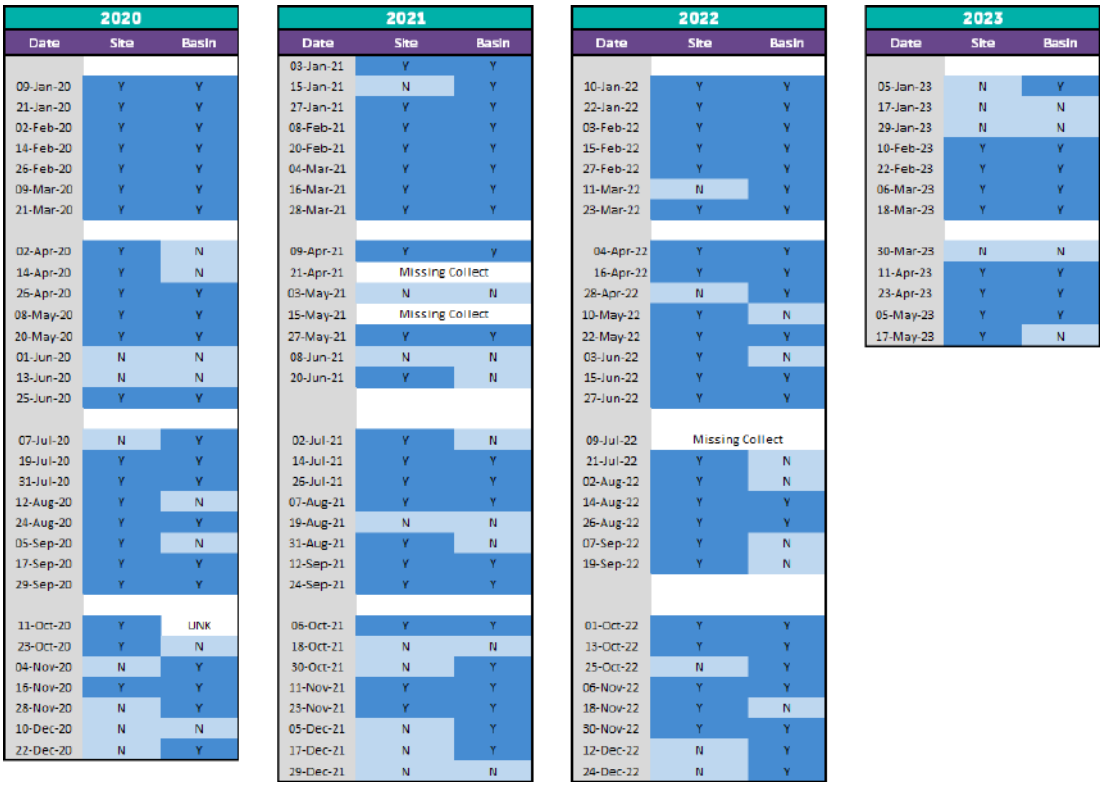
Fig. 3. ADCP mooring equipment configuration

3. Results & Discussion

The integration of Sentinel-1 SAR imagery and ADCP measurements provides a comprehensive assessment of soliton dynamics on the continental shelf within the area of interest, as this is the region principally sampled by the ADCP. The observed propagation speeds and packet spacing align well with global continental shelf internal wave characteristics. While SAR imagery offers wide spatial coverage extending across both shelf and deep-water areas, its sensitivity to surface winds and preference for downward-propagating solitons may lead to an underrepresentation of upward events. In contrast, the ADCP data enable detailed vertical profiling of shelf-generated internal waves but do not capture the larger deep-water solitons, which remain unobserved in this dataset and are interpreted here with reference to established findings from earlier studies. Moreover, the ADCP measurements are limited by reduced accuracy near the surface and a relatively short deployment period.

3.1 Satellite Observations

Figure 4 below lists the dates of S1 coverage along with presence (Y) or lack (N) of nonlinear internal wave signatures in the imagery. The "Site" column is for the area near the site of interest on the Borneo Shelf and the "Basin" column for the signature of large soliton in water depth > 1000m. Higher Ocean surface winds during the Monsoon season might explain why few signatures were noted in the December periods.



2020		
Date	Site	Basin
09-Jan-20	Y	Y
21-Jan-20	Y	Y
02-Feb-20	Y	Y
14-Feb-20	Y	Y
26-Feb-20	Y	Y
09-Mar-20	Y	Y
21-Mar-20	Y	Y
02-Apr-20	Y	N
14-Apr-20	Y	N
26-Apr-20	Y	Y
08-May-20	Y	Y
20-May-20	Y	Y
01-Jun-20	N	N
13-Jun-20	N	N
25-Jun-20	Y	Y
07-Jul-20	N	Y
19-Jul-20	Y	Y
31-Jul-20	Y	Y
12-Aug-20	Y	N
24-Aug-20	Y	Y
05-Sep-20	Y	N
17-Sep-20	Y	Y
29-Sep-20	Y	Y
11-Oct-20	Y	UNK
23-Oct-20	Y	N
04-Nov-20	N	Y
16-Nov-20	Y	Y
28-Nov-20	N	Y
10-Dec-20	N	N
22-Dec-20	N	Y

2021		
Date	Site	Basin
03-Jan-21	Y	Y
15-Jan-21	N	Y
27-Jan-21	Y	Y
08-Feb-21	Y	Y
20-Feb-21	Y	Y
04-Mar-21	Y	Y
16-Mar-21	Y	Y
28-Mar-21	Y	Y
09-Apr-21	Y	y
21-Apr-21	Missing Collect	
03-May-21	N	N
15-May-21	Missing Collect	
27-May-21	Y	Y
08-Jun-21	N	N
20-Jun-21	Y	N
02-Jul-21	Y	N
14-Jul-21	Y	Y
26-Jul-21	Y	Y
07-Aug-21	Y	Y
19-Aug-21	N	N
31-Aug-21	Y	N
12-Sep-21	Y	Y
24-Sep-21	Y	Y
06-Oct-21	Y	Y
18-Oct-21	N	N
30-Oct-21	N	Y
11-Nov-21	Y	Y
23-Nov-21	Y	Y
05-Dec-21	N	Y
17-Dec-21	N	Y
29-Dec-21	N	N

2022		
Date	Site	Basin
10-Jan-22	Y	Y
22-Jan-22	Y	Y
03-Feb-22	Y	Y
15-Feb-22	Y	Y
27-Feb-22	Y	Y
11-Mar-22	N	Y
23-Mar-22	Y	Y
04-Apr-22	Y	Y
16-Apr-22	Y	Y
28-Apr-22	N	Y
10-May-22	Y	N
22-May-22	Y	Y
03-Jun-22	Y	N
15-Jun-22	Y	Y
27-Jun-22	Y	Y
09-Jul-22	Missing Collect	
21-Jul-22	Y	N
02-Aug-22	Y	N
14-Aug-22	Y	Y
26-Aug-22	Y	Y
07-Sep-22	Y	N
19-Sep-22	Y	N
01-Oct-22	Y	Y
13-Oct-22	Y	Y
25-Oct-22	N	Y
06-Nov-22	Y	Y
18-Nov-22	Y	N
30-Nov-22	Y	Y
12-Dec-22	N	Y
24-Dec-22	N	Y

2023		
Date	Site	Basin
05-Jan-23	N	Y
17-Jan-23	N	N
29-Jan-23	N	N
10-Feb-23	Y	Y
22-Feb-23	Y	Y
06-Mar-23	Y	Y
18-Mar-23	Y	Y
30-Mar-23	N	N
11-Apr-23	Y	Y
23-Apr-23	Y	Y
05-May-23	Y	Y
17-May-23	Y	N

Fig. 4. S1 coverage dates with detected (Y) or undetected (N) internal wave signatures near site and deep basin

Figure 5 shows monthly distribution of internal wave detections (Y) and non-detections (N) near the site of interest, illustrating seasonal variability. A noticeable decline in detections occurs during the Northeast Monsoon period, which may be attributed to elevated ocean surface winds that obscure surface expressions of nonlinear internal waves. In contrast, higher detection frequencies during inter-monsoon and Southwest Monsoon periods suggest more favourable surface conditions for identifying these features.

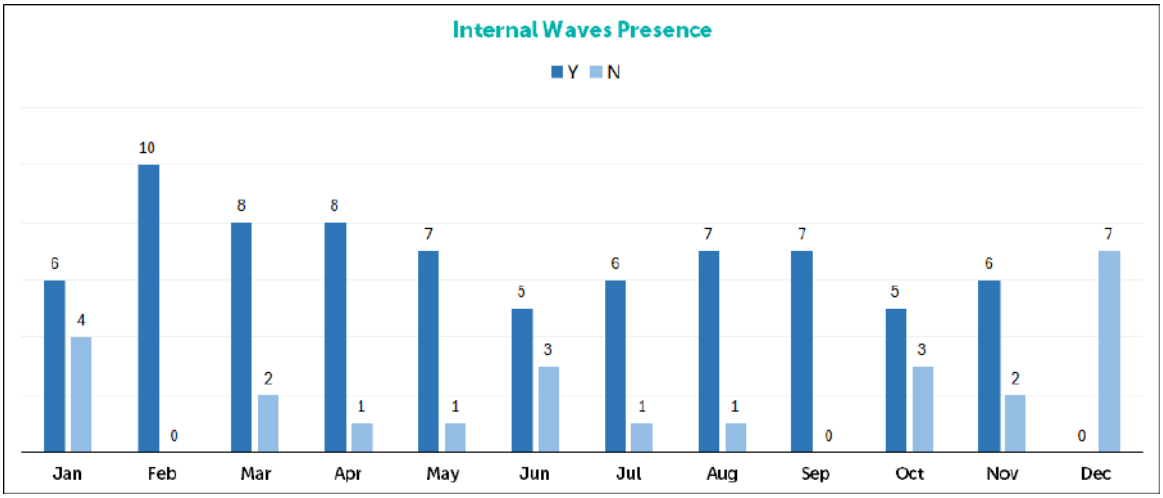


Fig. 5. Monthly count of detected (Y) and undetected (N) internal wave signatures from S1 imagery near the site of interest

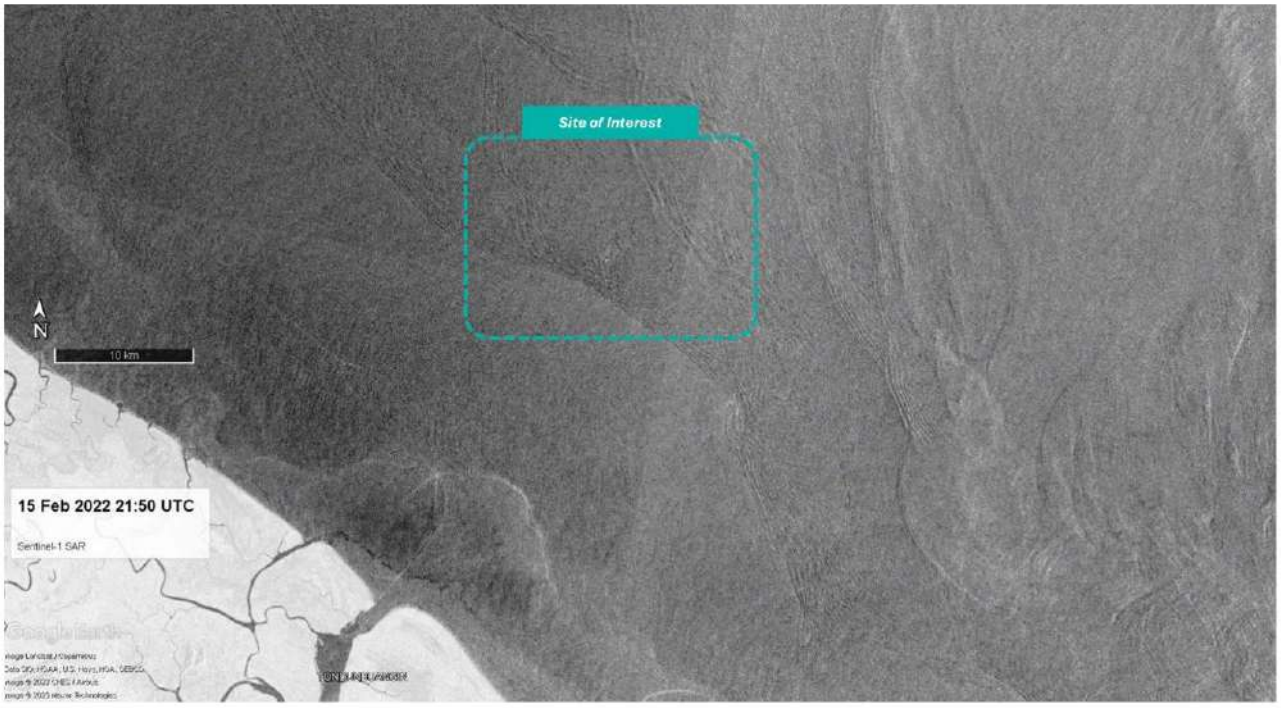


Fig. 6. Sentinel-1 SAR image on 15 February 2022 at 21:50 UTC showing multiple overlapping internal wave packets near the site

Meanwhile, Figure 7 shows a Sentinel-1 SAR image acquired on 23rd March 2022 at 21:50 UTC shows a series of relatively closely spaced internal wave packets (ranging from approximately 5 to 20 km apart) near the study site. While semi-diurnal packet separations are typically expected to be around 15–20 km, the presence of smaller separations (5–7 km) provides further indication that multiple generation sites—likely within the Sulu Archipelago or Sibutu Passage—may be contributing to the internal wave activity observed in the region.

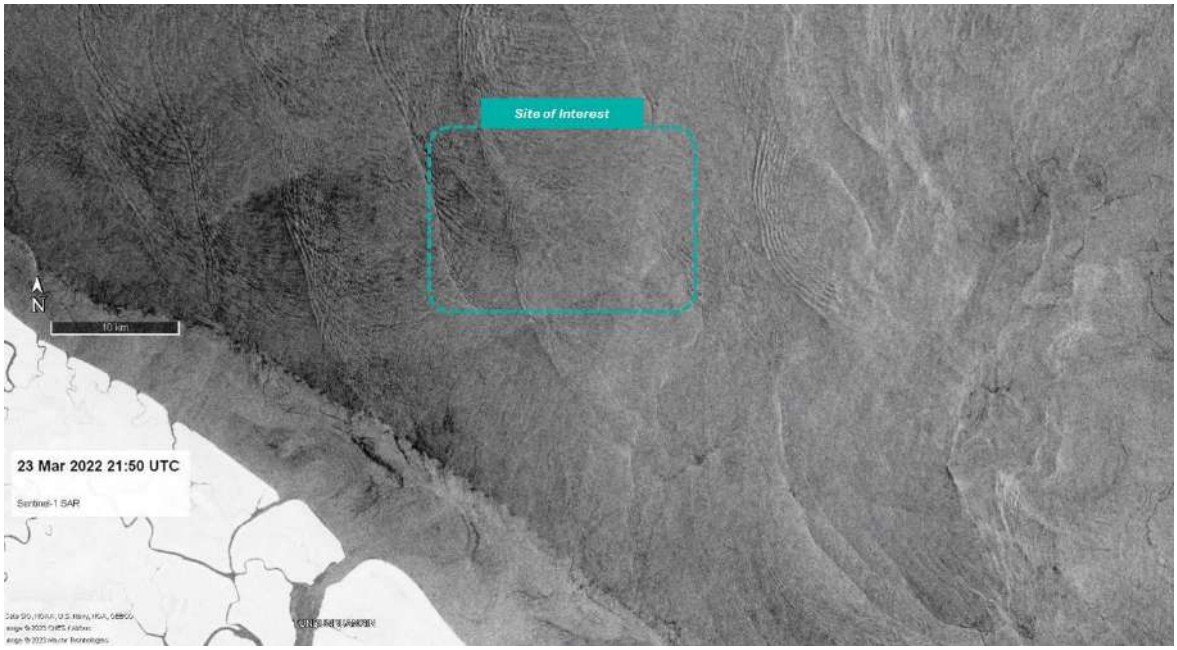


Fig. 7. Closely spaced wave packets in S1 image (23 Mar 2022) suggest multiple internal wave sources in the Sulu Archipelago or Sibutu Passage

Moreover, a Sentinel-1 SAR image acquired on 27th June 2022 at 21:50 UTC (Figure 8) displays clearly defined internal wave packets with separation distances ranging from approximately 13 to 20 km. Assuming a semi-diurnal generation frequency, these spacings imply propagation velocities between 0.3 and 0.45 m/s. These estimates align well with internal wave characteristics typically observed over continental shelves in other oceanic regions.

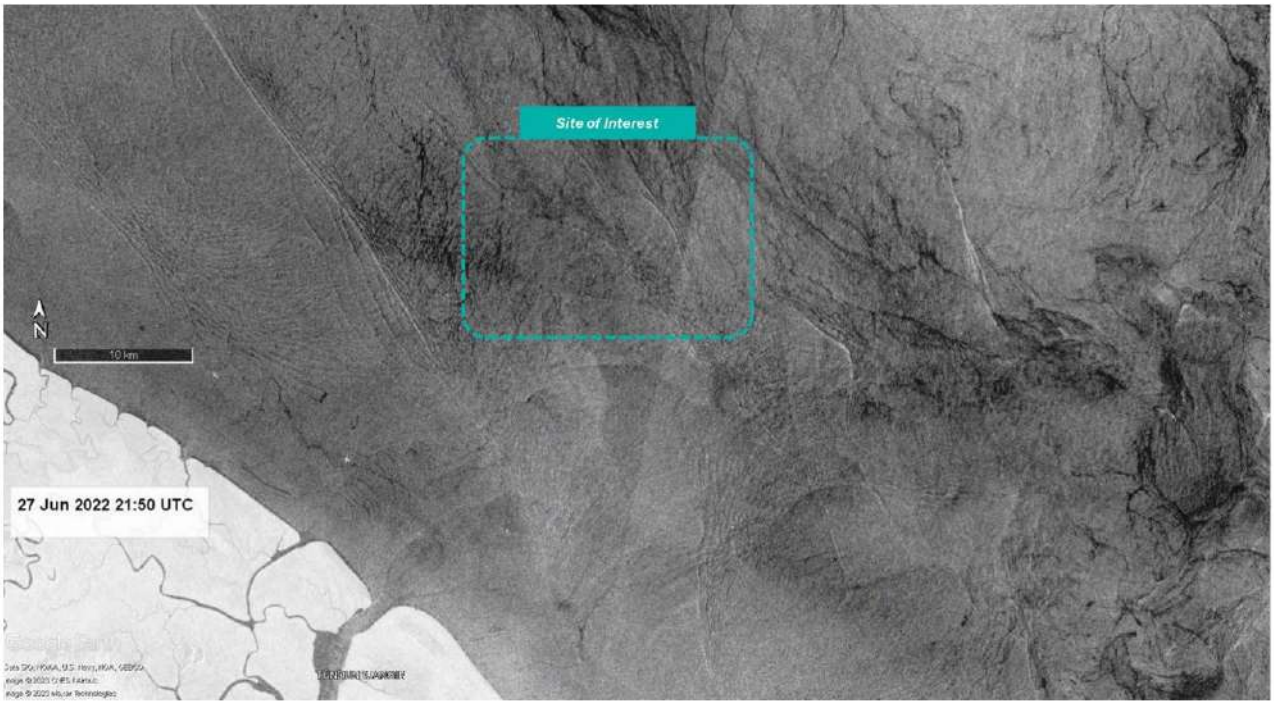


Fig. 8. Well-spaced wave packets in S1 image (27 Jun 2022) suggest typical shelf internal wave speeds of 0.3–0.45 m/s

3.2 In-Situ Observations

Acoustic Doppler Current Profiler (ADCP) data were reanalysed to extract additional variables and refine previous quality control. Further quality control excluded data with Percent Good Pings (PGP < 75%), calculated as the sum of PG1 and PG4 per IOOS guidelines [4], effectively removing erroneous velocities near the transducer.

As for soliton identification, short-period components of ocean current velocity were estimated by subtracting a 1-hour running mean to better identify rapid variations associated with solitons, whose durations were generally under 30 minutes. Initial analysis used daily plots of short-period velocities, followed by soliton detection based on vertical shear, calculated as the difference between maximum and minimum horizontal velocities in each profile. Events were flagged when shear or maximum short-period speed exceeded 0.25 m/s, with thresholds refined iteratively. All flagged events were manually reviewed to exclude noise or spikes, particularly around 25 December 2022, when satellite imagery indicated adverse weather, and isolated spurious records were discarded. A total of 107 solitons were confirmed, and representative examples shown in Figure 9 and Figure 10.

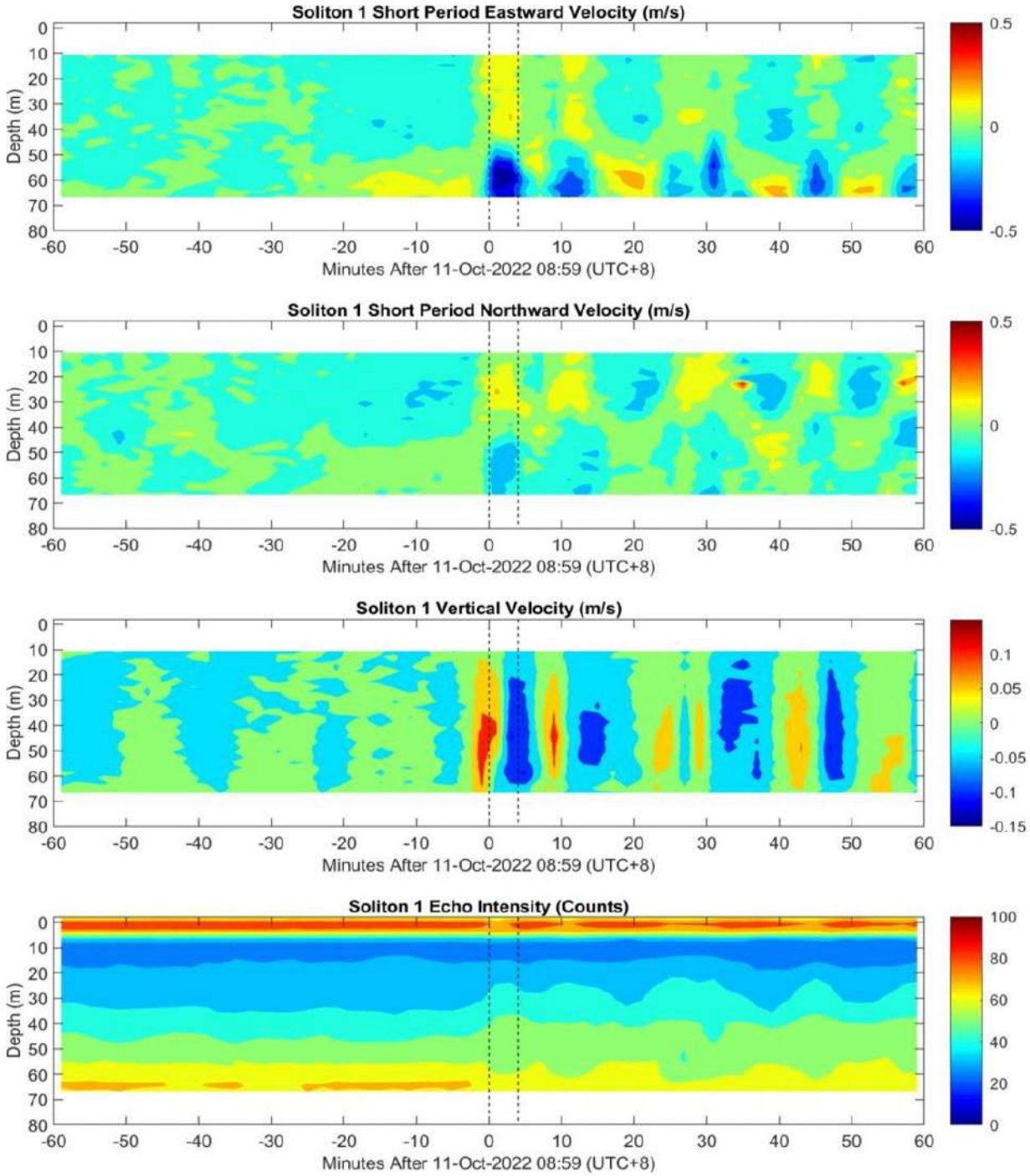


Fig. 9. Short period currents and other ADCP data around soliton 1

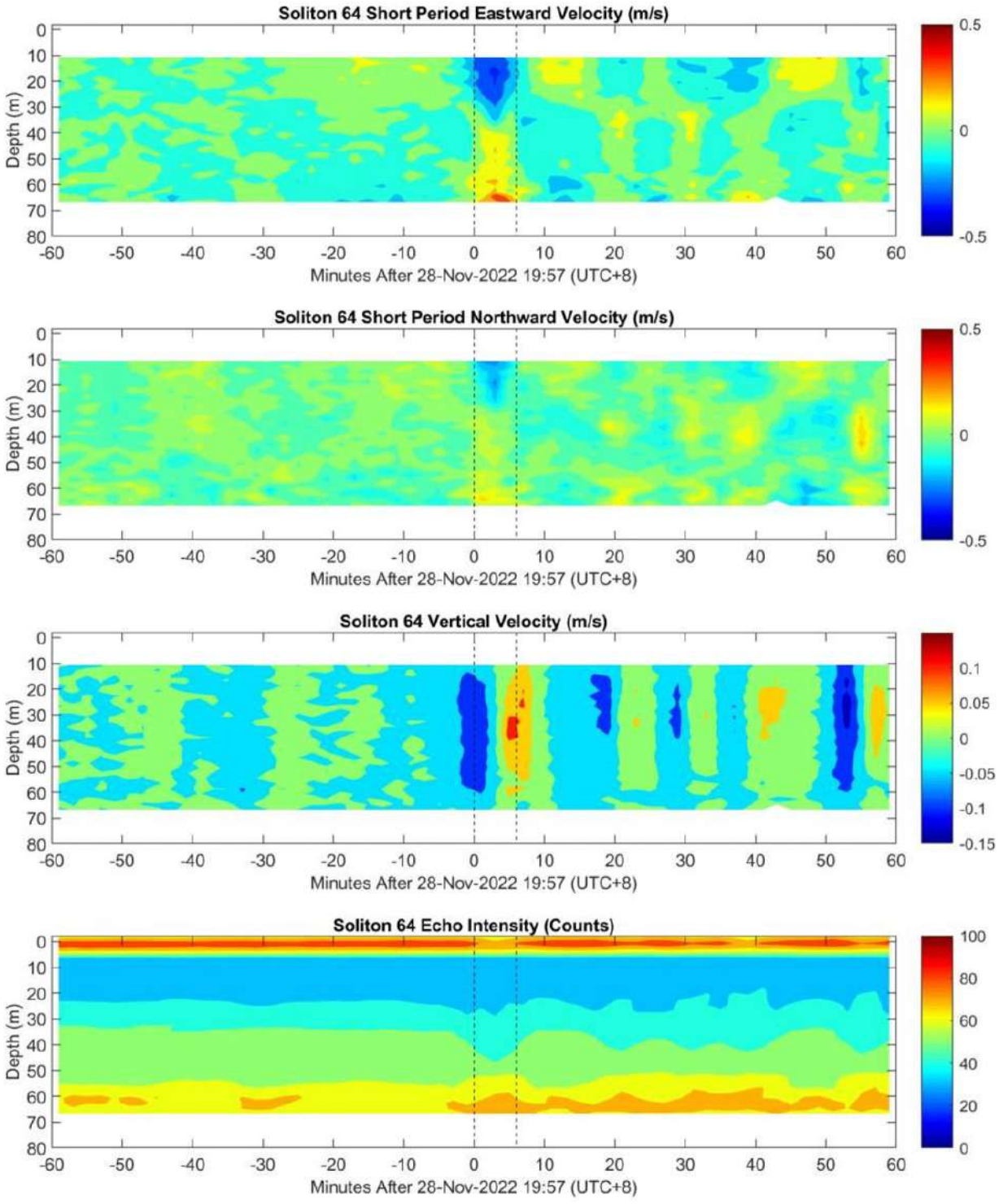


Fig. 10. Short period currents and other ADCP data around soliton 64

3.3 Cross-Validation of Satellite and In-Situ Observations

Figure 11 highlight the times the leading soliton was detected in the ADCP record. The SAR shows the “leading” and “trailing” waves have the same orientation (and propagating toward 225º from true north) suggesting a common generation location. The time between packet observations (at the mooring) is 12.83 hours, close the 12.42 hours semi-diurnal separation time. The ADCP record shows both the leading and trailing packet are internal waves of depression.

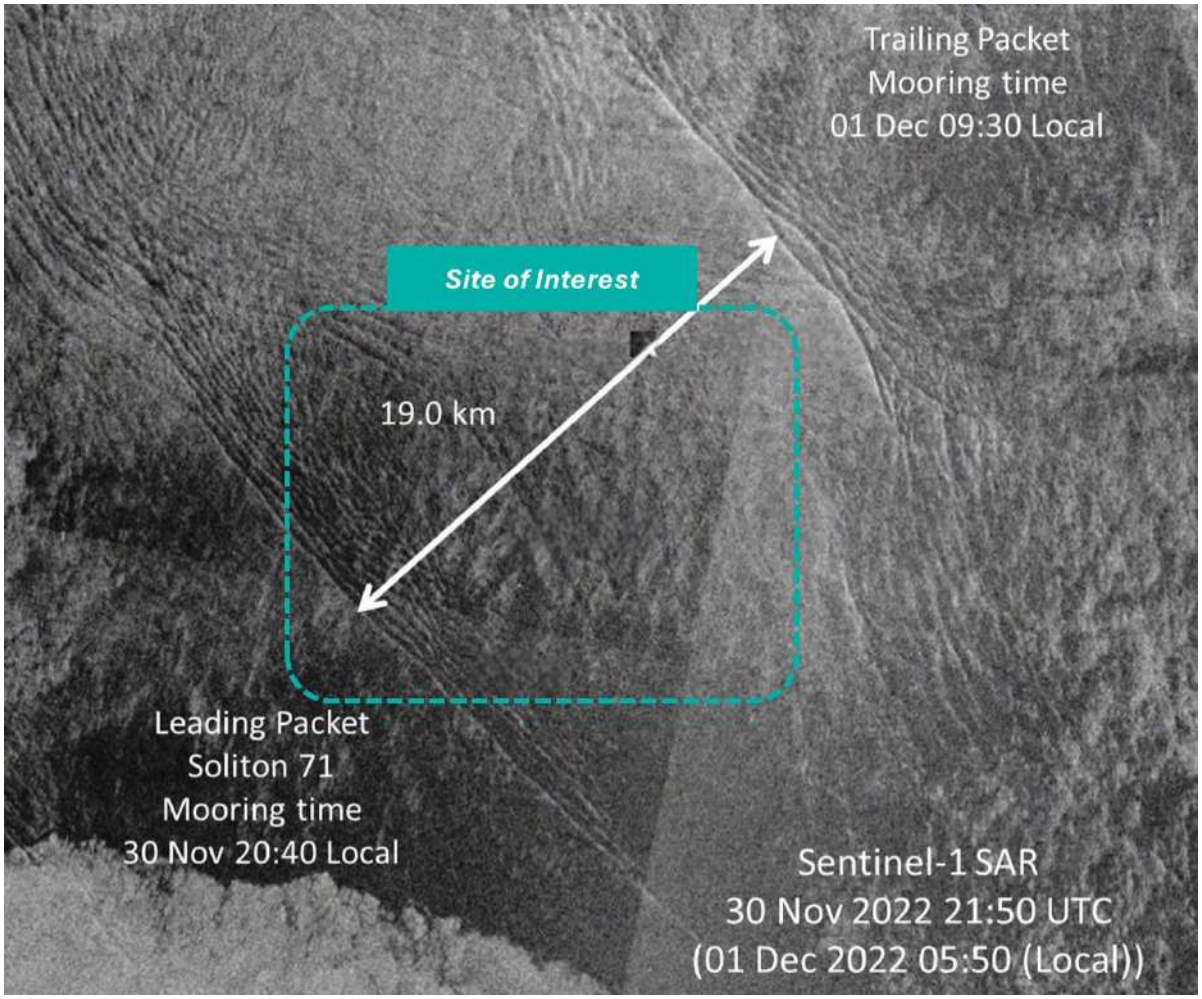


Fig. 11. Sentinel-1 image on 30 Nov 2022, showing "leading" and "trailing" wave packets confirmed as depressions by ADCP data

The ADCP record from 30 November 2022 (Figure 12) captures the “leading” soliton packet, visible in the vertical velocity profile between 20:30 and 21:30 UTC, characterized by a sequence of strong downward velocities followed by rapid upward shifts—indicative of a wave of depression. An expanded view (Figure 13) highlights seven individual waves within this packet, each exhibiting similar vertical velocity patterns. The record from 01 December 2022 shows the “trailing” packet between 09:30 and 11:30 local time, while the earlier “leading” packet remains evident around 20:30–21:30 UTC.

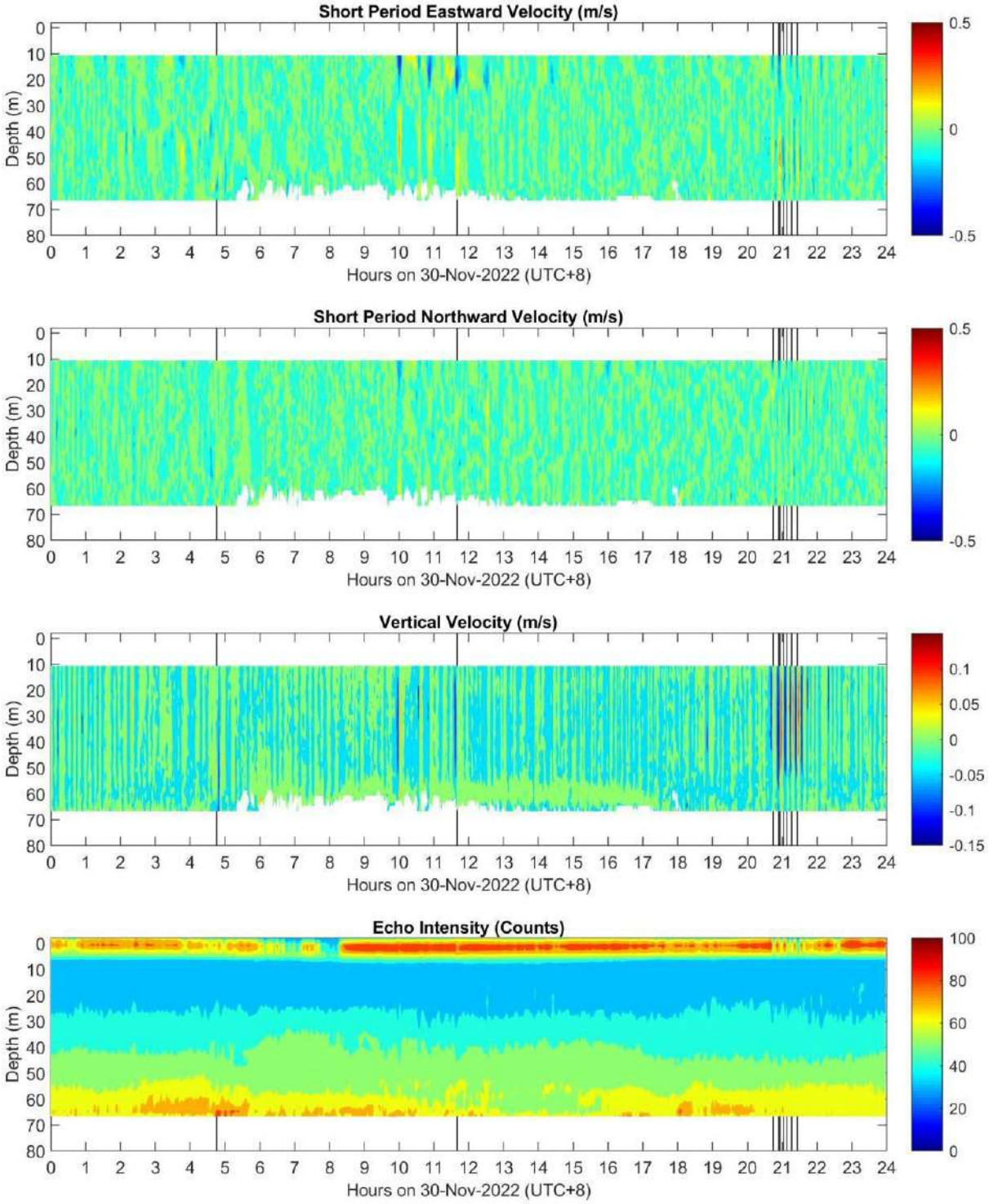


Fig. 12. ADCP vertical velocity on 30 Nov 2022 showing leading soliton packet (20:30–21:30 local time) with wave of depression signature

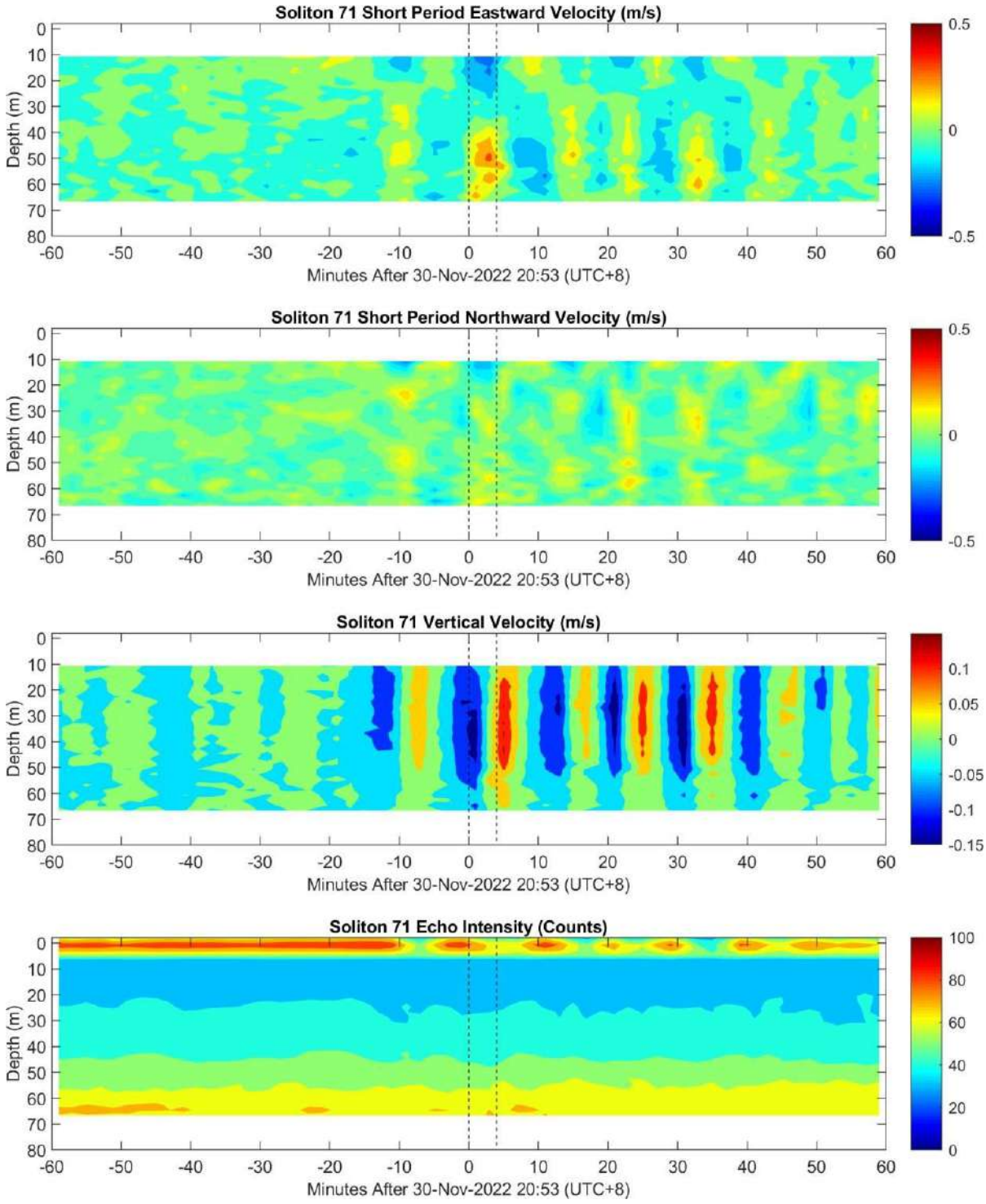


Fig. 13. Expanded ADCP view on 30 Nov 2022 showing 7-wave leading soliton packet with downward-to-upward vertical velocity shifts

4. Conclusion

This study combined satellite remote sensing and in-situ measurements to characterize internal solitary wave (soliton) activity near the study site. Analysis of 100 Sentinel-1 SAR images acquired between January 2020 and May 2023 identified internal wave signatures on 77 dates near the site and on 72 dates in the surrounding deep basin. The observed soliton packets predominantly propagated shoreward toward the southwest, although westward and north-eastward directions were occasionally recorded. The spacing between individual solitons ranged from 250 to 400 m, while packet spacing was typically 15–20 km, consistent with generation by semi-diurnal tidal forcing. These findings highlight the persistence and regularity of soliton activity over multi-year timescales and underscore the value of SAR imagery in detecting surface manifestations of internal wave processes.

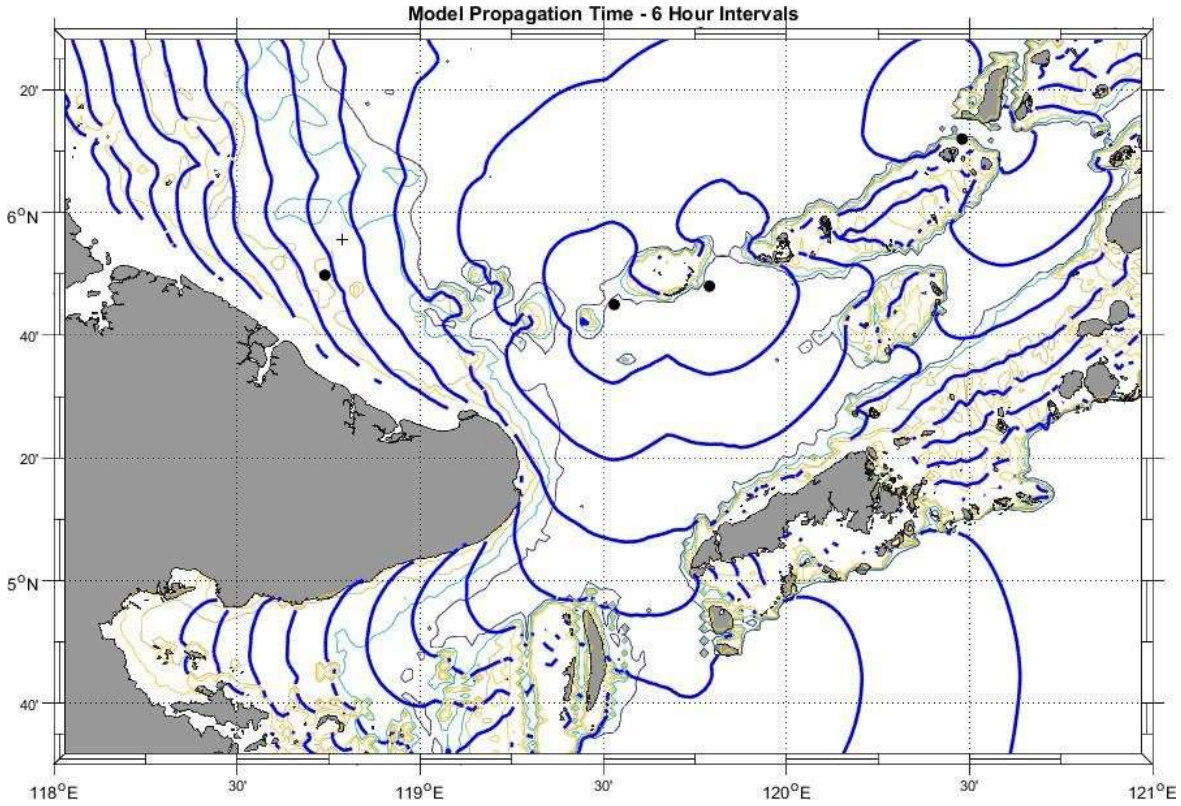


Fig. 14. Model wave fronts at 6-hour intervals for 3 origin location in the northern portion of the Sulu Archipelago

In-situ observations using ADCP data collected from October 2022 to January 2023 further confirmed the presence of 107 distinct soliton events. Solitons were classified into upward or downward types based on vertical velocity structure, with the majority being upward and associated with peak short-period current speeds generally below 0.5 m/s. Individual soliton durations ranged from 4 to 12 minutes, with wave packets lasting between 1 and 3 hours. A key event on 30 November 2022 showed excellent agreement between the ADCP record and Sentinel-1 imagery, capturing both leading and trailing soliton packets and validating the consistency between remote and in-situ observations. These results demonstrate the effectiveness of combining SAR and ADCP data to enhance soliton detection, classification, and understanding of internal wave dynamics in the region.

In an effort to better understand the origin and propagation characteristics of solitons in the region, including wave shape, position, path, and direction, the GOA[5] empirical wavefront propagation model was applied. This model utilizes a parameterized function relating internal wave phase speed to ocean depth to generate a phase speed map, which estimates propagation time and paths from defined origins. For this study, the model parameters were previously derived from satellite imagery specific to the region. Figure 14 and Figure 15 model-calculated propagation time contours at 6-hour intervals for three origins in the Sulu Archipelago and a site near the shelf break east of Sibutu, respectively. The simulations reproduced the general shape and orientation of soliton signatures observed in SAR imagery, although they do not account for advection by larger barotropic currents, which could influence variability in propagation direction.

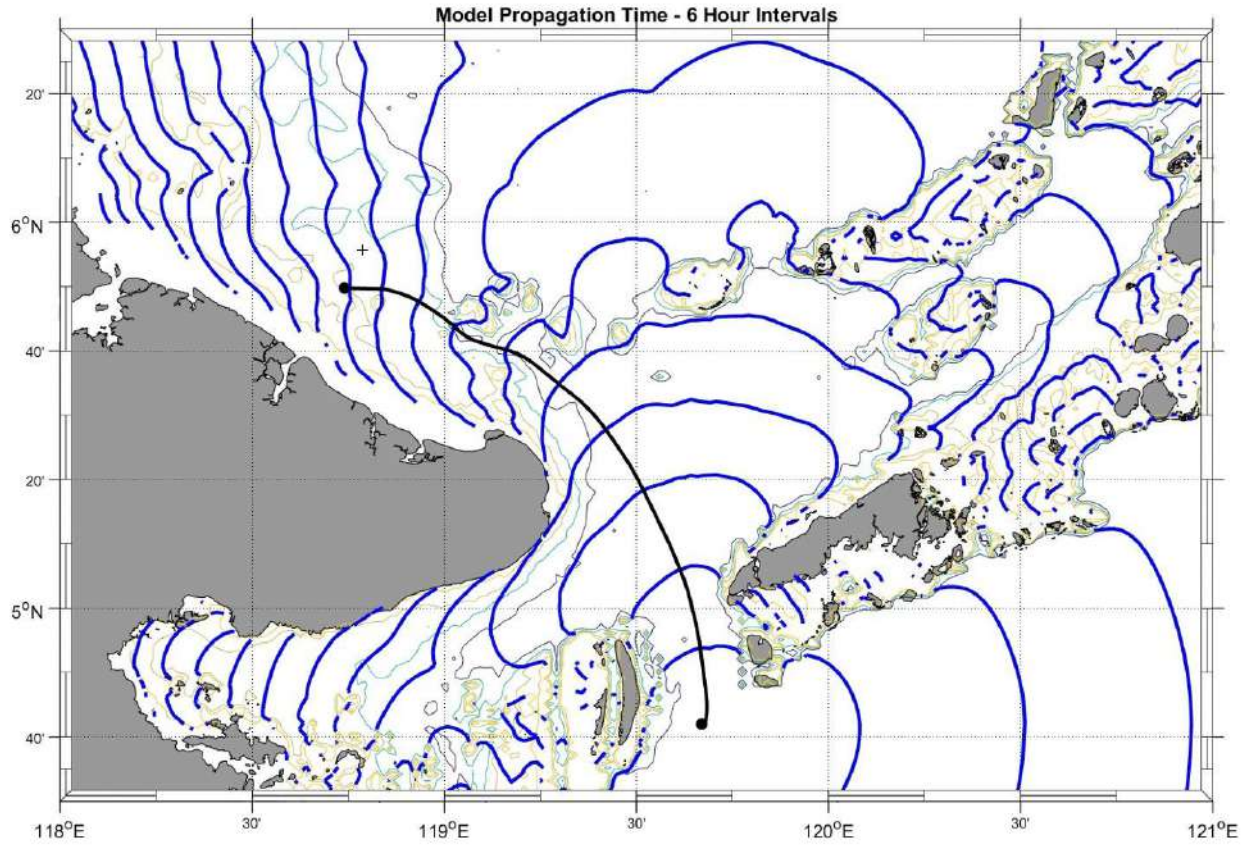


Fig. 15. Model wave fronts at 6-hour intervals for an origin at the shelf break near the Sibutu Shelf

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