JGISE Vol. 6 No. 2 (2023), pp. 111 - 124 | https://doi.org/10.22146/jgise.88613

JGISE

Journal of Geospatial Information Science and Engineering

ISSN: 2623-1182 | https://jurnal.ugm.ac.id/jgise

SAR Bathymetry Review and Its Possibility Implementation in Indonesia

Wening Aisyah Fauziana Koman[1], **Abdul Basith**[1], **Atriyon Julzarika**[2]

[1] Department of Geodetic Engineering, Gadjah Mada University, Yogyakarta, Indonesia
[2] Research Centre for Geospatial, National Research and Innovation Agency (BRIN), Cibinong, Indonesia

Correspondent Author: Wening Aisyah Fauziana Koman **| Email:** weningaisyahfauzianakoman@mail.ugm.ac.id

Received: 02/Sep/2023 Revised: 21/Nov/2023 Accepted: 22/Nov/2023

ABSTRACT

Indonesia needs bathymetry information for diverse applications as a maritime country. There are various methods of determining the water depth for bathymetry. The advancement of satellite imagery data has led to the increasing use of remote sensing data for depth measurements. With satellite imaging, wide area coverage can be achieved in a relatively short time, making depth data acquisition more cost-effective. SAR (Synthetic Aperture Radar) imagery is an active remote sensing technology developed to estimate depth data known as the SAR Bathymetry method. This method is still not widely applied, especially in Indonesia, even though it has considerable potential with cloud-free imageries, where it becomes a severe problem in tropical countries when using optical imagery. Therefore, this paper will discuss algorithms and techniques for depth data estimation using SAR Bathymetry and their possible implementation in Indonesia. The optimum depth, SAR image recommendation, and conditions required to apply this method will also be discussed.

Keywords: SAR Bathymetry; depth measurement; Synthetic Aperture Radar

1. Introduction

About 70% of the earth's surface is covered by water. Mapping water areas is urgently needed to help humans make their lives easier and predict dangerous phenomena so that they can be mitigated. Bathymetry survey is a process of mapping the bottom of the waters, which includes measuring the water depth (marine and inland waters) to produce bathymetry data (IHO, 2020; Poerbandono et al., 2005). The depth value is the primary data to map the underwater bottom topography (bathymetry). Therefore, the depth determination method is essential and significantly influences the accuracy of the bathymetric data results.

There are various methods of determining the value of water depth. On International Hydrography Organization (IHO) Standards for Hydrographic Surveys 6th Edition, 2020 written, several techniques for vertical or depth measurements such as echo sounder, side scan sonar, multibeam, diver, lead-line, wire-drag, photogrammetry, Satellite-derived Bathymetry (SDB), and Light Detection and Ranging (LiDAR). In all the methods mentioned in the IHO Standards, active remote sensing methods Synthetic Aperture Radar (SAR) is not specifically mentioned, even though SAR is a potential method for estimating water depth (Ashphaq et al., 2021; Gao, 2009; Jawak et al., 2015). This paper discusses literature reviews related to SAR bathymetry and its possibility implementation in Indonesia using 30 scientific publications sourced from international journals and reference books.

2. Depth Determination Technique

Various methods can measure the water depth. Not limited to direct measurements in the field, but also indirect measurements such as remote sensing. Ashphaq et al. (2021); Gao (2009); Jawak et al. (2015) classified depth measurement methods based on their output results (echosounders, non-imaging, and imaging), while Poerbandono et al. (2005) classified them based on the system and tools used (mechanical, optical, and acoustic). Based on these references, the data acquisition methods for depth measurement are summarized into two categories: direct (mechanical) and indirect methods, further divided into several subclasses, as shown in Figure 1.

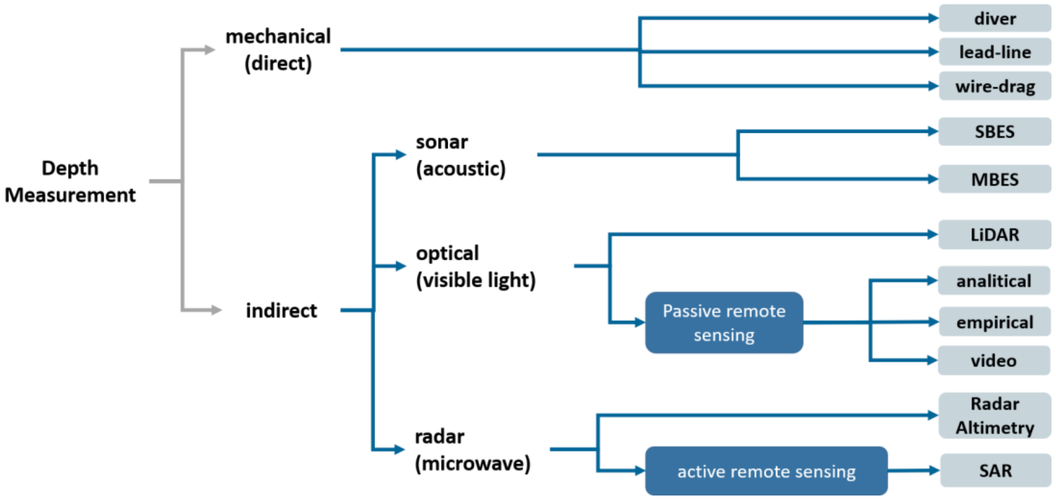


Figure 1 Summary of depth determination method [based on Ashphaq et al. (2021); Gao (2009); IHO (2005); Jawak et al. (2015); Poerbandono et al. (2005)]

A reliable method with the best accuracy for measuring depth is the acoustic method that utilizes ship-based echosounders such as Singlebeam Echosounder (SBES) or Multibeam Echosounder (MBES) (Santos et al., 2020; Stewart, 2008). Stewart (2008) revealed that the accuracy level reaches ±1%, but its operation requires high costs and carries higher risks due to the need for onboard operators. The utilization of echosounders remains the most effective despite the high operational costs. Therefore, a new emerging technology called Unmanned Surface Vehicle (USV) has emerged as a substitute for ships. With USVs, operators can remotely perform their tasks from land, minimizing work safety risks (Bai et al., 2022; Papatheodorou et al., 2023). The utilization of USVs is similar to Unmanned Aerial Vehicles (UAVs) in photogrammetry methods, which initially utilized aircraft platforms.

2.1. Mechanical method (direct depth measurement)

Direct depth measurements can be obtained using basic instruments. However, it is limited to relatively shallow and small-scale areas due to the extensive effort required, especially regarding human resources (Poerbandono et al., 2005). The IHO Standards 2020 outline mechanical depth measurement techniques, including diver, lead-line, and wire-drag methods. Furthermore, the Manual on Hydrography Publication C-13 2005 presents lead-line, sounding pole methods, and bar and wire sweeps (IHO, 2005).

2.2. Acoustic method

The acoustic method employs sound wave systems to acquire water depth values. This system, known as Sound Navigation and Ranging (SONAR), enables distance determination by measuring the time interval between transmitting underwater sonic or ultrasonic signals and detecting the resulting echo reflection (IHO, 2005). Acoustic-based instruments such as echosounders, interferometric sonars, side-scan sonars, and multibeam systems remain popular for conducting depth measurements. The data obtained from MBES will exhibit a higher density than SBES data, as SBES surveys provide a single depth point solution. In contrast, MBES surveys offer multiple-depth solutions for each emission of an acoustic wave (Khomsin et al., 2021).

2.3. Optical method

Optical methods such as LiDAR, photogrammetry, and optical remote sensing are developing for depth measurements (Gao, 2009; Jawak et al., 2015; Mandlburger, 2022). Mandlburger (2022) reviews the optical method for determining depth and illustrates it as shown in Figure 2. There are three methods, namely Airborne LiDAR Bathymetry (ALB), photogrammetry, and spectrally derived bathymetry, which can be operated using satellites, aircraft, and underwater vehicles. Mandlburger (2022) mentions the term “SDB” as an abbreviation of spectrally derived bathymetry, not satellite-derived bathymetry. It shows that the term SDB is more appropriate for optical technology methods, passive remote sensing, not SAR, although both can utilize satellite vehicles in data acquisition.

ALB for depth measurement is a popular technology due to it can obtain depth values with high accuracy. Green waves carried by ALB can penetrate to the bottom of the waters, while infrared waves can only reach the surface. So, the water depth value can be obtained by calculating the difference as shown in Figure 3 (Mandlburger, 2022; Syetiawan & Gularso, 2021). ALB (blue waves) is optimal to extract the depth of clear waters with maximum value 25 m while the ALB (green waves) is optimal to extract maximum 50 m of depth value in clear waters. The SDB is also optimal to extract maximum 25 m of depth value in clear waters.

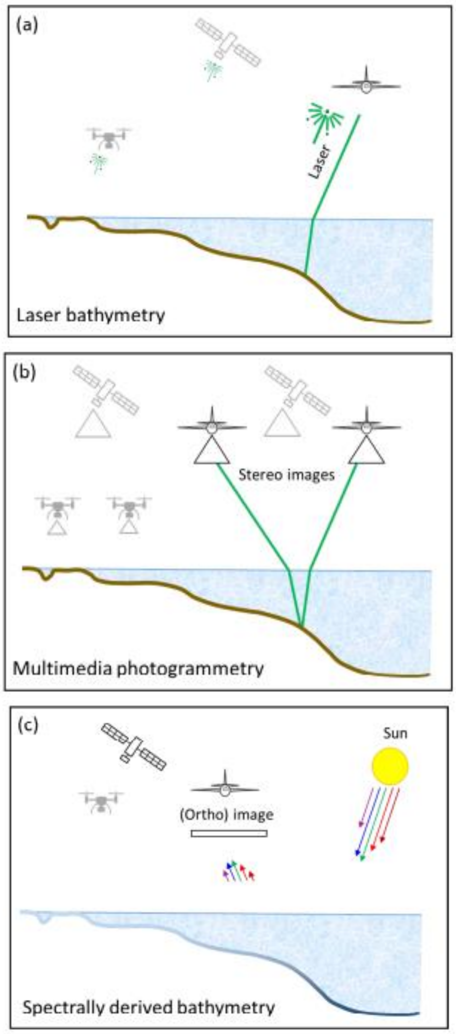


Figure 2 Optical method in depth determination (Mandlburger, 2022)

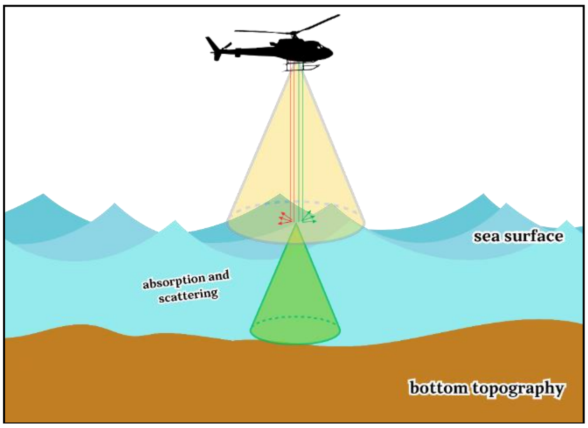


Figure 3 Airborne LiDAR Bathymetry (ALB) (modified from Syetiawan & Gularso, 2021)

The concept of stereo or Dense Image Matching (DIM) in photogrammetry can be utilized for creating Digital Elevation Models (DEMs) (Croneborg et al., 2015; Mandlburger, 2019). Digital Bathymetry Models (DBMs) can be derived from these DEMs, which can be generated from image data (Jawak et al., 2015). Current bathymetric mapping tends to employ hybrid multi-sensor systems that combine photogrammetry and LiDAR concepts, allowing for the simultaneous acquisition of coastal and underwater information (BIG, 2020; Legleiter & Harrison, 2019; Mandlburger, 2022; Toschi et al., 2018).

Passive remote sensing, also known as optical remote sensing, has seen positive improvements in mapping water bodies for large water areas and low costs. The primary data utilized in this method are passive remote sensing images such as Landsat 8/9 and Sentinel-2, which are satellite-based, hence also known as SDB. In acquiring water depth information, two main popular techniques are employed in SDB: the analytical and the empirical methods (Casal et al., 2019; Mavraeidopoulos et al., 2017). Apart from these two methods, researchers have developed various combinations and further categorized them in Figure 4 (Ashphaq et al., 2021). Additionally, video-based methods can be utilized to measure depths, particularly in monitoring tidal changes in the sea (Bergsma et al., 2016; Holman et al., 2013; Holman & Bergsma, 2021; Jawak et al., 2015).

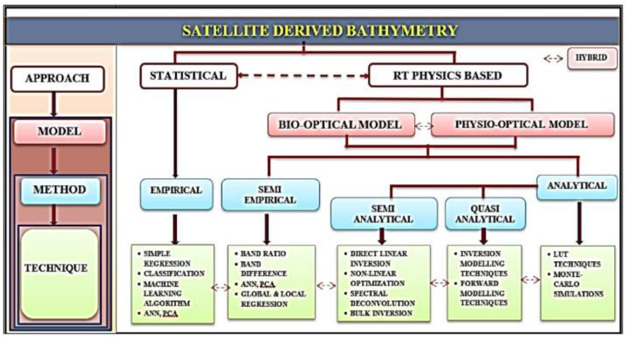


Figure 4 Various techniques in satellite-derived bathymetry (Ashphaq et al., 2021)

2.3. Radar method

In remote sensing, not only passive systems are developing. Active system remote sensing, such as SAR, is also experiencing development (Brusch et al., 2011; Huang et al., 2022; Julzarika et al., 2021; Ma et al., 2021; Rajput et al., 2021; Tarikhi, 2012). Radar methods utilize microwaves for determining water depths, consisting of Radar Altimetry and SAR techniques. Active remote sensing, particularly SAR, has been catching up with its predecessor, passive remote sensing. In addition to optical images, SAR images, which are also a remote sensing technology, have been investigated for bathymetric studies (Brusch et al., 2011; Huang et al., 2022; Julzarika et al., 2021; Ma et al., 2021; Rajput et al., 2021; Tarikhi, 2012; Wensink & Alpers, 2014). Active remote sensing data is commonly referred to as radar images. There are two commonly used types of radar images: Real Aperture Radar (RAR) and Synthetic

Aperture Radar (SAR). The spatial resolution of RAR images is directly related to the length of the antenna. In contrast, SAR images employ signal processing to synthesize an aperture much longer than the actual antenna, enabling better spatial resolution without requiring an excessively long antenna (Chan & Koo, 2008). Therefore, SAR images are more popular and widely utilized than RAR images.

Alpers & Hennings (1984) were early researchers who proposed the theory of Imaging Mechanism by SAR imagery for bathymetry, also known as Polarimetry SAR bathymetry. Researchers often refer to SAR imagery for bathymetric studies as "SAR bathymetry" rather than SDB, even though SAR platforms are satellite-based. In the academic and research community, the term "SDB" generally refers to optical imagery, while SAR imagery is specifically referred to as SAR bathymetry. Actually, the SAR bathymetry include Polarimetry SAR bathymetry and Liqui Interferometry SAR (LiSAR). Polarimetry SAR bathymetry has similar concept with SDB using optical imagery while the LiSAR using the interferometry approach to extract the depth value of bathymetry. The LiSAR not popular methods in SAR bathymetry due to there are only a few researchers who study this theme. The Polarimetry SAR bathymetry is popular method in extract the depth value due to it is similar concept with SDB. Consequently, this Polarimetry SAR Bathymetry method is often known to the common people as SAR Bathymetry. Polarimetry SAR Bathymetry use the amplitude and LiSAR use the phase for the input data of its calculation. All SAR data have the potential to be used for acquiring water depth values, but several popular SAR imagery datasets used by scientists include Sentinel-1, ALOS-PALSAR, ALOS-2, RadarSat, CosmoSky-Med, TerraSAR-X, RISAT-1, ERS, and ENVISAT (Bian et. al., 2018; Brusch et. al., 2011; Hesselmans et. al., 1995; Huang et. al., 2022; Huang & Fu, 2004; Julzarika et. al., 2021; Ma et. al., 2021; Mishra et. al., 2014; Pereira et. al., 2019; Rajput et. al., 2021; Santos et. al., 2022; Santosa, 2016; Song et. al., 2021; Tarikhi, 2012; Wiehle et. al., 2019). However, this depends on the data availability during the study year and its development since not all SAR satellites are still operational until today.

Unlike the SAR data concept, although both utilize active sensors, radar altimetry emits signals perpendicular to the earth's surface. In principle, satellite-based radar altimetry calculates the perpendicular distance between the satellite and the sea surface, thus obtaining information about the sea surface based on the desired geodetic reference framework, such as the ellipsoid or geoid (Grgić & Bašić, 2021). Depth determination using radar altimetry is unsuitable for navigation, construction, or high-precision object detection, as this technique has errors exceeding 100 meters (Grgić & Bašić, 2021). However, radar altimetry can cover large areas and optimal used for the depth more than 80 m, thus providing a general insight into global bathymetric conditions. The currently operational radar altimetry satellite is Sentinel-6, launched on November 21, 2020 (ESA, 2020).

3. Development of SAR Bathymetry Technique

SAR is an active remote sensing that utilizes microwaves. SAR can be an alternative method for determining water depth (Bian et al., 2020; Rajput et al., 2021). The primary use of Synthetic Aperture Radar (SAR) data in acquiring bathymetry is conducted indirectly, as SAR images cannot directly penetrate the water to measure the depth of the underwater bottom topography. Nonetheless, the surface roughness depicted in SAR imagery is employed to estimate the bathymetry (Alpers & Hennings, 1984; Hesselmans et al., 1995; Huang & Fu, 2004; Romeiser et al., 1997; Wensink & Alpers, 2014).

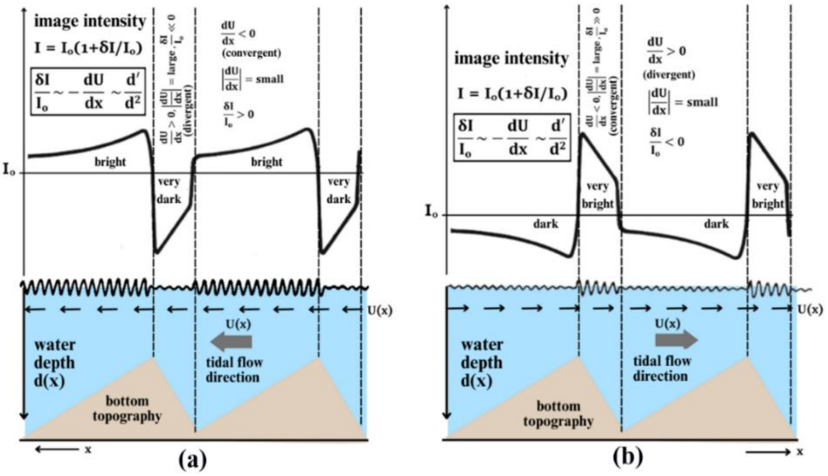


Figure 5 The relationship between radar image intensity, sea surface roughness, tidal flow, and underwater bottom topography with flow direction to the left (a) and to the right (b) (modified from Alpers & Hennings, 1984)

Figure 5 shows that the underwater bottom topography affected by waves will affect surface roughness. The sea surface roughness can be identified by SAR imagery based on its intensity value which shows the bright-dark appearance of the resulting image. It serves as the theoretical foundation suggesting that the intensity detected by SAR image sensors can be utilized to predict bathymetry or underwater bottom topography (Alpers & Hennings, 1984).

The development of SAR bathymetry methods from various references is presented in a network visualization using the Research Rabbit tool. This visualization is based on co-citations between each paper (Aria & Cuccurullo, 2017), and the resulting visual representation is displayed in Figure 6. The references were gathered from accessible online bibliographic databases like Google Scholar, Scopus, and Science Direct, as well as the search tools within Research Rabbit.

SAR images provide phase and amplitude data, both of which researchers have used to estimate water depth. Tarikhi (2012) introduced the Liqui-InSAR method, also known as LiSAR, which utilizes SAR phase data to determine water depth using Interferometry Synthetic Aperture Radar (InSAR) technique. Cloarec et al. (2016) conducted a comprehensive review of SAR techniques for bathymetry extraction and found that SAR amplitude data can be processed using current-based and wave-based approaches. **Error! Reference source not found.** presents a concise overview of different techniques employed in SAR Bathymetry methods.

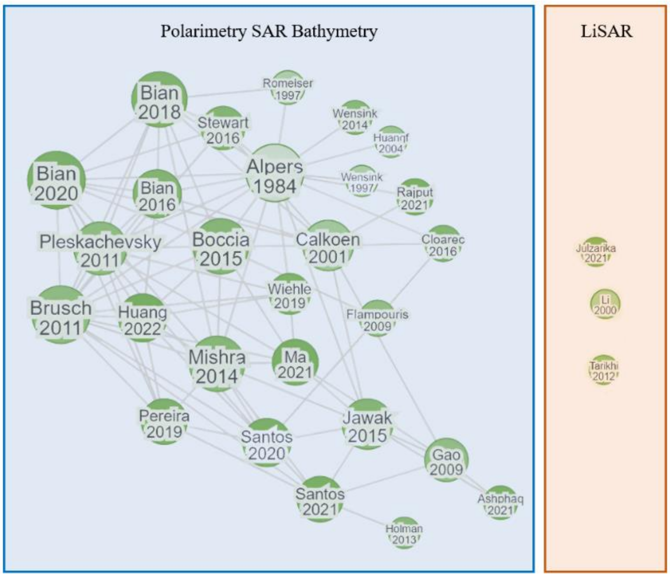


Figure 6 Co-citation network visualization of various SAR Bathymetry references (using Research Rabbit)

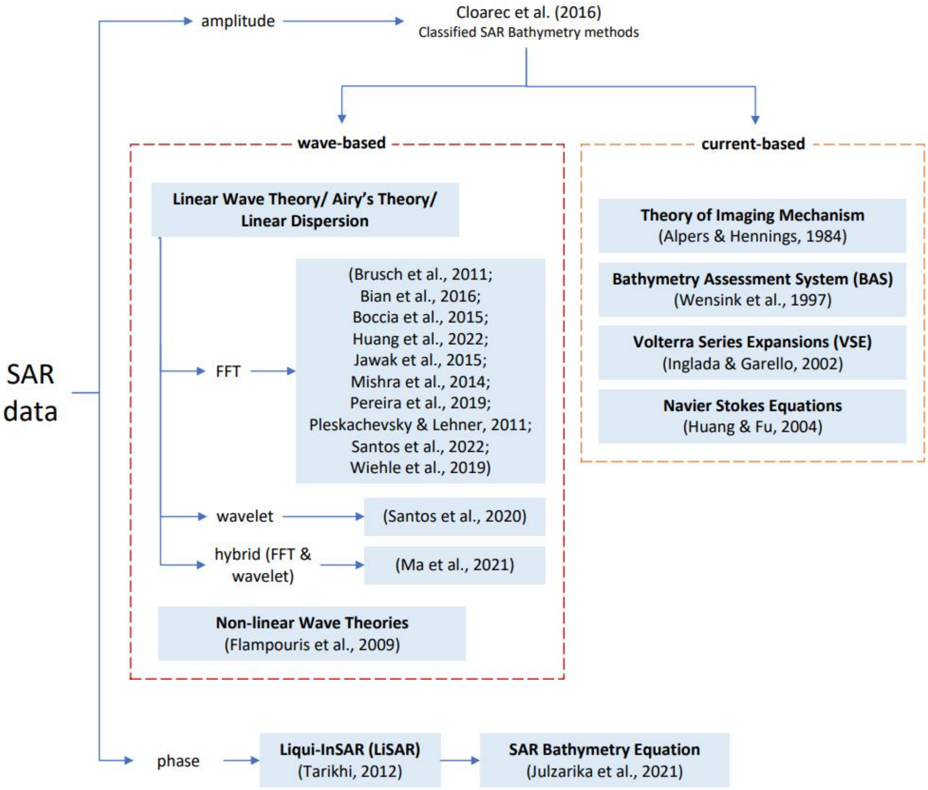


Figure 7 SAR Bathymetry development

Alpers & Hennings (1984) were the pioneering researchers who highlighted the potential of SAR data in estimating underwater bottom topography based on the theory of imaging mechanism, which remains a prominent reference source to date. Wensink et al. (1997) developed the Bathymetry Assessment System (BAS), a system that generates water depth maps (bathymetry) by combining radar image data and echosounder measurements. BAS's main limitation lies in its one-dimensional nature. It is only suitable for regions with uncomplicated underwater bottom topography, where surface currents are predominantly influenced by mass conservation or bottom friction. In more complex areas, subdivision into sub-areas is necessary to apply specific models (Calkoen et al., 2001).

Inglada & Garello (2002) have constructed the Volterra Series Expansions model that incorporates the nonlinearities present in the wave-current interaction, as well as in SAR processing. By incorporating these nonlinearities, the model aims to enhance the accuracy and effectiveness of SAR in capturing and visualizing ocean surface currents. Huang & Fu (2004) conducted a study on SAR bathymetry using ERS-1 SAR data and employing a numerical model based on the Navier-Stokes equations. However, the results were not perfect, and the errors observed in the findings could be attributed to the quality of the SAR images utilized and the calculation procedures involved (Huang & Fu, 2004).

The commonly used wave-based method is the linear dispersion equation, also known as linear wave theory or Airy theory. In obtaining the significant wave height required for calculations in the linear dispersion equation, researchers utilize the Fast Fourier Transform (FFT) technique (Bian et al., 2016; Boccia et al., 2015; Brusch et al., 2011; Huang et al., 2022; Jawak et al., 2015; Mishra et al., 2014; Pereira et al., 2019; Pleskachevsky et al., 2011; Santos et al., 2022; Wiehle et al., 2019); wavelet analysis (Santos et al., 2020); or hybrid, combination of FFT and wavelet analysis (Ma et al., 2021). FFT technique for obtaining peak wavelength can be done by ray tracing, fixed grid, or its combination called integrated mode (Bian et al., 2016). Figure 8 illustrates the comparison of wavelength by ray tracing and fixed grid modes. Another wave-based method for determining water depth is the non-linear wave theory (Flampouris et al., 2009). However, applying non-linear wave theory may not always be warranted when the data lacks sufficient accuracy, and implementing the linear dispersion relationship method is considered adequate (Cloarec et al., 2016).

Research on SAR Bathymetry has been conducted at several study locations, such as Europe (Alpers & Hennings, 1984; Boccia et al., 2015; Pereira et al., 2019; Santos et al., 2022; C. Stewart et al., 2016; G. J. Wensink et al., 1997; Wiehle et al., 2019); Asia (Bian et al., 2016, 2018; Hesselmans et al., 2000; L. Huang et al., 2022; W. Huang & Fu, 2004; Julzarika et al., 2021; Mishra et al., 2014; Rajput et al., 2021; Song et al., 2021; Tarikhi, 2012); North America (Ma et al., 2021; Tarikhi, 2012); Australia (Brusch et al., 2011; Pleskachevsky et al., 2011); and Africa (Ma et al., 2021). In Asia, study locations for SAR Bathymetry are distributed across several countries, such as China, India, and Indonesia, as depicted in Figure 9. The SAR Bathymetry research covers not only marine waters but also inland water bodies, such as lakes (Julzarika et al., 2021; Song et al., 2021).

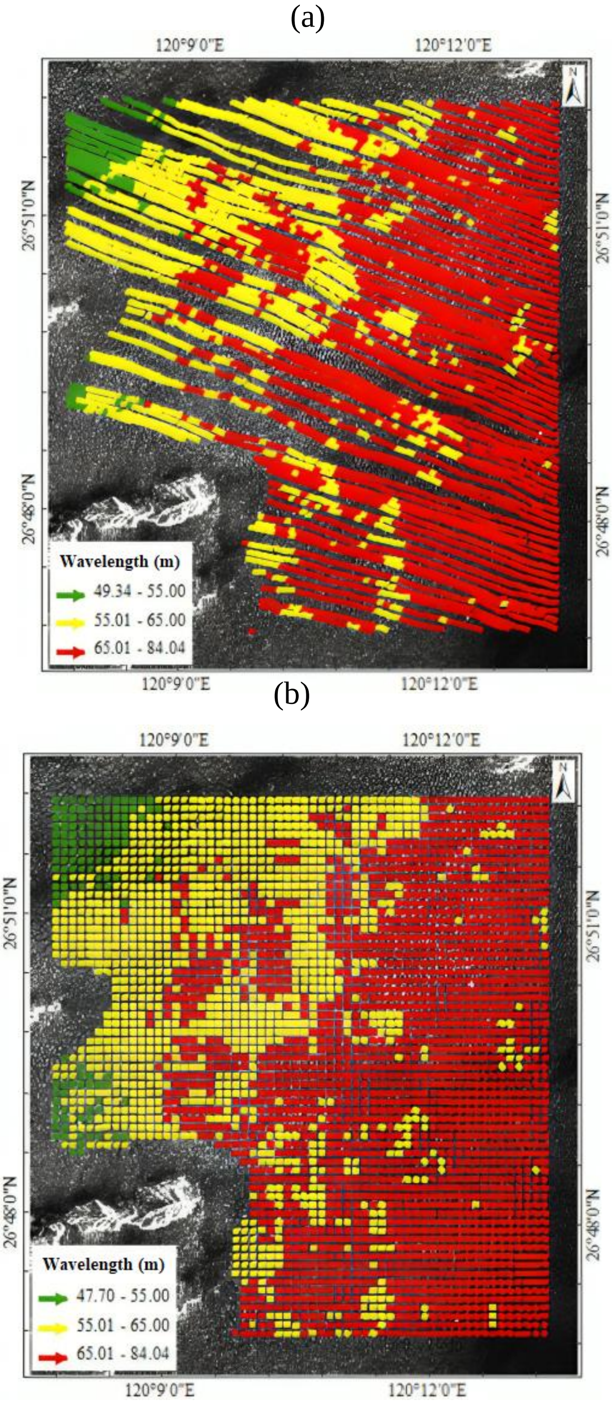


Figure 8 Wavelength calculated by ray tracing mode (a) and fixed grid mode (b) using FFT technique (Bian et al., 2016)

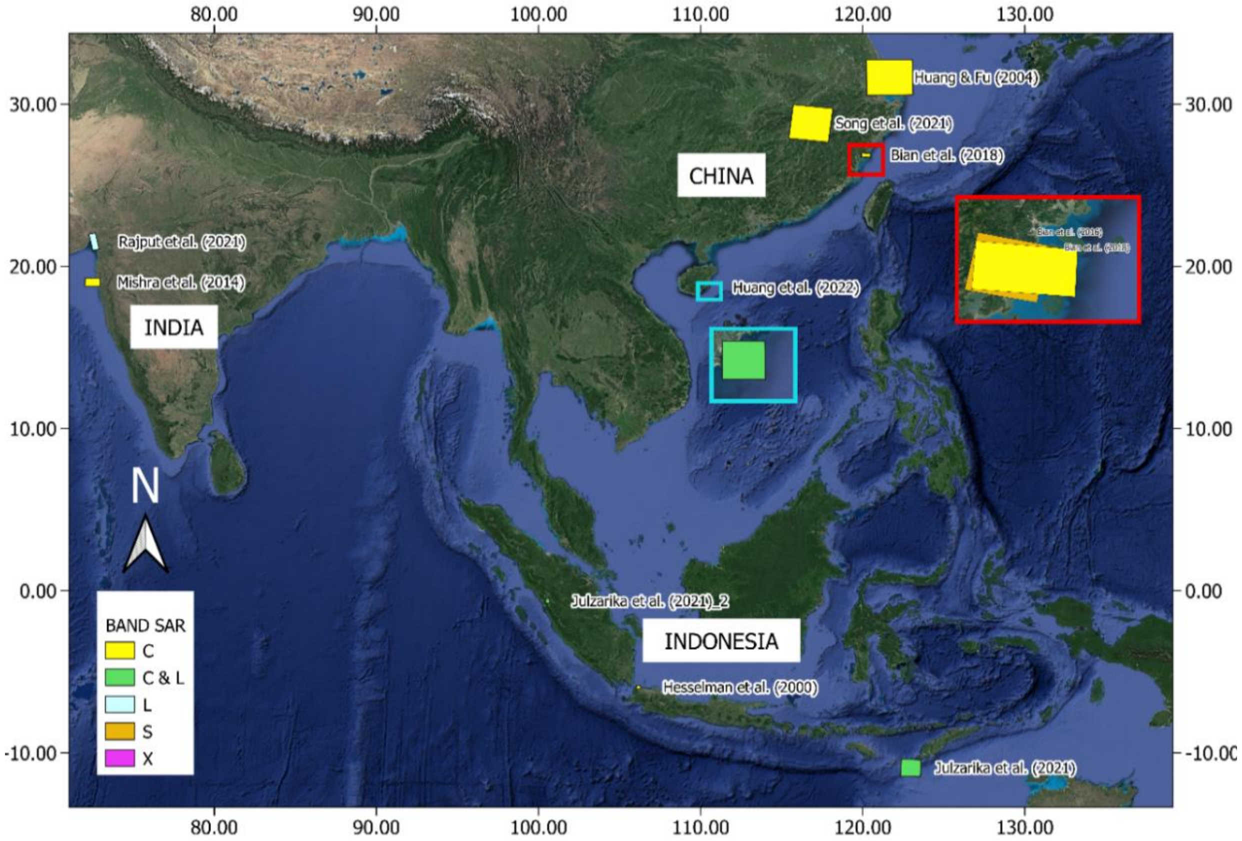


Figure 9 The distribution of study locations for SAR Bathymetry research in Asia (using a Google Earth base map, EPSG: 4326 coordinate system)

The currently popular and widely utilized SAR imagery by researchers is the Sentinel-1 SAR imagery, which operates in the C-band with a wavelength of approximately 5.6 cm (ESA, 2012). Several researchers have conducted previous studies on SAR Bathymetry using Sentinel-1 C-band SAR data (Bian et al., 2018, 2020; Huang et al., 2022; Julzarika et al., 2021; Ma et al., 2021; Pereira et al., 2019; Santos et al., 2022; Song et al., 2021; C. Stewart et al., 2016). The utilization of SAR imagery depends on the availability of image data during the research period.

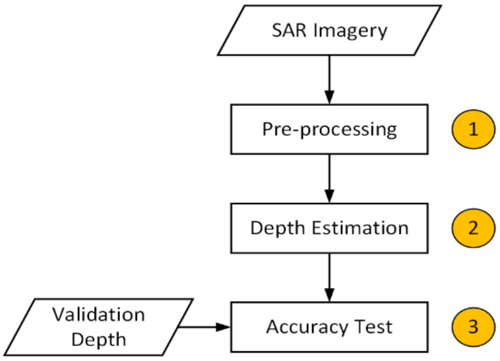


Figure 10 The main stages of processing SAR Bathymetry

Three main stages are involved in estimating depth using SAR imagery, starting with pre-processing to ensure that the SAR backscatter data is ready for further analysis. The subsequent stage is depth estimation, the core step for obtaining water depth values from SAR data. The most popular method researchers employ is the linear dispersion method, although InSAR processing also holds potential for further advancements. The final stage involves accuracy assessment, where field depth data or other higher-accuracy data sources are used to evaluate the accuracy of the depth results obtained through SAR Bathymetry. These three main stages are generally illustrated in Figure 10.

4. SAR Bathymetry Technique in Indonesia

As a maritime country, Indonesia requires bathymetry data, leading the government to issue regulations on methods for obtaining bathymetry data in the Regulation of the Geospatial Information Agency of the Republic of Indonesia Number 18 of 2021. However, the SAR Bathymetry method has not been mentioned in it. Despite Isardsat's findings (2017), cited in Julzarika et al. (2021), that SAR Bathymetry holds potential and is suitable for filling data gaps in shallow and deep waters, research on SAR Bathymetry in Indonesia remains underdeveloped. It is evident from the limited number of related studies found in the past two decades, comprising only two publications.

Table 1 presents the two published papers on SAR Bathymetry with study locations in Indonesia.

Table 1 Research on SAR Bathymetry conducted in Indonesia

Authors (Year)	Hesselman et al (2000)	Julzarika et al (2021)
Title	Mapping of Indonesian Coastal Waters by Synthetic Aperture Radar: An Indonesian-Netherlands Initiative for Starting New Business	Integration of the latest Digital Terrain Model (DTM) with Synthetic Aperture Radar (SAR) Bathymetry
Method	The Bathymetry Assessment System (BAS)	Liqui-InSAR (LiSAR)
Research location	Banten Bay	Rote Island and Lake Singkarak
SAR Image	ERS SAR	Sentinel-1 and ALOS PALSAR/PALSAR-2
Collaboration research	ARGOSS, BPPT, and PT Prakora Daya Mandiri	Trophical Inland Water (TIW), LAPAN, UGM, LIPI, BIG

5. Challenges and Opportunities of SAR Bathymetry

Indonesia presents opportunities and challenges in implementing SAR Bathymetry techniques for measuring water depths. Julzarika et al. (2021) revealed that SAR Bathymetry can be optimally utilized in water areas with depths ranging from 20 meters to 100 meters. Shallower waters (depths < 20 meters) often exhibit noise caused by irregular surface waves, while deeper waters tend to have more regular surface waves, making them more clearly captured by SAR sensors. Regions in Indonesia with regular surface wave patterns suitable for SAR Bathymetry implementation include the western region of Sumatra, eastern Indonesia, and the southern part of Java. It is due to their optimal sea depths and regular surface wave patterns. However, implementing this technique in island regions with irregular wave patterns can be challenging. The following subsections should be considered when applying SAR Bathymetry.

5.1. Data availability

5.1.1. SAR image

SAR imagery serves as the primary data required for SAR Bathymetry methods. In Indonesia, the only freely accessible SAR imagery is Sentinel-1, although its availability at specific locations and times is not guaranteed. Therefore, careful consideration should be given to the timing of image acquisition. Utilizing other SAR images, such as ALOS PALSAR, requires prior reservation. Among the various SAR images developed, Sentinel-1, TerraSAR-X, and ALOS PALSAR-2 show potential for application in Indonesia, as indicated in **Error! Reference source not found.**. The research duration should also be considered by the availability of the SAR imagery shown in Figure 11.

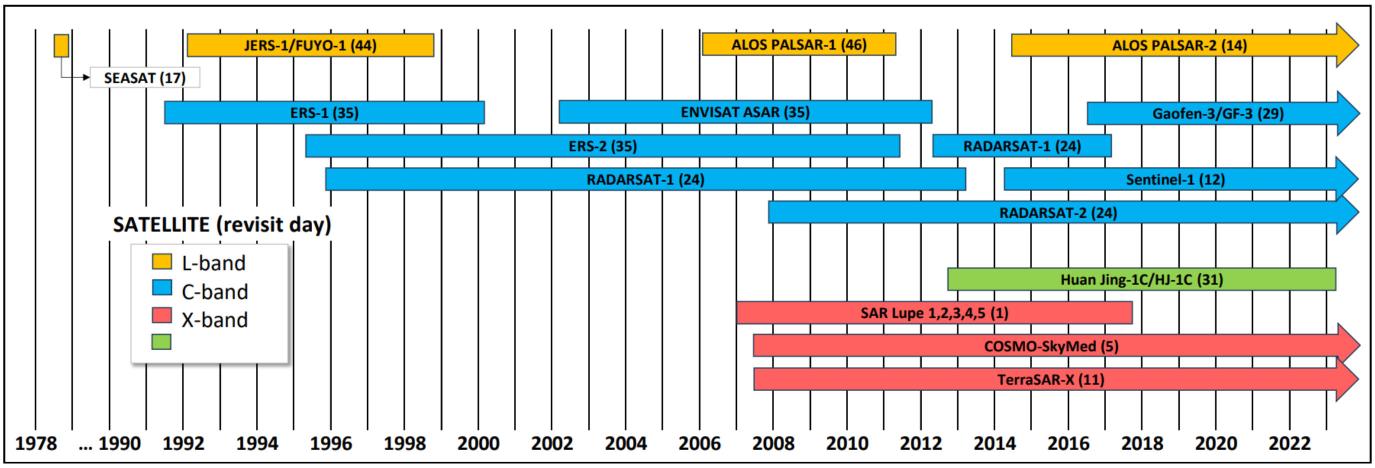


Figure 11 Availability of SAR imagery (number in round brackets represents the revisit time, measured in days) [updated from Tsai et al. (2019)]

Table 2 Developed satellite SAR images

Spaceborne SAR	The owner (country)	Band	Spatial Resolution [m]	Researches
ALOS PALSAR-1/2	JAXA (Japan)	L-band	7 – 100 * 25 (mosaic)	Boccia et al. (2015); Huang et al. (2022); Julzarika et al. (2021); Rajput et al. (2021)
COSMO-SkyMed	ASI (Italy)	X-band	< 1 – 100 *	
ENVISAT ASAR	ESA (Europe)	C-band	28 – 150 *	Huang et al. (2022); Tarikhi (2012)
ERS-1/2	ESA (Europe)	C-band	10 – 50,000 *	Hesselmans et al. (2000); Huang & Fu (2004); Li et al. (2000); Tarikhi (2012); Wensink et al. (1997)
Gaofen-3 (GF-3)	CRESDA (China)	C-band	1 – 500 *	Huang et al. (2022)
Huan Jing (HJ-1C)	CRESDA (China)	S-band	20	Bian et al. (2016)
JERS-1	JAXA (Japan)	L-band	18 x 24	
RADARSAT-1/2	CSA (Canada) & MDA (MacDonald, Dettwiler and Associates Ltd.)	C-band	8 – 100 *	
RISAT-I	ISRO (India)	C-band	1 – 50 *	Mishra et al. (2014)
SAR Lupe	Germany	X-band	0.5 (spotlight)	
SEASAT	ESA (Europe)	L-band	25	Alpers & Hennings (1984)
Sentinel-I	ESA (Europe)	C-band	5 – 100 *	Bian et al. (2018); Bian et al. (2020); Huang et al. (2022); Julzarika et al. (2021); Ma et al. (2021); Pereira et al. (2019); Santos et al. (2022); Song et al. (2021); Stewart et al. (2016)
TerraSAR-X	DLR (Germany)	X-band	0.25 – 40 *	Brusch et al. (2011); Pleskachevsky et al. (2011); Wiehle et al. (2019)

*based on imaging mode

▨ **used in previous SAR Bathymetry studies**

5.1.2. Wind data

The required wind data for SAR Bathymetry processing includes wind speed and direction. Ideally, this data can be obtained from field measurements or relevant institutions such as BMKG (Indonesian Meteorology, Climatology, and Geophysics Agency). However, the distribution of meteorological stations in Indonesia is limited. Moreover, the availability of field data obtained from measurements or observations at BMKG stations cannot be directly used due to their scattered point-based nature. Therefore, modelling is still necessary before conducting SAR Bathymetry processing. Additionally, the analysis will be conducted in marine or water areas, while meteorological stations are located on land. It poses a challenge for SAR Bathymetry methods. Another option to obtain surface wind data is to utilize SAR imagery to derive sea surface wind information. The Sentinel-1 Level 2 OCN (Ocean) SAR imagery provides direct wind direction and wind speed data that can be used. Alternatively, we can process Level-1 GRDH SAR imagery to derive sea surface wind, as shown in Figure 12.

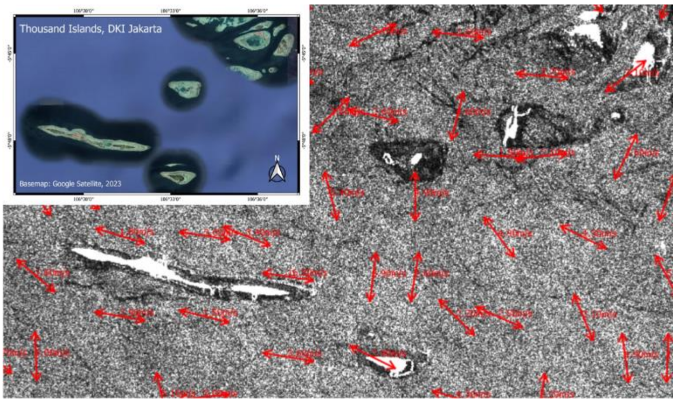
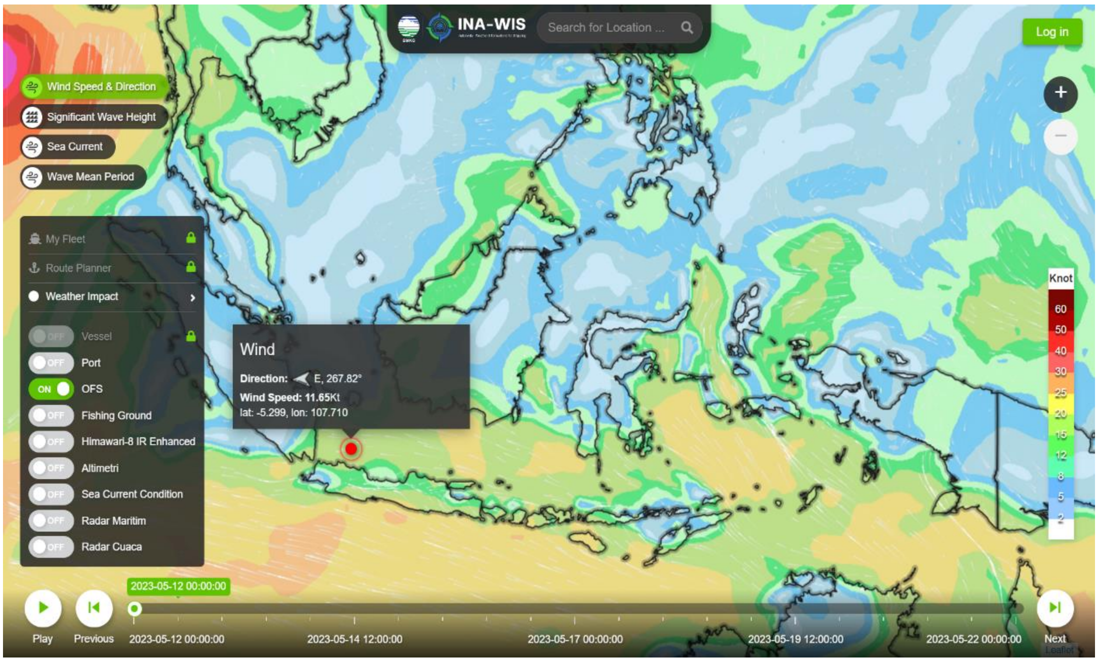


Figure 12 The results of processing the GRDH SAR image data into an experiment Sea Surface Wind (wind data) [Thousand Islands, August 12th, 2021; acquisition time based on the SAR imagery data used]

5.1.3. Current data

The required data for surface water currents include the speed and direction of the currents. Similar to wind data, obtaining accurate current data presents its challenges. Using model data can overcome difficulties in acquiring field measurements for current data. Daily global models of current data are openly accessible on the website https://marine.copernicus.eu/access-data. These models are in raster format with a resolution of 1/12° or approximately 9.25 km. In addition to current data, Marine Copernicus also provides wind data in raster format with the same resolution as the current data. In the Indonesian region, oceanographic data models such as wind and current data are available on the Indonesian – Weather Information for Shipping (INA-WIS) website managed by BMKG, as shown in Figure 13. The wind and current data models cover the entire Indonesian region, but only real-time and future predictions are available. It is not available online on the official INA-WIS website for time-series analysis or historical data requiring archival data.



Wind
Direction: E, 267.82°
Wind Speed: 11.65Kt
lat: -5.299, lon: 107.710

Figure 13 INA-WIS website (https://maritim.bmkg.go.id/inawis)

The wind and surface current data model is used as a correction to improve the results of water depth quality in the Liqui-InSAR (LiSAR) method. Wind and surface currents can affect the shape of the water waves that will be captured by the SAR sensor, so corrections using this data are needed (Julzarika et al., 2021).

5.2. Equipment

The essential equipment needed for SAR Bathymetry processing is a standard computer system (such as a PC or laptop), depending on the scope and the study area to be processed, along with SAR image processing software. For processing extensive and large-scale areas like the waters across Indonesia, a powerful computer is necessary to handle and store the data efficiently. Technically, SAR Bathymetry processing requires software capable of performing three main tasks: SAR image pre-processing, water depth estimation according to the chosen method, and geo-visualization of the obtained depth data. The LiSAR method requires InSAR processing, thus necessitating software capable of handling interferometry, not just SAR image pre-processing alone. On the other hand, the linear dispersion method requires software capable of processing SAR backscatter data using FFT techniques or similar approaches.

Table 3 provides an overview of several software options that can be used for SAR Bathymetry processing.

5.3. Geographical and weather conditions

As explained in the previous subsection, SAR Bathymetry does not directly measure water depth but indirectly captures the surface wave information through SAR. The geographical and weather conditions in water areas greatly influence the shape, height, and direction of waves and currents. The dynamic nature of waves and currents due to weather conditions significantly affects satellites' captured SAR sensor imagery. The timing of image acquisition at the study location may not necessarily be synchronized with the field data measured for validation, which can introduce information bias due to data discrepancies.

The water areas in Indonesia are vast and exhibit diverse conditions. It implies that a single method cannot be universally applied across all Indonesian regions. Research is needed to understand the varying characteristics of different water areas and their impact on the optimality of SAR Bathymetry methods, including the parameters and equations used in the algorithms. Alpers & Hennings (1984) revealed in the Imaging Mechanism theory that the optimal conditions for capturing wave information using SAR sensors include moderate wind speeds and strong current velocities. With wind speeds ranging from 3-10 m/s and current velocities exceeding 0.5 m/s, water areas can form distinct surface waves that can be captured by SAR (Cloarec et al., 2016; Hesselmans et al., 2000).

Table 3 Software options supporting SAR Bathymetry processing

Software	**SAR Processing**	**FFT Technique**	**Software**	**SAR Processing**	**FFT Technique**
GMT5SAR	✓	-	***ENVI SARSCAPE**	✓	✓
ISCE2	✓	-	***ERDAS Imagine**	✓	-
LIZARDTECH GeoView	✓	-	***GAMMA SAR**	✓	-
Sentinel-1 Toolbox (S1TBX) in SNAP	✓	-	***Geomatica**	✓	-
SARViews	✓	-	***DIAPASON**	✓	-
pyroSAR	✓	-	***Global SAR**	✓	-
Orfeo Toolbox (OTB)	✓	-	***SARPROZ**	✓	-
SARbian	✓	-	***Photomod Radar**	✓	-
Doris InSAR Processor	✓	-	Google Colab or another python Notebook + Library OpenCV and Numpy	-	✓
ROI_PAC	✓	-	MATLAB	✓	✓
Next ESA SAR Toolbox (NEST)	✓	-	GRASS GIS	-	✓
OSARIS	✓	-	StaMPS for PS-InSAR	✓	-
Radar Tools (RAT)	✓	-	GIAnT	✓	-

***commercial software**

6. Conclusions

The utilization of SAR for obtaining water depth or bathymetry data holds significant potential for application in Indonesian water areas. However, not all water areas can effectively employ SAR Bathymetry techniques in their application. The diverse conditions of Indonesian waters require collaborative efforts regarding data sources, platforms, and techniques to obtain depth data according to specific needs.

7. Conflict of Interest

The authors declare no competing interest.

8. References

Alpers, W., & Hennings, I. (1984). Theory of the Imaging Mechanism of Underwater Bottom Topography By Real and Synthetic Aperture Radar. *Journal of Geophysical Research*, *89*(C6), 10529–10546. https://doi.org/10.1029/JC089iC06p10529

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Ashphaq, M., Srivastava, P. K., & Mitra, D. (2021). Review of near-shore satellite derived bathymetry: Classification and account of five decades of coastal bathymetry research. *Journal of Ocean Engineering and Science*, *6*(4), 340–359. https://doi.org/10.1016/j.joes.2021.02.006

Bai, X., Li, B., Xu, X., & Xiao, Y. (2022). A Review of Current Research and Advances in Unmanned Surface Vehicles. *Journal of Marine Science and Application*, *21*(2), 47–58. https://doi.org/10.1007/s11804-022-00276-9

Bergsma, E. W. J., Conley, D. C., Davidson, M. A., & O'Hare, T. J. (2016). Video-based nearshore bathymetry estimation in macro-tidal environments. *Marine Geology*, *374*, 31–41. https://doi.org/10.1016/j.margeo.2016.02.001

Bian, X., Shao, Y., Tian, W., & Zhang, C. (2016). Estimation of Shallow Water Depth Using HJ-1C S-band SAR Data. *Journal of Navigation*, *69*(1), 113–126. https://doi.org/10.1017/S0373463315000454

Bian, X., Shao, Y., Wang, S., Tian, W., Wang, X., & Zhang, C. (2018). Shallow Water Depth Retrieval from Multitemporal Sentinel-1 SAR Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *11*(9), 2991–3000. https://doi.org/10.1109/JSTARS.2018.2851845

Bian, X., Shao, Y., Zhang, C., Xie, C., & Tian, W. (2020). The feasibility of assessing swell-based bathymetry using SAR imagery from orbiting satellites. *ISPRS Journal of Photogrammetry and Remote Sensing*, *168*(April), 124–130. https://doi.org/10.1016/j.isprsjprs.2020.08.006

BIG. (2020). *Kerangka Acuan Kerja (KAK) Akuisisi LiDAR dan Pemotretan Udara Digital serta Pembuatan Unsur Rupabumi Indonesia Skala 1:5.000 Wilayah OSS Tebing Tinggi, Kikim, dan Seputih Banyak Tahun Anggaran 2020*.

Boccia, V., Renga, A., Rufino, G., D'Errico, M., Moccia, A., Aragno, C., & Zoffoli, S. (2015). Linear dispersion relation and depth sensitivity to swell parameters: Application to synthetic aperture radar imaging and bathymetry. *Scientific World Journal*, *2015*, 1–10. https://doi.org/10.1155/2015/374579

Brusch, S., Held, P., Lehner, S., Rosenthal, W., & Pleskachevsky, A. (2011). Underwater bottom topography in coastal areas from TerraSAR-X data. *International Journal of Remote Sensing*, *32*(16), 4527–4543. https://doi.org/10.1080/01431161.2010.489063

Calkoen, C. J., Hesselmans, G. H. F. M., Argoss, G. J. W., & Vogelzang, J. (2001). The bathymetry assessment system: Efficient depth mapping in shallow seas using radar images. *International Journal of Remote Sensing*, *22*(15), 2973–2998. https://doi.org/10.1080/01431160116928

Casal, G., Monteys, X., Hedley, J., Harris, P., Cahalane, C., & McCarthy, T. (2019). Assessment of empirical algorithms for bathymetry extraction using Sentinel-2 data. *International Journal of Remote Sensing*, *40*(8), 2855–2879. https://doi.org/10.1080/01431161.2018.1533660

Chan, Y. K., & Koo, V. C. (2008). An introduction to Synthetic Aperture Radar (SAR). *Progress In Electromagnetics Research B*, *2*, 27–60. https://doi.org/10.2528/pierb07110101

Cloarec, M., Dubranna, J., & Ranchin, T. (2016). SAR-based techniques to extract bathymetric features. *XIVe Journées nationales du Génie Côtier – Génie Civil, Jun 2016, Toulon, France*, 351–360.

Croneborg, L., Saito, K., Matera, M., Mckeown, D., & Aardt, J. van. (2015). *Digital Elevation Models; A Guidance Note on how Digital Elevation Models are created and used – includes key definitions, sample Terms of Reference and how best to plan a DEM-mission*. International Bank for Reconstruction and Development.

ESA. (2012). *Sentinel-1 Acquisition Modes*. https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes

ESA. (2020). *Copernicus Sentinel-6 Michael Freilich liftoff replay*. European Space Agency. https://www.esa.int/ESA_Multimedia/Videos/2020/11/Copernicus_Sentinel-6_Michael_Freilich_liftoff_replay

Flampouris, S., Seemann, J., & Ziemer, F. (2009). Sharing our experience using wave theories inversion for the determination of the local depth. *OCEANS '09 IEEE Bremen: Balancing Technology with Future Needs*. https://doi.org/10.1109/OCEANSE.2009.5278331

Gao, J. (2009). Bathymetric mapping by means of remote sensing: Methods, accuracy and limitations. *Progress in Physical Geography*, *33*(1), 103–116. https://doi.org/10.1177/0309133309105657

Grgić, M., & Bašić, T. (2021). Radar Satellite Altimetry in Geodesy - Theory, Applications and Recent Developments. In B. Erol & S. Erol (Ed.), *Geodetic Sciences - Theory, Applications and Recent Developments* (hal. 77–88). IntechOpen. https://doi.org/10.5772/intechopen.97349

Hesselmans, G. H. F. M., Wensink, G. J., Calkoen, C. J., & Valk, C. F. de. (1995). ERS Data to Support Coastal and Offshore Applications. *The Second ERS Applications Workshop*, 325–327.

Hesselmans, G. H. F. M., Wensink, G. J., Prasetya, G., & Barnas, I. (2000). Mapping of Indonesian coastal waters by synthetic aperture radar: An Indonesian-Netherlands initiative for startinge new business. *European Space Agency, (Special Publication) ESA SP*, *461*, 527–536.

Holman, R., & Bergsma, E. W. J. (2021). Updates to and Performance of the cBathy Algorithm for Estimating Nearshore Bathymetry from Remote Sensing Imagery. *Remote Sensing*, *13*(19), 1–25. https://doi.org/10.3390/rs13193996

Holman, R., Plant, N., & Holland, T. (2013). cBathy: A robust algorithm for estimating nearshore bathymetry. *Journal of Geophysical Research: Oceans*, *118*(5), 2595–2609. https://doi.org/10.1002/jgrc.20199

Huang, L., Meng, J., Fan, C., Zhang, J., & Yang, J. (2022). Shallow Sea Topography Detection from Multi-Source SAR Satellites: A Case Study of Dazhou Island in China. *Remote Sensing*, *14*(20). https://doi.org/10.3390/rs14205184

Huang, W., & Fu, B. (2004). A Spaceborne SAR Technique for Shallow Water Bathymetry Surveys. *Journal of Coastal Research*, *SPEC. ISS. 43*, 223–228.

IHO. (2005). Depth Determination. In *Manual on Hydrography Chapter 3 Depth Determination* (hal. 119–197). International Hydrographic Bureau.

IHO. (2020). *International Hydrographic Organization Standards for Hydrographic Surveys* (6.0.0).

Inglada, J., & Garello, R. (2002). On rewriting the imaging mechanism of underwater bottom topography by synthetic aperture radar as a volterra series expansion. *IEEE Journal of Oceanic Engineering*, *27*(3), 665–674. https://doi.org/10.1109/JOE.2002.1040949

Jawak, S. D., Vadlamani, S. S., & Luis, A. J. (2015). A Synoptic Review on Deriving Bathymetry Information Using Remote Sensing Technologies: Models, Methods and

Comparisons. *Advances in Remote Sensing*, *04*(02), 147–162. https://doi.org/10.4236/ars.2015.42013

Julzarika, A., Aditya, T., Subaryono, Harintaka, Dewi, R. S., & Subehi, L. (2021). Integration of the latest Digital Terrain Model (DTM) with Synthetic Aperture Radar (SAR) Bathymetry. *Journal of Degraded and Mining Lands Management*, *8*(3), 2759–2768. https://doi.org/10.15243/jdmlm.2021.083.2759

Khomsin, Pratomo, D. G., & Saputro, I. (2021). Comparative analysis of singlebeam and multibeam echosounder bathymetric data. *IOP Conference Series: Materials Science and Engineering*, *1052*(1). https://doi.org/10.1088/1757-899x/1052/1/012015

Legleiter, C. J., & Harrison, L. R. (2019). Remote Sensing of River Bathymetry: Evaluating a Range of Sensors, Platforms, and Algorithms on the Upper Sacramento River, California, USA. *Water Resources Research*, *55*(3), 2142–2169. https://doi.org/10.1029/2018WR023586

Li, S., Jeffries, M., & Morris, K. (2000). Mapping the Bathymetry of Shallow Tundra Lakes Using INSAR Techniques. *IEEE 2000 International Geoscience and Remote Sensing Symposium. Taking the Pulse of the Planet: The Role of Remote Sensing in Managing the Environment. Proceedings*, 2230–2232.

Ma, Y., Yue, B., Chenier, R., Omari, K., & Henschel, M. (2021). Nearshore Bathymetry Estimation Using Synthetic Aperture Radar (SAR) Imagery. *Canadian Journal of Remote Sensing*, *47*(6), 790–801. https://doi.org/10.1080/07038992.2021.1954499

Mandlburger, G. (2019). Through-water dense image matching for shallow water bathymetry. *Photogrammetric Engineering and Remote Sensing*, *85*(6), 445–454. https://doi.org/10.14358/PERS.85.6.445

Mandlburger, G. (2022). A Review of Active and Passive Optical Methods in Techniques. *International Hydrographic Review*, *28*(November 2022), 8–52. https://doi.org/https://doi.org/10.58440/ihr-28-a15

Mavraeidopoulos, A. K., Pallikaris, A., & Oikonomou, E. K. (2017). Satellite Derived Bathymetry (SDB) And Safety of Navigation. *The International Hydrographic Review*, *May*, 7–20. https://ihr.iho.int/articles/satellite-derived-bathymetry-sdb-and-safety-of-navigation/

Mishra, M. K., Ganguly, D., Chauhan, P., & Ajai. (2014). Estimation of coastal bathymetry using RISAT-1 C-band microwave SAR data. *IEEE Geoscience and Remote Sensing Letters*, *11*(3), 671–675. https://doi.org/10.1109/LGRS.2013.2274475

Papatheodorou, G., Geraga, M., Fakiris, E., Papakonstantinou, M., & Mavrommatis, N. (2023, Juni 20). Exploring shallow lagoons with USV mapping technology. *Hydro International*. https://www.hydro-international.com/content/article/exploring-shallow-lagoons-with-usv-mapping-technology

Pereira, P., Baptista, P., Cunha, T., Silva, P. A., Romão, S., & Lafon, V. (2019). Estimation of the nearshore bathymetry from high temporal resolution Sentinel-1A C-band SAR data - A case study. *Remote Sensing of Environment*, *223*(December 2018), 166–178. https://doi.org/10.1016/j.rse.2019.01.003

Pleskachevsky, A., Lehner, S., Heege, T., & Mott, C. (2011). Synergy and fusion of optical and synthetic aperture radar satellite data for underwater topography estimation in coastal areas. *Ocean Dynamics*, *61*(12), 2099–2120. https://doi.org/10.1007/s10236-011-0460-1

Poerbandono, Djunarsjah, E., Bachri, S., Abidin, H. Z., & Adil, I. (2005). *Survei Hidrografi* (R. Herlina (ed.)). Refika Aditama.

Rajput, P., Ramakrishnan, R., Francis, S., Thomaskutty, A. V., Agrawal, R., & Rajawat, A. S. (2021). Investigating shallow water bottom feature using SAR data along Gulf of Khambhat, India. *Remote Sensing Applications: Society and Environment*, *23*(July), 1–11. https://doi.org/10.1016/j.rsase.2021.100592

Romeiser, R., & Alpers, W. (1997). An improved composite surface model for the radar backscattering cross section of the ocean surface 2. Model response to surface roughness variations and the radar imaging of underwater bottom topography. *Journal of Geophysical Research: Oceans*, *102*(C11), 25251–25267. https://doi.org/10.1029/97JC00190

Santos, D., Abreu, T., Silva, P. A., & Baptista, P. (2020). Estimation of coastal bathymetry using wavelets. *Journal of Marine Science and Engineering*, *8*(10), 1–16. https://doi.org/10.3390/jmse8100772

Santos, D., Fernández-Fernández, S., Abreu, T., Silva, P. A., & Baptista, P. (2022). Retrieval of nearshore bathymetry from Sentinel-1 SAR data in high energetic wave coasts: The Portuguese case study. *Remote Sensing Applications: Society and Environment*, *25*(August 2021). https://doi.org/10.1016/j.rsase.2021.100674

Santosa, P. B. (2016). Evaluation of satellite image correction methods caused by differential terrain illumination. *Jurnal Forum Geografi. Vol. 30, No. 1 (2016).* https://doi.org/10.23917/forgeo.v30i1.1768

Song, L., Song, C., Luo, S., Chen, T., Liu, K., Li, Y., Jing, H., & Xu, J. (2021). Refining and densifying the water inundation area and storage estimates of Poyang Lake by integrating Sentinel-1/2 and bathymetry data. *International Journal of Applied Earth Observation and Geoinformation*, *105*, 102601. https://doi.org/10.1016/j.jag.2021.102601

Stewart, C., Renga, A., Gaffney, V., & Schiavon, G. (2016). Sentinel-1 bathymetry for North Sea palaeolandscape analysis. *International Journal of Remote Sensing*, *37*(3), 471–491. https://doi.org/10.1080/01431161.2015.1129563

Stewart, R. H. (2008). *Introduction to Physical Oceanography*. Texas A&M University. https://doi.org/10.5860/choice.34-5103

Syetiawan, A., & Gularso, H. (2021, April). Towards a coastline base map in Indonesia. *Hydro International*. https://www.hydro-international.com/content/article/towards-a-coastline-base-map-in-indonesia

Tarikhi, P. (2012). Insar of Aquatic Bodies. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XXXIX-B7*(September), 85–90. https://doi.org/10.5194/isprsarchives-xxxix-b7-85-2012

Toschi, I., Remondino, F., Rothe, R., & Klimek, K. (2018). Combining airborne oblique camera and LiDAR sensors: Investigation and new perspectives. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(1), 437–444. https://doi.org/10.5194/isprs-archives-XLII-1-437-2018

Tsai, Y. L. S., Dietz, A., Oppelt, N., & Kuenzer, C. (2019). Remote sensing of snow cover using spaceborne SAR: A review. *Remote Sensing*, *11*(12). https://doi.org/10.3390/rs11121456

Wensink, G. J., Hesselmans, G. H. F. M., Calkoen, C. J., & Vogelzang, J. (1997). The Bathymetry Assessment System. In J. H. Stel, H. W. A. Behrens, J. C. Borst, L. J. Droppert, & J. v.d. Meulen (Ed.), *Operational Oceanography: The Challenge for European Co-operation* (hal. 214–223). Elsevier Science B.V.

Wensink, H., & Alpers, W. (2014). SAR-Based Bathymetry. In E. G. Njoku (Ed.), *Encyclopedia of Remote Sensing* (hal. 719–722). Springer Science+Business Media New York. https://doi.org/10.1007/978-0-387-36699-9

Wiehle, S., Pleskachevsky, A., & Gebhardt, C. (2019). Automatic bathymetry retrieval from SAR images. *CEAS Space Journal*, *11*(1), 105–114. https://doi.org/10.1007/s12567-018-0234-4