Four-dimensional wave refraction from Sentinel-1A satellite data

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Abstract. This investigation has incontestable a replacement technique for the modelling of wave refraction configuration from synthetic aperture radar data. To this end, the nonlinear of bunching rate exploited to exhibit the wave spectral peaks braced the novel progress of the 4-D B-spline algorithmic program. The study shows that convergence zone is conquered by breaking wave height of 4.5 m. The study also indicates that wave divergence array could be modelled from Sentinel-1A satellite in both divergence and convergence spectra energy arrays. This can impact the society through causing a coastal erosion. Lastly, 4-D wave refraction pattern in spite of nonlinearity between actual ocean wave spectra and Sentinel-1A data is simulated by 4-D B-spline algorithmic program supported Pareto optimization.

1. Introduction

Satellite microwave data such as SAR have the great potential for retrieving ocean wave parameters [1]. SAR wave spectra parameters retrieving are restricted to two ideas that are (i) linear and (ii) nonlinear [1-7]. These two notions do not seem to be ready to retrieve correct wave spectra parameters. Because the retrieving of wave spectra from SAR is principally influenced by nonlinearity besides the deformation of wave mathematical algorithms in SAR images owing to shadowing and speckles effects too [1].

Presently, there is a great interest in 4-D reform embarking remote sensing satellite data [10-14]. 4-D revolution of coastal studies shows the excellent promises [14]. In fact, Marghany and Mansor [14] remodelled 4-D of wave spectra refraction using 2-D synthetic Aperture radar (SAR) images. There are several efforts to reveal ocean wave spectra into SAR spectrum power by exploitation inverse spectra technique as documented on Schulz-Stellenfleth et al. [15]. Further, empirical algorithms are accustomed retrieve deep water vital wave height independent from wave model input. Pleskachevsky et al. [16], recently implemented the applied math analysis to compared between, input model i.e. coastal wave model (CWAM), buoy, and vital wave height was retrieved from TS-X image. However, this practice involves errors of uncertainty of peak wave amount, the comparative coefficient of dissimilar wave height, and therefore, the wind data used as contribution in the CWAM tool. SAR sensors, however, are still not absolutely operational for wave spectra studies[17-20].

Shoreline configuration is mainly function of wave refraction. This could be conferred in each convergence and divergence that may cause erosion and deposit, discretely. Wave refraction simulation, therefore, is demanded standard algorithms to recreate its precise physical parameters. Subsequently, the simulation of wave refraction pattern from retrieved wave spectra parameters can expertise with many limitations: (i) ambiguity in direction; (ii) nonlinearity due rate bunching and (iii) the retrieved vital wave height primarily based angle cut-off might be constant through the SAR image. In fact, 2-D FFT may be applied on SAR information with window kernel size of 512 x 512 pixels and features. This implies that the predictable wavelength from 2-DFFT cannot be more than 50 m. However, the wave spectra expertise shrinking on their wavelength as they're pending the shallow water. In this understanding, the simulated SAR image spectrum should be arrayed to be removed through the real ocean wave verities and slightly sophisticated post-processing is critical for mining computable wave statistics [16-20].
This work novelty remains to optimize the lapses occurring on retrieving wave spectra parameters from SAR information. The most hypotheses are 4-D wave spectra are encoded in 3-D wave spectra, as 2-D wave spectra are encoded in 1-D wave spectra. The most objective is to simulate 4-D of wave refraction pattern from Sentinel-1A. This study postulates that (i) 4-D spline able to reconstruct 4-D wave refraction patterns from SAR data and (ii) Pareto optimal solution provides a bet optimization for 4-D wave refraction patterns.

2. Data Acquisitions
Two styles of knowledge area unit needed to reconstruct 4-D wave refraction pattern: Sentinel-1 A of SAR; (ii) and therefore the real unaltered wave measuring throughout Sentinel-1 A overpassed.

2.1 Sentinel-1 Data
In this exploration, Sentinel-1 records with single polarization VV are used. Sentinel-1 (Figure 1) is that the measuring device European laboratory, expressive the primary innovative planetary share of the worldwide observation for location and safety outpost intimate, intended and established by ESA then sponsored by the international organization of European Directive. This SAR satellite consists of a assemblage of 2 satellites, Sentinel-1A and Sentinel-1B, apportioning a similar detour plane with a $2\pi^\circ$ detour period distinction (Figure 2).

![Figure 1. Sentinel-1 A satellite](image1.png)

![Figure 2. Orbital plane of Sentinel-1A and Sentinel-1B](image2.png)
Excluding for ocean wave and current studies, that may be one polarization mode (VV or HH) with C-band, the SAR device should sustain procedures through twofold polarization (HH-HV, VV-VH), necessitating the execution of one convey restraint (switchable to V or H) and dual equivalent obtain manacles for both V and H polarization. The particular wants of the four entirely dissimilar quantity manners with regard to antenna agility need the execution of an energetic phased array antenna. For every strip the antenna should be premeditated to come up with a ray with fastened ground and range inform. Applicable range pulse creating should be smeared in vary vagueness destruction. Additionally, the incident angle is ranged between 20º-46º [16].

2.2 In situ ocean wave measurement
The in situ wave spectra quantities, i.e. wavelength, spectra statistical heights such as \( H_s \), wave period, wave velocity, and bearing, are obtained using the Acoustic Wave and Current (AWAC) (Figure 3) from the east coast of Kuala Terengganu, Malaysia on March 8th till 12th March 2015, at 5°28’02” N and 103°07’48”E (Figure 3). AWAC recorded the water column current speed and directions.

![Figure 3. AWAC wave spectra in -situ measurements](image)

![Figure 4. Geographical location of AWAC instrument](image)

3. Algorithms

3.1 4-D Spline Algorithm
Let assume that \( i, j, \) and \( k \) are restrained to the interlude \( i, j, k \in [0, 1] \) and \( S(i, j, k, t) \in (x, y, z) \). This involves that the ocean wave is separated into hyperpatches. The hyperpatches are signified by means of exteriors and curvatures. Then the exterior definite by site one of \( i, j, k \) to a invariable integer assessment which is yelled a knot plane, which are the defining the surfaces of hyperpatches [12-14]. In fact, a volume as a set of 3-D area with a further scalar worth given in every of its points. If this scalar worth is taken as a further purpose direct, the quantity becomes a 4-D “height field” or a hypersurface in 4-D area [13]. The outlined field are often thought of as a variable of the spectra’s, height, period, etc. Computable quantities are often per the bulges of a lattice or by a uninterrupted function of 3 flexibles (so-named as implied exterior pattern or a ration of typically the operates illustration. Albeit traditional thought of area as three-dimensional, any object is often derived within the area of 4 and even higher dimensions. The most challenge is to work out logic strategies to reconstruct such high-dimensional stuffs. Equation 1 exploits 4-D spline to reconstruct 4-D of Sentinel-1A data as follows:
\[ p(i, j, k) = [x, y, z] = [x(i, j, k), y(i, j, k), z(i, j, k)] \] (1)

To implement the 4-D spline, the wave spectra parameters which are assimilated at individually knot period and knot planes become temporal functions. Then wave spectra pattern can be expressed in 4-D B-spline pattern as [3]:

\[ S(i, j, k, t) = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} F(\tilde{K}, H_s, t) O_i(i) O_j(j) O_k(k) O_M(m) t \] (2)

where \( O_i(i) \), \( O_j(j) \), \( O_k(k) \), and \( O_M(m) \) are rule functions of B-spline which combination regulator points of \( F(\tilde{K}, H_s, t) \) and \( i \times j \times k \times M \) is the entire quantity of algorithm regulator points. By shifting the command of B-spline abstract in eq. 2, a further operative technique to retrieve a extra-dimensional B-spline wave spectra refraction algorithm effects.

### 3.2 Nonlinear Algorithm

The simplified non-linear theory to record determined radar satellite nonlinear wave into the real ocean wave statistical information which dependable on the Gaussian algorithm, the correlation between ocean wave height and SAR data could be symbolized by slant modulation and hydraulics modulation. The slant modulation is lined to the innate wave slant within the differ in route i.e. within the smooth of backscatter radiance. The slant variation normally can be a function of wind stress and wind bearing for ocean spectra and Sentinel-1 A. In line with Vachon et al. [20] the slant variation is that the leading for HH polarization. Alpers et al. [1] and Alpers and Bruning [4] rumoured that hydraulics interface between the ripples and extended gravity waves shaped a grade of the reflection on the ocean wave surface. So as to estimate \( H_s \) from the quasi-linear remodel, we have a inclination to approve the algorithmic rule that was specified by Marghany [9] to be satisfactory for the geophysical circumstances of tropical zone as specified in eq.3:

\[ A_c = RV^{-1} \int W_0^{0.5} dW + \int H_s^{0.5} dH \] (3)

where \( A_c \) is cut-off azimuth wavelength, \( H_s \) and \( W \) are the in situ data of significant wave height and wind velocity. The restrained wind velocity was appraised at 10 m tallness over head the sea surface. The variations of \( H_s \) wind velocity along the azimuth direction are replaced by \( dW \) and \( dH_s \) correspondingly. The subscript zero denotes to the usual in situ wave data composed prior satellite overpass by two hours whereas the subscripts \( n \) denotes to the typical of ground wave data throughout the satellite overpass. \( R \) and \( V \) are the range to satellite velocity ratio timed by the interrupt of azimuth cut-off (c) when \( H_s \) and \( W \) are zero. Then, the subsequent equation was assumed by Marghany [9] to approximation the \( H_{ss} \) from the Sentinel-1 A satellite data as given by:

\[ H_{ss} = \left( c^{-2} R^{-2} V^{-2} \right)^{2} \int_{A_0}^{A_0} (A_c)^2 dA_c \] (4)

where \( H_{ss} \) is the significant wave height simulated from Sentinel-1 A data. The presented technique is considered for regular wave arenas as surfs can be create over the exposed ocean below bottomless water circumstance with regular bathymetry. A linear wave algorithm can be castoff to resolve the problematic of regular wave zones by pretending the sensible wave limitations [17-20].

On the word of Hasselmann and Hasselmann [7] and Herbers et al [6] the wave diversion algorithm in excess of the Sentinel-1A data is established on the evidence of frequency and wave energy exchange code, trivial bathymetry gradient, stable wave circumstances and an exclusively deepness refractive. It is repeatedly transformed \( H_s \) since the refraction codes into 4-D as given by:

\[ F(\tilde{K}, H_s, t) = p(H_s) S(H_{sl}, H_{sj}, H_{sk}, H_{sit}) \] (5)
where term of $S(H_{Si}, H_{Sj}, H_{Sk}, H_{Sit})$ is the distribution for the wave number and $p(H_{S})$ is the probability scattering of $H_{S}$ codes in 4-D.

3.3 Pareto Optimal Solution

Let us assume that $S_{i} [0,1,2,3,....m]$ are the wave refraction constraint quantities that can be appraised by the genetic process to imprecise the tiniest fault for wave diversion limitations. Pareto greatest elucidations are pragmatic to elevate the 4-D wave bending variation in SAR image. During this drawback, the gene entails of diversity wherever each gene resembles to a constant within the n$^\text{th}$-directive superficial appropriate mathematical polynomial algorithm as estimated by

$$f(S_{ijkl}) = S_{i0} + S_{ij} + S_{jk} + S_{ik} + S_{jit} + \ldots + S_{nlt}$$  

where $i,j,k$ and $t$ are indices of the pixel location in 4-D image respectively, $m$ is the measure of quantities. Formerly, the weighted quantity to fuse manifold objectives into one objective is specified by

$$f(S_{r}) = w_{1}f_{1}(S_{r}) + w_{2}f_{2}(S_{r}) + \ldots + w_{n}f_{n}(S_{r})$$  

where $f_{1}(S_{r}), f_{2}(S_{r}), \ldots, f_{n}(S_{r})$ are the unbiased functions and $w_{1}, w_{2}, \ldots, w_{n}$ are the weights of matching objectives that placate the following circumstances.

$$\sum_{i=1}^{n} w_{n} = 1$$

$$w_{i} \geq 0 \quad \forall i = 1,2,3,4,\ldots,n$$  

Formerly, the encumbrances square measure regulated, the looking out manner is fastened. To explore optimum solutions of Pareto algorithm where the maximum amount is as attainable, the examining orders ought to be modified once more. Further, once more to swing over the full resolution dimension. In this analysis, two objectives are thought of. One is retrieved vital wave height from SAR data and also the alternative is 4-D spline for wave refraction.

4. Results and Discussion

The wave spectra physical parameter of the significant wave height is retrieved and compared with in situ data. Figure 5 exposes significant wave height derived by Pareto optimization. The maximum significant wave height is 4.5 m with $r^2$ of 0.8 and RMSE± 0.87m. This approves with findings of Wrytki [22] and Zelina et al.[23]. Certainly, month of March is indicating the northeast monsoon period while ocean wave transmitted from the northeast concerning the Malaysian east coast [9].

![Figure 5. Significant wave height derived from Sentinel-1A image using Pareto optimization](image-url)
Figure 6 presents the 4-D wave refraction pattern which derived from 4-D B-spline based Pareto optimal solutions algorithm. 4-D wave refraction pattern displays clear convergence and divergence zone along the coastal water. The divergence zone conquered by breaking $H_s$ of 3 m while the convergence zone is subjugated by breaking $H_s$ of 4.5 m. Moreover, four-dimensional of spectra energy indicates that the convergence zone dominated by highest refractive index of 2.6. In additions, 4-D suggests a turbulent pattern flow which is noticeable by asymmetrical pattern either in convergence or divergence zone (Figure 6).

As said by Yudong et al. [21], the energy of 4-D spline is demarcated because the amount of individually knots energy that is pronounced because the integral of the matching apparent that is concluded to the knot plane surface [20]. All knot planes are optimized though the theoretical operate are fragmented. The 4-D algorithmic rule procedure is all over in the meantime the length is shorter than the edge. Finally, the implementation the Pareto optimum solution improved the 4-D visualization of the wave refraction pattern. Indeed, Pareto-front encompasses the Pareto-finest elucidations and just in instance of unremitting anterior, it splits the board perform universe into two constituents, that are non-ideal clarifications and unrealistic elucidations. In this context, it amended the strength of configuration pursuit and amended the convergence rate of 4-D B-spline algorithmic rule [12-14].

5. Conclusion
This study initiated a novel method for the model of four-dimensional wave diversion configuration in Sentinel-1A information. Other than that, the non-linear model castoff to retrieve the wave statistical parameters of $H_s$ which is created as the novel advance of the 4-D B-spline algorithm. The investigation reveals that wave diversion array can be simulated in the Sentinel-1A satellite data with highest refractive index of 2.6. The results spectacle that wave bending configuration can be pretend in the Sentinel-1A data with merging and deviation wave spectral momentum. In conclusion, 4-D wave refraction pattern in spite of nonlinearity between actual ocean wave spectra and Sentinel-1A data can be modelled by 4-D B-spline algorithm established by the Pareto optimization.

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