4-D Automatic detection of copper mineralization using TanDEM-X satellite data

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Abstract. This work presents a new approach for geological copper mining detection from synthetic aperture radar (SAR) data. In doing so, such an optimization algorithm of Particle Swarm is implemented with involving TanDEM –X satellite data. TanDEM-X with high-resolution spotlight mode of 1 m resolution and X-band with HH polarization are used. The four-dimensional view is reconstructed based on 3-D data obtained from TanDEM –X satellite data and 4-D phase unwrapping algorithm. The Particle Swarm Optimization algorithm is used with a 4-D phase unwrapping algorithm. The study shows that the Particle Swarm Optimization algorithm is used to optimize the 4-D reconstruction of copper mineralization after 2000 iterations with RMSE of 0.23. In conclusion, the Particle Swarm Optimization can be used as an automatic tool to monitor the copper mineralization. Further, 4-D visualization using TanDEM-X satellite can be achieved by involving PSO in the 4-D phase unwrapping.

1. Introduction
The TanDEM-X operational consequence involves the coordinated operation of two satellites flying in an adjacent configuration. The alteration constraints for the formation are: (i) the orbits ascending nodes, (ii) the angle between the perigees, (iii) the orbital eccentricities and (iv) the phasing between the satellites. The foremost aim of the TanDEM-X mission is to create a precise three-dimensional image (3-D) of Earth, which is consistent in superiority and extraordinary in precision [1]. Presently, the elevation models (DEMs) are accessible which are of low resolution, unreliable or imperfect. Furthermore, DEMs are generally established on diverse databases and ground survey approaches. In these regards, TanDEM-X, and TerraSAR-X additional for DEM quantity, which is premeditated to end these disparities and provide a precise DEM which should verify vital for numerous scientific and commercial requests[2-9].

The TanDEM-X satellite has been planned for a minimum lifetime of five years and has a deliberate correspondence with TerraSAR-X of three years. TerraSAR-X grips consumables and resources for up to seven years of operation nevertheless, theoretically permitting for a perpetuation of the overlay and the period of the TanDEM-X mission. Moreover, the key objective of the TanDEM-X mission, and numerous secondary mission aims based on along-track interferometry along with novel techniques with, bistatic SAR which have been well-defined and signify an imperative and advanced portion of the mission. TanDEM-X delivers the remote sensing, scientific, public not only with a global DEM of unique precision [1,9]. Nonetheless also with a unique reconfigurable SAR system to validate innovative bistatic and multi-static radar systems for improved bio- and geophysical parameter retrievals[2,3].
The TanDEM-X applications are based on (i) across-track SAR interferometry, (ii) along-track SAR interferometry and (iii) new SAR techniques. The three radar techniques evolve from the system specification defined by the TerraSAR-X satellite and the interferometric configuration itself. Due to its manifold system configurations, TanDEM-X is a flexible and multimode mission, which delivers a wide variety of application possibilities. Across-track SAR interferometry is a recognized method to determine the terrain topography [3-9]. The usage of this procedure is established for the calculation of phase variances calculated with two SAR antennas separated by an appropriate baseline. This permits approximating the radar elevation angle to the phase centre of each image resolution cell, where the height statistics are derived from the interferometric phase change [8-12]. Along-track SAR interferometry is used to compute the velocities of moving objects, which are a function of a phase modification measurement whereby the two SAR antennas attain complex SAR images of the same area with a short time lag. Consequently, new SAR techniques will establish the possibility of advanced SAR systems that have yet not or only incompletely been established on the ground or with aeroplanes [1].

DEMs deliver a vital footing for all subjects in geological science, hence the demand for precise and trustworthy DEMs is of certain prominence. DEMs, for instance, are a requirement for the improvement of geological maps. Supplementary, districts with volcanoes and predictable earthquake events require an extremely up to date high-resolution DEM to govern the deviations past occasions. Moreover, trustworthy and precise DEMs are required for the recognition of perilous developed regions being affected by disasters [9-14]. The global coverage of topographic data at an adequate extraordinary three-dimensional resolution is presently not accessible and would be delivered by the TanDEM-X mission. The accurate DEMs are important for geological, mining detections in spite of the disadvantages of synthetic aperture radar data due to speckles and object geometry distortions [15-20]. Recently, Marghany [1] developed a new approach for geological, mining detection in TerraSAR-X based Particle Swarm Optimization (PSO). In this regard, Marghany [1] stated that Particle Swarm Optimization has accurate performance in solving numerous single and multi-objective optimization problem in TerraSAR-X data, such as despeckles which agreed with Riccardo et al [5] and Jin et al [22].

This work has hypothesized that 4-D phase unwrapping using Particle Swarm Optimization can be used to reconstruct four-dimensional of copper mineralization from the TanDEM-X data. The main novelty of this work to use across track interferometry of TanDEM-X data by establishing 4-D phase unwrapping based Particle Swarm Optimization. The foremost aim of this work is to develop a 4-D phase unwrapping algorithm based on Particle Swarm Optimization for the 4-D copper mineralization reconstruction from TanDEM-X data.

2. Algorithms

In this study, the method used to reconstruct 4-D of a copper mine is based on the Particle Swarm Optimization (PSO). To this end, PSO is implemented to retrieve accurate 4-D phase unwrapping. In other words, two algorithms are used (i) 4-D phase unwrapping; and (ii) Particle Swarm Optimization (PSO).

2.14-D Phase Unwrapping Algorithm

The 4-D unwrapping is composed by using the temporal phase unwrapping method with a velocity of ground motion which is encoded instead of time as the unwrapping direction. This method creates use of four dimensions: x, y, t and V. Each voxel (x, y, z, and t) is unwrapped independently of the rest of the voxels using the velocity encoding dimension. The accurate 4-D phase unwrapping is obtained by modification of the phase matching algorithm proposed by Marghany [13]. Consistent with Hussien et al. [18], phase matching algorithm matches the phase of the wrapped phase with the unwrapped phase by the given equation:
\[
\psi_{i,j,k,V} = \phi_{i,j,k,V} + 2\pi\rho\left[\frac{1}{2\pi}\left(\phi_{i,j,k,V} - \phi_{i,j,k,V}^{'\prime}\right)\right]
\]

(1)

here \(\psi_{i,j,k,V}\) is the phase matched unwrapped phase, \(i, j, k\) and \(V\) are the pixel positions on the precise phase map, \(\phi_{i,j,k,V}\) is the given wrapped phase, \(\phi_{i,j,k,V}^{'\prime}\) is the approximated unwrapped phase and \(\rho[\cdot]\) is a rounding function.

Then the phase unwrapping based on the quality map can be modified to 4-D [13] as:

\[
Q_{m,n,l,t} = \frac{1}{m \times n \times l \times t} \left[ (\sum (\Delta \phi_x^m - \Delta \phi_x^{m,n,l,t})^2)^{0.5} + (\sum (\Delta \phi_y^m - \Delta \phi_y^{m,n,l,t})^2)^{0.5} + (\sum (\Delta \phi_z^m - \Delta \phi_z^{m,n,l,t})^2)^{0.5} + (\sum (\Delta \phi_t^m - \Delta \phi_t^{m,n,l,t})^2)^{0.5} \right]
\]

(2)

being \(\Delta \phi_x\), \(\Delta \phi_y\), \(\Delta \phi_z\) and \(\Delta \phi_t\) are the unwrapped-phase gradients in the \(x\), \(y\), \(z\), and \(t\) directions, respectively. \(\Delta \phi_x^m\), \(\Delta \phi_y^m\), \(\Delta \phi_z^m\) and \(\Delta \phi_t^m\) are the mean of the unwrapped-phase gradient in \(m \times n \times l \times t\) a cube in \(\Delta \phi_x\), \(\Delta \phi_y\), \(\Delta \phi_z\) and \(\Delta \phi_t\), respectively.

2.2 Particle Swarm Optimization

Following Marghany [1], Particle Swarm Optimization (PSO) is a population-based randomly searching process. It is assumed that there are \(N\) “particles” i.e., lineaments, faults, topographic breaks, bedding, depressions, lithologies, which are presented in SAR data. These geological features invasive contacts randomly seem in a “solution space”. Thus the optimization problem can be solved for data clustering, there is always a criterion (for example, the squared error function) for every single particle at their position in the solution space. The \(N\) particles will keep moving and calculating the criteria in every position the remainders, which is named as fitness in PSO pending the criteria reaches satisfied threshold. Therefore, each geological feature (particle) maintains its coordinates in the solution space of TanDEM-X which are combined with the finest fitness that has extremely accomplished by requested geological feature i.e. particle. In fact, the pixel of each feature i.e. particle \((m,n,l,t)\) denotes a probable solution to the optimization problem. Following Kennedy and Eberhart [23], each agent moves the particle with a direction and velocity \(v_{m,n,l,t}\),

\[
p_{m,n,l,t} = p_{m,n,l,t} + v_{m,n,l,t},
\]

where \(p_{m,n,l,t}\) represent particle and \(v_{m,n,l,t}\) is the velocity of the 4-D particle in the \(i,j,k,t\) agents, respectively.

\[
v_{m,n,l,t} = v_{m,n,l,t} + c_1 r_1 (l_{best_{m,n,l,t}} - p_{m,n,l,t}) + c_2 r_2 (g_{best_{m,n,l,t}} - p_{m,n,l,t})
\]

(4)

where \(l_{best_{m,n,l,t}}\) is the local best particle, \(g_{best_{m,n,l,t}}\) is the global best particle, \(r_1\) and \(r_2\) are random variables and \(c_1\), \(c_2\) are the swarm system variables. After each iteration, the global best \(g_{best}\) particle and the agent local best \(l_{best}\) particle are evaluated based on the maximum fitness functions of all particles in the solution space. Then equations 1 and 2 can be expressed as follows:
\[ v_{m,n,l,t} = w \cdot v_{m,n,l,t}(t-1) + \]
\[ c_1 \cdot r_1 (p_{m,n,l,t}(t-1)) + \]
\[ -c_2 \cdot r_2 (p_{m,n,l,t}(t-1)) \]
\[ -Q_{m,n,l,t}(t-1) \]
\[ Q_{m,n,l,t} = Q_{m,n,l,t}(t-1) + v_{m,n,l,t}(t) \]  

where \( Q_{m,n,l,t} \) is the position of the particle for phase unwrapping based on the quality map, \( v_{m,n,l,t} \) is the current velocity of the particles in \( mxnxlt \). The velocity is regulated by a set of rules that influence the dynamics of the swarm. Further, there are several parameters must be considered such as initial population, representation of position and velocity strategies, fitness function identification and the limitation. These parameters are for PSO performances. Following Ibrahim et al [21] the initial swarm particles proposed PSO is initialized to contain 3000 points of particles for \( Q_{m,n,l,t} \) and velocity \( v_{m,n,l,t} \). The points had been randomly selected in the azimuth and range directions in phase unwrapped of TanDEM-X data.

After reaching a precise number of iterations or an accurate, error threshold is performed, the optimal solution is obtained. \( p_i \) is the personal best position of the particle, \( w, c \), are all constant factors, and \( r \) is the random numbers uniformly distributed within the interval \([0,1]\). Thus the general swarm algorithm can be changed into a binary particle (Discrete Particle Swarm Algorithm DPSO) which handles particle values of either 0 or 1 by a given equation [20][23]:

\[ P(m,n,l,t) \left\{ \begin{array}{cl}
1 & \text{if } r_3 > p_{m,n,l,t} \\
0 & \text{if } r_3 < p_{m,n,l,t}
\end{array} \right. \]  

where \( P(m,n,l,t) \) are the numerical values of the particle and \( r_3 \) is a random variable.

On the word of El Meseery et al [20], the PSO can segment the geological features in SAR data. In this regard, the input TanDEM-X data \( T \) with \( N \) points can be represented by set \( T = \{ x_1, x_2, \ldots, x_N \} \) where \( x_i \) is the location of the 3-D geological feature on the point \( i \). The swarm algorithms consist of \( M \) agents which are represented by the set \( A = \{ p_i | i = 1, 2, \ldots, M \} \) where \( p_i \) is a single solution particle from the solution space. Each particle decodes the problem using a binary array with the same length \( N \) as the input SAR data. Consequently, the system denotes each particle \( p_{i,j,k,t} \) by \( P_i = \{ p_{j,k} | k = 1, 2, \ldots, N \} \) where \( p_{j,k} \) has only two values a) 1 (\( p_{j,k} = 1 \)); means that this point (\( k \)) is a dominant point, or b) 0 (\( p_{j,k} = 0 \)) which means that means this point (\( k \)) is not a dominate point [20]. The fitness is computed using the given equation:

\[ \text{max fitness}(p_{i,j,k,t}) = \begin{cases} 
\frac{-E}{\varepsilon N} & \text{if } E > \varepsilon, \\
D/\sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} p_{i,j,k} & \text{otherwise}
\end{cases} \]
where $N$ is the number of points in the TanDEM-X data, $D$ is the number of points in the solution that was previously labelled as a possible dominant point ($P_{pd}$), $E$ is the computed error and $\varepsilon$ is the error threshold. As said by El Meseery et al [20], it should be noticed that when the error is larger than the threshold $\varepsilon$ the fitness gives a negative value to lower the fitness value of the solution. Otherwise, the system favours the lower number of vertices.

3. Results and Discussion

The TanDEM-X data of high-resolution spotlight mode of 1 m resolution and X-band with HH polarization is shown in Figure 1. In the centre of the Atacama Desert near South America’s west coast lies the world’s largest open-cast copper mine. The mine was founded by Guggenheim Brothers at the beginning of the 20th century. Figure 1 spectacles the 400-m deep mine, which is corresponding to 1876 m below the sea level.

![Figure 1. 3-D copper mine from TanDEM-X data of high-resolution spotlight mode.](image1)

In addition, 3-D TanDEM-X data show clear infrastructures which are represented in water filtration tanks which can be observed clearly as square surfaces in the mine. Consistent with Marghany [1], the mine is located in the centre of the Atacama desert near South America’s west coast lies the world’s largest open-cast copper mine. The mine was founded by Guggenheim Brothers at the beginning of the 20th century. Figure 2 shows the coherence results of TanDEM-X data. It is clear that the coherence map is ranged from 0 to 1. It is interesting to find that the copper mineralization has the highest coherence value of 1 than the surrounding infrastructures. The infrastructures have a coherence value of 0.8 which can be seen along the road and building. The high coherence, perhaps because of the strong backscatter events accompanying with the steeper incident angle and short baseline. This finding does not agree with Marghany [1]. In fact, Marghany [1] examined the backscatter of single Terra-SAR-X data in the same area.

![Figure 2. Estimated coherence map of TanDEM-X data.](image2)
Figure 3 displays the result of 4-D Phase unwrapping using the PSO algorithm. It is obvious the clear appearance of fringe cycles. Figure 3a shows the lower fitness of 0.0005. Conversely, as the fitness increases, the RMSE decreases with clear fringes (Figure 3d). The 4-D phase unwrapping produces a clear fringe with a fitness value of 120 and RMSE of 0.23m (Figure 3d). In fact, the PSO circumvents a decreasing resolution by making a weighted combination of running average with the neighbour surrounding pixels of the 4-D phase unwrapping [15]-[17]. This reduced the noise in the feature s’ edge areas without losing edge sharpness. Clearly, PSO within approximately 7 hours within 2000 iterations is able to reconstruct the 4-D phase unwrapping with RMSE of 0.23.

Figure 3. Particle Swarm Optimization for 4-D phase unwrapping with different iterations (a) 0 , (b) 10, (c) 44 and (d) 2000 iterations.

Figure 4 spectacles the 4-D copper mineralization reconstruction from 3-D TanDEM-X data. It is obvious that from a different angle of view clear 4-D morphological feature detections. This includes deep of copper mine within 400 m depth and surrounding mountains. Besides deep descriptions of the edge of the infrastructures [18]. The geomorphology of copper mineralization being to be more obvious with the rotation angle of 180° (Figure 4b). The involving of 4-D dimension increases the deeper visualization of the scene as different features, which are observed with different view angles from 0° to 360°. The bright colour along the object edges is corresponding to the fourth-dimension, which represents the time of 5 days. This agrees with the work of Ibrahim et al [21].
The implementation of PSO with 4-D phase unwrapping assisted to determine optimal grows regions across the continuing unwrapping of edges. With this regard, PSO synchronized the voxels on both sides of the edge (Fig.4). In addition, 4-D phase unwrapped algorithms constructed the discontinuity in quality order. This is appropriate in the high-intensity line or curve of fixed length and locally low curvature boundary is known to exist between edge elements and high noise levels in TanDEM-X data. PSO, conversely, optimizes the gaps remains between discontinuity edges [15-19]. In this regard, 4-D phase unwrapping based PSO is an optimal search to real edge pixels which are existing on the boundary of copper mineralization and the optimization of 4-D phase unwrapping in hypercube can reconstruct the 3-D object displacement with additional 4th dimension. Finally, 4-D phase unwrapping based PSO permits for the reliable unwrapping of low signal to noise ratio (SNR). This study could improve 3-D phase unwrapping proposed by Hussien et al [18].

4. Conclusion
The work demonstrated a new approach to geological copper mining detection. In this regard, the optimization algorithm of Particle Swarm is used with the 4-D phase unwrapping of TanDEM –X satellite data. The study shows that the Particle Swarm Optimization algorithm is used to optimize the 4-D reconstruction of copper mineralization within 7 hours and post 2000 iterations with RMSE of 0.23. The results show that the 4-D of copper mineralization improved morphological feature detection such as the depth of a copper mine and surrounding infrastructures. It can be said that the integration of PSO with the 4-D phase unwrapping of TanDEM –X satellite data are an excellent promise approach for 4-D reconstruction of copper mineralization.

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