

Finding Flying Aircraft in Synthetic Aperture Radar Satellite Imagery

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Abstract

This study demonstrates the identification of high altitude flying aircraft in synthetic aperture radar (SAR) satellite imagery acquired by Sentinel-1 in the IW mode. Detecting airborne targets in spaceborne SAR data is particularly challenging because aircraft occupy a very small spatial extent, and are embedded within scenes dominated by ground clutter, ships, and imaging artifacts. In addition, moving targets induce Doppler shifts during SAR image processing that lead to azimuth displacements in the focused image. This work establishes and verifies that flying aircraft can be observed in Sentinel-1 SAR imagery and characterizes their observable signatures. OpenSky ADS-B flight data are correlated with Sentinel-1 acquisitions through spatial and temporal co-registration. The azimuth Doppler shift is calculated to provide a search area in which a statistical algorithm is applied. A total of 257 aircraft cases were examined, of which 15 yielded 17 identifiable SAR signatures, corresponding to a detection success rate of 5.84%. The identified signatures exhibited mean intensities ranging from 3.04 to 12.66 standard deviations above the local background mean, with minimum offsets from the predicted trajectories ranging from approximately 0.26 to 6.42 km. To assess the significance of the observations, the identified aircraft signatures are validated against ship Automatic Identification System (AIS) data, buoy and aid-to-navigation datasets, and visual inspection of co-located Sentinel-1 and Sentinel-2 repeat-pass imagery to exclude stationary objects, indicating that the observed signatures are unlikely to arise from static structures, clutter, or imaging artifacts alone. The analysis demonstrates that flying aircraft can be identified in Sentinel-1 IW GRD imagery without the need for complex algorithms or refocusing. These findings establish a foundation for future airborne target studies and the development of dedicated detection methodologies.

Keywords: synthetic aperture radar; aircraft detection; Sentinel-1; ADS-B; moving targets

Abbreviations: SAR: Synthetic Aperture Radar, ADS-B: Automatic Dependent Surveillance–Broadcast, AIS: Automatic Identification System

1. Introduction

Satellite-based observation of airborne aircraft offers a complementary perspective to conventional air traffic surveillance by enabling aircraft to be observed directly over large geographic areas, including regions with limited surveillance coverage. Such observations have potential applications in airspace monitoring and aviation research, including the attribution of satellite-observed contrails to individual flights [1, 2, 3]. However, detecting aircraft in flight from spaceborne sensors presents distinct challenges because aircraft move rapidly relative to the imaging platform, and their signatures may be affected by sensor acquisition geometry and target motion.

Electro-optical (EO) satellite imagery has demonstrated that airborne aircraft can be detected through characteristic motion-induced signatures. In particular, Sentinel-2 multispectral imagery can reveal aircraft through the spatial displacement between spectral bands acquired at slightly different times. This effect, commonly referred to as a “planebow,” enables aircraft detection and the estimation of their motion parameters from a single satellite observation [1, 4]. Optical satellite observations have

also been used to detect and attribute contrails to individual flights, supporting investigations of aviation's atmospheric impacts [2, 3]. Nevertheless, passive optical sensors are limited by illumination conditions and cloud obscuration, which can prevent observations of aircraft and contrails under unfavorable atmospheric or lighting conditions.

Synthetic Aperture Radar (SAR) provides a complementary sensing modality because it actively illuminates the scene with microwave radiation and can acquire imagery during both day and night, largely independently of cloud cover [5, 6]. However, detecting airborne aircraft in spaceborne SAR imagery remains challenging. Aircraft operating at cruise altitudes of approximately 9,000–12,000 m and speeds of around 200–260 m/s can exhibit substantial motion relative to the radar platform during data acquisition. This motion violates the stationary-scene assumptions underlying conventional SAR focusing and can introduce Doppler-related effects and phase distortions, causing moving-target signatures to appear displaced or distorted relative to their expected geographic positions [7, 8]. Research on spaceborne SAR moving-target detection has investigated approaches such as velocity-space searches, sub-aperture processing, and decomposition methods to address these effects [8, 9]. These methods demonstrate the importance of accounting for target motion when interpreting SAR observations, but specialised processing is not always available in standard geocoded imagery products.

An additional challenge is establishing whether a candidate SAR signature corresponds to a real aircraft. Automatic Dependent Surveillance–Broadcast (ADS-B) is widely used for civil air traffic surveillance, providing aircraft state information through onboard transponders [10, 11]. However, ADS-B-based observations may be incomplete due to coverage limitations, equipment failures, or transponder deactivation. Consequently, satellite-based observations could provide a complementary source of information for aircraft monitoring. Before SAR imagery can be evaluated as an independent observation source, however, candidate radar signatures must be associated with aircraft whose positions and trajectories can be estimated independently. Historical ADS-B observations from the OpenSky Network provide a reference dataset for this purpose [12, 13].

In this work, we investigate the detection of flying aircraft in standard Sentinel-1 Interferometric Wide Swath Ground Range Detected (IW GRD) imagery, using OpenSky Network ADS-B observations as reference trajectories. Rather than relying on sub-aperture decomposition or specialized refocusing algorithms, we examine whether candidate aircraft signatures can be identified in standard SAR products by accounting for the expected motion-induced displacement derived from aircraft trajectories. The observed signatures are then compared with the predicted locations of known aircraft to assess the feasibility of associating SAR detections with independently tracked targets.

The contribution of this study is an initial demonstration and performance assessment of airborne aircraft detection in standard Sentinel-1 IW GRD imagery using ADS-B for reference and validation. This approach provides a basis for further investigation of the relationship between aircraft motion and SAR image signatures, as well as the reliability of aircraft detection in routinely available SAR products. Ultimately, such work may support the development of satellite-based aircraft monitoring methods that complement conventional surveillance and, in the future, reduce their dependence on cooperative tracking data.

2. Data

Synthetic Aperture Radar (SAR) is a radar system that captures images using microwave signals. It operates day and night and penetrates cloud cover. The C-band SAR instrument aboard the Sentinel-1 satellite collects this data at a central frequency of 5.405 GHz ($\lambda \approx 5.55$ cm) and captures imagery in Interferometric Wide Swath (IW) mode [6].

This project uses Level-1 Ground Range Detected High Resolution (GRDH) products from Sentinel-1, acquired through the Copernicus Data Space Ecosystem [14]. Each image covers a 250 km swath width across incidence angles ranging from 29.1° to 46.0° [6]. The images have a $10\text{ m} \times 10\text{ m}$ pixel spacing, with spatial resolutions of 20 m in range and 22 m in azimuth [15].

Range is the direction perpendicular to the satellite flight path, measuring the sideways distance from the satellite to the target on the ground. Azimuth is the direction parallel to the satellite flight path. The analysis uses co-polarized vertical-vertical (VV) channel data because it provides strong contrast between aircraft radar backscatter and the surrounding ocean background. Figure 1 illustrates a full Sentinel-1 scene.

Historical flight data was retrieved from the OpenSky Network database [12, 13]. Aircraft broadcast periodic Automatic Dependent Surveillance-Broadcast (ADS-B) messages containing navigation state vectors derived from onboard GNSS and inertial reference systems [12]. State vectors were retrieved from the OpenSky historical database. Each record provides the unique 24-bit ICAO address, flight callsign, epoch timestamp, WGS84 latitude and longitude, geometric altitude, groundspeed, and true track angle [16].

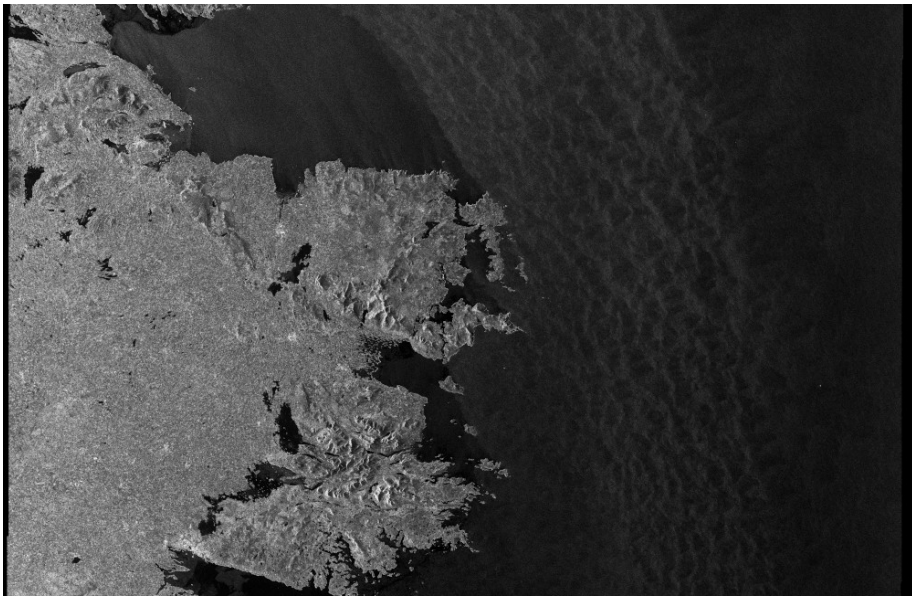


Figure 1. Sentinel-1 IW GRDH VV image acquired on 24 March 2025 at approximately 06:55 UTC, showing the northwestern coast of Ireland and the adjacent North Atlantic Ocean. The complete SAR scene is displayed in its native image orientation without annotations.

The study area comprises of an oceanic sector off the northwestern coast of Ireland. This region lies along the North Atlantic commercial air traffic routes, where aircraft typically operate at cruising altitude, and flights align with the Sentinel-1 acquisition time. Moreover, selecting a marine environment reduces interference from high-intensity terrestrial land clutter, urban point scatterers, and complex topographic reflections.

3. Methodology

This section describes the complete methodology used to detect flying aircraft in SAR imagery. The following paragraph provides a high-level overview of the method visualized in Figure 2.

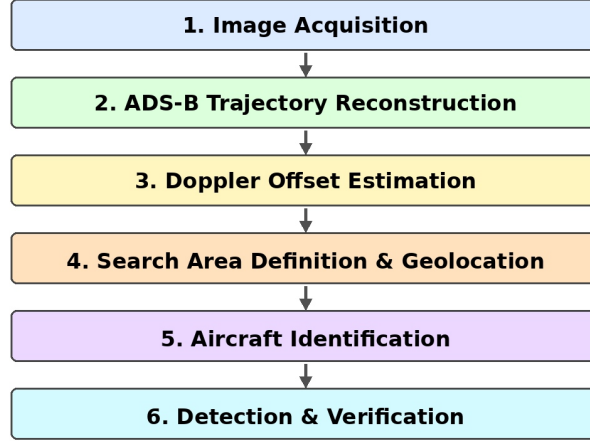


Figure 2. Overview of the six core stages of the SAR-ADS-B aircraft detection workflow.

3.1 SAR-Aircraft Alignment

A Sentinel-1 SAR scene takes approximately 25 seconds to record. During this period an aircraft can move several kilometers. The retrieved ADS-B records were spatially filtered to match the Sentinel-1 scene footprint expanded by a buffer of 0.1° . They were further filtered within 300-second prior to start and following completion of the scene recording. The ADS-B records were then grouped by ICAO24, de-duplicated, sorted by time, and linearly interpolated (accounting for heading circularity), yielding two state vectors for the SAR scene acquisition start and completion time.

The Sentinel-1 scenes ground control points available in product, were used to obtain the metadata values for the aircraft pixel position, slant-range time, t_{slant} , and incidence angle, θ , based on the aircraft state vector [15].

3.2 Azimuth and Range correction

Moving targets at altitude can exhibit both azimuth and range displacements in a SAR image. Consequently, the aircraft's image location cannot, in general, be obtained simply by converting the latitude and longitude provided by ADS-B into pixel coordinates using the ground-based image geocoding, as would typically be done for a georeferenced Sentinel-2 optical image.

Instead, the aircraft's image location must account for the effects of its motion on the azimuth position, primarily through Doppler-induced displacement, and its altitude on the range position, due to the difference in slant range between the aircraft and the corresponding ground location. These displacements depend on the SAR acquisition geometry and image formation and geocoding procedures.

The expected Doppler-induced azimuth displacement arises because a moving aircraft is focused by the SAR processor under the assumption of a stationary target, causing the aircraft signature to appear displaced from its true geographic position in the azimuth direction [17, 8]. The resulting

displacement, denoted d , is estimated from the aircraft ADS-B velocity and the relevant Sentinel-1 metadata according to [17]

$$d = \frac{v^{\text{ADS-B}} \sin(\phi) R_{\text{sr}} \sin(\theta)}{v_{\text{sat}}}, \quad (1)$$

where R_{sr} is the slant range distance between the satellite and the aircraft's ground-projected position, assuming the aircraft is located at ground level, θ is the local incidence angle, and $v_{\text{sat}} = 7.4 \text{ km s}^{-1}$ is the Sentinel-1 orbital velocity. ϕ describes the aircraft's heading relative to the SAR azimuth direction i.e. the true north heading projected into the SAR range/azimuth reference frame, and is given by

$$\phi = \theta^{\text{ADS-B}} - \arcsin\left(\frac{\cos(i)}{\cos(\text{lat}^{\text{ADS-B}})}\right), \quad (2)$$

where $\theta^{\text{ADS-B}}$ is the aircraft heading obtained from ADS-B data, $\text{lat}^{\text{ADS-B}}$ is the aircraft latitude, and i is the satellite inclination angle. For Sentinel-1, $i = 98.18^\circ$ for ascending passes and $i = 81.82^\circ$ for descending passes.

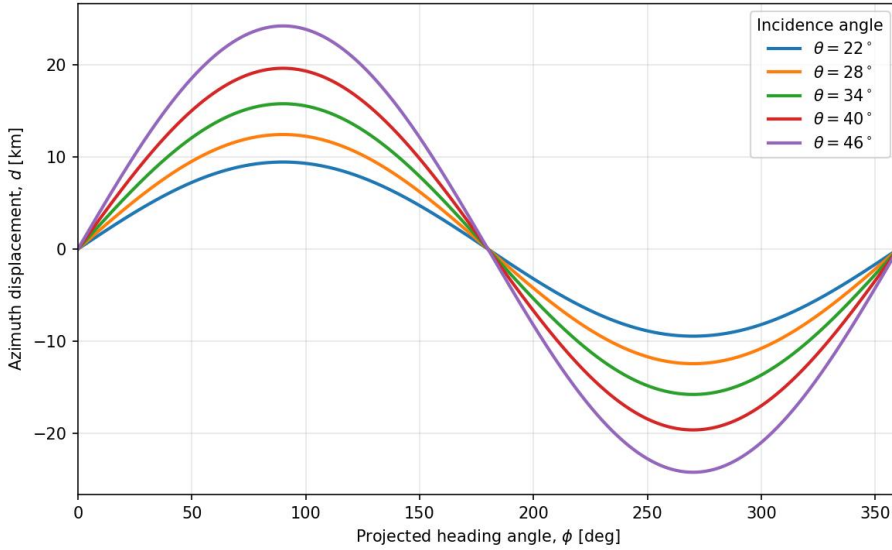


Figure 3. Azimuth displacement d (Equation 1) as a function of the projected heading angle ϕ (Equation 2) for incidence angles θ between 22° and 46° .

The range correction accounts for the displacement caused by the aircraft's altitude above the reference ground surface. An elevated aircraft is closer to the satellite than the ground point directly beneath it, resulting in a shorter slant range. Consequently, when the aircraft's radar return is mapped using ground-based SAR geocoding, its apparent position is displaced towards near range relative to its ground-projected position. The magnitude of this displacement can be approximated by [18]

$$d_{\text{range}} \approx \frac{h}{\tan(\theta)} \quad (3)$$

where h is the aircraft altitude above the reference ground surface and θ is the local incidence angle, as defined above. An altitude of 10 km corresponds to an apparent ground-range displacement of approximately 10–18 km.

3.3 Aircraft detection

The two ADS-B aircraft state vectors interpolated to the start and end of the SAR acquisition was then used to obtain a bounding box around the azimuth and range corrected position of the aircraft with a 5 km margin on each side (see Figure 4).

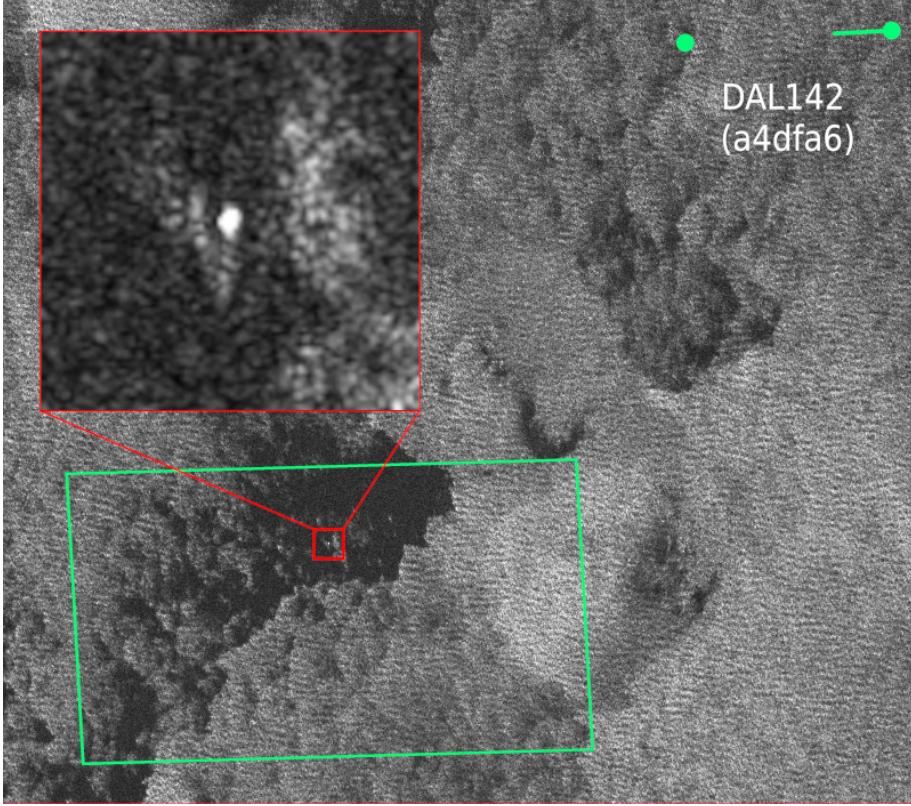


Figure 4. Example of the search-region construction for flight DAL142 on 4 January 2025. The upper-right markers show the ADS-B positions at the start and end of the Sentinel-1 acquisition, with the green line showing the aircraft heading. The search region (green box) is shifted in azimuth and range to account for the Doppler-induced and altitude-dependent displacements, respectively. The inset enlarges the selected area containing the candidate aircraft signature.

If either of the two state vectors or the resulting bounding box was outside the SAR scene, the aircraft was discarded.

Candidate signatures were identified through manual inspection of the predefined search regions. Their contrasts relative to the surrounding SAR background were subsequently quantified using a thresholding approach analogous to cell-averaging constant false alarm rate (CA-CFAR) detection [19]. For each candidate, the local background statistics were estimated from a surrounding 50×50 pixel region, excluding the candidate object region. The corresponding threshold was calculated as

$$T = \mu + N\sigma, \quad (4)$$

where μ and σ are the mean and standard deviation of the local background, respectively, and N is the threshold factor. A value of $N = 3$ was used in this study.

The contrast between the candidate signature and the surrounding sea clutter, was then expressed via the normalized mean and maximum intensities, z_{mean} and z_{max} , of the aircraft

$$z_{\text{mean}} = \frac{\mu_{\text{obj}} - \mu_{\text{bg}}}{s_{\text{bg}}}, \quad z_{\text{max}} = \frac{I_{\text{max,obj}} - \mu_{\text{bg}}}{s_{\text{bg}}}, \quad (5)$$

where μ_{obj} is the mean pixel intensity within the detected object region, $I_{\text{max,obj}}$ is the maximum object-pixel intensity, μ_{bg} is the mean local background intensity, and s_{bg} is the standard deviation of the local background.

3.4 Candidate Validation

Each detected aircraft detection was further validated using additional satellite and maritime data.

The location of each candidate signature was assessed using repeat-pass Sentinel-1 imagery to distinguish persistent from transient returns. Sentinel-2 imagery was also used to manually identify platforms and skerries.

Historical vessel data was obtained from Datalastic [20] within 20 NM of the targets. The Automatic Identification System (AIS) is a maritime transponder system corresponding to ADS-B for ships. Vessels broadcast their identity and navigation information, including position, course over ground, and speed over ground [21, 22]. The AIS records were linearly interpolated to the SAR acquisition time.

Registered weather- and wave-buoy positions was obtained from the Marine Institute's Irish Marine Data Buoy Observation Network and Irish Wave Buoy Network [23, 24]. These datasets contain the geographic positions of offshore weather-monitoring and wave-measuring buoys, including those at the Atlantic Marine Energy Test Site (AMETS). Navigational buoy and other aids-to-navigation positions were obtained from the Commissioners of Irish Lights Aids to Navigation dataset [25]. This register includes physical buoys, lighthouses, and beacons, as well as virtual aids to navigation. Virtual entries were excluded from the assessment of physical scattering sources. The NOAA National Data Buoy Center (NDBC) station catalog was additionally consulted as a supplementary source of registered buoy locations [26]. This catalog includes international partner stations and legacy entries, and therefore partly overlaps with the Marine Institute records.

An aircraft candidate was discarded if a stationary or maritime explanation was located in the search bounding box.

4. Results

A total of 257 aircraft cases were examined, of which 15 yielded 17 identifiable aircraft signatures, representing a detection rate of 5.84%. This conservative rate reflects that the primary objective of this study is to establish definitive physical proof of aircraft detection in standard SAR products rather than maximizing statistical recall. Lowering the detection threshold increases false alarms from ocean clutter, speckle, and azimuth ambiguities, which compromises target verification. Furthermore, aircraft feature smooth, aerodynamic geometries that deflect incident microwave energy away from the receiver, resulting in inherently low radar cross-sections. Target attitude variations, including roll, pitch, and yaw, induce further fluctuations in backscatter intensity. These physical constraints produce weak and intermittent signatures, necessitating strict selection criteria to confirm target presence with absolute certainty.

The detected signatures show substantial variation in intensity, spatial extent, and azimuth smearing, as illustrated in Figure 5.

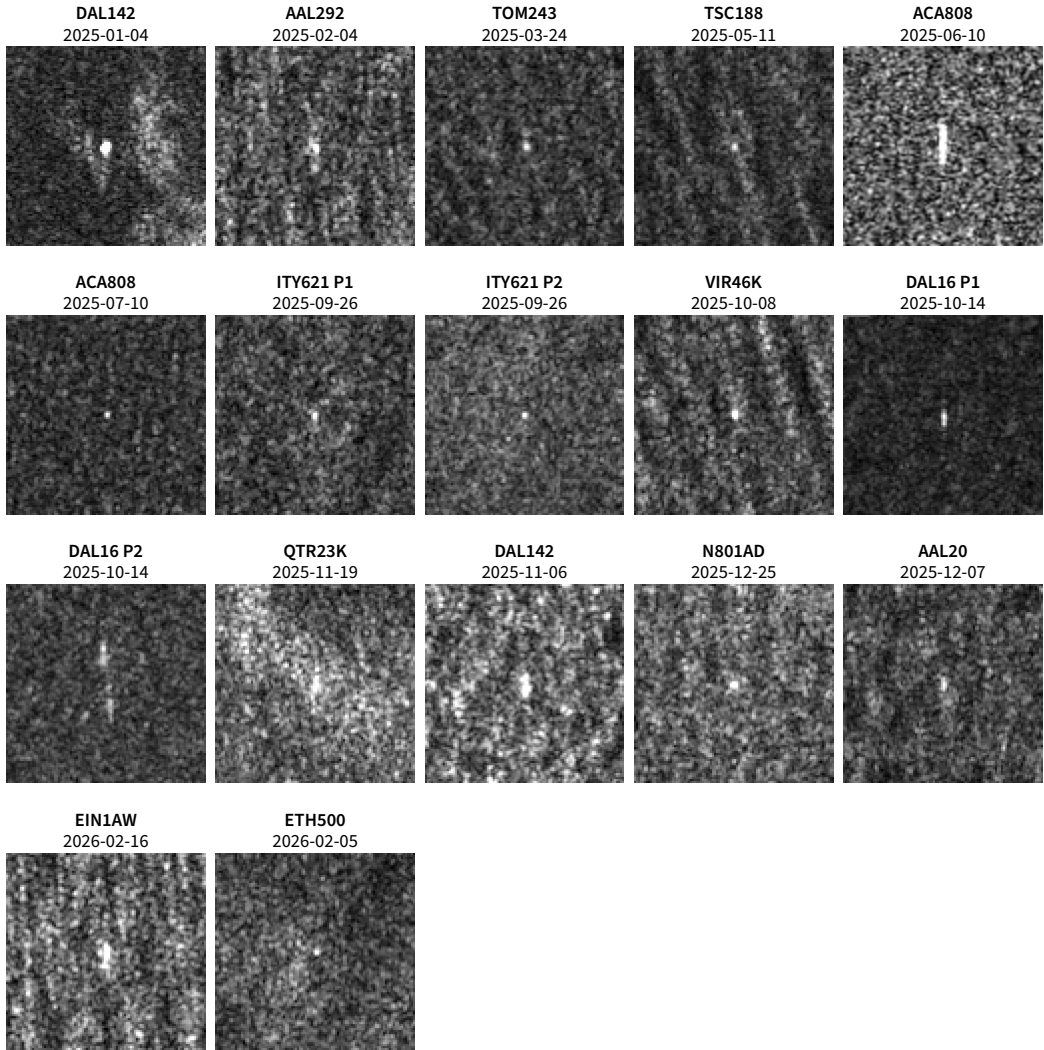


Figure 5. The 17 candidate aircraft signatures associated with 15 flight cases identified in descending-orbit Sentinel-1 VV imagery acquired at approximately 07:00 UTC between January 2025 and February 2026. Each panel shows a 100×100 pixel crop (approximately 1 km^2), with the flight callsign and acquisition date indicated above. Acquisitions containing multiple candidates contribute more than one crop.

Manual comparison with repeat-pass Sentinel-1 acquisitions, sentinel 2 Acquisitions, AIS observations, and buoy and aid-to-navigation datasets was used to assess whether the detected signatures could instead originate from persistent infrastructure, ships, buoys, or other stationary targets. No corresponding persistent target was identified at the reported locations, supporting the interpretation of the signatures as aircraft-related detections.

The minimum distance $d_{\min}$ describes the shortest spatial distance between the observed SAR signature and the predicted aircraft track within the SAR acquisition interval. It is measured to the nearest point on the altitude-corrected, Doppler-displaced track, without extending the track beyond its end-

points or including the search margins. The quantity Δ_D represents the predicted Doppler-induced azimuth displacement at that point. The normalized quantity $d_{\min}/|\Delta_D|$ expresses the spatial offset relative to the magnitude of the predicted Doppler displacement. The geometric and statistical properties of all candidate signatures are summarized in Table 1.

Table 1. Geometric and statistical results for the candidate aircraft signatures. Distances are measured to the nearest point on the predicted track within the SAR acquisition interval.

Date	Aircraft	POI	$d_{\min}$ (km)	Δ_D (km)	$d_{\min}/ \Delta_D $ (%)	z_{mean}	z_{max}
2025-01-04	DAL142	1	2.34	19.61	11.92	12.66	28.32
2025-02-04	AAL292	1	2.06	21.12	9.76	6.67	9.24
2025-03-24	TOM243	1	1.12	22.39	5.00	6.04	7.92
2025-05-11	TSC188	1	2.15	22.02	9.77	6.38	7.93
2025-06-10	ACA808	1	6.42	24.51	26.21	6.33	11.82
2025-07-10	ACA808	1	4.91	23.10	21.27	5.03	9.41
2025-09-26	ITY621	1	1.78	19.03	9.35	6.43	7.19
2025-09-26	ITY621	2	2.13	19.01	11.23	6.70	7.14
2025-10-08	VIR46K	1	1.47	22.91	6.41	7.77	10.04
2025-10-14	DAL16	1	4.38	21.16	20.71	7.71	13.39
2025-10-14	DAL16	2	3.37	21.13	15.96	4.07	7.44
2025-11-06	DAL142	1	0.80	15.80	5.06	3.94	9.27
2025-11-19	QTR23K	1	3.19	21.59	14.78	3.04	4.09
2025-12-07	AAL20	1	0.36	21.91	1.64	4.73	6.03
2025-12-25	N801AD	1	0.72	17.88	4.05	5.39	7.99
2026-02-05	ETH500	1	0.26	-20.10	1.31	5.31	5.31
2026-02-16	EIN1AW	1	1.55	19.42	7.99	5.02	7.23

$d_{\min}$ is the shortest distance to the finite altitude-corrected, Doppler-displaced acquisition track; the search margins are excluded. POI 1 and POI 2 distinguish separate signatures for the same flight case and are reported individually.

Only candidates within their predefined search regions and with a local mean contrast of at least three background standard deviations ($z_{\text{mean}} \geq 3$) were included in the final detection set. This was applied as a strict inclusion criterion, irrespective of maximum-pixel contrast.

The final set comprises 17 signatures associated with 15 flight cases. Their minimum distances to the predicted acquisition tracks range from approximately 0.26 to 6.42 km, with normalized offsets of 1.31% to 26.21%. Several signatures show close geometric correspondence with the predicted trajectories, while others have larger positional residuals. Mean object intensities range from $z_{\text{mean}} = 3.04$ to 12.66 standard deviations above the local background mean, and maximum-pixel intensities range from $z_{\text{max}} = 4.09$ to 28.32 standard deviations above that mean.

Figure 6 separates the positional differences into azimuth and range components for these 17 signatures. For each signature, both components are measured relative to the same nearest point on the altitude-corrected, Doppler-displaced track within the SAR acquisition interval, excluding the additional search margins.

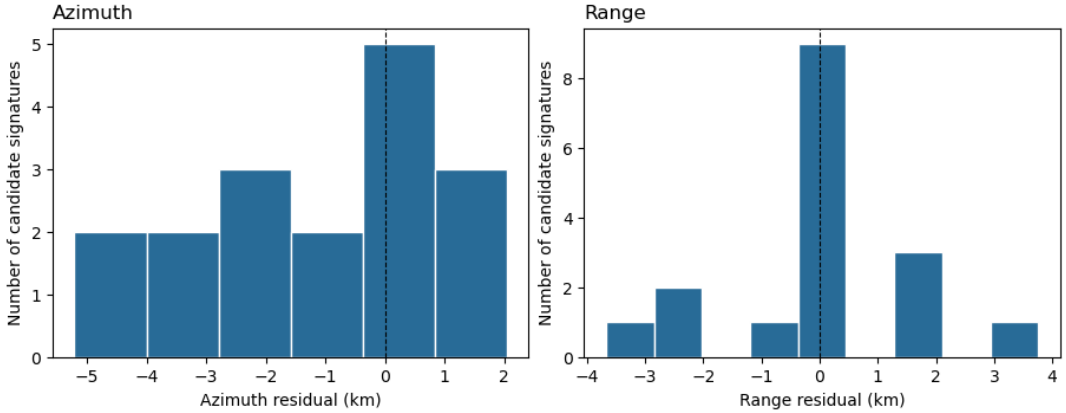


Figure 6. Azimuth and range distances between the 17 detected signatures and the nearest points on their predicted tracks. Each signature contributes one entry, including both POIs for ITY621 and DAL16. Zero indicates agreement in the corresponding image direction.

Among the 17 primary candidates, the azimuth residuals range from approximately -5.21 to 2.05 km, while the range residuals range from -3.68 to 3.76 km.

Two separate POIs were retained for ITY621 on 26 September 2025 and DAL16 on 14 October 2025. Both POIs in each case lie within the corresponding search region and satisfy $z_{\text{mean}} \geq 3$. They are reported separately in Table 1 and represent two candidate signatures per flight, rather than two independently detected flights.

Overall, the geometric correspondence, elevated local contrasts, and checks against repeat-pass imagery, AIS observations, and buoy databases support an aircraft-related interpretation of the primary candidates. These complementary checks reduce the likelihood of persistent stationary scatterers and known maritime targets, although they do not conclusively establish the association of every signature with an individual aircraft.

5. Discussion

The identified signatures exhibit considerable variation in backscatter intensity and spatial characteristics, while their positional offsets from the predicted Doppler-displaced trajectories provide insight into the accuracy and limitations of the displacement model. These observations motivate a closer examination of the signatures' radar characteristics and the factors influencing their detectability. The reliability of their attribution is then considered in light of the positional residuals, manual candidate selection, and validation against independent satellite imagery and maritime reference data.

5.1 Aircraft Detectability

The identification of 17 aircraft signatures from 15 flight cases within the predefined search regions and with a mean local contrast of at least 3 standard deviations, among 257 examined cases, corresponding to a detection success rate of 5.84%, represents a relatively small fraction of the aircraft considered. However, successful identification requires several favorable conditions to coincide. The aircraft must produce a sufficiently strong radar return, the surrounding background must allow this return to be distinguished, and the signature must remain detectable after processing designed for stationary ground targets. The observed detection fraction therefore reflects the combined effects of

target scattering, acquisition geometry, background conditions, and the detection procedure.

The ocean background is likely to be an important factor. Although offshore scenes avoid strong terrestrial scatterers, the sea surface can still produce substantial and spatially variable backscatter. Wind-generated roughness and wave-related structures can increase the background intensity or produce local variations that compete with a weak aircraft signature. Higher background variability reduces the normalized contrast of a given signature, potentially making weak aircraft returns harder to distinguish. [27]. Relatively low and homogeneous ocean backscatter should therefore favor detection. Wave height alone is unlikely to describe these conditions adequately, since radar backscatter also depends on surface roughness, wind direction, and incidence angle. These effects are consistent with the treatment of sea clutter in Sentinel-1 ocean processing [28].

In addition to background conditions, a favorable aircraft orientation is also expected to be important. The radar cross-section of an aircraft depends on how its surfaces and structural components are oriented relative to the radar [29]. For certain viewing directions, interactions between adjoining surfaces, such as the wings and fuselage, can produce strong multiple-reflection returns resembling the scattering mechanism of a corner reflector [30]. An aircraft should nevertheless be treated as a complex collection of scattering centers whose combined response changes with viewing angle [29, 30]. Differences in aircraft geometry, heading, bank angle, and radar incidence angle may consequently produce substantial differences in visibility. This provides a plausible explanation for why aircraft of comparable size may generate markedly different signatures, although the present observations do not establish which scattering mechanisms dominate the detected cases.

Target motion introduces an additional limitation. During SAR image formation, an aircraft can accumulate a phase history that differs substantially from that assumed for stationary terrain. The resulting defocusing can distribute its return over multiple resolution cells, reducing the peak intensity available to the detector [8]. Aircraft with similar total reflected energy may therefore have different detectability depending on how concentrated their responses remain. This offers a possible interpretation of the variation in brightness and spatial extent observed among the 17 signatures. Changes in velocity or attitude during illumination could further complicate the response, but their contribution would require a dedicated analysis.

5.2 Uncertainties and Confidence in Identification

Positional uncertainties are also evident when comparing the identified signatures with their predicted locations. Among the 17 primary candidates, the minimum distances to the predicted Doppler-displaced tracks range from 0.26 to 6.42 km, while the corresponding normalized offsets range from 1.31% to 26.21%. The smallest residuals support the usefulness of the displacement model for locating candidate signatures. The larger residuals indicate that the current prediction does not fully explain every observed position. The histograms in Figure 6 further separate the positional differences into azimuth and range components. Among the primary candidates, range residuals are concentrated near zero, whereas azimuth residuals are more broadly distributed and predominantly negative. Both the minimum distances and these components are measured to the nearest point within the predicted acquisition tracks. The distributions therefore also reflect the restriction to the acquisition interval and should not be interpreted as independent estimates of model accuracy.

Several factors may contribute to these residuals, particularly uncertainties in the reconstructed aircraft positions and velocities, which are estimated through linear interpolation of ADS-B data and subsequently used to predict the Doppler displacement. According to Equation 1, the displacement depends on the aircraft velocity projected along the radar line of sight, given by $v^{\text{ADS-B}} \sin(\phi) \sin(\theta)$. For an illustrative slant range of $R_s = 850$ km and satellite velocity of $v_{\text{sat}} = 7.4$ km/s, an error of 10 m/s in this projected velocity results in an azimuth displacement error of approximately 1.15 km.

This demonstrates how relatively small velocity uncertainties can produce kilometre-scale errors in the predicted Doppler displacement. However, such errors do not necessarily correspond directly to the minimum distances reported in this study, as these depend on the geometry of the predicted aircraft trajectory.

During the manual inspection described in the methodology, particular caution was exercised in areas containing numerous bright scatterers, where potential aircraft signatures were difficult to distinguish from the surrounding sea clutter. Preference was given to candidates that appeared distinct from the local background, while areas displaying patterns consistent with wave-related scattering were treated more cautiously. This conservative selection may have reduced the inclusion of sea-clutter features among the reported candidates. However, it may also have excluded aircraft signatures embedded in heterogeneous or strongly scattering sea backgrounds, potentially contributing to the low detection rate.

For ITY621 and DAL16, two candidate signatures satisfy the selection criteria within the same search region. For ITY621, POI 1 shows closer geometric agreement with the predicted trajectory, while both POIs have similar local contrasts. For DAL16, POI 2 is closer to the predicted trajectory, whereas POI 1 has the stronger contrast. Its smaller residual favors POI 2 geometrically, although this alone does not establish which signature is associated with the aircraft. The separate responses could reflect a fragmented aircraft-related return or an unrelated transient scatterer within the search region. The present observations do not distinguish between these possibilities, so the two POIs are retained as alternative or potentially related candidates rather than treated as independent flight detections.

Despite these uncertainties, the geometric correspondence, elevated local backscatter, and checks against repeat-pass imagery, AIS observations, and buoy databases support an aircraft-related interpretation. The absence of persistent scatterers reduces the likelihood of stationary sources, while the maritime checks reduce the likelihood of known vessels or buoys. Nevertheless, incomplete AIS coverage and transient scattering sources leave some alternative explanations unresolved [21].

6. Conclusion and Outlook

This study demonstrates that signatures of airborne targets are present and observable in standard Sentinel-1 IW GRD imagery. Integration of OpenSky ADS-B trajectory data with Doppler-induced displacement modeling allows systematic localization of candidate targets within predicted spatial search bounds. The identification of 17 distinct signatures across 15 independent flight cases confirms that standard geocoded SAR products retain clear radar returns from high-altitude aircraft without requiring specialized refocusing or sub-aperture decomposition. Verification against repeat-pass Sentinel-1 imagery, co-located Sentinel-2 acquisitions, and comprehensive maritime reference databases validates that these signatures represent physical airborne targets rather than static surface structures, sea clutter, or imaging artifacts.

Future work will extend the analysis to additional Sentinel-1 acquisitions and ADS-B trajectories to build a larger collection of aircraft signatures. Automating trajectory matching, candidate extraction, and validation will improve detection efficiency. A larger dataset will enable direct comparison of signature characteristics with aircraft type, motion, and acquisition geometry, while supporting machine-learning methods to distinguish aircraft from ships and sea clutter. These developments will support aircraft detection in SAR imagery without prior ADS-B information, enabling independent non-cooperative surveillance systems.

Author contributions

- Jacob Saarde: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.
- Johannes Pielmeier: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.
- Peder Heiselberg: Methodology, Supervision, Writing – review & editing.

Open Data Statement

Sentinel-1 SAR imagery was obtained through the Copernicus Data Space Ecosystem [14]. Historical aircraft ADS-B state vectors were obtained from the OpenSky Network [12], while vessel AIS data used for the maritime cross-checks were obtained from Datalastic [20]. Registered buoy positions were obtained from the Marine Institute's Irish Marine Data Buoy Observation Network and Irish Wave Buoy Network [23, 24]. The NOAA National Data Buoy Center station catalog was additionally consulted as a supplementary source of buoy locations [26]. Navigational buoy and other aid-to-navigation positions were obtained from the Commissioners of Irish Lights Aids to Navigation dataset [25]. The buoy and navigation-aid datasets were accessed on 18 October 2026. Access to and reuse of third-party data are subject to the respective providers' access policies, licensing conditions, and terms of use.

Reproducibility Statement

All datasets required to reproduce this study can be obtained from the sources listed in the Open Data Statement, subject to the respective providers' access conditions and licensing terms. A supplementary archive containing the Sentinel-1 acquisition identifiers, scene acquisition times, study-area definition, processing parameters, machine-readable candidate-signature results, workflow documentation, figure-to-product mappings, derived figure material, and selected figure-generation scripts is available through Zenodo:

<https://doi.org/10.5281/zenodo.23541400>

The study area, processing workflow, ADS-B trajectory reconstruction, Doppler-displacement estimation, search-area definition, candidate-selection procedure, and validation methodology are described throughout the manuscript. The supplementary archive provides the information required to identify the Sentinel-1 scenes analyzed and to reproduce the workflow using independently obtained source data.

The complete specialized research code used to generate the SAR image products and associated analysis outputs is available from the authors upon reasonable request.

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