

Study of Contrails Based on Ground-Based Observations Supported by Space Missions

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ABSTRACT

Condensation trails, also known as contrails, are the cloud filaments left behind by aircraft. They are visible from ground and from space. Contrails result from the emissions of soot and water vapor released by aircraft engines. They evolve rapidly in the atmosphere after their formation and can persist when the air is supersaturated with ice. They can even transform into cirrus clouds, depending on atmospheric thermodynamic conditions. These artificial clouds resulting from human activity contribute to the additional radiative forcing of the climate and warrant further study, particularly given the constant increase in air traffic. The formation thresholds of these artificial clouds, the growth rate of persistent contrails, and their optical characteristics remain areas requiring further research. This research framework has motivated the temporal, episodic, and/or continuous monitoring of contrails through the installation of ground-based instruments at the following French observatories: SIRTA (Atmospheric Remote Sensing Research Site), OHP (Haute-Provence Observatory), and SIRENE located close to OHP. The instrumentation consists primarily of a lidar, radiosondes, and one or two fisheye cameras that record hemispheric images of the sky in the visible and thermal infrared for continuous observations, including night-time. Ground-based meteorological data, along with global horizontal irradiance (GHI), are recorded simultaneously with the images. Simultaneous space-based observations alongside ground-based data, when available, are of considerable interest for understanding contrail characteristics. Observations from the geostationary satellite MTG will be used to track contrails over ground sites, thanks to the continuous imagery it provides. Data from the EarthCare satellite will also be used, despite a lower overflight frequency. Thermal images from its multispectral imager (MSI), which offers a spatial resolution of 500 m at ground level over a 150 km wide swath perpendicular to the satellite's orbit, will be prioritized because they increase the probability of detecting contrails at a given location. The synergistic AC-TC radar-lidar product of EarthCare, when available simultaneously with ground-based data, will also be highly valuable, as it enables the acquisition of aerosol and cloud profiles during the MSI image acquisition process. This work presents the temporal monitoring of ground-recorded contrails, notably the one observed at SIRTA on June 18, 2025. This date corresponds to the EarthCare satellite's pass over SIRTA, where the MSI TIR3 and AC-TC products enabled the co-location of the contrail's state at 1:15 AM. The AC-TC product allowed us to determine the contrail's altitude, which agrees with observations made using the IPRAL lidar at SIRTA. Finally, we will explain how the AC-TC product enabled the contrail's classification.

Keywords: Condensation trail, Instrumentation, Data processing, Thermal Infrared

1. INTRODUCTION

Cloud formation also results from human activity, as evidenced by the contrails produced by aircraft emissions of water vapor and soot. These trails rapidly change shape after formation and can persist in the atmosphere

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if the air is supersaturated with respect to ice. Depending on atmospheric thermodynamic conditions, they can subsequently evolve into cirrus-like clouds. These artificial clouds, which contribute to additional radiative forcing on the climate, warrant special attention given the significant increase in air traffic. The transformation of persistent contrails into cirrus-like clouds (often referred to as "contrail-cirrus") has been extensively studied above the Haute-Provence Observatory (OHP, in southern France) using lidar observations, as detailed in a recent climatological study.¹ However, the formation thresholds for these artificial clouds, the growth rates of persistent contrails, and their optical properties remain topics requiring further research. This situation has recently led to the implementation of temporal monitoring—whether intermittent or continuous—of contrails through the installation of ground-based instruments at French observation sites such as SIRTa (Site Instrumental de Recherche par Télédétection Atmosphérique, vicinity Paris (France), <https://sirta.ipsl.fr/>). They are mainly composed of a Lidar, radiosondes and one or two fisheye cameras recording hemispherical images of the sky in the visible and thermal infrared for nighttime observations. The Global Horizontal Irradiance (GHI) of the Sun and some meteorological data on ground are also recorded together with the images. The use of simultaneous space-based observations is also an asset for identifying the properties of condensation trails. The idea is to consider EarthCARE MSI (Multi Spectral Imager) images that have a spatial resolution of 500 meters at ground level over a 150 km wide swath perpendicular to the satellite's orbit, thus increasing the probability of detecting contrails at a given location on the ground. Furthermore, EarthCARE's synergistic radar-lidar AC-TC products,² acquired simultaneously, will also be used to obtain aerosol and cloud profiles during the MSI image acquisition process. This work presents a first attempt at a joint ground-space observation of a contrail, based on images recorded on June 18, 2025, by MSI and the thermal camera at the SIRTa site.

2. ABOUT CONDENSATION TRAILS: CONDITIONS OF FORMATION AND PERSISTENCE

According to recent studies, aviation could contribute significantly to climate change in the future when the effects of CO₂ and other factors are taken into account. Air traffic could even roughly triple over the next two decades (European Union Aviation Safety Agency, EASA: ICAO Aircraft Engine Emissions Databank) (last accessed: August 16, 2025). Consequently, contrail-induced cirrus clouds will become a major contributor to the aviation sector's radiative forcing (RF).³ Aviation is responsible for approximately 3.5% of global anthropogenic radiative forcing, with persistent contrails contributing more than half of this forcing.^{4,5}

Contrails form when hot, humid aircraft exhaust gases rapidly mix with cold, humid ambient air, causing the moisture within the exhaust to exceed the liquid-water saturation threshold.⁶ The Schmidt-Appleman criterion (SAC), based primarily on thermodynamics, defines the threshold temperature TSAC for contrail formation (TSAC, typically < 230 K).⁷

In addition to the formation condition, an ambient relative humidity (RH) with respect to ice ($RH_{ice} > 100\%$) is also required for the formed contrails to persist.⁸ These conditions are essential for the development and persistence of contrails.

The optical and morphological properties of contrails have been extensively studied by combining satellite data, ground-based lidar measurements, camera imagery, and numerical models.⁹ However, observational constraints—such as sampling frequency, spatial resolution, and the scarcity of certain data—significantly limit the measurement of contrail properties.¹⁰ Currently, uncertainties remain regarding humidity observations and forecasts, interactions between contrails and cirrus clouds, regional atmospheric variations, and so forth; these uncertainties affect the assessment of contrail lifetimes and, consequently, their radiative effects.¹¹ These challenges highlight the need for further research to reduce uncertainties and improve forecasting and mitigation strategies related to contrails.

3. THE SIRTa FACILITIES - DATA AND CALIBRATION

Instrumentation was installed on the SIRTa site (48.716°N, 2.212°E, 156 m asl) to study condensation trails by recording them in order to monitor their evolution and persistence.

3.1 Contrail observation equipment

The SIRTa facilities include the IPRAL lidar whose laser operates at wavelengths of 355, 532 and 1064 nm (<https://www.lmd.ipsl.fr/en/actulmd/the-new-life-of-the-ipral-lidar/>). It is dedicated to the study of dynamic processes in semi-urban environments in order to improve the understanding of the interactions between clouds and radiative and dynamic processes. The facilities include also radiosondes and a fisheye camera recording hemispherical images of the sky (Figure 1 Top). The Sky InSight™ is based on a thermal infrared camera which enables day and night observation of contrails. The camera is manufactured by the company Reuniwatt and used for different applications such as solar energy forecasting¹² or atmospheric characterization for optical communication links.¹³

Some meteorological data (humidity and temperature) and global horizontal solar irradiance (GHI) are also recorded on the ground, along with the images.¹⁴

The SIRTa ADS-B (Automatic Dependent Surveillance-Broadcast) receiver provides data from aircraft flying over the site. This data includes latitude, longitude, altitude, and the aircraft's identifier, making it possible to identify the specific aircraft producing a contrail.

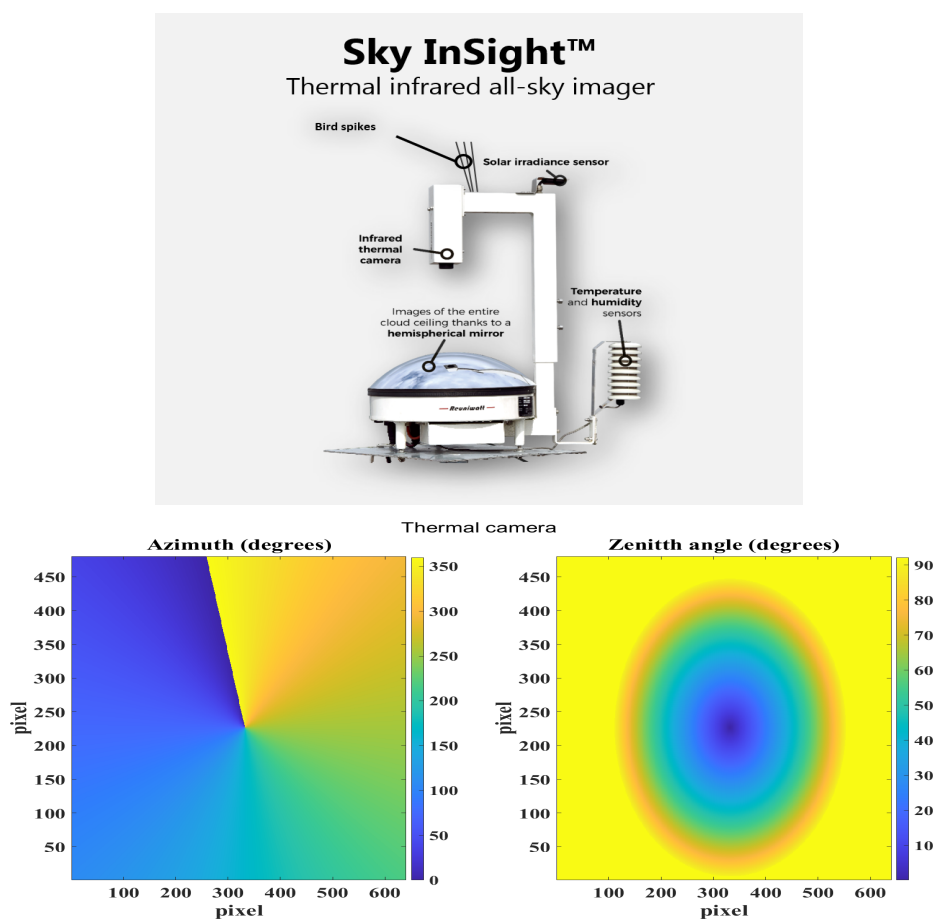


Figure 1. Top: Sky InSight™: Thermal infrared all-sky imager (reproduced courtesy Reuniwatt). Bottom: Azimuth (left) and zenith angle (right) calibration matrices for the thermal camera.

3.2 Images for contrail monitoring and calibration

Hemispherical images with the SIRTa thermal camera were taken every 30 seconds during May and June 2025. The number of images per day was then 2880 and their size is 480 x 640 pixels. Each image pixel is located on

the sky by its azimuth and zenith angles thanks to the calibration matrices provided by Reuniwatt (Figure 1 Bottom). These matrices allow each pixel of the acquired image to be transformed into the coordinate system (azimuth, zenith angle). They will then be transformed into the reference geographic frame (longitude, latitude) such as the aircraft trajectory.¹⁴ The same methodology as that used by Smith *et al.*¹⁵ was used here for this frame change. However, this requires knowing the altitude of the clouds or contrails—a tricky issue that will need to be addressed using assumptions or external measurements from lidars or other sources (see section 4). The calibration matrices provided by Reuniwatt were first validated using the Sun’s diurnal trajectory. The series of images recorded on March 21, 2024, at the OHP using the Sky InSight™ camera was considered first,¹⁴ given that the camera is identical to the one at SIRTa. The position of the Sun was detected in each image, making it possible to reconstruct the solar trajectory (Fig. 2 on the left). A comparison was then carried out, taking into account, on the one hand, the solar ephemerides (azimuth and zenith angle) for March 21, 2024 from the JPL’s Solar System Dynamics (SSD), and, on the other, those obtained from the calibration matrices. Very good agreement is observed, as shown in Figure 2 on the right. The clearly visible disturbances for the reconstruction of the Sun’s trajectory are due to parasitic objects at sunrise in the image field (camera antenna among others) which hinder its detection (left part of the curve) or to the presence of clouds in the sky on the horizon at sunset (right part of the curve).

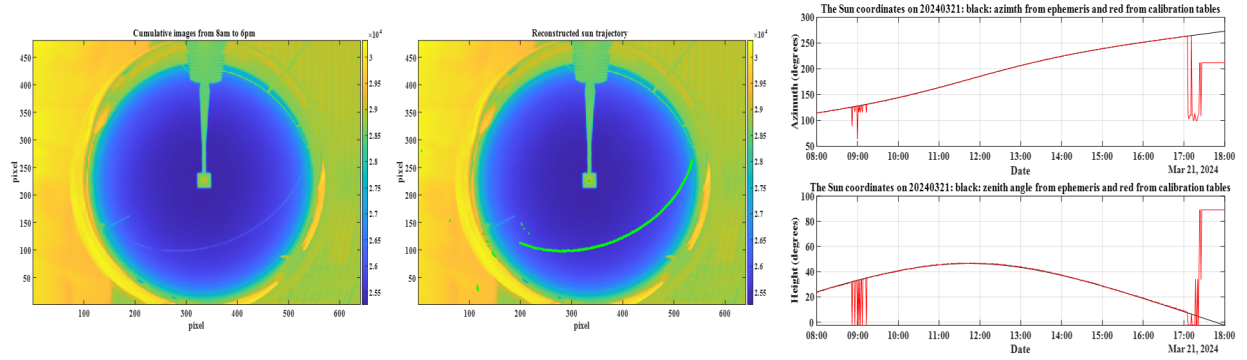


Figure 2. Left: Example image recorded with the thermal camera where the Sun is visible. Center: the cumulative thermal images recorded on the same day, where the Sun’s trajectory is clearly seen (green dots). Right: The reconstructed solar trajectory and its comparison with the ephemeris, respectively: good agreement is observed.

4. PROCESSING OF THE THERMAL IMAGES - CONTRAIL EXTRACTION

June 18, 2025, is a particularly interesting day, as images taken at the SIRTa observatory with the Sky InSight™ thermal camera revealed the presence of a nighttime contrail as the EarthCare satellite passed over the site. The images were first processed using the method described in Irbah *et al.* (2025)¹⁴ and then the contrails were extracted. The image recorded at 00:30 UTC, under clear skies, served as the reference image for the processing. Figure 3 shows, at the top and from left to right, the raw reference image followed by its processed version. The third image corresponds to the result obtained by applying the same processing to the image recorded on June 18, 2025, at 01:15 UTC. The first image, located at the bottom left of Figure 3, is the one obtained after subtracting the reference, while the second—located at the bottom right—clearly illustrates the identification and extraction of the contrail using the k-means method. The light cloud cover present that day makes the complete detection of contrails more complex.

A visual examination of the image sequence showing the contrail under study reveals that the first signs of its detection appear around 00:50 UTC. Subsequent analysis of ADS-B data identifies aircraft 3C7424, flying at an altitude of 11.58 km, as the source of its formation. Figure 4 (left) shows the aircraft’s flight path as well as the locations of SIRTa and the nearby airports, Orly (ORY) and Charles-de-Gaulle (CDG). The figure on the right shows the wind profile derived from ECMWF ERA5 data (<https://cds.climate.copernicus.eu/>) at the time the contrail left by the aircraft was forming over SIRTa. It can be seen that a wind of approximately 15 knots (28 km/h) is blowing from the northeast, while the aircraft is moving from the southeast toward the

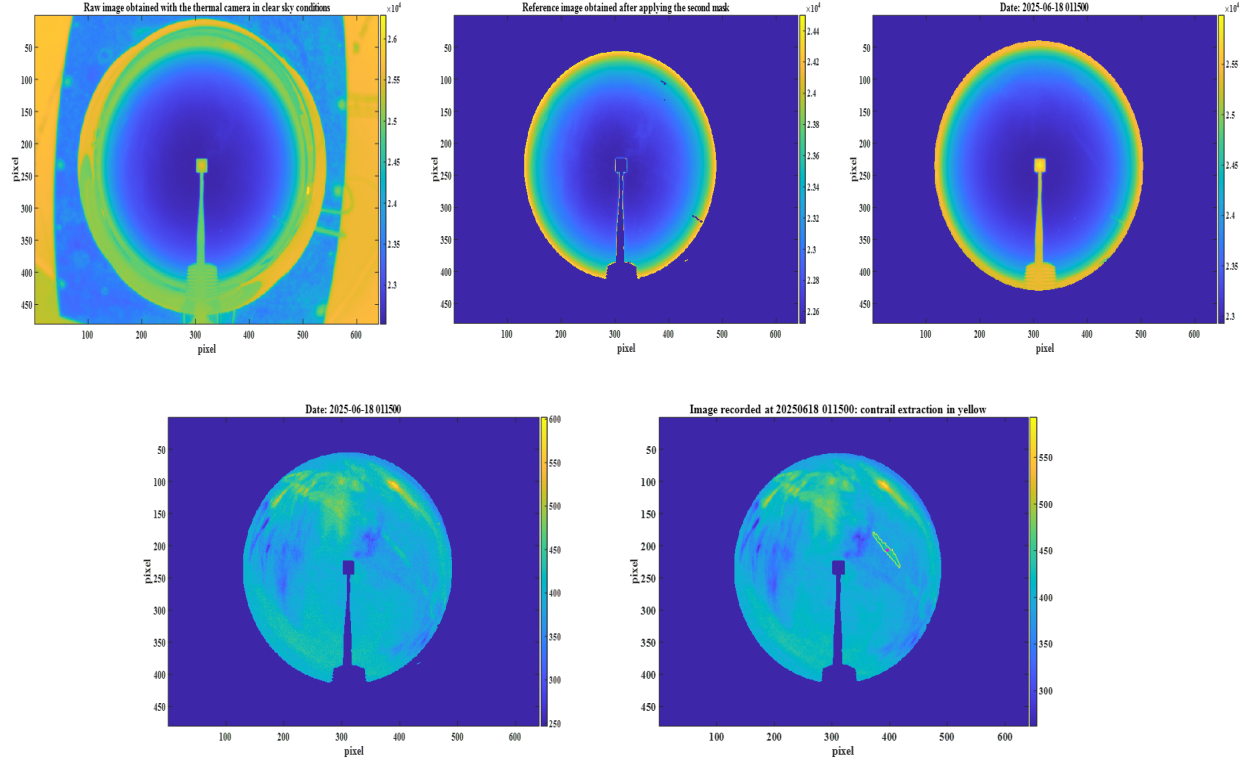


Figure 3. Top from left to right: raw reference image, reference image after processing and the image recorded at 01:15. Bottom from left to right: the same image after removing the reference and then extracting the contrail shape

northwest. Consequently, the contrail should not follow the aircraft’s flight path but rather undergo a shift to align with the wind direction. This is confirmed by Figure 5 (top), which shows the temporal evolution of the contrail’s shape—derived from images captured by the thermal camera every 30 seconds between 00:50 and 01:30 UTC—along with the aircraft’s trajectory (in green). This plot clearly shows that the contrail moves in an oblique direction (northwest–southeast) relative to the aircraft’s flight path. The contrail shapes, initially defined in image pixels, were calibrated (see section 3.2) and then converted into the aircraft’s geographic coordinate

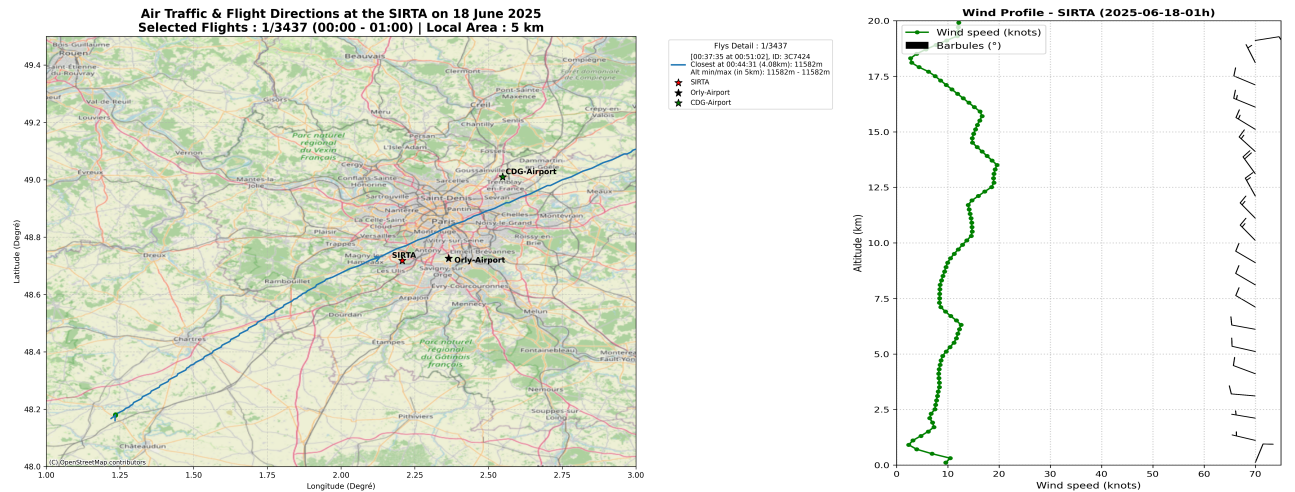


Figure 4. Left: flight path of the aircraft that produced the contrail observed at SIRTa on June 18, 2025. Right: ERA5 wind profile at the time of contrail formation over SIRTa (01:00 UTC).

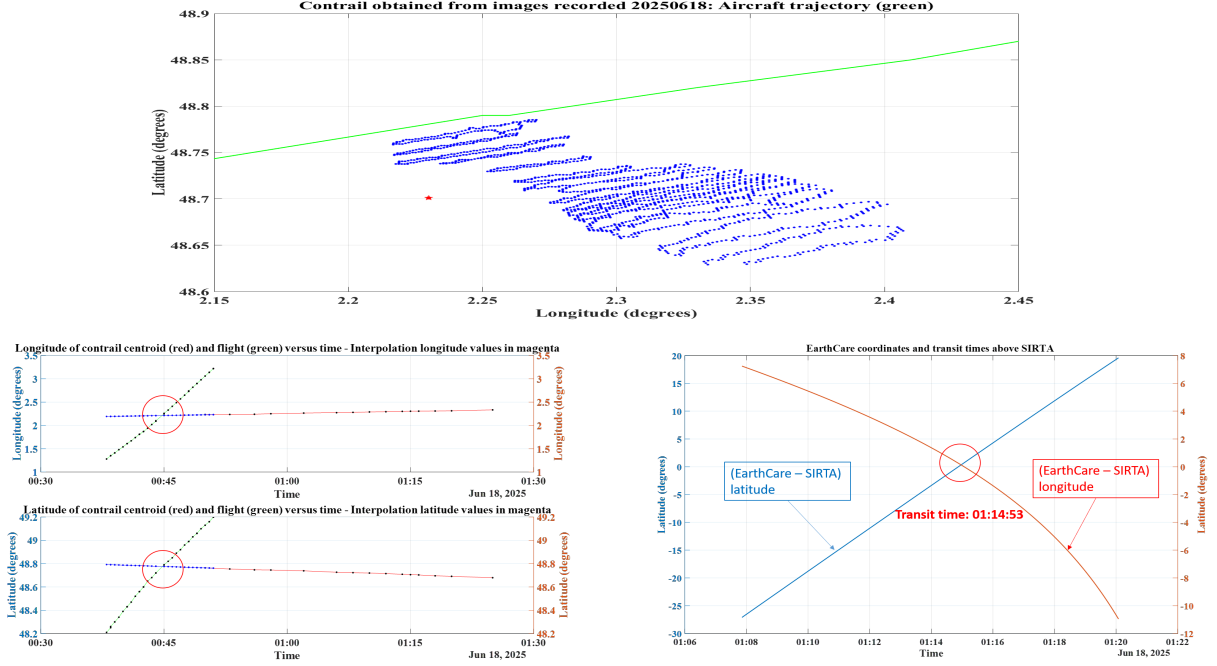


Figure 5. Top: Contrail extracted from images plotted in the geometric coordinate system using the aircraft’s altitude. Bottom left: Estimation of the initial time of the contrail. Right: Estimated overpass time of EarthCARE over SIRTAs.

system, assuming the contrail was located at the aircraft’s altitude (11.58 km). Plotting the contrail’s centroid and the aircraft’s position over time allows the initial moment of contrail formation to be determined via linear interpolation. This corresponds to the intersection of the two trajectories: the onset of contrail emission occurred around 00:44:30 UTC (see Fig. 5, bottom left).

5. OBSERVATION OF THE NIGHTTIME CONTRAIL AT SIRTAs: COLOCALIZATION WITH EARTHCARE AND MTG

5.1 Ground-space colocalization of the contrail

The formation period of the contrail observed over SIRTAs coincides with the passage of the EarthCare satellite. The Multispectral Imager (MSI) on board EarthCare records atmospheric radiance along the satellite’s orbit across seven spectral bands, covering a 150 km-wide swath with a resolution of 500 meters (see Fig. 6). The objective here is to analyze the MSI product corresponding to the SIRTAs overpass to determine whether a contrail is present, given that the instrument’s wide field of view increases the probability of detection. Figure 6 shows the brightness temperature difference between the TIR3 (12 μm) and TIR2 (10.8 μm) channels, seemingly indicating the presence of a contrail. The difference between these two MSI channels effectively highlights brightness temperature fluctuations, thereby facilitating the identification of the contrail. However, a key step involves determining the time of EarthCare’s passage over SIRTAs. This moment is estimated by plotting the temporal evolution of EarthCare’s coordinates (longitude, latitude) relative to those of SIRTAs, as shown in Figure 5 (bottom right): The intersection of the curves reveals that EarthCare’s overpass of SIRTAs occurs at 01:14:53 UTC. The joint observation of the contrail—from both space and the ground—relies on the transect segment recorded by EarthCARE’s MSI instrument over the SIRTAs site, as well as on contrail data derived from images captured by the ground-based thermal camera. Time-stamped samples of the contrail’s shape, obtained from the time series of images acquired at SIRTAs every 30 seconds between 00:50 and 01:30 UTC, were compared with the contrail recorded by the MSI instrument at 01:14:53 UTC. The contrail used for the comparison is therefore the one corresponding to the closest sample: the recording made at 01:15 UTC. Figure 7 shows the overlay of the contrail observed from space on June 18, 2025, by EarthCARE’s MSI instrument and the one observed from the

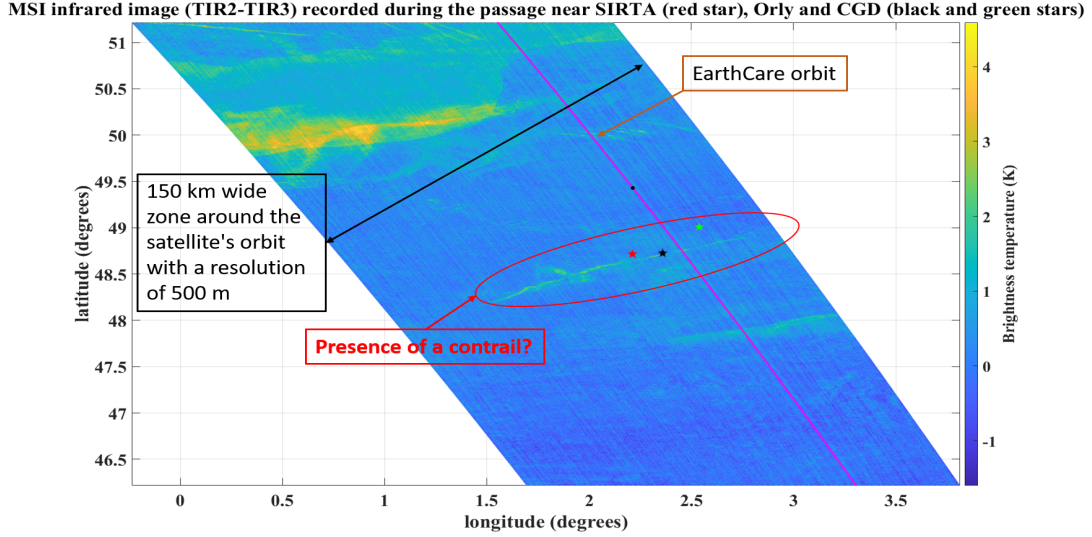


Figure 6. MSI (TIR3-TIR2) image over SIRTÀ showing the contrail observed from ground. SIRTÀ is the red star while, Orly and CDG airports are in black and green

ground at SIRTÀ (left-hand images and white dots). **The shape of the contrail at 01:15 UTC, derived from ground-based images, matches the shape observed by the MSI perfectly.** Images captured from space by the FCI (Flexible Combined Imager) instrument aboard the MTG (Meteosat Third Generation) satellite (<https://www.eumetsat.int/meteosat-third-generation-instruments>) were also used to track the contrail that formed over SIRTÀ on the night of June 18, 2025. The FCI instrument provides images of the full Earth disk (covering Africa and Europe) every 10 minutes across 17 spectral bands—including those of the MSI instrument, but with a spatial resolution of 2 km. The area of the image corresponding to the same latitude and longitude extent as the previously analyzed MSI image (see Fig. 7) is then extracted for comparison purposes. This process was carried out for the two images captured in the same spectral channels as the MSI (TIR2 and TIR3) and acquired at the same times—or at the closest possible times. Both images

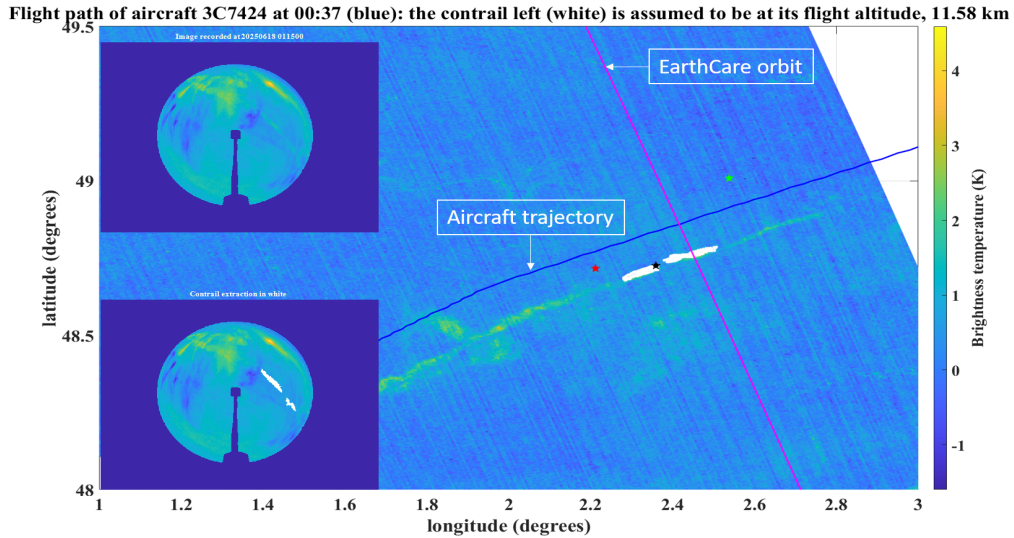


Figure 7. Left: image taken from ground at 01:15 UTC. Right: MSI image (TIR3-TIR2) above SIRTÀ highlighting the contrail and its colocalization with the ground image one (white dots). The EarthCARE orbit is shown in magenta.

underwent parallax correction, as required, and the difference between them was calculated. The formation of the contrail over SIRTa on June 18, 2025 (UTC), is clearly observed by the FCI between 00:50 and 01:30 UTC. Figure 8 (top) shows the MSI image acquired at 01:15 UTC over SIRTa, displaying the contrail as well as the shape detected from the ground by the thermal camera (white dots), while the bottom section shows the corresponding FCI image—at the same scale—acquired at 01:10 UTC. A strong resemblance is clearly visible between the two images—despite having been taken at slightly different times—as well as with the shape of the contrail extracted from the ground-based images. Similar brightness temperature dynamics are observed for MSI and FCI regarding the detection of the contrail.

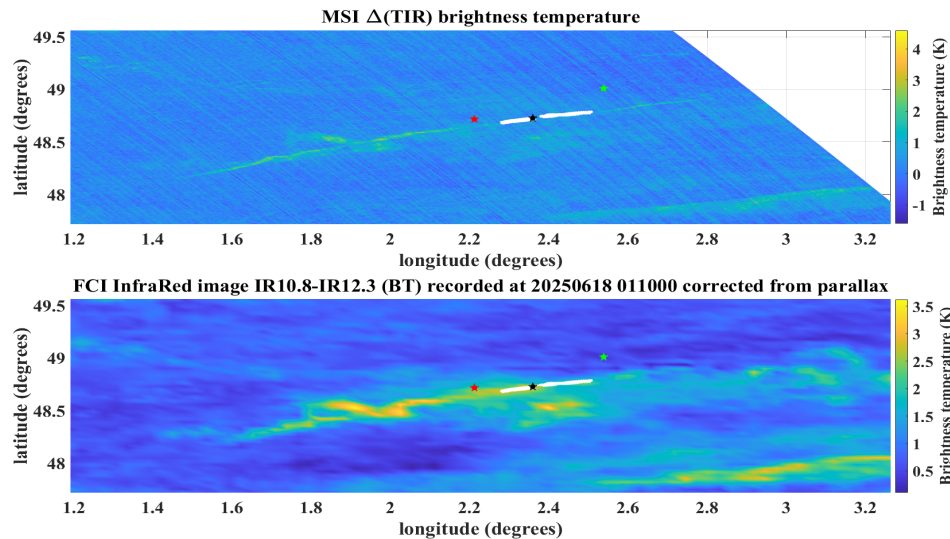


Figure 8. Contrail observed in the MSI image (TIR3-TIR2) acquired over SIRTa, its co-location with FCI/MTG, and the shape of the trail inferred from the ground-based image.

5.2 Probing the contrail using lidars and space-based observations

The IPRAL lidar installed at SIRTa (see section 3.1) was also in operation on June 19, 2025, during the formation of the nighttime contrail that began at 00:45 UTC. However, detection of the contrail by IPRAL is only possible when it passes through the instrument’s field of view; it is therefore necessary to know the time of its passage over the lidar. This moment is determined using images captured by the thermal camera during the contrail’s formation. SIRTa—and consequently IPRAL—is located at the center of the images, where the arm supporting the camera extends into its field of view (see Figure 1, top). The moment the contrail crosses the center of the image therefore corresponds to its passage over the lidar. Figure 9 (top left) shows the ground-based image with the contrail crossing the center, as evidenced by the extraction of its shape traced on the image. An enlargement of the central part of this image highlighting the contrail is shown at the bottom left. The image was taken at 00:58 UTC, the time at which the contrail was also observed by the IPRAL lidar. Figure 9 (top right) shows the apparent backscatter coefficient measured by IPRAL at 1064 nm during the formation of the contrail, while the image at the bottom right shows an enlargement of the altitude range of interest, extending from 10 to 13 km. IPRAL detects the contrail at 00:58 UTC at an altitude of 11.88 km (red circle in the figure), approximately 300 m above the aircraft’s altitude.

An enlargement of Figure 7, close to SIRTa, clearly shows that the contrail extends far enough to cross the nadir path of the EarthCARE orbit. This means that EarthCare’s nadir-pointing instruments—ATLID (Atmospheric Lidar) and CPR (Cloud Profiling Radar)—also probe the contrail. Figure 10 displays the particle backscatter measured by ATLID at 355 nm, revealing a peak at 01:14:53 UTC. This peak occurs at an altitude of 12.35 km and most likely corresponds to the top of the contrail. It is thus located 770 meters above the aircraft’s altitude, or 470 meters above the base of the contrail as measured by IPRAL at 00:58 UTC. This value therefore represents the height of the contrail, assuming it remained at the same altitude until 01:14:53 UTC.

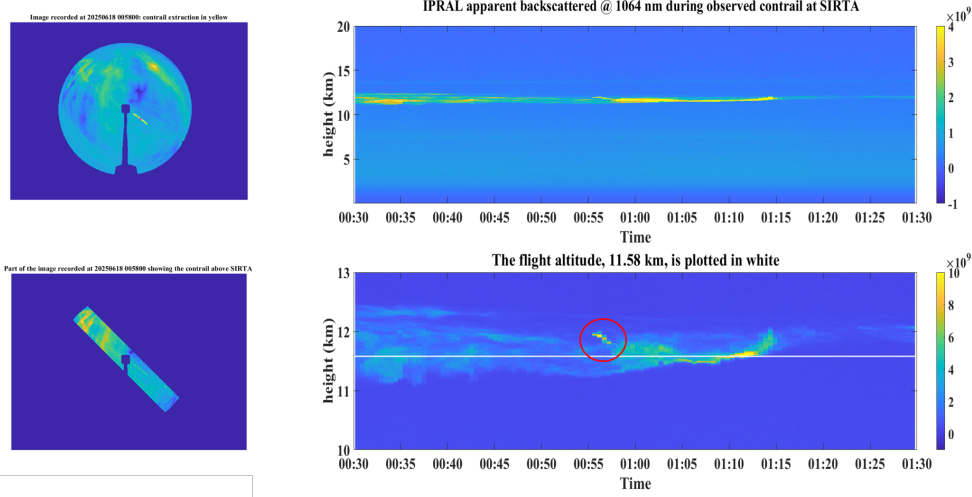


Figure 9. Left: image taken on June 18, 2025, at 00:58 UTC (top) and its central section showing the contrail passing over the center corresponding to Sirta location (bottom). Right: contrail detected by IPRAL at 1064 nm (red circle).

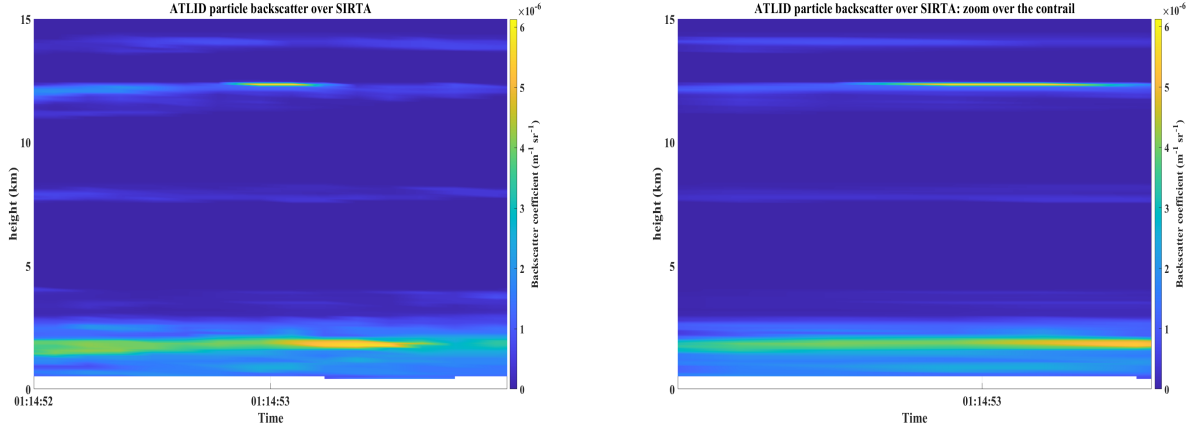


Figure 10. Left: ATLID backscatter coefficient at 355 nm obtained during the formation of the contrail on June 18, 2025, over Sirta. Right: close-up view of the backscatter from the contrail.

The EarthCARE AC-TC synergistic product (Fig. 11)—derived from ATLID and CPR observations (primarily ATLID, given the clear skies over Sirta at the time of contrail formation)—is also available for the study of the contrail. The AC-TC profiles over Sirta, obtained at 01:14:53 UTC (± 0.5 seconds), are extracted from this product. They show that the contrail located at 12.35 km is classified as **dusty smoke** and **ice cloud**.

6. CONCLUSION

This article follows up on previous work conducted at the OHP regarding condensation trails or contrails,¹⁴ which established the experimental framework—specifically the data processing methods required to determine the characteristics of these trails, namely their formation, persistence, and microphysical properties. It begins with a brief theoretical overview of the conditions governing the formation and persistence of condensation trails, followed by a description of the instrumentation used.

Instruments were deployed at the Sirta site (near Paris, in northern France) during May and June 2025 as part of a campaign to study atmospheric parameters and contrails, with the specific aim of utilizing simultaneous satellite observations. The setup included the IPRAL lidar (permanently installed at the site); a hemispheric camera capable of thermal infrared imaging by day and night—similar to the one installed at the OHP, the angular calibration of which had been previously validated; access to data from Sirta’s ADS-B system (which

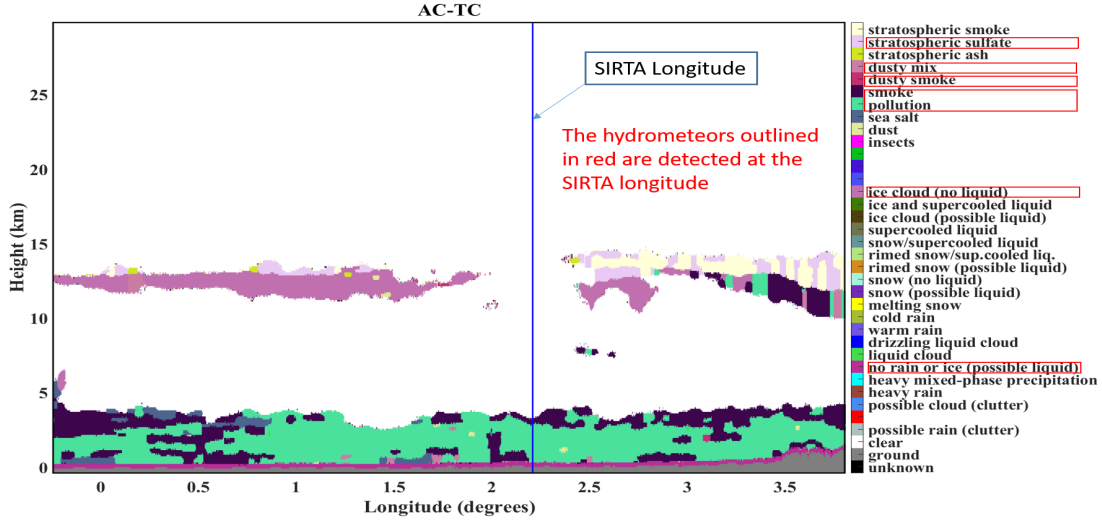


Figure 11. The EarthCARE AC-TC synergistic product: profiles above SIRTa probe the contrail.

records aircraft signals); and the recording of meteorological and atmospheric data via balloon launches (wind profiles, humidity, etc.). Additional auxiliary data—such as cloud fraction (CF) derived from imagery—were also collected. The camera calibration validation, summarized here, involves mapping image pixels to sky positions within a local coordinate system (azimuth, zenith angle) using the Sun’s trajectory, and then projecting them into a geometric reference frame (longitude, latitude) based on assumptions or measurements regarding altitude (of the contrail or the aircraft).

The study proceeded with an analysis of data acquired at SIRTa on June 18, 2025, between 00:30 and 01:30 UTC, revealing the presence of a nighttime contrail. This specific period was selected because it coincided with the EarthCARE satellite’s nighttime overpass of the SIRTa site, which occurred around 01:08 UTC. Ground-based images were processed to extract the shape of the contrail from each image. Combining the initial visible moments of the contrail with ADS-B data made it possible to identify aircraft 3C7424—flying at an altitude of 11.58 km—as the source of its formation. Analysis of the contrail’s temporal evolution, derived from the images, determined the start time of its formation to be 00:44:30 UTC. Knowing the time of the EarthCARE satellite’s overpass above SIRTa was also important; this was calculated using the satellite’s orbital parameters and the site’s geographic coordinates, placing the overpass at 01:14:53 UTC. Spectral images in the TIR2 (10.8 μm) and TIR3 (12 μm) channels from EarthCARE’s MSI instrument were used to analyze the contrail from space. The difference between these two channels (TIR2–TIR3) highlights brightness temperature fluctuations and, consequently, the contrail itself. Superimposing the contrail’s shape—extracted from the ground-based image taken at 01:15 UTC—onto the MSI difference image reveals excellent co-location. MTG FCI images acquired at 01:10 UTC in the same spectral channels were also analyzed. The difference between these two parallax-corrected images also bears a strong resemblance to the shape of the trail observed from the ground.

The study shows that the contrail extends far enough to cross the nadir track of the EarthCARE orbit. This means that EarthCARE’s nadir-pointing instruments (ATLID and CPR) also probe this contrail, thereby generating the AC-TC radar-lidar synergistic product.

Data from both the IPRAL lidar (SIRTa) and ATLID (EarthCARE) were therefore used for this study. Analysis of the apparent backscatter measured by IPRAL at 1064 nm over time reveals that the instrument detected the contrail at 00:58 UTC, at an altitude of 11.88 km. The time at which the contrail passed over the lidar was determined using ground-based thermal images. Particle backscatter, measured by ATLID at 355 nm, peaked at 01:14:53 UTC at an altitude of 12.35 km, which most likely corresponds to the top of the contrail. This point lies 470 meters above the base of the contrail as measured by IPRAL at 00:58 UTC. This value therefore represents the height of the contrail, assuming it remained at the same altitude until 01:14:53 UTC.

Finally, the AC-TC profiles over SIRTa, obtained at 01:14:53 UTC, classified the contrail located at 12.35 km into the “dusty smoke” and “ice cloud” categories.

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