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Investigating contrails within cirrus clouds

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Motivation

Effects of aviation on climate and Earth's radiation budget related to CO_2 emissions and from the formation of linear contrails and contrail cirrus have been the focus of detailed studies. Aviation effects on existing cirrus clouds are much less investigated. Contrail formation in existing cirrus clouds has the potential to increase the cloud optical thickness (COT) of optically thin cirrus, which might result in a net cooling effect.

Spaceborne remote sensing generally provides the means for studying the impact of aviation on climate. However, only active instruments such as lidar or radar can be used to study the effect of contrails that form within existing cirrus clouds. For such an investigation, the location of an aircraft at a given time needs to be matched with information on cloud coverage, cloud type, cloud layer height, and COT as can be retrieved from spaceborne CALIPSO lidar data.

We have developed an algorithm to find intersections of aircraft flight tracks with satellite tracks. The algorithm is highly adjustable so that it can be adapted for other applications such as investigation of ship tracks or cloud tracking. The new algorithm has been used to identify aircraft flying through cirrus clouds in remote regions of the Earth to study the effects of individual aircraft on existing cirrus.

Main Challenges

- Quantity of data
  - **Large number of flights needed** for statistically relevant analyses (associated with **high procurement costs**)
  - **Long computation times; huge data file**
- **Accuracy of track data**
  - May lead to inaccurate results or duplicate intersection finds (see below)
  - **Large gaps in the flight-track data**
- **Choice of algorithm/software**
  - Julia as suitable software with a focus on computation time and big data sciences
  - Packages not as complete as with established languages, needs to be complimented by MATLAB routines

The TrackMatcher Tool (Overview)

- Written in **Julia** and tested against versions **1.4.1 and 1.0.5** (LTS)
  - **MATLAB** used for reading CALIPSO HDF4 files and track interpolation **with PCHIP** (tested against versions **2016 and 2019a**)
- Processes **flight data** from different datasets
  - **VOLPE AEDT** fuel consumption and emissions inventory
  - **FlightAware commercial archive**
  - **FlightAware web content**
- Processes **CALIOP lidar data** onboard the **CALIPSO satellite**
  - Taken from the AERIS/ICARE database (http://www.icare.univ-lille1.fr/)
- Calculates **intersections** with the following options
  - Set allowed **maximum time difference** between aircraft passage and satellite overpass at intersection **(default: 30 min)**
  - **Save measured flight and satellite data** in the vicinity of the intersection **(default: closest flight measurement and sat measurement ± 15 time steps)**
  - Set **step width** of interpolation **(default 0.01°)**
- Flight, sat, and intersection data stored in structs for further analysis

The Track-Matching Algorithm

- **Filter** relevant data (e.g. altitude levels)
- **Split track into segments** with strictly monotonic x data (see also Fig. 1a)
  - Use lat as x data for satellite data
  - Chose lat or lon as x data for flights depending on prevailing flight direction
- **Interpolate tracks** with MATLAB's PCHIP method with a preset accuracy (default: 0.01°)
- **Minimise distance** between interpolated **lat/lon pairs** of flight and sat track
- **Find analytic solution** by linear interpolation between 4 closest points to intersection (see Fig. 1b+c)

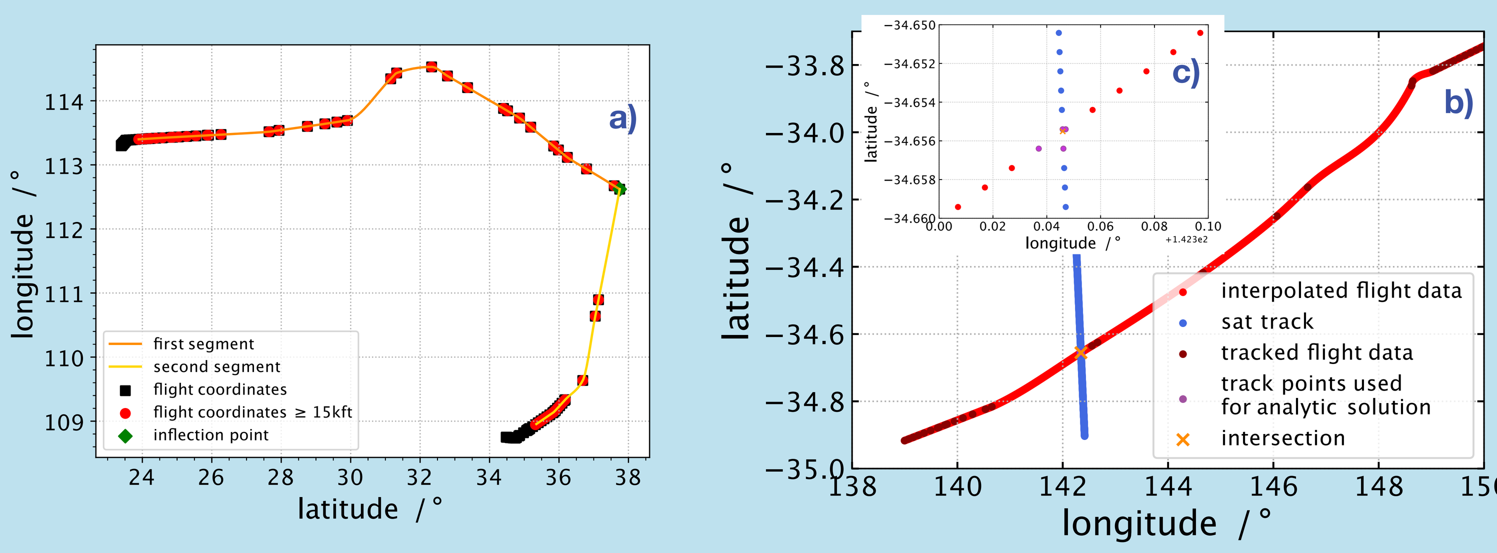

Fig. 1 Illustration of the TrackMatcher algorithm principles. Track data are filtered and relevant data split into segments with strictly monotonic x data (a). Segments are interpolated and the four closest points to a possible intersection are used to determine an analytic solution by linear interpolation (b+c).

Current Limitations

- Track data needs **splitting into segments** with strictly monotonic x data
  - Lat for satellite data; lat or lon for flight data)
  - Only segments with at least 3 data points are considered
  - Many small or disregarded segments for inaccurate track data (see Fig. 2)
  - Can lead to duplicate intersection finds at segment borders (Fig. 2)
- **Dependence on MATLAB licence**
  - For reading CALIOP HDF4 files
  - For track interpolation with PCHIP routine
  - Can be rewritten using open source software, e.g., a Python wrapper or directly in Julia

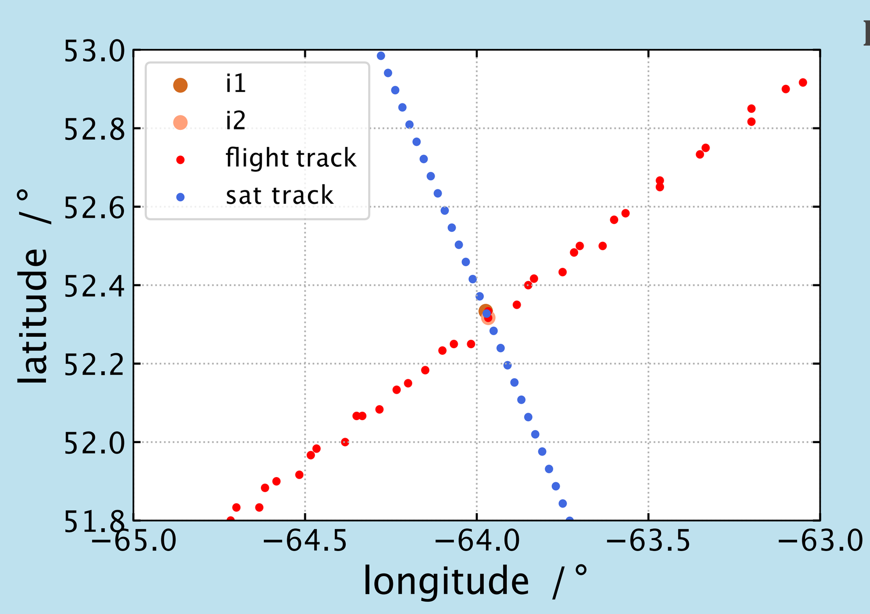

Fig. 2 Inaccurate flight-track data causing fragmentation of the flight track in many small segments with segment boundaries in the vicinity of the intersection. Points of each segment closest to the intersections are taken to derive the intersection. If the spread in the data is to wide, filters cannot find duplicate counts of intersections.

Preliminary Results

- VOLPE AEDT test set
  - Global routes for 1./2. January 2012
- **Very accurate results** within few meters of calculated intersections (see Tab. 1)
  - **Only a few outliers** demonstrated by mean in the range of the 95 percentile
- **Large datasets needed** to study effects of contrails on cirrus clouds (only 455 cases out of 156050; see Tab. 2)
- **Large gaps in the flight-track data** possible
  - demonstrated by a maximum distance to the nearest track point of a calculated intersection of 168 km and a mean distance of 73 km in Tab. 1)

Tab. 1 Accuracy of the intersection calculation (first column) and distance to the nearest available flight-track point (second column). All data is given in meters.

	Intersection	Flight track
Minimum	$2.08\cdot10^{-6}$	4.65
5 percentile	$1.58\cdot10^{-3}$	653.7
Median	0.057	9949.3
Mean	15.31	$2.35\cdot10^{4}$
95 percentile	14.53	$7.26\cdot10^{4}$
Maximum	1112.2	$1.68\cdot10^{5}$

Tab. 2 Total number of flights, number and percentage of intersections between flight and satellite tracks found, and meteorological conditions at the intersections.

	counts	percentage
Total flights	156050	100.00
Total intersections	6142	3.94
Single intersection/flight	5420	3.47
Multiple intersection/flight	722	0.46
No lidar signal	133	2.17*
Clear sky	5371	87.45*
Cirrus	**455**	**7.41***
Deep convective clouds	158	2.57*
Dust	14	0.23*
Altocumulus	1	0.02*
Altostratus	1	0.02*
Clean continental aerosol	1	0.02*
Stratospheric aerosol/cloud	8	0.13*

*percent of total intersections

Conclusions & Outlook

- **Working algorithm** to find intersections between trajectories
- Meant for **intersections between aircraft and satellite tracks**
- **Highly adaptable**, e.g. to ship or cloud tracks
- **Future release as open source project on GitHub** after rigorous testing
- Further **refinements of the algorithm**
- **Performance improvements**, e.g. parallelisation of code
- Use of **Mercator projection together with liner interpolation** to compensate for inaccurate flight data

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