Visual Analytics of Flight Trajectories for Uncovering Decision Making Strategies

Gennady & Natalia Andrienko, Georg Fuchs,
Stefan Rüping, Jose Manuel Cordero Garcia,
David Scarlatti, George A Vouros,
Ricardo Herranz, Rodrigo Marcos

http://geoanalytics.net/and

Big Data (Vs) & Data Science in ATM & ATC (As)

Variety of data

- Trajectories
  - Actually flown
  - Flight plans
  - Regulated flight plans
- Events
  - Regulations
- Spatial time series
  - Weather: actual and predicted

❖… all Vs of big data

Variety of stakeholders

- ATM
- ATC
- Airports
- Airlines

❖Restricted access to data

❖Limited understanding of decision making criteria, strategies and procedures

Origins of this work

- Informal collaboration with C.Hurter / ENAC 2010 –
- Basic research projects with Univ Constance 2008 –
- A Big Data Research project datAcron 2016 – 2018
- SESAR projects DART, INTUIT and BigData4ATM 2016 – 2018

We are grateful to funding agencies for enabling this research and to all or project and cooperation partners for great collaboration

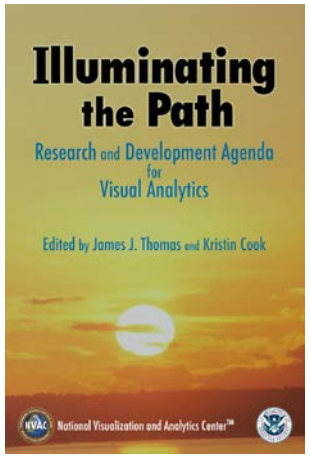
Who we are?

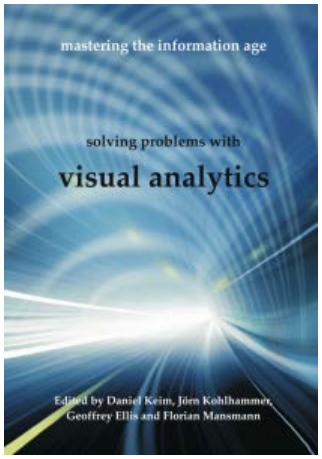
- A multidisciplinary team:
- Computer science researchers
  (Fraunhofer IAIS, City Univ London, Univ Piraeus)
  - KD & ML
  - VA
  - DB management
  - Data Science
- Data Science researchers and practitioners
  (Nommon)
- ATM and ATC researchers and practitioners
  (CRIDA, Boeing Research)

Who we are? Visual Analytics researchers

- Visual Analytics is the science of analytical reasoning* facilitated by interactive visual interfaces

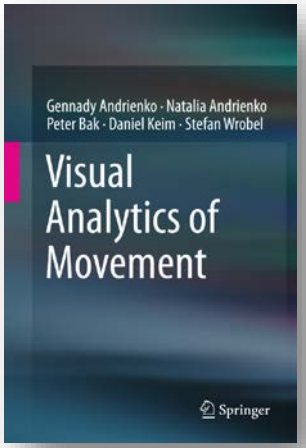
* **Analytical reasoning** =
data → information →
knowledge →
solution, decision, …





- Visual Analytics of Movement

1. **Introduction**
2. **Conceptual framework**
3. **Transformations of movement data**
4. **Visual analytics infrastructure**
5. **Visual analytics focusing on movers**
6. **Visual analytics focusing on spatial events**
7. **Visual analytics focusing on space**
8. **Visual analytics focusing on time**
9. **Discussion and outlook**



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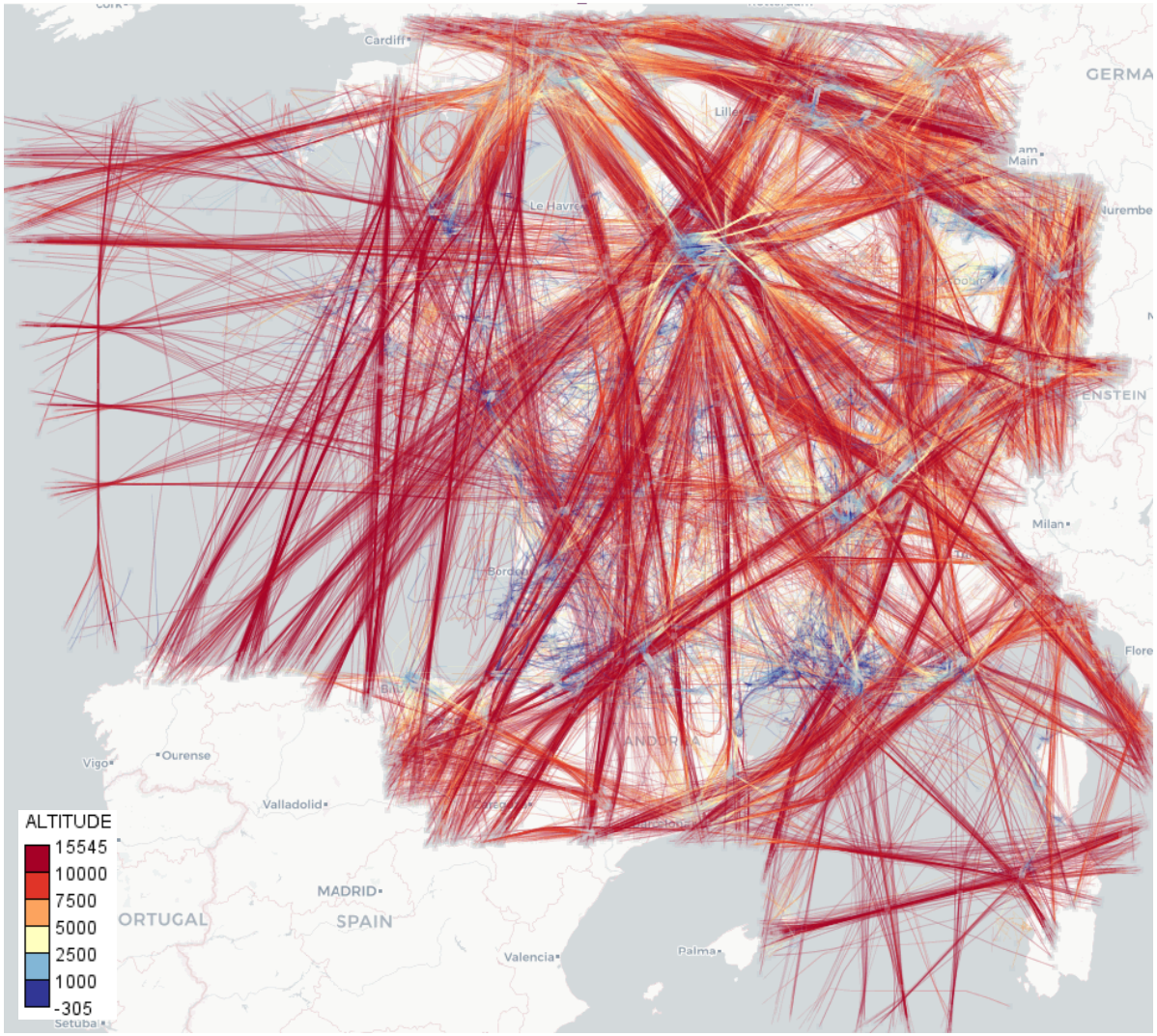
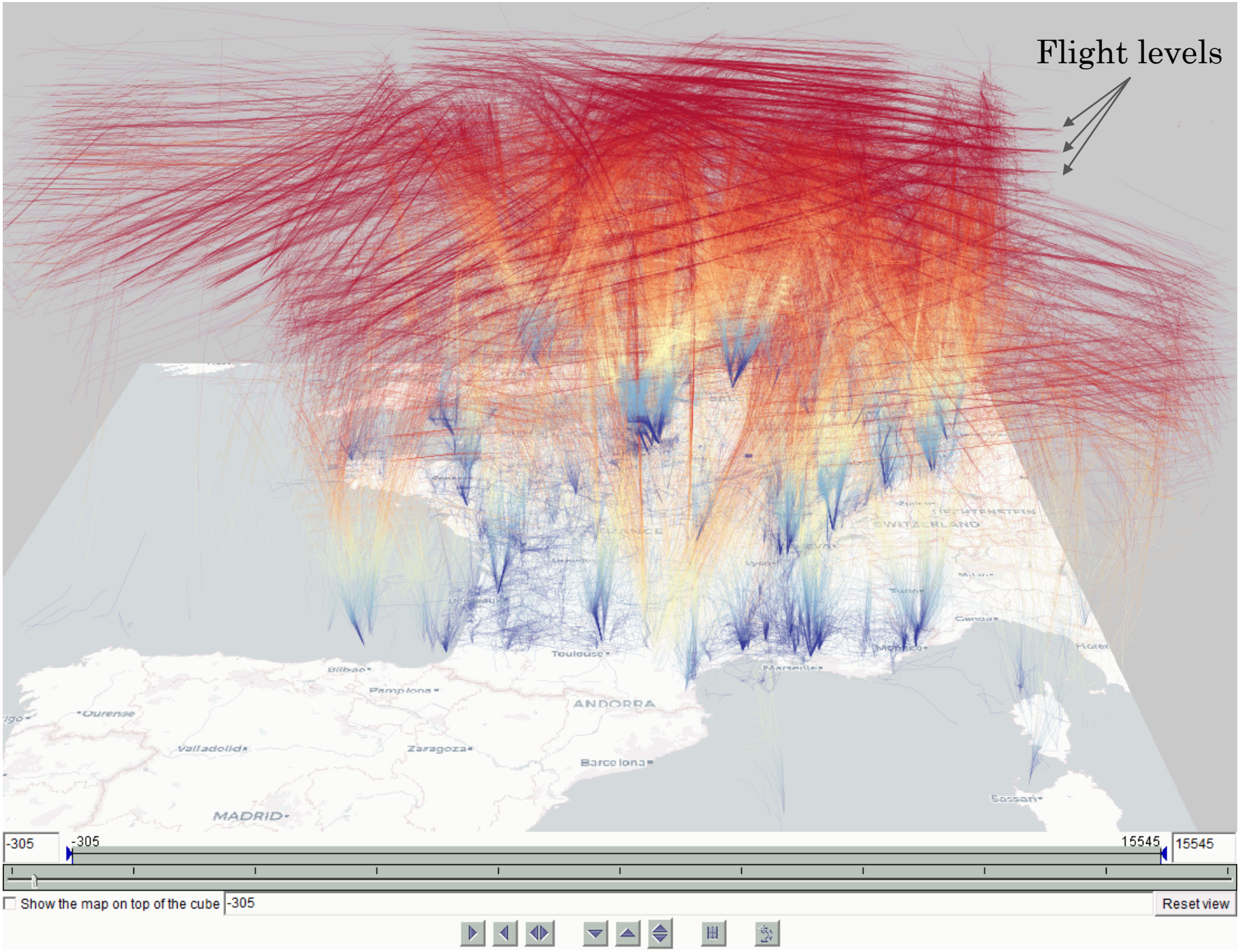
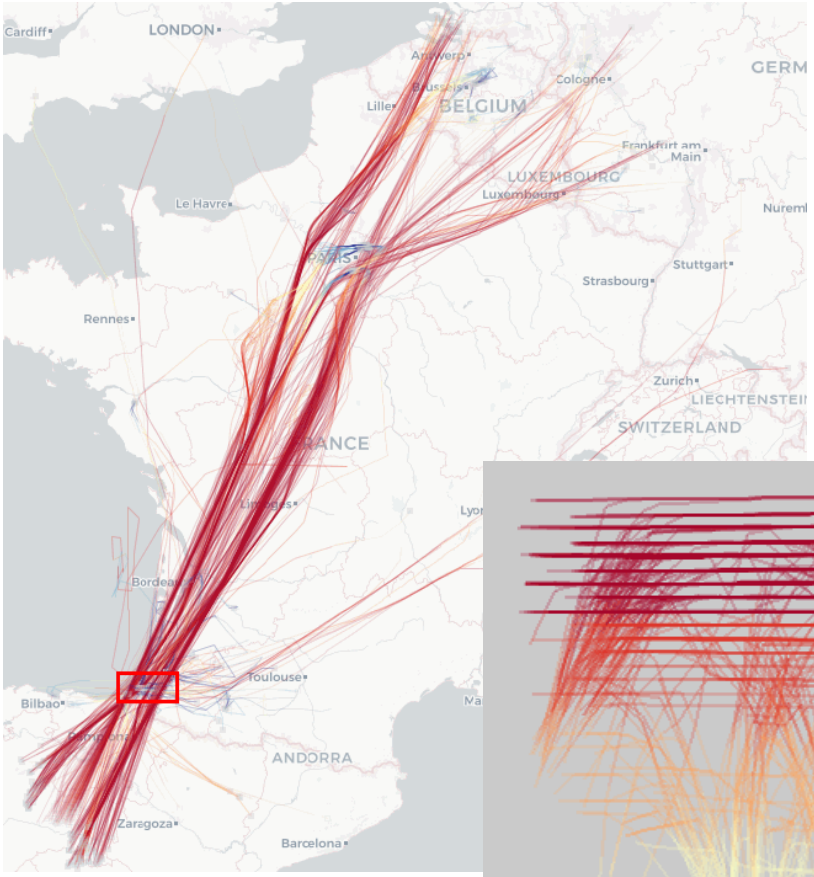
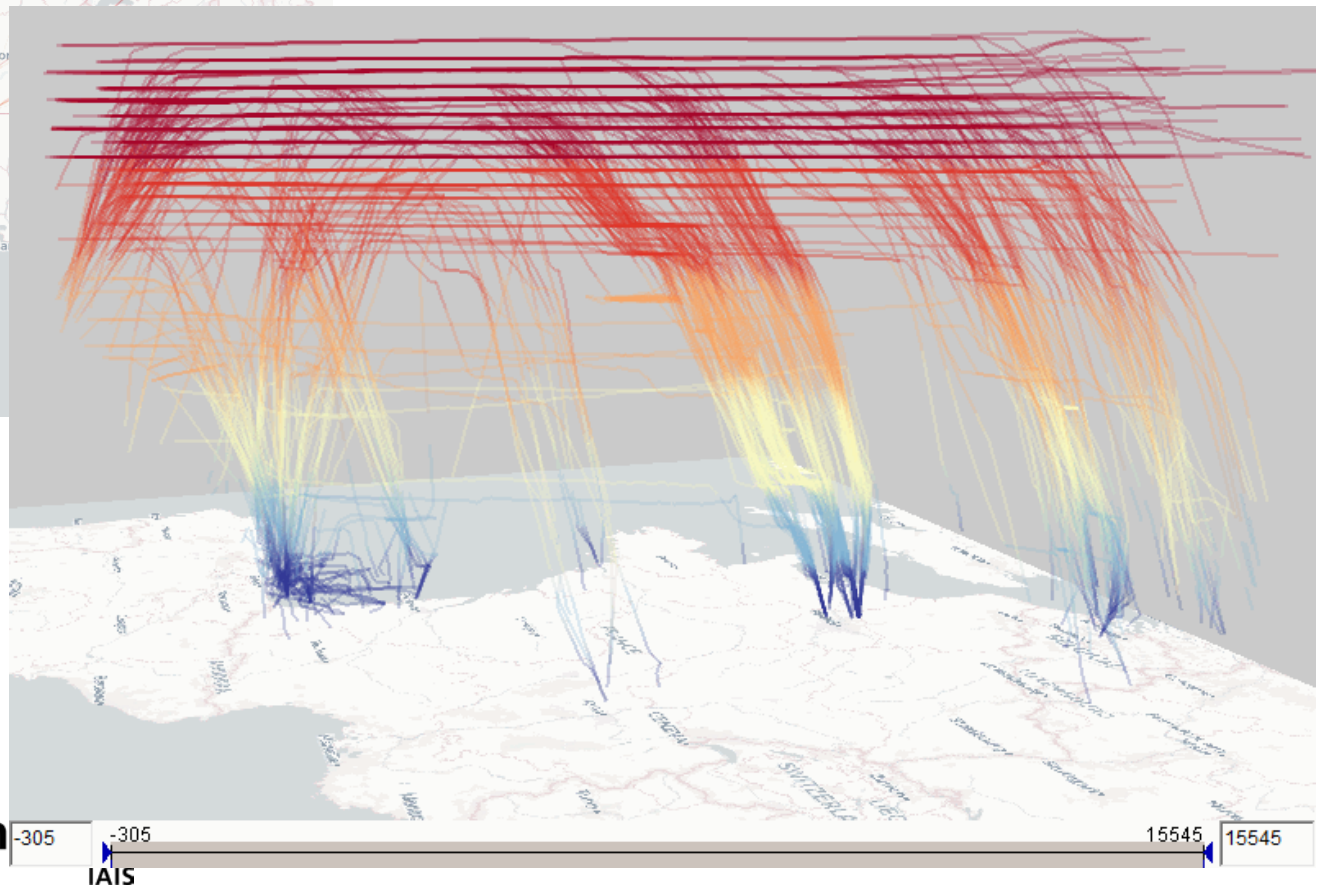
Aircraft trajectories … include altitudes!




Flight levels
-305
-305
15545
15545
Show the map on top of the cube
-305
Reset view
Toulouse
Bilbao
Pamplona
ANDORRA
Ourense
Valladolid
Zaragoza
Barcelona
MADRID
Marseille
Sassari
SWITZERLAND





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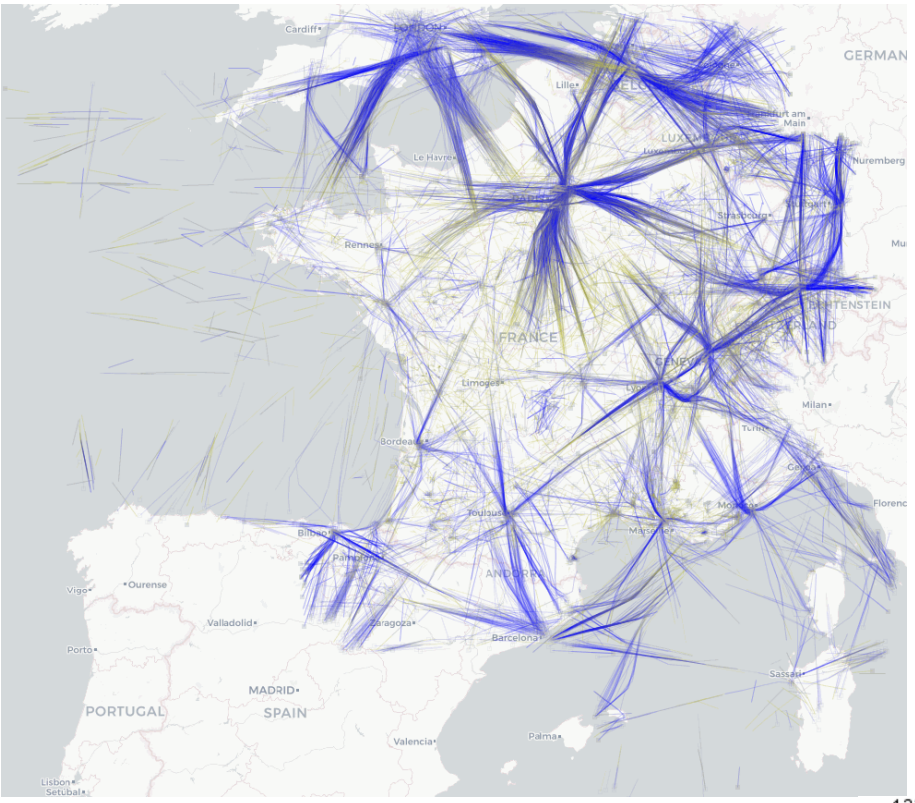
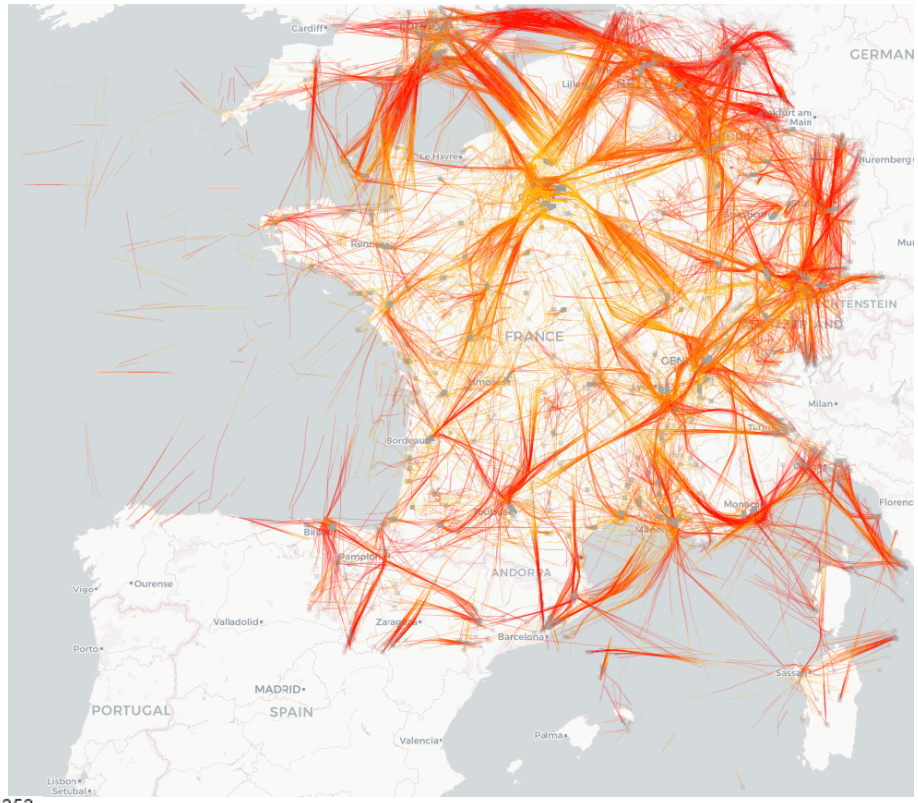
IAIS

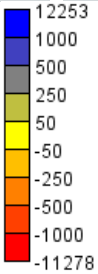
Altitude changes

Up



Down





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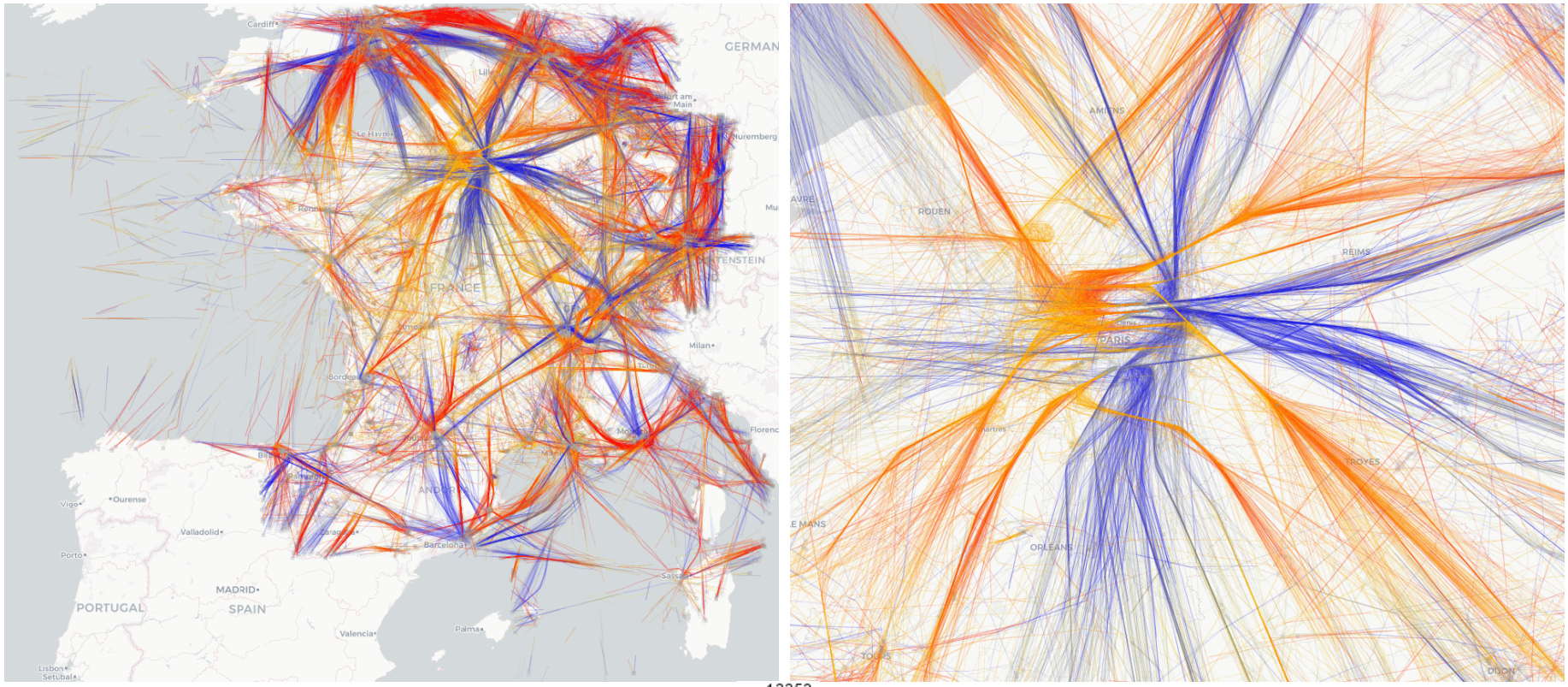
Up and down together



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Why Visual Analytics?

What we got from visuals:

- Data is complex: 3D space + time
- Space is continuous
- Space is often discrete
  - Flight levels
  - Flight routes
- Flights have different stages (semantics)
- Data is not perfect

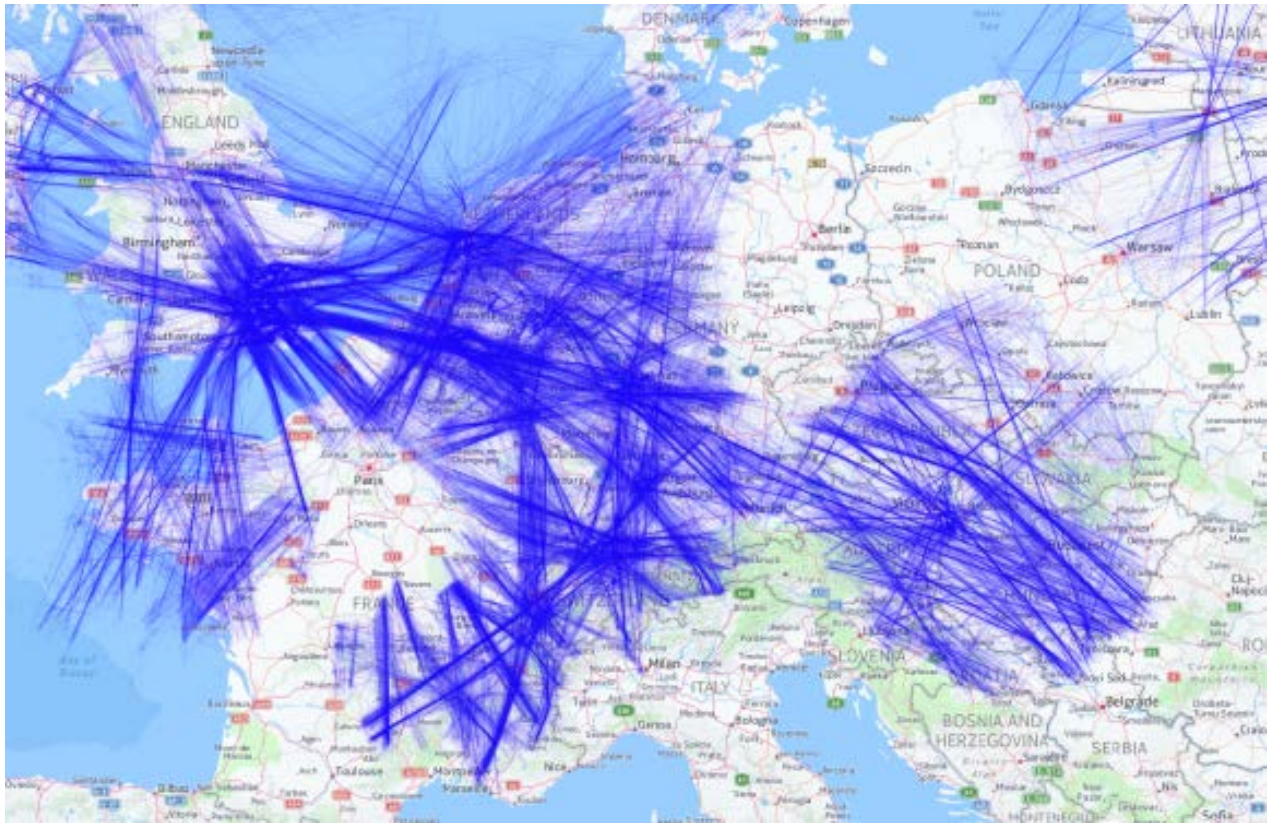
Before analysis starts:

- Identifying { & fixing } data problems
- Key ideas:
  1. Consider the data structure
  2. Support data transformations
  3. Take into account different types of problems: missing data, inconsistent sampling rates, precision errors, occasional and systematic errors in the data.

Gennady Andrienko, Natalia Andrienko, Georg Fuchs
Understanding Movement Data Quality
Journal of Location Based Services, 2016, vol. **10**(1), pp.31-46
http://dx.doi.org/10.1080/17489725.2016.1169322

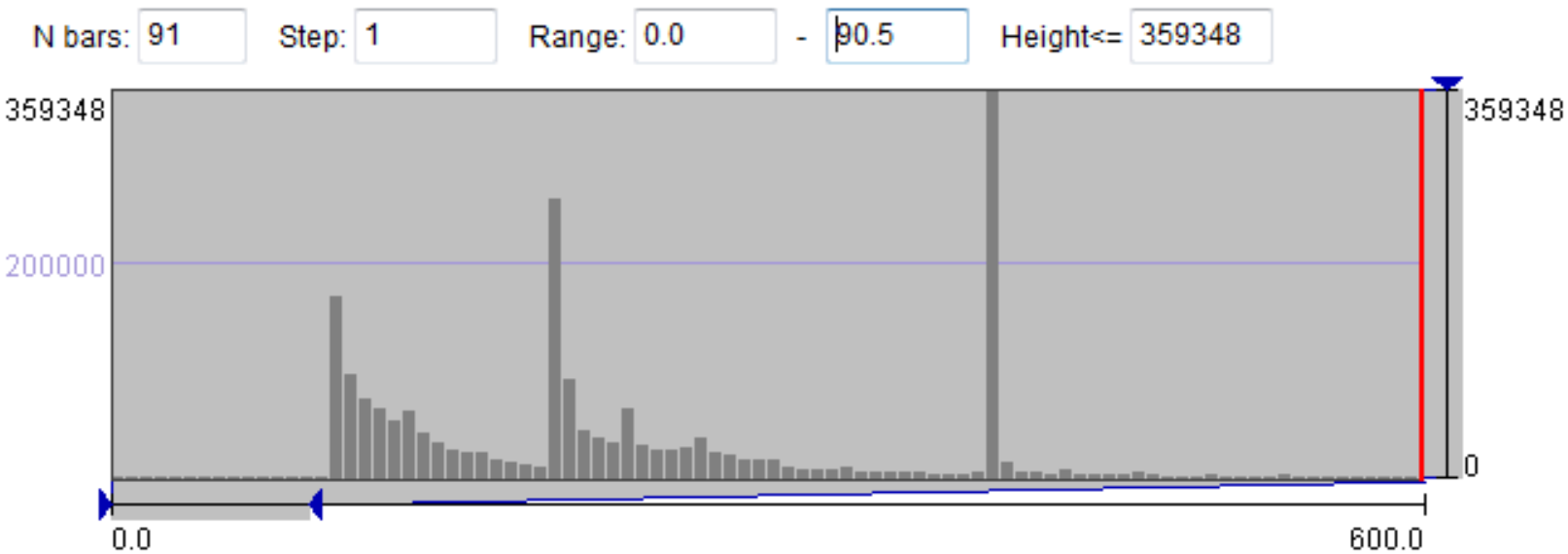
Identifying data problems

- Spatial coverage



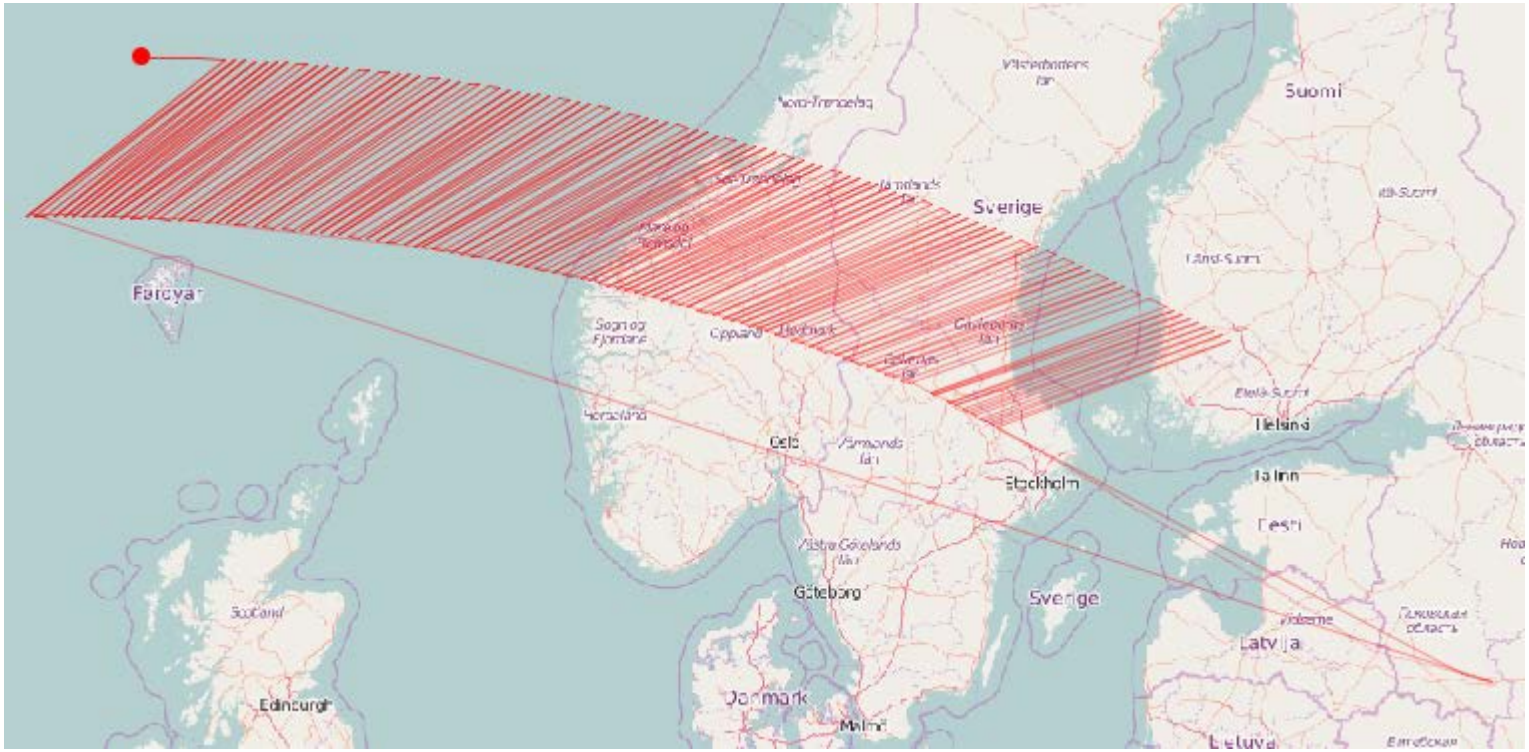
Identifying data problems

- Varying temporal resolution



Identifying data problems

- Duplicate IDs

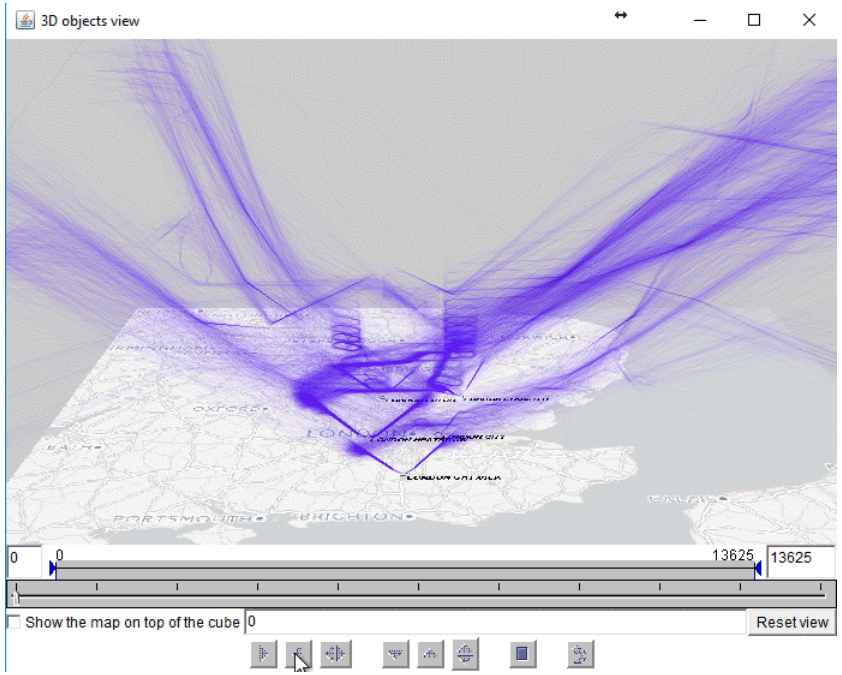


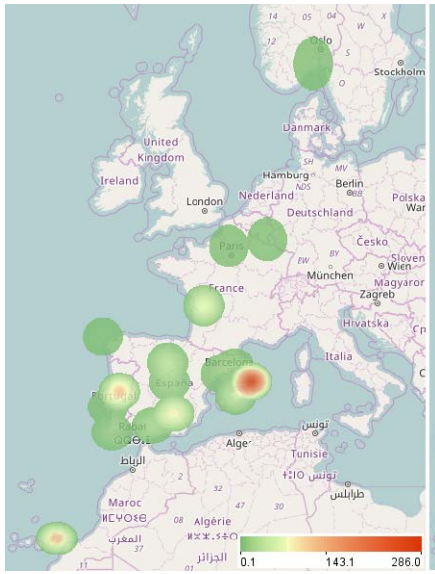
Understanding decision making of As

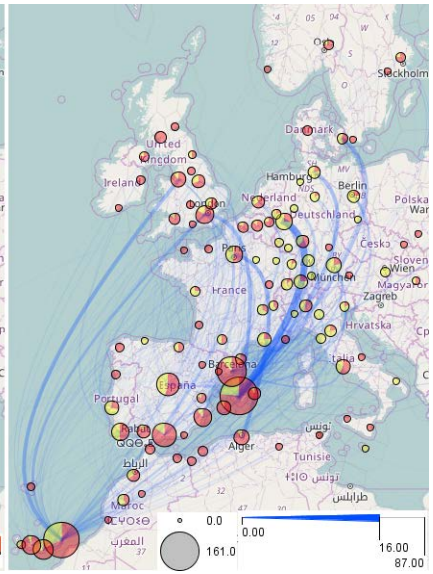
- Aircraft trajectories …

What else?

- Airports, departures, and arrivals
  - Impact of the environment
  - Impact on the environment
- Route choices
  - Criteria?
  - Deviations from the chosen routes
- Flight management
  - Airspace configurations
  - Flight regulations and delays



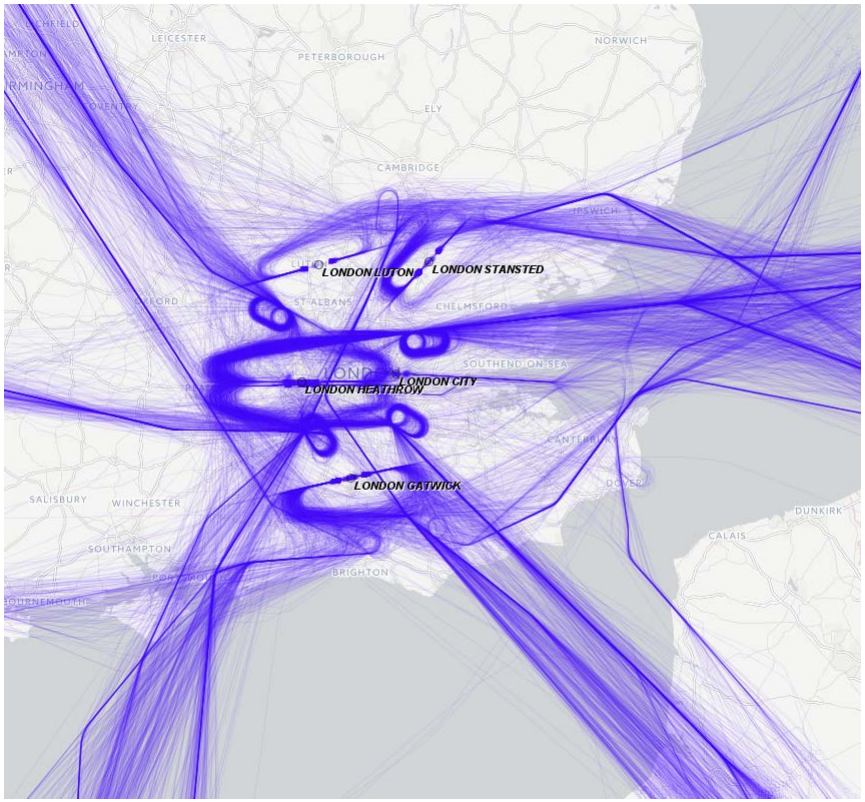


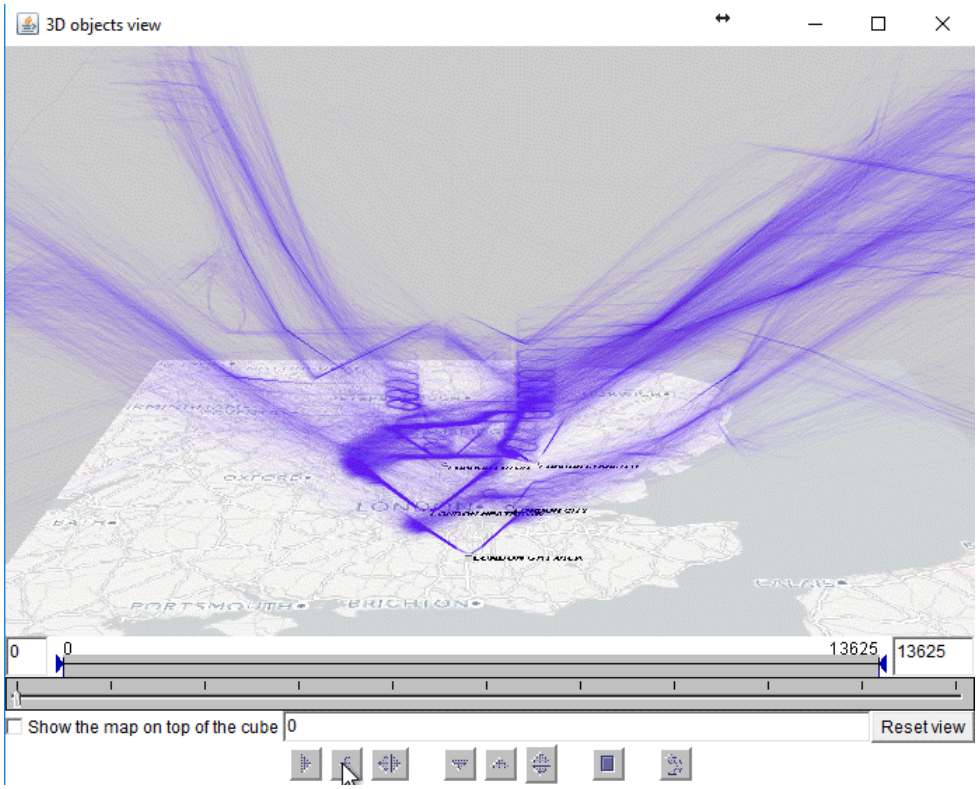


Airports, departures, and arrivals

- Impact of the environment: wind
- Impact on the environment: noise

Task: Extract the airport approach routes and observe the wind impact





Gennady Andrienko, Natalia Andrienko, Georg Fuchs, Jose Manuel Cordero Garcia

Clustering Trajectories by Relevant Parts for Air Traffic Analysis

IEEE Transactions on Visualization and Computer Graphics (proceedings IEEE VAST 2017), 2018, vol. **24**(1): 34-44

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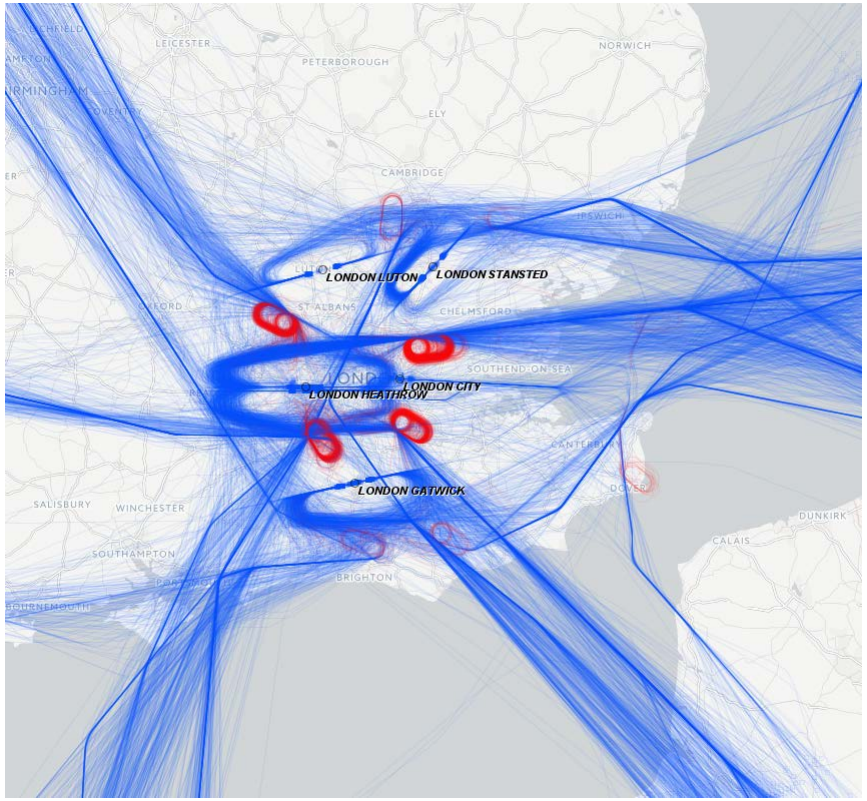
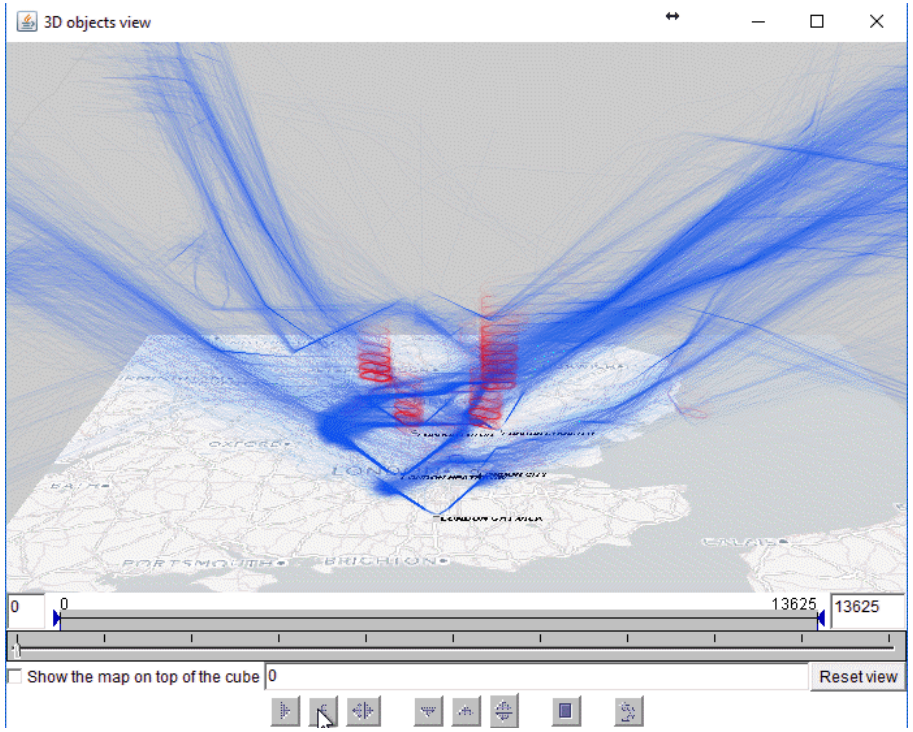
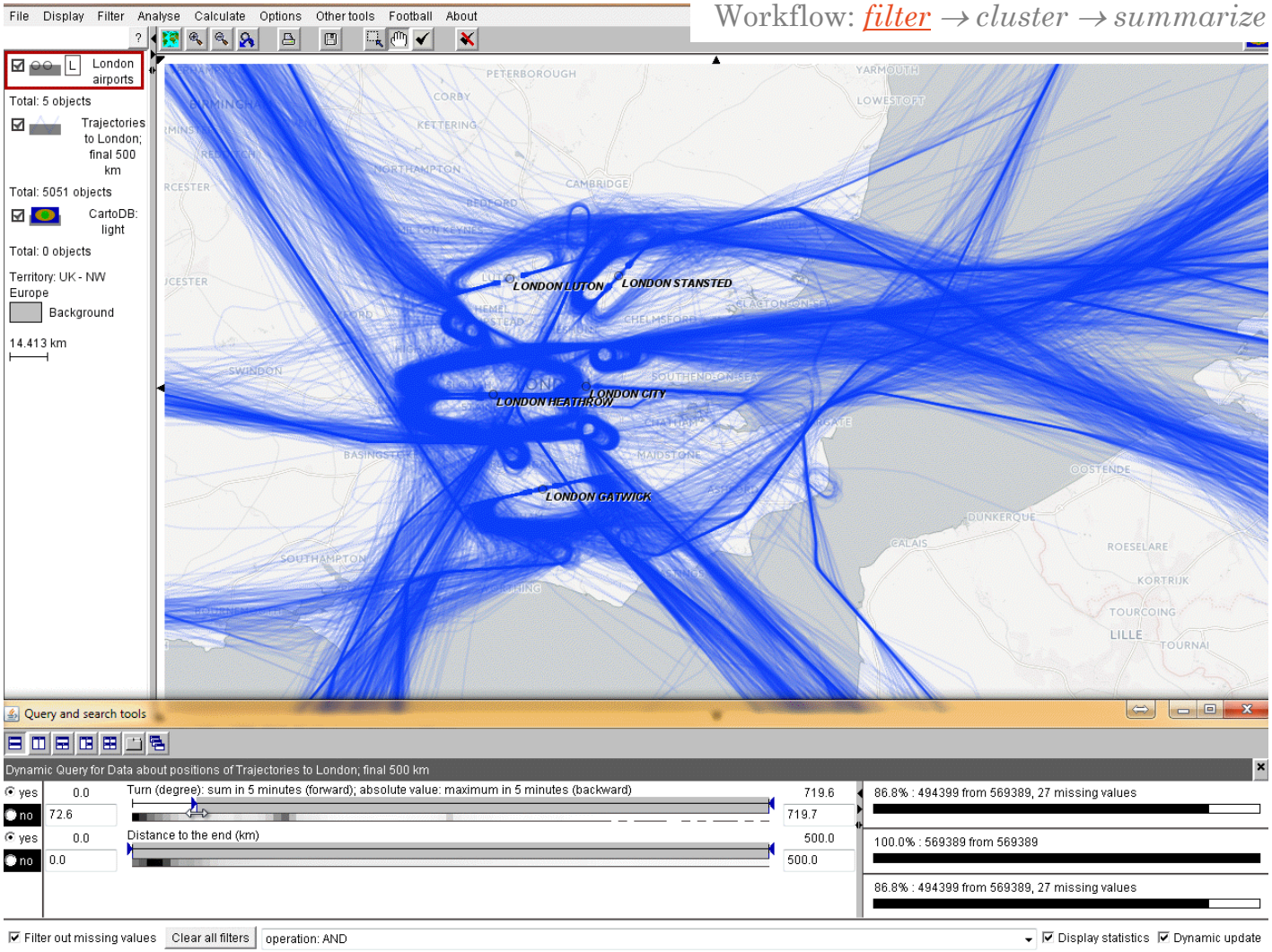
The holding loops are <u>not</u> essential parts of the approach routes





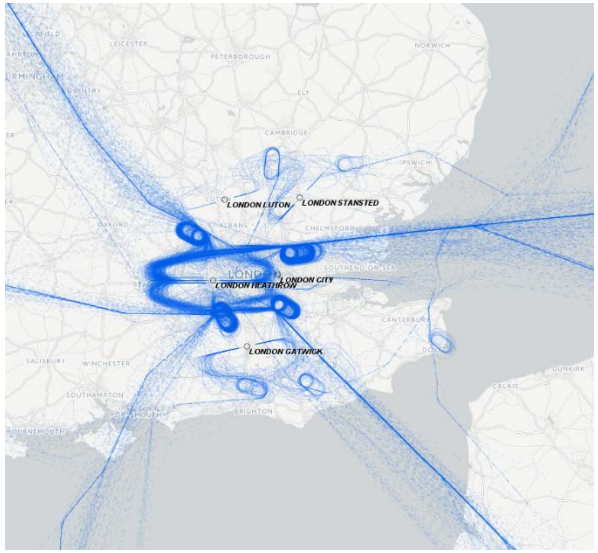
Interactive filtering

Workflow: *filter* → *cluster* → *summarize* → *analyse*

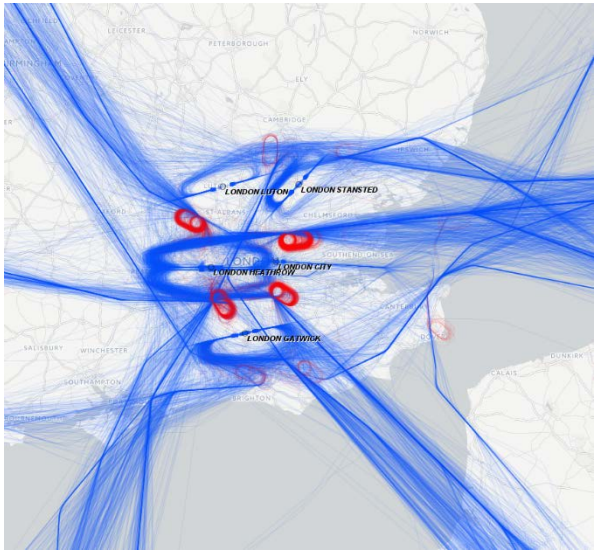


Visual support to interactive filtering

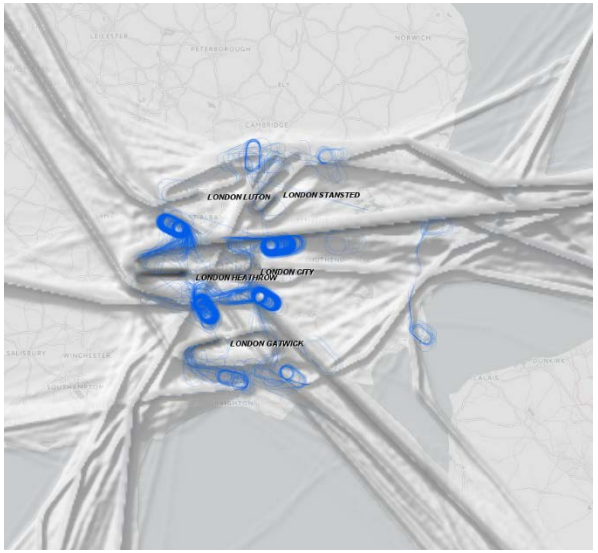
Workflow: *filter* → *cluster* → *summarize* → *analyse*



Filter-aware rendering



Filtering →
Boolean attribute →
visual encoding

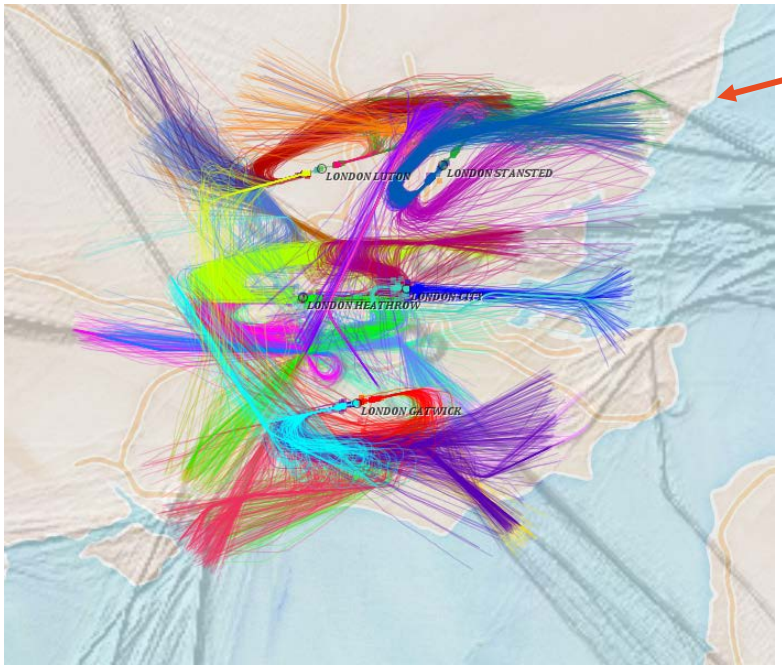


Different level of detail
for active and inactive
parts

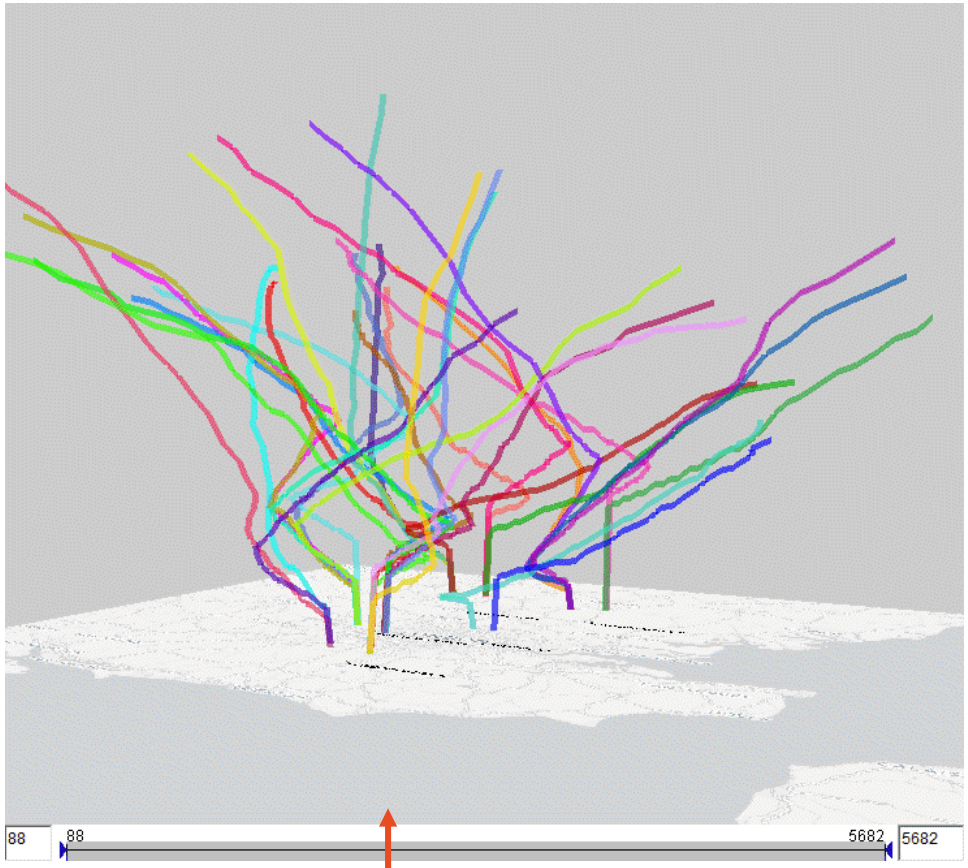
Clustering by relevant parts

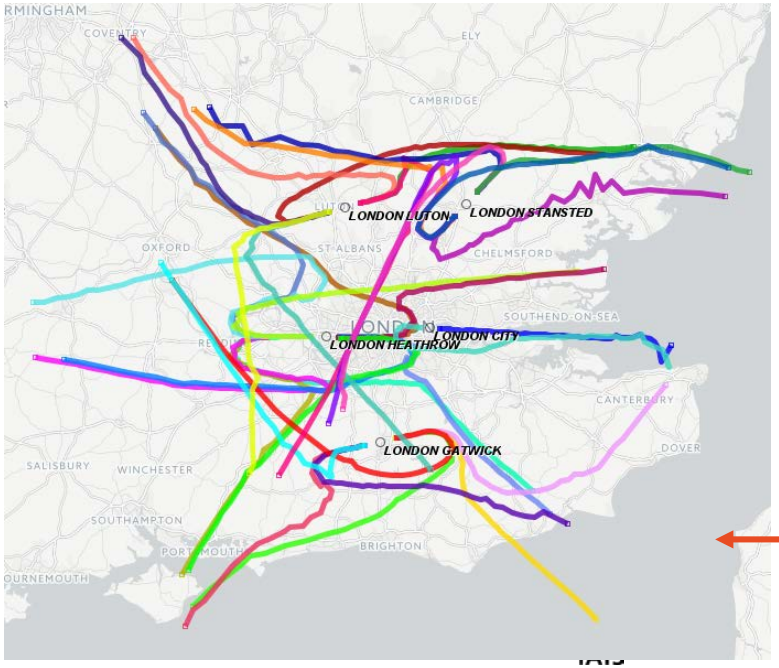
Workflow: *filter* → *cluster* → *summarize* → *analyse*

- Clustering engine is separated from similarity assessment
  - Allows the use of different distance functions (implemented externally)
- Implementation of a distance function (e.g., 'route similarity')
  - Inputs:
    - Two trajectories to compare
    - Relevance masks of the trajectories (specify which segments are active)
  - Compares only the active segments of the trajectories
- Progressive clustering
  - Application of clustering with different distance functions or parameter settings to different data subsets
    - Particularly, subsets may be defined by previous clustering runs
    - Useful when clustering of the whole set produces clusters of differing quality
      - "Bad" clusters (with high internal variation) can be refined through further clustering and good clusters can be preserved



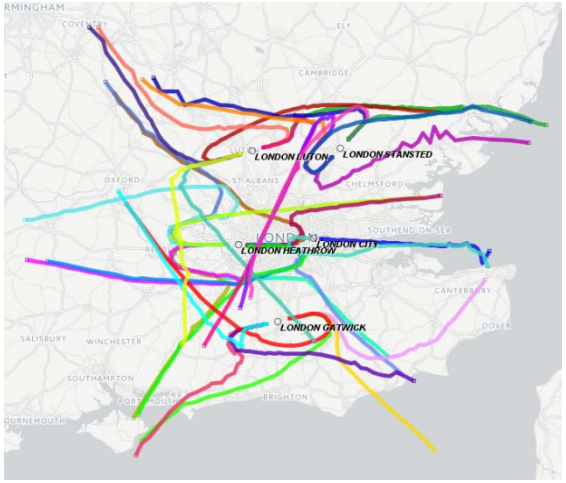
Resulting clusters by approach routes (loops disregarded)

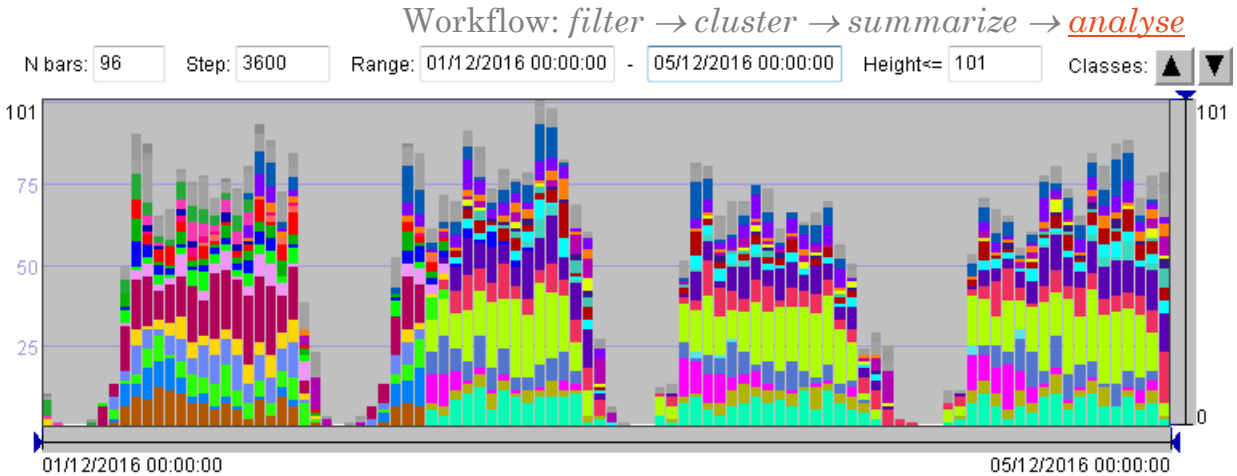


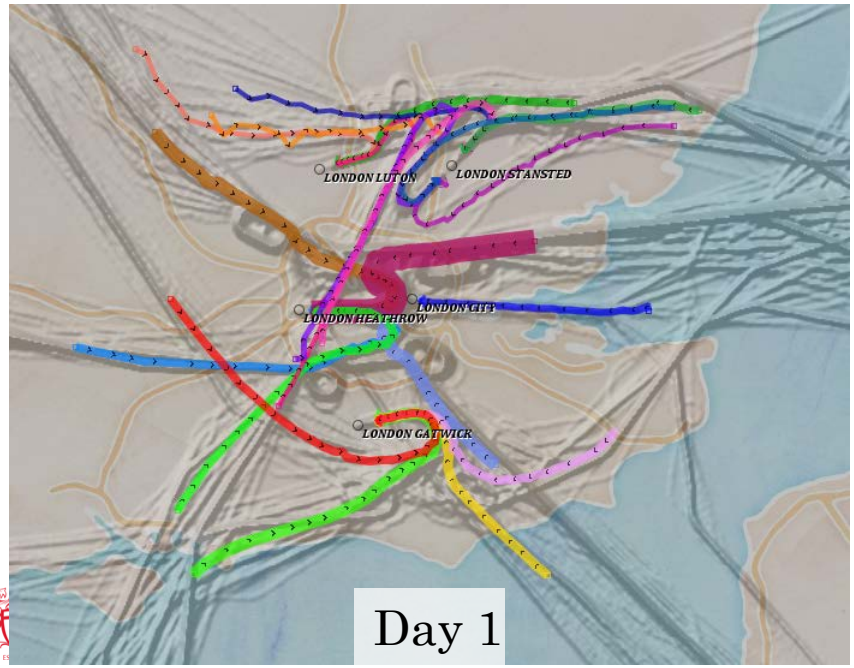


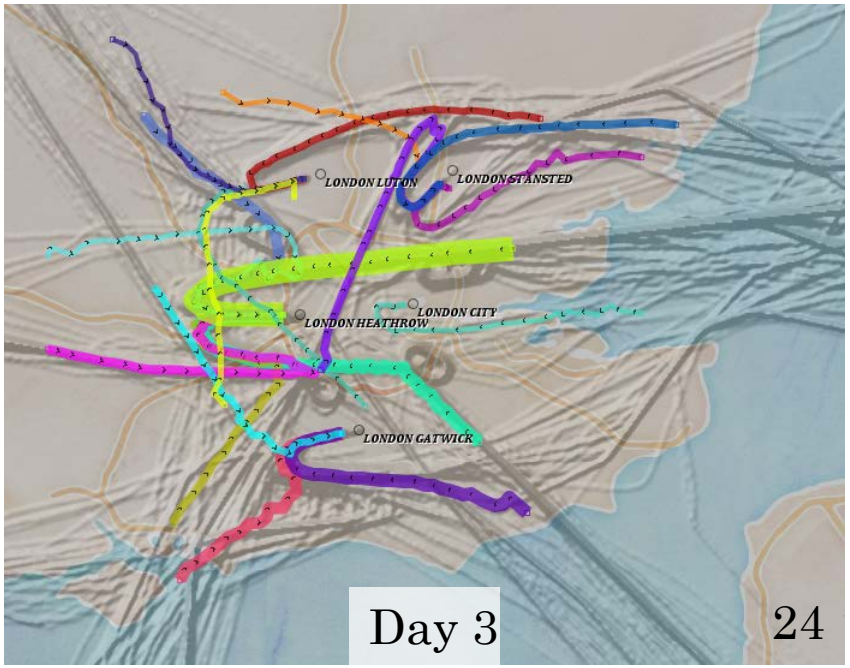
Central trajectories of the clusters represent the routes.

Use of the routes over time



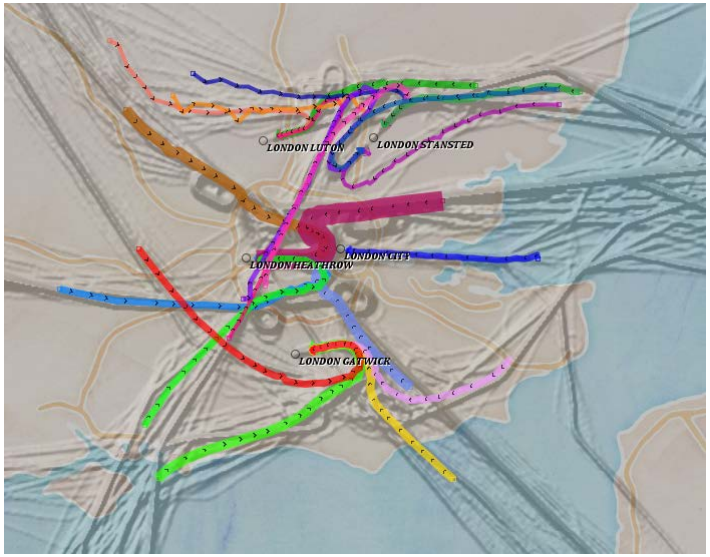


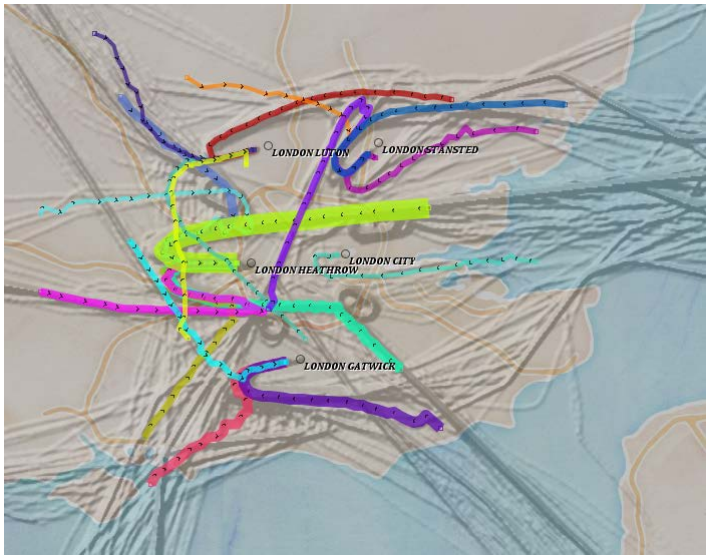


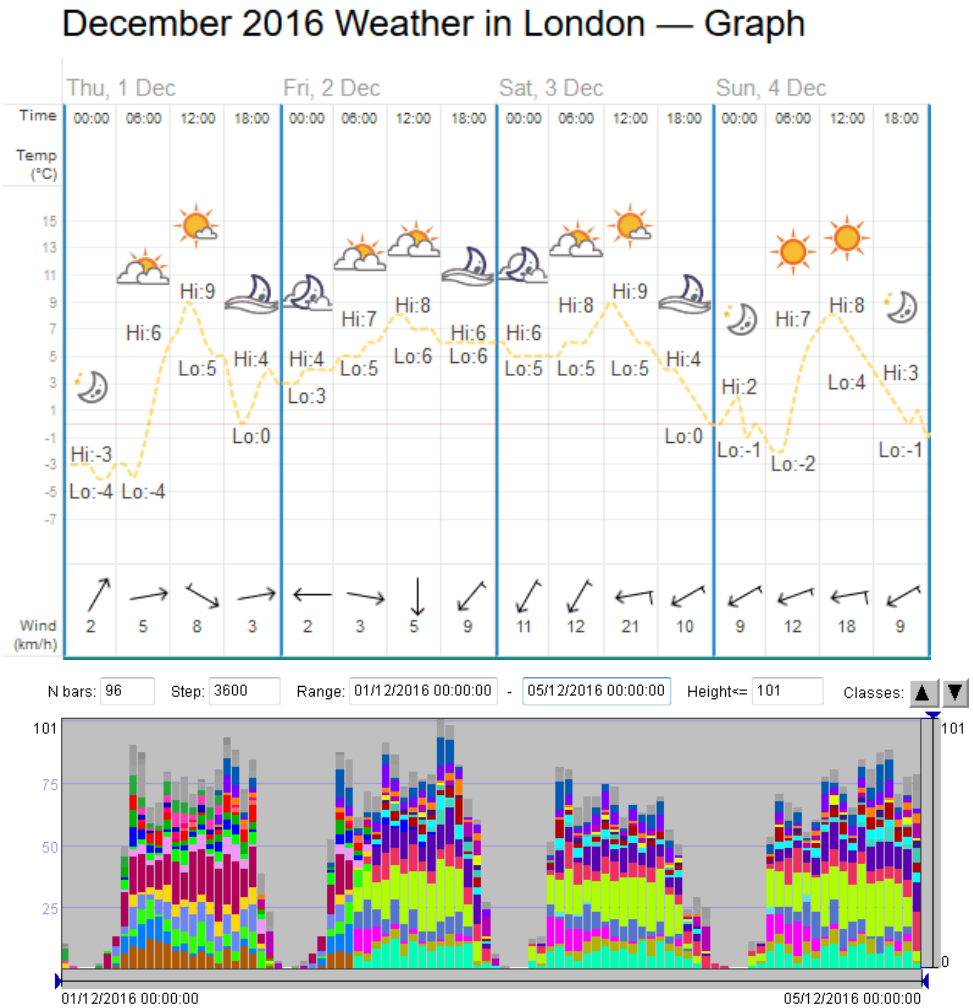


Understanding the wind impact

Workflow: *filter* → *cluster* → *summarize* → *analyse*

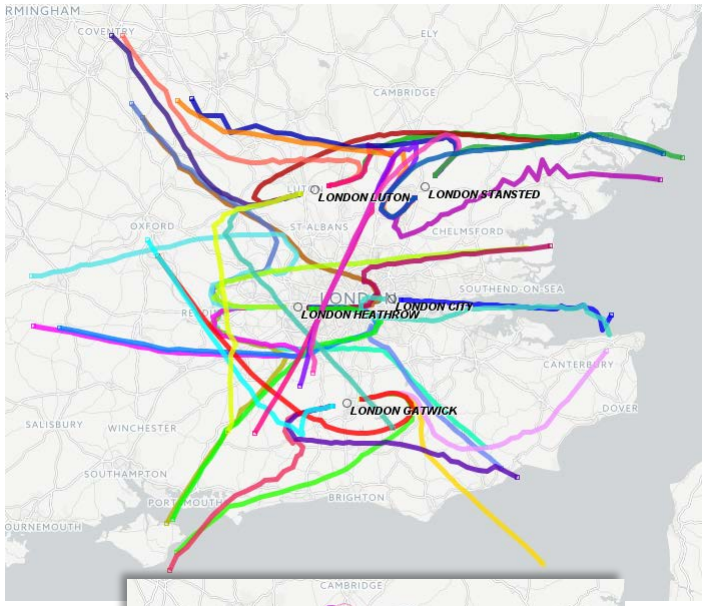


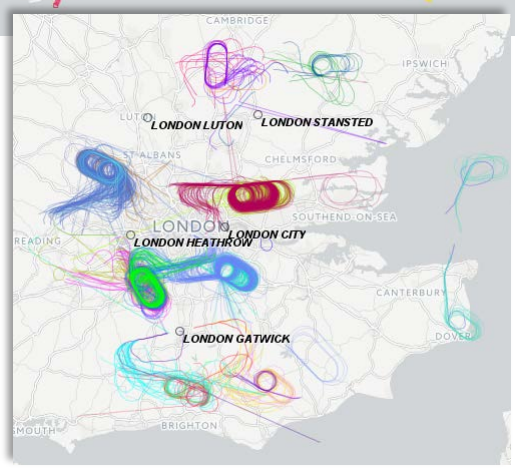




Loop statistics by the routes

Workflow: *filter* → *cluster* → *summarize* → *analyse*





	N members	N trajectories with loops	% trajectories with loops	Loop duration (minutes), sum	Loop duration (minutes), mean	Loop duration (minutes), std.dev.	Loop duration (minutes), min	Loop duration (minutes), q1	Loop duration (minutes), median	Loop duration (minutes), q3	Loop duration (minutes), max
2/2	99										
29/1	36										
27/1	36										
26/1	11										
25/1	32										
6/1	258	184	71.3	1892.10	10.283	4.4243	2.02	7.03	8.78	12.72	29.15
3/1	152	91	59.9	784.30	8.619	3.7594	2.68	5.82	8.27	11.02	19.95
2/1	137	80	58.4	644.92	8.061	3.4982	2.78	5.33	7.14	10.80	17.67
17/1	59	34	57.6	336.40	9.894	4.0622	3.15	7.04	9.22	12.64	17.18
5/1	89	50	56.2	402.63	8.053	3.6846	3.17	6.00	6.75	10.83	17.90
1/1	342	177	51.8	1340.78	7.575	4.1491	1.78	4.25	6.37	9.97	19.25
12/1	141	71	50.4	764.42	10.766	4.8091	4.77	7.55	9.28	12.87	25.67
8/1	746	374	50.1	2534.43	6.777	3.6097	2.52	3.86	4.97	9.34	19.07
28/1	12	6	50.0	42.42	7.069	2.7334	4.58	4.73	5.63	10.85	10.97
7/1	10	5	50.0	46.17	9.233	2.2277	7.15	7.33	8.07	11.72	13.08
14/1	314	136	43.3	1247.33	9.172	4.5198	3.13	4.30	9.18	12.63	22.63
19/1	35	15	42.9	132.80	8.853	2.3794	4.92	7.13	8.20	12.00	13.02
4/1	164	60	36.6	510.07	8.501	2.7680	2.95	6.55	8.71	10.25	19.32
22/1	113	23	20.4	128.00	5.565	1.9633	1.52	4.67	5.15	5.83	10.32
13/1	84	14	16.7	109.05	7.789	2.2688	4.90	6.38	7.16	8.08	13.07
15/1	75	8	10.7	74.67	9.333	2.4880	3.82	8.14	9.82	11.24	12.52
1/3	54	5	9.3	32.90	6.580	0.8281	5.28	5.77	6.57	7.40	7.78
5/2	179	16	8.9	110.05	6.878	0.8754	5.37	6.07	6.73	7.80	8.10
3/2	13	1	7.7	6.78	6.783	0.0000	6.78	6.78	6.78	6.78	6.78
10/1	123	7	5.7	52.02	7.431	2.1660	5.38	5.67	6.13	8.63	11.90
21/1	64	3	4.7	23.10	7.700	2.1741	4.70	4.70	8.62	9.78	9.78
18/1	69	3	4.3	17.48	5.828	1.8367	3.23	3.23	7.02	7.23	7.23
11/1	306	13	4.2	87.80	6.754	1.7163	4.23	5.02	6.75	8.47	9.60
2/3	201	8	4.0	41.38	5.173	0.8310	3.88	4.50	5.13	5.97	6.37
4/2	83	3	3.6	20.87	6.956	1.8968	4.47	4.47	7.33	9.07	9.07
20/1	62	2	3.2	12.78	6.392	0.1250	6.27	6.27	6.39	6.52	6.52
6/2	33	1	3.0	5.67	5.667	0.0000	5.67	5.67	5.67	5.67	5.67
16/1	363	9	2.5	45.70	5.078	1.1467	3.77	4.32	4.51	6.25	7.18
23/1	133	1	0.8	4.00	4.000	0.0000	4.00	4.00	4.00	4.00	4.00

group by classes Sort by: % trajectories with loops Descending TableLens condensed Attribute...

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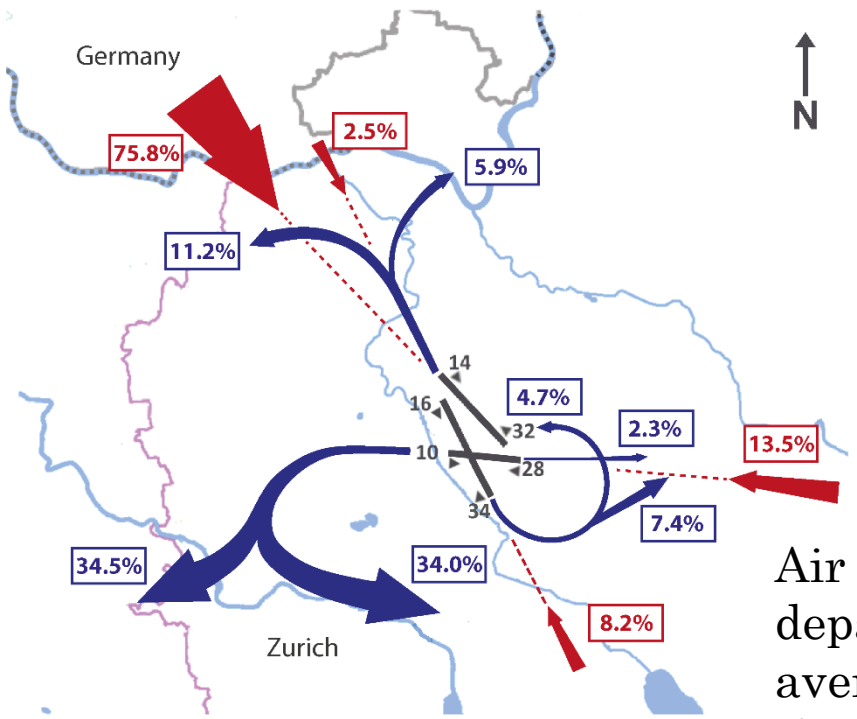
Task: explore the impact on the environment

J.Buchmuller, H.Janetzko, G.Andrienko, N.Andrienko, G.Fuchs, and D.A.Keim

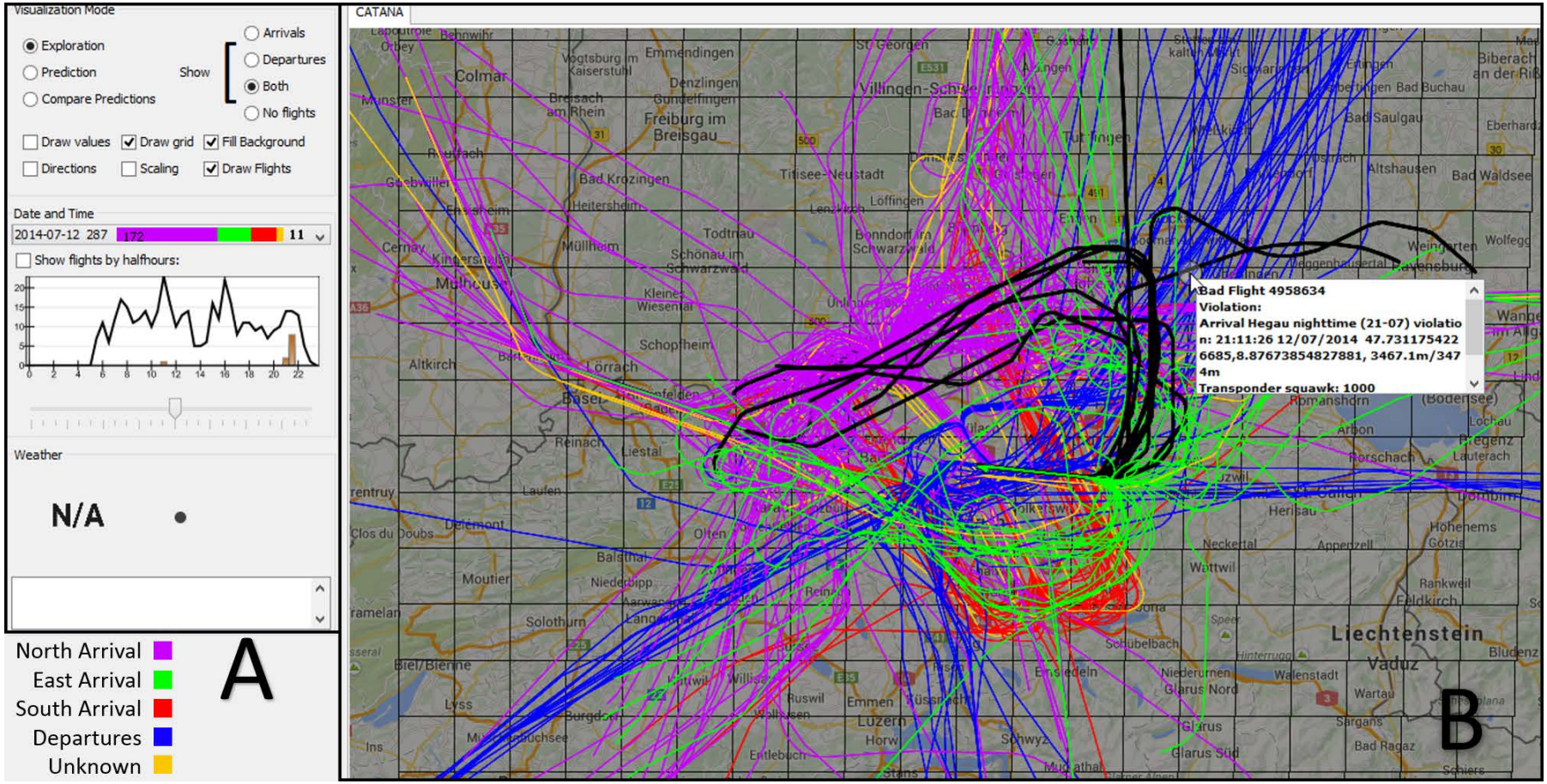
Visual Analytics for Exploring Local Impact of Air Traffic

Computer Graphics Forum (proceedings EuroVis 2015)
2015, **34**(3): 181-190



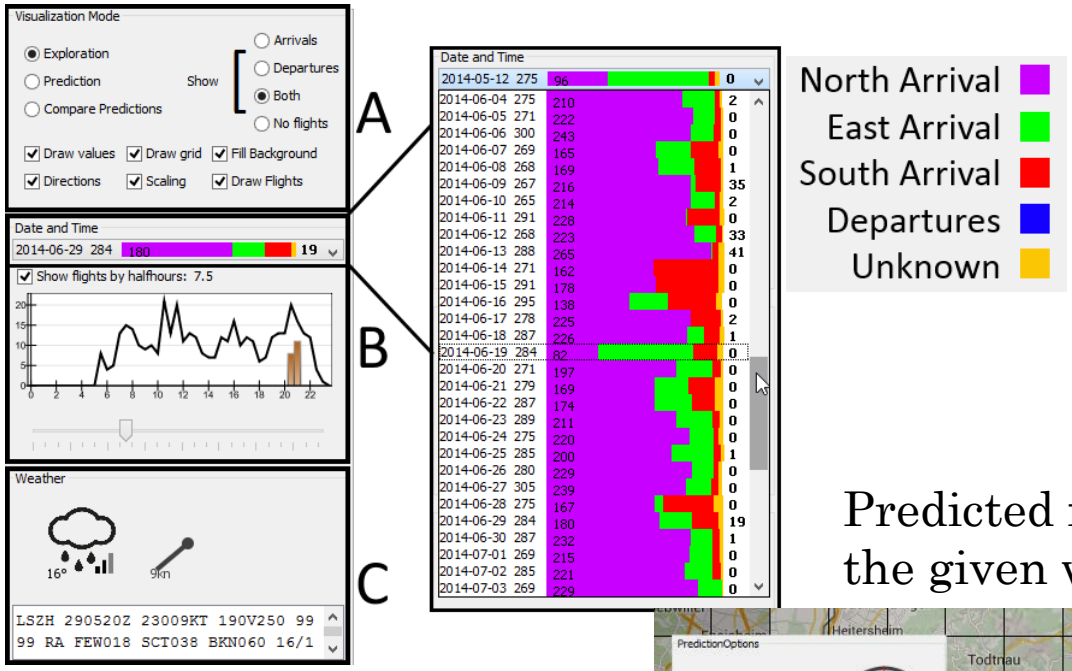
Air traffic routes for arrivals (red) and departures (blue) to Zurich airport and average distributions of flights amongst them. Note the Swiss-German border to the north.

Exploring the flights that violate rules

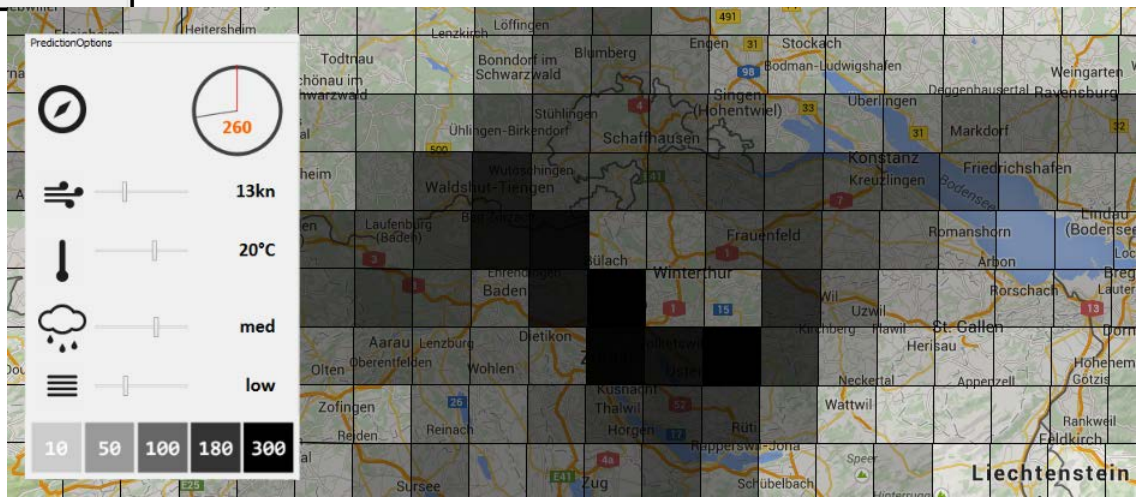


Part A denotes the management area. Part B contains a map view depicting all selected data and showing details on a flight violating a rule in a textbox-overlay. Black tracks denote flights that violate rules.

Exploration and predictive modelling



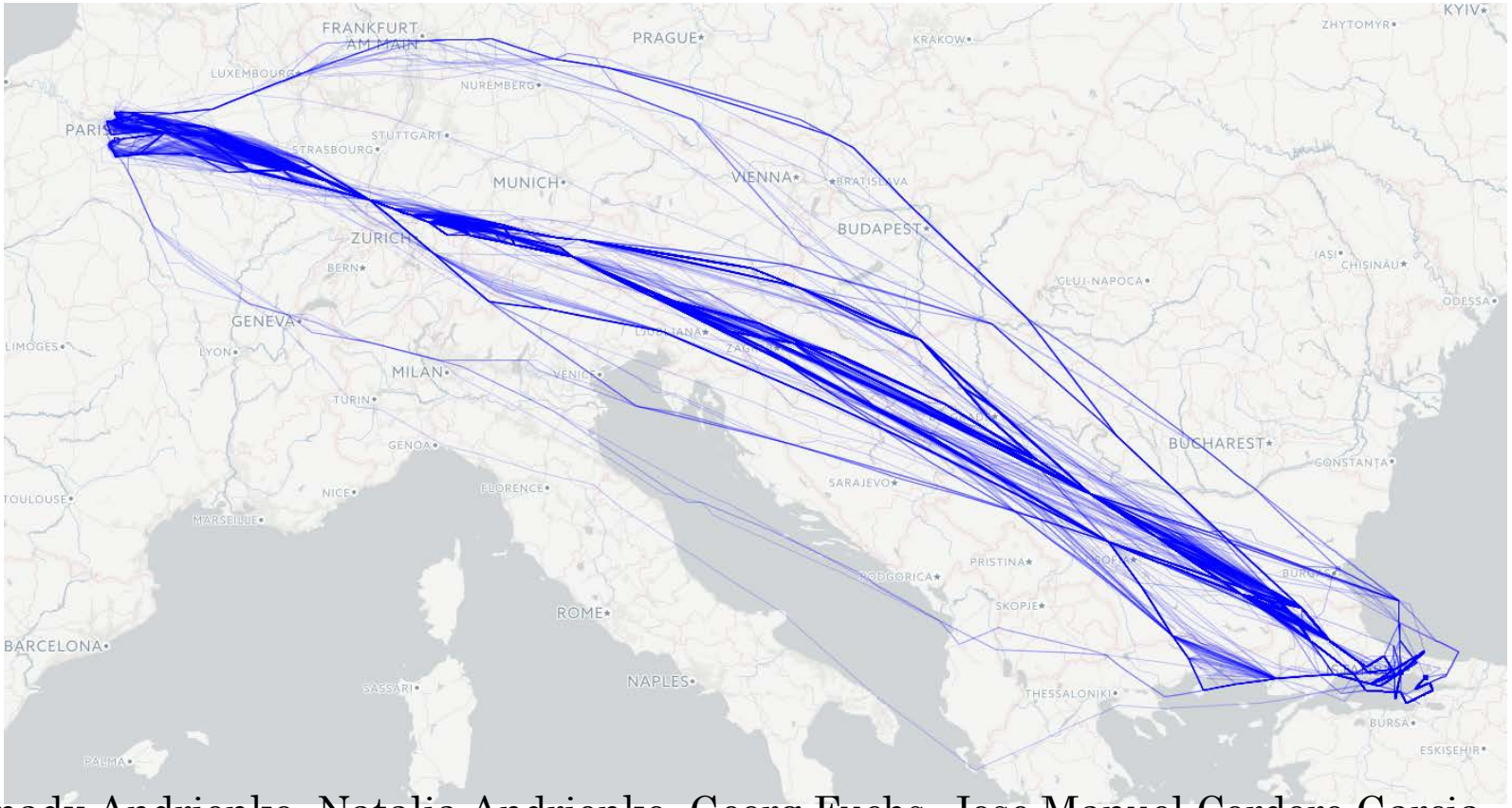
Predicted flight density distribution for the given weather conditions



Route choices

- Criteria?
- Deviations from the chosen routes

Task: Identify and compare the major flight routes from Paris to Istanbul



Gennady Andrienko, Natalia Andrienko, Georg Fuchs, Jose Manuel Cordero Garcia

Clustering Trajectories by Relevant Parts for Air Traffic Analysis

IEEE Transactions on Visualization and Computer Graphics (proceedings IEEE VAST 2017), 2018, vol. **24**(1): 34-44

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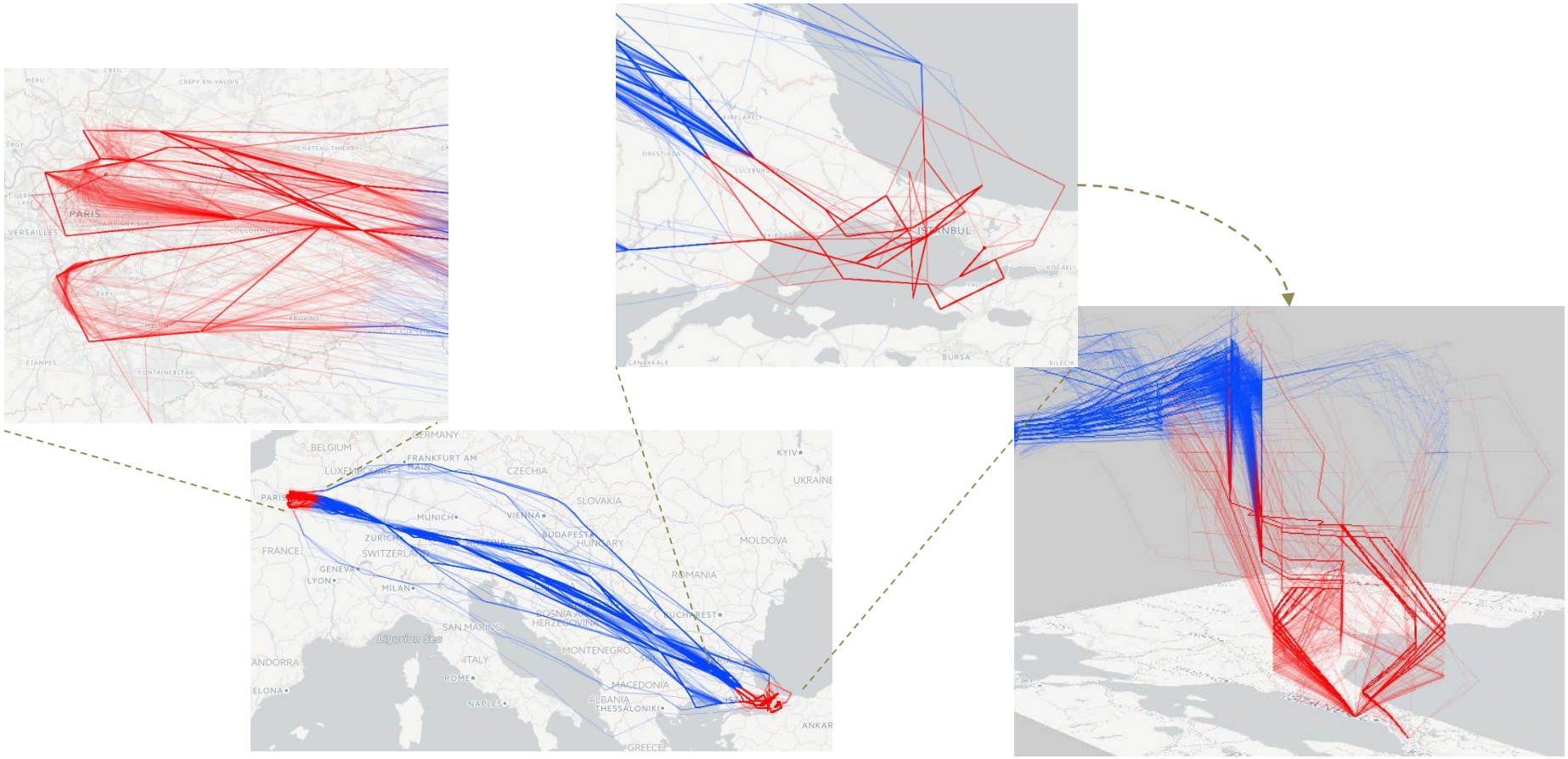
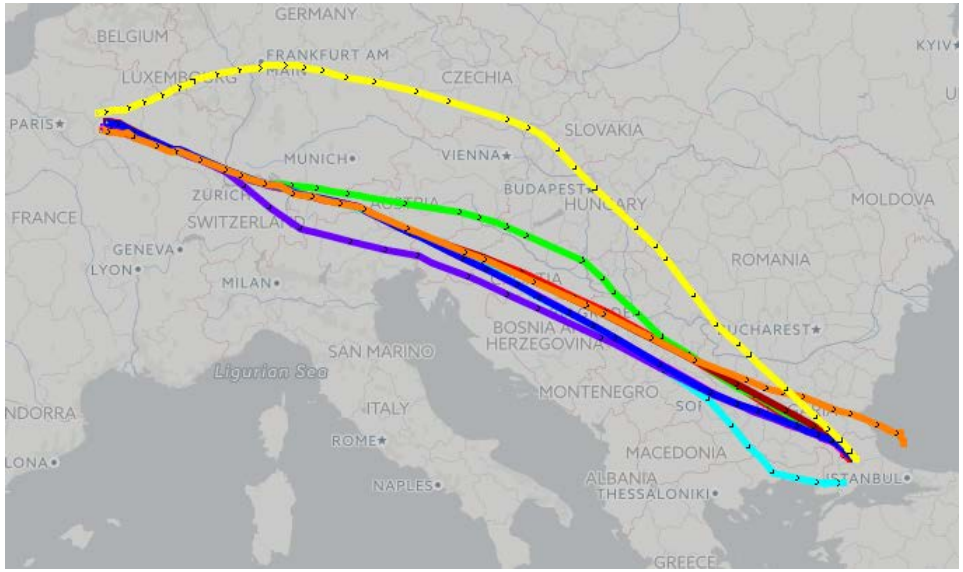
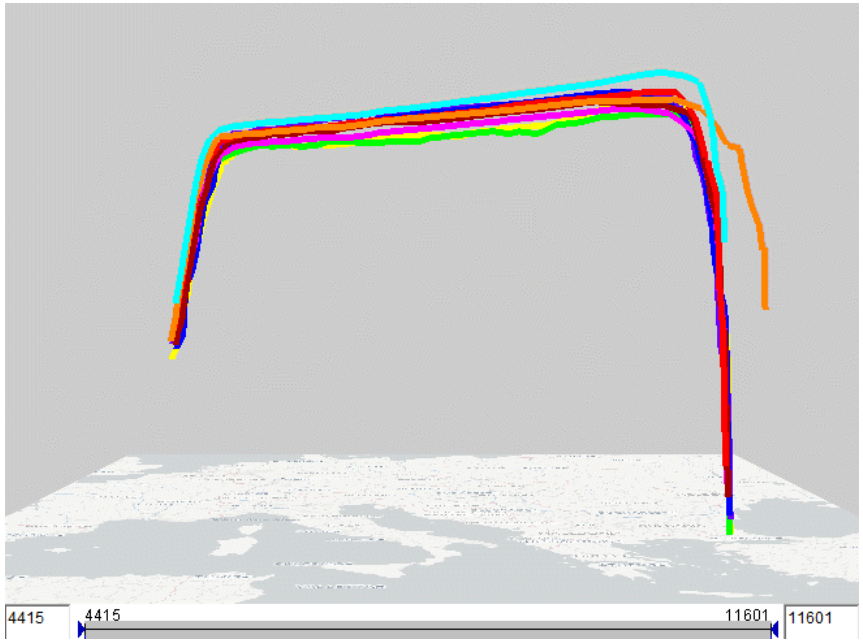
The movements around the airports are <u>not</u> parts of the routes



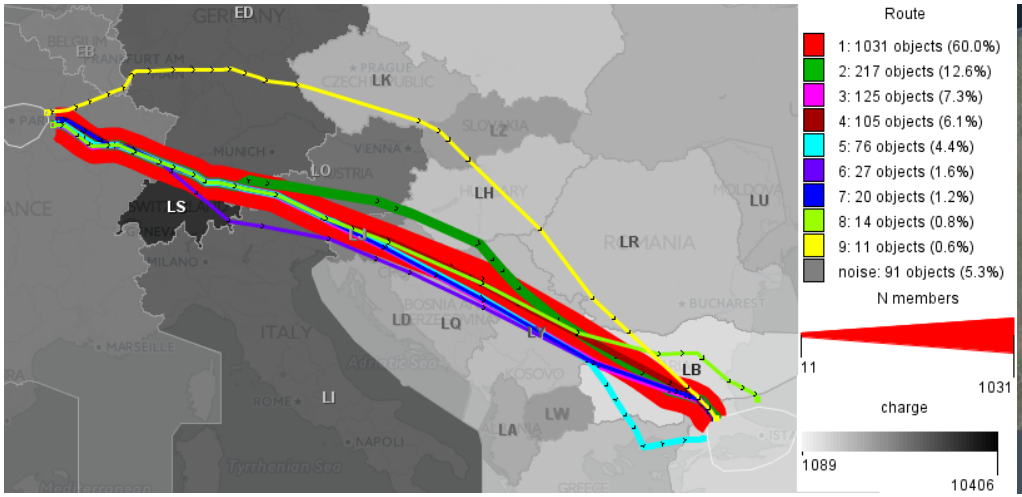
Routes extracted using the relevance-aware clustering of trajectories

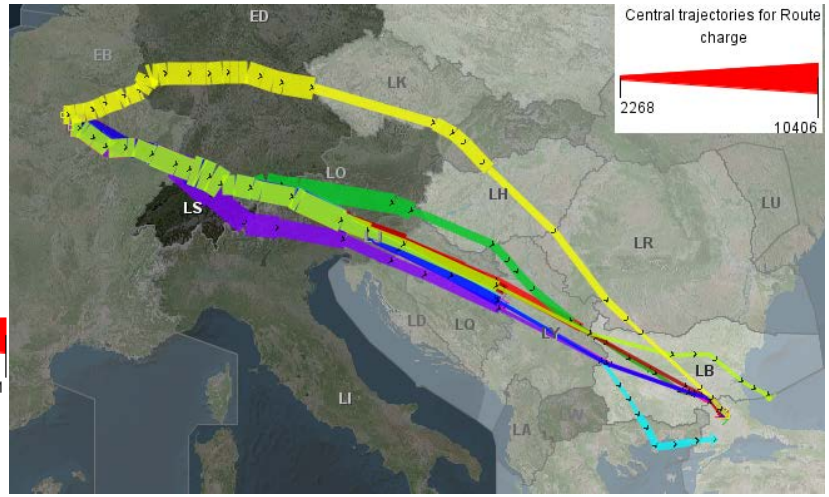




The routes are represented by the central trajectories of the clusters.

Route popularity and navigation charges





	N members	charges, min	charges, q1	charges, mean	charges, median	charges, q3	charges, max
2	217	434.9	457.8	459.10	459.4	460.2	492.8
4	105	486.4	508.1	512.67	513.8	517.0	528.2
8	14	476.6	512.4	511.43	515.5	517.2	517.5
1	1031	472.2	512.8	514.36	515.6	517.8	547.3
3	125	500.6	519.2	521.45	521.8	523.2	536.5
7	20	519.9	521.3	522.90	522.2	523.0	535.9
5	76	509.7	533.7	539.24	540.3	542.7	573.1
noise	91	454.2	510.0	565.12	544.6	650.0	745.8
9	11	609.3	609.4	610.60	609.6	612.5	614.2
6	27	646.6	654.2	655.47	655.7	656.4	660.3

group by classes Sort by: charges, median Ascending TableLens condensed Attribute...

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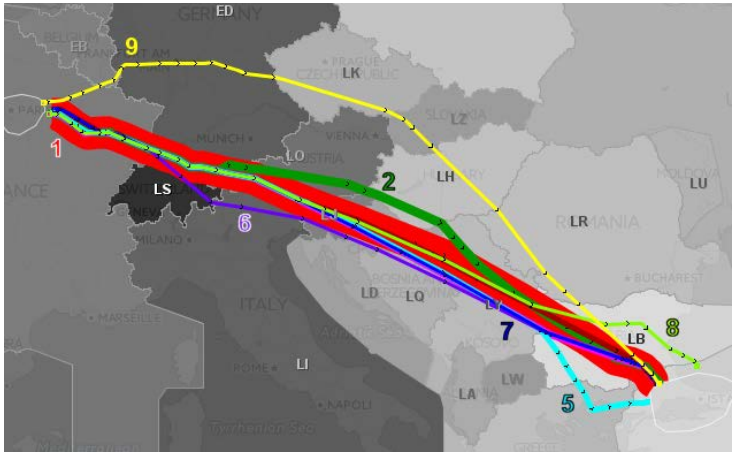
Route statistics



	N members	charges, min	charges, q1	charges, mean	charges, median	charges, q3	charges, max
2	217	434.9	457.8	459.10	459.4	460.2	492.8
4	105	486.4	508.1	512.67	513.8	517.0	528.2
8	14	476.6	512.4	511.43	515.5	517.2	517.5
1	1031	472.2	512.8	514.36	515.6	517.8	547.3
3	125	500.6	519.2	521.45	521.8	523.2	536.5
7	20	519.9	521.3	522.90	522.2	523.0	535.9
5	76	509.7	533.7	539.24	540.3	542.7	573.1
noise	91	454.2	510.0	565.12	544.6	650.0	745.8
9	11	609.3	609.4	610.60	609.6	612.5	614.2
6	27	646.6	654.2	655.47	655.7	656.4	660.3

group by classes Sort by: charges, median Ascending TableLens condensed Attribute...

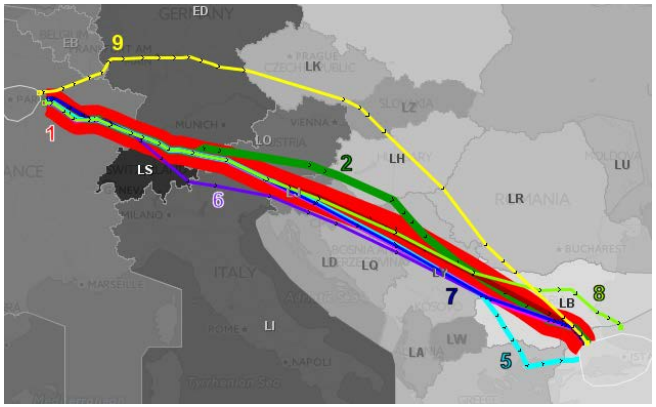
	N members	duration (min), min	duration (min), q1	duration (min), mean	duration (min), median	duration (min), q3	duration (min), max
6	27	161.00	170.00	177.150	176.00	183.00	201.00
4	105	160.00	173.00	180.997	179.00	188.00	231.00
8	14	163.00	171.75	177.633	179.18	182.25	191.00
1	1031	147.00	173.00	181.052	180.00	188.00	246.00
3	125	156.00	174.53	183.427	180.00	188.50	245.00
2	217	155.00	173.00	182.384	181.00	188.00	224.00
noise	91	155.00	175.00	183.752	182.00	191.00	230.00
5	76	158.00	178.00	184.128	183.00	189.00	242.00
7	20	164.00	177.25	186.600	184.00	195.00	211.00
9	11	173.00	178.00	188.909	189.00	198.00	209.00

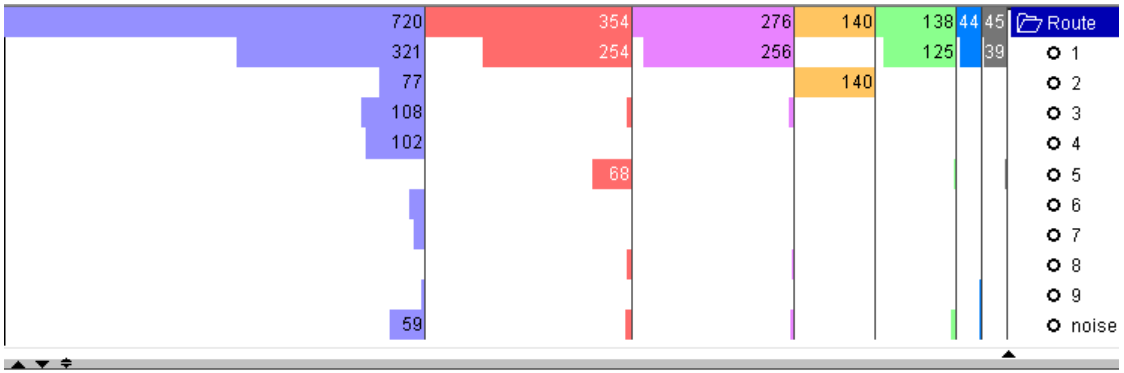
group by classes Sort by: duration (min), median Ascending TableLens condensed Attribute...

	N members	length, min	length, q1	length, mean	length, median	length, q3	length, max
5	76	1242.0	1255.3	1269.17	1268.5	1276.3	1321.2
8	14	1253.3	1261.6	1272.19	1272.8	1283.5	1287.2
7	20	1268.5	1272.0	1278.83	1274.9	1282.2	1301.7
1	1031	1186.8	1273.9	1285.59	1288.6	1294.1	1315.8
3	125	1266.8	1275.0	1285.89	1288.9	1294.1	1317.7
4	105	1225.5	1272.9	1285.30	1289.9	1294.0	1310.8
noise	91	1243.1	1280.2	1304.96	1295.4	1320.4	1409.2
6	27	1271.6	1283.5	1294.62	1296.7	1302.6	1315.2
2	217	1243.9	1286.0	1296.40	1300.4	1304.8	1325.0
9	11	1338.2	1340.8	1349.56	1349.0	1352.9	1377.3

group by classes Sort by: length, median Ascending TableLens condensed Attribute...

Route choices





	N members	charges, min	charges, q1	charges, mean	charges, median	charges, q3	charges, max
2	217	434.9	457.8	459.10	459.4	460.2	492.8
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8	14	476.6	512.4	511.43	515.5	517.2	517.5
1	1031	472.2	512.8	514.36	515.6	517.8	547.3
3	125	500.6	519.2	521.45	521.8	523.2	536.5
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noise	91	454.2	510.0	565.12	544.6	650.0	745.8
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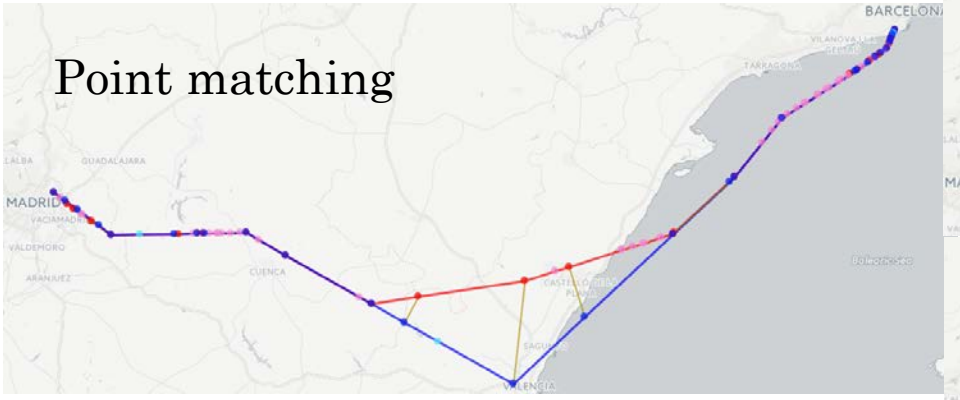
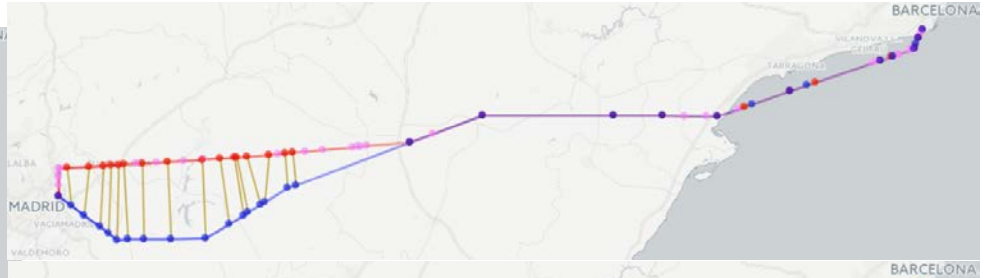
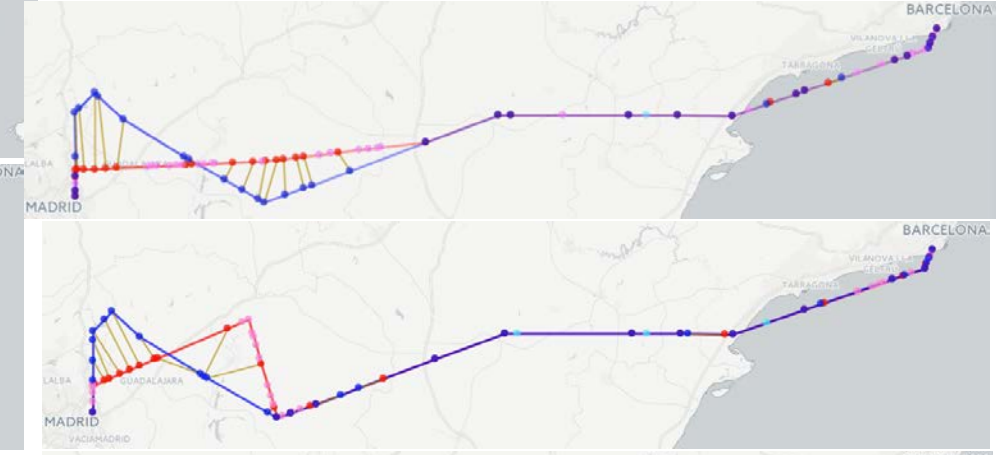
group by classes Sort by: charges, median Ascending TableLens condensed Attribute...

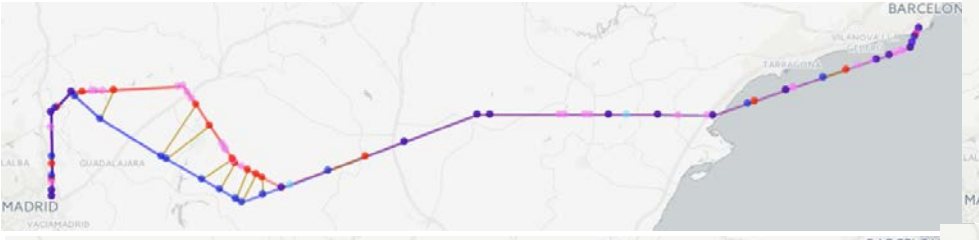
	N members	length, min	length, q1	length, mean	length, median	length, q3	length, max
5	76	1242.0	1255.3	1269.17	1268.5	1276.3	1321.2
8	14	1253.3	1261.6	1272.19	1272.8	1283.5	1287.2
7	20	1268.5	1272.0	1278.33	1274.9	1282.2	1301.7
1	1031	1186.8	1273.9	1285.59	1288.6	1294.1	1315.8
3	125	1266.8	1275.0	1285.89	1288.9	1294.1	1317.7
4	105	1225.5	1272.9	1285.30	1289.9	1294.0	1310.8
noise	91	1243.1	1280.2	1304.96	1295.4	1320.4	1409.2
6	27	1271.6	1283.5	1294.62	1296.7	1302.6	1315.2
2	217	1243.9	1286.0	1296.40	1300.4	1304.8	1325.0
9	11	1338.2	1340.8	1349.56	1349.0	1352.9	1377.3

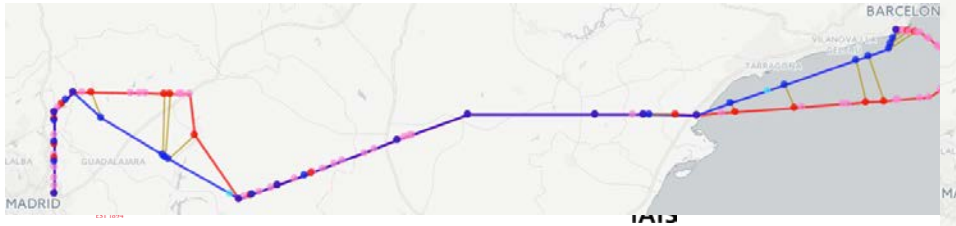
group by classes Sort by: length, median Ascending TableLens condensed Attribute...

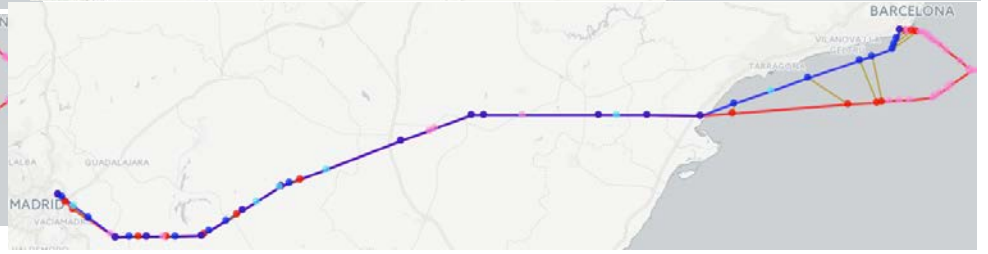








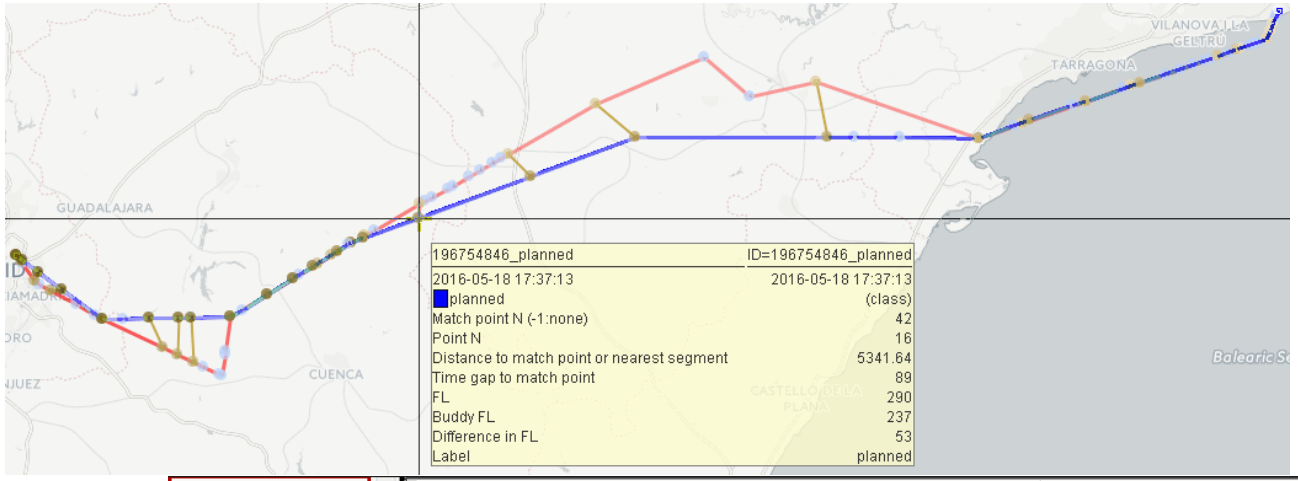


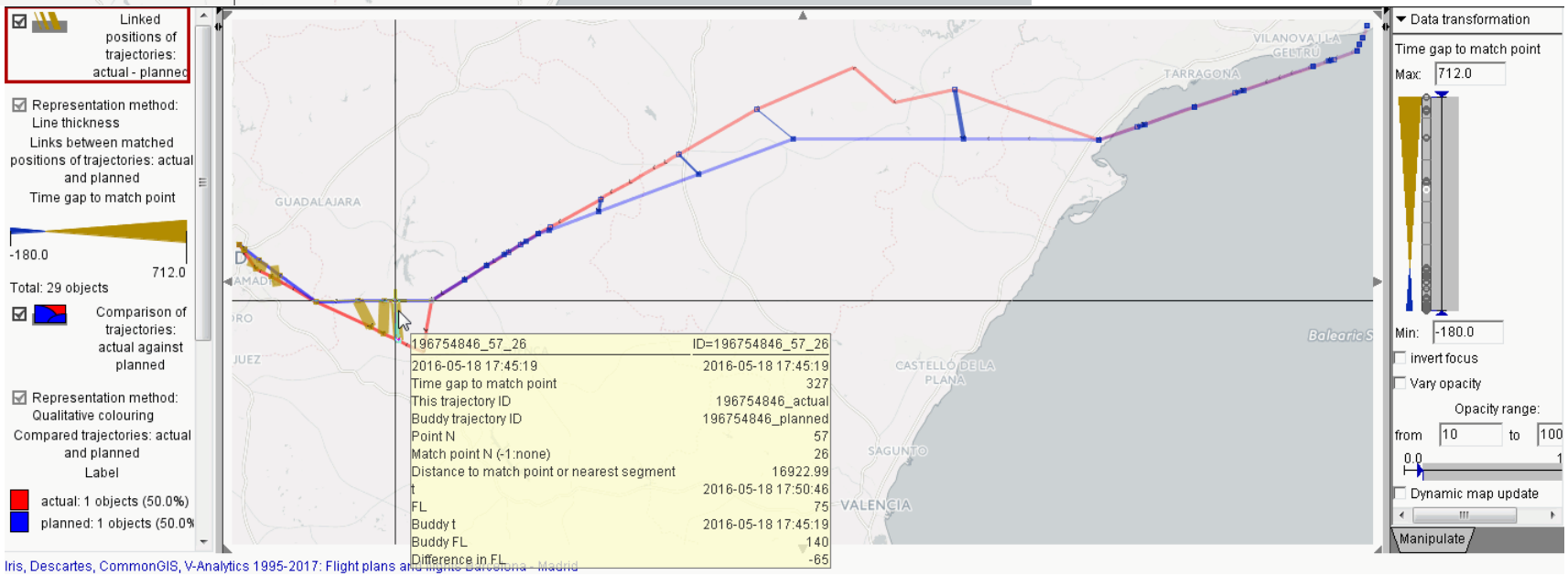


Task: compare the actual trajectories to the flight plans

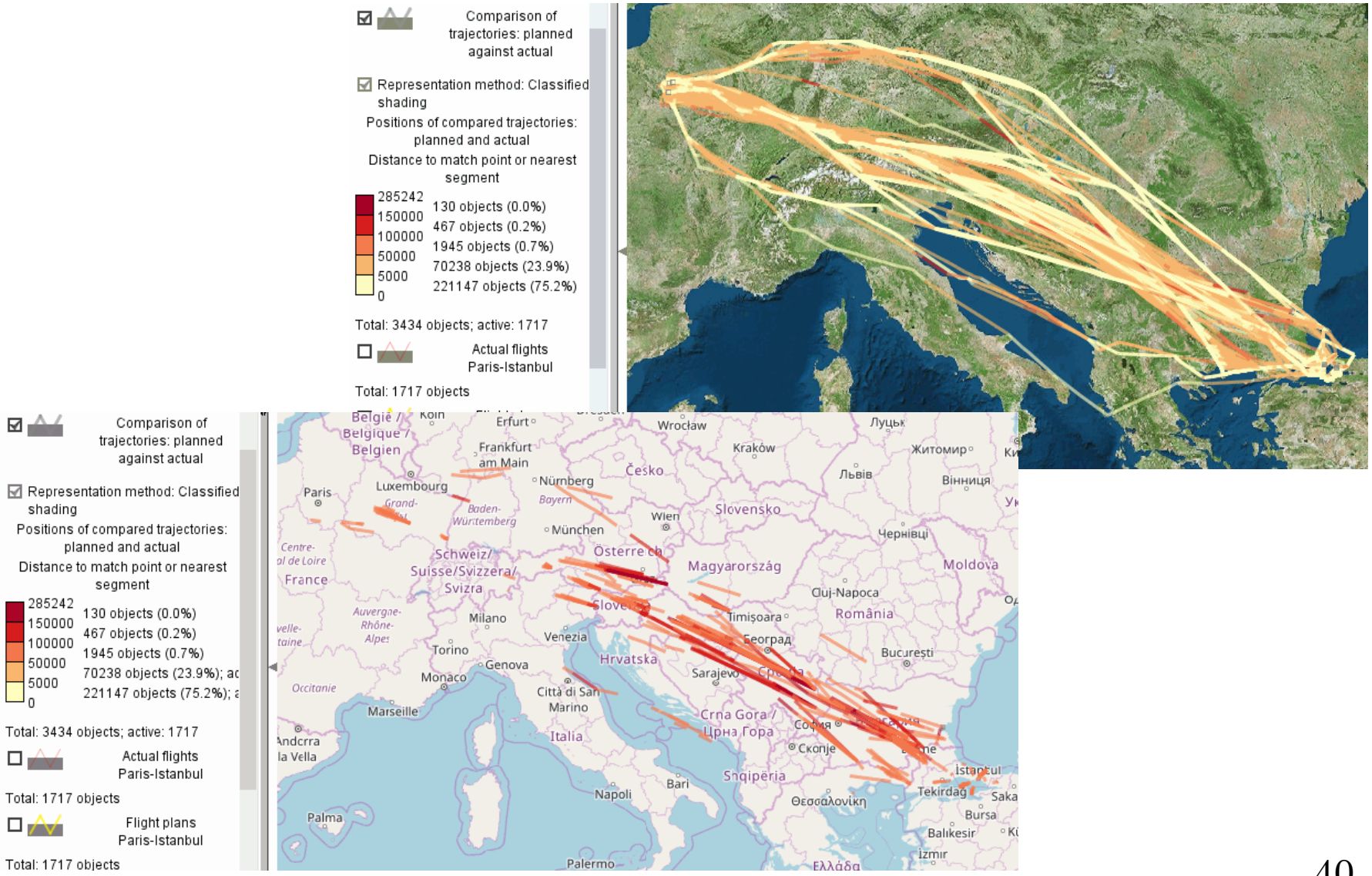
Point matching

Detailed comparison for a single flight

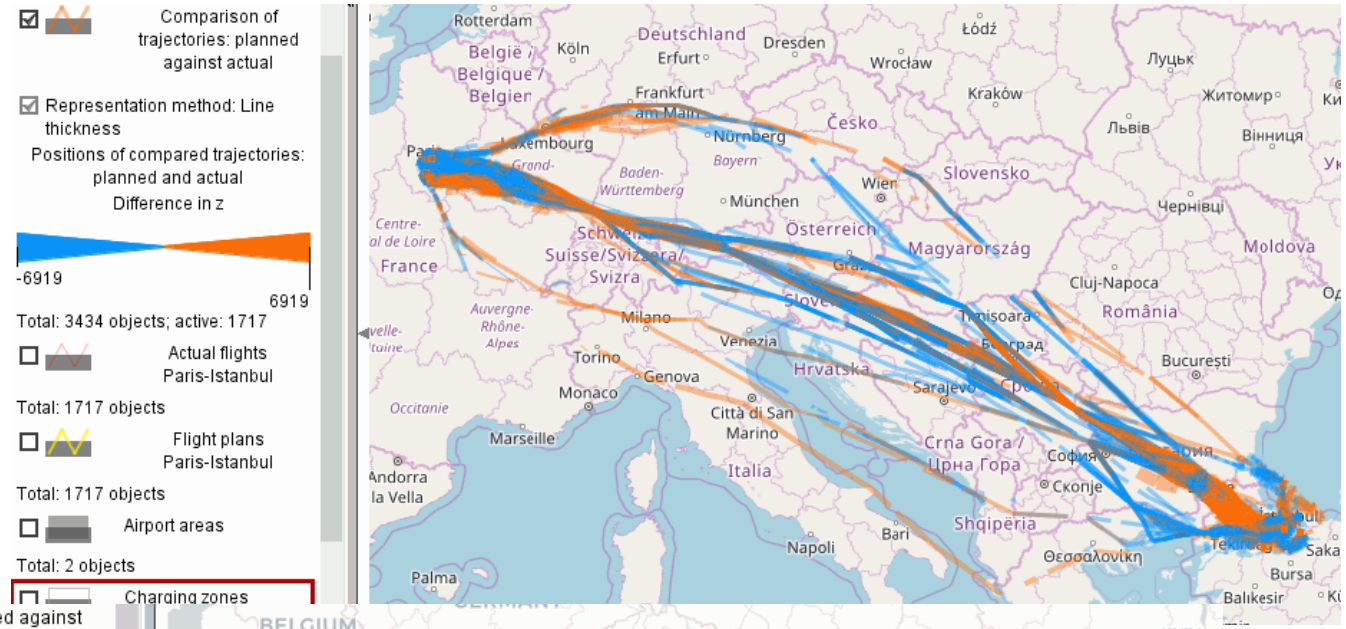


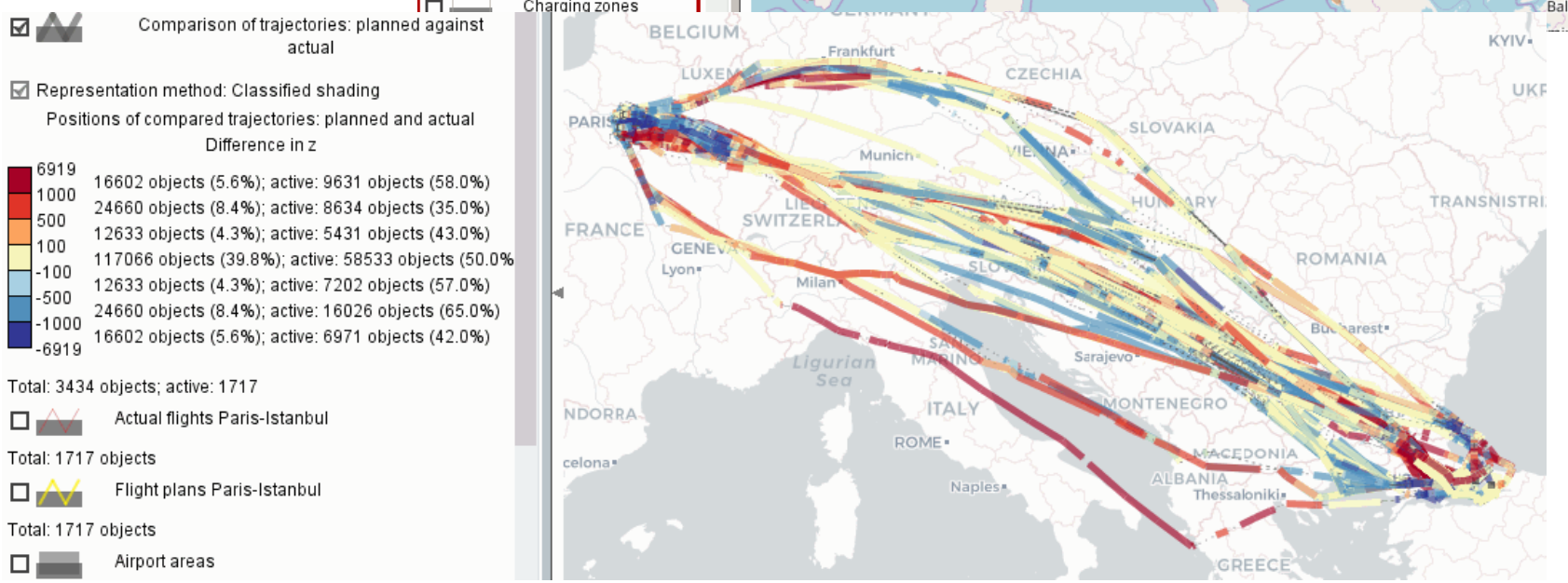


Deviations from the planned routes: distances

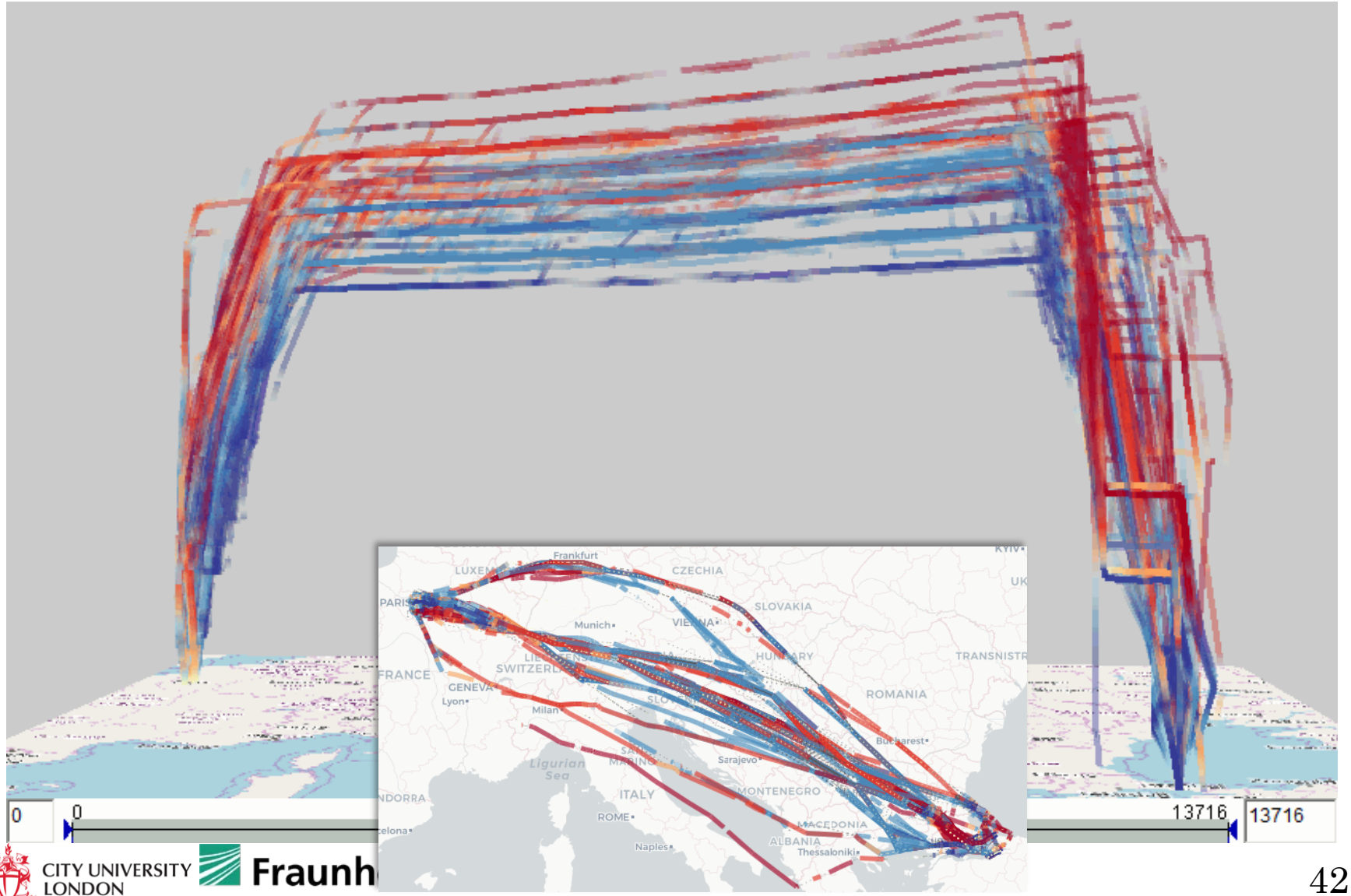


Deviations from the planned routes: altitudes

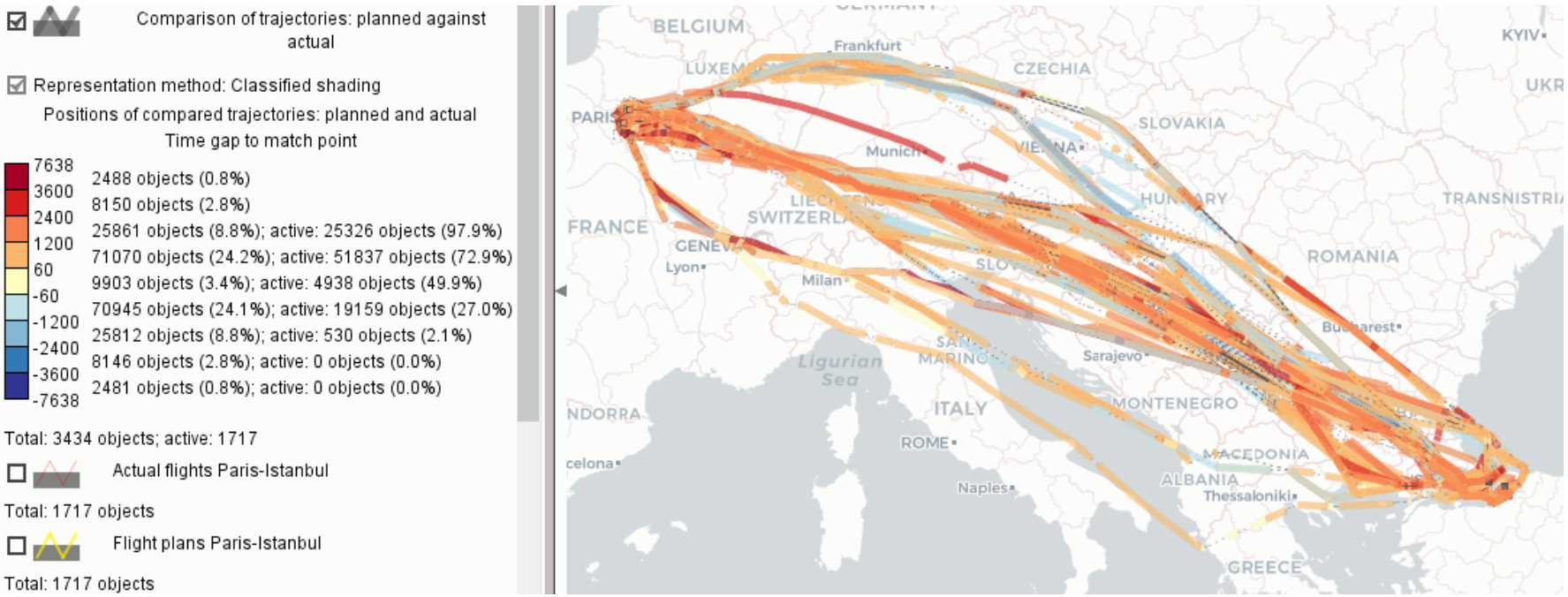




Deviations from the planned routes: altitudes



Deviations from the planned routes: time



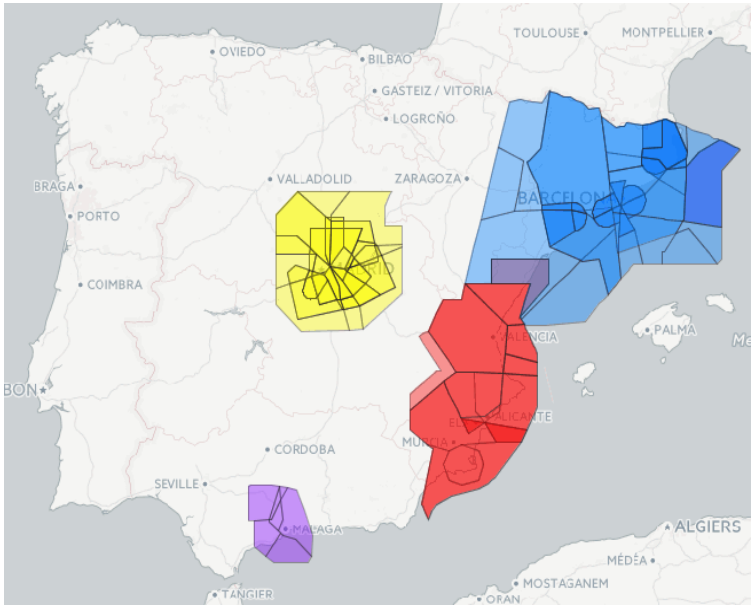
ATM* and ATC**

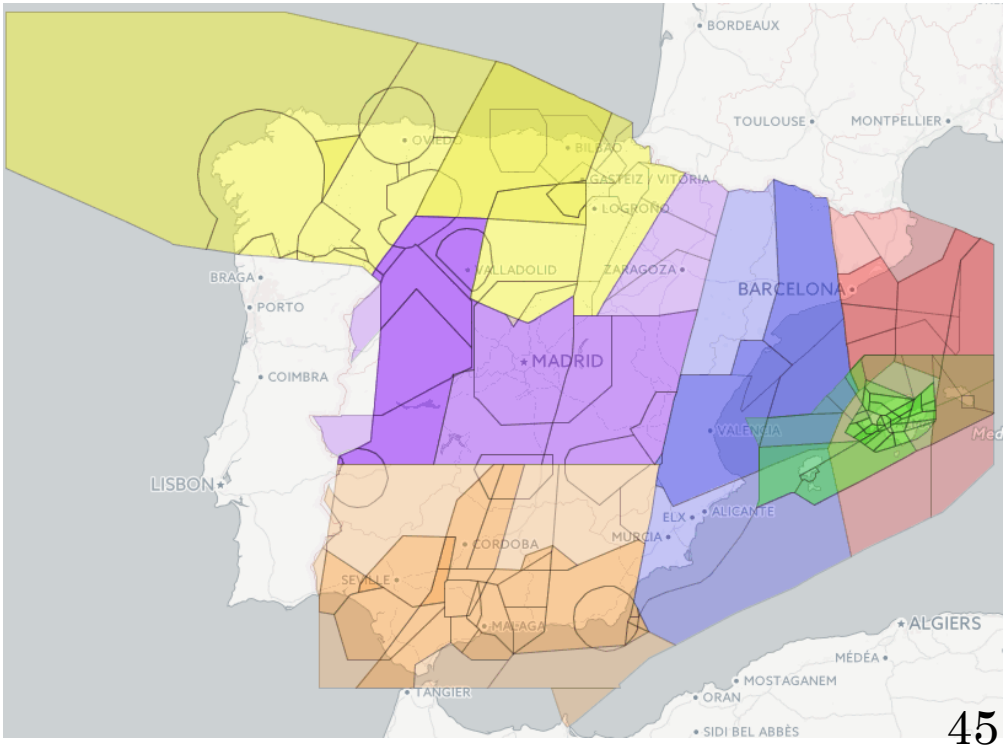
* ATM – air traffic management
** ATC – air traffic control

- Airspace configurations
- Flight regulations and delays

Airspace division (by example of Spain)

- The Spanish air space consists of 11 ACC (area control centres), of which 5 are terminal manoeuvring areas (TMA, left) around airports and 6 are control areas (CTA, right) covering the whole country.





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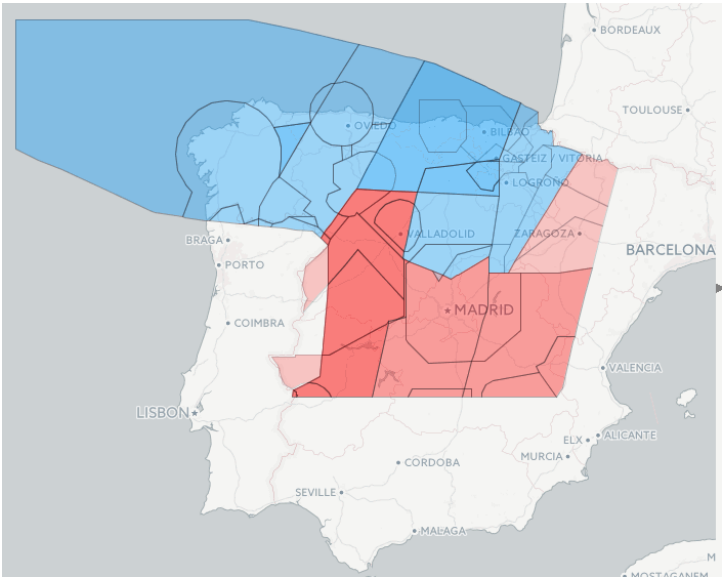
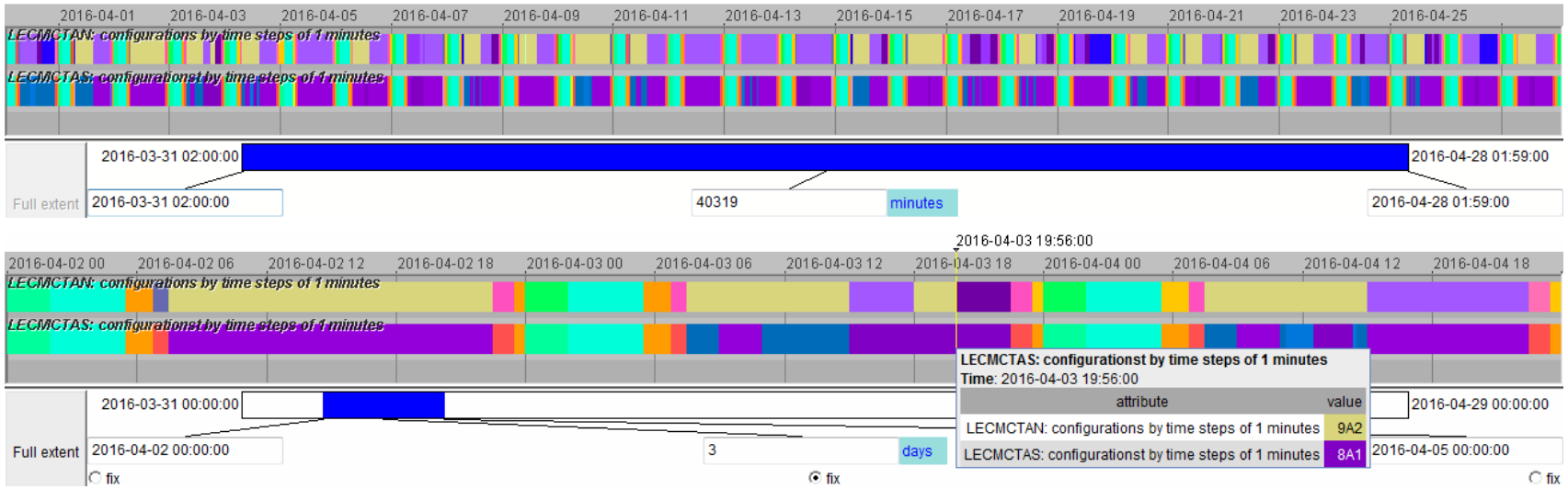
Exploration of configuration structure

Periodicity of changes

- configuration changes over time in selected ACCs





Periodicity of changes

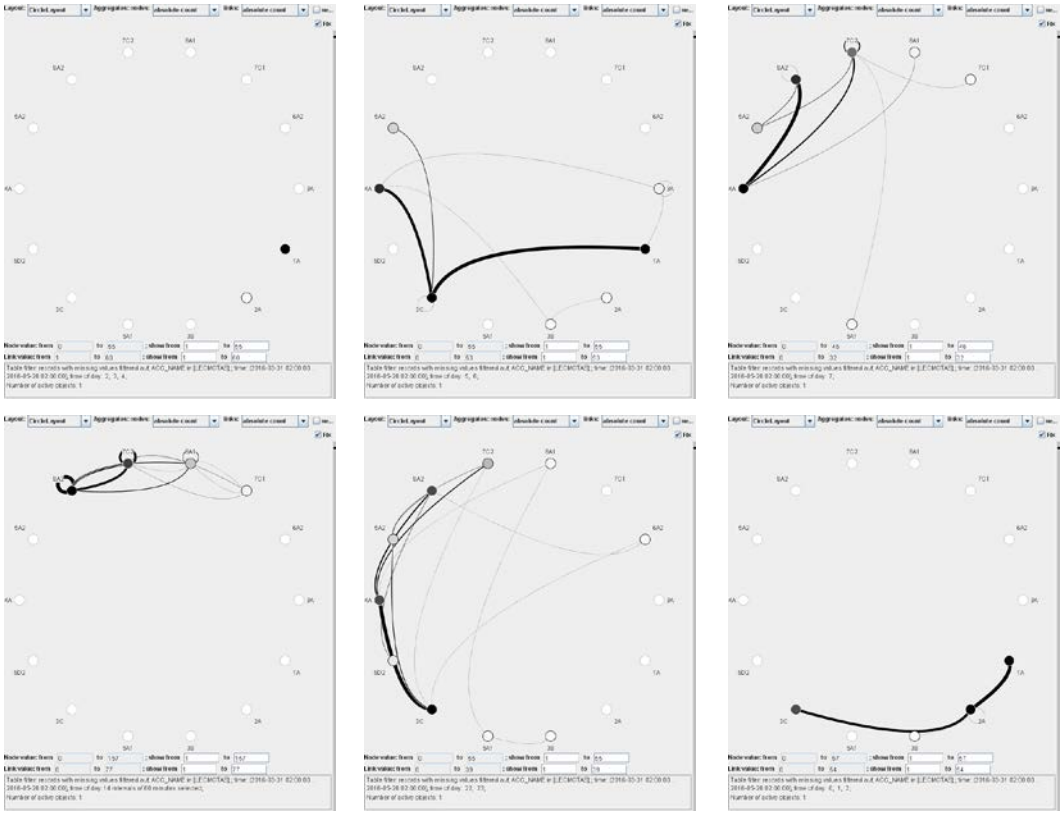
- Weekly patterns

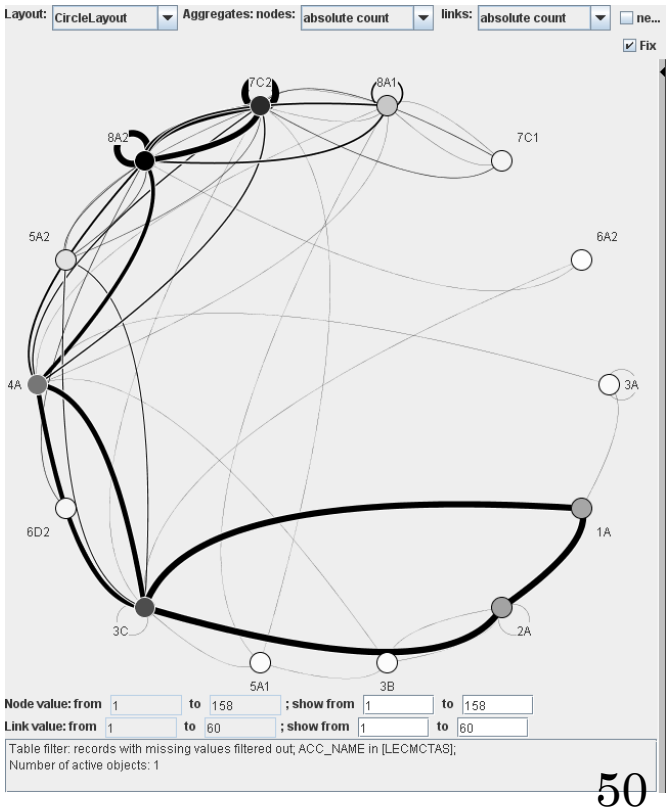
Periodicity of changes

- Daily patterns

Transitions between configurations

- Configurations and transitions between them by intervals of time of the day:
  [02:00, 05:00), [05:00, 07:00), [07:00, 08:00),
  [08:00, 22:00), [22:00, 24:00), [00:00, 03:00)





Task: Explore temporal and spatial patterns of flight regulations*

Natalia Andrienko, Gennady Andrienko, Elena Camossi, Christophe Claramunt, Jose Manuel Cordero Garcia, Georg Fuchs, Melita Hadzagic, Anne-Laure Jousselme, Cyril Ray, David Scarlatti, George Vouros

Visual Exploration of Movement and Event Data with Interactive Time Masks

Visual Informatics, 1(1): 25-39, 2017

Table view: Regulation groups by reasons

	N regulations	Total N delayed flights	CTOT - ETOT (minutes), sum	ATOT - ETOT (minutes), sum	Mean assigned delay per flight	Mean actual delay per flight
C	633	6904	116084	112168	16.81	16.25
P	118	2289	43845	41435	19.15	18.10
I	227	780	25032	24764	32.09	31.75
W	162	1095	23671	23008	21.62	21.01
S	220	975	23206	22390	23.80	22.96
O	138	911	16417	15890	18.02	17.44
G	383	981	14293	14120	14.57	14.39
V	31	412	8735	8261	21.20	20.05
M	92	218	2995	2828	13.74	12.97
R	553	99	1370	1383	13.84	13.97
T	18	54	908	878	16.82	16.26
N	4	12	880	872	73.35	72.67
A	2	3	222	244	73.97	81.33
E	3	1	10	9	10.33	9.00

Sort by: ATOT - ETOT (minutes), sum Descending TableLens

* Each airport and air traffic control sector has a published maximum capacity. When capacity is exceeded, measures are taken to reduce the traffic. This is termed ***regulation***.

Wikipedia article
"Air traffic flow management"

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Flight regulations

Table view: Regulation groups by reasons

	N regulations	Total N delayed flights	CTOT - ETOT (minutes), sum	ATOT - ETOT (minutes), sum	Mean assigned delay per flight	Mean actual delay per flight
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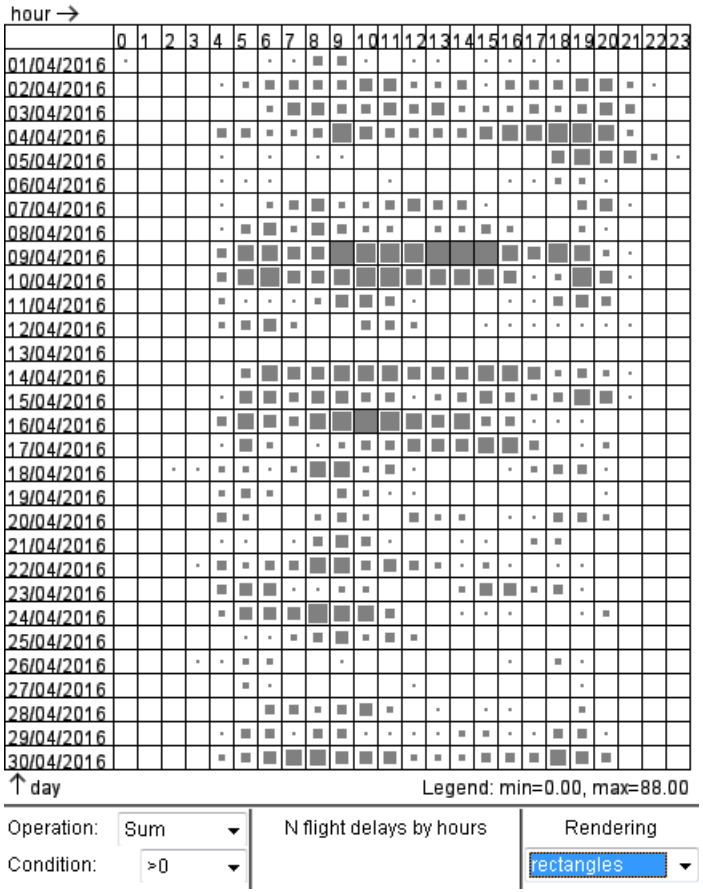
E	3	1	10	9	10.33	9.00

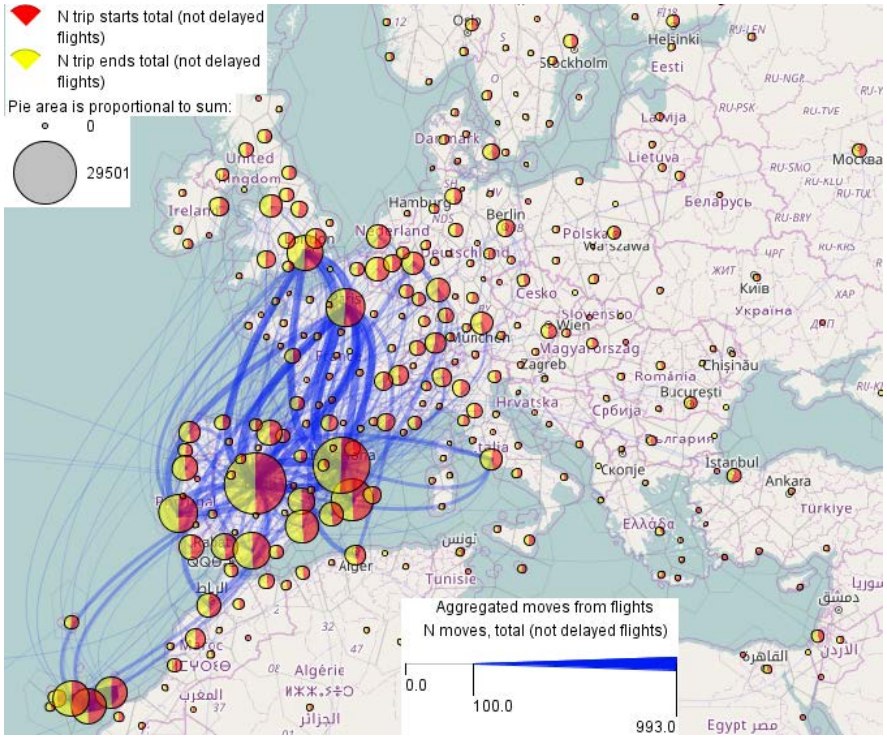
Sort by: ATOT - ETOT (minutes), sum Descending TableLens

C – ATC capacity deficit;
P – special event, including implementation of ATM systems;
I – ATC industrial action, including strikes;
W – bad weather conditions;
S – ATC staff deficit;
G – aerodrome capacity deficit;
O – other

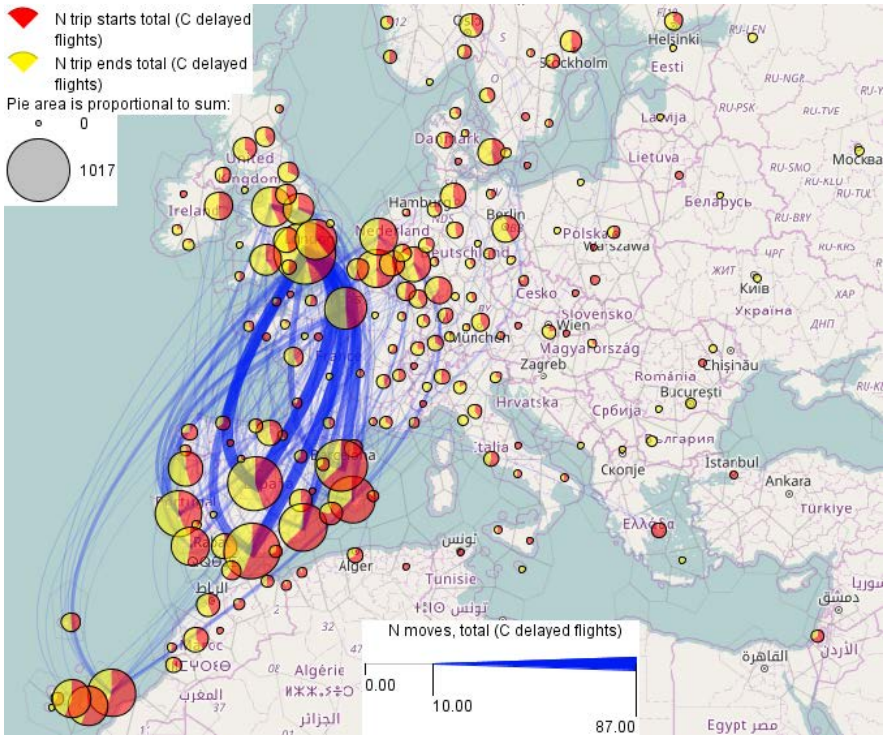


The distribution of the flight departures delayed for the reason C (ATC capacity) by the days (rows of the matrix) and day hours (columns).

Unregulated and regulated flights

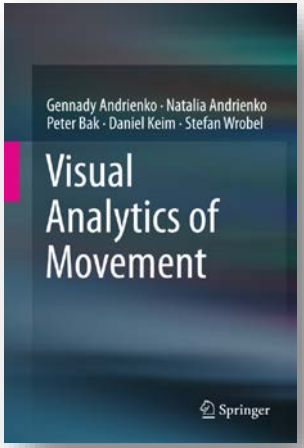


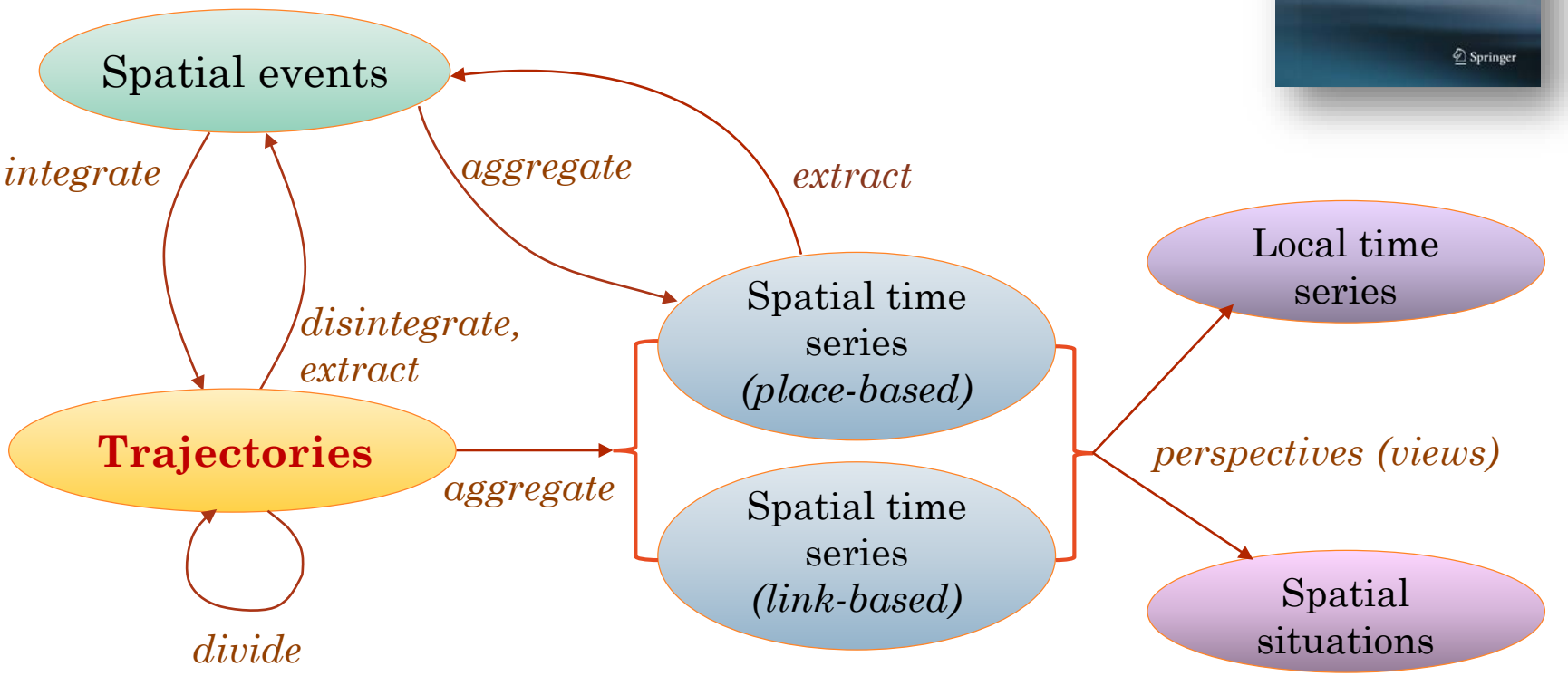
Aggregated unregulated flights



Aggregated flights delayed due to ATC capacity deficits

Transformations of spatio-temporal data





Conclusion

- To analyse and understand air traffic, it is not sufficient to look at flight trajectories only.
- Visual analytics has the potential to make intricate interrelationships understandable.
  - Impact of weather on flight planning and management
  - Flight planning ↔ choosing airspace configurations ↔ demand-capacity imbalances ↔ flight regulations ↔ deviations from the plans
- Visual analytics applied to real data helped us to gain some understanding of the aviation domain. Now we are prepared to addressing more complex analysis and modelling tasks.
- A long way still lies ahead … we are looking forward to new opportunities to continue.

<u>New projects are welcome!</u>