



UNITED NATIONS
Office for Outer Space Affairs

**United Nations/Finland Workshop on the Applications of
Global Navigation Satellite Systems
Helsinki, Finland,
23rd - 27th October, 2023**

**Airplane Trajectory Reconstruction and Analysis
Using GNSS-Based ADS-B Data:
What to Do with the Open Access Data Using Open-
Source Software**

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Krapina, CROATIA



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Airplane Trajectory Reconstruction and Analysis Using GNSS-Based ADS-B Data

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- Definition of a trajectory
- A set of chronologically collected observations about the current positions of an object in motion
- Formal vector representation of a trajectory:
$$\mathbf{P}_i = (t_i, x_i, y_i, z_i)$$
- According to the above notation, a trajectory is the observation matrix, which in the rows contains individual observation vectors, while in the columns are the time-instants of observation t_i and the observed coordinates of the position in the reference coordinate system x_i , y_i , and z_i ,

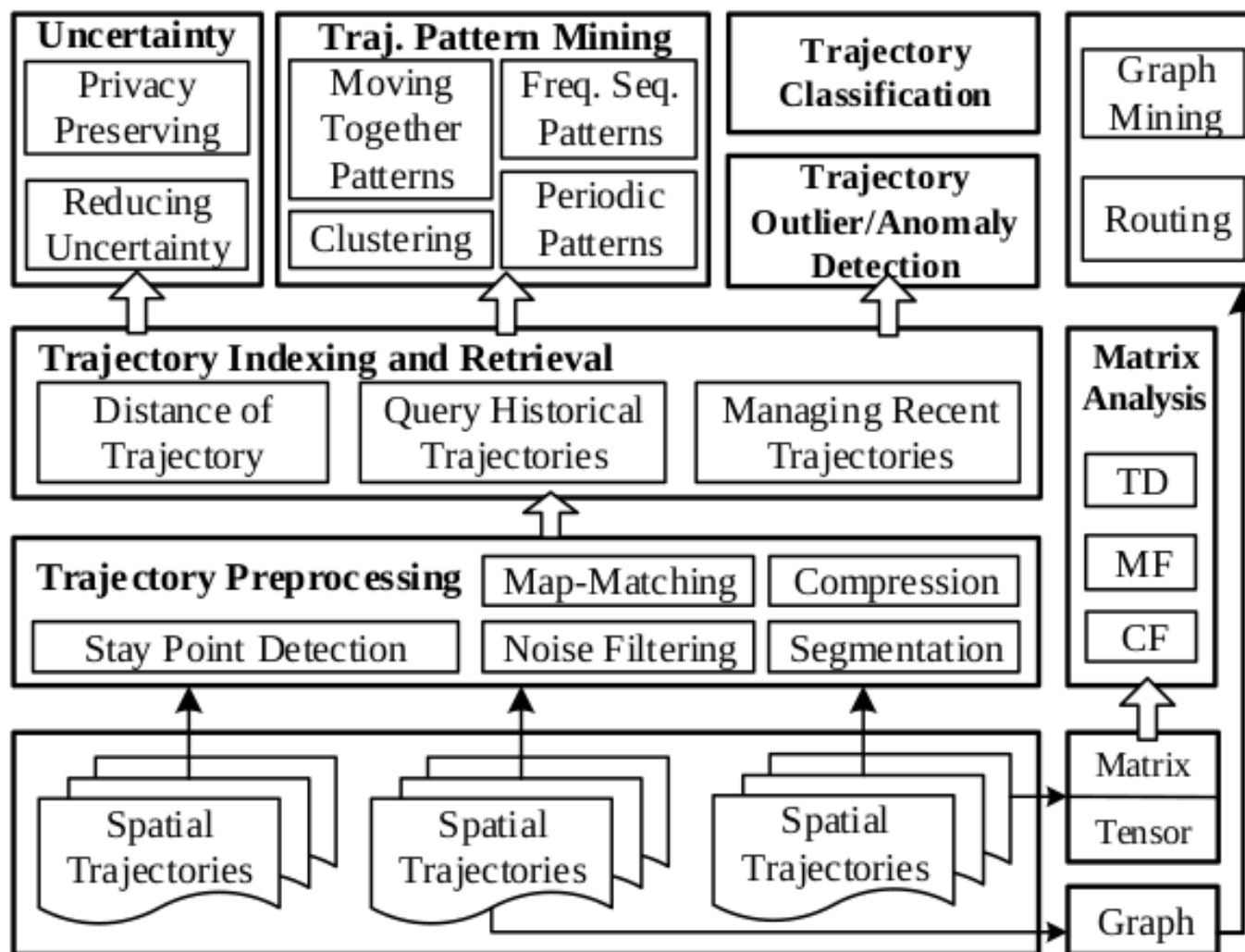
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Deep trajectory data analysis and its applications (Zheng, 2015)



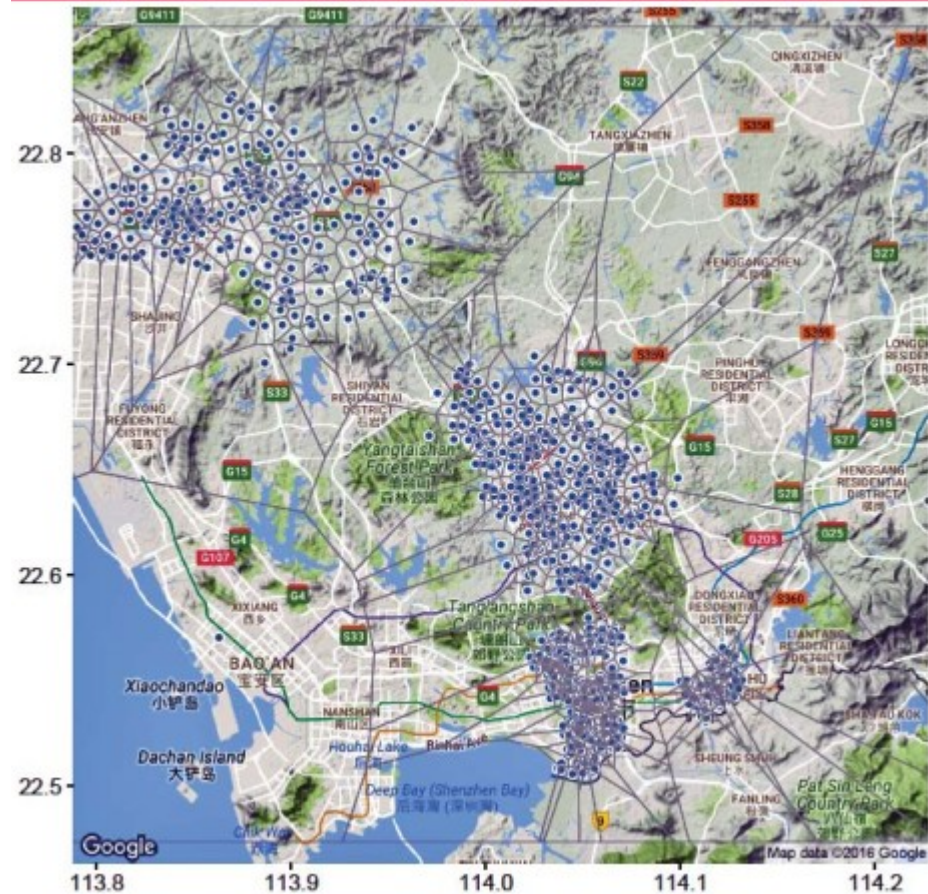
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- Trajectory data collection
- Trajectory of an individual
→ individual and group mobility research
- Routes/trajectories of public transport vehicles
- Paths of animals in their natural habitat
- Paths of natural phenomena (tornadoes, weather changes, ocean currents, etc.)



Filjar, R, Filić, M, Lučić, A, Vidović, K, Šarić, D. (2016). Anatomy of Origin-Destination Matrix derived from GNSS alternatives. *Coordinates*, 12(10), 8-10.

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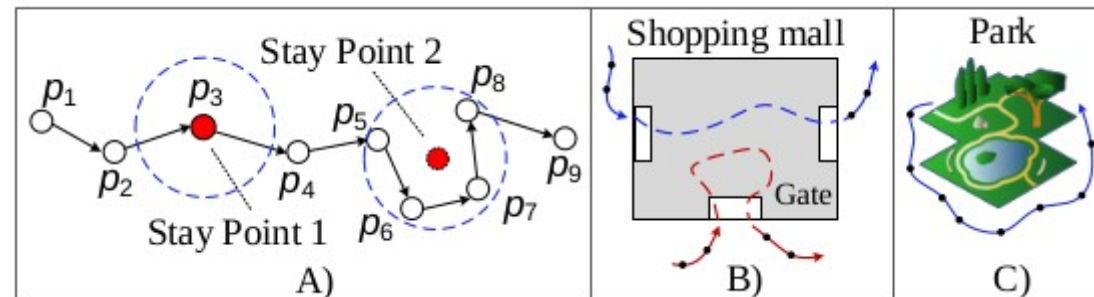
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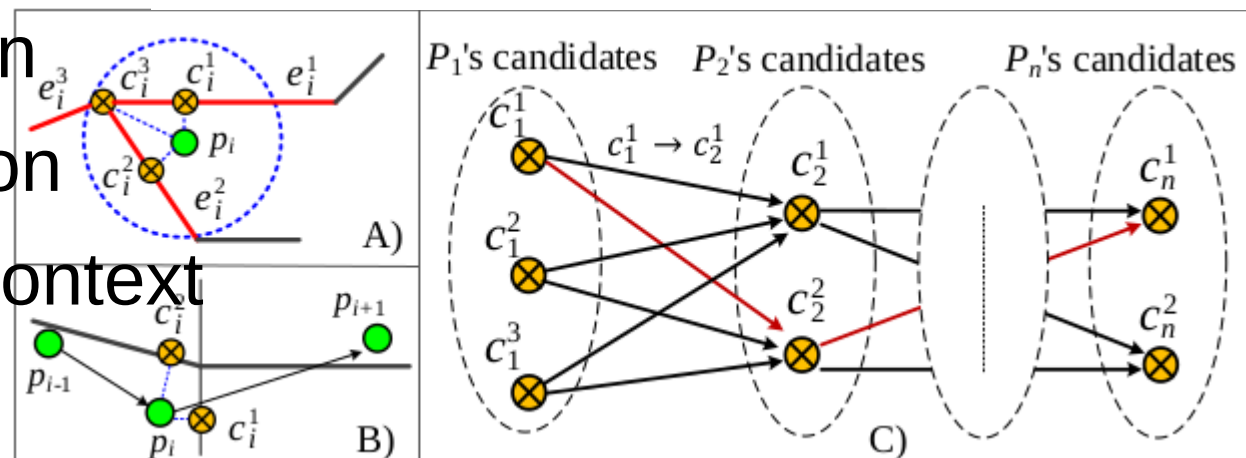
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- Exploratory trajectory analysis
- Filtering noise from trajectories (averaging, Kalman and particle filtering, heuristic extraction of outliers)
- Stopping point detection

Source: Zheng, 2015



- Data transforms
- Fractal dimension
- Hovering intervals
- Path compression
- Path segmentation
- Adapting to the context
(Map-Matching)



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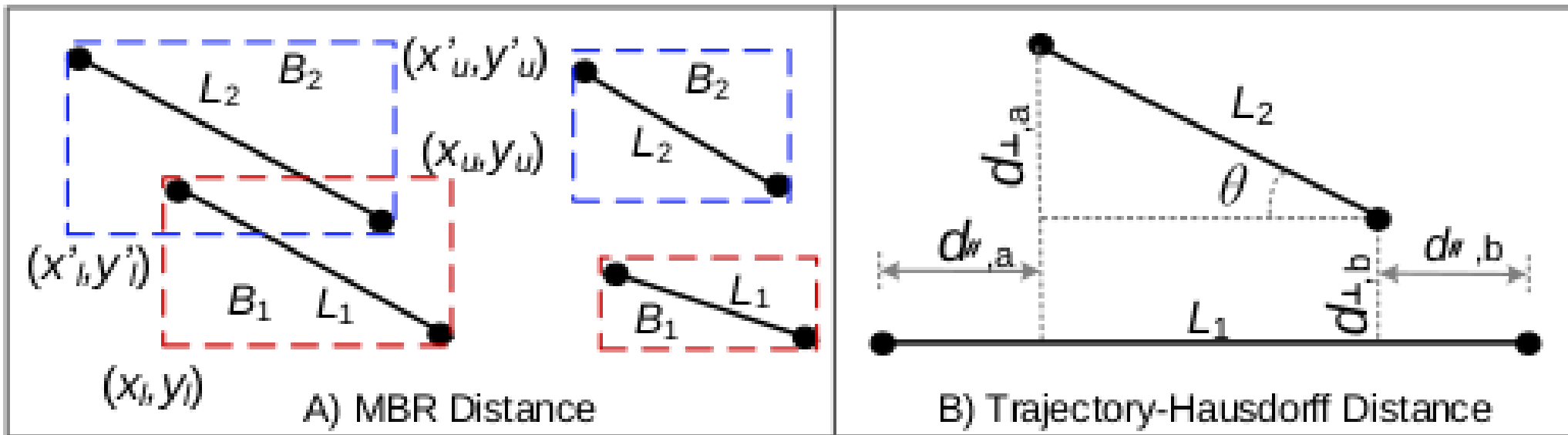
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- Exploratory trajectory analysis
- Indexing and retrieving path-related observations
- Mutual distance and path similarity measures

Source: Zheng, 2015



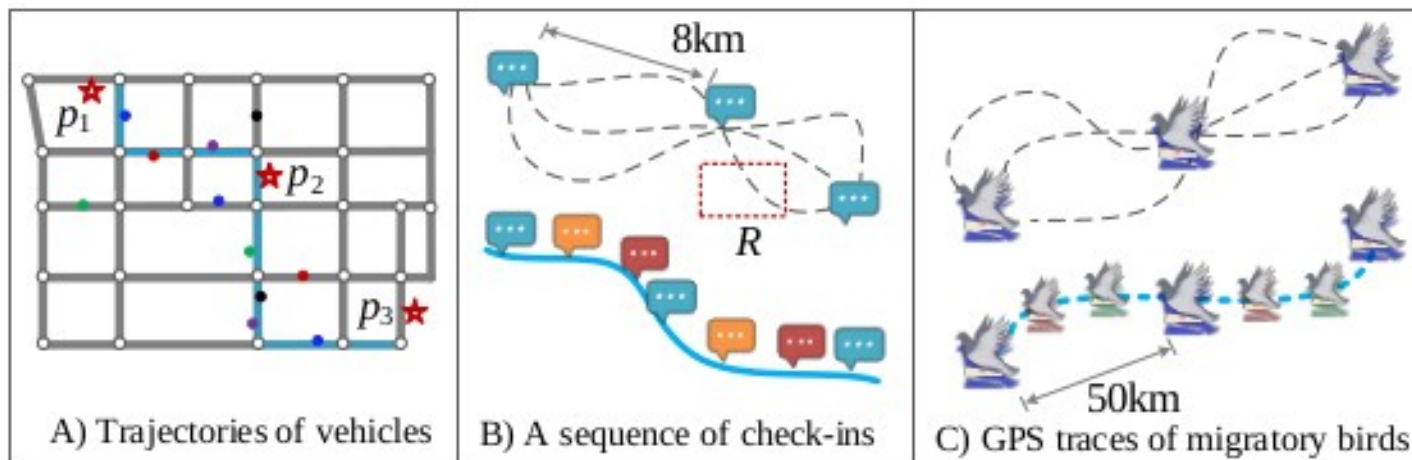
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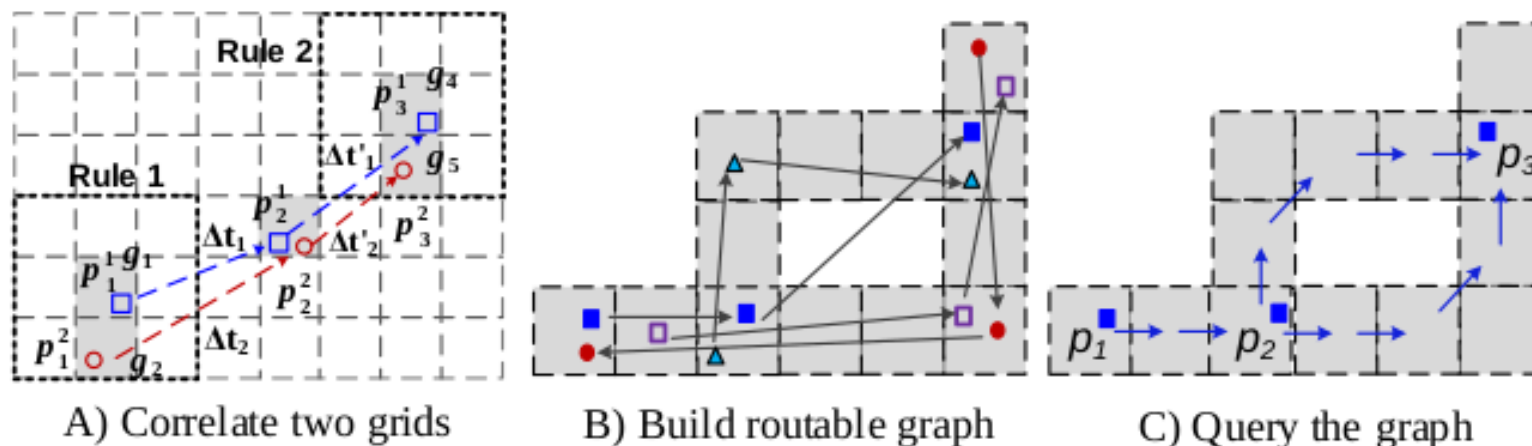
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- Uncertainty of trajectory
- Detection and identification of errors in positioning and trajectory determination & reconstruction



Source: Zheng, 2015



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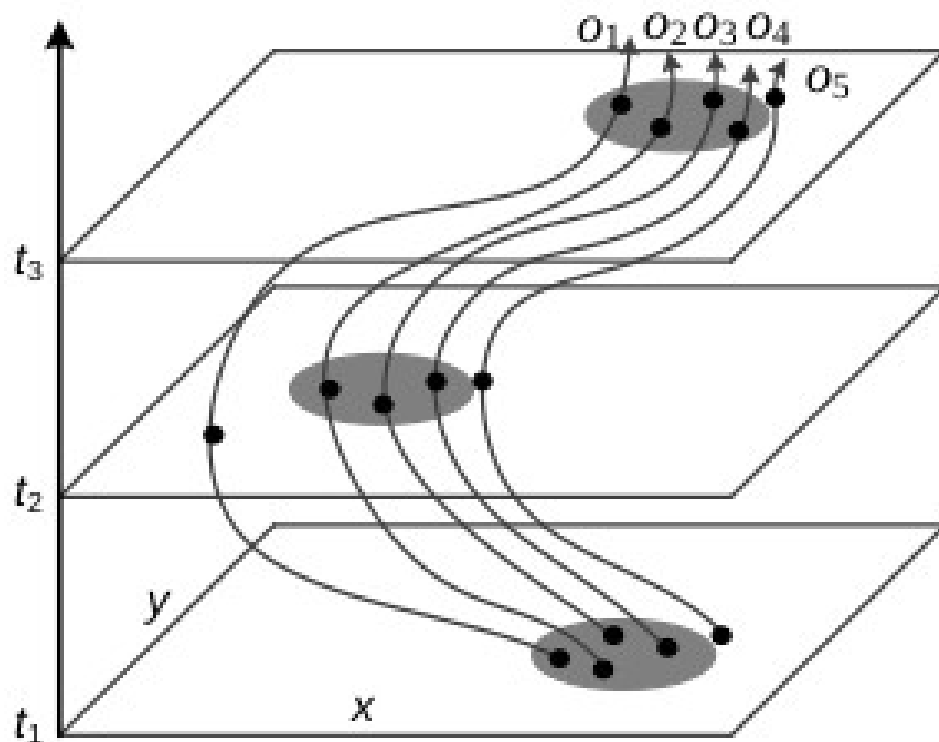
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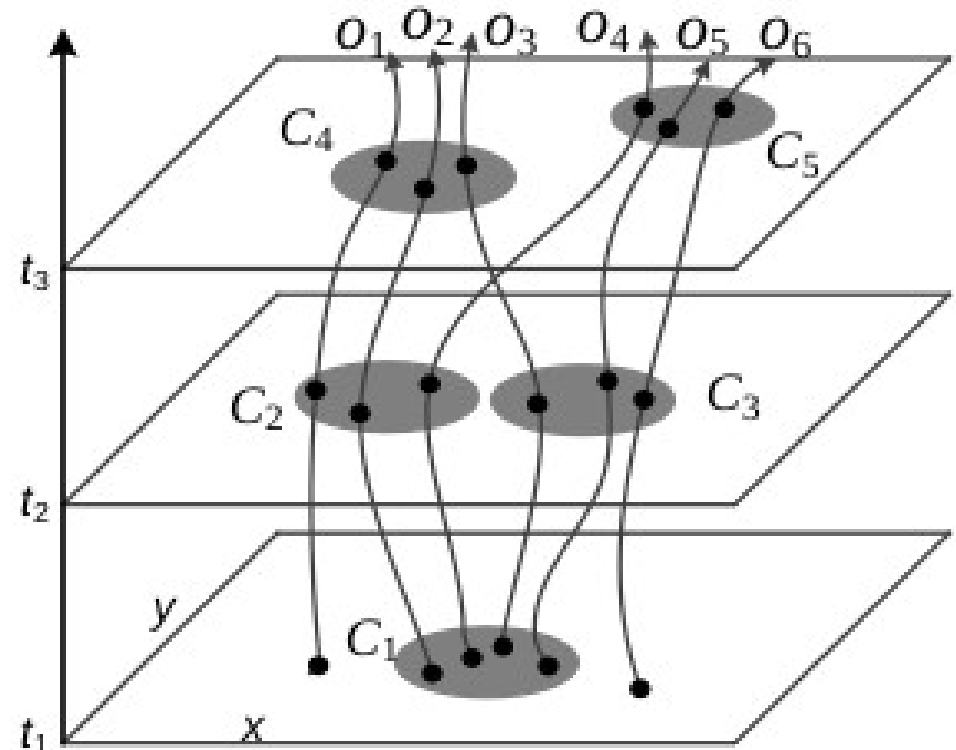
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- Deep analysis of trajectory
- Group movement

Source: Zheng, 2015



A) Flock, convoy and swarm



B) Gathering

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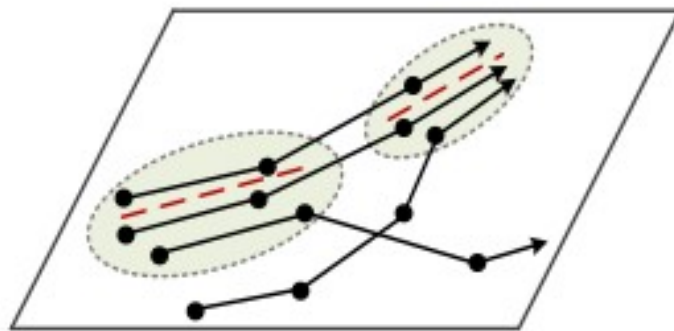
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- Deep analysis of trajectory
- Trajectory clustering

Source: Zheng, 2015



A) Clusters of segments

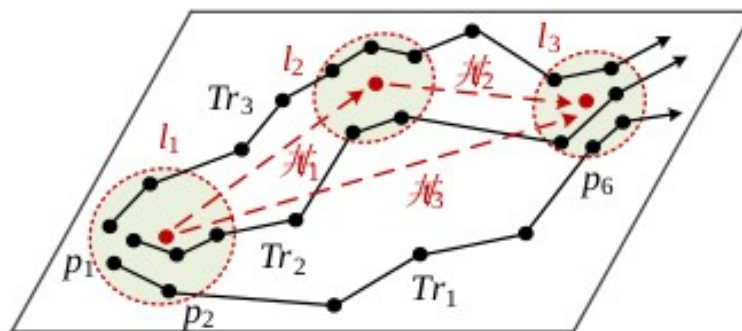


B) Micro-clusters

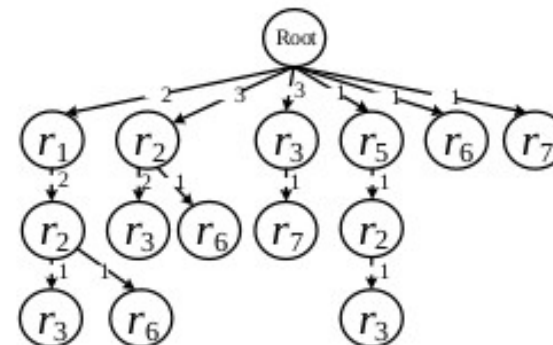


C) Macro-clusters

- Recognising sequential patterns in trajectories



A) Sequential trajectory patterns



B) Suffix Tree-based sequential pattern mining

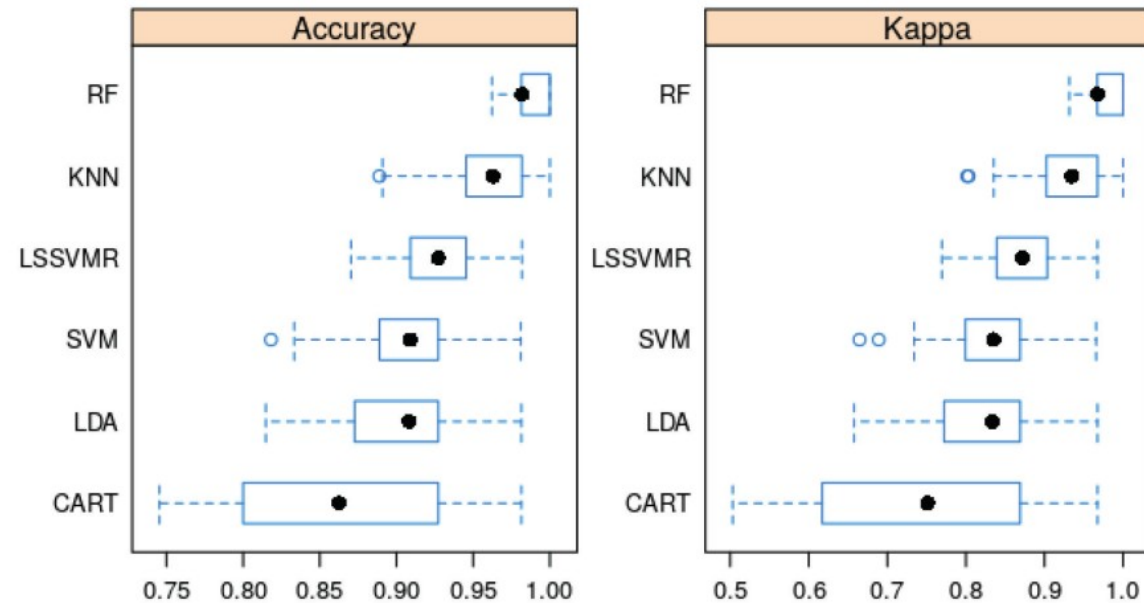
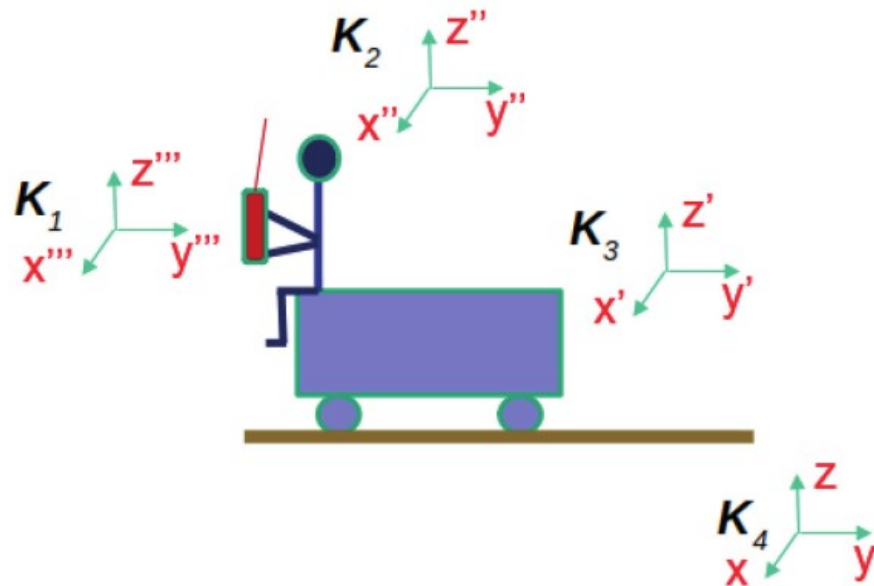
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- Trajectory classification
- Detection of mobility means



Filjar, R, Sklebar, I, and Horvat, M. (2020). A Comparison of Machine Learning-Based Individual Mobility Classification Models Developed on Sensor Readings from Loosely Attached Smartphones. Communications - Scientific Letters of the University of Zilina, 22(4), 153-162. doi: <https://doi.org/10.26552/com.C.2020.4.153-162>

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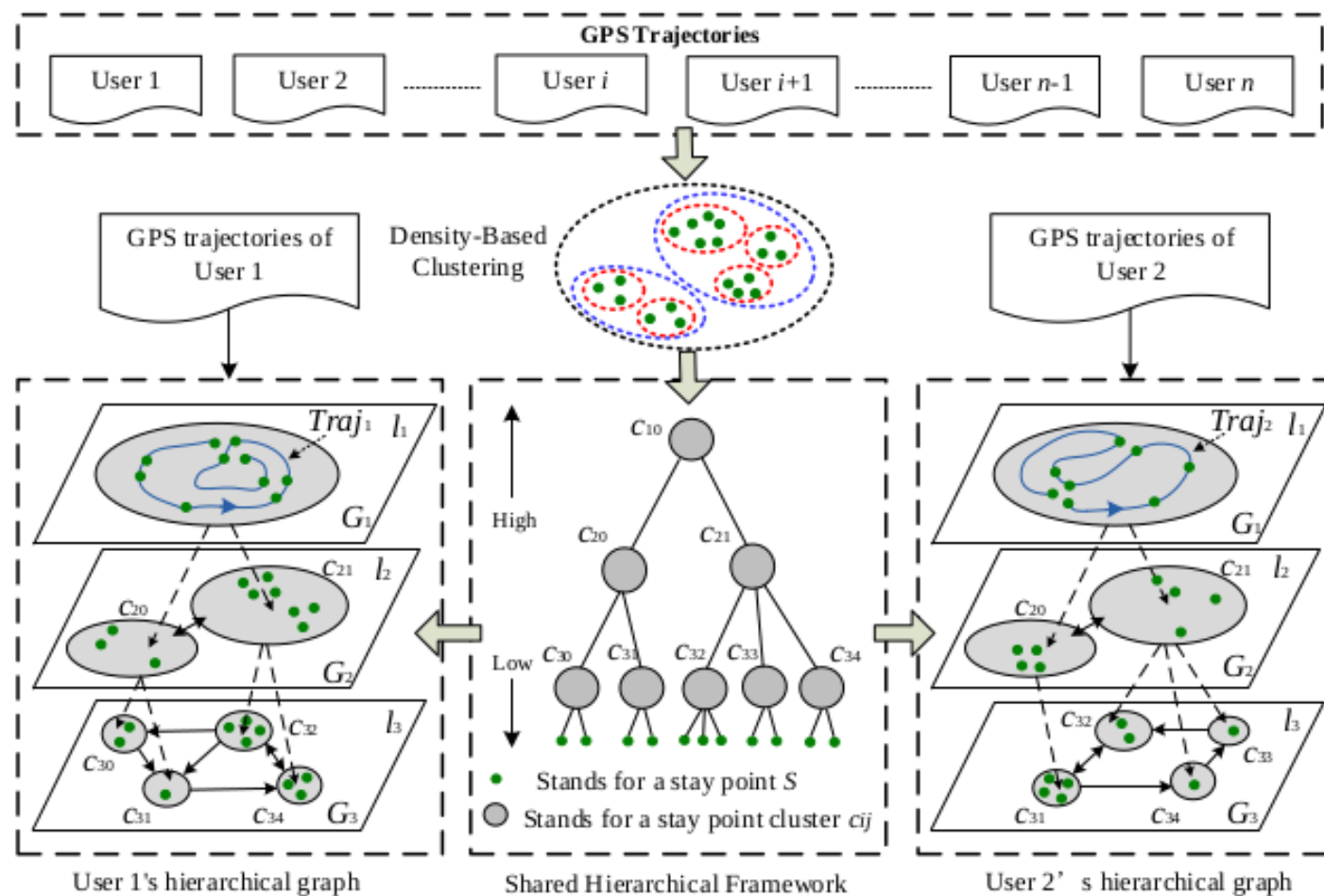
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- Outlier detection
- Hierarchical diagram of trajectory similarity

Source: Zheng, 2015



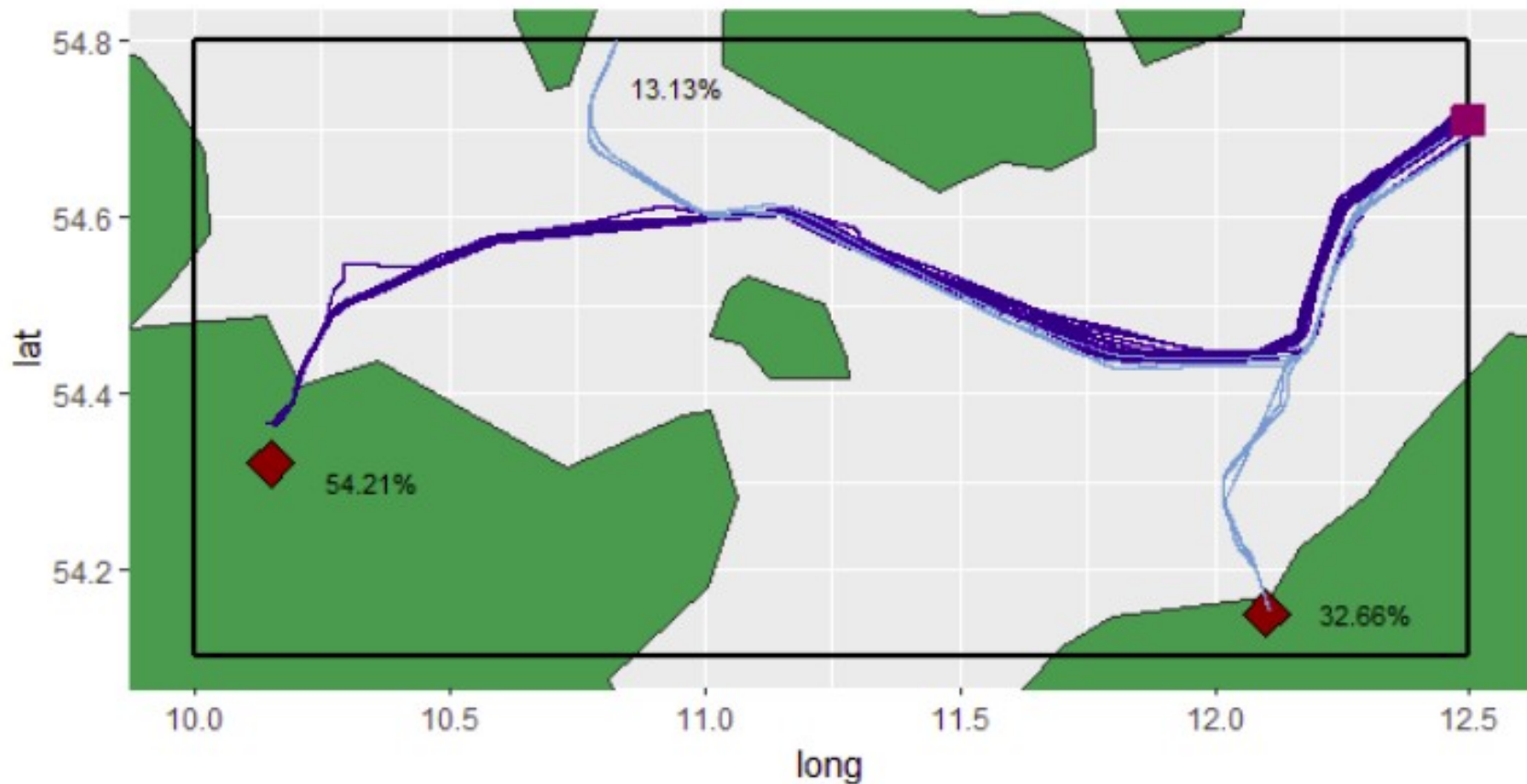
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- Bayesian (probabilistic) trajectory predictive model
- AIS data (vessels) (Gamulin, 2020)



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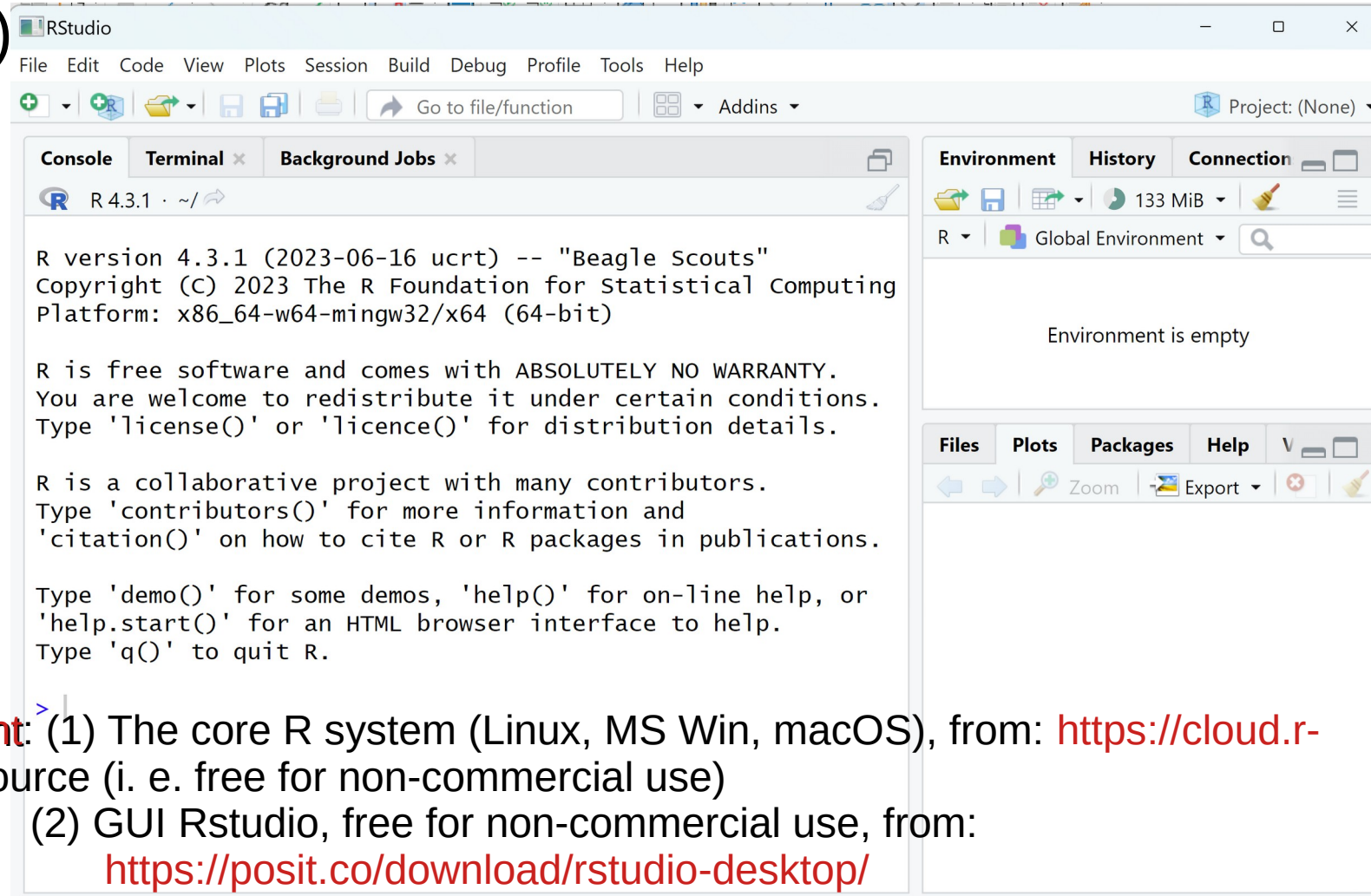
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- Research environment
- The R environment for statistical computing (open source)

R Core Team (2023).
R: A language and
environment for
statistical computing.
R Foundation for
Statistical Computing,
Vienna, Austria.
Available at:
[http://www.R-
project.org](http://www.R-project.org)



The screenshot shows the RStudio interface. The console window displays the following text:

```
R 4.3.1 · ~/>  
R version 4.3.1 (2023-06-16 ucrt) -- "Beagle Scouts"  
Copyright (C) 2023 The R Foundation for Statistical Computing  
Platform: x86_64-w64-mingw32/x64 (64-bit)  
  
R is free software and comes with ABSOLUTELY NO WARRANTY.  
You are welcome to redistribute it under certain conditions.  
Type 'license()' or 'licence()' for distribution details.  
  
R is a collaborative project with many contributors.  
Type 'contributors()' for more information and  
'citation()' on how to cite R or R packages in publications.  
  
Type 'demo()' for some demos, 'help()' for on-line help, or  
'help.start()' for an HTML browser interface to help.  
Type 'q()' to quit R.  
>
```

Below the console, the text reads:

Working environment: (1) The core R system (Linux, MS Win, macOS), from: <https://cloud.r-project.org/>, Open source (i. e. free for non-commercial use)
(2) GUI Rstudio, free for non-commercial use, from:
<https://posit.co/download/rstudio-desktop/>

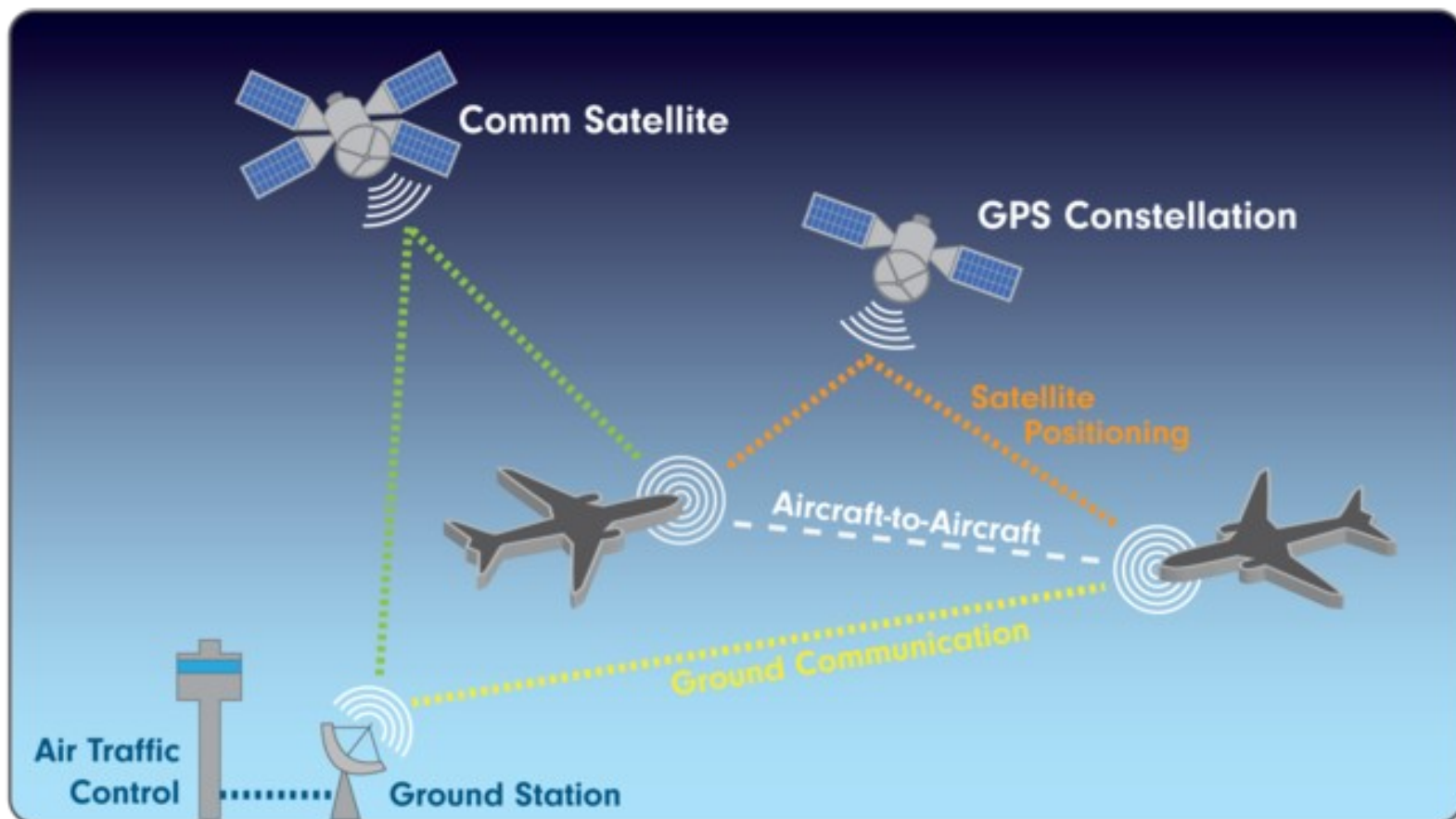
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- Data sources
- Automatic Dependent Surveillance – Broadcast (ADS-B) Software-Defined Radio (SDR) Receiver



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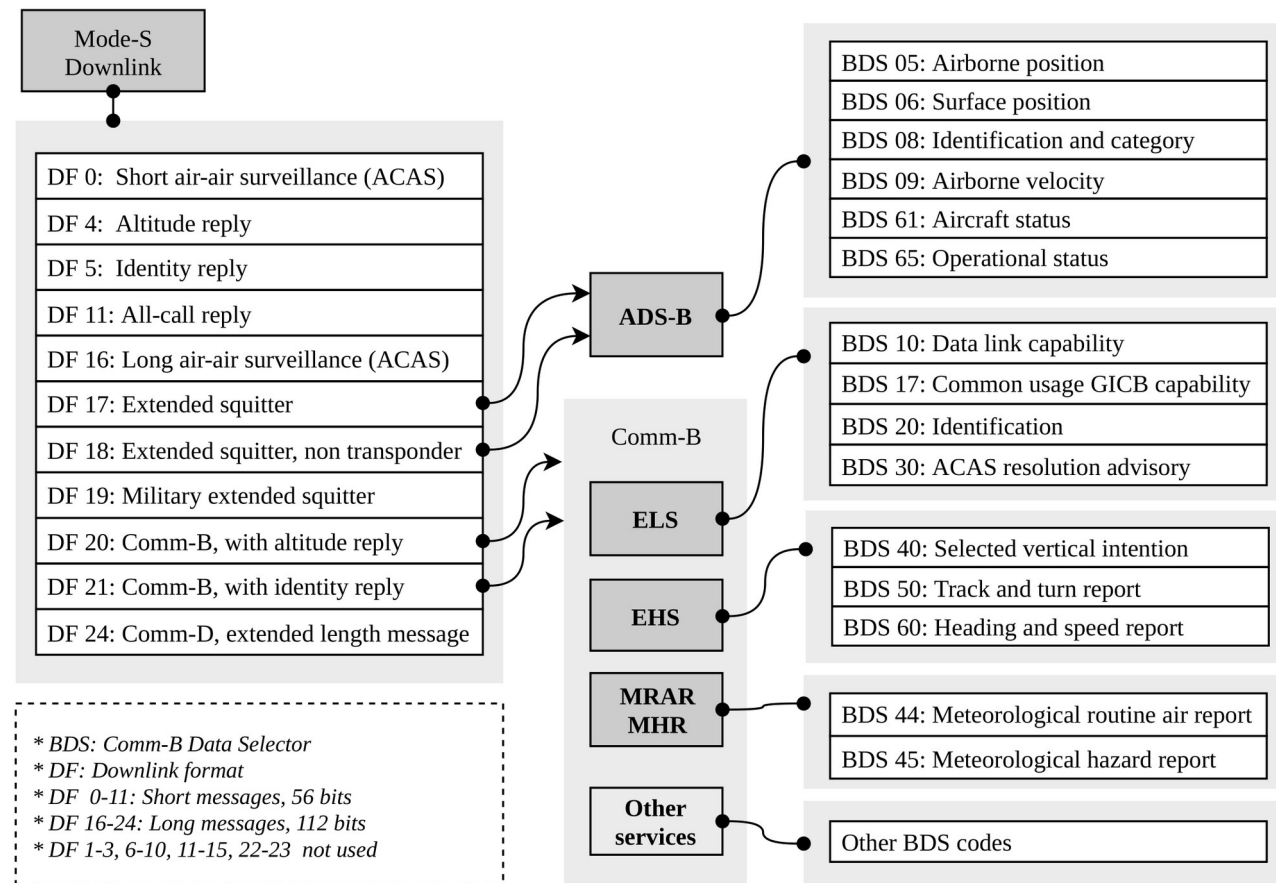
- Data sources
- ADS-B Software-Defined Radio (SDR) Receiver
- Data transfer protocol

Junzi Sun

THE 1090 MEGAHERTZ RIDDLE

(Second Edition)

A Guide to Decoding Mode S and ADS-B Signals



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- Data sources - FlightAware
- Crowdsourcing data with ADS-B SDR Receiver

The image shows a screenshot of the FlightAware website. On the left, a map of Europe is displayed with numerous yellow aircraft icons representing ADS-B data points. On the right, the website interface shows the details for flight British Airways 281 (BAW281 / BA281). The flight is shown as having arrived at Los Angeles International Airport (LAX) Terminal B on Wednesday, 10-May-2023 at 15:05 PDT (on time). The departure was from London Heathrow (LHR) at 11:50 BST (on time). The total travel time is 11h 15m. The page also includes sections for 'Set Up Unlimited Flight Alerts & More', 'Aircraft Details' (Boeing 777-300ER), and 'Flight Data' (Speed: 555 mph, Altitude: 9,750 m, Distance: 5,523 mi).

Source: <https://flightaware.com/>

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- Data sources – ADS-B Exchange



ADS-B Exchange

World's largest source of unfiltered flight data



Home

Share your data

Tracking Map

ADS-B Data Services

Forum

Store

About

Remove Ads



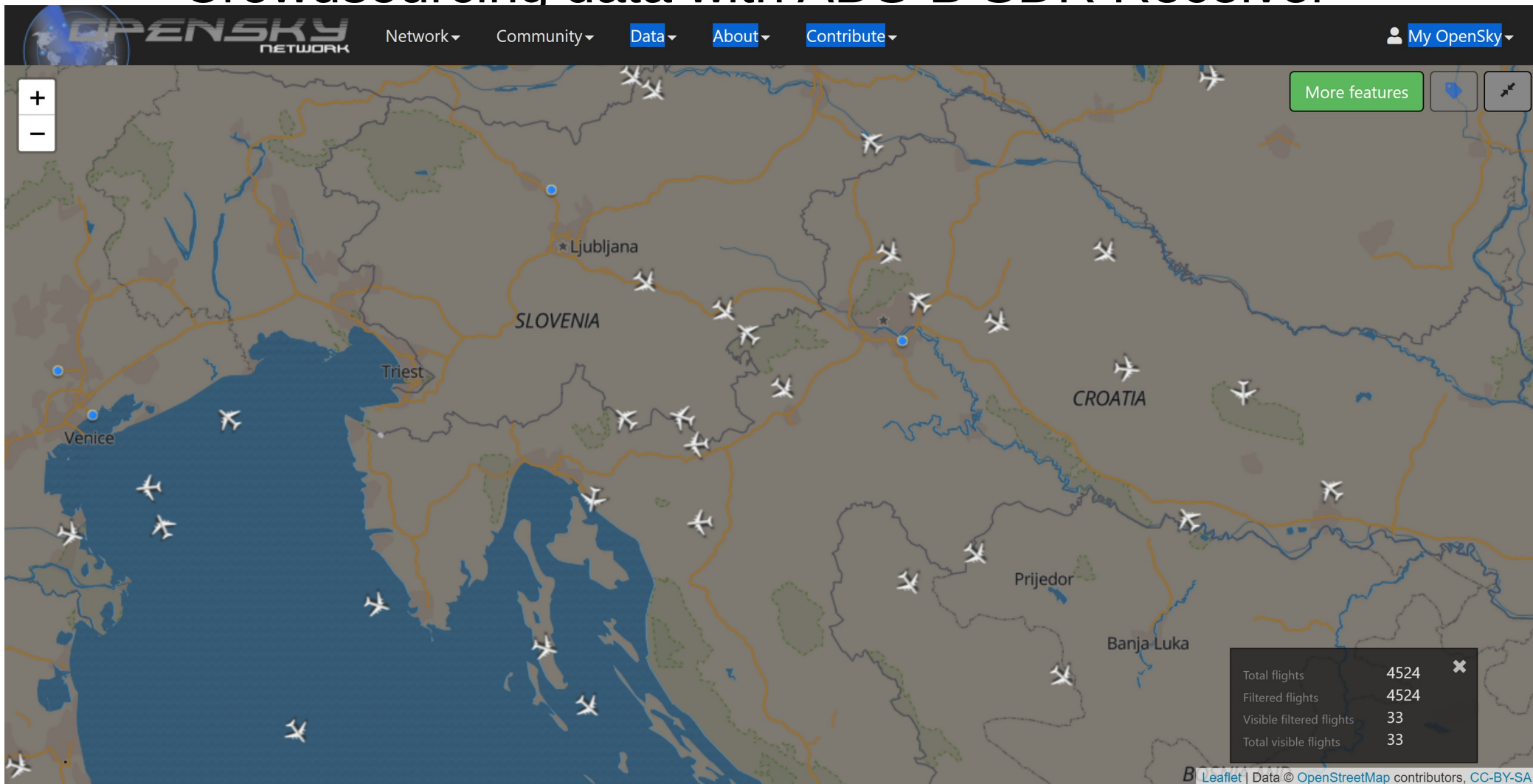
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- Data sources – OpenSky Network
- Crowdsourcing data with ADS-B SDR Receiver



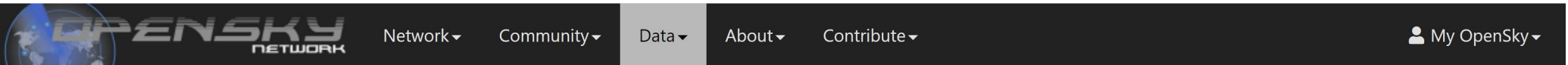
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- Data sources – OpenSky Network
- Crowdsourcing data with ADS-B SDR Receiver



On this page, we will collect and briefly introduce some of the OpenSky-related tools provided by our extraordinary community, covering different functionalities in the main data science languages Python, R and Matlab. Principally, these are tools to access and process data either via our [Impala shell](#) (access request required), our [live API](#) or our [prepared datasets](#).

Naturally, the OpenSky Network Association does not maintain these tools and thus cannot give any support. For further questions on any of these, you should ask the respective maintainer or try our forum. Pretty much all of these tools are developed as open source, so you can help improve them and report any bugs. This list is work in progress, if you want to add your OpenSky tool or know of one that should be on this page, please write us at contact@opensky-network.org

Further reading suggestions for better understanding of the air traffic data we use include:

- <https://atmdata.github.io/>
- <https://mode-s.org/decode/>
- <https://github.com/openskynetwork>

All data tools:

1. traffic – Air traffic data processing in Python
2. pyModeS + pyOpenSky
3. em-download-opensky + em-processing-opensky
4. R-based Wrappers: openSkies, osn, openskyr
5. ADSbDataParser
6. Stone Soup

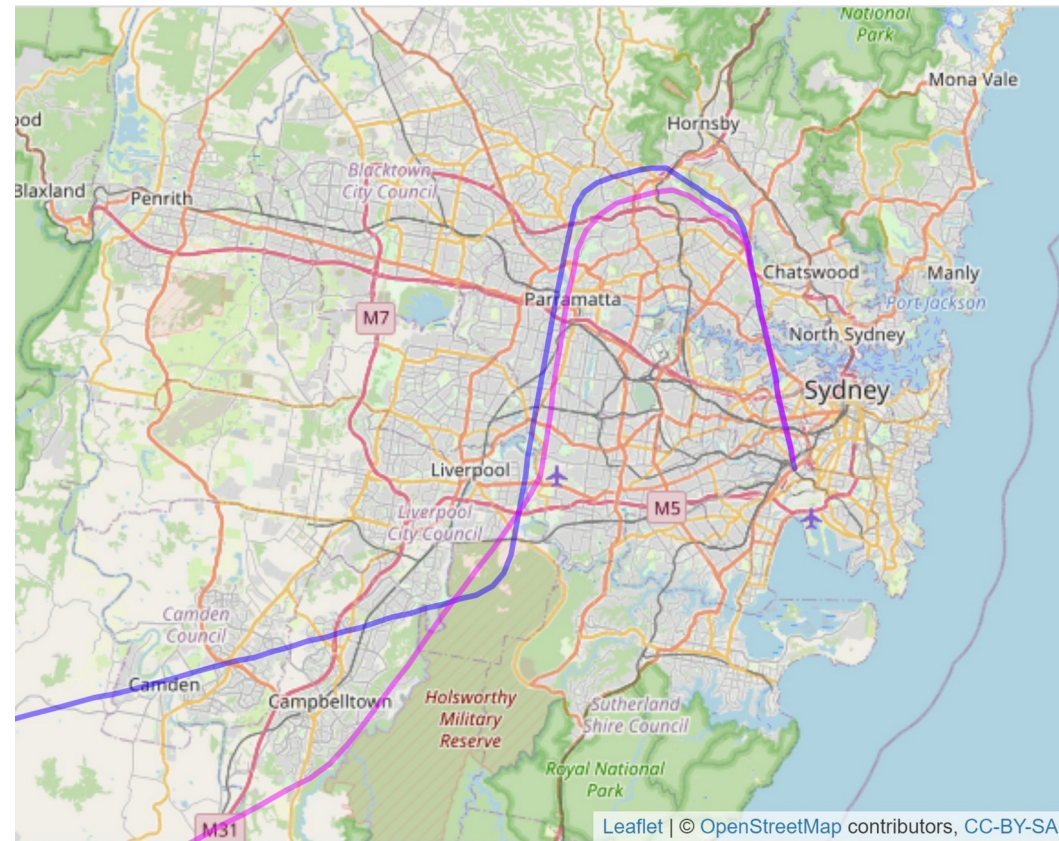
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Airplane Trajectory Reconstruction and Analysis Using GNSS-Based ADS-B Data

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- ADS-B airplane trajectory analysis and estimation
- Estimation methods and uncertainty quantification of PNT
- Statistical learning-based spatial predictive models
- Outlier detection
- Trajectory planning and estimation uncertainty (errors) in targeted environment conditions
- Ambient-based trajectory convergence towards corridors



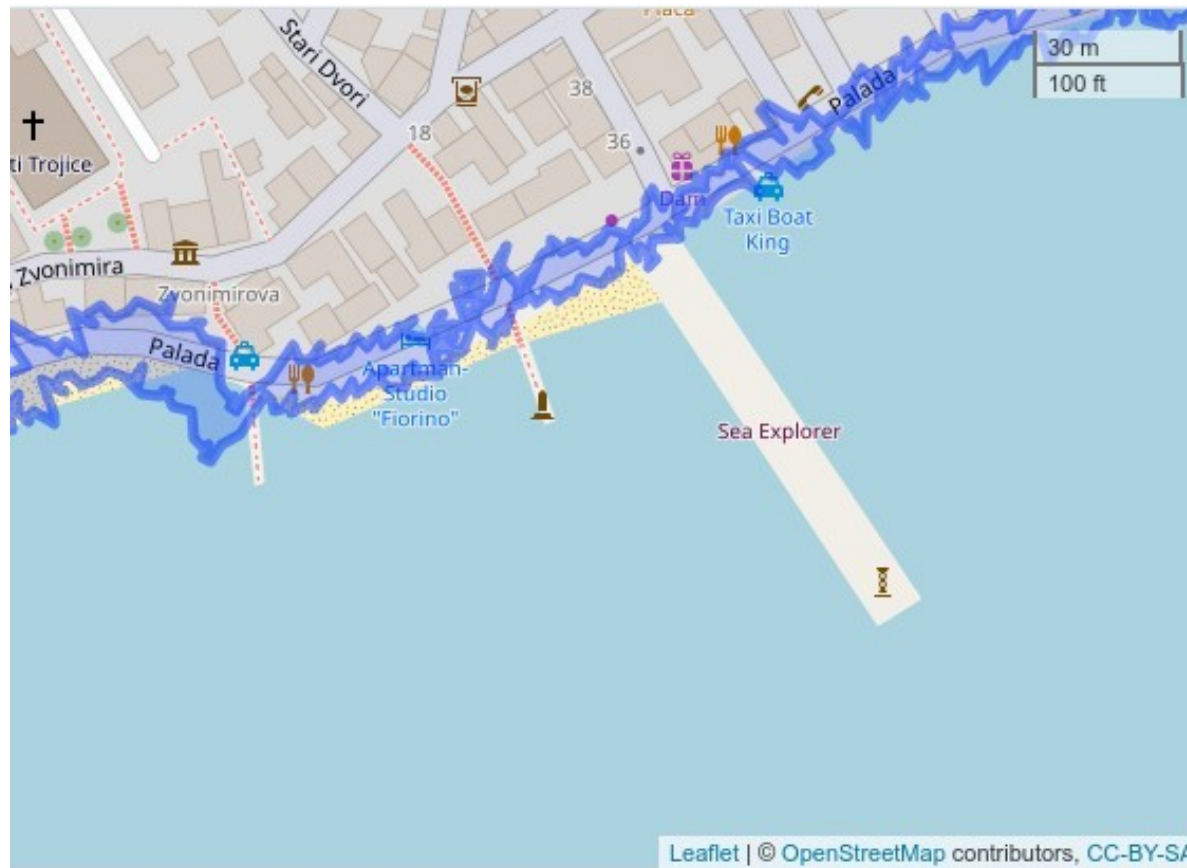
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- Spatial & PNT uncertainty quantification
- Estimation and quantification of positioning, navigation, spatial predictive models, trajectory planning and estimation uncertainty (errors)



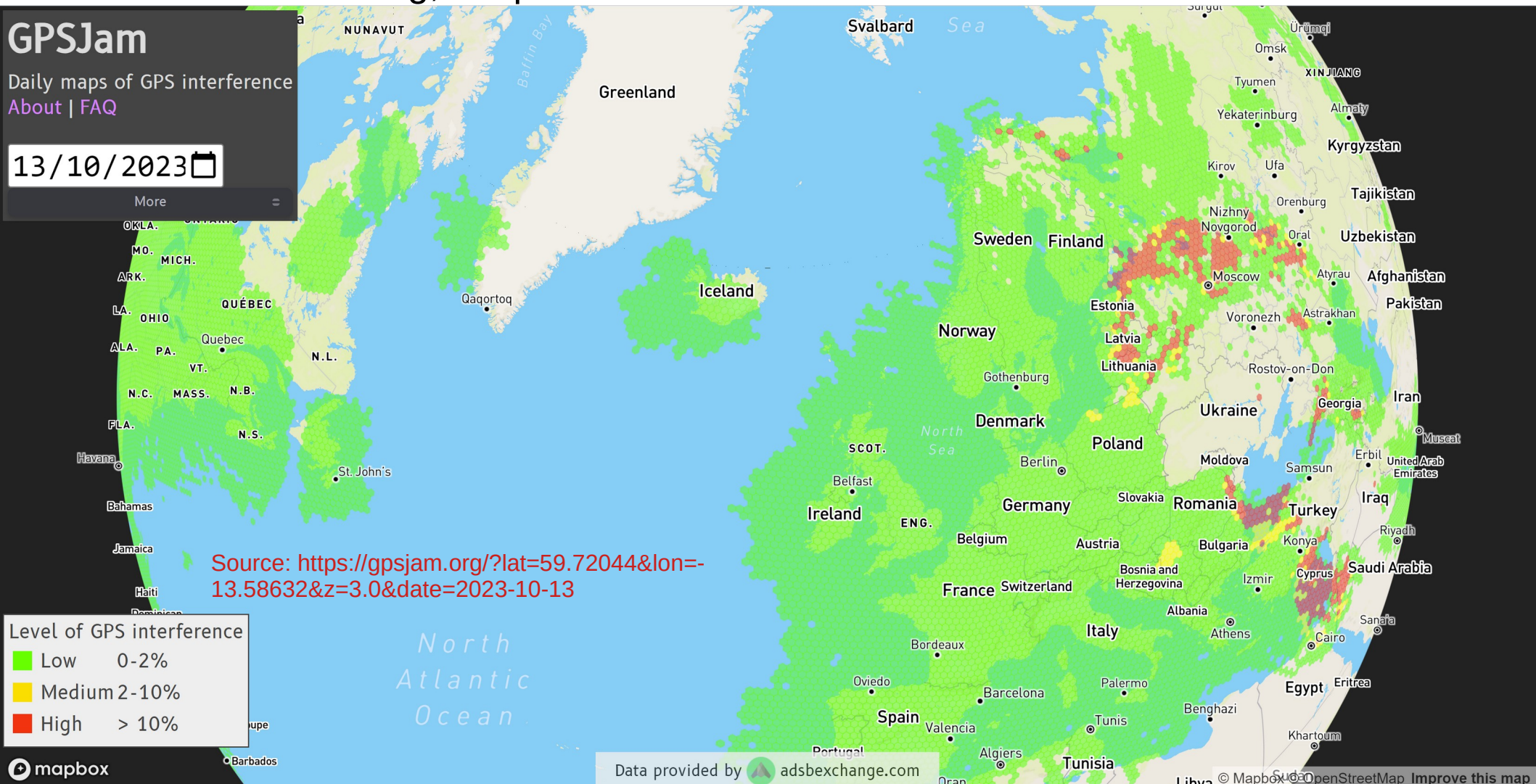
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- Spatial analysis of GNSS positioning uncertainty
- GPSJam.org, snapshot taken on 15OCT23 at 0941 CEST



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- Evidence and recommendations
- Formal ontology is established for trajectory description → statistical and machine learning analysis → programming frameworks available (R)
- Data collection through SDR receivers → large data bases of ADS-B observations are available in open access manner
- Stage is set → (1) **encourage international co-ordinated and collaborative framework for statistical methods development and trajectory analyses, inference and modelling**
 - (2) **facilitate international co-operation network on data exchange, analysis for targeted applications, and academic education in the field**

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- Laboratory for Spatial Intelligence,
Hrvatsko Zagorje Krapina University of Applied Sciences,
Krapina, Croatia



- Research, advisory, and academic education concerning:
 - Positioning, Navigation, and Timing (PNT) estimation methods, techniques, correction models, and algorithms
 - Spatial and PNT uncertainty quantification
 - Trajectory analysis, estimation/prediction, and convergence towards corridors
 - Spatial occupancy detection and modelling
 - Statistical learning-based spatial data modelling and predictions
- Research activities based on tailored software developed in the open source **R environment for statistical computing**

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- Reference

- Zheng, Y. (2015). Trajectory Data Mining: An Overview. Microsoft Research. Redmond, WA. Available at: <https://www.microsoft.com/en-us/research/publication/trajectory-data-mining-an-overview/>
- LaValle, S M. (2006). Planning algorithms. Cambridge University Press. Cambridge, UK. Available at: <http://lavalle.pl/planning/>
- Sun, J. (2019). Open Aircraft Performance Modeling Based on an Analysis of Aircraft Surveillance Data (PhD thesis). Delft University of Technology. Delft, the Netherlands. Available at: <https://tinyurl.com/2p8deydr>
- Gamulin, M. (2020). Određivanje pomorskih plovidbenih koridora zasnovano na statističkom učenju na zapisima automatskog sustava za identifikaciju plovila (in Croatian). Dept for Mathematics, Faculty of Science, University of Zagreb, Croatia. Available at: <https://repozitorij.pmf.unizg.hr/islandora/object/pmf:8475>

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- Reference

- Ceja, E G. (2021). Behavior Analysis with Machine Learning and R: A Sensors and Data Driven Approach. CRC Press. Boca Raton, FL. Available at: <https://enriquegit.github.io/behavior-free/>
- McLean, D J, and Skowron Volponi, M A. (2018). trajr: An R package for characterisation of animal trajectories. Ethology, 124, 440–448. Available at: <https://onlinelibrary.wiley.com/doi/full/10.1111/eth.12739>
- Mehdi Moradi, M, Pebesma, E, and Mateu, J. (2018). trajectories: Classes and Methods for Trajectory Data. J of Stat Software. Available at: <https://cran.r-project.org/web/packages/trajectories/vignettes/article.pdf>
- Clink, D J. (2020). behaviouR: R package and tutorials for teaching of fundamental concepts in behavior and ecology. Available at: <https://bookdown.org/djc426/behaviouR-R-package-tutorials/>

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- Reference

- Junzi, S. (2021). The 1090 Megahertz Riddle. A Guide to Decoding Mode S and ADS-B Signals. TU Delft Publishing. Delft, The Netherlands. Available using doi: <https://doi.org/10.34641/mg.11>
- OpenSky Network. (2023). Current situation, data archive, documentation. Available at: <https://opensky-network.org>
- OpenSky Network. (2023). Scientific datasets. Available at: <https://opensky-network.org/data/datasets>
- OpenSky Network. (2023). Data tools. Available at: <https://opensky-network.org/data/data-tools>
- Davey, S, et al. (2016). Bayesian Methods in the Search for MH370. Springer Open. Available at: <https://link.springer.com/book/10.1007%2F978-981-10-0379-0>

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- Reference (Laboratory for Spatial Intelligence, HZKUAS)
- Filjar, R. (2022). An application-centred resilient GNSS position estimation algorithm based on positioning environment conditions awareness. Proc ION ITM 2022, 1123 - 1136. Long Beach, CA. doi: 10.33012/2022.18247
- Stoyanovski, B, Iliev, T, Cesarec, R, Filjar, R. (2022). Spatial Machine Learning Personal Mobility Predictive Model Trained with Smartphone-Collected Trajectory Data. The Journal of CIEES, 2(2), 7–12. doi: <https://doi.org/10.48149/jciees.2022.2.2.1%20>
- Kalaminec, H, Popović, I, Spudić, R, Filjar, R. (2022). Mobility patterns as contributors to Covid-19 spread in Croatia. AIP Conference Proceedings 2570: Proc of International Scientific Conference on Communications, Information, Electronic and Energy Systems - CIEES 2021, 020001-1-020001-7. Ruse, Bulgaria. doi: <https://doi.org/10.1063/5.0099921>
- Filjar, R, Sklebar, I, Horvat, M. (2020). A Comparison of Machine Learning-Based Individual Mobility Classification Models Developed on Sensor Readings from Loosely Attached Smartphones. Communications - Scientific Letters of the University of Zilina, 22(4), 153-162. doi: <https://doi.org/10.26552/com.C.2020.4.153-162>

Happy 50th Birthday, GPS!



**INTERNATIONAL
GNSS DAY**

10.23

In recognition of the indispensable role that Global Navigation Satellite Systems (GNSS) play in shaping the modern world.

Source: ION,
<https://www.ion.org/>

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Thank you for your attention!

With an invitation to
Baška SIF (Spatial Information Fusion) Forum
to be held in Baška, Krk Island, Croatia
22nd - 26th September, 2024

Professor Dr Renato Filjar, FRIN
Faculty of Engineering, University of Rijeka, Croatia, and
Laboratory for Spatial Intelligence,
Hrvatsko Zagorje Krapina University of Applied Sciences, Croatia
E-mail: renato.filjar@gmail.com