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SATERA PPT: A Performance Prediction Tool for Satellite-Based Air Traffic Independent Localization and Surveillance †

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Abstract

This paper presents the Performance Prediction Tool developed within the SATERA project. The tool evaluates the performance of a space-based composite ADS-B and multilateration system for independent aircraft localization. It uses receivers deployed onboard a constellation of LEO satellites. Multilateration can be evaluated using time-based measurements, as well as additional measurements such as, frequency and angle of arrival of the received signals. The tool is based on the evaluation of the Cramér–Rao lower bound and it is implemented in MATLAB with a user-friendly graphical interface. The tool allows the user to define the satellite constellation, link budget, measurement types and errors, and to simulate the system performance over an aircraft trajectory or an area. Moreover, the outputs include DOP, number of visible satellites and system availability, which can be visualized and exported for further analysis.

Keywords: satellite localization; CRLB; multilateration; performance tool; ADS-B; ATC

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1. Introduction

This work is part of the project SATERA (space-based composite ADS-B and multilateration system validation through scalable simulations) [1], funded by SESAR JU and HORIZON Europe [2]. SATERA proposes a space-based composite ADS-B (Automatic Dependent Surveillance-Broadcast) and E-MLAT (Enhanced Multilateration) system, which uses receivers onboard small low Earth orbit (LEO) satellites. It aims to develop and validate a GNSS-independent air traffic control (ATC) surveillance solution able to provide an independent localization of the aircraft and integrity parameters to monitor the onboard-derived aircraft position. Such a system would be particularly valuable when GNSS data are unavailable, unreliable, or under intentional interference (e.g., spoofing or jamming), and in remote regions such as oceans or deserts where ground-based surveillance infrastructure is not available. It can help improve the air traffic capacity, security and safety over remote areas, as well as reduce the aviation environmental footprint by enabling more efficient trajectory-based operations (TBOs).

E-MLAT relies on the joint processing of measurements extracted from ADS-B signals received onboard LEO satellites. As in traditional ground-based MLAT systems, time of arrival (TOA) measurements are used; however, in this case, they are also complemented by frequency of arrival (FOA) and angle of arrival (AOA) observations. Depending on the chosen measurement types, the localization performance may vary. For this reason, one of SATERA's objectives was to develop a Performance Prediction Tool (PPT) able to forecast the performance achievable under multiple configurations. The PPT represents one of the key outcomes of the project, and it is fundamental to design and evaluation of the satellite constellation, the ADS-B receiver parameters, and the types of measurements to be combined.

The maximum achievable performance is assessed in terms of the achievable Root Mean Square (RMS) error through the use of the Cramér–Rao lower bound (CRLB) for all possible combinations of measurement types and for different constellation and ADS-B receiver parameters. The PPT also integrates CRLB computations with a graphical user interface (GUI), allowing one to simulate the expected performance of the system. Key features include:

1. *Measurement Configuration*: Selection of optimal combinations of TOA, FOA, and AOA measurements, considering satellite availability, geometric factors, and measurement error models.
2. *Constellation Design*: Ability to evaluate various satellite constellation configurations.
3. *Simulation and Visualization*: Dynamic simulation of system performance metrics, including CRLB, Dilution of Precision (DOP), and availability, with visualization capabilities for trajectories and area-based analyses.

By tweaking the scenario parameters, it was possible to find all the configurations that can achieve the desired localization accuracy and system availability, where availability is defined as the percentage of time during which the system can localize the user with an error lower than a given threshold; for example, 350 m is the ATC requirement for wide-area multilateration en-route applications [3].

Furthermore, the tool can generate time-evolving maps illustrating system performance over entire areas as the satellite constellation moves.

Overall, the PPT serves as a critical component in the iterative process of system validation and improvement within the SATERA project, providing valuable insights into the performance of the proposed space-based surveillance system. Moreover, it can be used in future applications for the optimization or evaluation of similar systems.

The rest of this paper is organized as follows: Section 2 presents the methodology, the CRLB mathematical formulations and the details of the MATLAB implementation (https://www.mathworks.com/products/matlab.html (accessed on 3 November 2025)); Section 3 shows the results of the final implementation, with example uses of the PPT; and Section 4 discusses the outcomes of this work, concluding the paper.

2. Methodology

The MATLAB tool is based on the implementation of the CRLB for all the measurement types considered (TOA, FOA and AOA). Then, the PPT is completed with a GUI that allows the user to compute the performance of a complete system in all the given configurations.

The PPT aims at evaluating the SATERA system while setting the following parameters as inputs:

- Satellite constellation parameters.
- Receiver link budget.
- Measurement types used.
- Measurement errors.

2.1. CRLB Theory

The CRLB [4] is used as a performance indicator for the SATERA system, as it provides the lower bound for the measurement error covariance matrix of the aircraft position estimator. This indicator alone can validate whether a system architecture can perform better in one configuration or another.

The first step in computing the CRLB is to provide a formulation for the E-MLAT measurements *characteristic equations*. These are the equations that express the relationship between the state vector $\boldsymbol{\theta}$ of the aircraft to be estimated (e.g., its position) and the measurement observed onboard the satellite (e.g., a timestamp). $\boldsymbol{\theta}$ depends on the measurement types used.

Considering the common case of measuring the time of arrival at the receiver (satellite), the TOA measured on the i-th satellite is expressed as follows:

$$m_i^{TOA}(\boldsymbol{\theta}) = TOA_i(\boldsymbol{\theta}) + n_i^{TOA}(\boldsymbol{\theta}) = \frac{1}{c}\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2} + dt_u + n_i^{TOA}(\boldsymbol{\theta}) \quad (1)$$

where c is the speed of light; (x, y, z) are the aircraft coordinates; (x_i, y_i, z_i) are the satellite coordinates; dt_u is the clock bias between the aircraft and the satellite clocks; and n_i^{TOA} is the TOA measurement noise. Note that the coordinates are expressed in the Earth-Centered Earth-Fixed (ECEF) reference frame and will be used as such throughout the rest of the paper, unless otherwise specified. In this case, the state vector is composed of the aircraft coordinates and the aircraft clock bias, that takes into account the unknown transmission time of the ADS-B message:

$$\boldsymbol{\theta} = [x, y, z, dt_u]^T \quad (2)$$

If the satellite is capable of estimating the frequency of arrival onboard, the FOA measured on the i-th satellite can be derived as follows:

$$m_i^{FOA}(\boldsymbol{\theta}) = FOA_i(\boldsymbol{\theta}) + n_i^{FOA}(\boldsymbol{\theta}) = f_0\left(\frac{v_{rel_i}(\boldsymbol{\theta})}{c}\right) + f_b + n_i^{FOA}(\boldsymbol{\theta}) \quad (3)$$

where $v_{rel_i}(\boldsymbol{\theta})$ is the relative velocity between aircraft and satellite; f_b is the frequency bias between transmitter and receiver; and n_i^{FOA} is the FOA measurement noise. In this case, the state vector is composed of the aircraft position, velocity and frequency bias:

$$\boldsymbol{\theta} = [x, y, z, v_x, v_y, v_z, f_b]^T \quad (4)$$

Finally, if the satellite is capable of estimating the angle of arrival, the vertical and horizontal AOA measured on the i-th satellite are as follows:

$$m_i^{AOA,V}(\boldsymbol{\theta}) = AOA_i^V(\boldsymbol{\theta}) + n_i^{AOA,V}(\boldsymbol{\theta}) = \tan^{-1}\left(\frac{z-z_i}{\sqrt{(x-x_i)^2+(y-y_i)^2}}\right) + n_i^{AOA,V}(\boldsymbol{\theta}))$$
$$m_i^{AOA,H}(\boldsymbol{\theta}) = AOA_i^H(\boldsymbol{\theta}) + n_i^{AOA,H}(\boldsymbol{\theta}) = \tan^{-1}\left(\frac{y-y_i}{x-x_i}\right) + n_i^{AOA,H}(\boldsymbol{\theta})) \quad (5)$$

where $n_i^{AOA,V}$ and $n_i^{AOA,V}$ are the vertical and horizontal AOA measurement noises, and the state vector becomes

$$\boldsymbol{\theta} = [x, y, z]^T \quad (6)$$

Note that the AOA measurements are expressed in the satellite local coordinates reference frame, North–East–Down (NED), and a transformation is needed to merge them with the other measurement types, which are expressed in the ECEF reference frame. The transformation matrix used to convert ECEF coordinates to NED coordinates is as follows

$$\mathbf{C}_{NED}^{ECEF} = \begin{bmatrix} -\sin(\phi)\cos(\lambda) & -\sin(\phi)\sin(\lambda) & \cos(\phi) \\ -\sin(\lambda) & \cos(\lambda) & 0 \\ -\cos(\phi)\cos(\lambda) & -\cos(\phi)\sin(\lambda) & -\sin(\phi) \end{bmatrix} \tag{7}$$

where ϕ and λ are the NED frame's origin latitude and longitude.

The CRLB formulation states that the estimator variance cannot be smaller than the Fisher Information [4]. Assuming the case of a multivariate Gaussian distribution with zero mean, the measurement error covariance matrix lower bound is equal to the Fisher Information Matrix (FIM):

$$\boldsymbol{Cov}(\boldsymbol{\theta}) = \boldsymbol{I}(\boldsymbol{\theta})^{-1} \tag{8}$$

Assuming that the covariance matrix of the measurement errors does not strongly depend on the state vector $\boldsymbol{\theta}$, the FIM can be written as

$$\boldsymbol{I}(\boldsymbol{\theta}) = \boldsymbol{J}^T \boldsymbol{N}(\boldsymbol{\theta})^{-1} \boldsymbol{J} \tag{9}$$

where $\boldsymbol{N}(\boldsymbol{\theta})$ is the measurement error covariance matrix, and $\boldsymbol{J}$ is the Jacobian matrix of the characteristic equations, which can be combined in case of multiple measurement types at once.

The CRLB can be computed along the horizontal, vertical and 3D dimensions [5]. For the horizontal and vertical dimensions, the covariance matrix has to be projected into the aircraft local East–North–Up (ENU) reference frame $\boldsymbol{Cov}(\boldsymbol{\theta_{enu}})$ by exploiting a rotation matrix similar to the previous one. The horizontal (H) and vertical (V) CRLB values are then computed as

$$CRLB^H = \sqrt{\mathbf{Cov}_{11}(\boldsymbol{\theta_{enu}}) + \mathbf{Cov}_{22}(\boldsymbol{\theta_{enu}})} \tag{10}$$

$$CRLB^V = \sqrt{\mathbf{Cov}_{33}(\boldsymbol{\theta_{enu}})} \tag{11}$$

The 3D CRLB can be computed in any reference frame, giving the same result:

$$CRLB^{3D} = \sqrt{\mathbf{Cov}_{11}(\boldsymbol{\theta}) + \mathbf{Cov}_{22}(\boldsymbol{\theta}) + \mathbf{Cov}_{33}(\boldsymbol{\theta})} \tag{12}$$

Note that $\boldsymbol{Cov}(\boldsymbol{\theta})$ is a square matrix, so the indices refer to the diagonal elements.

Finally, having determined the lower bound of accuracy for the horizontal error, it is possible to validate the localization system by comparing it with the minimum necessary accuracy.

Repeating this process for the different epochs of the constellations and the different waypoints of a trajectory makes it possible to verify the performance along a real trajectory during its evolution over time or within a coverage area.

2.2. Tool Characteristics

The PPT was developed in MATLAB using the App Designer environment. The propagation of the constellation and the analysis of communication between aircraft and satellites were implemented using the Aerospace Toolbox [6] and Satellite Communication Toolbox [7].

The user can choose to run analyses over either trajectories or areas. For trajectory analyses, there are a few predefined trajectories, though users may define custom trajectories by specifying origin and destination coordinates. The tool automatically computes the great-circle (orthodromic) path between the two points, and allows the configuration of the departure time, total flight duration, and temporal resolution (sampling period between waypoints).

For area-based analyses, users may either select one of the predefined regions or specify custom latitude and longitude boundaries. The grid resolution can be adjusted to control the spatial density of analysis points, and simulations can be performed over time windows defined by the user (start/stop times and time step), enabling time-evolving coverage evaluation. Aircraft parameters such as altitude, velocity, azimuth, and elevation are also configurable.

2.2.1. Constellation

The satellite constellation can be defined by the user by providing the following parameters: (i) *type*: Walker Star or Walker Delta; (ii) *orbit propagator*: two-body-Keplerian, SGP4 (Simplified General Perturbations-4) or SDP4 (Simplified Deep-Space Perturbations-4); (iii) *altitude*; (iv) *inclination*; (v) *number of planes*; (vi) *number of satellites per plane*; and (vii) *phasing*. Alternatively, existing constellations can be imported using Two-Line Element (TLE) files.

At each simulation step (epoch), the tool calculates satellite positions and determines line-of-sight (LoS) visibility with the aircraft, taking into account Earth curvature and elevation masks.

2.2.2. Link Budget

The link budget is computed to evaluate whether the ADS-B signal can be detected by the satellites in LoS with the aircraft. The user can set the following parameters: (i) *signal frequency*; (ii) *transmitter power*; (iii) *transmitter antenna gain*; (iv) *receiver antenna gain*; (v) *receiver bandwidth*; (vi) *receiver noise factor*; (vii) *total losses*; and (viii) *receiver sensitivity*.

This computation enables realistic availability estimation by excluding satellites whose received power falls below the sensitivity threshold.

2.2.3. Measurement Types and Errors

The tool supports multiple measurement configurations, allowing combinations of TOA, FOA, and AOA (horizontal and vertical). When frequency measurements are used, it is also possible to estimate the aircraft velocity.

Measurement errors are modeled as zero-mean Gaussian random variables, with user-defined standard deviations. For each measurement type, the user can separately set the standard deviation value due to different error sources, such as:

- *Time*: Ionospheric and tropospheric delays, receiver noise, satellite position and clock errors, and multipath.
- *Frequency*: Ionospheric and tropospheric offset, receiver noise, satellite velocity error and frequency drift, and multipath.
- *Angle*: Ionospheric and tropospheric bending, receiver noise, satellite position and attitude errors, and multipath.

The tool combines these contributions to compute the total standard deviation for each measurement type.

2.2.4. Outputs

The PPT generates different figures that illustrate the system performance:

- *CRLB*: Horizontal, vertical, and 3D RMS along a trajectory or over an area.
- *DOP*: Horizontal, vertical, and 3D Dilution of Precision along a trajectory or over an area.

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- *Number of satellites*: The number of available satellites along the trajectory or over the area.
- *Map*: A map showing the trajectory or area to be analyzed.
- *Constellation*: The globe of the Earth with the constellation design at the start of the simulation.
- *Availability*: A map of availability over the trajectory or area with a tunable threshold value.

The user can also export the following computed data in different datasets: (i) *Waypoints*: Coordinates of the waypoints analyzed in latitude, longitude, altitude. (ii) *Waypoint velocity*: Velocity of the aircraft at each waypoint. (iii) *Timestamps*: Timestamps of each waypoint analyzed. (iv) *Constellation parameters*: Configuration of the satellite constellation used. (v) *TLE file*: TLE set of each satellite in the constellation. (vi) *Link budget*: Link budget parameters used. (vii) *Number of satellites*: Number of available satellites at each waypoint. (viii) *Sigma values*: Standard deviations of the measurement errors used. (ix) *CRLB*: Horizontal, vertical and 3D RMS at each waypoint. (x) *DOP*: Horizontal, vertical and 3D DOP at each waypoint. (xi) *Availability*: Availability at each waypoint.

The above can be imported in MATLAB for further analysis.

3. Results

This section presents some examples of the PPT use, showing the GUI and some of the outputs.

Figure 1 shows the GUI setup for the configuration of the constellation and link budget parameters, together with an image of the satellites orbits.

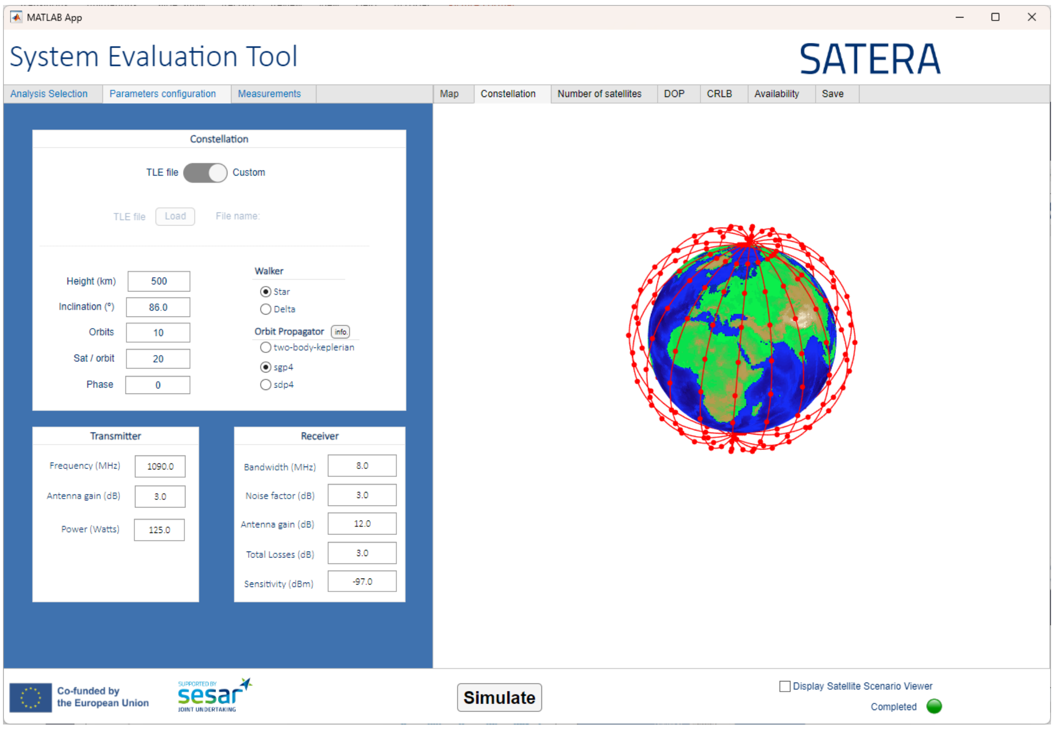


Figure 1. Setup of constellation and link budget.

Figure 2 shows the GUI setup for the configuration of the trajectory parameters, together with an image of the trajectory on the map.

Figure 3 shows a few examples of output figures: (a) the number of visible satellites on all the trajectory waypoints; (b) the horizontal CRLB on all the trajectory waypoints; (c) the horizontal DOP over an area at a given time.

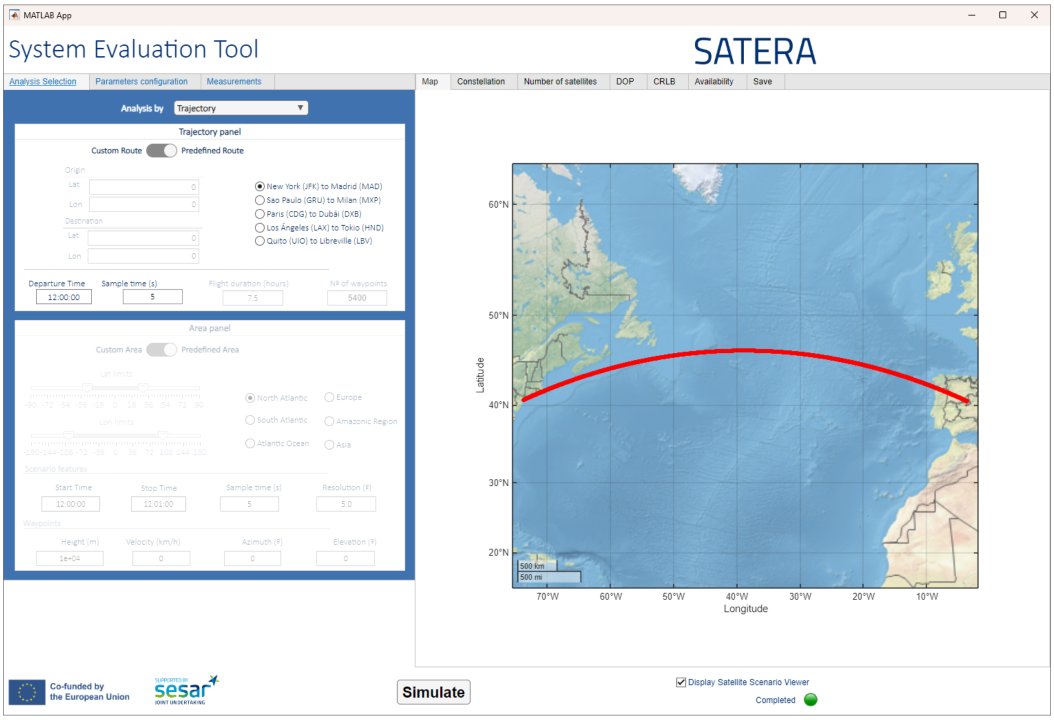
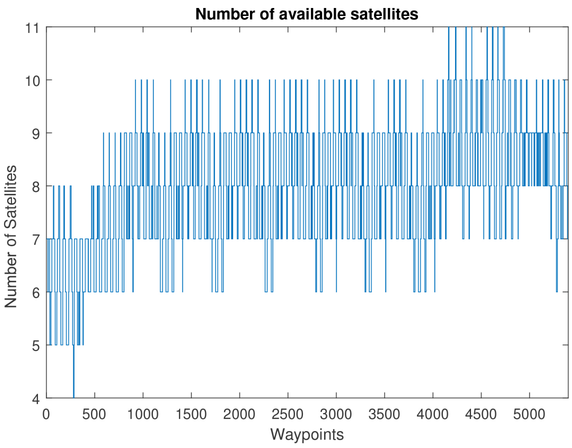
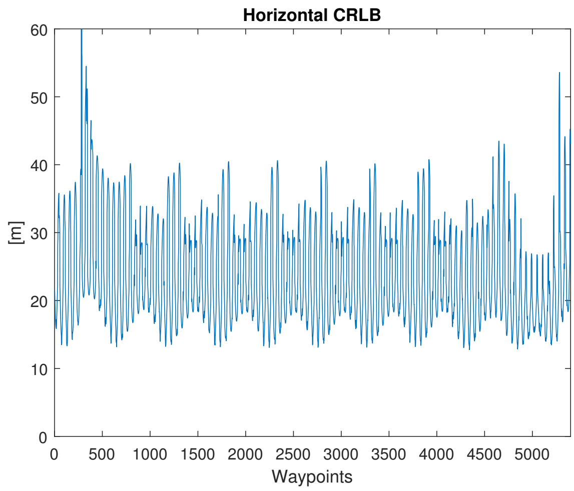


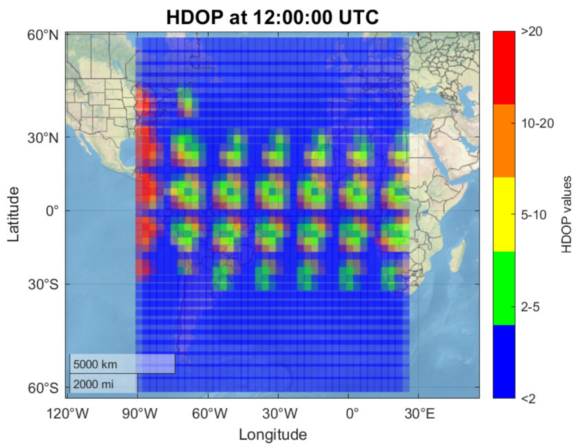
Figure 2. Setup of simulated trajectory.



(**a**)



(**b**)



(**c**)

Figure 3. Examples of output figures: (**a**) number of visible satellites along a given trajectory; (**b**) horizontal CRLB along a given trajectory; (**c**) horizontal DOP over a given area.

4. Conclusions

This paper presented the Performance Prediction Tool developed within the SATERA project to evaluate the performance of a space-based ADS-B and E-MLAT system for independent aircraft localization. The tool is based on the Cramér–Rao lower bound and it is implemented in MATLAB with a user-friendly graphical interface. The PPT allows the user to define the satellite constellation, link budget, measurement types and errors, and to simulate the system performance over a trajectory or an area. The outputs include CRLB, DOP, number of visible satellites and availability, which can be visualized and exported for further analysis.

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Data Availability Statement: The PPT is available on Zenodo: doi.org/10.5281/zenodo.17657765.

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