NASA/TM—20220015612

Cooperative Separation in Upper Class E Airspace

Baseline Functional Requirements for Enabling Cooperative Separation

Hyo-Sang Yoo
Universities Space Research Association, Moffett Field, California

Jinhua Li
Universities Space Research Association, Moffett Field, California

Ray Torres
ASRC Federal Data Solutions LLC., Moffett Field, California

Richard H. Jacoby
ASRC Federal Data Solutions LLC., Moffett Field, California

Jeffrey Homola
NASA Ames Research Center, Moffett Field, California

Christopher O'Hara
Universities Space Research Association, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

October 2022

NASA STI Program Report Series

The NASA STI Program collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the "General" help request type.

NASA/TM—20220015612

Cooperative Separation in Upper Class E Airspace

Baseline Functional Requirements for Enabling Cooperative Separation

Hyo-Sang Yoo
Universities Space Research Association, Moffett Field, California

Jinhua Li
Universities Space Research Association, Moffett Field, California

Ray Torres
ASRC Federal Data Solutions LLC., Moffett Field, California

Richard H. Jacoby
ASRC Federal Data Solutions LLC., Moffett Field, California

Jeffrey Homola
NASA Ames Research Center, Moffett Field, California

Christopher O'Hara
Universities Space Research Association, Moffett Field, California

October 2022

Acknowledgments

This work is under NASA Air Traffic Management – eXploration (ATM-X) Project. The authors wish to acknowledge the valuable inputs and support provided by our industry partners and the FAA. We would like to thank our fellow NASA researchers for their support.

This report is available in electronic form at

https://www.sti.nasa.gov

Table of Contents

1. Introduction

1.1 Purpose

This document presents baseline functional requirements for a prototype NASA research Upper Class E Traffic Management (ETM) system to enable the cooperative separation concept [1, 2]. The baseline functional requirements are developed by incorporating inputs from NASA and the FAA researchers and engineering staff, and industry partners while accounting for the unique performance characteristics and mission needs of various existing and future ETM vehicle types. The functionalities include information sharing for situational awareness, conformance monitoring, and operating practices for cooperative separation. Several realistic traffic scenarios were built to test, validate, and demonstrate the cooperatively managed operation in the ETM environment and the associated capabilities in a simulation environment.

1.2 Background

In the United States, Upper Class E airspace represents high altitude airspace at and above FL600 (60,000 ft pressure altitude). Reduced atmospheric density in the upper stratosphere and mesosphere, the primary airspace for ETM operations, has previously impeded airspace access. However, a wide range of new vehicles—e.g., High Altitude Long Endurance (HALE) balloons, HALE airships, supersonic and hypersonic aircraft—are expected to access the Upper Class E airspace more regularly due to recent innovations in autonomy and advances in aviation technologies (e.g., airframe and electric propulsion technology) [1, 3]. Such advancements are expected to enable new vehicle types to achieve mission objectives more safely and cost-effectively.

While advances have been made in the development of high-altitude flight technologies and platforms, current National Airspace System (NAS) infrastructure and Air Traffic Management (ATM) services provide limited air traffic management provisions for civil aircraft operations in the Upper Class E airspace. Although the FAA has established separation standards for surveillance (radar) and procedural (non-radar) operations in the Upper Class E environment, these standards have typically applied to military or State entities' operations (e.g., Military Authority Assumes Responsibility for Separation of Aircraft (MARSA) [1].

In response to this identified gap, the FAA, informed in part by NASA and industry, published an initial ETM Concept of Operations (ConOps) v1.0 [1]. The first version of the ConOps described Air Traffic Control (ATC) interactions with ETM operators transitioning to or from Upper Class E airspace and also operating just below FL600 in the Upper Class A airspace.

The Initial version of the FAA ConOps document also presented the foundational operating principles and vision for ETM operations near and above 60,000 ft. It is expected that "Radar and non-radar ATC services remain available to Instrument Flight Rules (IFR) aircraft above FL600 in ETM [1]." However, a key aspect of the ConOps document and the broader concept itself is that Upper Class E airspace operations present opportunities for an alternative traffic management concept that is not constrained by current limitations [1]. The subsequent version of the ConOps document is expected to provide a more comprehensive description of how the alternative traffic management approach could be practiced in such airspace. Currently, industry partners, FAA, and NASA are working together to identify cooperative separation strategies and solutions, including airspace equity and access rules, to further define the traffic management concept [3].

The ConOps document states that the development of the alternative traffic management concept for the ETM environment must [1]:

- *"Scale beyond the current NAS infrastructure and manpower resources to meet the needs of market forces;"*
- *"Support the management of operations where no air navigation service provider (ANSP) separation services are desired, appropriate, and/or available;"*
- *"Promote shared situation(al) awareness among Operators."*

As a precedent, Uncrewed Aircraft Systems (UAS) Traffic Management (UTM) has successfully introduced and practiced cooperative traffic management supported by industry-provided services. Within an ETM context, civil operators would be responsible for coordinating, executing, and managing operations within a regulatory framework under a paradigm similar to the UTM concept [4, 5] but uniquely tailored to the ETM environment. Thus, the UTM framework's foundational principles, architecture, and concept elements could be adopted, where applicable, for the ETM concept development [1]. The cooperative separation in the ETM environment is enabled by ETM operators cooperatively sharing flight intent and exchange information to identify strategic conflicts and collaboratively coordinate strategic deconfliction via an industry-defined set of operating practices, referred to as Cooperative Operative Practices (COPs).

This document provides a comprehensive description of the functional requirements for supporting the cooperative separation concept in the Upper Class E airspace. The functional requirements were developed with rapid prototyping in a newly developed ETM research simulation platform called ETMAutoSIM [See Appendix A and B for description]. The ETMAutoSIM is designed to demonstrate, test, and validate the functional feasibility of specific ETM principles and procedures using a scenario-based approach. The foundational operating principles and visions for the ETM environment stated in the FAA ETM ConOps v1.0 [1] were used as the basis during the functional requirements development. This baseline functional requirements document could serve as NASA's contribution to support the development of the subsequent version of the FAA's ConOps document. Moreover, the final product could be adopted as a part of the ETM ecosystem for the potential scenario-based live, virtual, and collaborative testing with industry partners.

1.3 Scope

The main focus of this document is on cooperative separation in the ETM environment (see Figure 1). Topics such as the design and organization of the cooperative airspace above Flight Level (FL) 600 as well as the climb and descent phases before entering and after exiting the cooperative airspace are outside the scope of this document. Such areas of research will be addressed in complementary activities such as those examining ATC and ETM interactions [6]. The initial regulatory framework and requirements of ETM and ATC interactions are well described in the FAA ETM ConOps v1.0 [1] with various use case scenarios, including management of contingency events (Please refer to the FAA ETM ConOps v.1.0 for more information).

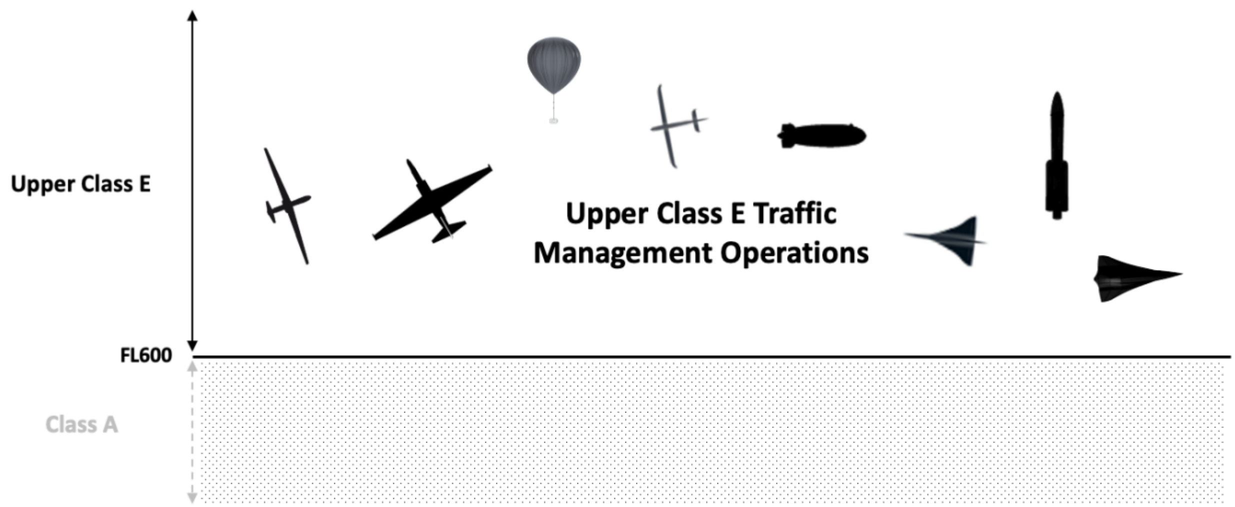


Figure 1: Schematic View of the Scope

A variety of new vehicle types are expected to enter the ETM environment. These new-entrant vehicles include: 1) Supersonic Transport (SST) carrying passengers, 2) HALE fixed-wing UAVs, 3) HALE balloons, and 4) HALE airships. The Upper Class E airspace will also be accessed by space launches, sub-orbital spaceflight operations, and hypersonic vehicles in the future. Those vehicle types will be operating together in the same airspace with wide-ranging performance characteristics—from stationary to extremely fast-moving—that are not common in other areas of the NAS.

Furthermore, there are various operating mission types such as constellation, point-to-point, and transitional operations. Those mission types have a wide variance of flight durations, from hours to months or even years. All these factors impose unique challenges for the ETM concept that must be accounted for in its development.

The cooperative separation concept development must account for substantial differences in vehicle performance characteristics and maneuverability profiles. In addition, the communication capabilities and Communications, Navigation, and Surveillance equipage of high-altitude vehicles operating in the ETM environment may differ from conventional aircraft, which must be considered during the cooperative separation concept development.

This document focuses on the ETM operations of low-speed HALE vehicle types with similar performance characteristics and missions, engaging in cooperative separation. For example, the HALE balloons may loiter to provide services for an extended duration up to many months and fly across multiple Flight Information Regions (FIRs). These balloons have very limited maneuverability. The HALE balloons are currently operational or ready to be deployed, thus requiring immediate solutions for the operations.

The functional requirements provided in this document present only a set of core functionalities to enable the cooperative separation in the ETM environment near and above FL600. The non-functional requirements—such as acceptable security level, communication latency, reliability of the system—are outside of the scope of this report. This document also does not specify airspace authorization, airspace constraints, flight data archiving (e.g., database design), and supplemental information acquisition. These topics require further discussion with industry partners and the FAA.

1.4 Intended Audience and Use

This document is not a formal standard. Rather, it is intended to guide the software modeling, design, and implementation of the baseline functional requirements for ETM systems to enable the cooperative separation concept. Also, it describes specific scenarios for each requirement. This report is an artifact from the NASA ATM-X xTM sur-project ETM research [7] designed to help converge on the cooperative separation concept. Hence, the document is intended to be a reference for the potential ETM operators to understand and help prepare the capabilities necessary, implement interoperable test systems, and lay the groundwork for the future mature specifications to effectively engage in cooperative separation.

1.5 Terms and Descriptions

This section provides description of several key terms used in this document.

- **Operational Intent (OI)**: OI is "a type of information that is exchanged between operators that can be used to identify strategic conflicts. It is four-dimensional (4D) (time and three-dimensional space) information that indicates, with a known a known level of confidence, where an aircraft will be at some given point in the future [1]."
  - OI bounds the intended flight operating volume. Operating volumes are 4D blocks of airspace with entry and exit times.
  - OI could be shared in a series of 4D OI volumes, which represents full flight intent prediction over the next *n* hours. The OI volumes could overlay each other due to uncertainties.
  - OI may be updated at a regular update rate using a "*rolling-window*" approach [8]. The approach enables high-altitude vehicles with less controllability to more frequently update their OI due to the relatively rapid accumulation of flight technical error. Moreover, it allows high-altitude vehicles with long-duration missions (e.g., weeks to months) to update their OI to support their operations.

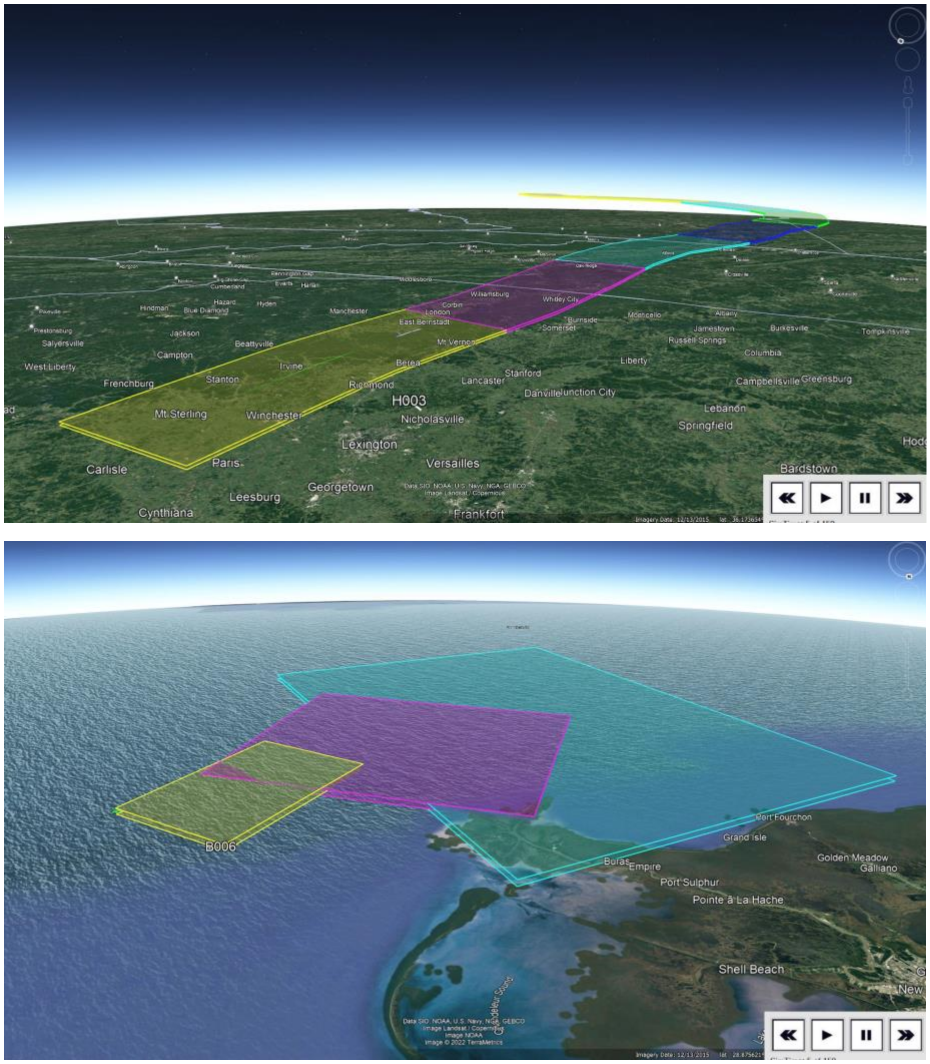


Figure 2: 4D OI examples (Top: OI of a vehicle with high maneuverability like HALE fixed-wing UAV, and Bottom: OI of a vehicle with limited/no maneuverability like HALE balloon): Each color-coded volume indicates one-hour OI volume (i.e., yellow represents OI between 0 to 1 hour; magenta represents OI between 1 to 2 hours; light blue represents OI between 2 to 3 hours)

The shape and size of the OI volume closely correlates with the vehicle's navigation performance capability. For example, vehicles with high maneuverability may share OI based on their specific 4D paths, with buffers in the vertical and lateral dimensions along the centerline that the vehicles could confidently adhere to. On the other hand, vehicles with low maneuverability may share OI based on their flight intent and uncertainty predictions. The uncertainties may grow quickly over the lookahead time horizon, possibly requiring very large areas. However, sharing an unnecessarily large size OI due to uncertainty could affect the efficient and fair access of the airspace.

Thus, restricting OI size could be required to support fair access of the airspace. However, the OI volume size restriction may adversely impact "the known level of confidence [1]," referred to in this document as the "Containment Confidence Level

(CCL)". Moreover, duration of each OI volume and OI update rate may need further investigation on their impact on the operations and the ability to maintain high CCL.

Standardization of sizes, update rate, duration, and the prediction horizons (*n*-hour) of OIs are an open research topic. Operators may agree to common OI sizes per vehicle type or other criteria to create transparency and predictability, with the potential cost of inflexibility in their operations.

- **Containment Confidence Level (CCL)**: Indicates the estimated level of confidence that the vehicle will stay safely within the OI volume. The CCL could be computed based on the probability of the vehicle staying within the OI volume [9]. Vehicles with high maneuverability can actively control their vehicles to stay within their OI volume with high CCL. Vehicles with low maneuverability could update their OI to ensure that the vehicles stay within their OI volume with high CCL. However, determining the CCL calculation methods in detail will require further investigation.

- **Strategic Conflict**: A situation where two or more OI volumes intersect in space and time.

- **Strategic Deconfliction**: A process of resolving conflict identified based on OI intersection via executing COPs that are collaboratively coordinated for strategic deconfliction.

- **Tactical Deconfliction**: A process of promptly executing required coordinated actions(s) to avoid an airborne conflict due to inexecution of strategic deconfliction.

- **Cooperative Operating Practices (COPs)**: A set of industry-defined operating rules and procedures for performing cooperative operations, encompassing cooperative separation for ensuring safe, efficient, and fair cooperative airspace usage.

2. Overview of Cooperative Separation Concept

The FAA envisions that "ETM operations above FL600 are predominantly cooperative; that is, they are coordinated and managed by the Operators themselves. ATC manages operations above FL600 upon request [1]." A key aspect of cooperative operations in the ETM concept is the ability to incorporate an approach to separation management that does not burden air traffic services.

The ConOps states that **"**cooperative separation is achieved via shared intent, shared awareness, strategic deconfliction of operations, conformance monitoring, technologies supporting strategic deconfliction, and the establishment of procedural rules of the road (e.g., right-of-way rules) [1]."

Figure 3 depicts the cooperative separation process. It is intended to serve as a high-level framework to identify the series of activities involved, areas of functionalities to be developed, and necessary information for performing each process to ensure cooperative separation between ETM operations.

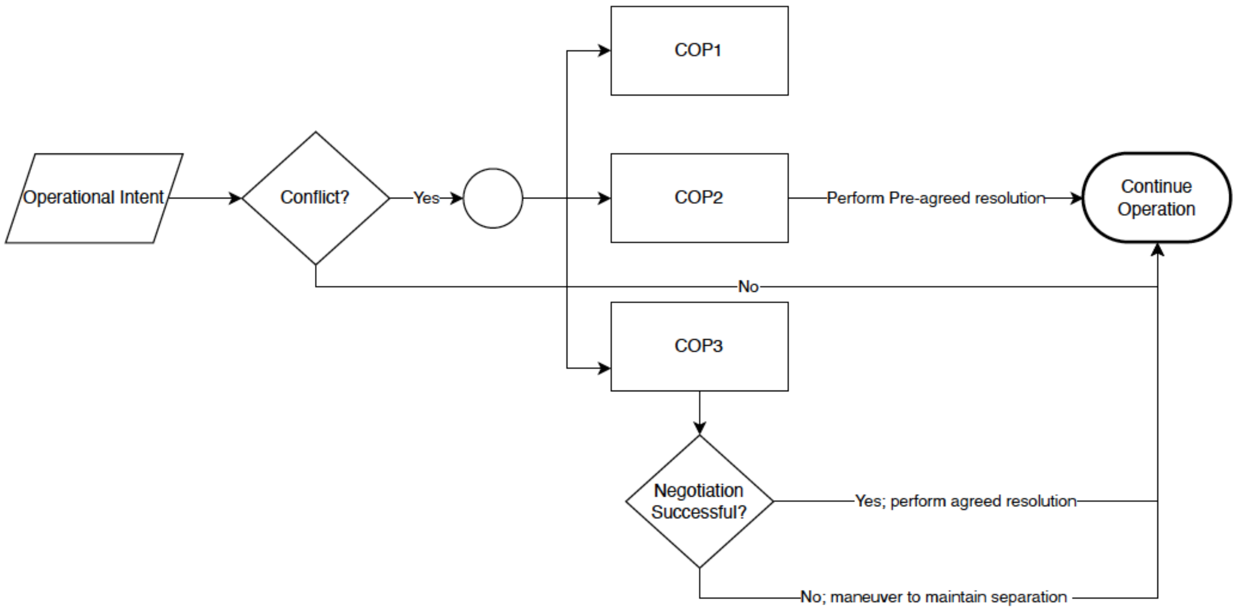


Figure 3: The Cooperative Separation Process in the ETM Cooperative Environment

Cooperative separation will be organized, coordinated, and managed by a group of ETM operators through a set of agreed-upon COPs. Through collaborative discussions with the FAA and industry stakeholders, three types of COPs have been identified as proposed strategic deconfliction methods:

- COP1 serves as the baseline (default) strategic deconfliction method based on a First-Reserved-First-Served (FRFS) principle
- COP2 indicates a pre-agreed method between ETM operators. The ETM operators coordinate their preferences and cooperatively decide on a strategic deconfliction strategy (e.g., a fixed-wing aircraft operator pre-agreed to revise its OI when it is strategically conflicting with the OI of a balloon operator). Such arrangements or negotiations are to be made in advance of operations.
- COP3 allows the ETM operators to communicate directly and make real-time decisions in an *ad-hoc manner*. This method may be available in the absence of pre-established bilateral agreements between ETM operators. Also, this method must be available to address unforeseen circumstances. For example, a solar-powered HALE vehicle may not be capable of moving due to a low state-of-charge condition.

COP1 and COP2 take a standard rule-based approach, which ensures outcomes are produced in a timely manner. COP3 takes an ad-hoc approach, which relies on a negotiation process that provides flexibility but may not guarantee that a solution is reached within the imparted time. In this case, the right-of-way rules specified in 14 CFR § 91.113 could be used as the initial default mechanism for tactical deconfliction to determine who has priority in a situation where no agreement is reached. However, setting this as the default may enable certain ETM operators to game the negotiation process during the strategic deconfliction process, since the outcome is always known beforehand. Hence, further investigation of alternative tiebreaker mechanisms is needed.

2.1 Executing Cooperative Separation in the ETM Environment

The cooperative separation process is managed by ETM operators, service suppliers, and the FAA. Unlike conventional air traffic management, ATC is not expected to be directly involved in cooperative operations in the ETM environment.

Specifically, ETM operators are responsible for operation planning with a focus on strategic deconfliction and collective situation(al) awareness. Throughout the cooperative separation process, the FAA maintains responsibility for airspace access and authorization in accordance with their regulatory and operational authority. A third-party service supplier could support the communication and coordination of cooperative separation between ETM operators. The role and responsibility of each participant could be further assisted by automated decision-making capabilities or reallocating tasks to other services to streamline the process and improve the scalability of the operations.

A key component of cooperative separation in the ETM environment is the ESS (ETM Service Supplier). An ESS is designed to serve a similar role as the USS in the UTM architecture [4, 5]. Per the FAA ETM ConOps v1.0 [1], the roles of an ESS could be as follows:

1) *"Act as a communications bridge between ETM participants to support Operators' abilities to meet the regulatory and operational requirements for Upper Class E operations;"*
2) *"Provide Operators with information about planned operations in and around a volume of airspace so that they can ascertain the ability to safely and efficiently conduct their mission;"*
3) *"Archive operations data in historical databases for analytics, regulatory, and Operator accountability purposes."*

An ESS may also support "operations planning, intent sharing, strategic deconfliction, conformance monitoring, and other airspace management functions [1]." This type of service is intended to support cooperative separation without the need for direct FAA involvement. The service is intended to facilitate the planning and decision-making of ETM operators and provide all parties with a common operating picture.

Figure 4 shows the system architecture for data exchange and shared situational awareness among ANSP, ESS, and the ETM operators. In this architecture, a gateway similar to the UTM Flight Information Management System (FIMS) [10] connects ETM operations to the ANSP. The block diagram shows the potential presence of multiple ESSs to provide services in a federated manner. Such inter-ESS communication and coordination could be achieved via "ESS Discovery." The ESS Discovery service is designed to support multiple ESS communication by sharing their coverage areas and endpoints for data exchange. The ESS Discovery would be similar to that of the UTM DSS concept [10]. The ETM operator is responsible for enabling ETM vehicle operation(s) controlled by a Pilot In Command (PIC) and/or Remote Pilots In Command (RPIC). Both the ETM operator and the PIC/RPIC could be a person or an entity. A set of ETM vehicle operations could be supported either by self-provisioning or third-party engagement. The block diagram could serve as a subsystem in the overall ETM ecosystem.

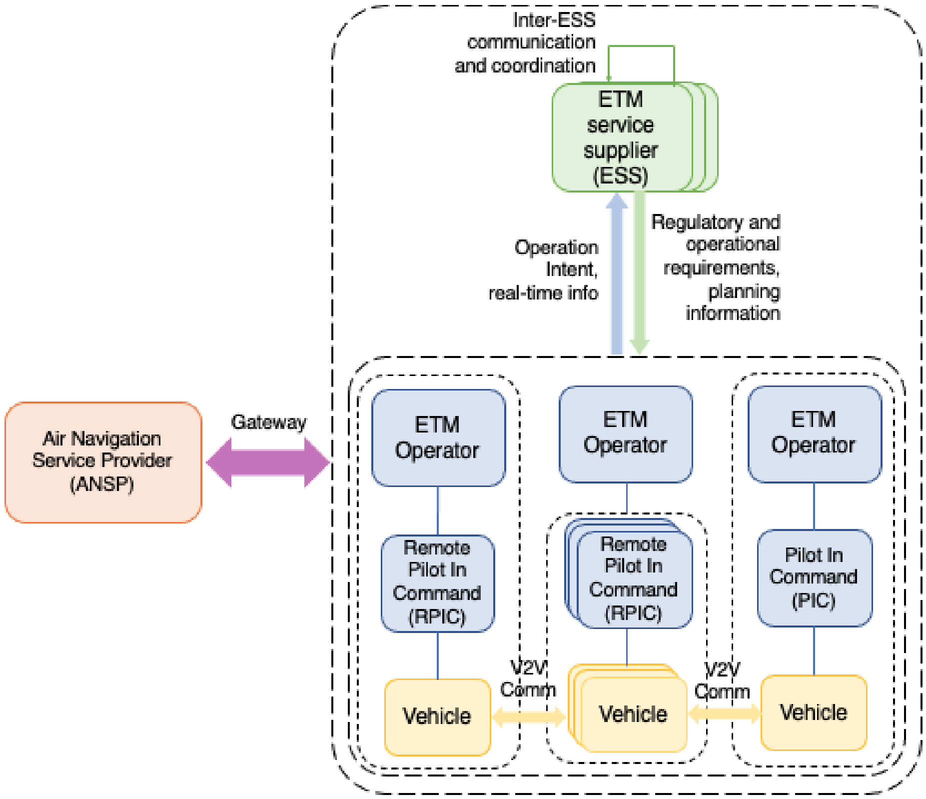


Figure 4: Notional representation of a potential part of the ETM system depicting interaction among the ANSP, ESS, ETM operators

2.2 Assumptions and Dependencies

The baseline assumptions and principles for the cooperative separation process were developed while considering limitations of current technological capabilities and ATC standards, services, and procedures for operations applicable to the ETM environment. Those limitations include:

- The vertical separation standard above FL600 for civil aircraft is currently undefined.
- Existing lateral separation standards may not accommodate vehicles with limited performance capabilities such as solar-powered high-altitude vehicles.
- Some high-altitude vehicles are incapable of executing Detect-and-Avoid (DAA) operations (e.g., tactical deconfliction maneuvers) due to having limited or no maneuverability. DAA standards have not been established for high-altitude vehicles operating in the ETM environment.
- Current ATM systems do not support long-endurance flight plans longer than 24 hours.
- Some high-altitude vehicles are susceptible to winds due to their light weight and limited propulsion system (if any). But short-term wind prediction for the

stratosphere often has significant error. Wind prediction errors tend to be greatest at higher altitudes and near the equator, and they grow with the forecast time horizon.
- Some high-altitude vehicles have limited payload capacity, which is critical to their mission, affecting their ability to meet equipage requirements.

3. Functional Requirements

This section presents the functional requirements needed for the ETM system to support the cooperative separation concept. Each requirement is first illustrated by a brief user story for background, followed by acceptance criteria on meeting the requirement, and finally a presentation of current prototype implementations designed to meet the requirement and associated criteria.

3.1 Operational Intent Sharing

OI specifies the airspace regions that the vehicle is predicted to be operating in at a certain time in the future given vehicle performance model and environmental uncertainties. OI can be represented as a three-dimensional airspace volume with a time duration denoted by an entry and exit time. Accurate and precise OI sharing is essential to achieve common situation(al) awareness.

User story:
An ETM operator must query the nearby high-altitude vehicles' operations and share OI as a part of an Operation Plan (OP) through ESS data exchanges.

Acceptance Criteria:
- ETM operator must request other all "accepted" and "activated" OI(s) and their OP (s) in the ETM environment (above or near FL600) to the ESS.
    - The "accepted" state indicates that the OI meets all requirements to access and operate in the ETM environment but is not yet in use.
    - The "activated" state indicates that the "accepted" operation is active and adhering to its requirements for operating in the prescribed airspace.
- ETM operator can visualize, and access all "accepted" and "activated" OI(s) to gather operation information in more detail for the airspace either planned for use or currently in use.
- ETM operator must share OP that includes OI (minimum and maximum time horizon are TBD) to ESS for information exchange among other ETM operators.
    - ETM operator can regularly update or revise their OP including OI (minimum update cycle is TBD)
    - ESS can notify ETM operator whether submitted OP is valid or invalid for acceptance and can provide rationale for invalidation when the OP is not accepted

Prototype:
- Active aircraft list

Figure 5 shows a list of active ETM operations in a table where ETM operators could view more detailed information by clicking through each row.

Aircraft Information

	Aircraft ID	Model	Type	Country	Altitude (m)	Ground Speed (ms)	Lat : Long	Wind (ms)	Vert Status
▸	B001	BALLOON	BALLOON	USA	18733.2	6.8	44.253 : -112.452	5.4	level_flight
	B002	BALLOON	BALLOON	USA	16688.4	34.7	43.636 : -72.527	18.3	level_flight
	B003	BALLOON	BALLOON	USA	17489	6.6	40.578 : -116.984	9.7	ascending
	B004	BALLOON	BALLOON	USA	19110.2	7.1	39.159 : -129.548	3.9	level_flight
	B005	BALLOON	BALLOON	USA	16343.2	31.8	35.272 : -104.569	17.4	level_flight
	B006	BALLOON	BALLOON	USA	17930.7	16.1	29.226 : -88.11	7.8	level_flight
	A001	BALLOON	BALLOON	USA	16623	14.8	15.994 : -119.731	7.8	level_flight
	H001	FW_HALE	FW_HALE	USA	18892.2	23.5	44.217 : -68.108	NA	level_flight
	H002	FW_HALE	FW_HALE	USA	19183.8	26.5	32.722 : -100.662	NA	level_flight
	H003	FW_HALE	FW_HALE	USA	18449.5	25.4	38.353 : -84.348	NA	level_flight
	H004	FW_HALE	FW_HALE	USA	17362.9	20.6	27.528 : -97.156	NA	level_flight

Figure 5: A prototype of active aircraft table

Figure 6 presents the data model used in the simulation environment for exercising information data flow between the components within the ETM system.


```
▾ aircraftList:
  ▾ 0:
    ▾ aircraft_properties:
        aircraft_id:                    "B001"
        aircraft_model:                 "BALLOON"
        aircraft_type:                  "BALLOON"
        lower_buffer_m:                 914.399970739201
        upper_buffer_m:                 914.399970739201
        max_ascent_rate_fpm:            600
        max_descent_rate_fpm:           1500
        ascent_descent_threshold_fpm:   100
        alert_threshold_min:            300
        copRule:                        "COP1"
        copDescription:                 ""
        conflicting_aircraft:           "U001%2"
        simtime_sec:                    0
        start_altitude_m:               18711.9
        start_latitude:                 44.280448
        start_longitude:                -112.461913
        vehicle_heading_deg:            175.3931447269262
        vehicle_speed_ms:               9.43870118417904
        wind_heading_deg:               175.3931447269262
        wind_speed_ms:                  4.855687386972106
        vertical_status:                "ascending"
        update_source:                  "regular"
        conformance:                    "Warning"
    ▾ intentList:
      ▾ 0:                              "-112.2475156671868,43.96622910591295,-112.50760139520247,44.012851841400284,-
                                        112.46025461949887,44.27697664015671,-112.2001688914832,44.23035390466938,-
                                        112.2475156671868,43.96622910591295"
      ▾ 1:                              "-112.65401173472857,43.646885215162214,-112.52633642931481,44.19915529497442,-
                                        111.87123371798596,44.047706860949646,-111.99890902339972,43.49543678113744,-
                                        112.65401173472857,43.646885215162214"
      ▾ 2:                              "-111.53308149371313,44.06369775168925,-111.55439924386974,43.19941332264302,-
                                        112.92592003305325,43.23324216015972,-112.90460228289663,44.09752658920595,-
                                        111.53308149371313,44.06369775168925"
      ▾ 3:                              "-113.01299302617325,44.22879122412185,-111.1606621977695,43.9133234937154,-
                                        111.40152058053282,42.499076124904846,-113.25385140893657,42.81454385531129,-
                                        113.01299302617325,44.22879122412185"
```


Figure 6. A sample data model of OI polygon vertices under “intentList” tag and other flight information of a HALE balloon in a standard json format

- OI on the situation display:

Figure 7 shows an example of a prototype situation display that allows ETM operators to view all active high-altitude vehicles operating in the Upper Class E airspace to promote situation(al) awareness and proactively plan for their operations. OIs from different vehicles could be temporally color-coded that potential strategic conflicts could be easily visualized for situation(al) awareness. Also, the ETM operator could zoom in and out of any regions to see the interaction more closely. Additional features will be explored to enhance usability of the interface.

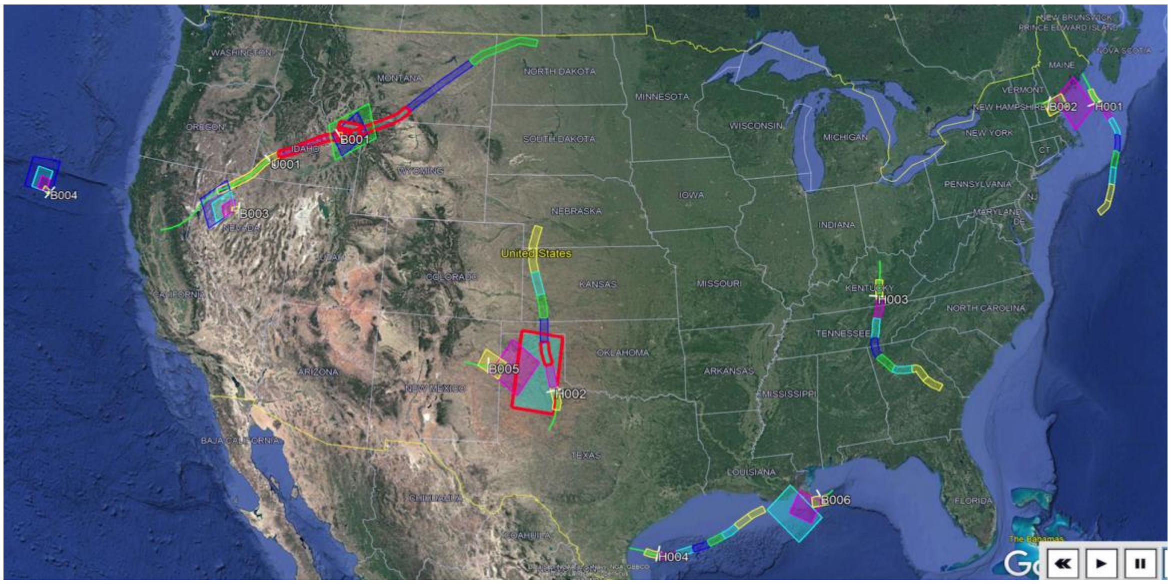


Figure 7: A prototype of situation display showing all active high-altitude vehicles

Figure 8 shows an example of a vehicle's data block on the prototyped display in the simulation environment. The user can click any part of the active aircraft's OI volumes to see the data block containing necessary information (e.g., COP type, Point of contact for coordination) for cooperative operations.

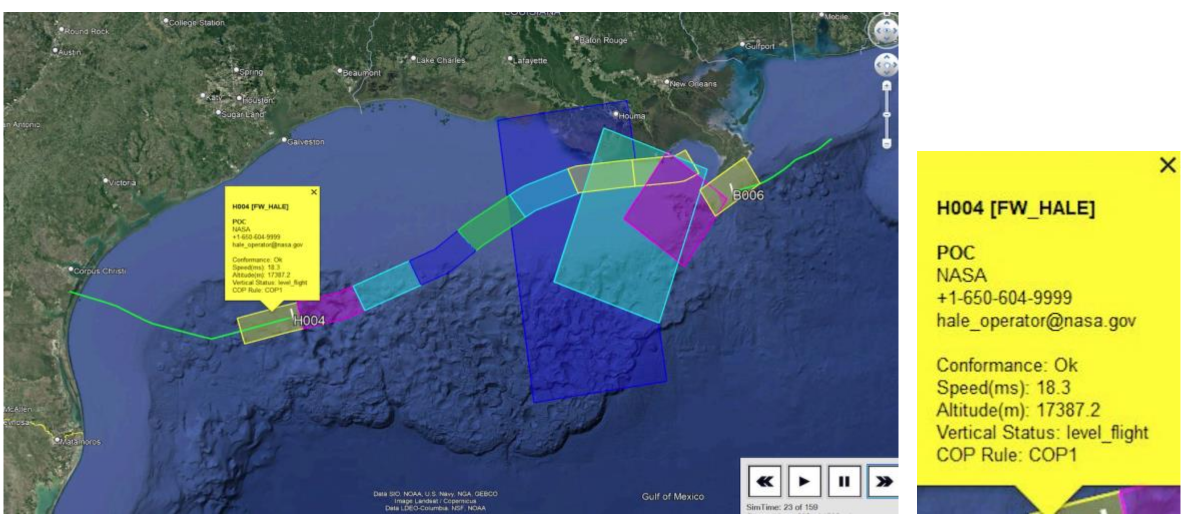


Figure 8: A prototype of data block

3.2 Conformance Monitoring

ETM operators are responsible for conformance monitoring to ensure their flight trajectories stay within the active 4D OI volume.

User story:
An ETM operator can ensure that their vehicle stays within the active 4D OI volume.

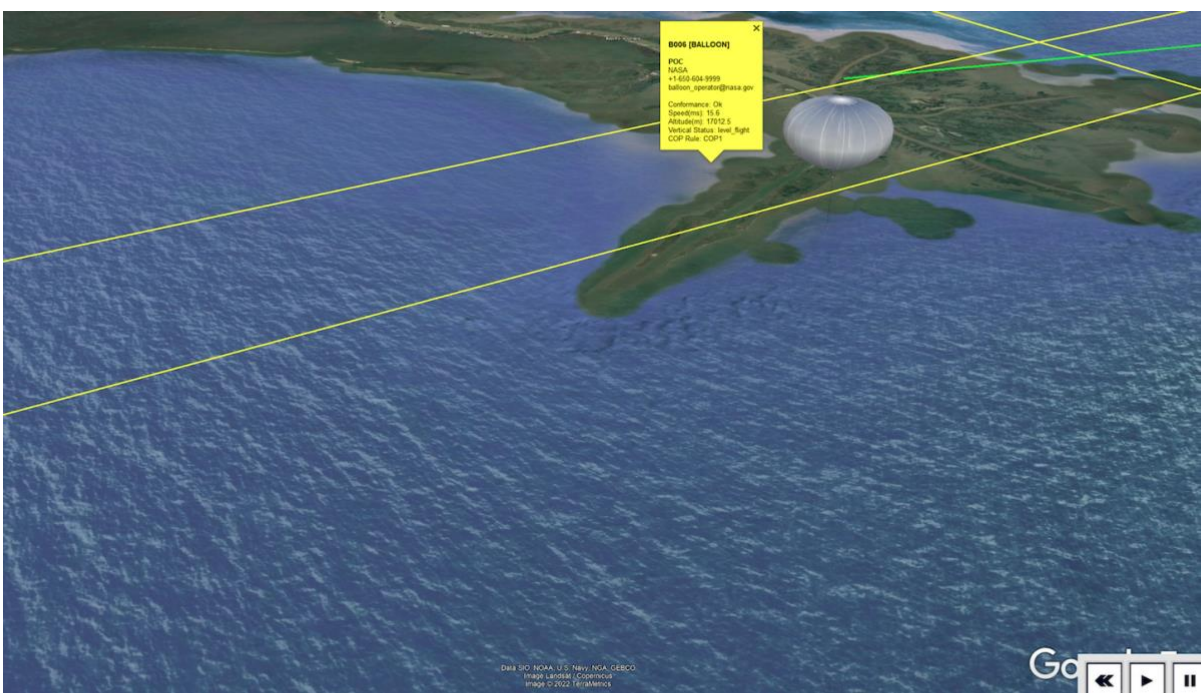
Acceptance Criteria:

- ETM operator(s) can view and track their operations in real-time.
  - Flight operations data (i.e., telemetry information) and OI data must be available to support real-time vehicle conformance monitoring.
- ETM operator(s) will be notified by ESS when the trajectory is "nonconforming" or "contingent."
  - "Conforming" state is when the vehicle is flying within its active OI volume.
  - "Nonconforming" state is when the vehicle is outside the spatial and/or temporal bounds of the OI volume but the situation is recoverable.
  - "Contingent" state is when the operation is unable to return to conformance with the OI.

Prototype:

- Conformance Monitoring:

A conformance monitoring table has been prototyped (see figure 9) and could be used to indicate the list of operations with their associated conformance status. Several additional alerting features could be adopted to improve the ETM operators' awareness and response to non-conformance or contingent event. The decision criteria and method for determining contingent state requires further discussion, and the number of the alert levels could be explored.



Conformance Monitoring

	Aircraft ID	Conformance
▸	B001	Conforming
	B002	Conforming
	B003	Conforming
	B004	Conforming
	B005	Conforming
	B006	Conforming
	A001	Conforming
	H001	Conforming
	H002	Conforming
	H003	Non-Conforming
	H004	Conforming
	U001	Conforming

Figure 9: A prototype of conformance monitoring table and data field in the data block

3.3 Strategic Conflict Detection

For Cooperatively managed separation, ETM operations must be free of OI intersection with all other known ETM operations before departure or OI intersection is recognized and allowed by all operators involved in the intersection, while in active operation, and at the moment of OI updates via the rolling-window approach [8].

User story:

An ETM operator must submit its OI to an ESS and be notified if it intersects with another OI to enable strategic deconfliction and promote safety.

Acceptance Criteria:

- ETM operator(s) (either or both) must be alerted in a timely manner (parameters TBD).
- ETM operator(s) must be notified with information to assess the criticality of the intersection.

Prototype:

- Conflict (Strategic) list:

Figure 10 presents an example of a prototype conflict list table. The table lists the aircraft pair (and their aircraft IDs) whose OIs are predicted to strategically conflict. The flight status indicates whether the vehicle is climbing (^), descending (v), or in level flight (-). The “Time” column indicates the start of the time window (in minutes) of the predicted OI intersection.

Conflict List

	Aircraft ID 1	Flight Status 1	Flight Status 2	Aircraft ID 2	Time
▸	B001	-	^	H001	60
	B002	-	V	H003	120

Figure 10: A prototype of Conflict (Strategic) list table

Figure 11 shows the prototype of the strategic conflict alert for a vehicle pair that is activated in the event of an OI intersection (i.e., spatial and temporal). The intersection is indicated by the red outline of the shaded polygon. Shading of neighboring OI volumes is inhibited to make the strategically conflicting OI volumes more salient.

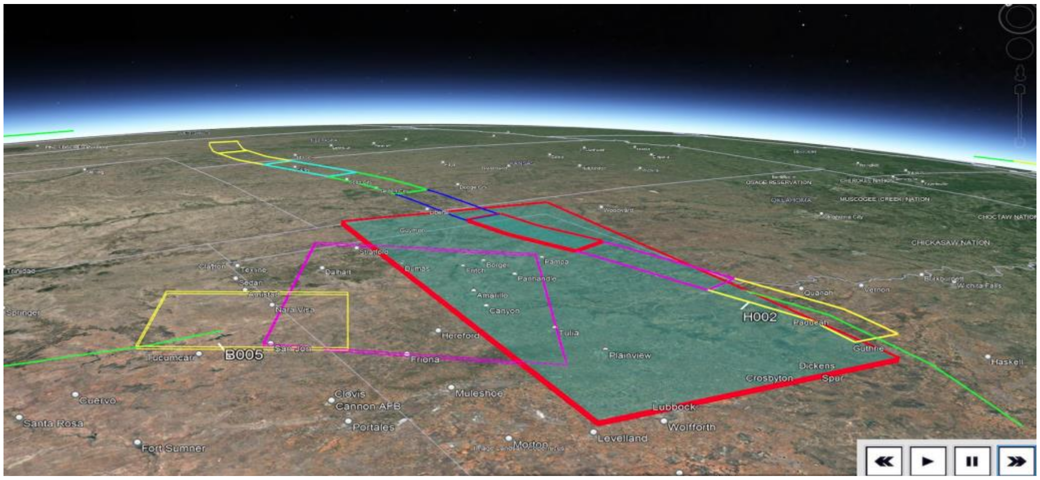


Figure 11: Strategic conflict alert- 4D OI intersection example case (projected strategically conflicting OI volumes highlighted with red outline)

The minimum set of required information to support ETM operators with assessment of criticality needs further exploration. For instance, a size of overlapping area could be an useful information.

3.4 Strategic Deconfliction

Once a strategic conflict has been detected, two types of resolution method are employed, according to the defined COPs:

1) Standard rule-based method (COP1 and COP2)
2) Ad-hoc negotiation method (COP3)

The rule-based methods nominally guarantee the existence of a resolution. They are relatively simple to execute based on pre-established bilateral agreements between ETM operators. In contrast, the ad-hoc negotiation method may offer greater flexibility and/or efficiency for the operators, but a resolution cannot be guaranteed. It should be noted that in the absence of a cooperative resolution, the resolution transitions to fallback, right of way rules.

User story:
In order to maintain separation of OIs, both ETM operators involved in a strategic conflict must be notified in a timely manner as to which pre-agreed resolution method (COP1 or COP2) is to be executed, **or** to coordinate ad-hoc negotiations (COP3) with both ETM operators.

Acceptance Criteria:
- ETM operator(s), who pre-agreed on the standard rule-based approach (COP1 or COP2), must be notified promptly regarding the type of resolution method to be executed.

- ETM operator(s) can resolve the strategic conflict through ad-hoc negotiation (COP3) if the method is coordinated with the other strategically conflicting ETM operator.

Prototype:
Figure 12 presents the working flow of the cooperative separation process. Indications of COP type preference for each ETM vehicle are submitted and updated as a part of the OI (Such COP type preference is found in the data block; see Figure 8).

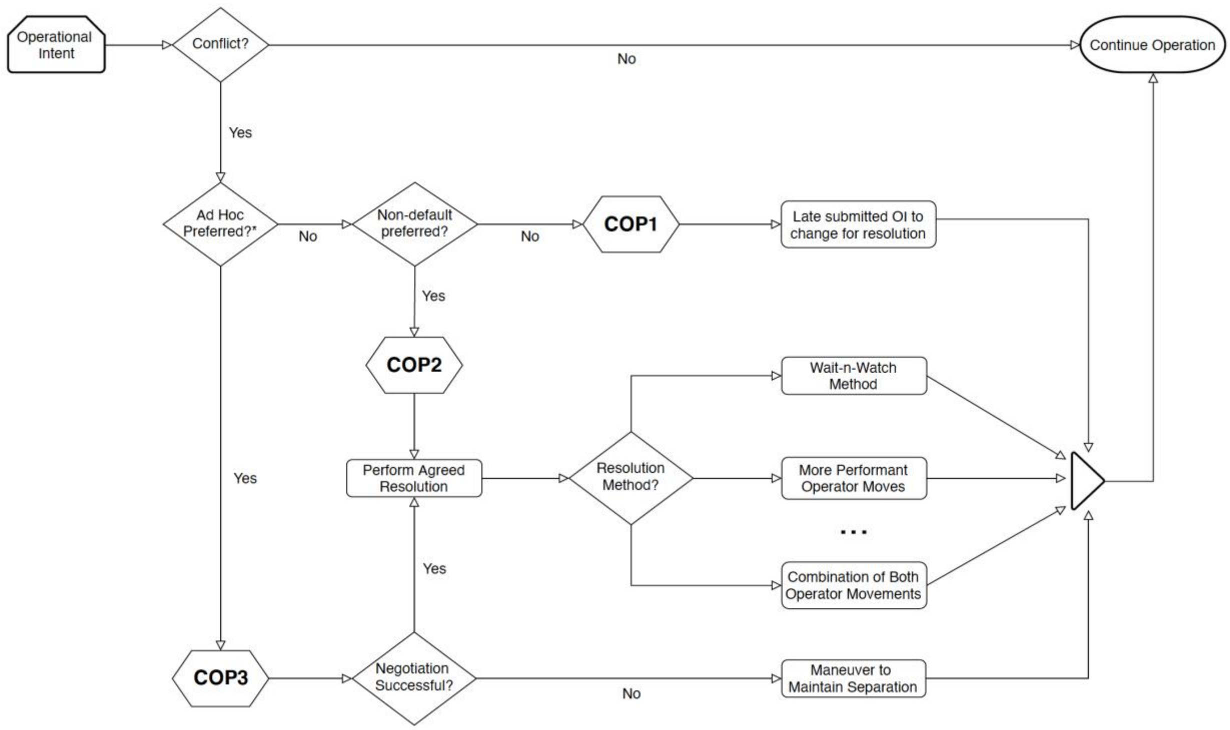


Figure 12: Flow diagram for the cooperative separation process

4. Overview of Scenario and Use Cases

A scenario-driven development process supports the progression of requirements for operating in the ETM environment and the refinement of the concept. As part of this approach, realistic traffic scenarios and use cases have been developed based on historical data and information collected from the FAA and industry partners to support the development and testing of cooperative separation requirements. Those scenarios were processed and simulated to test and validate the functionalities discussed in the previous section using the simulation platform.

This section provides an overview of scenarios and use cases, which will be updated regularly to test and validate enhanced functionalities and additional vehicle types from stakeholder inputs. The final scenarios and use cases will be adopted for potential live, virtual, and collaborative testing involving multiple ETM stakeholders to demonstrate and test concept elements and collaborative decision-making.

4.1 Traffic Setup

Figure 13 shows a traffic scenario with 12 high-altitude vehicles (six HALE balloons, four HALE fixed-wing UAVs, one HALE airship, and one high-speed unmanned fixed-wing UAV) operating in the ETM environment above North America and the Gulf of Mexico. The scenario is designed to last for approximately 12 hours. Multiple scenarios with use cases have been created from this baseline traffic scenario to demonstrate and test various cooperative separation concepts through simulation activities.

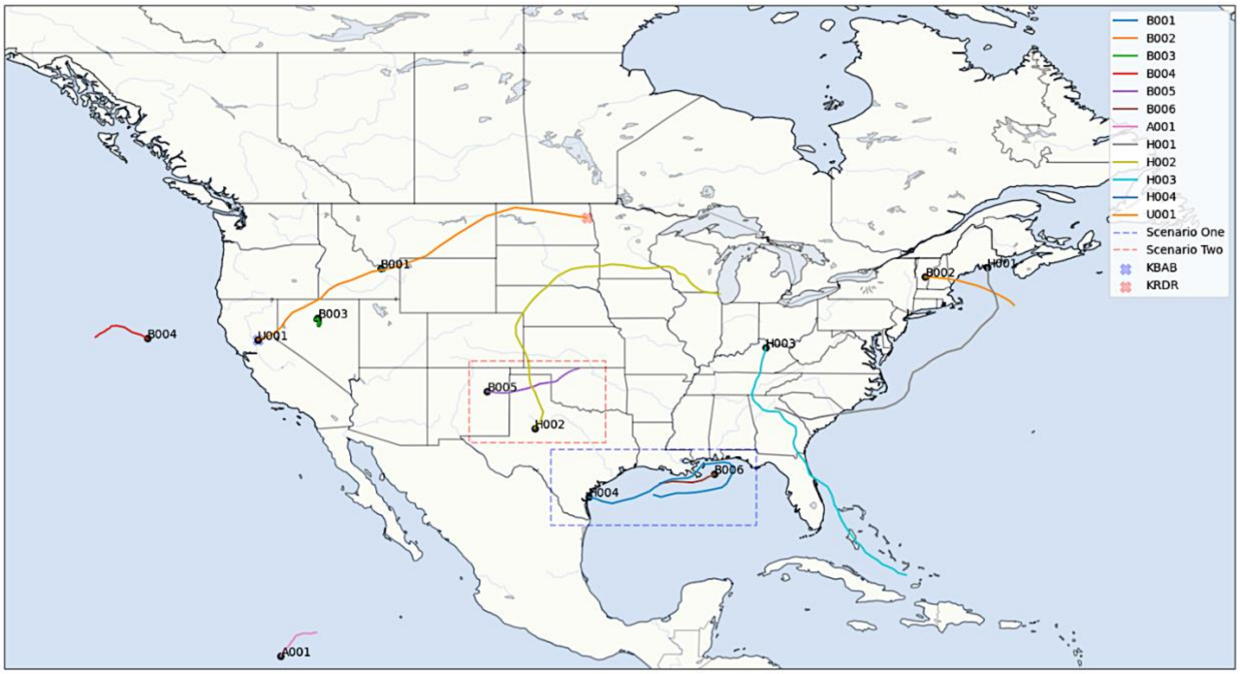


Figure 13: The traffic scenario for the preliminary assessment

Table 1 below summarizes the general assumptions incorporated into the scenarios used in simulation.

Table 1: General Assumptions

Element	Assumption
Airspace	• The Upper Class E airspace (near and above FL600)
Air Traffic Controller (ATC)	• ATC is not responsible for the provision of separation services for high-altitude vehicles operating in the Upper Class E airspace (near and above FL600). • Verbal communication cannot occur between ATC and ESS, since ESS only has data exchange capabilities and not a person. ATC is assumed to have pre-authorized the ETM operators to access the ETM environment.
Airspace Constraints	• No airspace constraints currently present in the Upper Class E airspace; prevailing weather conditions are assumed to be mild.
Operational Intent (OI)	• OIs of the high-altitude vehicles are updated via the rolling-window approach.
Cooperative Operating Practices (COPs)	• Pre-agreed resolution methods (COP1 and COP2) exist between high-altitude vehicles. • Ad-hoc negotiation method (COP3) is available via phone call/email between operators.

4.2 Operational Intent (OI) Generation Methods for Low-Speed HALE Vehicles

This section provides the assumptions and initial approach to OI generation methods for each vehicle type as well as the associated values used in simulation. This approach and the underlying parameters and characteristics of OI generation and handling in the ETM environment will be updated as more input is gathered through continued engagement with ETM stakeholders. The following description is provided as supplemental background information and should not be considered final. Several complementary investigations on the methods for generating OI and associated properties are currently being conducted [9, 11].

4.2.1 HALE balloon

The OIs for the HALE balloons used in simulation were generated and later submitted using the intended cruise altitude of operations as the initial basis with an additional +/- 3000 ft vertical buffer to account for uncertainties (e.g., wind-prediction errors, flight technical error, etc.). The HALE balloon was assumed to use an autonomous navigation system that controlled its lateral track by climbing or descending to altitudes where the prevailing winds best aligned with the accepted OI. Hence, a large vertical buffer of 3000 ft was needed. The lateral buffer was estimated by taking a probabilistic approach for computing uncertainty [8]. The lateral uncertainty buffer estimation for the HALE balloon was performed based on the assumption that wind information is regularly collected and available via onboard sensors such as radiosondes (i.e., battery-powered telemetry instrument package). Based on the wind speed and direction at every OI update, ten thousand possible trajectories were computed and encapsulated using a minimum bounding algorithm to develop an OI boundary for each OI volume. This approach was taken to accommodate the large errors in the short-term wind forecasts. To further ensure safety, an additional 5-nm lateral buffer was added to the initial OI boundary edges. In each one-minute step of each possible trajectory generation, the amount of heading and speed deviation from the balloon’s course was computed by adding independent random values drawn from $N(0, 1.3\text{ deg})$ and $N(0, 0.2\text{ m/s})$, respectively. These distributions were derived from historical balloon trajectory data [12].

4.2.2 HALE fixed-wing UAV

The HALE fixed-wing UAV OIs used in simulation were initially constructed based on the desired flight path of the vehicle with a 10-nm lateral buffer added to both sides (i.e., a total of 20 nm). The latitude-longitude positions along the specified path and the intended flying speed in the OI volume were used to estimate the entry and exit time of each OI volume. A linear interpolation method was used to compute equally spaced positions along the path with a 5-nm buffer added to the entry and exit points of each OI volume to account for along-track error. The vertical buffer was defined as +/- 500 ft in consideration of the vehicle’s capability to maintain its altitude, and this buffer was incorporated as part of the submitted OI.

4.2.3 HALE airship

In the simulation, an in-flight HALE airship at altitude is expected to share OI that is generated using the same approach used for a loitering HALE balloon. This is because airship operators prefer not to use the propulsion system while hovering. When the HALE airship is flying from point A to B, it operates like a HALE fixed-wing UAV with high confidence of adhering to its OI. Hence, the OI is generated in the same way as the fixed-wing UAV for transition phases of the airship's flights.

4.3 Scenario One (4D OI intersection)

4.3.1 Overview

Scenario one was created to evaluate OI intent sharing and strategic conflict detection. In this scenario, a HALE balloon (B006) is flying over the Gulf of Mexico at an average of 18.3 kts to monitor oil spills. Due to the inherently poor predictability of balloon trajectories, the HALE balloon (B006) operator shares its OI with a 3-hr lookahead. The OI is updated regularly at 60-min intervals. Meanwhile, a solar-powered HALE fixed-wing UAV (H004) is flying from Corpus Christi, Texas to the Gulf of Mexico to provide communication services in the area while tracking a recent hurricane. Its intended transit speed is 20 kts. The HALE fixed-wing UAV (H004) operator shares its OI with an 8-hr lookahead time and regularly updates its OI at a 60-min interval. Each polygon-shaped 4D OI volume represents a 1-hr period of flight.

Figure 14 shows multiple screenshots taken at different points during simulation run time to show the interaction between the operational intents of the HALE balloon (B006) and the HALE fixed-wing UAV based on the initial scenario parameters. As the simulation progressed, the OI Volumes intersection resulted in an alert to indicate a strategic conflict.

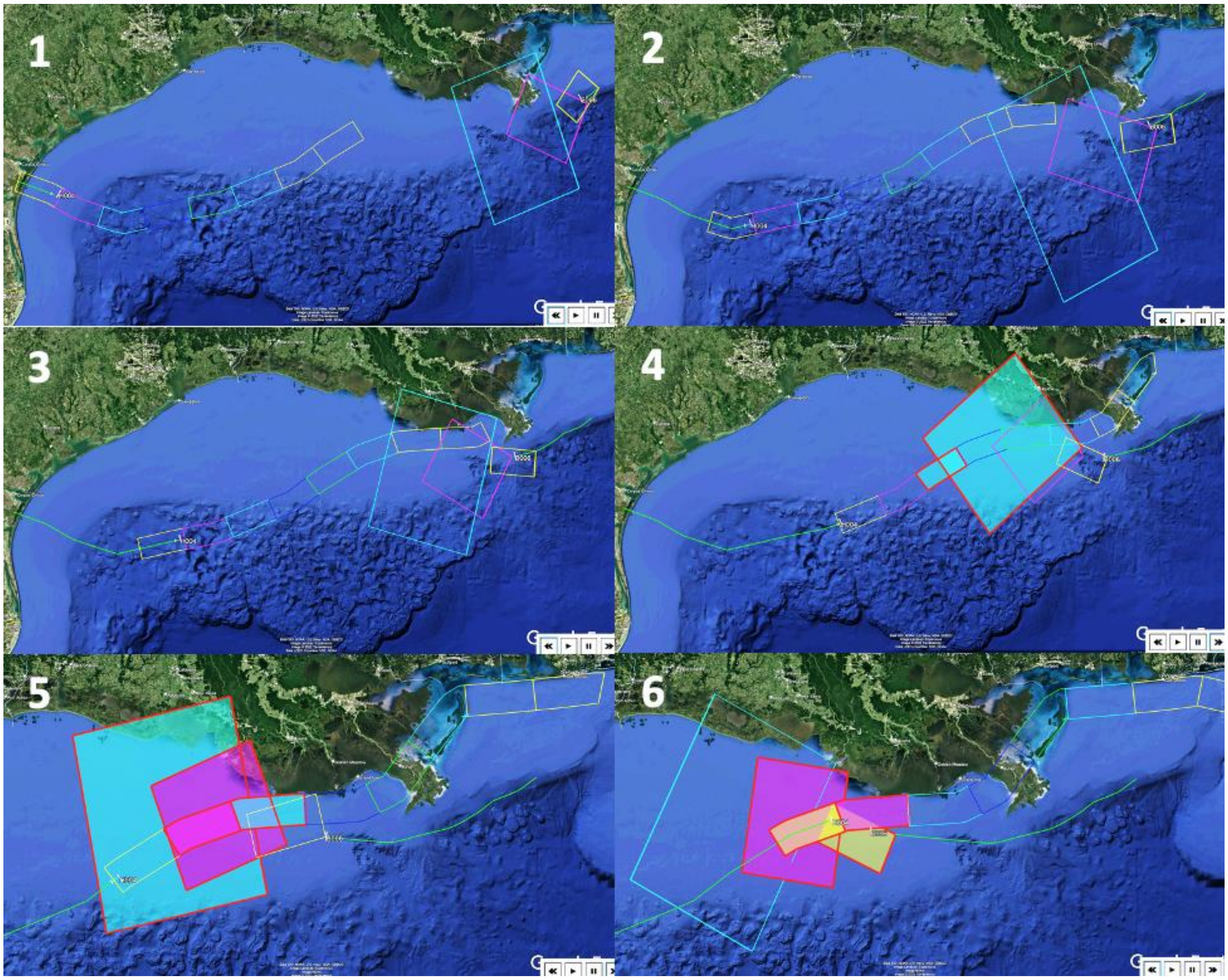


Figure 14: Use Case One - 4D OI intersection

Figure 14 shows the multiple screenshots taken at different simulation run times to show the interaction between the operational intents of the HALE balloon (B006) and the HALE fixed-wing UAV.

Three use cases are described below that show how the scenario could play out differently depending on the different resolution methods applied (i.e., COP1, COP2, and COP3).

4.3.2 Use Case One – COP1

In this use case, the HALE balloon (B006) operator and the HALE fixed-wing UAV (H004) operator pre-agreed to take the FRFS approach (COP1) at the occasion of a strategic conflict for resolution. The ESS determines the operator with priority based on the latest OI update time. It is determined that the HALE balloon (B006) operator updated its OI later than the HALE fixed-wing UAV (H004) operator. Hence, the HALE balloon (B006) operator is notified of the identified strategic conflict by the ESS. The HALE balloon (B006) operator assesses the criticality of strategic conflict and revises its OI (e.g., amending its intended altitude to ensure that lateral separation is maintained) up to when the OI becomes OI intersection-free.

4.3.3 Use Case Two – COP2

In use case two, the HALE balloon (B006) operator and the HALE fixed-wing UAV (H004) operator pre-agreed on a standard rule-based resolution method in advance of their operations and informed the ESS about the preferred resolution method, which is that the HALE fixed-wing UAV (H004) will revise its OI and maneuver as necessary whenever its OI strategically conflicts with that of the HALE balloon (B006). Hence, the moment that the strategic conflict is identified, the ESS notifies the HALE fixed-wing UAV (H004) operator of the strategic conflict and its burden to resolve. In response, the HALE fixed-wing UAV (H004) operator generates a new strategically conflict-free OI in consideration of its mission and updates the ESS and ETM network of the updated intent.

4.3.4 Use Case Three – COP3

In use case three, the HALE balloon (B006) operator and the HALE fixed-wing UAV (H004) operator have a pre-established agreement to resolve tactical conflict based on the FRFS principle. A strategic conflict of their OIs ensues, and the ESS determines that the HALE fixed-wing UAV's OI was approved first. Therefore, the ESS notifies the HALE balloon (B006) operator of the strategic conflict.

The HALE balloon operator subsequently makes the assessment of that all of the resolution maneuver options for the HALE balloon (B006). To resolve the issue of being the burdened operator with limited, non-preferred resolution options, the HALE balloon (B006) operator uses available information from the ETM network to identify, contact, and negotiate an agreeable resolution with the strategically conflicting operator.

As an example using the ETMAutoSIM research interface, the balloon operator clicks on the OI of the HALE fixed-wing UAV (H004) on the display, which pops up the data block (see Figure 15) of the vehicle in strategic conflict in order to find the point-of-contact (POC) information of the operator (included in the data used to establish the ETM operation). The HALE balloon (B006) operator contacts the HALE fixed-wing UAV (H004) operator for the OI revision request. The HALE fixed-wing UAV (H004) operator cooperatively agrees to revise its OI and update the ESS.

Figure 15: An example data block of the HALE fixed-wing (H004)

4.4 Scenario Two (4D OIs are separated by altitude)

In scenario two, a solar-powered HALE fixed-wing UAV (H002) and a HALE balloon (B005) are flying over Northern Texas. H002 is in transit toward the Midwest to provide communication services. Its desired flying speed indicated in the OI is 30 kts. The H002 operator shares its OI with an 8-hr lookahead and 60-min update rate. The B005 balloon is flying eastward while updating its OI regularly at 60-min intervals with a 6-hr lookahead time and flying at an average speed of 30.1 kts. Based on the shared OIs of the two operations, their lateral flight paths are predicted to intercept one another. However, no strategic conflict is identified or reported by the ESS, because both operators' OIs are adequately separated by altitude.

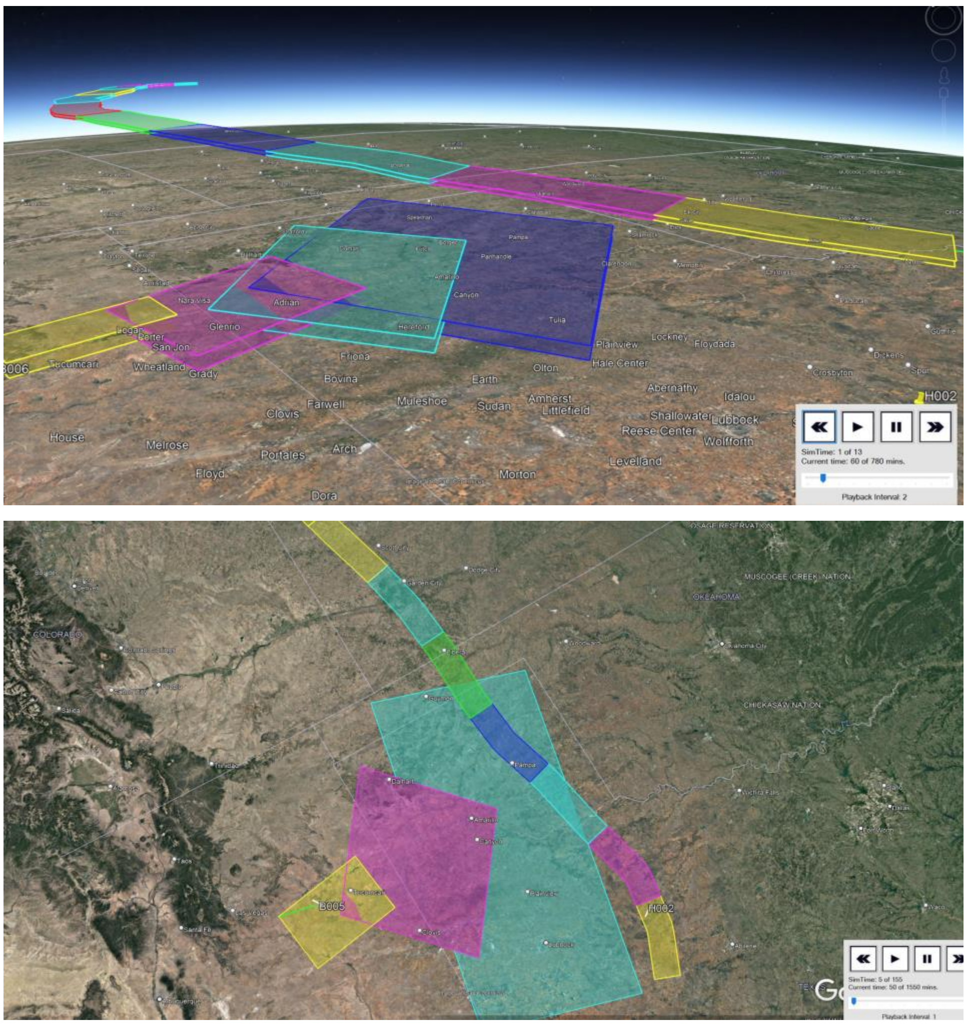


Figure 16: Scenario Two – OIs are separated by altitude (Top: side view, Bottom: top view)

4.5 Communication Procedures for Strategic Deconfliction

Figure 17 presents an example of communication procedures between operator A and B for strategic deconfliction via COP1 and COP2 methods. The COP3 requires a communication channel to enable ad-hoc negotiation, which is an area that needs more discussion and testing in the simulation environment.

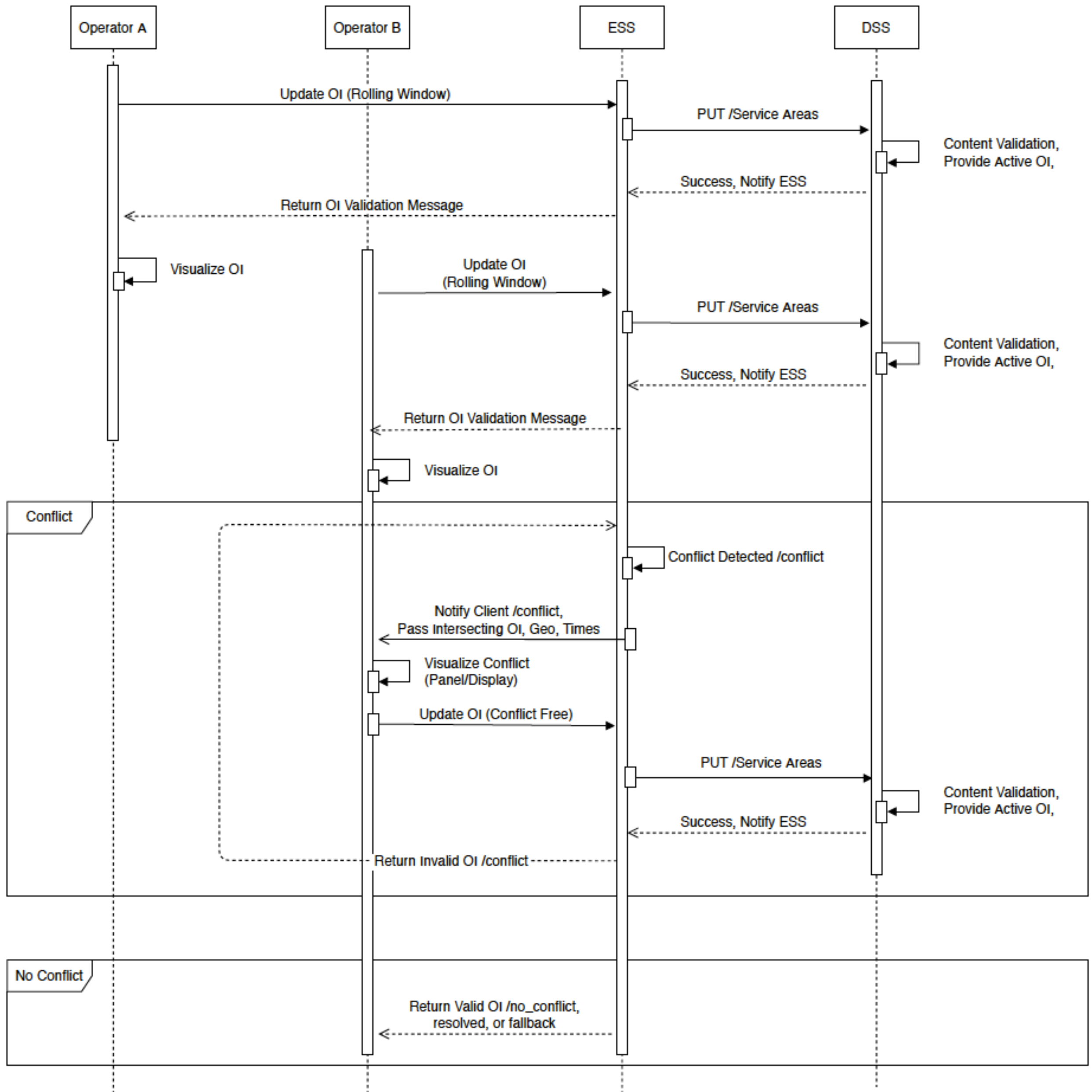


Figure 17: Sequence diagram for potential communication (COP1 Example)

In Figure 17, Operator A prepares an OP including OI. The OP is then submitted to the ESS via a client. If the OP is invalid (e.g., due to improper format, or 4-D OI intersection with other OI(s) or airspace constraints), operator A receives notification and needs to revise the OP with a new OI and resubmit. During the process, the ETM DSS can support the content validation of OP and provide active OI(s) near the airspace in which the operator is operating. The validated OIs will be updated on a regular basis via the rolling-window approach.

In the event that a 4D OI intersection is detected, operator A follows the pre-agreed solution from COP1 or COP2 and executes accordingly. In the case of COP2, it requires both operator A and B to revise their respective OIs. Both the operators then need to update their respective OIs as agreed and resubmit them to the ESS.

4 External Interfaces

The Application Programming Interface (API) specification for ensuring compatibility and interoperability between ETM operators and the ESS is currently being developed, addressing the need for a communication bridge among the ETM cooperative operation participants. The latest ESS and ETM operator API specification can be found in references [13, 14]. The APIs are documented in a format such that code can be generated from the API, where the current format is OpenAPIv2.0.

Through the availability and implementation of ETM APIs, a more collaborative and representative environment is made possible for research and testing not only within NASA but with industry and other stakeholders. Figure 18 illustrates a connectivity diagram of NASA operators and industry partners with a cooperative ETM environment enabled through ESS connectivity and associated data exchanges. ETM operations can be simulated using the capabilities described in this document to test representative scenarios. It should be noted that while the diagram in Figure 18 presents a single ESS as part of the internal testing framework, the ETM concept does not preclude an architecture that involves multiple ESS nor prescribe a single centralized ESS. Such architectural discussions will be addressed as the concept develops further.

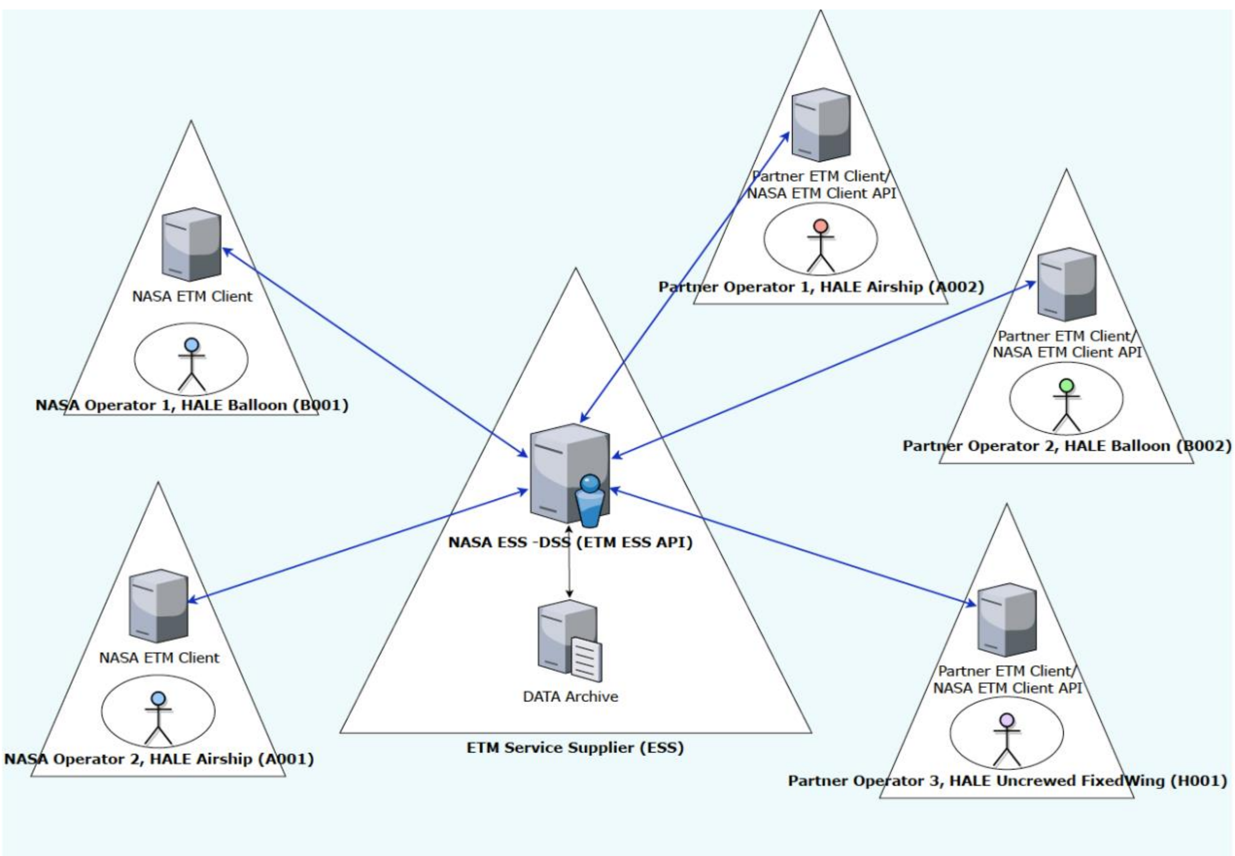


Figure 18: A connectivity block diagram showing potential connectivity exercise

5 Summary

The following summarizes the contents provided in this document:

- A minimum set of functionalities and capabilities for enabling cooperative separation with the user interface prototype
- A scalable system architecture for enabling information exchange and shared situational awareness among cooperative operations participants in the ETM environment
- The initial set of COPs for cooperatively maintaining separation in the ETM environment
- Sample scenarios that can be modified or extended to include multiple use cases, developed for testing feasibility in a simulated environment or combined live/simulation test environment

The functional requirements included in this document were driven by rapid prototyping exercises. The requirements may be iteratively refined though continued engagement with industry partners and the FAA. Several complementary research efforts [9, 11, 15, 16, 17] are currently being conducted to support the cooperative separation concept development and additional functional requirement development. Documents from additional efforts will be further explored and published in the future.

References

[1] Federal Aviation Administration (FAA). (2020). Upper Class E Traffic Management (ETM) Concept of Operations v1.0.

[2] Aerospace Industries Association (AIA). (2022). Cooperative Operations in Higher Airspace: A Proposal. https://www.aia-aerospace.org/wp-content/uploads/AIA-Cooperative-Operations-in-Higher-Airspace-Proposal-April-2022-Final33.pdf

[3] Federal Aviation Administration (FAA). (2020). Upper Class E Traffic Management (ETM)]. https://www.faa.gov/uas/advanced_operations/upper_class_etm/

[4] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., & Robinson, J. E. (2016). Unmanned aircraft system traffic management (UTM) concept of operations. In *AIAA Aviation and Aeronautics Forum (Aviation 2016)* (No. ARC-E-DAA-TN32838).

[5] Federal Aviation Administration (FAA). (2020). Unmanned Aircraft System (UAS) Traffic Management 2, 5(UTM) Concept of Operations v2.0.

[6] Bakowski, D. L**.,** Lee, P. U., Brasil, C. L., & Evans, M. (2022). Integrating Upper Class E Traffic Management (ETM) Operations into the National Airspace System: Use Cases and Research Questions. In *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*. IEEE.

[7] Jung, J., Rios, J. L., Xue, M., Homola, J., & Lee, P. U. (2022). Overview of NASA's Extensible Traffic Management (xTM) Work. In *AIAA SCITECH 2022 Forum* (p. 1916).

[8] Yoo, H., Li, J., Homola, J., & Jung, J. (2021). Cooperative Upper Class E Airspace: Concept of Operations and Simulation Development for Operational Feasibility Assessment. In *AIAA AVIATION 2021 FORUM* (p. 2356).

[9] Yoo, H., Li, J. O'Hara C., Jacoby, R., Torres, R. (2022). Sharing Operational Intent with Containment Confidence Level for Negotiating Deconfliction in Upper Class E Airspace. In *AIAA AVIATION 2022 FORUM*.

[10] Rios, J. L., Smith, I. S., Venkatesan, P., Homola, J. R., Johnson, M. A., & Jung, J. (2019). *UAS Service Supplier Specification* (No. NASA/TM-2019-220376).

[11] Xue, M., Jung, J., & Homola, J. (2022). Intent Modeling and Conflict Probability Calculation for Operations in Upper Class E Airspace. In *AIAA SCITECH 2022 Forum* (p. 1508).

[12] Candido, S. (2020). Loon stratospheric sensor data. https://doi.org/10.5281/zenodo.3763022

[13] NASA. (2021). [ETM-ESS-API]. https://github.com/nasa/utm-docs/tree/master/etm

[14] NASA. (2021). [ETM-ETM Operator-API]. https://github.com/nasa/utm-docs/tree/master/etm/operator-interface-spec

[15] Ishihara, A. K., & Xue, M. (2022). Conflict Resolution Strategies for Balloon-Airship Encounters in Upper Class E Air Traffic Management (ETM). In *AIAA AVIATION 2022 Forum* (p. 3825).

[16] Xue, M., & Ishihara, A. (2021). Define Minimum Safe Operational Volume for Aerial Vehicles in Upper Class E Airspace. In *AIAA Aviation 2021 Forum* (p. 2317).

[17] Xue, M., & Ishihara, A, Lee. (2022). Negotiation Model for Cooperative Operations in Upper Class E Airspace. In *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*. IEEE.

[18] Google Earth. (2022). https://earth.google.com/

Appendix A: ETMAutoSIM

Overview

ETMAutoSIM is a simulation platform designed to address the need to rapidly produce prototypes of various concept elements that are being proposed by ETM industry partners, NASA, and the FAA.

Architectural Overview

Figure A-1 below shows the simulation steps involved in reading in an input file, running the simulation, and producing the output JSON file for visualization.

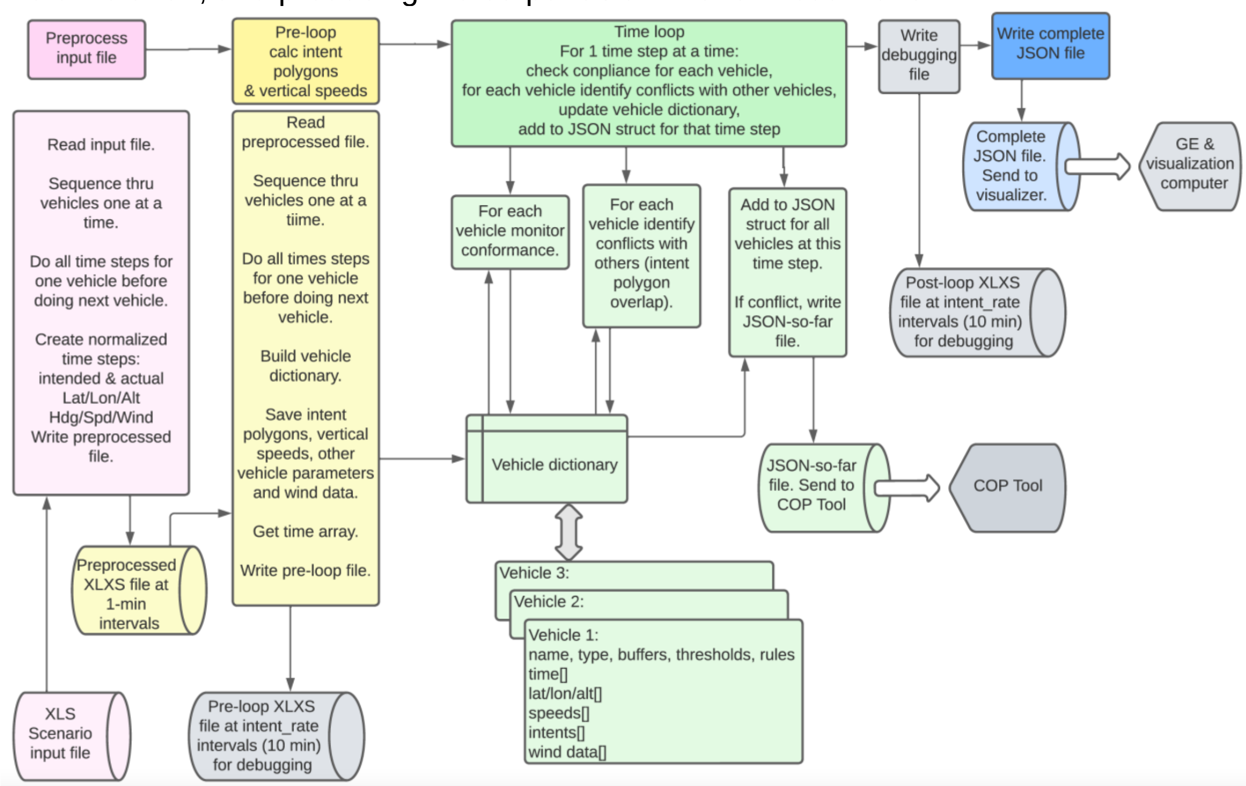


Figure A-1: ETMAutoSIM simulator architecture

Functional Description

The main functions of ETMAutoSIM are to 1) preprocess the data (pink), 2) perform pre-loop calculations (yellow), 3) perform the time loop (green), and 4) write the final JSON file (blue). These processes are performed sequentially finishing one function before performing the next.

The preprocessor reads the raw input data, makes some simple calculations and interpolates the data (actual and intended latitude, longitude, altitude, heading and direction, and wind speed and heading) into uniform one-minute time steps and writes the preprocessed file. Examples of the simple calculations are, for Balloons, converting U-V wind components to speed and heading, and for HALE aircraft, computing heading from latitude and longitude.

The pre-loop calculations read the data from the preprocessor step and compute the intents (OIs), vertical speeds and vertical statuses, and they compute some missing wind speeds and directions. The pre-loop calculations do this for one vehicle at a time – finishing one vehicle before processing the next vehicle. They store the computed data in each vehicle's dictionary section, compute an array of all times in the simulation, and write a pre-loop file that can be used for debugging.

The time loop goes through each time step for all vehicles in the dictionary – processing all the vehicles for that one time step before moving on to the next time step. It first calculates the conformance and then identifies conflicts – updating the vehicle dictionary section for each vehicle as it goes. When the time step is finished—and if no conflict was found—it moves on to the next time step. If a conflict was found at that time step, it writes a "conflict" JSON-so-far file before moving on to the next time step. The JSON-so-far file has all the data up to that point. This file is intended to be sent to the COP tool and receive back a conflict-free OI.

Once all time steps are processed, the time loop writes another debugging file, and it writes the final JSON file which is sent to the visualization software described in Appendix B.

Appendix B: ETM Viewer

Overview

ETM Viewer is a software application that provides a graphic visualization of the ETMAutoSIM simulator output.

Architectural Overview

The ETM Viewer application is designed using the Model-View-Controller (MVC) design pattern. This design is modular and decoupled providing the ability to reuse the software modules in other related applications. In this pattern, the User Interface is decoupled from the Data Model, so that either module can be changed without adversely affecting any other module. The JSON parser is also modularized to allow its reuse:

- *Operating Environment*: Microsoft Windows 10 (preferably a dual screen display)
- *Development Environment*: C# Language /Visual Studio / .NET / Windows Forms
- *Design Pattern*: Model View Controller (MVC)
- *Graphics Display*: Google Earth or other KML rendering application

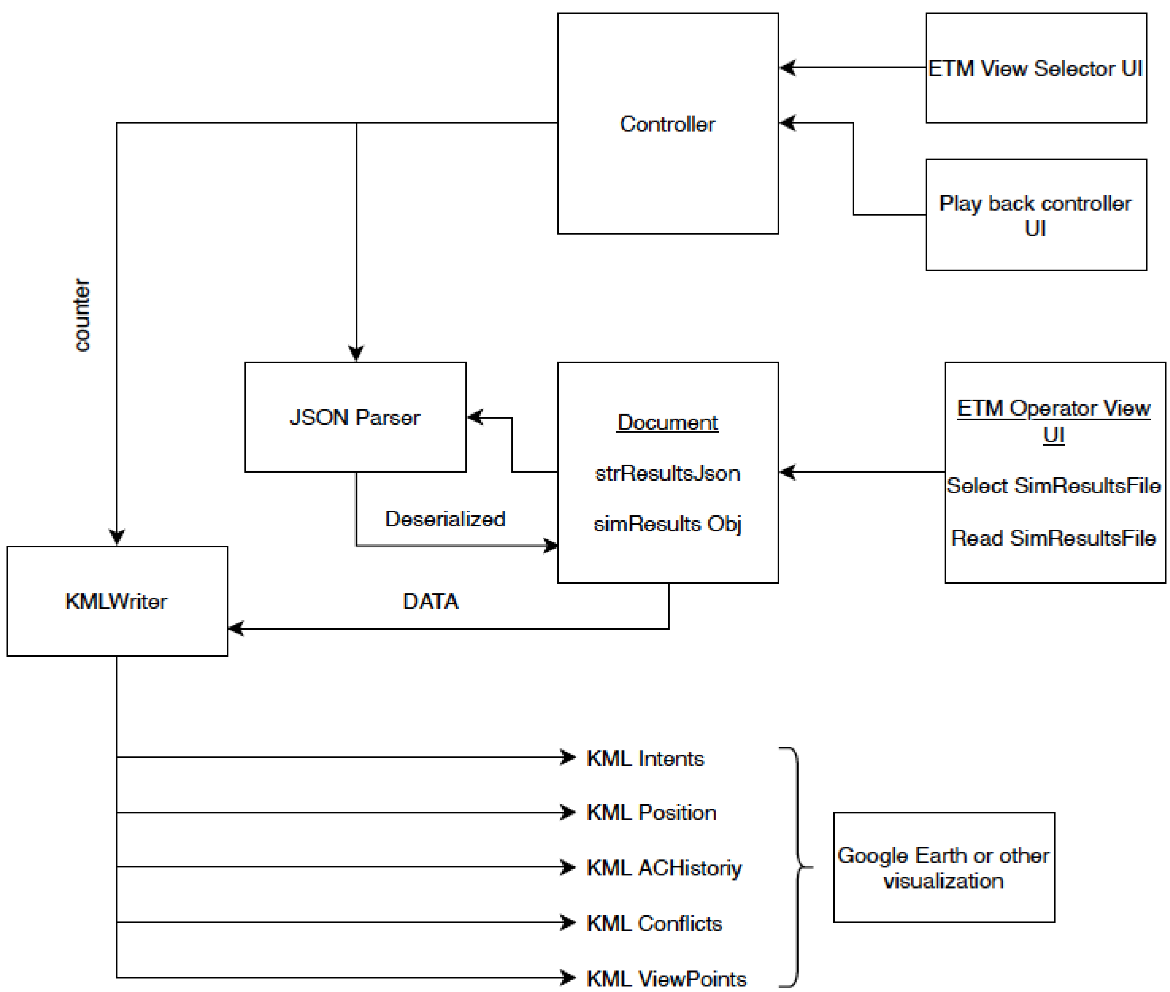


Figure B – 1: ETMAutoSIM visualizer architecture

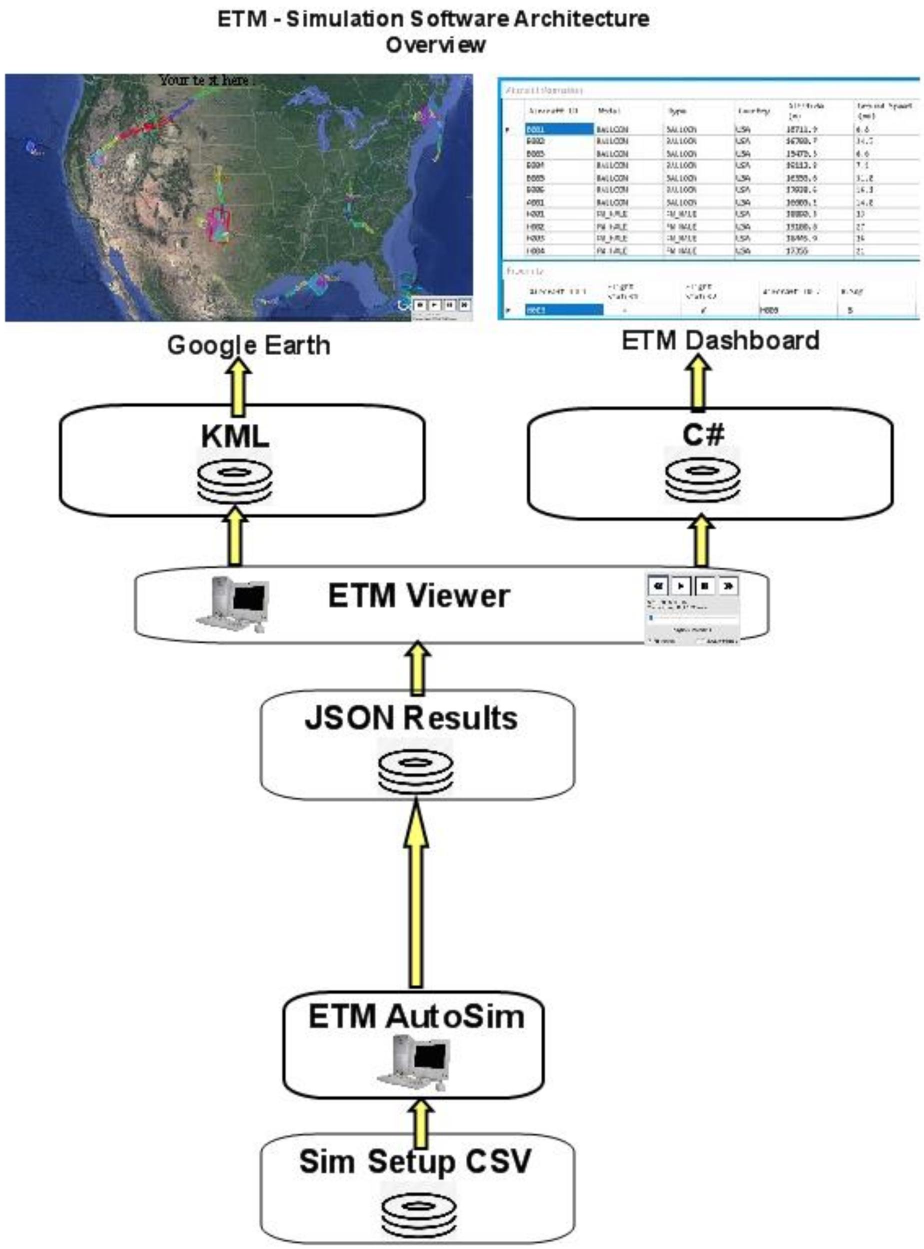


Figure B – 2: A lock diagram showing ETMAutoSIM and Visualizer interaction

Functional Description

The *ETM AutoSim* application generates its output in a JSON file. *ETM Viewer* reads this JSON file and generates a KML (Keyhole Markup Language) file for each time step of the simulation. The KML file is read by Google Earth and draws the ETM data on the earth display [18]. The Controller module accepts input from the User Interface to specify the JSON file to be processed, and to control the simulation time step to be displayed. The simulation time steps can be advanced automatically or manually via the *Playback Controller,* shown below. The Playback speed can be set using the slider control.

Checkboxes control the display of the trajectory history and toggle filled or wireframe display of Operational Intents (OIs).

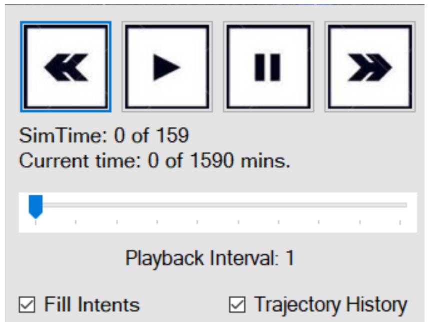


Figure B – 3: playback controller

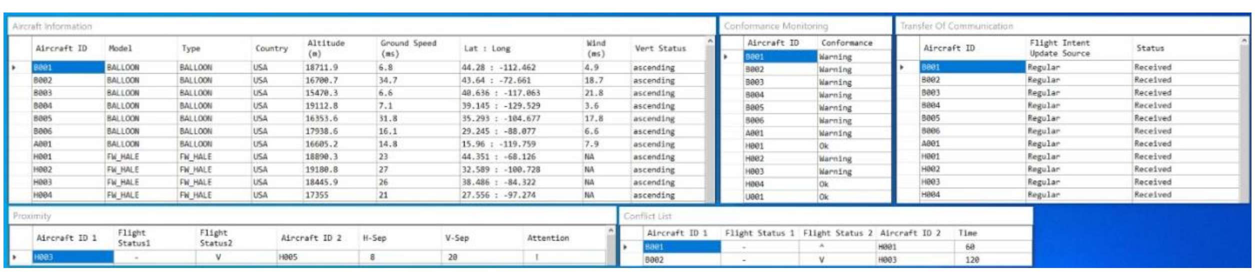
At each simulation time step, the predicted OIs are drawn for all active aircraft. OIs are drawn for all predicted time intervals. The OIs for all aircraft corresponding to the same time are drawn in the same color. In this way, the time dimension is conveyed. If OIs of the same color intersect, that indicates a predicted conflict between the corresponding aircraft. Conflicting OIs are displayed with thick red boundary lines and partially transparent shaded polygons.

In addition to the OIs, the history of each aircraft trajectory is displayed as a green line.

Dashboard

In addition to the graphics display of the ETM OIs and trajectories, several tables of ETM data are displayed. The data in the tables are updated at each time step, in sync with the graphics display.

The tables include Aircraft Info, Conflict List, Conformance Monitor, Transfer of Communication, and Proximity. See diagrams of the data tables in this document.



Aircraft Information

Aircraft ID	Model	Type	Country	Altitude (m)	Ground Speed (ms)	Lat : Long	Wind (ms)	Vert Status
B001	BALLOON	BALLOON	USA	18711.9	6.8	44.28 : -112.462	4.9	ascending
B002	BALLOON	BALLOON	USA	16700.7	34.7	43.64 : -72.661	18.7	ascending
B003	BALLOON	BALLOON	USA	15470.3	6.6	40.636 : -117.063	21.8	ascending
B004	BALLOON	BALLOON	USA	19112.8	7.1	39.145 : -129.529	3.6	ascending
B005	BALLOON	BALLOON	USA	16353.6	31.8	35.293 : -104.677	17.8	ascending
B006	BALLOON	BALLOON	USA	17938.6	16.1	29.245 : -88.077	6.6	ascending
A001	BALLOON	BALLOON	USA	16605.2	14.8	15.96 : -119.759	7.9	ascending
H001	FW_HALE	FW_HALE	USA	18890.3	23	44.351 : -68.126	NA	ascending
H002	FW_HALE	FW_HALE	USA	19180.8	27	32.589 : -100.728	NA	ascending
H003	FW_HALE	FW_HALE	USA	18445.9	26	38.486 : -84.322	NA	ascending
H004	FW_HALE	FW_HALE	USA	17355	21	27.556 : -97.274	NA	ascending

Conformance Monitoring

Aircraft ID	Conformance
B001	Warning
B002	Warning
B003	Warning
B004	Warning
B005	Warning
B006	Warning
A001	Warning
H001	Ok
H002	Warning
H003	Warning
H004	Ok
U001	Ok

Transfer Of Communication

Aircraft ID	Flight Intent Update Source	Status
B001	Regular	Received
B002	Regular	Received
B003	Regular	Received
B004	Regular	Received
B005	Regular	Received
B006	Regular	Received
A001	Regular	Received
H001	Regular	Received
H002	Regular	Received
H003	Regular	Received
H004	Regular	Received

Proximity

Aircraft ID 1	Flight Status1	Flight Status2	Aircraft ID 2	H-Sep	V-Sep	Attention
H003	-	V	H005	8	20	!

Conflict List

Aircraft ID 1	Flight Status 1	Flight Status 2	Aircraft ID 2	Time
B001	-	^	H001	60
B002	-	V	H003	120

Figure B – 4: ETMviewer – Dashboard