Indications of Adversary Actions Intended to Disrupt Space Operations: Simulation for Rehearsal of Detection and Response

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ABSTRACT

Earth orbit has transitioned from a benign environment to a congested, contested, and competitive one, with nations vying for space superiority. To maintain that superiority, space domain awareness (SDA) operators need advanced test and training capabilities as well as space surveillance data to power them. Unfortunately, real datasets for test and training are often hard to come by. Depending on the source, data may be classified, hard to locate, or too inflexible to support specific test and training requirements.

To overcome these challenges, designers of test and training exercises often resort to manufacturing artificial space surveillance data. This is a time consuming and error prone process that could be improved through automation.

This paper proposes features that an automated data generator should provide, and describes a system called ObsSIM built to meet this need. ObsSIM has been used to generate space surveillance data for twelve large-scale, internationally attended SDA exercises hosted by the U.S. Joint Task Force - Space Defense (JTF-SD). Additionally, it has supported a large number of smaller test events for civil, military, academic, and commercial organizations both domestically and internationally.

The result is an automated system capable of simulating many types of space events and generating observations of them. As of September 2023, ObsSIM has provided SDA operators with 165+ million space surveillance sensor observations. It has decreased the time to design SDA test and training events from months to minutes.

1. INTRODUCTION

Military space operations have transitioned from a benign environment to a congested, contested, and competitive one. Maintaining space superiority in this changing domain requires space domain awareness (SDA) operators to have advanced test and training capabilities. Those are necessary to rehearse the tactics, techniques, and procedures for threat detection and response. To be effective, test and training capabilities must be sufficiently realistic, consistently repeatable, and flexible enough for operators to explore different courses of action. Also, they often must be shared with allied forces to enable coalition space operations training.

Space surveillance sensor observations are the primary initial indicators of an adversary's hostile space activities. They come in many forms (satellite positional data, photometry, etc.) and from various sensor phenomenologies (radar, electro-optical, passive RF, etc.), but regardless of the type, they are critical to SDA operations. Therefore, designers of test and training exercises must be able to source observations that satisfy their unique test and training goals.

Unfortunately, sufficient sensor observations are often hard to find. Various strategies have been developed to com-pensate, but those often place limits on the exercises in which they are used. This paper discusses common solutions to obtain sensor observations and describes a new observation source that enables advanced SDA test and training without sacrificing exercise fidelity.

2. COMMON SOLUTIONS FOR SOURCING OBSERVATIONS

Ideally, SDA test and training exercises would occur with actual sensors and on-orbit satellites performing real actions in space. That would allow participants to execute the precise space events they need, view how those assets respond in real conditions, and gather exactly the space surveillance sensor observations they require.

While that would be the pinnacle of realism, it is not practical. The cost of dedicated on-orbit training assets is prohibitive. Borrowing them from operational systems would be at the expense of their primary missions. Even if those hurdles could be overcome, there are still space events, such as break-ups or uncontrolled reentries, that SDA operators want to practice, but are not willing to risk performing in the operational space environment.

2.1 Tabletop Exercises

Since they cannot generate sensor observations by manipulating real assets, one common approach is to dispense with them entirely and hold a tabletop exercise. In those, participants meet in a conference room setting for a discussion-based walk through of adversary actions and decide on appropriate responses. Exercise designers feed inputs to the participants via “white cards.” These may be physical paper cards or oral announcements summarizing what has happened in the fictitious scenario. A white card may contain information such as, “a launch has been detected from this location” or “an adversary satellite is approaching a high-value asset and is on course to perform proximity operations.”

Depending on the exercise format, a participant may have limited actions they can perform with semi-realistic tools and software, or they may be constrained to discussions only. In either case, their inputs are the information from the white cards.

Tabletop exercises are not ideal because it is easy for participants to gloss over details inaccurately assumed to be unimportant. They also miss out on practice with the tools and systems they would normally use to receive indications of adversary actions, perform analysis, and execute a chosen response.

2.2 Historical Observations

A higher-fidelity option for sourcing inputs is to find historical observations that meet the test or training requirements and replay them during the exercise. Doing so satisfies the realism and repeatability requirements mentioned above, but there are still significant trade-offs. First, datasets of historical observations describing adversary actions are often classified, especially those with high test and training value. Practically, that means they are often hard to obtain and may not be shareable with coalition or commercial space partners.

Another downside of using historical observations is that exercises are limited to what really happened. This means participants can only test and train on events that have previously been seen. Exercising on novel adversary actions is not possible. It also means that SDA operators cannot practice different courses of action and experience the resulting consequences.

Finally, if exercise designers want to overlay observations from multiple real space events into a single simultaneous multi-actor scenario, those observations may need to be temporally adjusted. That process requires highly skilled knowledge to maintain astrodynamic consistency in the data.

Because of these limitations, trying to use historical observations often fails and forces exercise designers to devolve their plans into the tabletop approach described above.

2.3 Pre-Generated Fictitious Observations

Another common approach for obtaining sensor data is to manually build datasets of fictitious observations and play those during an exercise. This approach is more flexible than using historical observations. Because they are custom, these observations can be made to fit arbitrary requirements including indications of adversary actions never before seen. Also, since the observations are not real, they are unclassified and shareable with coalition and commercial space partners.

However, this approach is not without its limits. While the observations are custom, they are still pre-generated. This constrains SDA operators to courses of action predetermined by the exercise designers. In some situations that is sufficient. In others it may not be.

Another limitation of this manual approach is that building realistic observation datasets takes great skill and time. It requires models and tools built for this purpose.

These problems could be lessened if exercise designers had an automated system to build complex space events and model sensors generating observations of them. The next section summarizes the features such a system would need to simplify the exercise design process while maintaining the flexibility to meet the SDA community's test and training needs.

3. AUTOMATED SYNTHETIC OBSERVATION GENERATOR

From the authors' experience as participants in and designers of SDA test and training exercises, they proposed a set of features an automated synthetic observation generator should provide to satisfy the most common exercise design needs. Specifically:

1. **Off-the-shelf event models -** To generate observations, the system needs models of on-orbit assets performing realistic space events (launches, break-ups, rendezvous and proximity operations, etc.). These event models become the "ground truth" from which the sensor observations are generated. They should be generic and configurable enough to cover common use cases. Exercise designers should be able to chain events together to build up larger scenarios.

2. **Off-the-shelf event model configurations -** Because some exercise designers may not have the time or skill to configure event models themselves, the system should have pre-built events that abstract away more detailed parameters. It should also provide the designers with pre-built configurations to replicate specific real events from the past on which SDA operators would want to train (e.g., a Russian anti-satellite weapon test).

3. **Support for externally generated events -** Exercise designers may have existing event models or may want more customization than what is provided by the generic off-the-shelf models packaged with the tool. In such instances, the system should allow them to import externally generated models to serve as the observations' source of ground truth.

4. **Event model visualizations and reports -** A visualization and reporting component is necessary for exercise designers to view an event's details in the context of other events and assets. For example, a report of sensor passes would tell them when participants should expect observation data. Three dimensional visualizations would allow them to validate that their events behave as expected in the context they will run.

5. **Off-the-shelf sensor models -** To generate observations, the system needs sensor models of different capabilities and phenomenologies (radar, electro-optical, passive RF, etc.). Like the event models, the sensors should be generic and configurable enough to cover common sensor capabilities and set-ups.

   The models should also allow designers to make unrealistic sensor configurations. While realism is a primary goal, from practical experience, reality sometimes needs to be suspended to accommodate the fixed requirements of a training exercise. For example, an electro-optical sensor may need to track a satellite's position during local daylight because the exercise participants need to receive observations at a particular time in support of the scenario narrative.

6. **Off-the-shelf sensor model configurations -** Because it may be burdensome for exercise designers to aggregate realistic sensor parameters, the system should have pre-built sensor configurations to mimic real military, civil, and commercial sensor networks.

7. **Support for external sensor models -** There are sensor models that exercise designers may want to use, but cannot leverage directly. There are several reasons for this. A model might be proprietary or security-controlled and therefore not shareable. A high-fidelity sensor model might require specialized hardware that is not available for the exercise. To overcome these challenges, the system should have a mechanism to import observations from external sources.

8. **Export data in a variety of formats and locations -** Test and training exercises are run in a variety of environments and have unique constraints. Therefore, an observation generator should be flexible enough to support many data distribution mechanisms. These include flat files, web services, publisher/subscriber ("pub/sub") systems, and the input formats of popular space mission planning tools (e.g., FreeFlyer®).

9. **Role-based data access -** "Red vs. blue" exercises are those where participants are segregated into teams to play as if they were from different adversary and allied groups. For this to work, control of satellites and sensors, as well as access to their data products, must be limited by team and role. An observation generator should allow exercise designers to create separate observation data sets that can be targeted to specific teams.

10. **Export ground truth data -** Event models output the ground truth from which sensor observations are then generated. For example, a close approach model would produce an orbit state that makes one satellite fly near another, and the generated observations would be evidence of that.

    It is necessary to compare the exercise outcomes with the ground truth data to evaluate the exercise participants' conclusions regarding event detections and characterizations of adversarial behavior. Thus, an observation generator should be able to export ground truth data to make these assessments possible.

4. OBSSIM: A REAL-TIME SENSOR OBSERVATION GENERATOR

To satisfy the SDA test and training needs of exercise designers, a.i. solutions built ObsSIM, an automated generator of synthetic sensor observations that provides this feature set. This section summarizes key information about ObsSIM, and some lessons learned from its use.

4.1 System Architecture

ObsSIM is structured as a group of containerized web services. This provides the flexibility to try out different deployment strategies including public clouds, on-premises servers, and air-gapped networks. Since it is not tied to a particular set of hardware, separate instances of the system can be deployed to different locations as exercise needs change. Indeed, from early in its inception, ObsSIM has produced exercise data while running on both commodity hardware and cloud servers.

The web service architecture allows for easy integration with other tools and external models. Application programming interfaces (APIs) enable machine-to-machine data transfer of both inputs and outputs. For example, the Air Force Research Laboratory (AFRL) DRAGON Army program built a custom user interface called the White Cell Console [2]. It calls an ObsSIM API allowing exercise designers of all skill levels to generate simulated events and sensor observations using simple inputs (see Fig. 1). Other ObsSIM APIs allow users and external systems to extract both the ground truth data as well as the generated observations on demand.

Many of the event and sensor models are powered by FreeFlyer®, an a.i. solutions astrodynamics and space mission planning tool.

4.2 Event Service

One of the primary system components is the ObsSIM Event Service. Users can leverage it to generate simulated space events that serve as the ground truth for the generated observations. It has built-in models for many space events including launches, close approaches, rendezvous and proximity operations (RPOs), anti-satellite weapons (ASATs), and common maneuvers (see Fig. 2 and Fig. 3).

Additionally, users can provide externally generated ground truth data if they have it. For example, a user wanting to simulate a satellite maneuver could provide an ephemeris from an external tool. In practice, users were seen to regularly leverage externally generated ephemerides for more complex space events or for events they repeatedly used. Therefore, this has proven to be a valuable feature.

4.3 Sensor Service

The other primary component of the system is the ObsSIM Sensor Service. It models many of the military and commercial sensor networks to generate realistic simulated sensor observations. Its library of sensors includes ground-based electro-optical, radar, and passive RF models, as well as several space-based models for global simulated sensor coverage (see Fig. 4).

ObsSIM's sensor models can be configured to mimic characteristics of a real sensor such as its field of regard, field of view, data rates, noise and bias values, lighting constraints, and more. The observations are generated in real time allowing users to modify sensor tasking or add additional simulated events in response to exercise conditions. With these detailed customizations, ObsSIM can accurately model a near complete portfolio of sensors as they behave in real operations.

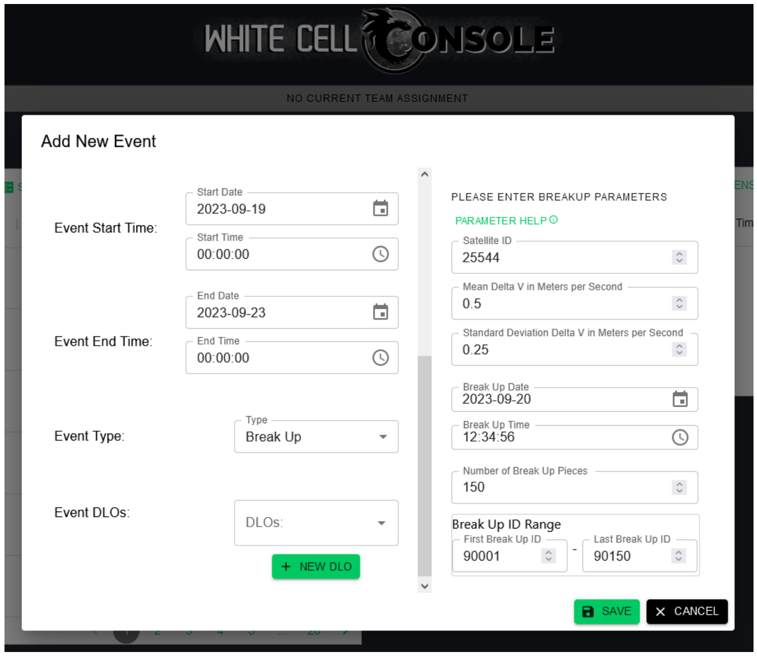

Fig. 1: DRAGON Army's White Cell Console configuration panel for the ObsSIM satellite break-up event [2]. It shows how a complex space event can be created using a small number of simple inputs.

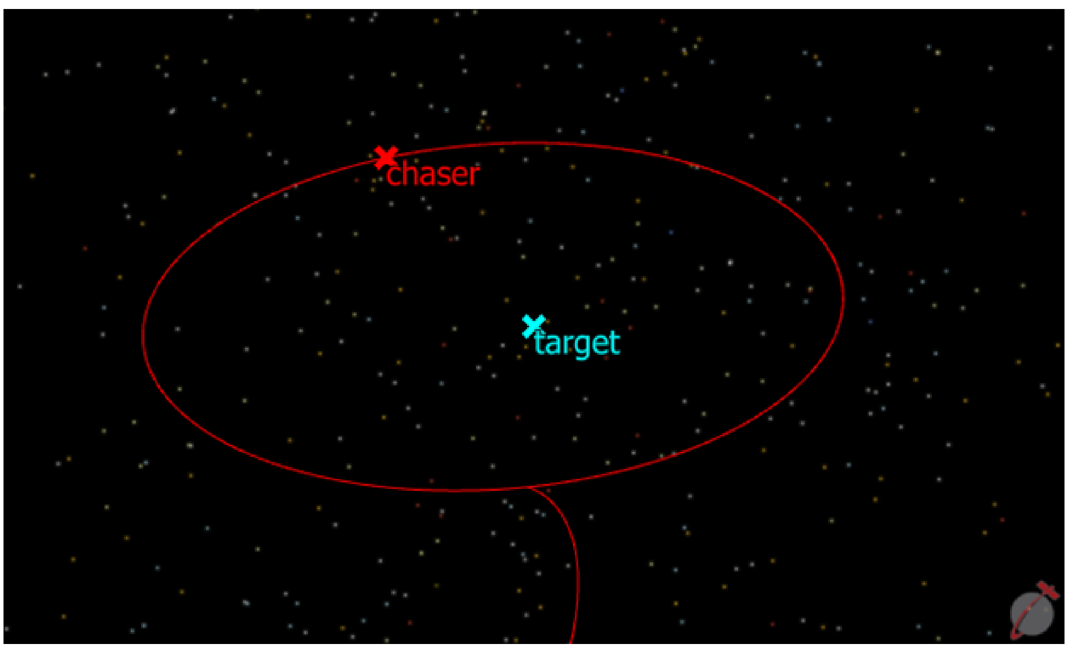

Fig. 2: Visualization of an ObsSIM RPO event, rendered in FreeFlyer®. A "chaser" satellite is performing a natural motion circumnavigation around the target satellite.

4.4 Data Distribution

As referenced above, ObsSIM has web service APIs to make data ingestion and distribution easy. The system is also fully compatible with the Unified Data Library (UDL), the United States Space Force's preferred system for storing space domain awareness data. By default, all generated sensor observations are published there.

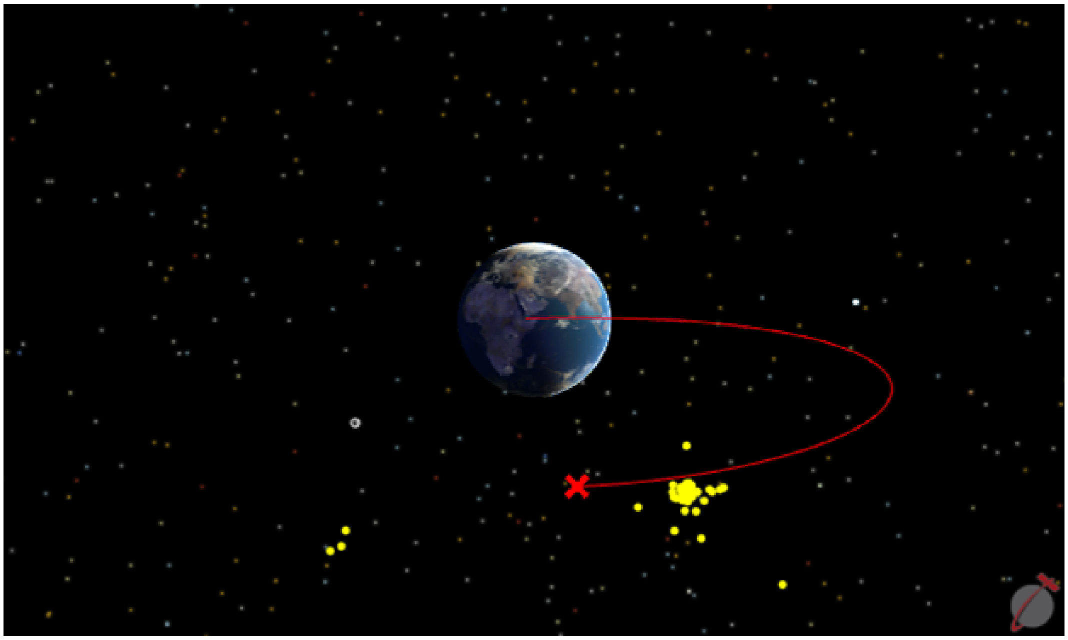

Fig. 3: Visualization of an ObsSIM ASAT launch (red) using a kinetic kill vehicle to break a GEO satellite into pieces (yellow). Rendered in FreeFlyer®.

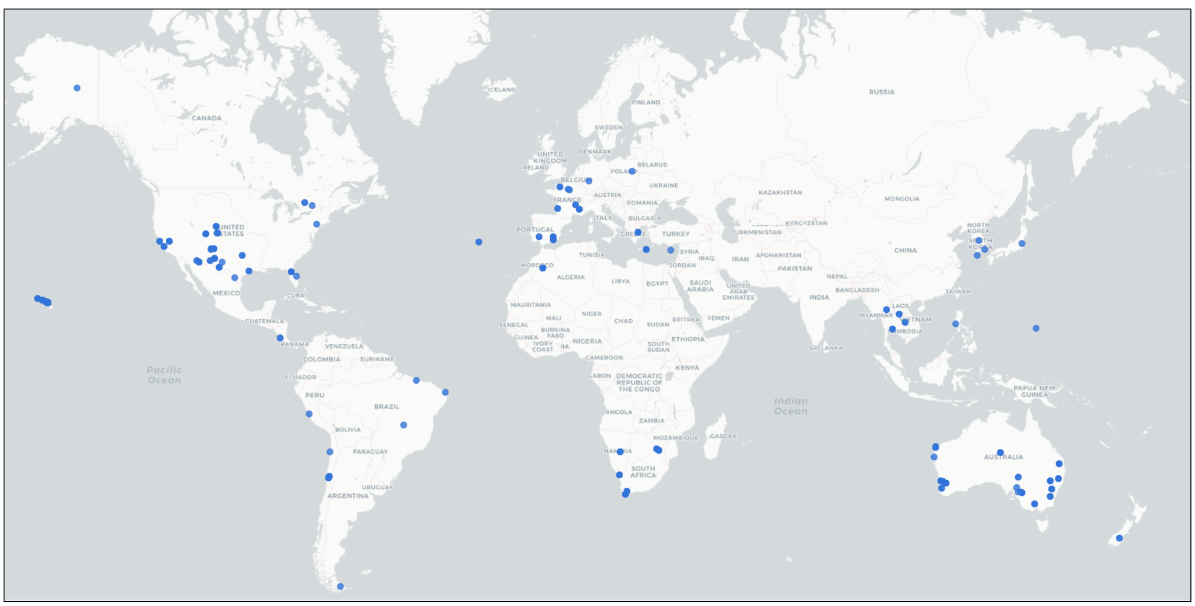

Fig. 4: Locations of ground-based sensors modeled by ObsSIM

Observations are also published by default to DRAGON Army's Live-Virtual-Constructive or "sim-over-live" data proxy called "Trogdor" [2]. Exercise participants can query that system for sensor observations and receive real data from the UDL intermixed with simulated data. The result is an exercise capability that merges specialized test and training events with the background noise experienced during real operations.

4.5 Usage Examples

ObsSIM is the primary simulated observation generator for the JTF-SD's Sprint Advanced Concept Training (SACT) exercise series [1]. These are large-scale SDA exercises bringing together representatives from over one hundred civil, military, academic, and commercial organizations around the world to advance the SDA state of the art. Fig. 5

describes a typical workflow that event designers use to create simulated space events and observations in ObsSIM for an exercise such as SACT.

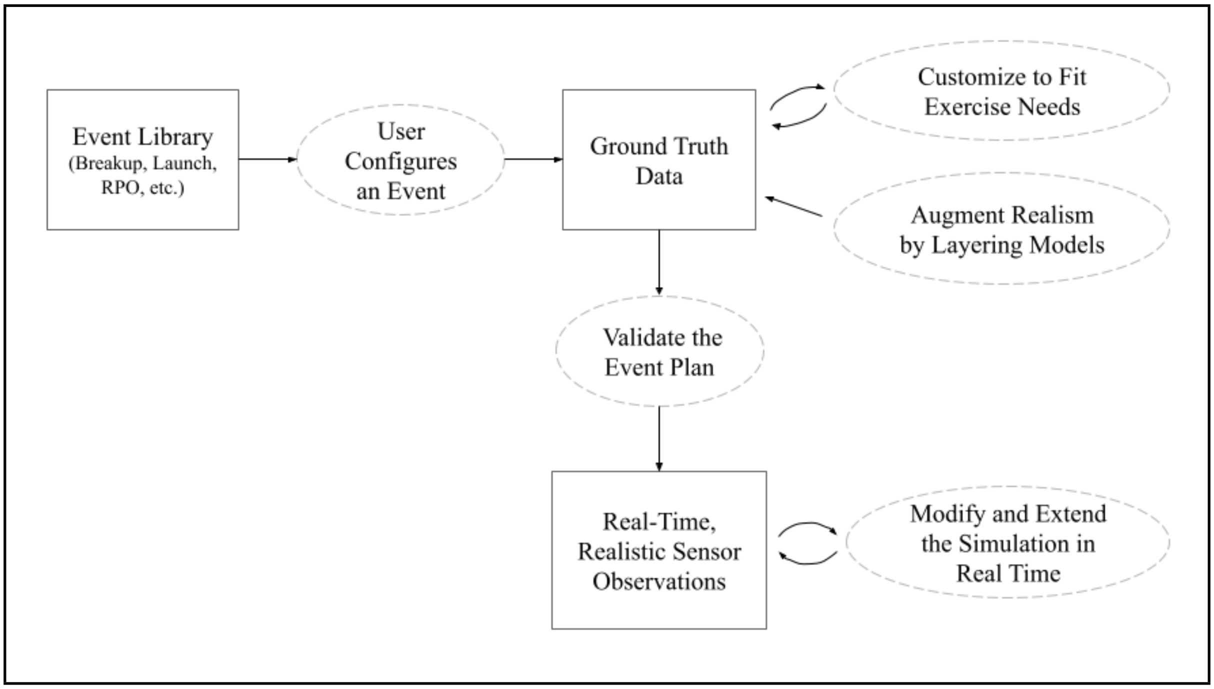

Fig. 5: A typical workflow for designing events in ObsSIM

The system also regularly supports biweekly DRAGON Army "ops days" where SDA providers bring their operators and latest tools to be tested and evaluated. In these ops days, participants practice procedures, refine their systems, and prepare for upcoming SACT exercises.

As of September 2023, ObsSIM has provided SDA operators with 165+ million space surveillance sensor observations spanning hundreds of test and training scenarios.

5. CONCLUSION

The ObsSIM system demonstrates the feasibility of automating space surveillance sensor observation generation for SDA test and training. By providing a library of automated, customizable event and sensor models, exercise designers can rapidly create and modify training simulations and have them respond in real time to operator actions. This methodology overcomes the limitations of tabletop exercises, historical data playback, and pre-generated synthetic observations. It provides an extensible training paradigm for future SDA capabilities and threats.

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