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Authoritative Broker of Truth (ABoT):

Synchronizing Model-Based System Engineering with Cross-Disciplinary Simulation to Create Digital Twins

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Abstract

Building digital twins is a cross-disciplinary endeavor, combining the efforts of modelers, system engineers, data analysts, UX designers and domain experts. For digital twins to be able to evolve with their paired, real-world system, the artifacts associated with these various disciplines must remain synchronized and coherent throughout the digital twin lifecycle. We provide a paradigm for harmonizing this multi-disciplinary effort using an Authoritative Broker of Truth (ABoT) process and apply this paradigm to a real-world case study: Can I 'cut the cord' on my cable provider and receive free over-the-air television?

Keywords

Digital Twins, Model Based System Engineering, Data Analysis, User Experience Designer, Virtualization, Simulation, Authoritative Source of Truth, Validation, Verification and Uncertainty Quantification (VVUQ).

Introduction

Motivation for the Authoritative Broker of Truth (ABoT)

Digital twins are forecasted to have a yearly market growth rate of over 35% per year (Lo, Chen, & Zhong, 2021), and are implemented for a variety of systems. While designing and manufacturing products is a common digital twin domain (Park, Nam, & Lee, 2019), digital twins may be usefully applied to other domains including bridge maintenance (Broo & Bravo-Haro, 2024), train routing (Boschert & Heinrich, 2018) and cardiovascular health (Coorey G, 2022).

Developing digital twins for real systems requires interdisciplinary cooperation. Building a digital twin for bridge maintenance (Broo & Bravo-Haro, 2024) requires mechanical engineers, sensor experts, software developers, civil engineers, system engineers, architects, project managers, and funding stakeholders. Each of these domains use their own digital artifacts including code, CAD drawings, 3D assets, system requirements, and sensor protocols.

Digital twins are directly and enduringly connected to their paired real system. A digital twin for bridge maintenance will receive sensor readings directly from its twinned system and manual inspections. If the bridge is modified, the digital twin will be modified. If the digital twin simulation requires higher fidelity due to new sensors, the twin must evolve with these new requirements.

Building digital twins is complex. Complexity comes both from the twinning mechanics and the connectivity and multidisciplinary considerations mentioned above. Managing this complexity requires a systematic approach, but the construction of digital twins is often domain specific or reliant on vendor specific tooling.

In this paper, we present a paradigm for managing this complexity.

Definition of a Digital Twin

We adhere to the digital twin definition provided by the Digital Twin Consortium (Digital Twin Consortium, 2024).

> *A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.*
>
> *Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in Information Technology/Operational Technology (IT/OT) systems.*

Decomposing this definition, we summarize the core properties of a digital twin:

- **Virtualization**: the twin digitally represents the real-world system
- **Synchronization**: operational data and parameters are regularly updated between the twin and the real-world system
- **Purpose**: there was a reason to build the twin: namely to better understand and control the real-world system

Restated, we further define digital twins as:

> *Digital Twins are living companions to real systems whose primary purpose is to answer meaningful questions about the past, current and future functioning of their twinned, real-world system.*

In this paper we will provide:

- The core processes needed to build and evolve a digital twin
- The relationship between these processes during the full life cycle of a digital twin
- A tangible, real-world example determining the necessary hardware for providing free over-the-air television to a customer's residence based on simulated radio-frequency coverage

The ABoT Paradigm

An Authoritative Broker of Truth (ABoT) is a paradigm for coordinating the development of a digital twin. The ABoT consists of a distinct set of processes, the data used by these processes, and the data relationships between the processes. A centralized Authoritative Source of Truth (ASoT) configures the data used by the ABoT and serves as the data transfer mechanism between the processes.

Within each process, different applications can be utilized depending on the domain and stakeholder needs. Example applications are demonstrated in Figure 1.

The ABoT core processes:

- **Design**: the determination of the constraints and requirements for the digital twin
- **Simulation**: the construction of the execution logic and stakeholder-oriented manifestation of the digital twin
- **Analysis**: the use of the digital twin to provide insight into the past, current and future behavior of the real system
- **Connection**: the mechanisms by which data is retrieved from the real system and control is provided to the real system
- **Evolution**: the method by which the above processes are updated to improve and maintain the synchronization between the digital twin and the real system

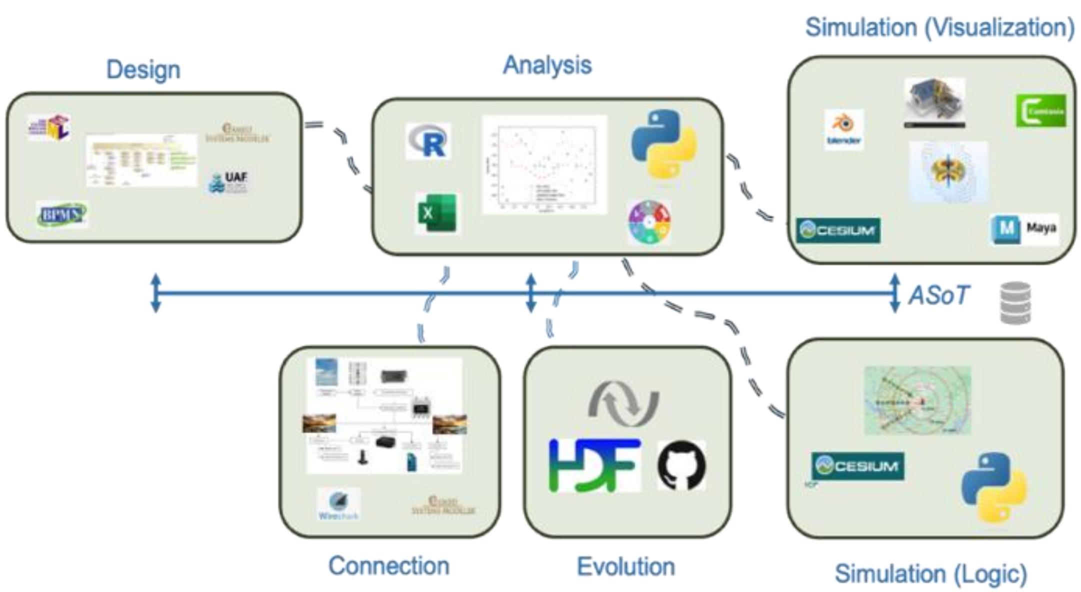

Figure 1 Example ABoT Core Processes

The general ABoT process flow is shown in Figure 2.

NEED TO DESCRIBE Figure 2 and how it works.

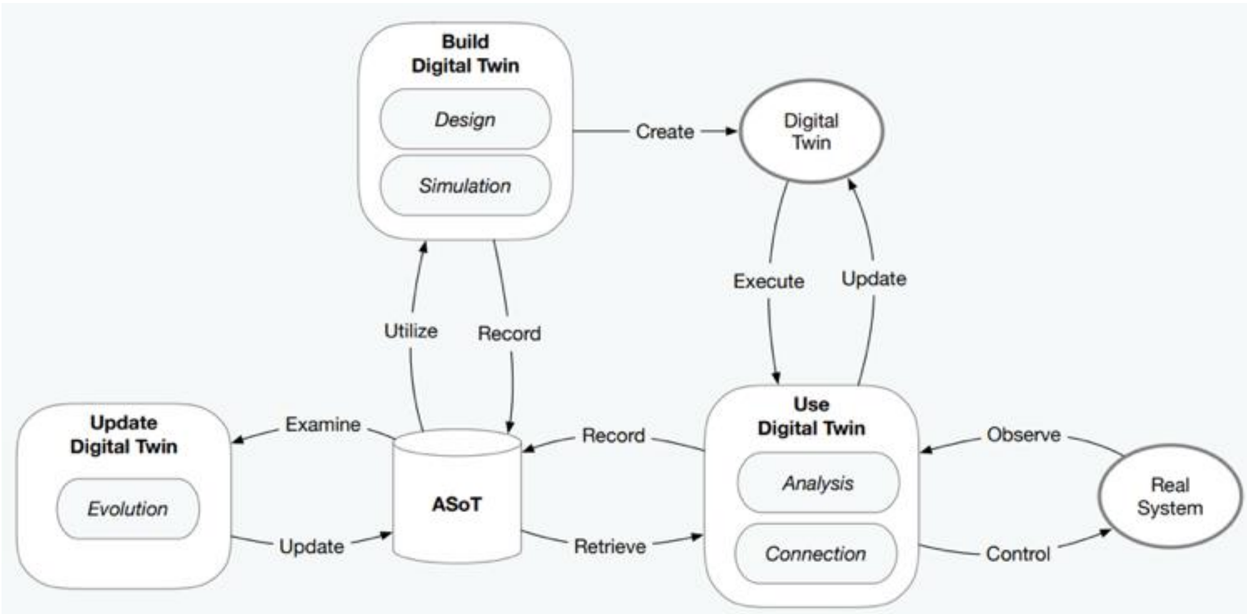

Figure 2 ABoT Process Flow

Figure 3 focusses on the data transfer between the processes.

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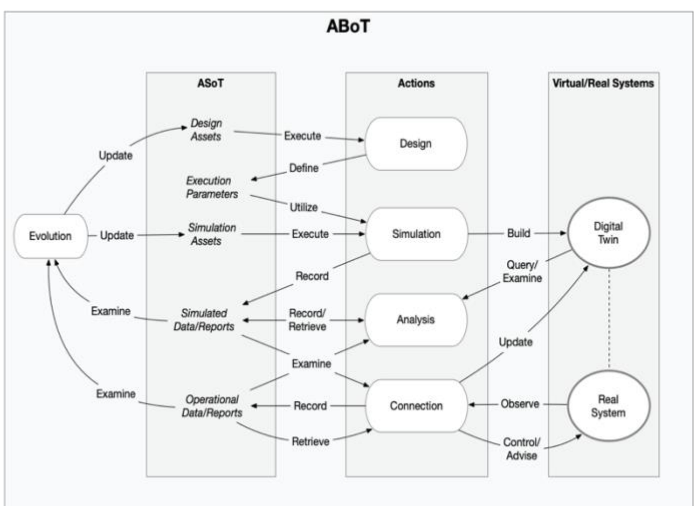

Figure 3 ABoT Data Flow

The Authoritative Source of Truth (ASoT)

The underlying data repository for an ABoT is the Authoritative Source of Truth (ASoT). The ASoT contains the artifacts necessary to construct the digital twin at any point in its life cycle (Note that ASoT *does not* contain the digital twin itself). The ASoT provides traceability as the system evolves, capturing historical knowledge and connecting selectable configuration-controlled versions of models and data for analysis. The ASoT is tasked with storing heterogenous data types across different domains with diverging file sizes and formats. Example assets associated with ABoT processes are shown in Figure 4. On the left side of Figure 4 are inputs to the processes. On the right side of this diagram are assets generated by the processes.

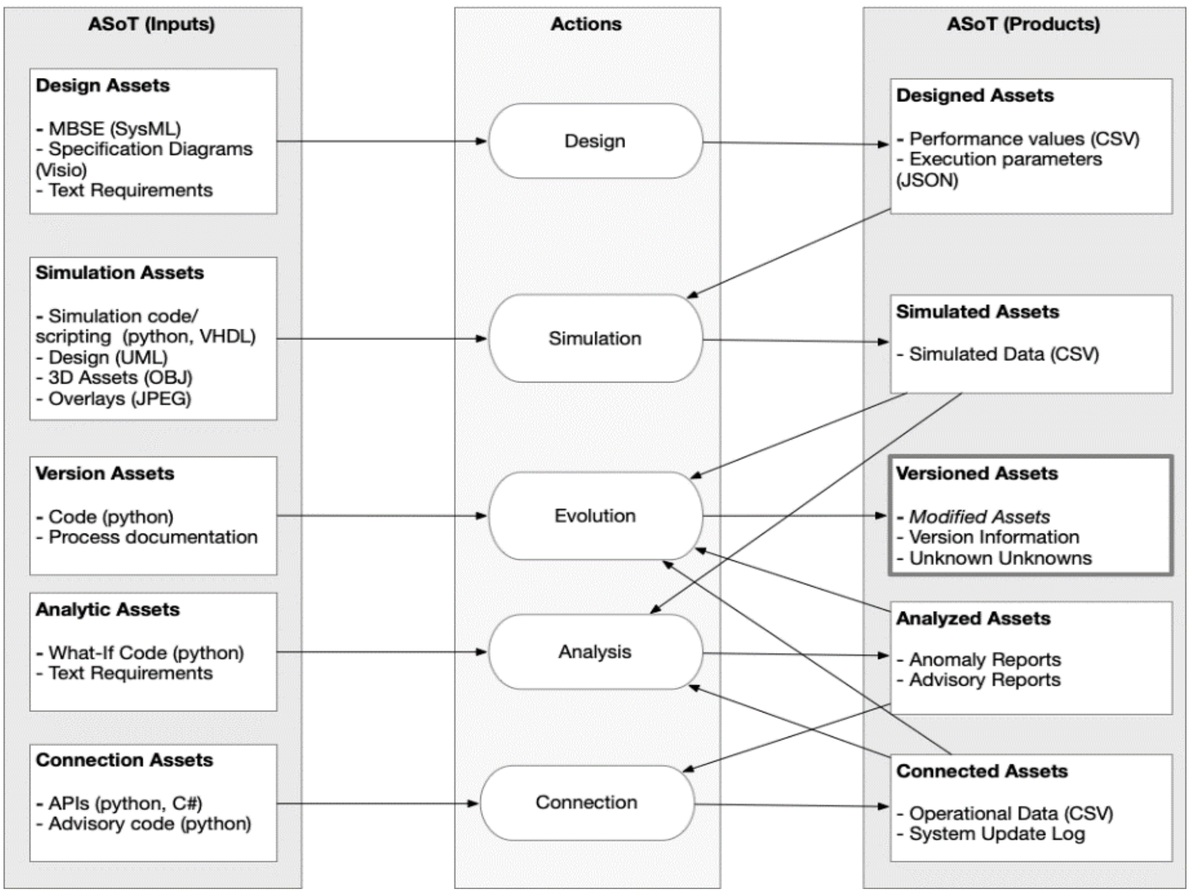

Figure 4 Example ASoT Assets

The ASoT has three functions (Figure 5):

1. **Asset Hierarchy**: defining the access and retrieval mechanism for the ASoT assets
2. **Configuration Manager**: providing versioning of individual assets and the ability to combine constellations of these versioned assets into different versions of a digital twin
3. **Asset Storage**: effecting the raw storage mechanism for the assets

The implementation of these ASoT functions may be performed by a single tool or multiple tools depending on the domain and nature of the digital twin.

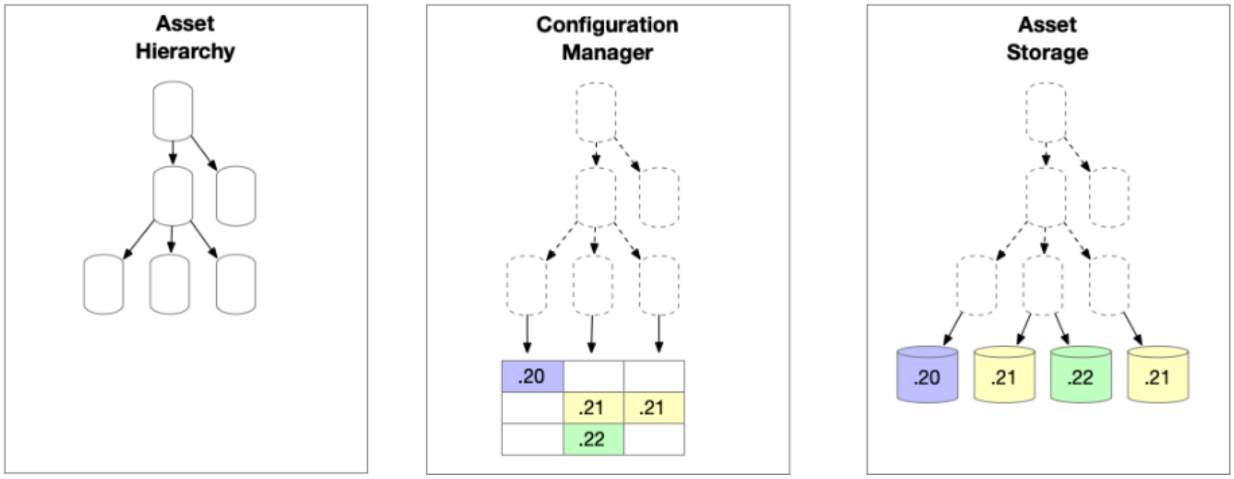

Figure 5 ASoT Structure

Validation, Verification and Uncertainty Quantification

In the National Academies of Sciences, Engineering, and Medicine study on Foundational Research Gaps and Future Directions for Digital Twins_(National Academies of Sciences, Engineering, and Medicine, 2022, p. 7) they state

Digital twins require Validation, Verification and Uncertainty Quantification (VVUQ) to be a continual process that must adapt to changes in the physical counterpart, digital twin virtual models, data, and the prediction/decision task at hand.

It is critical that VVUQ be deeply embedded in the design, creation, and deployment of digital twins.

Verification, validation, and uncertainty quantification (VVUQ) are essential processes in the development and application of computation models and simulations. This ensures the reliability and creditability of the model based digital twin.

Verification determines if the formal requirements of the digital twin are met. We assessed whether the computational model accurately implemented the intended mathematical model. We focused on the correctness of the code and numerical solution by testing the simulation code against known analytical solutions. This process confirmed the proper implementation of the simulation code correctly solved the intended equations.

Verification alignment to the ABoT processes:
- *Design*: Define system parameters and requirements
- *Simulation*: Provide verifiable simulated results using these parameters
- *Connection*: Obtain operational results for these parameters
- *Analysis*: Compare simulated and operational against design requirements

Validation determines the success of the system from the viewpoint of the stakeholder. We determined the extent of how accurately the simulation represented the real-world system. We compared the simulation outputs with the real-world observations. We compared the simulation results to the real-world physical process. We confirmed the model accurately represented the real-world system.

Validation alignment to the ABoT processes:

- *Design:* Document user intention
- *Simulation:* Display simulation results to users in comprehensible ways
- *Analysis:* Assure that edge cases produce meaningful results
- *Connection:* Obtain user input regarding system behavior

Uncertainty assesses unknowns associated with digital twin execution. We analyzed and quantified the various uncertainties within the simulation process, including input parameters, model assumptions, and numerical approximations. This process was used to assess the impact of the uncertainties of the simulation inputs. This enabled the understanding of the range of possible simulation outcomes and the ability to assess the reliability of our predictions. We confirmed our assessment of the simulation and accurately quantified the uncertainties in the simulation process and the effects on our predictions.

Uncertainty alignment to the AboT processes:

- *Design*: Document limits of requirements
- *Simulation*: Detect parts of simulation which cannot be adequately stress-tested
- *Analysis*: Note inability to test subsystems of a digital twin
- *Connection*: Anticipate future obsolescence scenarios

Within the context of ABoT, the Evolution Process realizes the results of the VVUQ activities and generates a new version of the digital twin. These version changes can impact any ABoT processes including the Evolution process itself. As VVUQ is quantifiable (the "Q" in the acronym), the level of VVUQ may be measured and compared between versions. A conceptual view of these metrics is shown in Figure 6.

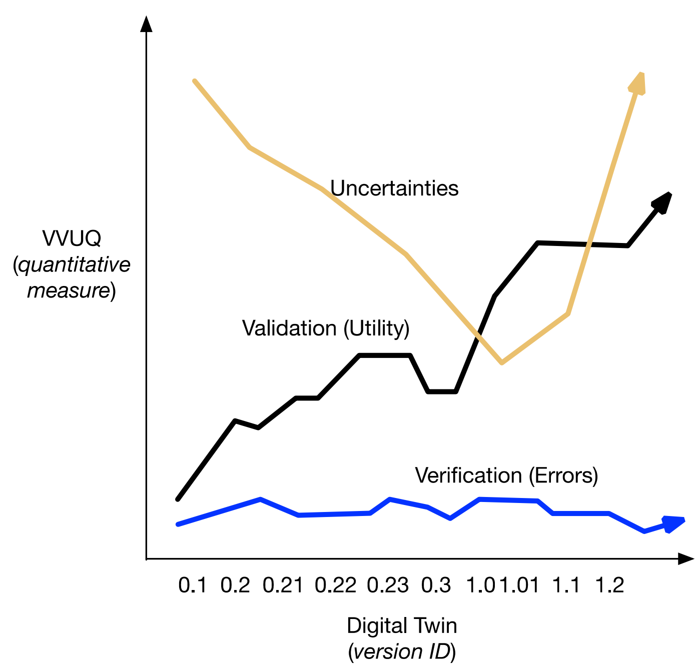

Figure 6 Conceptual VVUQ Metrics for an Evolving Digital Twin

Application of the ABoT

Over-the-air television is available in most areas of the United States, providing free television through antennas. Homeowners might be interested in saving money by replacing paid subscription-based cable television with these free services; however, determining whether reception is sufficient to cut-the-cord can be difficult and may vary with providers.

In the following sections, we discuss how the ABoT paradigm was used to create a digital twin for TV reception. We walk through each of the ABoT processes: building the digital twin (*Design, Simulation*), using the digital twin to obtain predictive coverage (*Analysis*) and updating the digital twin (*Evolution*) with new measurements (*Connection*).

We used HDF5 (The HDF Group, 2024) to implement our ASoT. HDF5 is designed to store n-dimensional data along with general file objects. Our ASoT stored design code (MBSE), simulation logic (python), simulation visualization code (Cesium JS), simulation 3D assets (OBJ) and analytic and physical measurements (HDF5 Datasets). HDF5 Attributes were used to tag these assets with versioning information.

Creating the Requirements (Design)

The design considered the following performance measures

- The distance between the transmitter and the receiver.
- The predicted TV signal Radio Frequency (RF) energy at the face of the receiving antenna.
- The predicted TV signal after the TV signal was received and distributed within the house to the back of the television set.
- The identification of components (antennas, pre-amplifiers, distribution amplifiers, etc.) needed to meet reliability and quality requirements for free TV reception (Figure 7).

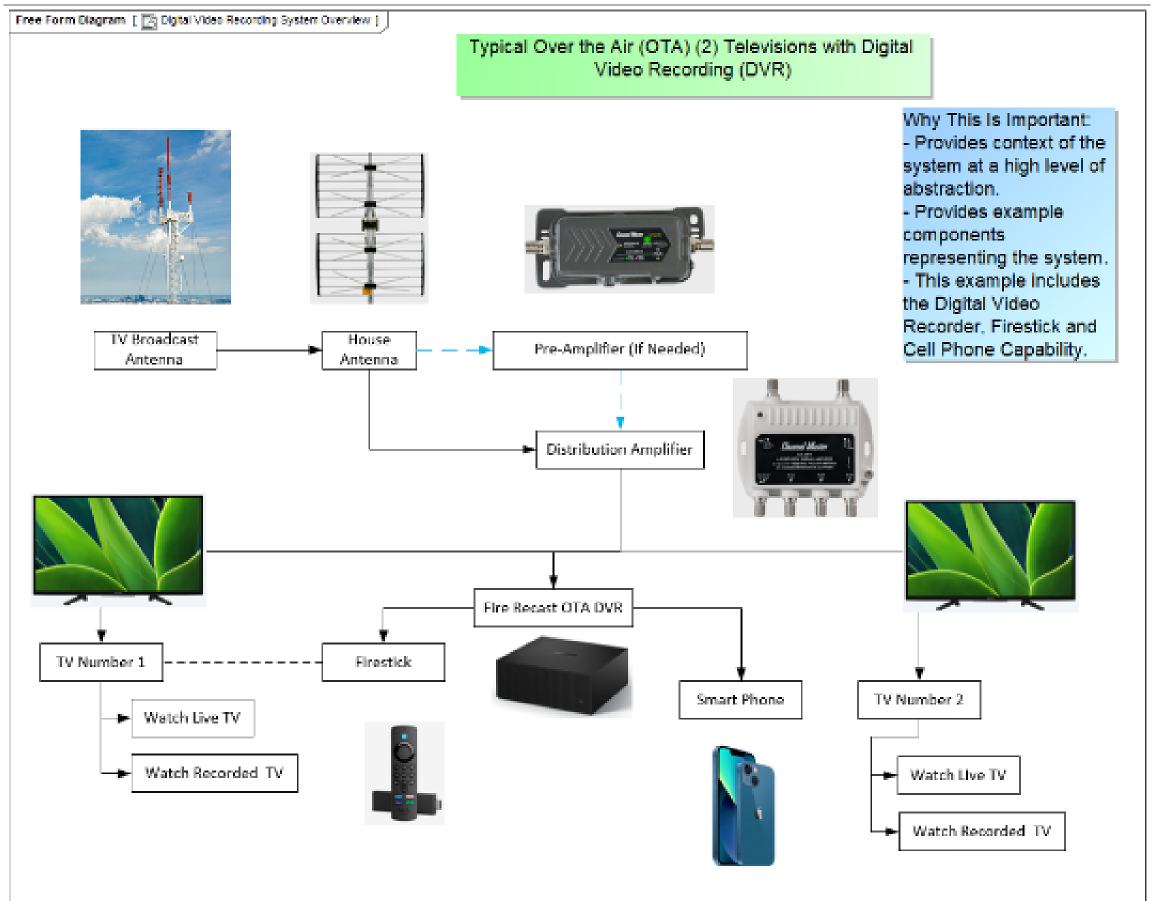

Figure 7 Over-The-Air TV Reception

A Model Based System Engineering (MBSE) approach (Object Management Group, Inc., 2011) was used to generate requirements and technical performance for RF signal strength and required system components. The model contains all nine types of diagrams of the SysML modeling language. In this paper, we highlighted three diagrams: Requirement, Block Definition, and Parametric Diagrams. The total model contained over 120 types of diagrams and 30,000 elements.

Requirement Diagrams (REQ)

The modeling process started by capturing stakeholders' needs to understand why the customer was interested in an over-the-air TV antenna system (Figure 8). The stakeholder needs were transformed into functional and non-functional requirements which were used later for automated verification (Figure 9). The SysML and all predictions from the MBSE model were stored in the ASoT (Figure 4).

Criteria

Scope (optional): Stakeholder 20 Questions ... Filter: Context (optional): Drag elements from the Model Browser ...

#	Owner	Name	Text	Rationale
1	Stakeholder 20 Questions	Ques-1 Cut the Cable	What is the primary reason you are considering cutting the cord (dropping paid for cable television and converting to Over-The-Air (OTA) free local channels?	Ensure we understand the reason why the customer is cutting the cord. Is it to save money? Poor performance over Dish TV, etc.
2	Stakeholder 20 Questions	Ques-2 Budget	What is your budget that you want to spend to be able to cut the cord?	To ensure the customer understand the value of switching from cable to over the air. Switching can be expensive - customer may not realize a quality installation will provide a nice return on investment in the future.
3	Stakeholder 20 Questions	Ques-3 Friends with OTA	Do you know any friends or relatives using OTA television? Are they happy with the reception of local channels?	Probing question to see if the customer has any experience of OTA channels in their local area and what to expect. Picture quality, number of channels, good or bad reviews, fading of channels during storms, etc.
4	Stakeholder 20 Questions	Ques-4 Major Local Channels	Are you only interested in receiving the major local channels (ABC, CBS, NBC, Fox)?	Sets the expectation of the customer, most as a minimum want to get the major networks. Other channels are bonus.
5	Stakeholder 20 Questions	Ques-5 Number of TVs	How many TVs are in your home? What areas are you planning to watch TV?	The number of TVs is a design constraint that drives equipment selection. More TV = more amplification and additional wiring if needed.
6	Stakeholder 20 Questions	Ques-6 OTA TV Expansion	Are you interested in expanding your OTA TV system to more than 2 TVs?	If the homeowner wants to expand the OTA system to other TVs in the future, the distribution amp came be upgraded during the initial installation.
7	Stakeholder 20 Questions	Ques-7 Brand of TVs	What brand of televisions are going to be connected to the OTA antenna system?	Probing question - if there are any non-digital TVs being used - they should be identified and a cable box converter will need to be used.
8	Stakeholder 20 Questions	Ques-8 Smart TVs	Are any of the television 'smart' TVs?	Probing question, if the TVs are Smart TVs and Fire TVs, it makes the installation less expensive. Try to keep it in the same product line for integration.
9	Stakeholder 20 Questions	Ques-9 Record TV	Do you record shows using your paid cable TV?	This is a probing question concerning recording live TV. Most cable companies offer this as a paid service. Does the customer want to continue to record live TV. If the answer is yes, there are additional costs involved.

Figure 8 Requirements Table Diagram

Requirement Verification: Pass Fail ...

#	Name	Text	Bounds	Value	Margin
1	50 Record multiple shows at the same time	The OTA TV system shall record up to 4 TV shows concurrently.	<=4	4	0
2	43 Save Money On Cable TV	The OTA TV system shall be less than or equal to 1200 dollars.	<=1200	1120.68	79.32
3	49 Store atleast 40 hours of live TV shows	The OTA TV system shall store greater than or equal to 150 hours of live HDTV broadcast.	>=150	150	0
4	45 ABC TV Signal Performance	The OTA TV system shall provide ABC TV signal strength of greater than or equal to -65 dBm at the TV tuner.	>=-65	-50.89	14.11
5	53 CBS TV Signal Performance	The OTA TV system shall provide CBS TV signal strength of greater than or equal to -65 dBm at the TV tuner.	>=-65	-54.673	10.327
6	51 NBC TV Signal Performance	The OTA TV system shall provide NBC TV signal strength of greater than or equal to -65 dBm at the TV tuner.	>=-65	-32.729	32.271
7	41 FOX TV Signal Performance	The OTA TV system shall provide FOX TV signal strength greater than or equal to -65 dBm at the TV tuner.	>=-65	-49.616	15.384

Figure 9 Requirements Verification Table Diagram

Block Definition Diagrams (BDD)

BDD (Figure 10) was used to identify the components of the system including antennas, pre-amplifiers, distribution amplifiers, cabling, and connectors.

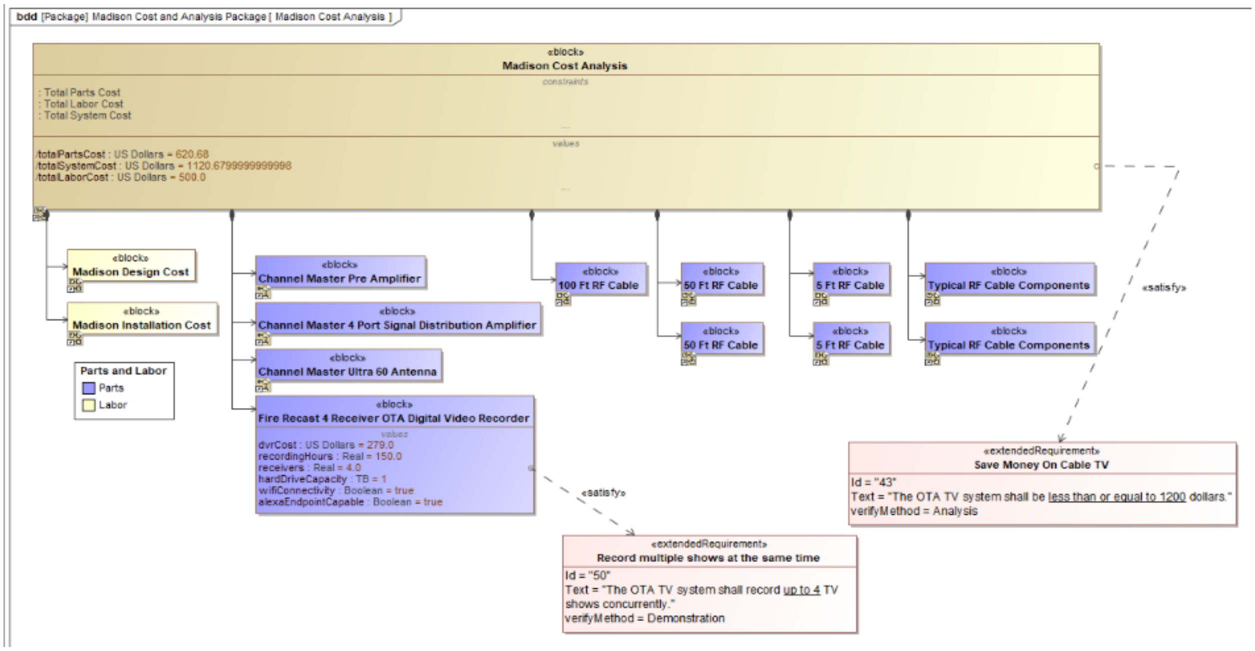

Figure 10 Block Definition Diagram (BDD) of Customer's Configuration and Cost Estimate

Figure 11shows the Channel Cost and Performance Analysis for the ABC Broadcast, a specific BDD. The values from this BDD were used in the parametric equations to obtain the RF link budget analysis and cost data.

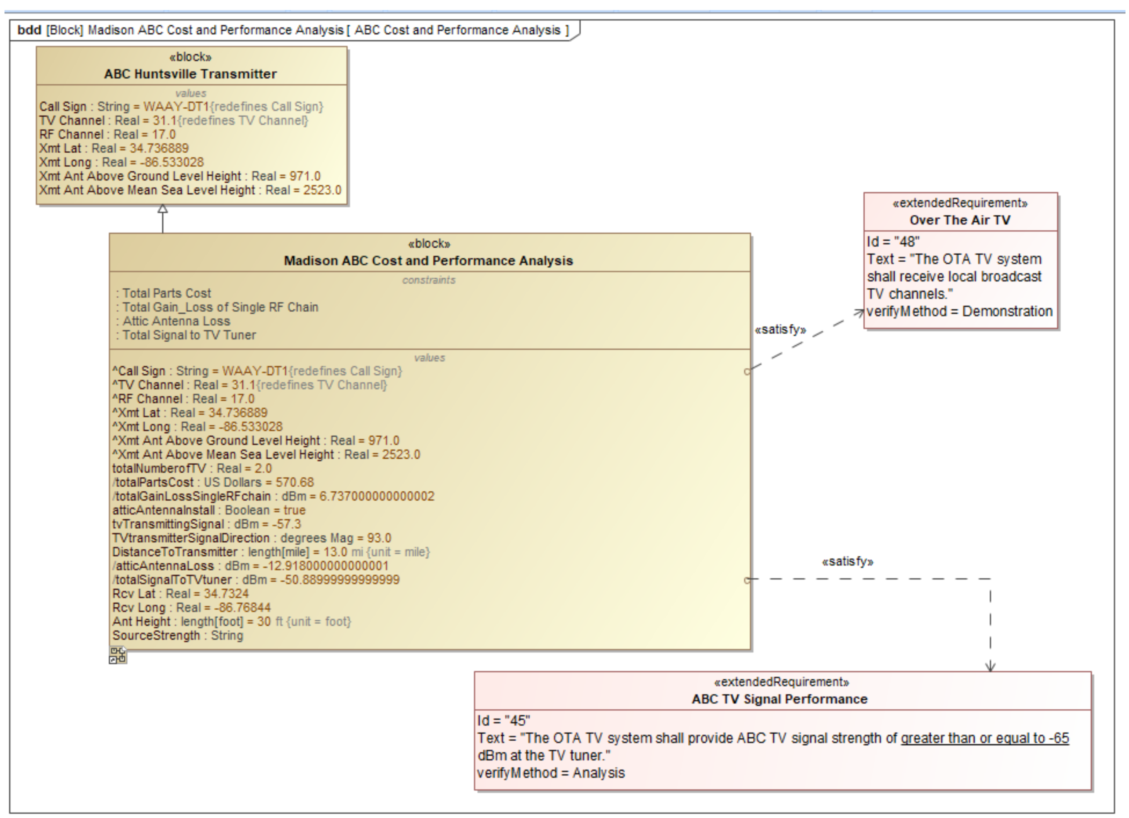

Figure 11 ABC Broadcast Channel with Attributes and Requirements

Parametric Diagrams (PAR)

PAR expresses how constraints are bound to the properties of the system. In our case PAR predicts RF energy levels at geographical locations within the TV viewing area. The ABC PAR (Figure 12) shows total signal level for the TV tuner.

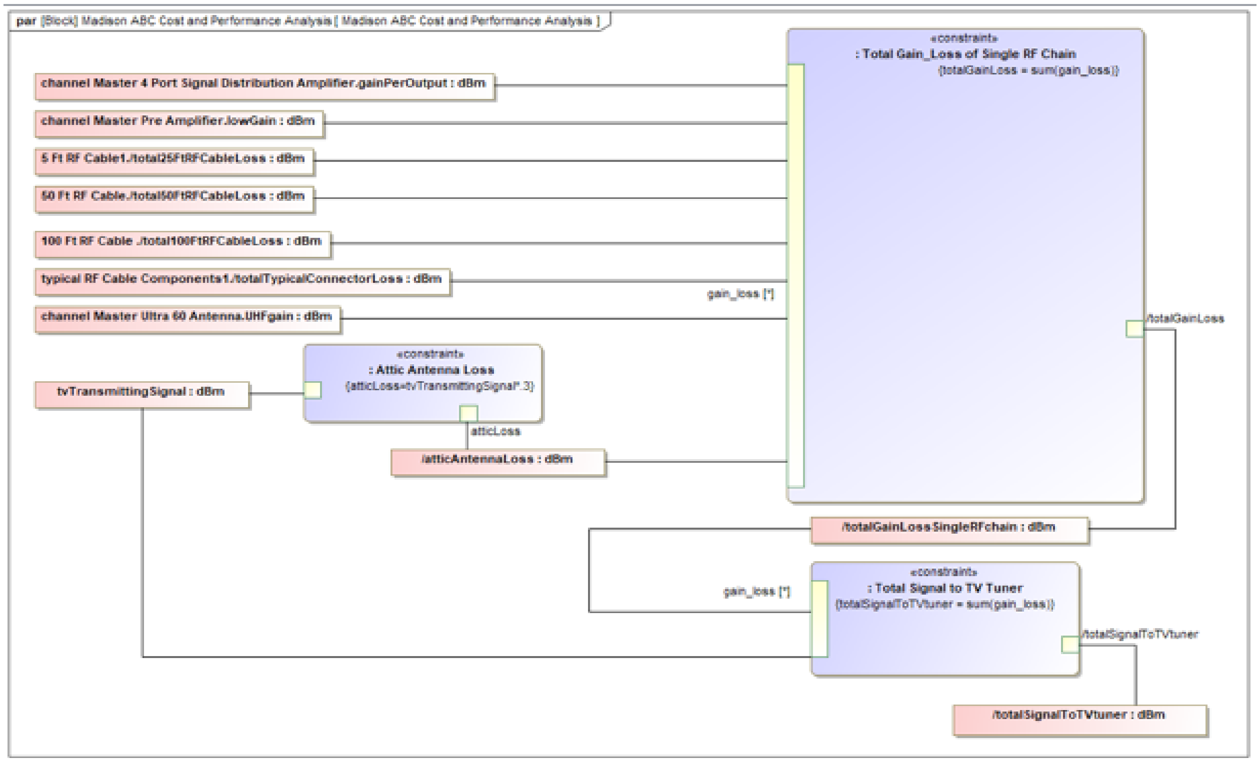

Figure 12 Parametric Diagram – ABC Television Signal Performance Analysis

The ABC Instance table (Figure 13) shows the performance characteristics of the ABC broadcast channel at various geographical locations. Of note is the red colored cell in Figure 13 which indicates the RF energy at that location does not meet the required minimum signal strength.

Criteria
Classifier: lison ABC Cost and Performance Analysis ... Scope (optional): Channel Master ABC Instance Table ... Filter:

#	Name	DistanceToTransmitter : length[mile]	TVtransmitterSignalDirection : degrees Mag	Rcv Lat : Real	Rcv Long : Real	totalSignalToTVtuner : dBm	Call Sign : String	TV Channel : Real	RF Channel : Real	SourceStrengt : String
1	(240) 15 Lake Forest Blvd SW, Huntsville, AL 35824	13 mi	60	34.6435	-86.7323	-31.494	WAAY-DT1	31.1	17	Channel Master
2	(240) 4147-4237 SW Bilow Rd, Madison, AL 35756	18 mi	60	34.6076	-86.8092	-34.601	WAAY-DT1	31.1	17	Channel Master
3	(240) 26647 Henderson Rd, Madison, AL 35756	21 mi	60	34.5861	-86.8546	-36.876	WAAY-DT1	31.1	17	Channel Master
4	(240) 65 Duncansby Dr SW, Decatur, AL 35603	24 mi	60	34.5646	-86.9009	-40.36	WAAY-DT1	31.1	17	Channel Master
5	(240) 3418 Hooper Ln SE, Decatur, AL 35603	27 mi	60	34.5426	-86.9469	-40.295	WAAY-DT1	31.1	17	Channel Master
6	(240) 4413 Dogwood Dr SW, Decatur, AL 35603	30 mi	60	34.5211	-86.9918	-106.387	WAAY-DT1	31.1	17	Channel Master
7	(270) 111 Kelvingrove Dr, Madison, AL 35758	13 mi	90	34.7379	-86.7627	-51.371	WAAY-DT1	31.1	17	Channel Master
8	(270) 26328 Beech Grv Ln NW, Madison, AL 35756	18 mi	90	34.738	-86.8506	-29.167	WAAY-DT1	31.1	17	Channel Master
9	(270) 12623 Cambridge Ln, Athens, AL 35613	21 mi	90	34.738	-86.9038	-32.768	WAAY-DT1	31.1	17	Channel Master

Figure 13 Instance Table of ABC Broadcasting Channel in Various Locations Within the Area of Interest

Creating the Prediction Mesh (Simulation)

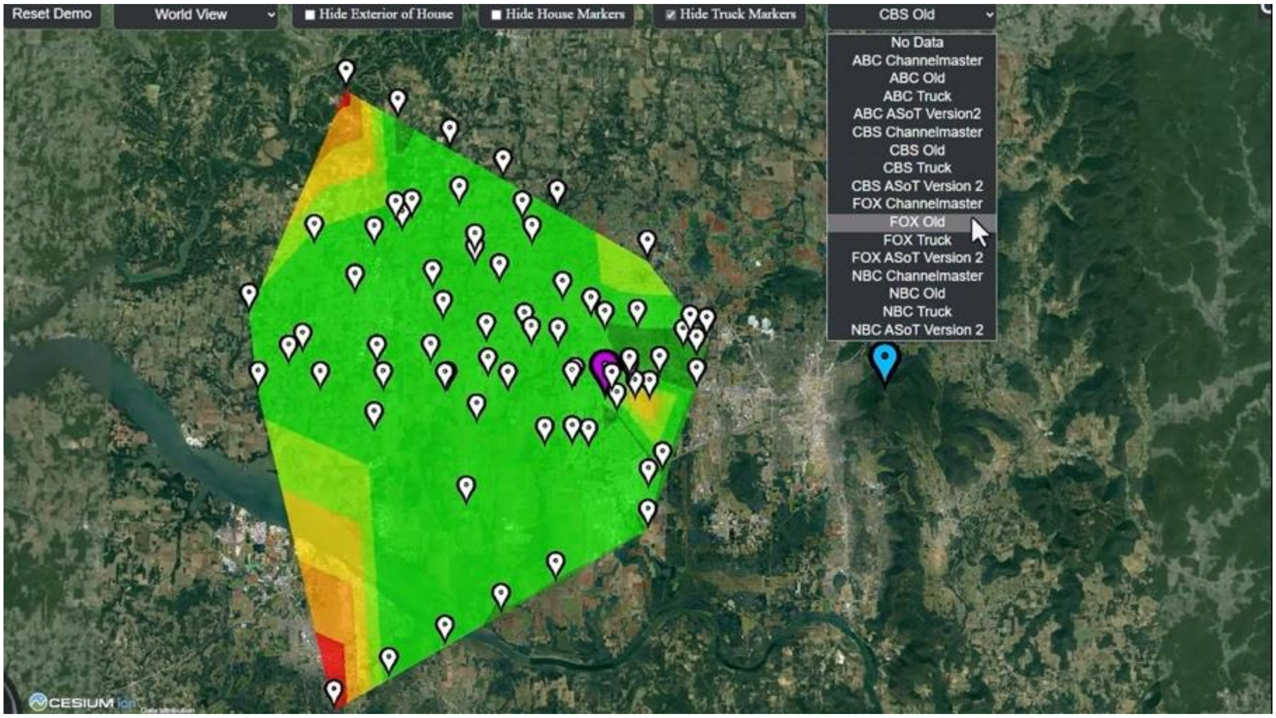

Figure 14 Interface to the Digital Twin (Huntsville, Alabama – USA)

Within the context of ABoT, the Simulation Process (Figure 3) contains the logical execution of the digital twin and the presentation of the results of that logic to a stakeholder. For our use case, the simulator generated a geographic signal strength map (Figure 14). The Design Process placed 86 MBSE signal strength predictions into the ASoT; these predictions were then extracted by the Simulation Process (Figure 2) and used to generate a signal source mesh. We developed our signal predictions using a finite element method (Larson & Bengzon, 2013) treating latitude, longitude, and signal strength as points in R^3. To discretize the surface, we used surface Delaunay triangulation (Berg, Cheong, Kreveld, & Overmars, 2008).

The simulation predictions were provided to the user through an interactive (Cesium, 2024) application (Figure 14). A drop-down menu was used to switch between different datasets and signal sources; the green areas of the RF heatmap corresponded to good signal strength, the red areas to poor signal strength. Within the Cesium application, locations could be zoomed (Figure 15) to obtain further geographic details. All code for the simulator logic and interface was stored within the ASoT (Figure 4).

Using the Digital Twin (Analysis)

Using the completed digital twin, a stakeholder in Huntsville, AL wanted to determine if they could replace their cable television with over-the-air radio transmission. From the ABoT perspective, they are performing Analysis (Figure 2). Entering their home coordinates, the stakeholder found that the signal strength at their house was borderline (Figure 15 - #4). Exploring the area with the simulation application they discovered that a mountain (Rainbow Mountain) blocked the line of sight between the transmitter and receiver location. (Figure 15 - #3).

Figure 15 (1) RF Heat Map, (2) Transmitting Antenna Location, (3) Rainbow Mountain Blocking Line-of-Sight Between Transmitter and Receiver, (4) Receive Location

Collecting Operational Data - Enter the Truck (Connection, Evolution)

Although the potential for inference from Rainbow Mountain was a reasonable explanation for the borderline signal, the stakeholder wanted additional data points to refine the prediction before purchasing signal boosting hardware. Within the ABoT paradigm, obtaining data from the real system is part of the Connection Process.

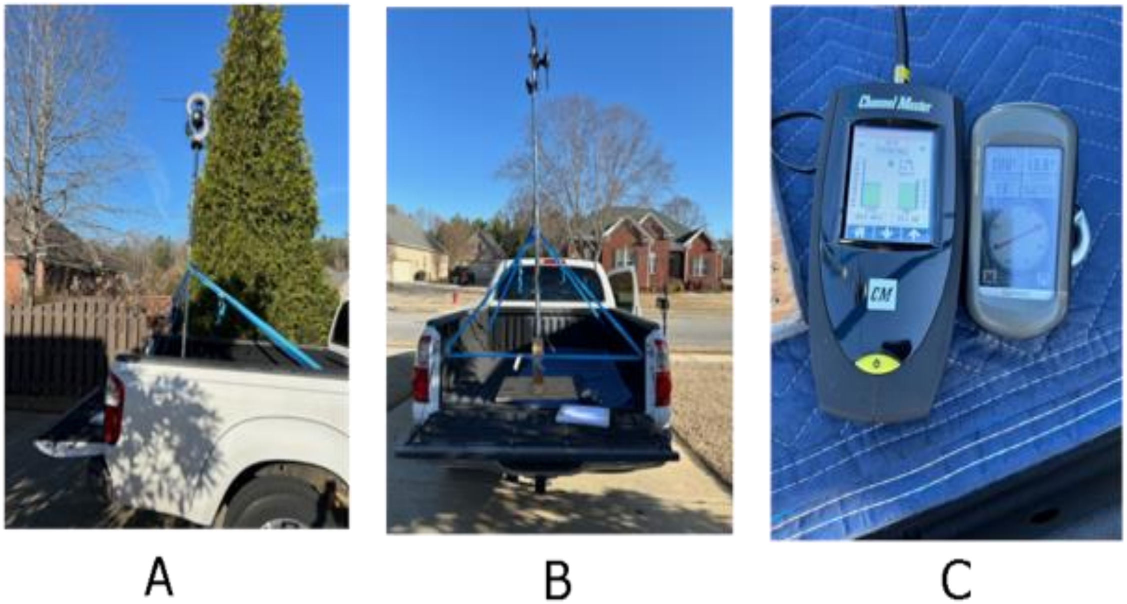

Figure 16 Antenna Test Fixture

To collect more data a portable test antenna fixture was used to measure RF signals including:

- A mobile antenna platform (Figure 16, A)
- A pickup truck (Figure 16, B)
- A hand-held GPS to point the antenna and measure distance from the transmitter (Figure 16, C)
- An antenna signal strength meter to measure and display RF signal level and signal to noise ratio (SNR) for each channel. (Figure 16, C)

The antenna test fixture was driven to different locations in the area-of-interest and RF signal strength measurements and position data were recorded. Figure 17 shows a comparative plot of the original predicted signal (dots) and the physical measurement (crosses). The prediction error can be measured at each location (*x*-axis) through subtraction of signal strength (*y*-axis). Examining the physical RF measurement at the stakeholder's house (*yellow highlight*) we see that the actual measurement was lower than predicted, thus confirming the need for an amplifier.

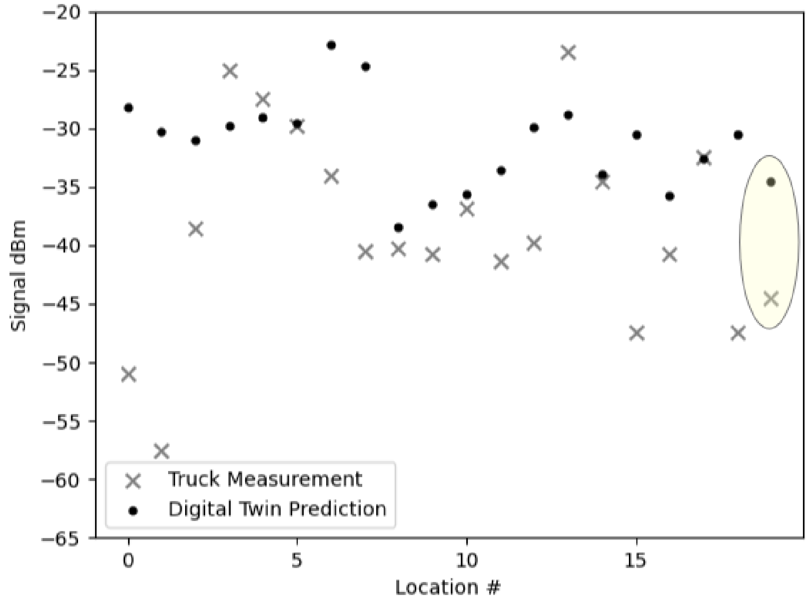

Figure 17 Comparison of Original Digital Twin Data and Collected Data

The new physical measurements were then added to the ASoT and incorporated as the basis for the simulation and the next version of the digital twin (Figure 18). Creating an updated version of a digital twin is performed within the ABoT Evolution Process. (Figure 2).

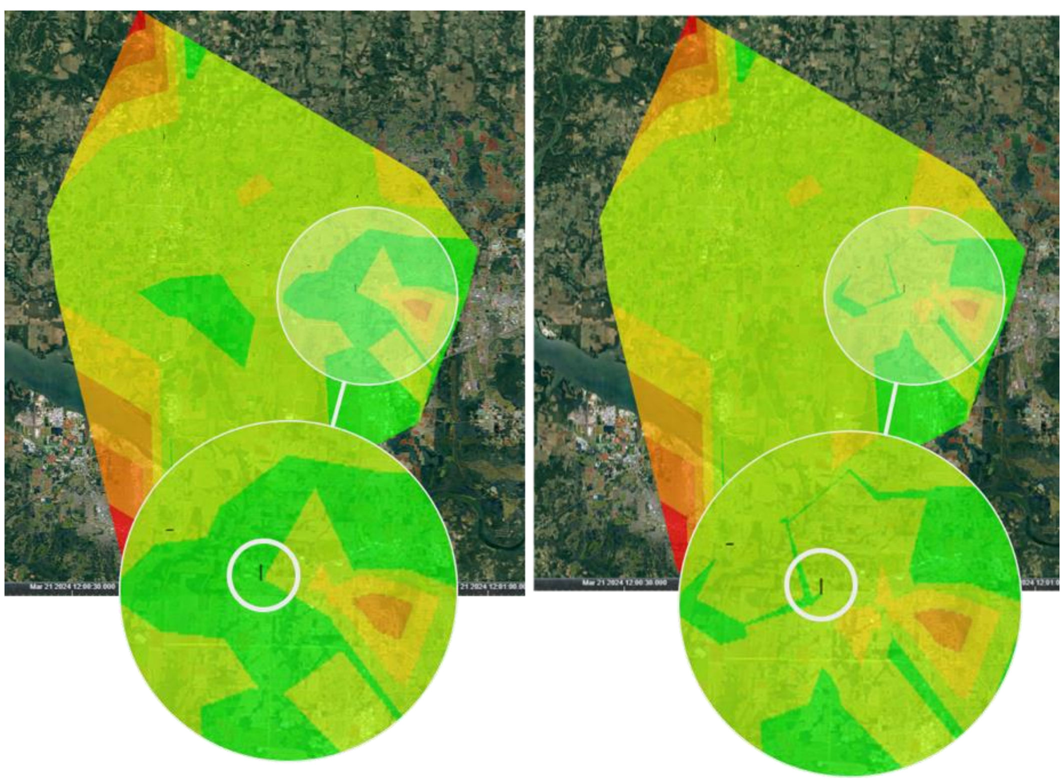

Figure 18 (Left) Original Digital Twin RF Heat Map, (Right) Next Version of Digital Twin

Conclusion

We provided a paradigm for constructing a digital twin: the Authoritative Broker of Truth (ABoT). ABoT provides the processes and data organization needed to build, utilize and evolve a digital twin. Our approach is vendor-neutral, cross-discipline, and allows the integration and versioning of disparate artifact types including code, documentation, operational measurements and simulation reports. ABoT is intended to be used across the full life cycle of a digital twin and to be useful to all digital twin stakeholders including digital engineers, system engineers, simulation and UX designers, project managers, and ultimately, the end user.

We applied the ABoT paradigm to a digital twin for TV reception, including RF signal coverage and amplifier considerations. We performed design analysis and trade studies using an MBSE model. We then used the predictions from the MBSE model to simulate a signal strength coverage mesh. Using this coverage mesh we analyzed the strength at our target location and identified an obstruction. We captured additional RF signal measurements at select locations to verify our digital twin and then used these measurements to refine and evolve our digital twin to its next version.

We chose a consumer-level use case and implemented our digital twin using open-source tooling so to be accessible to a broader audience. The ABoT paradigm could be utilized within a variety of tool suites and approach more sophisticated applications, for instance, communications mission planning within a hostile electromagnetic environment.

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Biography

Pat Meharg. Pat is a Senior Fellow–Digital Engineering at Noblis specializing in Digital Engineering, Systems Engineering, System Architecture, and Program Management in the areas of autonomy, aviation, communications, and maritime systems. Of particular interest is applying Model Based Engineering tools and techniques to architecture and designs. He is a certified Project Management Professional (PMP), OMG-Certified SysML Professional (OCSMP), and Software Architect Professional. He holds a Master of Science degree in Systems Engineering from Florida Institute of Technology and a Master of Business Administration from Troy State University.

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