# Leveraging Commercial Off-the-Shelf Software to Identify and Mitigate Risk during Launch Vehicle Operations

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As the global frequency of space vehicle launches is ever-increasing, so too is the industry's demand to mitigate risk and decrease cost. Launch and spacecraft operators must primarily rely upon real-time telemetry data during launch and initial spacecraft deployment to aid effective, time-critical decision making. In this environment, mere seconds can mean the difference between success and failure. During anomaly resolution, consensus between management, customers and technical analysts demands clear situational awareness. This time critical issue warrants the generation of an automated, hands-free tool that empowers these operators to efficiently analyze mission landmarks in order to achieve overall mission success. Using commercial off-the-shelf (COTS) software enables operators to leverage existing, proven technology-still allowing for customization-which in turn reduces development time and cost. Analytical Graphics Incorporated (AGI) develops STK, a COTS software suite that provides professional presentations of real-time, vehicle-centric visualization and analysis. The software gives instant insight into many spacecraft parameters, such as trajectory analysis and attitude determination, that would otherwise take significantly longer to analyze in their pure form. As a test case, the Real-Time Visualization (RTV) system for Space Vehicles, developed by Lockheed Martin Space Systems Company will be explored.

## Using Real-Time Telemetry Feeds during Launch Vehicle Operations

A flight controller sits behind a workstation in the command center on the day of launch, checking and rechecking the pre-flight status, noting on the schedule when major mission events will occur and when critical decisions need to be made. The countdown begins, the launch vehicle leaves the pad and clears the tower; instantaneously an abundance of data floods the screen. Along with trajectory, thrust vectors, and engine gimbal angles, one second attitude quaternions of yaw, pitch and roll immediately start flashing on the operator's screen as the live telemetry stream is downlinked from the launch vehicle. As the mission timeline elapses and the critical final burn and spacecraft separation events approach, the operator monitors the vehicle's attitude and position closely—an anomaly at this junction could cause a catastrophic loss of the payload. The data changes rapidly and immediately after the upper stage completes its final main engine burn the attitude rates increase unexpectedly. Spacecraft separation is scheduled to be only a couple of minutes later. The anomaly is later found to be caused by an unbalanced shutdown of the two main engines, inducing a rapid pitch up. The attitude data is being presented to the operator in raw numerical form. Now, under pressure the operator must observe the raw data and determine the potential impact of the anomaly upon the impending spacecraft separation. From the display screen it is determined that the anomaly has induced a 5 degree per second rotation, but what does that really mean? What is the actual vehicle doing? What is the trend of the attitude rates? Is the spacecraft correcting the situation or is the vehicle out of control? Should the payload customer be advised to perform a high risk maneuver and separate while tumbling ahead of the scheduled time? By simply looking at the instantaneous attitude data streaming from the telemetry it is difficult to determine the severity of the anomalous situation. The operators, analysts and mission directors need immediate situational awareness to clearly understand the events, to determine all possible outcomes—which there can be potentially dozens of outcomes in any given case and to make mission-critical decisions in real-time or they risk decreasing mission success.

The aforementioned case is an actual scenario that one of Lockheed Martin's Real-Time Visualization (RTV) system customers experienced during mission launch rehearsal. In this situation mission control needed to determine whether to hold on and allow the separation to occur at the scheduled time with the current 5 degree per second rotation or to "punch off" and subsequently risk damaging the payload [Fig. 1]. The mission rehearsal was using a recorded telemetry stream which included the unbalanced shutdown anomaly. This recorded data was played back during the real-time mission rehearsal; aiding the team in understanding how the satellite vehicle operators would react in such a situation. Guided by the telemetry-driven technical animations, text annotations, and model articulations generated by the RTV system in conjunction with STK, the controllers were able to quickly observe that the upper stage was responding with attitude control firings in the proper manner. It could be easily seen that the pitch rate was being arrested and nominal attitude would soon be restored [Fig. 2-4]. This allowed the team to make the proper decision to allow vehicle separation to occur once the vehicle recovered from the tumble [Fig. 5]. Without the RTV system it would have been more difficult to determine how the vehicle was positioned and how the anomaly would effect vehicle separation using only the instantaneous positioning and numerical attitude data from the telemetry of the spacecraft. In this example Lockheed Martin's customer was aided by using RTV and COTS with real-time data feed capabilities in pre-mission planning and rehearsals; better preparing mission operators and decision makers for an actual live event.

Live telemetry streams contain a wealth of vital information needed to assess several analytical factors: vehicle position and attitude; communication antenna azimuth and elevation; sensor pointing; solar array angle to sun; and trajectory analysis. This information, provided to operators is the sole insight into the progress of their mission, thus directly affecting decision making. While these core indicators are often telling and effective, mission-critical information oftentimes lay buried in the downlink of raw telemetry which can cause an analyst to be overloaded with information. This constant stream of numbers during launch and operation milestones can hinder an analyst from prioritizing and acting upon pertinent data, thus significantly decreasing the chance for optimal mission success. If the launch vehicle trajectory has strayed from the nominal configuration, an analyst might be able to determine the current course of the vehicle from the data provided by the mission control station. However, new calculations will need to be made in order to determine if the current trajectory will guide the vehicle into an acceptable orbit. This may cause an operator to record the numerical data from the telemetry screen and use a separate program or workstation in order to generate the projected path of the launch vehicle and payload. Consequently, time is lost in the transfer of data and the generation of new analysis. A more efficient solution would provide the operator with one picture that is calculating and displaying the trajectory for the nominal launch operations as well as the trajectory generated by the live telemetry stream. The planned vehicle trajectory can be shown along with the actual real-time vehicle in a direct comparison for instant insight into the success of the mission by juxtaposing the planned path versus the actual path [Fig. 6]. This solution allows mission directors, flight controllers, and guidance and navigation personnel to validate telemetry values and review mission milestones. With RTV an operator is no longer restricted to the raw data displaying on the screen but can perform on-the-fly analysis as the downlink of information is presented. Therefore, the time before a mission critical decision can be made has been drastically shortened without compromising data integrity and the risk of failing to meet a mission milestone has been decreased.

When an operator is observing positional data, battery temperature, engine firings, solar array deployment, vehicle staging, or payload fairing status, it can be difficult to completely understand the situation and position of all the vehicle components based on numerical data alone. Decision makers could better comprehend problems with the addition of visualizations driven by the real-time telemetry stream. Rather then relying solely on the downlink of raw data flashing on several operators' screens, one common picture can be derived from the raw data creating a clear solution that shows all configurations of the vehicle and displays rapidly changing data indicators. These visualizations will allow the operations chain of command to better conceptualize the current position of the vehicle, clearly display important health and status indicators, allow them to understand how one factor can create an anomaly, and generate possible optimal resolutions. It is an arduous task for mission control personnel to watch one screen with a constant influx of rapidly changing raw data while simultaneously determining if one of the indicators has fallen below nominal performance levels. Therefore, a situation occurs in which it become ineffective to make mission critical decisions based on raw data alone. Adding a visual component driven by the telemetry stream to the launch operations picture helps to create a concise picture of every aspect of the launch vehicle which can increase the opportunity to complete a successful mission.

This obstacle to mission success warrants a modern software solution with a faster, more efficient information processing workflow. The end product needs to provide situational awareness during all phases of launch and on-orbit operations; to be installed across a network of systems and worksites; to allow operators to quickly and easily disseminate mission critical information; and to aid in anomaly resolution. Data streaming from a live launch can come in several formats across different platforms, rather then creating a separate application to handle each feed, there is a need for one program to handle a variety of telemetry and data feeds and display them in one clear, data enriched environment. The ideal result would be a logical, concise picture and analysis platform of the launch from pre-mission to on-orbit success—like having an omnipresent camera filming every angle while displaying the pertinent data from the telemetry stream. Operators could therefore be virtually hands-free in mission milestone analysis, leaving them to better respond to critical events. The increasing number of proposals and missions creates a demand for a solution that has a short development cycle, is easy to implement, low in cost and reusable for several missions and systems.

## Commercial Off-the-Shelf Software vs. Proprietary Software

Now that a need for a new software solution has been established, the decision between building and buying a software package must be made. When looking for a solution to a recurring problem the traditional school of thought is to develop unique customized code for every new program, mission or requirement. This process requires a lengthy development and test timeline along with associated risks and costs. To avoid the generation of a single use product that adheres only to one strict set of requirements solving one operational problem, software engineers can utilize COTS and integrate their specific applications or legacy software with flexible commercially available software. If a complete solution is created solely with new conceptualized code then oftentimes the developers carry not only the burden of code generation, but of the validation and verification, debugging and supporting the end users through training and support. Also, if the overall mission changes in scope or carries additional operational requirements, added cost, timeline and mission risk are incurred. The launch program then has to add additional resources to their projects while trying to maintain an on-time delivery schedule. As it is often the case in the proposal phase of a program, independently developed software is only in the initial stages of maturity, therefore making it difficult to show end results to the prospective customer. Also the analysts rarely have a chance to generate hard analysis with the software that is in the development phase and must rely on other tools to achieve results for the proposal. With out-of-the-box software, the engineers can use preliminary requirements in the application to show analytic results, technical animations and proof of concept in order to gain an edge in winning the contract. The proposal will also carry a lower cost associated with the generation and implementation of mission control and systems analysis software and carry a reduced development risk, making the bid attractive to the customer.

Commercially available software often has hundreds of developers and testers behind it while a homegrown solution may have been developed only by a handful of engineers. Software developed by a breadth of coders provides the tool with a wide range of expertise which adds depth to the functionality of the end product. In STK, the analytic geometry engine is independently validated and verified, allowing the user to rely on the analytic output without testing the core capabilities of the application. Also, with over 32,000 worldwide installations, not only is the testing, development, product management and engineering staff working with the software every day but there is a constant stream of feedback and input from the customer base which is rapidly integrated into every new release. The software package is also thoroughly documented with user-friendly help files and with access to a technical support team staffed by engineers. Many COTS companies also provide training for their software along with onsite support during installation, deployment and operations. For example, AGI provides users with free introduction classes and a week of advanced training regularly in order to get users up to speed as quickly as possible. Using off-the-shelf software allows for operator longevity and mobility; knowledge and familiarity with one tool aids in producing faster analytic output and helps the operator move from one operational program to the next. STK is also flexible and allows for the integration with legacy software, the creation of custom applications or the ability to ingest their own proprietary data. Lockheed Martin took advantage of the integration capabilities of STK in the creation of RTV.

Moreover, customers with future or proposed payload enhancements can integrate current and future payload models with the RTV system to visualize overall system performance in STK, in both live and playback mode. One of Lockheed Martin's classified customers said the resulting future payload system visualization was "the best product that I have seen in 20 years."

## Test Case: Lockheed Martin's Telemetry Driven Real-Time Visualization System

Lockheed Martin developed the telemetry driven RTV system to support mission directors, flight controllers, payload operators, and program directors during pre-launch analysis and rehearsals, real-time launch operations, payload separation, and on-orbit phases. RTV is used to generate and distribute real-time, telemetry-driven analytic visualizations of launch vehicles and spacecraft. All aspects of vehicle flight operations are depicted by using accurate vehicle-based model geometry, in a 3D environment which creates a common operating picture (COP) for all decision makers. Within this COP, there is an accurate depiction of vehicle-based geometry by using 3D models built based on actual Computer Aided Design (CAD) drawings. These models show all articulations, deployment and component positioning during the entire mission. For example, not only does RTV display the charge on the solar arrays, but the animation shows the deployment, instantaneous position, sun angle and articulations of the arrays—all of which are driven by the actual live telemetry stream. Without this system an analyst could only observe vehicle activity based on the numerical data in the downlink of telemetry data, such as the instantaneous position and velocity vectors. With the Real-Time Visualization system he can understand not only where the vehicle is in the trajectory path but where it is in relation to the sun and other objects. RTV can also display critical information in the visualization such as the gimbal pitch of an engine or the temperature of the batteries.

Lockheed Martin created the RTV software solution in 1998, and it has been used to identify and mitigate risk during launch operations by several customers—both unclassified and classified—across several launch vehicle platforms such as Titan and

Atlas. Currently, the main objective of RTV is to support launch vehicle operations for the Office of Space Launch (OSL), and on-orbit operations for classified customers. However, as the need for better missile defense system grows, Lockheed Martin is prepared to enter the missile arena by supporting all aspects of missile operations, from launch to missile intercept. This front-end software tool was created as a solution for past and current programs in operations phase and thus has proven its effectiveness.

## *How RTV leverages COTS*

The Real-Time Visualization system leverages COTS by relying on STK to provide the key end-component in a system requiring real-time visualization of time-critical data in a simplified, easy-to-understand picture. STK is the core product that provides the front end to Lockheed Martin's comprehensive situational awareness tool. Specifically, RTV leverages AGI's physics-based geometry engine to accurately depict vehicle trajectory, position and attitude, calculate range, communication links, and sensor positioning and pointing and the flexibility of commanding STK via a TCP/IP socket by sending commands through the API. STK's 3-D environment allows for visualization of the vehicle model against actual geospatial data such as planet/vehicle relationships, positioning of the celestial background, live telemetry data display and accurate depiction of all vehicle articulations. For example, a real Titan IV launch from Cape Canaveral can be seen [Fig. 7] with several orbital parameters displayed. The system not only presents vehicle model attributes but also system health and status information via dynamic textual annotations, such as payload memory status, battery temperatures, solar panel voltages and rocket nozzle pitch angles [Fig 8]. RTV utilizes the flexibility of STK by commanding the software via a TCP/IP socket, allowing legacy software to interact seamlessly with COTS. Finally, the team at Lockheed Martin can create movie files or animations which can be easily shared by the use of AGI's Viewer product. These files can be broadcast across a variety of networks and platforms to communicate the launch vehicle mission via analytic visualizations.

## *RTV Success Story*

During launch operations, the command center receives a downlink of information from the launch vehicle through payload separation. However, the flight controllers cannot uplink to the launch vehicle during this entire launch sequence—they are in more of a "watch and wait" mode. Once the payload has separated, deployed, and has made contact with the ground station, the operations center can then uplink commands to the spacecraft and task the vehicle. The ground station receives live data but can also react to any anomalies or generate a sequence of events to accomplish the mission.

Much like the launch rehearsal, spacecraft mission operators want to test and verify mission sequences before commanding the spacecraft, therefore reducing the risk of tasking the vehicle with a maneuver or a condition that could cause the loss of a milestone occasion such as: completion of a communications link, payload preparation for an overflight opportunity, or proper sun positioning. By creating a software package that can ingest telemetry, whether live or recorded, and display the critical data and analytic demonstrations of all aspects of the spacecraft, the operators can then test any commands to task the vehicle prior to uploading the commands, in turn reducing on-orbit risk. Lockheed Martin aided a classified customer by using their legacy software in conjunction with STK to create a rapid mission test and simulation package. After successful deployment and initial on-orbit operations, the customer generated maneuver sequences needed to accomplish the mission, and these sequences were then run through their satellite hardware simulator. This recorded telemetry was then taken by the RTV team to create a 3D visualization and output the vehicle position and attitude, health and status and geospatial relationships used by the customer to depict the anticipated results of the maneuver. The mission team can then determine if the outcome of the tasking sequence achieved the desired result in a trial or "fly before you buy" environment. The results can then be shared across networks, among operators, mission managers and contractors via AGI's Viewer software and movie files to enable quick decision-making about on-orbit maneuvers prior to tasking the vehicle.

## *How AGI's Software Enables RTV*

AGI's software suite enables Lockheed Martin to create and continually improve their RTV system by providing a COTS solution with a user-friendly work environment and an open architecture that readily supports integration and customization. STK has a complex geodynamic geometry engine which incorporates complex algorithms that perform detailed mathematical calculations in a matter of seconds. AGI has been in the aerospace industry for 17 years and is constantly updating the product line to keep up with industry trends and needs; it has also been independently validated and verified by the Aerospace Corporation. To extend the basic analytic capabilities of STK Standard, there are additional specialized analysis and visualization modules. Specifically, the Real-time Visualization system not only leverages the core functions of STK Standard but utilizes additional modules that consist of capabilities such as: the inclusion of more complex analysis algorithms which broaden the investigative capabilities of the software; providing a 3-D environment allowing the user to view their mission dynamically; enabling the user to integrate STK with legacy applications, enterprise infrastructure and other mission-critical analysis tools via AGI's API; and the added functionality of providing the user with a format to easily create and share STK scenarios with users and non-users alike through AGI Viewer.

STK Standard is the free software product provided by AGI to assist in the analysis and 2-D visualization of land, sea, air and space. Standard allows the user to perform basic analytic functions for example, line-of-sight analysis between two assets. For more complex problems additional analytic modules extend the high fidelity geometry engine to include the use of additional orbit propagators; user-definable attitude profiles; coordinate types and systems; sensor types; extensive visibility constraints; and city, facility and star databases. Along with additional analytic features, STK provides a customizable interface; users can take advantage of the implementation of Microsoft Component Object Model (COM) to easily integrate with other COM-enabled applications. In addition, embedded HTML pages provide enhanced network file sharing and can easily be tailored so everyday tasks are easily repeated with a single mouse click. RTV employs the expanded analytic functionality by using the complex mathematical algorithms to predict and propagate orbits and trajectories, to ingest attitude quaternions directly from the live telemetry stream of the launch vehicle and to aid in the relationships between objects such as the sun and planets. Also, there is comprehensive data reporting in the form of standard charts and graphs that summarize mission critical information. The user also has access to hundreds of data elements and can create custom reports, graphs or data displays. 2-D graphics can also streamed or recorded as AVI files to share between users or for playback in post analysis efforts.

One of the major benefits of using Satellite Tool Kit is the option to add a 3-D window to the work environment. This environment provides the user with an interactive 3-D window displaying all the scenario information from STK. Land, air, sea and space assets can be displayed with detailed and scalable 3-D models with time-varying position, attitude and model articulations. Inter-object relationships and dynamic conditions can be displayed with visual cues. The 3-D setting provides a key piece in the creation of a common operating picture for launch operations; not only can an operator perform analysis on the launch vehicle but he can use the increased analytic capabilities to aid in understanding the orientation of the vehicle and spacecraft as well as providing an environment in which mission critical data can be transferred from the live telemetry screen and displayed on the 3-D models.

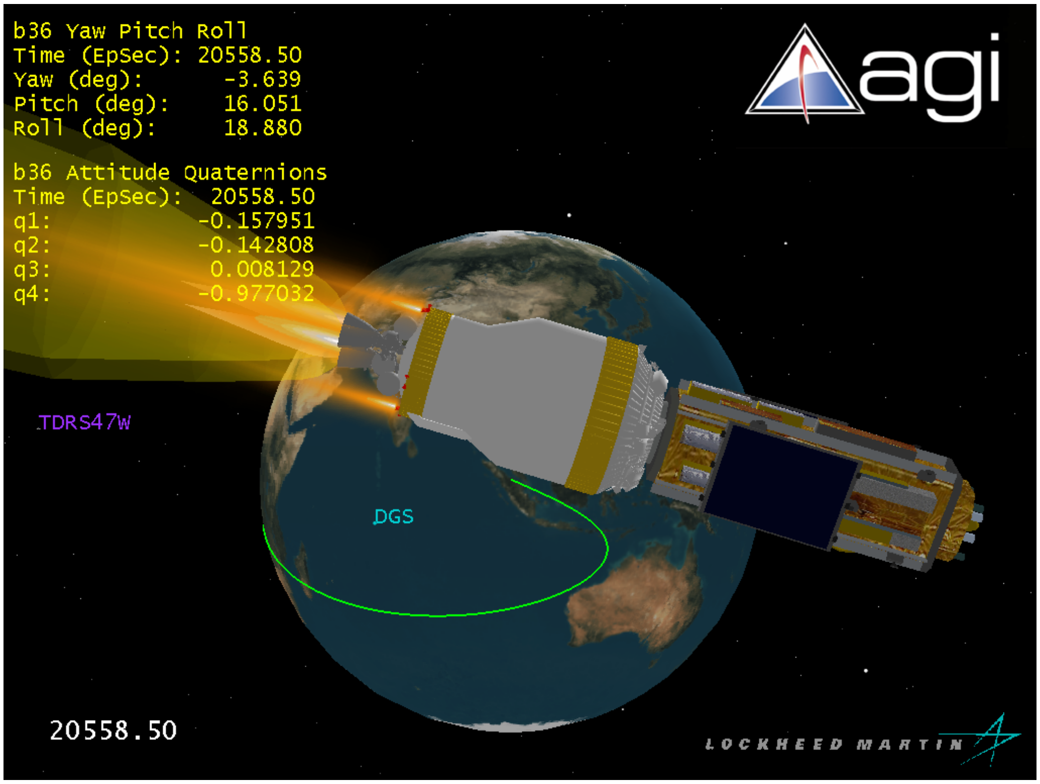
During launch operations it is useful to not only visualize all aspects of the mission but it is helpful to be able to share these animations with the customer, other analysts, and mission directors either live or in a playback mode. STK/Author provides the user with a new format in which they can save their STK scenarios and then share them across the user and non-user community. The new file format, Viewer Data Format (.vdf) has the ability to included stored viewpoints, camera paths and data displays. The free AGI Viewer can then open the .vdf files exposing the dynamic, 4-D scenes in which the user can interact, create snapshots and movies and embed into other applications such as Microsoft PowerPoint. One of the advantages of a .vdf is the relatively small file size and portability, allowing easy sharing via e-mail, across network connections or on disk. Also, the data behind the Viewer file cannot be changed, therefore protecting the analysis on which the scenario was built. Lockheed Martin uses STK Author and AGI Viewer to help broadcast their playback of live launch vehicle operations.

Flexibility of the software is incorporated by providing the user with an interface in which STK can be commanded remotely, receive and return commands and data and work seamlessly with additional 3rd party software such as MatLab. This capability is provided by AGI's API and TCP/IP socket described previously. AGI also provides additional solutions to further customize or embed STK in a custom made program by offering 4DX embedded technology. This embedded technology is built on Active X controls and enable the software developer to integrate STK into legacy software, custom applications and 3rd party products, it even allows the engineer to code in several different programming languages. In AGI's product line there are additional solutions that can aid the growing needs of the aerospace industry. As Lockheed Martin looks to support the building demand for Missile Defense support, RTV can take advantage of AGI's Missile Modeling Tools (MMT), which offers a high fidelity missile propagator that can simulate all events, design space to rapidly design new or existing missiles and simulates interceptor capabilities. The flexibility and additional solutions provided by COTS allows for rapid scope expansion and integration.

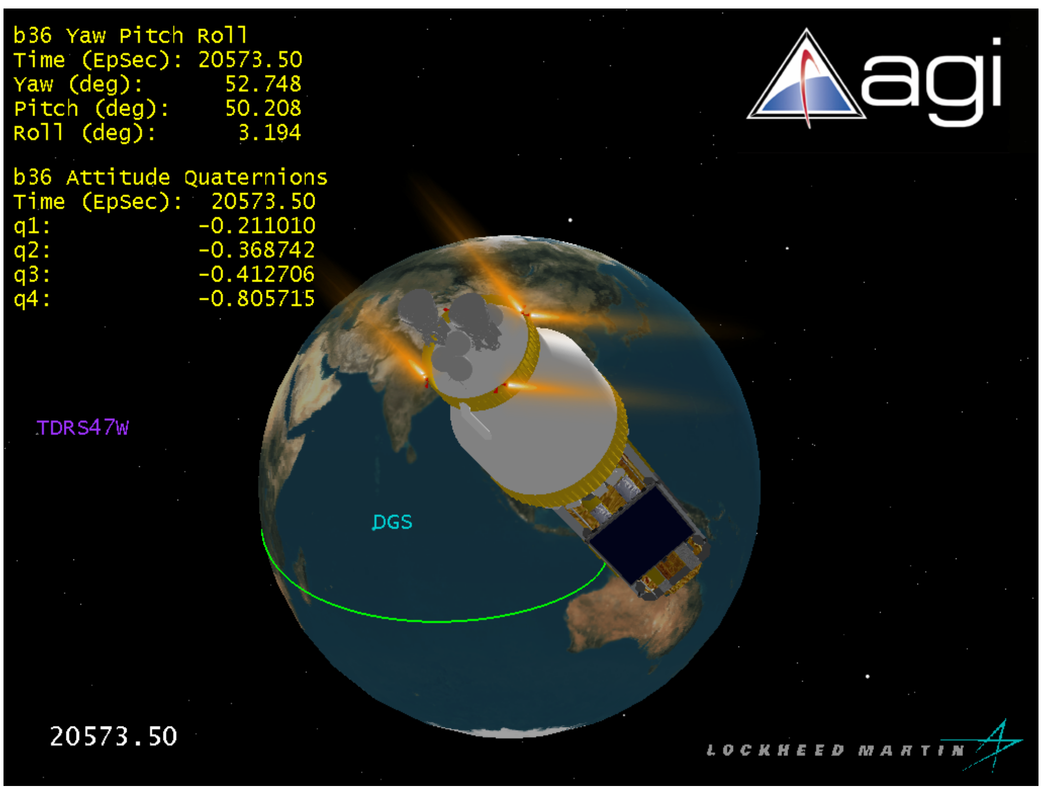
## Conclusion

Every team member of a program wants to ensure mission success during all mission milestones encountered in the launch vehicle operations process. Analysts and operators are highly trained to mitigate risk and effectively react to mission anomalies in order to create timely resolutions. However, the workflow of an analyst and operator can be hindered by the massive stream of live telemetry that floods a watch center screen during the pre-mission phase, mission launch and on-orbit activities. In order to aid decision makers, a solution that can ingest the live telemetry stream, generate mission critical analysis and clearly render a common operating picture must be created. Requirements, timeline, and cost of the overall mission from proposal to the last mission milestone are critical, therefore this solution must be easy to integrate into legacy systems, have a short development timeline, an overall low cost and be easy to use. A software solution can either be completely developed in house or can leverage commercial off-the-shelf technology. Considering the ever increasing number of launches every year along with the increasing cost, it becomes clear that it is beneficial to implement a solution that harnesses the rapidly expanding COTS technology. The developer can then use the COTS product in conjunction with legacy systems and proprietary data and rapidly create a piece of software that can be used across several launches and platforms. To validate this point Lockheed Martin's Real-Time Visualization system was explored, it was shown how RTV leveraged AGI's core technology, STK to deploy a solution that decreases cost and integration times, increases anomaly resolution success and ultimately aids decision makers in identifying and decreasing risk.

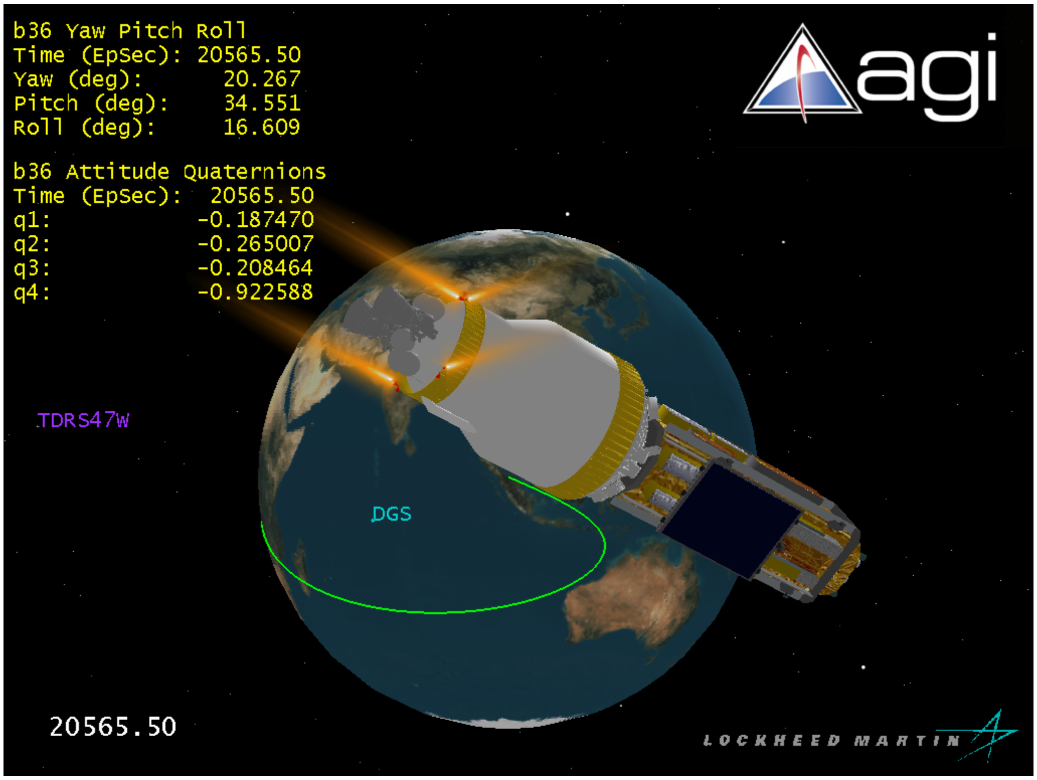
## Figures




**[Figure 1]**




**[Figure 2]**



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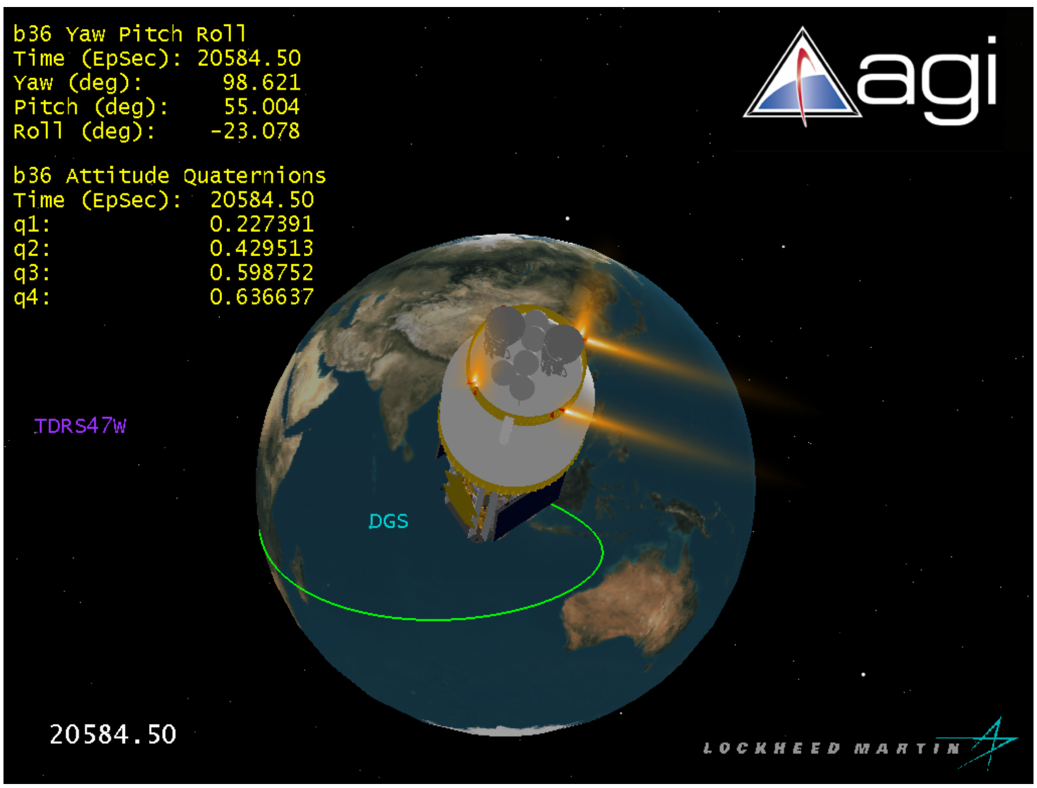

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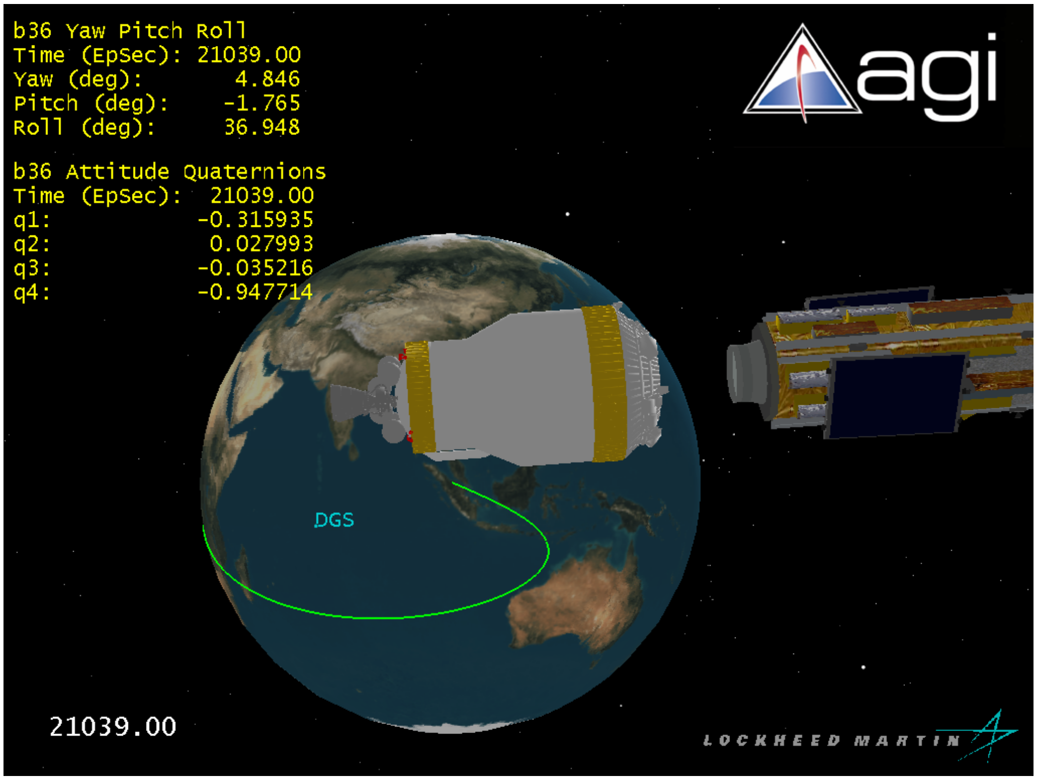


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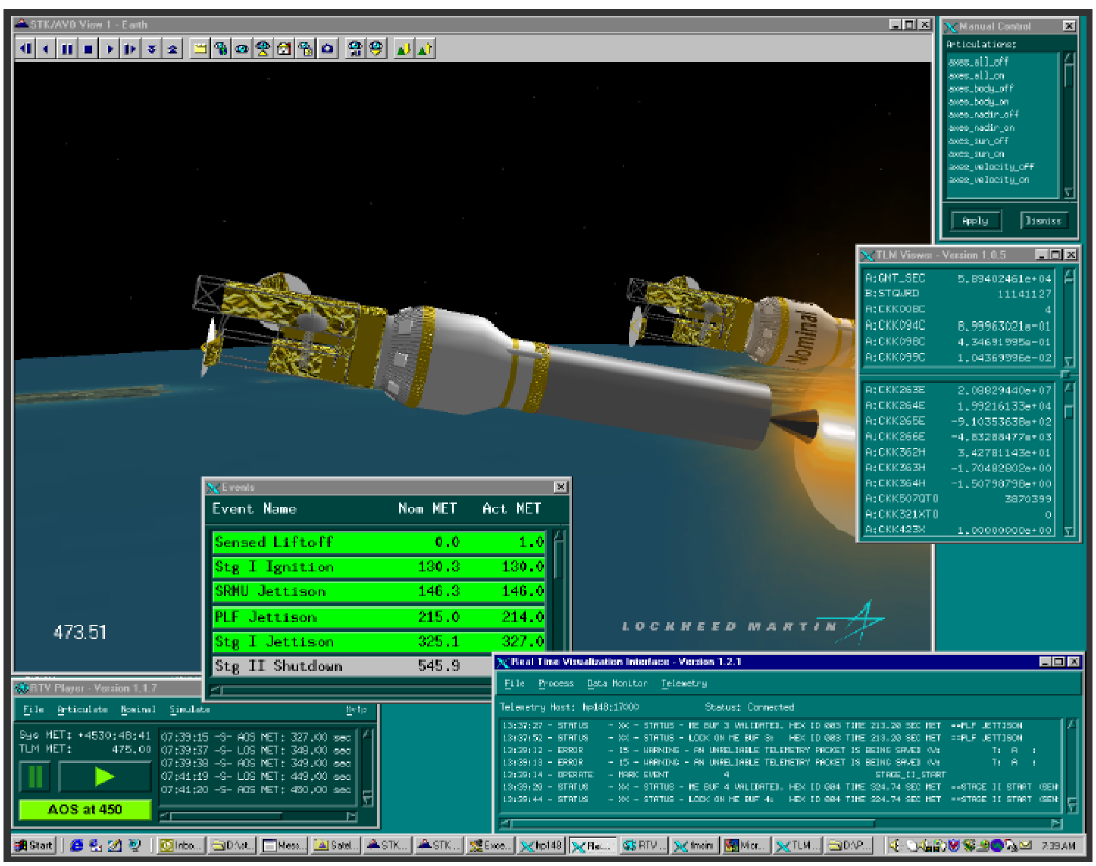
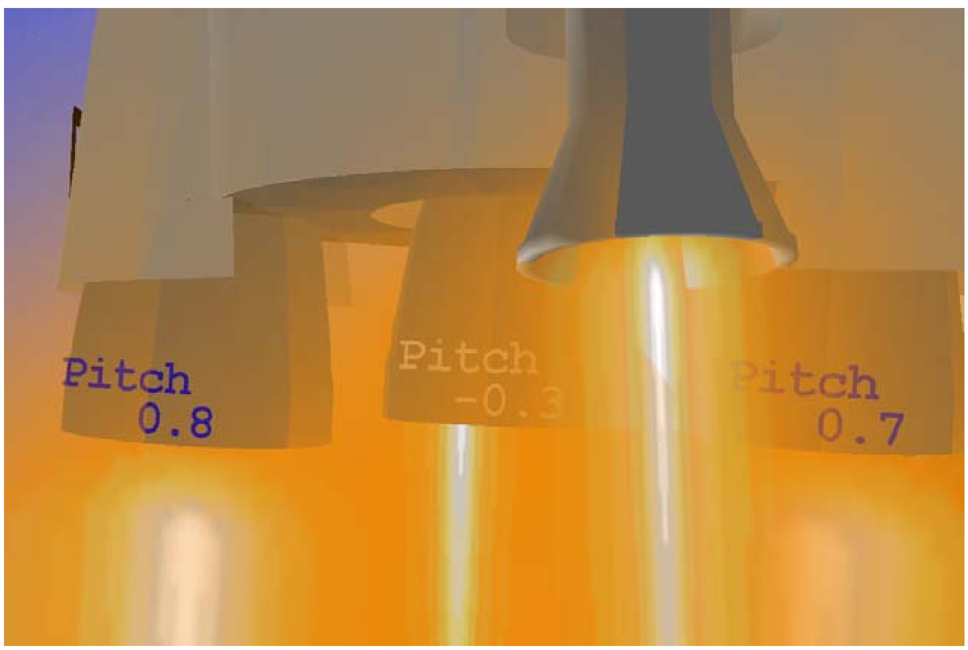



**[Figure 6]**


**[Figure 7]**




**[Figure 8]**