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SIMULATION STUDY (SIMSTUDY): A SIMULATION TOOL FOR ENGINEERS AND MISSION PLANNERS

Amy R. Kroeger and **Donald R. Ferguson**
System Simulation and Development Directorate
Aviation and Missile Research, Development,
and Engineering Center

And

Greg Lee
Torch Technologies, Inc.
4065 Chris Drive
Huntsville, AL 35802

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AMRDEC

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13. ABSTRACT ***(Maximum 200 Words)***

Simulation Study (SimStudy) is a simulation and mission planning software used by the United States (U.S.) Army to support aerial targets. The program is comprised of three main sections: a Six Degrees-of-Freedom (6-DOF) simulation, target and terrain graphics, and the user interface. Each of these provides users with a powerful tool that has the ability to record and display flight data, display flight instrumentation and vehicle animation, support mission planning, assist with data reduction, and conduct post-mission analysis. An array of conditions can be modified, including adding atypical winds and towed payloads, in addition to many 6-DOF simulation inputs. The methodology and usages of the simulator and mission planning software are presented.

14. SUBJECT TERMS			**15. NUMBER OF PAGES**
Simulation Study (SimStudy), Six Degrees-of-Freedom (6-DOF), Simulation, Trainer, Aerial Targets, Cable-Body Aerodynamic Simulation (CBAS), MissileLab, Missile Datcom, MQM-107, MK-66, Rocket-Assisted Takeoff (RATO)			21
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I. INTRODUCTION

Unmanned targets for air-, ground-, and sea-based systems are used extensively by modern military nations around the world to conduct research, development, and testing of a variety of technologies. Aerial target systems, in particular, have provided the United States (U.S.) military with affordable devices to impersonate, test, and evaluate missile systems. Over the years, the capabilities have increased dramatically. Aerial targets now range from miniature to full scale and can be fixed or rotary wing with several reaching supersonic speeds.

While each of the U.S. military branches has its own organizations to manage and promote the use of targets, the organization responsible for the Army's target systems is the Program Executive Office for Simulation, Training, and Instrumentation (PEO-STRI). The organization was created in 1974 and designed to develop new training technologies during the Cold War. Since then, PEO-STRI has grown exponentially and encompasses nearly a dozen project offices, including the Program Manager (PM) Instrumentation Targets and Threat Simulators' Targets Management Office (TMO), which manages aerial and ground targets [1]. The TMO's mission is to provide technically advanced targets with the best value and superior life-cycle operations and sustainment support for the Army, the other joint services, and foreign customers.

The most versatile subscale aerial target in the TMO repertoire is the MQM-107 Streaker, as shown in Figure 1. It is capable of performing advanced maneuvers up to transonic speeds, and with its external payload and towing capabilities, it has the ability to simulate practically any air defense threat. During the development of the later MQM-107 models, Beechcraft (a Raytheon company) developed Six Degrees-Of-Freedom (6-DOF) flight simulation software for the MQM-107 system. The program was designed to simulate the aircraft in translational and rotational degrees-of-freedom throughout all aspects of flight, including surface launch, climbs, dives, turn maneuvers, and recovery [2]. In the early 1990s, the simulation code was given to the U.S. Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) for internal use and development. Since then, the System Simulation and Development Directorate (SSDD), in conjunction with contractor Torch Technologies, Inc., has dramatically expanded the capabilities of the simulation and continues to make it a state-of-the-art software program that now plays a vital role in planning for MQM-107 missions and engineering development work. An early version of the simulation, known as the Stealth simulation, is shown in Figure 2.

Figure 1. MQM-107 Streaker Launch with Tows

Figure 2. Stealth V4.4 Display

Throughout the 1990s and 2000s, the Aerial Targets Laboratory (SSDD and Torch) redesigned and modernized the Stealth simulation and training program. It offered customers a single tool for engineers and operators to simulate the MQM-107 target, with the Beech code as its backbone. In 2011, the Stealth program was officially retired. The Operator Trainer (OpTrain) and Simulation Study (SimStudy) programs replaced the Stealth program and allowed developers to cater the software to two distinct user groups: target operators and engineers.

The OpTrain is designed primarily for field operator training while SimStudy caters to engineering and data analysis. This provides for increased flexibility and efficiency in meeting the various user groups because requirements and expectations often differ.

II. SIMSTUDY INTERFACE

The SimStudy simultaneously runs three executables: Graphical User Interface (GUI), 6-DOF simulation, and Three-Dimensional (3-D) target and world view rendering. The original 6-DOF simulation implements MQM-107 E model aerodynamics. It was developed in Fortran programming language, while the autopilot code was written in C. A Fortran-to-C interface written in digital Fortran allows the 6-DOF to call the C autopilot. Since Beech delivered the code, AMRDEC software developers have improved the actuator model, converted large portions of the code from Fortran to C, and integrated the digital avionics package. All of the Fortran code has been optimized to run at or faster than real time. Two additional Rocket-Assisted Takeoff (RATO) models and several tow target payloads have also been added. The MQM-107 E and D are modeled in the program. Since fiscal year 2012, additional targets from the Army and Navy continue to be incorporated as a user need arises, such as the BQM-34S (Army variant), BQM-74E (Navy variant), and Pioneer Unmanned Aerial Vehicle (UAV).

The SimStudy has a Windows-based Visual Basic GUI, as shown in Figure 3. Through the easy-to-use interface, SimStudy provides the user with the ability to record and display simulated flight data and instrumentation, modify 6-DOF inputs parameters, adjust the RATO motor, playback flight data, and generate scripts for profile repetition and controller card development.

Figure 3. SimStudy Display with Terrain

The GUI provides a 6-DOF Options window. Users now have the ability to modify 6-DOF input parameters without directly altering the input file code. Inertial parameters, fuel weights, virtual payloads, and RATO attachment angles are among the options.

A. Six-DOF Options Input Window

The 6-DOF Options window contains eight tabs: Output, Inertial, Fuel, Engine, Payload, Towed Targets, Actuators, and RATO. All tabs contain input text boxes, drop down menus, and/or checkboxes to modify the 6-DOF input parameters without having to change the actual input file. These inputs can be saved for future use or reset to the default values. For example, the Payload tab shown in Figure 4 allows users to add a virtual payload to the target. This can be used to mimic a weighted ballast or additional hardware at a certain location or simply shift the overall Center of Gravity (CG).

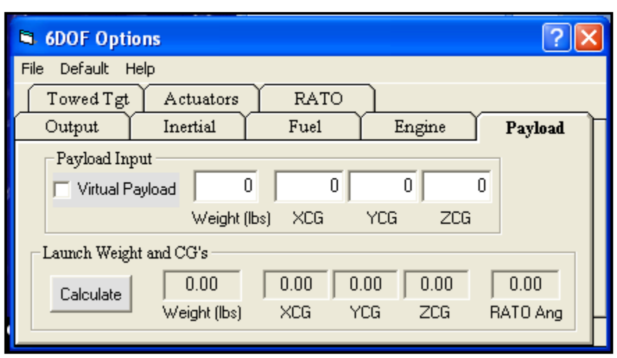

Figure 4. Six-DOF Options Payload Tab

B. 2.75 Rocket-Assisted Takeoff Input Window

In preparation to replace the SR-121 solid rocket motor that has been used to launch the MQM-107, the 2.75 Rocket RATO (RR) option was developed by AMRDEC engineers. The premise of the 2.75RR is to arrange 10 of the 2.75 hydra rocket motors (MK-66) in a custom-designed canister and ignite them in a sequence to best imitate the impulse of a SR-121. During the design phase and determining the timing of the sequencer, hundreds of simulations were run using SimStudy. To facilitate this, the Targets Lab created a 2.75RR Options window with three tabs: Methods, Temperatures, and Sequence. Through these tabs, users can specify whether or not to use basic forces, Computational Fluid Dynamics (CFD), set vertical or lateral offsets, core temperatures for individual motors, and alter the ignition sequence. The tabs are shown in Figure 5.

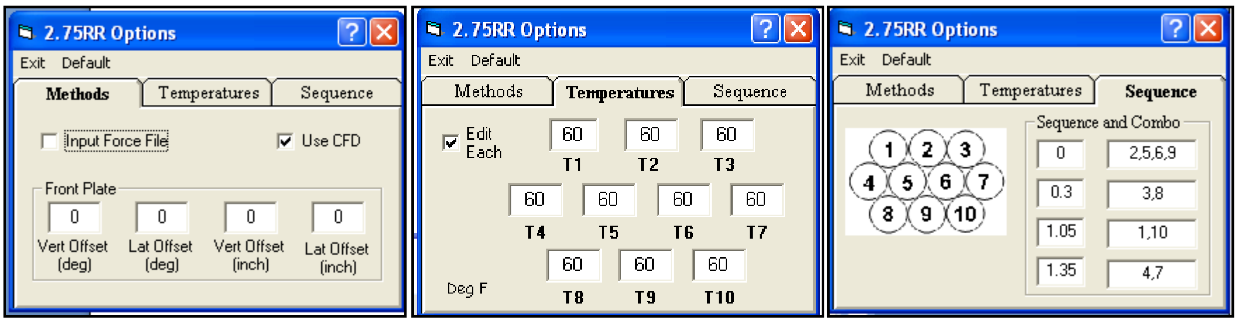

Figure 5. Options Windows for 2.75RR

III. SIMSTUDY AERODYNAMIC TOOLS

A. Tow Target Modeling

Significant effort has gone into the implementation of the payload and RATO capabilities. The SimStudy has the ability to simulate an MQM-107 carrying a virtual internal payload simulated by adding a mass and adjusting the CG or a number of external towed and non-towed targets. For accurate flight models with realistic drag and inertial data, the targets were individually modeled in the MissileLab program. A 3-D model from MissileLab is shown in Figure 6. MissileLab is a visual basic GUI developed by AMRDEC that assists users in running several aerodynamic prediction codes. Sets of geometric and atmospheric conditions for each towed target normalized by the MQM-107s reference CG and dimensions were input into MissileLab. MissileLab then generated an input file and executed the prediction code Missile Datcom [3].

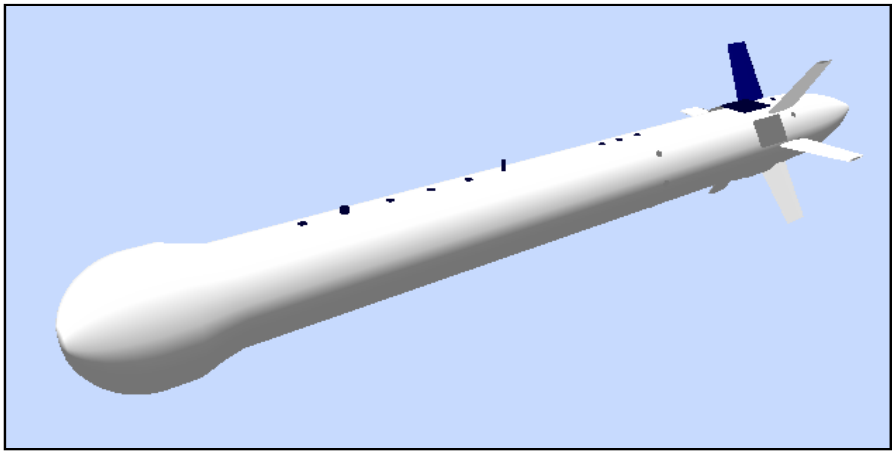

Figure 6. JCHAAT MissileLab Produced 3-D Model

The moments of inertia were determined through pendulum testing in the Aerial Targets Laboratory. The tow was balanced on a knife edge stand to determine the CG, and a pendulum system was clamped to the tow at the CG. Clamping at θ = 180 degrees is used for IZZ and IYY; clamping at 90 degrees is used for IXX measurements. The pendulum and tow assembly were hung on a frame, as shown in Figure 7. Swinging the pendulum at small amplitudes and measuring the time determined the natural period that, along with the mass, can be used to determine the moments of inertia.

Figure 7. JCHAAT Tow Swing Setup

The MissileLab program utilized Missile Datcom to produce a table of aerodynamic coefficients for a range of airspeeds and altitudes [4]. These data, along with the targets mass properties determined through laboratory testing, are incorporated into the 6-DOF flight simulation via a separate input file that SimStudy calls when a tow is selected from the GUI.

B. Tow Cable Prediction

For each of the towed targets, data for the cable tension, drag, and attachment angle are generated from the Cable-Body Aerodynamic Simulation (CBAS) derived program. The CBAS, originally known as Cable-Body Underwater Simulation (CBUS), was developed in 1984 by Bath University in the United Kingdom [5] to analyze the behavior of bodies (fish) towed underwater. The CBUS was later modified in a multinational effort between the United Kingdom's Ministry of Defense, the U.S., and Australia for use with aerial towed systems and became known as CBAS [6]. The version currently in use was a follow-on to the prior effort where the Aerodynamic Research Laboratory of Australia updated and improved cable modeling capabilities and fixed instabilities within the program.

The CBAS program is based on a Newton-Euler form of the equations of motion and accounts for the towing aircraft, tow cable, and towed body [7]. In the 1990s, AMRDEC developed a basic version known as CBAS Junior (CBASJr) that simplified the equations by considering only Two-Dimensional (2-D) aerodynamics along the X- and Z-axis. A plot of the CBASJr calculated droop and tension for a Japanese CHU-SAM Advanced Aerial Tow (JCHAAT) is shown in Figure 8.

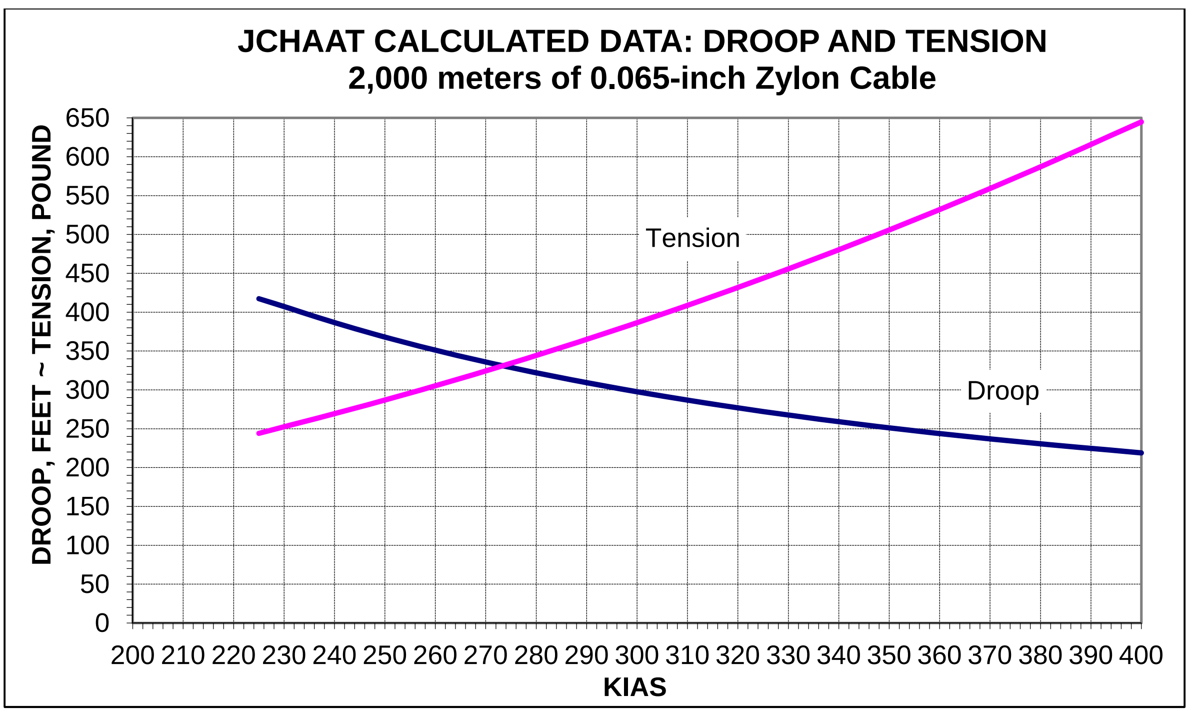

Figure 8. CBASJr Produced Droop and Tension for JCHAAT Target

The data tables input into the towed target input file for SimStudy are based on the towlines that are most commonly used for each particular tow. For instance, the TIX-4 is most often towed with 5,000 feet of 0.050-inch diameter Zylon, while the TRX-4A is towed with 8,000 feet of 0.032-inch diameter steel. The simulation is tailored for each tow's typical towing setup, but the user can modify the data file to change the tow line type and length.

C. Engine Modeling and Computational Fluid Dynamics

Extensive work was done with SimStudy leading up to the ultimately successful testing of alternative engines for the MQM-107 including the Williams WJ38-15 and Microturbo TRI 60-5+. The Microturbo TRI 60-5 model turbojet engine is standard on MQM-107 flights. It is throttled to 95 percent at launch, supplying approximately 800 pounds force of thrust. Because the MQM-107 is ground launched from a zero-length launcher, a RATO is required to provide more thrust and impulse to launch the drone and achieve steady flight. An additional 5,800 pounds force of thrust is supplied by the standard SR-121 RATO during its 2.5-second burn. The head end RATO mount utilizes an internal spring to disengage a RATO when the supplied thrust is less than 300 pounds force, after which the RATO falls to the ground. While the SR-121 single-stage RATO has been used for years, rising costs, decreased demand, and more stringent Environmental Protection Agency (EPA) restrictions have created a need to find new RATO systems. A single-stage motor by Bristol Aerospace Limited (a Magellan Aerospace Company from Winnipeg, Manitoba, Canada) and AMRDEC's 2.75 rocket RATO design have both been successfully flight tested and have proven to be viable alternatives to the SR-121 motor. The three RATOs are shown in Figure 9.

a. SR-121 *b. 2.75RR* *c. Bristol*

Figure 9. RATO Motors for MQM-107

Prior to flight testing, a heavy reliance was placed upon SimStudy to simulate both potential replacement motors. A critical aspect of the simulation is the RATO attachment angle, which is defined by the angle between the centerlines of the MQM-107 and RATO through which the RATO forces act. A difference of a few degrees can cause the aircraft to suffer severe nose-up or nose-down movements during the RATO burn that can ultimately result in the loss of the aircraft. The angle must be set to balance the pitching moment. A nose-up moment is produced by the turbojet since it is below the centerline of the MQM-107. The RATO thrust vector must pass just above the CG of the system. Beechcraft relied on a series of flight tests in the 1970s to determine RATO attachment angles. The angles for the MK-66 RATO and the Bristol RATO were determined by simulation in SimStudy and verified during flight tests.

AMRDEC used CFD to quantify the external aerodynamic effects on the drone and RATOs. The CFD results (thrust data acquired from ground testing of the motors) and existing turbojet models were combined and input into the SimStudy 6-DOF to predict the required RATO launch angle [8]. The CFD runs were initially completed for the SR-121 configuration to form a baseline. The CFD results for the MK-66 and Bristol motors were compared to the SR-121, and the differences were incorporated into the simulation. There was more confidence in deltas than absolute calculations because there was no full-up real data to compare CFD predictions to. Figures 10 and 11 show that the CFD results for the SR-121 and MK-66 motors are at two extreme RATO angles: 6.0 and 13.0 degrees.

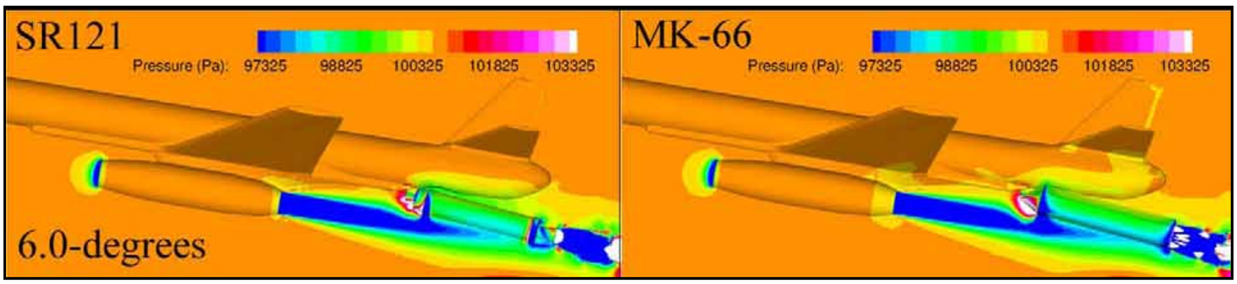

Figure 10. Pressure Contour Comparison for 6.0-Degree RATO Angle

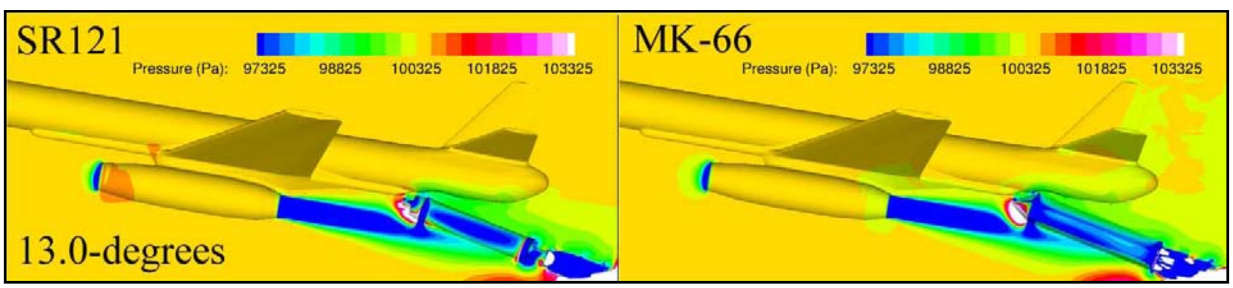

Figure 11. Pressure Contour Comparison for 13.0-Degree RATO Angle

IV. SIMSTUDY OPERATIONAL MODES

There are three modes of operation within SimStudy, each specifically designed to provide users with the capabilities necessary for pre- and post-mission analysis of the MQM-107 system. Through the various modes, engineers utilized SimStudy to plan for successful missions. Prior to significant hardware tests, engineers completed extensive simulation testing and development work with the simulation. The modes most utilized by engineers were script, standalone, and playback, while mission controllers used training, visualize, and playback modes in the field.

A. Script Mode

The script mode allows users to execute missions using a script file which contains a sequence of Autopilot commands written in standard text format. This allows engineers to modify 6-DOF inputs and other flight variables while ensuring that the drone executes identical autopilot commands by taking the man out of the loop. From this mode, controller cards can be produced for the controllers and chase pilots in the field to use during flights. The script mode offers a latitude/longitude trace feature that is critical when providing range safety teams with flight plans. From the trace output file, a layer can be generated on the ground station position display which saves on operator in the field workload.

B. Standalone Mode

The standalone mode provides a self-contained method for operating the MQM-107 6-DOF simulation without any external interaction. This mode is designed to use on standalone computers independently of ground control hardware. The associated GUI contains numerous switches, buttons, and dials as well as a virtual joystick. Each of these can be selected and adjusted using a computer mouse.

C. Playback Mode

The playback mode plays back files recorded by SimStudy or any actual flight data that has been converted to the SimStudy playback format. The playback mode is extensively used in crash investigations and post-flight analysis. The Command status buttons are illuminated on the GUI to show when commands were initiated and what maneuvers and modes were active throughout the flight, which assists not only engineers but operators as well.

V. EXAMINING OUTPUT

A. Six-DOF Data

The 6-DOF simulation writes data collected during the flight to an American Standard Code for Information Interchange (ASCII) text file that records over 70 variables. From the SimStudy toolbar, these can be automatically converted from a text file to a Microsoft Excel spreadsheet with 35 of the most frequently used variables plotted and labeled, most in regards to flight time. Also, SimStudy has the ability to plot two flight data files together for comparison or to plot the differences between them.

B. Controller Cards

When creating a script file, users can designate lines to use in the creation of flight control cards. The cards, known as pilot or flight cards, detail the flight plan activities and objectives, note areas of concern, specify parameters to monitor, and provide directions for the flight controllers [9].

These can include initial segment conditions, primary controller actions, backup controller actions, comments, and timings. The script parser understands four control card keywords: events, primary, backup, and comment. The control card lines are converted into a generic format, as shown in Figure 12.

SCRIPT TEST W CLEAN TARGET (DEFAULT)						
Segment Initial Conditions		Primary Controller Actions	Backup Controller Actions	Comments	Time Estimate	Time Actual
PREFLIGHT						
GND	Kft AGL	Complete Prelaunch Checklists	Control Room Technicians Launch Crew Personnel On Station		hh:mm:ss	mm:ss
0	KIAS					
0	% RPM					
PRELAUNCH WIGGLE						
GND	Kft AGL	Verify Proper Switch Settings; All Auto Functions Off; Rudder Neutral;	Coordinate Countdown With Range. Perform Wiggle Checks	Start Countdown @ X-15 Min; Hold @ X-2 Min	hh:mm:ss	
0	KIAS					
0	% RPM					
LAUNCH; HEADING HOLD OVERRIDE ON						
GND	Kft AGL	CMD - Launch; HH Override On	Auto Launch Mode	Launch Time: T=0	0:00:00	
0	KIAS					
95	% RPM					
#1 LAUNCH						
0.0 / 2.2	Kft AGL				00:00:00 00:00:31	
0 / 351	KIAS					
94 / 95.3	% RPM					
#2 hi-g turn						
2.2 / 4.1	Kft AGL	smoke	don't smoke	airspeed hold on	00:00:31 00:00:51	
351 / 367	KIAS					
95.3 / 95.3	% RPM					
#3 CLIMB; 20 deg PITCH; Up to 10,000 ft MSL; @ 96% RPM						
4.1	Kft AGL				0:00:51	
367	KIAS					
95.3	% RPM					

Figure 12. SimStudy Generated Controller Card

VI. CONCLUSION

In the near future, additional Three Degrees-of-Freedom (3-DOF) and 6-DOF models will be incorporated into SimStudy to support additional aerial and ground targets that will improve the capabilities of the simulation. It is also likely that this Windows-based simulation will be adapted to support additional Linux-based systems. Work is underway to incorporate a real-time strip charts tool and build additional terrain databases. The SimStudy continues to be updated to mimic the ever-improving capabilities and demands of simulation programs with more options and improved ease-of-usability for its users.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

%	percent
@	at
~	approximately
2-D	Two-Dimensional
3-D	Three-Dimensional
3-DOF	Three Degrees-of-Freedom
6-DOF	Six Degrees-of-Freedom
Acc	Acceleration
AGL	Above Ground Level
Ail	Aileron
Alt	Altitude
AMRDEC	Aviation and Missile Research, Development, and Engineering Center
Ang	Angle
ASCII	American Standard Code for Information Interchange
Ban Rel	Banner Release
Baro	Barometric
CBAS	Cable-Body Aerodynamic Simulation
CBASJr	Cable-Body Aerodynamic Simulation Junior
CBUS	Cable-Body Underwater Simulation
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CMD	Command
DAP	Digital Autopilot
deg	Degree
Depl	Deploy
Dist	Distance
E	East
EGT	Exhaust Gas Temperature
Elev	Elevator
Emer	Emergency
Eng	Engine

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (CONTINUED)

EPA	Environmental Protection Agency
Esc	Escape
F	Fahrenheit
ft/FT	foot
g	gravity
GND	Ground
GUI	Graphical User Interface
Hdg	Heading
HH	Heading Hold
HH:MM:SS	hour:minute:second
HHO	Heading Hold Override
Hi	High
IAS	Indicated Airspeed
JCHAAT	Japanese CHU-SAM Advanced Aerial Tow
kft	kilofoot
KIAS	Knots Indicated Air Speed
kt	knot
L	Left
Lat	Lateral
LATS	Low Altitude Threat Simulator
lb	pound
lbf	pound force
LOC	Loss of Carrier
Lvl	Level
Min	Minimum
MSL	Mean Sea Level
N	North
NE	Northeast
NW	Northwest
Nz	Normal Acceleration
OpTrain	Operator Trainer

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (CONCLUDED)

Pa	Pascal
PEO-STRI	Program Executive Office for Simulation, Training, and Instrumentation
Pitc	Pitch
PM	Program Manager
Prog	Program
R	Right
Rad	Radar
RATO	Rocket-Assisted Takeoff
Recov	Recovery
RPM	Revolution Per Minute
RR	Rocket RATO
Rud	Rudder
S	South
SE	Southeast
SimStudy	Simulation Study
SSDD	System Simulation and Development Directorate
SW	Southwest
TAS	True Airspeed
Tgt	Target
TMO	Targets Management Office
Trig	Trigger
U.S.	United States
UAV	Unmanned Aerial Vehicle
V	Version
Vert	Vertical
W	West
XCG	X-Axis CG
YCG	Y-Axis CG
ZCG	Z-Axis CG

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