The AEORA Mission Planning Tool (AMPT)
User's Guide Version 1.0

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AEORA Mission Planning Tool User's Guide

Version 1.0

1.0 Introduction

The ultimate goal of the US Army SBIR research efforts titled "A Doppler wind lidar based atmospheric energy harvesting system for autonomous in-flight guidance and path planning of small aircraft" was to document the feasibility of a hardware/software system that provides autonomous in-flight guidance and flight path control for small manned aircraft or Unmanned Aircraft Systems (Emmitt and O'Handley, 2007; Emmitt and O'Handley, 2007; Simpson Weather Assoc., Inc., 2012).

In particular, the goal was to define such a system that utilizes both forecasted and continuous real-time knowledge and description of the state of the atmosphere and atmospheric energetics within the mission corridor of the aircraft to provide the autonomous guidance for detailed and adaptive flight path planning. Such flight planning and control would reduce mission dependence upon preflight assumptions, extend flight duration and endurance, and allow for the optimum routing of the aircraft (Emmitt et. al., 2017; Greco et. al., 2015; Emmitt et. al., 2014).

1.1 The AEORA Mission Planning Tool (AMPT) Overview

The AEORA Mission Planning Tool (AMPT) serves as the pre-launch mission planning tool using a simple flight simulation model for a defined mission flight. The simulation uses inputs from WRF meso-scale model atmospheres and multiple generated flight tracks to an energy feature area to produce possible UAV flight performances. The user selected optimal flight from these multiple flights is used by EDC's sophisticated UAV model, CASSY, to fly to a feature area and to fly energy features. The AMPT major models (Mission Objectives and Mission Constraints (MOaMC) , Flight Trajectory Instruction Generator (FTIG), Sensor Energy Target Detection Model (SETDM) and inputs (WRF Model and UAV Specifications) are depicted in the flowchart Figure 1.0.

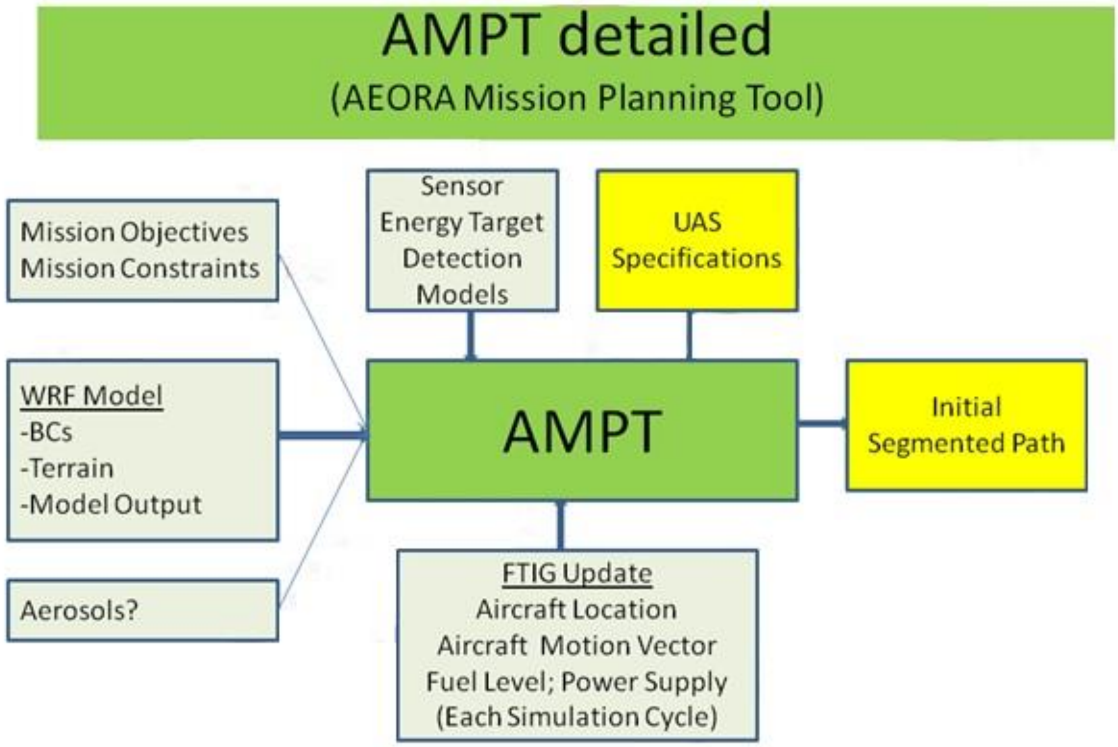

Figure 1.0 The AEORA Mission Planning Tool (AMPT) flowchart.

In 2005, Simpson Weather Associated began working with the Navy's Office of Naval Research (ONR) to develop an In-flight Lidar Integrated Mission Management System (I-LIMMS) that provides real-time 4-D visualization of airborne Doppler Wind Lidar (DWL) data aboard an aircraft as well as a real-time system managing of both mission flight strategy and the lidar scanning strategy (Emmitt, G. D. , S. Greco and S. A. Wood, 2012). The AMPT platform is based upon the SWA Launcher platform used in the I-LIMMS project.

The AMPT main screen, shown in Figure 2 below, is designed for three major functions; top bar - the Icon Viewer, side bar – the Model/Document Invoker and the middle screen - Main Screen Visual. The top bar contains picture icon stills and graphics that can be scrolled through (Figure 3.0), and images can be added to the icon inventory via the Screen Capture function. When a graphic is selected from the top bar, it is displayed full size in the Main Screen Visual. The side bar (Figure 4.0), contains links to documents, models and graphics. Additional documents, models and graphics can be added by the user via the SWALauncher.xml file that resides in the AMPT main directory. The side bar inventory at delivery date is as follows

- How to use the AMPT

  Overview and user’s guide for the AMPT (this document).

- Running WRF Model for AMPT

  Document explaining how to operate the WRF model and tools on the AEORA laptop.

- WRF Model Manual

  This User's Guide describes the Advanced Research WRF (ARW) Version 3.3 modeling system, released in April 2011.

- WRF Conversion Model

  Tool to convert WRF NetCDF files to binary format for the AMPT.

- ncBrowse

  ncBrowse is a Java application NetCDF File Browser that provides flexible, interactive graphical displays of data and attributes by NOAA/PMEL/EPIC (Donald Denbo).

  www.epic.noaa.gov/java/ncBrowse/

- WRF Feature Mining Tool

  Tool to extract WRF fields and generate secondary fields for graphics.

- Mission Objectives and Constraints (MOaMC)

  The MOaMC defines the mission for the simulated flights. Simulation mode, UAV, spatial and temporal inputs and limits are inputs.

- Flight Trajectory Instruction Generator (FTIG)

  The FTIG produces an initial flight based upon the mission inputs. For a UAV simulation mission; up to four waypoints, energy feature intercept point and sampling distance are inputs . For a DWL simulation; flight and scanner modifiers are inputs to be operated on an existing DWL flight.

- Sensor Energy Target Detection Model (SETDM)

  The SETDM either produces numerous potential flights and flight performance based upon the initial flight generated in the FTIG or compares DWL winds (simulated or real) with a WRF Forward model. In the former, the SETDM dashboard allows the user to scroll through all flights' performances and choose a flight to be used in flying the EDC CASSY simulator.

- EDC MODEL CASSY

  CASSY is a nonlinear, six-degree of freedom rigid body representation aircraft model with the same control inputs available on an actual aircraft. The aerodynamic parameters of the model can be set to represent any typical fixed wing platform. Attached to the aircraft model is an automatic flight control system which uses a model predictive controller to generate commands to the aircraft control surfaces to track a desired three-dimensional trajectory. The guidance logic to generate the desired flight trajectory is based on the current aircraft state and estimates of the surrounding atmospheric features.

- GEO-VISUALIZER

  CESIUM is an open source JavaScript library for world-class 3D maps and global visualization. The AMPT using CESIUM to visualize the aircraft output flights.

  https://cesiumjs.org/

- VOXLER

  Voxler is a 3D graphics COTS software package that SWA bought from Golden Software to produce Contour, Scatterplot, Iso-surface and vector graphics. Voxler is not included in the AMPT delivery. If the customer wants to produce these types of graphics, the customer must either buy Voxler from Golden Software or add their own graphic package to the SWAlauncher.

  http://www.goldensoftware.com/products/voxler

- GRAPHER

  Grapher is a 2D graphics COTS software package that SWA bought from Golden Software to produce Line/Symbol, Bar/Polar, Contour, Statistical graphics. Grapher is not included in the AMPT delivery. If the customer wants to produce these types of graphics, the customer must either buy Grapher from Golden Software or add their own graphic package to the SWAlauncher.

  http://www.goldensoftware.com/products/grapher

- SURFER

  Surfer is a graphics COTS software package that SWA bought from Golden Software to produce Class Post, Wireframe, Contour and Image graphics. Surfer is not included in the AMPT delivery. If the customer wants to produce these types of graphics, the customer must either buy Surfer from Golden Software or add their own graphic package to the SWAlauncher.

http://www.goldensoftware.com/products/surfer

- Google Earth

  A link to Google's GoogleEarth is included in the AMT. While no AMPT outputs are currently converted to KMLs for GoogleEarth, GoogleEarth is still a useful tool for global visualization and thus has been included. If the customer intends to make additional use of GoogleEarth capabilities, they should review the Google's license web page.

- Time Zone Converter

  A useful web tool for converting time zones.

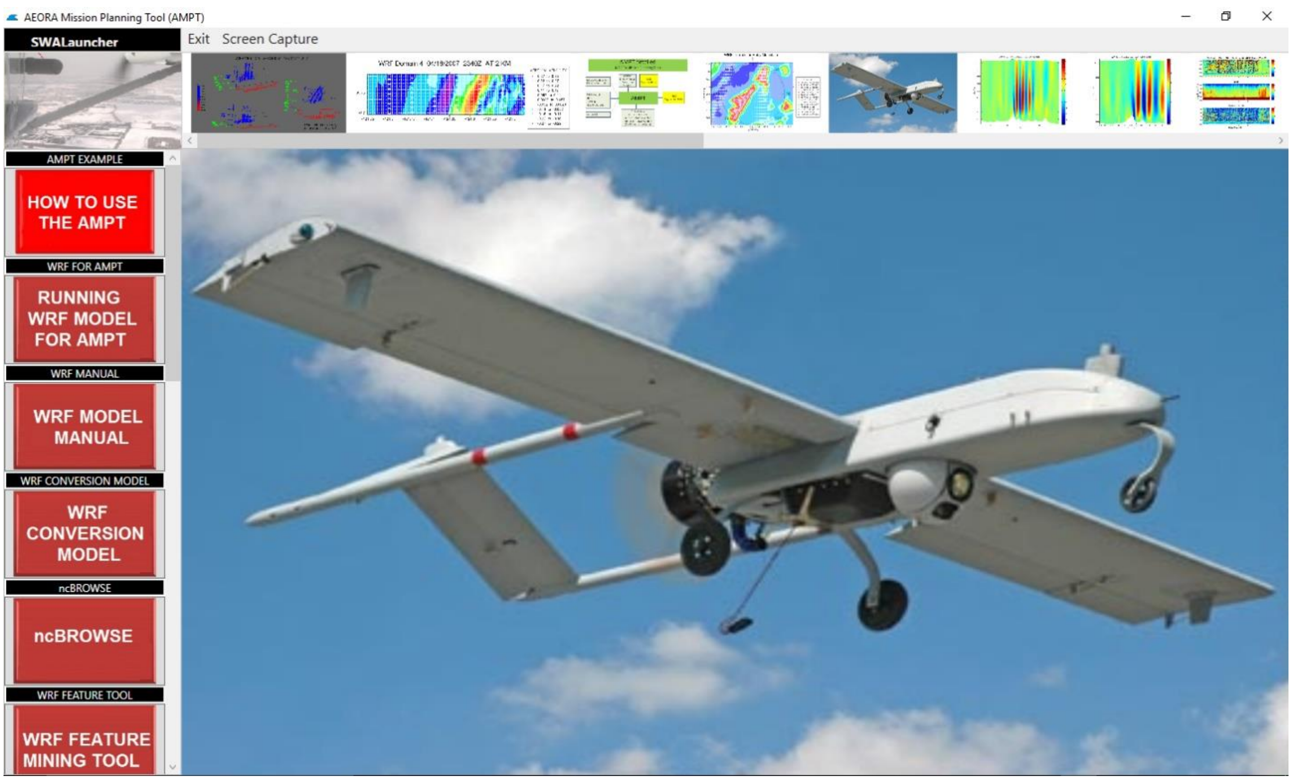

Figure 2.0 AEORA Mission Planning Tool Main Screen

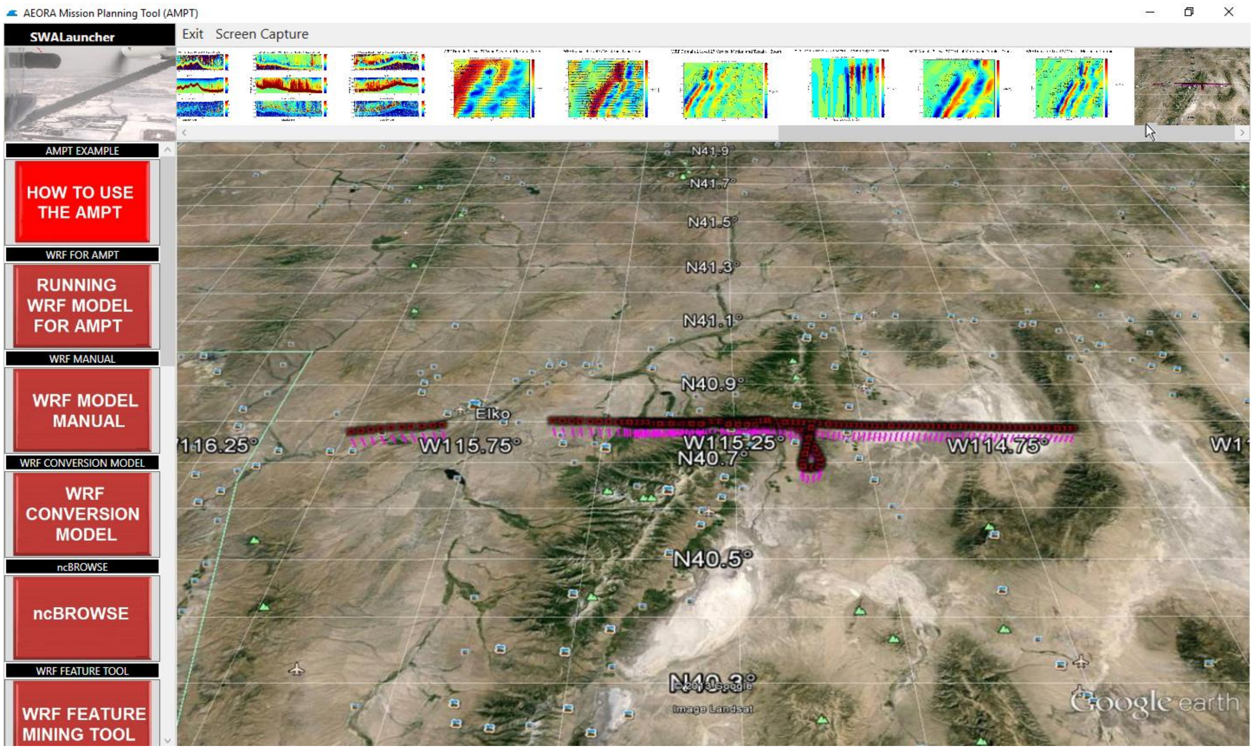

Figure 3.0 Top Panel Bar – The Icon Viewer. When an icon is click, the image is displayed in the Main Screen Visual Area. This image is of the Ruby Mt. TODWL flight coverage 2012.

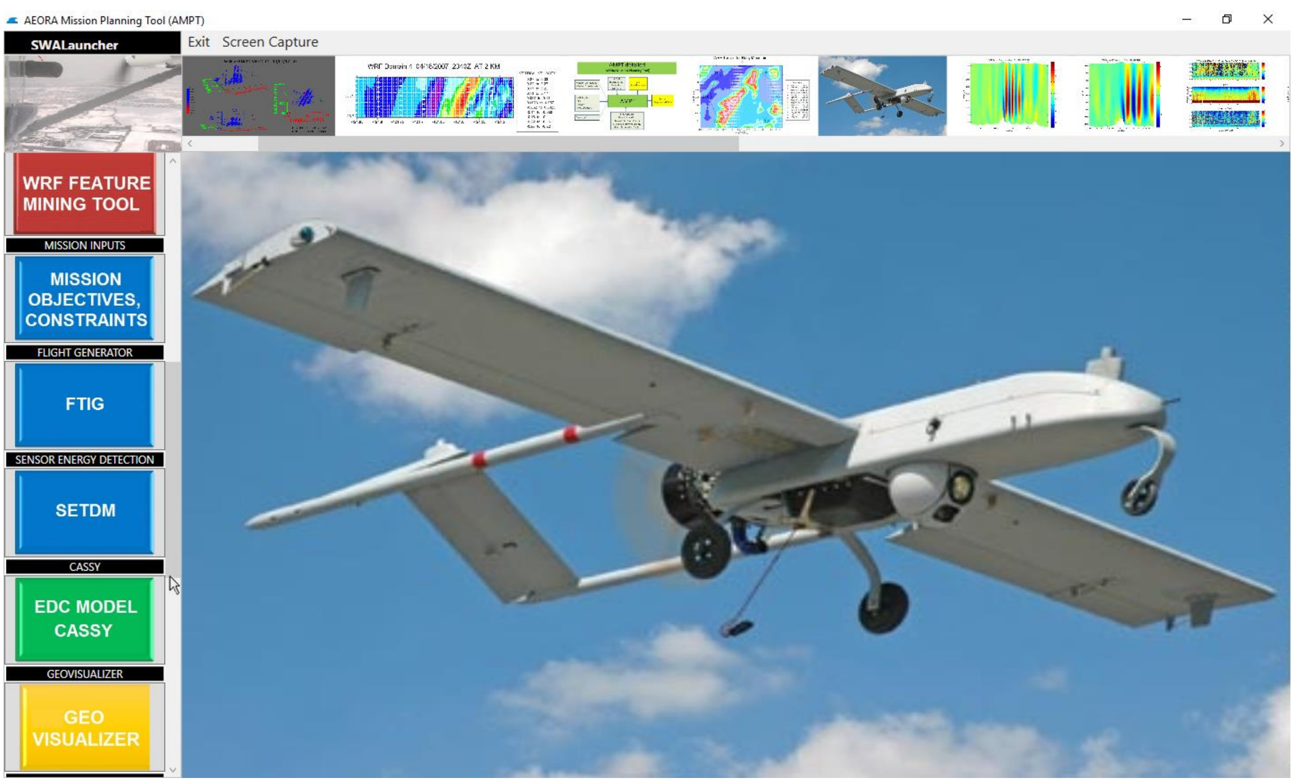

Figure 4.0 Side Panel - contains links to documents, models and graphics.

2.0 The AEORA Mission Planning Tool - Models, Links, Graphics and Documents

2.1 WRF Model

The RUNNING WRF MODEL FOR AMPT button invokes a MS Word document (Figure 5.0), providing instructions for running the WRF model on the AEORA laptop. The running of the WRF model operates under a Ubuntu Linux virtual box and is a very complex operation. A knowledge of Linux commends and editor protocols is strongly suggested before running the WRF. The WRF MODEL MANUAL button opens a PDF (Figure 6.0) for NCAR's Advanced Research WRF (ARW) Version 3.3 modeling system, released in April 2011. Email questions regarding the documents can be made to SWA (Steve Greco at sxg@swa.com).

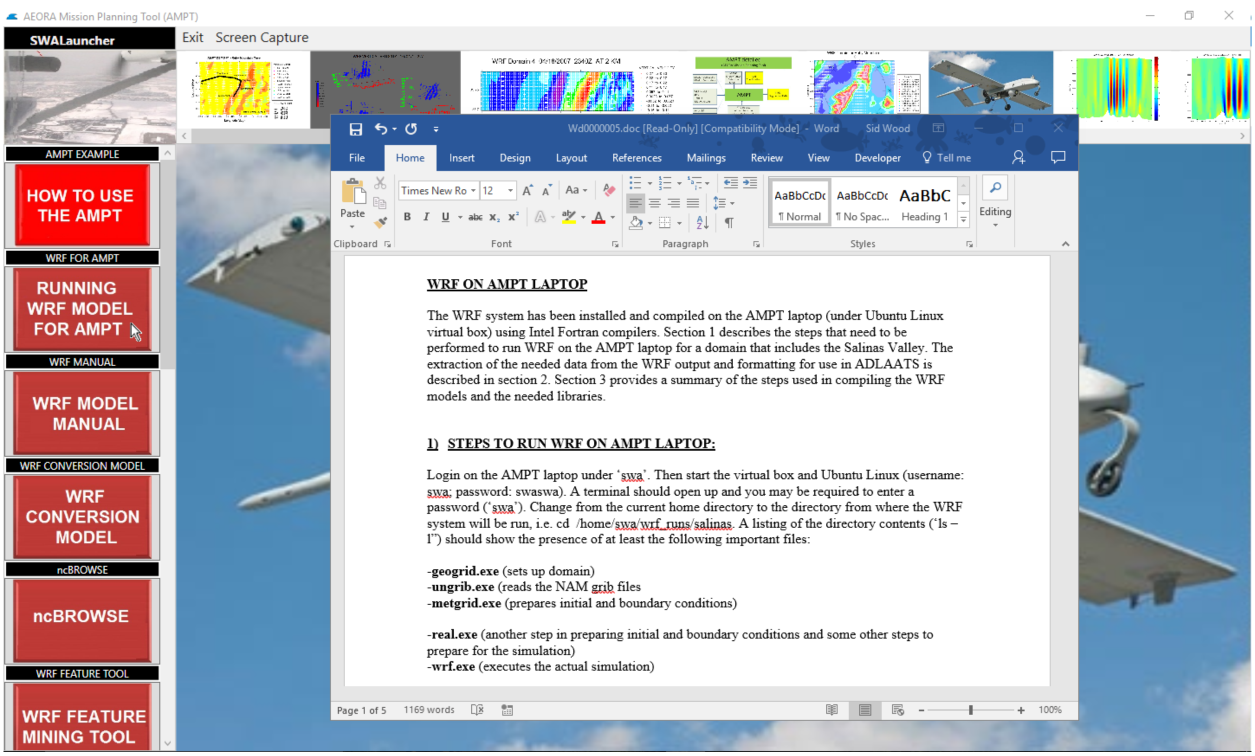

Figure 5.0 Instructions for setting up the WRF model on the AEORA laptop and running the WRF.

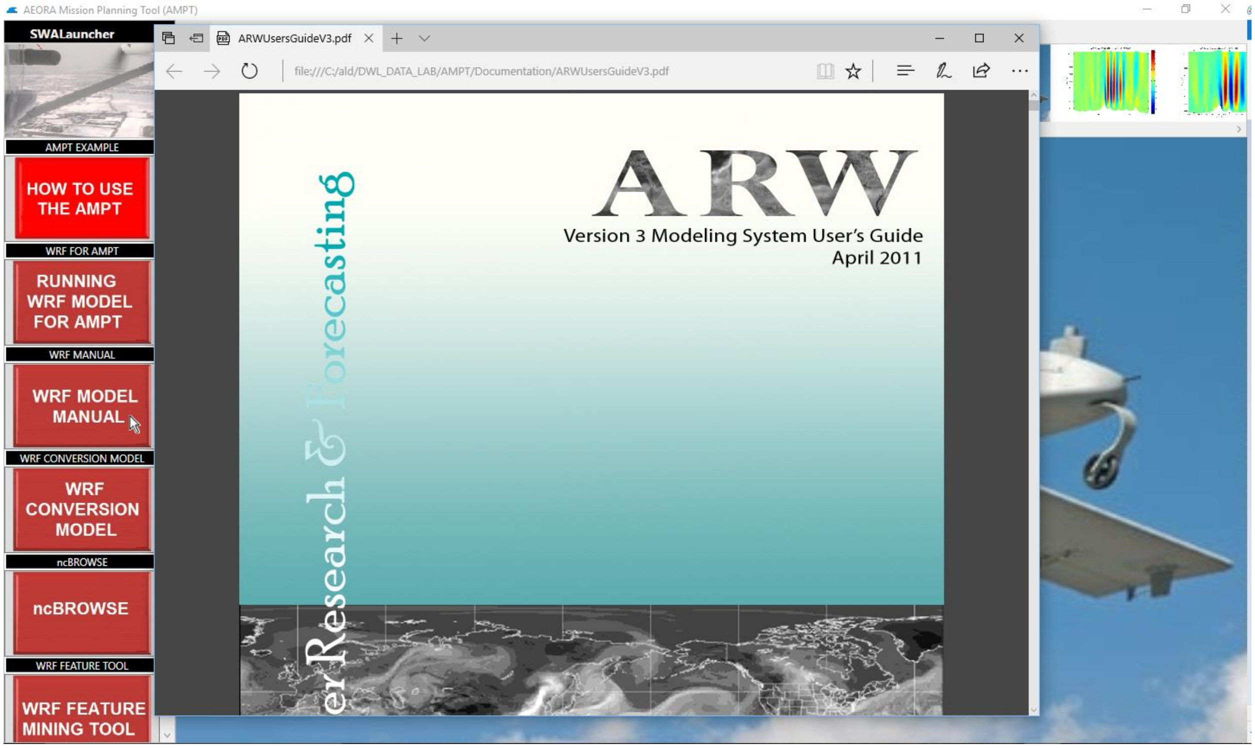

Figure 6.0 NCAR's Advanced Research WRF (ARW) Version 3.3 modeling system, released in April 2011.

2.1.2 WRF Model Data Conversion

The WRF Conversion Model button invokes a MATLAB algorithm running in OCTIVE that converts WRF NetCDF files to binary format for the AMPT in the ~\AMPT\WRFfiles\BIN directory. When invoked, a WRF NetCDF menu will pop up (Figure7.0) for the user to choose a WRF NetCDF file (ex. Wrfout_d03_2012-10-04_2100.nc). The conversion process (Figure 8.0) in OCTIVE may require long run times.

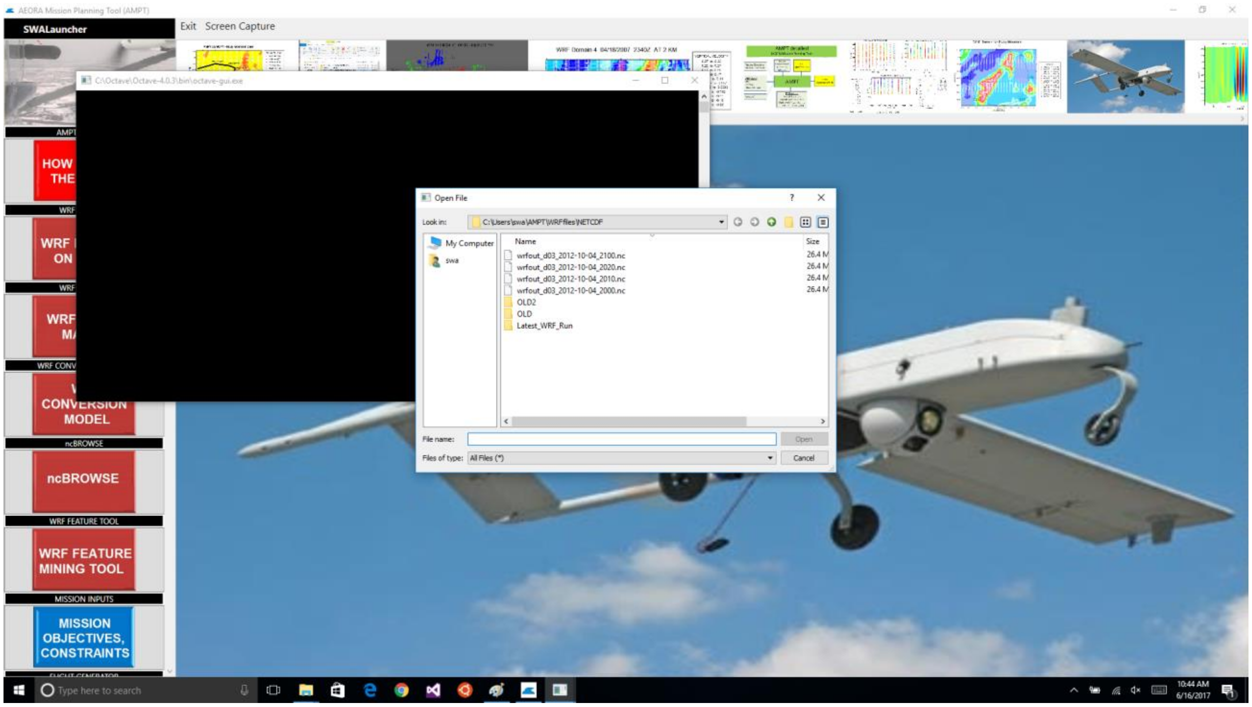

Figure 7.0 WRF Conversion Model Menu Screen

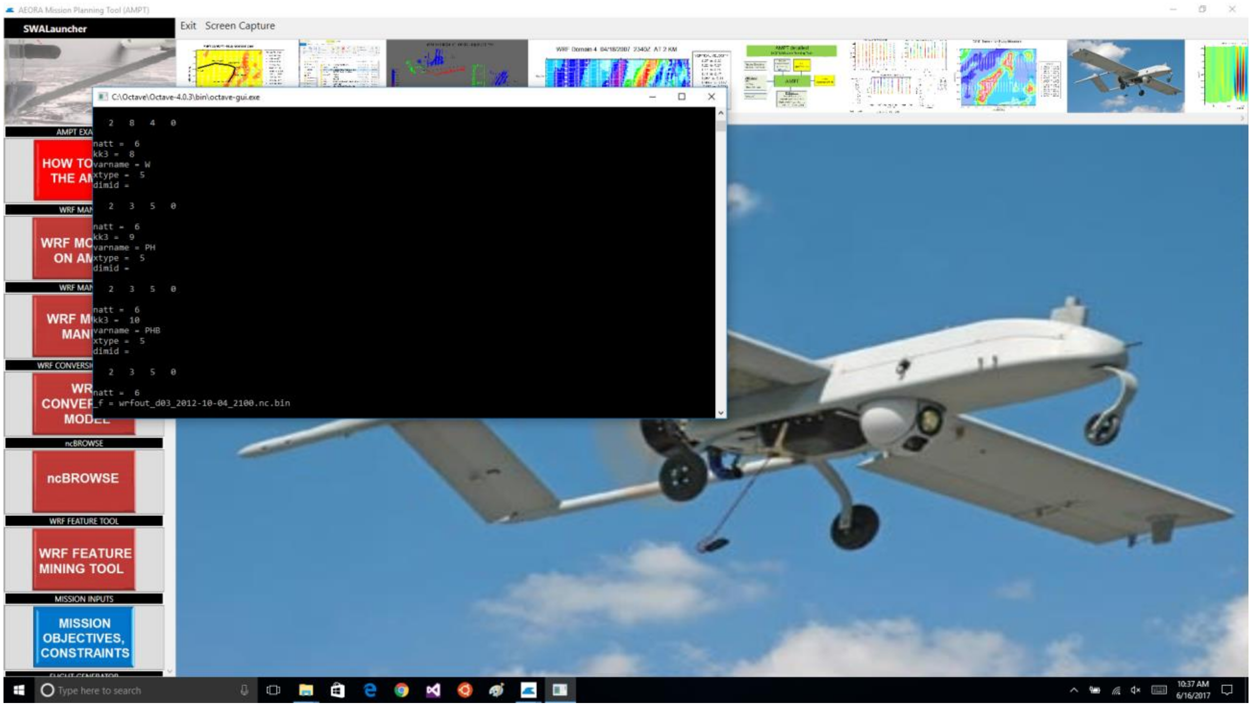

Figure 8.0 WRF Conversion Model OCTIVE Screen

2.1.3 ncBrowse for WRF Model outputs

The ncBrowse button invokes NOAA/PMEL/EPIC's Java application NetCDF File Browser (Figure 9.0) that provides flexible, interactive graphical displays of data and attributes. After loaded a WRF NetCDF file, the user chooses a WRF field, sets graphic options and ncBrowse will plot the field. The model does not extract data.

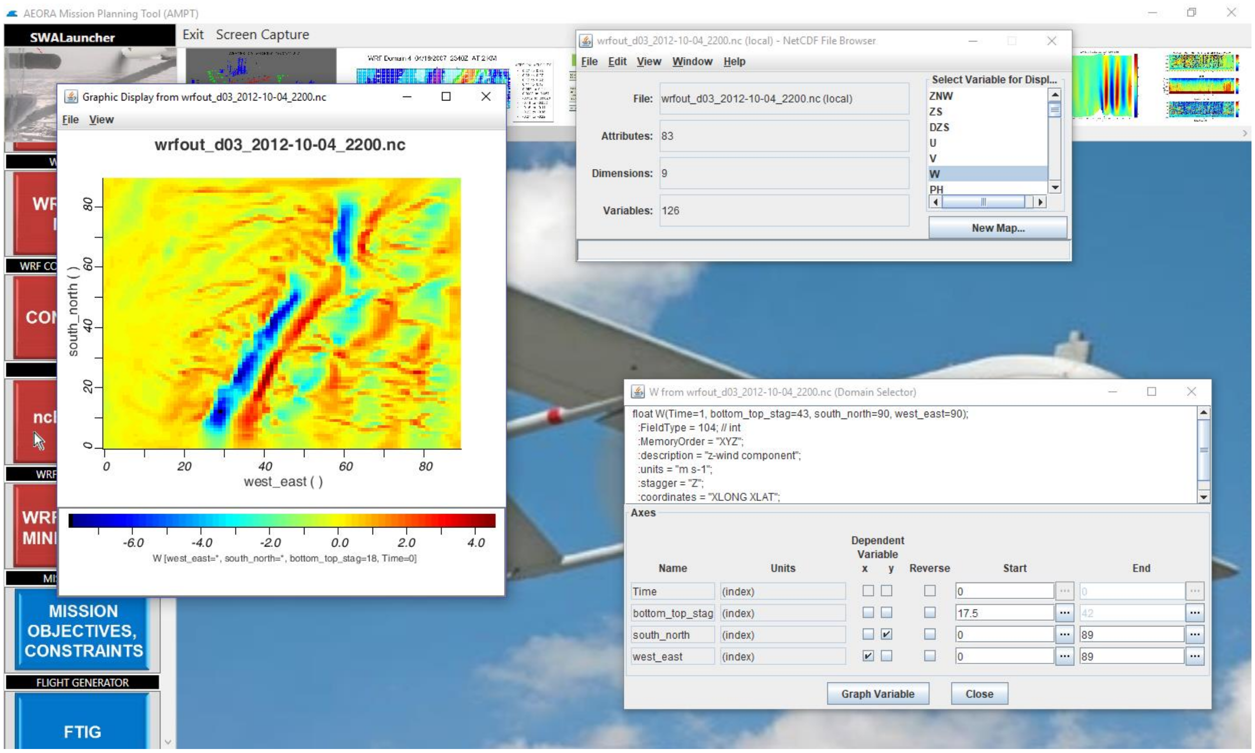

Figure 9.0 An example of the use of ncBrowse to look at a WRF field.

2.1.4 WRF Feature Tool

The WRF Feature Tool (Figure 10.0) reads in a WRF atmosphere binary file and allows the user to extract variables in ASCII format for graphics. The tool also generates additional variables from the WRF variables that might be useful when visualized to find potential energy sources.

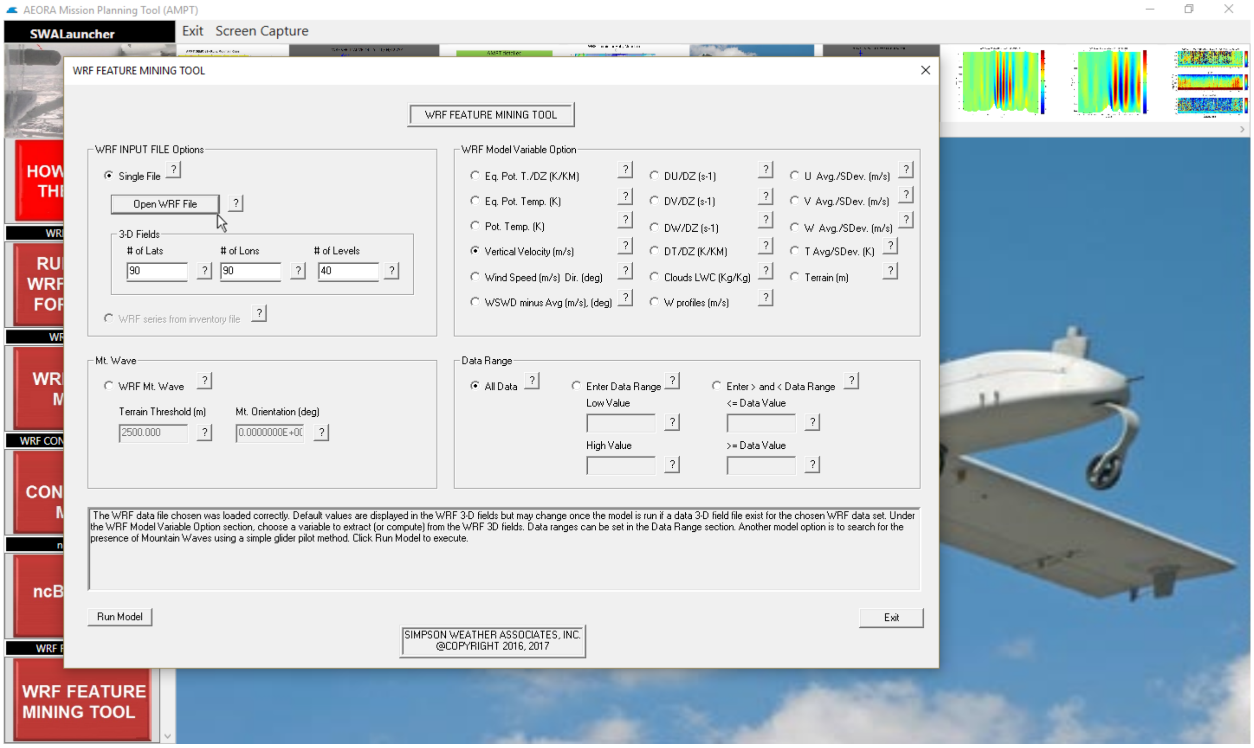

Figure 10.0 The WRF Feature Tool Main Screen.

The WRF variables to choose from are as follows.

- The change in Equivalent Potential Temperature (ThetaE) as a function of layer thickness (K/Km) can be derived from the WRF File. ThetaE is the temperature a parcel of air would reach if all the water vapor in the parcel were to condense, releasing its latent heat, and the parcel was brought adiabatically to a standard reference pressure, usually 1000 hPa (1000 mbar) which is roughly equal to atmospheric pressure at sea level. In stable conditions, ThetaE increases with altitude. If ThetaE decreases with height, convection can occur. The comparison of the equivalent potential temperature of parcels of air at different pressures thus provides a measure of the instability of the column of air

- The Equivalent Potential Temperature (K) (ThetaE) can be derived from the WRF File. ThetaE is the temperature a parcel of air would reach if all the water vapor in the parcel were to condense, releasing its latent heat, and the parcel was brought adiabatically to a standard reference pressure, usually 1000 hPa (1000 mbar) which is roughly equal to atmospheric pressure at sea level. In stable conditions, ThetaE increases with altitude. If ThetaE decreases with height, convection can occur. The comparison of the equivalent potential temperature of parcels of air at different pressures thus provides a measure of the instability of the column of air.

- The Potential Temperature (K) (Theta) can be derived from the WRF File. The potential temperature of a parcel of fluid at pressure, P, is the temperature that the parcel would acquire if adiabatically brought to a standard reference pressure, usually 1000 millibars.

- Vertical velocity (m/s) can be extracted from the WRF File.

- Wind speed (m/s) and wind direction (deg) can be derived from the WRF File.

- Wind speed (m/s) and wind direction (deg), minus their average, can be derived from the WRF File.

- The change in the U horizontal wind component with the respect to the change in atm. layer (s-1) can be derived from the WRF File.

- The change in the V horizontal wind component with the respect to the change in atm. layer (s-1) can be derived from the WRF File.

- The change in the vertical velocity with the respect to the change in atm. layer (s-1) can be derived from the WRF File.

- The change in the Temperature with the respect to the change in atm. layer (K/Km) can be derived from the WRF File.

- Cloud Liquid Water Content (kg/kg) can be extracted from the WRF File

- Profiles of vertical velocity (m/s) can be extracted from the WRF File.

- The average and standard deviation (9 pt., 27 pt., 3 pt.) of the U horizontal wind components (m/s) can be derived from the WRF File.

- The average and standard deviation (9 pt., 27 pt., 3 pt.) of the V horizontal wind components (m/s) can be extracted from the WRF File.

- The average and standard deviation (9 pt., 27 pt., 3 pt.) of the vertical velocity (m/s) can be extracted from the WRF File.

- The average and standard deviation (9 pt., 27 pt., 3 pt.) of the temperature (K) can be extracted from the WRF File.

- Terrain (m) (AGL) can be extracted from the WRF File.

Figure 11.0 shows the choosing of a WRF atmosphere file from the binary directory …\AMPT\WRFfiles\BIN (test case Ruby Mountain 10/04/12 2020Z). Vertical velocity is the desired WRF variable (default) for extraction (Figure 12.0). Once the model has been run, an ASCII file for the variable is written in the ASCII directory for graphics. The graphics is intended to be a tool for helping a user define the flight mission. Figures 13.0 and 14.0 are examples of WRF 3D vertical velocity that a flight mission can target. Figure 15.0 is a 2D multi-level example of the vertical velocity fields.

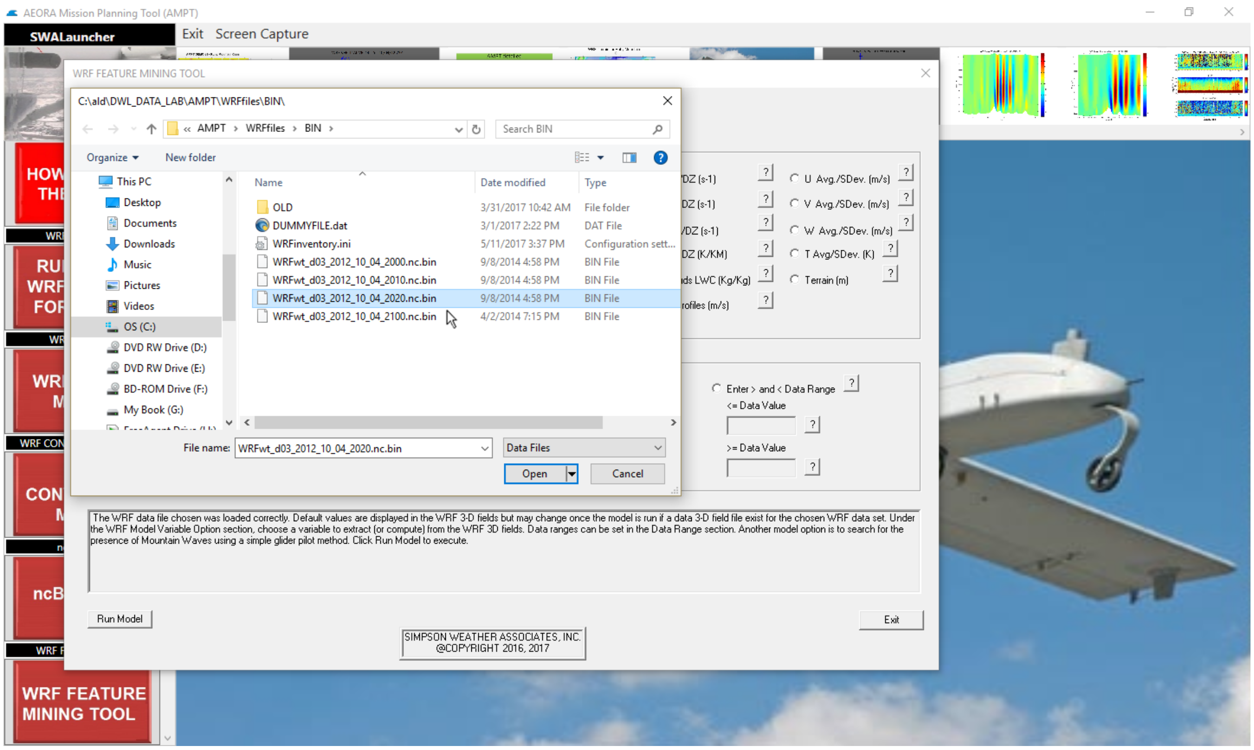

Figure 11.0 Loading a binary WRF atmosphere file from the subdirectory …\AMPT\WRFfiles\bin using the WRF Feature Tool.

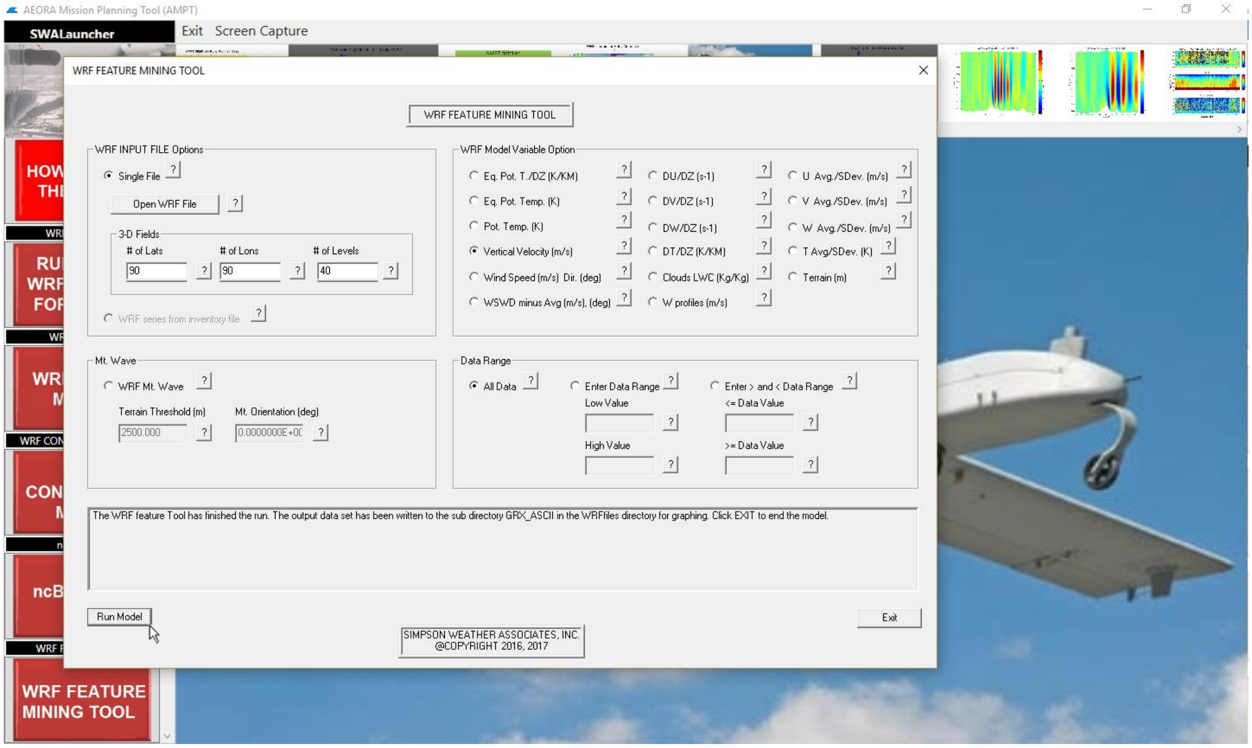

Figure 12.0 Extracting vertical velocity (default) from the WRF atmosphere file and writing it to an ASCII file in the subdirectory …\AMPT\WRFfiles\GRX_ASCII for graphics.

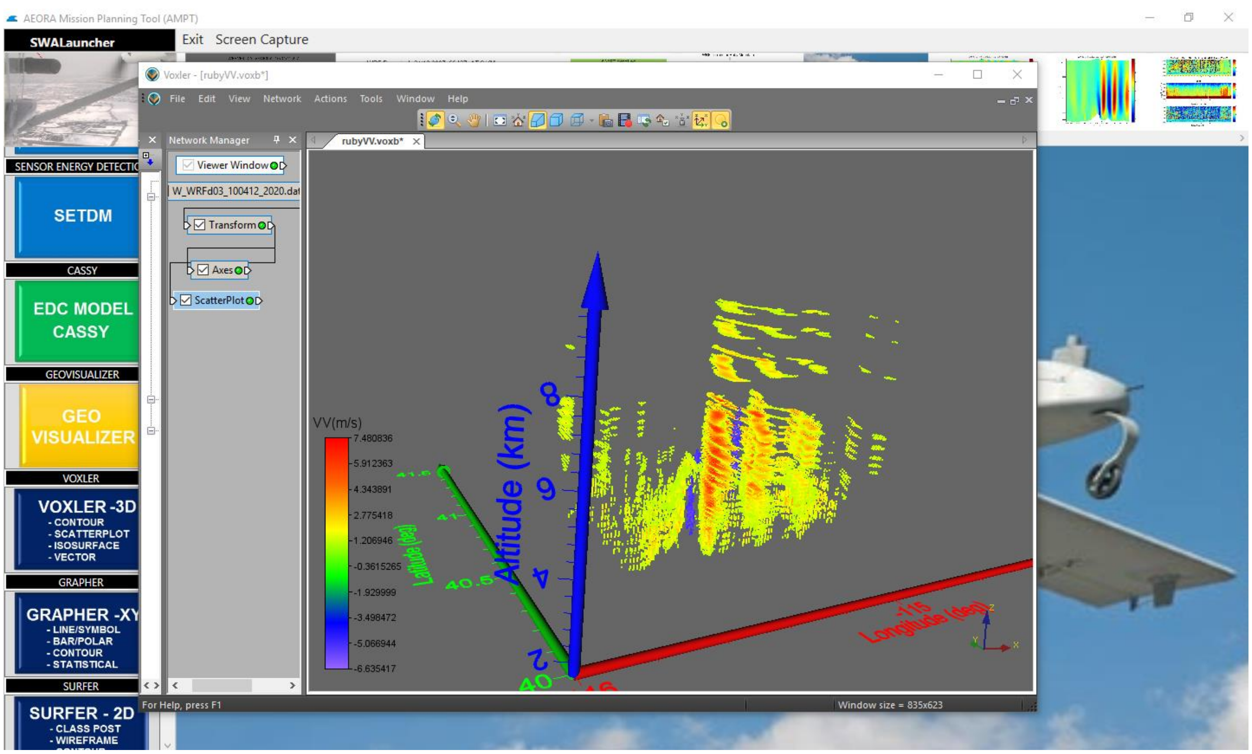

Figure 13.0 3D Graph of the 10/04/12 2020Z WRF variable vertical velocity showing the areas of upward vertical motion.

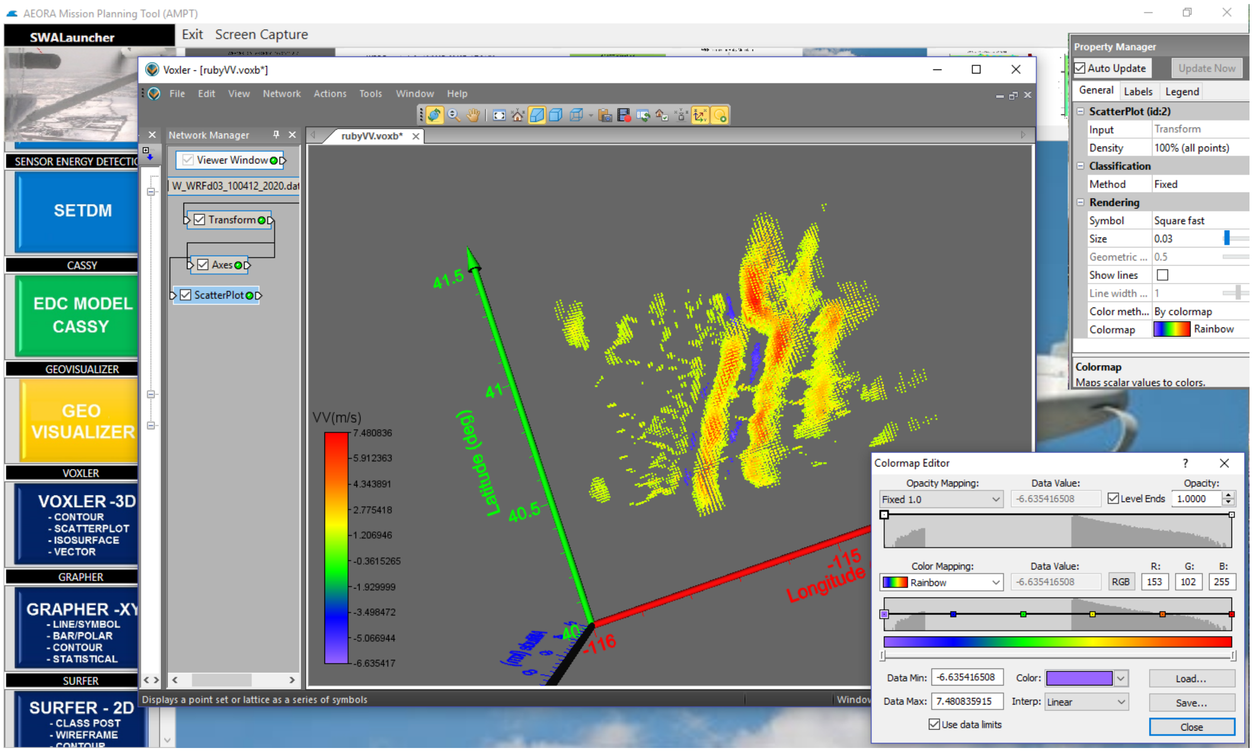

Figure 14.0 Top view of a 3D Graph of the 10/04/12 2020Z WRF variable vertical velocity showing the areas of upward vertical motion. The histogram distribution of vertical velocity in the data base is also shown.

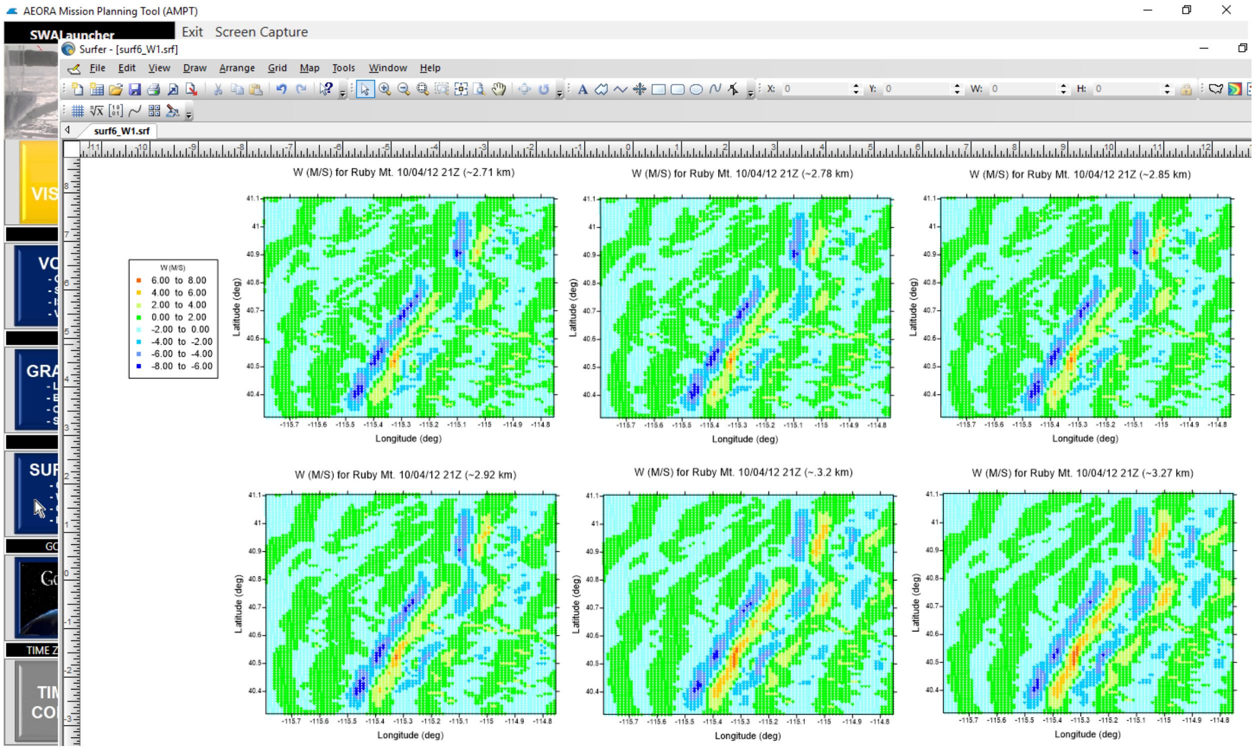

Figure 15.0 A 2D multi-level example of the WRF vertical velocity fields for the Ruby Mountain area (10/04/12 2020Z).

When running the WRF Feature tool, the user can choose to set boundaries on the variables being extracted/derived. All data is the model default, however lower and upper ranges can be set for greater than/less than or range limit to stay within.

Another option to a search for mountain waves in the WRF atmosphere based upon a glider technique. Note - This method has not been fully tested.

Prediction of a formation of mountain waves occurring (90% accuracy) in the following conditions:

- Wind direction within 30 degrees of the perpendicular to the ridge of high ground and no change in direction with height.
- Wind speeds at the crest of the ridge in excess of 15-20 kts, increasing with height.
- Stable air above the crest of the ridge with less stable air above and below that stable layer.

Using the WRF Feature Tool to extract terrain and graphics can be used to determine the orientation a mountain ridge as shown in Figure 16.0. With WRF wind speed and direction, Equivalent Potential Temperature profile, terrain and mountain orientation information, the WRF Feature Tool computes the likelihood of Mountain Wave presence.

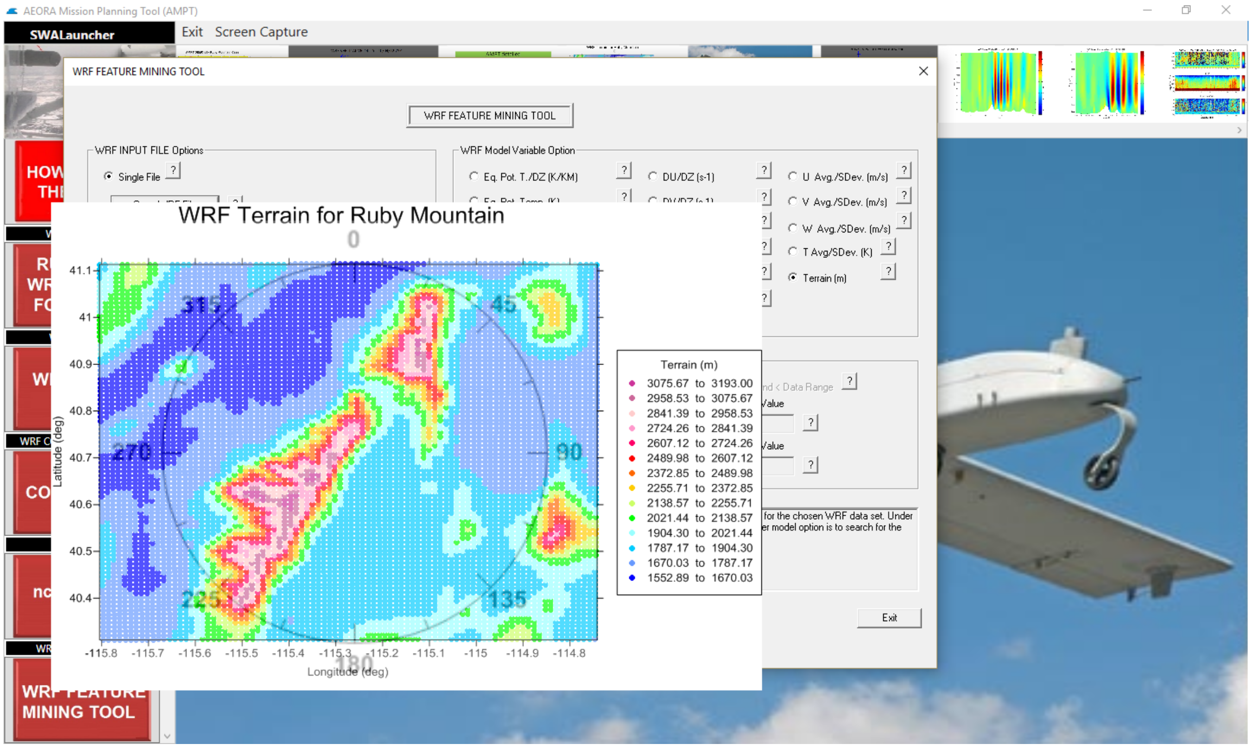

Figure 16.0 WRF terrain for Ruby Mountain case 10/04/12.

2.2 Mission Objectives and Mission Constraints (MOaMC)

Once a user has explored the wind features and terrain from a WRF atmosphere, a mission can be constructed for a flight. There are two simulation modes for the AMPT (shown in Figure 17.0): UAV simulations (main mode) and DWL simulation mode. The UAV simulation mode allows the user to construct a flight mission by defining spatial and temporal constraints, UAV inputs, incorporating a WRF atmosphere, exploratory flights to a feature area and running the feature flying EDC model, CASSY, along the user chosen "best" flight. This mode is used as an example in this user's guide.

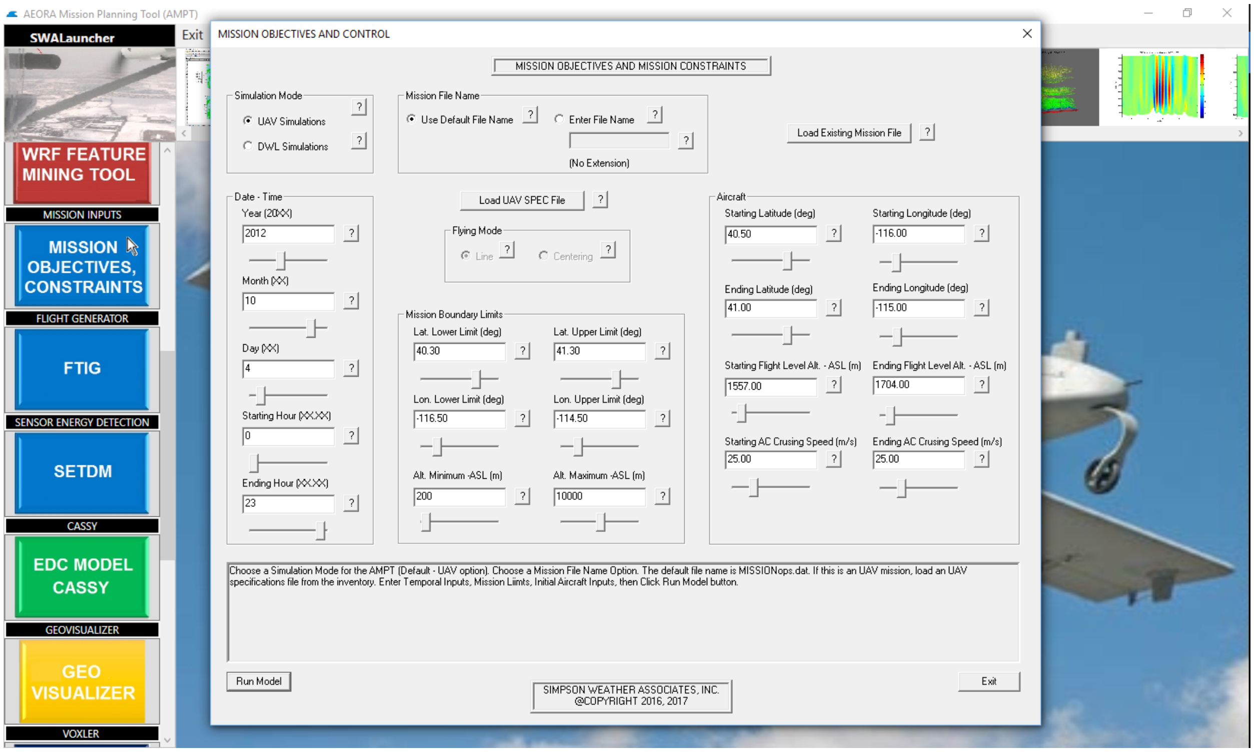

Figure 17.0 The Mission Objectives and Mission Constraints model (MOnMC) main screen.

The Mission Objectives and Mission Constraints variables to choose from are as follows.

- Under Simulation Mode, Run the AMPT for a UAV mission using EDC's CASSY model to simulate flying energy features.
- Under Simulation Mode, Run the AMPT using TODWL data to simulate ADWLs to explore searching energy features from WRF outputs.
- Under Mission File Name, the user can choose to create an unique name or use the default, MISSIONops.dat
- Load Existing Mission File button will open up a directory tree to allow the user to load a previously created mission file where the inputs are re-loaded. The user may have to change the directory to the one listed at the top of the load MISSION screen
- Load UAV SPEC File button will open up a directory tree to allow the user to choose an UAV from a menu for the mission. The user may have to change to the UAV Inventory directory to the one listed at the top of the load UAV screen
- Under Date - Time, enter the year (20XX) of the mission flight (it needs to match WRF atmosphere chosen in the SETDM).

- Under Date - Time, enter the month (XX) of the mission flight (it needs to match WRF atmosphere chosen in the SETDM).
- Under Date - Time, enter the Day (XX) of the mission flight (it needs to match WRF atmosphere chosen in the SETDM).
- Under Date - Time, enter the starting hour (XX.XX) of the mission flight.
- Under Date - Time, enter the ending hour (XX.XX) of the mission flight.
- Under Mission Boundary Limits, southern most latitude (lowest) limit for the mission area. (deg)
- Under Mission Boundary Limits, southern most longitude (lowest) limit for the mission area. (deg)
- Under Mission Boundary Limits, minimum altitude (lowest) limit for the mission area. (deg)
- Under Mission Boundary Limits, northern most latitude (upper) limit for the mission area. (deg)
- Under Mission Boundary Limits, northern longitude (highest) limit for the mission area. (deg)
- Under Mission Boundary Limits, maximum altitude (highest) limit for the mission area. (deg)
- Under Flying Mode, Line tells CASSY to fly the UAV in a line pattern while surfing WRF energy features. (Not incorporated at this time)
- Under Flying Mode, Centering tells CASSY to fly the UAV centering pattern while surfing WRF energy features. (Not incorporated at this time)
- Under Aircraft, the starting latitude (deg) of the UAV flight.
- Under Aircraft, the starting longitude (deg) of the UAV flight.
- Under Aircraft, the ending latitude (deg) of the UAV flight, post flying the energy feature. It may be the same location as the starting point.
- Under Aircraft, the ending longitude (deg) of the UAV flight, post flying the energy feature. It may be the same location as the starting point.
- Under Aircraft, the starting altitude (m) minus ASL of the UAV. This input should be set to zero if UAV is on the ground.
- Under Aircraft, the ending altitude (m) minus ASL of the UAV. This input should be set to zero if UAV is on the ground.

- Under Aircraft, the starting aircraft cruise speed (m/s). This input should be set to zero if UAV is on the ground.
- Under Aircraft, the ending aircraft cruise speed (m/s). This input should be set to zero if UAV is on the ground.

Next to all AMPT inputs there is a small question mark that when clicked a brief description will be displayed. Figure18.0 is a MOaMC message example.

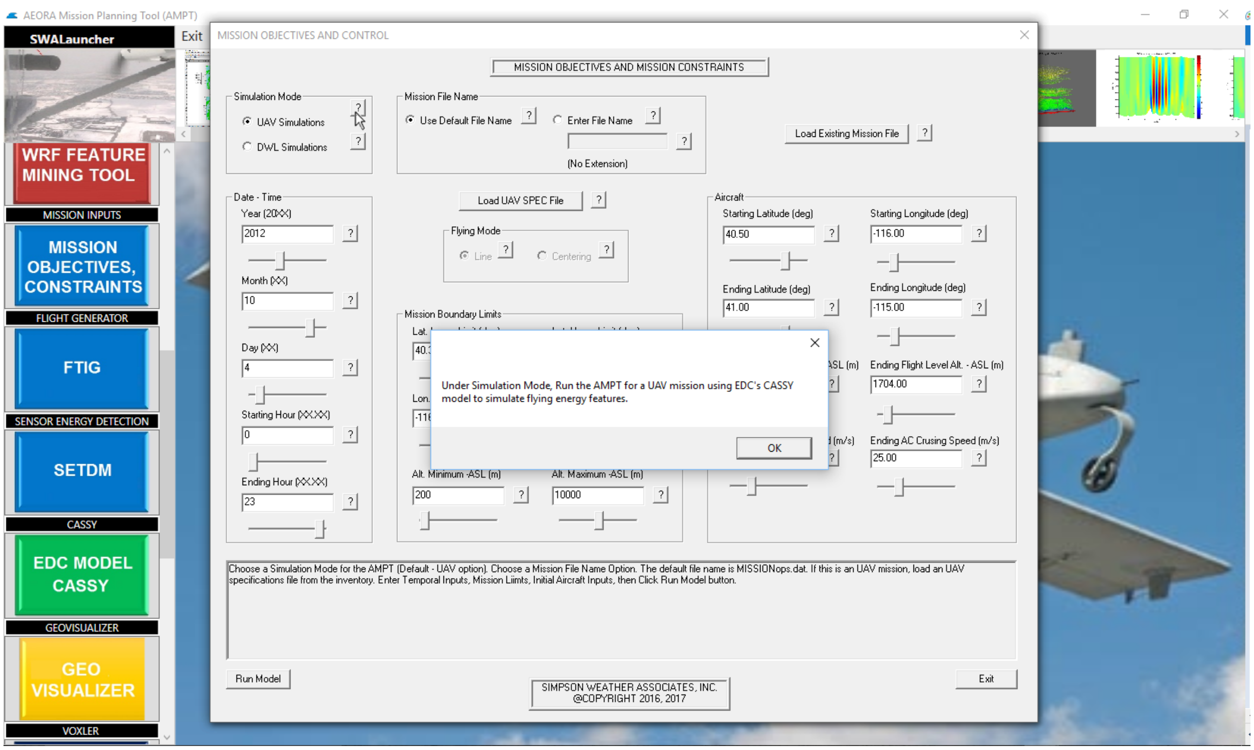

Figure 18.0 Example of AMPT input variable message box.

For UAV simulation mode, after the output file has been defined, the user should click the Load UAV SPEC FILE and load a UAV specifications file from the UAV inventory (Figure 19.0 and Figure 20.0).

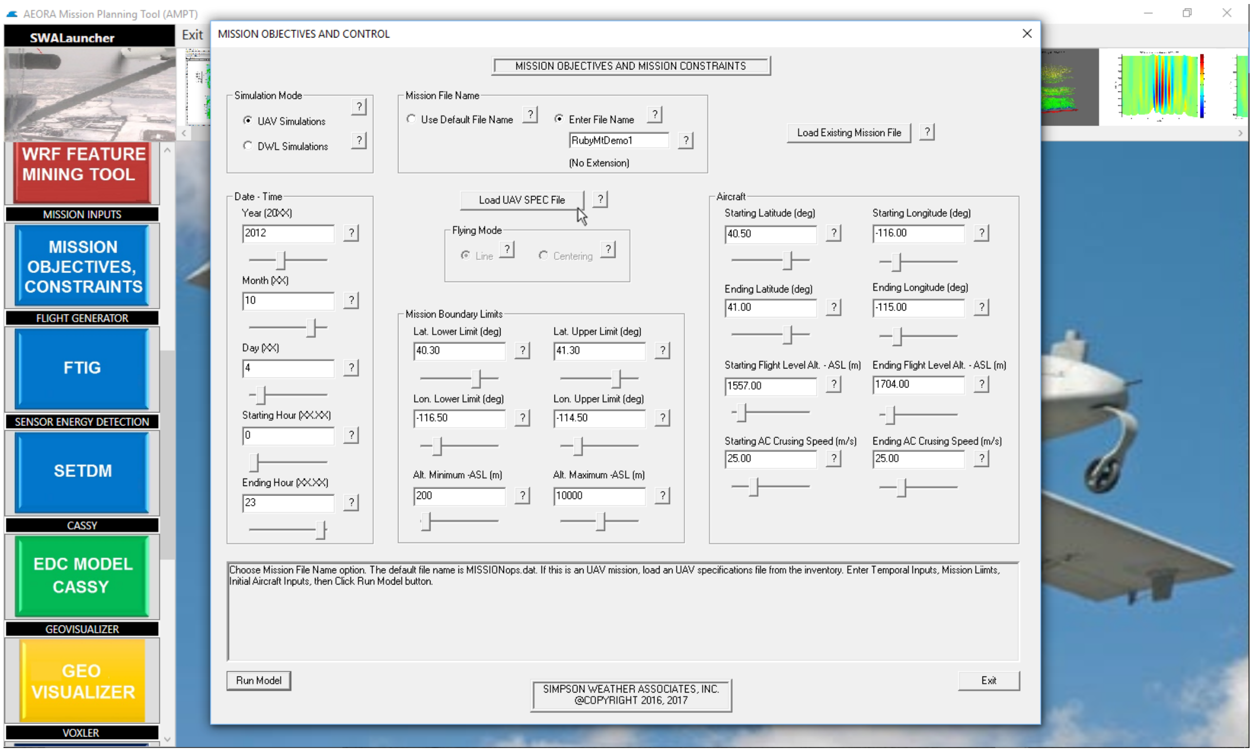

Figure 19.0 Example of clicking the Load UAV SPEC FILE to load a UAV specifications file from the UAV inventory

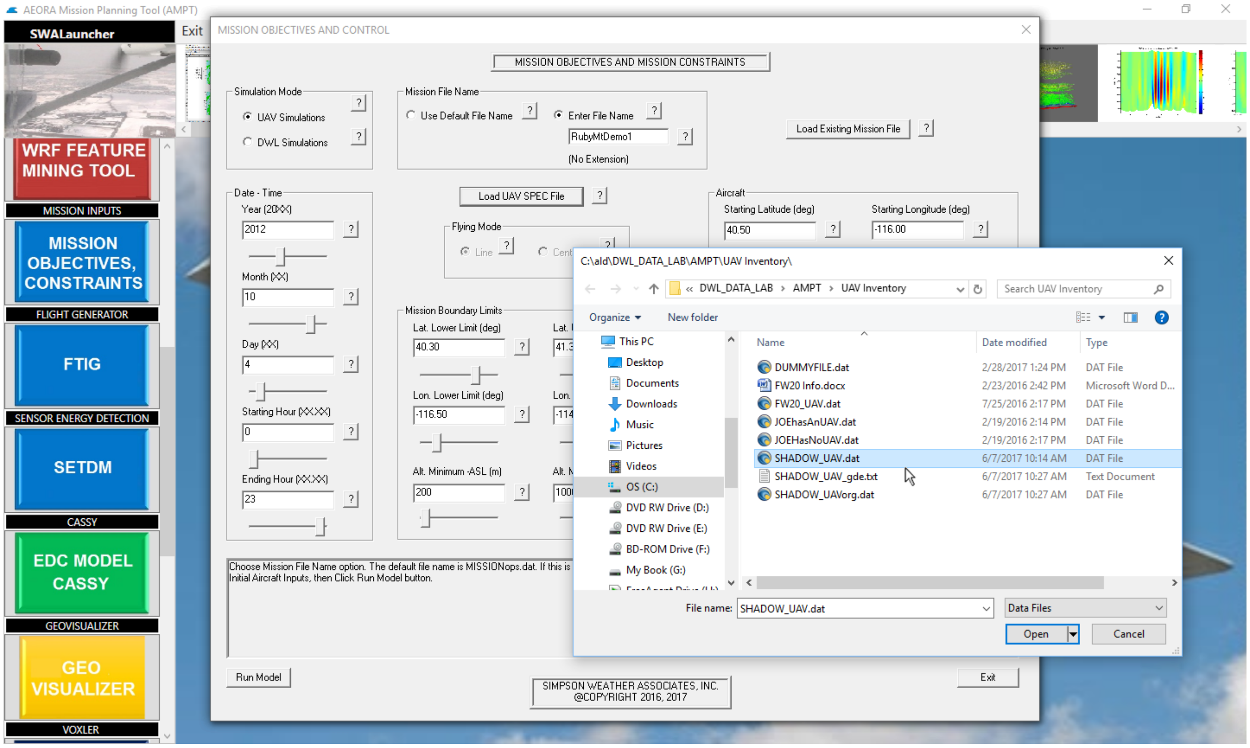

Figure 20.0 Loading an ASCII UAV SPECS File for the SHADOW UAV from the sub-directory …\AMPT\UAV Inventory.

Table 1.0 below list the SHADOW UAV specifications numbers. 1.0 is used for values yet to be obtained. Table 2.0 below list the FW20 UAV specifications numbers.

Table 1.0 SHADOW UAV

<u>**Measurements**</u>

168	Wingspan (in)
134	Fuselage length (in)
24	Body diameter (in)

<u>**Weight**</u>

186	Empty weight (lbs)
375	Maximum gross takeoff weight (lbs)

<u>**UAV Performance**</u>

14764.0	Maximum Altitude (ft) AGL
360.0	Maximum Endurance (min)
120.0	Maximum One Way Range (km)
57.	Maximum Airspeed at a flying weight of 20 lbs (m/s)
73.0	Cruise Speed (kts)
350.	Maximum rate of Climb (ft/min)
500.	Maximum rate of descent - <350 (ft/min)
45.	Maximum bank angle (deg)

80.	Payload capacity (lbs)
50	Maximum L/D

Motor

38	Max power hp/motor
1.0	Each motor has a max current draw of xx Amps in flight (xx tbd)
1.0	Number of xx

Temperature and Wind speed limitations

1.0	Lower Temperature Threshold (F)
1.0	Upper Temperature Threshold (F)
1.0	Maximum Headwind (kts)
1.0	Maximum Crosswind (kts)
1.0	Maximum Gusts (kts)
1.0	Minimum visibility conditions (mi)

Fuel

45.0	Fuel (liters)
0.003	Climb Burn Rate (liters/s)
0.002	Cruise Burn Rate (liters/s)
0.0005	Idle or descent burn rate (liters/s)

Table 2.0 FW20 UAV

Measurements

120.0	Wingspan (in)
65.0	Fuselage length (in)
6.0	Body diameter (in)

Weight

13.75	Empty weight (lbs)
20.0	Maximum gross takeoff weight (lbs)

UAV Performance

5000.0	Maximum Altitude (ft) AGL
90.0	Maximum Endurance (min)
108.0	Maximum One Way Range (km)
30.2	Maximum Airspeed at a flying weight of 20 lbs (m/s)
40.0	Cruise Speed (kts)
5.0	Maximum rate of Climb (m/s)
350.0	Maximum rate of descent - <350 (ft/min)
55.0	Maximum bank angle (deg)
6.28	Payload capacity (lbs)
16.0	Maximum L/D

Motor - lithium polymer batteries

1.2 Max power is 1.2 hp/motor
40.0 Each motor has a max current draw of 40 Amps in flight
3.0 Number of Li Batteries

Temperature and Wind speed limitations

0.0 Lower Temperature Threshold (F)
90.0 Upper Temperature Threshold (F)
25.0 Maximum Headwind (kts)
15.0 Maximum Crosswind (kts)
30.0 Maximum Gusts (kts)
2.0 Minimum visibility conditions (mi)

Fuel

1000.0 Fuel (X)
0.05 Climb Burn Rate (X/s)
0.03 Cruise Burn Rate (X/s)

Once a UAV file has been loaded, the user can define the flight mission by defining spatial and temporal constraints (Figure 21.0) and the starting and ending UAV 3D locations and speeds. To create a Mission output file for the FTIG and SETDM, click the Run Model button (Figure 22.0). Click Exit button to end the MOaMC model run.

If this is a DWL Simulation mode, following all the preceding inputs except the loading of a UAV Specification file.

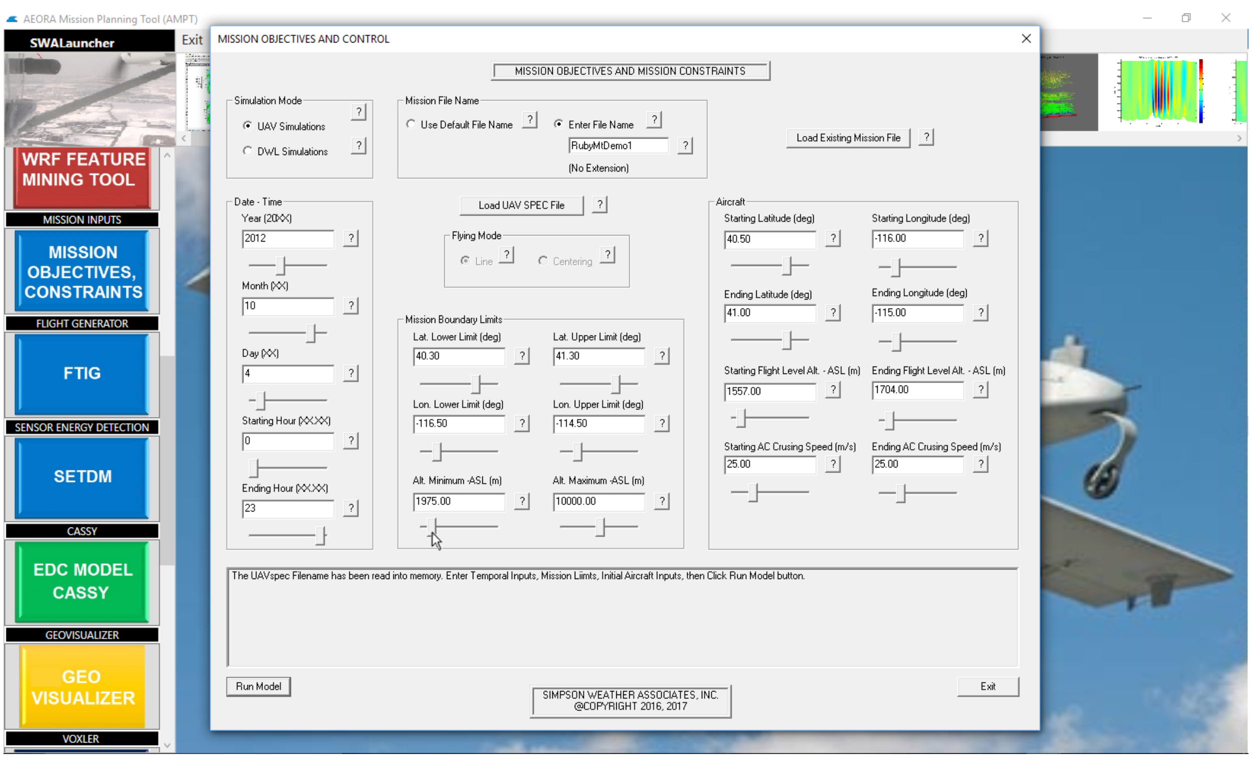

Figure 21.0 Example of modifying the Minimum Flight Altitude (m) via a slider.

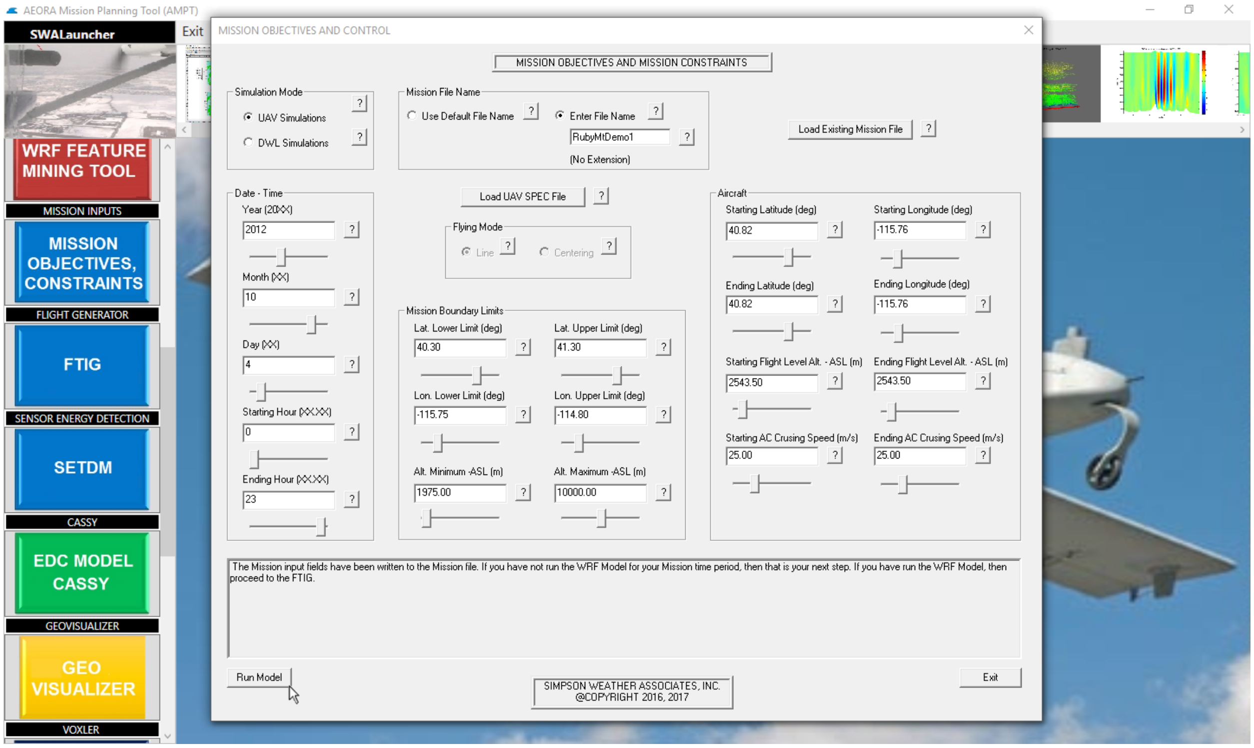

Figure 22.0 Example of MOaMC model execution and post instructions.

2.3 Flight Trajectory Instruction Generator (FTIG)

The Flight Trajectory Instruction Generator's (FTIG) main purpose is to generate an initial UAV flight from the starting 3D location from the mission file, up to four user defined way points and to the energy Feature Intercept Point. This flight, the may or may not be the best flight to use to fly to the Feature Intercept Point. Other flight options include using a simulated EDC flight file or an actual TODWL flight files to produce a flight with a simulated DWL on the aircraft. Performance of the flight with the DWL flying through a WRF atmosphere is executed in the SETM.

The Flight Trajectory Instruction Generator (FTIG) input variables to choose from are as follows.

- Load Mission File button will open up a directory tree to allow the user to load a Mission File created in MISSION OBJECTIVES AND MISSION CONSTRAINTS model. The user may have to change the directory to the one listed at the top of the loading Mission screen.

- Output filename for the FTIG simulation. The file will be written to the sub-directory …\AMPT\FTIGfiles.

- Open Existing FTIG File loads an existing FTIG file's inputs into the fields so they can be edited for a new simulation. The user may have to change the correct directory to load the file, AMPT FTIGfiles.

- Under Flight File Option, the user can generate a simple flight from the starting Mission's location to the feature intercept point. Up to four way points can be defined for the flight.

- Under Flight File Option, The user can open a pre-generated EDC flight and the FTIG will save it in FTIG format for the SETDM. The flight can be modified via Aircraft Modifiers and a simple “DWL” with geometry can be added via Scanner Modifiers for various simulations.

- Under Flight File Option, The user can open a processed LOS file from TODWL and the FTIG will save it in FTIG format for the SETDM. The flight can be modified via Aircraft Modifiers and a simple “DWL” with geometry can be added via Scanner Modifiers for various simulations.

- Under Way Point Inputs, aircraft latitude #1 is the intended latitude (deg frac) of the UAV once it reaches the way point one. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft latitude #2 is the intended latitude (deg frac) of the UAV once it reaches the way point two. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft latitude #3 is the intended latitude (deg frac) of the UAV once it reaches the way point three. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft latitude #4 is the intended latitude (deg frac) of the UAV once it reaches the way point four. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft longitude #1 is the intended longitude (deg frac) of the UAV once it reaches the way point one. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft longitude #2 is the intended longitude (deg frac) of the UAV once it reaches the way point two. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft longitude #3 is the intended longitude (deg frac) of the UAV once it reaches the way point three. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft longitude #4 is the intended longitude (deg frac) of the UAV once it reaches the way point four. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft altitude #1 is the intended altitude (m) of the UAV once it reaches the way point one. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft altitude #2 is the intended altitude (m) of the UAV once it reaches the way point two. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft altitude #3 is the intended altitude (m) of the UAV once it reaches the way point three. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft altitude #4 is the intended altitude (m) of the UAV once it reaches the way point four. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft target cruise speed #1 is the intended cruise speed (m/s) of the UAV once it reaches the way point one. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft target cruise speed #2 is the intended cruise speed (m/s) of the UAV once it reaches the way point two. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft target cruise speed #3 is the intended cruise speed (m/s) of the UAV once it reaches the way point three. The check box to use the way point is set to yes as default.

- Under Way Point Inputs, aircraft target cruise speed #4 is the intended cruise speed (m/s) of the UAV once it reaches the way point four. The check box to use the way point is set to yes as default.

- Under Aircraft +/- Modifiers, the altitudes in an EDC flight file or TODWL LOS file can be adjusted by a constant altitude value.

- Under Aircraft +/- Modifiers, the headings in an EDC flight file or TODWL LOS file can be adjusted by a constant heading value.

- Under Aircraft +/- Modifiers, the latitudes in an EDC flight file or TODWL LOS file can be adjusted by a constant latitude value.

- Under Aircraft +/- Modifiers, the longitudes in an EDC flight file or TODWL LOS file can be adjusted by a constant longitude value.

- Under Energy Feature Intercept Point, aircraft latitude is the intended latitude (deg frac) of the UAV at the energy feature intercept point.

- Under Energy Feature Intercept Point, aircraft longitude is the intended longitude (deg frac) of the UAV at the energy feature intercept point.

- Under Energy Feature Intercept Point, aircraft altitude is the intended altitude (m) of the UAV at the energy feature intercept point.

- Under Energy Feature Intercept Point, aircraft cruise speed is the intended cruise speed (m/s) of the UAV at the energy feature intercept point.

- The UAV sampling distance for wind (and performance) along the aircraft's flight (m).

- Under Scanner +/- Modifiers, the azimuth angles in a TODWL LOS file can be adjusted by a constant azimuth angle value.

- Under Scanner +/- Modifiers, the elevation angle in a TODWL LOS file can be adjusted by a constant elevation value.

Once invoking the FTIG (Figure 23.0), the user should load a mission file (Figure 24.0) and enter a filename for the FTIG output flight file. If the user has run the FTIG before and wants to re-run or edit an existing flight inputs, the input fields can be loaded via a saved file from the sub-directory …\AMPT\FTIGfiles\FTIGinputFiles as shown in Figure 25.0. These input files are created every time the FTIG is run and are named after the FTIG output name with the prefix Input4_ attached to the name. Once all inputs have been satisfied, click the Run Flight Model Button to run the FTIG (Figure 26.0). After the run has been completed the user will be instructed to exit the FTIG and to proceed to the SETDM to use the flight in liaison with a WRF atmosphere for performance evaluations (Figure 27.0).

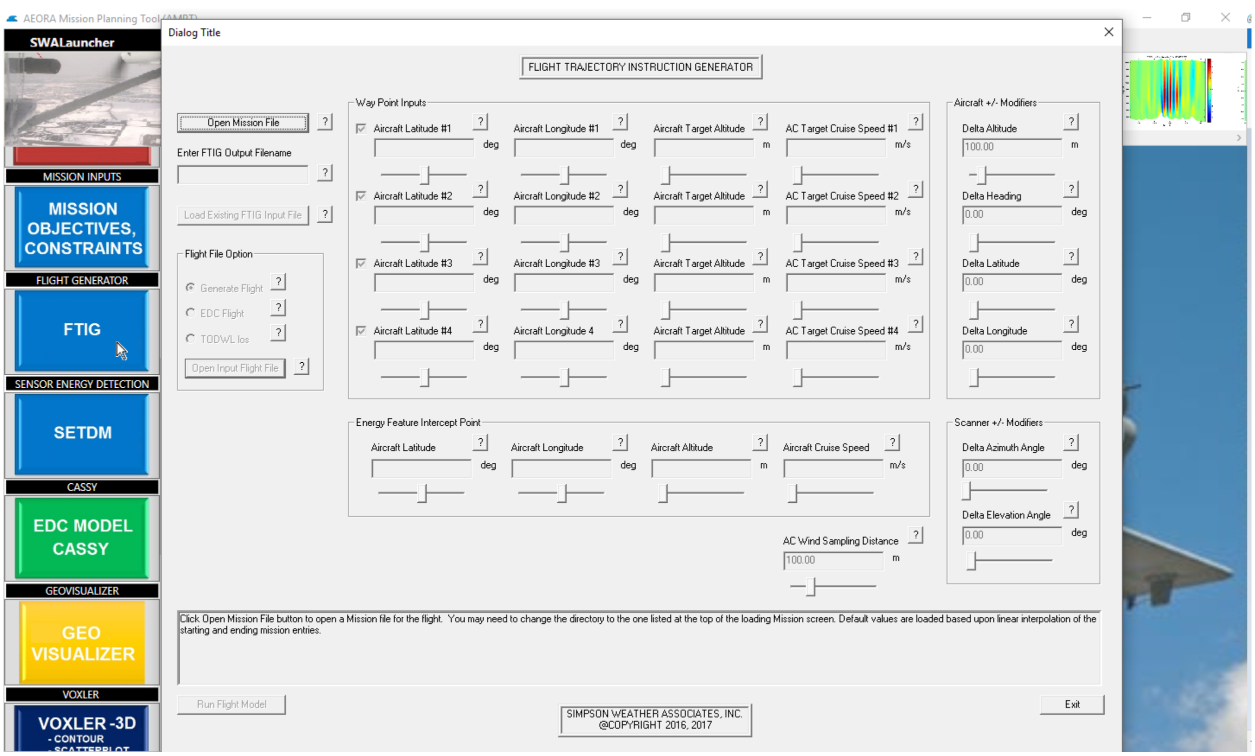

Figure 23.0 The Flight Trajectory Instruction Generator (FTIG) main screen.

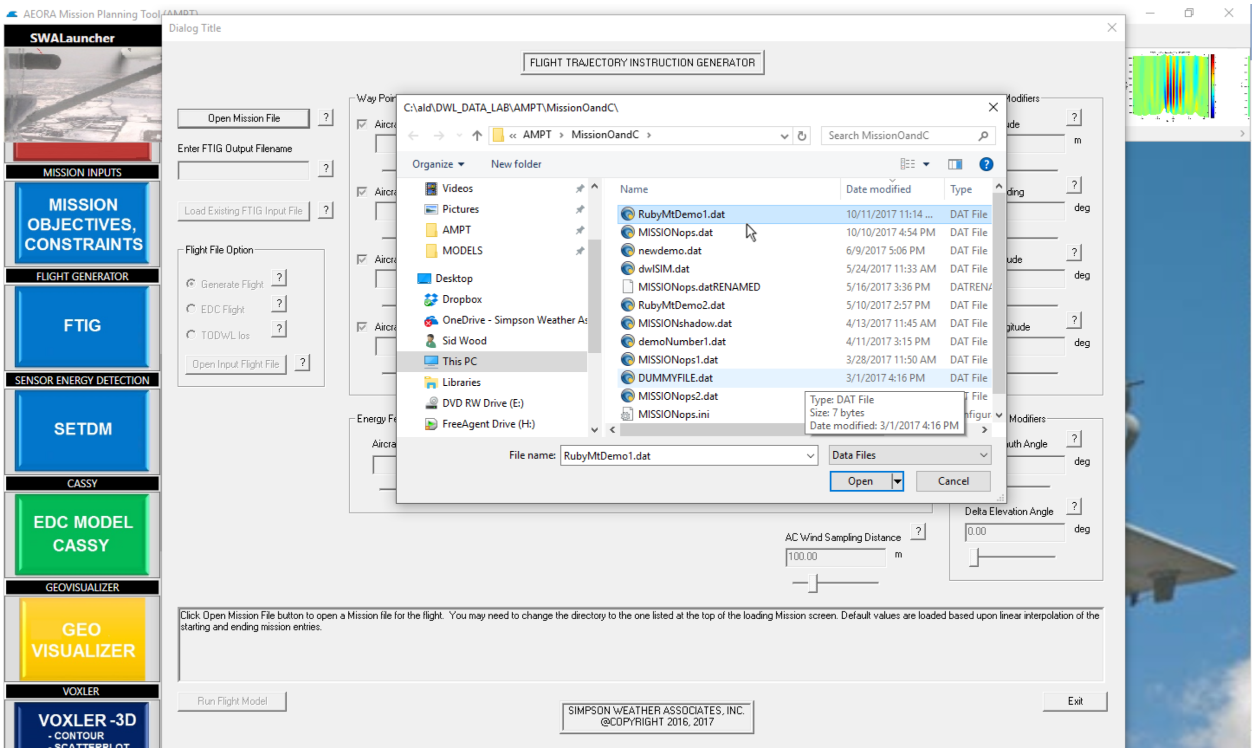

Figure 24.0 Example of the user loading mission file (RubyMtDemo1) from the subdirectory …\AMPT\MissionOandC.

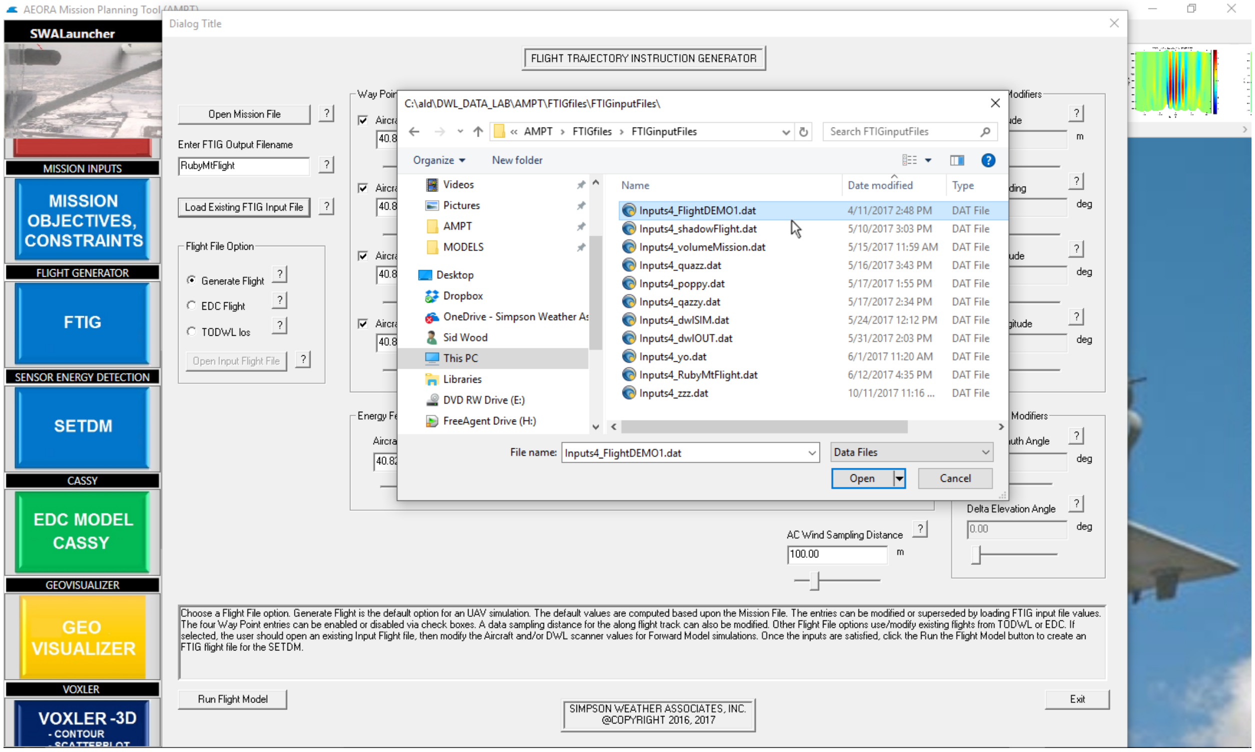

Figure 25.0 An example of loading a saved FTIG input file from the sub-directory …\AMPT\FTIGfiles\FTIGinputFiles that allows a user to re-run or edit an existing flight inputs.

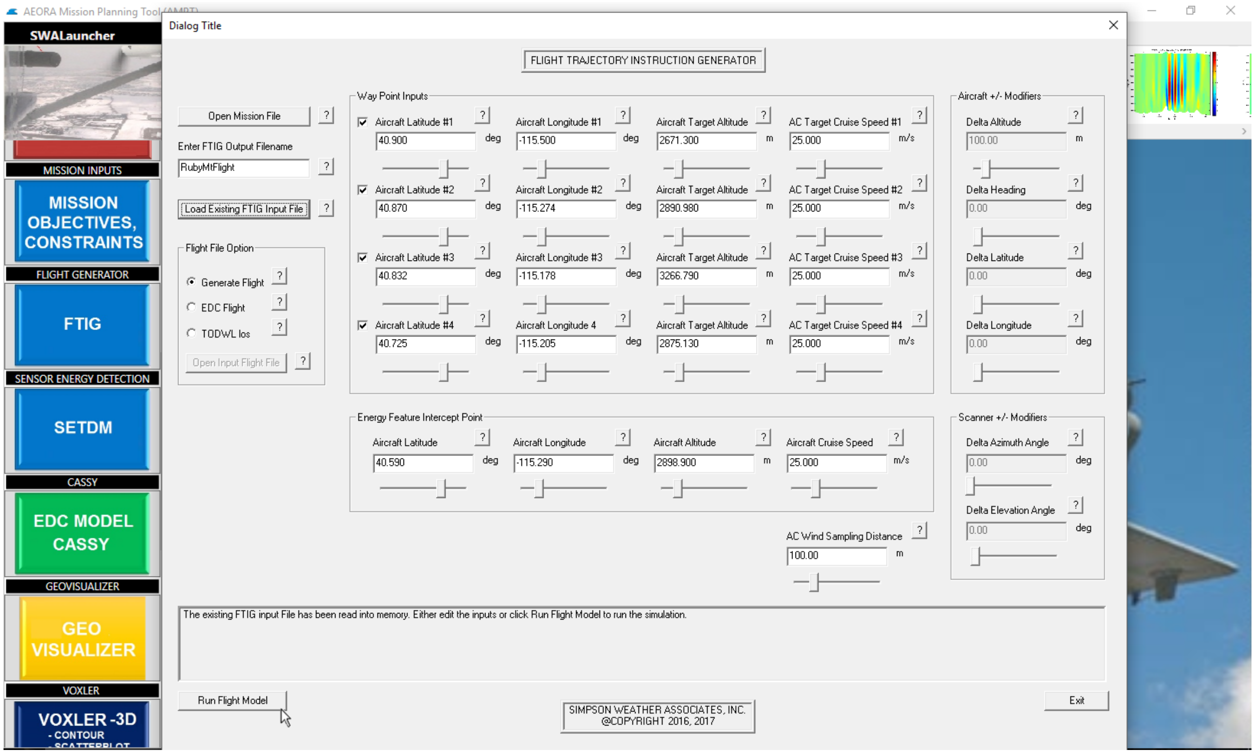

Figure 26.0 Example of running the FTIG after all inputs have been satisfied.

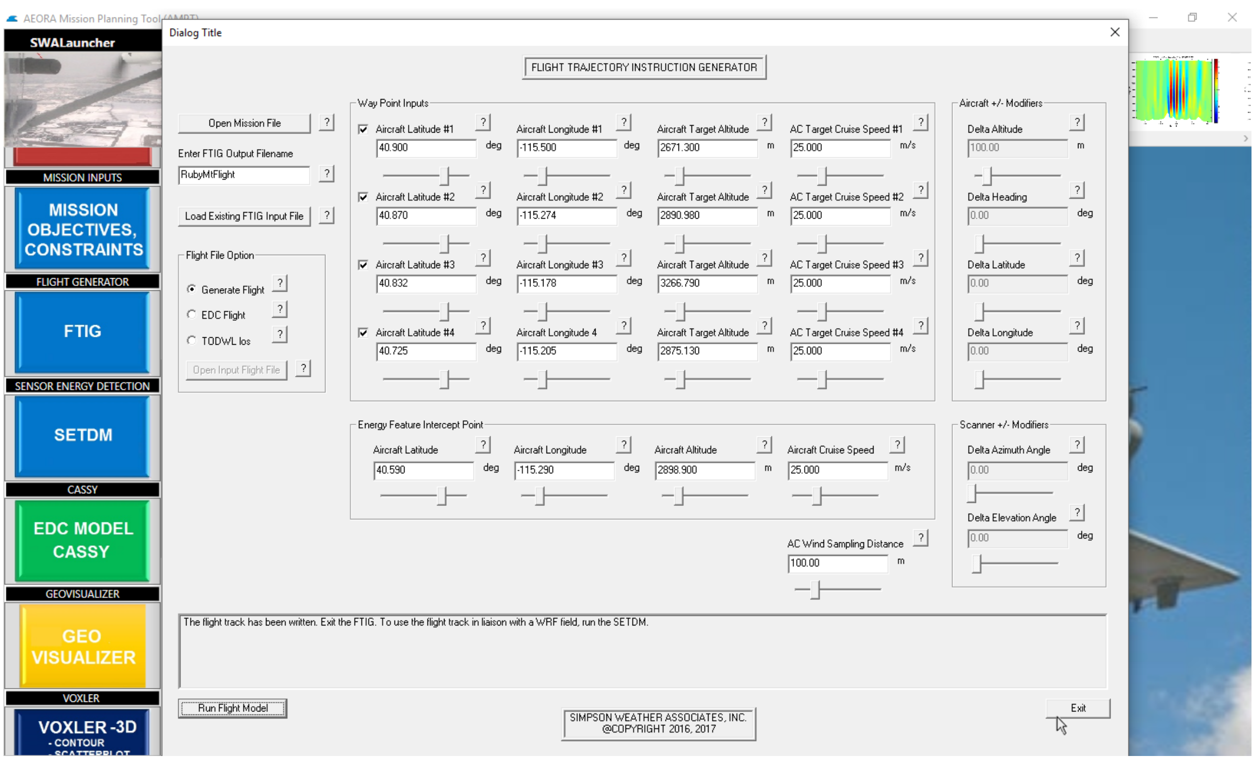

Figure 27.0 Example of a completed run of the FTIG.

It might be prudent to graph the FTIG initial flight data (Figure 28.0) before proceeding to the SETDM as a double check.

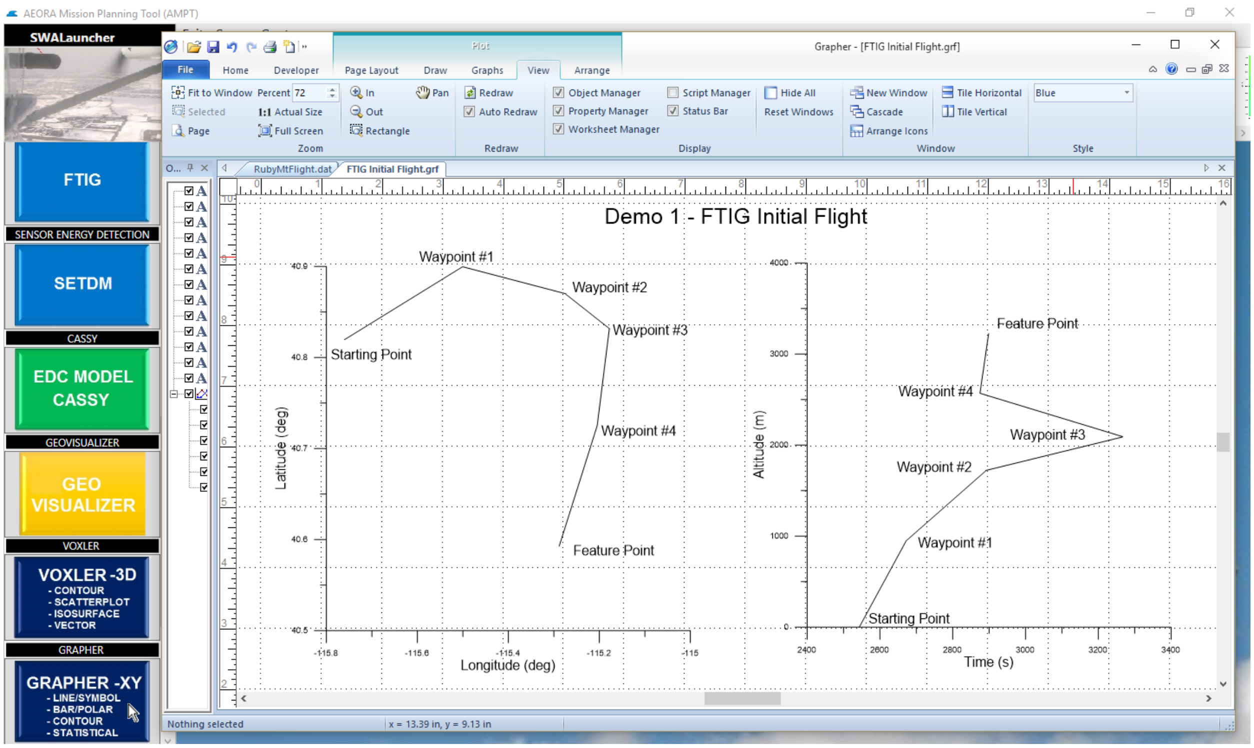

Figure 28.0 Grapher plot of the FTIG initial flight, location and altitude, for Demo 1.

2.4 Sensor Energy Target Detection Model (SETDM)

The Sensor Energy Target Detection Model (Figure 29.0) produces numerous potential flights and flight performances based upon the initial flight generated in the FTIG and flying through a WRF atmosphere from Home to the Feature Entry Point or the model computes simulated DWL winds for comparison with a WRF Forward model or it compares real DWL winds for comparison with a WRF Forward model. In the former, the SETDM dashboard allows the user to scroll through all flights' performances and choose a flight to be used in the EDC CASSY simulator.

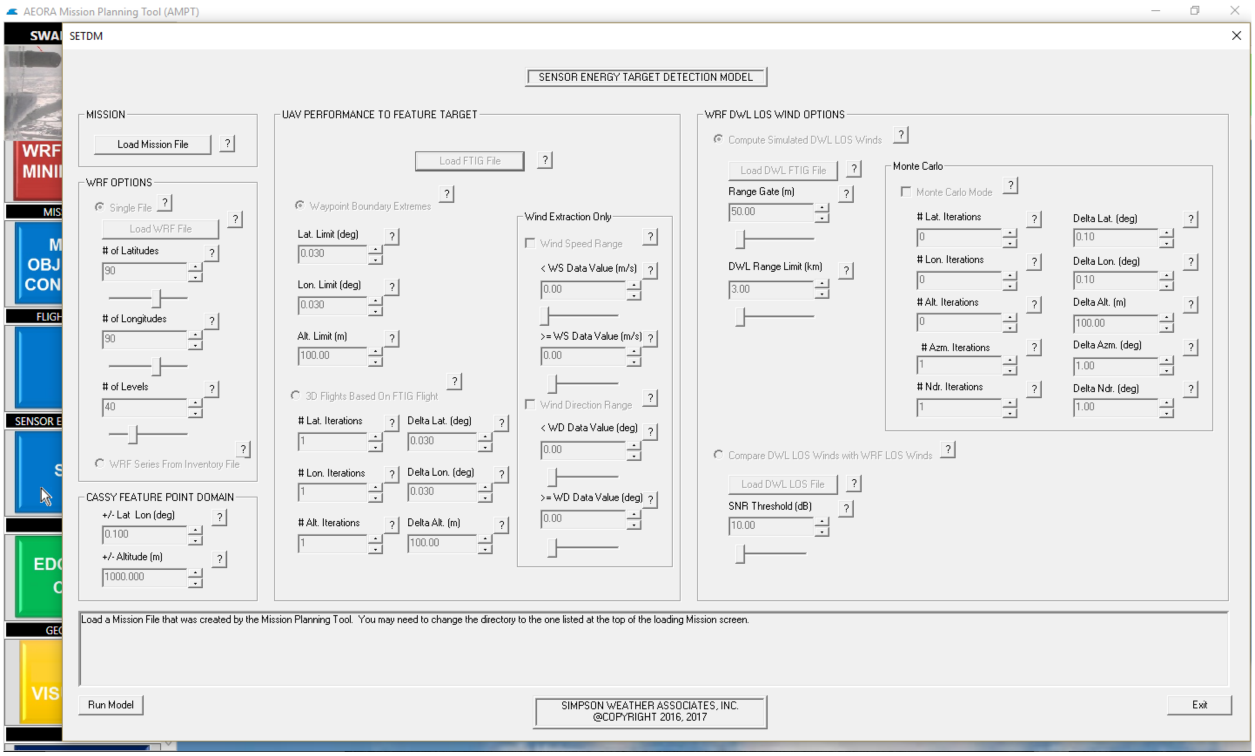

Figure 29.0 The Sensor Energy Target Detection Model main screen.

2.4.1 SETDM Inputs

The Sensor Energy Target Detection Model (SETDM) input variables to choose from are as follows.

- Under MISSION, The Load Mission File button will open up a directory tree to allow the user to load a Mission File created in MISSION OBJECTIVES AND MISSION CONSTRAINTS model. The user may have to change the directory to the one listed at the top of the loading Mission screen.

- Under WRF OPTIONS, the Single File (default) option instructs the SETDM that only a single WRF file, one time period, will be used in the simulation.

- For the Single File option, the Load WRF File button will open up a directory tree to allow the user to choose a single binary WRF File that was created by the WRF Model and then converted to binary format by the WRF Conversion Model. The filename format is WRFwt_dXX_YYYY_MM_DD_HHMM.nc.bin. The user may have to change the directory to the one listed at the top of the loading WRF screen which should be …\AMPT\WRFfiles\BIN.

- For the Single File option, the number of latitudes in the WRF file chosen is read in from file if present. If not the file is not present, then the user must enter the value for the single file option. The value can be obtained by ncBROWSE model. 90 is the AMPT default value.

- For the Single File option, the number of longitudes in the WRF file chosen is read in from file if present. If not the file is not present, then the user must enter the value for the single file option. The value can be obtained by ncBROWSE model. 90 is the AMPT default value.

- For the Single File option, the number of altitudes in the WRF file chosen is read in from file if present. If not the file is not present, then the user must enter the value for the single file option. The value can be obtained by ncBROWSE model. 40 is the AMPT default value.

- Under WRF OPTIONS, the WRF Series From Inventory File option instructs the SETDM read an inventory file in the …\AMPT\WRFfiles\BIN subdirectory. The inventory file contains the names of multiple WRF files along with Lat., Lon., and Alt. information. THIS IS NOT OPERATIONAL AT THIS TIME (9/20/16).

- Under CASSY FEATURE POINT DOMAIN, the user sets the horizontal range from the feature point in latitude and longitude (deg). This is used in the EDC CASSY model to establish a flying area for the UAV. (default – 0.03 deg)

- Under CASSY FEATURE POINT DOMAIN, the user sets the vertical range from the feature point in altitude (m). This is used in the EDC CASSY model to establish a flying area for the UAV. (default – 1000.0 m)

- Under UAV PERFORMANCE TO FEATURE TARGET, the Load FTIG File button will open up a directory tree to allow the user to load an FTIG File created in FLIGHT TRAJECTORY INSTRUCTION GENERATOR model. The FTIG file contains the user created initial flight to the Feature Target. The user may have to change the directory to the one listed at the top of the loading FTIG screen (…\AMPT\FTIGfiles).

- Under UAV PERFORMANCE TO FEATURE TARGET, the user can simulate many UAV performances by flying 33 waypoint boundary extremes to the Feature Target. In addition wind information such as Speed, Direction, Sidewind and Headwind (Figure 30.0).

- For the Under Waypoint Boundary Extremes option, the user enters the upper/lower range of latitude (deg) to iterate around the initial flight track waypoint latitudes. (default – 0.03 deg)

- For the Waypoint Boundary Extremes option, the user enters the upper/lower range of longitude (deg) to iterate around the initial flight track waypoint longitudes. (default – 0.03 deg)

- For the Waypoint Boundary Extremes option, the user enters the upper/lower range of altitude (m) to iterate around the initial flight track waypoint altitudes. (default – 100.0 m)

- Under UAV PERFORMANCE TO FEATURE TARGET, the user can simulate many UAV performances by flying the initial flight repeated in user defined 3D space to the Feature Target. In addition wind information such as Speed, Direction, Sidewind and Headwind (Figure 31.0).

- For the Under 3D Flights Based On FTIG Flight option, the user enters the number of latitudes to iterate around the initial flight track latitudes (default – 1).

- For the Under 3D Flights Based On FTIG Flight option, the user can enter the number of longitudes to iterate around the initial flight track longitudes (default – 1).

- For the Under 3D Flights Based On FTIG Flight option, the user can enter the number of altitudes to iterate around the initial flight track altitudes (default – 1).

- For the Under 3D Flights Based On FTIG Flight option, the user enters the delta latitude (deg) range to iterate around the initial flight track latitudes (default – 0.03 deg).

- For the Under 3D Flights Based On FTIG Flight option, the user can enter the delta longitude (deg) range to iterate around the initial flight track longitudes (default – 0.03 deg).

- For the Under 3D Flights Based On FTIG Flight option, the user can enter the delta altitude (m) range to iterate around the initial flight track altitudes (default – 100.0 m).

Under Wind Extraction Only, the user can set ranges for wind speed and wind direction restrictions on wind speeds along the flight. This input is mainly intended for closely examining the WRF wind speed fields along the flight track. THIS HAS NOT BEEN FULLY TESTED AT THIS TIME.

- For the Under Wind Speed Range option, if the user enters a high value for < WS Data Value (m/s) and a low value for >= WS Data Value (m/s), only wind speeds that fall within this range are written to the output file (default – 0.0 m/s).

- For the Under Wind Speed Range option, if the user enters a low value for < WS Data Value (m/s) and a high value for >= WS Data Value (m/s), only wind speeds that fall beyond this range are written to the output file (default – 0.0 m/s).

- For the Under Wind Direction Range option, if the user enters a high value for < WD Data Value (deg) and a low value for >= WD Data Value (deg), only wind directions that fall within this range are written to the output file (default – 0.0 deg).

- For the Under Wind Direction Range option, if the user enters a low value for < WD Data Value (deg) and a high value for >= WD Data Value (deg), only wind direction that fall beyond this range are written to the output file (default – 0.0 deg).

- Under WRF DWL LOS WIND OPTIONS, the user can compute simulated DWL line of sight winds for an FTIG flight with WRF simulated Line of Sight Winds. The option uses azimuth and elevation inputs from the FTIG file that was generated using a TODWL LOS processed file. The user can define range gate and a range distance limit of a fictional lidar. It is assumed to have sufficient backscatter return for signal. This option also allows for many iterations of the flight and simulated lidar.

- For Compute Simulated DWL LOS Winds `option, the Load DWL FTIG File button will open up a directory tree to allow the user to load a TODWL FTIG File created in FLIGHT TRAJECTORY INSTRUCTION GENERATOR model. The FTIG file contains flight data and signal processed DWL LOS data from a TODWL flight. The user may have to change the directory to the one listed at the top of the loading FTIG screen (…\AMPT\FTIGfiles).

- For Compute Simulated DWL LOS Winds option, the user must define a range gate for sampling (m) for the simulated LOS values (default – 50.0 m).

- For Compute Simulated DWL LOS Winds option, the user must define a range limit (km) for the simulated LOS values (default – 3 km).

- For Compute Simulated DWL LOS Winds option, the Monte Carlo Mode option allows for many iterations of the flight and simulated lidar to compute many DWL LOS winds for exploratory flights.

- For Compute Simulated DWL LOS Winds option, the user enters the number of latitudes to iterate around the initial flight track latitudes (default – 0).

- For Compute Simulated DWL LOS Winds option, the user can enter the number of longitudes to iterate around the initial flight track longitudes (default – 0).

- For Compute Simulated DWL LOS Winds option, the user can enter the number of altitudes to iterate around the initial flight track altitudes (default – 0).

- For Compute Simulated DWL LOS Winds option, the user enters the delta latitude (deg) range to iterate around the initial flight track latitudes (default – 0.1 deg).

- For Compute Simulated DWL LOS Winds option, the user can enter the delta longitude (deg) range to iterate around the initial flight track longitudes (default – 0.1 deg).

- For Compute Simulated DWL LOS Winds option, the user can enter the delta altitude (m) range to iterate around the initial flight track altitudes (default – 100.0 m).

- For Compute Simulated DWL LOS Winds option, the user can enter the number of DWL azimuth angles to iterate around the TODWL azimuth angle (default – 1).

- For Compute Simulated DWL LOS Winds option, the user can enter the number of DWL nadir angles to iterate around the TODWL nadir angle (default – 1).

- For Compute Simulated DWL LOS Winds option, the user can enter the delta azimuth angle (deg) range to iterate around the TODWL azimuth angle (default – 1.0 deg).

- For Compute Simulated DWL LOS Winds option, the user can enter the delta nadir angle (deg) range to iterate around the TODWL nadir angle (default – 1.0 deg).

- Under WRF DWL LOS WIND OPTIONS, the user can compare existing DWL line of sight winds from a TODWL flight with WRF simulated Line of Sight Winds. The flight must be within the chosen WRF 3D domain.

- For Compare DWL LOS Winds with WRF LOS Winds option, the Load DWL FTIG File button will open up a directory tree to allow the user to load a TODWL FTIG File created in FLIGHT TRAJECTORY INSTRUCTION GENERATOR model. The FTIG file contains flight data and signal processed DWL LOS data from a TODWL flight. The user may have to change the directory to the one listed at the top of the loading FTIG screen (…\AMPT\FTIGfiles).

- For Compare DWL LOS Winds with WRF LOS Winds option, a signal to Noise threshold (dB) is optional to eliminate poor lidar returns (default – 10.00 dB).

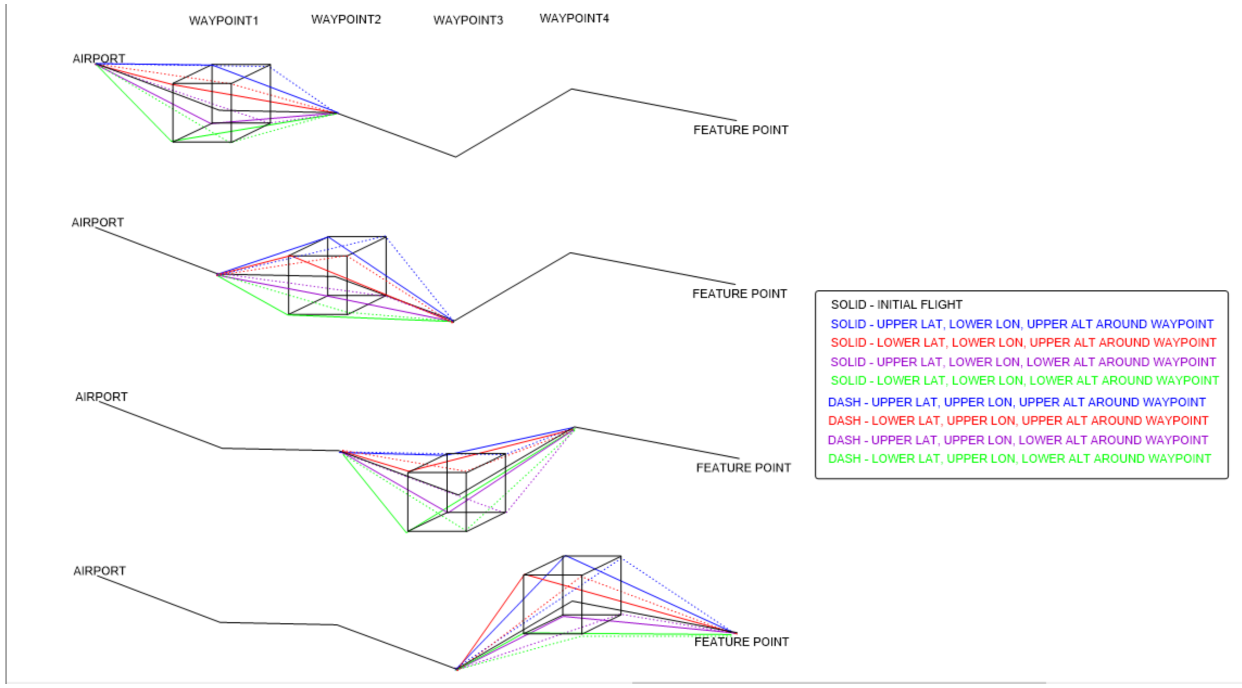

Figure 30.0 Schematic for 33 boundary UAV performance flights to the feature entry point. The initial FTIG flight is represented by the black line. The solid and dashed colored lines represent the flights with waypoint boundary flight legs sections.

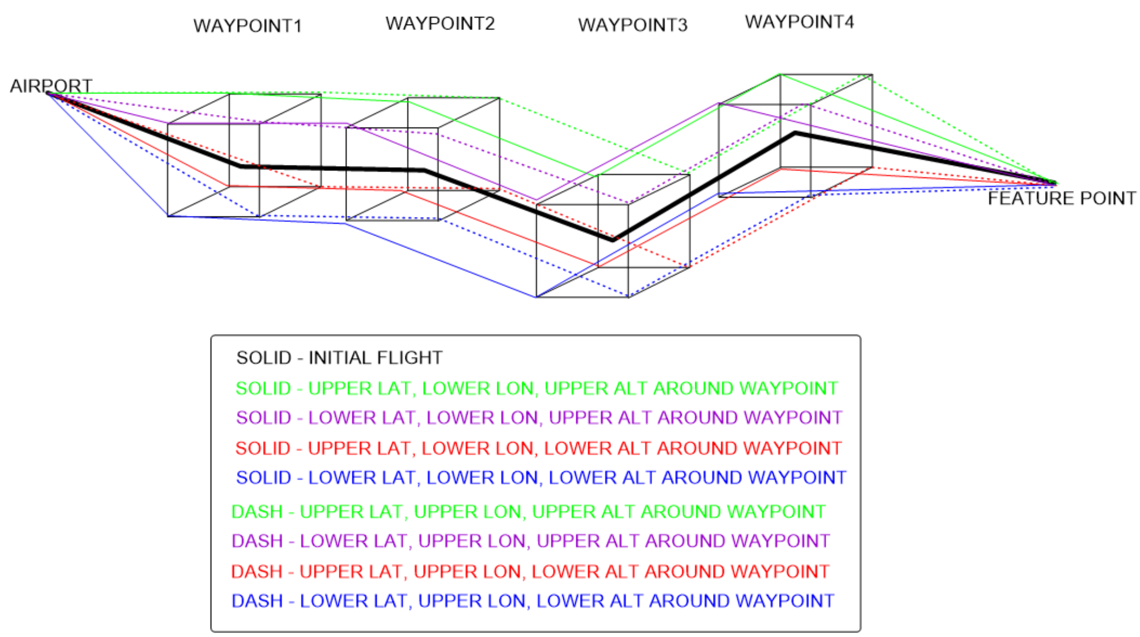

Figure 31.0 Schematic for the initial flight and the repeated flight pattern in user defined 3D space to the Feature Target. The user can set as many flight iterations from the initial flight to boundary

extremes as desired. The initial FTIG flight is represented by the black line. The solid and dashed colored lines represent the flights with waypoint boundary flight legs sections.

2.4.2 UAV Simulation Mode

Once invoking the SETDM, the user should load a Mission file (Figure 32.0) from the ..\AMPT\MissionOandC subdirectory. The SETDM will use the Simulation Mode chosen in the MOaMC, in this case, the UAV Simulations mode. Under WRF OPTIONS, the default is set to Single File only (WRF series of files option is not operational at this time. Click Load WRF File button to choose a WRF atmosphere file (Figure 33.0) from the subdirectory …\AMPT\WRFfiles\BIN (use test case Ruby Mountain 10/04/12 2020Z). The number of latitudes, longitudes and altitudes in the WRF file chosen is read in from file if present and loaded into the input fields. If not the file is not present, then the user must enter the value or accept default values.

Once the WRF atmosphere inputs have been satisfied, under WRF FEATURE POINT DOMAIN, 3D boundaries should be defined for the EDC CASSY model. The SETDM will use the latitude/longitude range and altitude range inputs to define a 3D domain around the FTIG's feature Entry point once a FTIG file has been loaded.

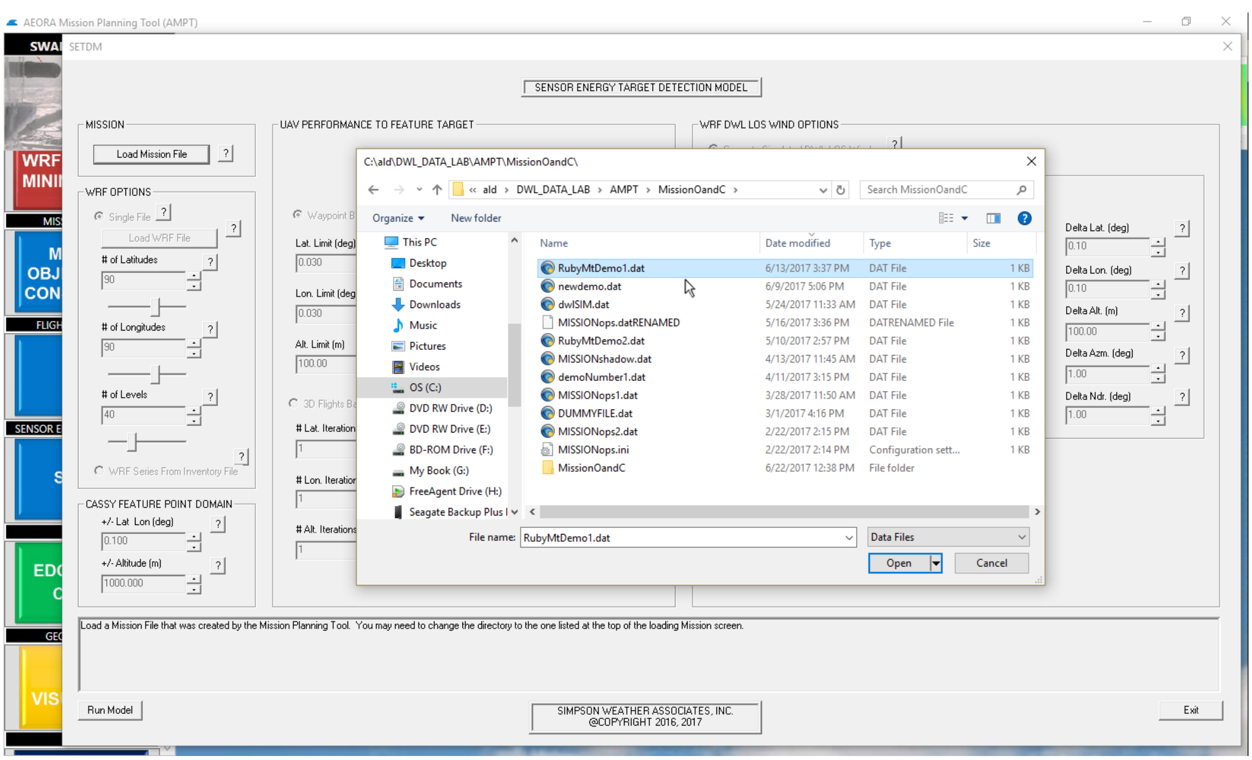

Figure 32.0 Example of the user loading mission file (RubyMtDemo1) from the subdirectory …\AMPT\MissionOandC.

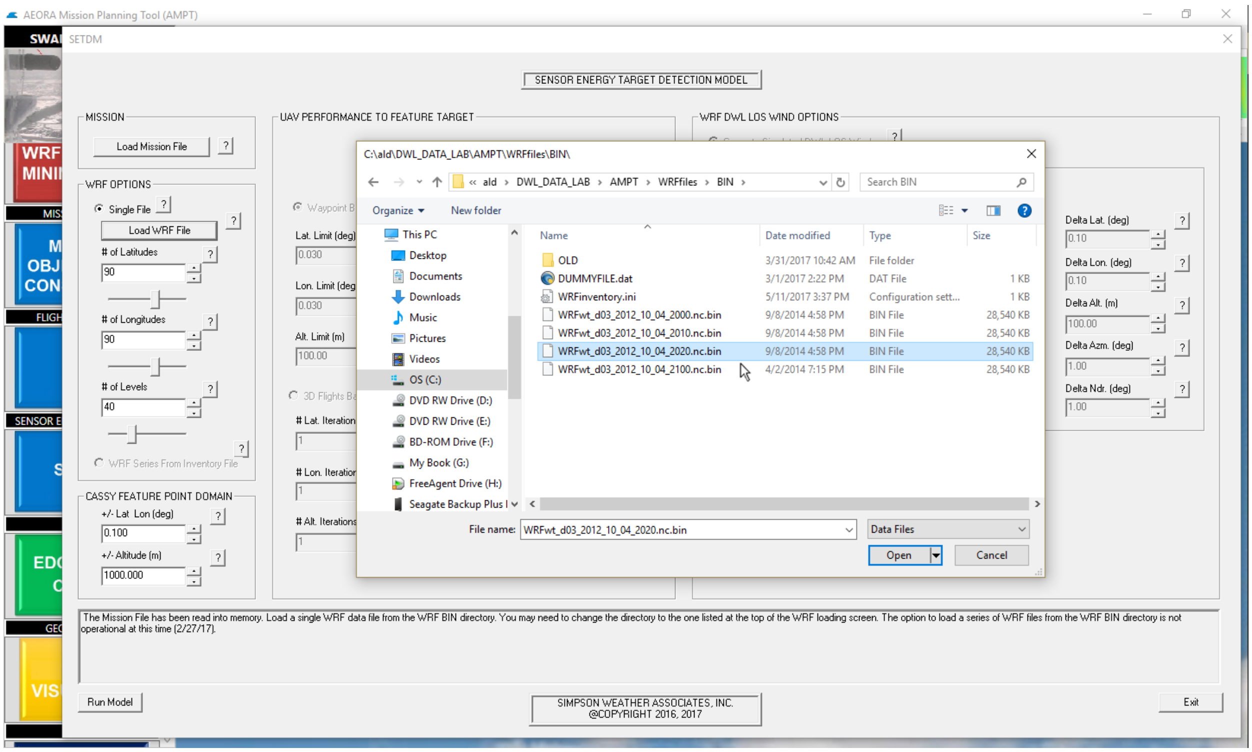

Figure 33.0 Loading a binary WRF atmosphere file from the subdirectory …\AMPT\WRFfiles\bin.

If an UAV mission was defined in the Mission Objectives and Constraints model, then Under UAV PEFORMANCE TO FEATURE TARGET, load an FTIG file (Figure 34.0) from the subdirectory …\AMPT\FTIGfiles. After the FTIG file is loaded, the user can choose from iterating on the initial FTIG flight via the waypoint boundary extremes (default) or the 3D volume flights option. See SETDM input descriptions for more information on the choices. Once all inputs have been satisfied, click the Run Model Button to run the SETDM (Figure 35.0) and wait for further instructions. After the simulation of all flight iterations are completed the user is instructed to exit the main screen (Figure 36.0) . After the exit, the Dashboard Performance screen will pop up.

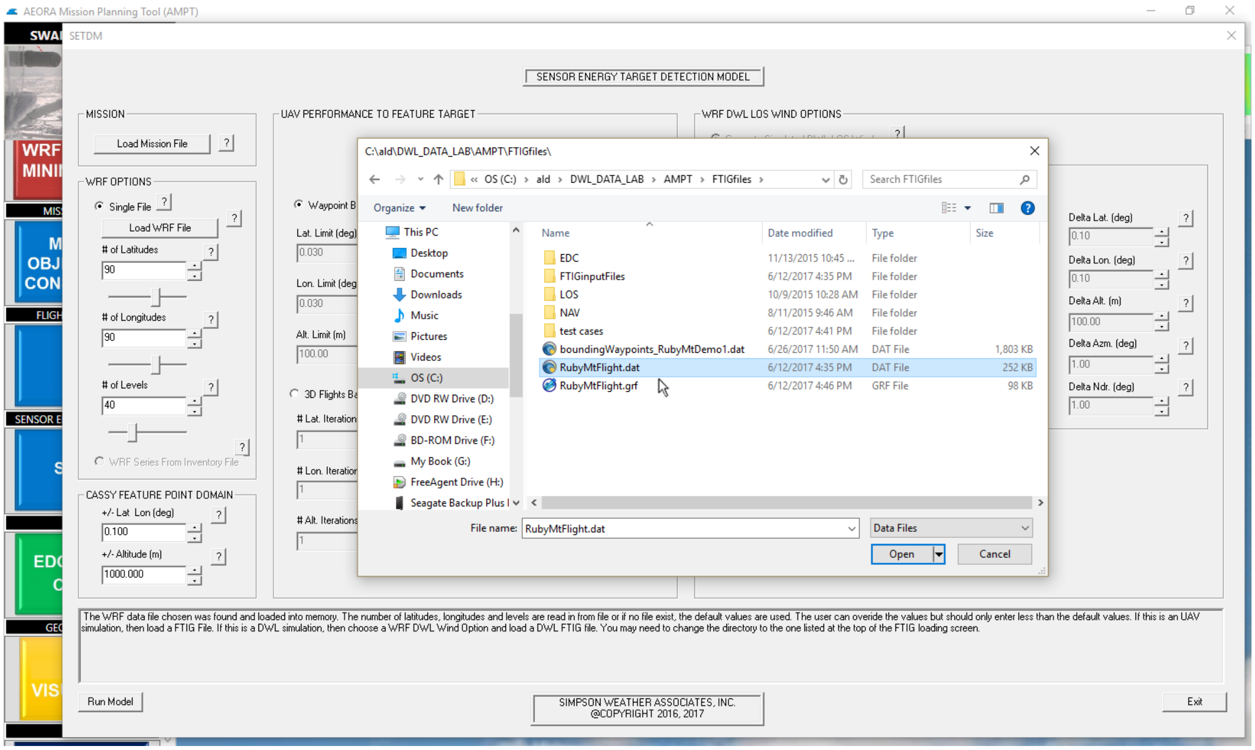

Figure 34.0 Example of loading an FTIG initial flight file from the subdirectory …\AMPT\FTIGfiles.

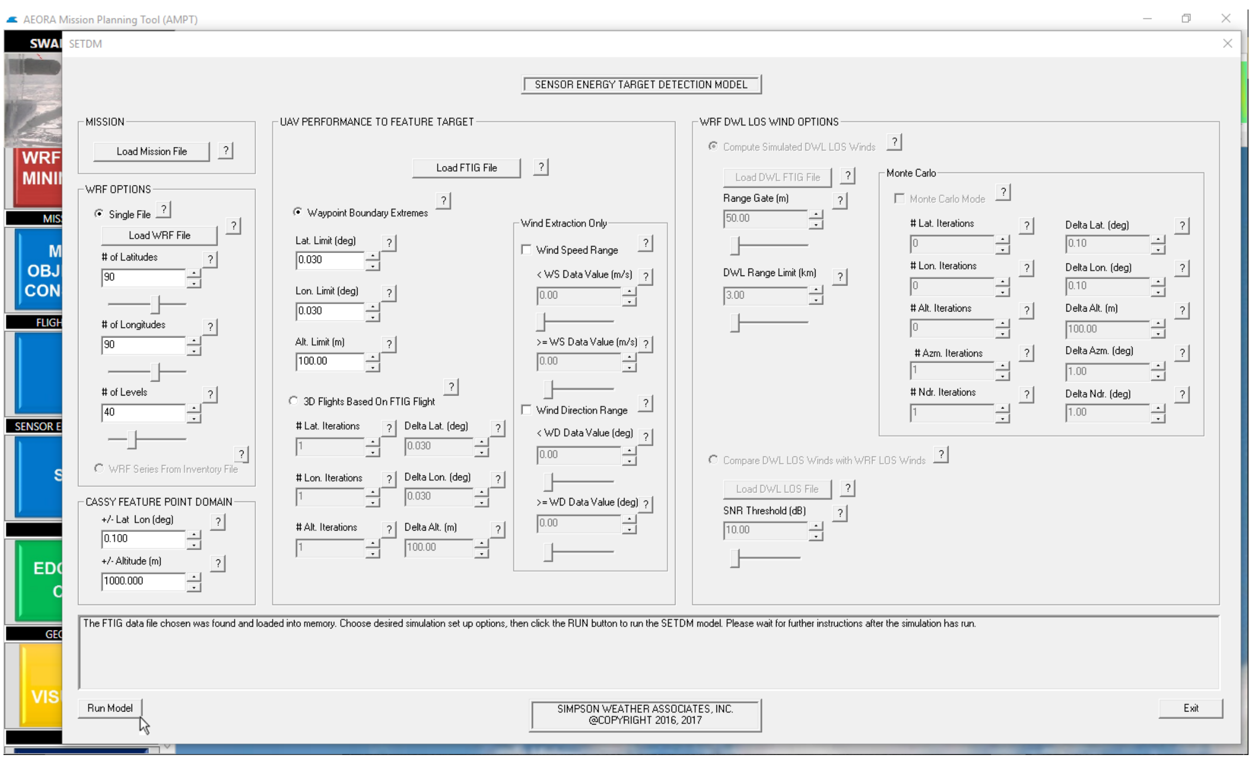

Figure 35.0 Example of running the SETDM execution.

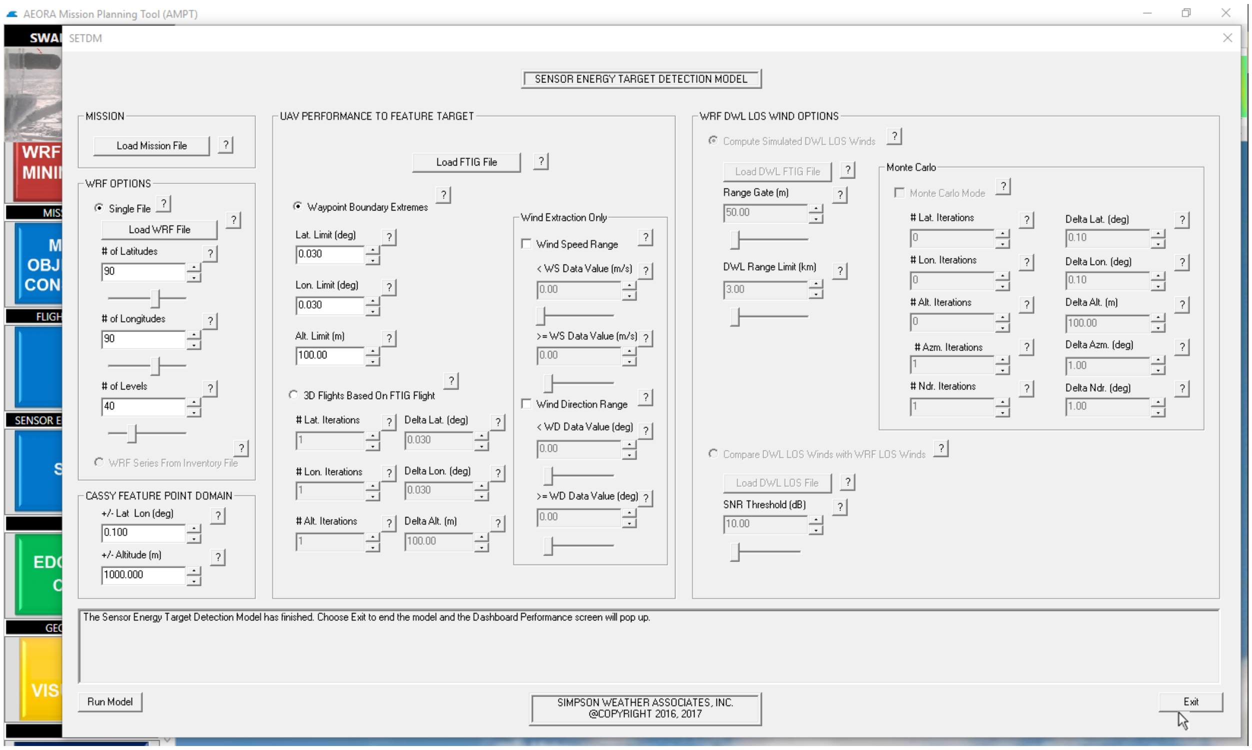

Figure 36.0 Example of a finished run for the SETDM.

2.4.2 The Dashboard Performance Screen

Once the flight iterations section of the SETDM simulation are completed, a Dashboard (Figure 37.0) will pop up to let the user view flight performances for evaluation. There are two “along the flight” model information sections: the Performance Cost Functions and Atmospheric Winds. Under the Performance Cost Functions are available fuel percentage, altitude of the UAV, variometer readings, tailwind/headwind and cross wind. Under Atmospheric Winds are wind speed, wind direction and vertical velocity. All information values are at aircraft altitude. The Dashboard starts with the initial flight generated by the FTIG (Flight Path- 1). As the user slides the Flight Record from left to right, the DASHBOARD will display the flight information for each aircraft sampling distance that was defined in the FTIG. In addition to the color gauges, numeric displays are shown for flight time, flight distance from origin, latitude, longitude, heading, UAV speed and terrain. Figure 38.0 shows a user moving the slider for the initial flight from record 1 to record 807 (the feature entry point). It is noted that in Figure 38.0, fuel has decreased to about 88% for the initial flight. The user can save the flight as the chosen flight for EDC’s CASSY model or continue to explore the other simulated flights. In Figure 39.0, the user has decided to look at the best of all 33 boundary flights (performance - fuel consumption). The Flight Record has been moved to 168. In Figure 40.0, the Flight Record has been moved to 811 showing the fuel has only decreased to about 93% due to avoiding the upward motion before entering the feature point area. The user chose to save the 31th flight parameters, which was the best flight to the feature energy point. This flight can now be re-run with EDC's more sophisticated flight model, CASSY. A png of a surfer plot (Figure 41.0) shows the chosen flight's path laid over the WRF vertical velocity field for 10/04/2012 2020Z ~3 Km. Notice that the best flight chose a different forth way point than the initial flight to save fuel to reach the feature point.

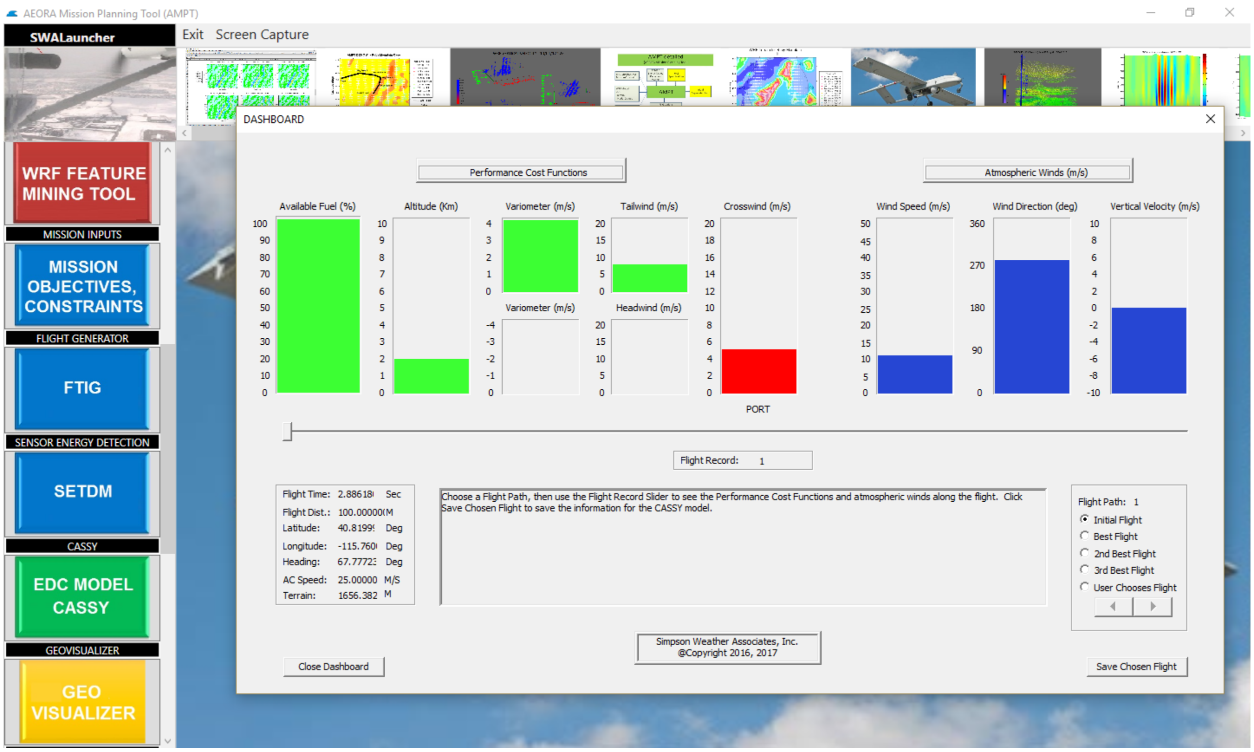

Figure 37.0 The DASHBOARD screen depicting the initial flight performance t the start of the flight.

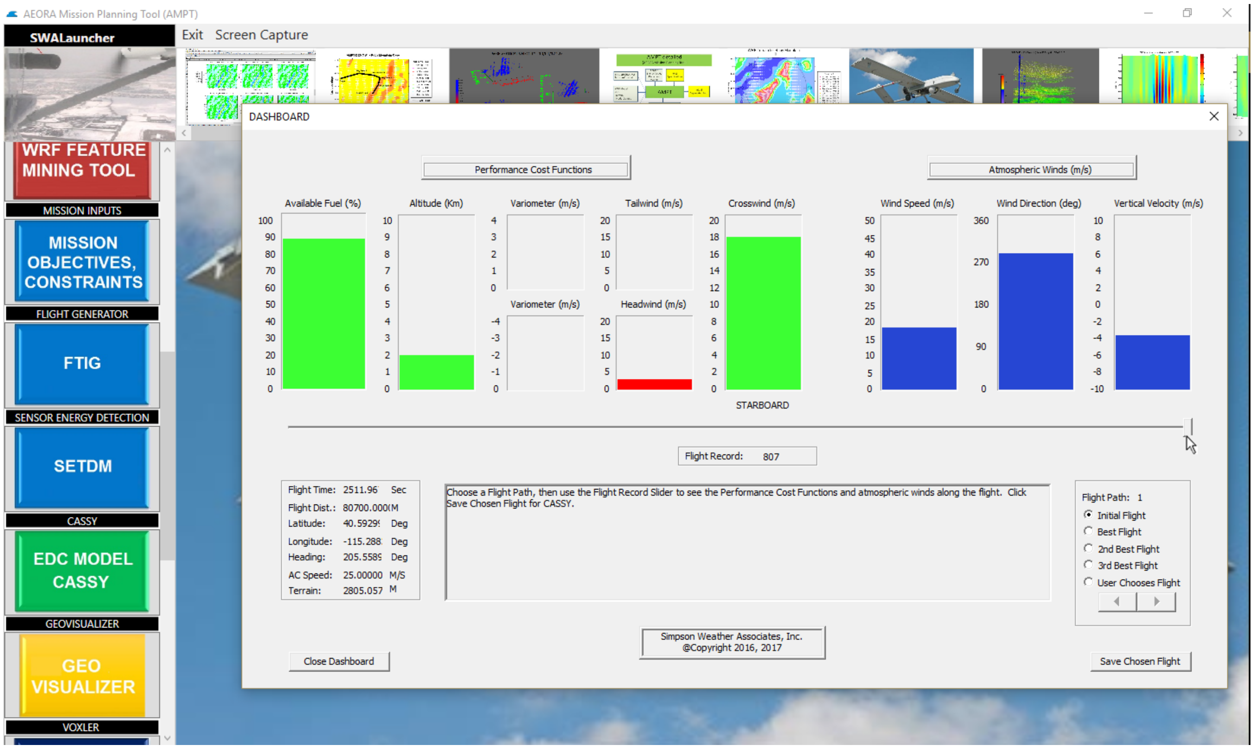

Figure 38.0 shows a user moving the slider for the initial flight from record 1 to record 807 (the feature entry point).

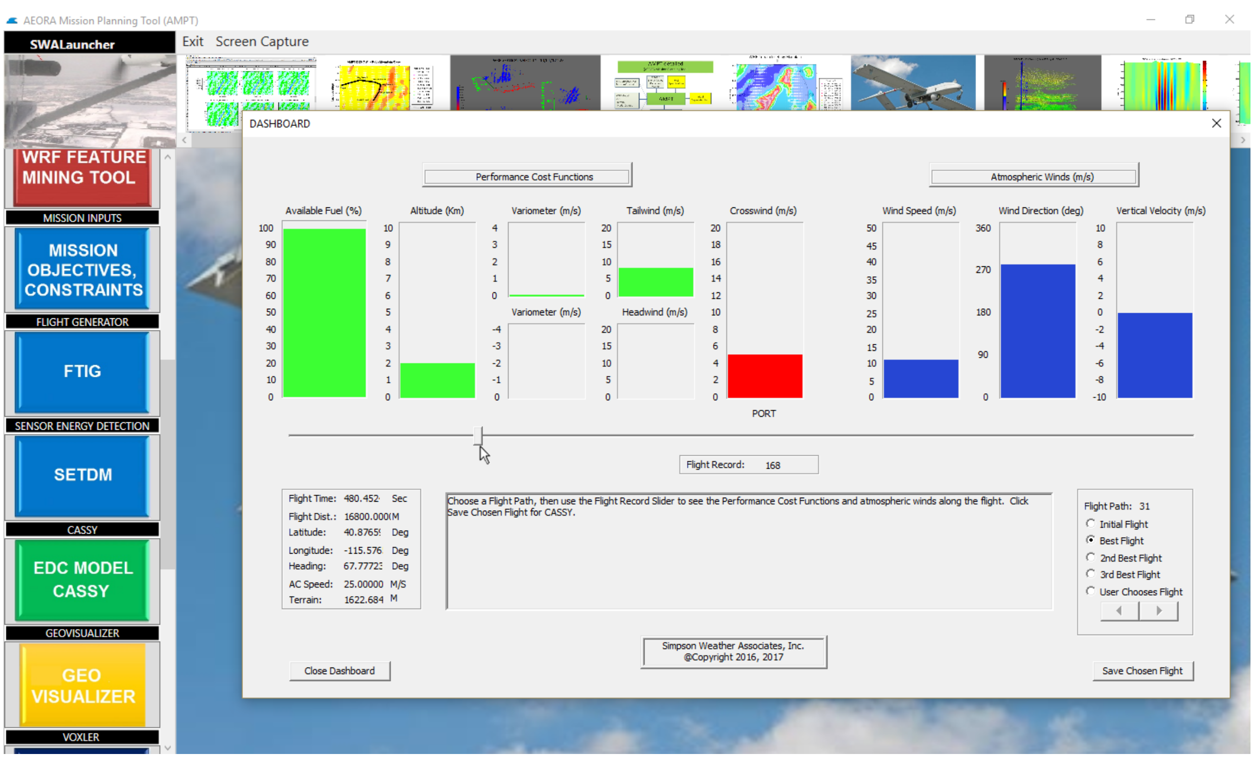

Figure 39.0 Shows the user has decided to look at the best of all 33 boundary flights with performance based upon fuel consumption.

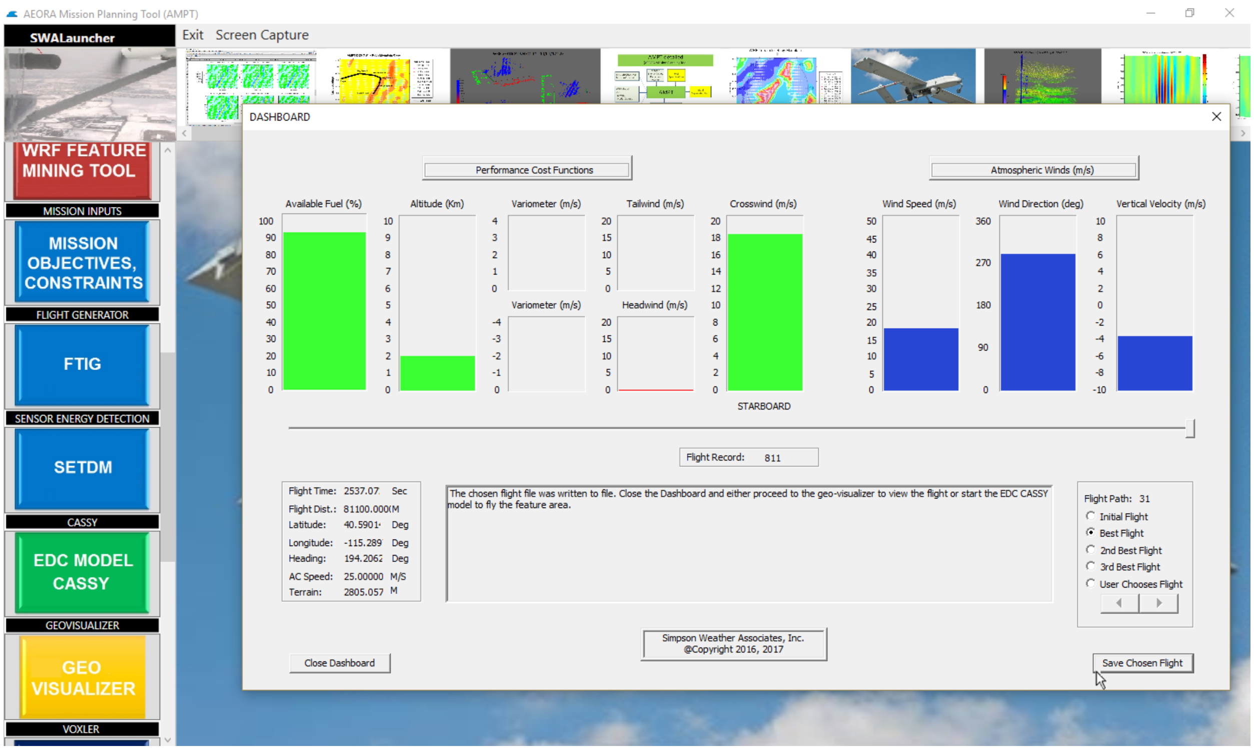

Figure 40.0 The Flight Record has been moved to 811, showing the fuel has only decreased to about 93%. The user chose to save the 31th flight parameters.

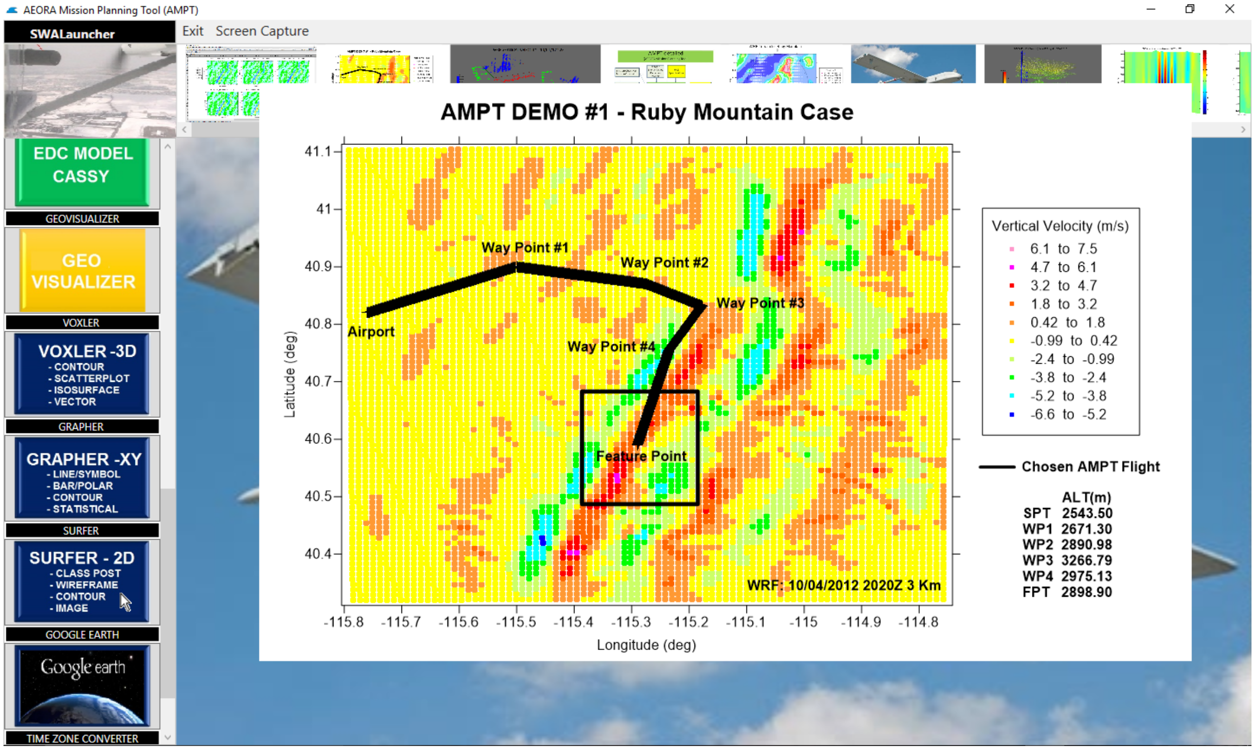

Figure 41.0 The chosen flight's path laid over the WRF vertical velocity field for 10/04/2012 2020Z ~3 Km.

The SETDM outputs 5 flight files: Chosen, Best, 2nd Best, 3rd Best and Initial in the directory ~\AMPT\SETDMfiles named with the mission name as a suffix. Table 3.0 is an abridged example containing a header, the UAV latitude, UAV longitude, UAV altitude, UAV fuel percentage and flight time to be used for graphics. A 6th file, named with a prefix, fltChosen, and a suffix, the mission flight name, contains the information needed for CASSY to simulate the chosen flight. Table 4.0 is an example of the file containing header information and five UAV waypoint latitudes, longitudes, altitudes and speed.

Table 3.0 Abridged output example of SETDM flight.

Mission: RubyMtDemo1.dat
UAV: SHADOW_UAV.dat
WRF: WRFwt_d03_2012_10_04_2020.nc.nc.kjizuvw.txt
Feature pt. lat boundaries: 40.49000 40.69000 0.1000000
Feature pt. lon boundaries: -115.3900 -115.1900 0.1000000
Feature pt. alt boundaries: 2272.856 3537.122 5
WRF Terrain high points- WRF, miniWRF: 3192.802 3149.375
FTIG: RubyMtFlight.dat _10_04_202
FLIGHT: 31
REMAINING FUEL: 40.65157
~~

40.819999695	-115.760002136	2543.412353516	100.000000000	2.886180401
40.820339203	-115.758903503	2543.956542969	99.980758667	5.772172451

40.820678711	-115.757804871	2544.500244141	99.961524963	8.657976151
40.821018219	-115.756706238	2545.044189453	99.942291260	11.543591499
40.821357727	-115.755607605	2545.588134766	99.923049927	14.429018974

Table 4.0 Chosen flight information needed for CASSY.

Mission: RubyMtDemo1.dat
UAV: SHADOW_UAV.dat
WRF: WRFwt_d03_2012_10_04_2020.nc.nc.kjizuvw.txt
Feature pt. lat boundaries: 40.49000 40.69000 0.1000000
Feature pt. lon boundaries: -115.3900 -115.1900 0.1000000
Feature pt. alt boundaries: 2272.856 3537.122 5
WRF Terrain high points- WRF, miniWRF: 3192.802 3149.375
FTIG: RubyMtFlight.dat _10_04_202
FLIGHT: 31
REMAINING FUEL: 40.65157
~~

40.90000	40.87000	40.83200	40.75500	40.59000
-115.5000	-115.2740	-115.1780	-115.2350	-115.2900
2671.300	2890.980	3266.790	2975.130	2898.900
25.00000	25.00000	25.00000	25.00000	25.00000

2.4.3 DWL Simulations Mode

Once invoking the SETDM, the user should load a Mission file (Figure 32.0) from the ..\AMPT\MissionOandC subdirectory. The SETDM will use the Simulation Mode chosen in the MOaMC, in this case, the DWL Simulations mode. Under WRF OPTIONS, the default is set to Single File only (WRF series of files option is not operational at this time. Click Load WRF File button to choose a WRF atmosphere file (Figure 33.0) from the subdirectory …\AMPT\WRFfiles\BIN (use test case Ruby Mountain 10/04/12 2020Z). The number of latitudes, longitudes and altitudes in the WRF file chosen is read in from file if present and loaded into the input fields. If not the file is not present, then the user must enter the value or accept default values.

Under WRF DWL LOS Wind options, the user can choose to compute simulated DWL LOS winds (default) for many viewing angles using an FTIG flight flying through the WRF atmosphere or can compare actual DWL winds with generated WRF LOS winds using a forward model.

2.4.3.1 Compute Simulated DWL LOS Winds

For Compute Simulated DWL LOS Winds option, the Load DWL FTIG File button will open up a directory tree to allow the user to load a TODWL FTIG File created in FLIGHT TRAJECTORY INSTRUCTION GENERATOR model. The FTIG file contains flight data and signal processed DWL LOS data from a TODWL flight. The user may have to change the directory to the one listed at the top of the loading FTIG screen (…\AMPT\FTIGfiles). The user must define a range gate for sampling (m) and a range limit (km) to emulate a DWL for simulated LOS winds. The user can also define iterations on the aircraft altitude, aircraft location, scanner geometry variables in the flight file providing Monte Carlo like simulations on the WRF fields. These Monte Carlo simulations are intended to be used to help define feature detection PDFs.

A simple simulation was used to test this model option. A existing flight file (from the Ruby Mountain case study) from the TODWL flight inventory was reformatted using the FTIG. A fictional DWL was added with a fixed scanner azimuth angle of 90 degrees and a fixed nadir angle of 45 degrees. A 50 meter range gate was used. The FTIG file was used by the SETDM in liaison with a WRF field, generated for 10/04/12 21Z, to produce simulated DWL LOS winds based upon the fictional DWL (Figure 42.0). The lidar had a limited range of 3 km. Aerosol returns are assumed.

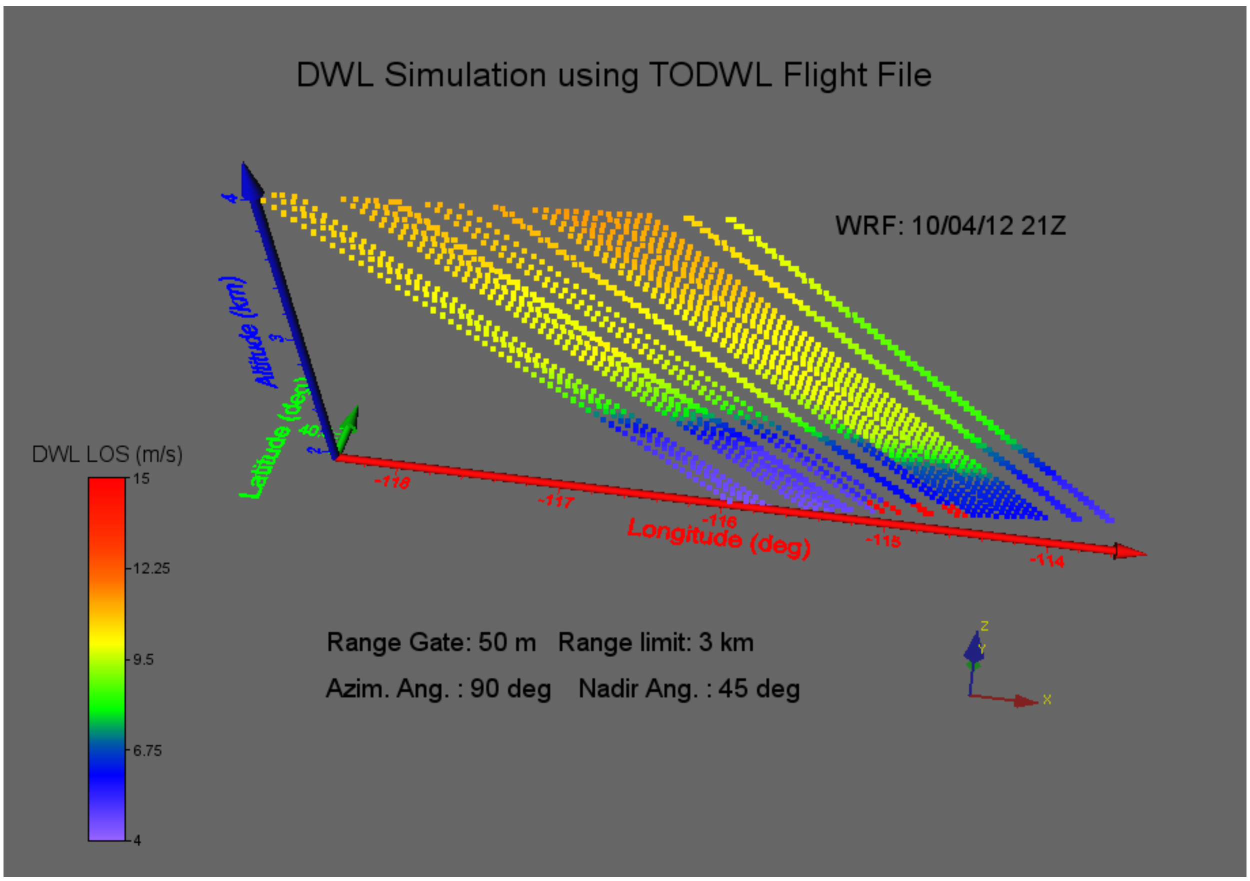

Figure 42.0 Simulated DWL on a TODWL flight file generated by the SETDM.

2.4.3.2 Compare DWL LOS Winds with WRF LOS Winds

Under WRF DWL LOS WIND OPTIONS, the user can compare existing DWL line of sight winds from a TODWL flight with WRF simulated Line of Sight Winds. The flight must be within the chosen WRF 3D domain. The Load DWL FTIG File button will open up a directory tree to allow the user to load a TODWL FTIG File created in FLIGHT TRAJECTORY INSTRUCTION GENERATOR model. The FTIG file contains flight data and signal processed DWL LOS data from a TODWL flight. The user may have to change the directory to the one listed at the top of the loading FTIG screen (…\AMPT\FTIGfiles). A Signal to Noise threshold (dB) is optional to eliminate poor lidar returns (default – 10.00 dB).

A simple LOS wind comparison (Figure 43.0) was made to test this model option. A existing flight file (from the Ruby Mountain case study) from the TODWL flight inventory was reformatted using the FTIG. Forward model LOS winds were computed using the WRF wind fields generated for 10/04/12 21Z, in addition to FTIG aircraft altitude, aircraft location, DWL scanner azimuth angle and DWL nadir angle.

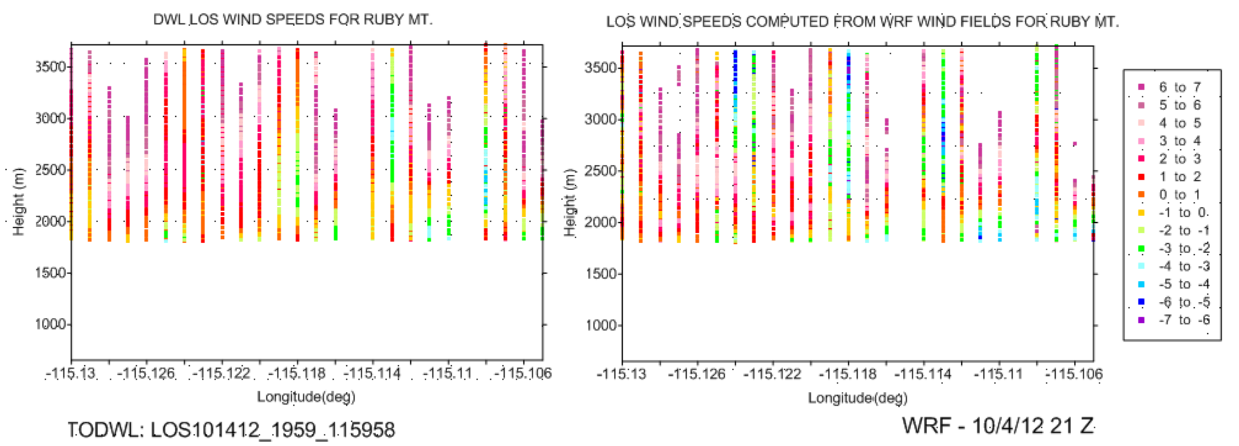

Figure 43.0 A simple LOS wind comparison using the Ruby Mountain TODWL case study. Forward model LOS winds were computed using the WRF wind fields generated for 10/04/12 21Z, in addition to aircraft altitude, aircraft location, DWL scanner azimuth angle and DWL nadir angle.

3.0 EDC’s CASSY Model

Utilizing and modifying existing flight control algorithms developed by Earthly Dynamics Corp., development of an aircraft simulation environment to explore and evaluate various energy harvesting flight strategies was undertaken. The environment consists of an autonomous aircraft flying through a user input, three-dimensional wind field which can vary in both space and time. The aircraft model, CASSY, is a nonlinear, six-degree of freedom rigid body representation with the same control inputs (Table 5.0) available on the actual aircraft. The aerodynamic parameters of the model can be set to represent any typical fixed wing platform. Attached to the aircraft model is an automatic flight control system which uses a model predictive controller to generate commands to the aircraft control surfaces to track a desired three-dimensional trajectory. See Appendix 1 - AEORA Program Meeting presentation from Earthly Dynamics for technical information on CASSY and Appendix 2 - Aurora Report Number: AR16-338 for a non AMPT application of the CASSY models.

Table 5.0 Example of the CASSY input variables (abridged).

9.81	gravity (m/s^2)
1	aircraft dynamics simulation off on flag (nd, 0=off, 1=on)

0	turbulence filter simulation off on flag (nd, 0=off, 1=on)
1	auxiliary dynamics simulation off on flag (nd, 0=off, 1=on)
1	control system simulation off/on flag (nd, off=0, on=1)
1	miscellaneous simulation output off/on flag (nd, off=0, on=1)
1	time simulation output skip parameter (nd)
1	simulation mode (nd, 1=trajectory, 2=horizontal plane impact, 3=vertical plane impact)
1	debug flag (nd, 0=no output, 1=yes output)
1	index for time simulation output (nd)
0.05	integration time step (sec)
-50.0	initial simulation time (sec)
1000.0	final simulation time (sec)
32	number of misc simulation outputs (nd)
0.05	update time for control computations (sec)
2	number of control system outputs (nd)
0	wind feature mode (nd, 0=out of feature search volume, 1=in feature search volume)
0	wind feature explore/exploit flag (nd, 0=explore, 1=exploit)
5.0	number of initial way points (nd)
1	initial way point number (nd)
1000.0	initial x way point (m)
333.0	initial y way point (m)
-2000.0	initial z way point (m)
1000.0	x way point 1 (m)
2000.0	x way point 2 (m)
3000.0	x way point 3 (m)
4000.0	x way point 4 (m)
5000.0	x way point 5 (m)
333.3	y way point 1 (m)
666.7	y way point 2 (m)
3000.0	y way point 3 (m)
1000.0	y way point 4 (m)
1000.0	y way point 5 (m)
-2000.0	z way point 1 (m)
-2000.0	z way point 2 (m)
-2000.0	z way point 3 (m)
-2000.0	z way point 4 (m)
-2000.0	z way point 5 (m)
0.05	kp airspeed (0.035 -0.5)
-0.07	kd airspeed (-0.035 0.7)
0.02	ki airspeed (0.02)
0.03	kp altitude (0.03 0.015)
-0.022	kd altitude (â€”0.22, 0.11)
0.0000005	ki altitude (0.0000005, 0.0005)
1.0	kp psi
-0.01	kd psi
0.001	ki psi
14.0	kp phi

-2.0	kd phi
8.0	ki phi
0.4	k pitch rate (0.15)
50.0	altitude error maximum (m)
4.0	airspeed error maximum (m/s)
0.5235	psi error maximum (rad)
0.08726	phi error maximum (rad)
0.5235	phi command maximum (rad)
30.0	airspeed command (m/s)
100.0	distance threshold for way points change (m)
60.0	wind feature search time threshold (sec)
120.0	minimum time to exploit wind feature (sec)
-1.0	vertical gust threshold for lift (m/s)
10.0	minimum number of lift points (nd)
5000.0	x centroid of wind feature (m)
1000.0	y centroid of wind feature (m)
-2000.0	z centroid of wind feature (m)
1600.0	x range of wind feature (m)
1600.0	y range of wind feature (m)
4000.0	z range of wind feature (m)
10.0	number of lift points (nd)
1.0	minimum time interval between two registered strong lift points (sec)
0.0	x home way point (m)
0.0	y home way point (m)
0.0	z home way point (m)
-1000	abort altitude threshold (m)
30.0	abort energy burn (throttle sec)

Atmosphere

0	density model type (nd, 0=constant, 1=equation, 2=table)
1.2250	air density (kg/m^3)
0.5000	turbulence intensity (m/s)
2	gust model flag (nd, 0=constant, 1=1d table, 2=3d table)
4	number of x gust points (nd)
4	number of y gust points (nd)
3	number of z gust points (nd)
	x gust data point 1 to number of x gust points (m)
	y gust data point 1 number of y gust points (m)
	z gust data point 1 number of z gust points (m)
	vx gust data point 1 number of x gust points (m/s)
	vy gust data point 1 number of y gust points (m/s)
	vz gust data point 1 number of z gust points (m/s)

1	gravity force off on flag (nd, 0=off, 1=on)
0	injection force and moment off on flag (nd, 0=off, 1=on)

1	fuselage aerodynamics force and moment off on flag (nd, 0=off, 1=on)
1	lifting surface aerodynamics force and moment off on flag (nd, 0=off, 1=on)
1	propulsion system force and moment off on flag (nd, 0=off, 1=on)
4	number of lifting surface elements (nd)
1	number of propulsion system elements (nd)
0.0	nominal elevator position (rad)
0.1	nominal aileron position (rad)
0.0	nominal rudder position (rad)
0.0	initial i-inertial position of the mass center (m)
0.0	initial j-inertial position of the mass center (m)
-2000	initial k-inertial position of the mass center (m)
0.0	initial roll angle (rad) == SWA Original = -1800
0.3351000	initial pitch angle (rad)
0.0	initial yaw angle (rad)
30.0	initial i-body velocity of mass center (m/s)
0.0	initial j-body velocity of mass center (m/s)
1.0	initial k-body velocity of mass center (m/s)
0.0	initial i-body angular velocity (rad/s)
0.0	initial j-body angular velocity (rad/s)
0.0	initial k-body angular velocity (rad/s)
170.0	mass (kg)
0.0	stationline center of mass (m)
0.0	buttline center of mass (m)
0.0	waterline center of mass (m)
114.0	ixx (kg m^2)
58.0	iyy (kg m^2)
170.0	izz (kg m^2)
0.0	ixy (kg m^2)
-3.6	ixz (kg m^2)
0.0	iyz (kg m^2)
0.0	stationline of fuselage aerodynamic center (m)
0.0	buttline of fuselage aerodynamic center (m)
0.0	waterline of fuselage aerodynamic center (m)
2.45	fuselage reference area for aerodynamic calculations (m^2)
6.2	fuselage reference span for aerodynamic calculations (m)
0.88	fuselage reference chord for aerodynamic calculations (m)
…\AMPT\CASSY_OUTPUT\acout.txt	aircraft state simulation output filename
…\AMPT\CASSY_OUTPUT\turbout.txt	turbulence filter simulation output filename
…\AMPT\CASSY_OUTPUT\auxout.txt	auxiliary state simulation output filename
…\AMPT\CASSY_OUTPUT\csout.txt	control system simulation output filename
…\AMPT\CASSY_OUTPUT\miscout.txt	miscellaneous simulation output filename
…\AMPT\CASSY_OUTPUT\runlog.txt	run log filename

Figure 44.0 shows the CASSY gui main screen providing user file inputs from the AMPT. The screen is divided into 7 sections:

- Model Settings

1.	Integration time step (s)	(default: 0.05)
2.	Update time for control computations (s)	(default: 0.005)
3.	Initial simulation time(s)	(default: -50.00)
4.	Final simulation time (s)	(default: 5000.0)
5.	Fuel abort level	(default: 0.0)
6.	Altitude Threshold (m)	(default: 0.0)
7.	Return to base Fuel	(default: varies)

- EDC File Display
    1. SETDM Chosen Flight file
    2. AMPT Mission File
    3. WRF Atmosphere File

- Mission Data Display
    1. UAV Filename
    2. Date (yyyy-mm-dd)
    3. Starting Latitude(deg)
    4. Starting Longitude (deg)
    5. Starting Altitude (m)
    6. Ending latitude (deg)
    7. Ending Longitude(deg)
    8. Ending Longitude (deg)
    9. Lower Latitude Boundary (deg)
    10. Lower Longitude Boundary (deg)
    11. Upper Latitude Boundary (deg)
    12. Upper Longitude Boundary (deg)
    13. Flight Number Chosen
    14. Remaining Fuel at feature from SETDM Simulation
    15. FTIG file used

- Way Points Display
    1. Way Point #1 lat, lon, alt, speed
    2. Way Point #2 lat, lon, alt, speed
    3. Way Point #3 lat, lon, alt, speed
    4. Way Point #4 lat, lon, alt, speed
    5. Way Point #5 lat, lon, alt, speed (Feature Point (FP))
    6. FP Lower Boundary lat, lon, alt
    7. FP Upper Boundary lat, lon, alt

- Aircraft Information
    1. UAV file
    2. Initial Fuel

3. Climb Burn Rate
4. Cruise Burn Rate
5. Idle Burn Rate

- Process Message

- Commands
  1. Run the EDC Model
  2. Run Quick EDC Model (i.e. use existing IObuilder files)

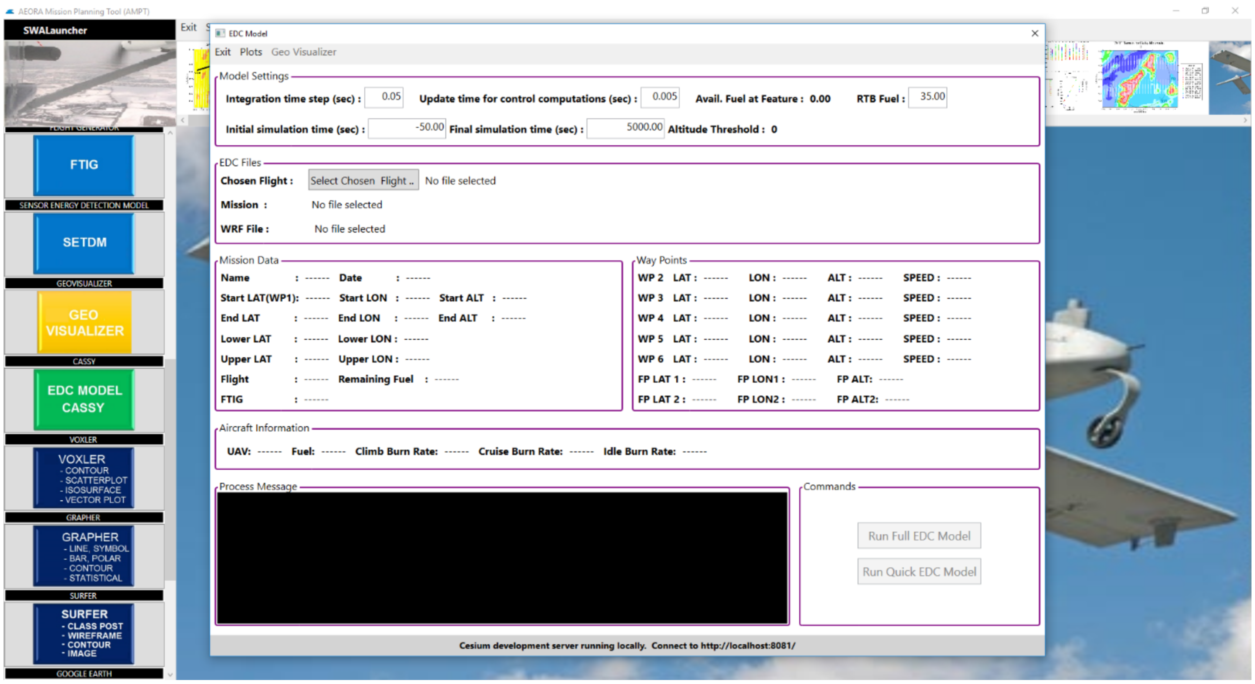

Figure 44.0 The CASSY model main screen.

For the Ruby Mt. example case, click Select Chosen Flight button and load the SETDM created chosen file (Figure 45.0). Once loaded, the CASSY model main screen will display the EDC File, Mission Data, and Way Point information (Figure 46.0). The RTB Fuel value should be updated with respect to the run time of the simulation. In this case, the initial fuel was changed from 35 to 7. To run the CASSY model, click the Run EDC Model button. Once input files have been loaded, time, altitude, location, vertical motion and fuel burn is displayed throughout the simulation, shown in Figure 47.0- 49.0. In the display, Search = 0, Feature = 0 indicates the UAV is traveling towards the Ruby Mt. feature area. Search = 1, Feature = 1 indicates the UAV has traveled to the Ruby Mt. feature area and is searching for energy opportunities. A message, Done, is shown when the simulation has been completed. Search = 0, Feature = 0 indicates the UAV left the Ruby Mt. feature area and traveled back to the start location.

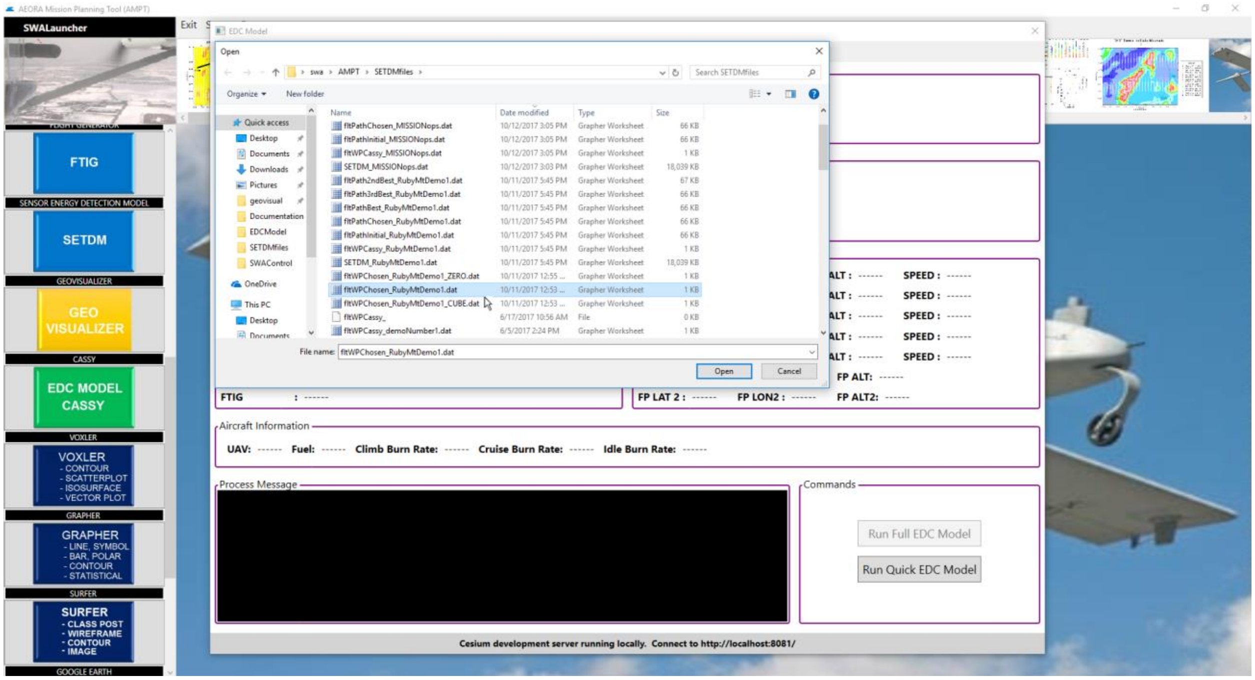

Figure 45.0 Example of selecting the chosen SETDM flight for the Ruby Mt. example case.

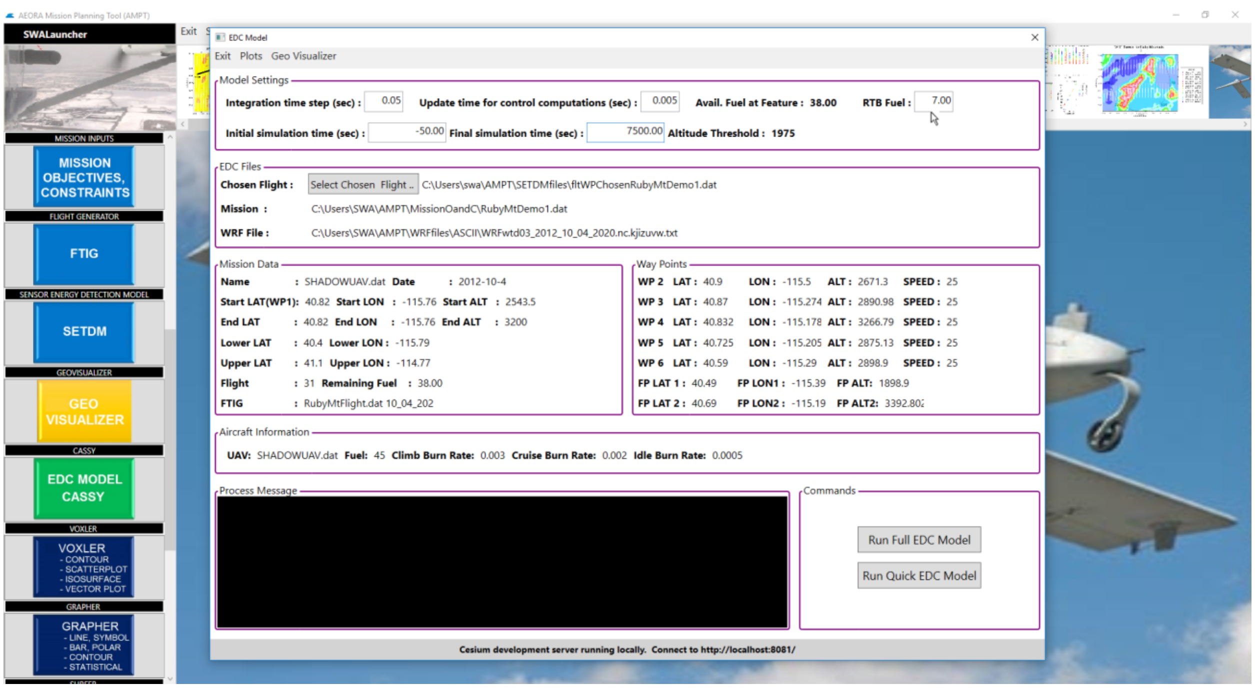

Figure 46.0 Example of the loaded fields from the chosen SETDM flight for the Ruby Mt. example case.

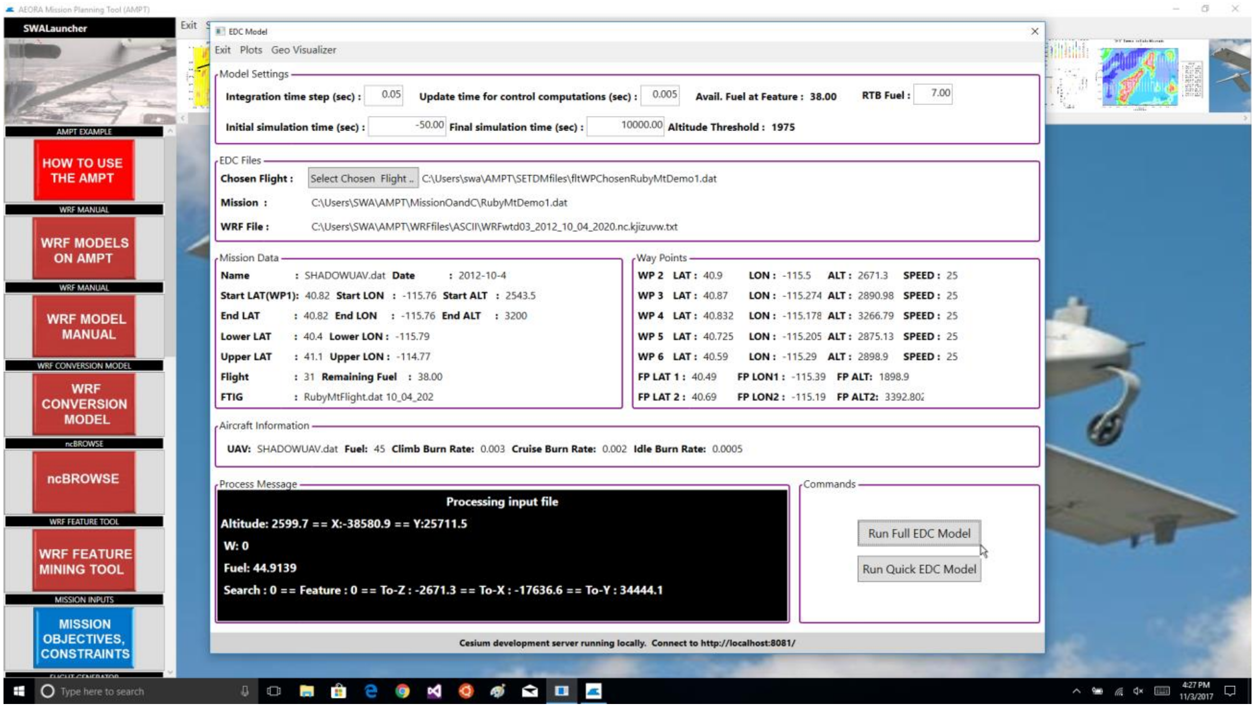

Figure 47.0 Example of the CASSY model running. Search = 0, Feature = 0 indicates the UAV is traveling towards the Ruby Mt. feature area.

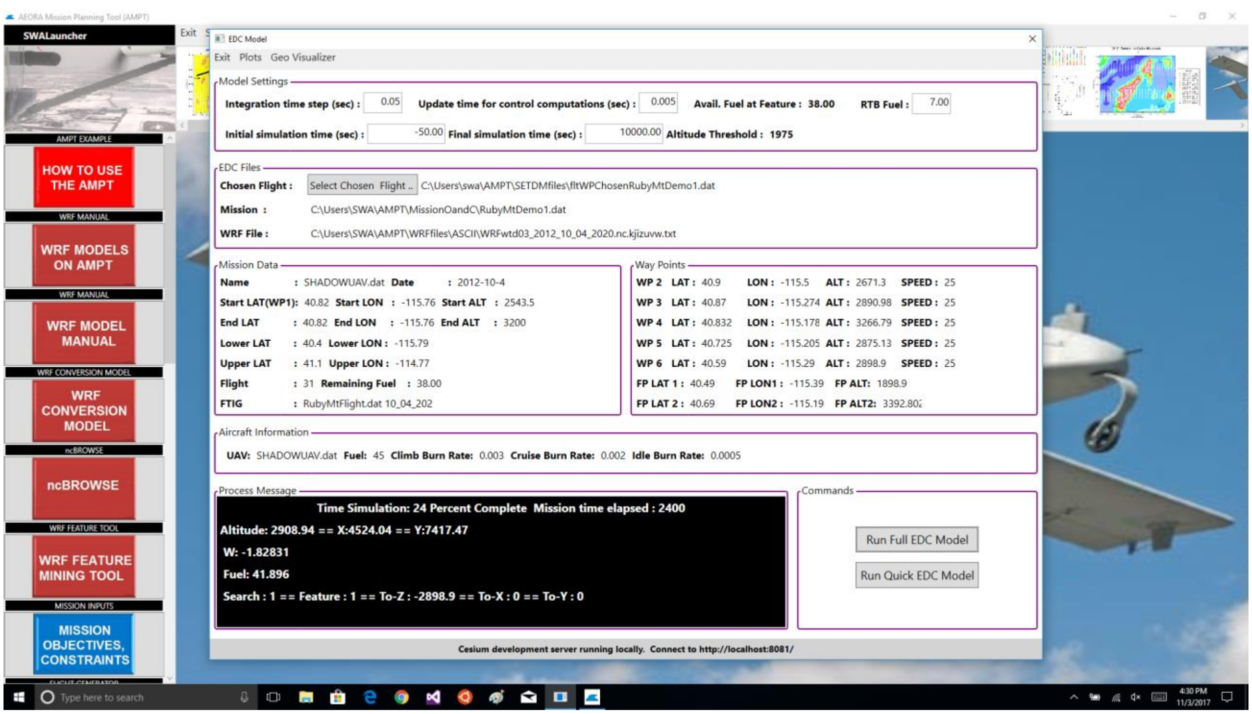

Figure 48.0 Example of the CASSY model running. Search = 1, Feature = 1 indicates the UAV has traveled to the Ruby Mt. feature area and is searching for energy opportunities.

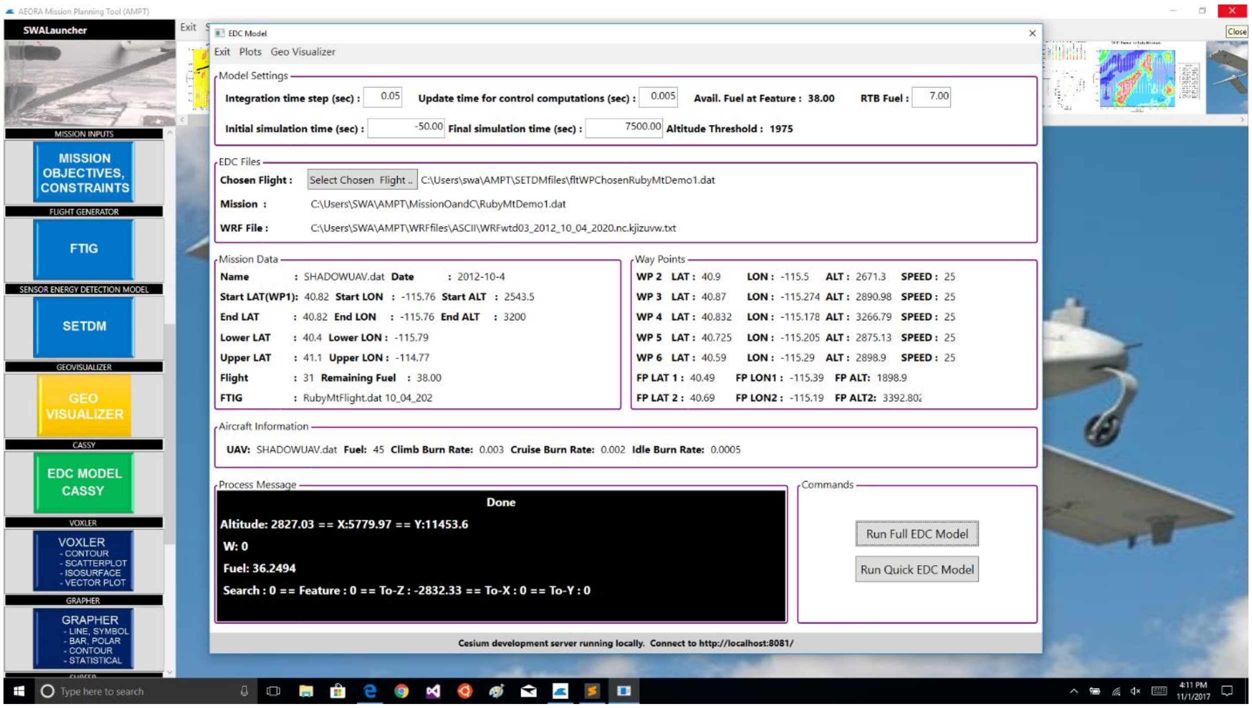

Figure 49.0 The comment, Done, is shown when the simulation has been completed. Search = 0, Feature = 0 indicates the UAV left the Ruby Mt. feature area and traveled back to the start location.

After the CASSY simulation, click Plots from the top menu options to view twenty different 2 dimensional graphs listed in Table 4.0. A top view of the flight from the starting point to feature area to a flight back to the starting point is shown in Figure 50.0. Fuel burn for the Ruby Mountain test case flight is shown in Figure 51.0.

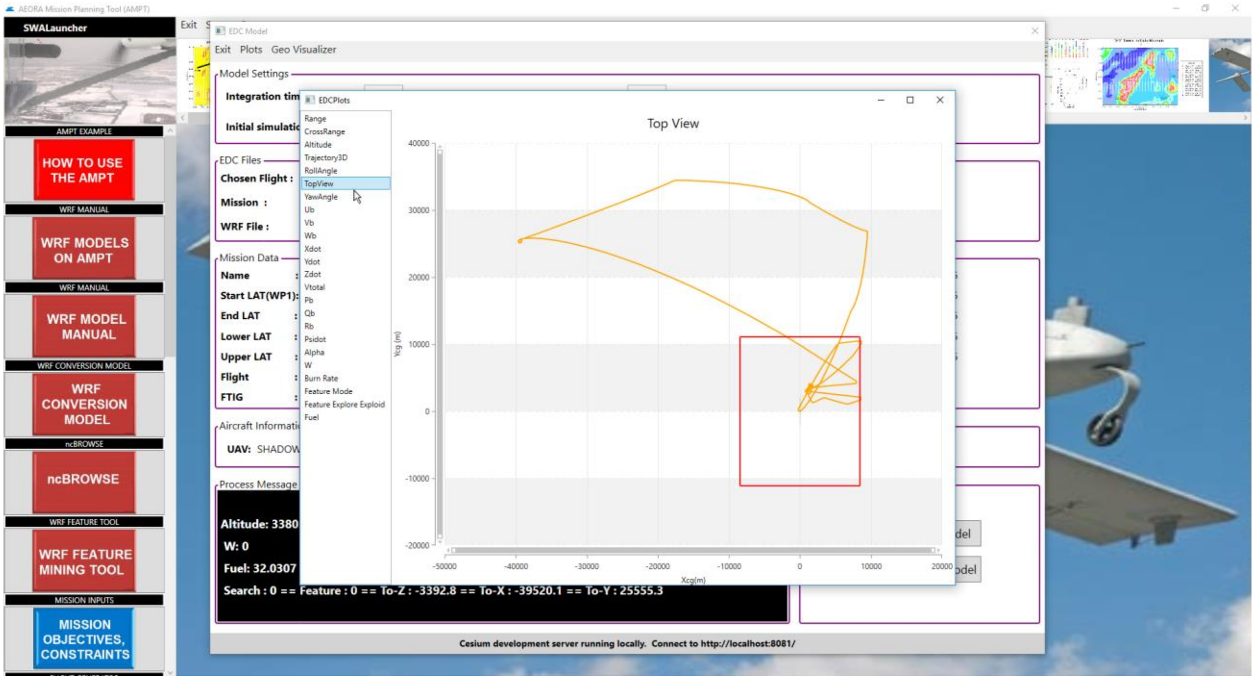

Figure 50.0 Top View of the CASSY flight path for the Ruby Mountain test case.

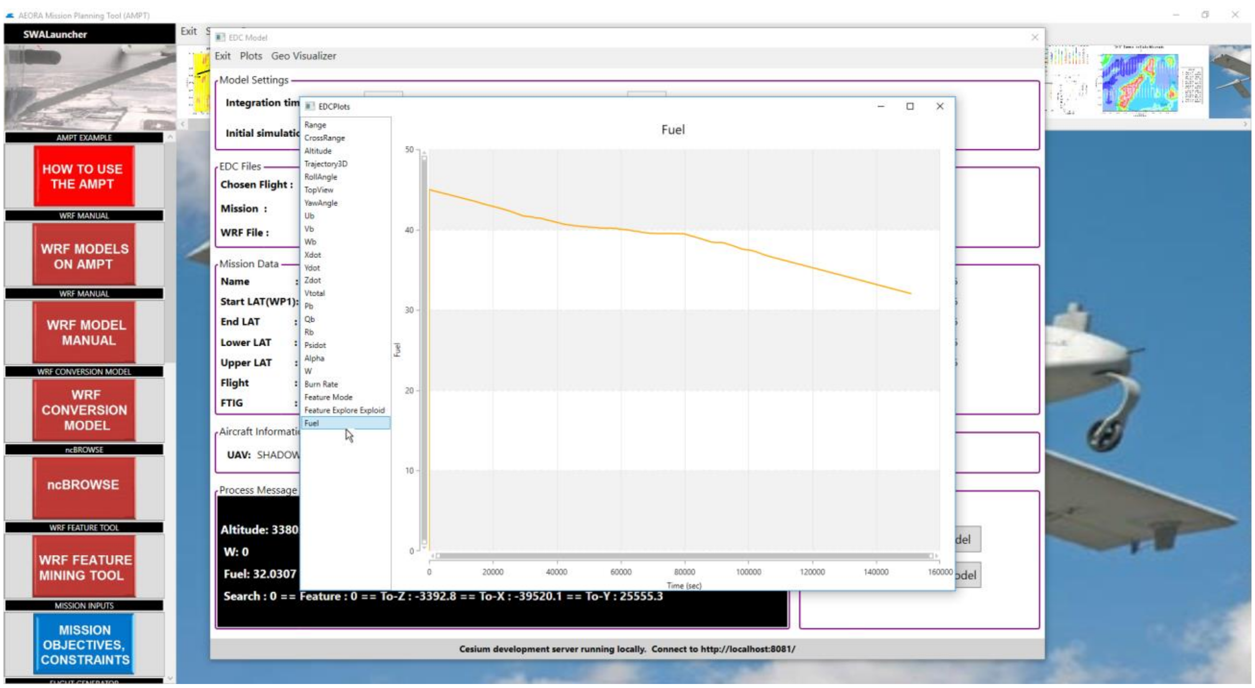

Figure 51.0 Fuel burn for the Ruby Mountain test case flight.

Table 4.0 List of EDC CASSY Output Graphics

1 - Range versus Time
2 - Cross Range versus Time

3 - Altitude versus Time
4 - 3D Trajectory versus Time
5 - Cross Range versus Time
6 - Roll Angle versus Time
7 - Top View versus Time
8 - Yaw Angle versus Time
9 - Ub versus Time
10 - Vb versus Time
11 - Wb versus Time
12 - Xdot versus Time
13 - Ydot versus Time
14 - Zdot versus Time
15 - Vtotal versus Time
16 - Pb versus Time
17 - Qb versus Time
18 - Rb versus Time
19 - Psidot versus Time
20 - Alpha versus Time

4.0 Graphics

4.1 CESIUM, the Geo-Visualizer

CESIUM is an open source JavaScript library for world-class 3D maps and global visualization (https://cesiumjs.org/). The AMPT using CESIUM to visualize various views (top, side, aircraft) for the aircraft output flights and performance over the terrain. Figures 52.0 - 54.0 depicts a top view, Side View and Aircraft view, respectively, of the UAV flying the chosen route including fuel and altitude gauges.

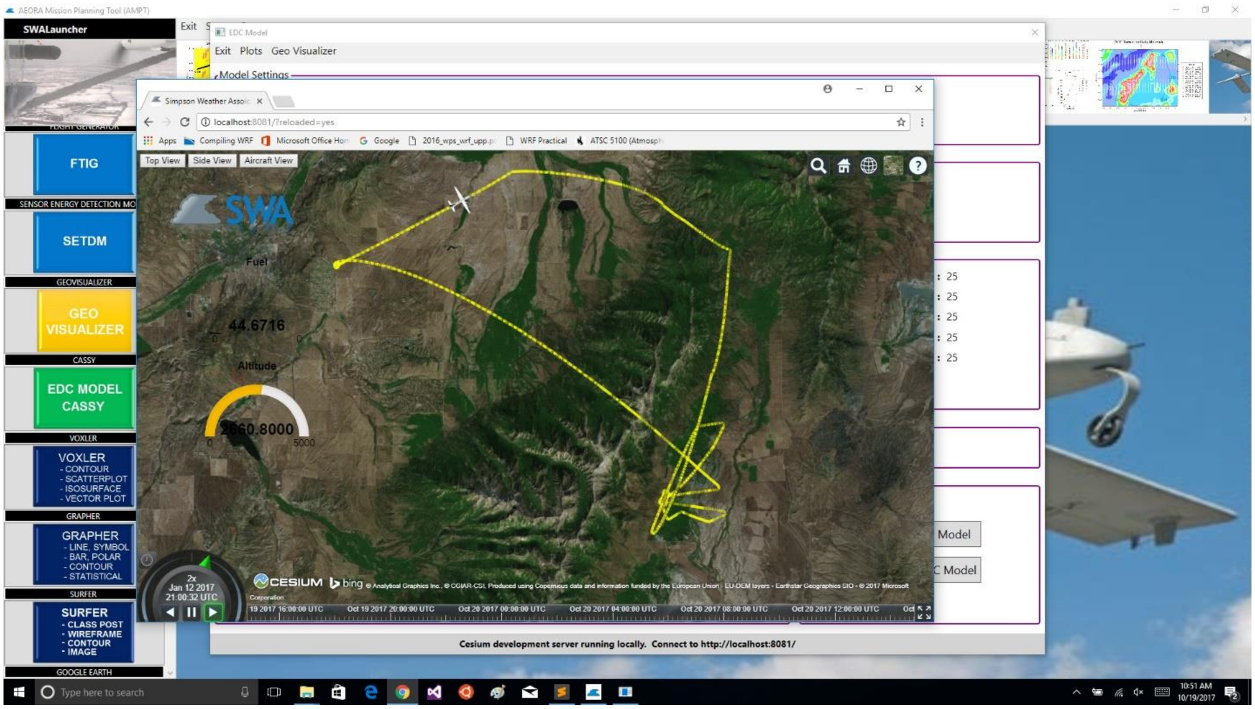

Figure 52.0 Top View of CESIUM visualization of UAV flying the chosen route including fuel and altitude gauges.

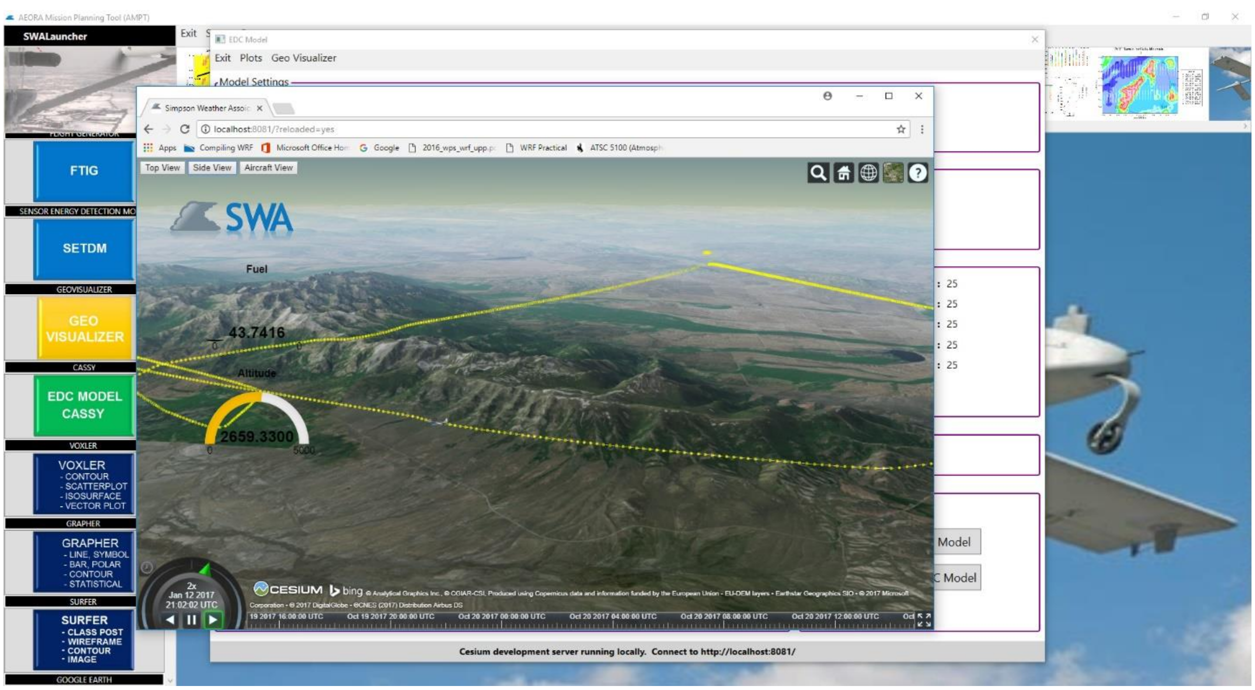

Figure 53.0 Side View of CESIUM visualization of UAV flying the chosen route including fuel and altitude gauges.

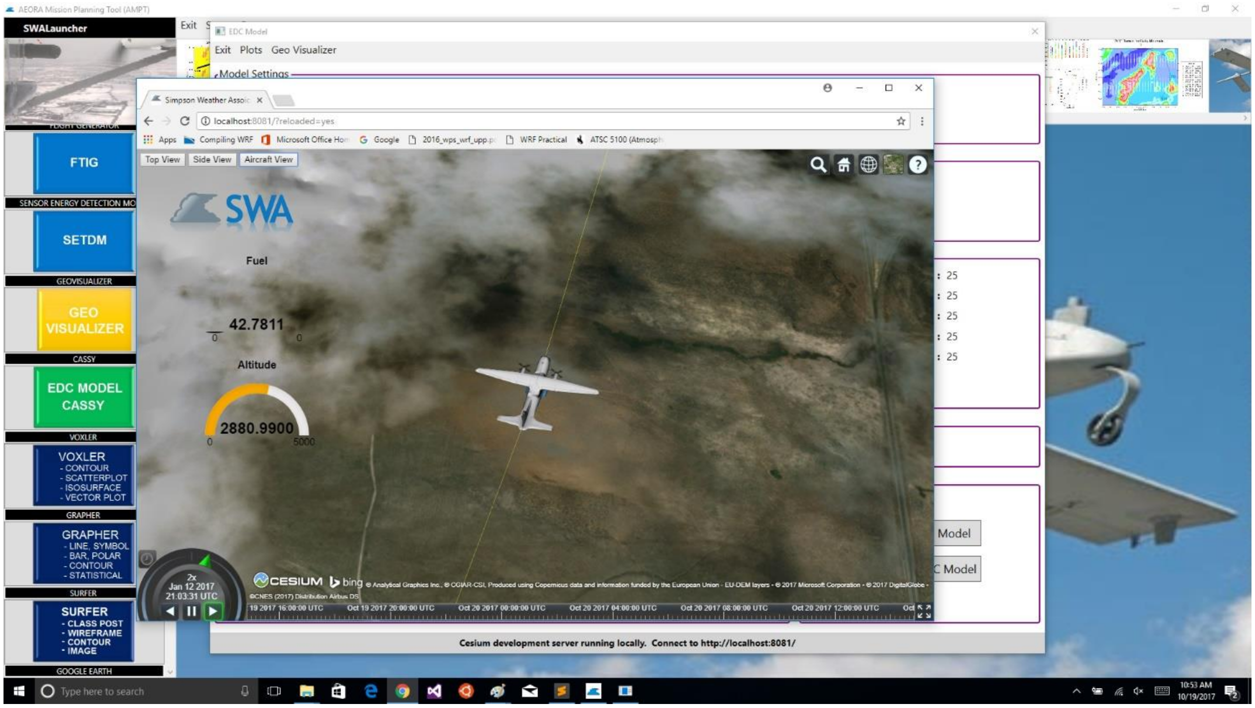

Figure 54.0 Aircraft View of CESIUM visualization of UAV flying the chosen route including fuel and altitude gauges.

4.2 Commercial off the Shelf (COTS)

SWA's version of the AMPT contains three commercial off the shelf graphic software packages from Golden Software: VOXLER, GRAPHER and SURFER. These COTS are useful tools providing data visualization and statistics. It is recommended that the customer either buy these COTS from Golden Software or add their own graphic packages to the SWAlauncher. http://www.goldensoftware.com

4.3 GoogleEarth

A GoogleEarth (Figure 55.0) link has been added as another tool to view AMPT output data. While no AMPT outputs are currently converted to KMLs for GoogleEarth, GoogleEarth is still a useful tool for global visualization. If the user wishes to display AMPT outputs in GoogleEarth, the user will need to convert the outputs to KML format via a software tool (Shipley, et. al., 2008). If the customer intends to make additional use of GoogleEarth capabilities, they should review the Google's license web page.

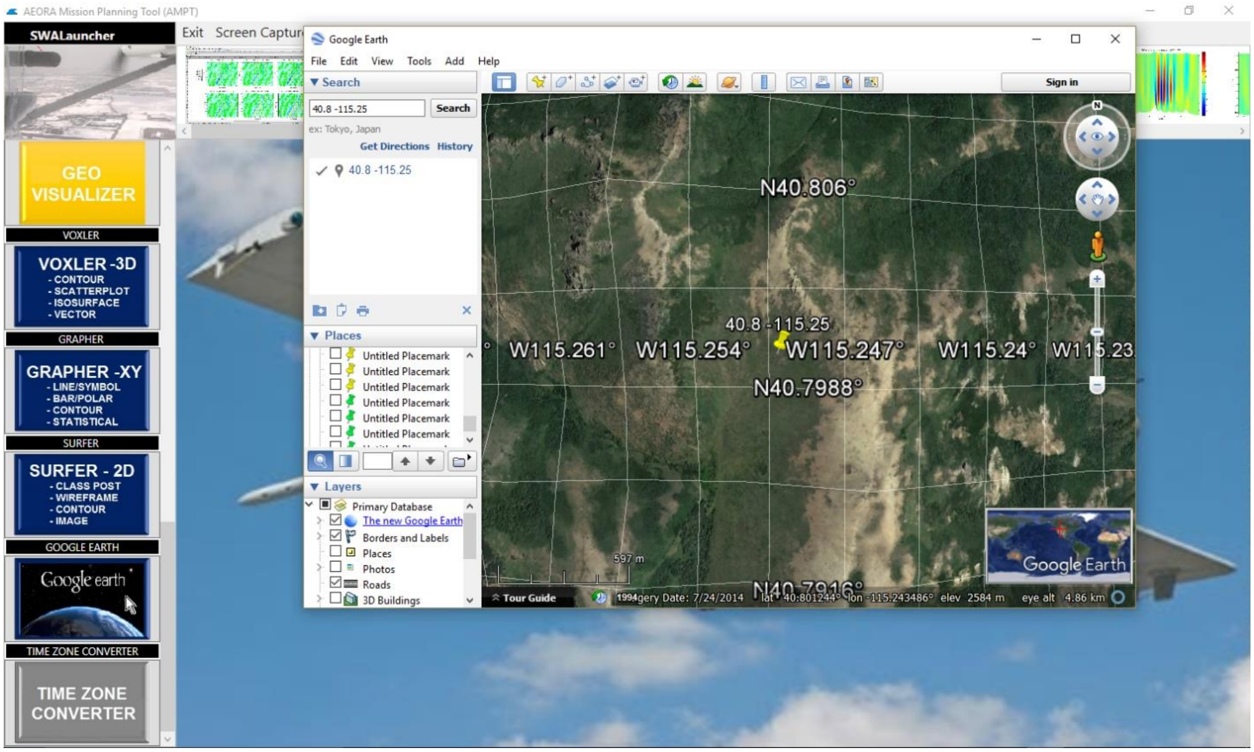

Figure 55.0 Example of Google Earth

5.0 Time Zone Converter (web only)

A link to a web based time zone converter (Figure 56.0) has been included in the AMPT menu as a useful field resource.

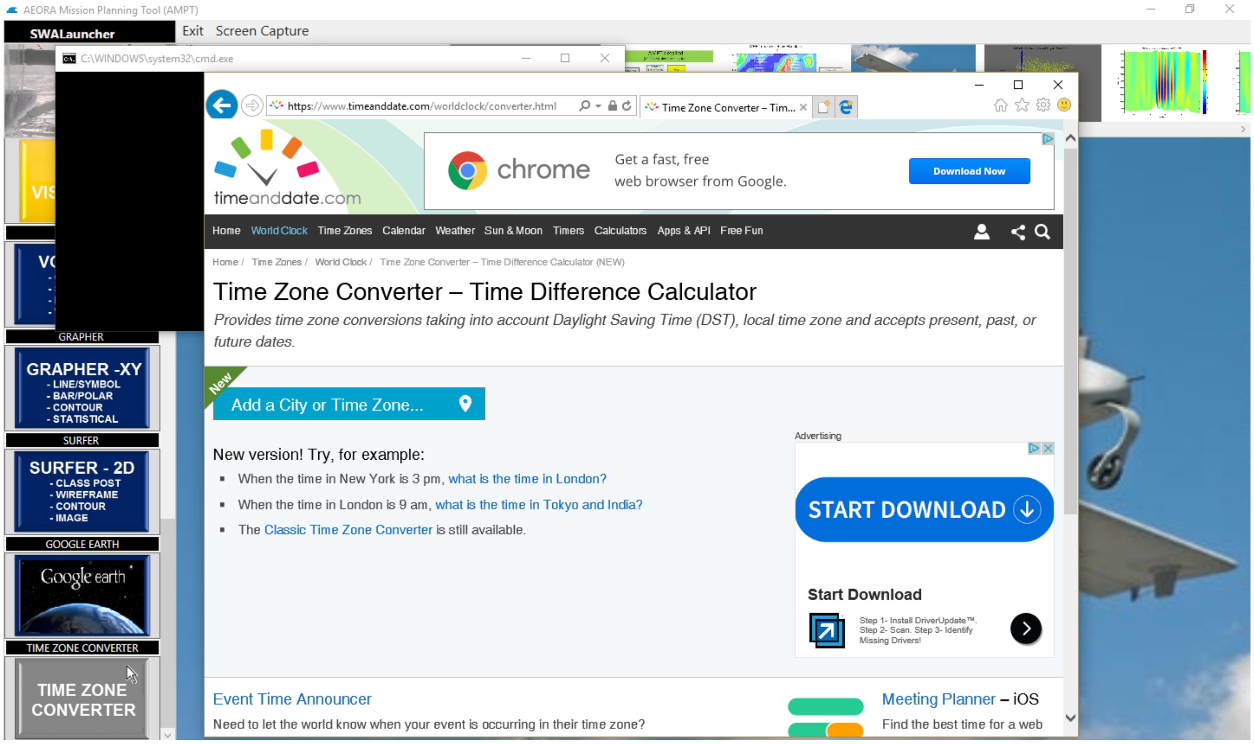

Figure 56.0 Time Zone Converter

5.0 References

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Emmitt, G. D., S. A. Wood, S. Greco and C. O'Handley, 2017: Atmospheric energy harvesting for autonomous in-flight path planning of a UAV instrumented with Doppler Wind Lidar. Working Group on Space-based Lidar Winds, Hampton, Va, March 21-13.

Greco, S., G. D. Emmitt, S. A. Wood, M. Costello, and M. Chtangeev, 2015: The utilization of numerical forecast models and airborne Doppler Wind Lidars for UAS flight path planning and energy extraction. Session: Seventh Symposium on Lidar Atmospheric Applications. AMS annual meeting, January 04 - 08, 2015, Phoenix Az.

Shipley, S. T.; Greco, S.; Emmitt, D. and S.A. Wood, 2008: In-flight Visualization of Airborne Doppler Wind Lidar Data Using KML and Google Earth. American Geophysical Union, Fall Meeting 2008, abstract #IN41A-1129.

Simpson Weather Assoc., Inc., 2012: A Doppler wind lidar based atmospheric energy harvesting system for autonomous in-flight guidance and path planning of small aircraft. SBIR Phase I Final Technical Report.

Appendix 1.0 AEORA Program Meeting Technical Presentation (EDC)

The slides of the original PDF document did not convert to WORD. PNG images are shown for the slides in this appendix.

AEORA Program Meeting
15 December 2015

earthlydynamics

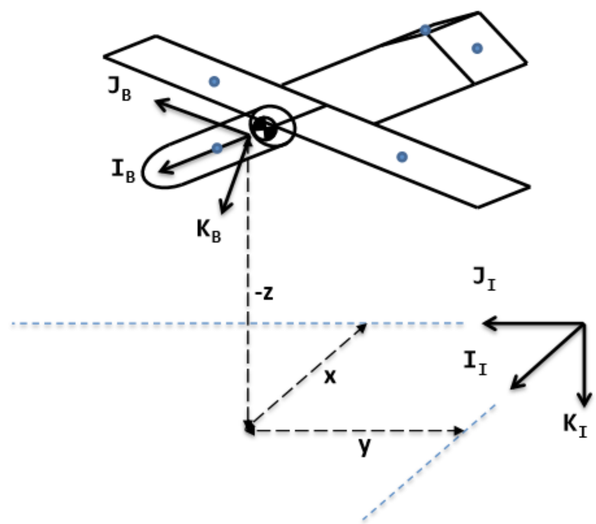
1

Agenda for Presentation

- Flight Dynamic Simulation Model
- Thermal Centering Controller
  - Example Results
- Lift Line Controller
  - Example Results
- Control Software Handoff
  - Overview
  - Thermal Centering
  - Lift Line

Simulation Model Overview

- Aircraft Modeled As Rigid Body With 6 Degrees of Freedom (Position of Mass Center and Orientation)
- Left Wing, Right Wing, Left Tail, and Right Tail Modeled As Separate Aerodynamic Surfaces
- Each Aerodynamic Surface Has Flap Control to Modify Lift and Drag of Surface
- Fuselage Produces Drag
- Parameters Set To Match RQ7B Shadow Aircraft



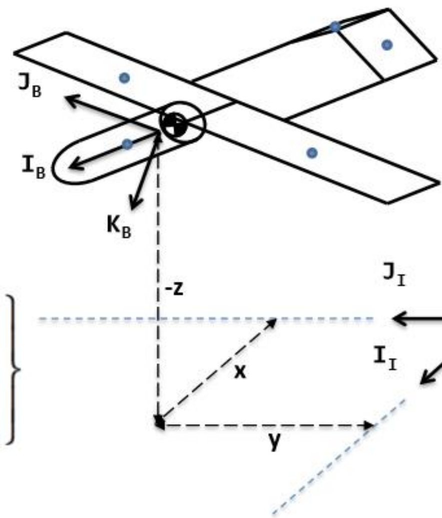
Simulation Model Equations

$$\begin{Bmatrix} \dot{x}_I \\ \dot{y}_I \\ \dot{z}_I \end{Bmatrix} = R^T \begin{Bmatrix} u_b \\ v_b \\ w_b \end{Bmatrix}$$

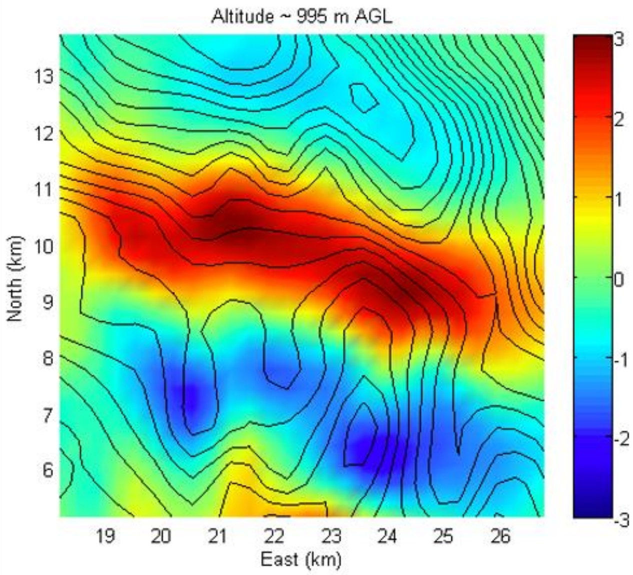
$$\begin{Bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{Bmatrix} = \begin{bmatrix} 1 & s_\varphi t_\theta & c_\varphi t_\theta \\ 0 & c_\varphi & -s_\varphi \\ 0 & s_\varphi / c_\theta & c_\varphi / c_\theta \end{bmatrix} \begin{Bmatrix} p \\ q \\ r \end{Bmatrix}$$

$$\begin{Bmatrix} \dot{u}_b \\ \dot{v}_b \\ \dot{w}_b \end{Bmatrix} = \frac{1}{m} \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} + g \begin{Bmatrix} -s_\phi \\ s_\phi c_\theta \\ c_\phi c_\theta \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{Bmatrix} u_b \\ v_b \\ w_b \end{Bmatrix}$$

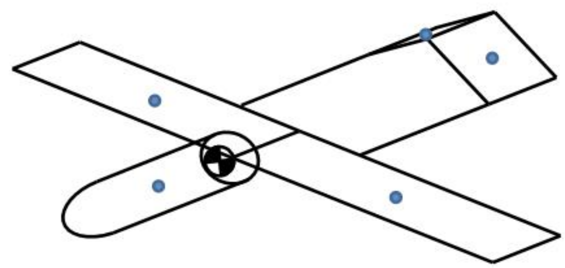
$$\begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix} = I^{-1} \left(\begin{Bmatrix} L \\ M \\ N \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} I_T \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} \right)$$



Simulation Model Wind Interfacing



Complex Wind Field From WRF Model Defines Wind Velocity Vector As a Function of Time and Space

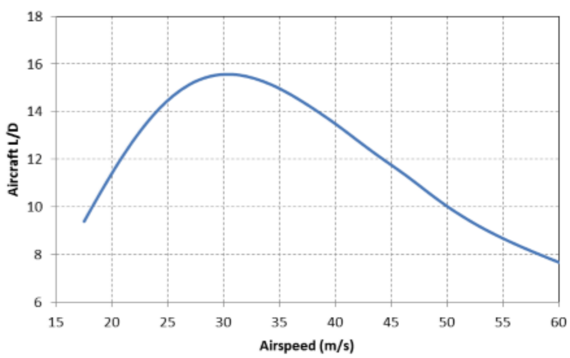


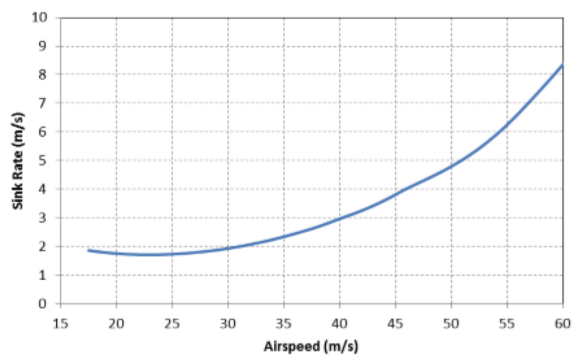
All Aerodynamic Computation Points Sample Complex Wind Field As They Fly Through Wind Field (Frozen Field Concept)

Wind Velocity Added To Motion to Form Relative Aerodynamic Velocity Used to Compute Lift/Drag of Aerodynamic Element

RQ7B Shadow Simulation Model Trim Performance

- Peak Lift to Drag Ratio = 15.5 at an Airspeed of 30 m/s
- Minimum Sink Rate = 1.8 m/s at 23 m/s





Atmospheric Energy Extraction

- **Assume**
  – Information Provided On the Type, Shape, Location, and Strength Of An Atmospheric Feature
- **Goal**
  – Develop Robust Control Algorithms Which Can Fly Features To Extract Energy While Being Robust To Uncertainties In Feature Characteristics
- **Features of Interest**
  – Thermals
  – Lift Lines (Ridge Lift, Mountain Waves)

Thermal Centering

- Basic Implementation Flight Tested By Naval Post Graduate School
  - Andersson, Kaminer, Dobrokhodov, Cichella, “Thermal Centering Control for Autonomous Soaring: Stability Analysis and Flight Test Results,” *Journal of Guidance Control and Dynamics*, 2012
- Flight Control Logic Seeks To Find A Circular Flight Path Around Thermal Core
- Desired Final Steady State Bank Angle Is Prespecified
- Perturbations On Bank Angle Command Are Made To Center Flight Path On Thermal Core
  - If Lift Is Increasing: Bank Angle Is Decreased Which Straightens The Flight Path And Brings Aircraft Closer To Core
  - If Lift Is Decreasing: Bank Angle Is Increased Which Turns The Flight Path Into Stronger Lift

$$\phi = \phi_{nom} + kh$$

Commanded Bank Angle

Nominal Thermalling Bank Angle

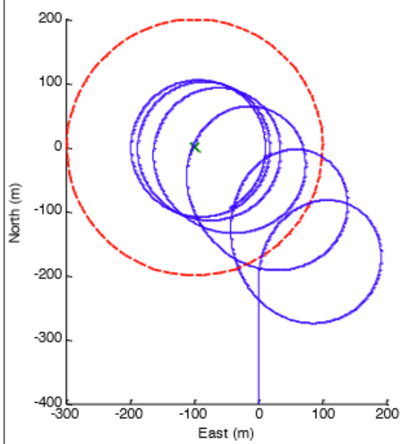
Control Gain

Rate of Change of Climb Rate

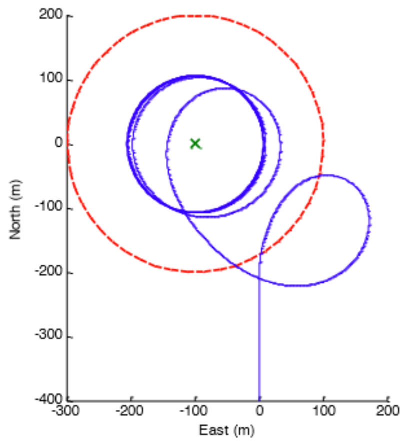
Thermal Centering

- Effect of Control Gain on Thermal Coring Trajectory (Nominal Bank Angle Equals 20 Degrees)

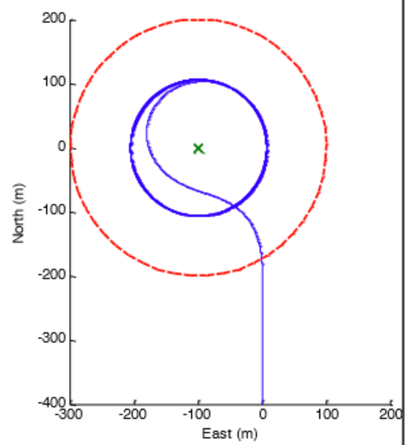
K=1



K=2

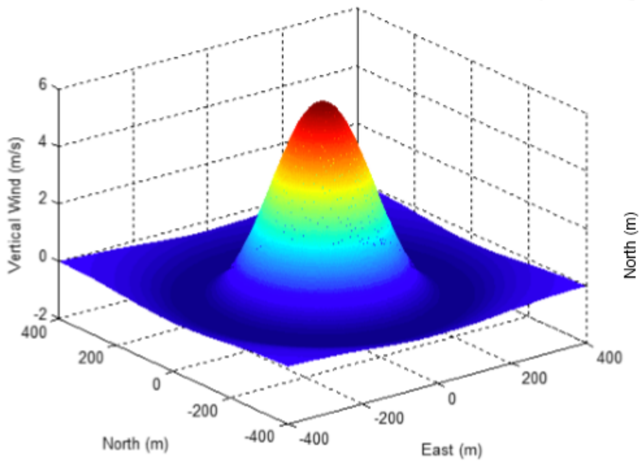


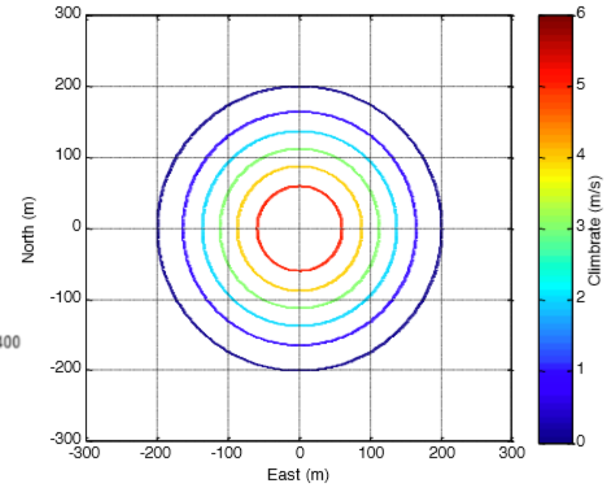
K=5



Thermal Centering Examples

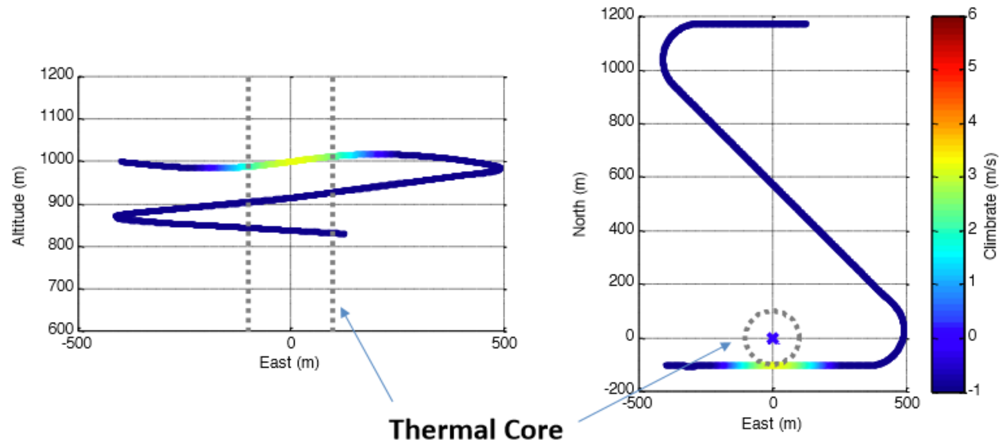
- Simple Exponential Thermal Model
- The thermal is actually surrounded by a slight amount of sinking air
- For this case the thermal radius is 200, and the radius to a 3 m/s lift (which would allow the aircraft to climb at 1 m/s) is roughly 100 meters





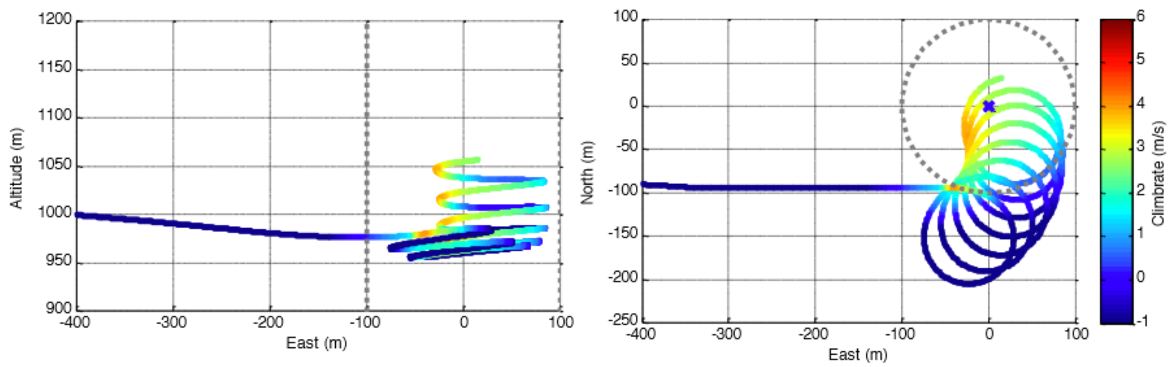
Thermal Centering Examples

- The system is initially set to following a waypoint pattern in a fixed area
- Simulation results shown for a 2 minute flight performing simple waypoint tracking
- The aircraft climbs briefly as it passes through the edge of the thermal



Thermal Centering Examples

- Thermal centering controller enabled with a very small gain (k = 0.2 rad/(m/s^2))
- The controller engages when a significant climb rate is detected (in the case > 1m/s), and the aircraft begins circling
- The nominal bank angle for thermalling is set to 45 degrees (this is a control parameter)
- The thermal centering controller acts to perturb the bank angle to very slowly push the center of the turning circle towards the core of the thermal



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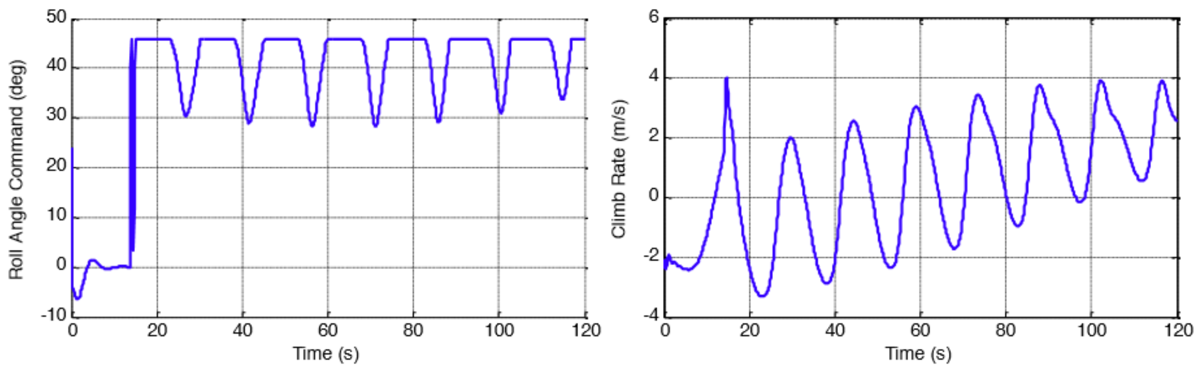
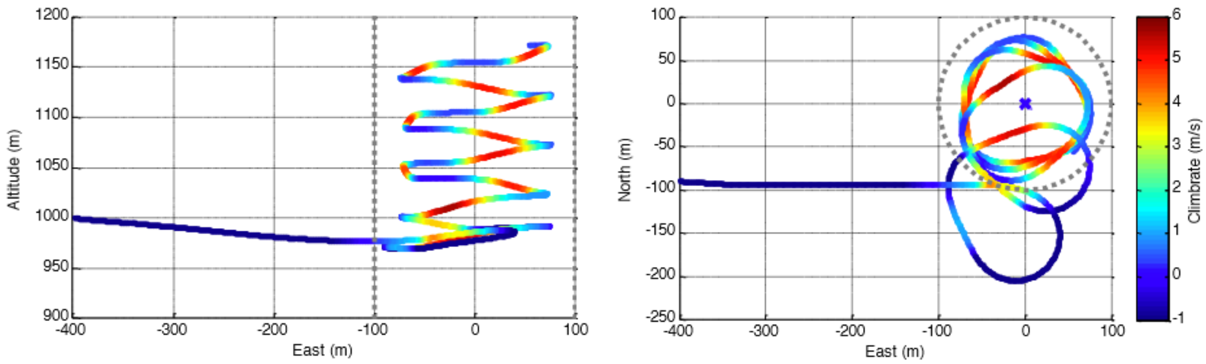


Thermal Centering Examples

- Thermal centering controller enabled with a very high gain ($k = 1.0$ rad/(m/s^2))
- The aircraft attempts to center on the thermal very aggressively
- The controller alternates between commanding straight flight in increasing lift, and maximum bank in decreasing lift



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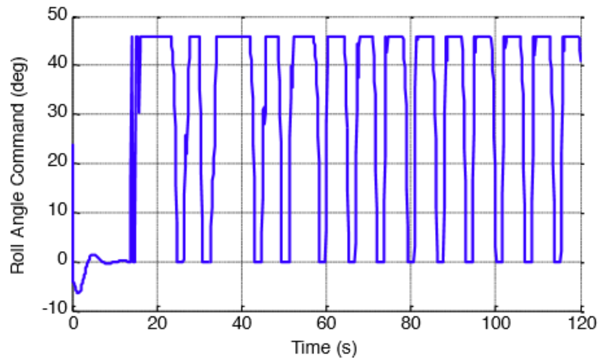
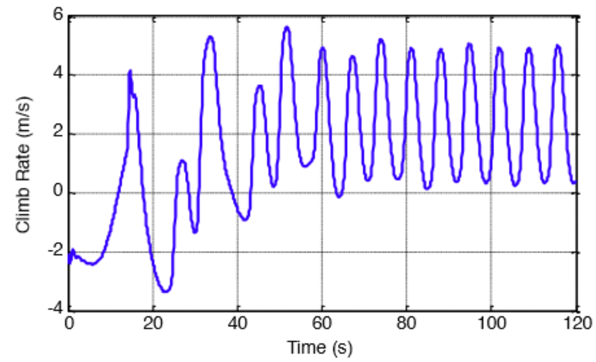
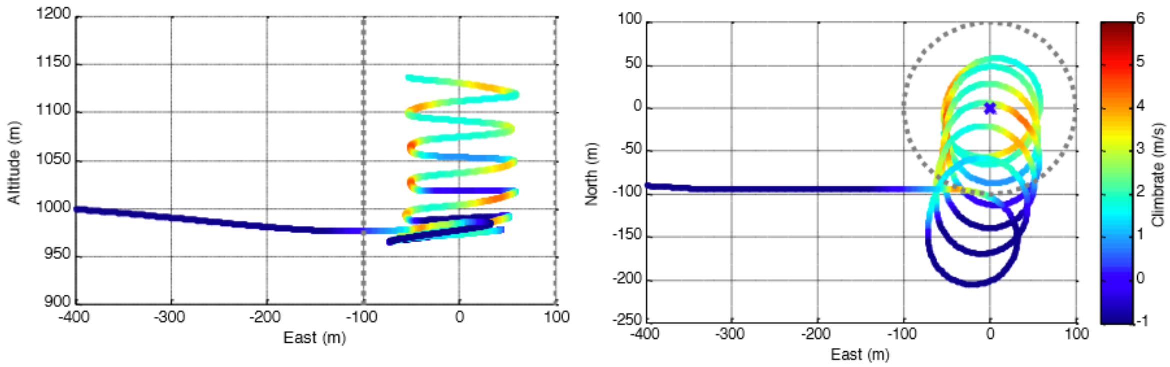




Thermal Centering Examples

- Thermal centering controller enabled with a moderate gain (k = 0.33 rad/(m/s^2))
- The aircraft is always turning, but the circles are shifted quickly towards the thermal core
- This is the target performance for the controller as it will give good performance and be more robust to turbulence and sensor noise than a high gain controller



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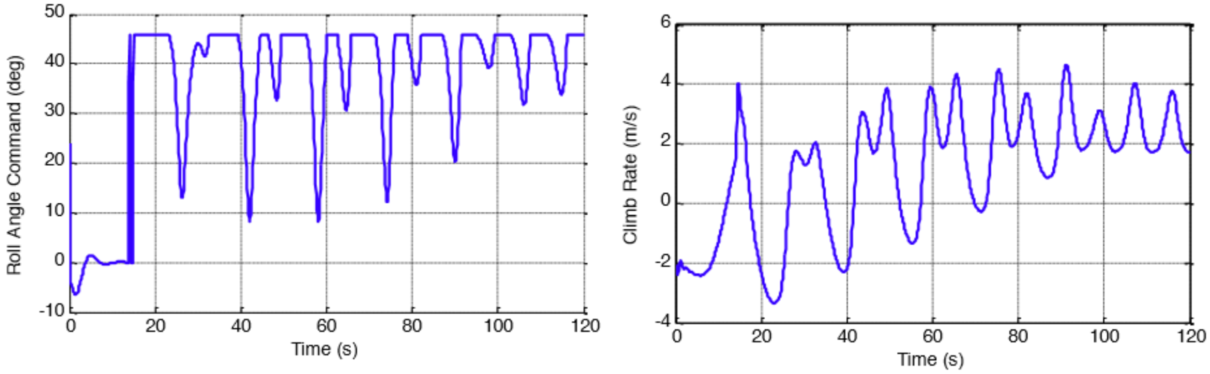


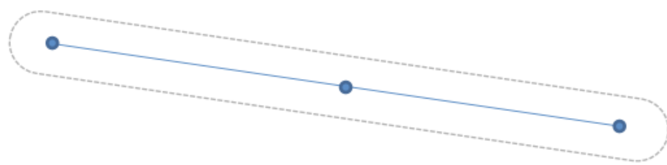
Lift Line Controller

Lift Line Controller

- Assume there is a known area of lift with a roughly linear shape

Lift Line Controller

- Assume there is a known area of lift with a roughly linear shape
- This is represented by a line with waypoints at the ends and middle



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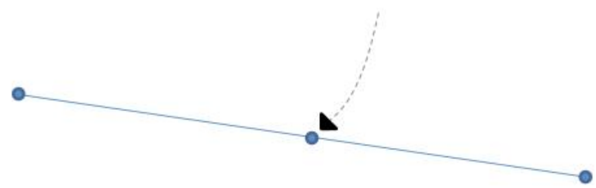

Lift Line Controller

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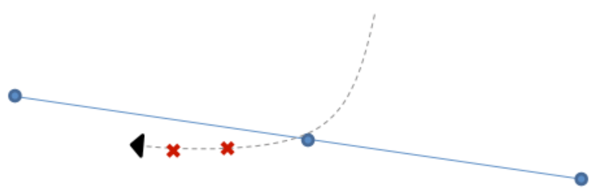
- As the aircraft flies the waypoints, points of strong lift are recorded



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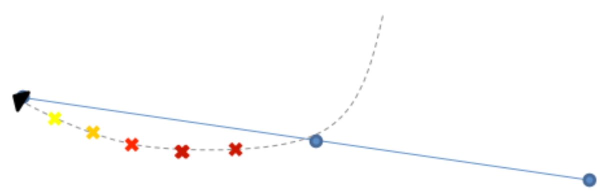

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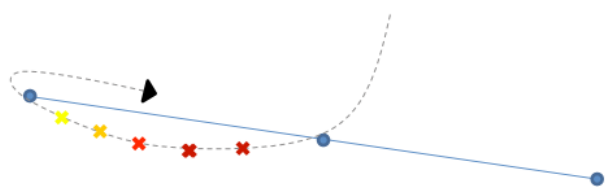

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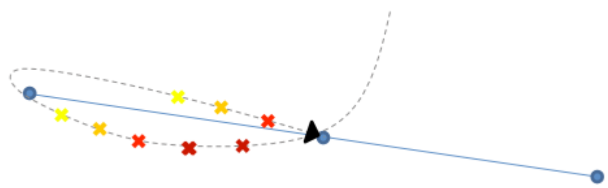

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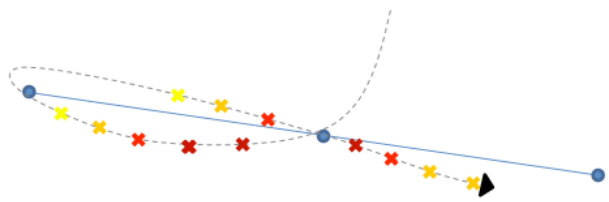

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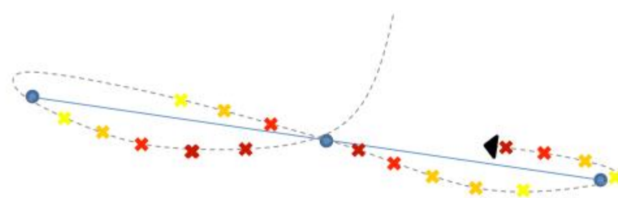

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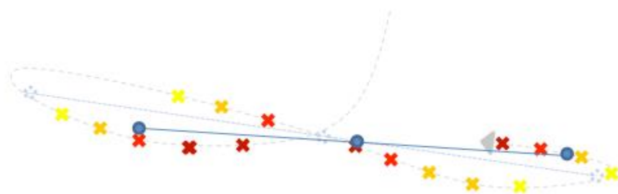
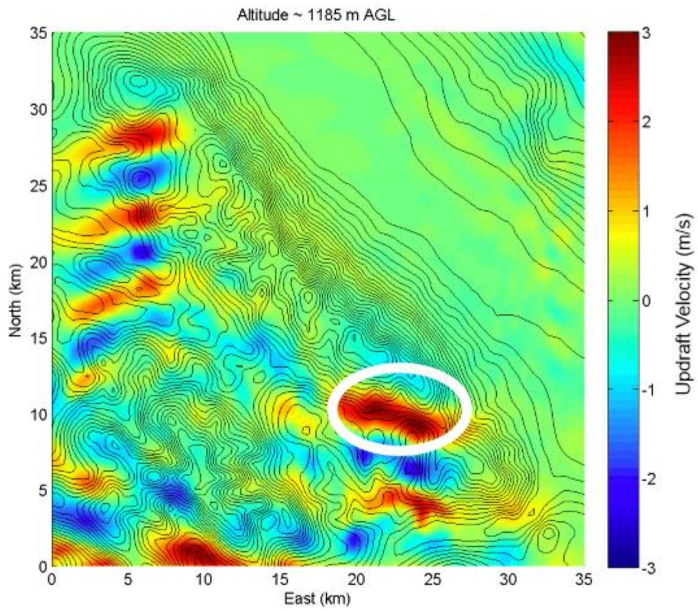


- Periodically, these stored points are used to compute a new line running through the points of strongest observed lift

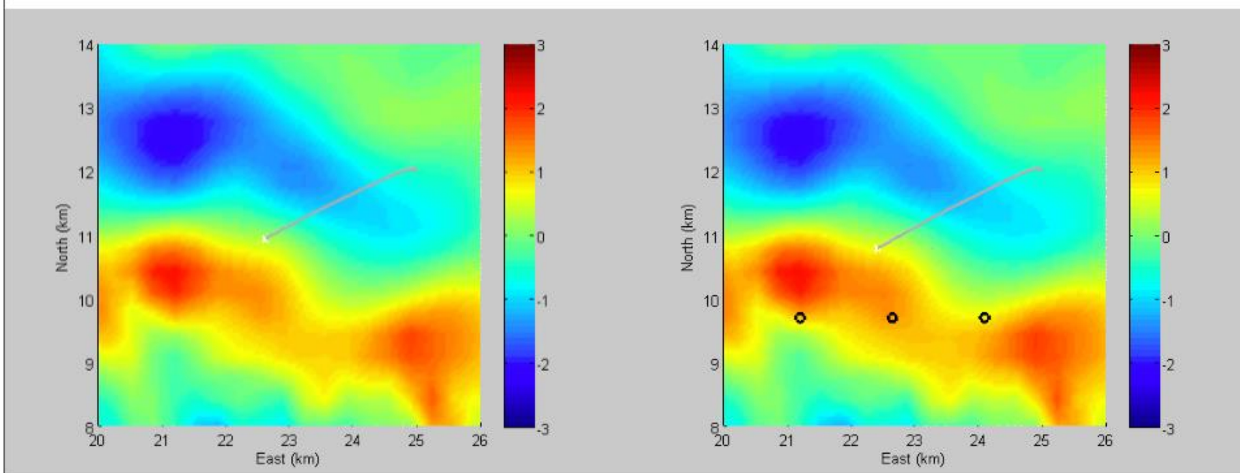
WRF Wind Field

- WRF data from a single instant in simulation time of a 35km x 35km grid was provided by Simpson Weather
- Simulation results presented here focus on the mountain wave circled below



Lift Line Controller

- Comparing Trajectories using Thermal Centering and Lift Line Controller flying Mountain Wave in WRF simulated wind field



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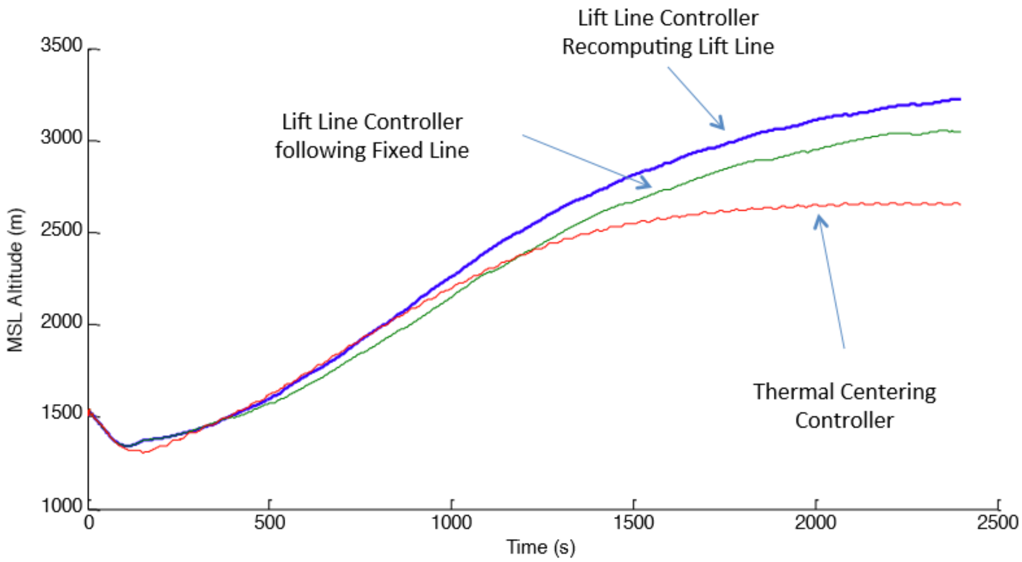
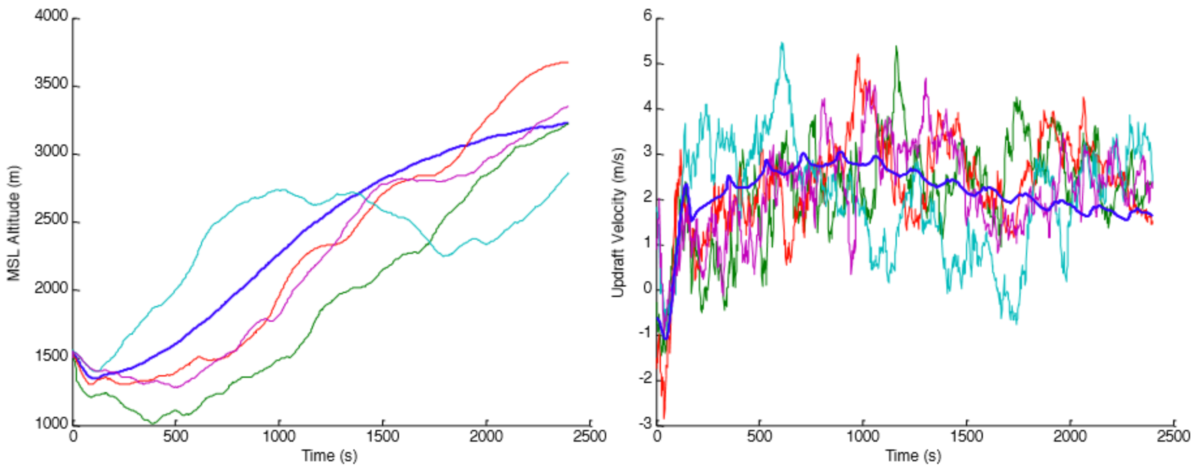


Lift Line Controller

- Effect of Dryden Turbulence (Simulation repeated 4 times with standard deviation of vertical component = 1m/s)



Notes on Flight Software Implementation

Assumptions

- Unpowered flight
- Effective inner loop control available
  - Hold a commanded roll angle
  - Hold a commanded airspeed
- Effective waypoint tracking is available
  - Fly to a fixed point in space
  - Hold a commanded airspeed
  - Navigation for the lift line control is done in terms of the North distance, East distance, and altitude from an arbitrary reference point
    - Conversion of Lat/Lon/altitude to a North/East/altitude coordinate system is done externally from the lift line controller
    - The selection of the reference point is not critical, but there are two likely choices
      - The origin of a volume of airspace defining the desired flight test area
      - The aircraft coordinates when the soaring controller is engaged

Total Energy Compensation

- In unpowered flight at constant airspeed, the total specific energy of the aircraft is simply the altitude, and the rate of change of energy is the climbrate
  - Both the thermal centering and the lift line controller utilize climbrate as a measure of total aircraft energy
  - Both thermal centering and lift line algorithms actually work best when the aircraft is flying at constant airspeed, so compensation for airspeed effects should not be needed
- For practical flight test operations and missions, it will be desirable to ensure the aircraft stays above a specified altitude, which may require a thrust input
- This constraint can be applied externally and both the thermal centering and lifting line controller will still be effective as long as the following conditions are met
  - Aircraft should continue to maintain constant airspeed
  - The “climbrate” fed to the thermal centering and lift line control should be compensated with an estimate of the power applied from the propulsion to ensure that the application of thrust is not interpreted as atmospheric lift

Control Framework

- Typical aircraft flight control is performed with a layered approach
  - Mission planner: select flight modes, handle ground station commands, generate waypoints
  - Outer loop control: generate attitude and speed commands to fly to the desired waypoints
  - Inner loop control: generate control surface and throttle commands to achieve the outer loop attitude and airspeed and commands
- The two soaring strategies described here fit into this framework in slightly different ways
  - Thermal centering control
    - When this is enabled, the controller itself is looking for thermals
    - Until the controller "sees" a thermal, the aircraft should follow its mission waypoints
    - Once the controller sees a thermal and sets its activation flag, the outer loop control should be bypassed so that the inner loop controller follows the bank angle and airspeed commands from the thermal centering controller
  - Lift line control
    - When this is enabled it can simply act like a way-point generator
    - The conventional outer and inner loop controllers are used to follow waypoints generated by the lift line controller to keep the aircraft in favorable atmospheric conditions

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Flight Test Considerations

- Example lift line flight test
  - The mission planner enables the lift line controller and hands over the waypoint generation task to the lift line controller
  - The lift line controller has been preprogrammed with a set of waypoints that defines an expected line of lift
  - The aircraft will fly the preset waypoints first while the lift line controller is periodically recording the observed climbrate along the aircraft's path
  - Once the waypoints have been flown, the lift line controller computes an estimate of the actual lift line location and orientation, then generates a new set of waypoints
  - Currently this process of generating and following waypoints continues until an external source (i.e. the mission planner) disables the lift line control
- Integration of this control strategy will require some discussion between EDC and Aurora on some key low-level implementation details as well as the overall flight test strategy
  - Computational implementation of the regression algorithm used by the lift line controller
  - Termination conditions for the lift line control
  - Ensuring terrain/obstacle avoidance
    - of course this is a consideration for any flight test, but the lift line tests in particular will likely focus on features found near terrain, e.g. ridge lift

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Appendix 2.0 Aurora Report Number: AR16-338

AEORA Input for Final Report

Aurora Report Number: AR16-338

Date: 5 OCT 2016

Prepared by:

Christopher Courtin

Theo Hoffer-Schaefer

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TABLE OF FIGURES

1. Introduction

1.1. Report Overview and Program Summary

This report documents the efforts of Aurora under the AEORA subcontract, contract number W911QX-13-C-0091-AFSC.

Aurora's focus over the course of this program was to prepare its FW-20 aircraft for flight testing of the energy harvesting algorithms developed by Georgia Tech and Simpson Weather under this program. To this end, Aurora conducted some initial characterization flight tests of its FW-20 aircraft in August 2015, to measure drag polars and other key performance characteristics used to tune algorithm gains to the specific FW-20 vehicle. These flight tests covered three days, and produced the results needed for the algorithms to be tuned to the vehicle.

After receiving updated algorithms and gains from Georgia Tech, Aurora then implemented the energy harvesting algorithms in the Pixhawk flight controller and tested them using an open-source processor-in-the-loop simulation (PILSIM). Both the thermal centering algorithms and lifting line algorithms were implemented. The thermal centering algorithms integrated well into the Pixhawk and was demonstrated to be effective in our simulations. The lifting line controller also integrated well, but was very computational-resource-intensive in its original format. Modifications were made to adapt it to operation on the more resource-constrained flight controller, and were tested in the PILSIM.

2. FW-20 Aircraft

2.1. Vehicle Overview

The Aurora FW20 was designed as a long endurance small unmanned aerial systems (sUAS) platform that was to be fully modular and accommodates production and post-production modifications through subcomponent exchange either in the field or at the depot level. Sensor payloads, propulsion systems, and batteries can be interchanged on the aircraft to meet changing mission requirements. When configured with electric-propulsion, the FW20 aircraft can fly for a total of 3 hours in an all-electric configuration. The aircraft launches using two high power motors, allowing for hand launching from close quarters. Once at altitude, it will shut one motor down and will continue the flight on the second motor.

Physical structural aircraft components were designed to have multiple mounting locations for certain electrical components and sensors adding to the ease of integration and postproduction modifications. Power for additional electrical components can occur at different locations within the airframe and regulated to the proper operational voltage. Common payload interface cables and a wing harness allow for a cost-effective way to integrate new hardware and additional capabilities to production FW20s.

The FW-20 aircraft has a 5lb maximum payload capacity, and a maximum takeoff weight of 20lbs. As of the release of this report there are over 50 hours of flight time on the platform, with no crashes or serious failures.

For this program, the FW-20 vehicle was fitted with an open source Pixhawk autopilot system (discussed below), paired with the QGroundControl GCS software. The data link is on a 915mHZ radio. For safety purposes, RC control is also possible over a 2.4 GHz link.

3. Characterization Flight Tests

At the end of August 2015 flight tests were conducted on the FW20 vehicle that will be the integration platform for AEORA energy utilization maneuver (EUM) algorithms. The vehicle was flown for 4 total hours, over the course of three days. The main goal was to verify the functionality of the aircraft and accurately map the glide polar, which is shown in Figure 2. This vehicle-specific information is necessary for the EUM algorithms. There is some discrepancy between our predicted and measured glide polars at low speeds, which is to be expected. Our modeling approach is based on a vortex-lattice representation of the aircraft shown in Figure 1. This method does lose accuracy as the aircraft approaches stall, but is otherwise very accurate for low-speed flight.

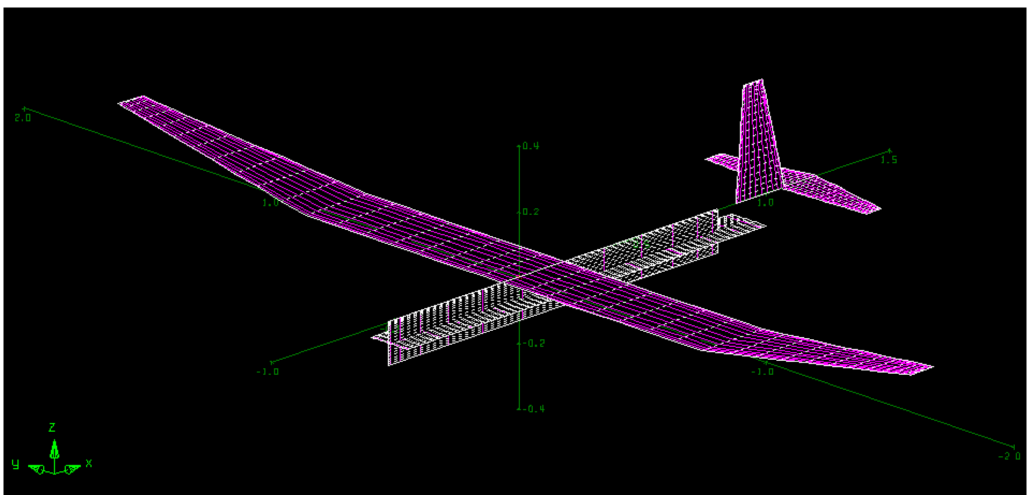

Figure 1: Athena Vortex Lattice (AVL) was used to model the FW-20 aircraft and compute the predicted glide polar. The model was calibrated based on the results of the flight tests.

The windmilling propellers on the FW20 add significant drag to the vehicle, making its gliding sink rate relatively high for a glider that size but actually very close to the predicted Shadow sink rates used in the initial Georgia Tech simulations.

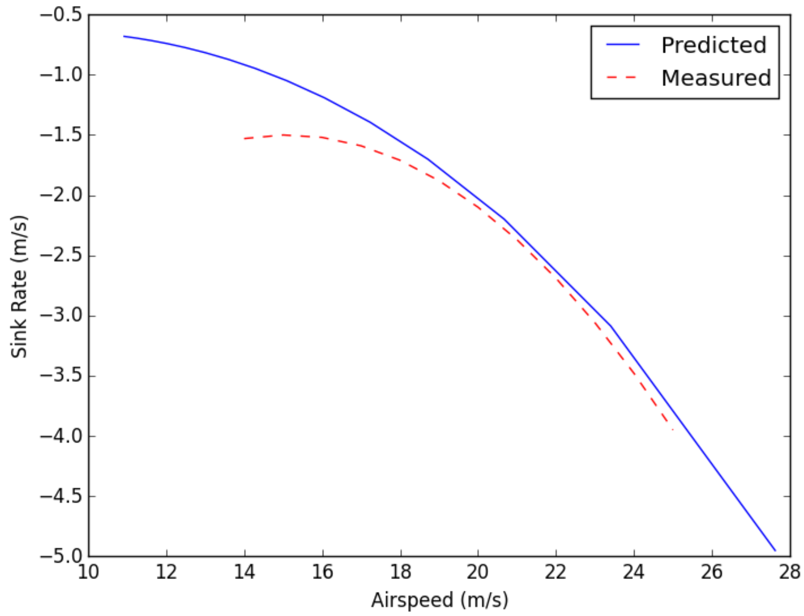

Figure 2: The measured drag polar for the FW-20 vehicle shows good agreement with the predicted polar until the aircraft nears stall

4. Algorithm Description

The algorithms implemented were those developed by Georgia Tech and transferred to Aurora in Dec. 2015. The primary controller is on the commanded bank angle, which is related to the vertical acceleration by the equation $\boldsymbol{\varphi} = \boldsymbol{\varphi}_{nom} + \boldsymbol{k}\ddot{\boldsymbol{h}}$, where $\boldsymbol{\varphi}$ is the aircraft bank angle, $\boldsymbol{\varphi}_{nom}$ is the nominal thermalling bank angle, $\ddot{\boldsymbol{h}}$ is the measured vertical acceleration from the barometric pressure altimeter, and $\boldsymbol{k}$ is a constant set to ~ .33. Further details of the algorithm can be found in the AEORA Program Meeting presentation from earthlydynamics, 15 Dec 2015.

5. Pixhawk Integration

Pixhawk is a high-performance mixed-platform autopilot-on-module that is supported by the open-source PX4 Pro Drone Autopilot flight control solution. PX4 runs on top of a powerful open-source real-time operating system (RTOS), and is architectured so that most non-driver-level processes are implemented as self-contained daemons called modules. Modules communicate with one another using a publish/subscribe routine that is handled by the micro object request broker (uORB) module. For example, the attitude controller is a separate module from the control surface actuator control module. The attitude controller generates attitude setpoints, which are subscribed to and interpreted by the control surface actuator module, as well as the telemetry transmission module, etc.

This architecture allows for the creation of new modules to add or modify features while having a minimal impact on the rest of the system, so it is an ideal platform for development and integration. Integration efforts on this program began by branching off of the most stable release of the PX4 flight stack, which at the time was cc7929937505c34d06b070c708e3f56a755cbda7.

5.1. Soaring Mode / Total Energy Control System

In order to allow complete control over all navigation parameters, a new navigation mode was added to the flight mode commander module. The main purpose of this was to be able to bypass the throttle control, since it will not be used for thermal soaring. As such, hooks for the new navigation mode were added to the attitude controller and the position controller. Stability controls for roll, pitch, and yaw are used un-modified, but the total energy control system (TECS) that controls the aircraft’s altitude and throttle was modified to hold altitude without power.

The current implementation for flight testing has the soaring mode mapped to a switch on the remote control, so that the vehicle can be flown to a desired location as normal. Soaring mode currently supports the thermal centering algorithm and the lifting line algorithm, although both cannot be used concurrently. In the future, this mode could be activated by another process or off-board mission computer when thermal centering is desired.

The most significant of the modifications made my by the Aurora development team can be found in the following source code:

- src/modules/commander/commander.cpp
- src/modules/fw_att_control/fw_att_control_main.cpp
- src/modules/fw_pos_control_l1/fw_pos_control_l1_main.cpp

All “tunable” parameters in the thermal centering controller and lifting line controller were made available to the ground control station. There parameters can be changed on-the-fly.

Figure 3: Version control software history showing addition of "soaring mode" to the attitude control module

5.2. Thermal Centering Controller

The thermal centering controller has some activation logic that monitor's the vehicle's sink-rate with respect to time. Changes in the sink-rate can come either from vehicle changes in attitude or from the vehicle entering an area of lift or sink. When in soaring mode, the motors are shut down, so there is no way for the vehicle to generate its own lift. The vehicle's controls are expected to close around a stable airspeed to maintain heading without stalling. As such, we can assume that any negative change in sink rate is coming from a thermal.

Once the vehicle is known to be in a thermal, the thermal controller begins to add a small delta to the attitude controller's bank-angle set-point. This causes the vehicle to initiate an orbital path around the perimeter of the thermal. The thermal controller continues to measure the lift by differentiating the sink-rate, and adjusts the delta to maintain a state of equilibrium.

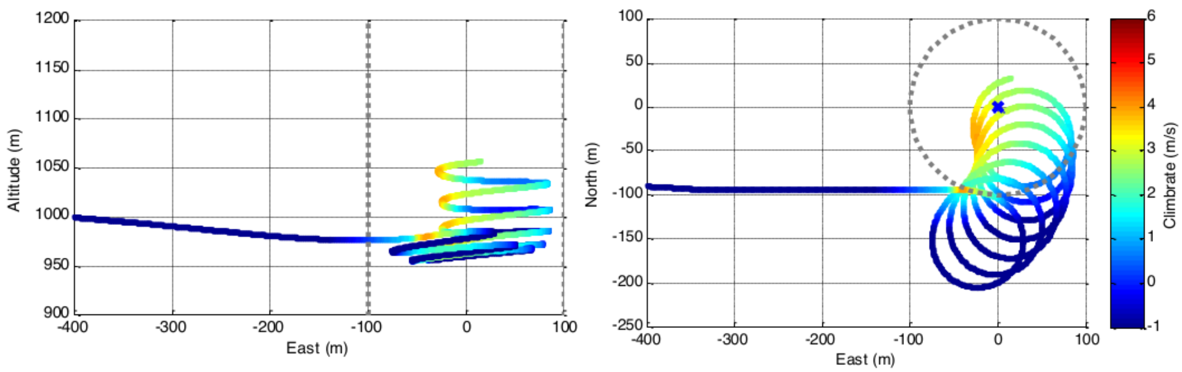

Figure 4: **Matlab simulation of thermal centering controller**

The soaring mode controller has a unique set of set-points for roll and yaw. Roll/yaw commands are generated by the algorithm and passed forward into the attitude stability controls. In the current implementation, a test pilot still has control over the vehicle, and the thermal centering controller's set-points are added as offsets to the stability control set-points.

During flight testing, it was determined that yaw input was needed to maintain altitude in addition to the bank angle. A parameter for yaw gain was added to the controller so that the amount of yaw mixed with roll could be tuned between airframes.

5.3. Lift Line Controller

The lift line controller implementation proved to be challenging in that the original algorithm was developed using Matlab, and as such it made extensive use of native matrix operations. These matrix operations do not translate very nicely into C, as each matrix element must be indexed specifically. Performing an operation such as matrix multiply in C would require two loops to iterate across both array element by element. Care must be taken when performing multiple loop iterations so as not to keep the CPU from servicing other processes like the flight controls.

Another constraint of the system is memory. A desktop running Matlab is more than capable of handling the types of data that the algorithm was designed for, but a low-power ARM processor runs out of space much more quickly. The algorithm originally used 30 lift points for calculating the lifting line, but current Pixhawk implementation supports up to 15 lift points before the memory allocation for the required matrices grows too large. Matrix operations were simplified where possible in order to increase this number. Further data structure and memory allocation optimizations need to be performed if the desired number of lift points is higher.

In order to access with the aircraft's stored and active waypoints, it was necessary to interface with Pixhawk's datamanager module. This module stores waypoints and other data on the SD-card. This allows the lift line controller to modify the position of a waypoint, re-write it to memory, and notify the mission controller that a waypoint has changed. In the current implementation, the algorithm does not publish its updated waypoint list to the datamanager, and the output waypoint list of the algorithm has not been verified. Some additional development and testing is required to meet this end and ensure robust operation of the algorithm.

6. PILSIM TESTING

QGroundControl is a companion application to the PX4 Pro flight stack. It is a free, open-source UAV Ground Control Station that supports PILSIM and HILSIM plugins to several open-source flight simluators. Among these simulators, FlightGear was chosen because it has a weather simulator that supports thermals.

PILSIM testing was invaluable because it allowed rapid verification of the algorithm integration efforts without the added risks and logistics of flight testing. Since these algorithms are very much tuning-dependent, it took many simulations to get the expected performance.

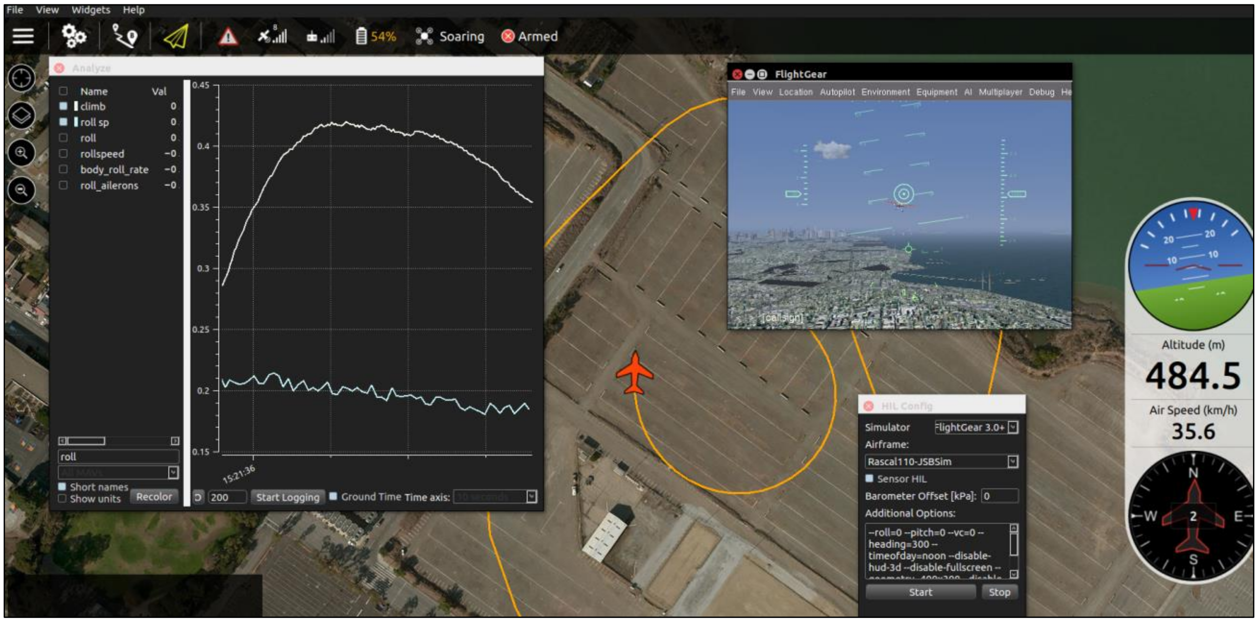

Figure 5: Autopilot HILSIM running the thermal centering algorithm. Top line displays lift over time, bottom line is the roll angle setpoint.

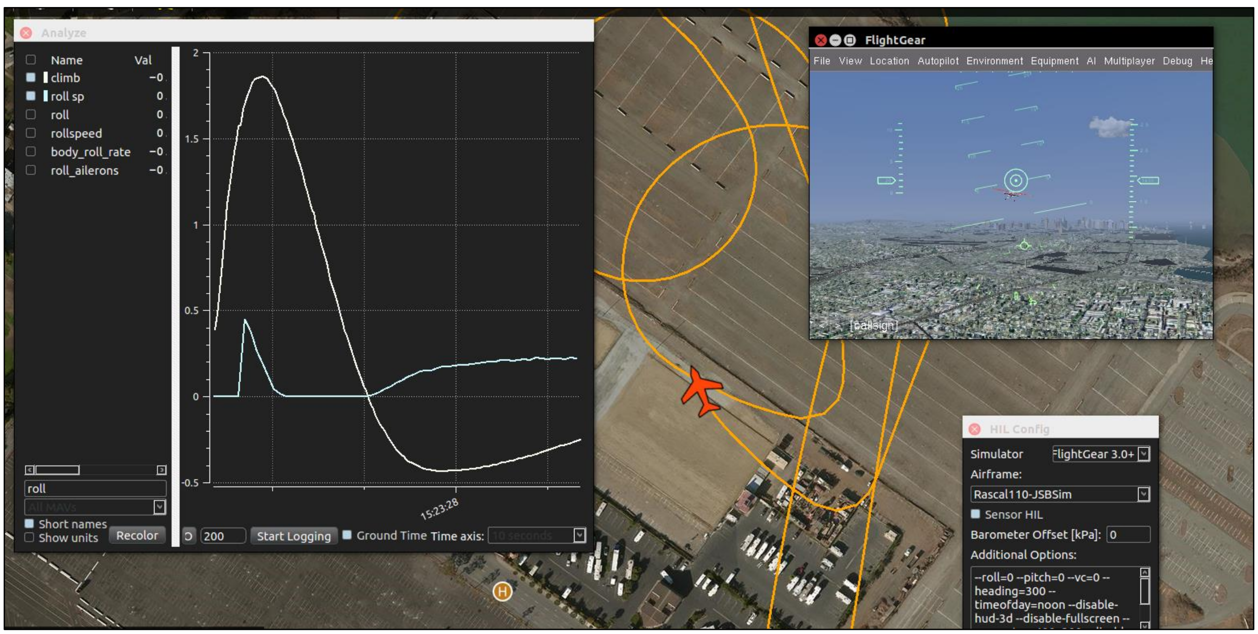

Figure 6: Autopilot HILSIM running the thermal centering algorithm . Vehicle exits and re-enters thermal area.