6 DOF Trade Studies

1.0   Introduction

A new trade study capability has been added to the 6DOF trajectory module. There are two related capabilities in this extension of the 6DOF. First, users can easily perform a trade study varying the values of any of the inputs to the 6DOF. A table of values can be used or a minimum, maximum and increment can be entered for each parameter to be studied. A scenario generator then creates a set of initial conditions for all permutations of the inputs. These scenarios can be edited by the user if desired and then executed with a single execute command. The second capability is a mini system effectiveness module. One standard deviation errors can be entered for each parameter. Then the number of rounds to be simulated is entered. A single click generates a set of initial condition errors that are then run with each scenario. Terminal conditions for each run and statistics are the outputs of the analysis. Together these capabilities provide an efficient way to determine ammunition dispersion, develop safety fans in support of testing or to perform trade studies.

This change adds three input tabs to the existing 6DOF Trajectory module. There are no changes to the existing input tabs for a single trajectory run. Single trajectories are run exactly as they were with the previous version of PRODAS.

2.0   Description and Example

2.1   Trade Study Tab

Let's start by taking a look at the Trade Studies tab (Figure 1) which is used to define scenarios for trade studies. The tree on the left contains a list of inputs to the trajectory that are available for use in a trade study. Below the tree is an editor where the user can specify values of each parameter to be evaluated. The top third of the tab contains analysis control functions. There are two very useful tools on the left. The first loads all the inputs defined in the single trajectory analysis into the trade study as nominal values. The second button will return all parameters to use the nominal value. Below these Global Options are a couple of options for handling of the "Spin" parameter. These are explained later in this paper. Once inputs are defined using the editor, the trade study scenarios are generated using the middle top block. Once the scenarios are generated, they are executed using the button at the top right of the tab. This will run a trajectory for each scenario and capture data at the end of the trajectory for each run. The table at the bottom of the tab lists all inputs for each scenario.
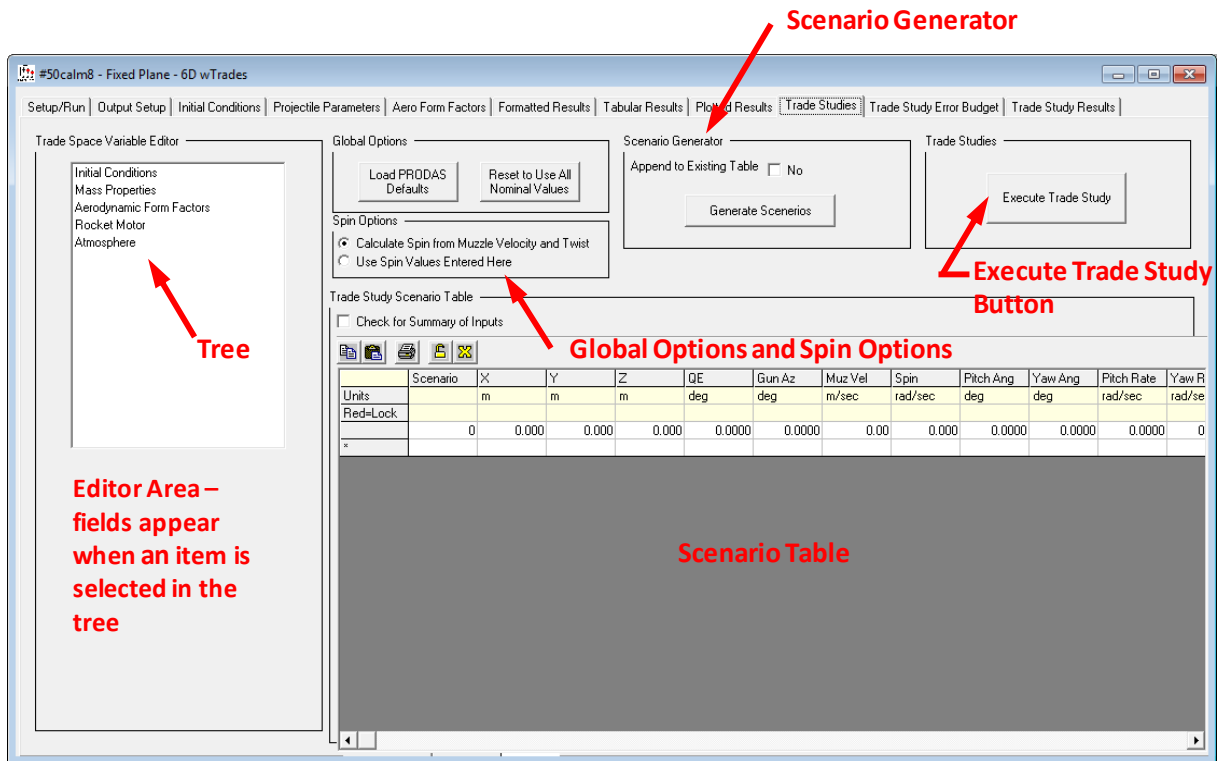
Figure 1 – Trade Studies Tab Overview

Let's do a simple trade study as an example. You can use any projectile to follow along with this example. I'm using an M8 .50 cal. We'll do a trade study that looks at the impact of cross wind on rounds fired at three different muzzle velocities.

First click on "Load PRODAS Defaults" to transfer all data from the single Trajectory run to the trade study. You'll receive a message (Figure 2) indicating that this operation is complete. Click OK to dismiss this message
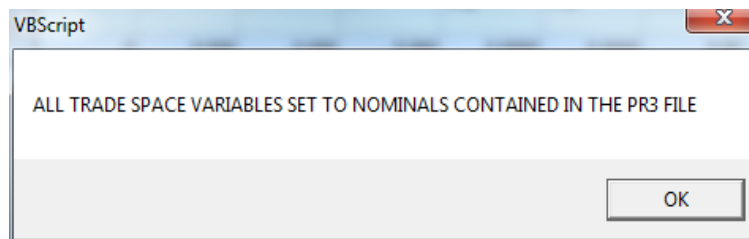

Figure 2 – Message Indicating that Load Defaults is Complete

Then click on Initial Conditions in the tree and drill down to Muzzle Velocity. You'll now see a list box below the tree and the nominal value for this parameter. Click on the list box to see the options. Let's use the Range and Increment option and specify 820 m/s as the beginning value, 30 m/s as the increment and 880 m/s as the ending value. The list box controls which option is used by the scenario generator, so it's OK to have data populated in the other options. See Figure 3 below.
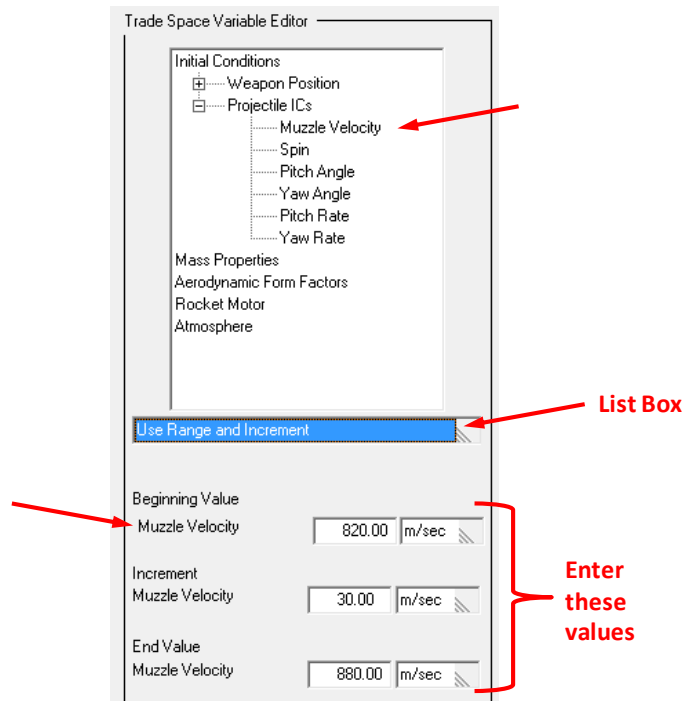
Figure 3 – Trade Space Editor for Muzzle Velocity

Next, let's select Cross Wind under Atmosphere in the tree. You may receive a message at this point because "User Met" must be selected on the Initial Conditions tab in order to include the atmosphere variables in the trade study. In my case the single trajectory had been run with Std Met so I received this message (Figure 4).
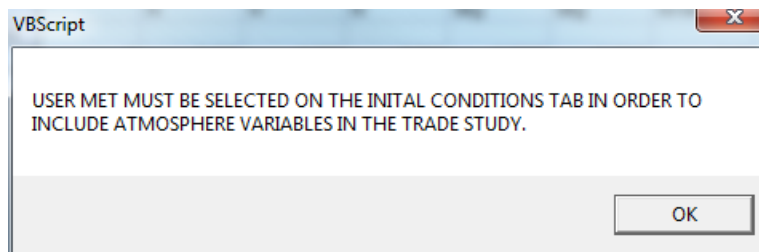

Figure 4 – User Met Warning Message

Once you've selected User Met, select the Table of values option and enter 0, 10 m/s and -10 m/s as the values to be evaluated. Note that when using the Table of Values option, the system will generate scenarios for all entered values until it hits all zeros. In other words if we had entered our "0" value last, it would not have been included as a scenario. See Figure 4.
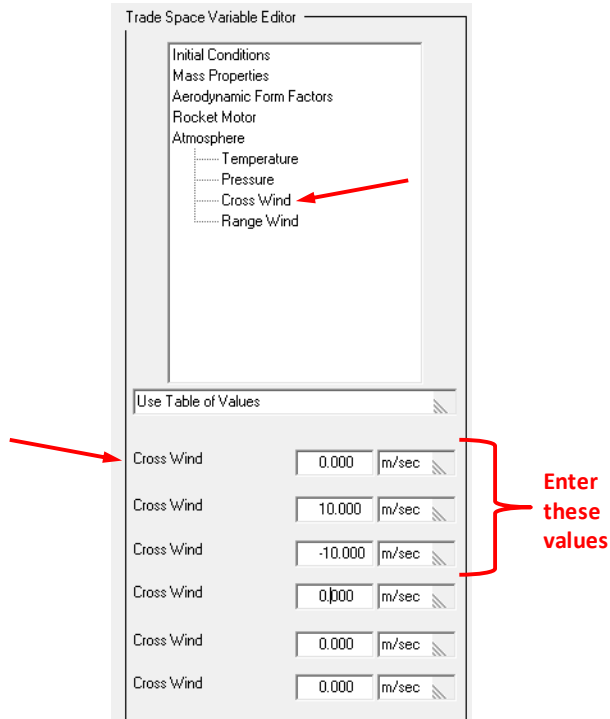
Figure 5 - Trade Space Editor Showing Cross Wind Entries

For this example we'll leave all other inputs at nominal and generate the scenarios. Click the Generate Scenario button now. The system generates a scenario for all permutations of the inputs. Since we have two variables involved in the trade study with three values for each variable we'll get a total of nine scenarios. A confirmation message (Figure 6) will appear indicating that 9 scenarios have been generated. You can review the table and note the three values of muzzle Velocity and Cross Wind. Note that the Spin values have been calculated from the entered Muzzle Velocity for each scenario.
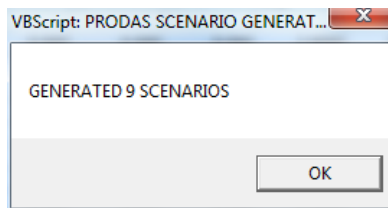

Figure 6 – Confirmation from Scenario Generator

If you click the "Check for Summary of Inputs" checkbox just above the table, you'll see a summary of the inputs that were used to generate these scenarios (See Figure 7).
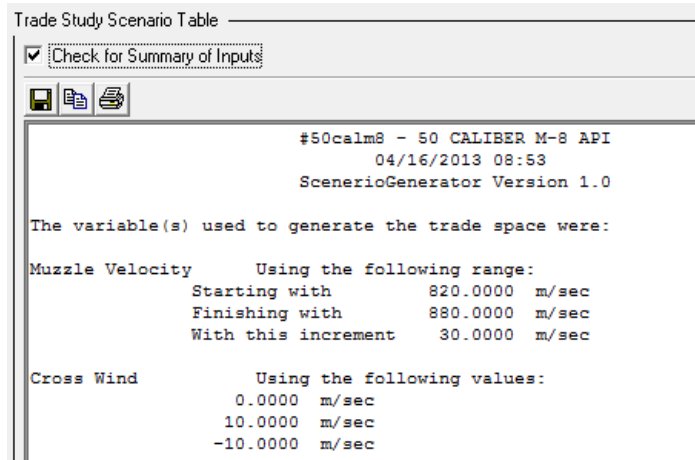
Figure 7 – Summary of Scenario Generator Inputs

The scenario Generator includes an option to "Append to Existing Table". If this is selected, the new scenarios will be added to the table in addition to those already generated. This option can be useful in setting up a trade study.

The nine trajectories defined by the scenarios can now be executed with a single click of the "Execute Trade Study" button. Click this button now.

Results are found on the Trade Study Results tab. First there's a table (Figure 8) showing the Position, Velocity and Time of Flight of the projectile at the end of the trajectory. Note that the termination is controlled by the parameters on the Setup/Run tab. Selecting these options appropriately is important to getting meaningful data from the trade study.

Figure 8 – Tabular Output from Trade Study

The list box makes plots and formatted output available. Take a look at both of these. Note that the plots are basically two views of the termination positions of the projectiles. By choosing the termination parameters carefully these can show impacts on the ground (horizontal target) or on a vertical target. The vertical target plot for our example is shown in Figure 9.
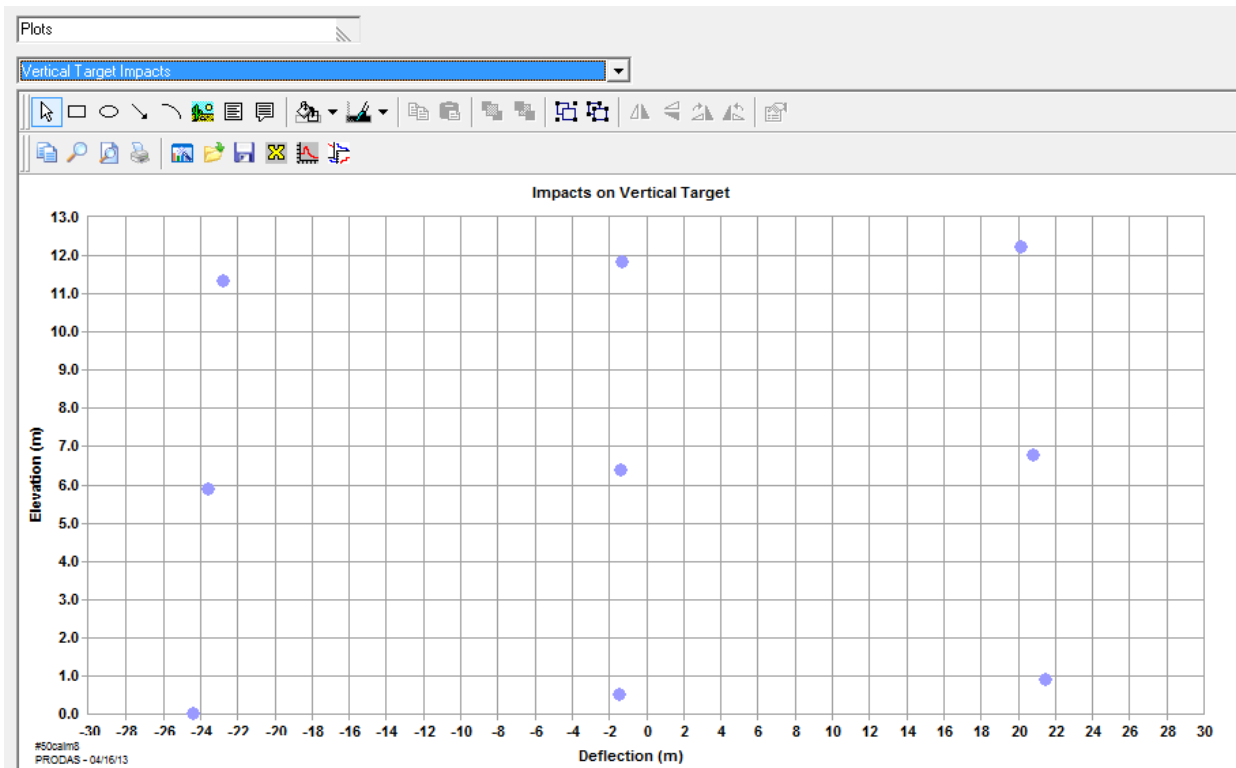
Figure 9 – Vertical Target Plot from Trade Study

Finally there is formatted output that summarizes both inputs and outputs to the trade study.

2.2   Error Budget

Now let's go one step further by implementing an error budget and evaluating miss distance at 2000 meters with the three different muzzle velocities we have defined. First, go back to the trade study tab and change Cross Wind to the "Use Nominal Value" option and make sure the nominal winds are zero. Then generate scenarios. You should have three scenarios at the three muzzle velocities we used before.

Now go to the Trade Study Error Budget tab and define the error budget. On the left we have the same tree of parameters and an editor that allows entry of a one standard deviation error. We'll set the following errors.

Variable	Error
Quadrant Elevation	0.5 miliradian
Azimuth	0.5 miliradian
Muzzle Velocity	3 mps
Mass	0.2 gram
Drag (axial force FF)	0.5%
Cross Wind	1.5 mps
Range Wind	2.0 mps

Let's enter the first one together. Click on Quadrant Elevation in the tree and note that there are two entries required. First is a check to include the error and second is the value of the error. Enter 0.0005 radian and click the checkbox to include the error. Then repeat for the other errors in this analysis.

Figure 10 – Trade Study Error Budget Tab showing input for Quadrant Elevation

Once all errors are entered, the next step is to decide on the number of Monte Carlo trials. I'm going to enter 100 trials (See Figure 11). This will result in a total of 303 trajectory runs as a nominal plus the 100 error runs will be completed for each of our three scenarios.

Figure 11 – Error Generator

Once this is entered we click Generate Errors to generate the random errors. A message box will appear with the number of errors generated. The errors appear in the table. Clicking the check box above the table will display summary information including statistics of the generated errors. "Mean shift" is the average of all the error values. The standard deviation is also calculated for the generated errors. I often scan these values to make sure the sample size is sufficient to get reasonably accurate results.

Figure 12 – Summary Output from Error Generator

Next, run the trade study with the errors applied by clicking the "Execute Trade Study with Errors" button. Since this will run 303 trajectories, it will take some time to run. On my machine it took just over 20 seconds. You may see the popup shown in Figure 13 because of the long run time. You can simply ignore this until the run completes or click "Continue".

Figure 13 – Script Control Warning

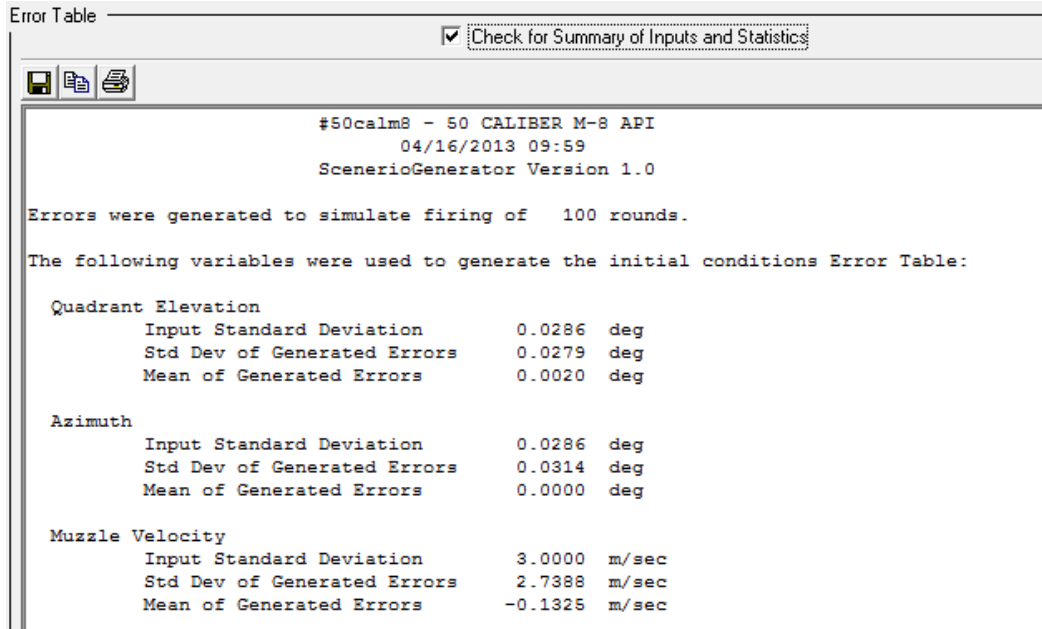Now let's look at the tabular results (Figure 14) from this run. Note that the first two columns (circled) show the Scenario Number and Error Number. These correspond to the numbers on the tables displayed on the Trade Studies and Error Budget Tabs and therefore provide traceability back to the inputs. The last four columns show the miss distance in the three axes from the termination point of the nominal trajectory for each scenario. These miss distances are used to calculate statistics on the results. In our example, the termination parameters were set up to stop at 2000 meter slant range, 5 seconds and 0 altitude. Most rounds made it to the 2000 foot slant range before hitting the ground. You can see this scanning the "X Miss" column. Most values are small numbers but a few rounds fell short and impacted the ground.

	Scenario	Error #	X Final	Y Final	Z Final	Velocity	TOF	AOF	Spin	X Miss	Y Miss	Z Miss	R Miss
Units			m	m	m	m/sec	sec	deg	rad/sec	m	m	m	m
Red=Lock													
	1	0	1999.98	-1.43	0.51	276.55	4.7284	4.9328	8534.5700	0.000	0.000	0.000	0.000
	1	1	1999.97	-4.39	0.58	276.52	4.7154	4.8887	8525.8500	-0.004	-2.955	0.070	2.956
	1	2	1992.33	1.55	0.00	275.13	4.7551	5.0219	8503.3700	-7.642	2.984	-0.506	8.220
	1	3	1996.57	-4.33	0.00	274.53	4.7473	4.9606	8477.8600	-3.405	-2.900	-0.506	4.501
	1	4	1991.48	0.02	0.00	276.99	4.7255	4.9531	8476.7400	-8.500	1.451	-0.506	8.638
	1	5	1999.97	-5.14	1.36	279.93	4.6956	4.8828	8586.0000	-0.002	-3.708	0.859	3.806
	1	6	1999.98	-2.11	0.35	276.27	4.7293	4.9473	8560.4300	-0.001	-0.678	-0.152	0.695
	1	7	1999.26	3.09	0.00	278.83	4.6930	4.9034	8590.1600	-0.713	4.517	-0.506	4.600
	1	8	1982.90	1.54	0.00	278.11	4.6531	4.8519	8610.6300	-17.081	2.973	-0.506	17.345
	1	9	1999.98	-0.13	0.35	277.11	4.7392	4.9599	8496.4700	0.000	1.301	-0.156	1.311
	1	10	1987.28	-9.46	0.00	275.80	4.7014	4.9257	8569.7900	-12.692	-8.029	-0.506	15.027
	1	11	1999.98	-3.08	1.79	274.88	4.7361	4.8994	8543.0300	0.004	-1.647	1.281	2.087
	1	12	1997.94	-6.87	0.00	275.47	4.7152	4.9168	8567.0700	-2.033	-5.440	-0.506	5.829
	1	13	1985.09	-1.63	0.00	277.61	4.7075	4.9499	8509.0500	-14.892	-0.200	-0.506	14.901
	1	14	1999.98	1.19	1.38	276.00	4.7318	4.9076	8529.3600	0.004	2.619	0.873	2.760
	1	15	1981.02	1.23	0.00	277.24	4.6792	4.9010	8559.1300	-18.962	2.659	-0.506	19.154
	1	16	1999.98	2.25	1.41	277.59	4.7169	4.8996	8561.4700	0.003	3.677	0.901	3.786
	1	17	1999.98	-0.66	1.11	276.04	4.7358	4.9353	8546.4600	0.003	0.771	0.603	0.978
	1	18	1999.98	4.21	2.81	281.81	4.6798	4.7969	8533.6800	0.006	5.643	2.306	6.096
	1	19	1982.57	-3.25	0.00	275.24	4.7033	4.9132	8508.4300	-17.405	-1.824	-0.506	17.507
	1	20	1999.98	0.63	1.95	280.39	4.6635	4.7848	8598.4000	0.007	2.062	1.441	2.516
	1	21	1994.49	0.11	0.00	278.30	4.6891	4.8890	8555.9900	-5.488	1.542	-0.506	5.723
	1	22	1999.98	-1.83	1.45	280.64	4.6988	4.8749	8529.7800	0.004	-0.397	0.944	1.024
	1	23	1999.98	-1.99	1.10	281.76	4.6809	4.8731	8585.1400	0.002	-0.559	0.593	0.815
	1	24	1994.23	-5.32	0.00	277.94	4.7041	4.9128	8522.8900	-5.746	-3.893	-0.506	6.959
	1	25	1999.97	-5.01	0.95	279.62	4.6800	4.8339	8562.7100	-0.004	-3.576	0.445	3.604
	1	26	1999.98	0.45	0.29	272.02	4.7805	5.0147	8510.7300	0.000	1.885	-0.215	1.897

Figure 14 – Tabular Output from Trade Study with Errors

The plotted output (Figure 15 and Figure 16) also shows this effect. The ground impact pattern shows the rounds that fell short. Note that I have expanded the scale to see this more clearly. The vertical target shows distinct groupings of the rounds fired at the three muzzle velocities.
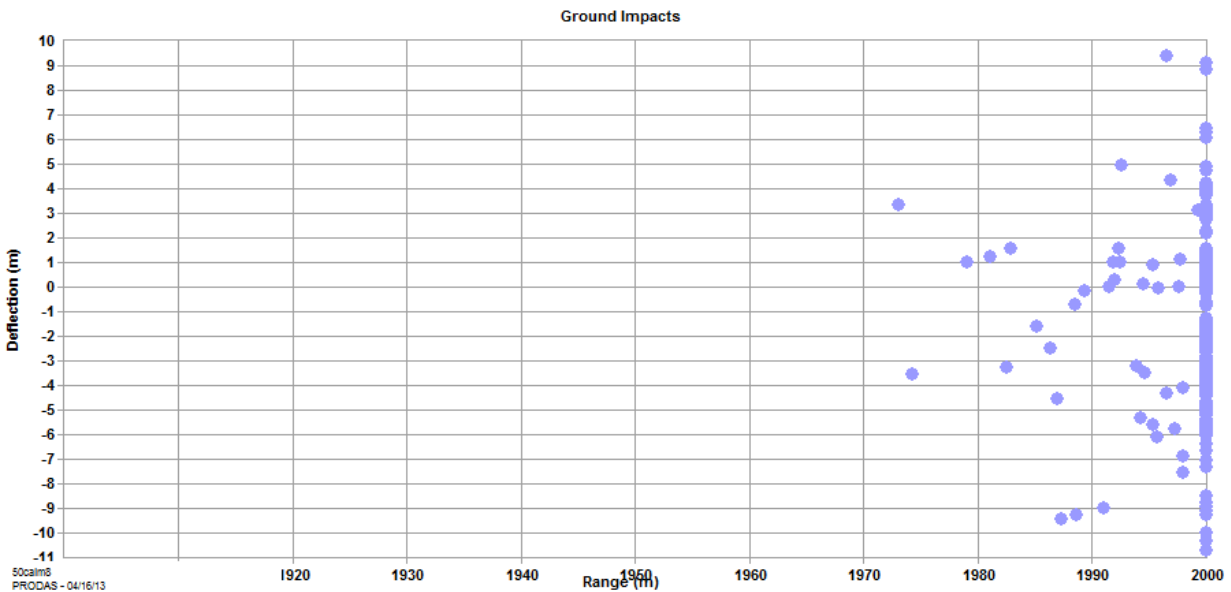

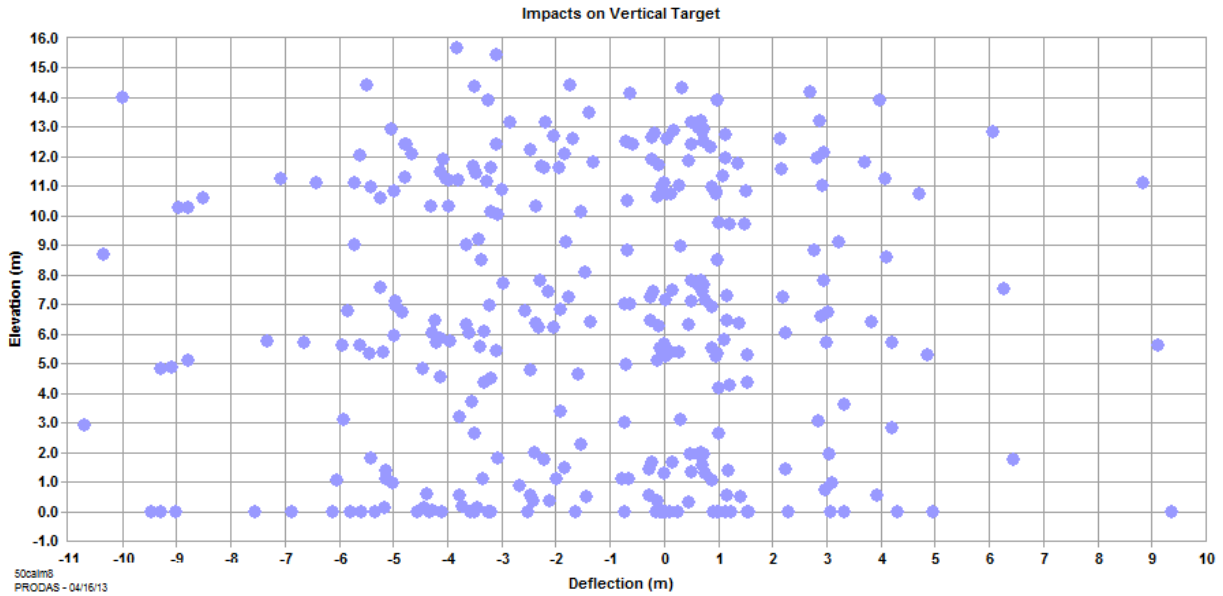Figure 15 – Ground Impact Plot from Trade Study with Errors Example

Figure 16 – Vertical Target Impacts Plot from Trade Study with Errors Example

The formatted output contains three sections. First is an echo of all inputs to the trade study for each scenario. Second is a summary of the errors that will be used in the analysis. Finally is a summary of the output for each scenario. This is shown below as Figure 17. The coordinates and time of the termination point for each nominal trajectory is shown along with the mean and standard deviation of the impacts of the error runs.
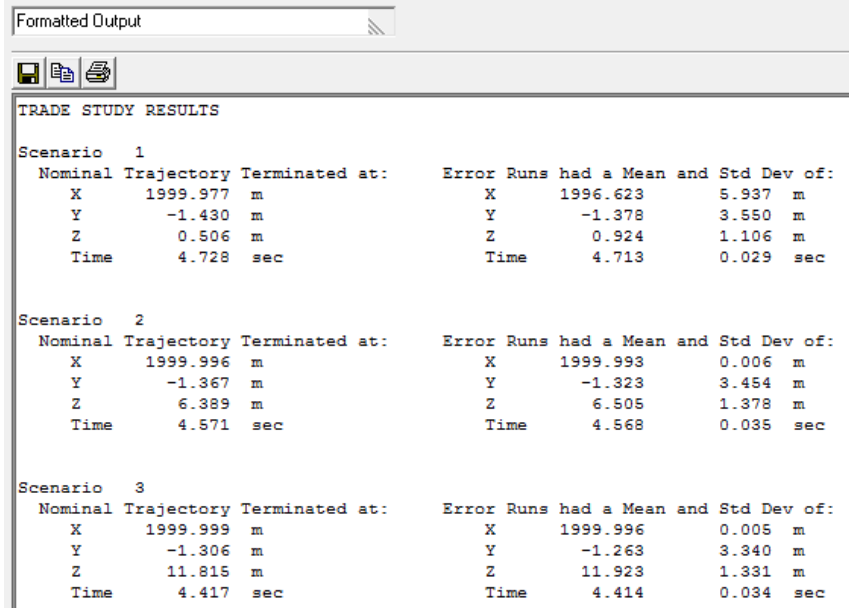

Figure 17 – Results section of Formatted Output for Trade Study with Errors Example

3.0   *Hints for Successful Trade Studies*

3.1   Scenario Generator Notes

In our example, we had only one or two variables (Muzzle Velocity and Cross Wind) involved in the trade study. If multiple variables are involved, then a scenario will be generated for each permutation of the inputs. For example if we had four QE's and three Muzzle Velocities plus two Masses then we would get 24 scenarios. Sometimes this is what you want and sometimes it's not. For example you might want to do a trade study looking at three different masses of the round and have the corresponding axial and transverse inertias for each mass. The scenario generator won't do this for you automatically but with a little effort you can do this study. Input the three mass values you want to study and let the scenario generator generate a scenario for each mass. Then you can edit the scenario table by pasting in the values of the inertias that go with each mass. The point is that the scenario table can be edited to meet the needs of your trade study

3.2   Special Note on Spin

Spin is a unique input to the trade study analysis. You may have noticed that there are two options for spin on the Trade Studies tab (See Figure 18). The default is to calculate the initial spin from the muzzle velocity using twist, reference diameter and bore diameter for each scenario. This is the option we used in the example. This is appropriate for Spinners where slip is not an issue. There may be cases where you wish to do a trade study to evaluate different spin rates or to look at spin errors associated with a slip Obturated round. Selecting the second option will use the spin values that you enter in the Trade Space and Error Editors to generate scenarios. You'll notice a warning popup if you attempt to include multiple values of spin in a trade study while having "Calculate Spin from Muzzle Velocity and Twist" selected.
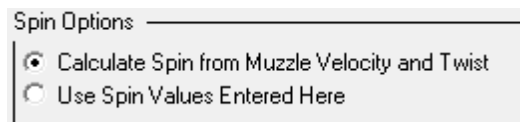

Figure 18 – Spin Options

If the spin value in the single trajectory analysis is locked, the locked value will transfer into the Trade Space Editor as the nominal value. However, spin will still recalculate when Scenarios are generated unless "Use Spin Values Entered Here" is checked.

3.3   Other Useful Tips

1. Remember to use the "Load PRODAS Defaults" button the first time you go to the Trade Studies Tab. If you forget this step, you're likely to leave a parameter set to zero and get unexpected results. You will see a reminder if you attempt to execute a trade study with no data in the Scenario Table.
2. Changes made on the single run trajectory input tabs like Initial Conditions are not automatically passed to the trade studies tab. They are only transferred to the trade study when you click "Load PRODAS Defaults". Data entered on the Trade Study or Error Budget tabs will never overwrite or change data used by the Single 6DOF
3. Remember to Generate Scenarios and/or Generate Initial Conditions after making changes in the Editors. This is the only way to update the tables that pass the inputs to the Trajectory analysis.

4. In order to vary the Atmosphere parameters in a trade study or to introduce errors for these parameters, User Met must be selected on the Initial Conditions tab. Note also that temperature inputs are all in Degrees C and that these units cannot be changed.

5. Set the Simulation Termination options to get the results you're looking for. Generally, you'll want to select these parameters so that all trajectories in the trade study terminate due to one of the stop values. For instance to evaluate impact on the ground, make sure that "Stop at Time" and "Stop at Slant Range" are set to large numbers so all rounds make it to the ground.

6. In rare cases, lack of gyroscopic stability or very high angle of attack can result in the trajectory simulation integration algorithm becoming unstable and producing erroneous results. If this occurs during a trade study run, you will receive a warning message at the end of the run and the output table will contain all zeros in the row(s) for the unstable runs. This allows the user to see the input conditions that caused the unstable condition. Note also that output statistics will not be valid as the zeros would have been included in the calculation.

4.0   *Summary*

This white paper is intended as an introduction to this new tool. This is one of several methods available within PRODAS to perform trade studies or to automatically run multiple trajectories. Arrow Tech offers an Advanced PRODAS Users Course that covers all the options thoroughly.