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Mission Capture Rate versus Turnaround Time and Fleet Size for the Military Spaceplane

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ABSTRACT

The United States Air Force Research Laboratory (AFRL) is conducting research into a military spaceplane (MSP) through the Military Spaceplane System Technology Program Office. The goal of this program is to provide the Air Force with safe, reliable, affordable, and routine access to space.

An important mission performance metric of the MSP program is the mission capture rate. The mission capture rate is a measure of the MSP's ability to meet mission sortie requirements. Extending this to a fleet of MSPs, the mission capture rate is defined as the total number of sorties the fleet is capable of divided by the total required number of sorties.

This research analyzes the relationship between mission capture rate and both turnaround time and fleet size. The turnaround time is the time between when the vehicle lands and when it can take off again. During this time the vehicle is refueled, maintenance and repair work is done, and the payload is loaded.

As turnaround time decreases and fleet size increases, the mission capture rate will increase. A precise definition of this relationship is made in order to determine the necessary fleet size for a given turnaround time subject to a desired mission capture rate.

A Monte Carlo simulation is performed to probabilistically analyze the mission capture rates. This analysis takes into account uncertainties in the utilization requirements of the MSP fleet. These uncertainties include the number of wars within the simulation period, the starting date & duration of each war, and each war's required sortie rate.

This analysis utilizes Crystal Ball Pro® along with Microsoft Excel®. This gives the analysis technique compatibility with commonly used computer platforms.

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NOMENCLATURE

AFRL	United States Air Force Research Laboratory
CAV	Common Aero Vehicle
MIS	Modular Insertion Stage
MSP	Military Spaceplane
NASP	National Aerospace Plane
OTV	Orbit Transfer Vehicle
RSE	Response Surface Equation
SMV	Space Maneuver Vehicle
SOV	Space Operations Vehicle

INTRODUCTION

The Air Force has shown an interest in space operations vehicles since the late 1950s. Programs such as X-20 and X-15 which took place from the 1950s-1970s to NASP, DC-X, X-33, and X-34, which took place from the 1980s to today all provided scientific and technological development for a future Air Force presence in space[1].

Today, the Air Force Research Laboratory (AFRL) is continuing this research and development of a military spaceplane (MSP) through the Military Spaceplane System Technology Program Office. The goal of this program is to provide the Air Force with safe, reliable, affordable, and routine access to space. In order to do this, the Air Force will need new space launch and operations capabilities, because current systems cannot sufficiently meet these Air Force goals[1].

The MSP system, partially shown in Figure 1, consists of a launch vehicle called the Space Operations Vehicle (SOV), three different types of payloads, and an Orbit Transfer Vehicle (OTV). The SOV will be some future expendable or reusable launch vehicle such as the Delta Clipper[1,6].

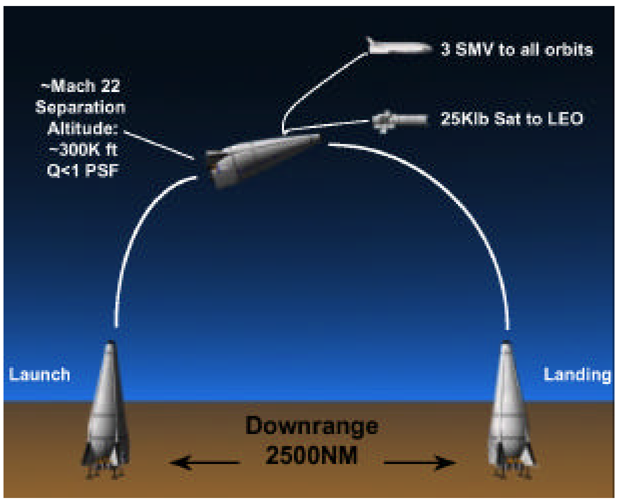

Figure 1 – MSP Mission Profile

The three types of payloads are the Space Maneuver Vehicle (SMV), the Common Aero Vehicle (CAV), and the Modular Insertion Stage (MIS). The SMV is a reusable satellite for a variety of orbital operations. The CAV is a reentry vehicle capable of bringing payloads back through the atmosphere from orbit. The MIS is an expendable upper stage used for orbit changing. The OTV is similar to the MIS, but is a reusable vehicle capable of moving satellites into different orbits.

This research focuses on the SOV portion of the MSP system, by analyzing the turnaround time and fleet size of the SOV in order to address mission capture rates.

Table 1 provides the SOV mission requirements threshold and objectives. This data is from the AFRL's "System Requirements Document for a Military Spaceplane System". The requirements of interest in this research project are the "emergency war or peace turn time" and the "mission capable rate" (mission capture rate).

Table 1 – SOV Mission Requirements

Requirement	Threshold	Objective
• **Sortie Utilization Rates Per MSP (sorties/day)**		
Peacetime Sustained	0.10	0.20
War/Exercise Sustained – for 30 days	0.33	0.50
War/Exercise Surge – for 7 days	0.50	1.00
Emergency Surge	3.00	4.00
• **Turn Times (hrs)**		
Emergency War or Peace	8	2
Peacetime Sustained	48	24
War/Exercise Sustained – for 30 days	18	12
War/Exercise Surge – for 7 days	12	8
• **System Availability**		
Mission Capable Rate (capture rate)	0.80	0.95

SIMULATION METHOD

Figure 2 illustrates the analysis process used in this research project. This analysis process allows for the determination of uncertainty through Monte Carlo simulation.

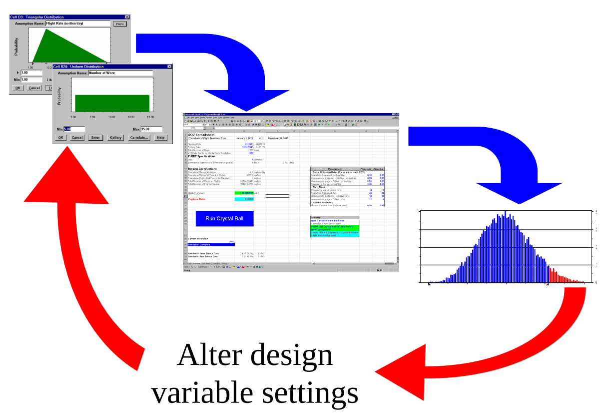

Figure 2 – Illustration of Analysis Process

Monte Carlo simulation is an accurate means of determining the uncertainty in a design. However, this method is rather computationally inefficient, because it requires many simulation runs in order to create probability distributions that are then used to compute confidence levels and predict corresponding uncertainties. Fortunately, the model used for calculating the mission capture rate is fairly simple and does not require a large computational time. As a result, many thousands of runs can be performed in a reasonable amount of time in order to produce mission capture rate distributions.

The first step in the analysis process, illustrated in the upper-left of Figure 2, is to determine the probability density functions for the uncertain variables. These uncertain variables, also known as noise variables, are the number of wars within the simulation period of 30 years, the starting date of each war, the duration of each war (in days), and each war's required sortie rate. Table 2 provides the probability distribution specifics for each noise variable. Several simplifying assumptions are made in creating these probability distributions. The required war sortie rate is assumed constant throughout the war. The war sortie rate is also assumed independent of the war duration. The types of wars or exercises considered are relatively short duration conflicts that have become more common over the last 15 years.

Table 2 – Noise Variable Probability Distributions

Noise Variable	Distribution Type	Minimum	Most Likely Value	Maximum
Number of Wars (in 30 years)	Uniform	5	N/A	15
War Starting Date	Uniform	1/1/2010	N/A	12/31/2039
War Duration (days)	Triangular	5	30	200
War Flight Rate (sorties/day)	Triangular	1	10	50

The second step in the analysis process, illustrated in the center of Figure 2, is to compute the mission capture rate based upon the two control variables (fleet size and turnaround time), and the random values generated for the four noise variables. The random values for the noise variables are generated by Crystal Ball Pro®, and are based upon the prescribed probability distributions shown in Table 2. The mission capture rate is computed by a Microsoft Excel® spreadsheet. This step is shown in more detail in Figure 3.

The Excel spreadsheet starts off by taking, as manual input, the following variables:

- Simulation starting and ending dates
- Number of data points for the Monte Carlo simulation
- Fleet Size
- Peacetime sustained sorties/day
- Peacetime sustained turnaround time
- Emergency war turnaround time

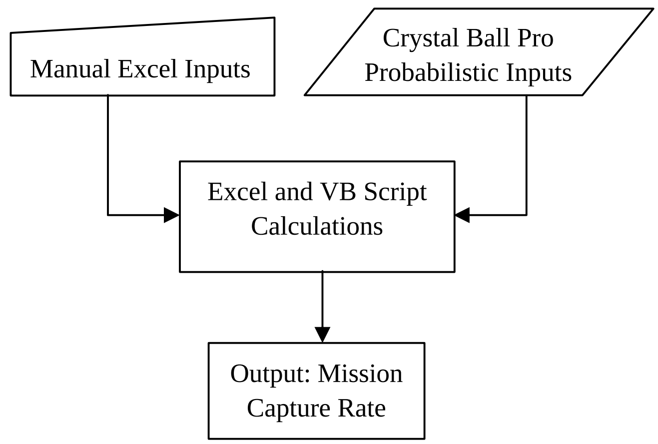

Figure 3 – Analysis Process Execution and Data Flow

In addition to these inputs, the probabilistic inputs listed in Table 2 are also provided by Crystal Ball Pro. The spreadsheet then calculates the following variables:

- Number of days for the simulation
- Peacetime usage based upon the fleet size and the peacetime sustained sorties/vehicle/day
- Total number of peacetime flights based upon the number of days and the peacetime usage
- Peacetime flights that cannot be handled based upon the number of days, the fleet size, and the peacetime sustained turnaround time
- Emergency available flights/day based upon the fleet size and the emergency war turnaround time.

A Microsoft Visual Basic script then iterates through every day of the simulation. For each day, the script checks to see if a war is occurring. If one is occurring, the required flights/day for that war is added to the total required flights/day (which also includes the peacetime sustained flights per day).

Once this is done for every war, the required flights/day for the current day is compared against the fleet's available flights/day. The number of flights made and the number of flights missed are recorded for that day. They are then added to the total flights made and the total flights missed. Figure 4 is an example of the resulting sortie rate distribution. The peaks in the distribution indicate times of war. If the total sorties/day exceeds the maximum capable sorties/day, then the excess sorties count as flights missed.

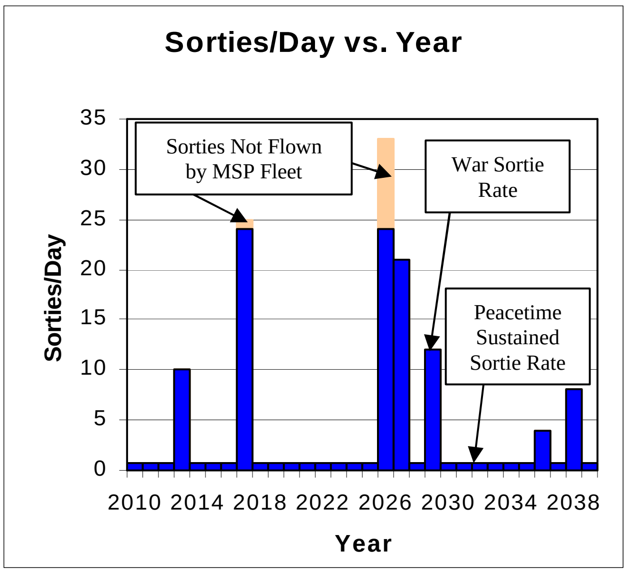

Figure 4 – Example Resulting Sortie Rate Distribution

After this calculation process is completed for every day in the simulation period, the capture rate is calculated. The capture rate is shown in Equation 1:

$$captureRate = \frac{totalFlightsMade}{totalFlightsMade + totalFlightsMissed} \qquad (1)$$

The third step in the analysis process, illustrated in the right of Figure 2, is the tabulation of the mission capture rate values computed in the second step. By repeating this process for different values of the noise variables, a probability distribution of mission capture rates is created. Figure 5 shows a sample probability distribution from a given set of manual Excel inputs. From this distribution of data, confidence intervals can be created. For this research, an 80% confidence lower bound on the mission capture rates is found in order to get a conservative estimate of the necessary fleet size and turnaround time to achieve the calculated mission capture rate.

RESULTS

This lower bound value is the mission capture rate in which 80% of the Monte Carlo simulation run values are larger. As a result, one can be 80% confident that the mission capture rate will be at or above the values provided.

Figure 5 illustrates how the Monte Carlo simulation process can yield confidence levels. The probability distribution shown in Figure 5 is simply a histogram of the mission capture rates for a given fleet size and turnaround time. The 80% lower bound is the dividing line between the two colors.

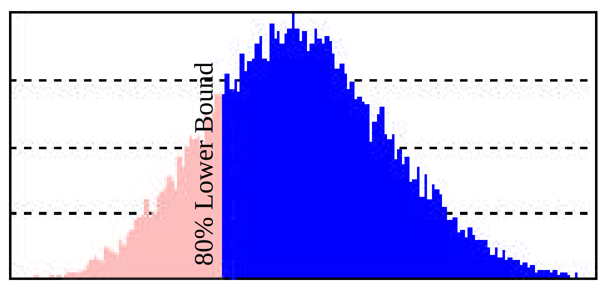

Figure 5 – Illustration of 80% Lower Bound

Applying this technique for several values of fleet size and turnaround time, Table 3 can be produced. Table 3 summarizes the results of 16 Monte Carlo simulation runs. Each simulation run consists of 2,000 iterations of the analysis process describe previously and illustrated in Figure 2.

From these results, fleet size predictions can be made for an assumed emergency turnaround time and a desired mission capture rate. For example, using the threshold mission capture rate of 0.80 and emergency turnaround time of 8 hours as defined by the AFRL's "System Requirements Document for a Military Spaceplane System", a minimum fleet size of approximately 8 is found using Table 3.

Table 3 – 80% Confidence Mission Capture Rates for the MSP Fleet

		Emergency Turnaround Time (hrs)			
		4	**8**	**16**	**32**
Fleet Size	**4**	0.8501	0.6266	0.4651	0.3725
	8	1.0000	0.8468	0.6229	0.4726
	16	1.0000	0.9999	0.8464	0.6273
	32	1.0000	1.0000	0.9996	0.8474

To get a better feel for the design space at design points not investigated by any of the Monte Carlo simulation runs, a contour plot is created. Figure 6 shows this contour plot of the 80% confidence mission capture rates. This allows us to see very easily what the relationship is between fleet size and turnaround time at some mission capture rate constraint.

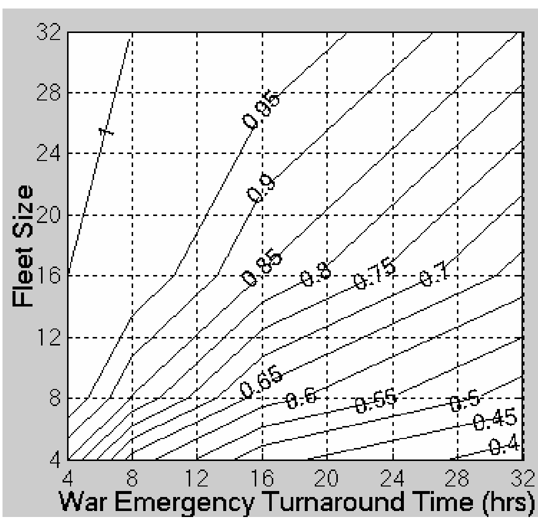

Figure 6 – Contour Plot of 80% Confidence Mission Capture Rates

Going back to our previous example, using the AFRL's threshold mission capture rate of 0.80, we see that with an emergency turnaround time of 8 hours, the fleet size would need to be at least 7 vehicles. However, if we then used the AFRL's objective mission capture rate of 0.95, we see that with an emergency turnaround time of 8 hours, the fleet size would need to be at least 14 vehicles.

Instead of the above graphical method, we can investigate the design space by creating a response surface equation (RSE). An RSE is typically a polynomial equation used to approximate a value computed by some analysis code. In other words, the RSE is an equation that approximates the design space.

To create an RSE, we start by transforming our problem into a more general form:

y = 80% Confidence Mission Capture Rate
x_1 = Fleet Size
x_2 = Turnaround Time

Interactions and 2nd order effects are included in order to capture any nonlinearity in the design space. With this in mind, the following general RSE equation is shown by Equation 2:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 \qquad (2)$$

The coefficients (b_i's) are computed using Equation 3:

$$\mathbf{b} = \left(\mathbf{X}^T * \mathbf{X}\right)^{-1} * \mathbf{X}^T * \mathbf{y} \qquad (3)$$

Where **b** is the vector of coefficients, **y** is the vector of mission capture rates from the 16 runs, and **X** is the design matrix for the 16 runs. In this case, **X** is a 16x6 matrix and is shown in Equation 4:

$$\begin{array}{c} \begin{array}{cccccc} 1 & x_1 & x_2 & x_1 x_2 & x_1^2 & x_2^2 \end{array} \\ \mathbf{X} = \begin{bmatrix} 1 & 4 & 4 & 16 & 16 & 16 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & 32 & 32 & 1024 & 1024 & 1024 \end{bmatrix} \end{array} \qquad (4)$$

Solving for **b** using the 16 data points, we obtain Equation 5:

$$\mathbf{b} = \begin{bmatrix} 0.813975 \\ 0.031752 \\ -0.031848 \\ 3.946923*10^{-4} \\ -6.821631*10^{-4} \\ 3.433915*10^{-4} \end{bmatrix} \qquad (5)$$

This model works fairly well on the interior points, but does not fair as well at the edges of the part of the design space explored by the Monte Carlo simulation runs. Further Monte Carlo runs are necessary to extend the capability of the RSE, and can be built upon previous simulation runs.

The model used for calculating the mission capture rate is relatively simple, and could benefit from taking into account additional system requirements defined by the AFRL. However, this analysis method allows relationships between mission capture rate and both turnaround time and fleet size to be analyzed for a variety of initial assumptions.

CONCLUSIONS

A method for determining the mission capture rate for a given fleet size and turnaround time was presented. In additional to this method, a probabilistic Monte Carlo simulation was used in order to create a probability distribution of mission capture rate subject to several key uncertain variables.

Sixteen Monte Carlo simulation runs were performed, each for a different combination of fleet size and turnaround time. Each Monte Carlo simulation run consists of 2,000 data points. In addition to the fleet size and turnaround time, each data point has, as input, a random value for the uncertain variables (number of wars, war duration, and required war sortie rate) based upon the probability distributions assigned to these uncertain variables.

These data points form the distribution of mission capture rates for a given fleet size and turnaround time. From this distribution, confidence levels have been obtained. A contour plot and an RSE have been made of the mission capture rate as a function of both fleet size and turnaround time so one can determine the value of any variable if the values of the other two are known.

ACKNOWLEDGMENTS

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