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LOW EARTH ORBIT RENDEZVOUS STRATEGY FOR LUNAR MISSIONS

Grant R. Cates
Operations Integration Division
Shuttle Processing Directorate
Kennedy Space Center, FL 32899, U.S.A.

William M. Cirillo
Systems Analysis and Concepts Directorate
Langley Research Center
Hampton, VA 23681-2199, U.S.A.

Chel Stromgren
Science Applications International Corp.
1710 SAIC Drive
McLean, VA 22102, U.S.A.

ABSTRACT

On January 14, 2004 President George W. Bush announced a new Vision for Space Exploration calling for NASA to return humans to the moon. In 2005 NASA decided to use a Low Earth Orbit (LEO) rendezvous strategy for the lunar missions. A Discrete Event Simulation (DES) based model of this strategy was constructed. Results of the model were then used for subsequent analysis to explore the ramifications of the LEO rendezvous strategy.

1 INTRODUCTION

The Vision for Space announced by President George W. Bush on January 14, 2004 called for NASA to return humans to the moon. In 2005 NASA chose a Low Earth Orbit (LEO) strategy for the lunar missions. One of the benefits of this strategy was that it avoided the need to develop an extremely large and expensive rocket capable of launching a mission to the moon.

The LEO rendezvous strategy instead allows NASA to develop two smaller rockets using heritage Space Shuttle hardware. One of these rockets will be a Cargo Launch Vehicle (CaLV) that will carry an Earth Departure Stage (EDS) and a Lunar Surface Access Module (LSAM). The other rocket will be a Human Rated Launch Vehicle (CLV) that will loft the crew exploration vehicle into LEO.

The operational concept calls for the CaLV to be launched first in order to place the EDS and the LSAM in a parking orbit in LEO. The CLV is launched next with the Crew Exploration Vehicle (CEV). The CEV will then rendezvous and dock with the EDS/LSAM in LEO. The EDS is used to provide the delta velocity required to depart LEO for the moon—Trans Lunar Injection (TLI). While the EDS and LSAM are waiting in LEO for the arrival of the CEV, the cryogenic propellants in the EDS and LSAM are boiling off.

The current specification calls for the EDS to have sufficient propellant to provide 95 days of loiter capability in LEO. Should the CEV fail to rendezvous with the EDS such that a TLI burn can be initiated during that 95-day period, then the lunar mission would be lost. The EDS and LSAM would be de-orbited and destroyed. The crew would return to earth in the CEV.

The question of whether or not the 95-day capability provided sufficient margin to provide a high probability of mission success became the focus of interest. The 95-day requirement also has a significant impact upon the design of the EDS. A larger volume of propellants is required increasing the size, weight, and cost of the EDS. Reducing the 95-day requirement would allow a smaller, lighter, cheaper EDS to be developed.

2 MODEL OVERVIEW

The Constellation-Manifest Assessment Simulation Technique (C-MAST) was used to perform a preliminary exploration of the 95-day requirement that has been imposed upon the EDS. C-MAST is a discrete event simulation environment using Rockwell Software's Arena, ExpertFit by Averill M. Law and Associates and the Microsoft Office suite of Excel, Word, PowerPoint, and Visio.

C-MAST provides NASA with an in-house capability to perform assessments of the proposed Constellation architecture, infrastructure, and requirements and for executing mission manifests. C-MAST is similar to the Manifest Assessment Simulation Tool (MAST) that was developed for the Space Shuttle program (Cates 2004; Cates and Mollaghasemi 2005). MAST benefited from the space shuttle model developed in 2001 (Cates et al. 2002).

The model shown in Figure 1 for the 95-day requirement begins at the point in time in which the CaLV has been launched. Thus, it assumes that the Flight Readiness Review (FRR) for both the CaLV and CLV have occurred and that a go has been given for launch of both vehicles.

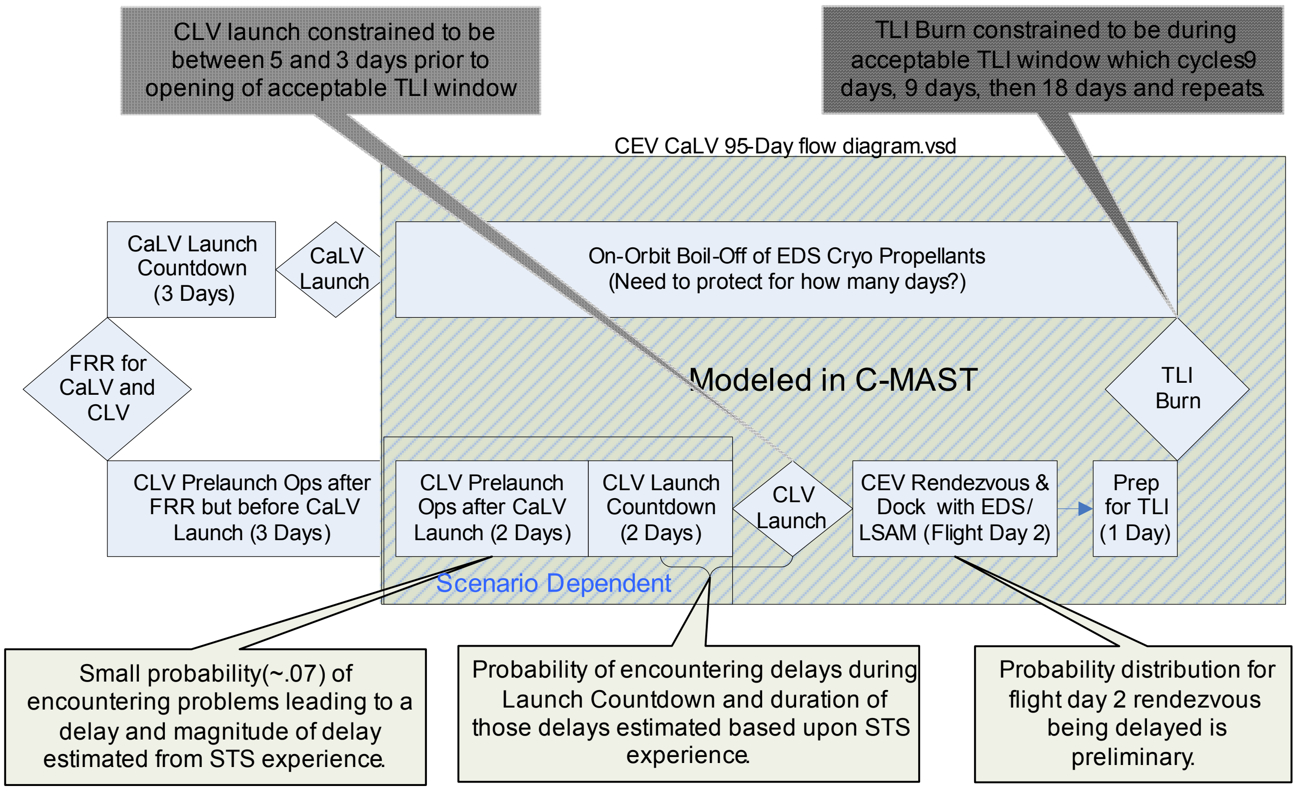

Figure 1: C-MAST Model Architecture

It is assumed that the EDS cryogenic propellant tanks were continuously replenished during launch countdown until just moments before launch. This implies that the tanks are essentially full at the time that the EDS is inserted into LEO. Furthermore, it is assumed that the CLV is at a second launch pad and can be ready to launch nominally soon e.g., four days after the CaLV launch.

The model takes into account the uncertainty associated with pre-launch operations and delays/scrubs during launch countdown. Launch delays can have a significant impact upon how long the EDS and LSAM are waiting in LEO. Following launch of the CLV, the CEV has a flight day-2 planned rendezvous with the EDS/LSAM. The model includes a probability distribution for when the rendezvous might actually occur e.g., flight day-3 or later. Preparations for the TLI burn are assumed to require one day.

The windows of opportunity for the TLI burn are determined primarily by orbital mechanics, vehicle performance, and significantly by the desired solar lighting conditions at the planned lunar landing sight. The orbital mechanics of the earth-lunar system along with the likely vehicle performance of the integrated EDS/LSAM/CEV provide lunar injection windows from LEO approximately every nine days as shown in Figure 2. These windows are assumed to be open for sufficient time to allow for a primary attempt to initiate the TLI burn and a secondary attempt on the next orbit (approximately 90 minutes later). Injection Window 1 puts the lunar landing site in highly desired “morning” lighting conditions. Window 2 puts the landing site in acceptable “afternoon” lighting conditions. Window 3 puts the landing site in undesirable darkness.

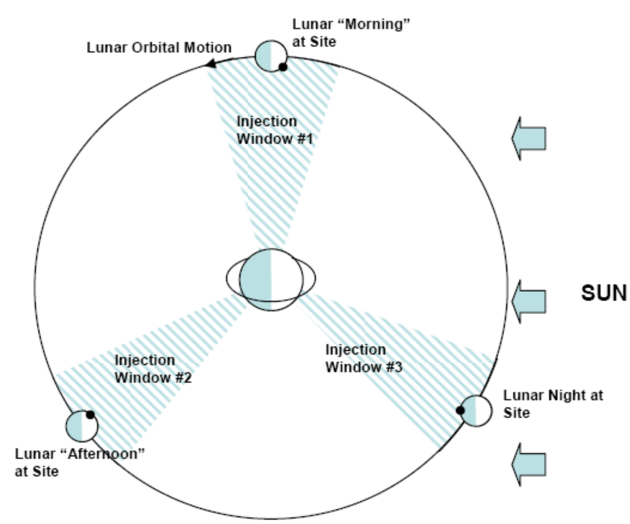

Figure 2: Trans-Lunar Injection Windows

3 MODEL BASIS OF ESTIMATE

Input analysis for the model followed techniques identified by Law and Kelton (2000). Shuttle historical data, along with inputs from subject matter experts, were used to estimate the appropriate durations and event probabilities in the model. It should be noted that there is uncertainty in the estimates, which is greater for those portions of the model in which there is little historical information. The utilization of shuttle data may also be questioned since the new launch vehicles should be less complex. Due to the configuration of the CLV and the supporting infrastructure, it may be beneficial to investigate the use of Apollo era data in the future.

3.1 CLV Pre-Countdown Uncertainty

The model picks up at the point in time in which the CaLV has launched and is further assumed that the CLV is at a launch pad in a position to launch in as few as two days. The uncertainty with respect to being in a position to conduct the launch countdown is therefore limited to the likelihood of a problem occurring between the time that the CaLV has launched and the CLV begins the launch countdown.

Historical data from the space shuttle was reviewed to determine the probability of a problem being encountered during a two-day period and the magnitude of the delay it might cause. This information was then used to derive the discrete distribution shown in the equation below.

Added Pad Days =
DISC (0.925,0, 0.9352,1, 0.9443,2, 0.9489,3, 0.9580,4, 0.9636,5, 0.9705,6, 0.9750,7, 0.9761,8, 0.9784,9, 0.9807,10, 0.9841,12, 0.9898,14, 0.9943,21, 0.9989,28, 1.0,31)

3.2 Countdown Uncertainty

The probability of launch occurring was estimated using the space shuttle history which was thought to be conservative. After reviewing the historical data, estimates were made for launch event probabilities for the CLV and CaLV. The historical data includes information regarding when the delays actually occurred. This information was used to estimate different event probabilities based upon reaching later points in the countdown; i.e., to T-90 minutes and to T-9 minutes. Table 1 shows the event probabilities for launch outcomes.

Should a delay or scrub occur during the launch countdown, there will then be a delay of several days before the next launch attempt. In the case of weather delays or minor non-weather delays, a subsequent launch attempt may be made the very next day. The historical data from the space shuttle was reviewed to develop discrete distributions for three of the delay categories as shown below.

Weather =
DISC(.7895,1, .8947,2, .9475,3, .9737,5, 1,23)

Flight Hardware =
DISC(.351,1, .459,2, .486,3, .541,4, .622,5, .649,6, .703,7, .784,8, .811,10, .838,11, .865,12, .892,14, .919,18, .946,19, .973,75, 1,99)

Infrastructure =
DISC(.533 , 1 , .733,2, .800,3, .933,4, 1, 7)

Table 1: Launch Countdown Outcomes

		Delays or Scrubs During Launch Countdown				
	Launch Occurs	Weather	Flight Hardware (Less Engine Abort)	Infrastructure or Operational Prerogative	Main Engine Abort	Total
STS Experience	0.54	0.18	0.18	0.07	0.02	1.00
CLV Estimate	0.62	0.17	0.15	0.06	0.01	1.00
T-90 Minutes to Launch	0.90	0.02	0.05	0.03	0.01	1.00
T-9 Minutes to Launch	0.94	0.00	0.03	0.02	0.01	1.00
CaLV Estimate	0.65	0.12	0.15	0.05	0.02	1.00

A main engine abort is handled differently because in the case of the CLV, there are no main engines like there are on the first stage of space shuttle. The CLV first stage consists solely of a single solid fueled rocket. The upper stage of the CLV, however, does have a liquid fueled engine similar to the first stage engines of the space shuttle.

The probability for a CLV main engine abort shown in Table 1 reflects the estimated probability that the upper-stage engine on the CLV will indicate a problem prior to launch such that the engine has to be removed and replaced. This scenario would necessitate a return to the vehicle integration facility. The time to return to the integration facility has been estimated at three days and the time to destack the upper stage was estimated at four days. Then the normal process of stacking and going out to the launch pad for pre-launch preparations and countdown would begin again.

3.3 Ascent Events

The model currently assumes that following launch, the CEV is placed into low earth orbit without incident. This assumption can be changed to include probabilities for ascent anomalies.

3.4 Low Earth Orbit Operations

The CEV is assumed to rendezvous and dock with the EDS two days after the launch of the CLV. This is referred to as a planned Flight-Day-2 rendezvous. The model includes a discrete distribution for the probability that the actual rendezvous and dock will occur later than planned.

Delay to Rendezvous & Dock =
DISC(.80,0, .90,1, .96,2, .99,3, 1.0,4)

The distribution for a delay to rendezvous and dock is considered an educated guess at this time and requires additional validation by subject matter experts.

Following a successful dock between the CEV and the EDS/LSAM, the model assumes that one day is required for preparations to be in position for a TLI burn.

4 INITIAL RESULTS

The 95 percent confidence band for the simulation results are shown in Figure 3. With an 18-day capability there is approximately a 62 to 71 percent probability of a successful TLI burn for windows 1 or 2. A 45-day capability would provide an increased probability range of 79 to 85 percent. Increased capability beyond 45 days provides only modest improvement such that a 95-day capability provides nearly a 90 percent probability of a successful TLI burn for Windows 1 or 2.

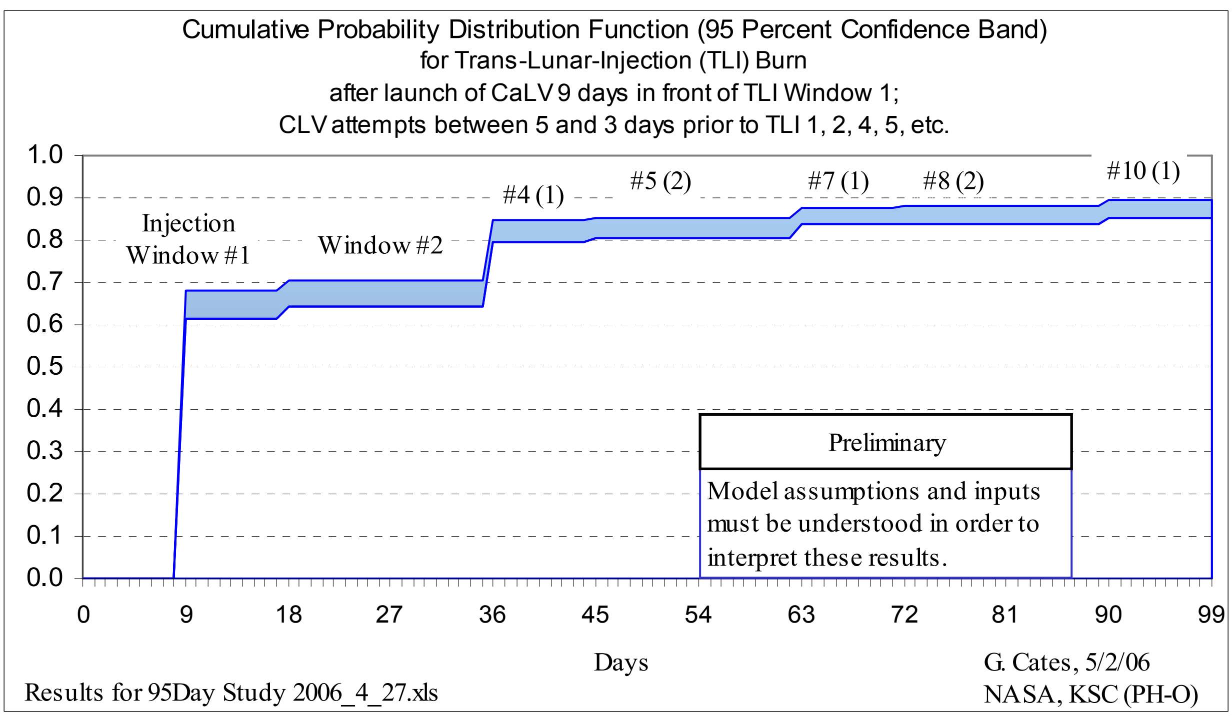

Figure 3: Results

5 FORWARD WORK

The assumptions that went into this analysis are currently being validated and the model is being improved where possible. For example, in addition to using shuttle historical data, similar data from the expendable rocket experience is being acquired and analyzed, and will then be considered for use in the future revisions of the model. The Kennedy Space Center Weather Office is reviewing and commenting upon the probabilities for weather related delays to launch. The Mission Operations Directorate at the Johnson Space Center will be reviewing and commenting upon how LEO operations have been modeled.

It is anticipated that the model will be used to explore various alternatives to improve the cumulative probability distribution function. Alternative exploration, in addition to potentially being able to improve the input probabilities, could include launching the CLV on the same day as the CaLV.

It is also intended that the scope of this model be extended in the future to include the entire lunar campaign architecture and concept of operations.

ACKNOWLEDGMENTS

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APPENDIX: ACRONYMS

CaLV	Cargo Launch Vehicle
CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle
C-MAST	Constellation Manifest Assessment Simulation Technique
DES	Discrete Event Simulation
EDS	Earth Departure Stage
FRR	Flight Readiness Review
LSAM	Lunar Surface Access Module
MAST	Manifest Assessment Simulation Tool
NASA	National Aeronautics and Space Administration
STS	Space Transportation System
TLI	Trans Lunar Injection

REFERENCES

Cates, G. R, M. Mollaghasemi, G. Rabadi, and M. J. Steele. 2002. Modeling the space shuttle. In *Proceedings of the 2002 Winter Simulation Conference*, ed. E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, 754-762. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Cates, G.R. 2004. Improving project management with simulation and completion distribution functions. Doctoral dissertation. Department of Industrial Engineering and Management Systems, University of Central Florida, Orlando, Florida. Available via <http://purl.fcla.edu/fcla/etd/CFE0000209> [Accessed April 10, 2005].

Cates, G. R., and M. Mollaghasemi. 2005. Supporting the vision for space with discrete event simulation. In *Proceedings of the 2005 Winter Simulation Conference*, ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, 1306-1310. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Law, A.M., and W.D. Kelton. 2000. *Simulation Modeling and Analysis*. 3rd ed. McGraw-Hill.

AUTHOR BIOGRAPHIES

GRANT R. CATES is assigned to the Operations Integration Division in the Space Shuttle Operations Directorate at the Kennedy Space Center. He received his Ph.D. from the University of Central Florida in 2004. He is a member of IIE, INFORMS, and AIAA. His e-mail address is <grant.r.cates@nasa.gov>.

WILLIAM M. CIRILLO is a Senior Researcher in the Systems Analysis and Concepts Directorate at NASA's Langley Research Center. He received his B.S. in Aerospace Engineering from the University of Michigan in 1983. His e-mail address is <william.m.cirillo@nasa.gov>.

CHEL STROMGREN a Senior Scientist at Science Applications International Corporation (SAIC). His e-mail address is <chel.stromgren@saic.com>.