TRANSLATIONAL RESEARCH INSTITUTE FOR SPACE HEALTH

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USING BAYESIAN ESTIMATION TO QUANTIFY THE RISKS OF SPACEFLIGHT

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Presentation key points

- **Big Picture:** Bayesian estimation is a powerful way to integrate prior belief with continually accruing knowledge to get a better estimate of probability in real-time.

- **Translational nature:** Simple Bayesian estimation can be used as a check against more complex methods commonly used in probabilistic risk assessments.

- **Space Health application:** Any domain where probability of an outcome is evolving over time.

- **TRISH Factor:** This method is surprisingly easy in that it requires almost no input data and simple calculations, but provides results comparable to more complex approaches.

Apollo 8

- First lunar circumlunar space flight by a manned spacecraft, December 1968
- Crewed by Frank Borman, William Anders and Jim Lovell
- “Earthrise” photo, Christmas Eve reading from Book of Genesis
- Chris Kraft to Susan Borman: 50/50 odds of success

Apollo Program

- Record:
  - Eight successes: Apollo 8, 10, 11, 12, 14, 15, 16, 17
  - One (successful) failure: Apollo 13
- Mission success in this context: Loss of Mission (LOM)
- Was Kraft wrong?
- What was the true probability of LOM during the Apollo program?

Frequentist probability

- Assume binomial distribution:

MLE = (failures)/(trials)
P(LOM) = 1/9 = 0.111 or 11.1%

- Do we believe it?
- What about Kraft's 50/50? Is this somehow useful information?
- If we use Bayesian methods to integrate the prior information provided by Kraft, P(LOM) = 1/3 = 0.333 or 33.3%

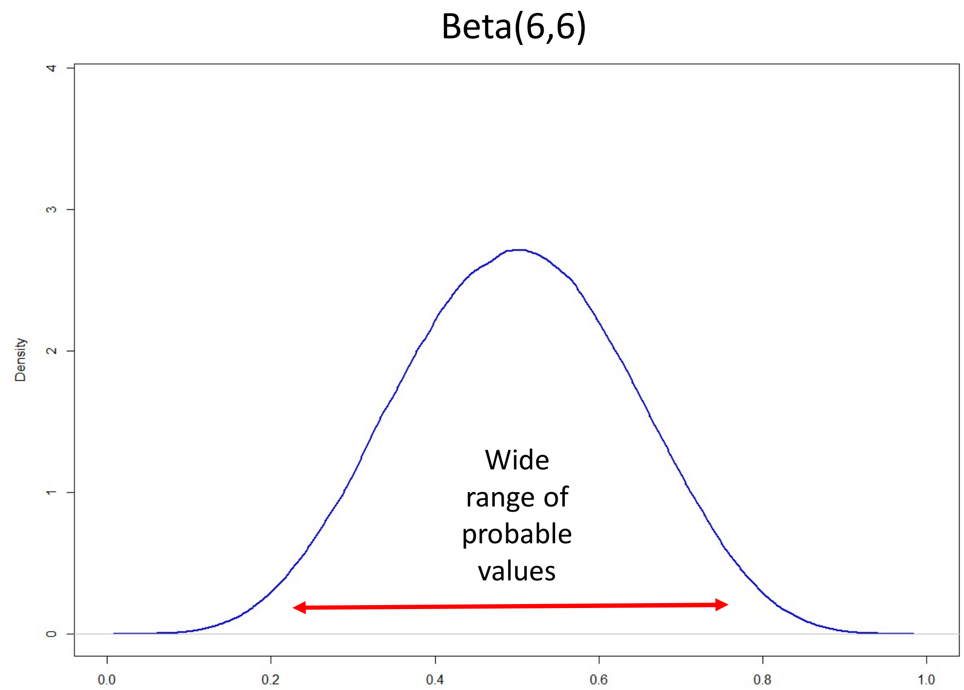
Bayesian probability

- Allows us to estimate posterior probability using both our prior beliefs and the observed data
  - Posterior = P(LOM)
  - Likelihood = Prior belief of the probability
  - Data = Spaceflight experience
- For the binomial distribution, Beta distribution is a convenient prior
- Formula for posterior:

$$\mathrm{P(LOM)} = \frac{\text{(observed failures + prior failures)}}{\text{(observed trials + prior trials)}}$$

Apollo prior

- For the Apollo missions, 50% failure rate is our “Kraftian prior”
- But how sure are we about this estimate? Imagine we think this would hold over 12 missions: this means 6 failures, 6 successes for a prior of Beta(6,6)
- Not a strong prior, as shown by plot



Posterior formula

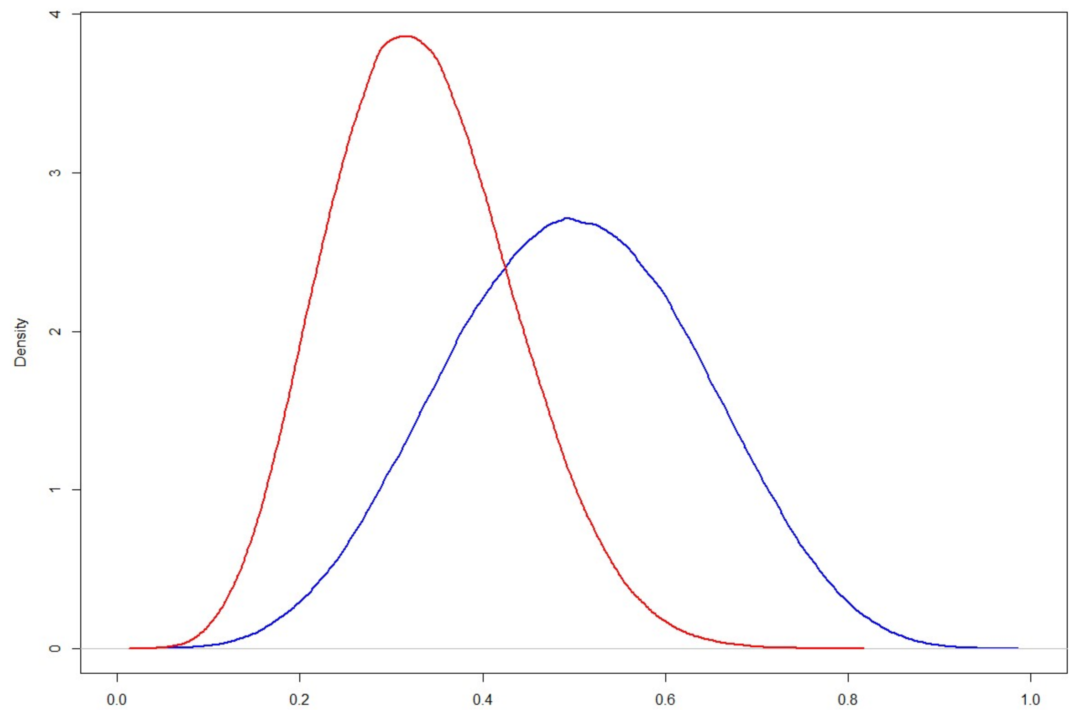
$$P(\text{LOM}) =$$

$$\frac{\text{(observed failures + prior failures)}}{\text{(observed trials + prior trials)}}$$

$$=$$

$$\frac{(1+6)}{(9+12)} = \frac{7}{21} = 0.333$$

95% CI = (0.11, 0.61)




USA

SHUTTLE PRA EVOLUTION

Presenter **Roger Boyer**
Date 10/26/10 | Page 5

- **The Shuttle PRA has been incrementally developed over many years**
  - Mission Phases (Ascent, Orbit, Entry)
  - Number of Systems Modeled
  - Risk Factors considered (systems failures, phenomenological failures, human reliability, external events, etc.)
- **The advent of established NASA requirements, standards, and tools - as well as the development of a strong shuttle program PRA team have resulted in significant recent progress**
- **Iteration 3.2 is the most comprehensive Shuttle PRA to date**

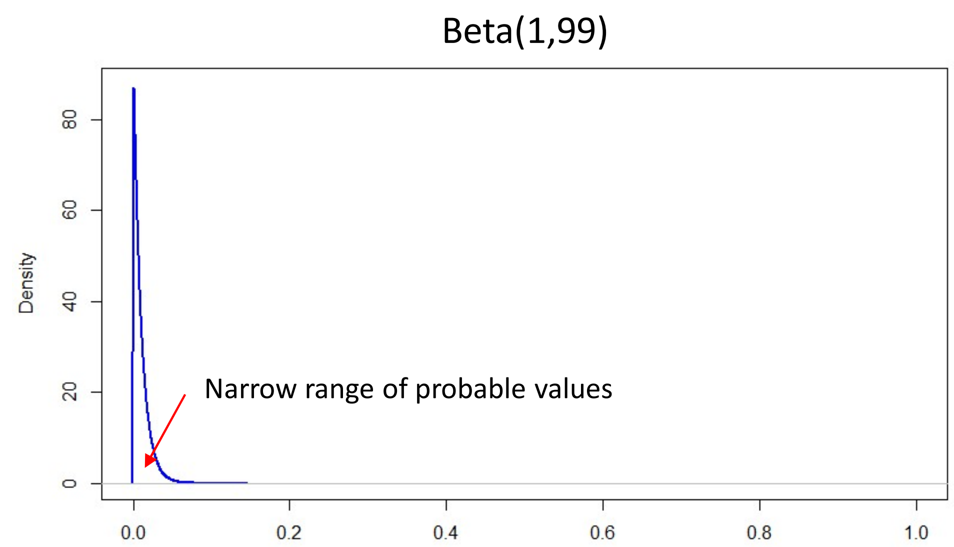
Mean Probability of LOCV

1:70	1:55	1:73	1:131	1:234	1:78	1:61	1:67	1:77	1:81	1:85	1:89
1987 Proof of concept study for applying PRA to Space Shuttle. Scope was limited to APUs for Orbiter and SRB	1988 First somewhat integrated PRA conducted on the Space Shuttle. Done in support of Galileo Mission. (Ascent Only).	1993 Update of the Galileo study results to reflect then current test and operational base of the shuttle. (Ascent Only)	1995 First major integrated (multi phase) shuttle PRA. Done with input from prime contractors.	1998 Unpublished analysis using QRAS. No integration of elements. Limited to three Orbiter systems and the Propulsion elements	2003 Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Presented to Peer review Team.	2004/2005 Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Peer reviewed.	2005 Integrated PRA with all elements, 18 Orbiter Systems, MMOD and human actions included. Peer reviewed. Updated Pre-valve modeling	2006/2007 Updated SPRA iteration 2.1 with Inspection with Repair and Crew Rescue. Updated MMOD and Ascent Debris Modeling	2008 Updated SPRA iteration 2.2 with Abort modeling, Rendezvous and Docking. Updated Functional Data, MMOD and Ascent Debris	2009 Updated SPRA iteration 3.0 with corrected APU Hydrazine Leak Probabilities	2010 Updated SPRA iteration 3.1 with updated MMOD, Ascent Debris, Orbiter Flight Software, Incorporated Orbiter Review Summit Comments
Proof of concept Study 1987	Galileo 1988	Phase 1 1993	Shuttle PRA 1995	Shuttle PRA 1998	SPRAT PRA Iteration 1.5 2003	*SPRAT PRA Iteration 2.0 2004/2005*	*SPRAT PRA Iteration 2.1 2005*	*SPRAT PRA Iteration 2.2 2006/2007*	*SPRAT PRA Iteration 3.0 2008*	*SPRAT PRA Iteration 3.1 2009*	*SPRAT PRA Iteration 3.2 2010*

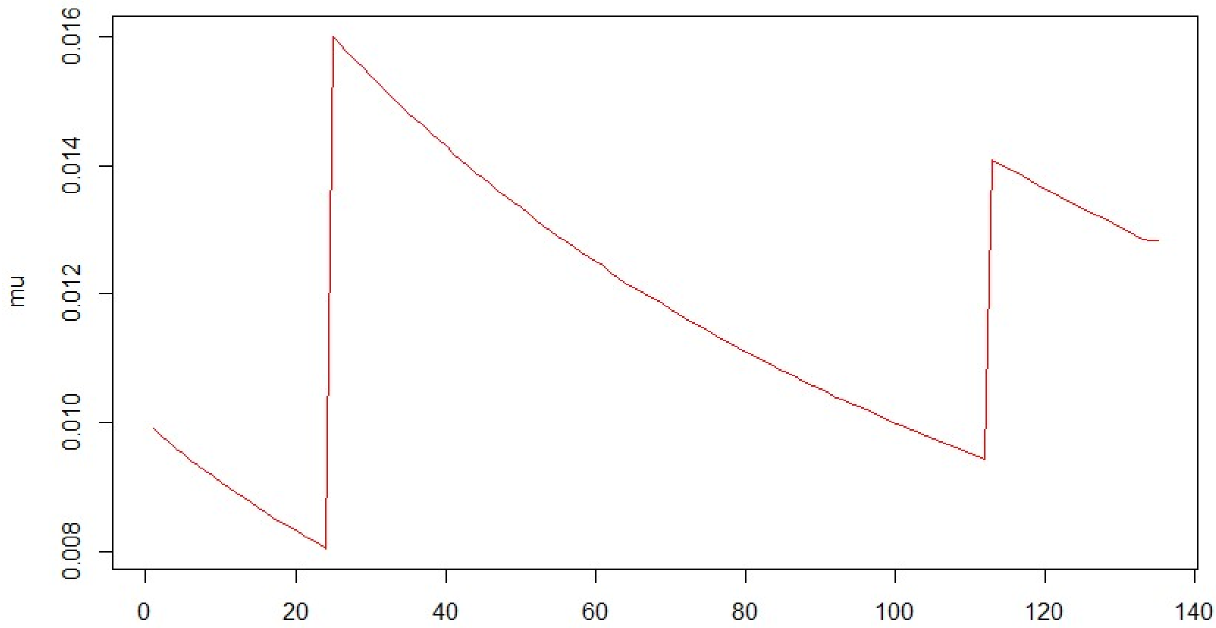
INCREASING FIDELITY AND EXPANDED SCOPE

Space Shuttle

- We can use this same technique on space shuttle program – much more data
- Prior
  - NASA estimate for LOCV prior to STS-1 was 1% or 0.01
  - Certainty: 100 flights
  - Prior = Beta(1,99)
  - Updated posterior after each mission, or at milestones



Mission-by-mission

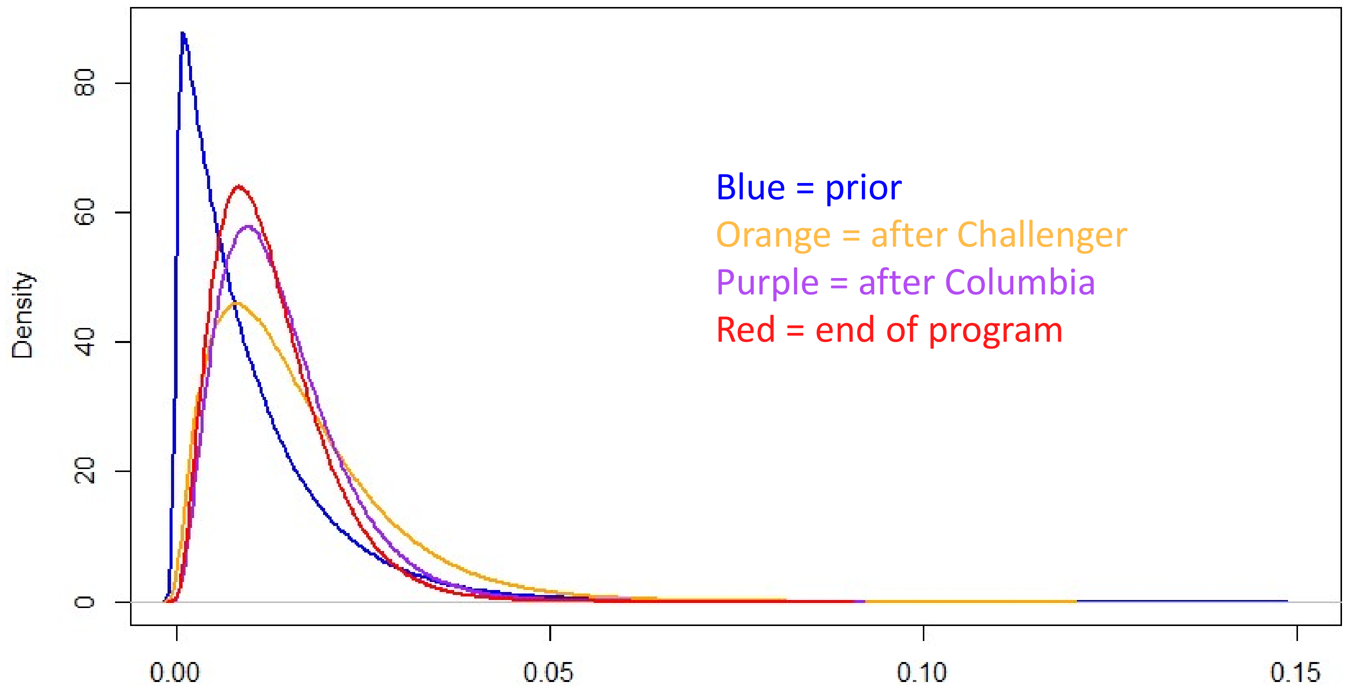


- The longer we go without a failure, the lower we believe the probability of failure to be.
- Similarly, periodic failures make us believe the failure probability is higher, depending on how many successes between failures.

Updates at milestones

Flight #	Event	Failures	Successes	Estimate		95% CI
	Start of program (prior)	1	99	1/100 =	0.010	(0.001, 0.052)
25	Challenger disaster	2	123	2/125 =	0.016	(0.002, 0.059)
113	Columbia disaster	3	210	3/213 =	0.014	(0.003, 0.043)
135	End of program	3	232	3/235 =	0.013	(0.001, 0.039)

- Recall our prior adds 1 failure and 99 successes to the tallies
- Estimate is for mean and 95% CI of Beta(Failures,Successes) distribution


Blue = prior
Orange = after Challenger
Purple = after Columbia
Red = end of program
Density
0
20
40
60
80
0.00
0.05
0.10
0.15

How does this compare?

Flight #	Event	Bayesian	Frequentist	SPRA
	Start of program (prior)	0.010	0.000	0.010
25	Challenger disaster	0.016	0.040	0.014
113	Columbia disaster	0.014	0.018	0.016
135	End of program	0.013	0.015	0.011

SPRA = Shuttle Probabilistic Risk Assessment

What does it all mean?

- Complex PRA is the best method and current gold standard, as it allows us to reflect changes (improvements) in individual spacecraft system risks over time.
- Yet, Bayesian methods – using simple inputs – allowed us to get estimates that are in line with high-complexity PRA.
- Here Bayesian estimation acts as a “gut check” on PRA (supposing a “reasonable” prior is used).
- Frequentist calculations can overestimate P(failure), especially when total number of trials are few (e.g., after Challenger).

➢ In general, Bayesian probability estimation can be used in any risk assessment situation to integrate what we think we know ahead of time with what we observe over time.

This work is supported by the Translational Research Institute for Space Health through NASA Cooperative Agreement NNX16AO69A.

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