Comparative Analysis of Spacecraft Schedule by Classical and Quantum Monte Carlo Simulations

by

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Outline

- Study Approach
- Interviewees
- Common Schedule
- “Risk Driver” Classical Approach
- Quantum Approach
- Overall Results
- Conclusions & Recommendations

Study Approach

- In mid-2008, I was made aware of an approach to schedule risk that involved using quantum mechanics
- While somewhat skeptical, I convinced NASA cost management to modestly fund a study
- The study was designed <u>not</u> to understand ***<u>how</u>*** quantum mechanics produces the confidence level of reaching a planned milestone
- The study was designed to ***<u>compare the results</u>*** of the quantum mechanics approach to the more trusted traditional "classical" approach to schedule risk analysis
- The idea was to see if using the same schedule for analysis the results from both approaches were anywhere near the same
- We did this knowing full well that results that were close or far apart from only one common schedule example would not "prove" anything
- It could, however, give an indication that further experimental use of the quantum approach was warranted

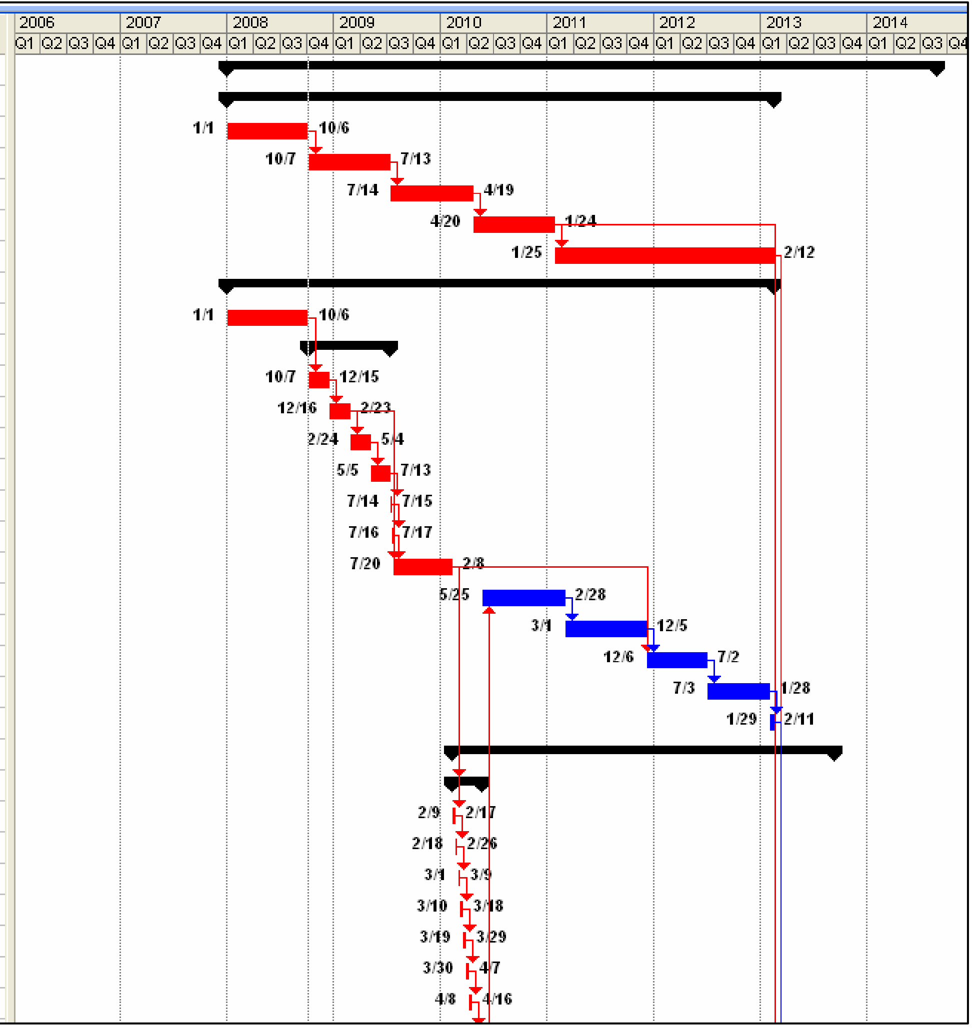
Interviewees

- Tom Coonce, NASA
- Charles D. Hunt NASA
- David R. Graham, USAF

(Usually there are 30 or so interviewees from high-level to discipline leads and even contractors. This provides the context and credibility for the results.

Schedule Used for Both Approaches

WBS	Task Name	Duration
1	**Mission**	**1737 d**
1.1	**Government Entity**	**1336 d**
1.1.1	Project Management prior to procurement	200 d
1.1.2	Procurement (including insurance)	200 d
1.1.3	Analysis (Resource, Schedule)	200 d
1.1.4	Mission Systems Engineering	200 d
1.1.5	Other	536 d
1.2	**Science Instrument Build**	**1335 d**
1.2.1	Instrument Design	200 d
1.2.2	**Instrument Build**	**200 d**
1.2.2.1	Thermal Environment	50 d
1.2.2.2	Communication	50 d
1.2.2.3	Cleanliness	50 d
1.2.2.4	MASS	50 d
1.2.3	Vision Protection	2 d
1.2.4	Vibration/Shock Protection/Isolation	2 d
1.2.5	Instrument Bench Tests	146 d
1.2.6	Science Payload Package Design	200 d
1.2.7	Science Payload Package Build	200 d
1.2.8	Science Payload Package Integration & Te	150 d
1.2.9	Software	150 d
1.2.10	Storage and Shipment to Lockheed Martin	10 d
1.3	**Satellite Manufacturer**	**936 d**
1.3.1	**Requirements & Necessary Host Satellit**	**75 d**
1.3.1.1	Bus Design	7 d
1.3.1.2	Transponder Design	7 d
1.3.1.3	Power Generation Systems Design	7 d
1.3.1.4	Battery Design	7 d
1.3.1.5	Data Buffer Design	7 d
1.3.1.6	Launch Interface Design	7 d
1.3.1.7	Pointing Design	7 d



Project Summary Integrated Schedule

"Risk Driver" Classical Approach

“Risk Driver” Classical Approach

- The traditional “classical” approach applies uncertainty on Low-ML-High estimates of duration as characterizations of activity-level triangular distributions
- The Risk Driver classical approach applied in this study focused uncertainty on the risks themselves
- Risks were then associated with activities and their task durations to characterize their distributions
- Risks took the form of estimates on risk likelihoods of occurrence and factors representing the effects risks could have on the planned activity duration estimates to represent the Low-ML-High durations on activity triangular distributions

Risk Factors' Likelihoods & Range Estimate Factors

	Risk Factor	Probability	Minimum	Most Likely	Maximum
1	Because multi-year funding, funding may not be stable	55%	100%	106%	116%
2	Some small suppliers may not be stable	20%	100%	106%	112%
3	Since technology is immature, the TRL may be lower than assessed	50%	100%	110%	120%
4	Requirements may not be stable, may be volatile	55%	100%	108%	114%
5	May not have accurate est. of reuse of software / hardware	90%	98%	106%	114%
6	Immature design, may not know the weights or mass of components	70%	98%	102%	108%
7	May not have estimated accurately the S/W Lines of Code	65%	98%	104%	116%
8	There may be uncertainty in the Launch Vehicle	45%	100%	104%	108%
9	Project complexity may lead to poor staffing of multi-contractor teams	50%	100%	104%	110%
10	There may be conflicting schedules and workload	15%	94%	102%	104%
11	Article may fail systems testing and require re-testing	60%	102%	114%	126%
12	Coordination between project sites may be difficult	40%	100%	104%	108%
13	Sufficient trained/experienced technical personnel may not be available	60%	100%	106%	112%

Risk Factor Assignments to Activities

RF #	Assignment of the Risk Factors	Government Entity	Science Instrument Build	Satellite Manufacturing	Launch & Vehicle Services	Launch Facility
1	Because multi-year funding, funding may not be stable	X	X	X	X	X
2	Some small suppliers may not be stable		X		X	
3	Since technology is immature, the TRL may be lower than assessed		X	X		
4	Requirements may not be stable, may be volatile		X	X		
5	May not have accurate est. of reuse of software / hardware		X			
6	Immature design, may not know the weights or mass of components	X		X		
7	May not have estimated accurately the S/W Lines of Code		X			
8	There may be uncertainty in the Launch Vehicle				X	
9	Project complexity may lead to poor staffing of multi-contractor teams		X	X	X	
10	There may be conflicting schedules and workload	X	X	X	X	X
11	Article may fail systems testing and require re-testing			X	X	
12	Coordination between project sites may be difficult		X	X	X	
13	Sufficient trained/experienced technical personnel may not be available	X				

Some Comments on Data

Interviewee	Prob.	Min	ML	Max
# 1	25%	100%	115%	140%
# 2	75%	100%	105%	110%
Average	50%	100%	110%	125%

Gather data from several people so we can get different inputs
Start with Averages, but sometimes round the values to avoid suggesting more accuracy than is available
On occasion some interviewees will be deemed to be more expert in the area and get greater weight

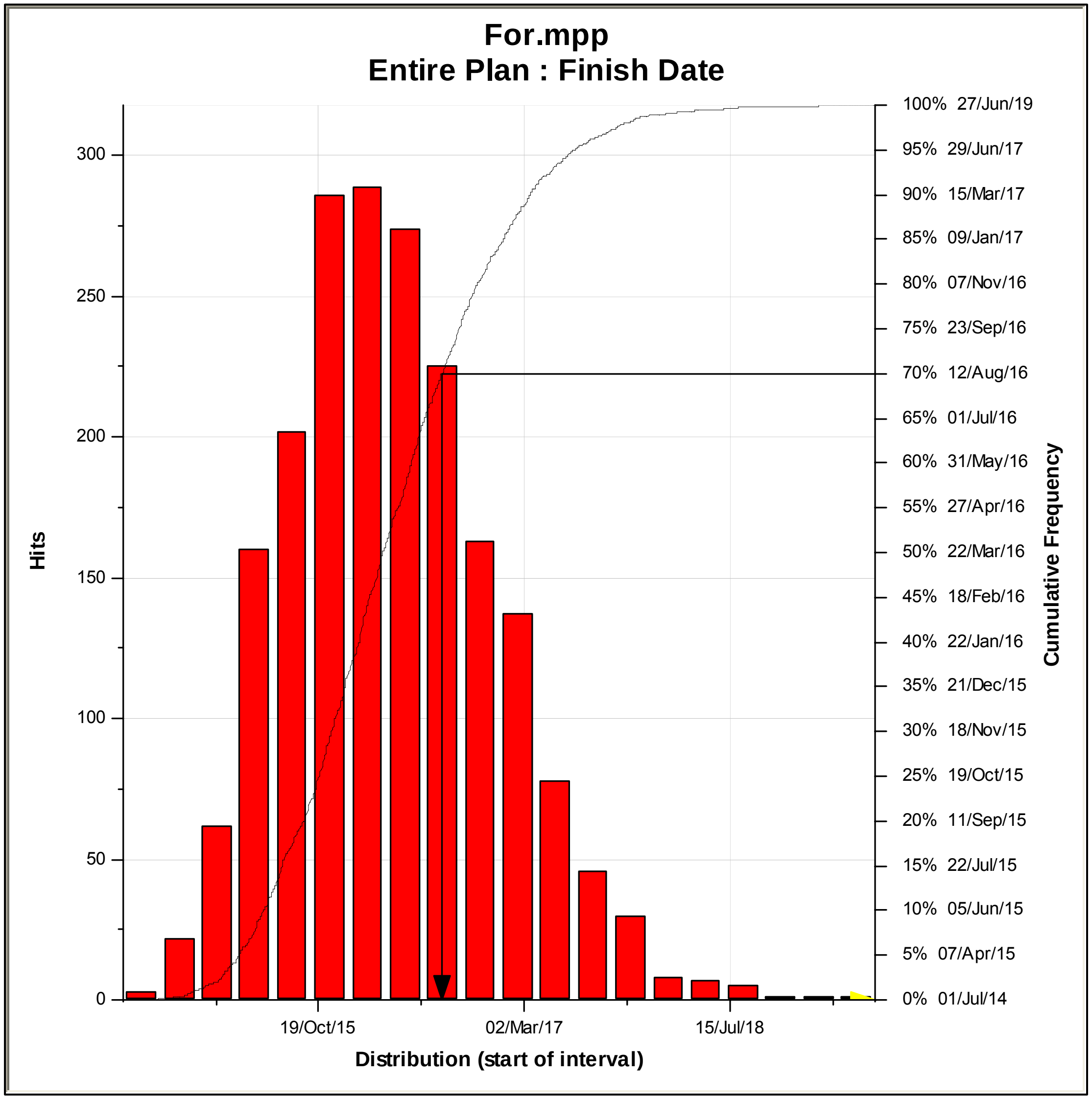
Need to Adjust the Ranges to Account for Many Risks Assigned to Activity

Adjust the Ranges Because of Many Risks on Same Activity				
	Prob.	Min	ML	Max
Average	50%	95%	110%	125%
Adjust 60%	50%	98%	104%	110%

In schedule risk the impact of two risks can occur simultaneously rather than in series
The multiplicative nature of the Risk Factors approach tends to overstate the cumulative impact of several risks assigned to the same activity. We have many activities with multiple risks assigned
The Classical approach has used a factor of .4 (adjusting by .6) which seems to give reasonable results when there are 5-10 risks applied to the same activity. In Science Instrument Build, Satellite Manufacturing and Launch & Vehicle Services we have multiple risks assigned.

Risk Driver Classical Approach Schedule Risk Results

Preliminary indications are that the P-70 target is 2 years delayed to 12 August 2016 from 27 August 2014



Risk Factors Tornado Chart

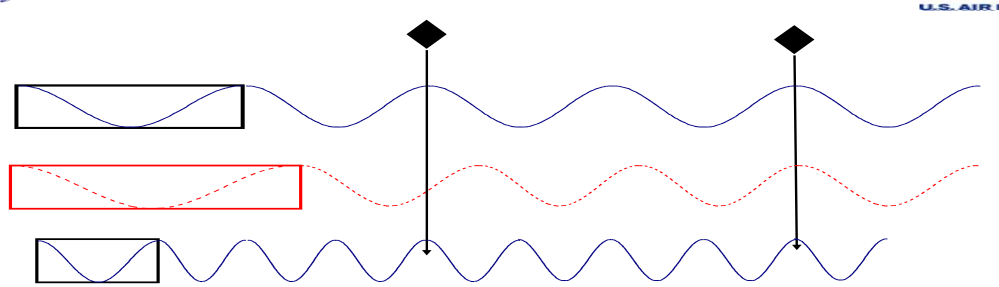
Top 3 risks:
TRL may be low
Multi-year funding
Requirements not Stable

Quantum Approach

Bridge Between Quantum Mechanics & Schedule Risk

- Quantum mechanics is the study and prediction of elementary particle behavior
  - e.g., photons, electrons, neutrons, neutrinos, quarks, etc.
  - Elementary particles have both particle and “wave” characteristics
- The *activity* is the analog to the elementary particle in schedule risk
  - Activities have both particle and “wave” characteristics
  - Activities are driven by human behavior so quantum mechanics can be seen as modeling human behavior
- However, can’t predict individual elementary particle behavior like normal size objects
- Can only predict elementary particle behavior <u>probabilistically</u>
  - Can say only that there is a probability that a photon will be in a specific location with a certain probabilistic confidence
- Quantum mechanics then works in the probabilistic realm which is the same way we traditionally treat schedule duration

Task "Wave" Interference Patterns



$$\Delta Q = \left(\frac{\partial Q}{\partial \varphi_1}\frac{d\varphi_1}{dt} + \frac{\partial Q}{\partial \varphi_2}\frac{d\varphi_2}{dt} + \frac{\partial Q}{\partial \varphi_3}\frac{d\varphi_3}{dt} + \ldots\right)\Delta t_{risk}$$

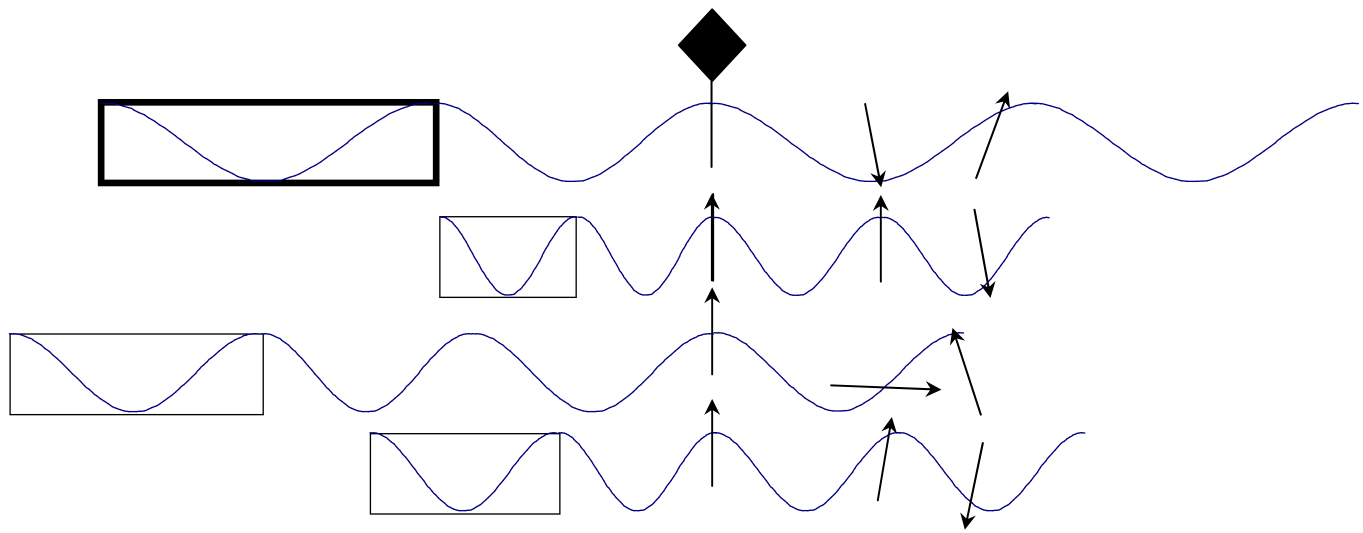
- It is the conjectural analogous wave-like properties of people's managerial behavior performing tasks that the quantum approach assumes and takes advantage
- When the wave functions of particles (i.e., tasks) are coherent (i.e., peaks line up) and the tasks represented by the sinusoidal wave functions peak at the same time, the milestone is met. The top and bottom black boxes represent the planned tasks
- One wave period represents the task duration. The periods of the waves can be different as depicted. They line up at the milestones represented by the diamonds and the lines

Three Dimensions of the Quantum Schedule Risk Approach

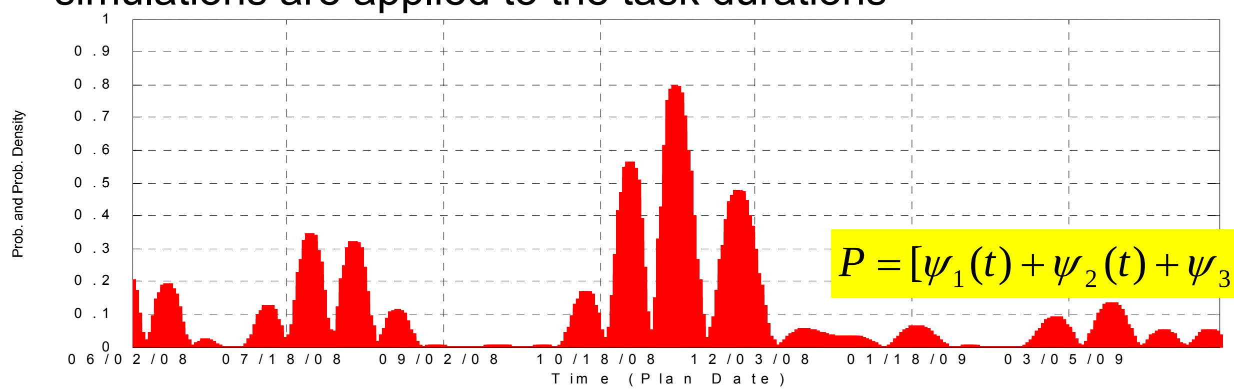
- There are three dimensions of risk at work in the quantum approach
  - **Project structure risks**
  - **Task duration risks**
  - **Risk register risks**
- **Project structure risks** are a function of the internal project schedule itself
  - Number of tasks; task durations; links; and, distance to milestone
- **Task duration risks** result from the natural coefficient of variation (CoV) of task durations within the project schedule as a function of monte carlo simulations that use the **N**umerical **I**nverse **F**ourier **T**ransform (NIFT) method of summarizing random harmonics along the full time axis vice one point at a time as with individual task duration distributions in the classical application of monte carlo statistical summing *(in later chart)*
  - The natural CoV can be manually overriden by the user
- **Risk register risks** are implemented by identifying the likelihood and consequence qualitatively using the 5X5 risk matrix

Project Structure Risk

Task “Wave” Interference Patterns



- This picture corresponds to the quantum condition where no monte carlo simulations are applied to the task durations

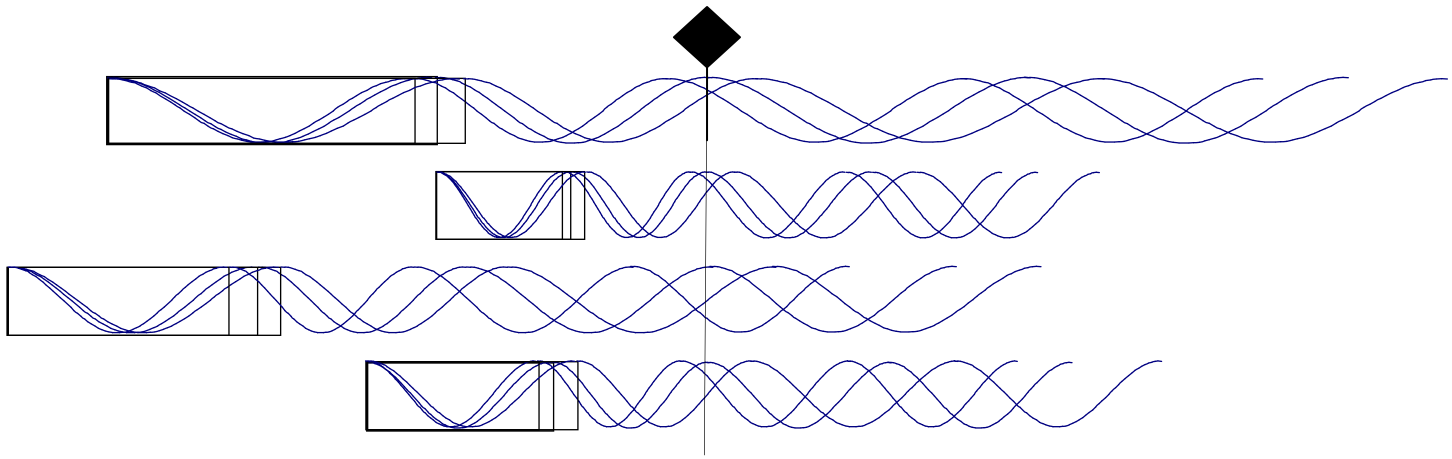


$$P = [\psi_1(t) + \psi_2(t) + \psi_3(t) + \psi_4(t)]^2$$

- The result is that the CoV is large
- Meeting the milestone is highest at the peaks but spread out

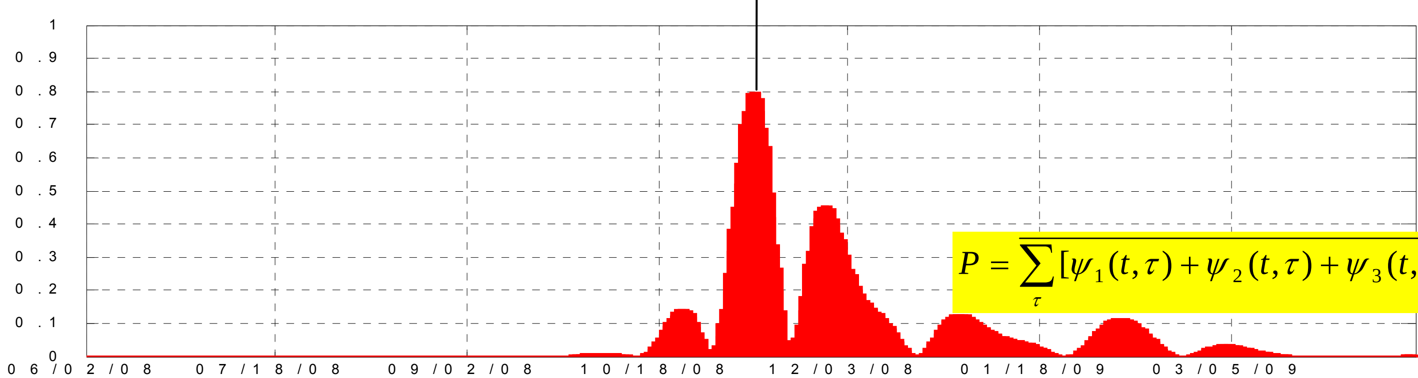
Task Duration Risk

300 Monte Carlo Simulated Project Samples



- This picture corresponds to the quantum condition where monte carlo simulations are applied to the task durations

Mean of milestone image is shifted ***to later date***



$$P = \overline{\sum_{\tau} [\psi_1(t,\tau) + \psi_2(t,\tau) + \psi_3(t,\tau) + \psi_4(t,\tau)]^2}$$

- The result is that the CoV has been reduced
- Meeting the milestone is highest at the peaks and less spread out

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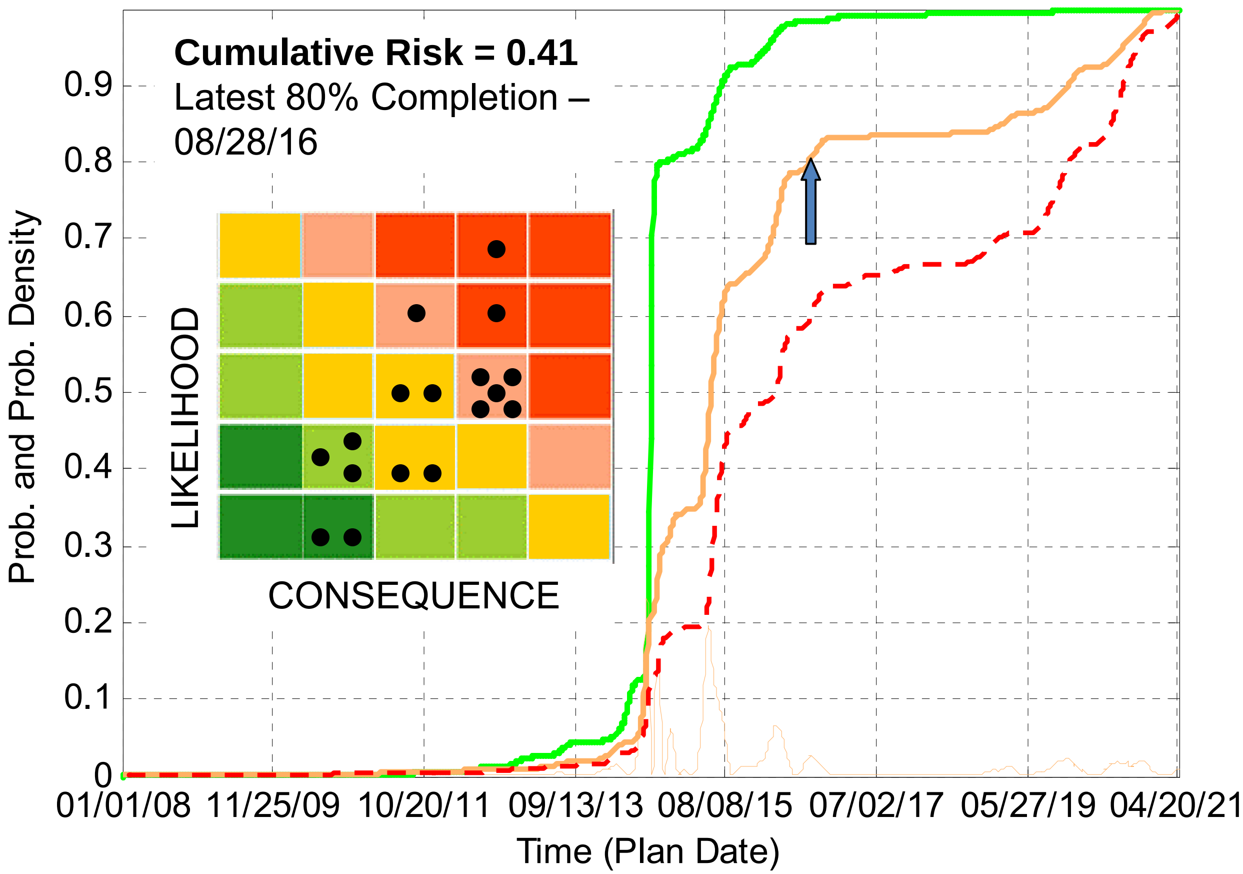
Risk Register Risks

Quantum Risk Register

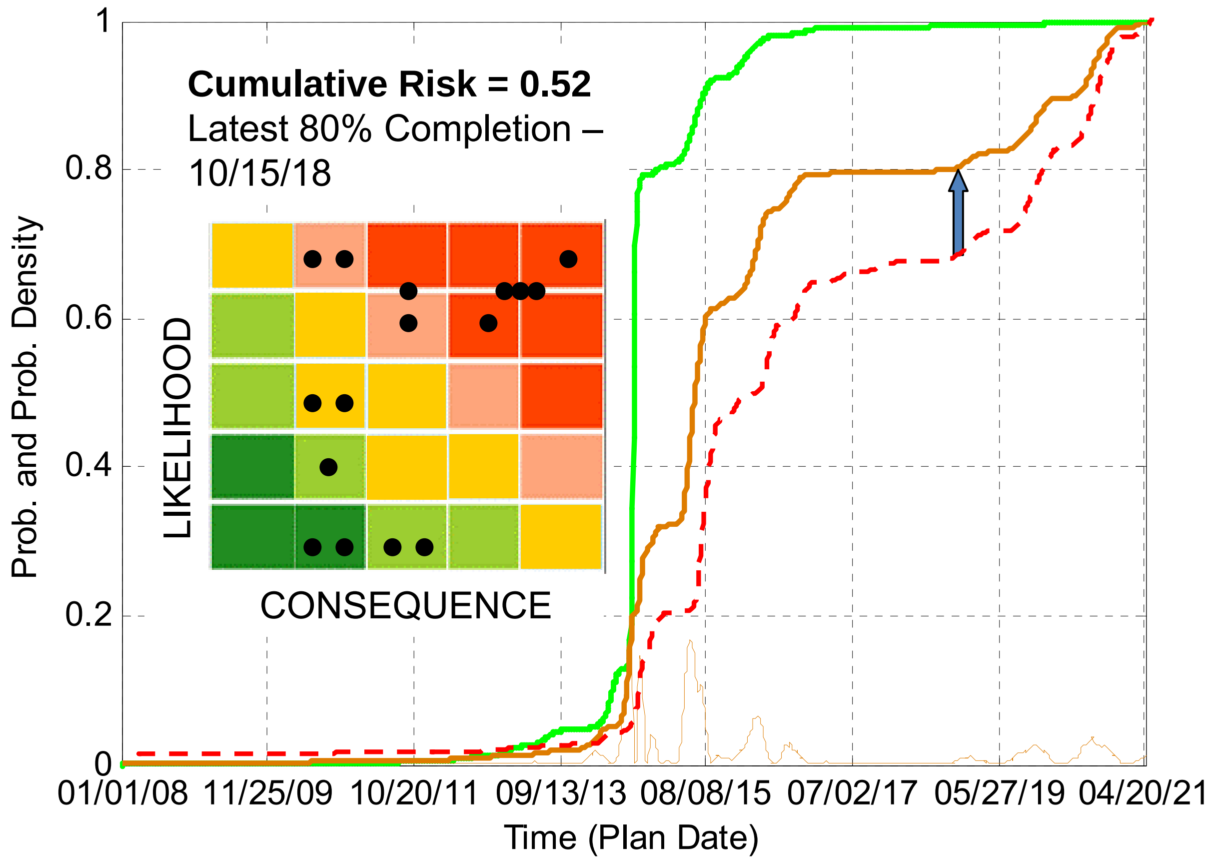
- There are19 risk categories in the quantum risk register separated into 3 groups: Cost Risk, Performance Risk and Management Risk
- Entries are made by selecting a single square in the 5X5 risk matrix
- Each square has a pair of assignments associated with it: likelihood and consequence
- L=C=1 (upper right red square); L=C=0 (lower left green square)
- Formula for total risk: $CR = \sqrt{[(L_1C_1)^2 + (L_2C_2)^2 + ... + (L_kC_k)^2 + 0.25(19-k)]/19}$

S-curve and Probability Density Risk Expert #1



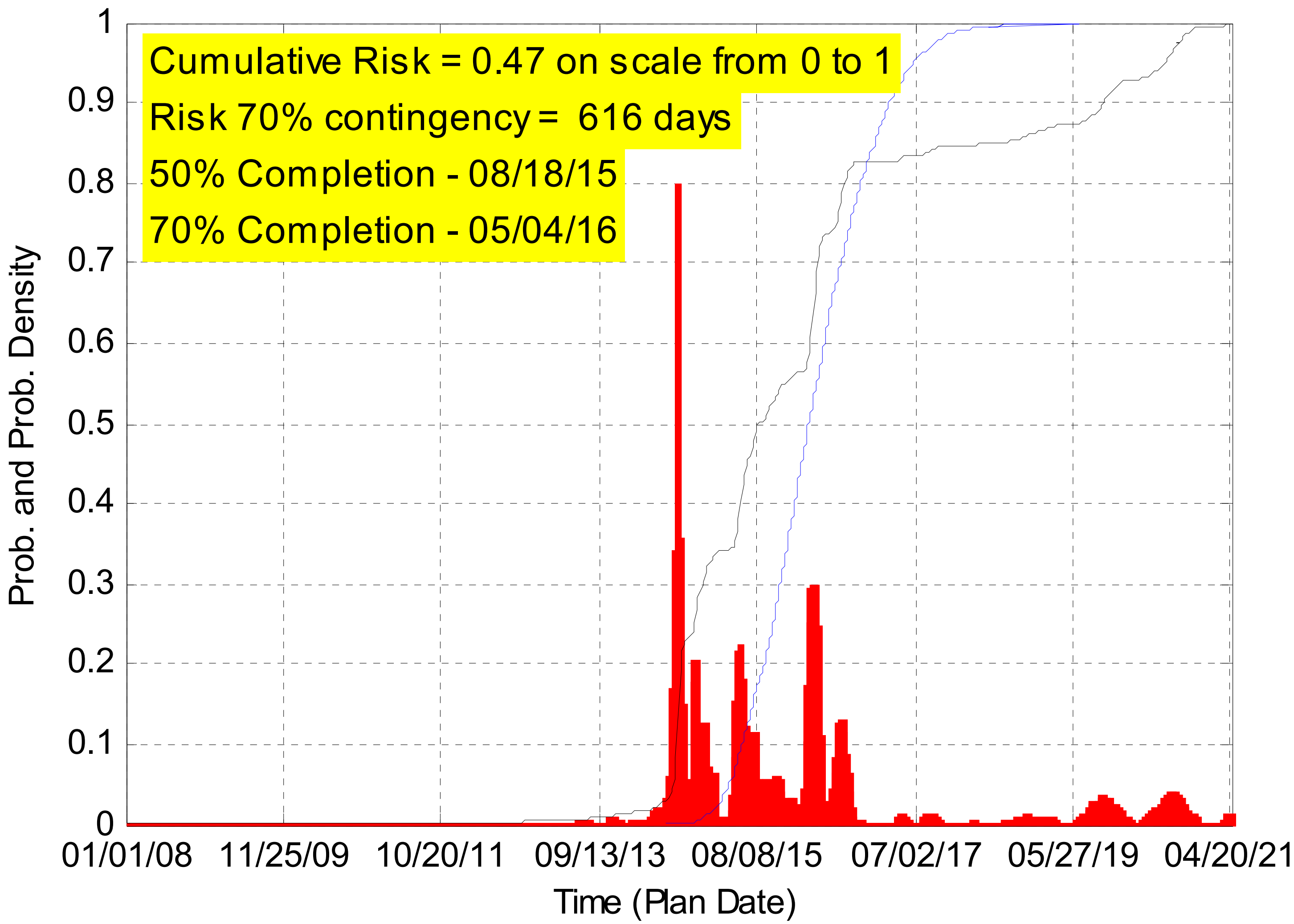
- *Risk is calculated on scale from 0 (no risk - green line) to 1 (maximum risk - red dashed line)*
- *Risk from one interviewee is illustrated as the brown line*

S-curve and Probability Density Risk Expert #2

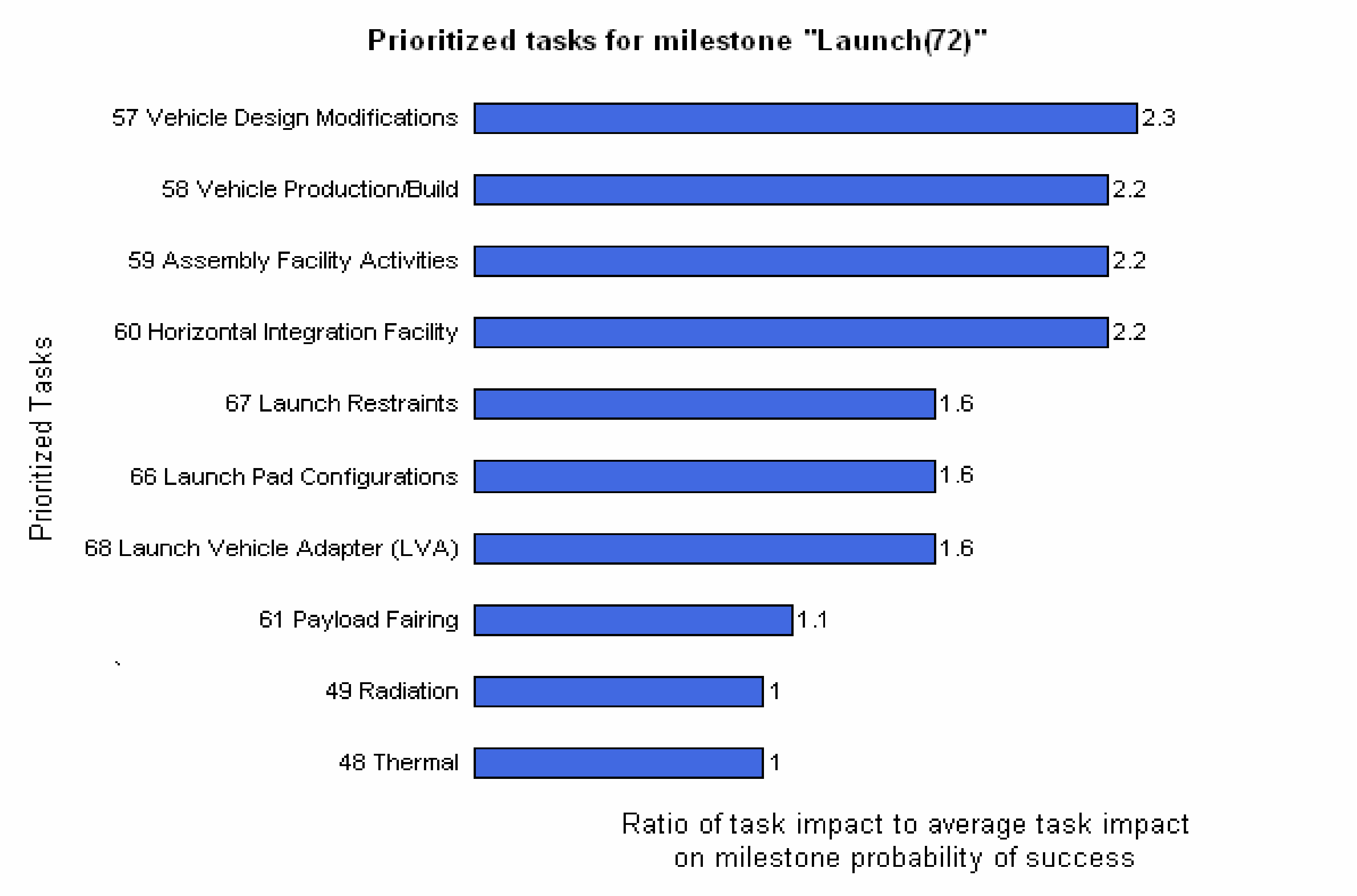


"Shoulder" in S-curve originates from low probability density between end of 2016 and beginning of 2019

Average of Two Risk Experts Assessments



Quantum Approach Tornado Graph



OVERALL RESULTS

Summary Comparison
Classical and Quantum Schedule Risk Results

	SCHEDULE	DATE	DELTA%	50% CL	50% CL	DELTA%	70% CL	70% CL	DELTA%
				TRADITIONAL	QUANTUM		TRADITIONAL	QUANTUM	
TOTAL PROJECT	27-Aug-14	27-Aug-14	0%	22-Mar-16	18-Aug-15		12-Aug-16	4-May-16	
CONTINGENCY DAYS	0	0	0%	565	351	37.9%	705	607	13.9%
PROJECT START	1-Jan-08	1-Jan-08							
PROJECT DAYS	2396	2396	0%	2961	2747	7.2%	3101	3003	3.2%
CONTINGENCY %				19.1%	12.8%		22.7%	20.2%	

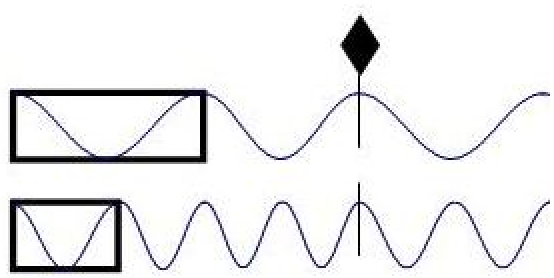
Conclusions & Recommendations

- Overall results indicate comparable performance between "Risk Driver" classical vs quantum approaches to the determination of schedule risk
- There were differences at the 50% and 70% confidence levels
  - Less difference at the 70% level of confidence
- Traditional classical approach is well understood and has shown credible results over many years of application
  - Requires significant effort to construct activity-level triangular distributions
- "Risk Driver" classical approach is straightforward but is relatively new and not as proven as traditional classical approach
  - Requires less effort to construct activity-level triangular distributions
- Quantum approach is new and unproven
  - Requires the least effort to construct activity-level uncertainty distributions
  - Takes advantage of the quantum approaches ability to extract uncertainty out of the project schedule structure itself, through the NIFT-based monte carlo application and implementation of the risk register to generate overall schedule risk
- Recommend early-in-project application of quantum approach as an early indicator with validation from more trusted classical approaches

BACKUP

Particle and Wave Characteristics of Project Schedule Tasks

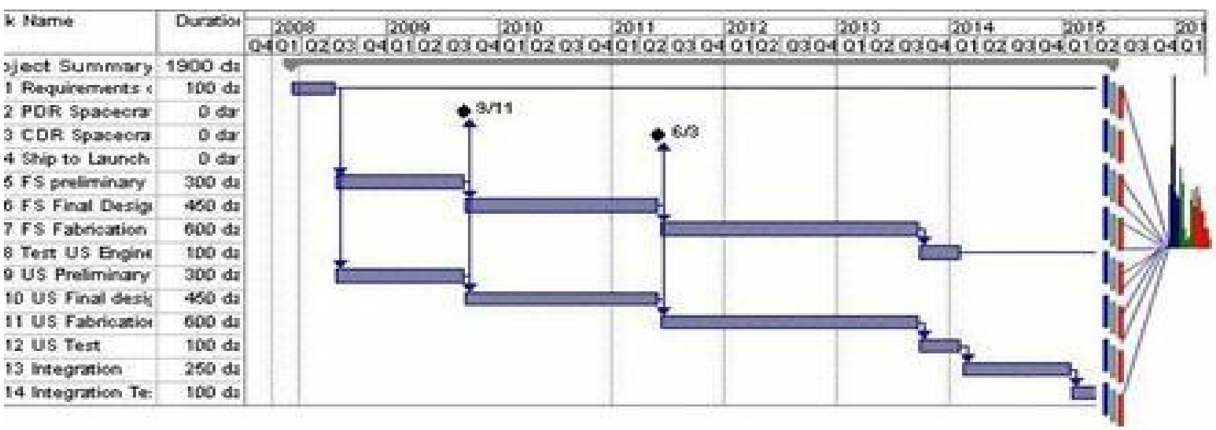
- The project “task” is the analog to the quantum mechanic’s elementary particle – a photon, for example – and each project task has “wave” and “particle” characteristics
- The task’s “wave” characteristic is illustrated with this diagram:



- Each task “emits” a waveform and all waveforms are “focused” (arrive at the same phase) at the milestone
- The task is also characterized as a particle *"i"*, and the wave associated with it is a wavefunction: $\Psi_i \sim \cos(2\pi t/D)$ where ***D*** is task duration (cost and duration of WBS elements are suggested to be proportional to each other) & “*t*” is project time
- The probability that a milestone will meet its planned duration is: $P = [\Sigma(\Psi_i)]^2$

Task-to-Task Correlation as Milestone Collective Image

- To account for unknown task-to-task correlation, the quantum approach models the milestone as a "*collective image*" of all associated tasks

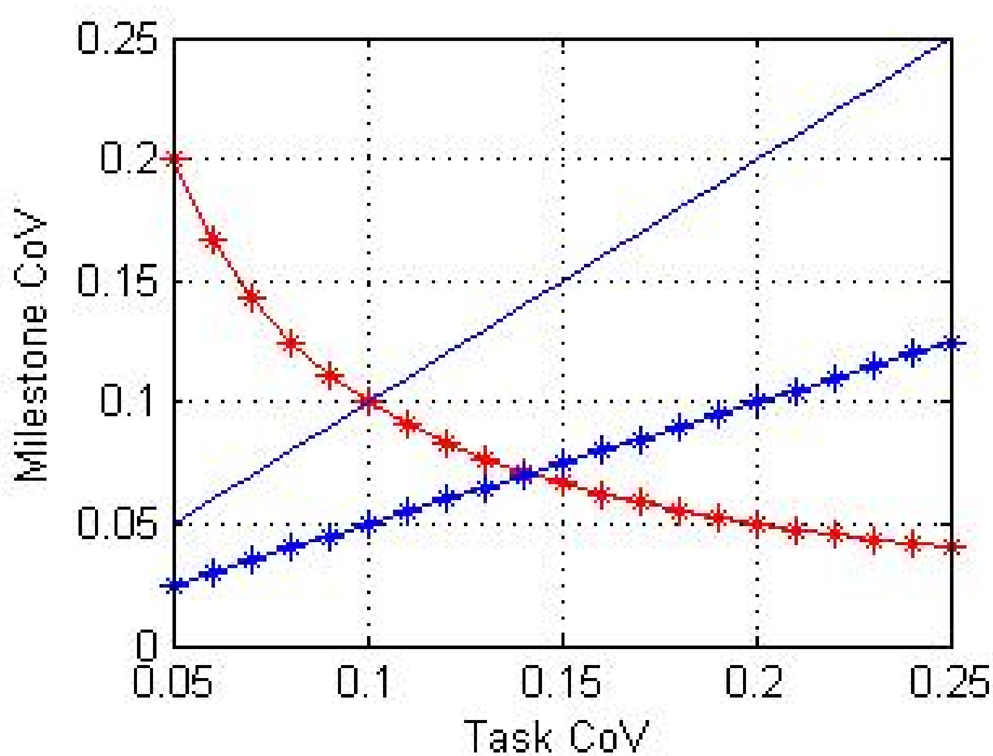


- Monte carlo simulations provide randomization of variation in task durations in order to "focus" the task *fields* emitted towards the milestone image as each task (each wavelength) contributes to the field intensity at the milestone
  - The milestone image is a diffraction pattern of task wavefunctions (i.e. an "interference" pattern)

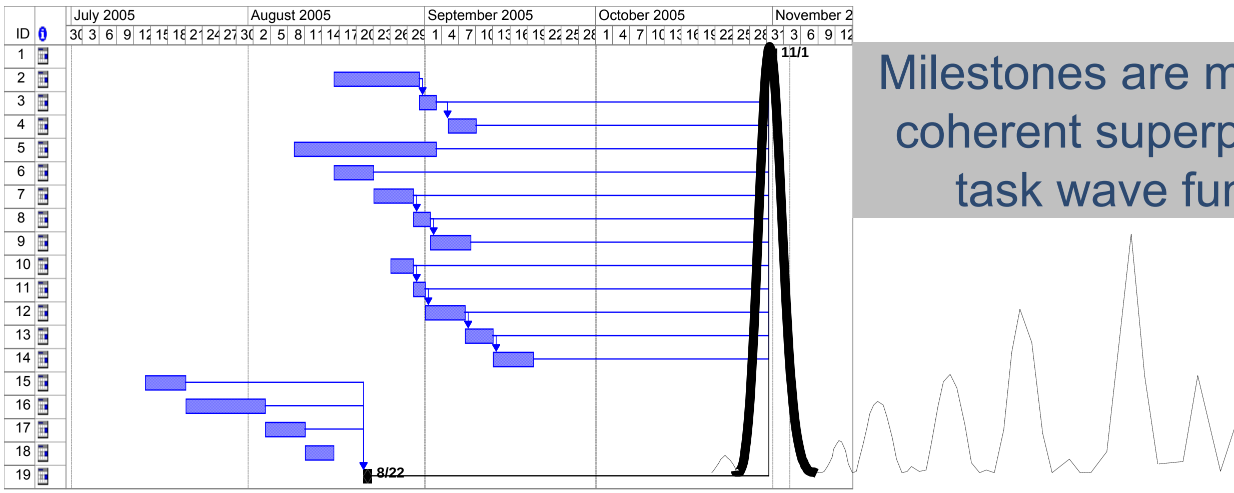
Systematic Right-Shift of Milestone Probability

- Qualitatively, risk is understood as a uni-directional manifestation of uncertainty towards poor project outcome
- The quantum approach introduces risk as a systematic shift of milestone probability as a function of task uncertainty
- The mathematical object describing risk is the milestone correlation function of task wavefunctions
- The correlation function of randomly delayed tasks – using only symmetric duration distributions with the NIFT-based monte carlo – is larger than the correlation function of randomly shortened tasks which causes a systematic right-shift of milestone probability as a function of task uncertainty
- The quantum image of fully symmetric task distributions is thus naturally asymmetric which provides, even without risk driver user input, some measure of expected project delay and cost increase

Relationship of Task CoVs to MS CoVs



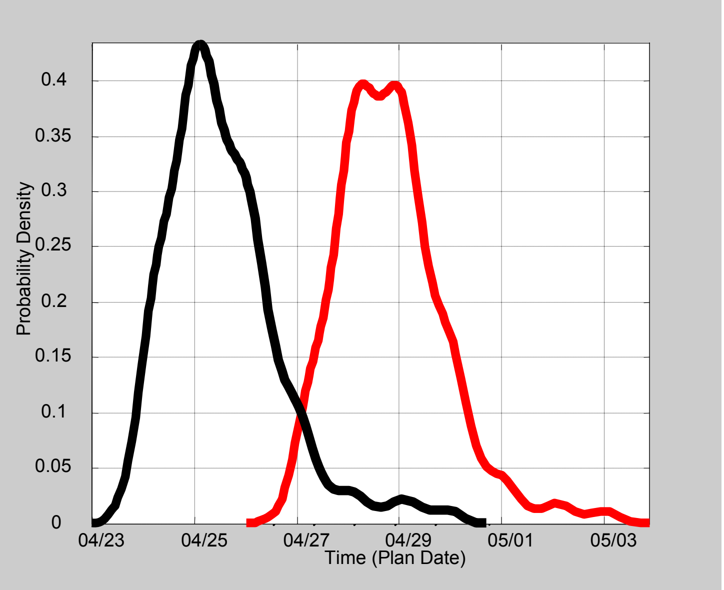
Wave Interference and Milestone Shifts



Milestones are modeled by coherent superposition of task wave functions

$$P = [\Sigma(\Psi_i)]^2$$

- If the top box in the previous chart were to be affected by some kind of risk causing the endpoint to exceed its planned date, its wave function would become out of phase with the planned date of the first milestone and the wave functions would then not be "coherent" or in-phase and destructive "interference" would result precluding meeting the milestone as planned
- The distribution associated with meeting the planned milestone would then be shifted to the right as depicted in the graph to the right



Risk quantification for Slides 22 & 23

The slide presents probability density and S-curve for risk parameters suggested by Expert # 1. Curve is light brown, qualitatively corresponding to cumulative risk factor = 0.41 calculated between limits of 0 (no risk) to 1 (maximum risk). Dashed red is S-curve corresponding to maximum risk.

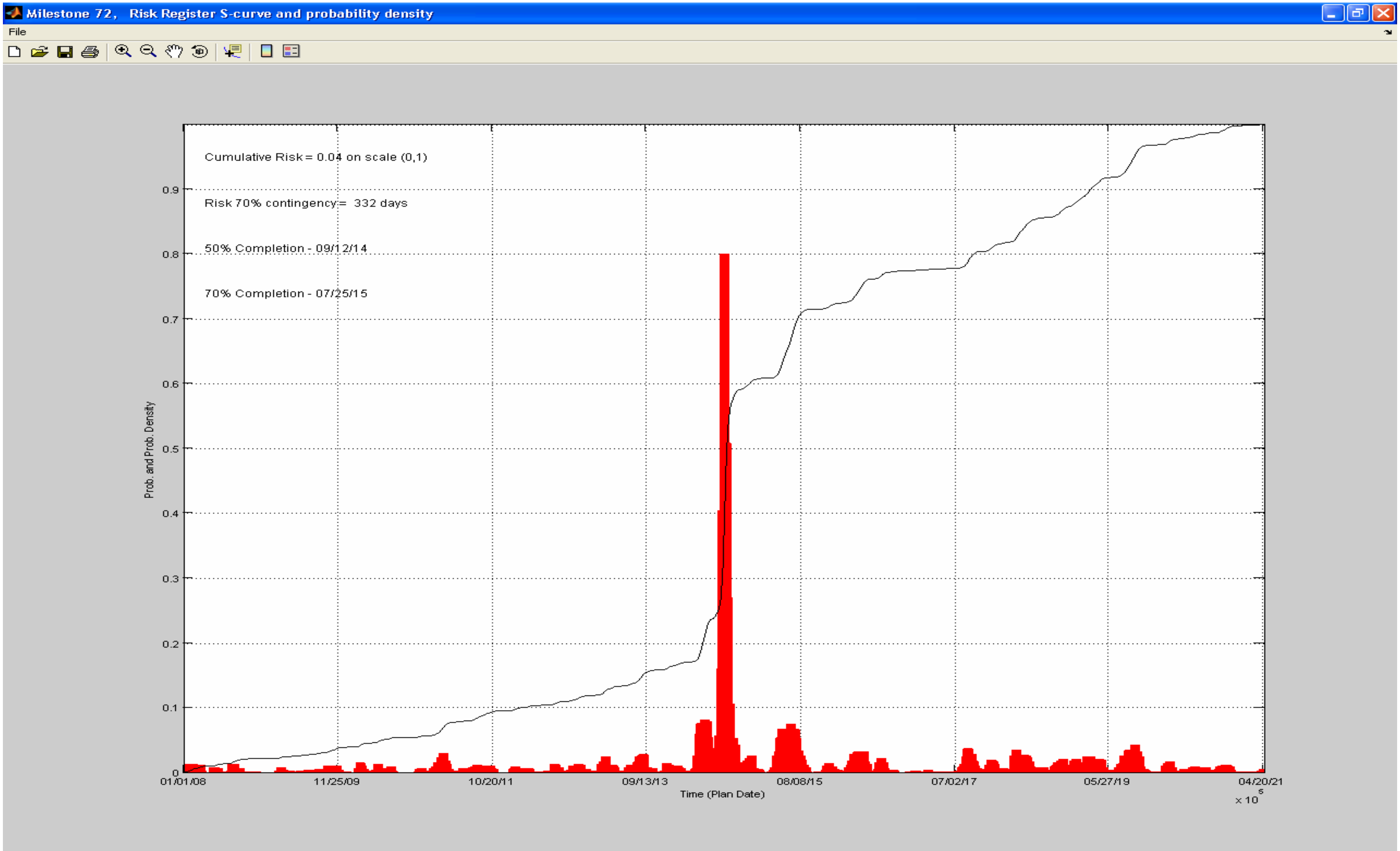
Individual risk likelihoods L and impacts (consequences) I are indicated by dots; cumulative risk R is calculated as

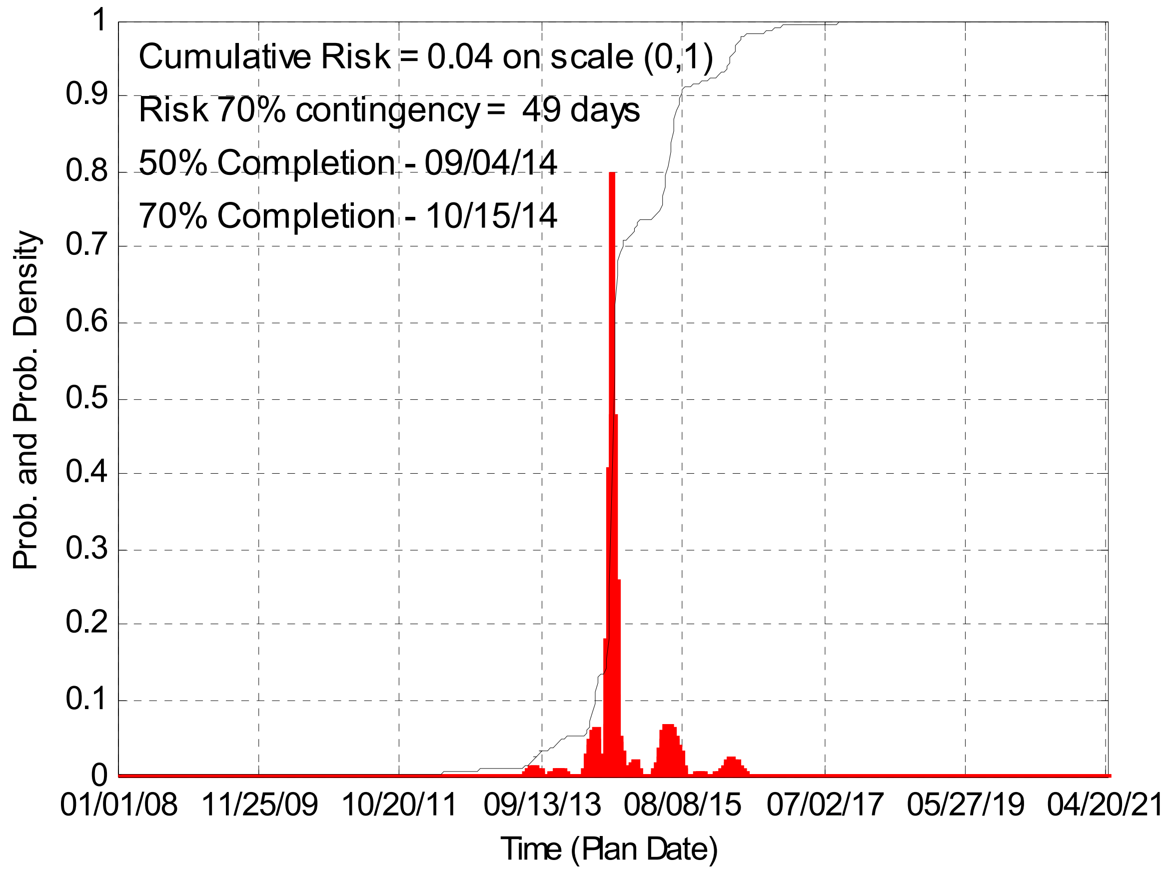
$$R = \sqrt{\frac{1}{N}[(L_1 I_1)^2 + (L_2 I_2)^2 + (L_3 I_3)^2 + \ldots.. + (L_N I_N)^2]}$$

N is total number of risk categories selected. Cumulative risk accumulates as square root of number of risk categories, emphasizing biggest risks and following classical asymptotics.

All Best Case 5X5 Risk Register Inputs

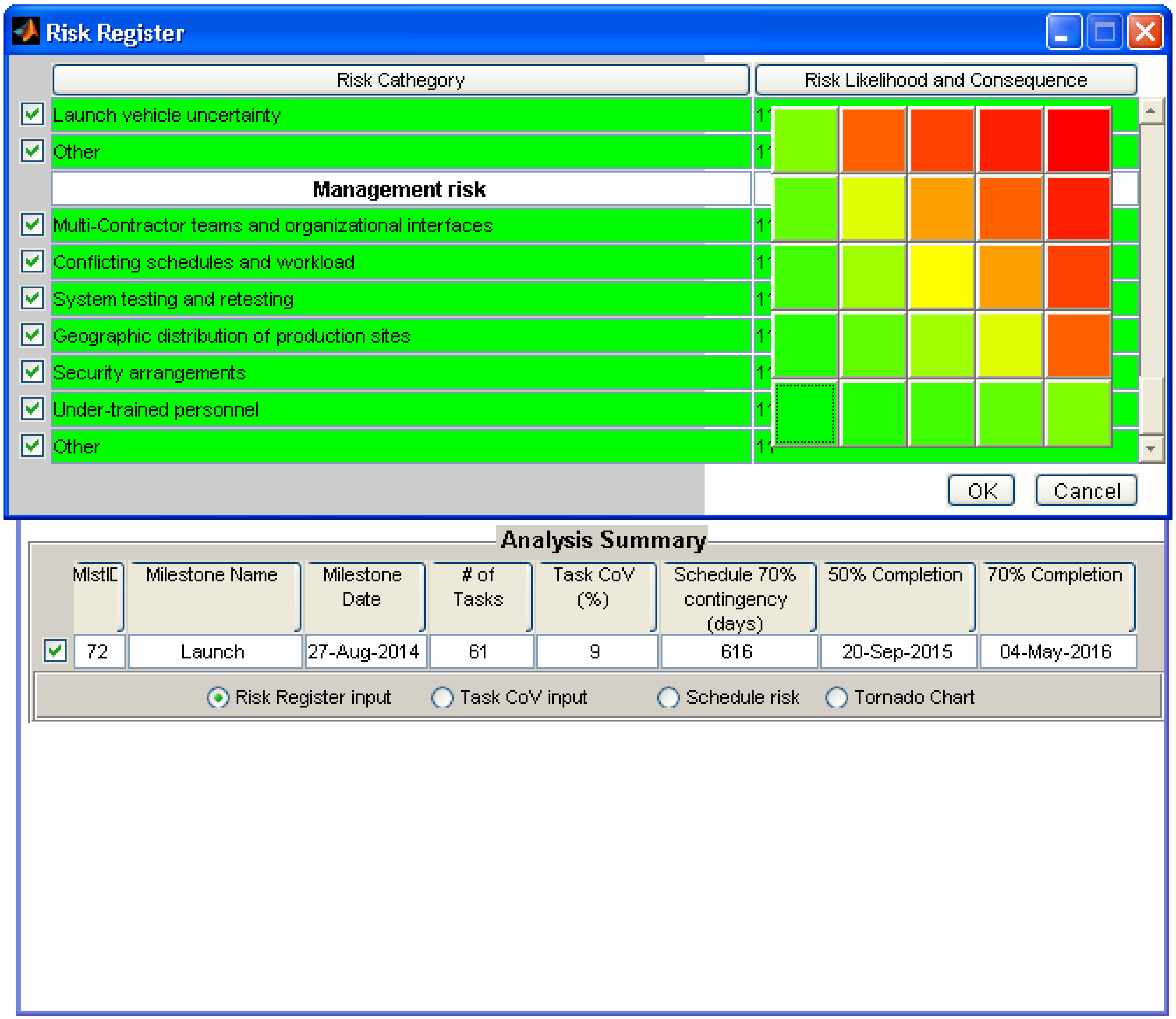
CoV Small; S-Curve Very Steep





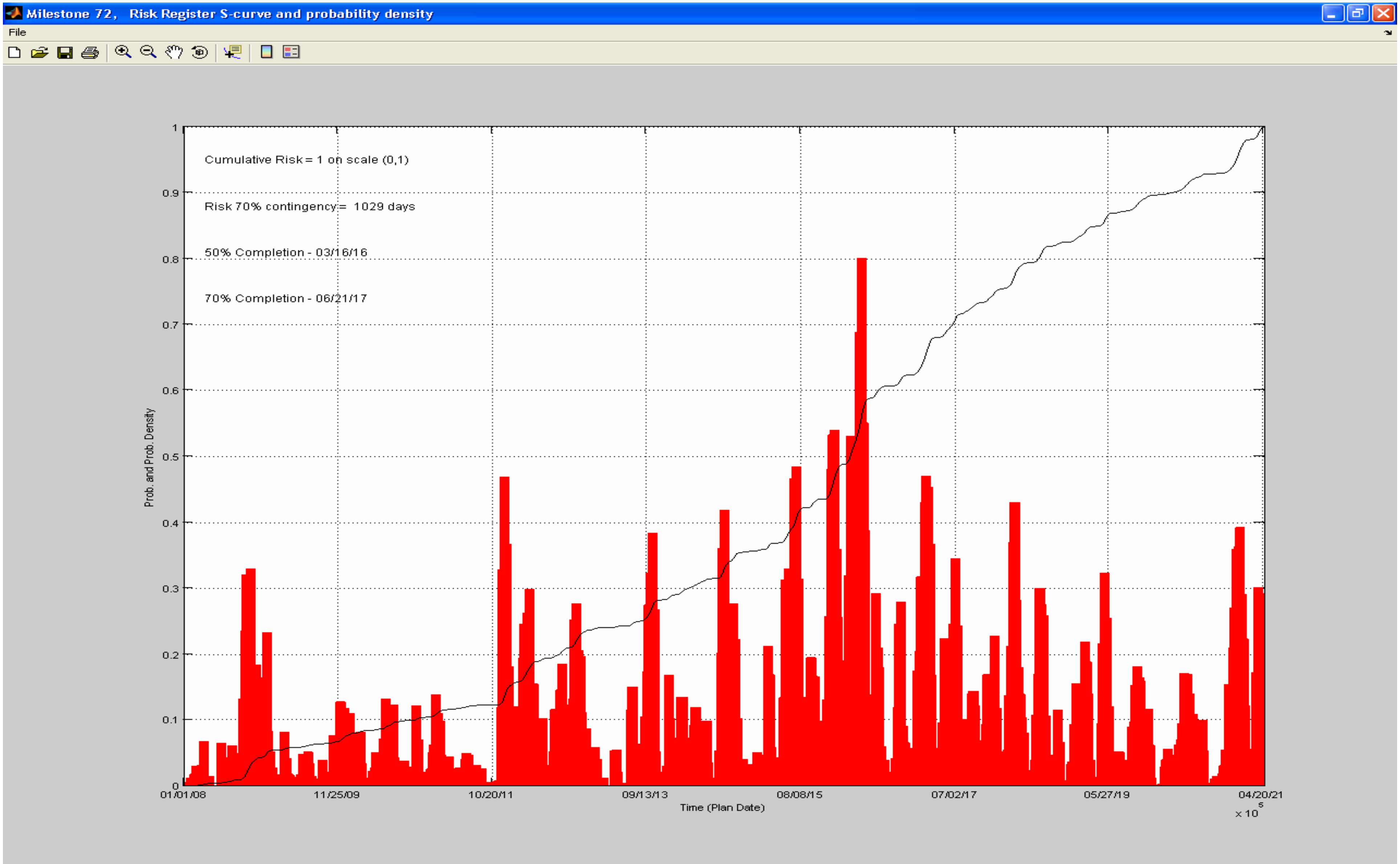
Cumulative Risk = 0.04 on scale (0,1)
Risk 70% contingency = 49 days
50% Completion - 09/04/14
70% Completion - 10/15/14
Prob. and Prob. Density
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
01/01/08
11/25/09
10/20/11
09/13/13
08/08/15
07/02/17
05/27/19
04/20/21
Time (Plan Date)

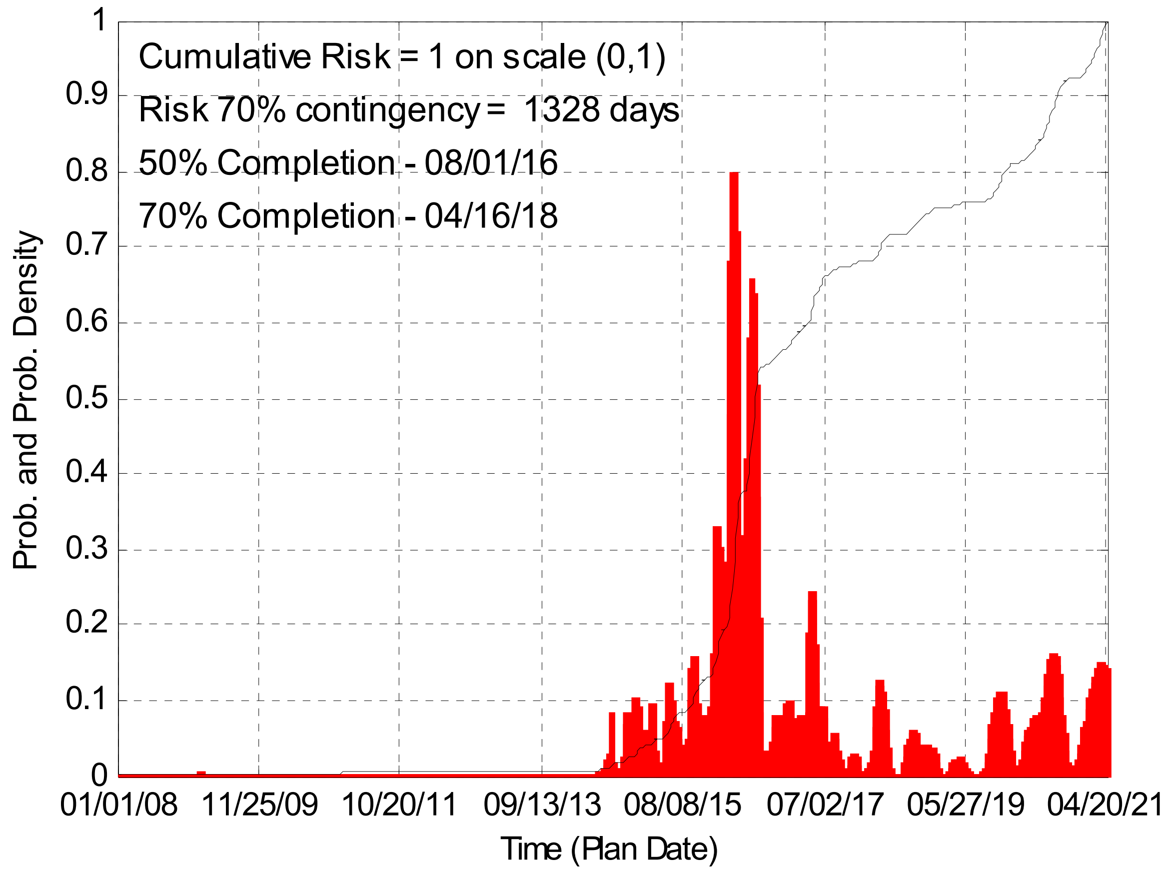
All Best Case 5X5 Risk Register Inputs



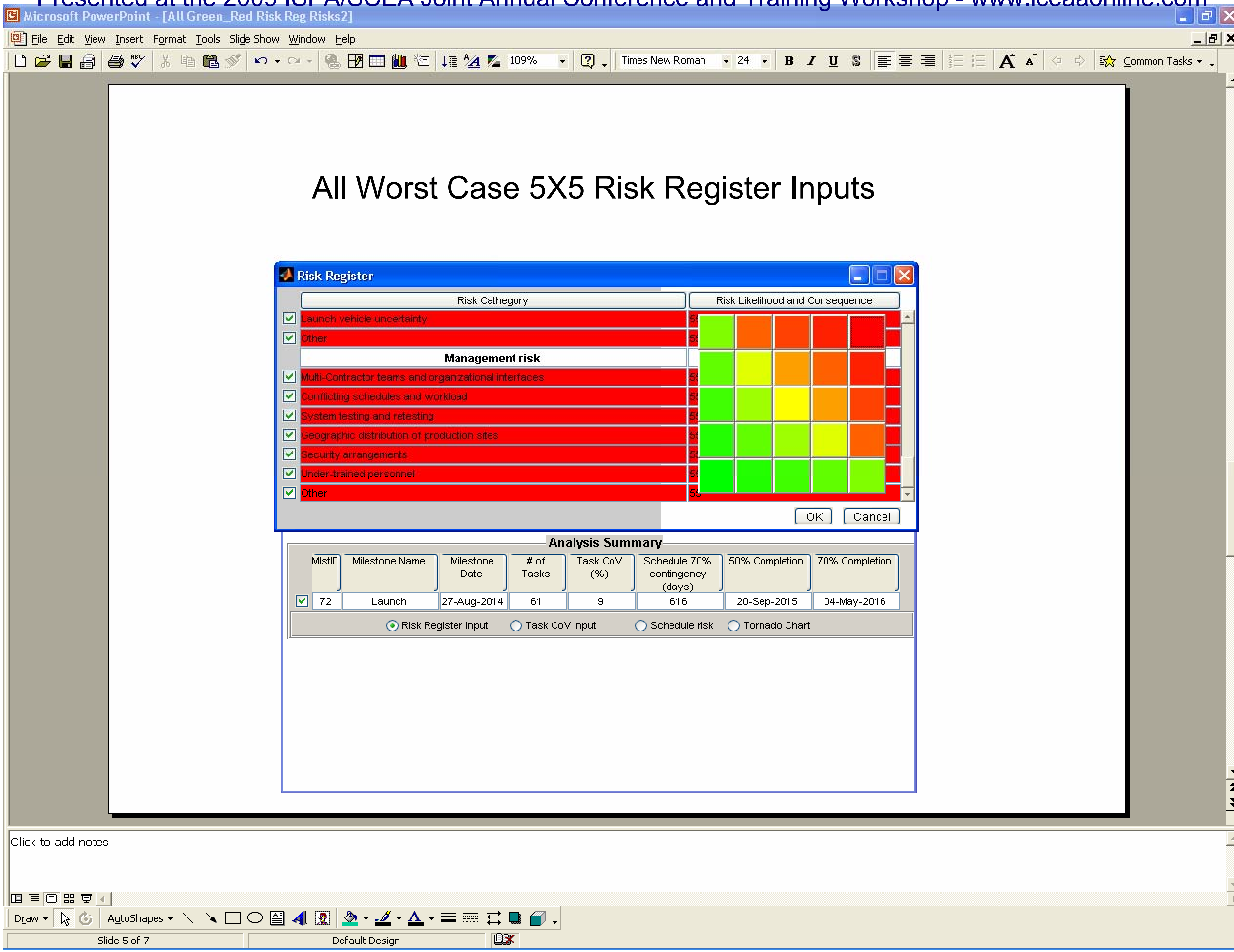
All Worst Case 5X5 Risk Register Inputs

Increases CoV; Flattens S-Curve

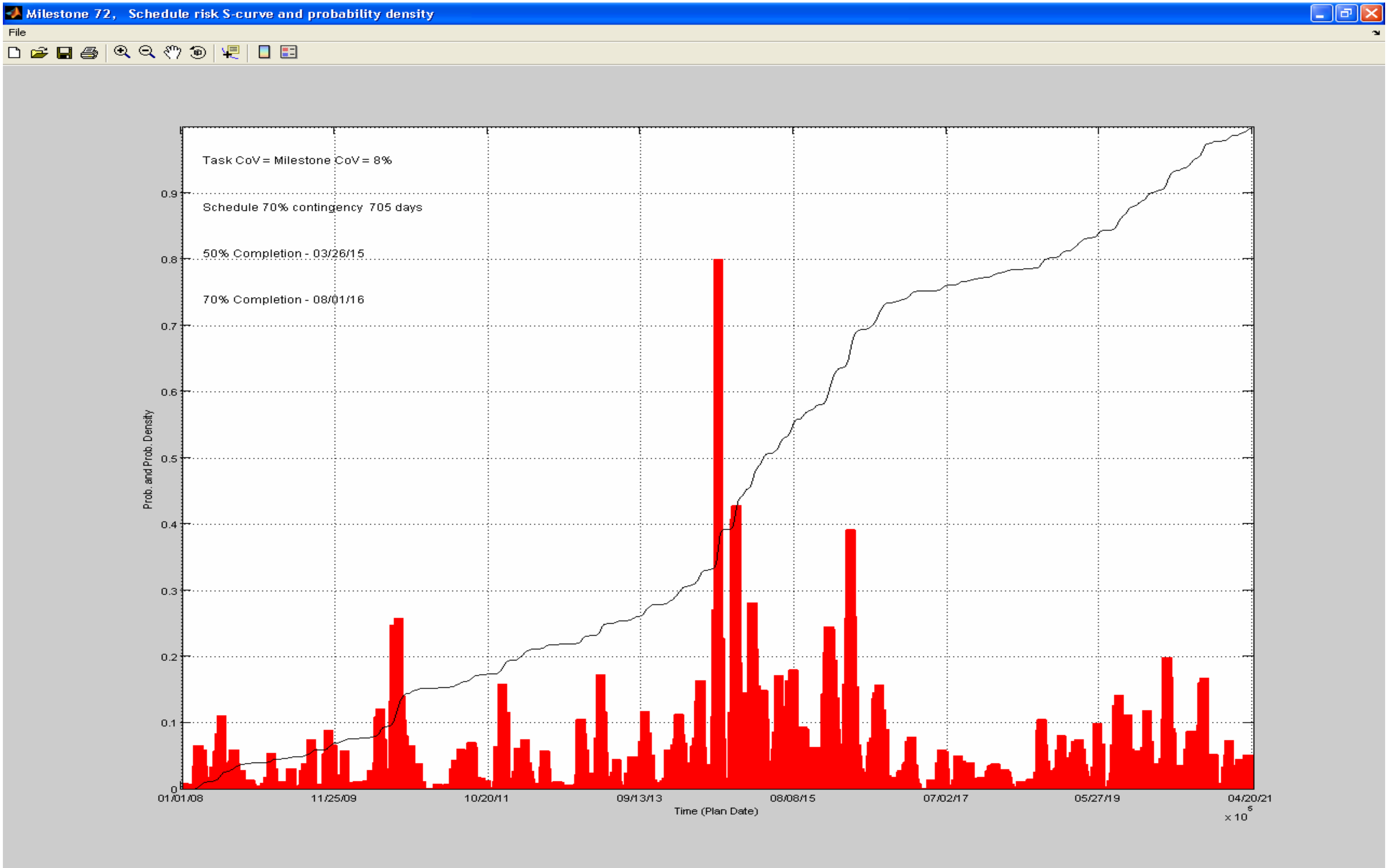



Cumulative Risk = 1 on scale (0,1)
Risk 70% contingency = 1328 days
50% Completion - 08/01/16
70% Completion - 04/16/18
Prob. and Prob. Density
Time (Plan Date)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
01/01/08
11/25/09
10/20/11
09/13/13
08/08/15
07/02/17
05/27/19
04/20/21

Presented at the 2009 ISPA/SCEA Joint Annual Conference and Training Workshop - www.iceaaonline.com



NIFT Monte Carlo Simulations = 3
(“Pure” Quantum Effects on Schedule Risk Only)



NIFT Monte Carlo Simulations = 300
(“Pure” Quantum Effects PLUS NIFT Monte Carlo)