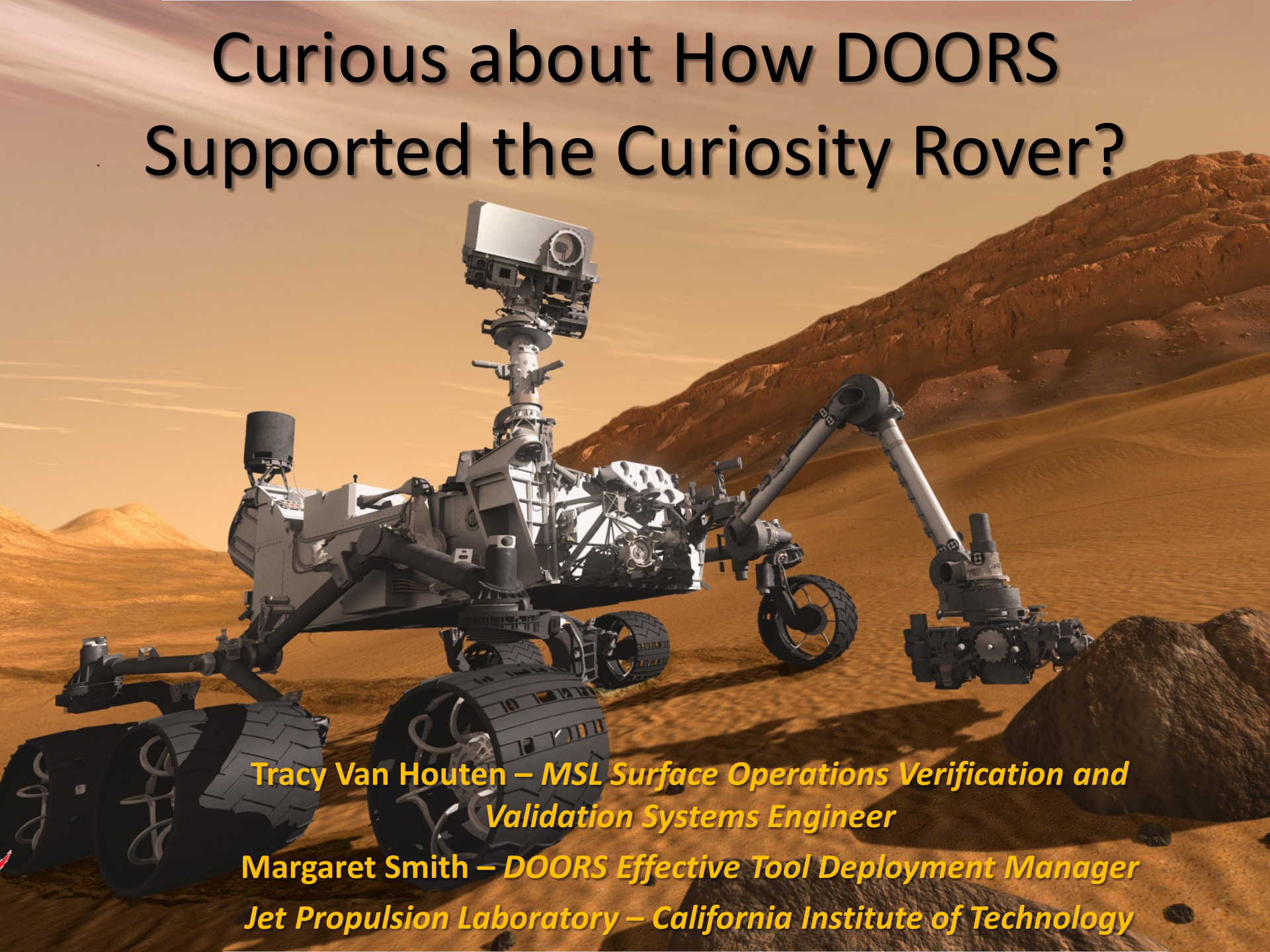
Curious about How DOORS Supported the Curiosity Rover?



Tracy Van Houten – ***MSL Surface Operations Verification and Validation Systems Engineer***

Margaret Smith – ***DOORS Effective Tool Deployment Manager***

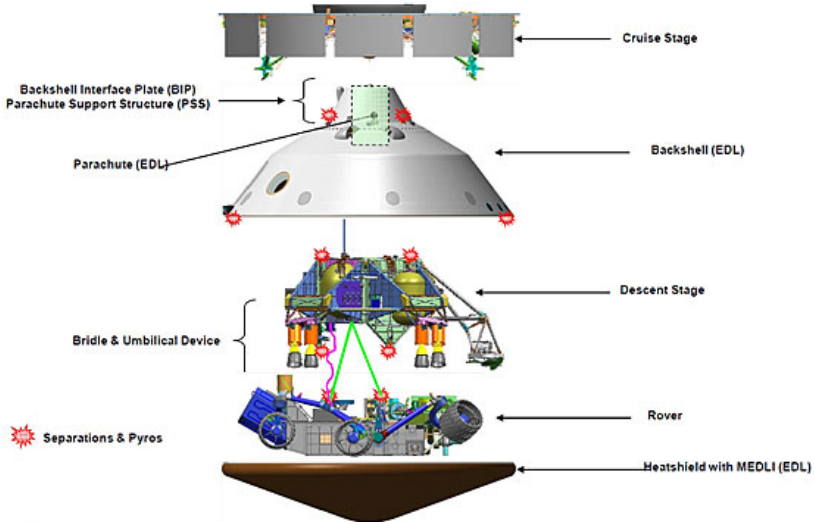
Jet Propulsion Laboratory – California Institute of Technology

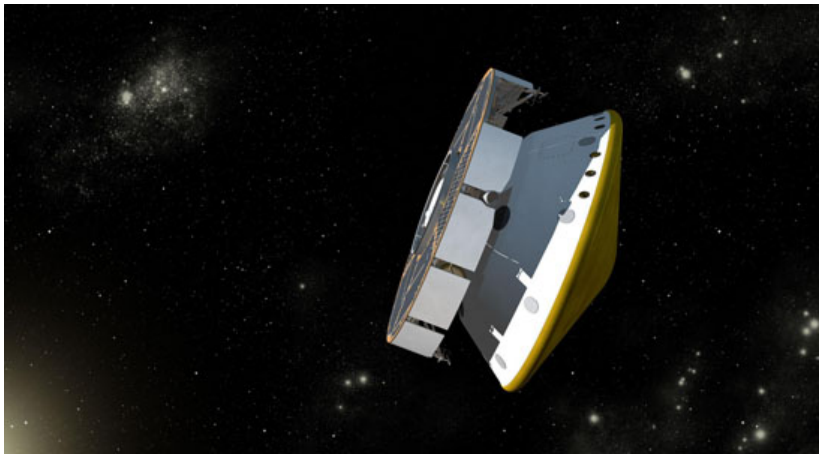
Outline

- **Curiosity Overview**
- **Use of DOORS for Curiosity Requirements**
- **Verification Planning and Tracking**
  - **For the Flight System (Launch and Cruise phases)**
  - **For Surface Operations (Mars landed phase)**
- **Benefits realized and Lessons Learned**
- **Status of Curiosity's Surface Operations**

Cruise Stage in Assembly, Test, Launch, Operations (ATLO) cleanroom at JPL

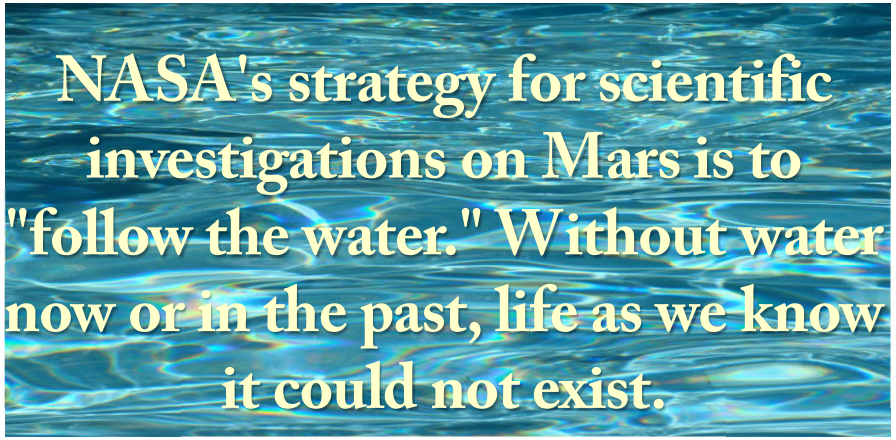
MSL Spacecraft Major Elements





Eight-month long Cruise to Mars

Curiosity Science Goals



Goal 1: Determine whether life ever arose on Mars

- Previous rovers established that water once existed on Mars.
- Curiosity will look for chemical elements that are the building blocks of life: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur.

Goal 2: Characterize the climate of Mars

- Study Martian weather patterns.
- Characterize distribution of water, carbon dioxide, and hydrogen.
- Measure surface radiation bombarding Mars from space.

Goal 3: Characterize the geology of Mars

- Look for evidence of rocks that formed in the presence of water.

Goal 4: Prepare for human exploration

- Develop/Demonstrate Mars Landing Technique for large, heavy payloads.

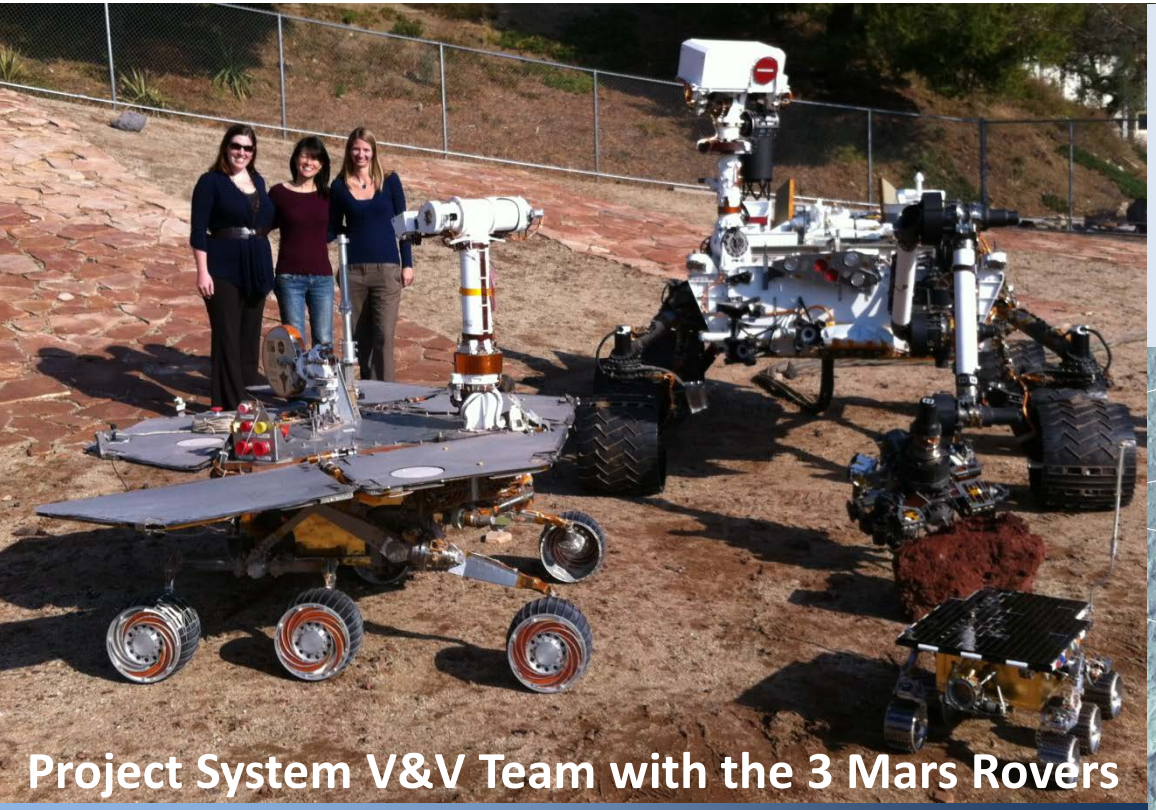
Project Organization & Partnerships

- Curiosity was an assigned mission, funded by NASA, managed by JPL.
- JPL design with heritage from Mars Exploration Rovers (MER).
- Many parts sourced from industry.
- Many unique components designed and developed by JPL.
- 10 Instruments supplied by industry, academic and international partners.
- Assembly, Integration and Test performed at JPL
- Launched from Kennedy Space Center on November 26, 2011.

Curiosity launches from KSC and begins its eight month cruise to the red planet

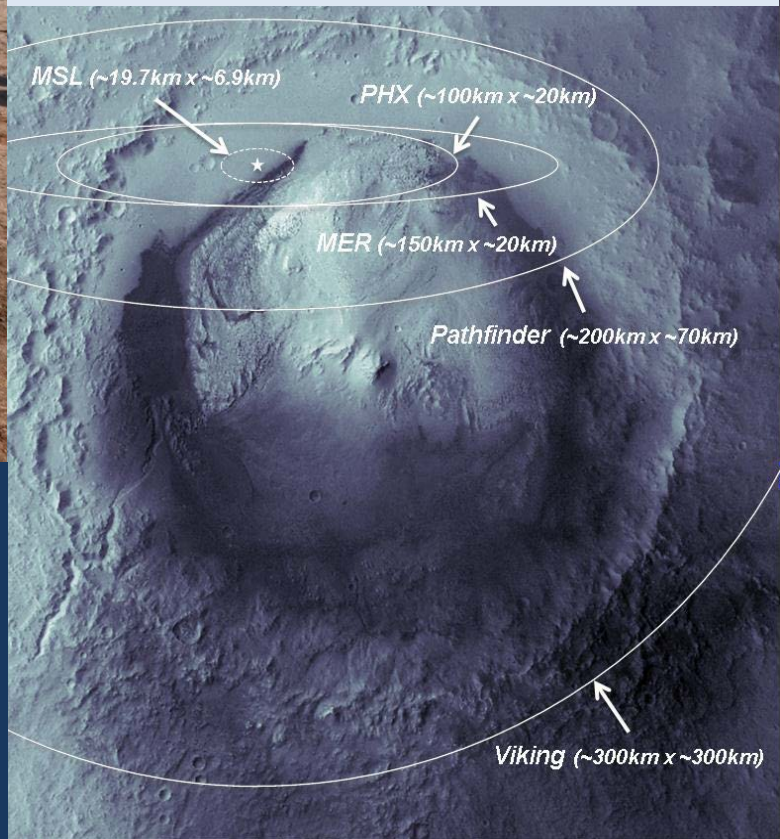
Launch day souvenir sticker

Evolutionary Steps in the Mars Rovers



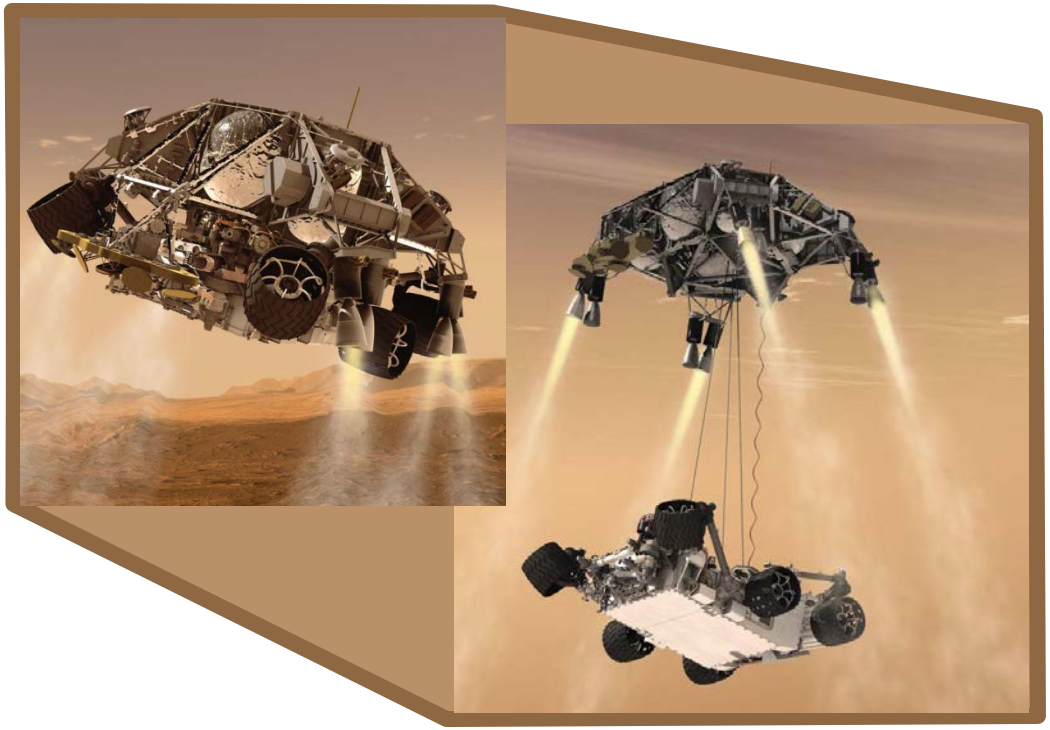
Project System V&V Team with the 3 Mars Rovers

MSL is the first spacecraft with landing accuracy and terrain tolerance good enough to reach a target with as much scientific potential as Gale Crater.

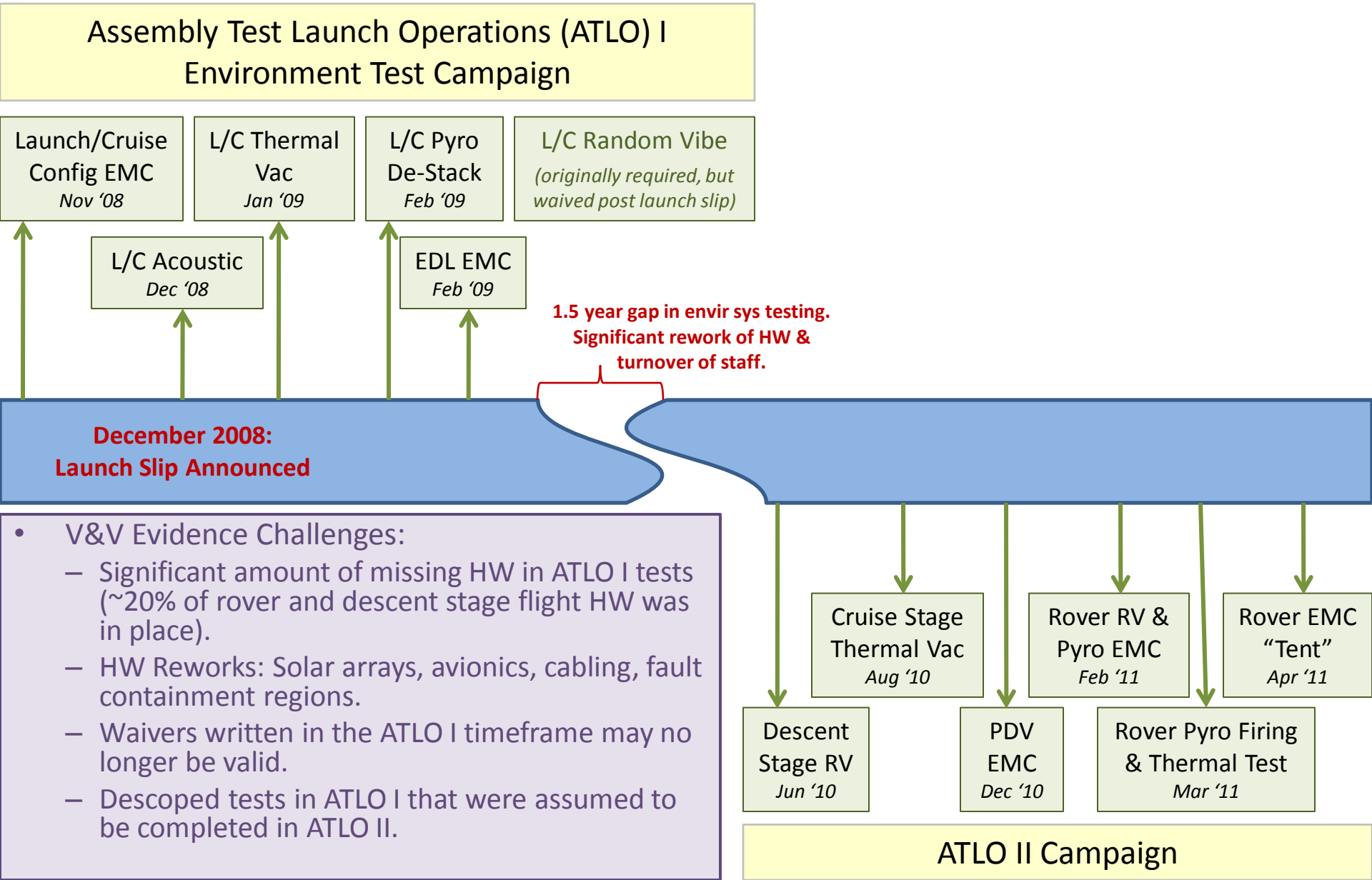


MSL's Engineering Challenges

- **Behavior/Software Complexity**
  - Ever-increasing Science goals drive complexity and software size.
  - MSL continues the trend of exponential growth in Flight Software size.
    - MER Flight Software was about 600,000 lines of C code – MSL was over 3 million lines of C code.
- **Large weight and Mars Atmospheric considerations required new Entry, Descent and Landing Solution**
  - MER rovers (2004) weighed almost 400 lbs – MSL weighs almost 1 ton.
  - Mars has just enough atmosphere to be a problem/factor.
  - Mars has 1% the atmospheric pressure and 38% of the gravity of Earth so it's difficult to test on Earth.



Example of MSL's V&V Challenges



- V&V Evidence Challenges:
  - Significant amount of missing HW in ATLO I tests (~20% of rover and descent stage flight HW was in place).
  - HW Reworks: Solar arrays, avionics, cabling, fault containment regions.
  - Waivers written in the ATLO I timeframe may no longer be valid.
  - Descoped tests in ATLO I that were assumed to be completed in ATLO II.

MSL's Surface Operations Engineering Challenges

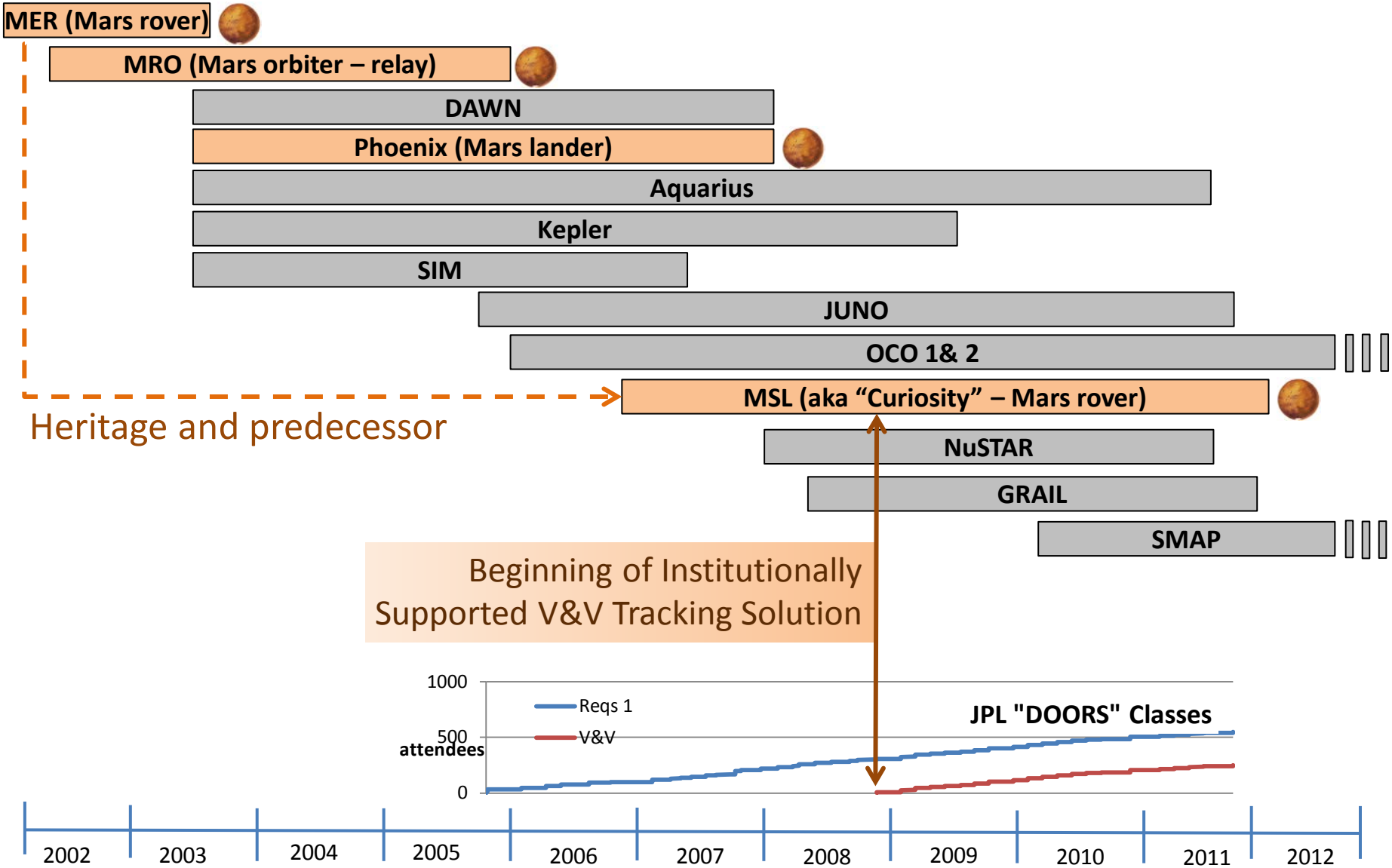
- Though a Martian year is nearly twice that of a year on Earth, the Martian day, called a sol, is only 40 minutes longer than an Earth day.
  - This resulted in the team living on Mars time for the first 90 sols of the mission and working to Curiosity's 9am-4pm "work day."
  - Surface Ops team works while Curiosity sleeps.
  - Now that the team has transitioned back to Earth time, there are "restricted sols", meaning that the comm passes happen too late to give sufficient data for planning the next day's activities.
- One-way light time ranges from 4 to 24 minutes
  - There is no "joysticking" of Curiosity.
  - A full sol's-worth of activity (and sometimes up to 3 sols) has to be planned in advance, meaning the rover has to have a significant amount of autonomy to avoid hazards, know when something has gone wrong, etc.

Programmatic Challenges

- Peek staffing around 1200 Full Time Equivalents;
  - More than 3000 JPLers have worked on Curiosity over about 10 years from Formulation to Operations.
- Once Curiosity Launched, the non-EDL engineering workforce split into two teams:
  - An Operations team – responsible for commanding and monitoring health and status of cruising spacecraft
  - Surface Operations Development and V&V team – Project had already done significant work in this area, but only had 8 months of Cruise for surface operations to be the main focus of Project attention.
    - Post-launch development of Flight Software, and updates several times prior to EDL and after landing was part of the nominal plan.
- Surface Operations development was a significant effort;
  - Held nearly 40 table top reviews for different aspects of Surf Ops.
  - All parts needed to be V&V'ed.
  - Surface ops team had to plan, test, and track hundreds of Verification Items (VIs)

Calendar Context

Start of Preliminary Design to Launch For Recent JPL Missions

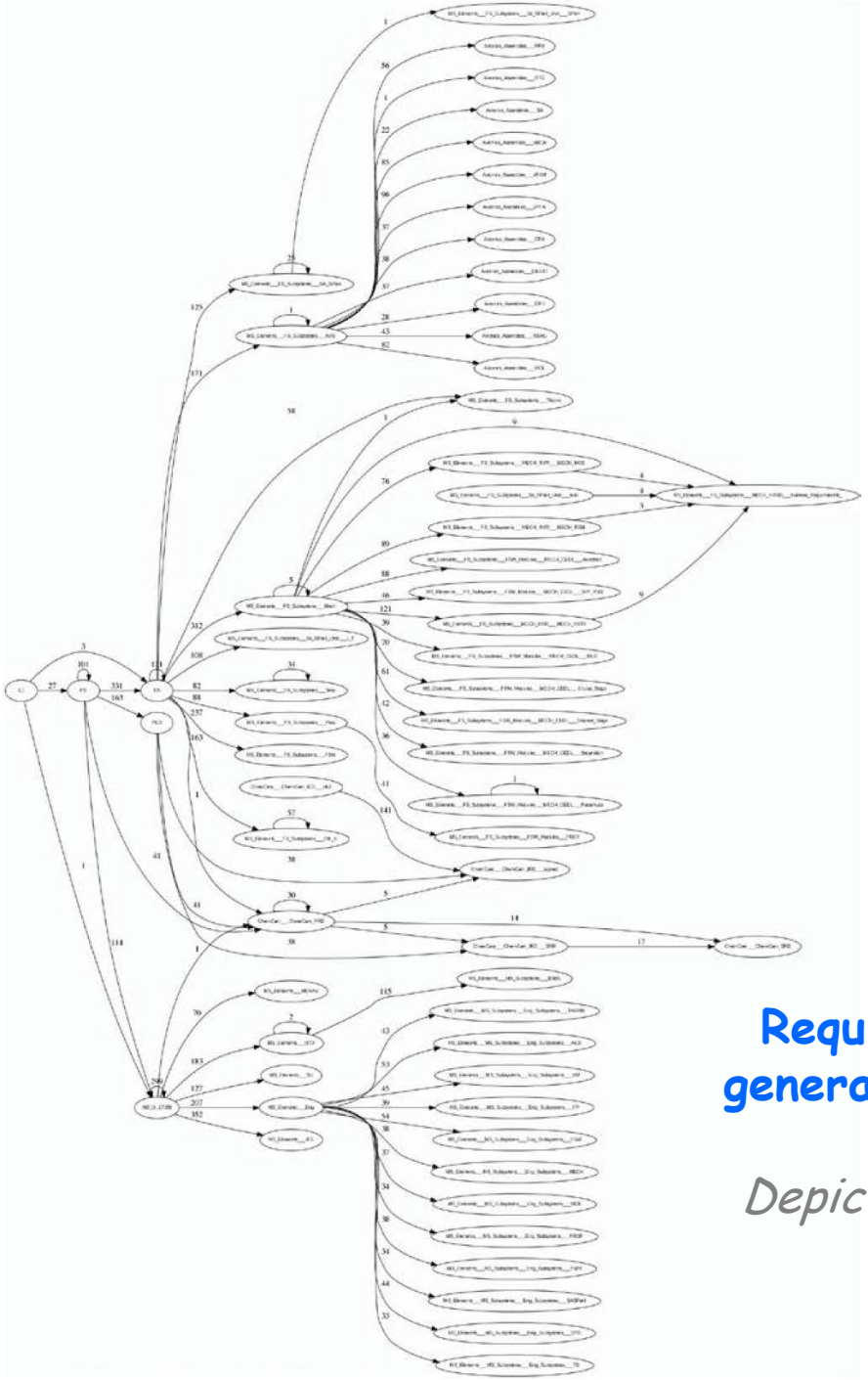


How DOORS Helped Curiosity

- DOORS provided:
  - Collaboration environment for an extremely large team
  - Visibility of latest version to a large team
  - Capture of the flow down of requirements to elements and into the V&V program
  - Traceability/path from requirements to test to V&V evidence stored outside DOORS
    - Captured closure statements/rationale when requirement to V&V traceability was complex and there were many sources of evidence.
  - Ability to generate custom tracking reports
  - Aide for test planning, fed into test Readiness Reviews

MSL Requirements and Verification Data Stored in DOORS

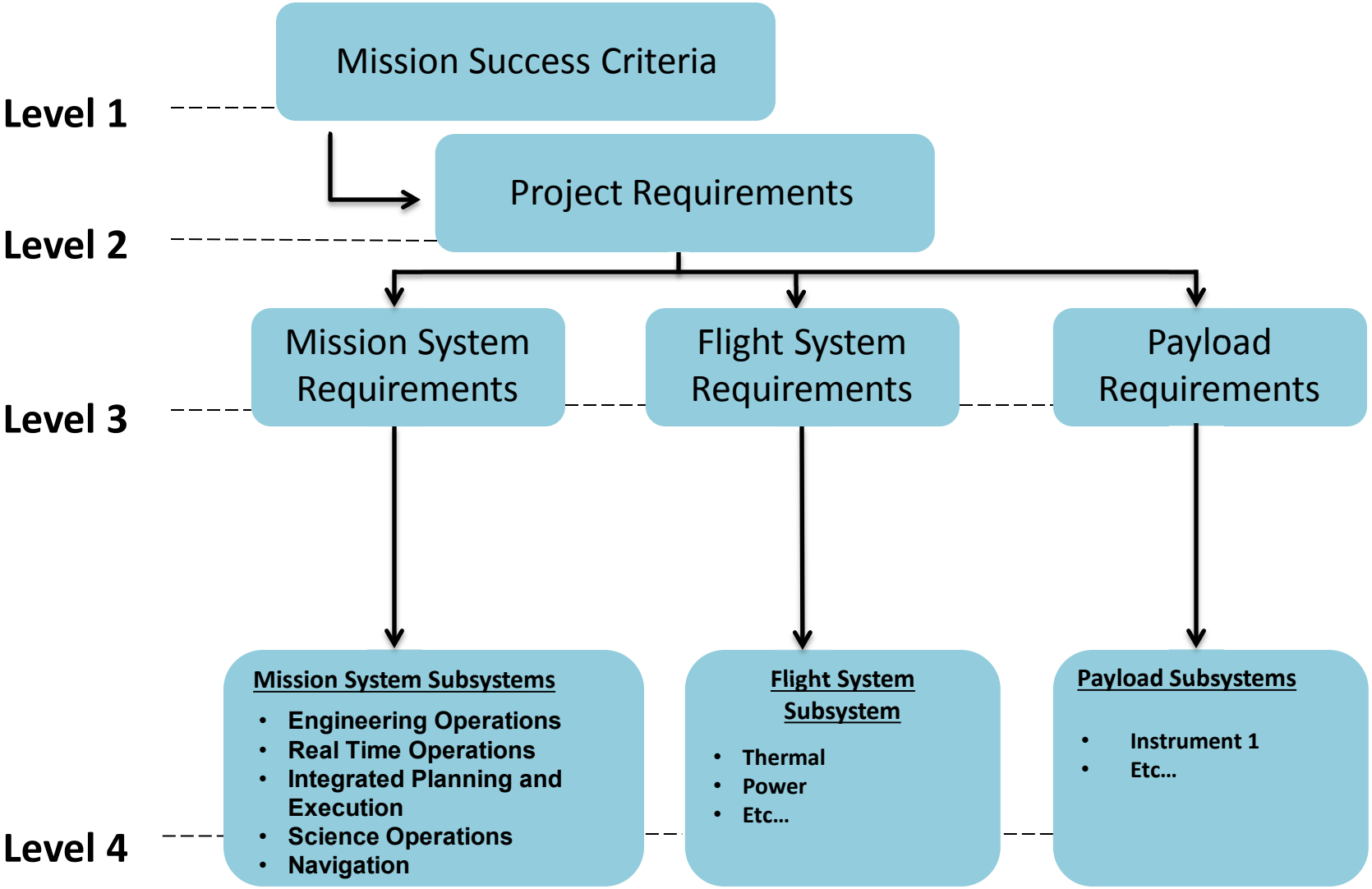
16,000 requirements
11,000 links



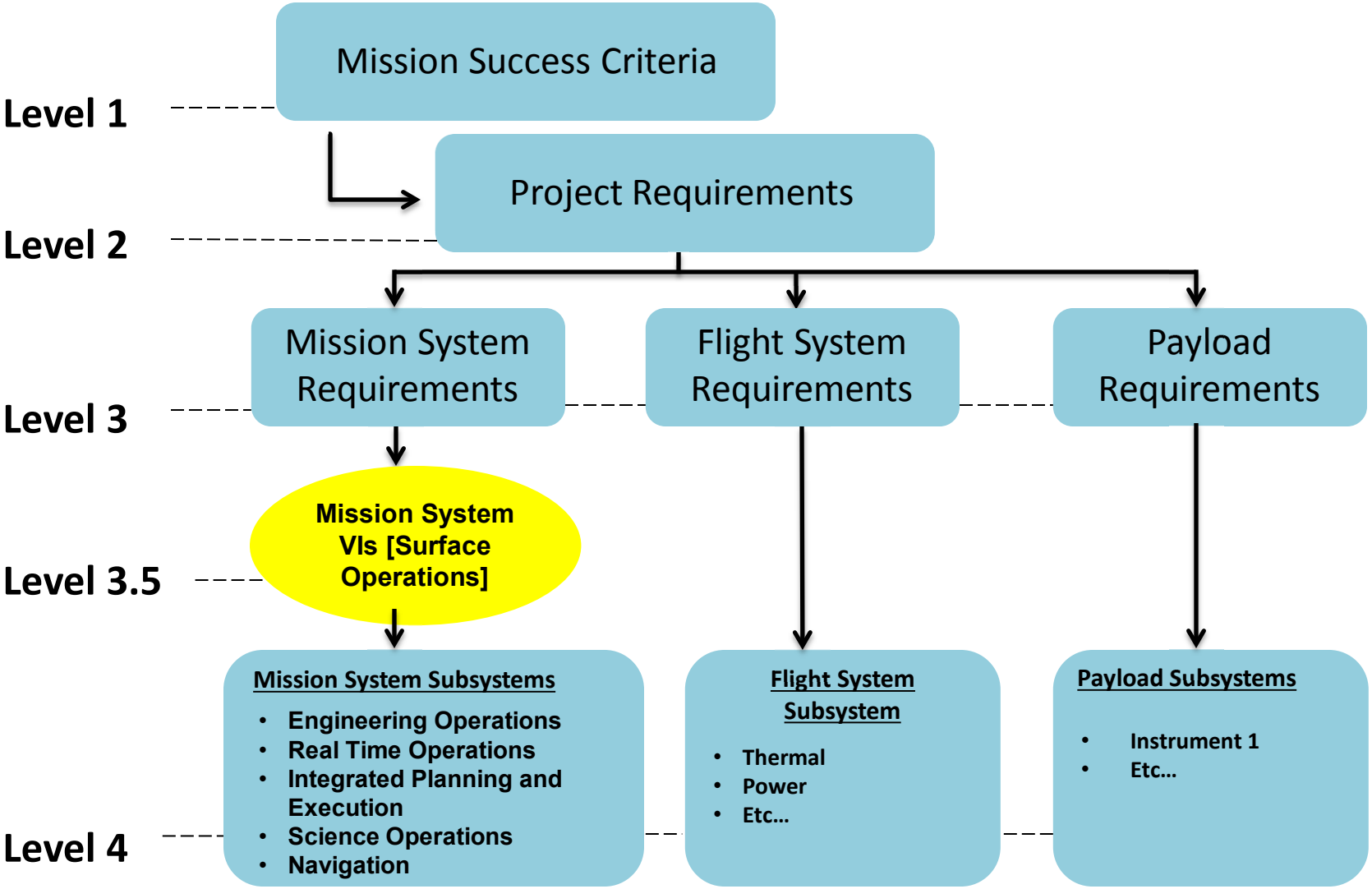
Requirements Link Tree – generated by the JPL Trace Tree Tool

Depicting only Requirements modules

Requirement Levels



Requirement Levels



Operational Readiness Tests (ORTs)

- ORTs were performed in preparation for launch, cruise, EDL, and surface operations
  - ORTs were performed pre-launch in ATLO on the actual flight vehicle, and post-launch on the identical vehicle test rover at JPL
- ORTs were the primary venue for testing surface operations readiness
  - Each ORT would exercise large swaths of Curiosity and team member capabilities.
- ORTs basically simulated several “Days in the life” of Curiosity to test team member preparedness, operational tools, interactions between the many teams and tools, and anomaly responses

Surf Ops V&V role in ORTs

- 5 ORTs were conducted specifically for surface ops
  - Each spanned 4-10 days and were done mostly on “Mars time”
  - Many lower-level “Thread Tests” were also completed to test specific team/tool functionalities
- Surface Ops V&V’s job was to show that all needed capabilities were working properly prior to ORT, to plan which system-level capabilities would be tested within each ORT, and to track/report-out the results.
  - Burndown charts and horserace charts were an effective way to track the pre- and post-ORT verification of capabilities and depict progress visually.

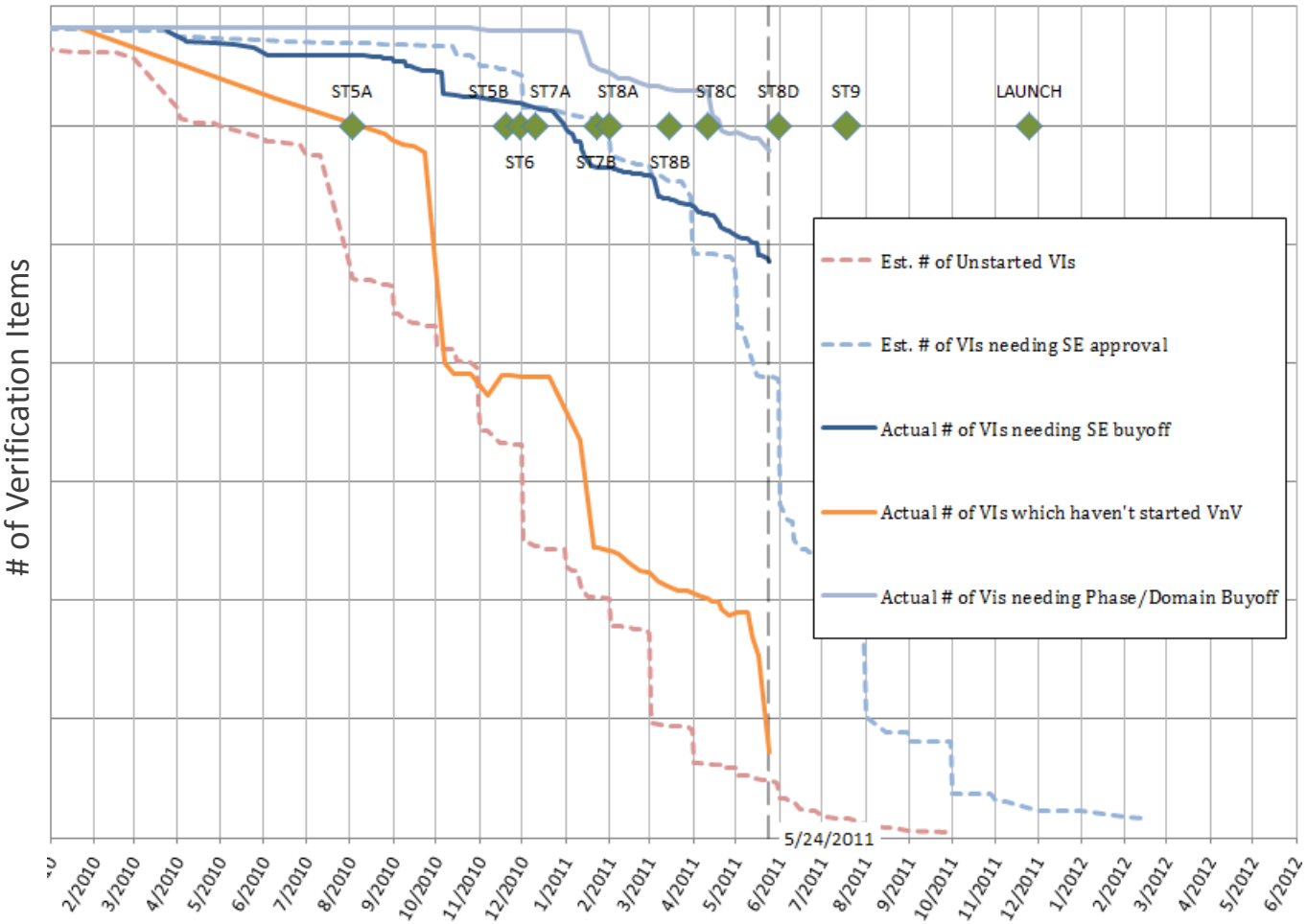
Burndown Charts

- A Burndown chart compares:
  - The **Schedule** for Work that still needs to be done.

    …against…
  - **Actuals**, which are:
    - Work that has **actually** been started,
    - Work that has **actually** been completed,
    - Work that has **actually** been audited/approved.

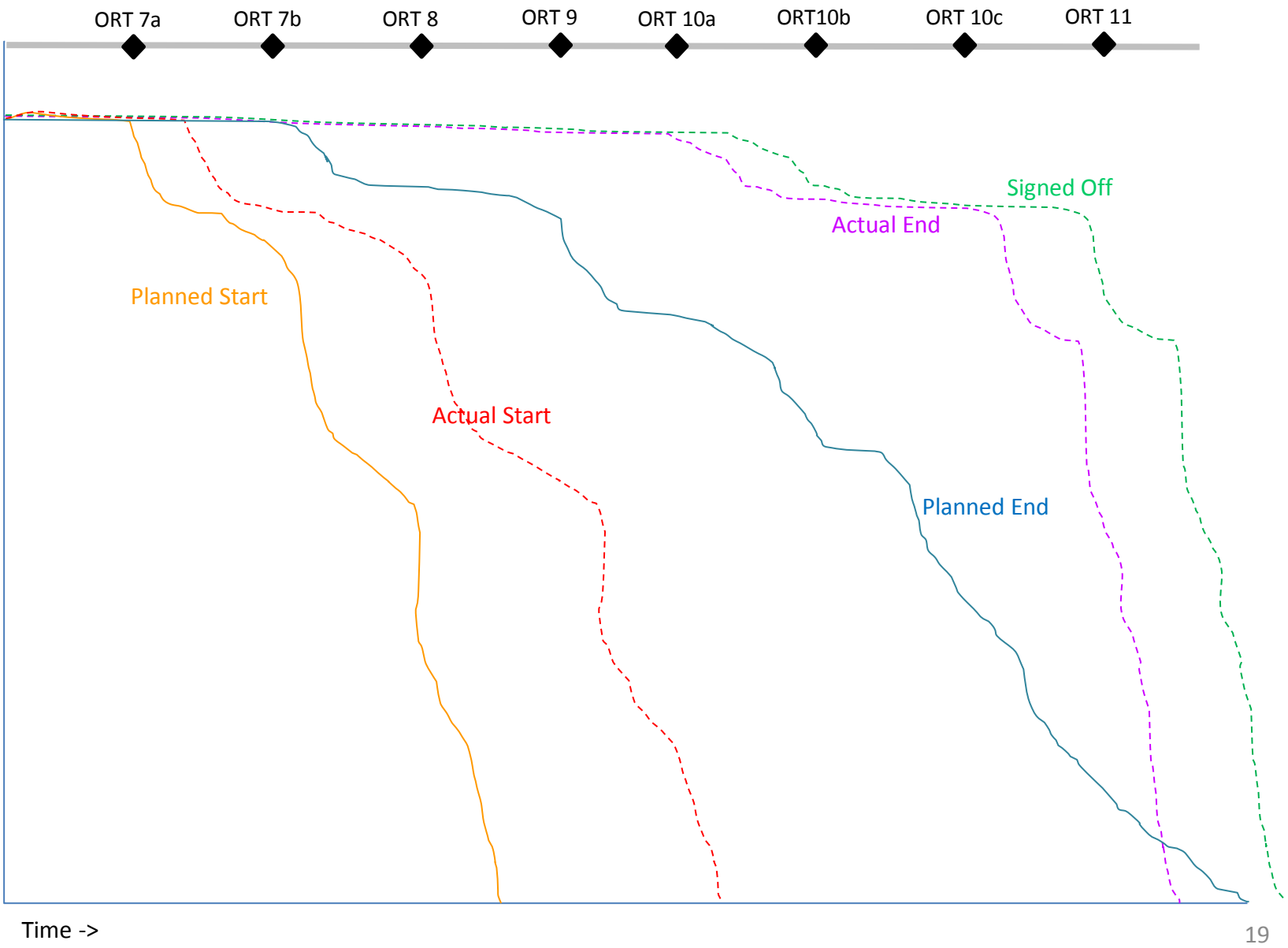
- The Flight System (FS) had been providing burndown charts prior to Launch and the Project found them useful.
- There was a desire to produce Burndown curves for Surf Ops V&V too,
  - but due to small team size and time limitations, needed a fully automated generation and post-processing, which had not been achieved for the FS.
- There were significant Lessons Learned from the FS burndown implementation that were leveraged in developing a new DOORS DXL for Surf Ops V&V Reporting.

Example Flight System Burndown Curve



- The flight system used burn down curves to compile a lot of DOORs info into one chart.
- Tracked many thousands of VIs from nearly 50 modules.
- Provided an additional 7+ lower level curves like this one in order to understand the details.
- Management liked this solution and expected to see more of the same during surface ops development;
  - Unfortunately the somewhat tedious process did not fit into the tight surface ops development timeline

Surf Ops Burndown – from the Script Specification



Burndown Script Implementation

- Script evaluates ‘scheduled work’ and actual ‘work to go’, creating data points for each day in a range of dates.
- Daily counts of requirements scheduled to start, scheduled to complete, actually started, actually completed, and audited were calculated by summing the number of:
  - Requirements for which Verification was not scheduled to be **started** by this day – generates the ‘Planned Start’ plotline,
  - Requirements for which Verification was not scheduled to be **completed** by this day – generates the ‘Planned End’ plotline,
  - Requirements for which Verification was not “Started”, or ‘Completed’ by this day – generates the ‘Actual Start’ plotline,
  - Requirements for which Verification was not “Completed” by this day – generates the ‘Actual End’ plotline,
  - Requirements which were not marked as “Audited” by this day – generates the ‘Signed off’ plotline.
- DXL used to export data from DOORS and Excel Macros (Visual Basic) used to perform calculations and display graphical results in a spreadsheet form.

Milestone2Date DXL Script

- Due dates for verifications were typically aligned with milestones, which for Surf Ops V&V were ORTs.
- Automation need:
  - Painless way to populate “Due Dates” for hundreds of Tests using Milestone/Date pair relationships,
  - Painless way to modify “Due Dates” when Milestones/Dates change.
- Milestone2Date DXL script demo script developed to demonstrate capability by scripter in a couple hours as a weekend project.
- Demo script helped to refine requirements for the Final version.

Milestone Module

'Milestone Date' current 0.0 in /MSL 2.0/Utilities (Formal module) - DOORS

File Edit View Insert Link Analysis Table Tools User Help

View Milestone View | All levels

- Milestone Date
  - 1 Project Milestones

ID	Headings and Description (optional)	Milestone Name (required)	Milestone Date (required)
1	**1 Project Milestones**		
21	Sample Analysis Thread Test	SATT	Friday, January 27, 2012
2	CAP 1 & CAP 2 ORT	ORT-7B	Friday, March 09, 2012
3	Surface Nominal ORT	ORT-8	Monday, April 23, 2012
5	CAP 1 & CAP 2 with Faults	ORT-11	Tuesday, May 29, 2012
7	CAP1a V&V Thread Test	CAP1a TT	Wednesday, June 13, 2012
24	FSW Transition Thread Test	FSW Trans TT	Friday, June 15, 2012
25	Comm Thread Test	Comm TT	Thursday, June 21, 2012
26	Tactical Activity Planning & Sequencing	TAPST	Wednesday, June 20, 2012
27	End to End Sampling Thread Test	E2E-SSS	Friday, June 22, 2012
28	Data Management Thread Test	DM TT	Tuesday, July 03, 2012
22	Surface Ops Dress Rehearsal	ORT-14	Sunday, July 15, 2012
32	Gold ORT	ORT-13	Friday, June 29, 2012
33	DEFERRED (Post-CAP)	DEFERRED	Monday, October 01, 2012
31	Relay Thread Test	Relay TT	Monday, June 25, 2012
10	Chart First	Chart First	Friday, January 20, 2012
11	Landing	LANDING!	Sunday, August 05, 2012
29	Chart Last	Chart Last	Wednesday, October 31, 2012
12	Report Date	Report Date	Tuesday, July 24, 2012

Tool proved to be hugely helpful during major Surface Ops V&V program refactoring

Surface Ops Module

Milestone name – hand populated

Milestone date – auto-generated

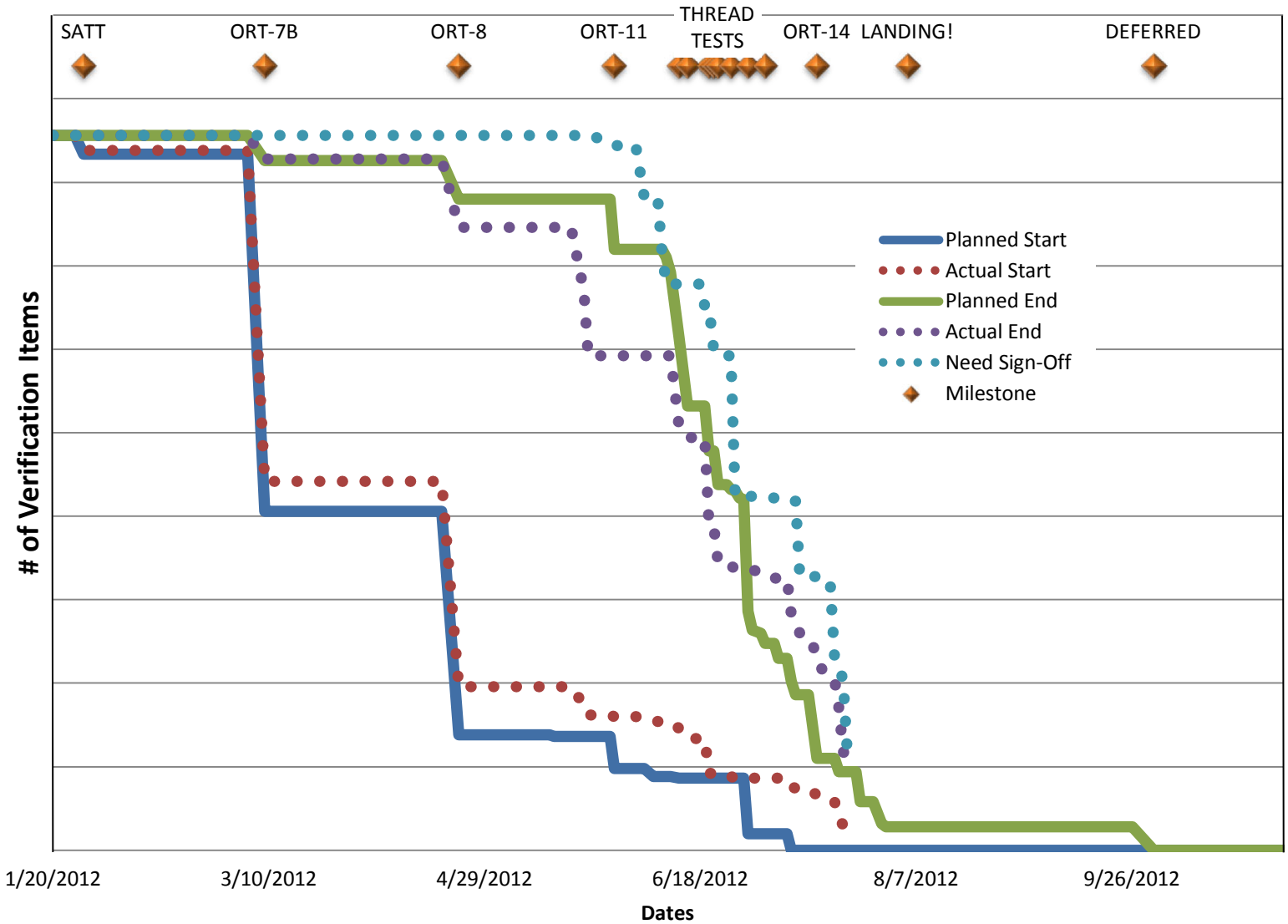
'L3.5 MS SURF Ops' current 0.0 in /MSL 2.0 (Formal module) - DOORS

File Edit View Insert Link Analysis Table Tools User Help

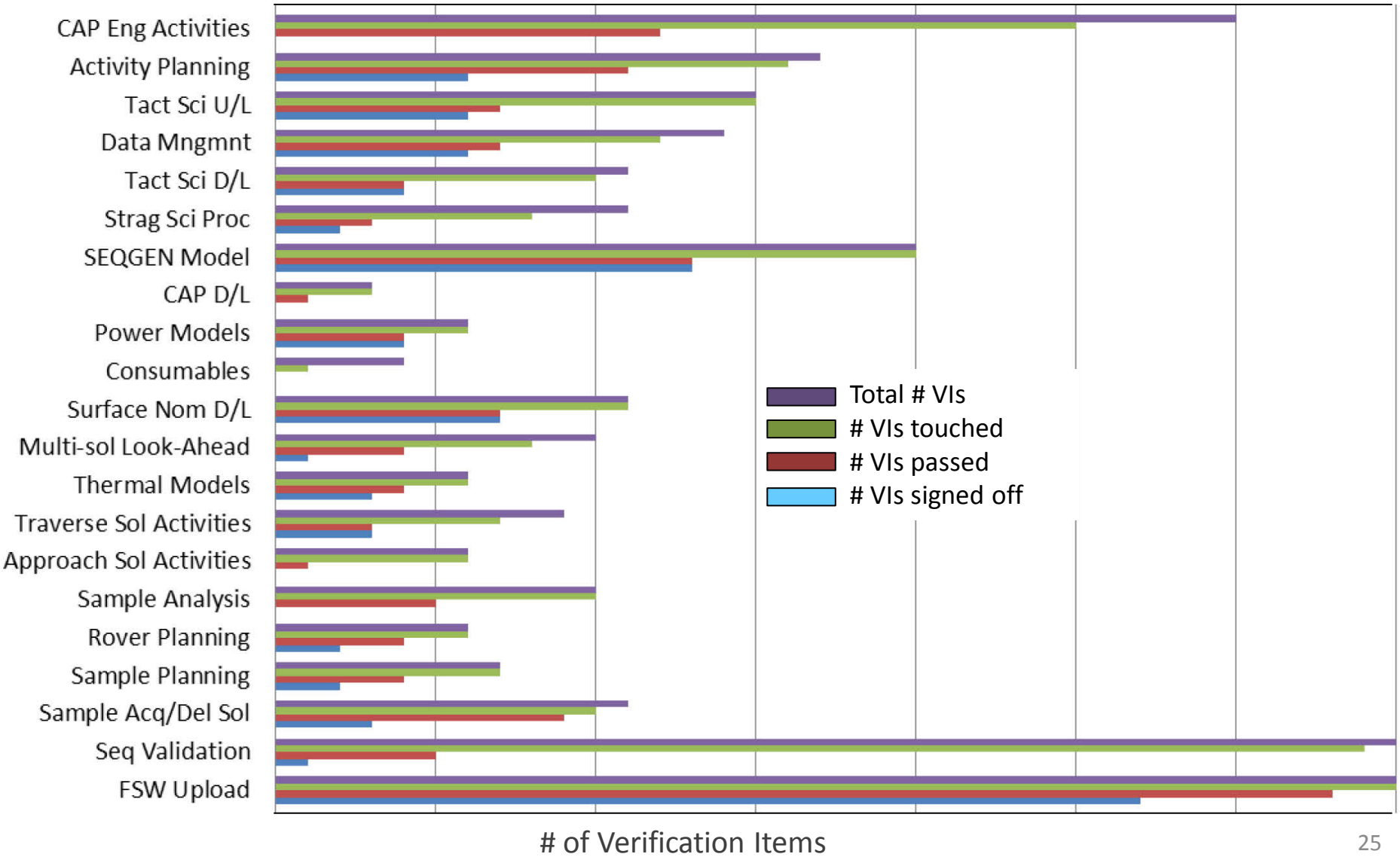
View [MS] Surf Ops V&V | All levels

[MSL] VI ID	[MSL] VG	[MSL] Scheduled Start Milestone	[MSL] Scheduled Start Date	[MSL] Scheduled End Milestone	[MSL] Scheduled End Date	[MSL] Status	[MSL] Status Date (Partial)	[MSL] Status Date (Passed)	[MSL] Status Date (Final Approval)
VI-MSSurfOps-447	Multi-sol Look-Ahead	ORT-8	4/23/2012 00:00:00		Wednesday, June 27, 2012	Passed	Monday, April 23, 2012	Monday, July 16, 2012	Thursday, July 19, 2012
VI-MSSurfOps-448	Multi-sol Look-Ahead	ORT-13	6/29/2012 00:00:00		Wednesday, June 27, 2012	Passed		Monday, September 10, 2012	Thursday, September 13, 2012
VI-MSSurfOps-449	Multi-sol Look-Ahead	ORT-11	5/29/2012 00:00:00	ORT-14	7/15/2012 00:00:00	Passed		Tuesday, May 22, 2012	Saturday, June 09, 2012
VI-MSSurfOps-450	Multi-sol Look-Ahead	ORT-8	4/23/2012 00:00:00	E2E-SSS	6/22/2012 00:00:00	Passed	Monday, April 23, 2012	Friday, June 22, 2012	Tuesday, June 26, 2012
VI-MSSurfOps-451	Multi-sol Look-Ahead	ORT-8	4/23/2012 00:00:00	TAPST	6/20/2012 00:00:00	Passed	Monday, April 23, 2012	Wednesday, June 20, 2012	Thursday, July 19, 2012
VI-MSSurfOps-482	New SAM Script Val		Tuesday, May 15, 2012	E2E-SSS	6/22/2012 00:00:00	Passed	Friday, March 09, 2012	Wednesday, September 19, 2012	Thursday, September 20, 2012
VI-MSSurfOps-483	New SAM Script Val		Monday, July 09, 2012	DEFERRED	10/1/2012 00:00:00	Passed		Wednesday, September 19, 2012	Thursday, September 20, 2012
VI-MSSurfOps-452	Surface Nominal D/L	ORT-8	4/23/2012 00:00:00	ORT-11	5/29/2012 00:00:00	Passed	Monday, April 23, 2012	Tuesday, May 22, 2012	Saturday, June 09, 2012
VI-MSSurfOps-453	Surface Nominal D/L	ORT-8	4/23/2012 00:00:00	ORT-14	7/15/2012 00:00:00	Passed	Monday, April 23, 2012	Sunday, July 15, 2012	Tuesday, July 17, 2012
VI-MSSurfOps-454	Surface Nominal D/L	ORT-8	4/23/2012 00:00:00	ORT-11	5/29/2012 00:00:00	Passed	Monday, April 23, 2012	Tuesday, May 22, 2012	Saturday, June 09, 2012
VI-MSSurfOps-455	Surface Nominal D/L	ORT-8	4/23/2012 00:00:00	ORT-11	5/29/2012 00:00:00	Passed	Monday, April 23, 2012	Tuesday, May 22, 2012	Saturday, June 09, 2012
VI-MSSurfOps-456	Surface Nominal D/L	ORT-8	4/23/2012 00:00:00	ORT-11	5/29/2012 00:00:00	Passed	Monday, April 23, 2012	Tuesday, May 22, 2012	Saturday, June 09, 2012

Surface Ops VI's Burndown Curve



Surface Ops Horserace Chart



Experience, Benefits and Lessons Learned

- Automation and time savings that was hoped for when undertaking this work, was realized.
- Investment:
  - Script development was 1.5 months for a non-DXL/VBA programmer working part-time.
  - 1 week to debug on actual DOORS data.
- Ran script monthly (provided 6 snapshots for management during Surf Ops V&V).
- Outputs were used at Certification of Critical Event Readiness (CoCER) Reviews, although not anticipated initially.
- Developed data validation mode for the script that was run before running the script.
  - Effective for debugging data quickly prior to running data generation script (which took ~1 minute to run and generate outputs and graphics).

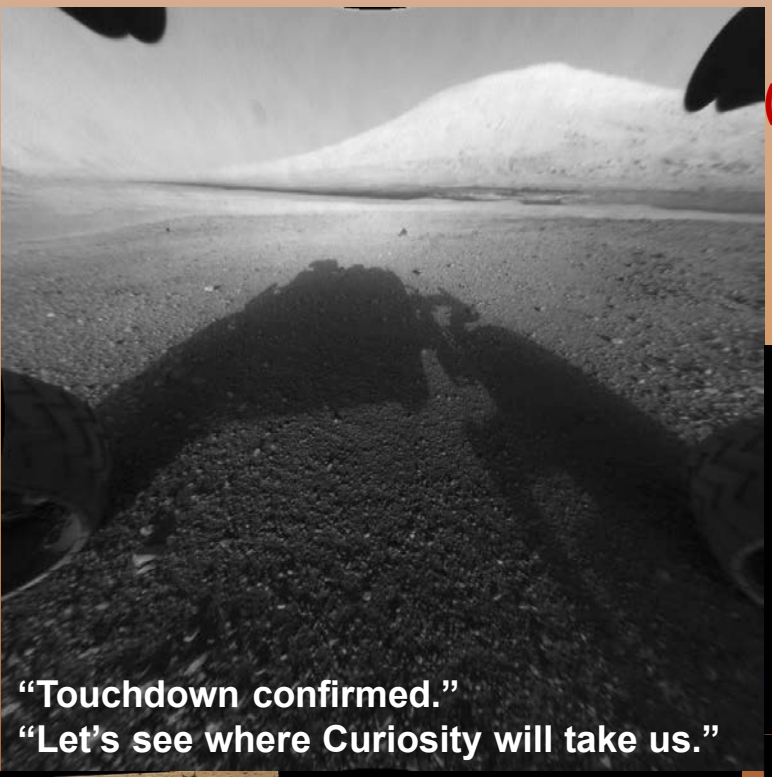
Experience, Benefits and Lessons Learned, Continued

- Would customize Excel charts after running the script and this took ~15 minutes.
- Should have created all the needed attributes up front so that people would start thinking about and filling them in, and it does not become a burden to collect values later in the Project.
- Should have established better ownership of individual VIs and all the data for them so that owners would feel they were required to enter data into DOORS themselves.
- DOORS Improvement: Eliminate the fixed relationship that a requirement belongs to a single module.
  - We needed requirements to be owned by a module but to be members of several other modules.

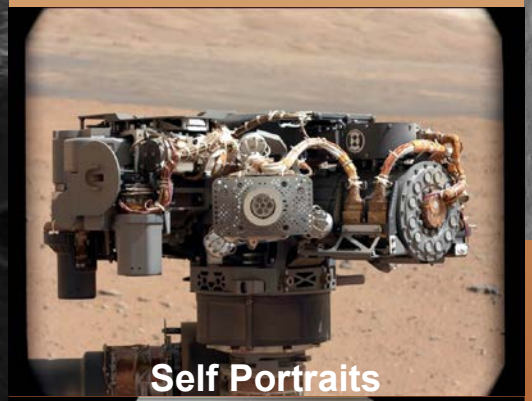
Today is sol 120 on Mars and Curiosity has performed exceptionally well!

(Total Odometry = ~640m)

Some highlights….

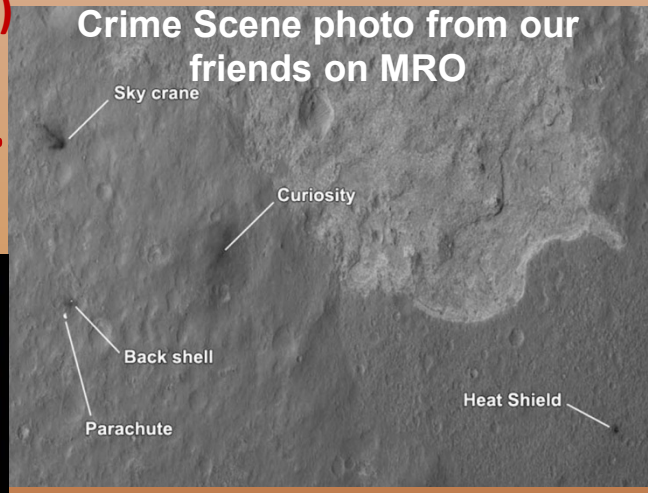


"Touchdown confirmed."
"Let's see where Curiosity will take us."

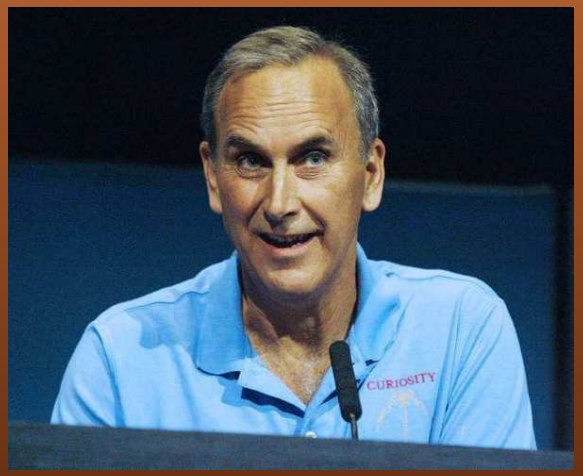


Self Portraits

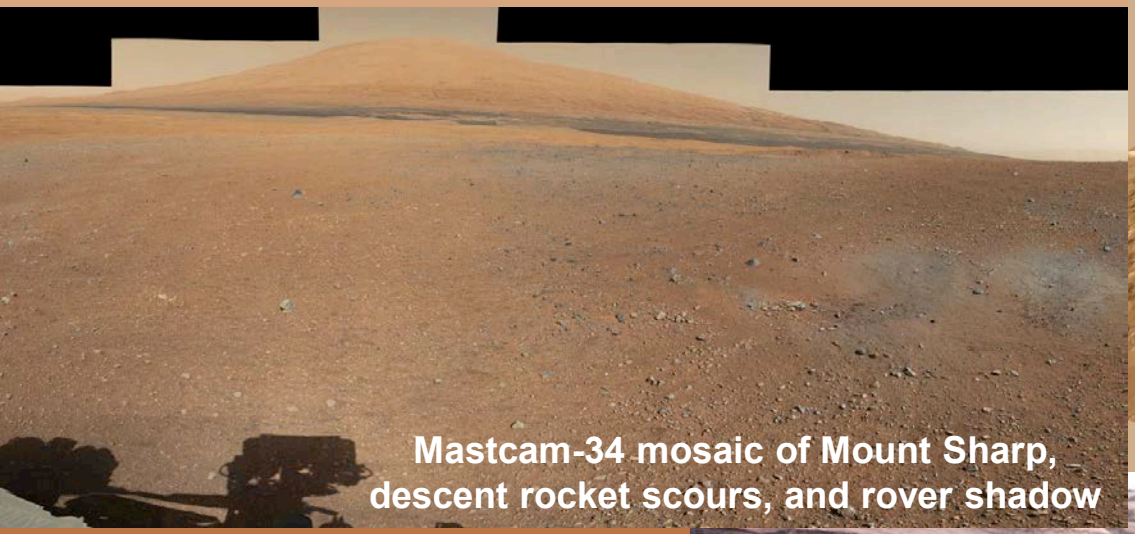
"Hottah" reveals pebbly conglomerate, evidence of an ancient streambed



"The data is going to be one for the history books."
– John Grotzinger, Project Scientist



Where Curiosity is headed…



Mastcam-34 mosaic of Mount Sharp, descent rocket scours, and rover shadow

NASA/JPL-Caltech/ESA/DLR/FU Berlin/MSSS

- Curiosity has a 2 year mission lifetime and will take time to get to the base of Mt. Sharp, which is more than 6km away.
- Then it'll be time to climb! Mt. Sharp is 5.5 km (18,000 ft) tall

Mastcam-100 image of Mount Sharp's layers, canyons and buttes

Conclusions

- Due to Project timing, most of the DOORS solution for Curiosity was designed and built by the Project.
- This proved a worthwhile investment as DOORS enabled requirements collaboration and communication on a large team, and was effective for capturing requirements flow-down.
- MSL leveraged DOORS for V&V Planning and Tracking and used DXL scripts for reporting and tracking Status and as input to management decisions.
- Surface Operations V&V scripting experience shows that it was possible to quickly create an automation solution in DXL.