A Design for Self-Reliant Rovers to Increase Mission Productivity

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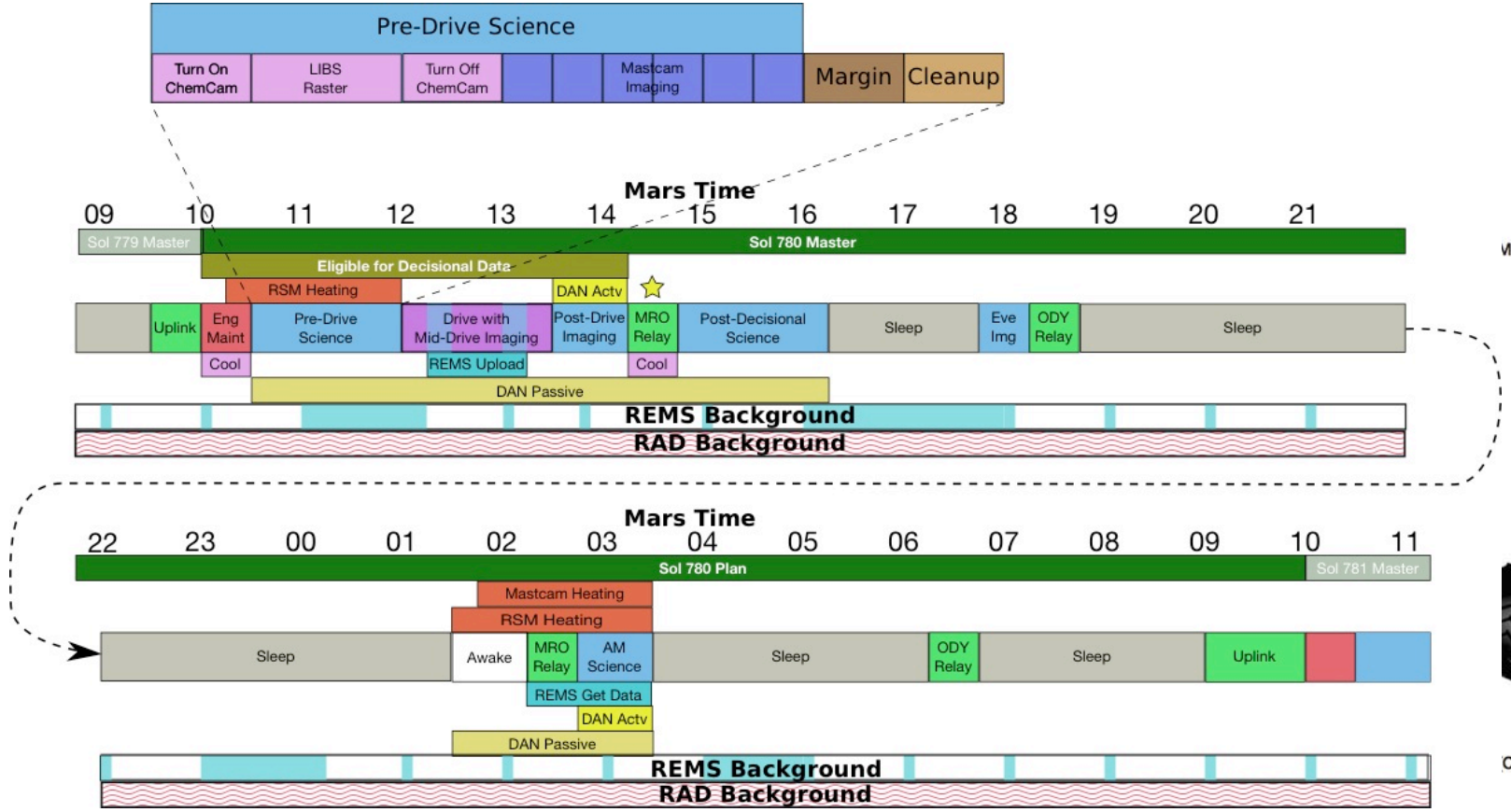
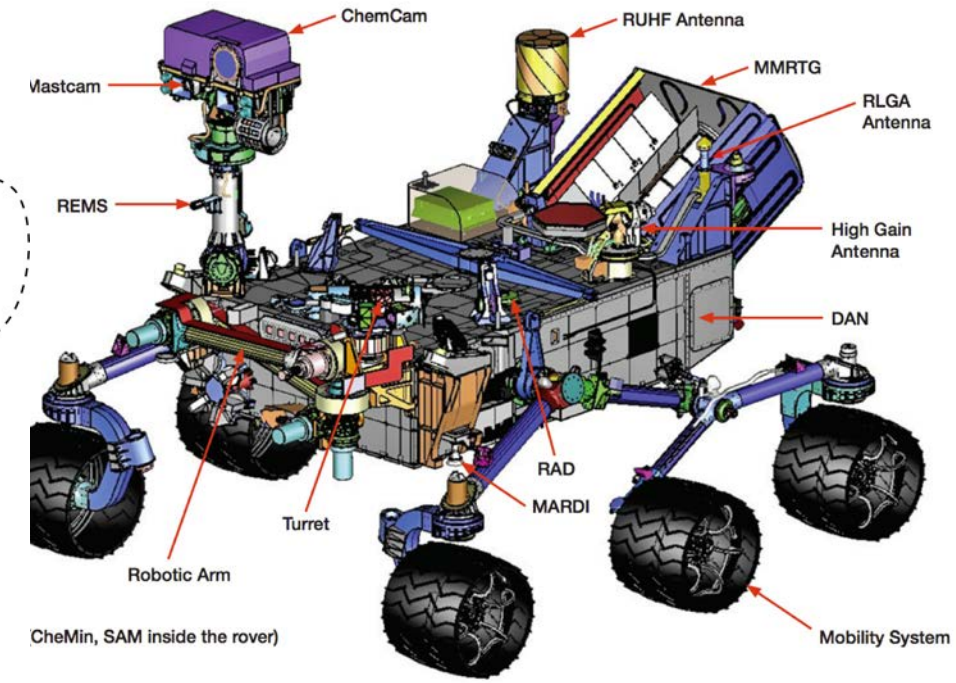
Overview of Project

- **Maintaining high levels of productivity for surface missions is a challenge**
  - Significant human effort required to develop command products
  - Can take more sols than anticipated to accomplish objectives
- **Productivity challenge anticipated to become even larger liability in future**
  - Aging sun-synchronous relay orbiters being replaced with non-sun-synchronous orbiters
  - Do not provide consistent “end-of-day” downlink pattern
- **Our goal:**
  - Identify changes to flight software and ground operations to address productivity challenges
  - Implement and evaluate prototype to demonstrate ability to address challenges
- **Approach:**
  - Conduct case study of MSL operations to understand productivity challenges
  - Identify design for flight software and ground operations to address challenges
  - Implement prototype of approach and deploy on research rover
  - Evaluate prototype on realistic, multi-sol scenarios

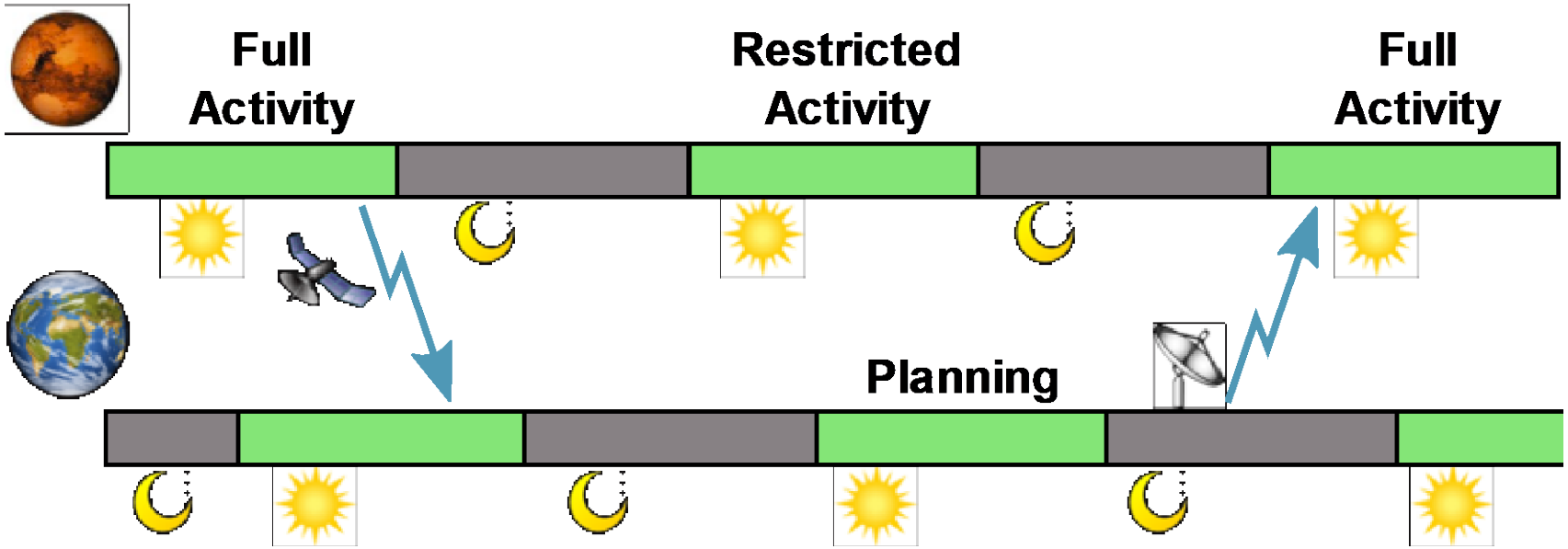
An Example Sol in the Life of the Rover





- Typical drive sol
  - Sol begins with morning uplink
  - **Data needed to inform next plan must be acquired before decisional pass**
  - Sol roughly organized into **blocks of activity, includes margin and cleanup**
  - Rover sleeps to conserve energy, recharge batteries
    - Some instruments can collect data while rover sleeps

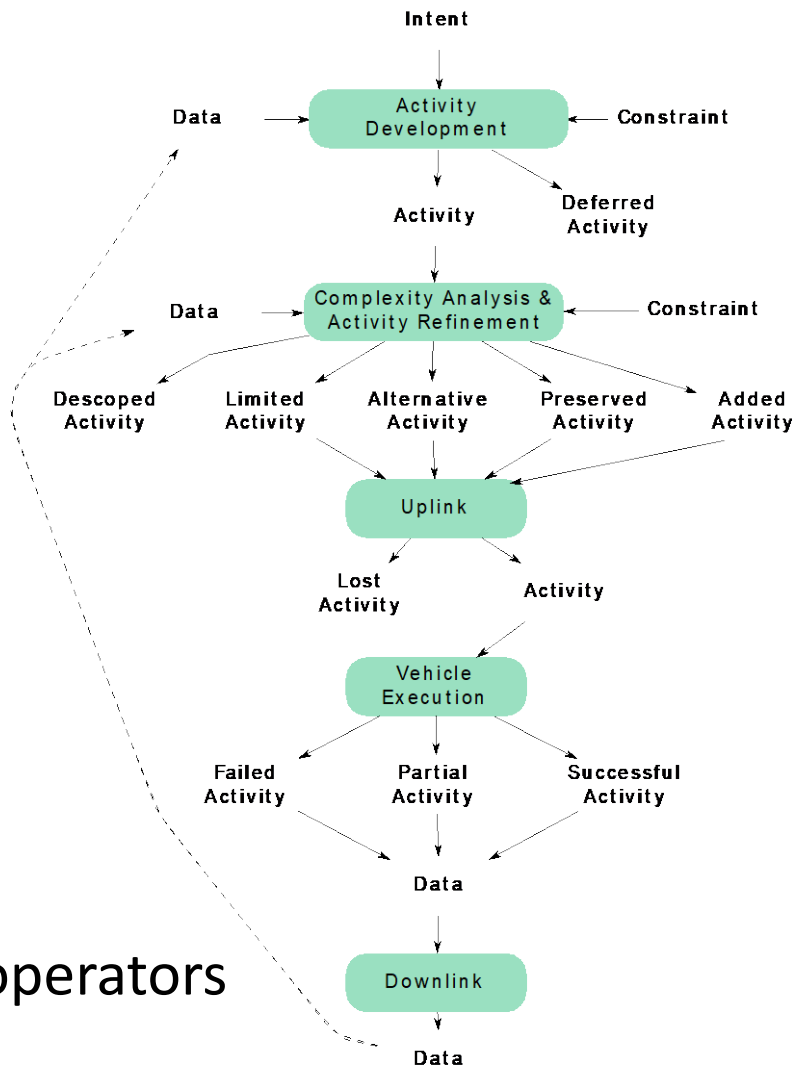
Restricted Sols



- Reception of rover end-of-day state “drifts” across Earth day over time
  - Mars day ~40min longer than Earth day
  - About ⅓ to ½ of the time, data arrives too late for team to create plan before rover’s next day (unless team works “Mars Time”)
- Team creates multi-sol plans to cover time between ground-in-the-loop cycles
  - Team restricted in what can be done second sol as data from this sol will not be available when next plan is developed

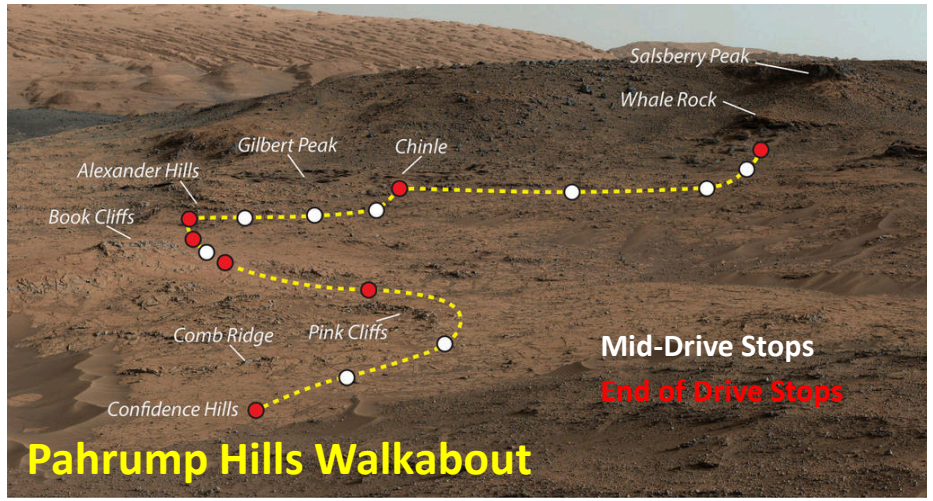
Case Study Overview

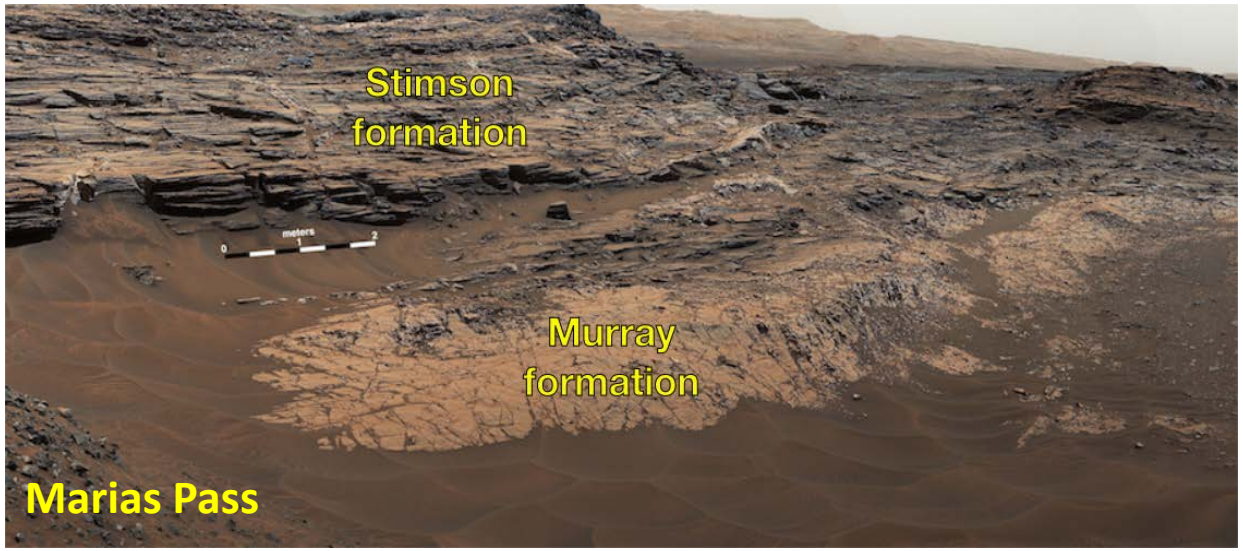
- Case study questions
  - Primary questions
    - How does the operations team define productivity?
    - What factors tended to increase productivity?
    - What factors tended to decrease productivity?
  - Secondary questions
    - How did the team select activities to accomplish intent?
    - What types of ground-in-the-loop decisions were made?
- Approach
  - Structured interviews with science and engineering operators
  - Detailed study of selected MSL campaigns



Selected MSL Science Campaigns

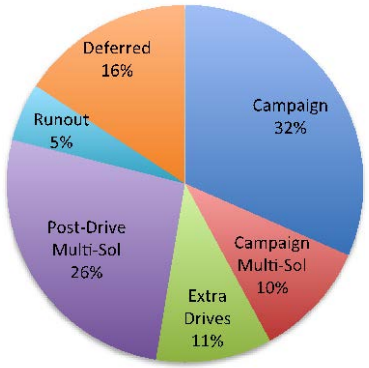
- Selected campaigns **provided mix of objectives, exploration strategies, mission contexts**
- Pahrump Hills Walkabout
  - Characterize basal layer of Mt. Sharp
  - Sols: 780 – 798 (19 sols)
  - Season: Spring
  - Drive dist: 152m
- Artist's Drive
  - Reach higher level of Mt. Sharp
  - Sols: 949 - 972 (24 sols)
  - Season: Late Summer
  - Drive dist: 567m
- Marias Pass
  - Characterize contact between two formations
  - Sols: 991 – 997; 1027 – 1043 (24 sols)
  - Season: Late Summer, Early Fall
  - Drive dist: 130m



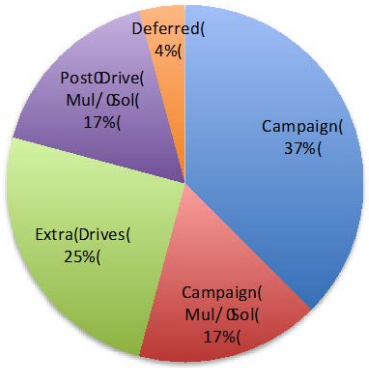


Summary of Campaign Activity by Sol

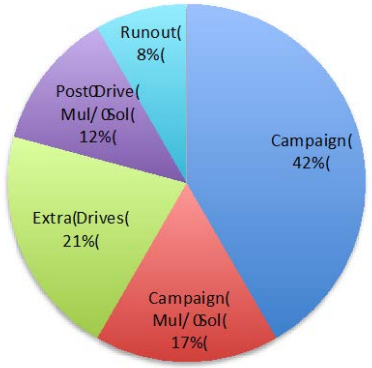
Pahrump Hills



Artist's Drive



Marias Pass

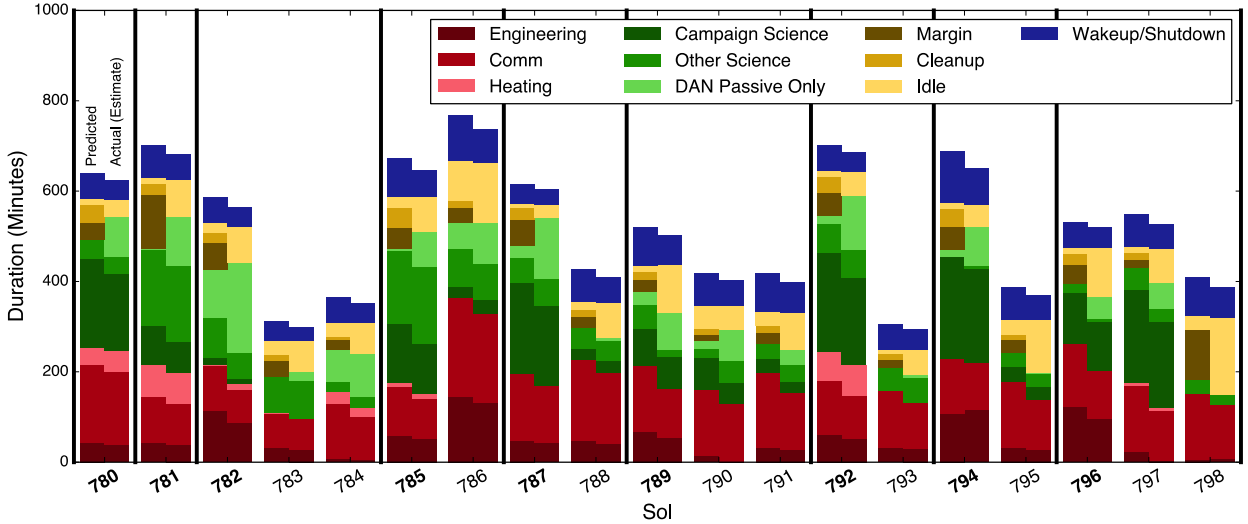


- **Large percentage of sols not making significant contributions to campaign**
- Most significant factors in summary:
  - **Restricted sols**
  - **Terrain conditions**
- Artist's Drive and Marias Pass have similar breakdown
  - Different objectives
  - Similar terrain
  - Similar pattern of restricted sols
  - Indicates terrain and restricted sols more significant factors for these types of objectives

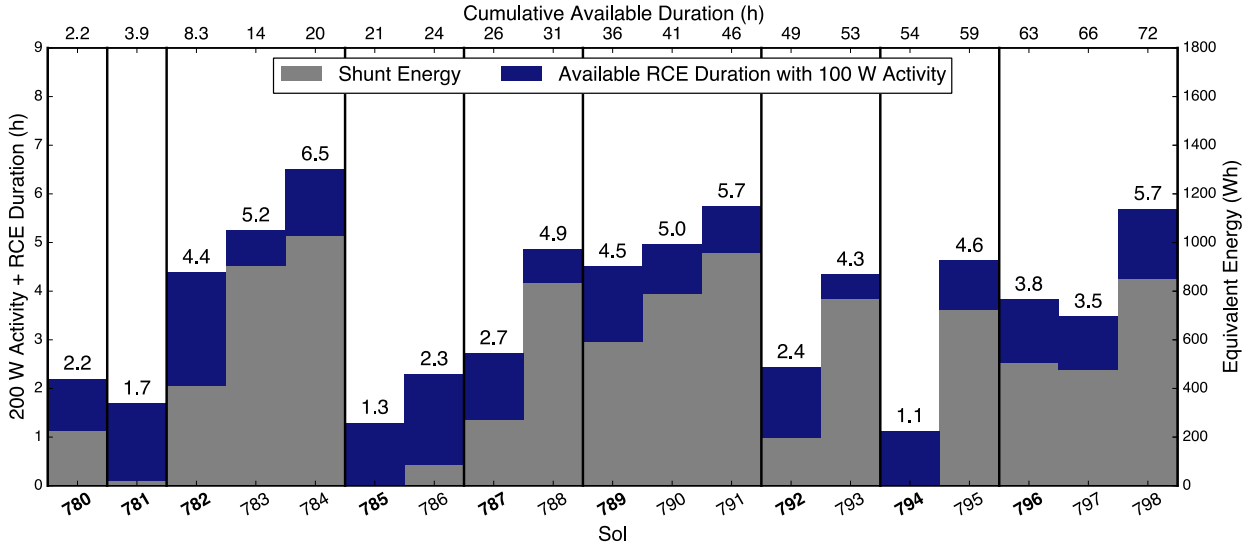
Sol Type	PH Sols	AD Sols	MP Sols
Campaign	6	9	10
Campaign Multi-Sol	2	4	4
Extra Drives	2	6	5
Post-Drive Multi-Sol	5	4	3
Deferred	3	1	0
Runout	1	0	2
Total Sols	**19**	**24**	**24**

Resource Utilization Analysis

- Conducted extensive set of resource usage analyses
  - Duration, data volume, energy
- Reduced resource utilization in multi-sol plans compared to single-sol plans
  - 2-sol plans: 12% reduction in CPU duration, 7% reduction in energy use
  - 3-sol plans: 15% reduction in CPU duration, 11% reduction in energy use
- Significant reduction in campaign activity following drives in multi-sol plans
  - Typical 0 to 30min of campaign activity on sol following drive
  - Note: this will differ for different campaign types
- Non-productive CPU duration
  - Activities usually run shorter than predicted
  - Margins and cleanups largely unused
  - Constraints on type of activities allowed to follow decisional pass
- Large discrepancies in predict vs. actual resource use
  - Due to: uncertainties in activity duration, conservatism in models, inaccuracies in deriving and propagating state of charge value
  - Potential to unnecessarily limit activities in plan
- Estimates indicate there was significant extra duration available for additional campaign activities
  - PH: 72 hrs, AD: 62 hrs, MP 70 hrs
  - If productivity challenges can be overcome



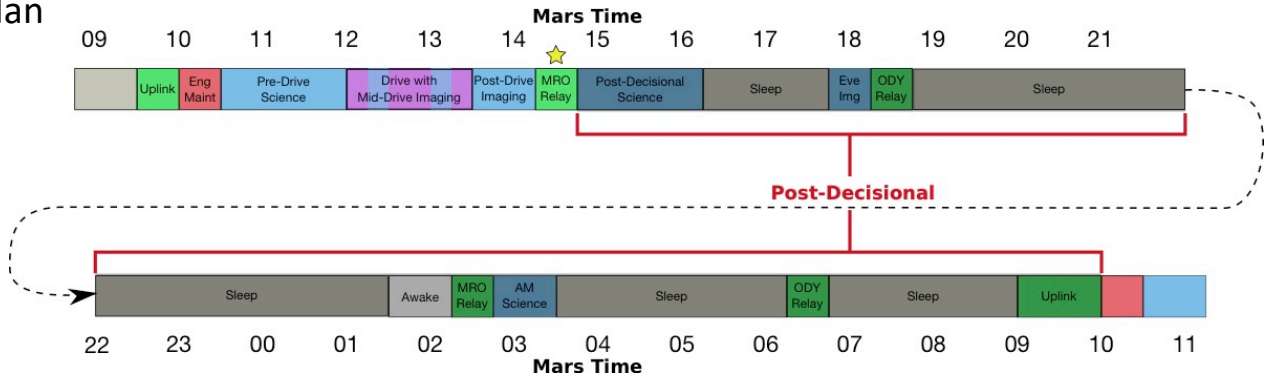
Pahrump Hills CPU Duration Allocation



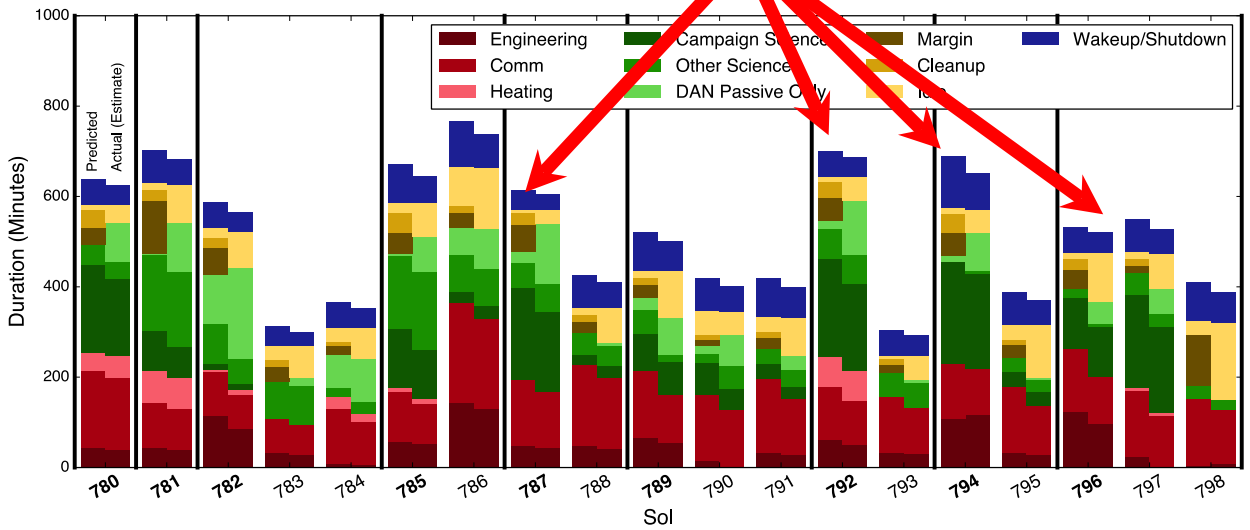
Pahrump Hills Estimate of Extra Available Duration

Major Productivity Challenges

- Ground-in-the-loop requirements for target selection and effective drive planning
  - Restrictions on when certain activities can be performed in plan (prior to decisional pass), resulting in non-productive time in plan
  - Significant drop in productivity on sols following drive in multi-sol plan
- Ground-in-the-loop requirements to respond to outcome of activity
  - Drive faults, poor lighting in imaging, missed ChemCam targets, insufficient material under APXS
- Capacity of tactical timeline to fill multi-sol plans
  - Overhead in command product generation
  - Overall drop in productivity across multi-sol plans
- Managing tactical timeline complexity
  - Ability to judge how much activity can be accomplished in timeline
  - Difficulty in taking into account staffing variations
- Use of margin and cleanup duration allocations
  - Results in un-productive CPU duration
- Predicting available vehicle resources
  - May unnecessarily limit activity
- Ability to exploit supratactical work
- Communication among teams
- Science team engagement
- Time to analyze data, make decisions

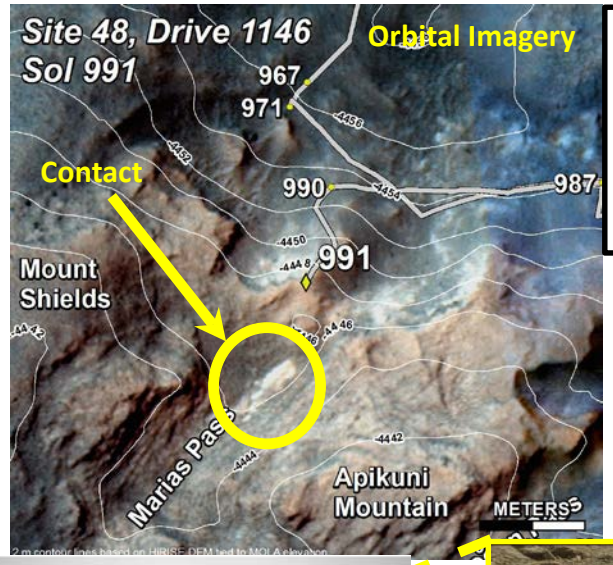


Example drives in multi-sol plans

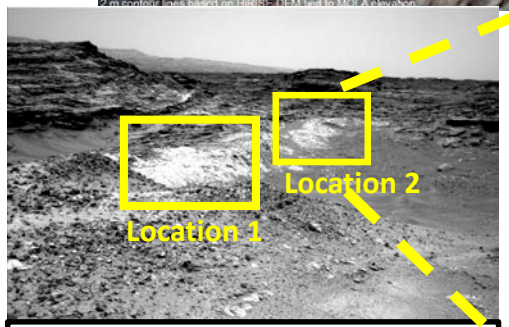


Major Types of Ground-in-the-Loop Decisions

- Selecting science targets for ChemCam, Mastcam and contact science
  - Use of high quality imaging from rover's immediate surroundings to select science targets
  - Requirement of high degree of accuracy in position of rover relative to targets for pointing small FOV instruments
- Drive planning
  - Selecting end drive location
  - Selecting drive route (terrain conditions, hazards)
- Stability assessment for contact science
- Responding to problems in activity executions
  - Re-planning failed drives
  - Re-acquiring observations (or potentially losing opportunity if rover drove away)
- Science discovery
  - Changing strategic objectives (e.g. Logan's Run in Artist's Drive)
  - Backtracking to prior locations (e.g. Marias Pass)



Can identify location of contact, but **insufficient detail to pick targets and plan actual drive**

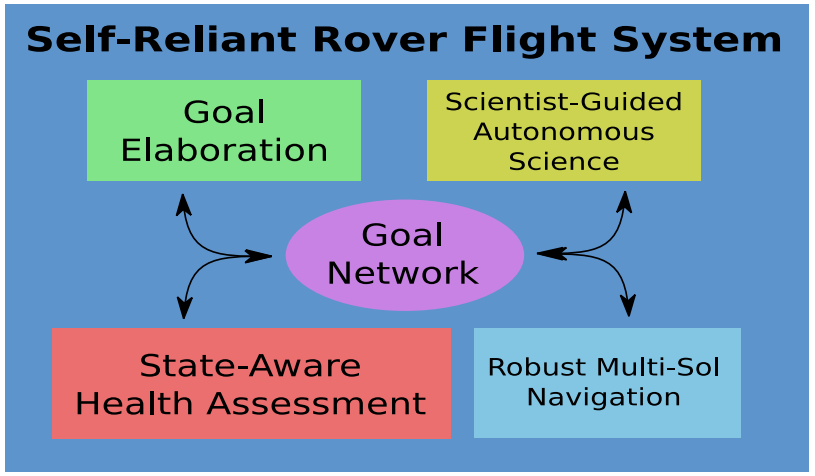


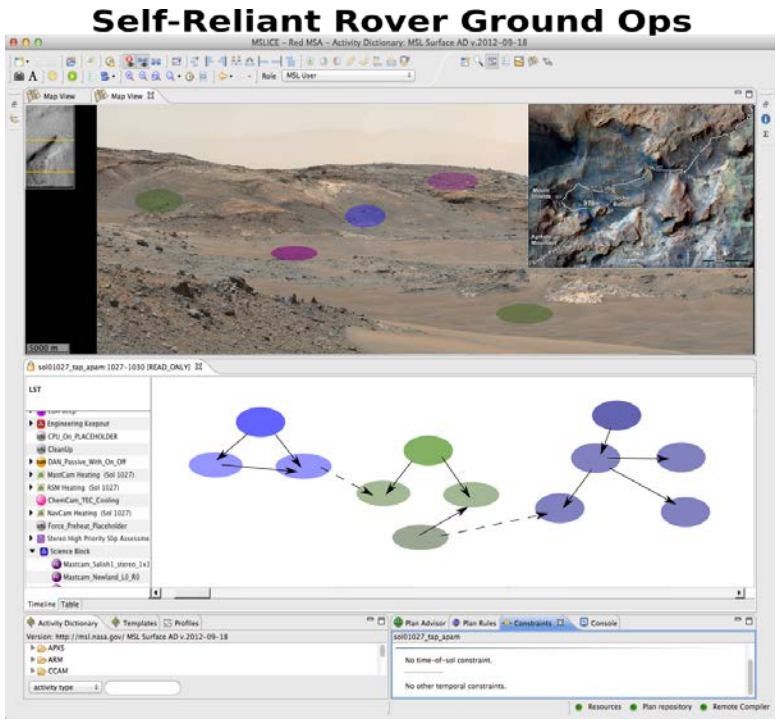
First view of contact from rover. Can **identify locations of interest but insufficient detail to pick out specific targets**. **Drive planning limited by occlusions** blocking view to Location 1.

Example of target that would eventually be selected, but **insufficient detail to select it from this distance** (about 30m away)

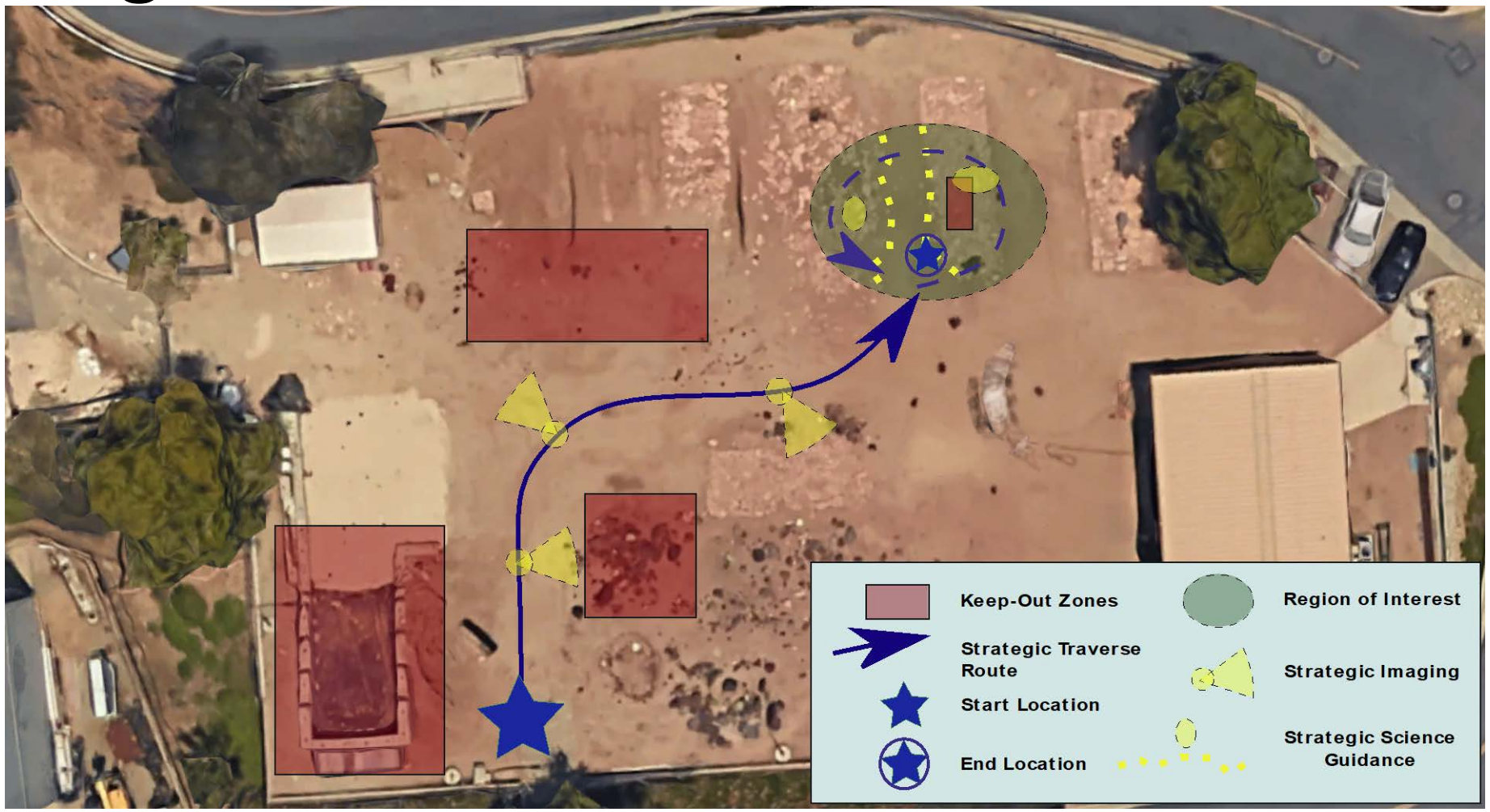
Self-Reliant Rover Approach

- **Goal Elaboration**
  - Reduce effort in interacting with vehicle
  - Increase productivity through onboard resource management
- **Scientist-Guided Autonomous Science**
  - Increase science productivity with reduced reliance on ground-in-the-loop
  - Increase expressivity of science intent
  - Enable scientists to guide vehicle
- **State-Aware Health Assessment**
  - Improve onboard state tracking by incorporating health assessment into nominal vehicle operation
  - Safely sustain productivity when problems occur
- **Robust, Multi-Sol Navigation**
  - Develop slip-aware navigation
  - Safely respond to unexpected conditions for robust multi-sol navigation
- **Ground Operations**
  - Make it natural for team to interact with vehicle without knowing state vehicle will be in when command products are received



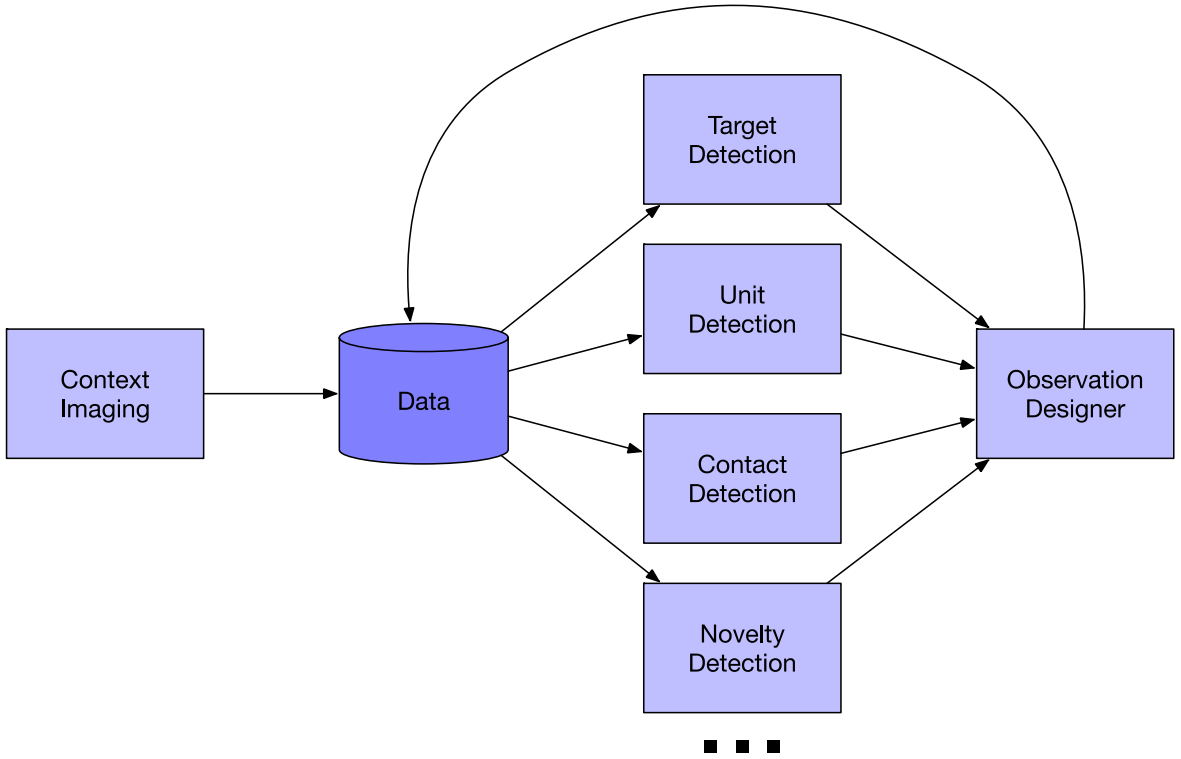


Guiding Scenario

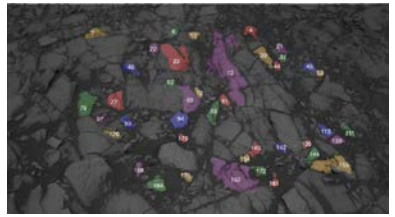


- Increased science during long-range driving campaigns
- Reduced overhead for walkabout exploration

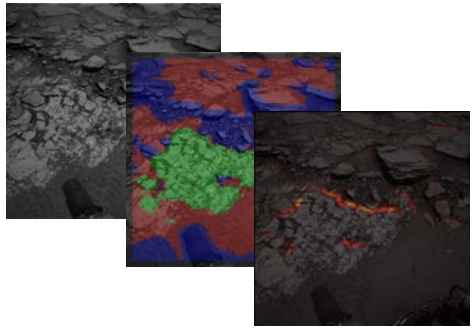
Scientist-Guided Autonomous Science



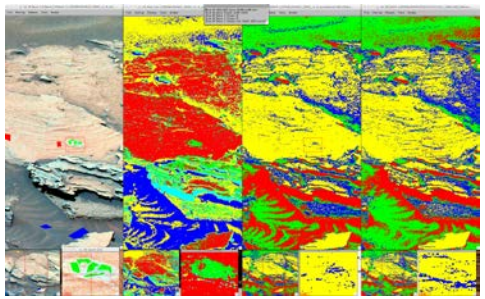
Target Detection



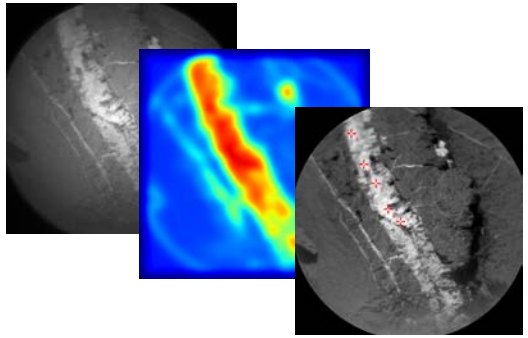
Contact Detection



Multispectral Analysis

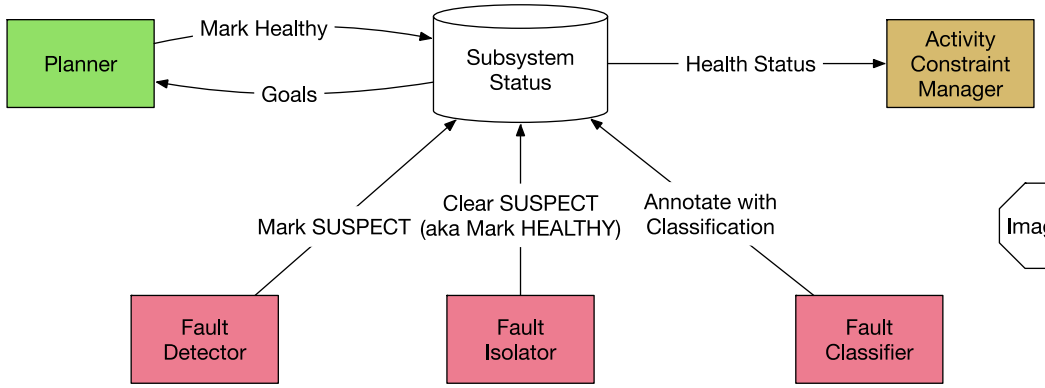


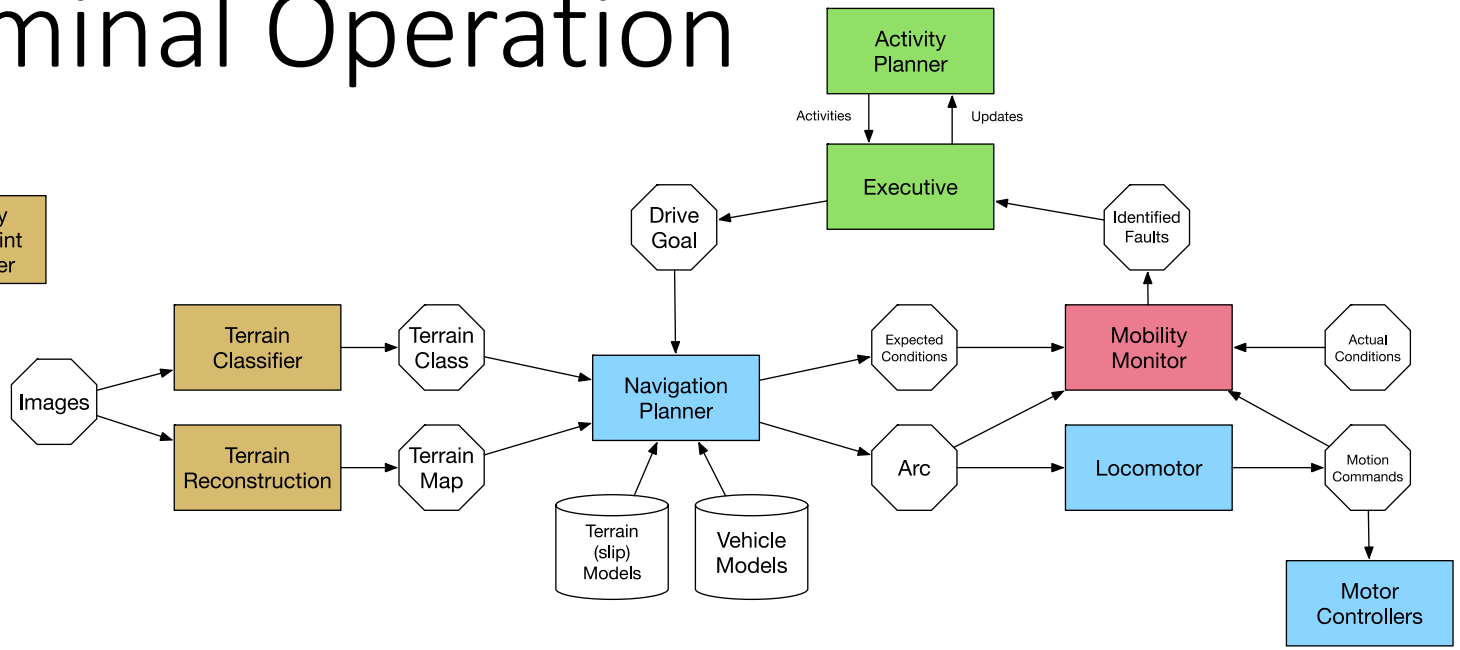
Raster Designer



- Developing an onboard characterization process
  - Enables rover to assist scientists in characterizing an area or documenting traverse when ground-in-loop not available
  - Includes collecting wide field-of-view contextual imagery along with high-quality, detailed observations
  - Documents representative features and diversity of an area
  - Provides means for scientists to guide process

Incorporating Health Assessment and Response into Nominal Operation

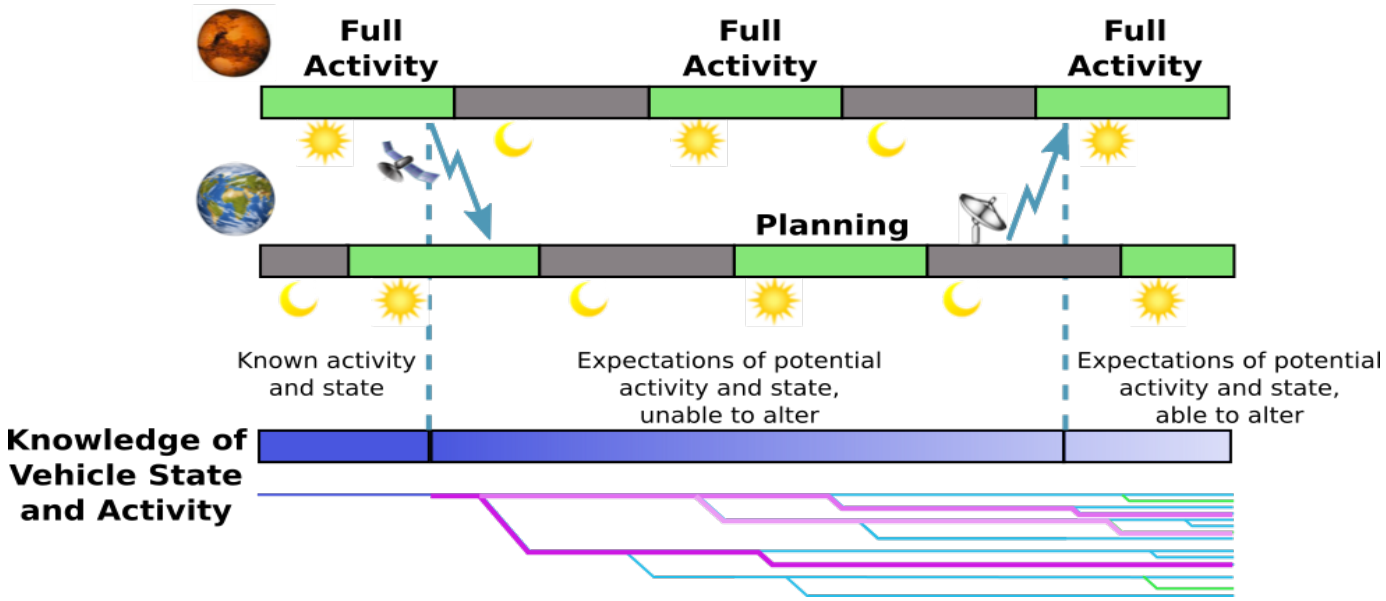


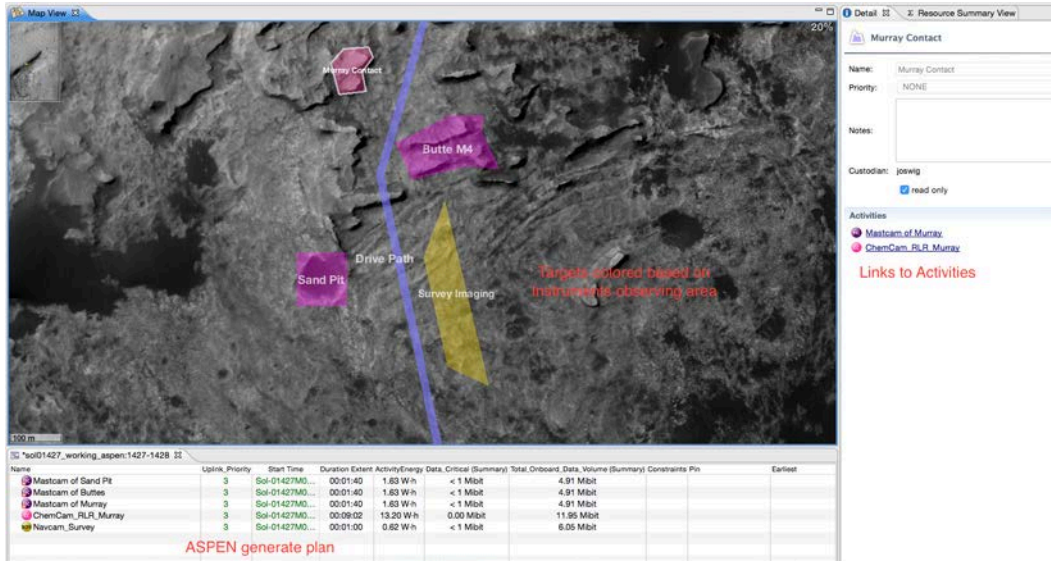


- System forms expectations of activity performance / behavior
- Monitors execution for expectations
  - Detects faults if actual conditions deviate from expected
- Combination of Fault Detection, Fault Isolation and Fault Classification used to identify “suspect” subsystems
  - Suspect subsystems unusable until cleared for use
- Fault resolution posted as goals for Planner to resolve
  - May result in addition of diagnostic activities, recovery activities or shedding activities that are no longer allowed due to subsystem health status

Interaction with Ground Operations

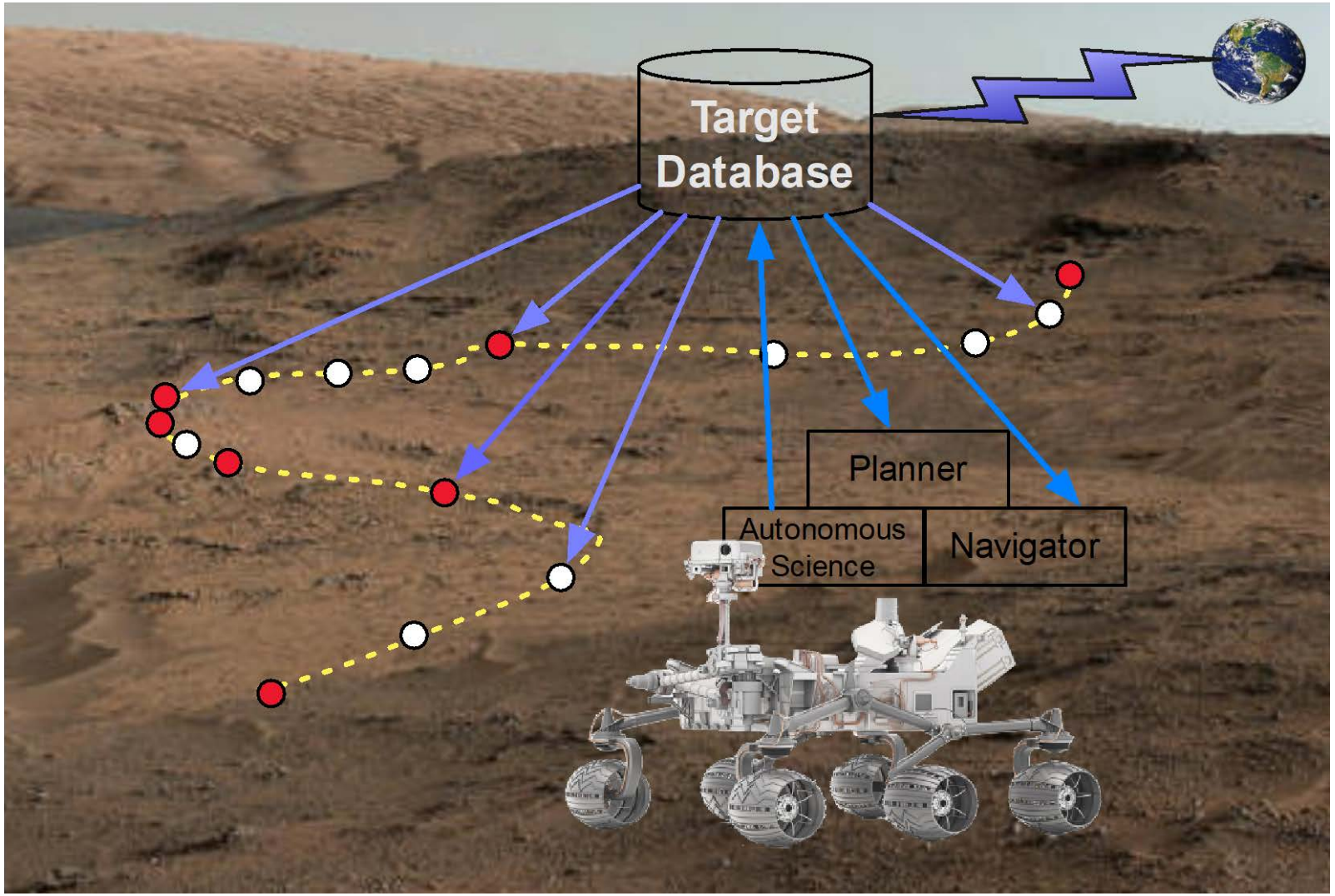
- Developing concept of operations with “loose” ground-in-the-loop interaction
  - Interaction with vehicle without requiring detailed information about vehicle state
  - Provide expectations of potential vehicle state/activity given assumptions of conditions
  - Updated when additional telemetry received
- Developing new ground tools to express mission intent as goals and guidance
  - Map view for specifying goals and visualizing actual and predicted plans
  - Semantics for periodic goals to express campaign objectives





Flight Software Infrastructure Support

- Target database
  - Facilitates interaction among onboard autonomy
  - Synchronized with ground DB
- Onboard data product access
  - Provide convenient access to onboard autonomy
  - Identify new science opportunities
  - Summarize data to maximize limited bandwidth
- Onboard telemetry access
  - Make telemetry available for onboard autonomy
  - Supports onboard health assessment and resource management



Conclusions

- Complete case study report available at:
  - ai.jpl.nasa.gov → Publications → 2016
- Case study has **identified several challenges for maintaining high levels of surface mission productivity**
- Case study also **identified opportunities for increasing productivity** if these challenges can be overcome
- We are leveraging study results to identify changes to flight system and ground practices to overcome these productivity challenges

Acknowledgements

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