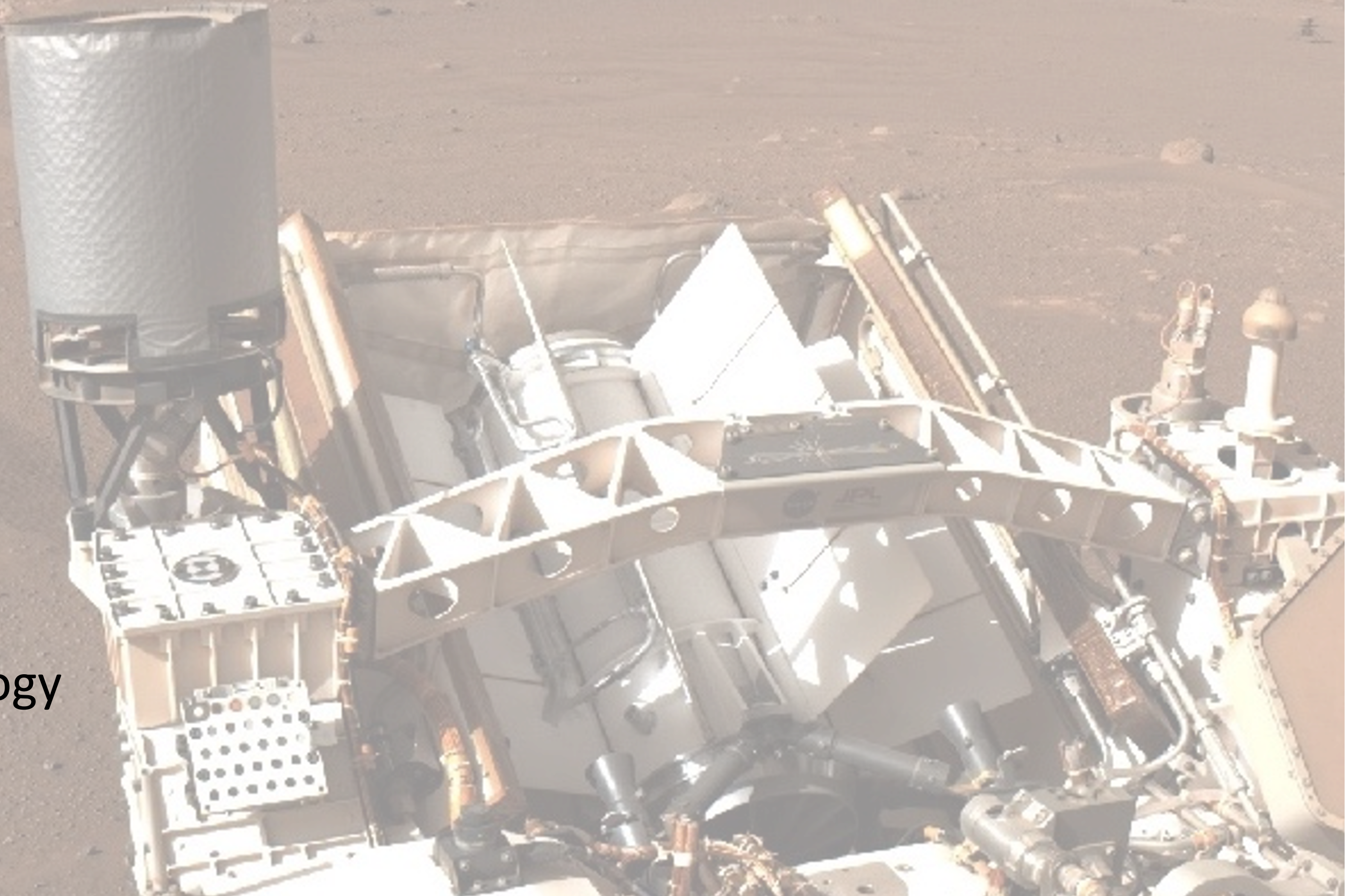
# The Mars 2020 On-Board Planner

## Balancing Performance and Computational Constraints



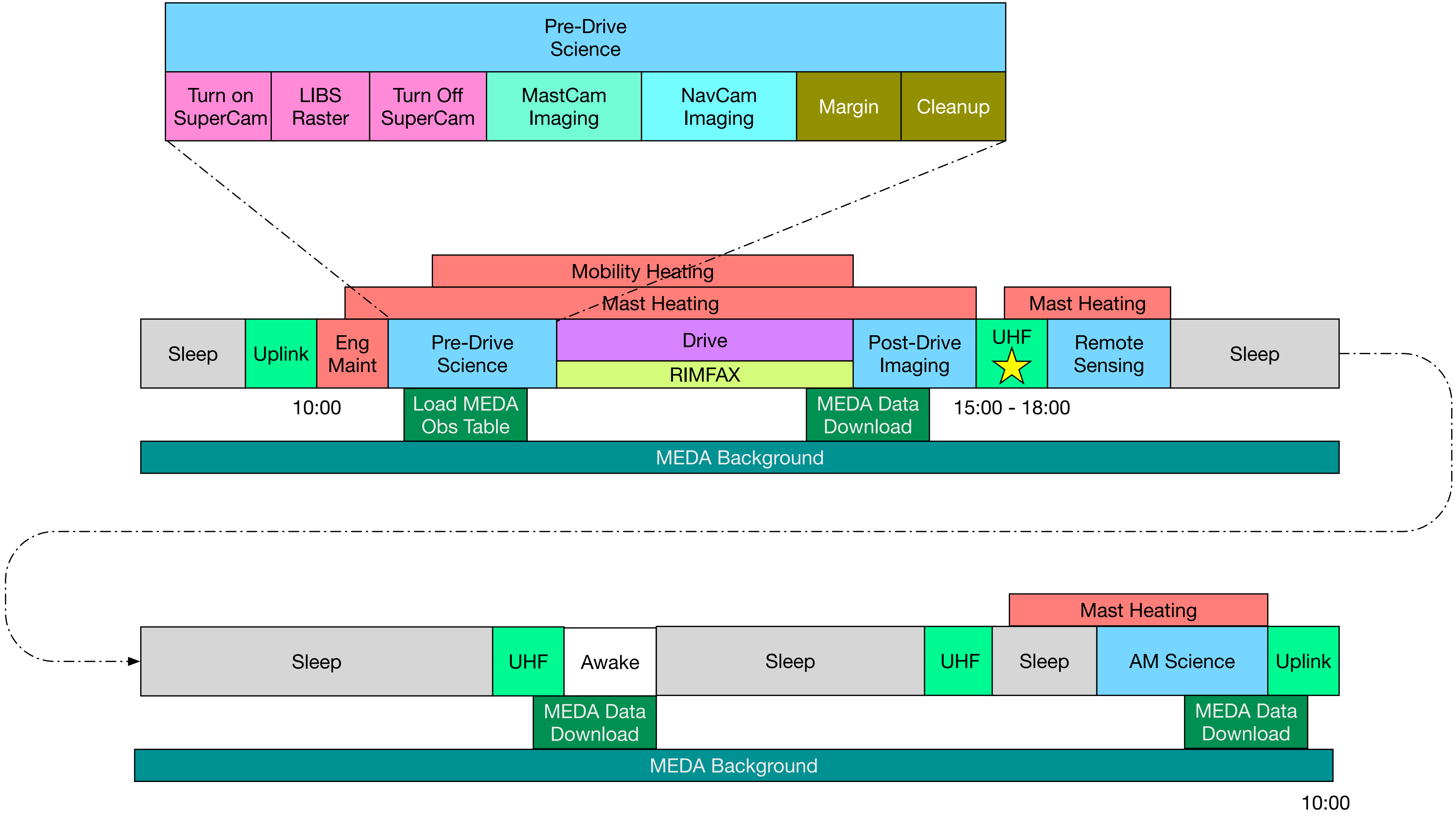
**Dan Gaines**

gaines@jpl.nasa.gov

Jet Propulsion Laboratory,

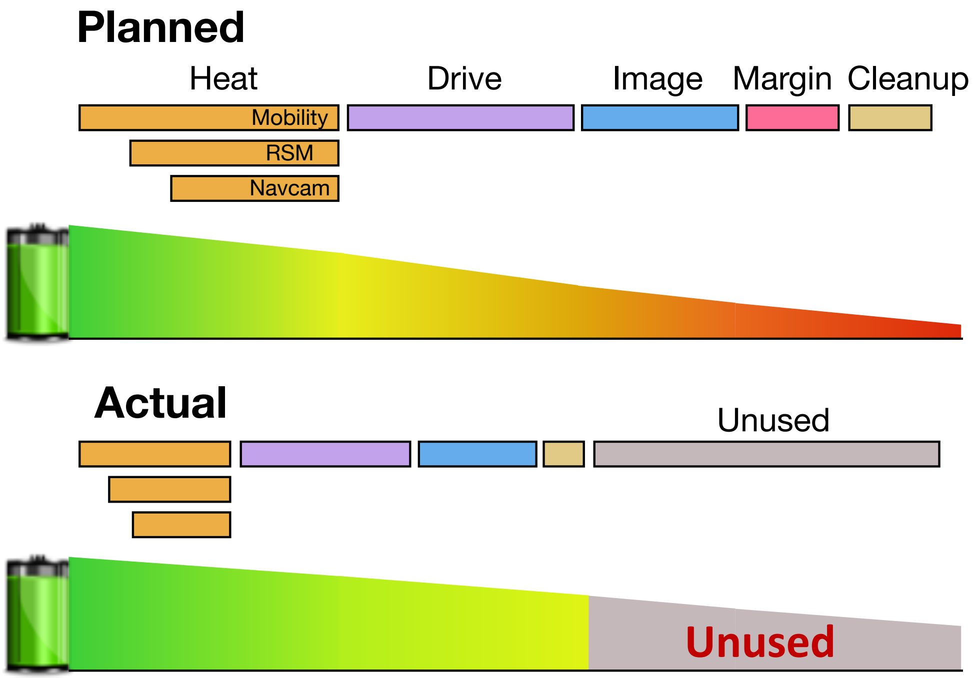
California Institute of Technology

# Example Sol in the Life

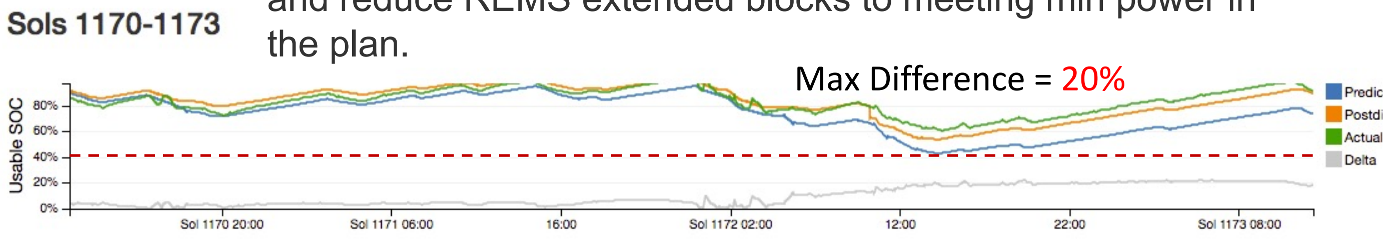


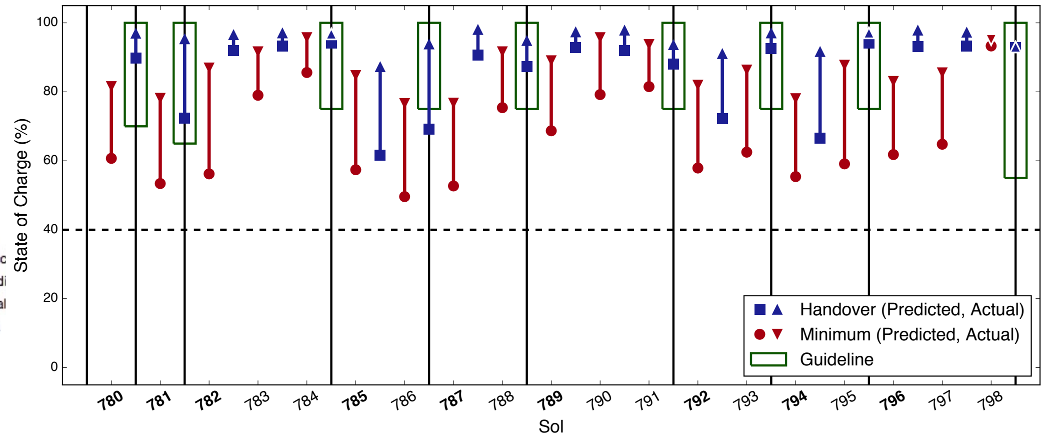
# Productivity Challenge: Predicting Rover Resource Usage

- Difficult to estimate amount of resources an activity will consume
  - Largely due to difficulty in **predicting activity duration and actual temperatures**
  - Resources: **time, energy, data**
- Operations takes conservative approach
  - Typically overestimate and add margin
  - **Can unnecessarily limit activity**



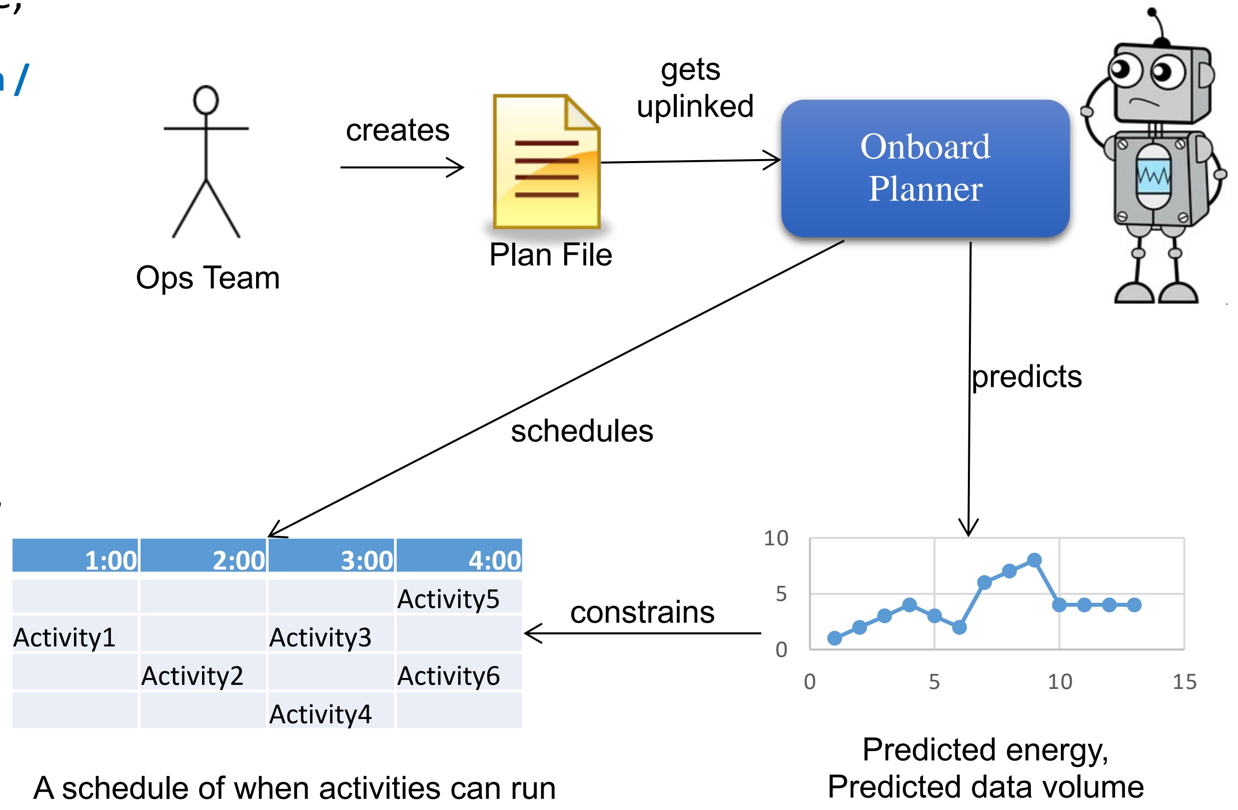

Sol 1170 ML Report: Power problems making minimum and handover percentages - Had to drop CheMin dump sample and reduce REMS extended blocks to meeting min power in the plan.



# On-Board Planner: Move Decision Making On-Board

- **Resource management**
  - Time, power, energy (battery state-of-charge), data volume, atomic resources, sequence engines
    - Operator provided constraints: **handover battery SOC**, **minimum / maximum battery SOC**, **delta data volume**
- **Activity types**
  - **Mandatory** vs. **optional**
  - **Expanding** (extend duration to the extent resources allow)
  - **Switch groups** (select among options for a given activity with differing resource usage)
- **Activity dependencies**
  - Not Started, In Progress, Completed with Success / Failure, Aborted, …
- **Heating**
  - Pre-heating, maintenance heating, merging of heating activities, support for heating while rover sleeps
- **Awake / asleep management**
  - Scheduling awake / asleep periods
- **Activity execution**
  - Starting, aborting (if needed), cleaning-up (if needed)
  - Pausing activities across communication windows



# Challenge: Balancing OBP Performance with Computational Constraints

- **OBP has a lot of work to do**
  - Generate plans, execute plans, monitor plans, re-generate plans
- **Plan execution will deviate from predictions**
  - Actual temperatures, activity durations, energy use, data acquired
- Frequent **re-planning would increase responsiveness** to deviations
- However, **re-planning is computationally expensive**
- Limited rover computational resources:
  - RAD 750 running at **133 MHz**
  - **CPU shared** with many FSW tasks (of varying criticality)

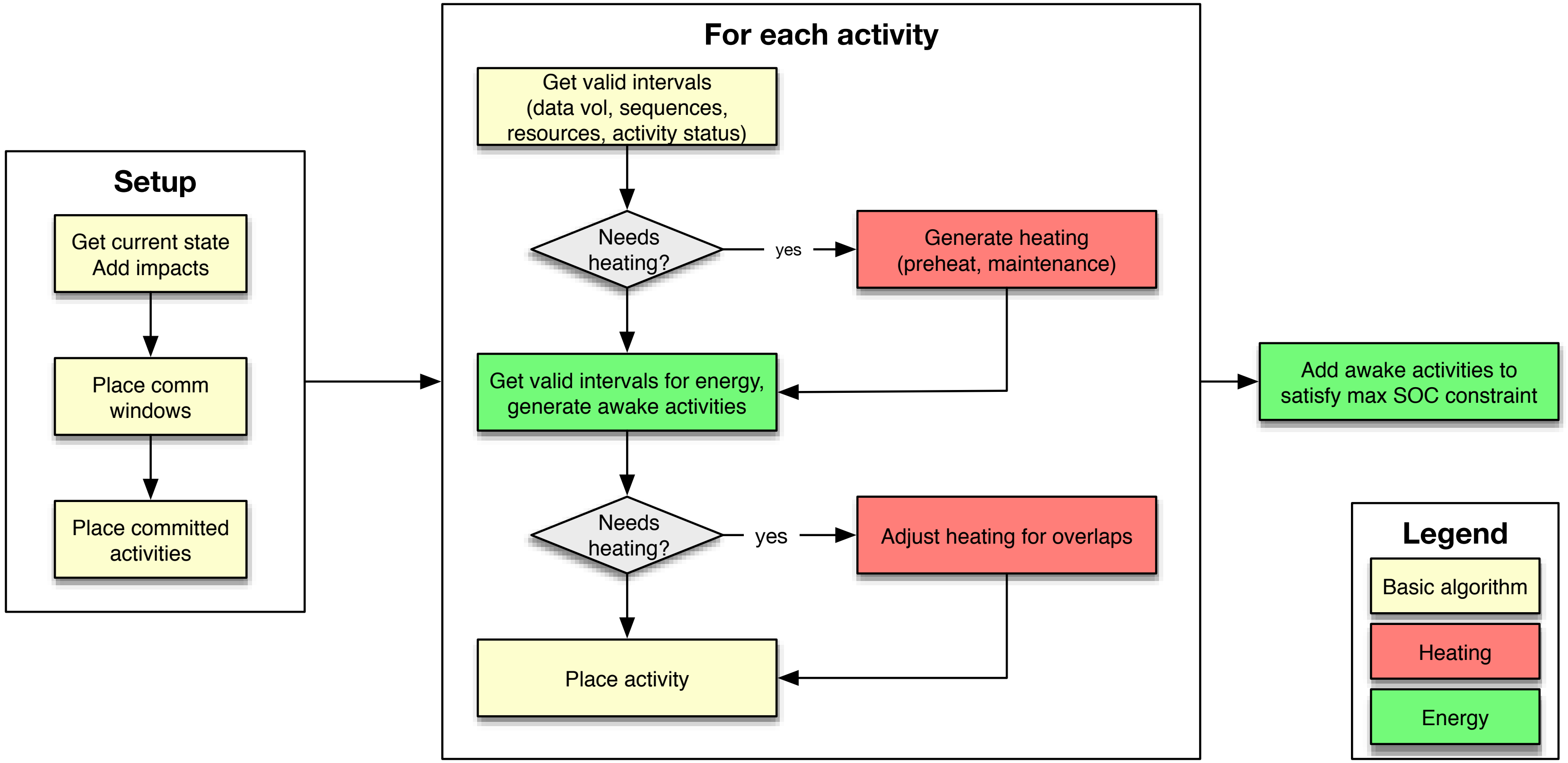
# Managing Computational Complexity

- **Plan generation techniques**
  - Greedy algorithm
  - Discretized thermal intervals
  - Hopper to extend set of activities to schedule
- **Plan execution techniques**
  - Flexible plan execution
    - Respond to deviations in execution without re-scheduling
  - Event-based re-planning
    - Limit re-planning to significant deviations in execution
- **FSW Task priorities**
  - Playing nice with other tasks in the system

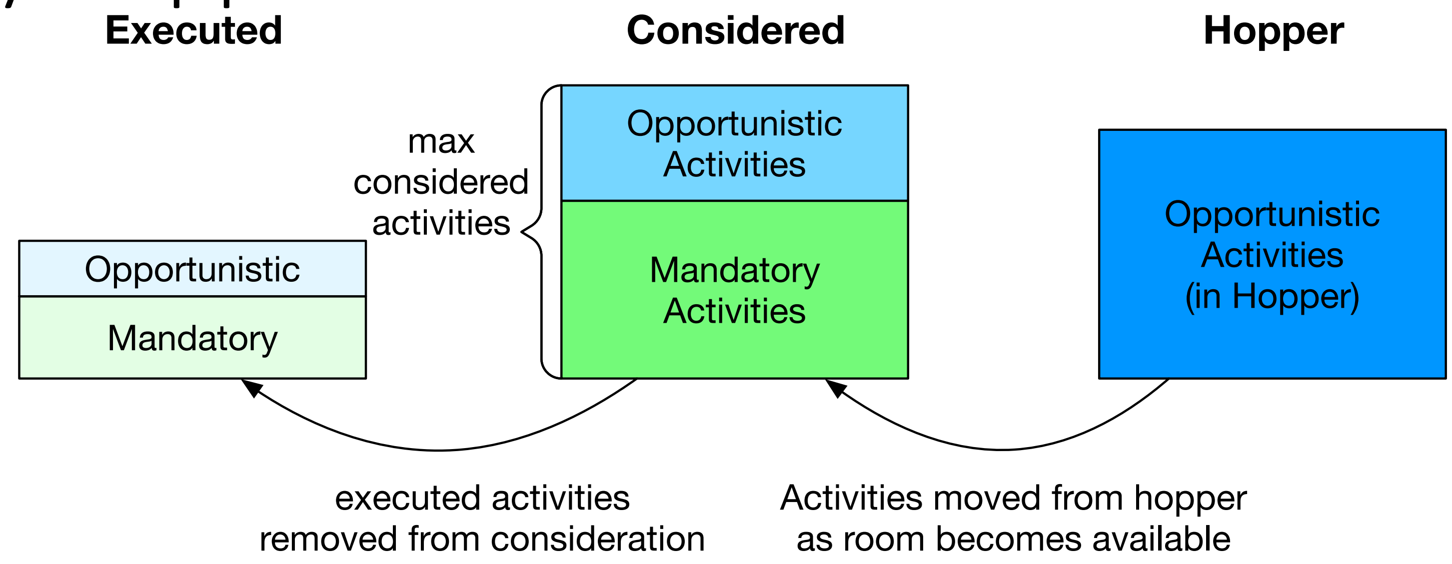
# Plan Generation Techniques

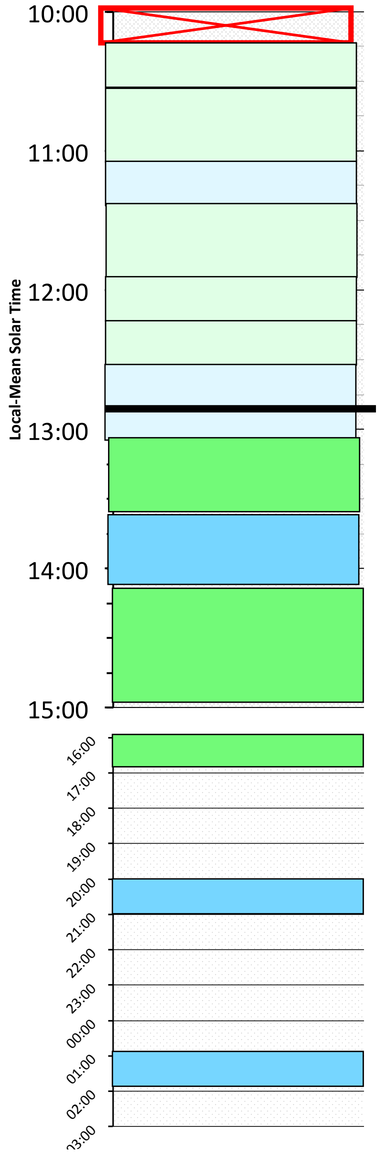
# High Level Planning Algorithm

- **Greedy algorithm**
  - No lookahead
  - No backtracking
  - Find good spot for an activity, move on to next
  - Reduces completeness of planner but significantly reduces computation cost
    - Mitigated by ground tool finding optimal scheduling order for activities
- **Discretize thermal intervals**
  - Duration and energy needed for heating depends on temps when heating starts
  - Reduce search space by discretizing to intervals (e.g. 15min) where temps assumed to stay constant



# Activity Hopper



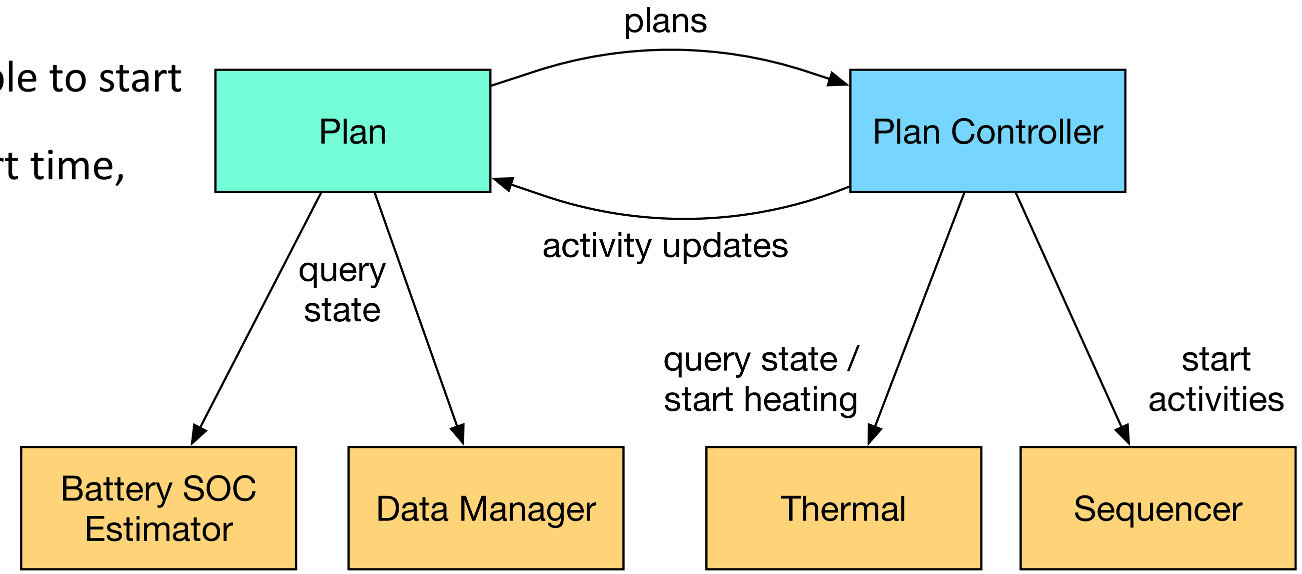




- More activities **allows rover to accomplish more** but **increases planning cost**
- Hopper increases set of activities that are included in a sol without increasing planning cost
- **Considered activities**
  - Set of activities eligible for scheduling
  - Restricted in number to limit planning curation
  - Must be large enough to include all mandatory activities to ensure resources are reserved for mandatory activities
  - Activities removed when they are executed
- **Hopper**
  - Additional opportunistic activities added to considered set as space becomes available

# Plan Execution Techniques

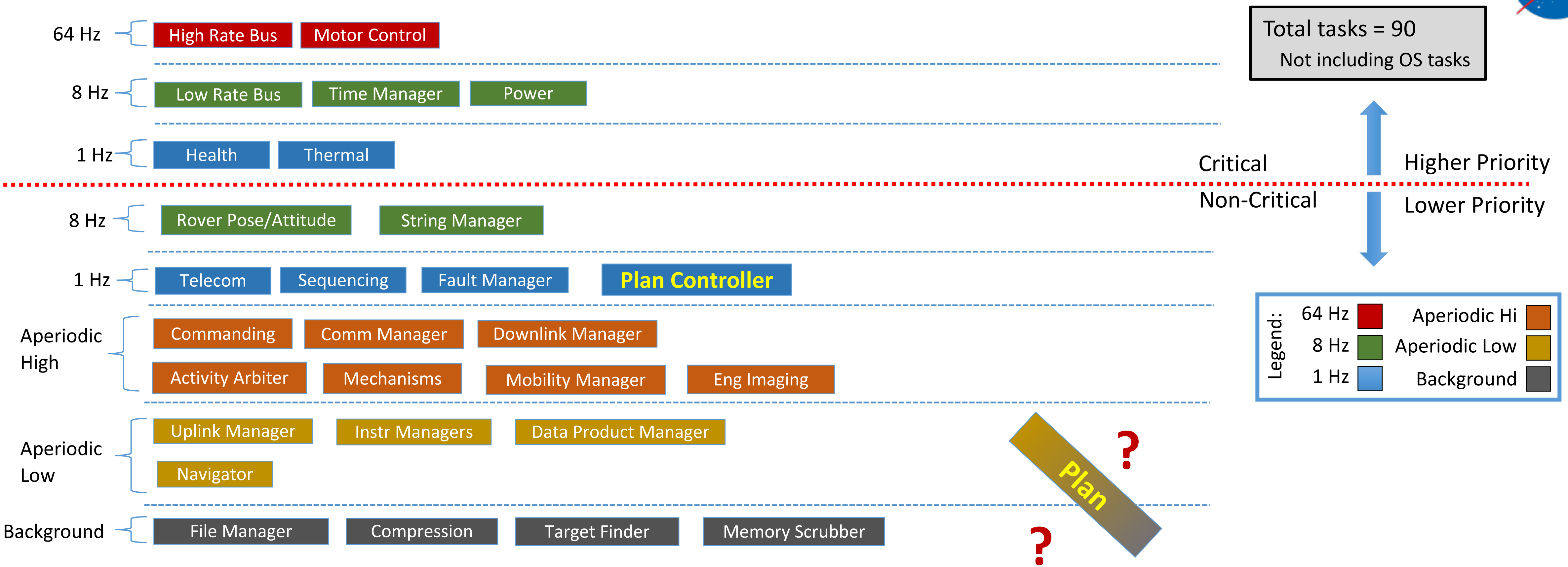
# Flexible Plan Execution & Event-Based Re-Planning

- **Plan Task:** generates plans given operator input and current vehicle resources
- **Plan Controller Task:** has authority to alter start time of activities
  - **Pull:** if rover is idle, determine if future activity is eligible to start now
  - **Push:** if activity is not eligible to start at scheduled start time, delay activity
    - Activity vetoed if delayed too long
  - **Thermal monitoring:** monitors actual temperatures to determine when heating needs to start
- **Event-Based Re-Planning:** reserve re-planning for significant deviations, e.g.
  - Activity ending significantly early/late
  - Activity vetoed
  - Activity fails or is aborted
- Benefits:
  - **Increases utilization of vehicle resources** by increasing responsiveness to actual conditions
  - **Reduces planning overhead** allowing more CPU availability for other flight software tasks



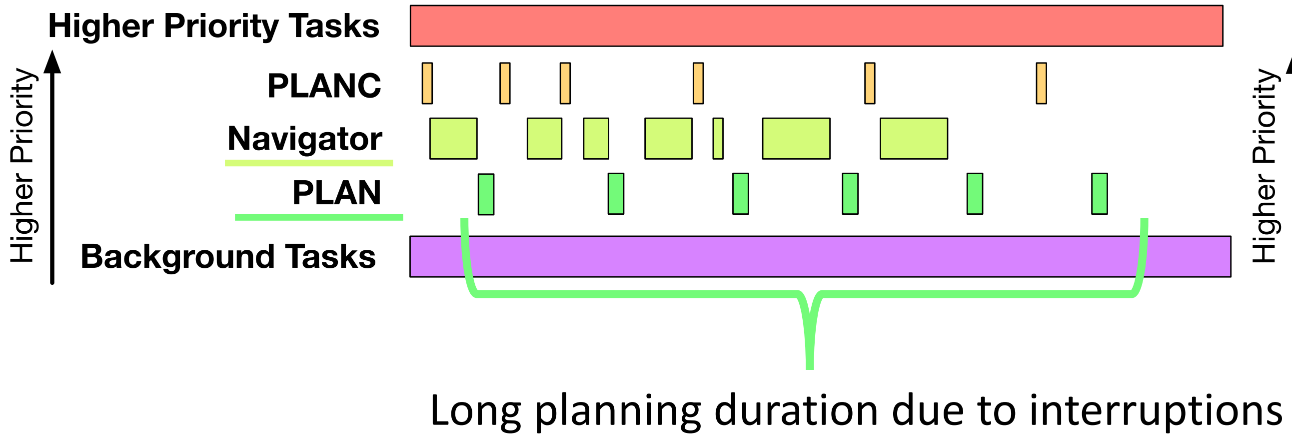
# Task Priorities

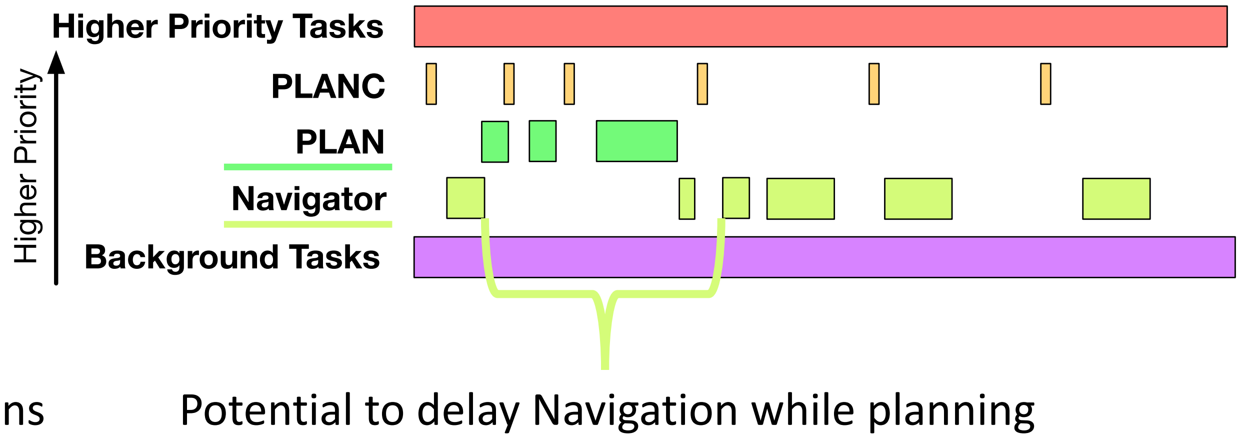
# Overview of FSW Task Priorities




- Plan Controller fits well in Non-Critical 1 Hz group
- **Challenge is finding a spot for Plan task**
  - Aperiodic Low or Background?

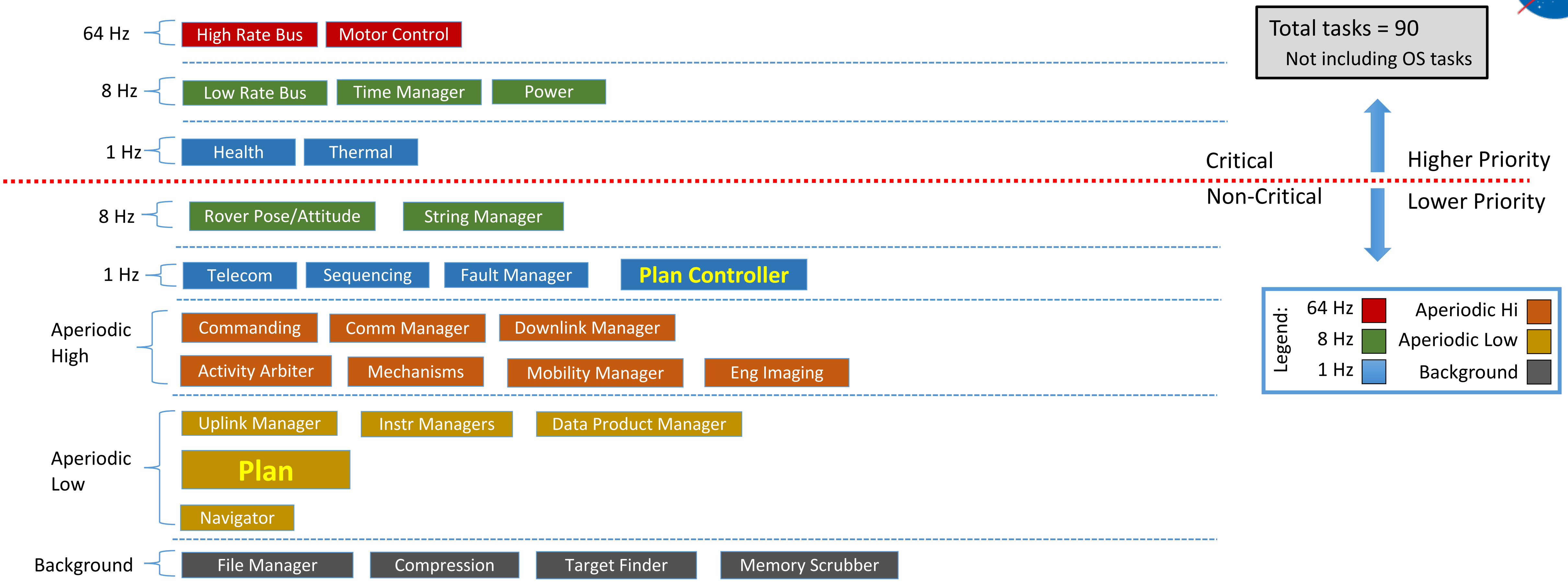
# Plan Task Prioritization




- Considered two main strategies for plan generation task
  - **Low priority:** less disruptive to other tasks but significantly reduces responsiveness to execution deviations
  - **Medium priority:** more responsive, but disruptive to some activity
- Motivating consideration was impact on Autonomous Navigation
  - **Want to avoid frequent delays to Navigator**

# Overview of FSW Task Priorities




- **Event-based re-planning enables us to give Plan relatively higher priority**
  - Reduced amount of re-planning means we can tolerate the occasional burst of planning work at medium priority
  - This in turn **reduces the time it takes to generate plans**, further increasing responsiveness
    - Fewer interruptions by other tasks

# Conclusion

- **Mars 2020 On-Board Planner increases rover productivity**
  - Moves decisions about what activity can be accomplished onboard
  - Uses up to date knowledge of rover state and resources
- **Challenging to balance OBP performance with computational constraints**
  - FSW employs several strategies to get the most from OBP while sharing limited computational resources with other FSW tasks
- **Coming Soon to a Planet Near You!**
  - Currently finishing up flight and ground development and V&V
  - Anticipated readiness for Mars in Fall of 2022

# For Further Details

https://ai.jpl.nasa.gov/public/projects/m2020-scheduler/

Agrawal, J.; Chi, W.; Chien, S. A.; Rabideau, G.; Gaines, D.; and Kuhn, S. Analyzing the Effectiveness of Rescheduling and Flexible Execution Methods to Address Uncertainty in Execution Duration for a Planetary Rover. *Robotics and Autonomous Systems*, 140 (2021) 103758. 2021.

Agrawal, J.; Chi, W.; Chien, S. A.; Rabideau, G.; Kuhn, S.; Gaines, D.; Vaquero, T.; and Bhaskaran, S. Enabling Limited Resource-Bounded Disjunction in Scheduling. *Journal of Aerospace Information Systems*, 18:6: 322-332. 2021.

Yelamanchili, A.; Rabideau, G.; Agrawal, J.; Wong, V.; Gaines, D.; Chien, S.; Fosse, E.; Biehl, J.; Kuhn, S.; Connell, A.; Hazlerig, J.; Ip, I.; Guduri, U.; Maxwell, K.; Steadman, K.; and Towey, S. Ground and Onboard Automated Scheduling for the Mars 2020 Rover Mission. In *International Workshop on Planning & Scheduling for Space (IWPSS)*, July 2021.

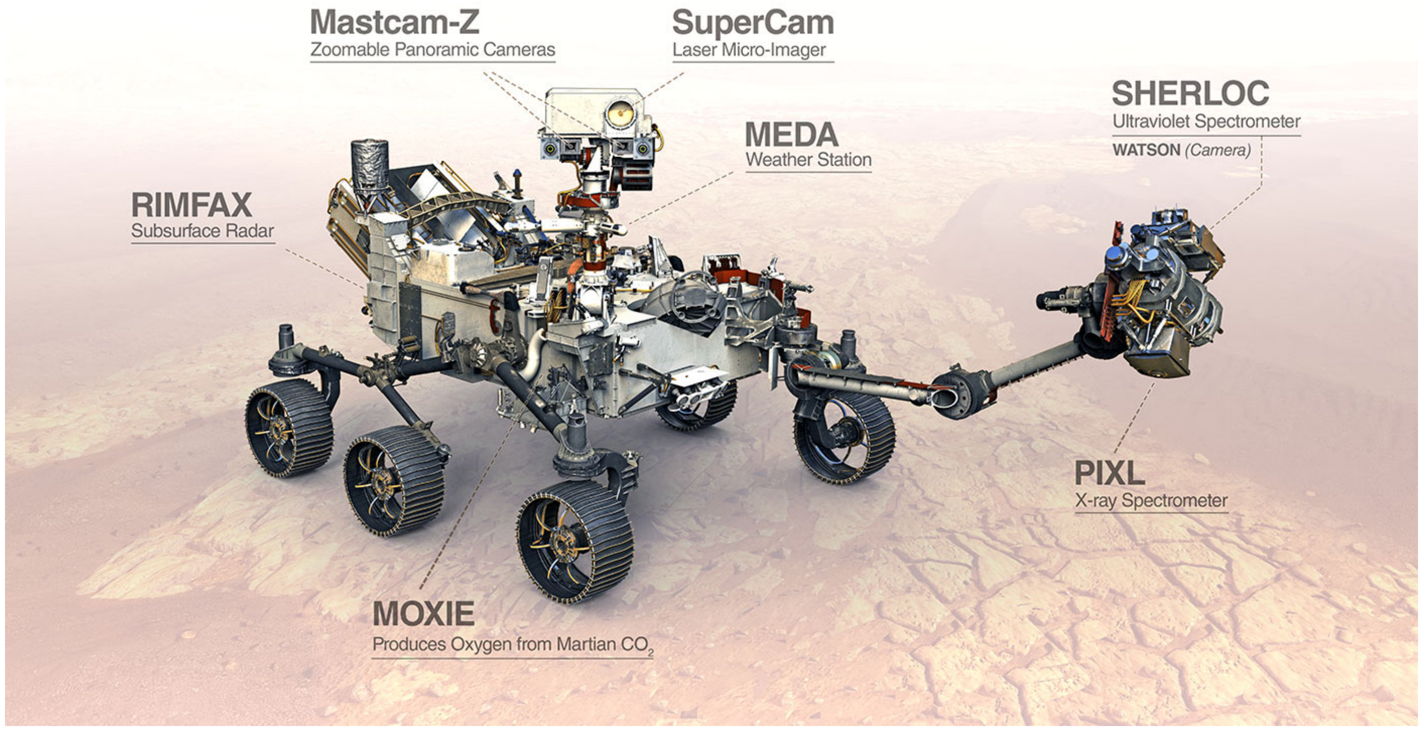
Chi, W.; S.Chien; and Agrawal, J. Scheduling with Complex Consumptive Resources for a Planetary Rover. In *International Conference on Automated Planning and Scheduling (ICAPS 2020)*, Nancy, France, October 2020.

Rabideau, G.; Wong, V.; Gaines, D.; Agrawal, J.; Chien, S.; Kuhn, S.; Fosse, E.; and Biehl, J. Onboard Automated Scheduling for the Mars 2020 Rover. In *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation for Space*, of *i-SAIRAS'2020*, Noordwijk, NL, 2020. European Space Agency

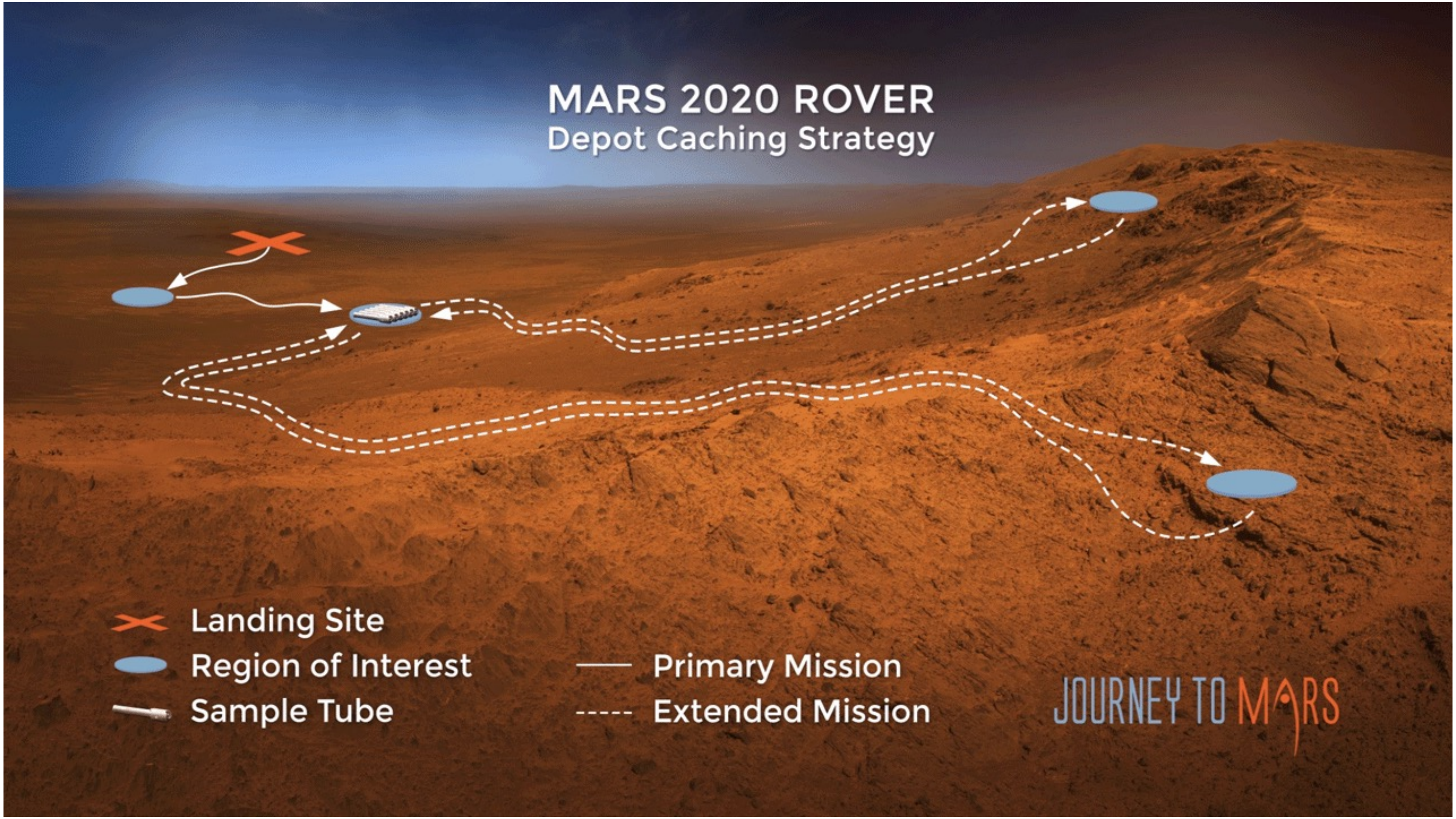
# Backup

# Mars 2020 Surface Mission Objectives

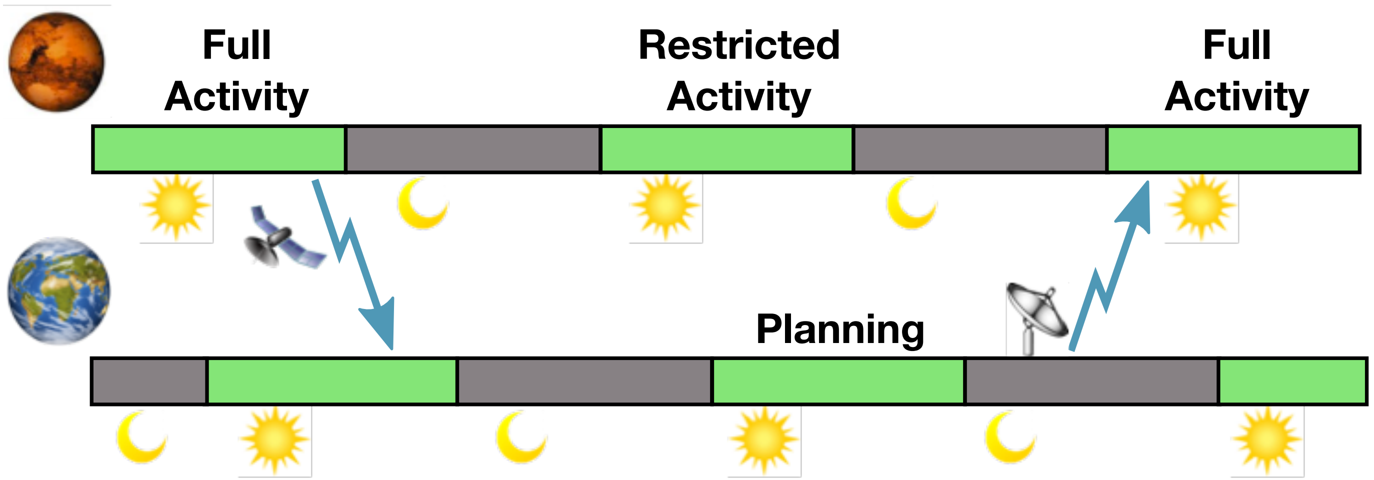
- Search for signs of ancient life
  - Imagers, spectrometers, radar
- Collecting samples for potential return to Earth
  - Coring, regolith collection, sample handling
- Prepare for human exploration
  - Weather, climate, radiation, dust
  - Oxygen generation



# Sample Caching Strategy



# Mars Time vs. Earth Time




- **Mars day ~40min longer than Earth day**
- Reception of rover end-of-day state "drifts" across Earth day over time
- 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 on second sol** as data from first sol will not be available when next plan is developed

# Overview of Operations

- Campaign Planning: long-term plan
  - **Guides long-term objectives** (e.g. Region of Interest investigation)
- Campaign Implementation Planning: mid-term plan
  - **Coordinates complex instruments and helps manage vehicle resources**
  - Bridges campaign planning and tactical planning
- Tactical Planning: near-term plan
  - **Reacts to latest vehicle data**
  - Develops and validates command products
- **Mars time vs. Earth time**
  - Mars day ~40min longer than Earth day
  - Reception of rover end-of-day state “drifts” across Earth day over time
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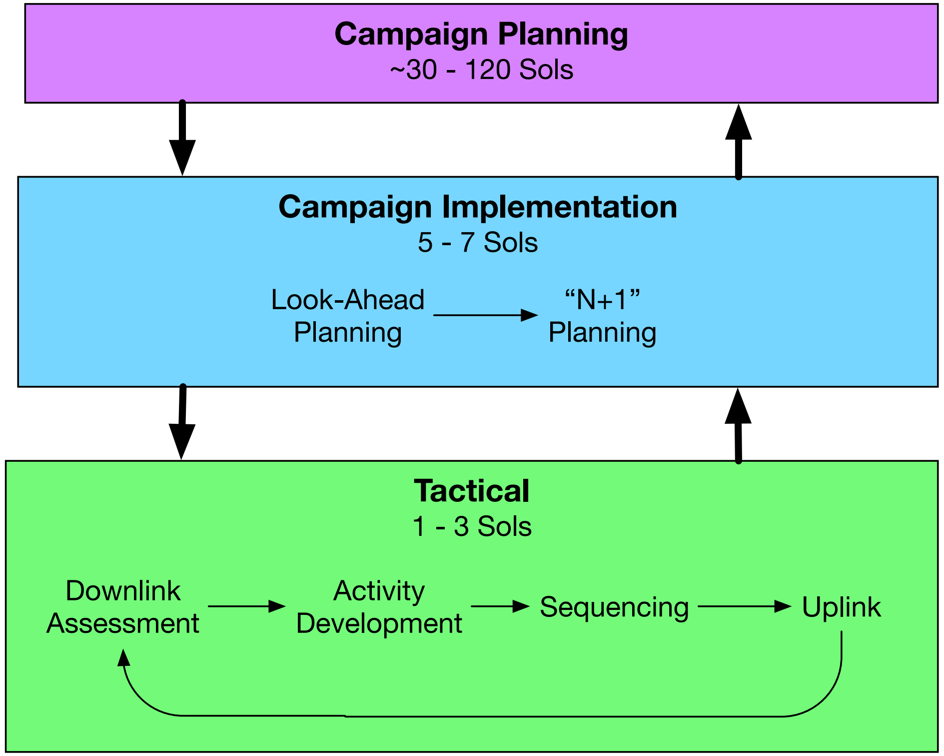
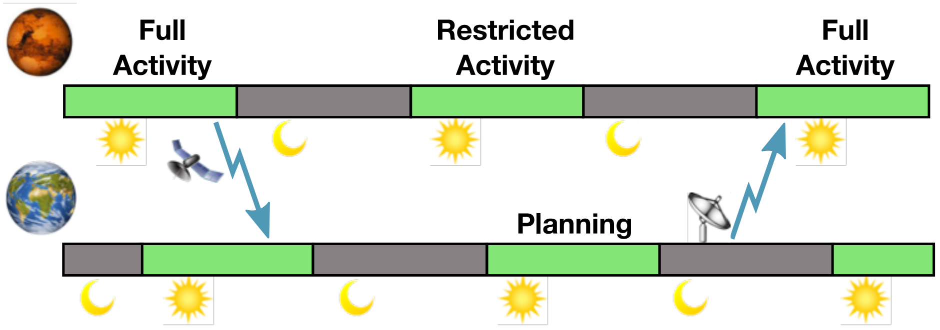
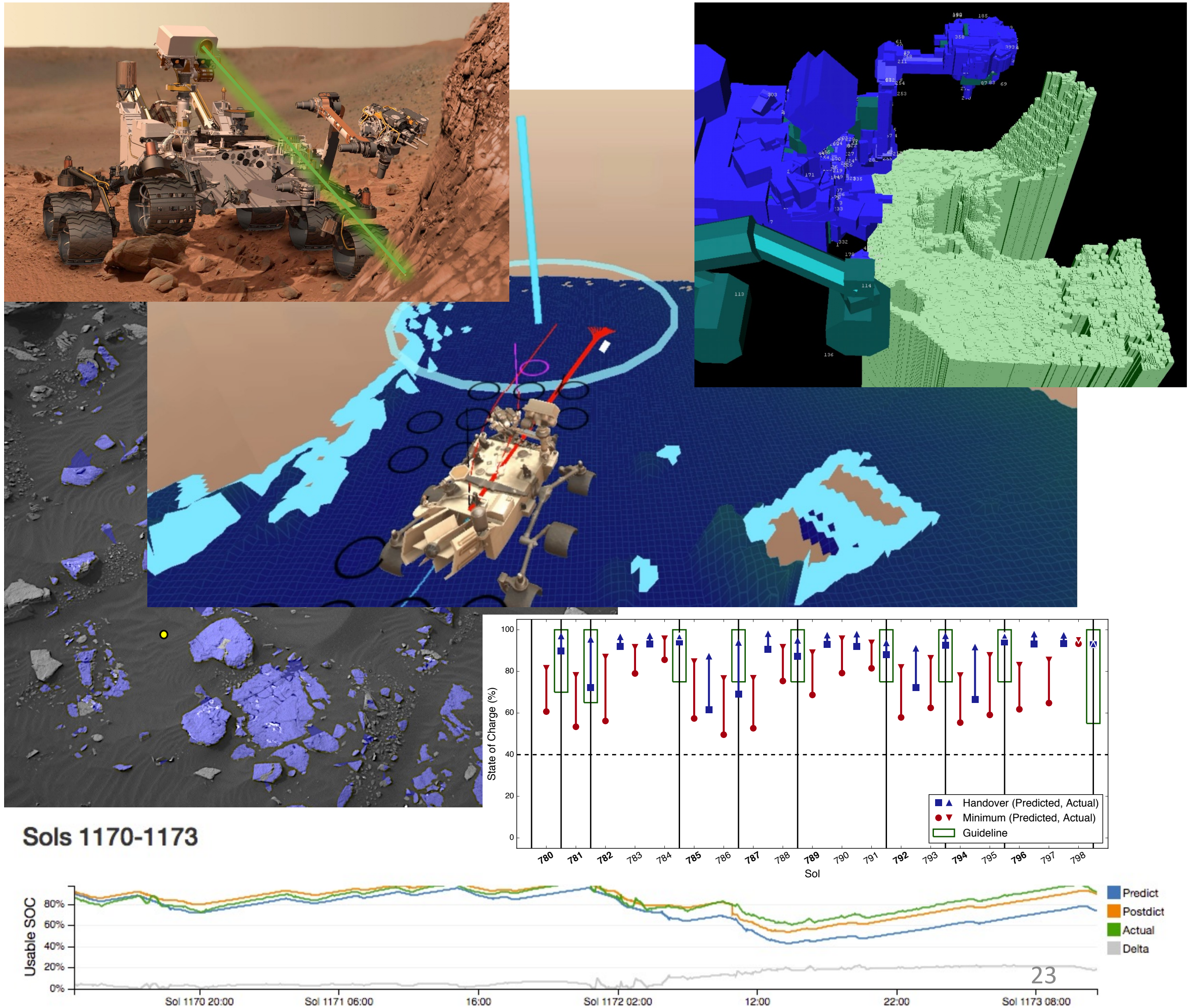


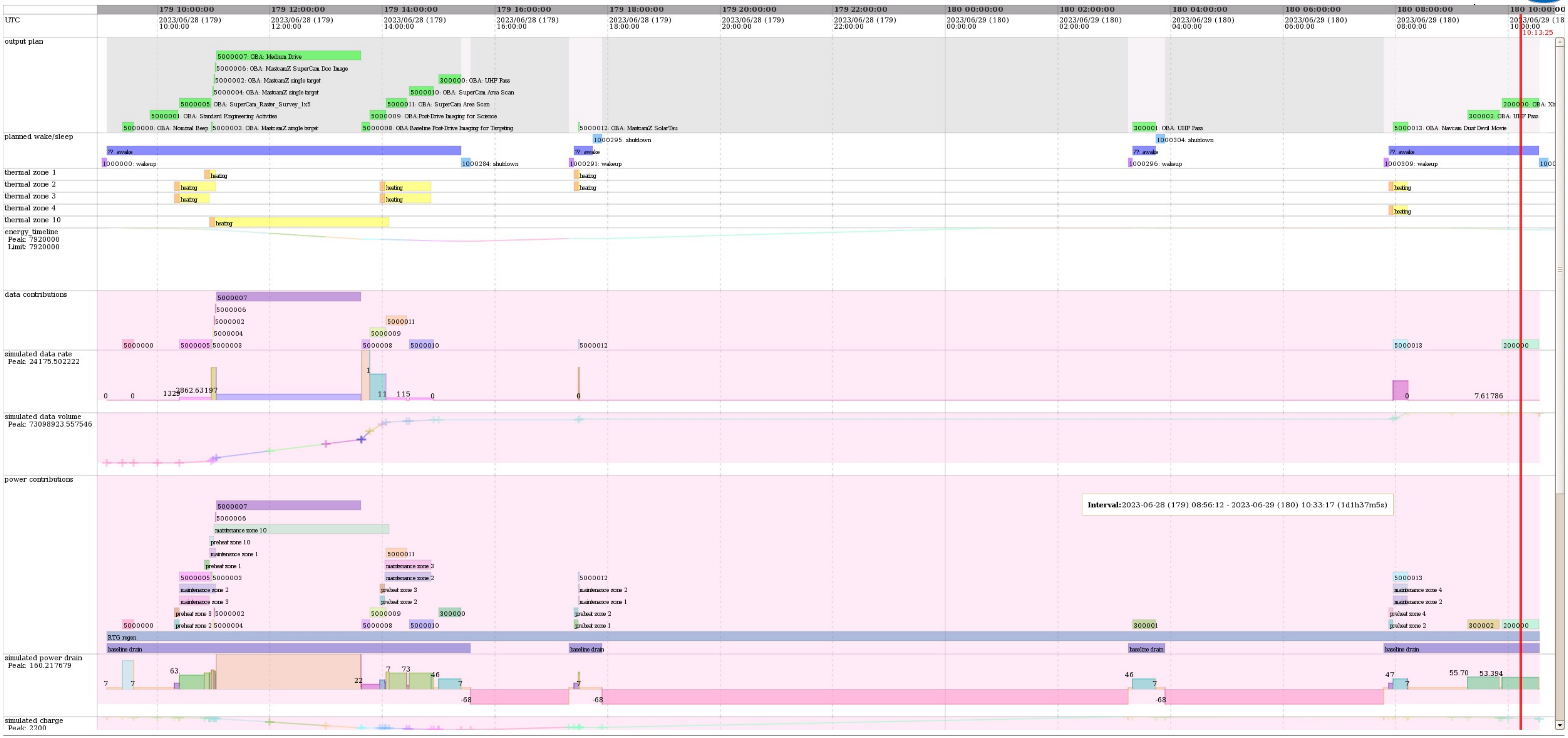



# Autonomy Capabilities for Mars 2020 Rover

- **Enhanced Autonomous Navigation**
  - Faster traverse / thinking while driving
- **Go and Hover**
  - Terrain modeling for safe arm deployment without ground-in-the-loop
- **Closed-Loop RSM**
  - Image-based targeting of mast-mounted instruments
- **Autonomous Target Finding**
  - AEGIS target finder
- **On-Board Planner**
  - Onboard resource management / scheduling



# Example Plan



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