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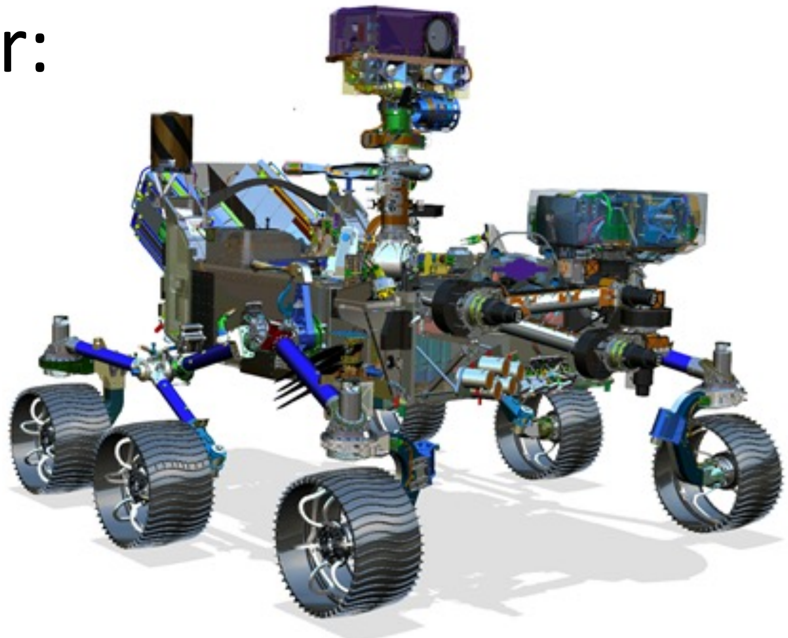
The Mars 2020 OnBoard Planner: Flight Software



Mars 2020 OBP Team

Presenter: Dan Gaines

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Mars 2020 Project

JPL Clearance CL#25-0036 URS330369

Talks on the Mars 2020 Simple Planner

Topic	Speaker	Date
Overview of Simple Planner	Moffi	5th December 2024
Onboard Planner Flight Software	Gaines	4th February 2025
Onboard Planner: Trusted AI on Mars	Reich, Chien	18th February 2025
Simple Planner: Ground Tools for Operations	Connell	25th February 2025
Simple Planner: Systems Engineering Operations with Autonomy	Hazelrig	11th March 2025
Rollout of the Simple Planner	Waldram	18th March 2025

You are here

Location: All talks are in Pickering Auditorium, Building 321
Time: All talks are 12n-1p PST
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Example Sol in the Life of Mars 2020 Rover

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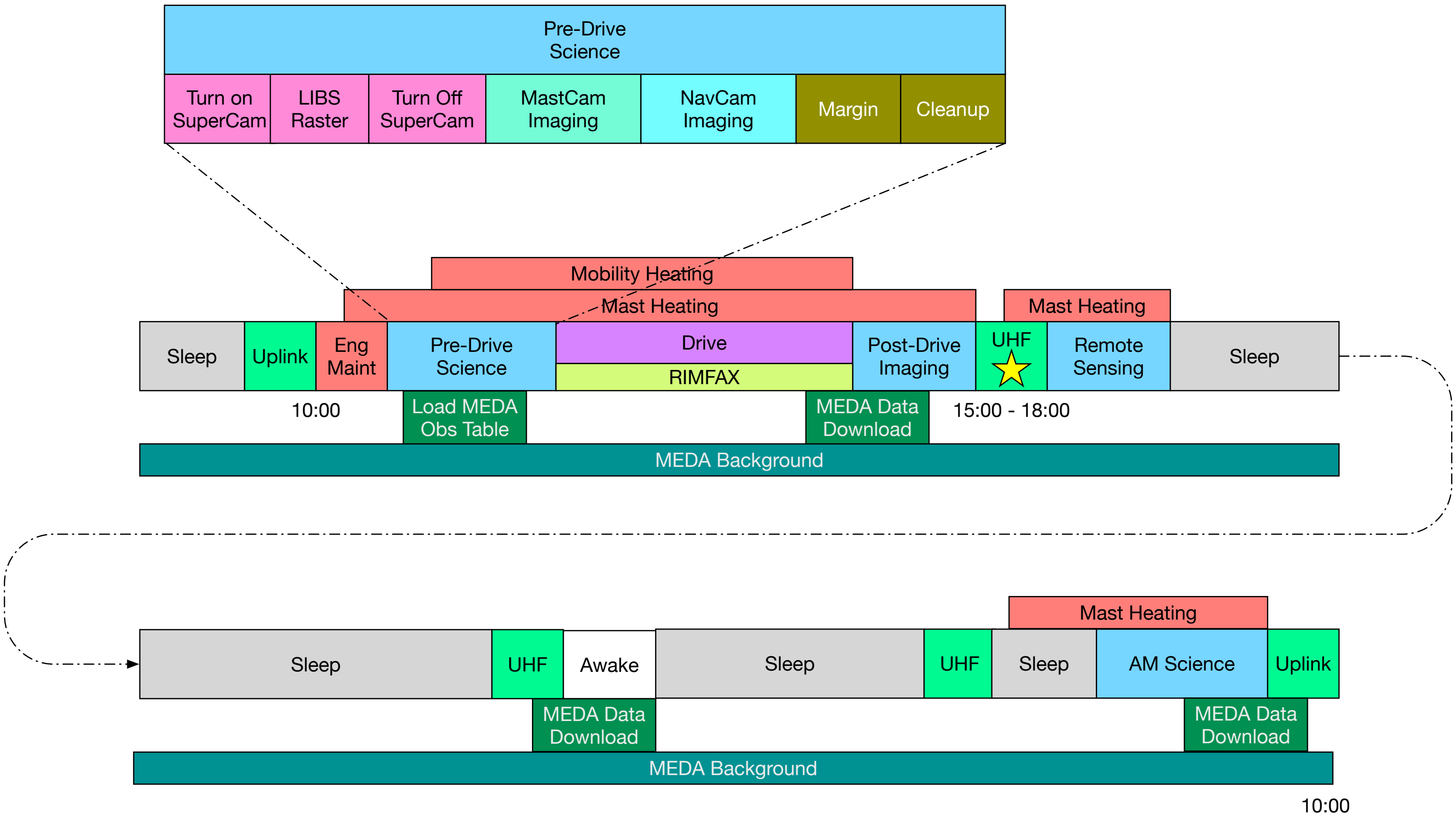
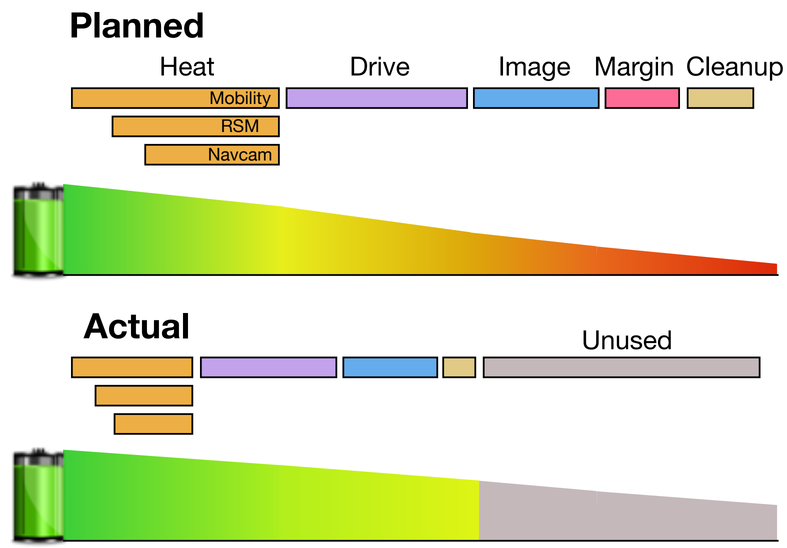


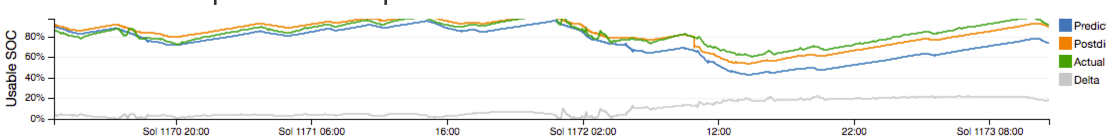
Productivity Challenge: Predicting Rover Resource Usage

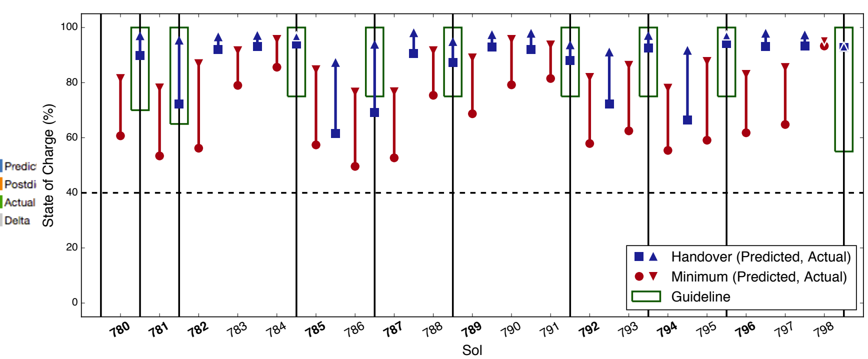
- Difficult to estimate activity resource consumption
  - Largely due to difficulty in **predicting activity duration and actual temperatures**
  - Resources: **time, energy**
- Operations takes conservative approach
  - Typically overestimate and add margin
  - **Can unnecessarily limit activity**
  - **Can result in unused vehicle resources**



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

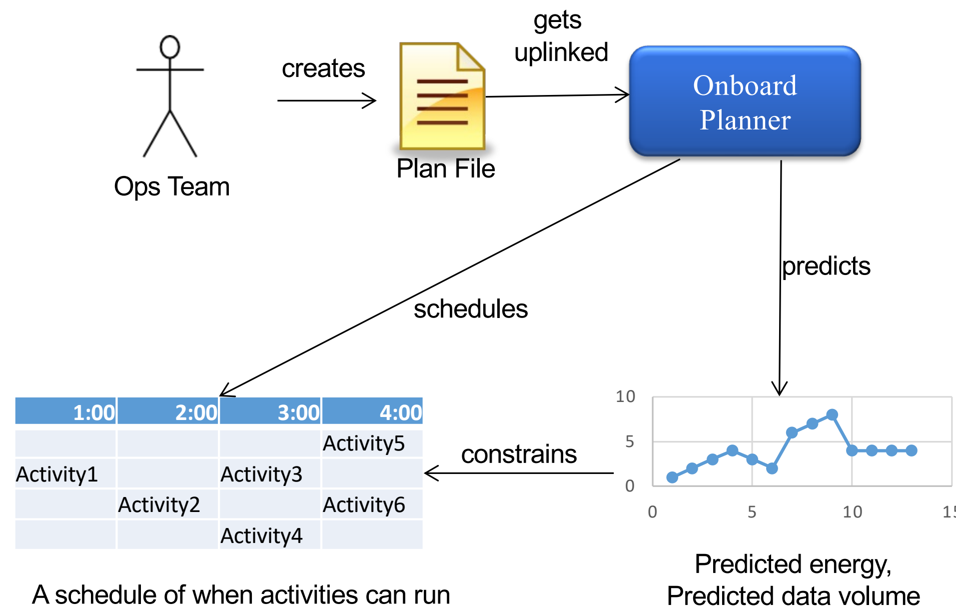
Sols 1170-1173





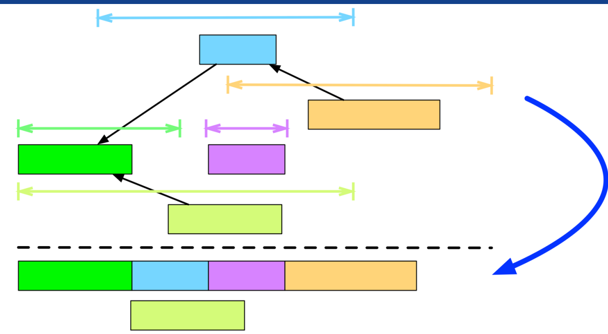
OnBoard Planner: Move Decision Making On-Board

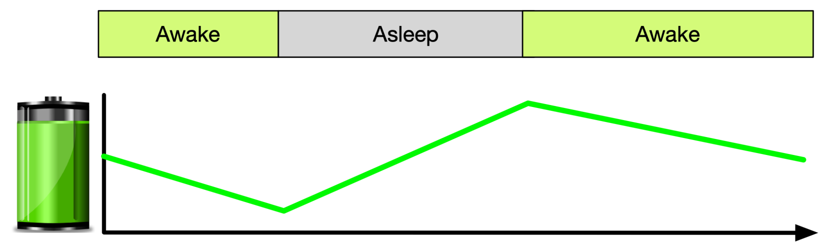
- **Take advantage of knowledge available onboard**
- **Resource management**
  - Time, power, energy (battery state-of-charge), atomic resources, sequence engines, data volume
    - Operator provided constraints: **handover battery SOC**, **minimum / maximum battery SOC**, **delta data volume**
- **Activity types**
  - Communication
  - Mandatory
  - Optional
- **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

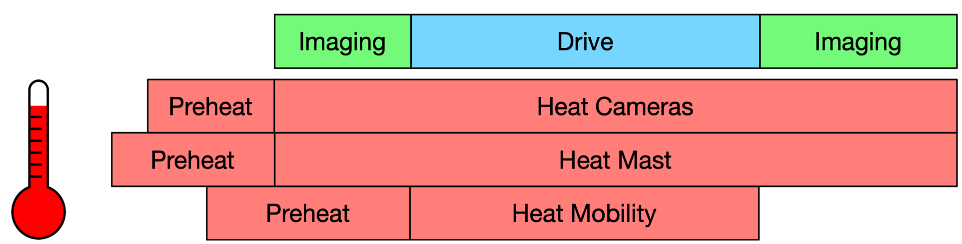


Challenges for OnBoard Planner Flight Software

- OnBoard Planner represents **significant increase in scope of autonomy**
  - Deciding what actions to perform, when to perform them
  - Scheduling shutdowns and wakeups to manage battery state-of-charge
  - Managing heating for device safety
- OnBoard Planner expected to **respond correctly and safely to a highly diverse set of dynamic conditions**
  - Responding to **deviations in execution**
    - Activities running long, ending early; thermal conditions warmer / colder than predicted; battery SOC greater or less than predicted







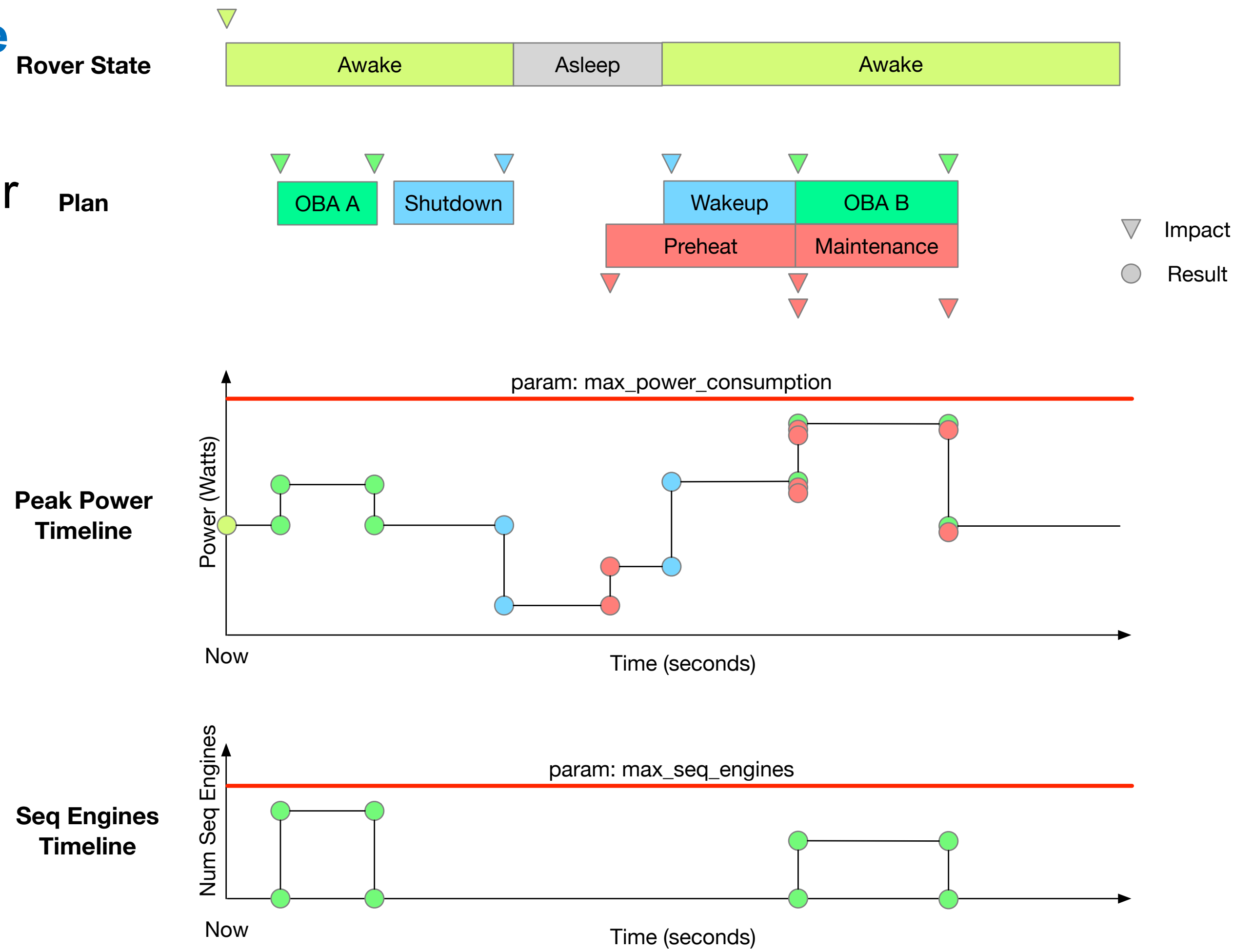
Challenges for OnBoard Planner Flight Software

- Balancing performance with computational constraints
  - **OBP has a lot of work to do**
    - Generate plans, execute plans, monitor plans, re-generate plans
  - Limited rover computational resources:
    - RAD 750 running at **133 MHz**
    - **CPU shared** with many (~90) FSW tasks (of varying criticality)
- Balancing scope of control with restrictions for system protection
  - Limit control to only what is required and help protect from errors (ground or flight software)

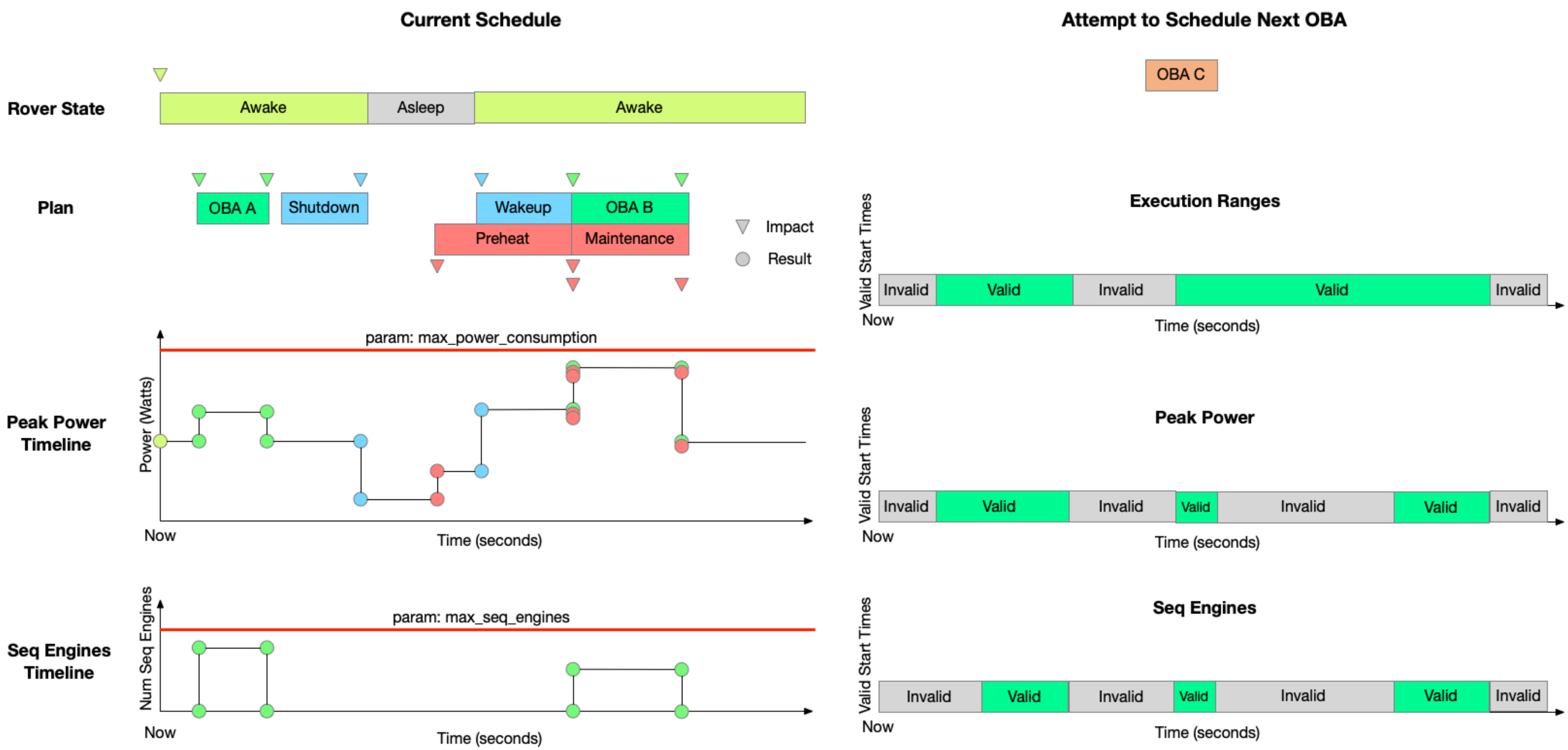
Timelines and Valid Intervals

- **Timelines project resource or state** over the schedule
- Used in scheduling to **identify valid start times** for activities
- Valid intervals begin with activity's execution range(s) and are **successively pruned by considering timelines**
  – Note: intervals also pruned by activity dependencies

- OnBoard Planner and MEXEC share the Timeline library

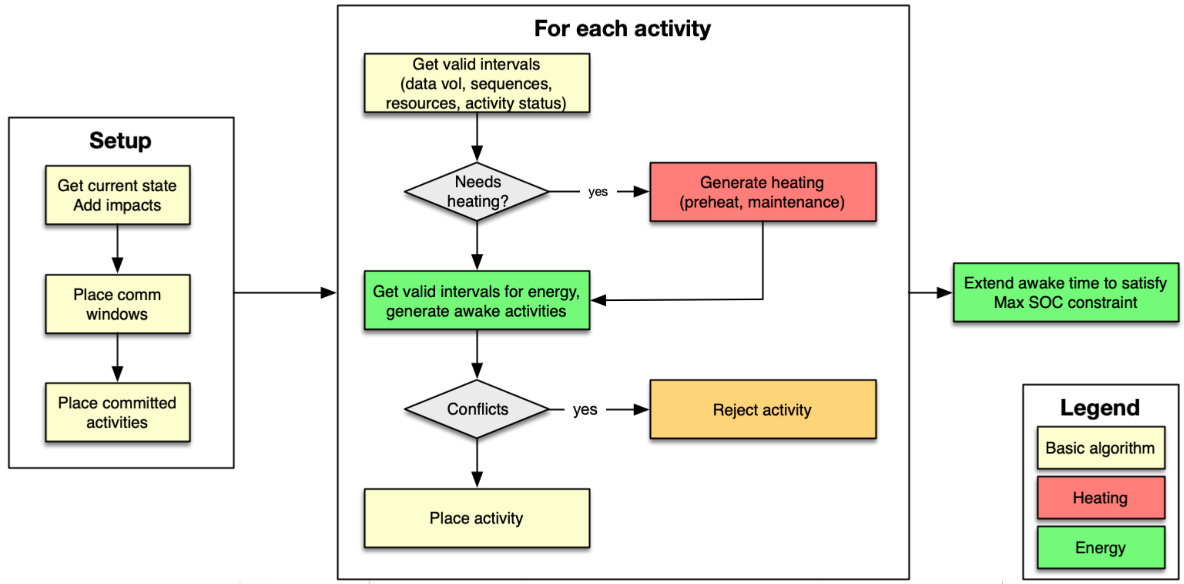


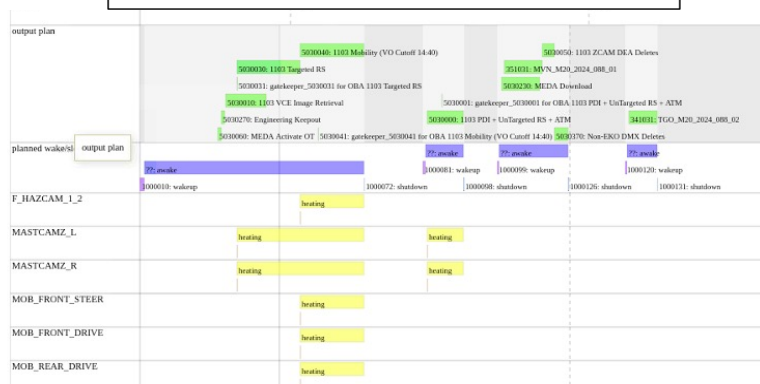
Example Valid Activity Start Interval Calculation



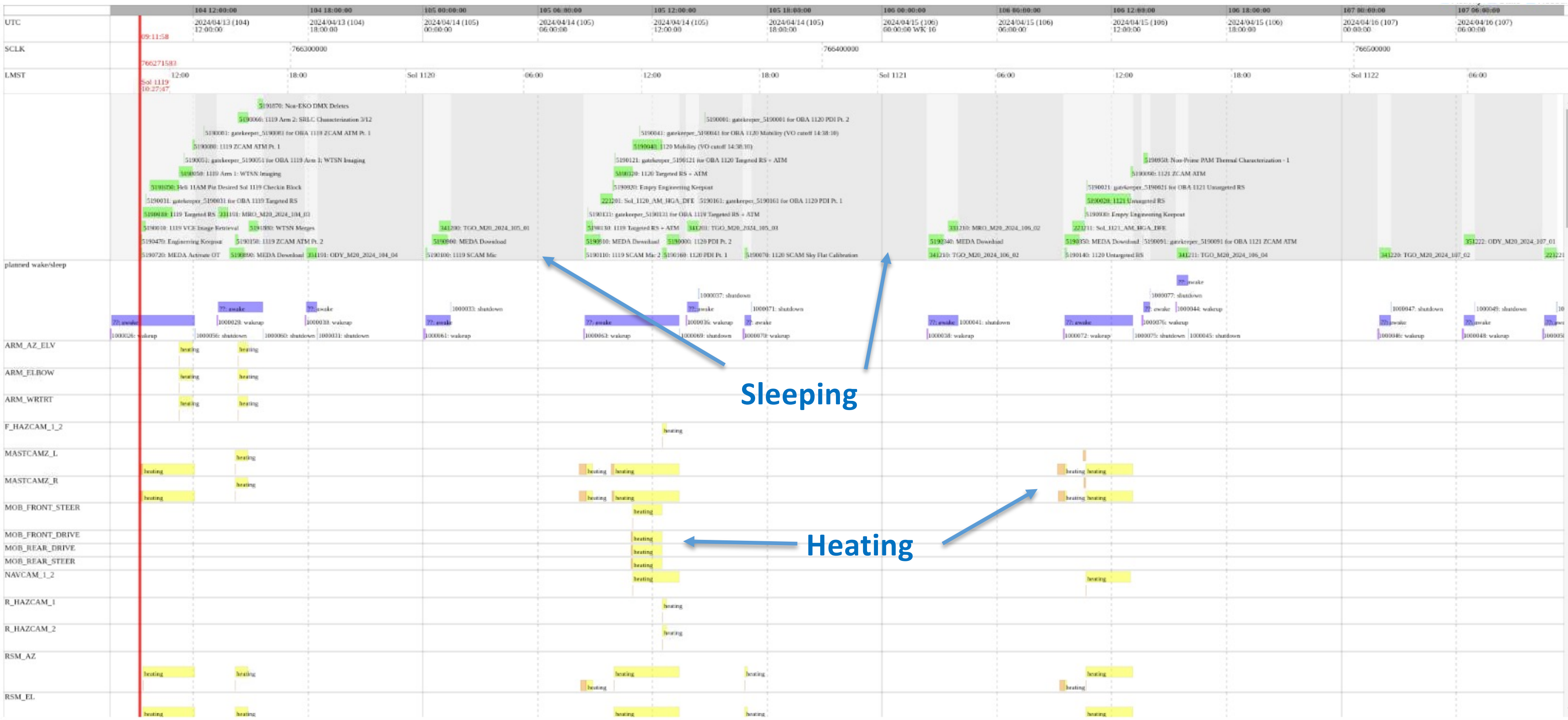
Overview of Scheduling Algorithm

- **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
- **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



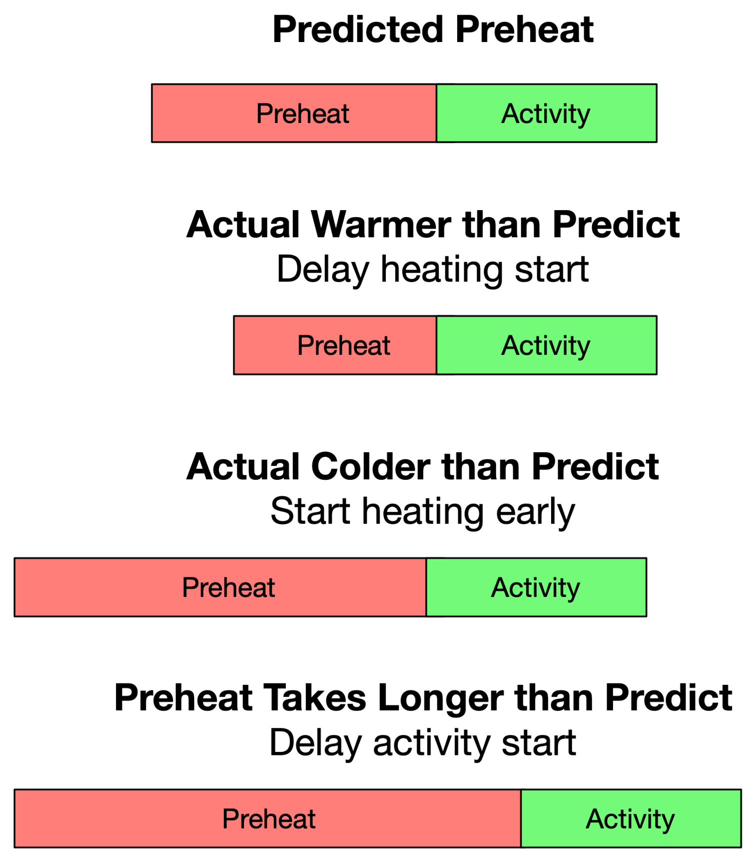


Example Schedule



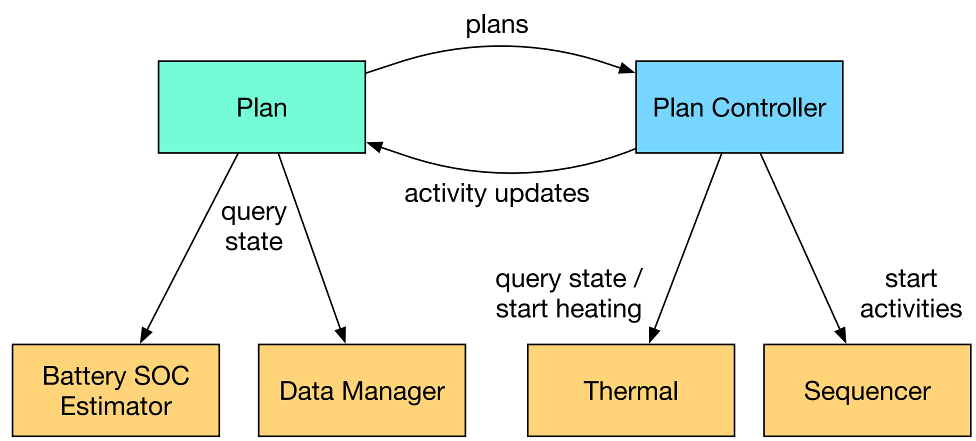
OBP Thermal Management

- **Objective**: improve efficiency over traditional thermal management
  - Bonus: improve robustness to incorrect thermal predictions
- **Strategy**: reduce conservativism of thermal predictions
  - Heating prescriptions based on temperature predictions that are closer to actual expected conditions
  - Requires onboard behavior to adjust prescriptions based on actual temperatures
    - Increase heating if temperatures colder than predicted
    - Decrease heating (saving resources) if temperatures warmer than predicted



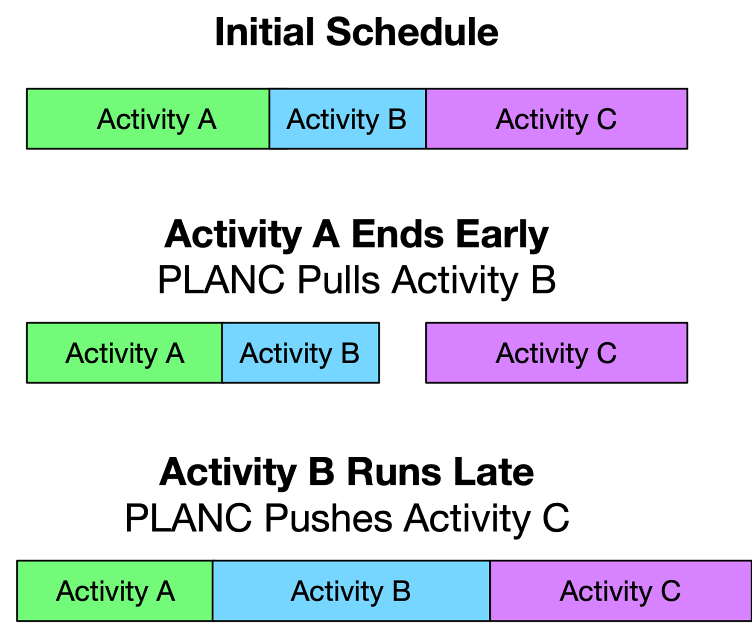
Generating Schedules vs. Executing Schedules

- Generating schedules takes times
  - Can take 10s of seconds
- Plan execution must be responsive to meet user expectations
  - Start / stop activities within a couple seconds of scheduled times
- Necessitates separate tasks in a Real-Time Operating System
  - Plan execution requires relative high priority to be responsive
  - Generating plans at such a high priority would be disruptive
    - Starve CPU from other high priority tasks
- **Plan Task:** generates schedules
  - Based on operator input and current vehicle resources
- **Plan Controller Task:** executes schedules
  - Starts / stops activities based on current vehicle / resource state



Flexible Execution & Event-Based Re-Planning

- **Flexible Execution:** Plan Controller 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
    - Don't have to wait for full re-scheduling cycle
  - **Reduces planning overhead** allowing more CPU availability for other flight software tasks

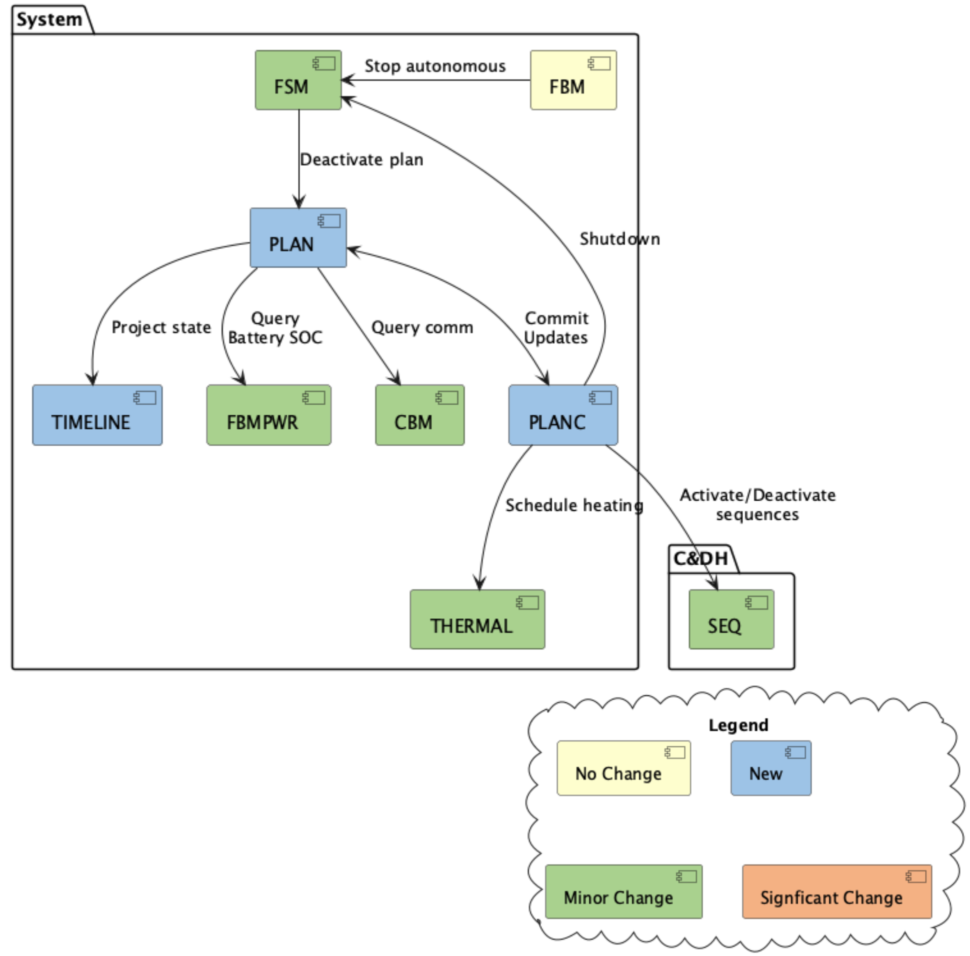


OBP Flight Software Stats

- Lines of code
  - 45K non-comment source lines of code
    - 12K of this is auto-generated
  - 5% of Mars 2020 flight software
- RAM usage
  - 4 MB
  - Less than 1% of available RAM

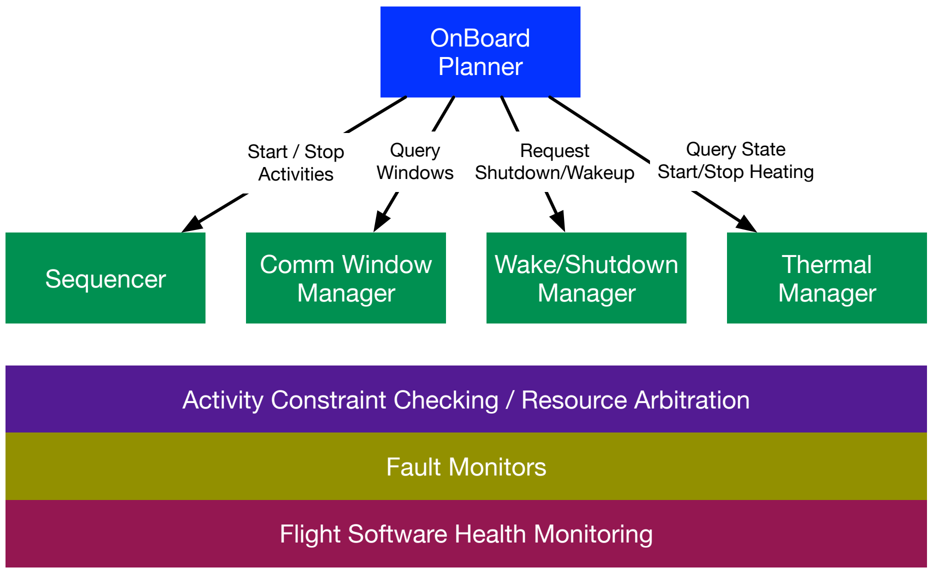
Integration with Flight Software

PLAN	Generate schedules
PLANC	Execute schedules
TIMELINE	State projection library
FSM	Shutdown control
CBM	Comm window queries
THERMAL	Preheat / maintenance heating
FBMPWR	Battery SOC estimation
FBM	Safing
SEQ	Sequence activation / deactivation using Activity IDs

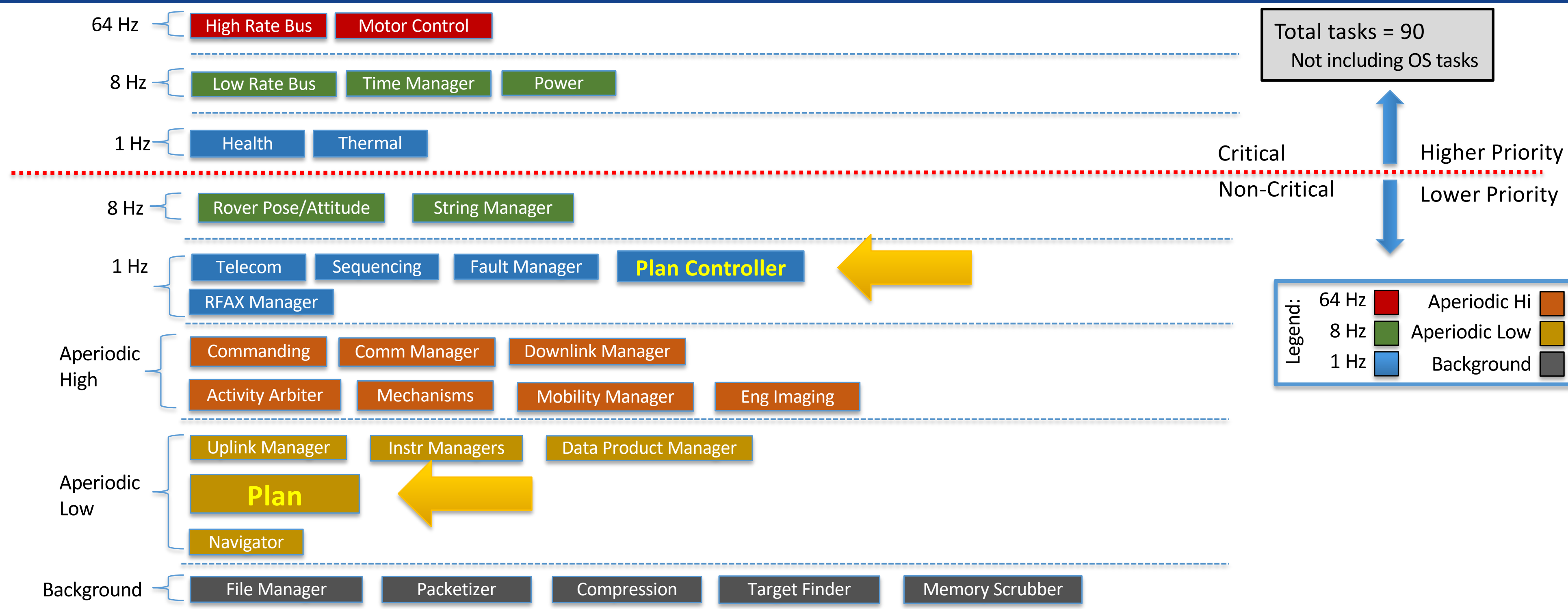


System Design: Layering and Restricting

- OnBoard Planner exists on top of **layers of flight software protection**
  - Same protections used to guard against human command errors
  - Activity constraint checking and resource arbitration
  - Vast array of fault monitors (power draw, state of charge, temperatures, …)
  - Flight software Health monitoring
  - Additional fault monitors for Battery SOC and Plan errors
- **Restrictions on how OnBoard Planner interacts with the system**
  - OnBoard Planner does not control communication windows
    - Checks verify OnBoard Planner input and execution are consistent with comm windows
  - OnBoard Planner does not directly perform activities
    - Instead, invokes sequences; same as in traditional rover operations
  - Shutdown/wakeup requests go to same task as ground-commanded
    - Same checks verify sleep will not interfere with comm windows

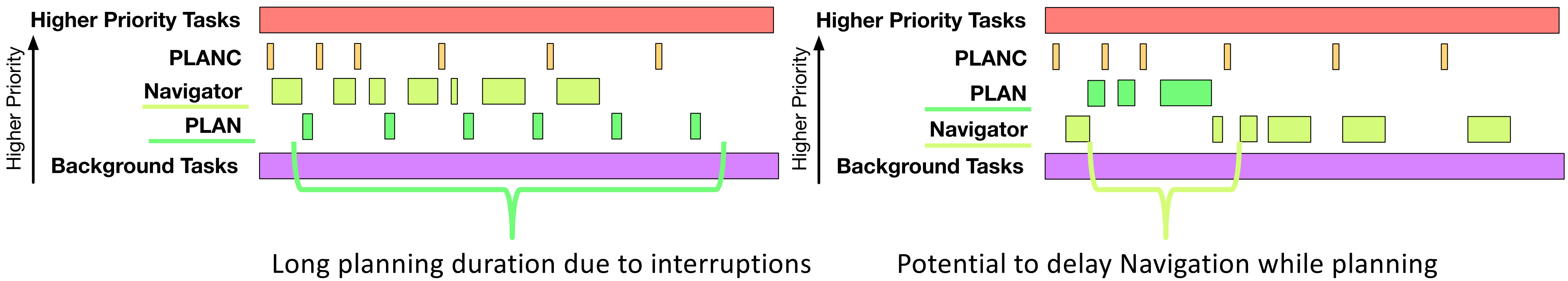


FSW Task Priorities



- **Plan Controller:** runs at ~ 1Hz
- **Plan:** Low priority to avoid interfering with other tasks during scheduling
  - **Higher priority than Navigator** to enable rescheduling during drives (support expanded drive OBAs)
  - Expect planning to be sufficiently infrequent to not significantly impact drive performance

Plan Task Prioritization



- Considered two main strategies for schedule 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**
- Flexible execution and event-based scheduling enabled Medium priority approach
  - Reduces frequency of re-scheduling

OnBoard Planner Results from 1st year in Flight

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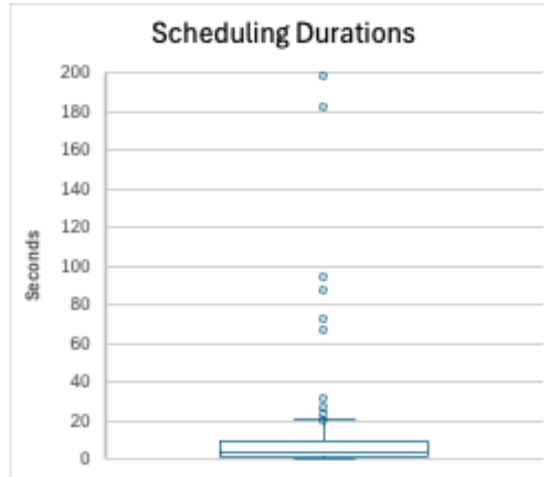
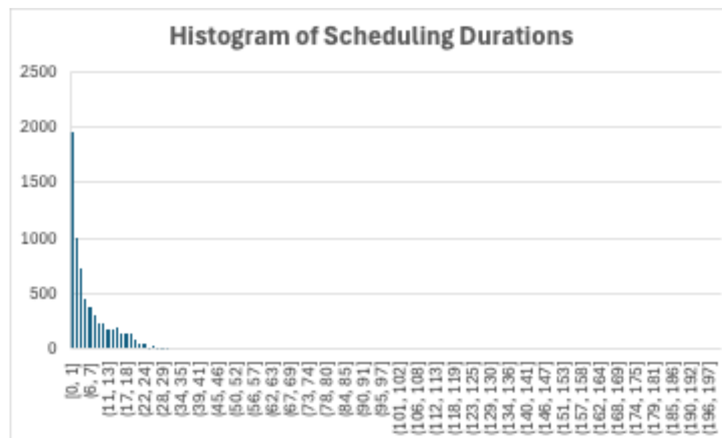
- **OnBoard Planner became part of standard Mars 2020 operations** in October 2023, during that time:
  - OBP has executed more than 200 plans spanning 350+ sols
    - Comprising more than 7,000 user requested activities, more than 22,000 total activities
- OnBoard Planner **computation performance has been excellent**
  - Executed 6,500+ scheduling cycles
    - Average 6 seconds (wall clock) per scheduling cycle
    - Average 8 seconds for initial schedules
    - Longer durations due to scheduling during higher pirority CPU activity





OnBoard Planner Results from 1st year in Flight

- OnBoard Planner has **improved vehicle resource utilization**
  - Improved energy efficiency (importance increases as rover ages)
  - Enables operators to include more activities into plans
- OnBoard Planner has **increased drive distance**
  - Added nearly **800 meters of drive distance**
  - Tens of meters of additional distance per drive, as far as 75m for an individual drive
- OnBoard Planner has led to **improved science quality**
  - Sherloc spectroscopy quality improved through OBP's more efficient heating strategy
  - Opportunistic atmospheric observations have occurred at more favorable times

OnBoard Planner Flight Anomalies from 1st Year

- To date, have encountered only a **small number of OBP FSW anomalies**
  - 5 ISAs involving flaws in OBP FSW
  - Two ISAs resulting in loss of activity
    - One case in which an activity failed to schedule (flight software contributed but was not the only cause)
    - One in which an off-nominal plan activation (via UHF forward link) uncovered a flaw resulting in plan file rejection
  - Some cases in which activity failed to schedule at expected time but still able to be scheduled
  - **Anomalies have not prevented operations from using OBP on subsequent planning cycles**

Conclusion

- OnBoard Planner has become part of standard Mars 2020 operations for over a year and has **increased mission productivity and science quality** during this time
- OnBoard Planner represents a **significant increase in the scope of space autonomy**
- The flight software and V&V **teams overcame many challenge**s in the successful development and testing of OnBoard Planner:
  - Enabling OnBoard Planner to operate robustly and effectively within tight computational constraints
  - Ensuring OnBoard Planner would respond correctly and safely to highly diverse and dynamic conditions
- Future for onboard planning for spacecraft
  - MEXEC: CADRE, Endurance, Federated Autonomous MEasurement (FAME)
  - OnBoard Planner: Potential applications for SRL

Acknowledgements

- **OBP FSW Team**
  - Dan Gaines
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  - Eddie Benowitz
  - Vincent Wong
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  - Shreya Parjan
  - Kevin Reich
  - Ansel Rothstein-Dowden
  - Danny Tran
  - Nick Waldram
  - Sean Wenzel
- **5x R&TD Team**
  - Steve Chien
  - Wayne Chi
  - Jagriti Agrawal
- **M2020 Operations Team**

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References

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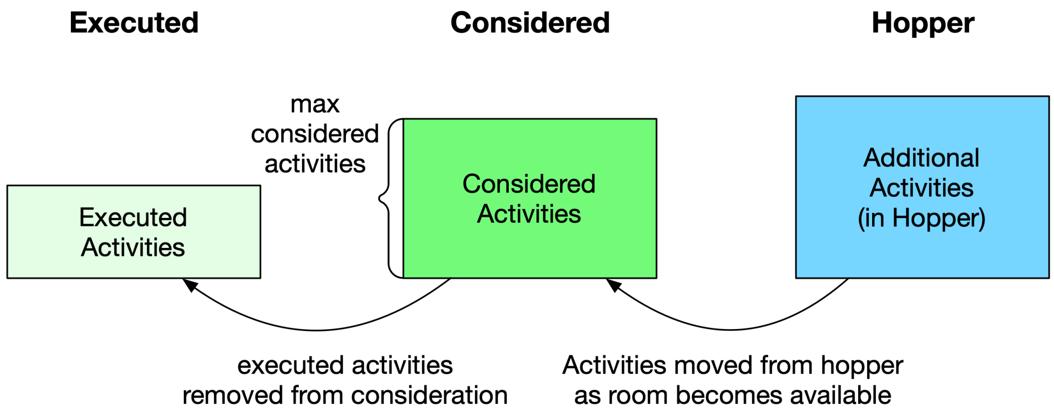
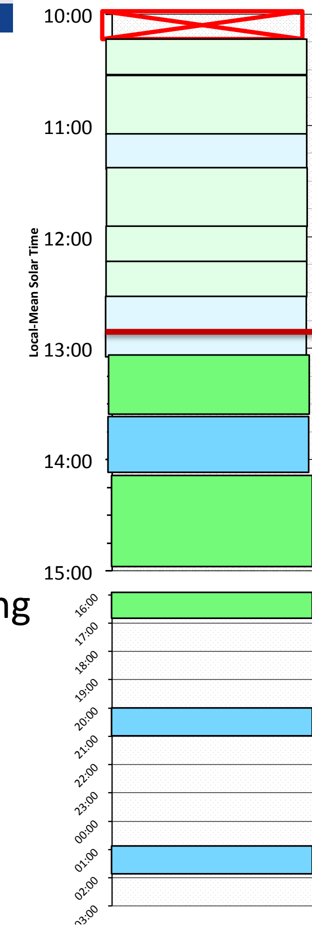
Backup

OBP Thermal Management

- Thermal management is by far the **most complicated part of OBP**
  - Heating duration and energy **varies with start time**, complicating activity scheduling
  - Determine when to **”merge” heating** across activities versus starting a new preheat
  - Support **re-scheduling** when some, but not all, preheats for activities have started
  - Respond to differences between **predicted vs. actual temperatures**
  - Support heating that is **Dream Mode** eligible (rover can be asleep) vs. Non-Dream Mode eligible (rover must be awake)
  - Support for "no-heat" windows, warm enough to not require heating (needed to avoid peak power violations)
  - Support for "can't-heat" windows, too cold to sufficiently heat

Considered Set





- Time required to generate schedules depends on number of activities to be scheduled
- More activities **allows rover to accomplish more** but **increases scheduling cost**
- Hopper increases set of activities that are included in a sol without increasing scheduling cost
- **Considered Set of activities**
  - Set of activities eligible for scheduling
  - Restricted in number to limit scheduling duration
  - Activities removed when they are executed
- **Hopper**
  - Additional activities added to considered set as space becomes available

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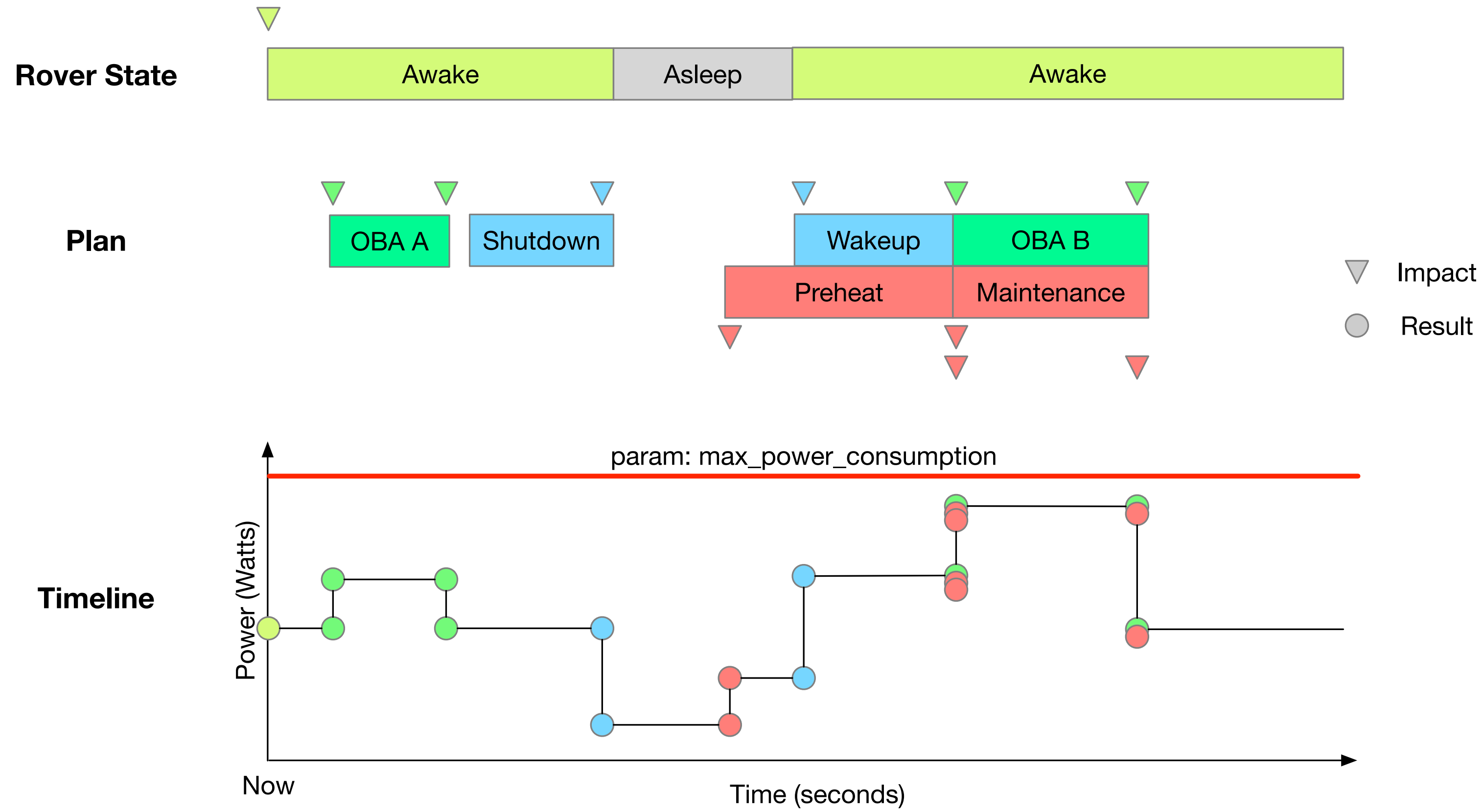
Peak Power Timeline: Non-Depletable



Battery State Of Charge Timeline: Rate Change