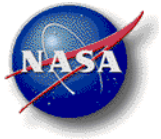

Applications of Quantum Computing: Human Spaceflight Mission Operations

Jeremy Frank
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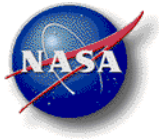
NASA Ames Research Center

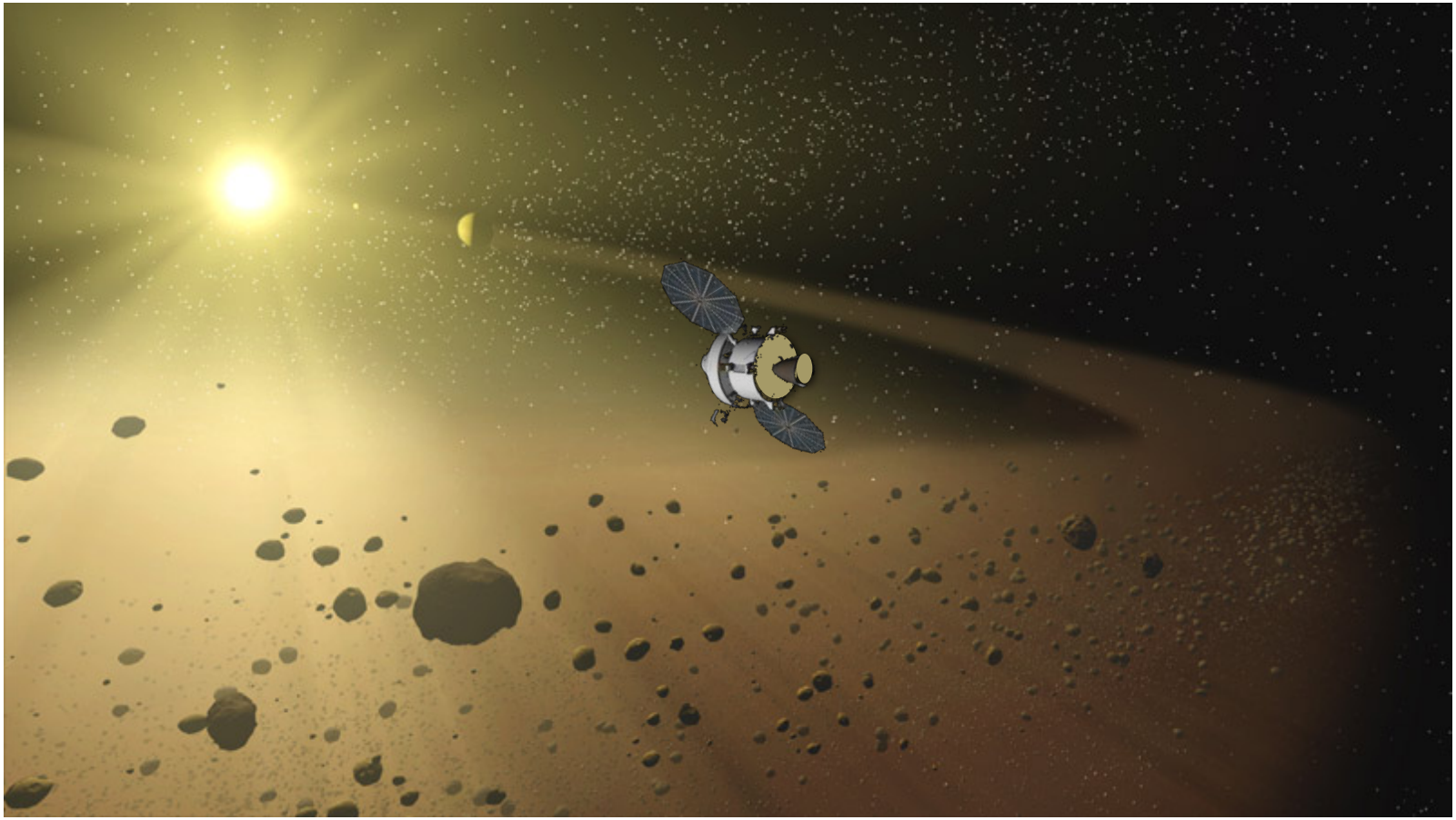


Talk Organization

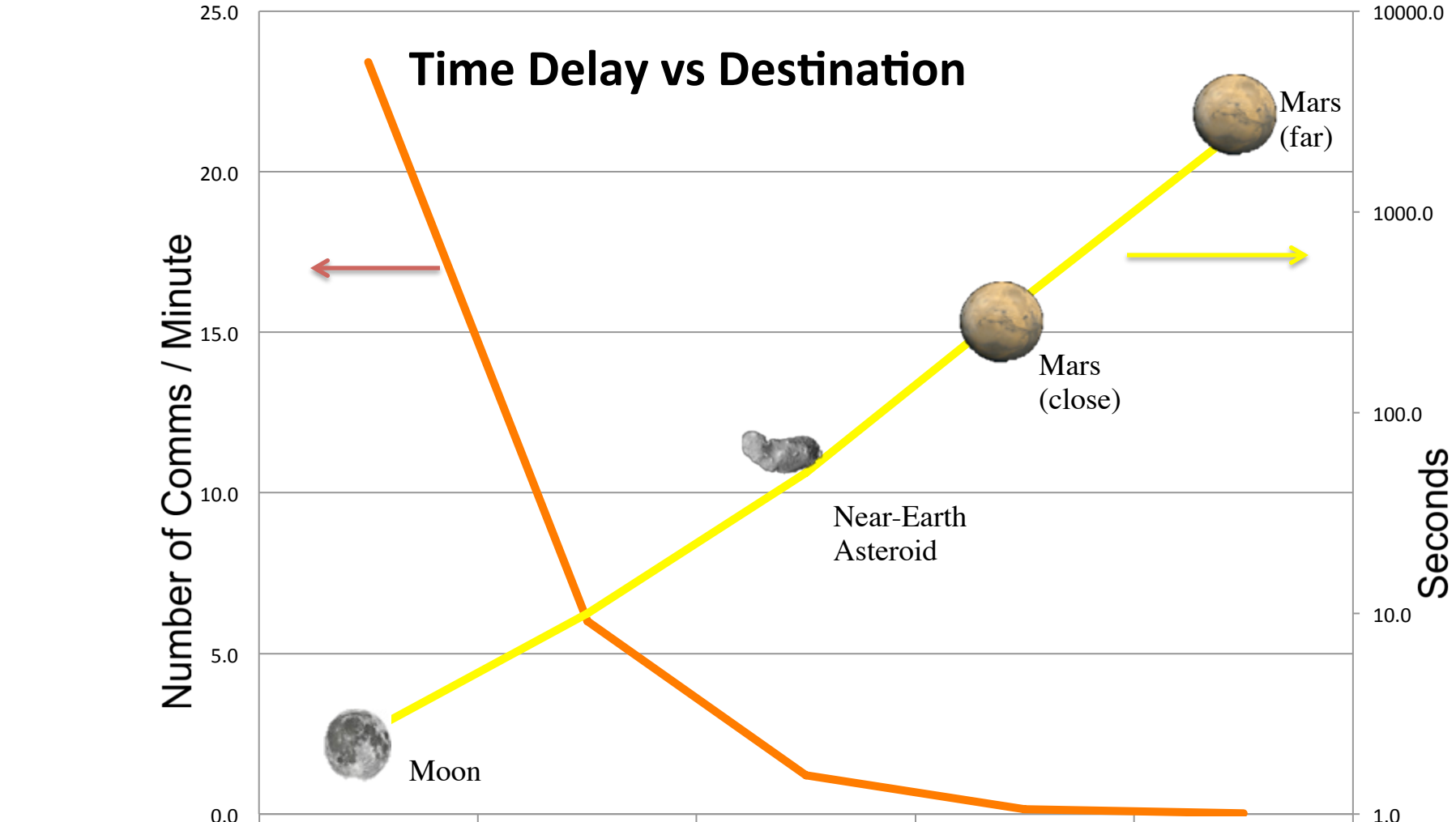
- Introduction
- Mission Operations
- Planning and Scheduling
- Model Based Planning and Scheduling
- Quantum Computing for Mission Operations
- Conclusion

Introduction

How will NASA *operate* a crewed mission with a *long communication delay* between the spacecraft and Earth?



Introduction



	Lunar	S-E L1/2	NEO	Mars (min)	Mars (max)
# Comms per Min	23.4	6	1.20	0.16	0.02
Roundtrip Time (Secs)	2.6	10.0	50.0	373.3	2673.3

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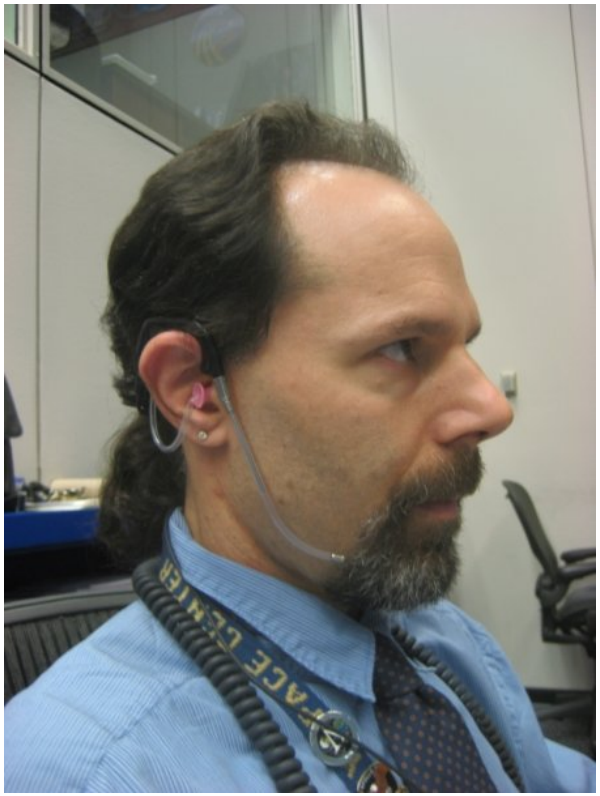
Mission Operations

Mission Operations



- Flight – Flight Director
- Attitude Determination and Control Officer (ADCO)
- Thermal Operations and Resources (THOR)
- Communications and Tracking Officer (CATO)
- Assembly and Checkout Officer (ACO)
- Operations Planner (OpsPlan)
- Environmental Control and Life Support Systems (ECLSS)
- Extravehicular Activity (EVA)
- Robotics Operations System Specialist (ROBO)
- Power Heating Articulation Lighting Control (PHALCON)
- Operations Support Officer (OSO)
- Onboard Data Interfaces and Networks (ODIN)
- Trajectory Operations Officer (TOPO)
- Ground Controller (GC)
- Biomedical Engineer (BME)

Mission Operations

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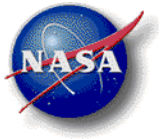
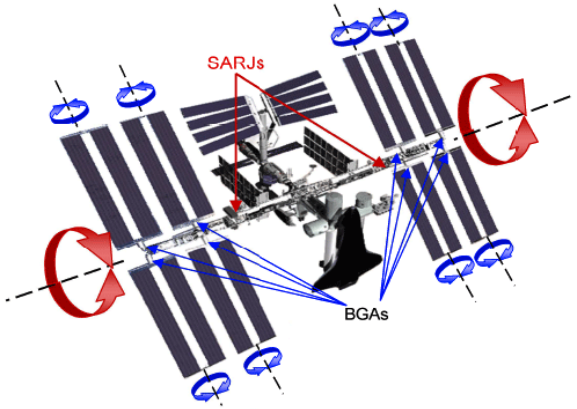


Planning and Scheduling

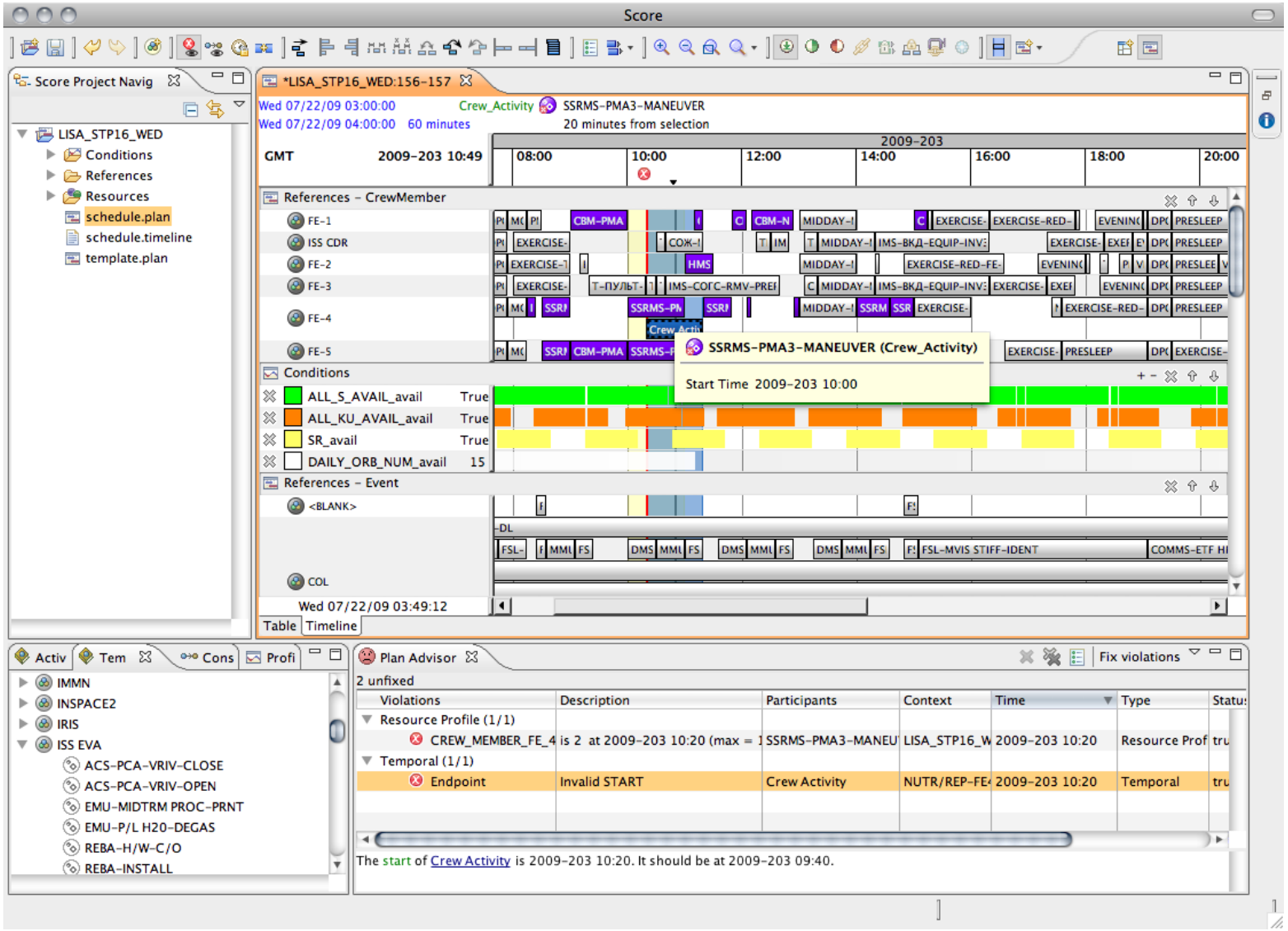
- Many different plans are built by different parts of the flight control team using disparate tools.
  - Crew plan
  - Power plan
  - Attitude plan
  - EVA plans
  - Procedures are plans too!
- Many plans are built and integrated by hand
  - There is some independence of these products, e.g. procedures can often be developed individually
  - Final integration still requires trades and replanning
- Depend on other plans built by other organizations
  - E.g. Communications plans for DSN

Planning and Scheduling

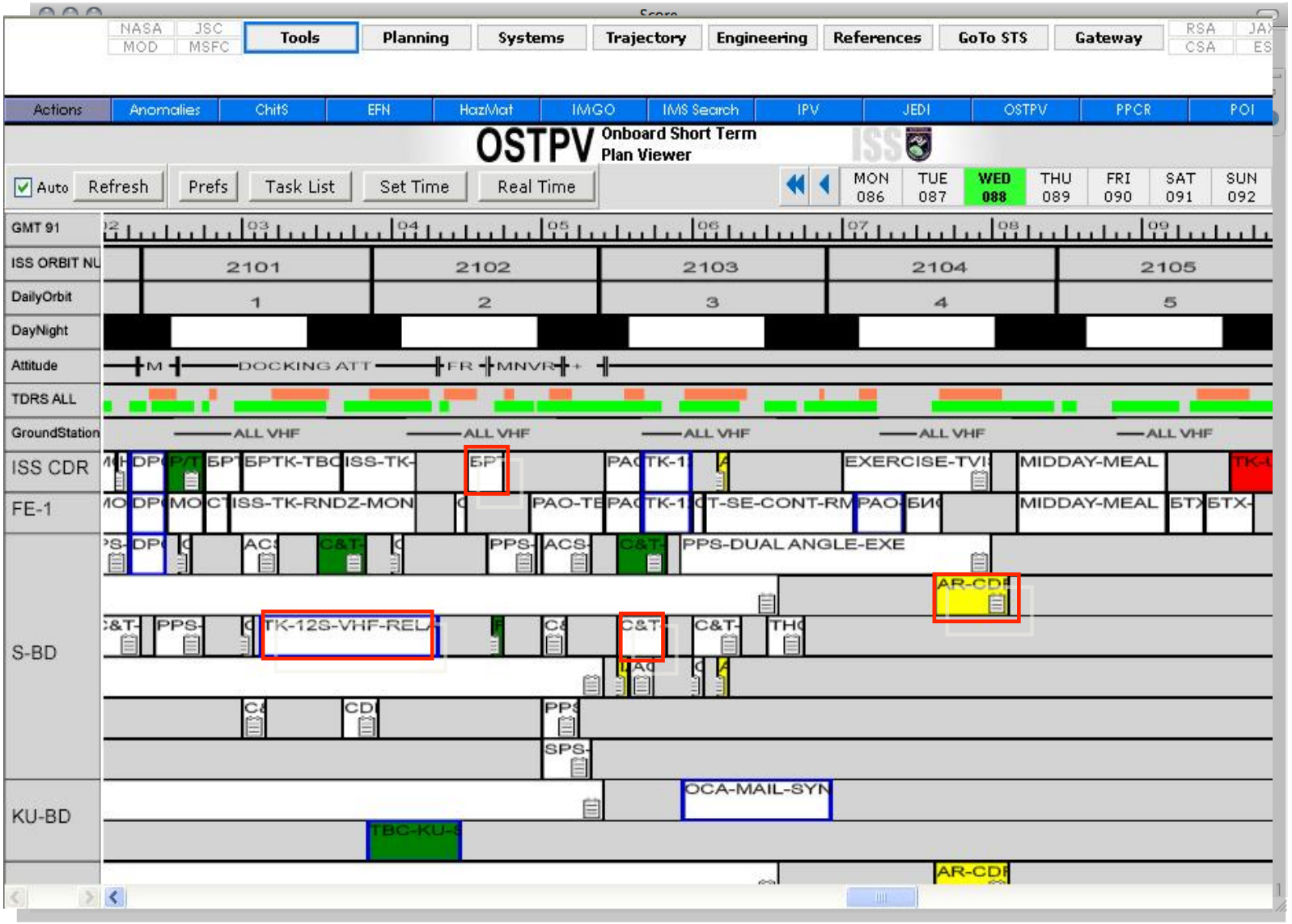


- ISS Solar Array Planning:
  - 8 arrays, 2 angles control pose
  - 3 array modes: autotrack, park, lock
  - 4 classes of constraint (Power, Load, Erosion, Shadowing) dictate mode
  - Constraints on mode duration, array turn rate, etc.
- Computational complexity:
  - With simple version of shadowing constraints, tractable (linear in length of plan, polynomial in no. of arrays)
  - With full version of shadowing constraints becomes much harder
  - Building contingent plans is even harder yet.

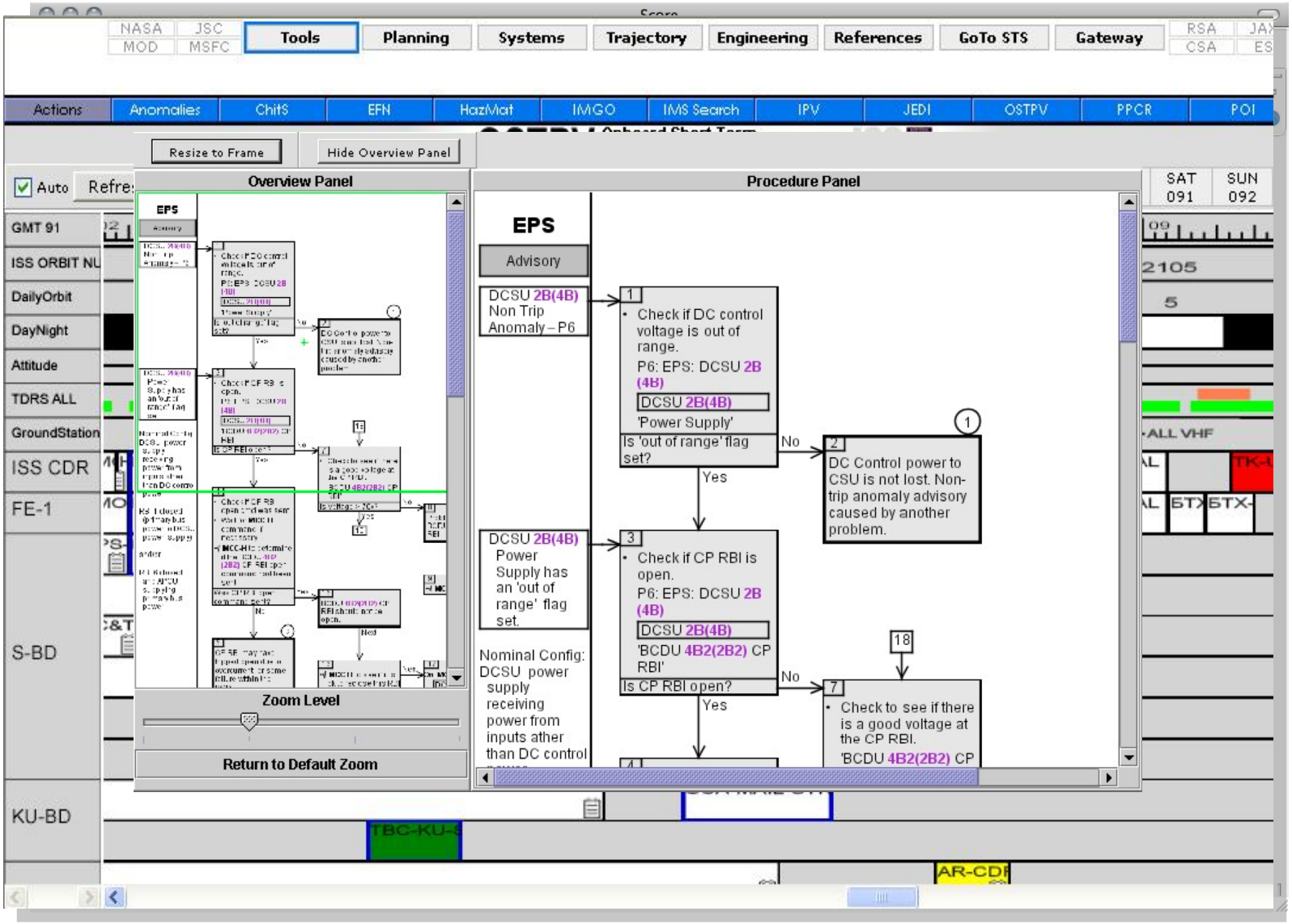
Planning and Scheduling



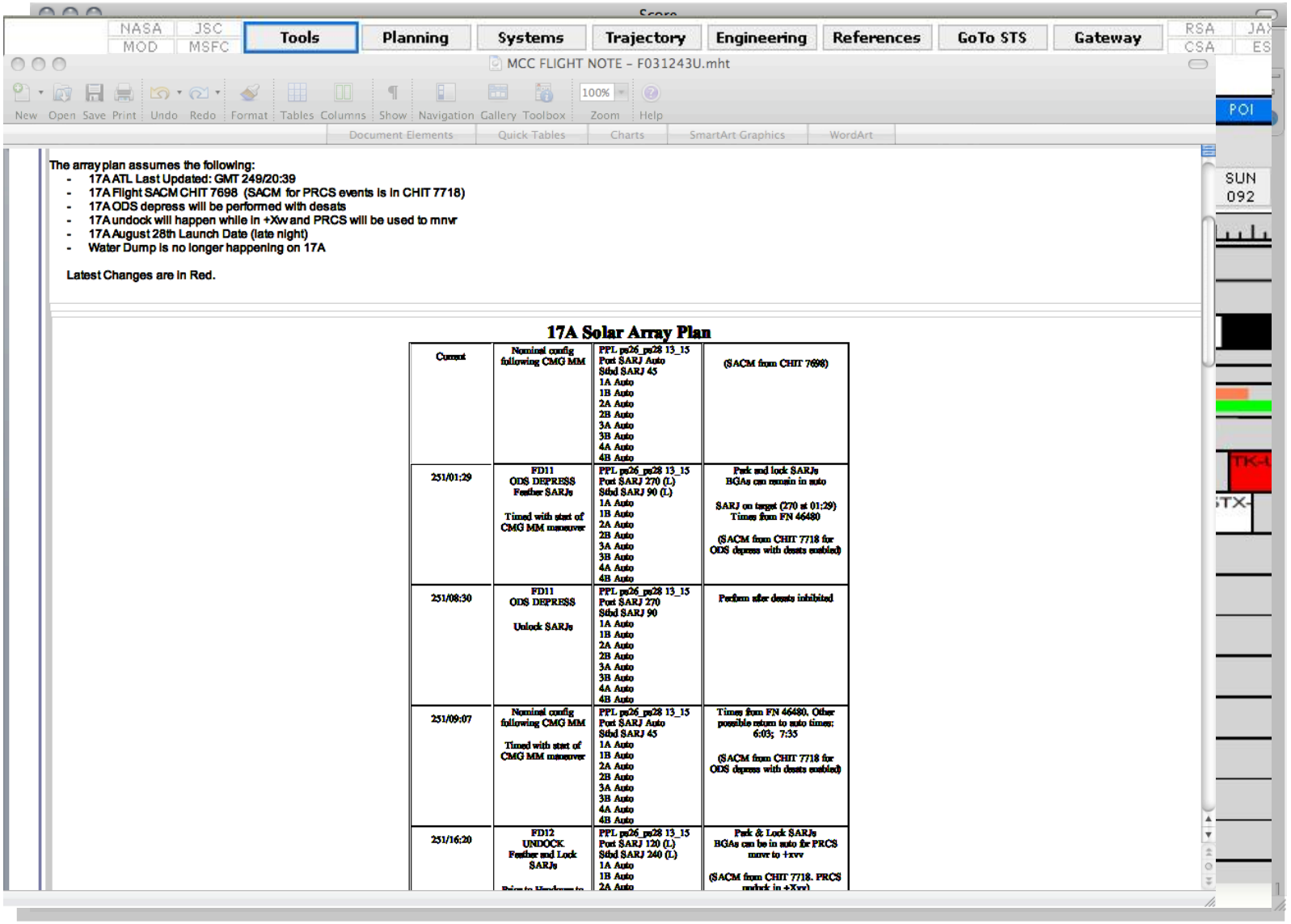
Planning and Scheduling



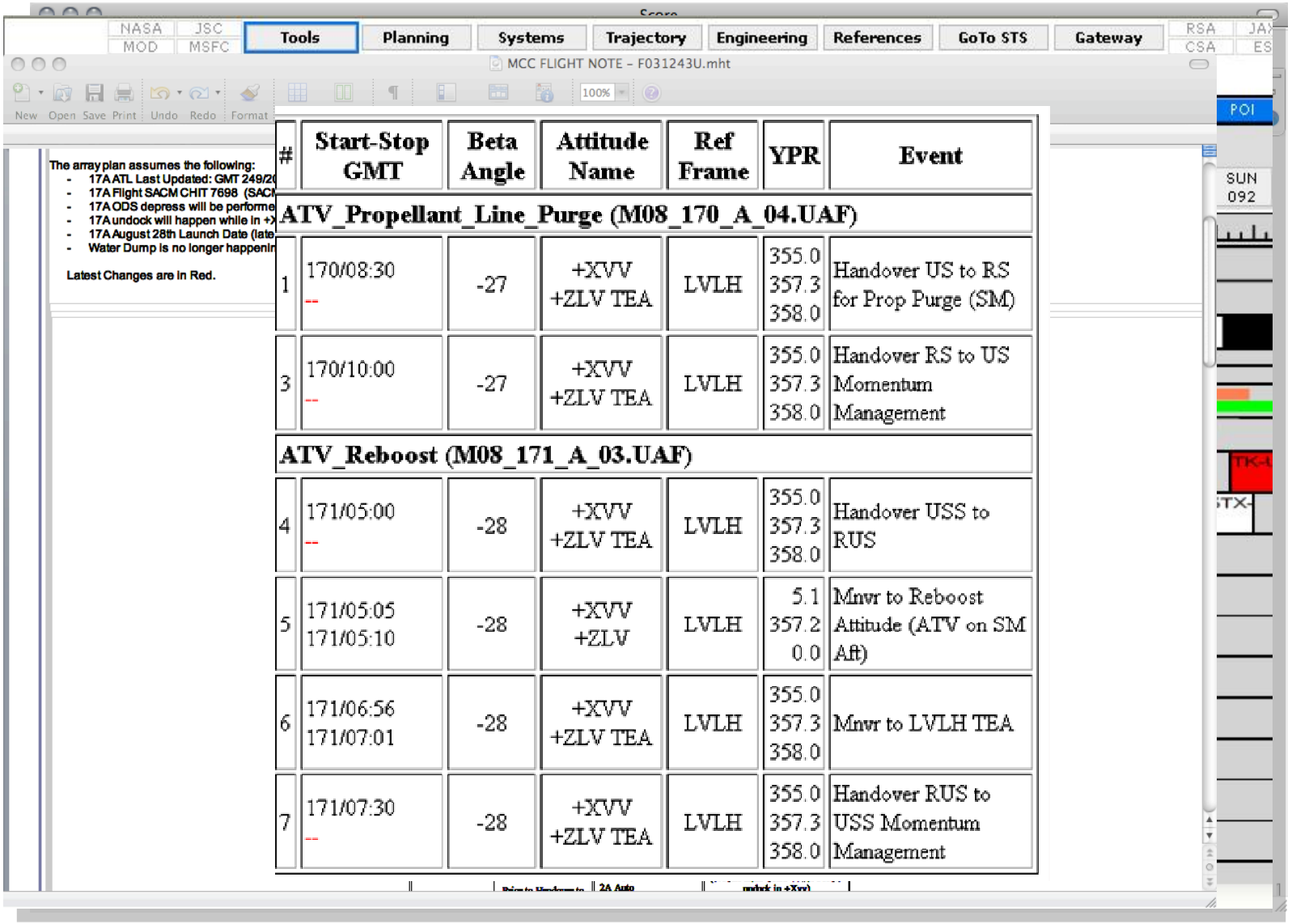
Planning and Scheduling



Planning and Scheduling



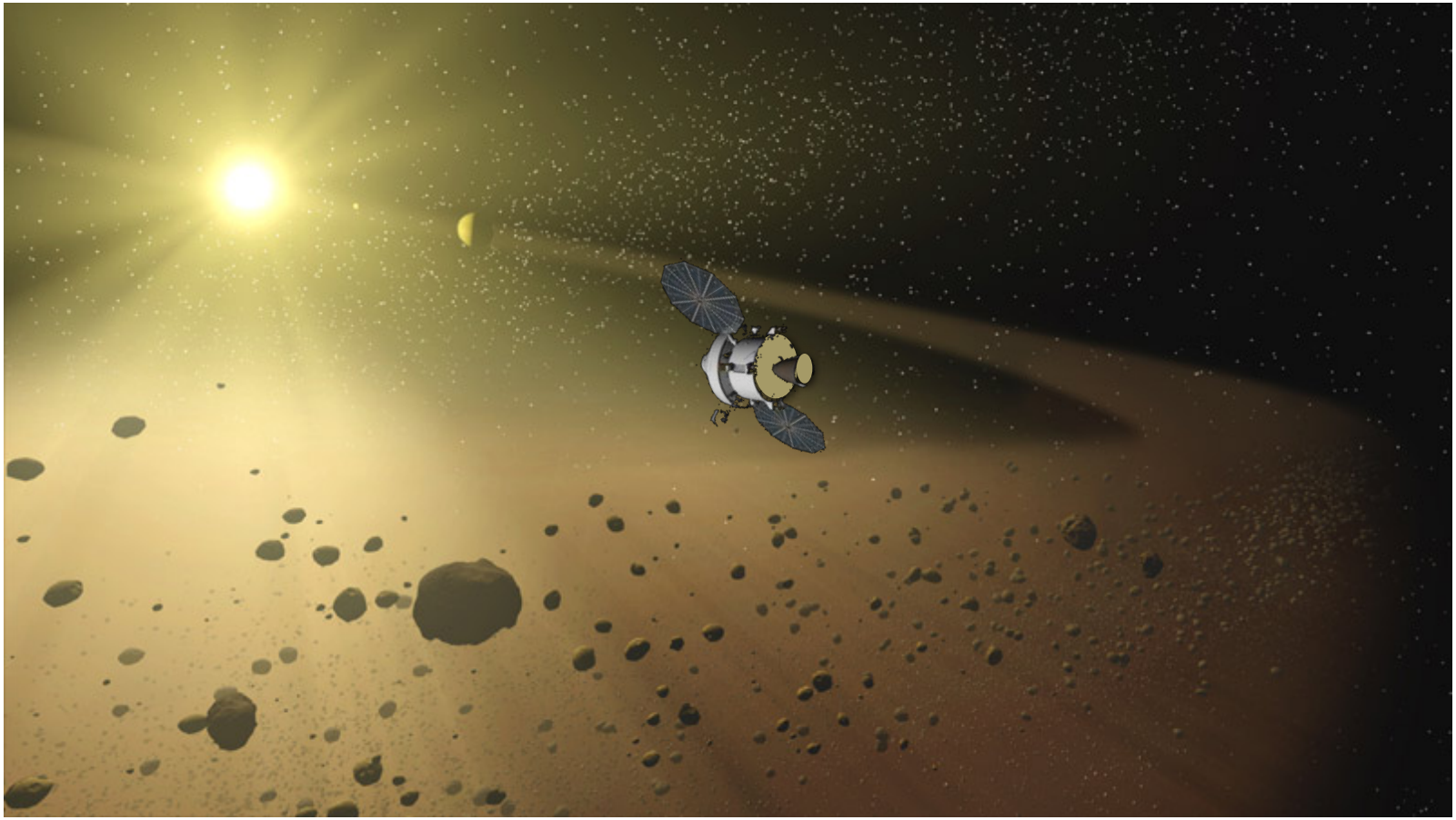
Planning and Scheduling

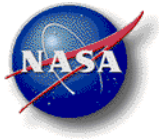


#	Start-Stop GMT	Beta Angle	Attitude Name	Ref Frame	YPR	Event
ATV_Propellant_Line_Purge (M08_170_A_04.UAF)						
1	170/08:30 --	-27	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover US to RS for Prop Purge (SM)
3	170/10:00 --	-27	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover RS to US Momentum Management
ATV_Reboost (M08_171_A_03.UAF)						
4	171/05:00 --	-28	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover USS to RUS
5	171/05:05 171/05:10	-28	+XVV +ZLV	LVLH	5.1 357.2 0.0	Mnvr to Reboost Attitude (ATV on SM Aft)
6	171/06:56 171/07:01	-28	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Mnvr to LVLH TEA
7	171/07:30 --	-28	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover RUS to USS Momentum Management

Planning and Scheduling

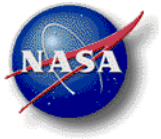
How will NASA *plan and schedule* a crewed mission with a *long communication delay* between the spacecraft and Earth?





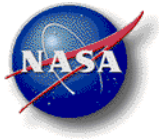
Planning and Scheduling

- The planning and scheduling problems solved by a large flight control team may now need to be solved by the crew.
- These problems will be solved on those computers flying onboard the spacecraft
  - Fewer and less capable than those in the MCC



Model Based Planning and Languages

- A planning problem consists of
  - A model
  - An initial state description
  - A set of goal states
- The software reads the description and produces a plan
- There are myriad algorithms with many different properties



Model Based Planning and Languages

- Model elements in more detail
  - Objects – things in the world
    - E.g. targets, spacecraft components
  - States – properties of the world
    - E.g. available power, mode of system
  - Actions
    - Conditions – what must be true for an action to have the desired effect
    - Effects – what changes when the action is executed

Model Based Planning and Languages

```
(action slew
  :parameters (?from – attitude ?to - attitude)
  :condition
   (and (pointing ?from)
        (cpu-on)
        (>= (sunangle) 20.0)
        (communicating)
  :effect
   (and (not (pointing ?from)
        (pointing ?to)))
```

Object

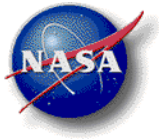
Action

Condition

State

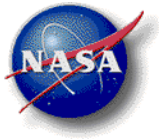
Effect

State



Model Based Planning and Languages

- Planning vs Scheduling
  - Scheduling is the ordering of a given set of tasks in order to satisfy constraints.
  - Planning is the selection of operators to transform the world from one state to another while satisfying constraints.
- Scheduling is NP-complete
- Planning is:
  - Undecidable (in general)
  - PSPACE-complete (STRIPS)
  - NP-complete (Restrictions on STRIPS)
- Optimizing makes either planning or scheduling harder



Quantum Computing for Mission Operations

- To summarize:
  - Planning and scheduling is hard
  - Either the crew or automated systems may be forced to do more planning and scheduling for future missions
- The use of quantum algorithms and computers can reduce the time to build and manage the mission plan:
  - Assist crew in planning nominal mission
  - Automatically respond to unexpected events or failures
  - Assist crew in responding to failures

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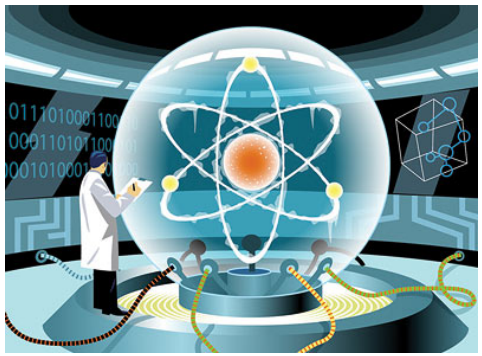
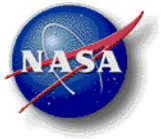
Quantum Computing for Mission Operations

- STRIPS planning is 'easily' reducible to an quadratic unbounded optimization problem (QUBO)
  - Create a PlanGraph
  - Generate quadratic optimization problem from the PlanGraph s.t. feasible plans cost is ≤ 0
- The QUBO can be solved by Quantum Annealing.
  - For more details see references at the end of the presentation.



Quantum Computing for Mission Operations

- Pros: enabling crew autonomy
  - Fast
  - Responsive to faults / failures
  - eliminating risk due to communication delay
- Cons
  - Mass, size, power of quantum hardware?
  - Susceptibility to space environment? (Thermal, radiation)
  - Programmability? (complex translation of planning to many bits, esp. for non-STRIPS problems)
  - Dependability? (termination / convergence of algorithms, guaranteed results of algorithms)



Summary

- Human spaceflight travel to distant destinations raises the problem of crew autonomy.
- Quantum computers and algorithms onboard spacecraft address the problem directly.
- Whether such computers introduce other operational constraints remains unobserved at this time.

Thank you.

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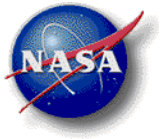

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- J. Frank. *When Plans are Executed By Mice and Men*. Proceedings of the IEEE Aerospace Conference, 2010.
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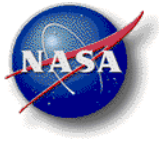
- (A survey of applications of QC is in preparation.)



BACKUP

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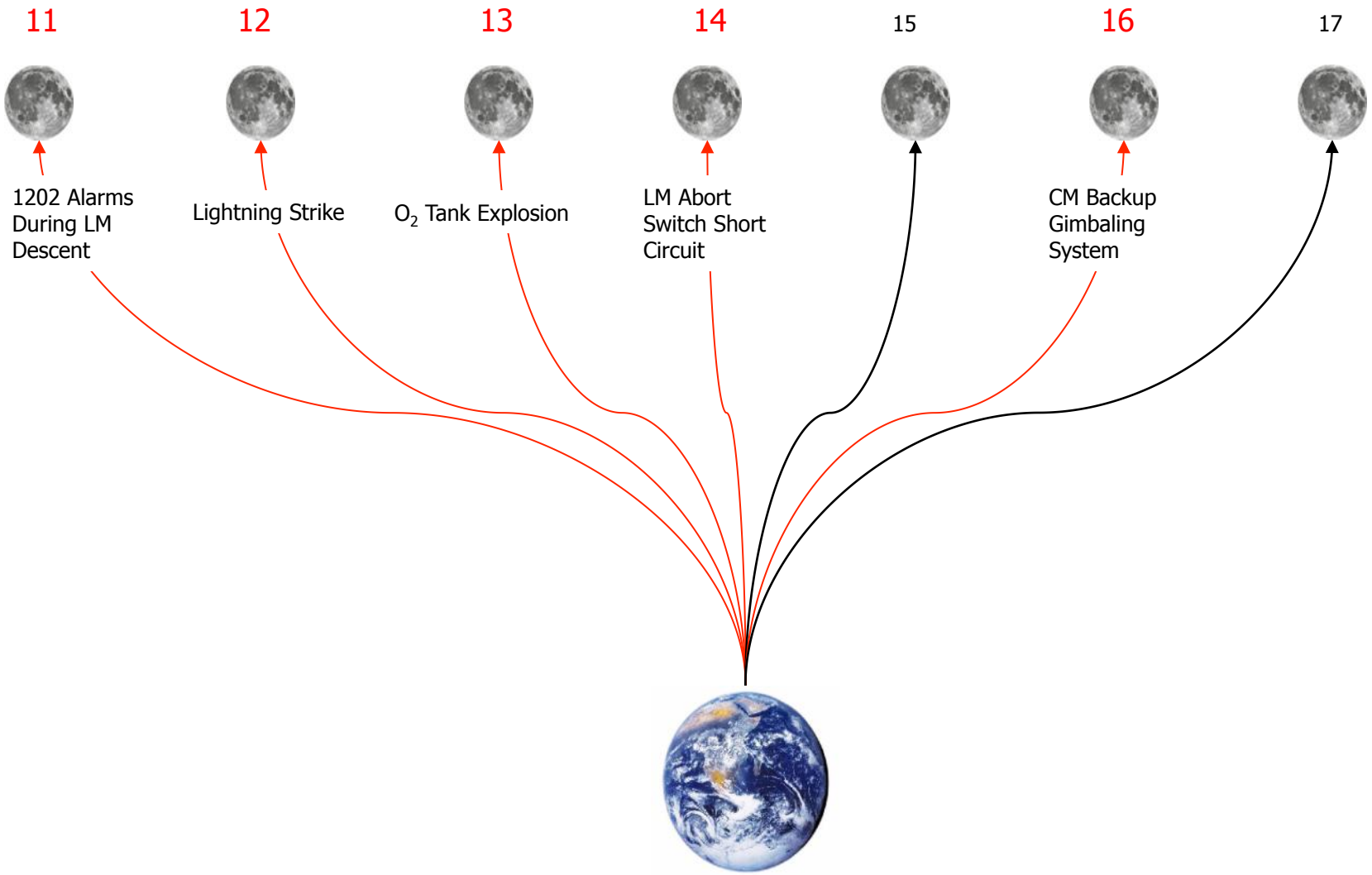
Integrated Systems Health Management (ISHM)



Integrated Systems Health Management (ISHM)

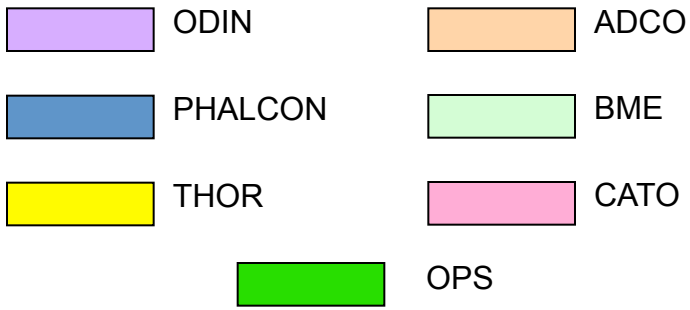
- When problems occur:
  - Fault detection, isolation, and recovery must take place.
  - Detection is often not difficult. Isolation, however, can be.
  - Immediate recovery (safing) is also often not difficult. Longer term recovery requires planning, which we have already seen, can be.

Quantum Computing for Mission Operations

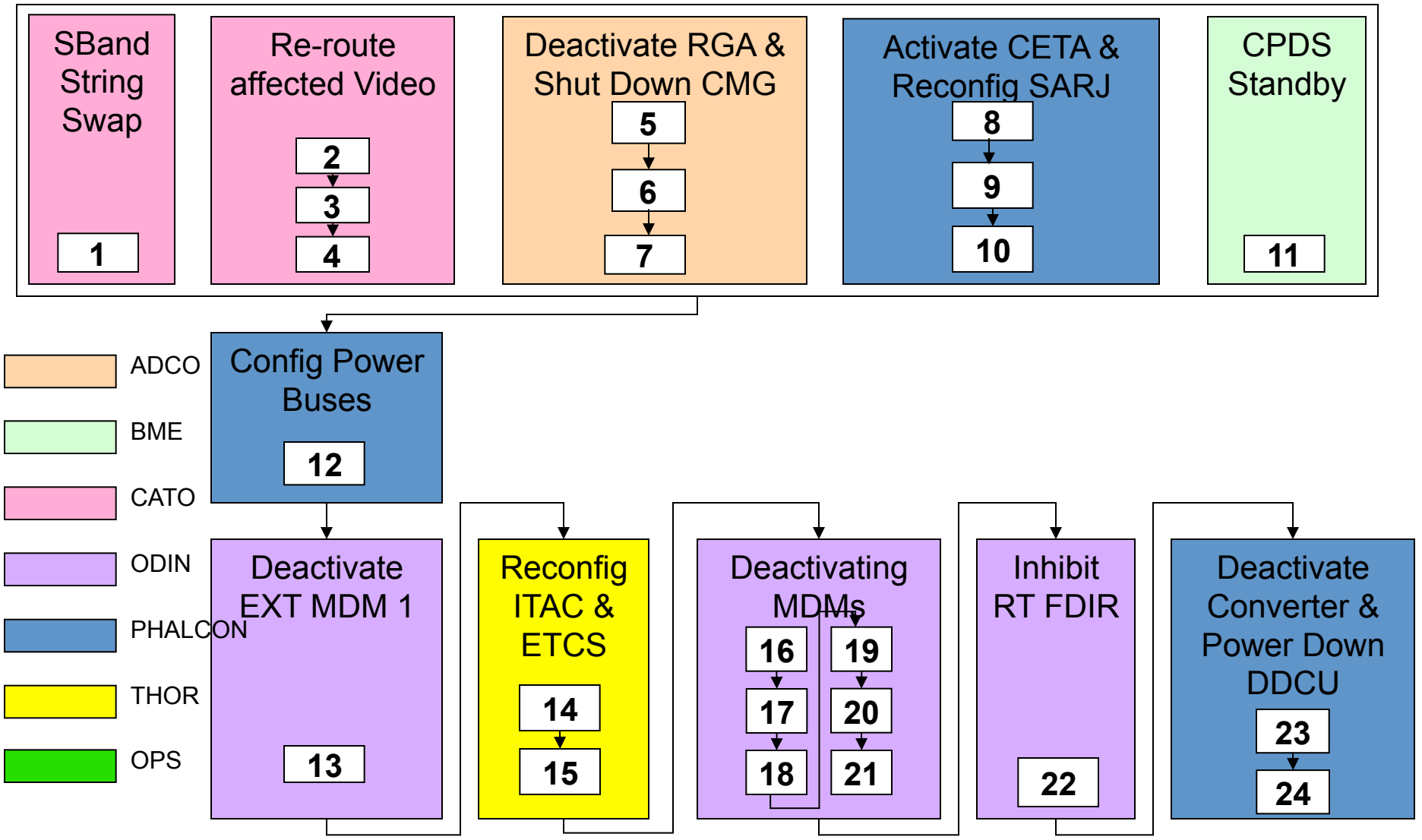
- ISHM
  - Some combinatorial problems for ISHM are similar to those of planning; QC for planning probably benefits ISHM with little modification.
- Communication
  - Can entanglement eliminate communication delays, as an alternative to crew autonomy?
  - Solution for space-communication security concerns
  - Perhaps quantum compression to increase bandwidth?
- Navigation
  - Improved navigation especially in hazardous zones (e.g. near NEAs)

Planning and Scheduling

- PHALCON - Power Heating and Lighting Control Officer
  - "Owns" the procedure
- ODIN - Onboard Data Interfaces and Networks
- BME - Biomedical Flight Controller
- THOR - Thermal Operations and Resources
- ADCO - Attitude Determination and Control Officer
- CATO - Communications And Tracking Officer
- OpsPlan – Operations Planning



Planning and Scheduling



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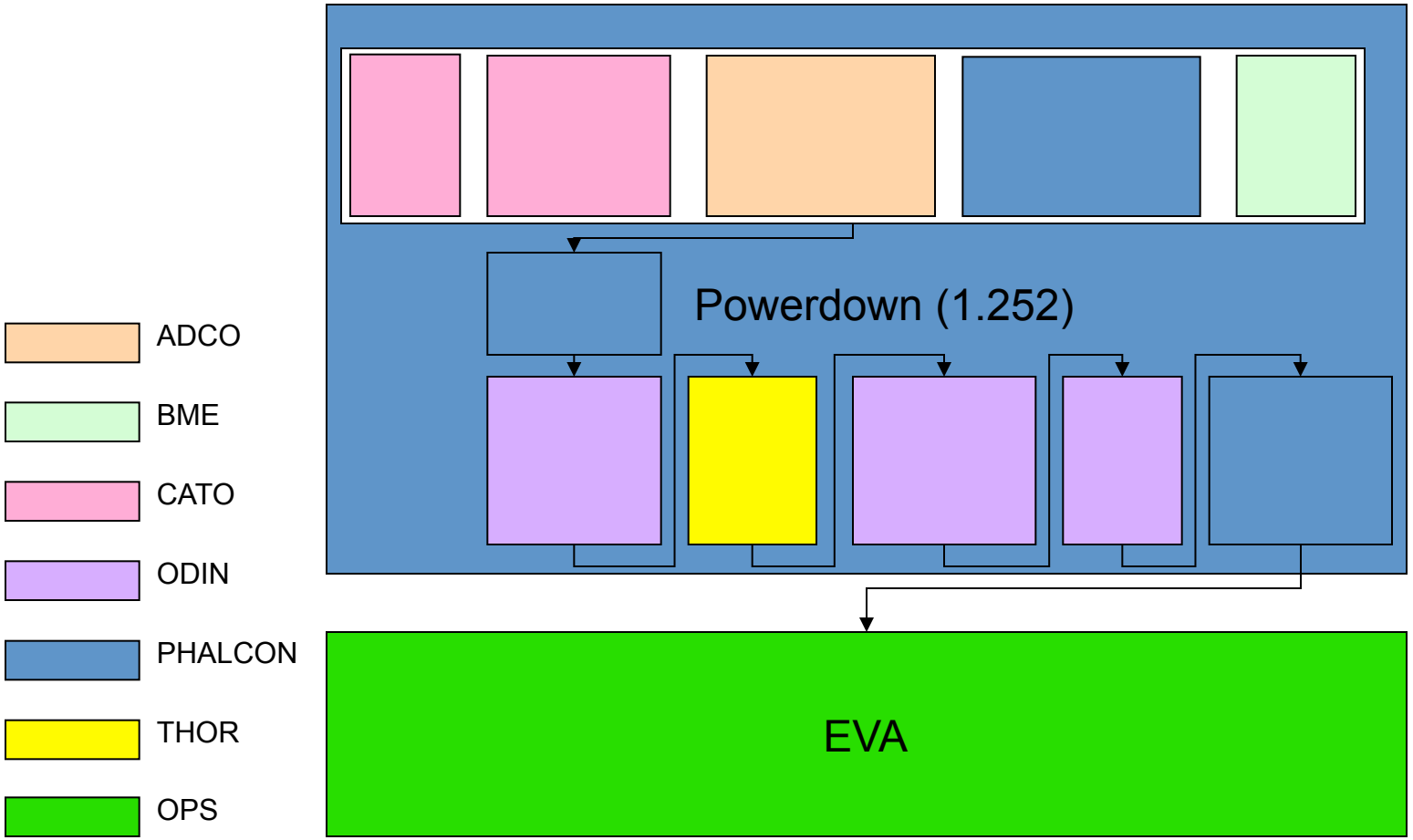
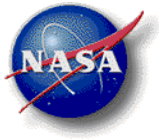
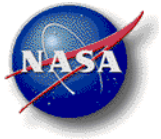




Computational Complexity (for dummies)

- Problem: a set of problem instances sharing some characteristics. (e.g. scheduling n tasks.)
- *P*: a class of problems whose solution can be calculated in polynomial time
- *NP*: a class of problems for which a proposed solution can be determined correct or incorrect in polynomial time
- *PSPACE*: a class of problems whose solution can be computed in polynomial space (memory)

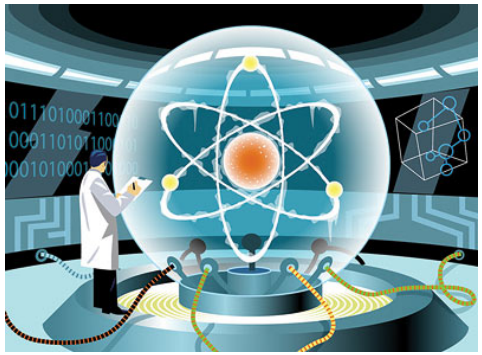


Computational Complexity (for dummies)

- Reduction: a transformation of a problem into another problem.
  - We only care about reductions that take polynomial time.
- *NP*-Hard: a problem P for which every other *NP* problem Q can be reduced to P.
- *NP*-Complete: an *NP*-Hard problem that is also in *NP*.

Quantum Computing for Mission Operations

- Planning and Scheduling Algorithms: state of the art
  - There are no scholarly publications on specific quantum algorithms for planning or scheduling.
  - STRIPS planning is 'easily' reducible to SAT, which is amenable to quantum computing.



Quantum Computing for Mission Operations

- The PlanGraph:
  - Alternating graph of actions and states.
  - First level is the initial state.
  - Even indexed levels contain every action whose conditions apply in the state.
  - Odd indexed levels contain every proposition 1) not deleted by an action 2) in the effect list of an action in the prior level
  - Classically,the PlanGraph also contains action and state mutual exclusions; these are captured in the QUBO (p. 45-46 of the survey paper).