

Applications of Quantum Computing: Human Spaceflight Mission Operations

Jeremy Frank
Autonomous Systems and Robotics
Intelligent Systems Division
NASA Ames Research Center





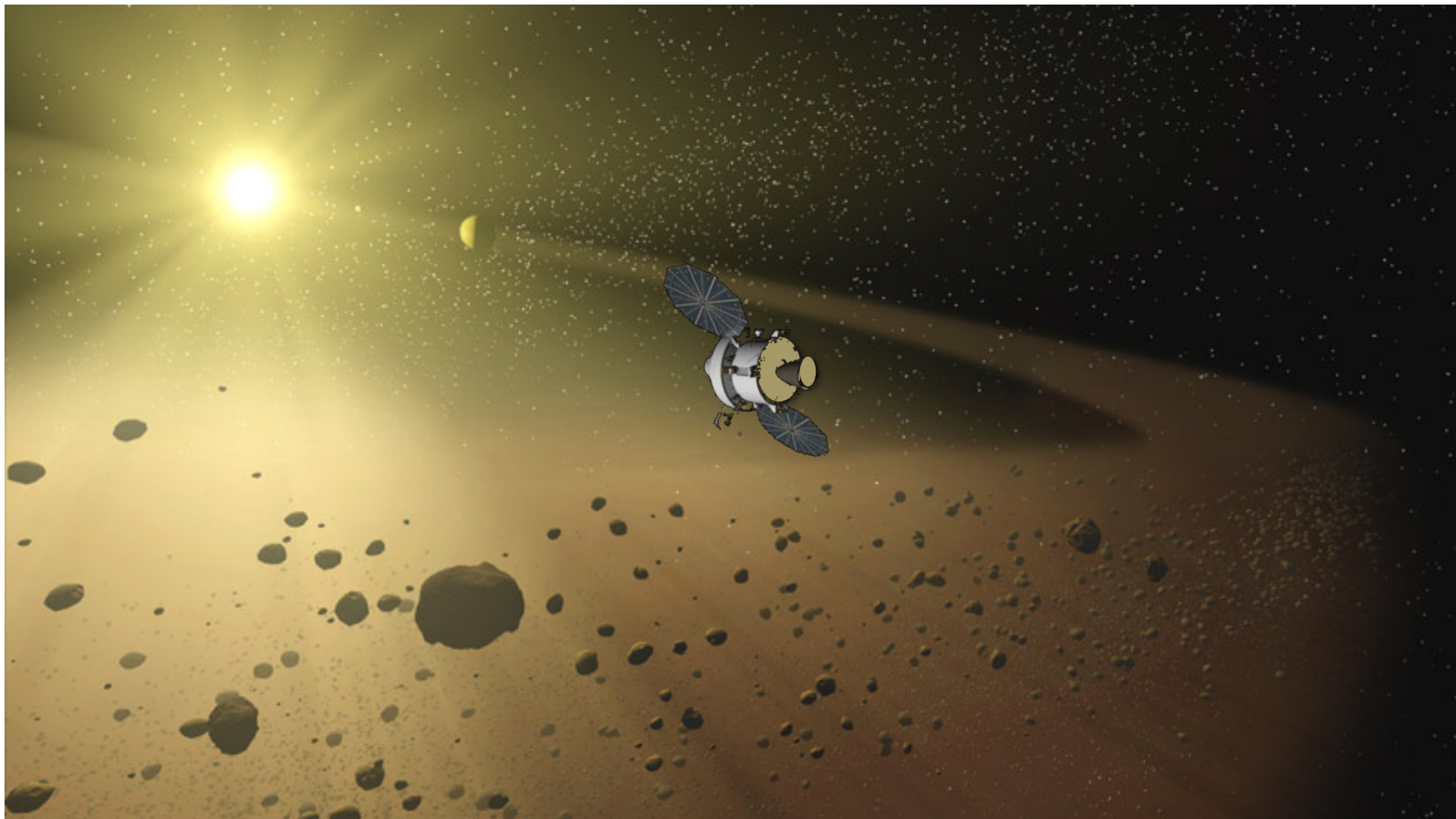
Talk Organization

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



Introduction

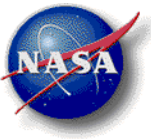
How will NASA *operate* a crewed mission with a *long communication delay* between the spacecraft and Earth?



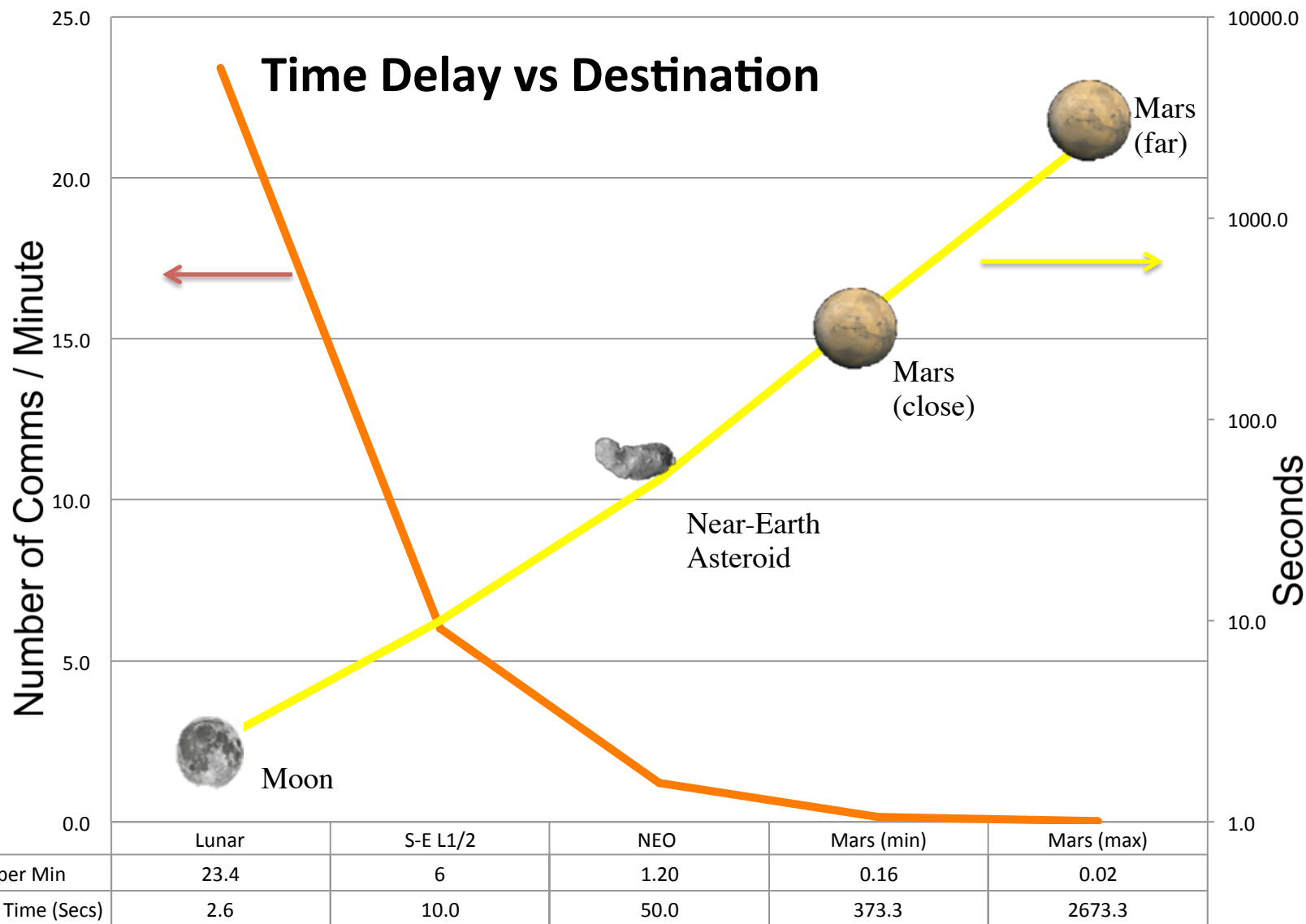
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QFT 1.0



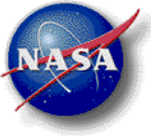
Introduction



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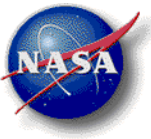
Mission Operations



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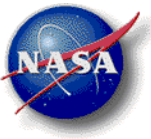
QFT 1.0



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)

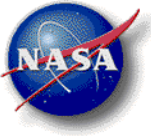




Mission Operations

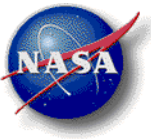
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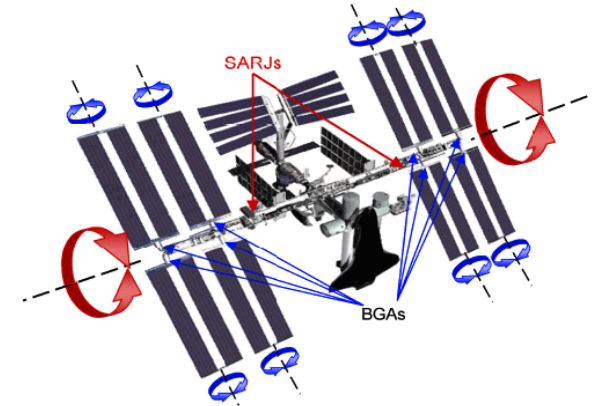
Planning and Scheduling

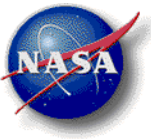
- Many different plans are built by different parts of the flight control team using disparate tools.
 - Crew plan
 - Power plan
 - Attitude plan
 - EVA plans
 - Procedures are plans too!
- Many plans are built and integrated by hand
 - There is some independence of these products, e.g. procedures can 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

The screenshot displays the Score software interface for mission planning. The main window shows a timeline for the period 2009-203, with a specific activity 'SSRMS-PMA3-MANEUVER' highlighted. The interface includes a project navigation pane on the left, a main timeline area with various activity bars, and a Plan Advisor window at the bottom right.

Score Project Navig

- LISA_STP16_WED
 - Conditions
 - References
 - Resources
 - schedule.plan
 - schedule.timeline
 - template.plan

***LISA_STP16_WED:156-157**

Wed 07/22/09 03:00:00 Crew_Activity SSRMS-PMA3-MANEUVER
Wed 07/22/09 04:00:00 60 minutes 20 minutes from selection

GMT 2009-203 10:49

References - CrewMember

Resource	Activity	Start Time	End Time
FE-1	CBM-PMA	08:00	10:00
FE-1	CBM-N	12:00	14:00
FE-1	EXERCISE-RED	16:00	18:00
ISS CDR	EXERCISE	08:00	10:00
FE-2	EXERCISE	08:00	10:00
FE-3	EXERCISE	08:00	10:00
FE-4	SSRM	12:00	14:00
FE-5	SSRM	12:00	14:00

Conditions

- ALL_S_AVAIL_avail True
- ALL_KU_AVAIL_avail True
- SR_avail True
- DAILY_ORB_NUM_avail 15

References - Event

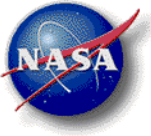
- <BLANK>

Plan Advisor

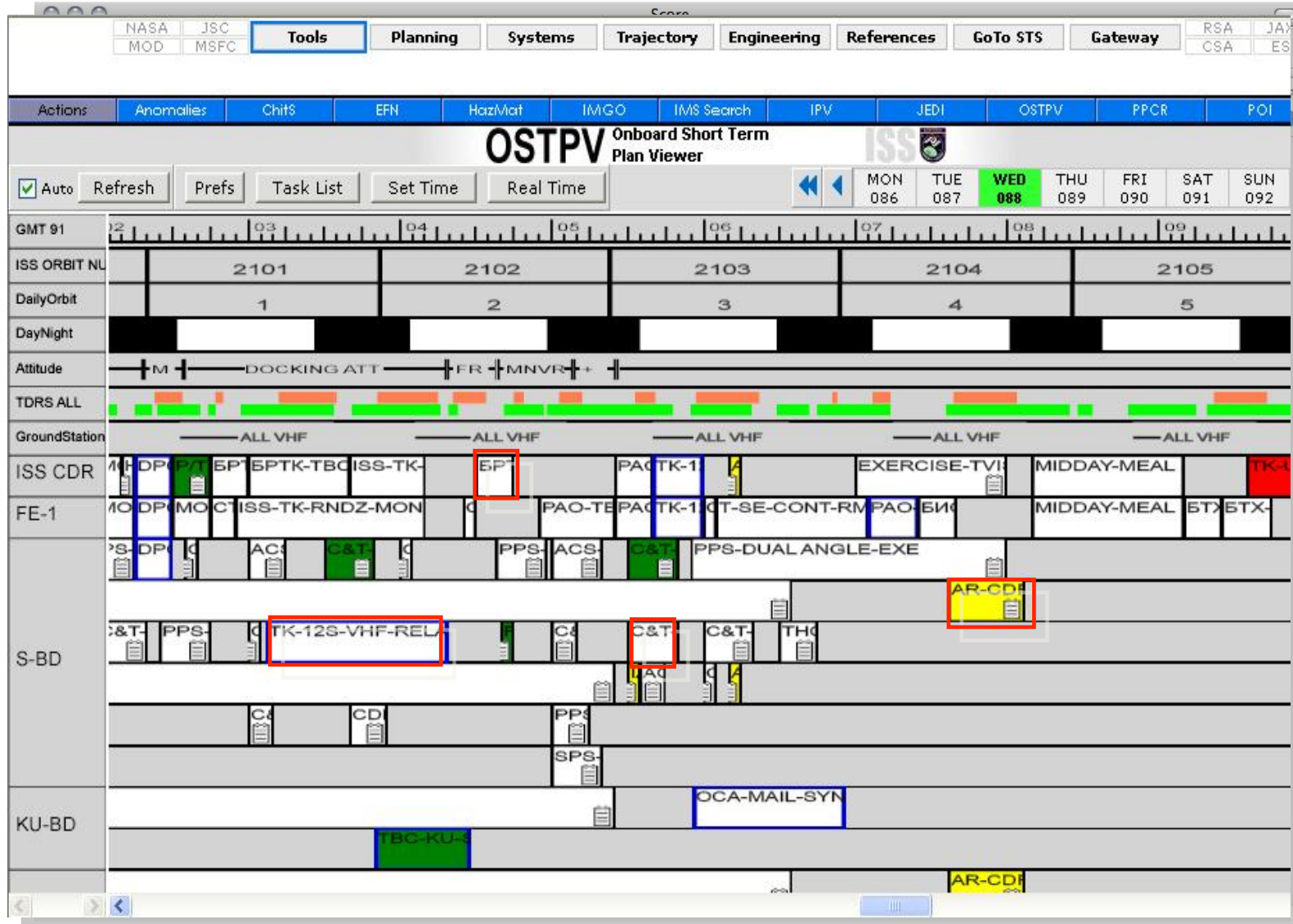
2 unfixed

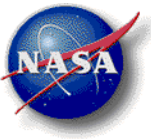
Violations	Description	Participants	Context	Time	Type	Statu
Resource Profile (1/1)						
CREW_MEMBER_FE_4	is 2 at 2009-203 10:20 (max = 1)	SSRMS-PMA3-MANEU	LISA_STP16_W	2009-203 10:20	Resource Prof	tru
Temporal (1/1)						
Endpoint	Invalid START	Crew Activity	NUTR/REP-FE	2009-203 10:20	Temporal	tru

The start of Crew_Activity is 2009-203 10:20. It should be at 2009-203 09:40.



Planning and Scheduling

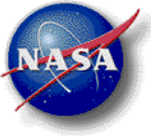




Planning and Scheduling

The screenshot displays the QFT 1.0 software interface, which is used for mission planning and scheduling. The interface is divided into several panels:

- Tools Panel:** Contains tabs for NASA, JSC, MOD, MSFC, Tools, Planning, Systems, Trajectory, Engineering, References, GoTo STS, Gateway, RSA, JAX, CSA, and ES.
- Actions Panel:** Contains tabs for Anomalies, ChitS, EFN, HazMat, IMGO, IMS Search, IPV, JEDI, OSTPV, PPCR, and POI.
- Overview Panel:** Shows a high-level flowchart of the procedure. It includes a 'Zoom Level' slider and a 'Return to Default Zoom' button.
- Procedure Panel:** Displays a detailed flowchart for the 'EPS Advisory' procedure. The steps are:
 - Check if DC control voltage is out of range. P6: EPS: DCSU 2B(4B) DCSU 2B(4B) 'Power Supply'. Is 'out of range' flag set? If No, proceed to step 2. If Yes, proceed to step 3.
 - DC Control power to CSU is not lost. Non-trip anomaly advisory caused by another problem.
 - Check if CP RBI is open. P6: EPS: DCSU 2B(4B) DCSU 2B(4B) 'BCDU 4B2(2B2) CP RBI'. Is CP RBI open? If No, proceed to step 7. If Yes, proceed to step 18.
 - Check to see if there is a good voltage at the CP RBI. BCDU 4B2(2B2) CP
- Right Panel:** Shows a timeline with 'SAT 091' and 'SUN 092' at the top, and a scale from 09 to 2105. Below the scale are various status indicators and labels like 'ALL VHF', 'TKA', 'BTX', and 'AR-CDI'.



Planning and Scheduling

Tools Planning Systems Trajectory Engineering References GoTo STS Gateway

MCC FLIGHT NOTE - F031243U.mht

New Open Save Print Undo Redo Format Tables Columns Show Navigation Gallery Toolbox Zoom Help

Document Elements Quick Tables Charts SmartArt Graphics WordArt

POI

SUN 092

The array plan assumes the following:

- 17A ATL Last Updated: GMT 249/20:39
- 17A Flight SACM CHIT 7698 (SACM for PRCS events is in CHIT 7718)
- 17A ODS depress will be performed with desats
- 17A undock will happen while in +Xv and PRCS will be used to mnvr
- 17A August 28th Launch Date (late night)
- Water Dump is no longer happening on 17A

Latest Changes are in Red.

17A Solar Array Plan

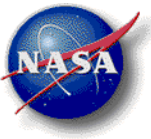
Comment	Nominal config following CMG MM	PPL ps26 ps28 13_15 Post SARJ Auto Sched SARJ 45 1A Auto 1B Auto 2A Auto 2B Auto 3A Auto 3B Auto 4A Auto 4B Auto	(SACM from CHIT 7698)
251/01:29	FD11 ODS DEPRESS Feather SARJs Timed with start of CMG MM maneuver	PPL ps26 ps28 13_15 Post SARJ 270 (L) Sched SARJ 90 (L) 1A Auto 1B Auto 2A Auto 2B Auto 3A Auto 3B Auto 4A Auto 4B Auto	Peak and lock SARJs BGAs can remain in auto SARJ on target (270 at 01:29) Times from FN 46480 (SACM from CHIT 7718 for ODS depress with desats enabled)
251/08:30	FD11 ODS DEPRESS Unlock SARJs	PPL ps26 ps28 13_15 Post SARJ 270 Sched SARJ 90 1A Auto 1B Auto 2A Auto 2B Auto 3A Auto 3B Auto 4A Auto 4B Auto	Feather after desats inhibited
251/09:07	Nominal config following CMG MM Timed with start of CMG MM maneuver	PPL ps26 ps28 13_15 Post SARJ Auto Sched SARJ 45 1A Auto 1B Auto 2A Auto 2B Auto 3A Auto 3B Auto 4A Auto 4B Auto	Times from FN 46480. Other possible return to auto times: 6:03; 7:33 (SACM from CHIT 7718 for ODS depress with desats enabled)
251/16:20	FD12 UNDOCK Feather and Lock SARJs Return to Nominal	PPL ps26 ps28 13_15 Post SARJ 120 (L) Sched SARJ 240 (L) 1A Auto 1B Auto 2A Auto	Peak & Lock SARJs BGAs can be in auto for PRCS manue to +xv (SACM from CHIT 7718. PRCS undock in +Xv)



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Planning and Scheduling

NASA JSC Tools Planning Systems Trajectory Engineering References GoTo STS Gateway

MOD MSFC

MCC FLIGHT NOTE - F031243U.mht

New Open Save Print Undo Redo Format

100%

POI

SUN 092

TKA

TX

MO

The array plan assumes the following:
 - 17A ATL Last Updated: GMT 249/24
 - 17A Flight SACM CHIT 7698 (SACM)
 - 17A ODS depress will be performed
 - 17A undock will happen while in +X
 - 17A August 28th Launch Date (late)
 - Water Dump is no longer happening

Latest Changes are in Red.

#	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

2A Auto

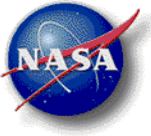
redef in +Xxx



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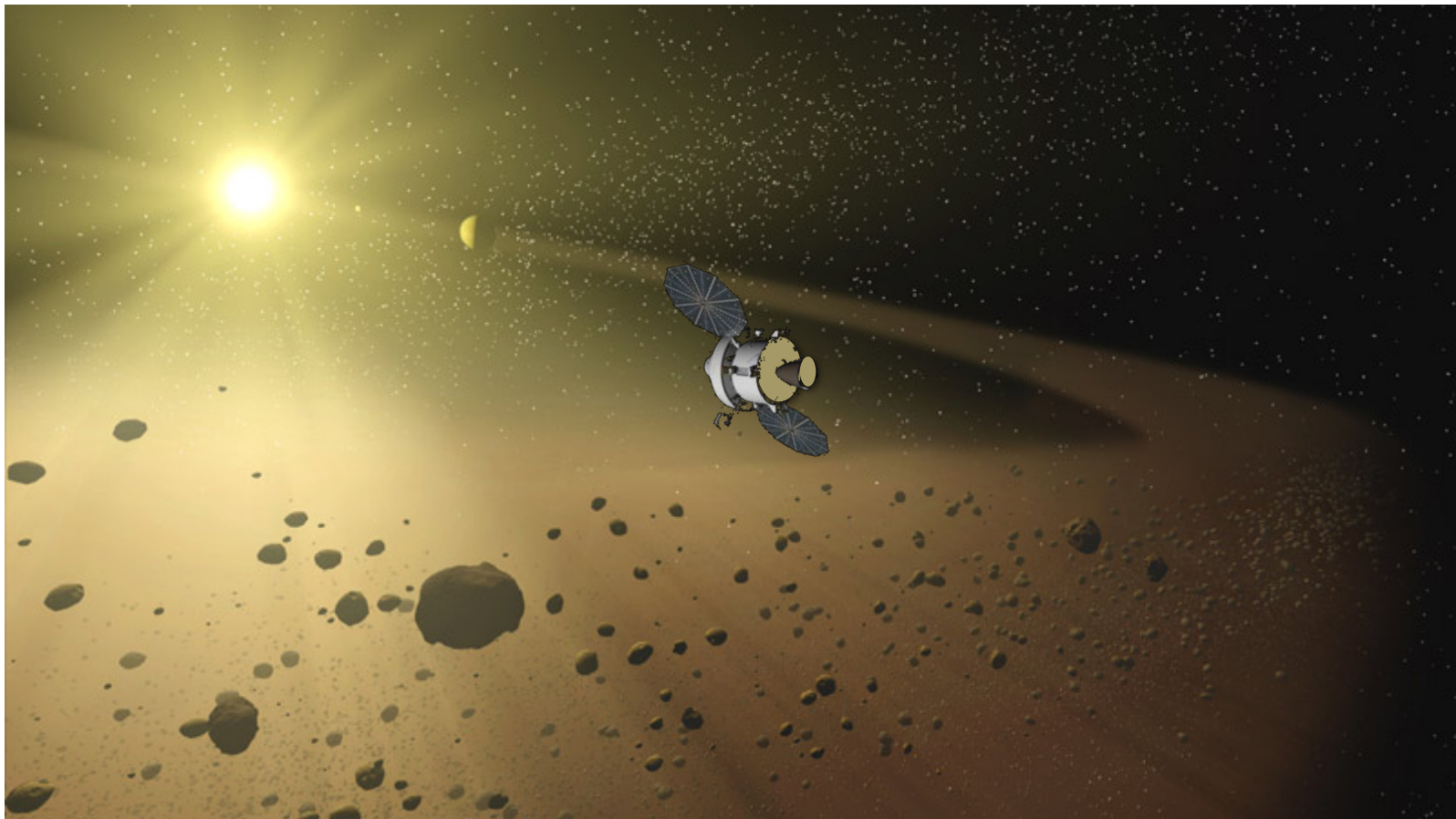


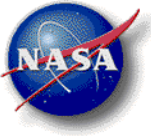
QFT 1.0



Planning and Scheduling

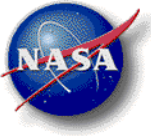
How will NASA *plan and schedule* a crewed mission with a *long communication delay* between the spacecraft and Earth?





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



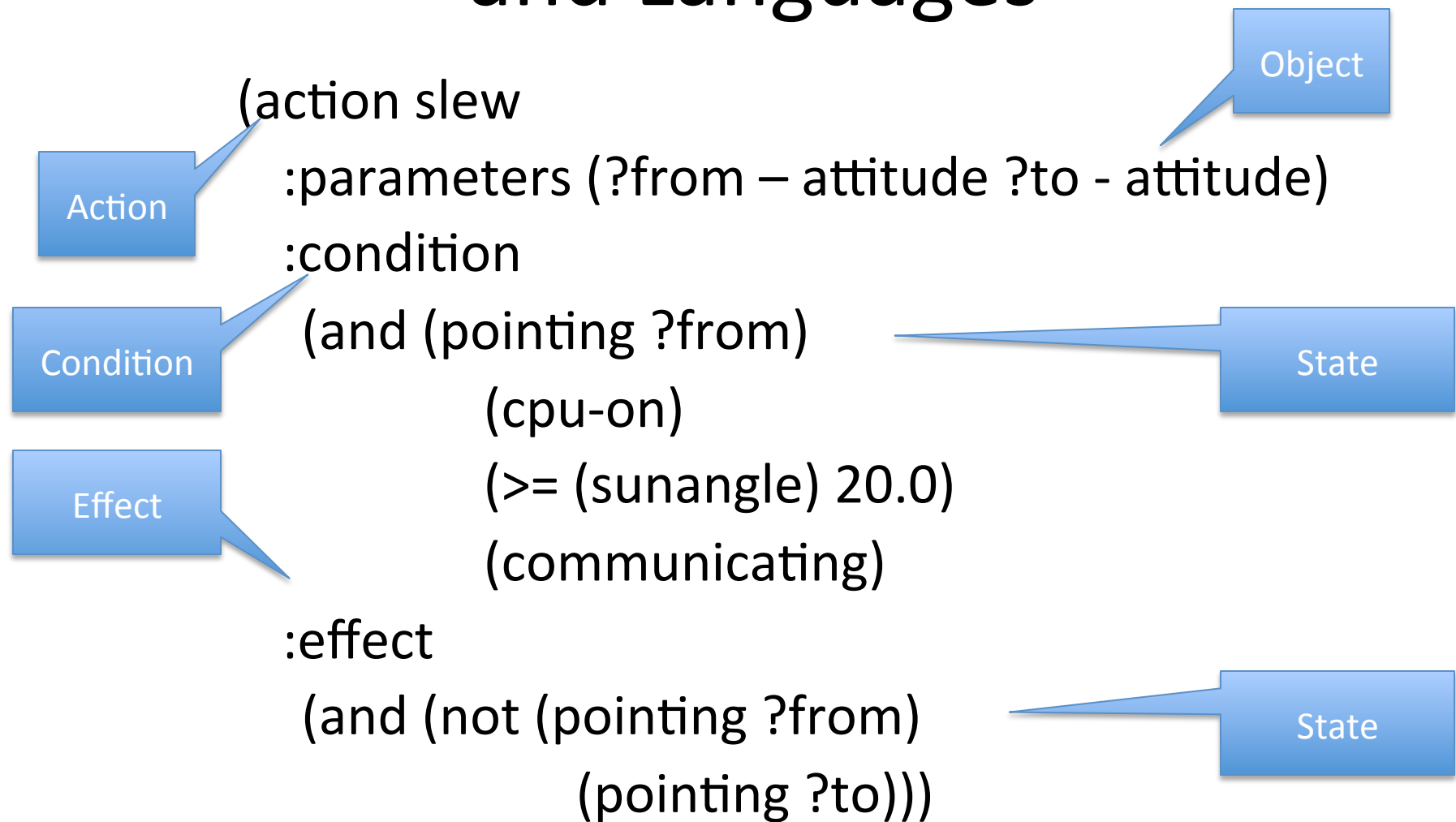
Model Based Planning and Languages

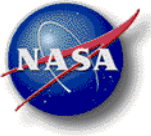


- Model elements in more detail
 - Objects – things in the world
 - E.g. targets, spacecraft components
 - States – properties of the world
 - E.g. available power, mode of system
 - Actions
 - Conditions – what must be true for an action to have the desired effect
 - Effects – what changes when the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



Model Based Planning and Languages

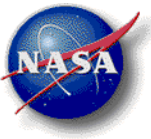




Model Based Planning and Languages



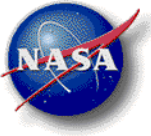
- Planning vs Scheduling
 - Scheduling is the ordering of a given set of tasks in order to satisfy constraints.
 - Planning is the selection of operators to transform the world from one state to another while satisfying constraints.
- Scheduling is NP-complete
- Planning is:
 - Undecidable (in general)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



Quantum Computing for Mission Operations

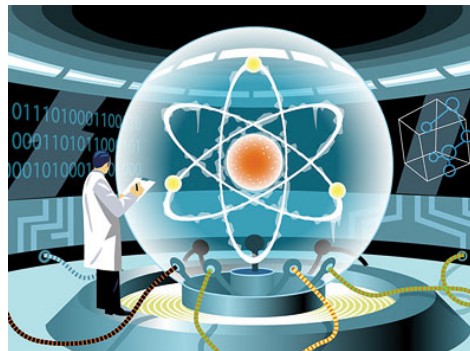


- To summarize:
 - Planning and scheduling is hard
 - Either the crew or automated systems may be forced to do more planning and scheduling for future missions
- The use of quantum algorithms and computers can reduce the time to build and manage the mission plan:
 - Assist crew in planning nominal mission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



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.

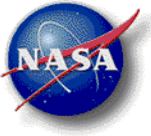


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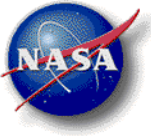
QFT 1.0



Quantum Computing for Mission Operations

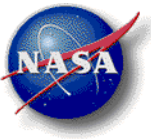


- Pros: enabling crew autonomy
 - Fast
 - Responsive to faults / failures
 - eliminating risk due to communication delay
- Cons
 - Mass, size, power of quantum hardware?
 - Susceptibility to space environment? (Thermal, radiation)
 - Programmability? (complex translation of planning to many bits, esp.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

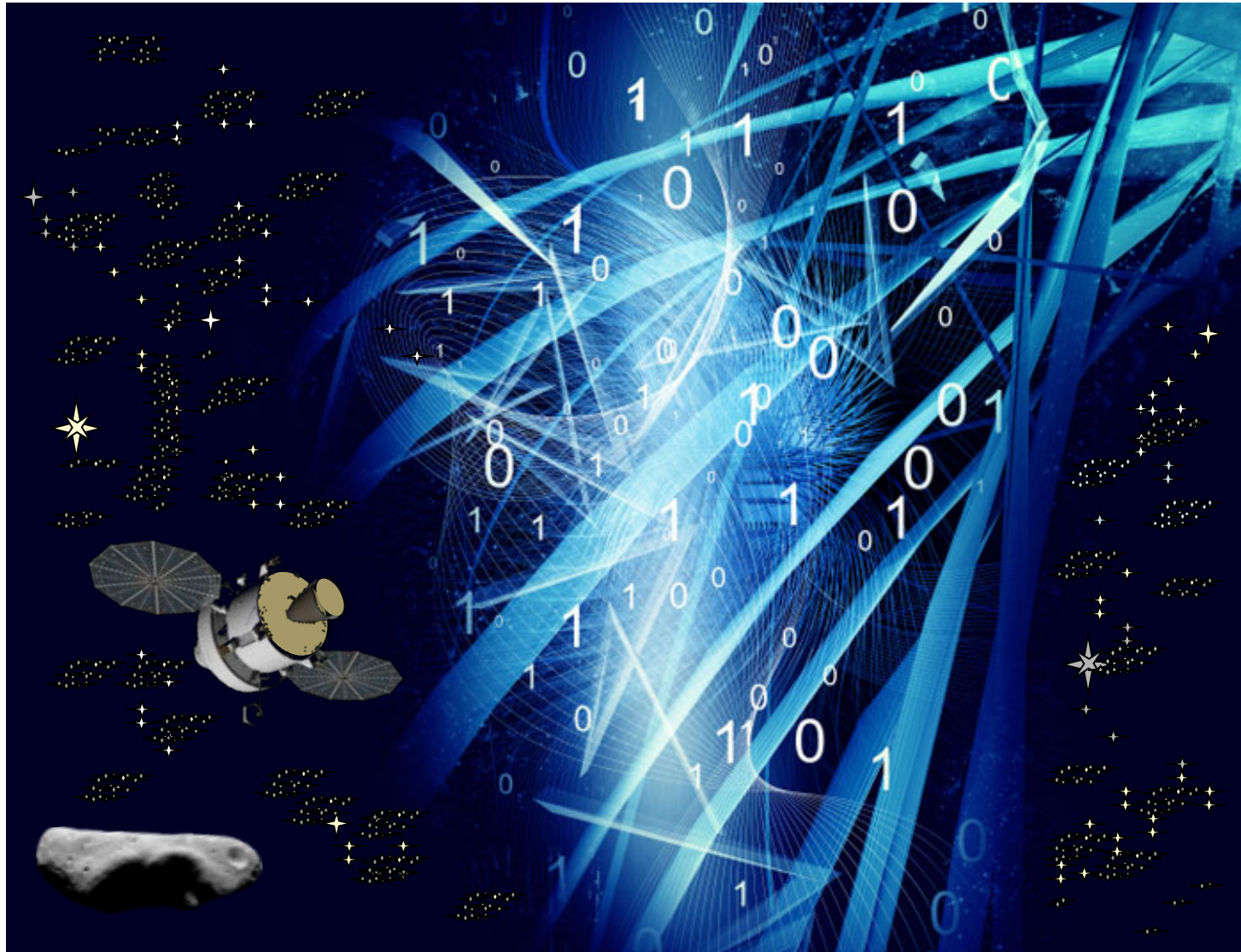


Summary

- 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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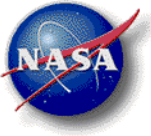


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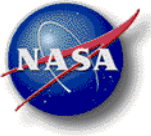


References

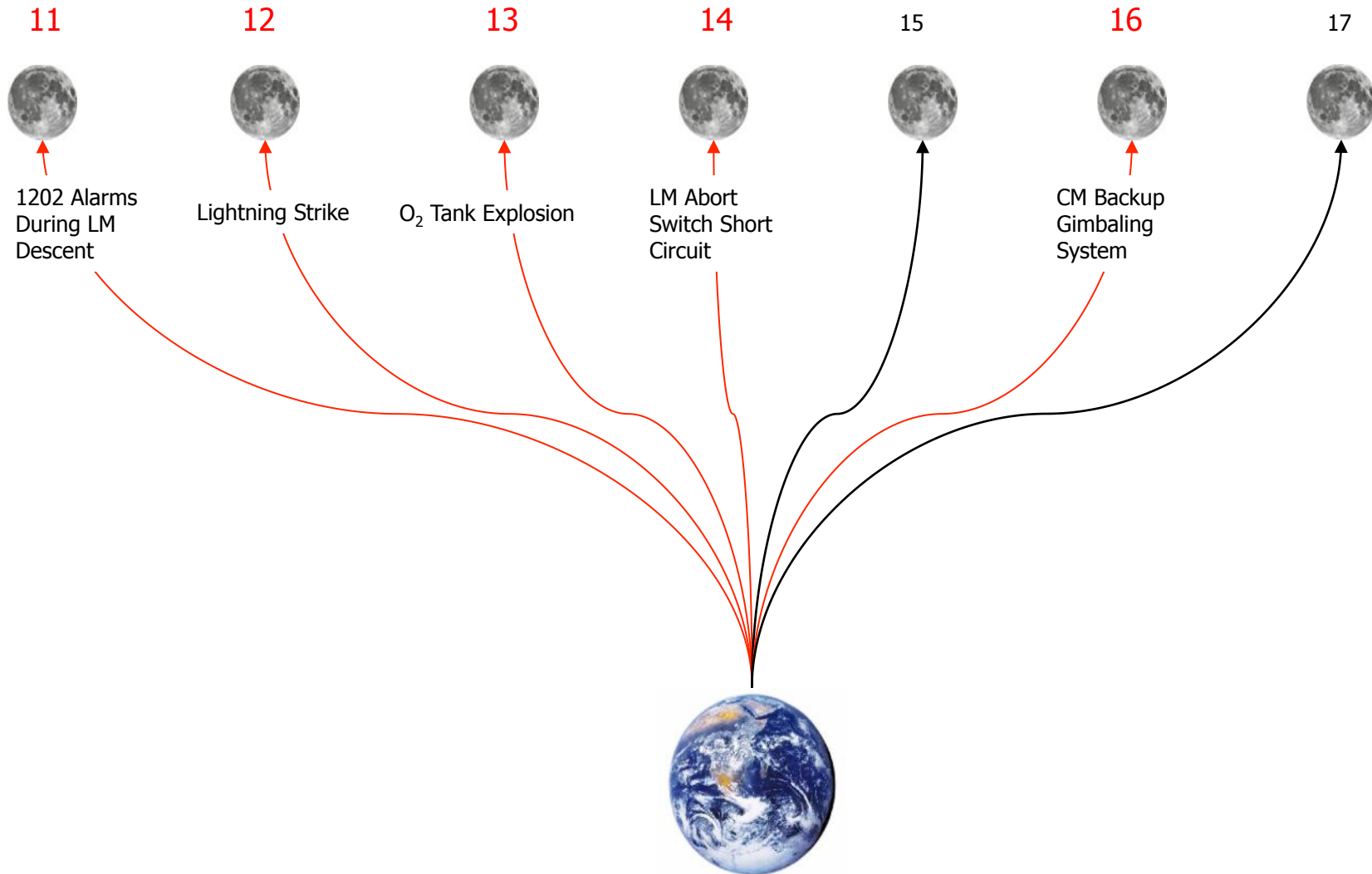
- M. Ghallab, D. Nau, P. Traverso. Automated Planning: Theory and Practice. Morgan Kaufman, 2004.
- M. R. Garey, D. Johnson. Computers and Intractability. W. H. Freeman, 1979.
- D. Smith, J. Frank, A. Jónsson. *Bridging the Gap Between Planning and Scheduling*. Knowledge Engineering Review, Special Issue on Artificial Intelligence and Operations Research. Volume 15, no. 1, 2000.
- J. Frank. *When Plans are Executed By Mice and Men*. Proceedings of the IEEE Aerospace Conference, 2010.
- S. Y. Reddy and J. D. Frank, M. J. Iatauro, M. E. Boyce, E. Kurklu, M. Ai Chang and A. K. Jonsson. *Planning Solar Array Operations on the International Space Station*. Special Issue on Applications of Automated Planning, ACM Transactions on Intelligent Systems and Technology vol. 2 no. 4, July 2011.
- (A survey of applications of QC is in preparation.)



BACKUP



Integrated Systems Health Management (ISHM)

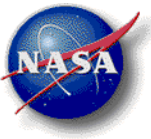


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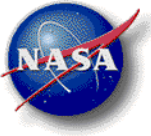
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Integrated Systems Health Management (ISHM)



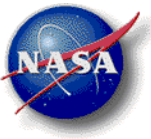
- When problems occur:
 - Fault detection, isolation, and recovery must take place.
 - Detection is often not difficult. Isolation, however, can be.
 - Immediate recovery (safing) is also often not difficult. Longer term recovery requires planning, which we have already seen, can be.



Quantum Computing for Mission Operations

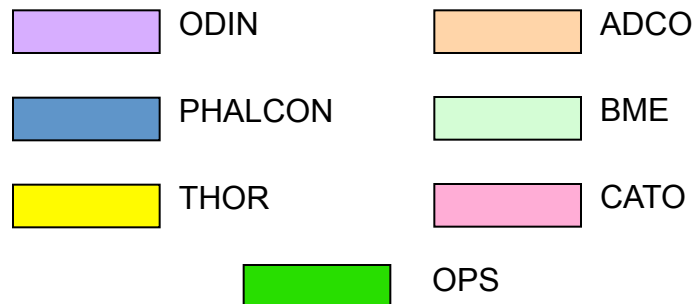


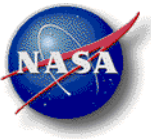
- ISHM
 - Some combinatorial problems for ISHM are similar to those of planning; QC for planning probably benefits ISHM with little modification.
- Communication
 - Can entanglement eliminate communication delays, as an alternative to crew autonomy?
 - Solution for space-communication security concerns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



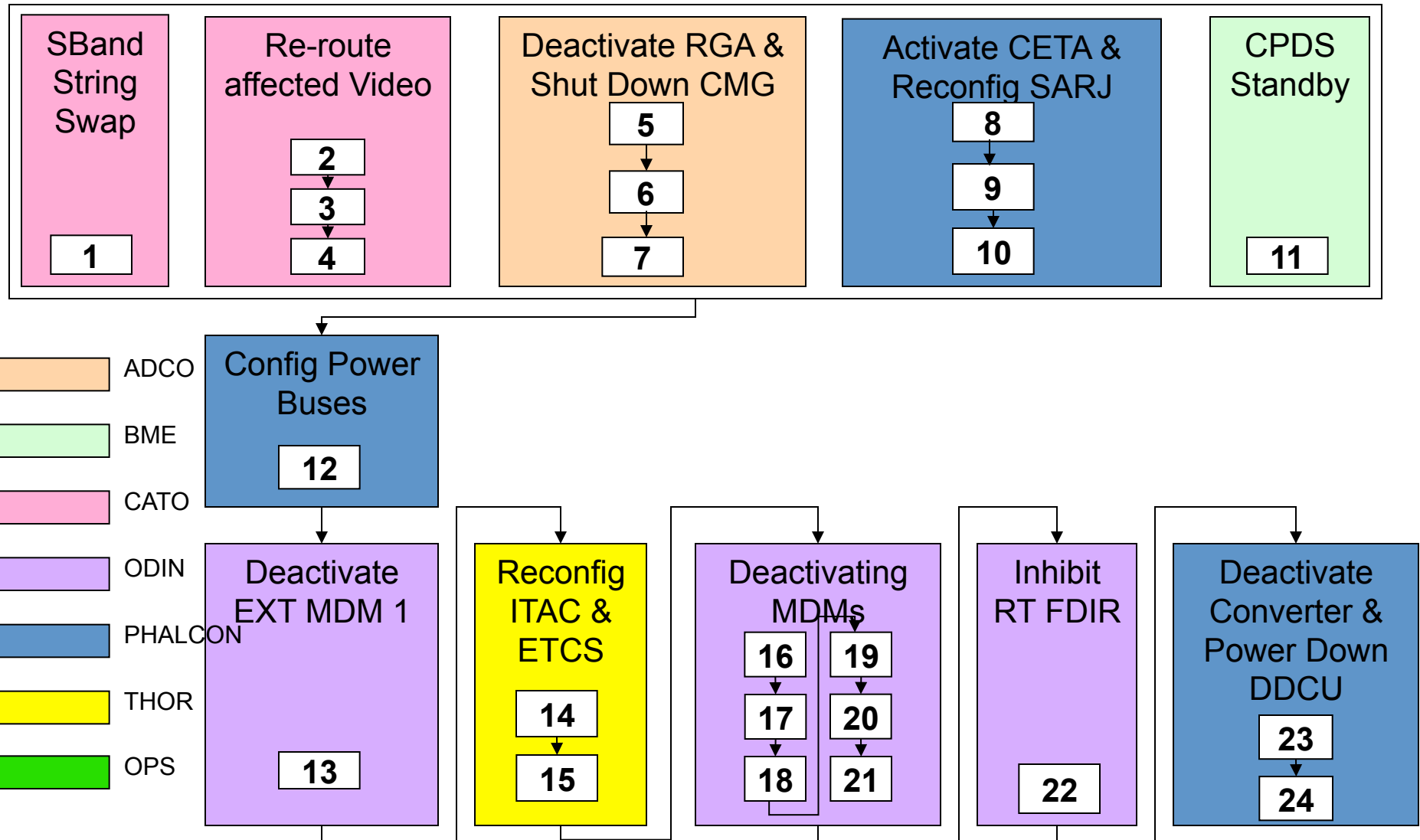
Planning and Scheduling

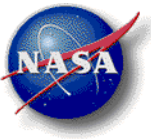
- **PHALCON** - Power Heating and Lighting Control Officer
 - “Owns” the procedure
- **ODIN** - Onboard Data Interfaces and Networks
- **BME** - Biomedical Flight Controller
- **THOR** - Thermal Operations and Resources
- **ADCO** - Attitude Determination and Control Officer
- **CATO** - Communications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



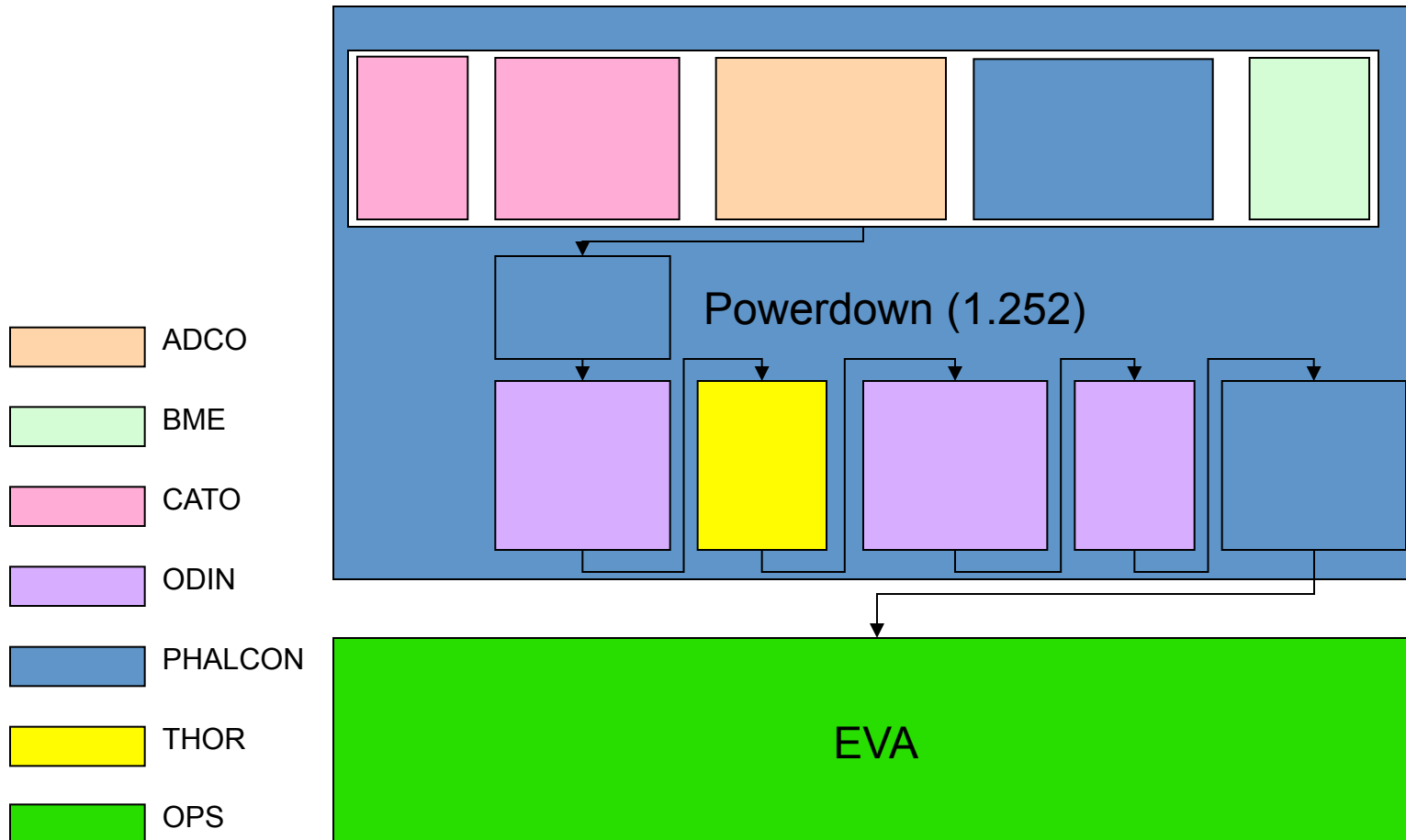


Planning and Scheduling





Planning and Scheduling





Computational Complexity (for dummies)



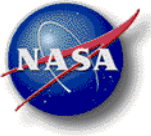
- Problem: a set of problem instances sharing some characteristics. (e.g. scheduling n tasks.)
- P : a class of problems whose solution can be calculated in polynomial time
- NP : a class of problems for which a proposed solution can be determined correct or incorrect in polynomial time
- $PSPACE$: a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



Computational Complexity (for dummies)

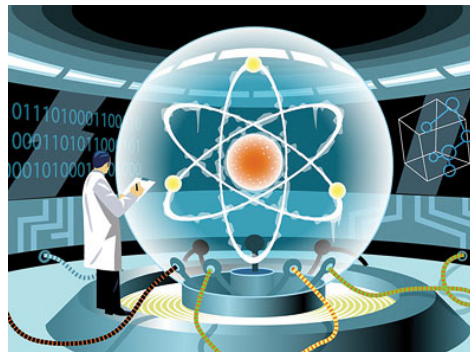


- Reduction: a transformation of a problem into another problem.
 - We only care about reductions that take polynomial time.
- *NP*-Hard: a problem P for which every other *NP* problem Q can be reduced to P .
- *NP*-Complete: an *NP*-Hard problem that is also in *NP*.



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.

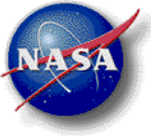


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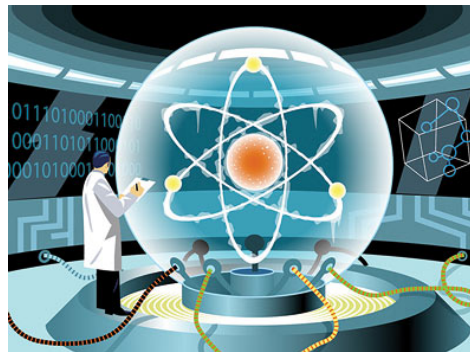
QFT 1.0



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).



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