Agile Science Operations

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Machine Learning and Instrument Autonomy

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Engineering Resilient Space Systems

Keck Institute Study, July 31 2012.

A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Image: Hartley 2 (EPOXI), NASA/JPL/UMD

Agenda

Motivation: science at primitive bodies

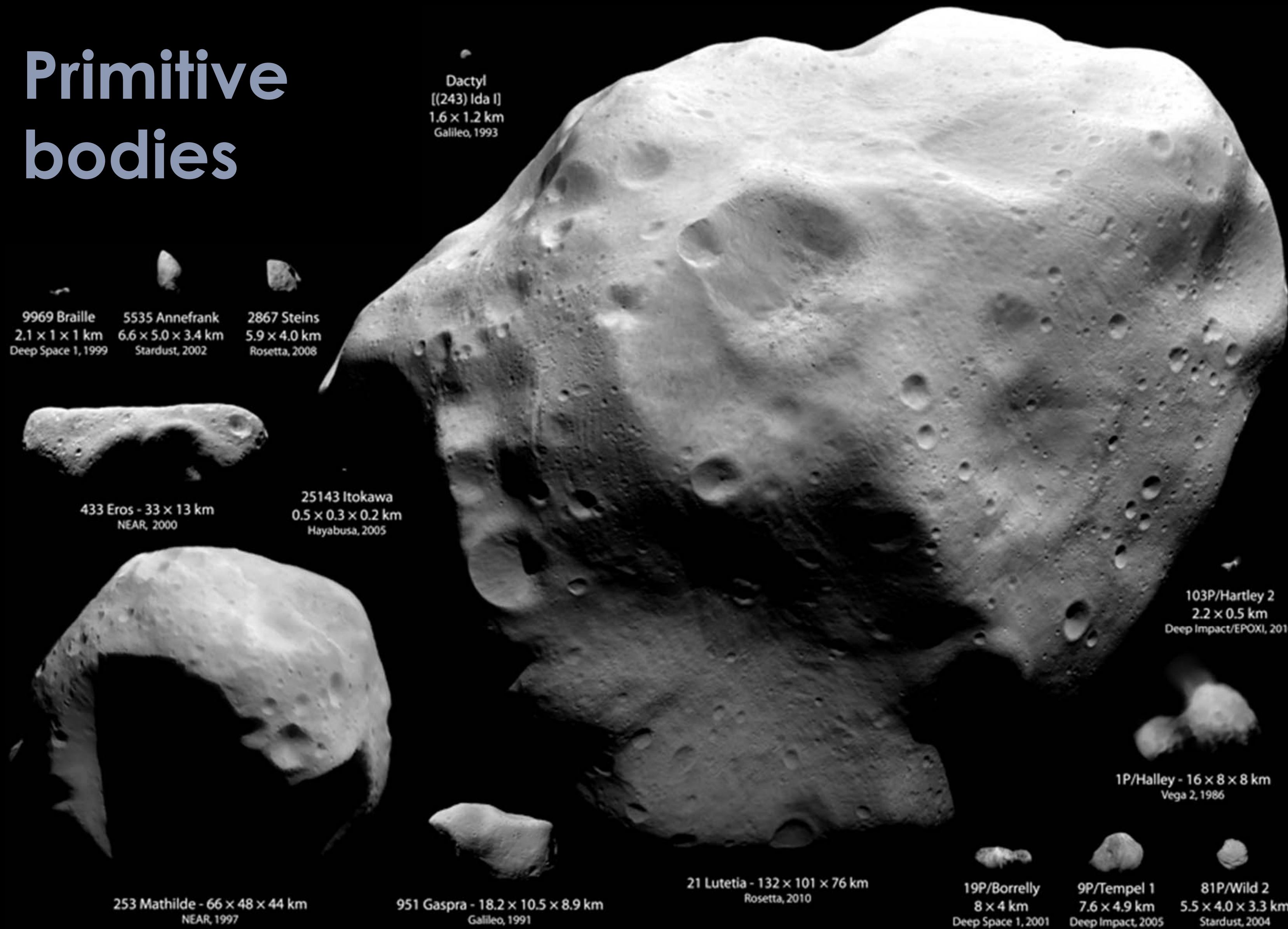
Critical Path Analysis and reaction time

A survey of onboard science data analysis

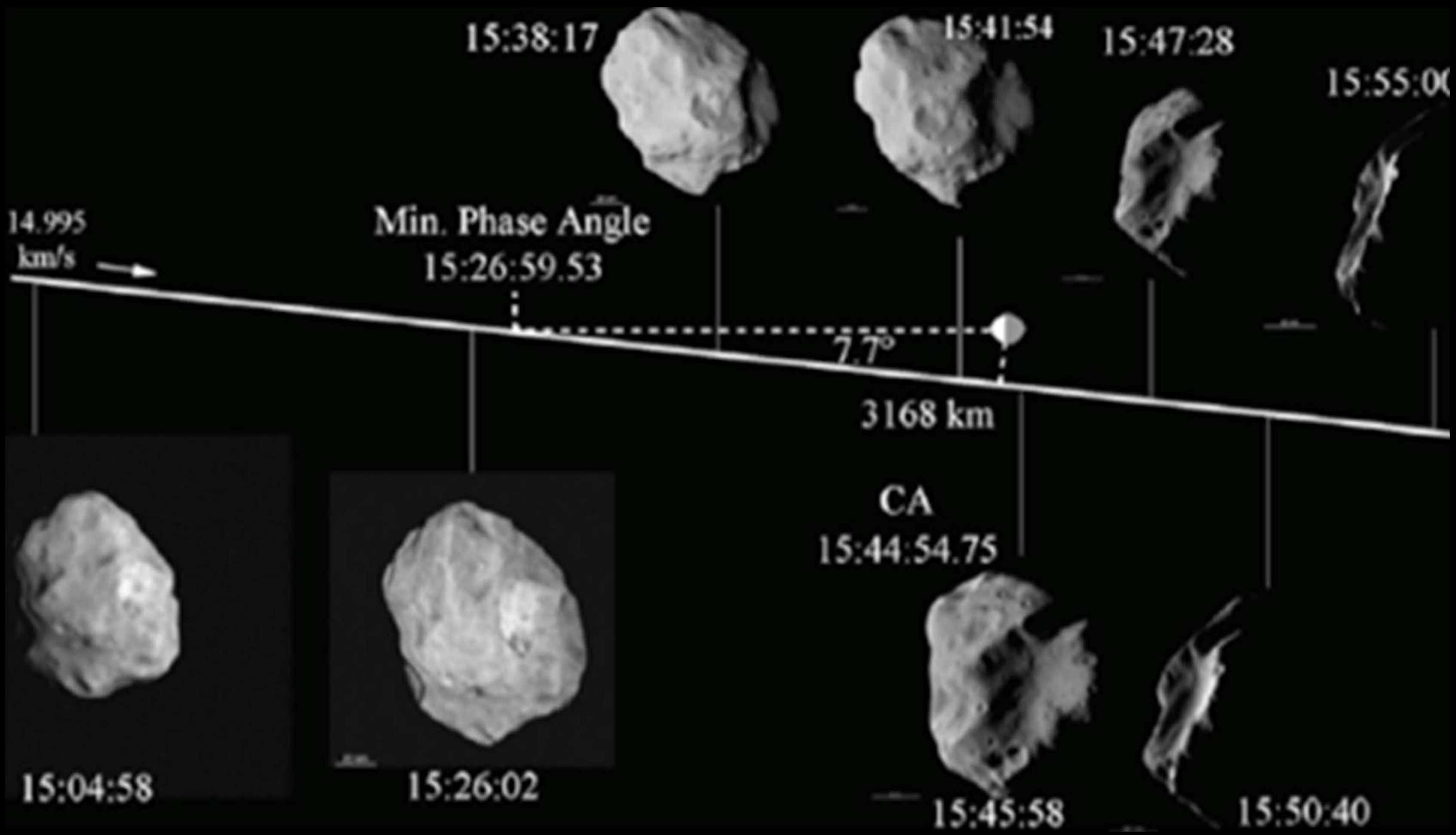
Case study – how could onboard data analysis impact missions?

Image: Hartley 2 (EPOXI), NASA/JPL/UMD

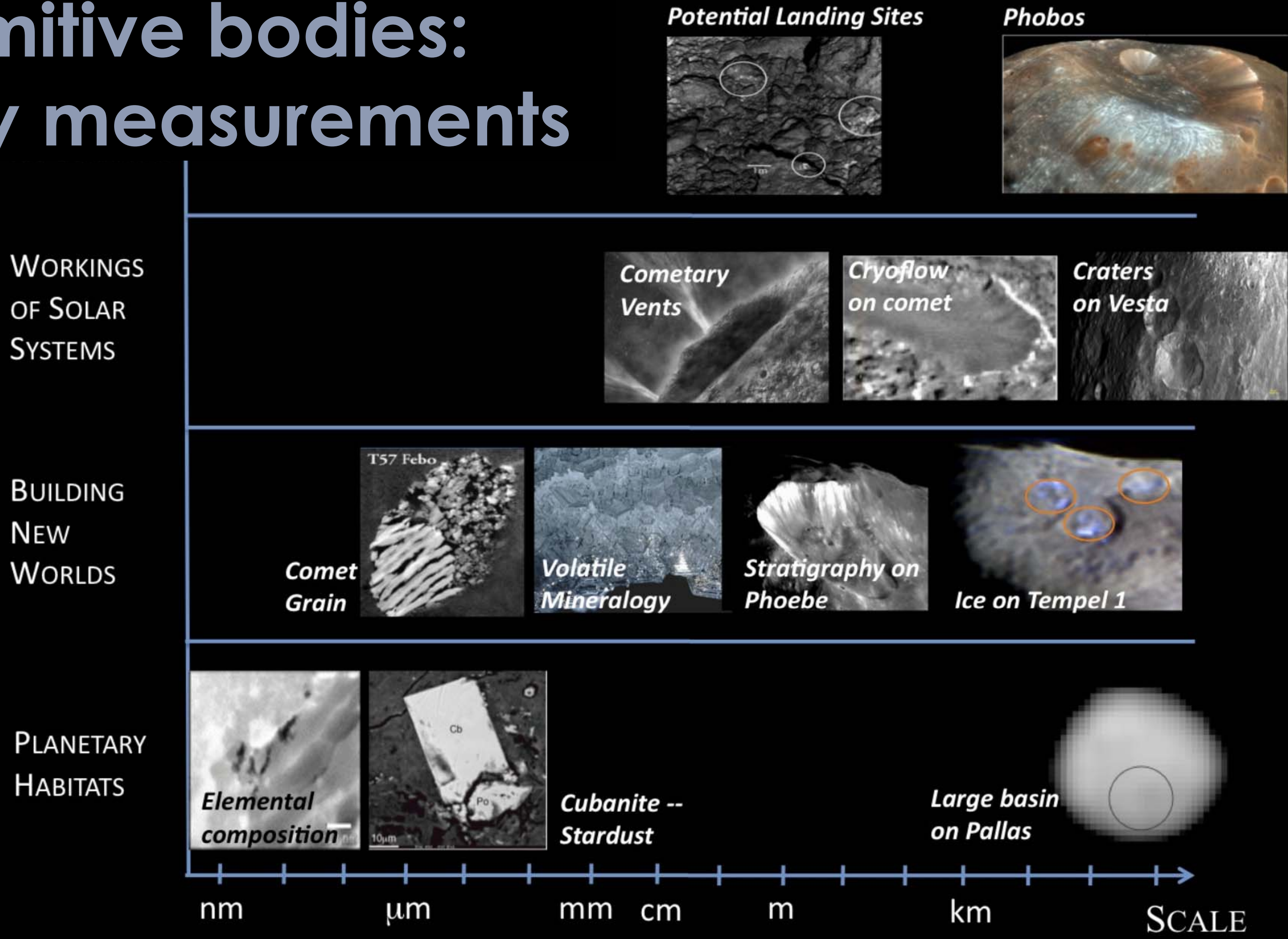
Primitive bodies



Typical encounter (Lutetia 21, *Rosetta*)

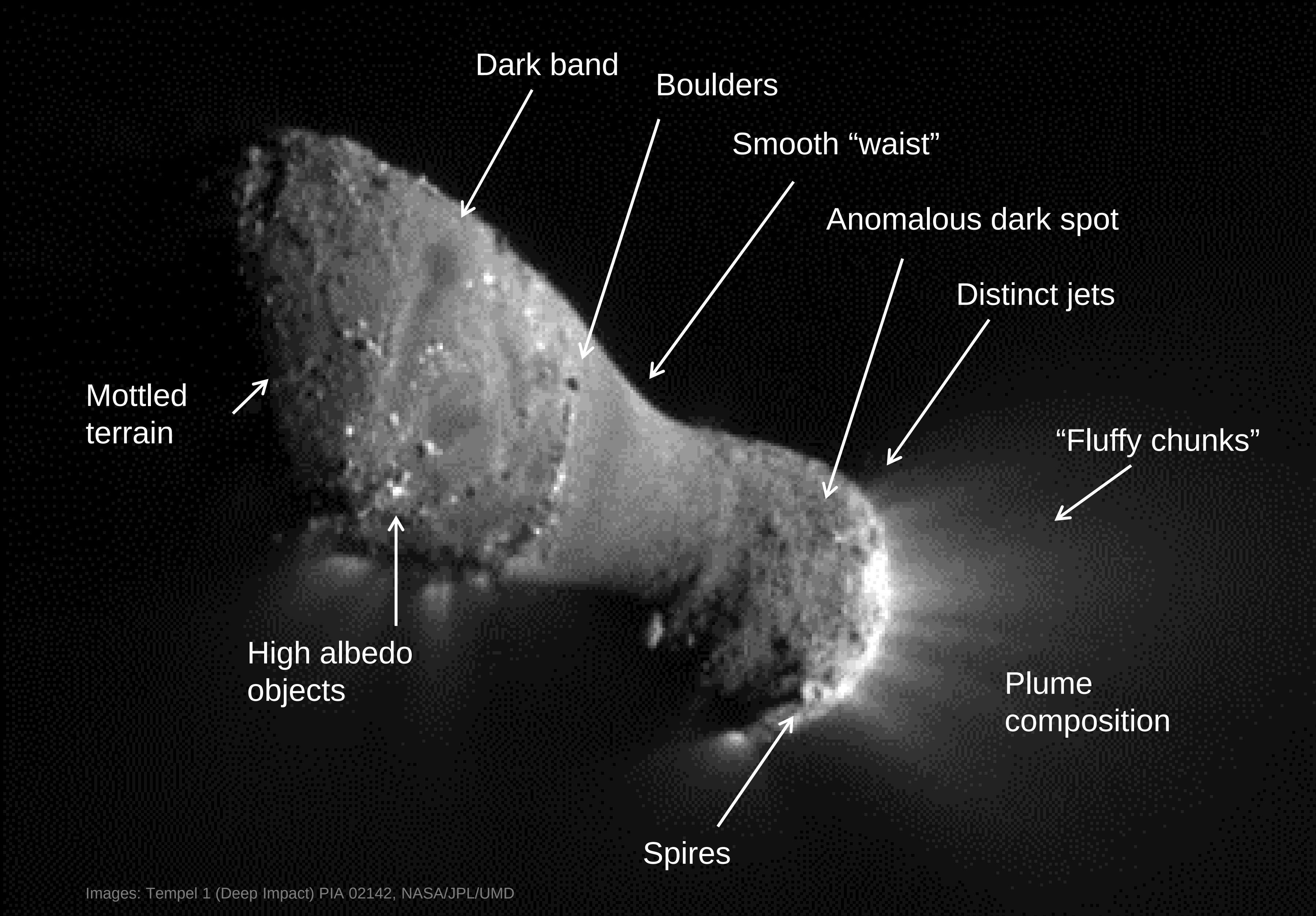


Primitive bodies: key measurements



Reproduced from Castillo-Rogez, Pavone, Nesnas, Hoffman, "Expected Science Return of Spatially-Extended In-Situ Exploration at Small Solar System Bodies," *IEEE Aerospace* 2012.

A short exercise in science agility



Images: Tempel 1 (Deep Impact) PIA 02142, NASA/JPL/UMD

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Challenges for primitive bodies science

Limited bandwidth and intermittent communications

Closest approach may pass quickly (sub-hour timescales)

Target locations are not known in advance

Geometry and illumination constraints

Features of interest are highly localized

Surface activity is transient, time-variable

Images: Tempel 1 (Deep Impact) PIA 02142, NASA/JPL/UMD

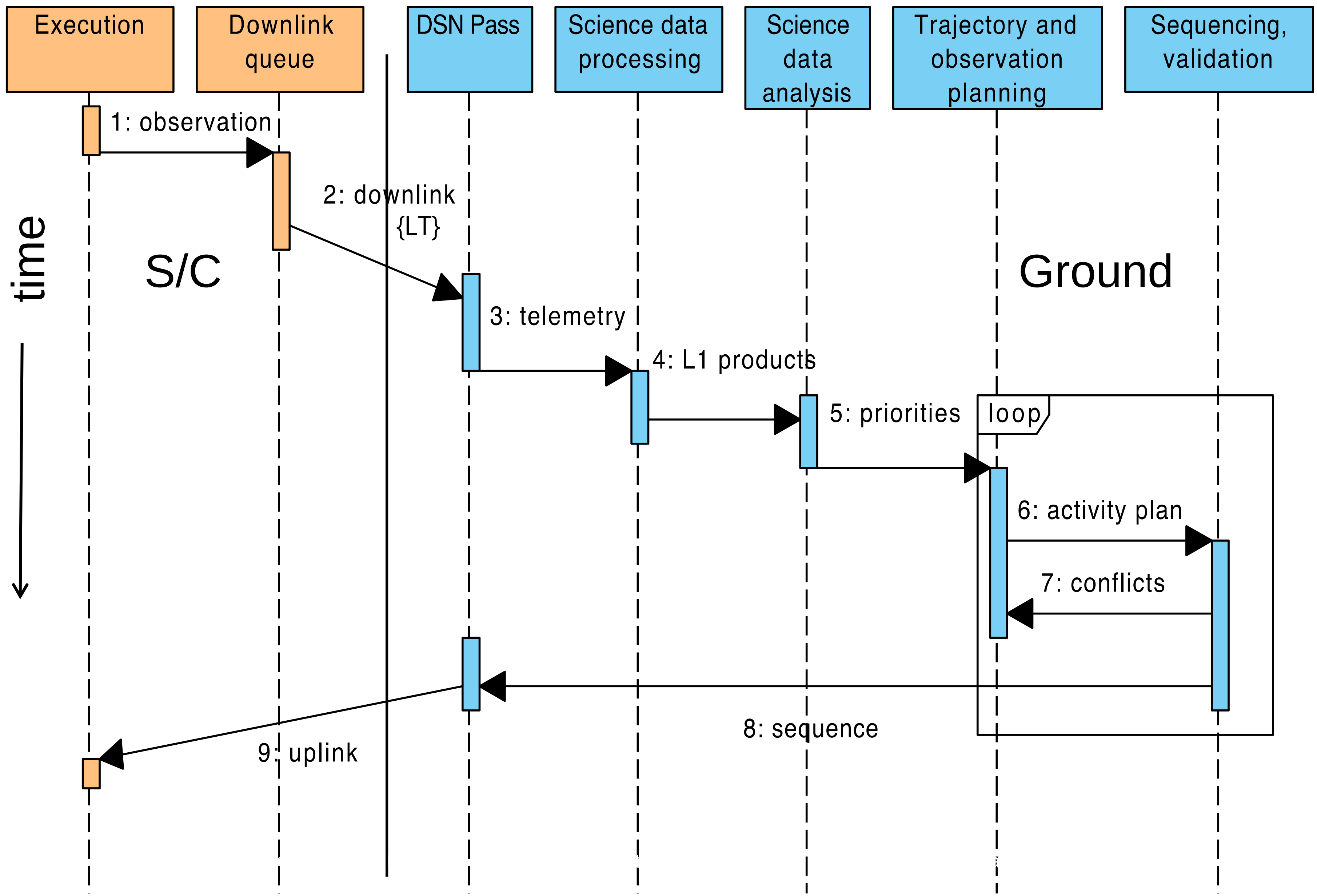
Reaction Time

The minimum time required for a new science measurement to affect spacecraft action.

Image: Hartley 2 (EPOXI), NASA/JPL/UMD

Critical path analysis

Thompson et al., SpaceOps 2012



Factors driving mission reaction time

	Certainty of prior schedule	Flexibility and Redundancy
EO-1 Earth Orbiting [Chien 2011]	High	High
Cassini Grand Tour [Paczkowski 2009]	High	Low
MER Rover [Mishkin 2006]	Low	High
Rosetta Comet Encounter [Kochny 2007]	Low	Low

Image: Hartley 2 (EPOXI), NASA/JPL/UMD

Representative command cycles

	Light time delay	DSN Pass	Science data analysis	Trajectory Generation	Activity Planning	Sequencing / Validation	Reaction time
EO-1 Earth Orbiting [Chien 2011]	-	1-2d	1-2d	-	7d	-	6-20d
Cassini Grand Tour [Paczkowski 2009]	1.25h	~9h	-	-	70d	70d	>140d
MER Rover [Mishkin 2006]	15m	23h	2-10h	~1h (driving)	5-7h	8-11h	23h
Rosetta Comet Encounter [Kochny 2007]	~1h	7d	Varies	~25d	4d	5d	14d (nominal)

Image: Hartley 2 (EPOXI), NASA/JPL/UMD

Challenge: rapid tactical operations for primitive bodies missions

- Get the most science from time-limited missions
- Achieve MER-style operational flexibility under deep space constraints
- Speed the “learning curve” to identify key science questions

Challenge: get the most science from time-limited missions

- Achieve MER-style operations agility under deep space constraints
- Enable time-domain science investigations
- Collect data from targets of opportunity
- Provide high-resolution targeted data during flybys
- Improve planning turnaround to speed the science “learning curve”
- Spring back from failures

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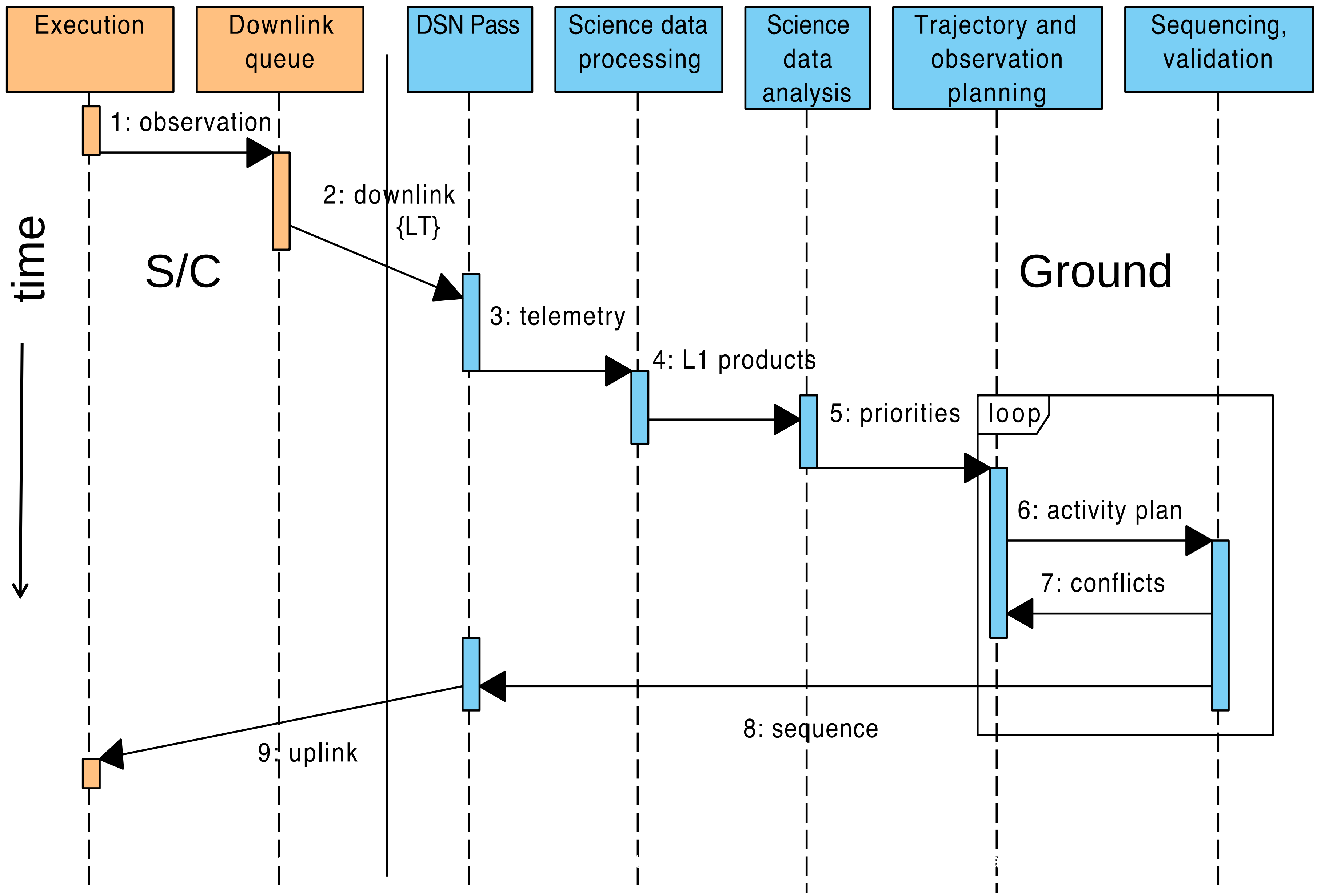
Critical Path Analysis and reaction time

A survey of onboard science data analysis

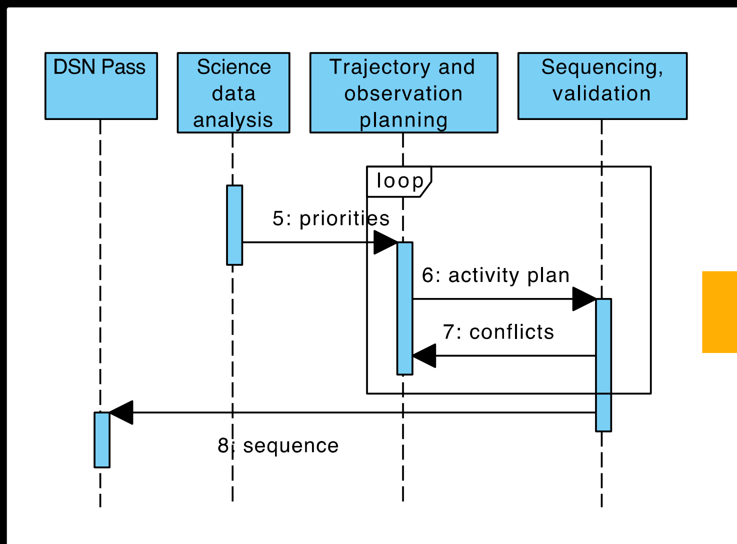
Case study – what could we do with onboard data analysis?

Image: Hartley 2 (EPOXI), NASA/JPL/UMD

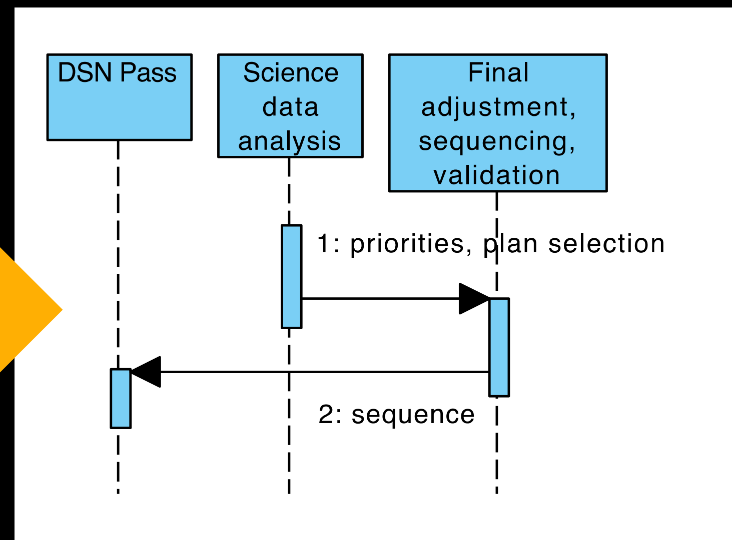
Where can we optimize?



Approach 1: Faster replanning cycle



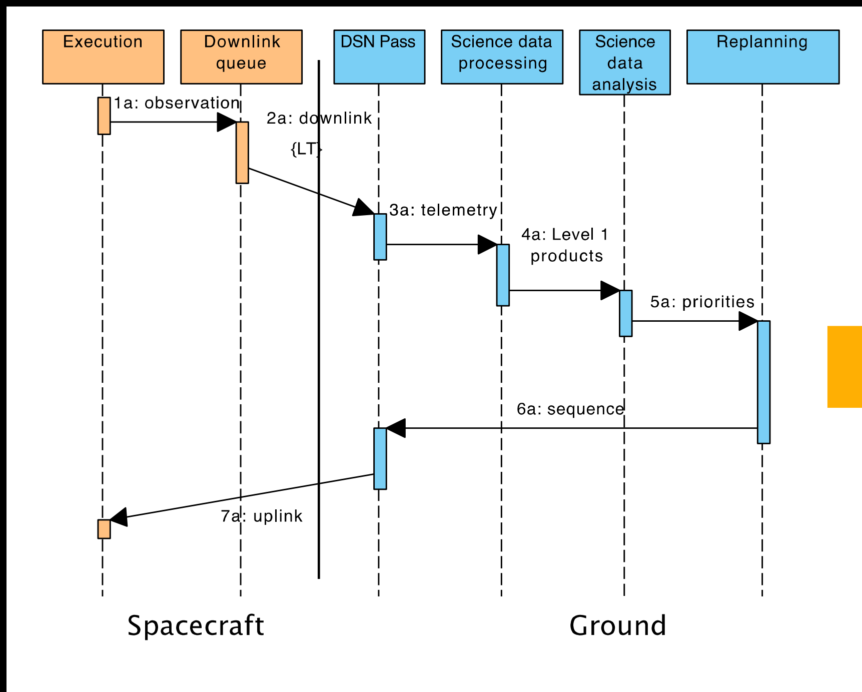
From this…



To this

- Contingency planning (maintain a pool of valid plans for different objectives)
- Expedited ground science data analysis, smart "quicklook" products

Approach 2: Onboard data analysis



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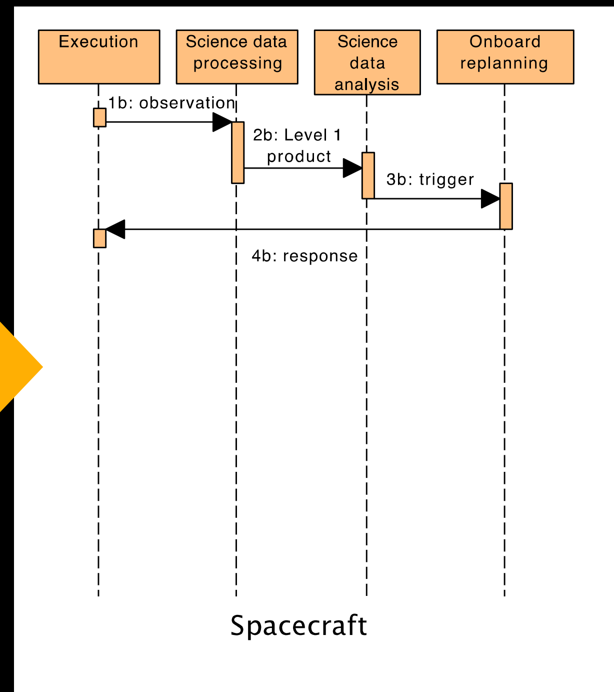
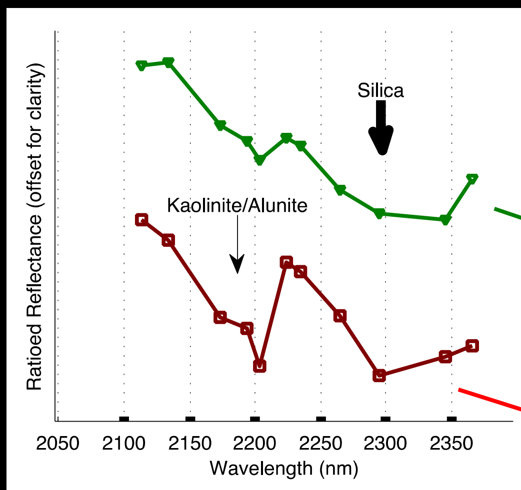


To this

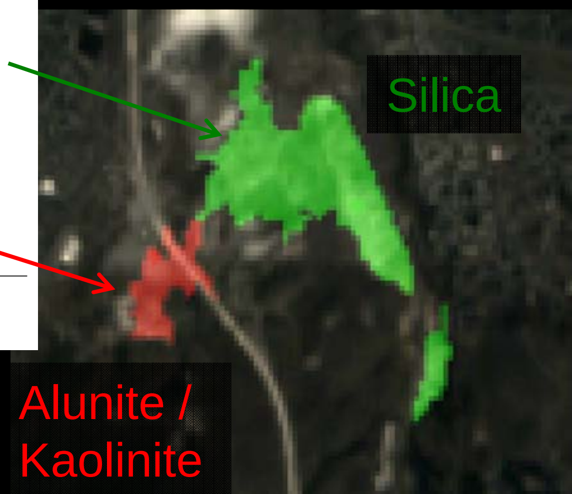
- Selective targeted data collection and return to exploit targets of opportunity (erosion features, outgassing, etc).
- Enable time-critical decisions onboard

EO-1 Hyperspectral novelty detection

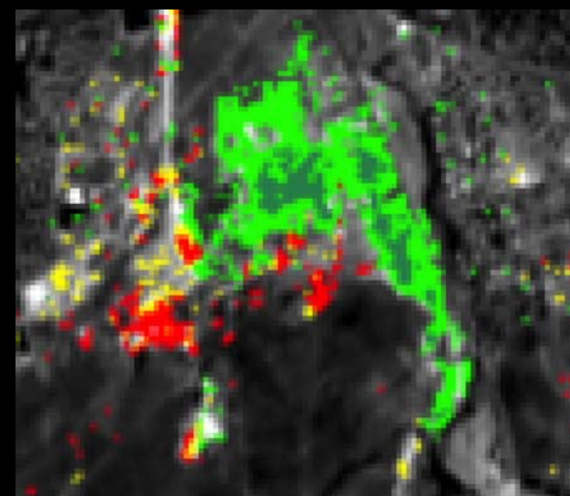
Endmember detection followed by spectral angle mapping



Compositional map generated onboard



Authoritative version of [Kruse et al., 2003]



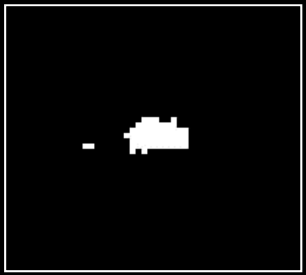
Steamboat, NV. Nov 2011 overflight

EO-1 Thermal signature detection

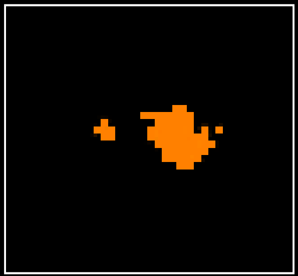
Black Body model used to trigger a second observation [Chien et al. 2005]

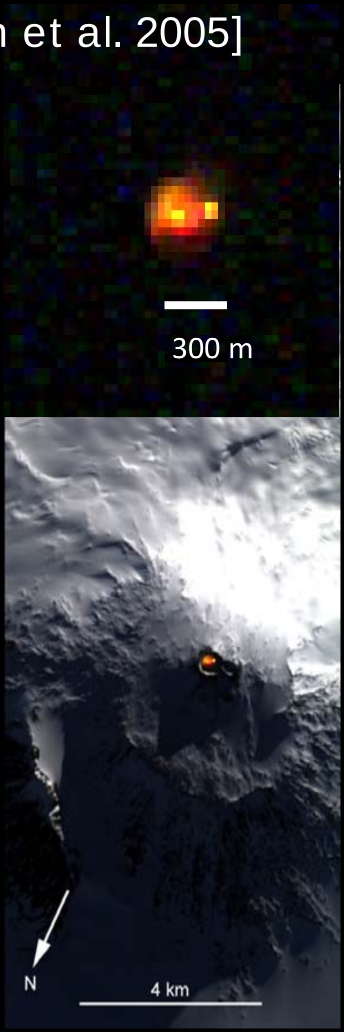
ASE images Erebus Night	13:40 GMT
ASE initiates band extraction	} +10 min
ASE runs thermal classifier	} +28 min
THERMAL TRIGGERED	} +29 min
Planner selects reaction observation (Stromboli observation replaced)	} +20 min
Thumbnail downlinked (S-band)	15:58 GMT
ASE images Erebus again	20:10 GMT + 06:30

ASE Onboard
Thermal Classifier
Thumbnail



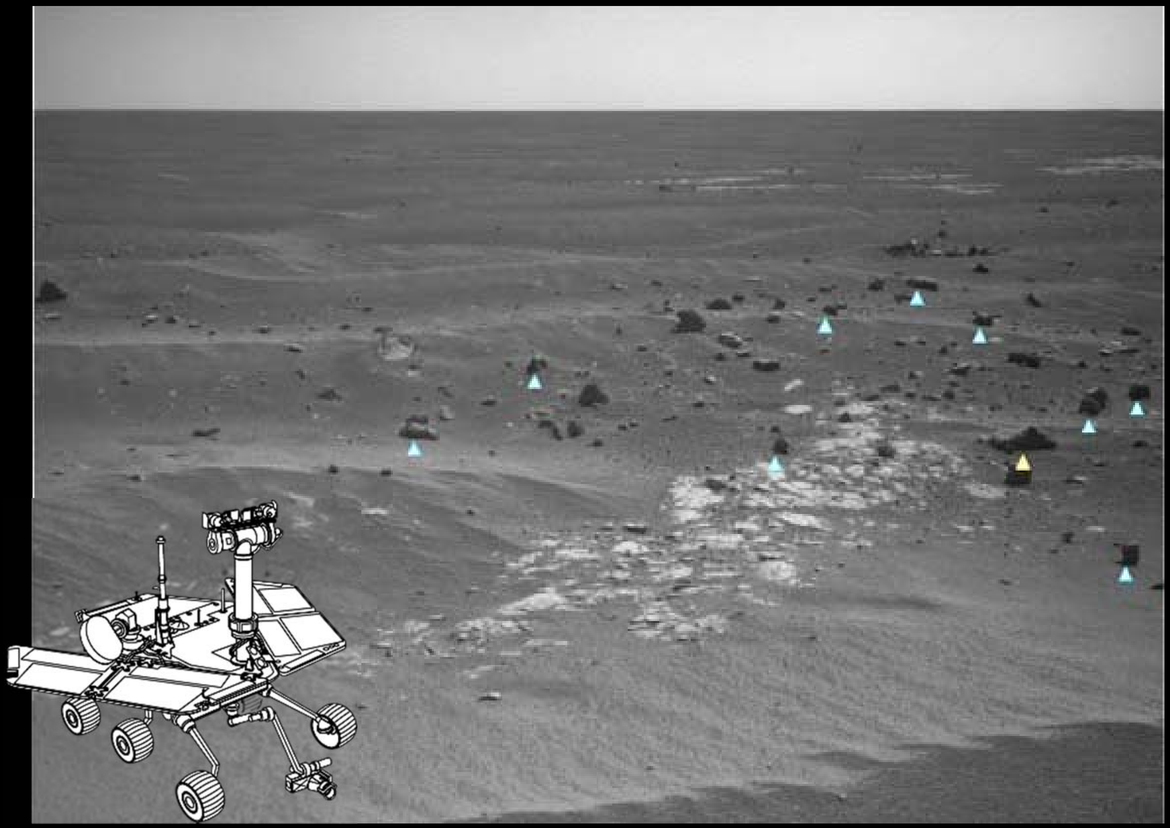
ASE Onboard
Thermal Classifier
ASE Onboard
Thermal Classifier





Target detection in images (AEGIS)

Contour-based rock detection. targeted followup of high-value targets [Estlin et al., 2012]

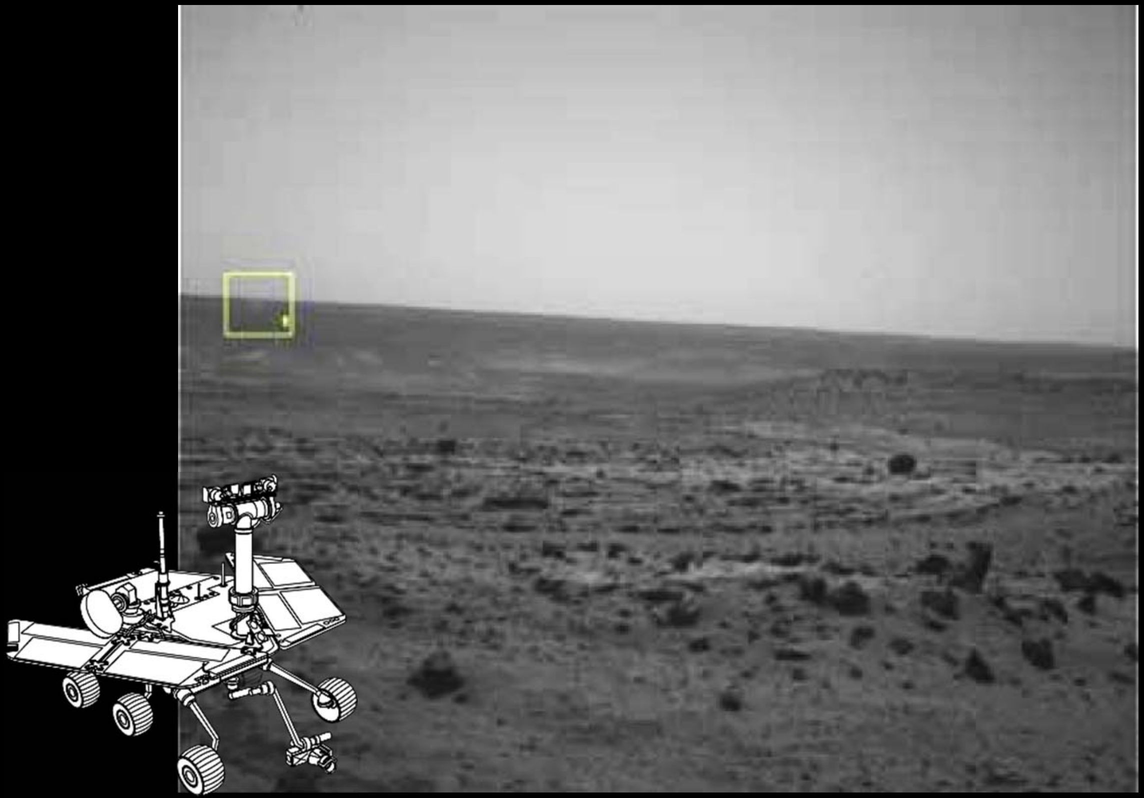


Automatic data collection from top target matching “dark” profile

Images: Cornell / NASA/ JPL / Caltech

Dust Devil Detection on Mars (WATCH)

Frame differencing with change detection to trigger selective downlink [Castano et al., 2008]



Automatic data collection from top target matching "dark" profile

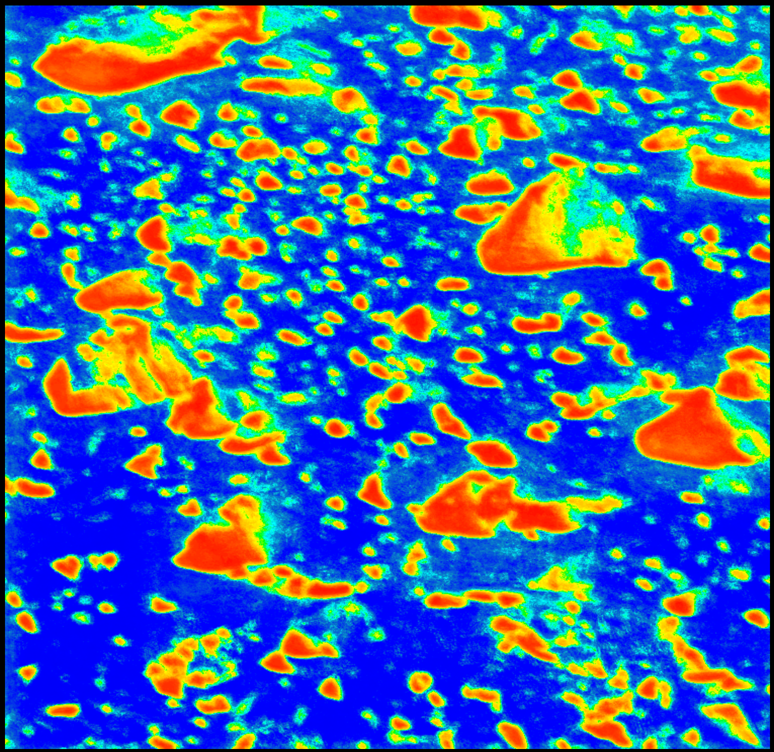
Images: Cornell / NASA/ JPL / Caltech

Surface classification (TextureCam)

Pixel-wise surface mapping with a trained decision forest classifier

Legacy panorama (Mars)

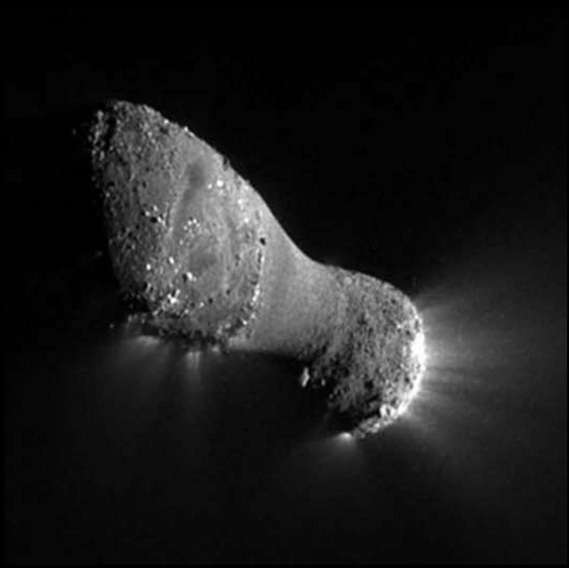
Rock probability map



Images: Cornell / NASA/ JPL / Caltech

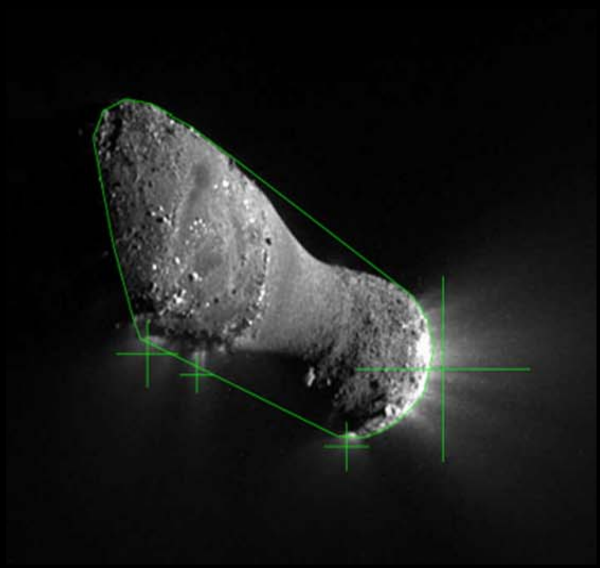
Plume detection

Horizon identification approach



Original image

Edge detection finds points on the target body

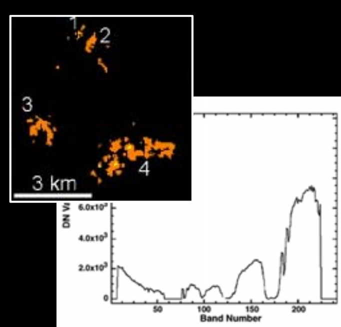


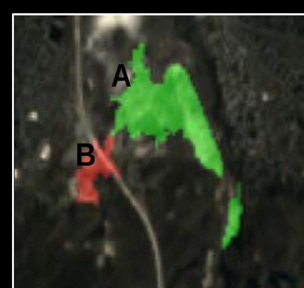
Illuminated material outside the “convex hull” is part of a plume

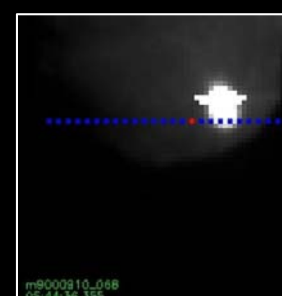
Image: Hartley 2 (EPOXI), NASA/JPL/UMD

Onboard data analysis: reaction times

	ASE (EO-1)	HiiHAT (EO-1)	Autonav (Deep Impact)	AEGIS (MER)
	Prioritize downlink	Prioritize downlink	Trajectory updates	Target detection
Data analysis	~2hr	5hr	1.5-8h	10-20m
Trajectory Generation	-	-	10-200m	-
Activity Planning	30m	-	-	2m
Followup execution	90m	-	1m	<1m
Total reaction time	~2-4hr M5 (Rad3000)	5h M5 (Rad3000)	2h Rad750	<25m Rad6000







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Case study – what could we do with onboard data analysis?

Image: Hartley 2 (EPOXI), NASA/JPL/UMD

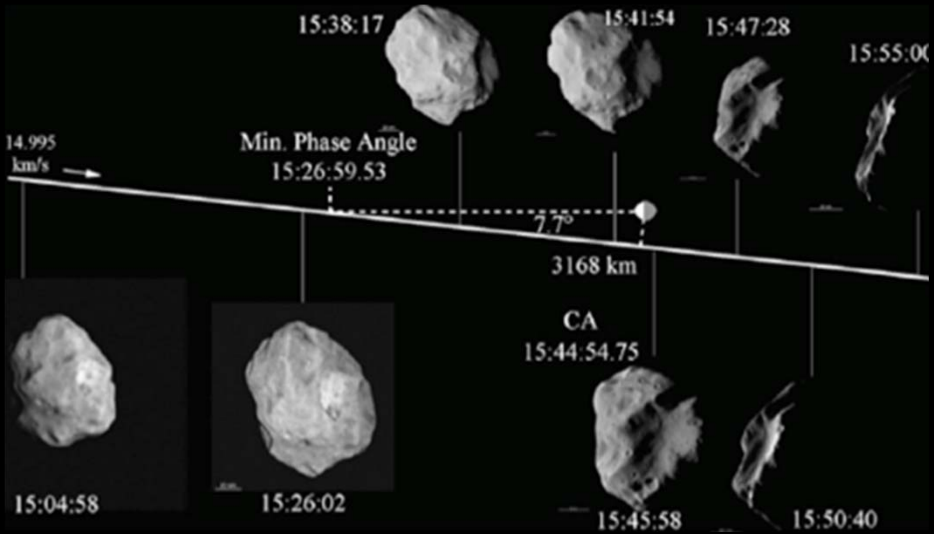
Case study 1: Smart flyby

Simulate targets distributed randomly

- erosion features
- surface activity
- spectral anomalies

Enforce illumination, geometry constraints

What fraction of the time can we capture the target with followup images (high-res images, VNIR or UV spectroscopy)?



Smart flyby performance

Case 2: Plume activity monitoring

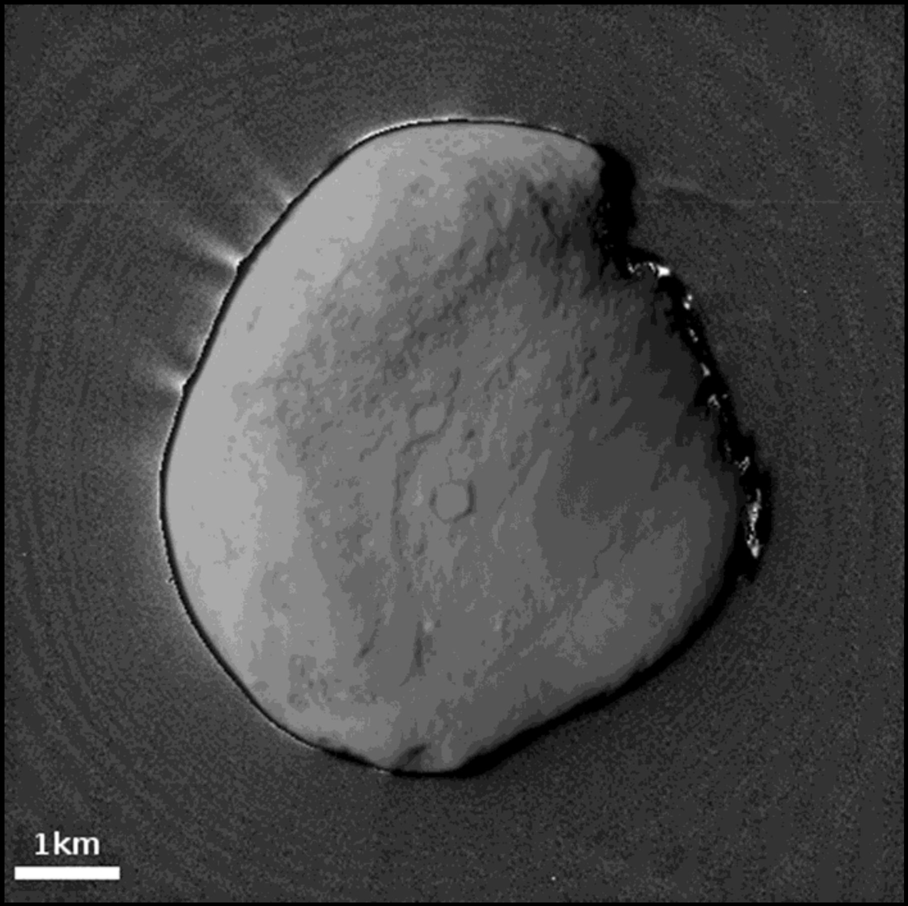
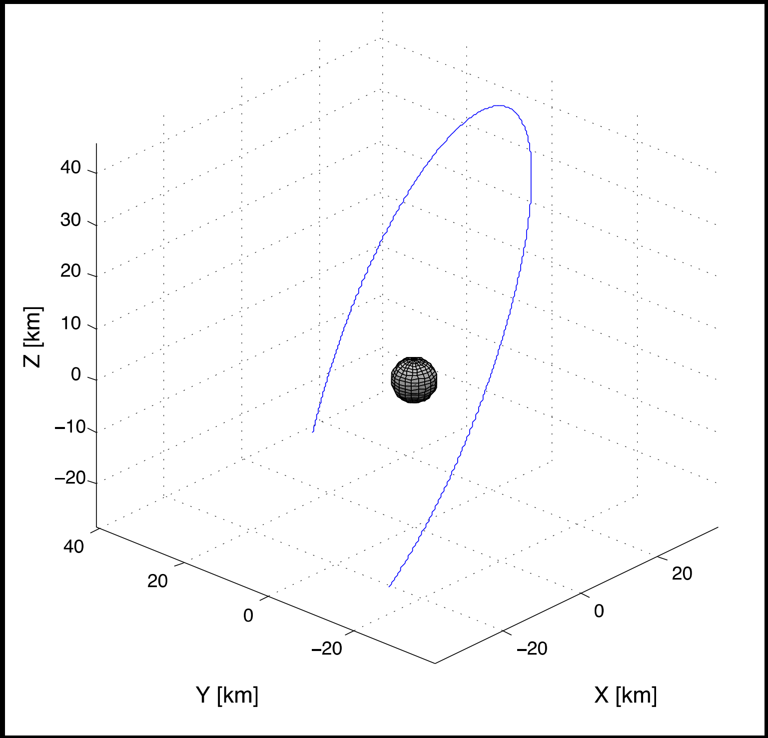


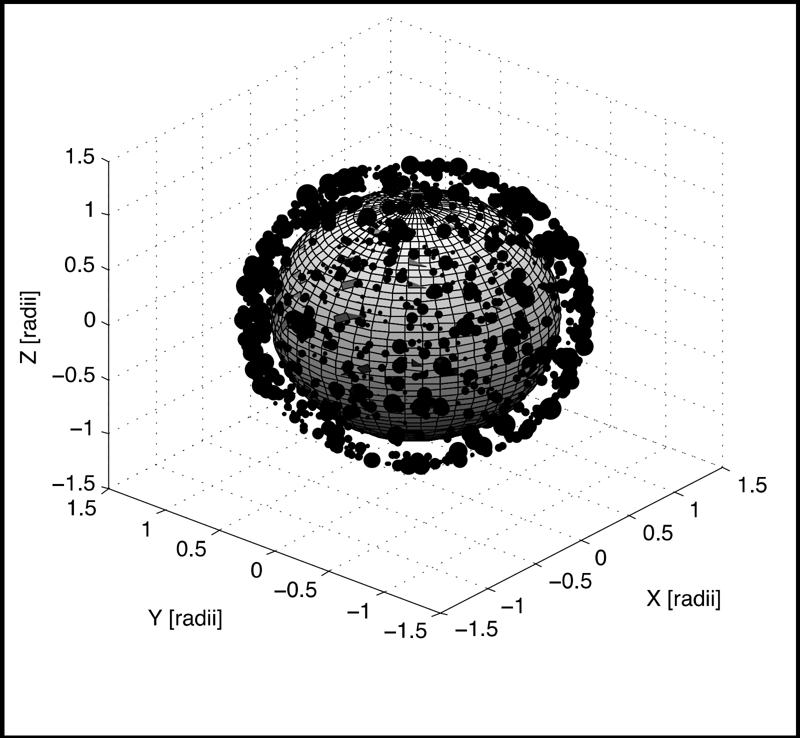
Image: J. Veverka et al., *ICARUS 2012*

Simulated plume monitoring campaign

3 week trajectory

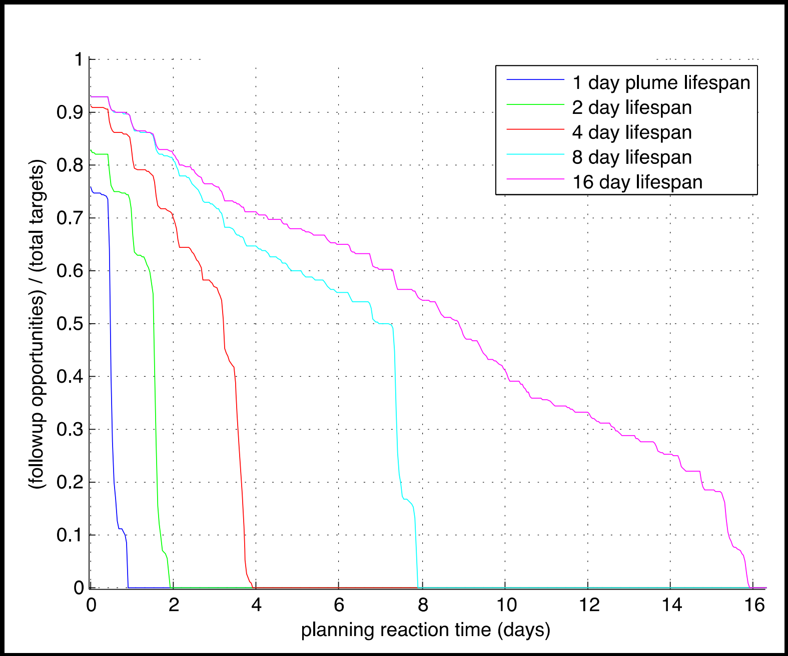


1000 simulated events

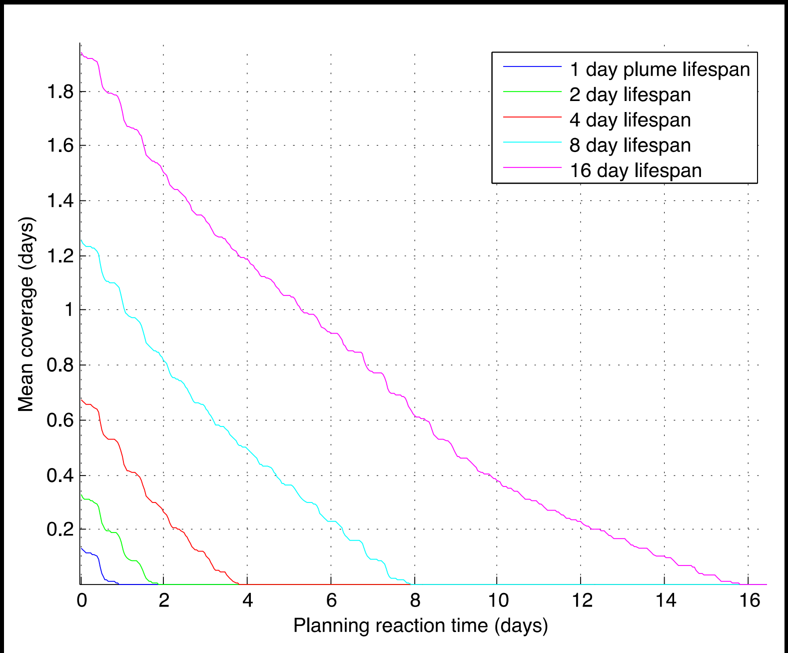


Simulated plume monitoring campaign

Fraction of plumes with targeted followup



Time duration of followup coverage



Agile ops techniques across missions

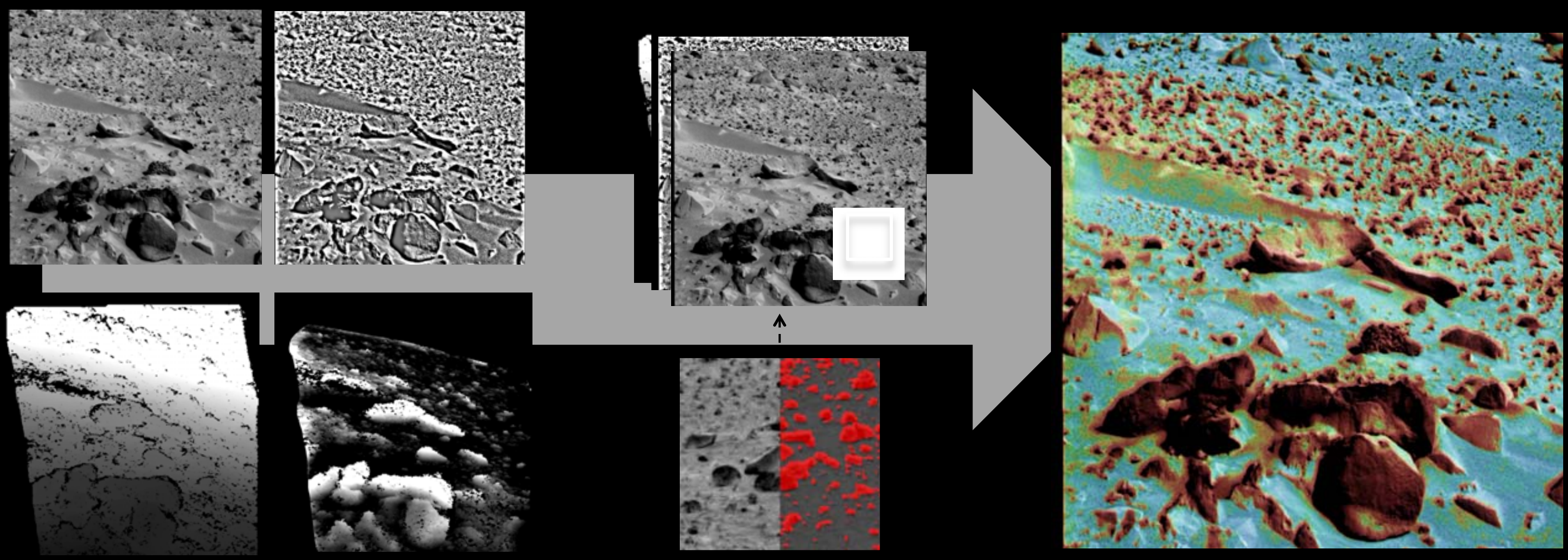
		Missions									
		Asteroid / inert					Comet / active				
		Dawn-style mapping	Hayabusa II	OSIRIS-Rex	Trojan Tour	Chiron Orbiter	Rosetta	Comet Hopper	CSSR	CNSR/CCSR	Coma Sampler
Mission and science unknowns	Morphological units	x	x	x	x	x	x	x	x	x	x
	Surface composition, mineralogy	x	x	x	x	x	x	x	x	x	x
	Localized targets (boulders, crater walls, etc)	x	x	x	x	x	x	x	x	x	x
	Satellites	x			x						
	Plume activity, distribution over space and time				x		x	x	x	x	x
	Gravity field	x									
	Location of site for sampling/landing		x	x			x	x	x	x	
	Surface conditions at sample site		x	x			x	x	x	x	
	Rotation rate and pole location	x	x	x	x		x	x	x	x	x
	Spacecraft performance / faults	x	x	x	x	x	x	x	x	x	x
Applicable ground ops technologies	Single-cycle trajectory/observation selection	x	x	x	x		x	x	x	x	x
	Fast instrument data processing	x	x	x	x		x	x	x	x	x
	Fast instrument data interpretation	x	x	x	x		x	x	x	x	x
Applicable onboard technologies	Trajectory replan (fault or hazard recovery)		x	x	x		x	x	x	x	x
	Observation replan (opportunistic targeting)	x	x	x	x		x	x	x	x	x
	Morphological pattern recognition	x	x	x	x		x	x	x	x	x
	Spectral pattern recognition	x	x	x	x		x	x	x	x	x
	Plume/change detection						x	x	x	x	x
	Satellite detection	x									
	TRN / optical navigation for prox. ops		x	x			x	x	x	x	
	Onboard planning / execution for prox. ops		x	x			x	x	x	x	

Conclusions

- Resilient missions should accommodate changing science objectives
- New Decadal Survey mission targets will require innovative operations strategies
- Can quantify mission flexibility using the principle of reaction time
- Technological solutions
  - Better ground-side automation and fast replanning
  - Limited transfer of authority onboard for time-critical decisions

Extra slides

Computer Vision for automatic scene interpretation



Test set performance

Image	Target	Plume present	Plume detection	√(# pixels)	Runtime (s)
PIA02124	Tempel 1			256	0.10
PIA02125	Tempel 1			256	0.08
PIA02140	Tempel 1	x	x	271	0.09
PIA05571	Wild 2			370	0.21
PIA00228	Gaspra			400	0.15
PIA02123	Tempel 1	x	x	471	0.32
PIA03505	Borrelly	x		500	0.32
PIA03501	Borrelly	x		500	0.90
PIA03504	Borrelly			500	0.29
PIA02127	Tempel 1			500	0.33
PIA03500	Borrelly			500	0.29
PIA13578	Hartley 2	x	x	501	0.32
PIA13601	Hartley 2	x	x	501	0.23
PIA13600	Hartley 2	x	x	501	0.28
PIA13579	Hartley 2	x	x	501	0.31
PIA13570	Hartley 2	x	x	501	0.28
PIA02133	Tempel 1	x	x	505	0.28
PIA02134	Tempel 1	x		623	0.37
PIA00297	Dactyl			700	0.38
PIA00069	Ida			769	0.37
PIA02137	Tempel 1	x		900	0.91
PIA00299	Dactyl			1000	0.81
PIA00118	Gaspra			1024	0.91
PIA06285	Wild 2			1165	1.40
PIA00136	Ida			1463	1.18
PIA00135	Ida			2114	4.77
PIA05004	Wild 2			2506	7.02