Beagle-2 Aftermath:
Post-landing phase and lessons learned

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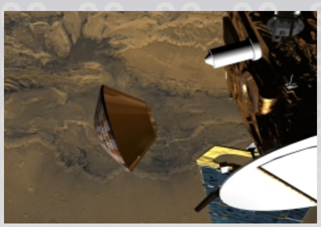
3rd Interplanetary Probe Workshop, Anavyssos, Greece
27 Jun – 1 Jul 2005



- Summary of Events
- Ejection
- Landing and Comms
- Sols 1-3
- Recoverable Failure Scenarios
- Non-recoverable Phase
- The Search
- Failure Analysis and Lessons Learned
- Future?

Summary of Events

- Beagle-2 was switched on and checked out 10 times during cruise phase
- Thermal and power telemetry were as predicted
- Several software/electronics anomalies encountered - all investigated, repeatable on ground, and fixed or worked around. “Learning to fly”.
- TM dropout twice for different reasons, but both were related to unexpected transceiver behaviour.

Date	*Time*	*Event*
02/06/2003	17:45	Mars Express launch
04/07/2003	20:04	Checkout A – Post-launch checkout
05/07/2003	19:03	Checkouts B,C - Heater/Timer tests
12/07/2003	16:46	
01/09/2003	12:40	Checkout D - Memory scrub
07/10/2003	11:03	Checkouts E,F – Software upload tests
09/10/2003	11:48	
21/11/2003	08:00	Checkouts G,H – Software uploads
22/11/2003	10:15	
17/12/2003	06:34	Checkout I - Ejection timer load
18/12/2003	06:33	Checkout J - Pre-ejection timer check and final system checkout
19/12/2003	08:31	Ejection from Mars Express
25/12/2003	02:51	Predicted atmospheric entry

Summary of Events 2

- Battery and energy management as expected
- Landed phase software completed replaced on 20-21 Nov 03, after ground validation.
- Heater circuit configuration for 1 payload item was repaired in flight.
- Ground validation performed using Ground Test Model – a full set of avionics hardware/software in flight configuration.

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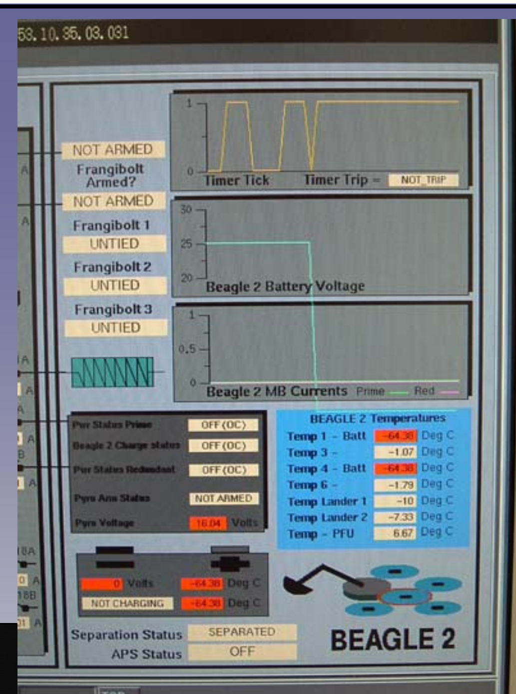
Ejection

- EDLS managed by probe-phase software PSW; pre-programmed and autonomous.

- Parameters updated and tuned as models were refined.

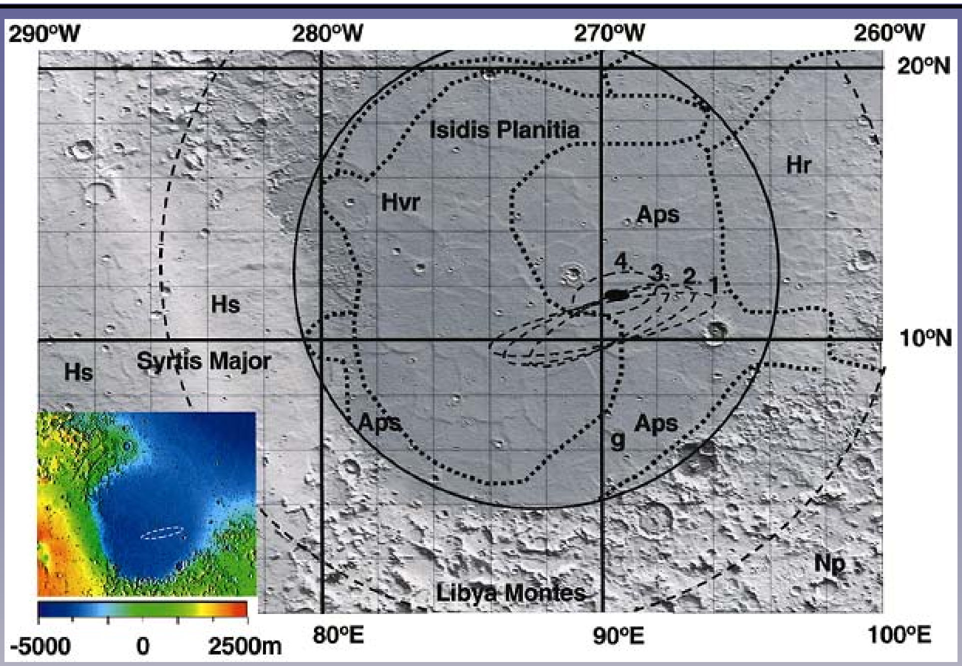
- Ejection confirmed in multiple ways:
  - Responsive ‘glitch’ in S-band Doppler at pyro firing
  - Spacecraft telemetry showing Beagle 2 disconnected
  - Spacecraft AOCS data
  - Monitoring camera images showing separation

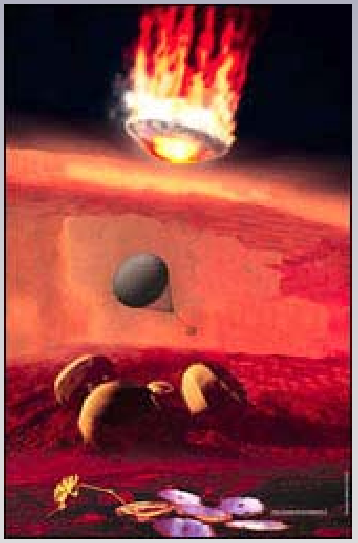
- State at ejection:
  - Separation δV was $0.31 ms^{-1}$, as required
  - Battery charge level was verified >98%
  - Confirmed software status and critical data area integrity
  - Descent timer, clock and latches in required state
  - EDL system parameters as expected

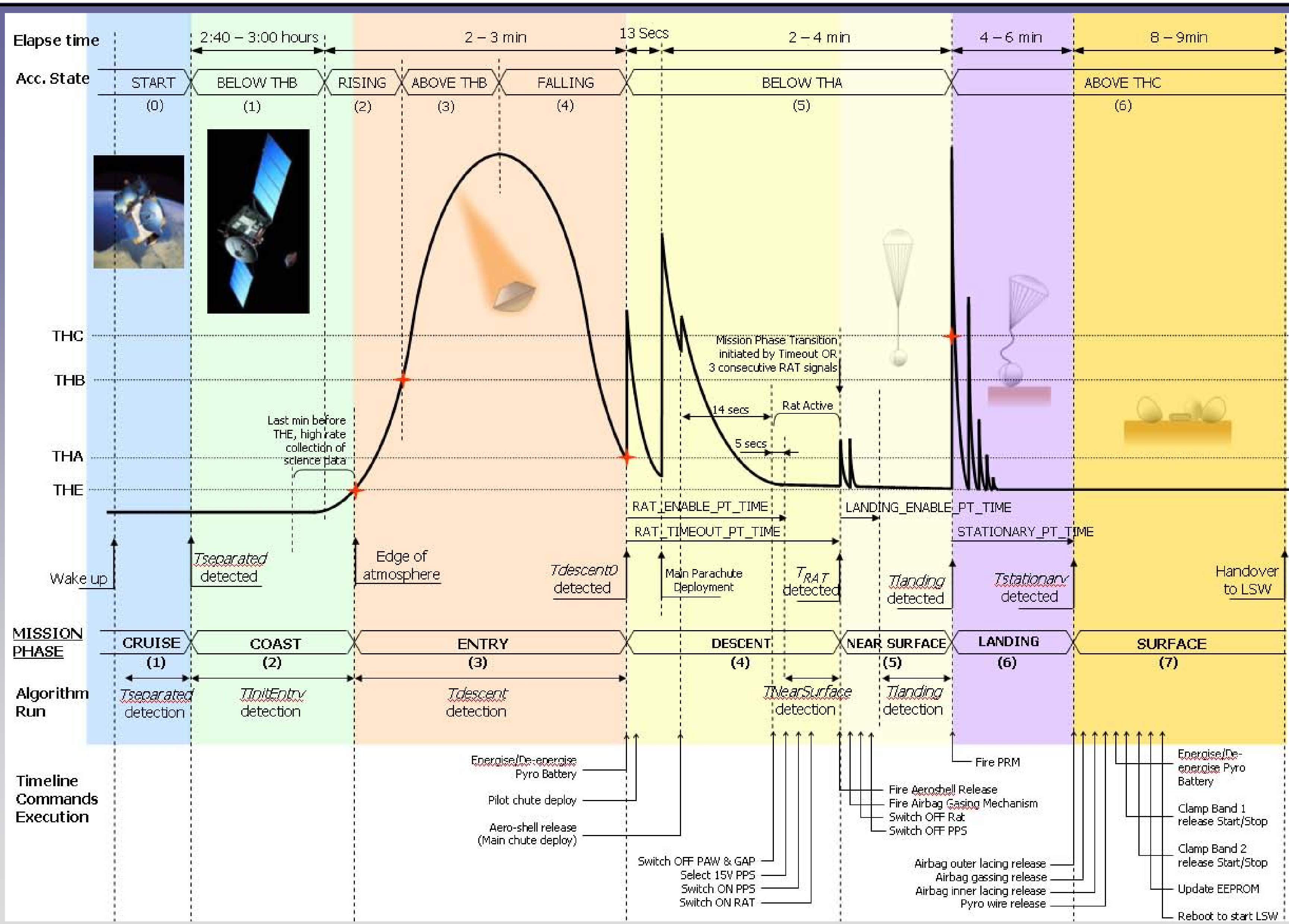


Landing

- Landing site chosen ~2 years before launch
- Initial ellipse 495 x 93 km
- Available imagery low resolution, but flat overall and achievable.
- But – cratering and rock distribution hazards were unknown.
- Final ellipse 57 x 7.6 km
- Accuracy only possible with DDOR navigation







Elapse time
2:40 – 3:00 hours
2 – 3 min
13 Secs
2 – 4 min
4 – 6 min
8 – 9min
Acc. State
START
(0)
BELOW THB
(1)
RISING
(2)
ABOVE THB
(3)
FALLING
(4)
BELOW THA
(5)
ABOVE THC
(6)
THC
THB
THA
THE
Mission Phase Transition initiated by Timeout OR 3 consecutive RAT signals
14 secs
Rat Active
5 secs
Last min before THE, high rate collection of science data
RAT_ENABLE_PT_TIME
RAT_TIMEOUT_PT_TIME
LANDING_ENABLE_PT_TIME
STATIONARY_PT_TIME
Wake up
Tseparated detected
Edge of atmosphere
Tdescent0 detected
Main Parachute Deployment
TRAT detected
Tlanding detected
Tstationary detected
Handover to LSW
MISSION PHASE
CRUISE
(1)
COAST
(2)
ENTRY
(3)
DESCENT
(4)
NEAR SURFACE
(5)
LANDING
(6)
SURFACE
(7)
Algorithm Run
Tseparated detection
TInitEntry detection
Tdescent detection
TNearSurface detection
Tlanding detection
Timeline Commands Execution
Energise/De-energise Pyro Battery
Pilot chute deploy
Aero-shell release (Main chute deploy)
Switch OFF PAW & GAP
Select 15V PPS
Switch ON PPS
Switch ON RAT
Fire Aeroshell Release
Fire Airbag Gasing Mechanism
Switch OFF Rat
Switch OFF PPS
Fire PRM
Airbag outer lacing release
Airbag gassing release
Airbag inner lacing release
Pyro wire release
Energise/De-energise Pyro Battery
Clamp Band 1 release Start/Stop
Clamp Band 2 release Start/Stop
Update EEPROM
Reboot to start LSW

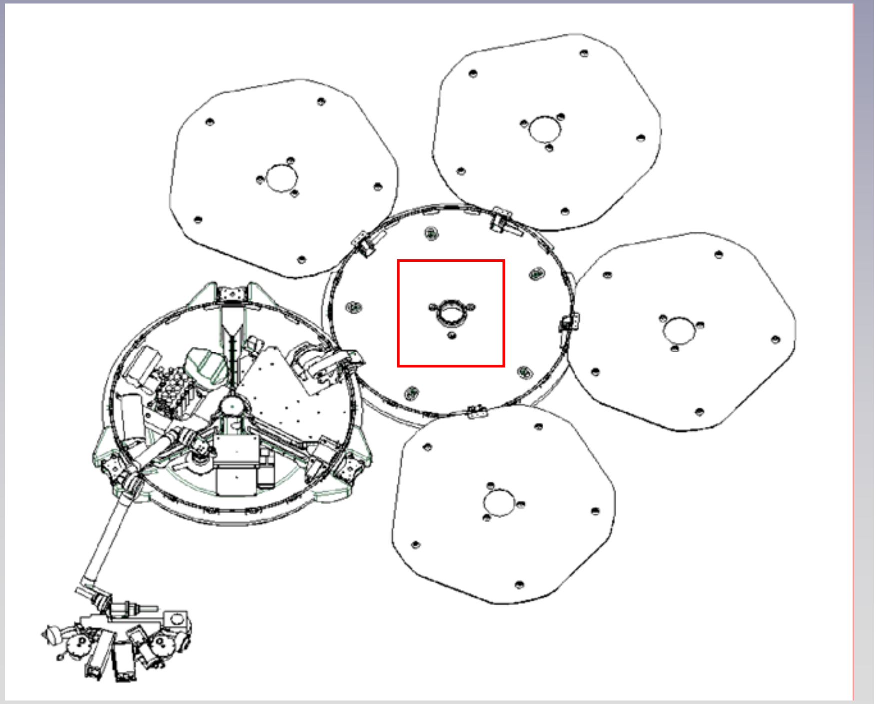
Comms

- Post landing communications modes guided the strategy for the ‘search’, and gave entry points for failure analysis.

- **Design of communications modes for remote landers is critical!**

- All comms were contingent on sufficient power being available – a power monitor can veto communication sessions to protect the lander.

- 3 levels of autonomy implemented to deal with unpredicted scenarios:



Comms Search Modes

- CSM-1: B2 adds NASA Odyssey overflights to the timeline – these occur at the same local true solar time (LTST) every day

- CSM-2: adds intelligence to CSM-1, but also assumes that the clock data is incorrect, and computes approximate LTST from sunrise/sunset (proxied by solar panel output); then:

  Day (10h – 18h):
  - Tcvr on for 59/60 minutes; 10s of TM; 9 mins Tx off; 1 min carrier only

  Night (18h – 10h):
  - 10 min cycle reduced to 5 min cycle – so carrier transmit never happens

- Auto-transmit mode: CSM-2, but with extended TM transmit period, regardless of time

Sol 1

Autonomous handover
- PSW hands over control to LSW
+1min: Lid and solar panels deploy

Programmable operations
- initial set uploaded during cruise
- Mission Events Timeline (MET)
- onboard catalogue of Activity Sequences
- 15 default communication sessions

+20min: imaging landing site (wide angle mirror, no mechanisms involved)

⇨ *location of airbags, orientation, local gradient, preliminary science targets*

+22min: image compression (x10 to fit image into first pass)

First Pass

NASA Odyssey, rise 05:25:20, visible for 17m 35s (mid afternoon on Mars).

First Night

Phobos transit imaging ⇨ *localisation of landing site*

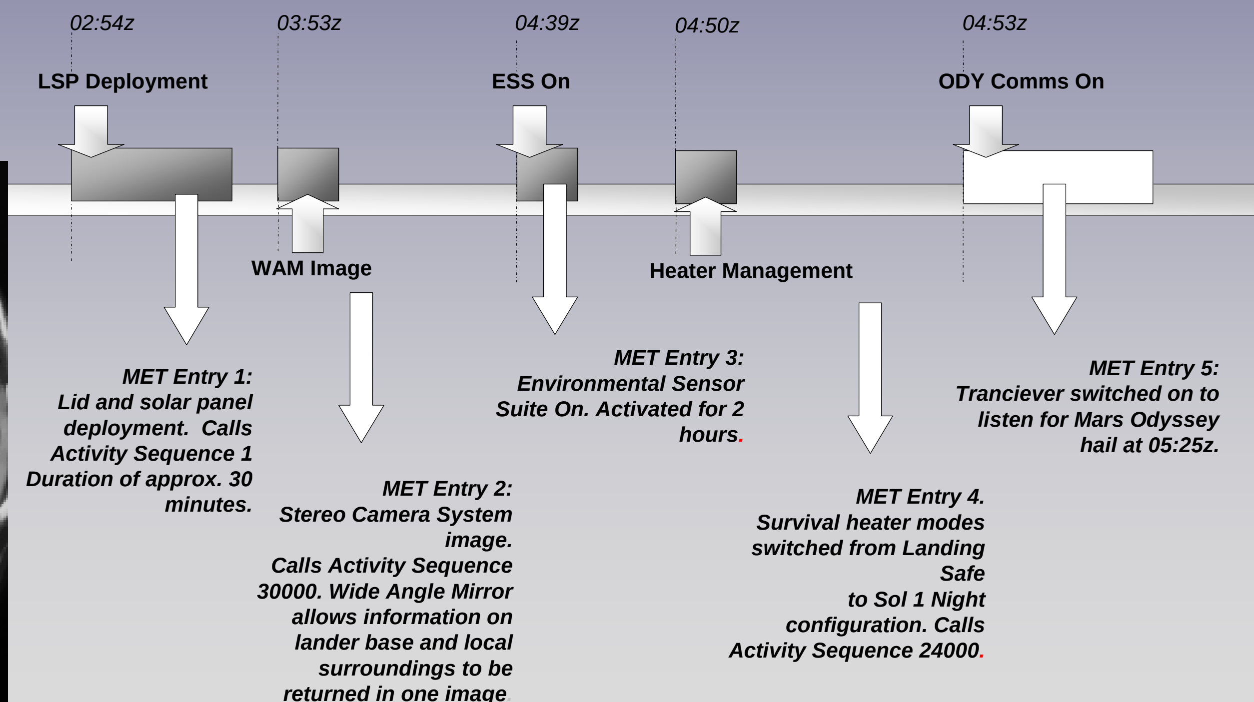
Sols 2-3

2nd afternoon

- start payload management (engineering HK from GAP)
- frangibolts fired on ARM and PAW

  ⇨ *removes thermal path to electronics*

- PLUTO (“mole”) launch lock released
- more imaging
- PTUVWD (!)

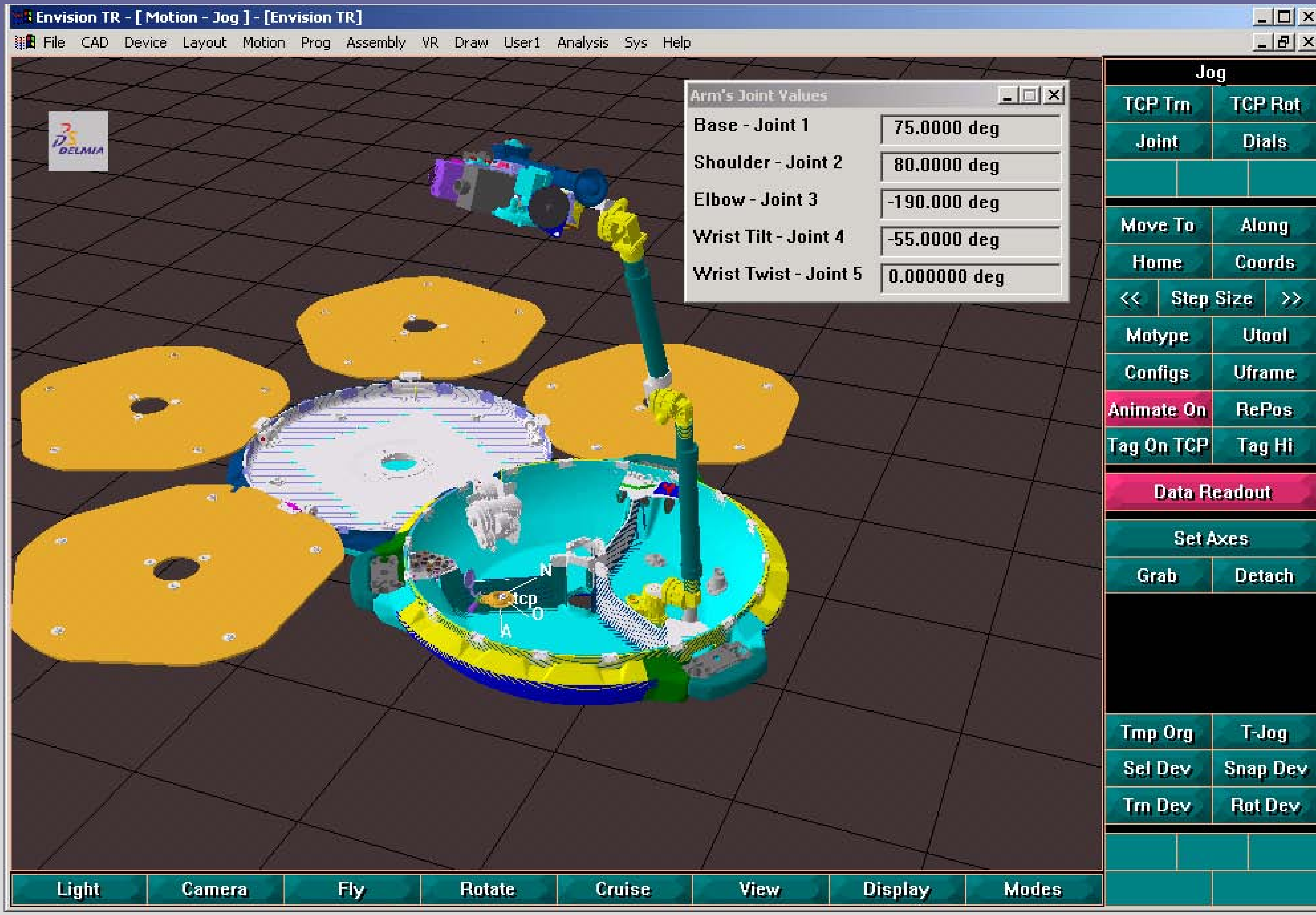


Ground Test Model

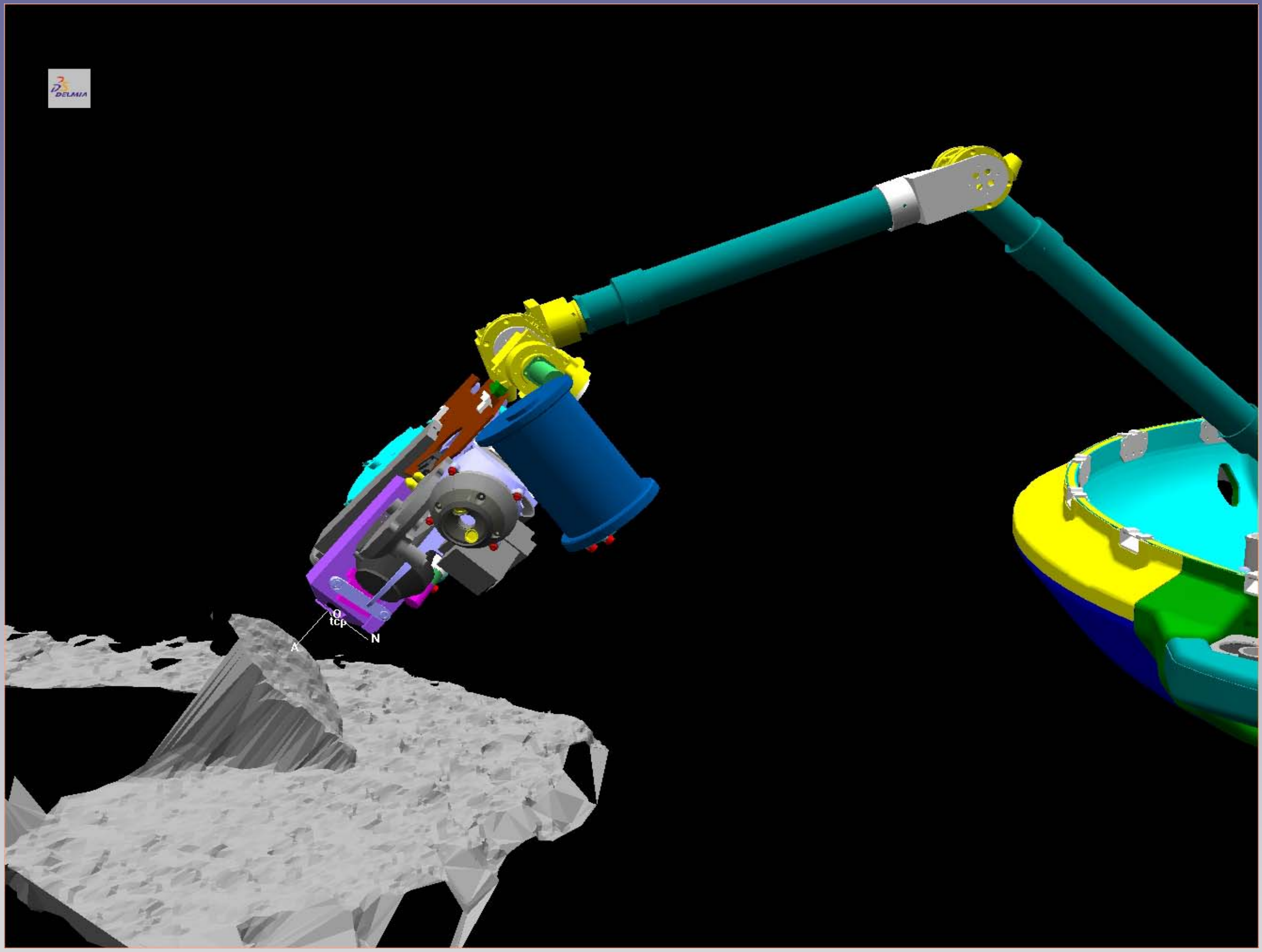
- Ground Test Model is a working replica of the Flight Model
- Majority of components are from Development Model, e.g.
  - Lander Base with dummy Solar Panels
  - Common Electronics, running PSW or LSW
  - ARM
  - Transceiver

- Third mass instrument PAW used to simulate weight under Martian gravity
- QM PAW with real instruments also available for testing

- Surface terrain can be recreated for use with GTM
- Digital Elevation Model (created here from mock terrain) used for ARM VR


Envision TR - [Motion - Jog] - [Envision TR]
File CAD Device Layout Motion Prog Assembly VR Draw User1 Analysis Sys Help
Arm's Joint Values
Base - Joint 1
75.0000 deg
Shoulder - Joint 2
80.0000 deg
Elbow - Joint 3
-190.000 deg
Wrist Tilt - Joint 4
-55.0000 deg
Wrist Twist - Joint 5
0.000000 deg
Jog
TCP Trn
TCP Rot
Joint
Dials
Move To
Along
Home
Coords
<<
Step Size
>>
Motype
Utool
Configs
Uframe
Animate On
RePos
Tag On TCP
Tag Hi
Data Readout
Set Axes
Grab
Detach
Tmp Org
T-Jog
Sel Dev
Snap Dev
Trn Dev
Rot Dev
Light
Camera
Fly
Rotate
Cruise
View
Display
Modes
DELMIA
tcp
N
O
A

- Complex manoeuvres – such as rock contact – can be planned with VR
- Additional information given by the system includes
  - Motor torques
  - Potentiometer values
  - Motor currents
  - Manoeuvre durations



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Recoverable Failure Scenarios

Goal
- find scenarios that can be changed by telecommand
- prioritise these according to models, urgency, and practicality

Outputs
- command loads prepared (and validated on ground) for uplink 25/12 – 2/3
- 23 stacks sent via Odyssey and Mars Express

Results
- progressive elimination of failure modes
- no outstanding recoverable scenarios
- exhausted resources :

    Worst-case power situation onboard
    Mars Express operational requirements
    Industrial team increasingly returned to ‘normal life’
    Remaining team increasingly asleep

Recoverable Failure Scenarios

Desperation Factor
2

Clock reset / synch loss

- shift/loss of LOBT ⇨ comms attempts out of orbiter visibility
- new clock values commanded corresponding to max elevation of overflight
- >=sol 3

Comms Search Modes

- entry into search modes checked against model; many possibilities
- comms sessions selected to correspond to most likely modes
- force worst-case CSM-2 by staying silent between 12/1 and 22/1
- parameters for CSM transitions (delays, durations, etc.) updated
- >=sol 14

Comms-free Timeline

- failure of timeline to load comms sessions from memory
- additional later sessions added
- >=sol 1

Recoverable Failure Scenarios

Marginal solar power

- failed/partial panel deployment?
- unfavourable orientation
  ⇨ transceiver disabled
- panels re-commanded, also to a 'flatter' configuration
- comms at various times of day in various power regimes
- obstruction monitoring thresholds raised
- >=sol 1 (panel 2)
- >=sol 14 (panels 1,3,4)

Desperation Factor
4

Battery monitor / power management limiting tcvr operations

- software flag enables/disables battery threshold monitoring in each mode
- flag reset by command
- >=sol 8 / 14

Desperation Factor
6

Recoverable Failure Scenarios

Desperation Factor
10

Sequential commanding failure

- fault in forward link; or general failure of the handshaking protocol (e.g. physical/hardware fault)
- 'blind' commanding via Odyssey (not possible via MEX)
- sol 7,36,37

Reboot required

- general / bizarre / unexpected software or boot problem
- reset commands included at start of stack
- sol 36,37

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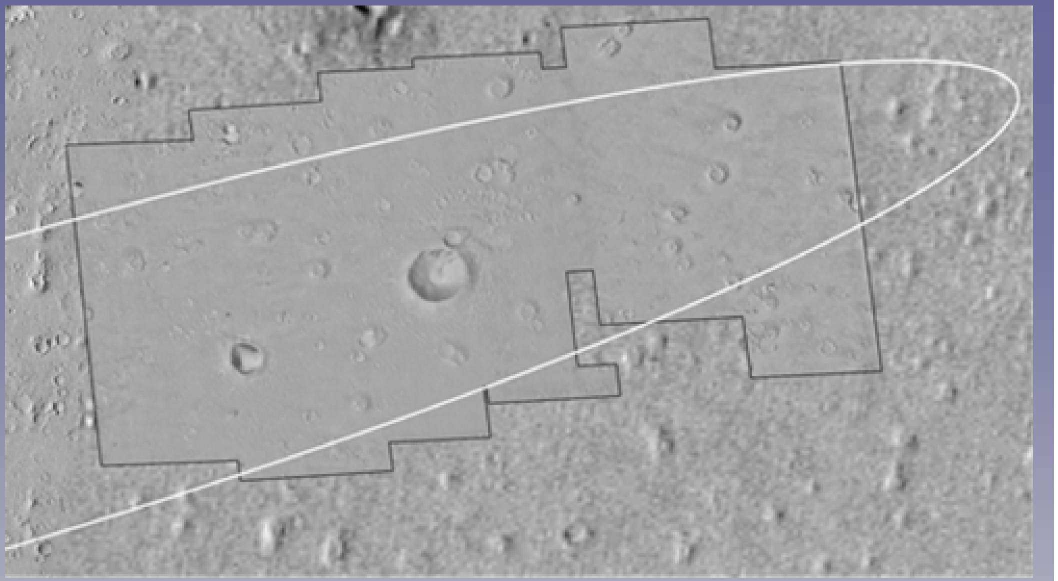
The Search

MOC camera on MGS operated by Malin Space Science Systems imaged series of mosaics in the down-range half of the ellipse.

Close analysis of features, following success of Spirit imaging.



10 images, 72% of the half ellipse + 2 of short side, to approx. 2m resolution.

Analysed for possible EDL components or other new features/inexplicable stuff.

1 candidate feature, approx. 20m diameter, roughly circular, internal structure . . . but 20m is too big for even worst case (entire system) impact:

rim diameter ~2m   ejecta radius ~4m   total size ~5-6m   upper bound ~9m

(Schmidt & Holsapple method scaled from terrestial impacts)

Failure Analysis

⇨ Re-consider every aspect of the mission design, and critically examine the design for failure modes.

Electrical Performance in Cruise

- full TM review, every event correlated to commanding
- battery charge >98%, voltages nominal, no overall trend in 6 months
- no unplanned resets, no multibit memory errors (10 single bit, all corrected)
- timer behaviour and correlation continually updated during cruise checkouts
- full landed-phase software replacement (verified by full set of checksums, and partial memory contents dump)
- 3 s/w upload anomalies (fixed same or following day)

⇨ no identifiable evidence linked to a failure mode

Thermal Performance in Cruise

- close correspondence to FEM thermal model
- increased heating rates in power supply during checkouts, but steady-state as expected

⇨ no identifiable evidence linked to a failure mode

Failure Analysis

EDLS and Atmosphere

- all modelling and simulations performed again in light of MER EDL experiences
- some evidence for reduced density above Isidis on day of arrival
- a late parachute opening would be fatal ☹
- ballistic properties re-examined

⇨ no useful conclusions either way

VMC Image Analysis

- 8 images captured of receding probe after ejection
- Images 3-6 analysed independently given minimal context information
- Confirmed: ejection δV ($0.3025 \pm 0.0083 ms^{-1}$),
  solar aspect angle $133 \pm 10°$
  colinear trajectory
- Possible MLI anomaly (triggered investigation of ARM cover disbond)

⇨ positive evidence for things being as nominal

Failure Analysis

Outgassing

- MEX δV in cruise on +Z
- SUEM ice-up ? (possible incorrect trajectory, but confirmed OK)
- Airbag gassing system leak ? (would be fatal)

⇨ no conclusions leading to evidence of a failure mode

Parachute Deployment, Heatshield Separation

- EDL design critically reviewed. Again.
- Particular attention to difference in ballistic coeffs of the parachute, heatshield and rear cover.
- Bag/PC recontact analysed and found unlikely

⇨ Additional 10m strop would have reduced to negligible

Ejection

- Attitude control system response analysed, and uncertainty ellipse verified and refined (monte carlo)
- slight over-performance of 1.29% identified

⇨ positive evidence of perfect targetting

Failure Analysis

Design Failure Modes

- collection established of failure modes in the design itself
- probabilities assigned, along with evidence for/against
- include variants and consequences
- no 'most likely' or favourite failure modes identified, but it is clear that the mission was probably lost during EDL, or the deployment.

Electronics too cold for start up after coast phase due to MLI damage during cruise
Lander electronics malfunction and failure to operate one or more systems during EDL
Excessive velocity during entry due to unusual atmospheric conditions
Front heatshield break-up or aerodynamics corrupted leading to hypersonic failure
Parachute envelopes airbags after first bounce leading to problems with bag release and deployment
Airbags fail on impact, during subsequent bounces, or are punctured
Thermal protection tiles detached from aeroshell during entry
Parachute(s) inflation problems
Airbag/gassing system leak at connection point resulting in incomplete inflation
Airbag jettison failure or damage to lander as part of release process
Damage to lid or clampband following impact of lander with ground, causing failure of release or deployment of lid and solar panels
Antenna damaged on impact
Return or forward link failure causing an unknown protocol problem, or random component failure.

Lessons Learned

1. Descent telemetry of any kind (e.g. tones) is crucial
2. Lander/Probes/Rovers are not payload items – they are distinct spacecraft and need to managed and operated as such
3. Funding and appropriate resources need to be available at the outset, at system level, for any lander elements
4. Descent telemetry of any kind (e.g. tones) is crucial

'Lessons Learned' report publicly available, in fairly raw form (not endorsed by any organisation other than the team that contributed the lessons):

- *categorised by subsystem or mission aspect*
- *indication of which lessons are derived from B2 operations and development that were positively applied...*
- *... and those we wish we had applied (or were not constrained by)*

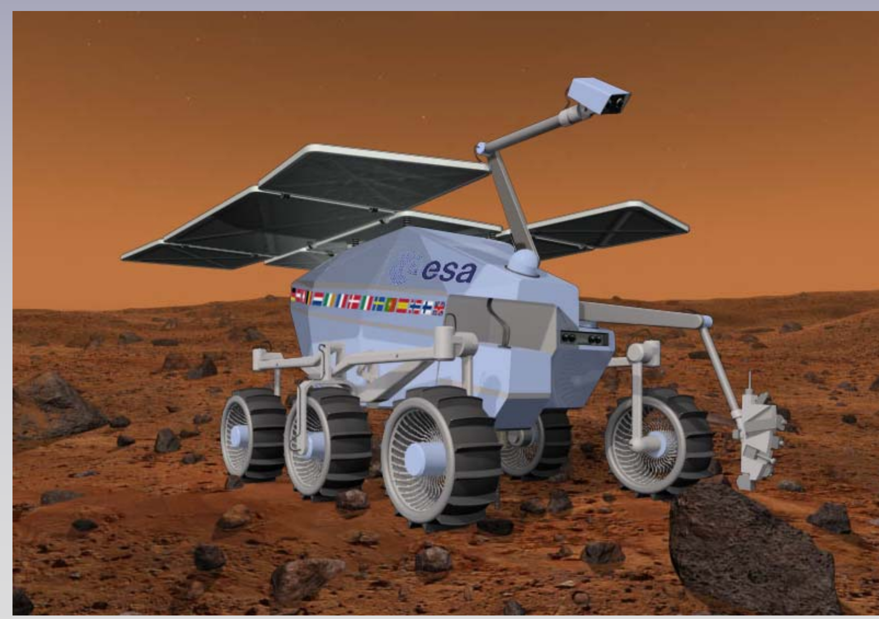
Future?

Activity undertaken by some members of the consortium including Astrium UK and University of Leicester to address the criticisms of the ESA Commission of Inquiry, and other known design issues. Phase A design for networked lander mission with partial mobility

Wide spin-off applications of payload concepts to medical and security applications

Instrumented ‘mole’ including subsurface in-situ X-ray fluorescence

Payload ideas/designs suitable for Exomars? / Aurora?



Thanks

We wish to thank everybody in ESA and NASA who supported the mission, especially the ESOC MEX teams and the JPL GDS, MMO and Odyssey teams.

Particular thanks for huge support during the 'Search' and mission failure phases:

The NASA Odyssey team that kept up UHF overflights far longer than reasonable;

Mike Malin and MSSS for operations and analysis support of the MOC camera;

Jodrell Bank radio telescope team from Manchester University.