Mars Sample Return

Precursor Missions
Pre-Phase A

Mission M-2
Final Presentation
Presentation Content

- Study Overview
  - Study context, requirements, objectives
  - Mission baseline description
  - Technology demonstration & science aspects

- Mission Analysis & GNC
  - Lunar transfer
  - Lunar descent & landing
  - Lunar surface hopping

- Mechanical System & Lay-Out

- Parametric Cost Assessment

- Summary & Conclusions
Study Overview
Major User Requirements for MSR Precursor Missions

- Validation of critical technologies and capabilities needed for the MSR mission shall be achieved (PRE-SYS-10)
- To the greatest extent possible, make use of MSR identified technologies (PRE-SYS-10)
- In case of subscale demonstration, the results of the pm shall be scalable to the MSR mission (PRE-SYS-50)
- The launch date for the pm should be not later than 2016 (PRE-SYS-60)
- The pm shall use as reference launcher, Soyuz 2-1b or smaller (PRE-SYS-70)
- The pm shall be Earth, Lunar, Mars, NEO or Phobos-based (PRE-SYS-80)
- As far as possible European/Canadian technologies and development shall be used (PRE-SYS-100)
Major User Requirements for MSR Precursor Missions

☒ The precursor mission shall provide resources to a TBD scientific payload (PRE-SYS-210) in terms of
  - Available volume
  - Mass
  - Electrical power
  - Data

☒ The resources to science shall be maximized (PRE-SYS-220)
Recent Lunar Landing Studies at Astrium GmbH 2006 / 2007

- MSR NEXT M2 (this study)
  - Key technologies for Mars Sample Return
  - Science potential for improved acceptance
  - Soyuz launch, 700 – 800 kg landed mass

- Lunar Applications
  - For DLR, to be finished by Nov 2007
  - Future Lunar Lander, Ariane5 launch, 2700 kg landed mass
  - Demonstrator concept (further evaluated for MSR NEXT)

- Small Lunar Lander
  - In House Study, finished June 2007, later merged with Lunar Applications
  - Soyuz Launch, 700 kg landed mass (design value)

- Moon Descent and Landing
  - For ASI, finished July 2007
  - VEGA / Soyuz Launch, 500 / 700 kg landed mass
Introduction to M2 Mission and Programmatic Concept

- The mission proposed hereafter is a landing mission to the lunar south pole combining
  - key technology verification of “Autonomous Soft Precision Landing with Hazard Avoidance” to prepare for future exploration missions like MSR
  - a self standing Moon landing mission shall provide a platform for ambitious In-situ Scientific Measurements
- The mission will be launched from Kourou by Soyuz-Fregat placing the Lander into GTO
- The concept focuses on innovative GNC & Sensor technology
- The Propulsion System is composed of mature components
- A Reference P/L is given to scale servicing needs and interfaces
- A “Hopping” capability of the lander is foreseen expanding mobility during scientific mission
- Early practical Demonstration to minimize development risks
- Reliable Programmatic Data ensure realistic program planning
- Rendezvous and Capture
  *not applicable to M2 but comparable systems involved*
  - Optical navigation sensors
  - Closed loop position & attitude control

- Entry, Descent and Landing on Mars
  *main feature of M2*
  - Entry point accuracy
  - Complete last landing segment
  - GNC & navigation strategy, HW & sensors
  - Autonomous hazard avoidance
  - Structure and mechanism e.g. landing legs

- Ascent from Mars surface
  *partly applicable to M2*
  - Propulsion system features for hopping
  - Re-initialization GNC system, propulsion

- Earth Re-Entry
  *not applicable to M2*

- Sample Handling
  *not applicable to M2*
Study Goals and Activities

- Mission analysis and trade off for maximum payload mass
- Analysis of the propulsion system concept feasibility with the goal to use existing and mature components
- Pre-Development of a GNC strategy for descent, entry and soft precision landing based on autonomous optical navigation
- Investigation of hopping capability
  - to address the ascent aspect of MSR to the extent possible
  - to provide added value to the lunar mission by means of expanded mobility after first landing
- Spacecraft system definition, preliminary design and justification of all major subsystems design
- Preliminary definition of a sound development logic defining the actual TRL level of key subsystems and their maturity required at start of a phase C/D
- Definition of an early demonstration concept minimizing the technical and programmatic risks
S/C Design Issues

- Use of existing Technology (structure & propulsion)
- Launcher Compatibility (mass, volume)
- Landing Site Location
  - Illumination conditions
  - Temperatures
  - Day / night cycles
- Structural DesignAnalyses
  - Launch
  - Landing
- Science Operations
  - Assets needed for hopping
  - Experiment deployment & operations support
  - Hibernation services
Twofold Objectives on Mission Capability for Science

- Optimization of available payload mass and servicing features
- Expanded mobility by Rover and/or “Hopping” on Moon surface

Possible Reference Payload

Science package used for system analysis:

- **Lunar GEP**
  - Landing site geology
  - Mineralogy and chemistry
  - Earth-Moon system dynamics
  - Seismic measurements
  - Heat Flow measurements
  - Physical properties of regolith

- **Radio Astronomical Test Package**
  - 3 low frequency antennas
  - Measurement of lunar electromagnetic environment

- **Mobility**
  - Mobile robot for deployment and/or in situ science
  - Fuel reserved for hopping

### Lunar Lander Instruments

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**TOTAL GEP** 20.9

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<td>Remote Controlled End Effector</td>
<td>Camera (others possible, tbd by rover design)</td>
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**TOTAL SCIENCE** 42.9

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**TOTAL SCIENCE & MOBILITY** 99.3
Resources provided to Science

- **Power**
  - Power supply prior to deployment (configuration & check-out)
  - Battery loading for science period extension, if needed
  - Requires joint interface design (mechanic, electric)

- **Communication**
  - Data relay service using the lander’s data management system
  - Requires joint interface design (connection, coding standards)

- **Hibernation**
  - Supply of stand-by power during lunar night, if needed
  - Supply of thermal control during lunar night

- **Mobility**
  - Deployment of GEP or single experiments using the rover
  - Retrieval for hibernation or position change
  - Controlled transfer to another location ("hopping")
Mobility by mobile robots

different options with respect to scientific requirements

Nanokhod-type Rover
- 250 x 160 x 65 mm, 3.2 kg
- Science load 0.8 kg, range ≈ 100 m

Solero-type Rover
- 860 x 560 x 510 mm, 10-25 kg
- Science load 4-10 kg, range ≈ 10 km

Scorpion-type legged Rover
- 500 x 300 x 180 mm, 15 kg
- Science load TBD, range ≈ 1 km

Hopping

complementary or alternate option for mobility expansion

- Lander designed for ascent after landing & surface ops
- Fuel options:
  - Using planned fuel reserve (P/L performance minus P/L mass)
  - Using residual fuel not consumed during first landing
Lunar Transfer Mission Analysis
Mission Trade Off and Analysis

- Launch and Lunar Transfer
  - Transfer strategy, launch window assessments
  - Maneuver planning, navigation strategy, fuel budget including ACS, maneuver dispersion analyses

- Mapping Operations (Low Lunar Orbit Operations)
  - Definition of a preliminary plan for landing preparation
  - Use of onboard resources for landing area selection

- Descent & Landing Simulation, Hopping
  - Propulsion subsystem proof of concept
  - Analysis of optical navigation subsystem constraints
  - 6 DoF control simulation for proof of concept, fuel budget analysis

- Navigation Subsystem Modeling
  - Navigation filter representation with realistic error parameters
  - Transients and non linearities still to be implemented

- Autonomous Landing Site Selection and Hazard Avoidance
  - Considered by appropriate trajectory design
  - Not yet part of the (pre phase A study) simulation
Lunar Transfer Mission Analysis

- Two scenarios have been studied
  - Direct insertion into LTO with Soyuz Fregat upper stage
  - Soyuz Fregat insertion into GTO from Kourou and Transfer into LTO by own propulsion

- Gain in landed mass expected due to lower mass to be accelerated from GTO to LTO speed

- Mass gain reduced by
  - higher need of Delta-V due to inclination change
  - need for more fuel, larger tanks ⇒ heavier structure
  - smaller thrust / mass ratio if engine pattern unchanged

- Question: larger payload for science and/or mobility?
Analysis Concept

- Compare launcher performance
  - use optimum mass at separation (disregard effect of launch windows) for same launch pad
  - reduce given value by 5% and by adapter mass

- Analyze fuel budget phase by phase
  - accounting for ACS and RCS efficiency (Isp)
  - add 5% to all Delta-V's

- Landed Mass analyzed further for
  - effect of increased volume on dry mass (more surface)
  - effect of increased S/C mass (more stiffness required)

- Remaining delta mass is payload gain
Key Parameter Launcher Performance:

- Defines initial mass at separation from Fregat
- Difficulty to find a single source describing both scenarios
- Soyuz Fregat from Kourou into LTO (incl S/C adapter):
  - JAQAR Lunar Transfer Orbit Calculator: 2162 kg
  - Lavochkin ISTC presentation (2007): "up to 2350 kg"
  - Reverse engineering of GTO performance: 2303 kg
  - ESA information (received 11-07-2007): 2150 kg
- Soyuz Fregat from Kourou into GTO (incl S/C adapter):
  - ESA information (received 11-07-2007): 3230 kg
Applied Margin Philosophy:

- Ref: E-Mail from F. Mura, 29-May-2007
- Launch Mass: 5% (on launch window minimum mass)
- Delta-V: 5% flat across all phases
- No additional margin on calculated propellant
- Dry mass:
  - 20% on system level
  - 5% ... 20% on subsystem, depending on TRL
Required structural changes for GTO scenario w.r.t. LTO direct

- Fuel mass & volume increased by >60%
  - Larger tanks (preferably off the shelf)
  - Larger fuselage surface & frame length (radius restricted)

- Launch mass increased by 50%
  - Reinforcement of frame & hull (modal analysis pending)
  - Reinforced launcher adapter (longer & heavier S/C)
  - Reinforced tank support structure

- Best case calculated landed mass gain: 114 kg

- Preliminary Assessment of mass penalties:
  - structure: +30 kg
  - propulsion: +40 kg

- Calculated remaining payload mass gain: 44 kg

- GTO scenario retained as baseline
Mission Timeline

- Launch / Lunar Transfer / LLO Operations

**Geostationary Transfer Orbit Insertion (GTOI)**
- **Lunar Transfer Insertion (LTI1 ... LTI3)**
- **Fregat Separation**
- **Geo Transfer Orbit (GTO)**
- **Lunar Transfer Orbit (LTO)**
- **Hyperbolic LTO Arrival**
- **Descent Orbit 10 x 100 km**
- **Mapping Orbit 100 x 100 km**
- **Capture Orbit 100 x 300 km**
- **Circularization (LOI + 4 ... 8 h)**
- **Lunar Orbit Insertion (LOI = LTI3 + 5 days = GTOI + 8 days)**
- **Braking, Approach, Landing (DOI + 60 min ... DOI + 80 min)**

**T₀: Start Kourou**

**Launch & Transfer Analysis**

Final Presentation, ESTEC, 02-Oct-2007
Delta-V and Fuel Planning

- Phase by phase analysis accounting for applied engines
- ESA margin policy applied
- Initial wet mass (at Fregat separation) 3230 kg - 5% (margin) - 110 kg (adapter) = 2959 kg

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Descent & Landing Strategy
Descent & Landing Overview

- Starting from 100 x 100 km (TBC) circular orbit
  - Hohmann transfer to 10 x 100 km descent orbit (DOI)
  - landmark navigation (camera)

- Powered Descent Initiation (PDI) at perilunium
  - maximum thrust braking
  - landmark navigation (camera)
  - closed loop trajectory control

- Landing Gate about 1 km above landing site
  - landing site acquisition (camera)
  - acquire landing attitude

- Final descent to surface
  - optical navigation and obstacle avoidance (LIDAR / camera)
  - approach along camera / LIDAR line of sight
  - closed loop trajectory control
Descent & Landing Overview

- **Duration**
  - ≈ 1:20 h

- **3 Phases**
  - unpowered descent
  - full thrust braking
  - low speed final descent
Landing Site Selection During Final Descent (1)

- Perform precision approach to landing gate (+/- 250 m)
- During descent, evaluation of the landing area by means of autonomous processing of landing camera images
- Final landing site selection between 50 and 15 m (below 15 m, dust is expected to obstruct visibility)
- Skewed camera requires inertial GNC during last meter vertical descent
- Avoid obstacles > 30 cm (avoiding unwanted contact or tip-over)
  - Obstacle identification by autonomous image processing
  - Fuel reserve of 30 seconds for landing site search while hovering (not counting for planned hopping fuel)
Landing Site Selection During Final Descent (2)

- **Nominal Scenario**
  - Nominal landing point is known and identified (visible details required)
  - Calculation of a nominal flight path to this site, following landmarks
  - Compensation of initial position errors (max. 250 m)

- **Alternate Scenario**
  - Nominal landing point has not been defined or not been identified
  - Nominal landing point has been declared as unsafe (slope, obstacles)
  - Calculation of a nominal flight path to an alternate site, following landmarks
Simulation of the Descent Orbit

- **Navigation Precision at DOI**
  - Position +/- 20 m (1-σ)
  - Velocity +/- 3.5 cm/s (1-σ)

- **DOI Maneuver Precision**
  - Thrust vector +/- 2° (3-s)
  - Thrust level +/- 3% (3-s)

- **Resulting Position Errors**
  1/2 revolution later (braking point)
  - Strongly correlated (orbital mechanics)
  - Not safety critical
  - However, compensation prior to or during braking is mandatory for precision landing
Design of the Braking Maneuver

- Depending on Errors from Preceding Descent Orbit
  - Range Error
  - Altitude Error

- Depending on Errors Accumulated During Braking
  - Navigation errors
  - Thrust calibration error
  - Attitude control & thrust vector error

- Moreover: Engines with fixed rated thrust are used
  - Required thrust = real thrust is only the ideal case
  - Unlike during DOI, burn duration cannot be used for control
  - For precision arrival at landing gate, the thrust must be modulated along track and across track
  - Continuous main engine thrust, pulse mode operated assist engines
Simulation of the Braking Maneuver

- Pitch program is calculated during descent orbit, accounting for DOI errors (numerically optimized time optimal transfer).
- Delay of program start compensates DOI range error.
- Pitch program and thrust modulation compensate DOI altitude error and braking thrust error.
- Discontinuous thrust regulation requires pitch maneuvers.

Pitch program and thrust vector control.

Discontinuous thrust regulation.

Adapted Trajectory

Nominal Trajectory
Mission Phase Landing

- After Arrival at Landing Gate
  - Shut down most braking engines
  - Reduce average thrust to about hovering level
  - "Pitch-Over": transition into landing attitude
  - Compensation of residual velocities

- Descent to Landing Point
  - Approach along camera line of sight
  - Altitude proportional descent rate reduction
  - Lateral position and velocity control
  - Touchdown vertical descent rate < 3 m/s
Design of the Descent Profile

- **Spacecraft Guidance**
  - Guided pitch-over to vertical attitude
  - Constant speed
  - Constant thrust

- **Design parameters**
  - Landing gate altitude (higher=faster)
  - Available thrust (in 3 or 4 stages)
  - Available fuel (landed mass)

- **Design Criteria**
  - Realize nominal duration (120 ... 150 s, incl. hover reserve)
  - Have thrust margin for ACS

- **Mass variation always requires pulse mode operation of the assist engines**
Simulation of the Landing Maneuver

- Final descent along camera LoS
- Landing with
  - 1 m/s +/- 0.5 m/s descent rate
  - Less than 0.1 m/s ground speed
Lunar Surface Hopping
Why Hopping?

- Hopping expands mobility radius of the science mission
  - Using hopping for relocation of science experiments
  - Using low scale mobile robots for deployment / retrieval

- Hopping allows to ‘pinpoint’ scientifically interesting targets after careful evaluation of the area around the first landing spot
  - Interesting surface features (rocks, cliffs)
  - Permanently dark areas nearby (hop in & out)

- Risk due to terrain uncertainty is reduced
  - Hopping starts from rest, no high speed, full thrust arrival
  - Possibility for refinement & terrestrial processing of
    - Post landing onboard panorama / stereo camera images
    - In flight landing site imagery from mapping phase
  - Prior to ascent, there is enough time for careful calibration of the navigation system and trajectory planning
Benefit for MSR Key Technology Validation

- Although environment and spacecraft design are different, lunar surface hopping can provide significant added value to the MSR mission design process

- **Propulsion**
  - Propulsion subsystem initialization after extended surface stay (propellant and supply mechanisms exposed to lunar environment)
  - Ground effect during initial ascent (platform proximity for MSR)

- **GNC**
  - GNC system configuration (navigation, trajectory planning)
  - Ascent planning based on estimated initial conditions

- **Operations**
  - Configuration of the spacecraft for ascent (mechanisms, payload)
  - Provide best initial conditions for autonomous GNC operations
  - Provide optimum planning support for autonomous GNC operations
Spacecraft Design Constraints

- **Navigation**
  - Initial climb must allow to stay clear of dust (optical navigation)
  - Prior to landing site identification, the lander shall navigate with IMU plus known (from 1st landing) & unknown landmarks
  - Ceiling altitude must provide sufficient surface area overview
  - After landing site identification, a descent duration of about 30 seconds is recommended

- **Propulsion**
  - Thrust range and modulation capability of the lander is sufficient
  - Minimum safe hop requires about 25 kg of fuel
  - Modifications for safeguard and re-ignition of the propulsion subsystem after first landing needs to be analyzed

- **Subsystems**
  - Retrieved science experiments must be locked in place
  - Unfolded mechanisms must be reversible
Trajectory Planning

Precursor Mission M-2
Lunar Surface Hopping

Standard Landing Sequence

- Approach Path Acquisition
- Hover & Decelerate (may be skipped for short hops)
- Finish Climb & Accelerate
- Yaw to Target
- Vertical Ascent

- First Retargeting
- h=50 m: second retargeting & final target selection
- h=15 m: start of vertical descent

Final Target Initial Target

Final Presentation, ESTEC, 02-Oct-2007
Simulation Proof of Concept (1)

- 6-DoF rigid body with variable mass
- continuous plant, discrete GNC
- fixed thrust, fixed gimbal engine cluster
- linearized dynamics model of navigation filter
  - discontinuities of optical navigation still have to be implemented in later phases
  - range dependent noise & bias (ref. NPAL study) implemented
- implemented system parameter uncertainties
  - thrust magnitude and direction
  - mass, inertia, and center of mass uncertainty
  - asymmetric fuel depletion
  - initial position estimation (Nav error, mapping error)
- main goal: preliminary proof of clustered engines concept
Simulation Proof of Concept (2)

Precursor Mission M-2
Lunar Surface Hopping

- Descent Rate [m/s]
  - Altitude [m]

- Descent Rate [m/s]
  - Downrange [m]

- SC Mass [kg]
  - Time [sec]

- Descent Thrust [kN]
  - Time [sec]

- Euler Angles [deg]
  - Time [sec]

- ACS Torques [Nm]
  - Time [sec]
Fuel Demand Assessment

- Hop starts at rest and h=0, and ends at rest, h≈0
- Average thrust for entire hop is "hover thrust"
  - altitude increasing for thrust > weight
  - altitude decreasing for thrust < weight
- Mass change during hop << average vehicle mass
- ACS fuel demand is small
  - differential thrust for roll & pitch control
  - small yaw control demand

Required Delta-V assessment

- duration of hop (gravity compensation $\Delta V = 1.62 \times T_{\text{Hop}}$)
- lateral acceleration, deceleration ($\Delta V = 2 \times V_{\text{Max,Lat}}$)
Parametric Fuel Budget Analysis, Input

- **Variables**
  - Take off mass 750 kg, 800 kg, 850 kg
    - Top down best case calculated landing mass 876 kg
    - Top down worst case calculated landed mass 810 kg
    - Bottom up design dry mass + reference science payload 730 kg
  - hopping range 50 ... 500 m
  - ceiling altitude 50 ... 200 m

- **Mission plan parameters**
  - Fixed thrust vertical ascent up to min. 30m or optimized value
  - Ascent to ceiling and translation to new target
  - Maximum pitch angle 20 deg
  - No ballistic phases for continuous lateral maneuverability
  - Velocity profile guided descent to landing
### Parametric fuel budget analysis, Results (fuel per hop [kg])

**Take Off Mass = 750 kg**

<table>
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<tr>
<th>Ceiling [m]</th>
<th>Hopping Distance [m]</th>
<th>50</th>
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**Take Off Mass = 800 kg**

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**Take Off Mass = 850 kg**

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Precursor Mission M-2

Propulsion Subsystem Performance Analysis
Propulsion Subsystem Requirements

- Provision of the required thrust level
  - Design drivers: braking phase, landing phase

- Thrust modulation capability (for trajectory control)
  - Mandatory for precision approach (goal is to arrive at landing gate with +/- 250 m)
  - Mandatory for soft landing

- Three axes attitude control
  - Free flight (coasting) phases
  - Boost phases (large orbital maneuvers)
  - Variable pointing requirements
  - Variable perturbations & mass properties
Propulsion Concept:

- **Main Engines & Assist Engines for orbit / trajectory control**
  - Use of existing engines (from now up to 5 years ahead)
    - Clustered engine pattern for wide mass range
    - Fixed rated thrust, no thrust vector control
  - Lateral thrust by pitch / roll maneuvers of the spacecraft
  - Thrust modulation by pulse mode firing of assist engines
  - Roll & pitch control by differential assist engine thrust

- **Low thrust Attitude Control Thruster Pods**
  - Fuel efficient cruise phase 3-axes attitude control
  - Yaw axis control for all phases
Available Engines (high TRL today)

- 4 x EAM: 500 N, MON / MMH, Isp = 325 s, steady state operation (restart possible, almost no pulse-mode capability)
- 6 x ATV RCS: MON / MMH, 280 N, Isp <= 287 s, pulse-mode capability < 100 ms
- 4 x 4 x 22 N, Isp <= 287 s, pulse-mode capability < 50 ms
Transfer Orbit Maneuvers (GTO ⇒ LTO, LOI)

- Requirements & Constraints
  - Gravity losses small (thrust not correlated to fuel)
  - Specific impulse mainly affects fuel demand
  - Lower thrust requires longer burn
    - increased fuel expense for attitude control
    - small efficiency losses due to curved trajectory

- No driver for propulsion subsystem design
Braking Maneuver (Powered Descent Initiation, PDI)

- **Functional Requirement**
  - Braking thrust: maximize thrust / mass ratio
  - Thrust modulation capability for range control +/- 5%

- **Configuration**
  - Continuous thrust
    - 4 x 500 N + 4 x 280 N (3120 N)
  - Assist thrust 2 x 280 N for range control
  - Longitudinal axis ACS with 22 N
  - Lateral axes ACS with differential thrust of assist engines

- **Use less engines?**
  - Saves propulsion S/S mass and complexity
  - Increases fuel demand (see chart)
Landing Phase Trajectory Control

- Variable mass requires controllable thrust
  - Uncertain mass at landing gate arrival
  - Landing phase consumption (≈300 m/s)

- Analysis of the landing phase
  - Propulsion Constraints
    - No pulse ops for EAM's
    - Pulse ops of 280 N engines
  - Design goal of thrust level stages
    - F1 = 75% Hover (descent)
    - F2 = 100% Hover (hover)
    - F3 = 125% Hover (ascent)
    - F4 = 175% Hover (hopping ascent)
  - Configuration analysis with variation of initial mass (see chart)
  - First verification on 6 DoF simulator

- Configuration applicable for anticipated landed mass range 

![Descent Engine Configuration Chart](chart.png)
Attitude Control (1)

- Cruise and Coasting Phases
  - Small perturbation torques
  - Partially fine pointing requirements
  - Long duration (5 ... 10 d transfer, up to 2 d survey)
  - Engines with low MIB reduce fuel demand

- Boost Phases
  - Main and assist engines cannot be gimballed
  - Main and assist engines produce parasite torques while operating (thrust bias/noise in magnitude & direction)
  - Too small engines may result in unstable ACS
Attitude Control (2)

- **Pointing Requirements**
  - Lunar transfer and passive lunar orbit: +/- 4 deg
  - Imaging, orbit maneuvers, landing: +/- 0.5 deg

- **Cruise Flight**
  - 4 x 4 x 22 N MON / MMH
  - MIB < 50 ms
  - Control Torques
    - Roll (XB): 90 Nm
    - Pitch (YB): 90 Nm
    - Yaw (ZB): 90 / 180 Nm
  - Perturbations negligible
Attitude Control (3)

- Boost Phases
  - Lateral Axes (XB, YB):
    - Differential pulse mode operation of assist engines
    - No additional fuel required (engines also used for braking)
    - Condition 1: assist engines are not always on (positive thrust reserve)
    - Condition 2: perturbation torques < 25% control torques
  - Longitudinal Axis (ZB)
    - Reduced pointing requirement
    - Stability mandatory
    - Perturbation torques along z-axis
      - have to be < 30 Nm
      - verified by analysis
    - Use of 22 N ACS engines is possible
Navigation Subsystem Concept Analysis
Navigation and Guidance Concept

- **Transfer Orbit, Low Lunar Orbit up to Descent Orbit**
  - classic deep space orbit control, autonomous attitude control

- **Descent Orbit (10 x 100 km), Braking & Approach Phase down to Landing Gate (h ≈ 1000m)**
  - IMU + optical navigation using landmarks (position and attitude)
  - landmarks registered pre flight and during in situ mapping

- **Landing Phase (Landing Gate to Touchdown)**
  - IMU + optical navigation using landmarks (position and attitude)
  - Autonomous hazard identification and avoidance using LIDAR

- **Autonomous Landing Site Selection**
  - Successive improvement of terrain evaluation while approaching
  - Target identification possible from landing gate minus 60 sec
  - Target re-designation expected at h ≈ 500 m
  - Final landing spot selection at h ≈ 50 m
  - Vertical touchdown based on inertial navigation
Optical navigation system: functional requirements

- Optical navigation support required during descent to PDI
  - small fuel reserve for final descent
  - small horizontal range during final decent
  - inertial navigation only is insufficient
  - precision arrival at landing gate is required

- Required control window dimensions at start of final descent
  - Altitude +/- 50 m, horizontal position +/- 100 m
  - Velocity (ground speed, descent rate) +/- 1 m/s

- Maximum allowed estimation error
  - At h = 100 km: +/- 1000 m; +/- 10 m/s
  - At h = 10 km: +/- 100 m; +/- 1 m/s
  - At h = 1 km: +/- 10 m; +/- 0.1 m/s
  - For landing: free of obstacles (defined by tip over stability and structural clearance of the bottom of the lander, probably < 50 cm)
## Optical navigation system: CCD camera vs. LIDAR

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<th>CCD Camera</th>
<th>LIDAR</th>
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<td>small</td>
<td>large</td>
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<tr>
<td><strong>Illumination</strong></td>
<td>passive</td>
<td>active</td>
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<tr>
<td><strong>Field of view</strong></td>
<td>70 deg (NPAL)</td>
<td>≈30 deg</td>
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<tr>
<td><strong>Pixles</strong></td>
<td>1024 x 1024</td>
<td>400 x 400</td>
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<tr>
<td><strong>Max range</strong></td>
<td>limited by selected resolution (m/px)</td>
<td>≈1000 m, depending on frame rate</td>
</tr>
<tr>
<td><strong>Frame rate</strong></td>
<td>20 Hz</td>
<td>≈1 Hz, depending on range</td>
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<td><strong>Sensor information</strong></td>
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<td>3-D</td>
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<td><strong>Navigation</strong></td>
<td>feature tracking across multiple frames</td>
<td>feature tracking across multiple frames</td>
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<tr>
<td><strong>Hazard avoidance</strong></td>
<td>&quot;shape from shading&quot;</td>
<td>single frame 3-D surface map</td>
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<td><strong>Maturity</strong></td>
<td>MER used camera for velocity estimation</td>
<td>TRL 3 today</td>
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<td></td>
<td>NPAL expected at TRL 5/6 in 2009</td>
<td>Expected to be 5/6 in 2010</td>
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</table>
Optical Navigation with CCD Camera (1)

- Navigation using unidentified landmarks (NPAL)
  - Tracking of unidentified, but distinct landmarks ("features")
  - Robust feature selection algorithm
    - no recognition required, no data base search
    - large number of features can be tracked at the same time
  - Requires good initial state estimation
  - Limited capability for horizontal error reduction on near circular and zero-g orbits
Optical Navigation with CCD Camera (2)

- Navigation using pre-registered landmarks
  - Star mapper analogy
  - Improves all three dimensions

- Sensor measurements
  - Relative landmark position
  - Relative speed by differentiation

- Processing & data fusion
  - Landmark recognition depends on distance (field of view) and illumination conditions
  - Pre-flight image data required
  - Combination with IMU & radar altimeter
  - Number of landmarks can be small
  - Simultaneous tracking of unknown features
Autonomous Hazard Avoidance

- Successive improvement of terrain evaluation while approaching
- Target identification expected at landing gate minus 60 sec
- 1st target update expected at \( h \approx 500 \, m \)
- Final landing spot selection at \( h \approx 50 \, m \)
  - Dust expected below
  - Preparation for touchdown
  - Resolution sufficient for obstacle identification
- Goal: avoid all obstacles > 30 cm
Terrain Evaluation and Obstacle Avoidance (1)

- Proposal of LIDAR-Sensor
  - Active illumination device
  - 3-D data acquisition

- Design drivers
  - Maximum range (⇒ acquisition time, number of channels)
  - Minimum object size (⇒ resolution, field of view)

- Algorithm:
  - Definition of a 3D data base for terrain evaluation
  - Recognition of objects based on abstract definition
  - Estimation of surface slope and detection of obstacles
  - Contribution to surface relative position and speed update
Terrain Evaluation and Obstacle Avoidance (2)

- Existing LIDAR Technology
  - 400 x 400 pixles
  - Field of view 30° x 30°
  - 1 Hz frame rate at 1000 m possible

- Image processing tasks:
  - IMU sensor fusion filter
    - Image correction for spacecraft motion (using IMU data)
    - Simultaneous improvement of spacecraft motion estimation
  - Hazard Assessment (risk map calculation)
  - Proposal of alternate landing sites

Risk map calculation process:
- Smoothened raw data
- Roughness analysis
- Risk map
Mechanical System & Lay-Out
Launch Configuration

- Use of standard launch adapter as baseline
- Minimize adapter mass requires “upside down” position launch
- Simplification of separation, because of no major interference of adapter with landing leg or main thruster
Lay-Out of Lander

**Main Dimensions**
- Diameter = 2.4 m
- Height (incl. landing legs) = 2.8 m
- Height (cylinder + cone) = 1.6 m

**Avionics**
- ACS 16x22N
- Main Engine (EAM) 4x500N
- Assist Engine (ATV 6x280N)

**Experiment & communication platform**

**Central cylinder (CFRP)**

**X-band Antenna**

**Solar arrays (foldable)**

**Landing legs**

**Experiment lift**

**4 Tanks (OST25/0)**

**Main Engine (EAM) 4x500N**

**Assist Engine (ATV 6x280N)**

**Thales Alenia Space**

**Precursor Mission M-2**

**Spacecraft Lay-Out**

Final Presentation, ESTEC, 02-Oct-2007
Precursor Mission M-2

Spacecraft Lay-Out

Front view
Scale: 1:15

Left view
Scale: 1:15

Top view
Scale: 1:15

Bottom view
Scale: 1:15
Mechanical System Analysis

- **Launch phase:**
  - Normal Mode Analysis to demonstrate the compliance with the frequency requirement from Launcher

- **Launch phase:**
  - Determination of buckling modes and stress level of the Lander main structural components under Quasi Static Loads (QSL)

- **Landing phase:**
  - Estimation on QSL level the Landing Gears performance in dependence to landing velocity and moon surface landscape (friction and slope)
**System dimensioning (Soyuz requirements)**

- Lateral Frequency >15 Hz
- Axial Frequency >35 Hz
- Max. Acceleration (QSL):
  - -5/+1.5g axial
  - ±1.8g lateral

**Construction**

- Main structure
  - Shell structure (CFRP)
  - Sandwich panels (CFRP, Aluminum SW core)
- Tank platform
  - Sandwich plate
- Engine platform
  - Aluminum plate (stringer reinforced)
Normal Modes (launch configuration)

Lateral Frequency 18.3 Hz

Axial Frequency 45.5 Hz
Buckling:
- load factor margin about 20% (conservative value)
- taking into account factor of 1.25 on flight loads

Strength:
- locally high stress in cone at attachment of shear walls
Landing Gear Assessments

- **Scope of Analyses**
  - Check of Static Stability
  - Forces in Struts
  - Leg Deformation
  - Ground Contact Forces (sliding risk)

- **No analysis of landing dynamics yet**

- **Design Landing speeds**
  - Vertical <3m/s
  - Horizontal <1m/s
Landing Gear Trade Off Criteria (1)

- Static Stability after touch down (safe contact of all foot pads with the soil without sliding)
  - Required contact surface of the foot pads
  - Margin of balance stability
  - Sensitivity of design to local slope
  - Sensitivity of design to soil friction coefficient
  - Penetration of foot pads number

- Dynamic Stability (at touchdown)
  - Accounting for landing speed
  - Accounting for direction of motion
  - Accounting for asynchronous touchdown of the pads (slope, ACS errors)
Landing Gear Trade Off Criteria (2)

- Failure tolerance (risk due to non nominal deployment or/and damage of one landing gear)
- System budgets (mass, stowed volume)
- Structural Design Criteria
  - Required stroke length of the attenuation system
  - Forces within the landing leg structure
  - Forces inserted into the main structure

Landing Gear Trade Off Result

- Design using 4 landing legs proposed as baseline
Propulsion Subsystem (1)

Unified propulsion subsystem concept (UPS)
MON / MMH - 1300 kg fuel
4 Ti propellant tanks (OST 25/0 incl. PMD OST2)

Special attention to be given to the “upside down” launch condition by modified PMD design and specially required bubble traps to assure that no gas is inside the fuel lines at operation.
Propulsion Subsystem (2)

- 500N EAM (European Apogee Motor)
  - High Performance \( \text{Isp} = 325 + \text{sec} \)
  - Non-ITAR Product, universal applicability
  - Competitive Price

- 220N Attitude Control & Braking thruster of ATV
  - Multi Purpose Thruster \( \text{Isp} = 287 \text{ sec} \)
  - High Reliability & Safety
  - Non-ITAR Product as far as possible
  - High performance (280N) version by reduction of cycles & pulse requirements
  - Development of thruster derivate proposed to ESA

- 22 N Thruster
  - Upscale of reliable 10N thruster \( \text{Isp} = 287 \text{ sec} \)
  - Reliable double swirl injector
  - Non coated combustion chamber
  - Interface compatible with standard 10N thruster
  - Non-ITAR Product possible
Preliminary Thermal Analysis: Environment

Moon surface temperature in a day
(t=0 at local dawn)

Surface Temperature

Definition of solar incidence angle

Solar Intensity at lunar surface
Preliminary Thermal Analysis: Scope

- Preliminary thermal model analysis using I-DEAS software
- Estimate the temperature of the electronics in upper compartment from solar heating during the lunar day
- Estimate the power requirement to heat the electronics above their minimum temperatures during the lunar night
- Estimate power requirement for rover to avoid extreme cold by sheltering on the lower platform of the lunar probe
Preliminary Thermal Analysis: Results

- **Lunar Day**
  - Current estimates suggest active thermal control required to keep electronics in upper compartment below their maximum temperature during the lunar day.

- **Lunar Night**
  - Design of interface between electronics and CFRP skins should minimise heat loss through conduction to reduce power requirement of heater.
  - Current estimates suggest a heater of 12.8 W required to keep battery in upper compartment above +5 deg C.
  - To keep the lunar rover above a temperature of -30°C for the duration of the lunar night requires special insulation of lower platform surface and a heater with a minimum power of approximately 16.5 Watts.

- Further thermal analyses required to establish final thermal control concept.
Preliminary Assessment of Link Budget

X - Band: Downlink for Pictures / Video (2000 kbps)
S - Band: Telemetry / Telecommand (64 kbps)

Lunar Lander:
- 2 Low Gain Antenna for TM/TC (-2dBi)
- High Gain Antenna für X-Band (0.9m;35dBi)
- SSPA for TM/TC: 30W
- TWTA for X-Band: 10W

X - Band Ground Station

<table>
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<tr>
<th></th>
<th>CEBREROS (Spanien)</th>
<th>KOUROU (KOUROU)</th>
<th>New Norcia (Australien)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennengröße (m)</td>
<td>35</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>Downlink G/T (dB/K)</td>
<td>50.8</td>
<td>37.5</td>
<td>50.1</td>
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<tr>
<td>EIRP (dBm)</td>
<td>122</td>
<td>113</td>
<td>137</td>
</tr>
</tbody>
</table>

Low Data Rate für TM / TC (max. 64 kbps)
S-Band: 2025 - 2110 MHz (Erde - LL)
2200 - 2290 MHz (LL - Erde)

High Data Rate for Pictures/ Video (max. 2000 kbps)
X-Band: 7190 - 7235 MHz (Erde - LL)
8450 - 8500 MHz (LL - Erde)
## Subsystem Mass Budget (1)

### Avionics, Power & TCS

<table>
<thead>
<tr>
<th>Source of Data</th>
<th>Mass (kg)</th>
<th>Quantity</th>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
<th>Margin (%)</th>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equipment:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery estimation</td>
<td>16,30</td>
<td>1</td>
<td>16,30</td>
<td>19,56</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDMU estimation</td>
<td>12,00</td>
<td>1</td>
<td>12,00</td>
<td>14,40</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMU estimation</td>
<td>8,30</td>
<td>1</td>
<td>8,30</td>
<td>9,96</td>
<td>20%</td>
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<tr>
<td>UHF LGA estimation</td>
<td>0,44</td>
<td>1</td>
<td>0,44</td>
<td>0,53</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-Band 4 Port Switch estimation</td>
<td>0,16</td>
<td>3</td>
<td>0,47</td>
<td>0,57</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-Band Port 4 Port estimation</td>
<td>0,16</td>
<td>1</td>
<td>0,16</td>
<td>0,19</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCDU estimation</td>
<td>17,40</td>
<td>1</td>
<td>17,40</td>
<td>20,88</td>
<td>20%</td>
<td></td>
<td></td>
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<tr>
<td>XBAND LGA estimation</td>
<td>0,17</td>
<td>2</td>
<td>0,33</td>
<td>0,40</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harness estimation</td>
<td>20,00</td>
<td>1</td>
<td>20,00</td>
<td>24,00</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Panel estimation</td>
<td>4,00</td>
<td>4</td>
<td>16,00</td>
<td>19,20</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrain Camera (HRSC) Mars Express</td>
<td>19,60</td>
<td>1</td>
<td>19,60</td>
<td>21,56</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIDAR estimation</td>
<td>12,00</td>
<td>1</td>
<td>12,00</td>
<td>13,20</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>141,15</td>
<td></td>
<td></td>
<td>165,17</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Avionics System:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>123,00</td>
<td>144,44</td>
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<tr>
<td>RHU+ Thermal switch estimation</td>
<td>1,25</td>
<td>3</td>
<td>3,75</td>
<td>4,50</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MLI 500g/m² CATIA (10m²)</td>
<td>0,50</td>
<td>10</td>
<td>5,00</td>
<td>5,50</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiators (OSR) 700g/m² estimation</td>
<td>0,70</td>
<td>2</td>
<td>1,40</td>
<td>1,68</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Heater estimation</td>
<td>2,00</td>
<td>1</td>
<td>2,00</td>
<td>2,40</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Paints (50g/m²) CATIA (10m²)</td>
<td>0,05</td>
<td>10</td>
<td>0,50</td>
<td>0,60</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW Insolation (3.5kg/m²) estimation</td>
<td>3,50</td>
<td>1</td>
<td>3,50</td>
<td>3,85</td>
<td>10%</td>
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</tr>
<tr>
<td>TW Heatshield estimation</td>
<td>2,00</td>
<td>1</td>
<td>2,00</td>
<td>2,20</td>
<td>10%</td>
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</table>
# Subsystem Mass Budget (3)

## Propulsion

<table>
<thead>
<tr>
<th>Components</th>
<th>Source of Data</th>
<th>Mass (kg)</th>
<th>Quantity</th>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
<th>Margin (%)</th>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank 516 ltr</td>
<td>Analysis TP43</td>
<td>29.00</td>
<td>4</td>
<td>116.00</td>
<td>127.60</td>
<td>10%</td>
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</tr>
<tr>
<td>Pressure Tank</td>
<td>Analysis TP43</td>
<td>12.35</td>
<td>2</td>
<td>24.70</td>
<td>27.17</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Thruster (500 N Bipropellant)</td>
<td>Analysis TP43</td>
<td>4.30</td>
<td>4</td>
<td>17.20</td>
<td>18.92</td>
<td>10%</td>
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<tr>
<td>Auxiliary Thruster (280 N Biprop)</td>
<td>Analysis TP43</td>
<td>2.00</td>
<td>6</td>
<td>12.00</td>
<td>13.20</td>
<td>10%</td>
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<tr>
<td>RCS Thruster (22 N -S22-02 Biprop)</td>
<td>Analysis TP43</td>
<td>0.40</td>
<td>16</td>
<td>6.40</td>
<td>7.04</td>
<td>10%</td>
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<tr>
<td>Components</td>
<td>Analysis TP43</td>
<td>8.93</td>
<td>1</td>
<td>8.93</td>
<td>9.82</td>
<td>10%</td>
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<tr>
<td>Support Structure</td>
<td>Analysis TP43</td>
<td>22.50</td>
<td>1</td>
<td>22.50</td>
<td>27.00</td>
<td>20%</td>
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<td></td>
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<tr>
<td>Tubing</td>
<td>Analysis TP43</td>
<td>10.00</td>
<td>1</td>
<td>10.00</td>
<td>12.00</td>
<td>20%</td>
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<td></td>
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<tr>
<td>Helium</td>
<td>Analysis TP43</td>
<td>5.00</td>
<td>1</td>
<td>5.00</td>
<td>5.50</td>
<td>10%</td>
<td></td>
<td></td>
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</tbody>
</table>

**Propulsion Subsystem**

<table>
<thead>
<tr>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>222.73</td>
<td>248.25</td>
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## Structure

<table>
<thead>
<tr>
<th>Components</th>
<th>Source of Data</th>
<th>Mass (kg)</th>
<th>Quantity</th>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
<th>Margin (%)</th>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure:</td>
<td>I-DEAS</td>
<td>18.00</td>
<td>1</td>
<td>18.00</td>
<td>19.80</td>
<td>10%</td>
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<td></td>
</tr>
<tr>
<td>Upper Cone</td>
<td>I-DEAS</td>
<td>109.20</td>
<td>1</td>
<td>109.20</td>
<td>120.12</td>
<td>10%</td>
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</tr>
<tr>
<td>Cylinder incl. Tank Platform</td>
<td>I-DEAS</td>
<td>22.50</td>
<td>1</td>
<td>22.50</td>
<td>27.00</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payload Platform</td>
<td>I-DEAS</td>
<td>4.40</td>
<td>1</td>
<td>4.40</td>
<td>4.84</td>
<td>10%</td>
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<tr>
<td>Spindle drive</td>
<td>Estimation</td>
<td>5.00</td>
<td>4</td>
<td>20.00</td>
<td>24.00</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing Leg:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leg Struts</td>
<td>Estimation</td>
<td>1.30</td>
<td>8</td>
<td>10.40</td>
<td>12.48</td>
<td>20%</td>
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<td></td>
</tr>
<tr>
<td>Damper Leg</td>
<td>Estimation</td>
<td>3.90</td>
<td>4</td>
<td>15.60</td>
<td>18.72</td>
<td>20%</td>
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<tr>
<td>Foot</td>
<td>Estimation</td>
<td>1.30</td>
<td>4</td>
<td>5.20</td>
<td>6.24</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attachments</td>
<td>Estimation</td>
<td>0.23</td>
<td>12</td>
<td>2.81</td>
<td>3.37</td>
<td>20%</td>
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<td></td>
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<tr>
<td>Adapter Ring:</td>
<td>I-DEAS</td>
<td>49.40</td>
<td>1</td>
<td>49.40</td>
<td>59.28</td>
<td>20%</td>
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</table>

**Structure Subsystem**

<table>
<thead>
<tr>
<th>Subtotal (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>235.01</td>
<td>268.85</td>
</tr>
</tbody>
</table>
System Mass Budget

- Applied ESA margin policy
  - Launcher performance (mass at separation) to be reduced by 5%
  - Total Delta-V to be increased by 5%
  - No extra margin on propellant
  - System and subsystem design mass margins according to maturity (between 5% and 20%)

Results

- Current top down mass capability for science & mobility ~100 kg
- Unused (but usable) propellant can further increase mobility mass (hopping fuel)

<table>
<thead>
<tr>
<th>Launcher Performance [kg]</th>
<th>3230</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% Margin</td>
<td>162</td>
</tr>
<tr>
<td>Launcher Adapter</td>
<td>110</td>
</tr>
<tr>
<td>Mass into GTO</td>
<td>2959</td>
</tr>
<tr>
<td>Used Propellant</td>
<td>2083</td>
</tr>
<tr>
<td>Delta-V Margin (5%)</td>
<td>66</td>
</tr>
<tr>
<td>Unusable Fuel</td>
<td>25</td>
</tr>
<tr>
<td>Landed Mass</td>
<td>785</td>
</tr>
<tr>
<td>Avionics &amp; Power</td>
<td>144</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>21</td>
</tr>
<tr>
<td>Propulsion</td>
<td>250</td>
</tr>
<tr>
<td>Structure</td>
<td>270</td>
</tr>
<tr>
<td>Science &amp; Mobility</td>
<td>100</td>
</tr>
</tbody>
</table>
Flight Demonstrators and Early Technology Demonstration
## Maturity Improvement by Pre-Development

Straight forward development logic and concurrent engineering requires pre-development activities on the most critical subsystems.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>MAIT Models</th>
<th>today</th>
<th>Ph. C/D</th>
<th>Design Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>System AIT</td>
<td>1 STM, 1 EM, 1 PFM</td>
<td></td>
<td></td>
<td>New System-Level AIV</td>
</tr>
<tr>
<td>Flight SW</td>
<td>3 Versions: DM, EM and PFM</td>
<td></td>
<td></td>
<td>New Development</td>
</tr>
<tr>
<td>STR &amp; Mech.</td>
<td>1 DM, 1 STM, 1 FM</td>
<td>TRL 5</td>
<td>TRL 5</td>
<td>Re-design, components and technology is available</td>
</tr>
<tr>
<td>P/L Platform Mech.</td>
<td>1 DM, 1 STM, 1 QM, 1 FM</td>
<td>TRL 3</td>
<td>TRL 5</td>
<td>Re-design, existing Spindle-Drive Actuators to be used</td>
</tr>
<tr>
<td>Landing Gear</td>
<td>1 DM, 4 STM, 1 QM, 4 FM, 2 SP</td>
<td>TRL 3</td>
<td>TRL 5</td>
<td>New Development</td>
</tr>
<tr>
<td>Propulsion S/S</td>
<td>2 EM, 1 FM</td>
<td>TRL 6</td>
<td>TRL 6</td>
<td>New S/S-Level AIV, existing Thrusters, Simple Modifications of components</td>
</tr>
<tr>
<td>Thrusters</td>
<td>1 EM, Set, 1 FM Set, 1 SP each type</td>
<td>TRL 3</td>
<td>TRL 8</td>
<td>Re-design</td>
</tr>
<tr>
<td>SGS</td>
<td>1 EM, 4 FM</td>
<td>TRL 7</td>
<td>TRL 7</td>
<td>Existing Batteries, Extensive Modification of PCDU</td>
</tr>
<tr>
<td>EPDS</td>
<td>1 EM, 1 FM</td>
<td>TRL 8</td>
<td>TRL 8</td>
<td>New Design, but existing components</td>
</tr>
<tr>
<td>Harness</td>
<td>1 EM, 1 FM</td>
<td>TRL 8</td>
<td>TRL 8</td>
<td>Extensive Modification</td>
</tr>
<tr>
<td>TCS incl. RHU’s</td>
<td>1 STM, 1 FM</td>
<td>TRL 5</td>
<td>TRL 6</td>
<td>New Design, existing components</td>
</tr>
<tr>
<td>DHS</td>
<td>1 EM, 2 FM</td>
<td>TRL 8</td>
<td>TRL 8</td>
<td>Minor Modification</td>
</tr>
<tr>
<td>Comms</td>
<td>1 DM (APM only), 1 EM, 2 FM</td>
<td>TRL 8</td>
<td>TRL 8</td>
<td>New Development</td>
</tr>
<tr>
<td>GNC</td>
<td>2 EM, 2 FM</td>
<td>TRL 5</td>
<td>TRL 6</td>
<td>Extensive Modification</td>
</tr>
<tr>
<td>LIDAR</td>
<td>1 DM, 1 EM, 1 QM, 1 FM</td>
<td>TRL 3</td>
<td>TRL 5</td>
<td>Extensive Modification</td>
</tr>
</tbody>
</table>
Terrestrial Landing Demonstrator Program

- **Step 1: "Lab tests"**
  - Representative environment (terrain, slope, illumination etc.)
  - Demonstrator moved and released by means of a crane
  - No active propulsion system
  - Study static and dynamic stability at touch down
  - Study navigation sensor sensibility to illumination, resolution
  - Study navigation filter dynamics
  - Study thresholds and functions of automated mission planning

- **Step 2: "Cold test"**
  - Captive flight underneath a helicopter
  - Navigation sensor testing and calibration from landing gate altitude down to engine shut down altitude
  - "Open loop" testing and calibration of GNC system

- **Step 3: "Hot Test"**
  - Releasing the demonstrator from a helicopter
  - Closed loop testing of complete system
Terrestrial Flight Demonstration of Final Landing Segment

- Identical landing trajectory
- Identical GNC algorithms, navigation sensors and propulsion subsystem components
- Thrust to weight ratio similarity
  - additional thrusters compensating higher Earth gravitation
  - Higher mass variation due to increased thrust and fuel demand
- This flight demonstration provides a validation of the complete landing system to the maximum extent possible on Earth
Summary & Conclusions
In the frame of the M2 study of the MSR Phase A2 a concept for a medium size mission to the Moon was developed which is focused on the essential key capability “Soft Precision Landing and advanced Optical Navigation” mandatory for all future applications.

The propulsion system is composed of components already existing or subject to final qualification in short term.

Available P/L mass, volume and as well servicing systems will allow for best science.

Built in “hopping” capability offers an innovative alternative for mobility on the Moon in combination with a rover.

Early practical demonstration is proposed for risk mitigation and a straight forward and cost effective development planning.

Self standing Moon mission concept for technology demonstration & science.

High technology verification potential for MSR without overloading the mission concept.
Schedule

- M2 mission schedule compliant with NEXT master schedule
- No “show stopper” identified in this Pre-Phase A study

Technical assessment indicates launch readiness earlier, if
- Phase A can be started in early 2008
- Pre-Development / Early Demonstration activities are started as complementary activities together with phase B
Thank you for your Attention!