Status of ESA’s SMART-1 Mission to the Moon

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M. Grande, J. Huovelin, J.L. Josset, H. Keller, A. Nathues, D. Koschny, M. Almeida, J. Zender and SMART-1 Science & Technology team

– SMART-1 Technology Mission: Solar Electric Propulsion to the Moon
– Payload Technology and Science objectives
– Lunar and planetary science with SMART-1
– Performances, Status and first results data integration
– SMART-1 Contribution to preparing Future Planetary exploration
SMART-1 Mission

SMART-1 web page (http://sci.esa.int/smart-1/)

• ESA SMART Programme: Small Missions for Advanced Research in Technology
  – Spacecraft & payload technology demonstration for future cornerstone missions
  – Management: faster, smarter, better (& harder)
  – Early opportunity for science
SMART-1 Mission

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  - Management: faster, smarter, better
  - Early opportunity for science

**SMART-1 Solar Electric Propulsion to the Moon**

- Test for Bepi Colombo/Solar Orbiter
- Mission approved and payload selected 99
- SMART-1 cost 110 MEuro
- 19 kg payload (delivered August 02)
- 370 kg spacecraft
- launched Ariane 5 on 27 Sept 03, Kourou
Primary Solar Electric Propulsion

The ion engine:
- SNECMA -SEP (F) (Stationary Plasma Thruster SPT-100, PPS-1350)
- High specific impulse (~1500 s)
- Low thrust (~70 mN = 7 grams) and low power consumption (~20 W/mN)
The Launch

- V162 lift-off on 27 September 2003 at 23:14:39 UTC – The launch was perfect
- SMART-1 separated at 23:56:03 into a GTO (656 x 35,881 km): perfect injection
- 100 s later telemetry was received by Perth GS
- Automatic activation sequence worked flawlessly
Solar Electric Propulsion to the Moon

- Launched 27 Sept 2003 as Auxiliary passenger on Ariane 5 into Geostationary Transfer Orbit with INSAT3 E and e-Bird
  (a bargain hitchhike to space)
- Spiral out cruise (15-18 month), SPT/coast arcs, lunar resonance swingbys & capture
Solar Electric Propulsion to the Moon

- Launched 27 Sept 2003 as Auxiliary passenger on Ariane 5 into Geostationary Transfer Orbit (a bargain hitchhike to space)
- Spiral out cruise (15-18 month), SPT/coast arcs, lunar resonance swingbys & capture, and spiral in
- lunar science orbit
  (300-1000 km perilune - 10000 km apolune, 6 month + extension)
United States (US)
- General Dynamics: Hydrazine Propulsion System
- Ithaco Space Systems Inc.: Reaction wheels
- L3 Communications: Electrical Ground Support Equipment
- TECSTAR: Solar Cells

Finland (FIN)
- Finish Meteorological Institute: Space plasma electron and dust detection (SPDE)

Sweden (S)
- Swedish Space Corporation: Prime Contractor
- Omnisys Instruments AB: Power Control and Distribution Unit
- SAAB Ericsson Space AB: Flight Module Assembly Integration and Testing, Antennae, Remote Terminal Unit, Electromagnetic Compatibility, Thermal Subsystem

United Kingdom (UK)
- Rutherford Appleton Laboratory: Compact imaging X-ray spectrometer (C-CDMS)

Denmark (DK)
- Terma A/S: On-board Independent Software Validation
- DTU Technical University of Denmark: Star tracker

The Netherlands (NL)
- Fokker Space: Solar Arrays
- TNO/TPD: Sun acquisition sensors

Germany (D)
- Astrium GmbH: Deep space X/Ka-band (KaTe)
- MPI Aeronomies: Near Infrared Spectrometer (SIR)

Belgium (B)
- Spacebel S.A.: On-board software detailed design
- Alcatel ETCA SA: Electric propulsion power processing

Switzerland (CH)
- APCO Technologies SA: Structure and Mechanical Ground Support Equipment
- Contraves Space AG: Electric propulsion mechanism
- CSEM: Asteroid-moon micro imager (AMIE)

France (F)
- SAFT Division Défence et Espace: Batteries
- Snecma Moteurs: Solar Array Mechanism, Electric Propulsion System (EPS)
- ATERM ES: Electric propulsion pressure regulation
- ArianeSpace: Launcher (Ariane 5)

Spain (E)
- Alcatel Espacio: S-band transponder
- CRISA: Battery management electronics

Italy (I)
- LABEN SpA: Electric Propulsion Diagnostic (EPDP)
- RSIS: Radio science investigation (RSIS)
From the first moment of ignition, the Hall effect propulsion has been used quasi-continuously to raise the altitude of the perigee (and the apogee) as quickly as possible.
Overview of SMART-1 instruments status and first results

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Instrument Technology

- **D-CIXS (Compact Imaging X-ray Spectrometer)**
  - Swept charge CCD, advanced micro structure collimator

- **SIR (IR Spectrometer)**
  - Monolithic quartz commercial grating spectrometer

- **AMIE (High Resolution micro-Camera)**
  - Micro-camera, 3D electronics and integrated Data Processor
  - Multicolour imaging, lightweight high resolution optics
  - Laser link with ESA Optical Ground Station in Tenerife
  - On Board Autonomous Navigation experiment

- **SPEDE Spacecraft Potential Electron Dust Experiment**
- **EPDP Electric Propulsion Diagnostics Package**
- **KATE Deep Space X-Ka Communications &**
- **RSIS radio science**
- **Star tracker**
<table>
<thead>
<tr>
<th><strong>Experiment</strong></th>
<th>Description</th>
<th>Mass</th>
<th>Power</th>
<th><strong>PI Investigator</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPDP</strong></td>
<td>Electric Propulsion Diagnostic Package</td>
<td>2.4</td>
<td>18</td>
<td>G. Noci (I)</td>
</tr>
<tr>
<td><strong>SPEDE</strong></td>
<td>Spacecraft Potential Electron and Dust Exp.</td>
<td>0.8</td>
<td>1.8</td>
<td>A. Malkki (SF)</td>
</tr>
<tr>
<td><strong>KATE</strong></td>
<td>Ka-Band TT&amp;C Experiment</td>
<td>6.2</td>
<td>2</td>
<td>R. Birkl (D)</td>
</tr>
<tr>
<td><strong>RSIS</strong></td>
<td>Radio-Science Investigations for SMART-1</td>
<td>(KATE/AMIE)</td>
<td></td>
<td>L. Iess (I)</td>
</tr>
<tr>
<td><strong>D-CIXS</strong></td>
<td>Demo Compact Imaging X-ray Spectrometer</td>
<td>5.2</td>
<td>18</td>
<td>M. Grande (UK)</td>
</tr>
<tr>
<td><strong>XSM</strong></td>
<td>X-ray Solar Monitoring</td>
<td>(with D-CIXS)</td>
<td></td>
<td>J. Huovelin (SF)</td>
</tr>
<tr>
<td><strong>SIR</strong></td>
<td>SMART-1 Infrared Spectrometer</td>
<td>2.3</td>
<td>4</td>
<td>H.U. Keller (D)</td>
</tr>
<tr>
<td><strong>AMIE</strong></td>
<td>Advanced Moon micro-Imager Experiment</td>
<td>2.1</td>
<td>9</td>
<td>J.L. Josset (CH)</td>
</tr>
<tr>
<td><strong>Laser</strong></td>
<td>Experimental Deep-space Laser link</td>
<td></td>
<td></td>
<td>(using AMIE) Z. Sodnik (ESA)</td>
</tr>
<tr>
<td><strong>OBAN</strong></td>
<td>On-Board Autonomous Navigation Exp.</td>
<td></td>
<td></td>
<td>(using AMIE) F. Ankersen (ESA)</td>
</tr>
</tbody>
</table>
SMART-1 Startracker commissioning image
(J. Joergensen, DTU, DK)
SMART-1 plasma diagnostics

Ion peaks at 30 and 50 eV

LP Floating Potential Monitoring: Continuous Thrust

AsUT 2003-12-16T13:06:46.995
AsUT 2004-01-07T08:31:36.650
SMART-1 KATE
Deep Space X Ka comm.

- X band experiment
- First European Ka experiment
AMIE camera: multicolour eyes
PI: J.L. Josset (CSEM - CH); Co-I’s from I, F, CH, Fin, NL, ESTEC

Science and Technology Objectives

- Miniature camera for Cruise and Lunar phase
- Lunar science high-res. multi-spectral imaging (40 m Moon Southern hemisphere)
- Extension of data-set Apollo/Clementine
- Support laser-link, OBAN, RSIS; aligned to SIR.
- Online data and projects for Public Outreach

- 1st Moon quarter Image from AMIE
AMIE multicolour microcamera
PI: J.L. Josset (Space-X - CH); Co-I’s from I,F,CH, Fin, NL, ESTEC

Main Experiment features:
• CCD electronics & Micro-DPU in high-density packaged 3-D interconnect technology.
• Shielded Off The Shelves components.
• 5.3° FOV, 16.5/154 mm d/f optics
• 1024 x 1024 Si-CCD
• 3 fixed wide-band filters coating (0.75÷0.96 µm) + panchromatic + laser-link filter (847)
• Mass 2.1 kg (Opt.Head 400 gr), Power 9W
AMIE camera science

- **Multicolour:**
  - White light +3 filters 750, 900 and 950 nm
- **High Resolution Geology**
  - 40 m/pixel near perilune, 80 m average
  - Geological context for SIR & D-CIXS data
  - Multi-colour complement
  - Stereo/ multi-phase angle observations
  - Survey landing sites for sample return
AMIE camera science

- **Multicolour:**
  - White light +3 filters 750, 900 and 950 nm
- **High Resolution Geology**
  - 40 m/pixel near perilune, 80 m average
  - Geological context for SIR & D-CIXS data
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- **Repeated deep imaging of south pole**
  - Mapping ‘eternal light’ and ‘shadow’
  - Search for potential ‘water ice traps’
  - Potential for lunar bases, power, resources
  - Preparation for future lunar exploration
SIR IR spectrometer science

- **0.93 to 2.4 \( \mu \text{m} \), 256 channels, Lunar Spectral mapping**
  - Discrimination of minerals: pyroxenes and olivine
  - Olivine from mantle: crustal differentiation/evolution
  - Basins exposed materials from mantle (e.g. South-Pole Aitken)
  - Deep spectra in permanent shadows (ice spectral features)

- **SIR highest spatial resolution 300 m**
  - Resolve units on central peaks, walls, rims and ejecta blankets of large impact craters >>> stratigraphy of lunar crust
SIR commissioning

- 1\textsuperscript{st} SMART-1 SIR infrared spectrometer Moon scan
- 6 Feb 04
D-CIXS spectrometer

PI: M. Grande (RAL-UK), co-I’s UK, Fin, F, E, S

Science and Technology Objectives

• Demonstrate compact X-ray imaging spectrometer
• Technologies: Swept Charge Devices (Detectors)
• Photo-lithographic Micro-structure collimator
• Global lunar elemental composition mapping of surface via X-ray fluorescence
• X-ray celestial sources, Earth aurora and magneto-tail during cruise

Main features

• Energy range: 0.5 - 10 keV, 140 eV resolution.
• 24 (3 x 8) SCD detectors (12 x 32 deg FOV, noise 3 e⁻)
• Operat. temperature ~ -20°C, door shield (proton damage)
• 5.2 kg, 18 W (including XSM)
D-CIXS science

- D-CIXS map, 50 km resolution
- Absolute abundances Mg, Si, Al, (Fe)
- Bulk crustal composition
• **Bulk crustal composition**
  – Constrain theories of origin and evolution of the Moon.

• **Mapping of Mg# = Mg/Mg+Fe:**
  – Mg# as trace of evidence for a primitive source
  – Constraints on magma ocean model, evolution, impact effects
  – Study of South Pole-Aitken Basin (SPA) and other lunar basins
How did the Moon form?
## Resolution range vs previous lunar missions

<table>
<thead>
<tr>
<th>FOV/RES</th>
<th>AMIE</th>
<th>SIR</th>
<th>D-CIXS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View (deg)</td>
<td>5.3</td>
<td>0.06</td>
<td>12x32</td>
</tr>
<tr>
<td>Resolution (mrad)</td>
<td>0.08</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>FOV in km</td>
<td>25</td>
<td>0.3</td>
<td>60x150</td>
</tr>
<tr>
<td>Res. Pixel</td>
<td>30 m</td>
<td>300 m</td>
<td>40 km</td>
</tr>
<tr>
<td>– from perilune</td>
<td>300 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral channels</td>
<td>5</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>Spectral range</td>
<td>500-950 nm</td>
<td>0.9-2.4 µm</td>
<td>.5-10keV</td>
</tr>
</tbody>
</table>

### Comparison with previous missions:
- **Clementine**: 25 m B&W high res, **colour 160 m** (no spectra)
- **Prospector**: neutron, gamma-ray **(150-50 km)**
SMART-1 Science Opportunity

- **LUNAR SCIENCE**
  - 1st X-ray mapping for Mg, Al, Si at <50 km resolution
  - 1st infrared spectral mineralogy mapping 0.9-2.5 microns +
  - Local multi-band mapping at res. 30 m from 300 km
  - Polar areas illumination and resource mapping
  - Stereo mapping for Digital Elevation Models

- **CRUISE SCIENCE**
  - Earth and magnetospheric imaging
  - Long term X-ray monitoring of Sun & cosmic sources
# Lunar Targets for SMART-1

<table>
<thead>
<tr>
<th></th>
<th>D-CIXS</th>
<th>SIR</th>
<th>AMIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global composition</td>
<td>Al, Mg, Si, (Fe) olivines/pyroxenes</td>
<td>“”</td>
<td>“”</td>
</tr>
<tr>
<td>Local Resources</td>
<td></td>
<td>“”</td>
<td>“”</td>
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<tr>
<td>Highlands</td>
<td>Composition</td>
<td>Lateral chemical variations</td>
<td></td>
</tr>
<tr>
<td>Mantle</td>
<td>source Mg#</td>
<td>basalt distribution</td>
<td></td>
</tr>
<tr>
<td>Vertical lithology</td>
<td>basins, central peaks, small craters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impacts</td>
<td>SPA, basins</td>
<td>Rims, ejecta, Crater counts</td>
<td></td>
</tr>
<tr>
<td>Exotic targets</td>
<td>Swirls, young volcanoes</td>
<td>Deep images</td>
<td></td>
</tr>
<tr>
<td>Polar areas</td>
<td>Ice spectra</td>
<td>weathering, phase angle, T effects</td>
<td></td>
</tr>
<tr>
<td>Regolith</td>
<td></td>
<td>Stereo DEM</td>
<td></td>
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<tr>
<td>Topography</td>
<td></td>
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</tbody>
</table>
SMART-1 Data integration

- Intercalibration / Integration of data
  - between the SMART-1 instruments
  - with existing data from Clementine and Lunar Prospector
- Validated data released to Planetary Data System after 6 months

- SMART1 use for future Missions
  - Lunar-A/Selene,
  - Chandrayaan-1, Chang’e,
  - South Pole Aitken Basin Sample Return, US Lunar Reconnaissance Orbiter,
  - Future landers (US, Japan, China, ESA Aurora, ..)
SMART-1 Themes

• FORMATION AND EVOLUTION OF ROCKY PLANETS
  - chemical composition: Earth-Moon origin and evolution
  - signatures of accretional processes and giant bombardment

• COMPARATIVE GEOPHYSICAL PROCESSES
  - volcanism, tectonics, cratering, erosion,
  - deposition of ices and volatiles

• PREPARING FUTURE LUNAR/PLANETARY EXPLORATION
  - survey of lunar resources (minerals, volatiles, illumination)
  - high resolution studies for future landing sites and outposts
  - the Moon technology/science test-bed for planetary exploration
International Lunar Exploration

- Clementine (US, BMDO) 1994
  - Multi-band Imaging, technology demonstration
- Lunar Prospector (US, NASA Discovery) 1998
  - Neutron, gamma ray low resolution mapping
- SMART-1 (ESA Technology Mission) 2003
  - Instrument technology, geochemistry, high resolution,
- Lunar A (J, ISAS Science) 2004
  - 2 Penetrators with seismometers + equator cameras
- SELENE (J, ISAS/NASDA) 2006
  - Ambitious orbiter instruments for science
- Chandrayaan-1 (ISRO, India) 2008
  - Lunar Orbiter, launch PSLV
- US Lunar reconnaissance orbiter 2008
- South Pole Aitken Basin Sample Return (NASA New frontiers) 2009
- Soft landers (US, China, Japan, Europe) 2010
Commissioning and present status

• Subsystem commissioning completed in four days: AOCS, power, thermal, DH, TT&C, EP

• Radiation effects on electronics (SEU) and on star tracker (low E protons) were overcome. On 30 September the EP was fired successfully, and then thrusting. We survived Halloween solar storm!

• Escape of inner radiation belts in January 2004

• March 04 eclipse season

• In April 2004 apogee 80000 km, period 30 hours

• April 04 end payload commissioning, May 04 start cruise science

• Lunar resonances passes: 20 Aug, 15 Sept, 13 Oct 2004,

• Capture 17 Nov 04, arrival lunar science orbit Feb 05

• Further reports: COSPAR Paris 19-23 July 04, ILEWG6 Lunar Conference Udaipur India 22-26 Nov 04
How to get involved

• Science data distributed to community (PDS) after 6 months
• Training opportunities
  – Engineering/science stages at ESTEC or instrument teams
  – ESTEC Young Graduate Trainee Programme
  – PhDs or engineering thesis using ESA missions
  – ESA post-doctoral programme (internal and external)
• Education/outreach projects and PR
  – Organise follow up students workshops
  – PR events
• Exploitation of SMART-1, Mars Express, Venus Express,
• SMART-1 follow up
  – Indian lunar mission 2008 (AO 10kg)
  – SMART-1 collaborations Japan Lunar-A/Selene,
  – US Lunar Reconnaissance orbiter
  – Future lunar landers (US, Japan Selene B, Europe)
• Synergies with future missions (Moon, Mars, Venus, Mercury)
• Follow-up : Aurora industrial, academic activities