SMART-1

esa SCIENCE

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

Bernard H. Foing*,

**Chief Scientist, ESTEC/SCI-SR, ESA Science Directorate, Bernard.Foing@esa.int*

G.Racca, A. Marini and SMART-1 Project team

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

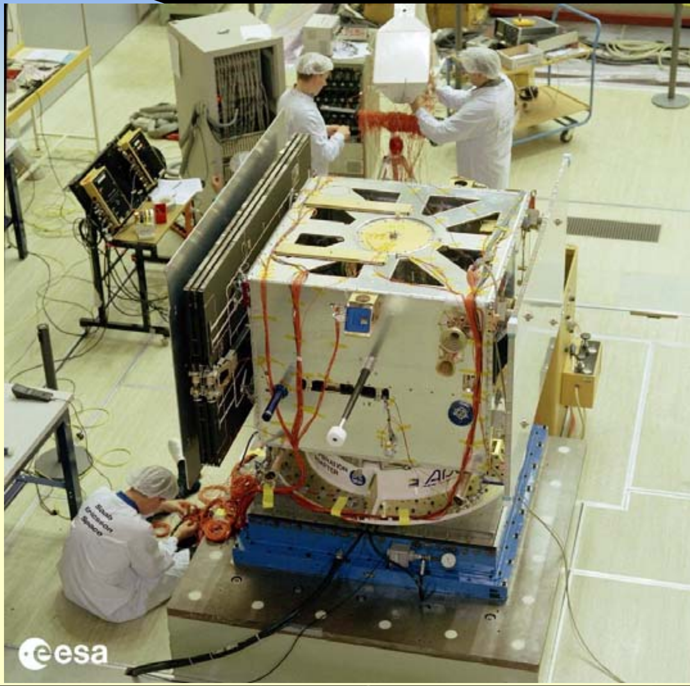
SMART-1 web page (http://sci.esa.int/smart-1/)

- **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

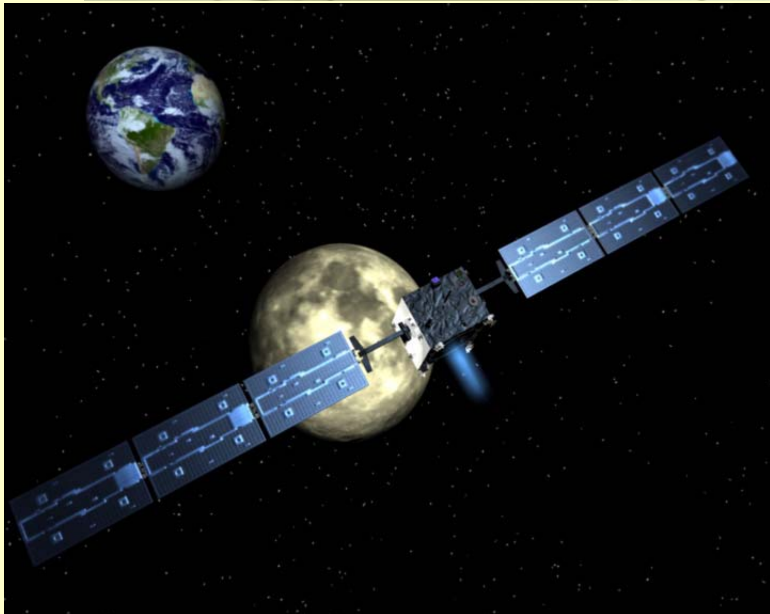
SMART-1 web page (http://sci.esa.int/smart-1/)

- **ESA SMART Programme: Small Missions for Advanced Research in Technology**
  - Spacecraft & payload technology demonstration for future cornerstone missions
  - Management: faster, smarter, better
  - Early opportunity for science



SMART-1 Solar Electric Propulsion to the Moon

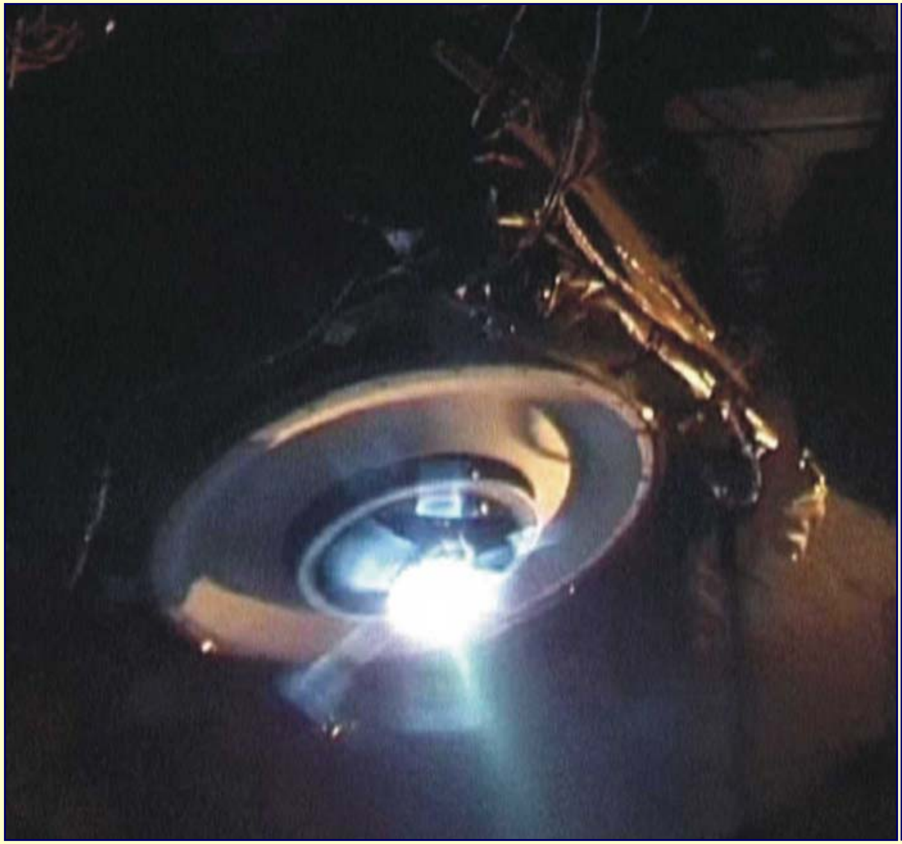
- Test for Bepi Colombo/Solar Orbiter
- Mission approved and payload selected 99
- SMART-1 cost 110 MEuro
- 19 kg payload (delivered August 02)
- 370 kg spacecraft
- launched Ariane 5 on 27 Sept 03, Kourou



Primary Solar Electric Propulsion

The ion engine:

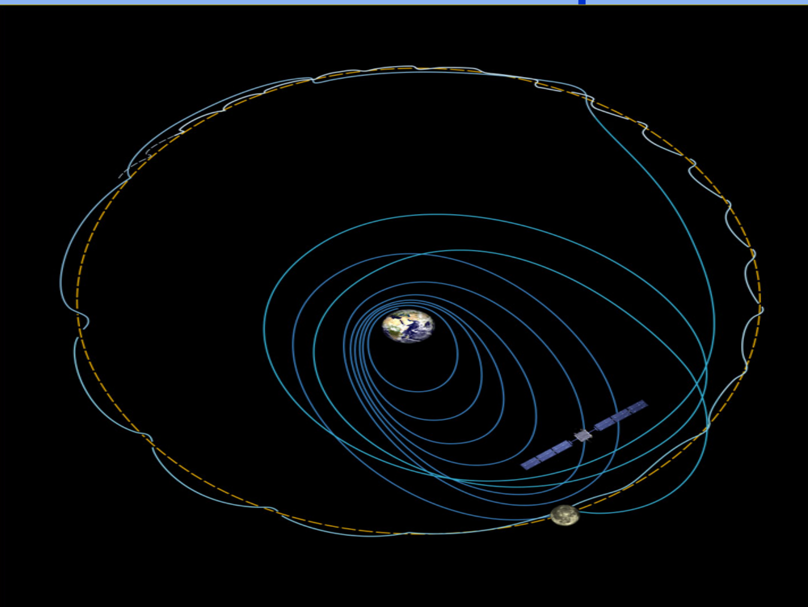
- SNECMA -SEP (F) (Stationary Plasma Thruster SPT-100, PPS-1350)
- High specific impulse (~1500 s)
- low thrust (~70 mN = 7 grams) and low power consumption (~20 W/mN)



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

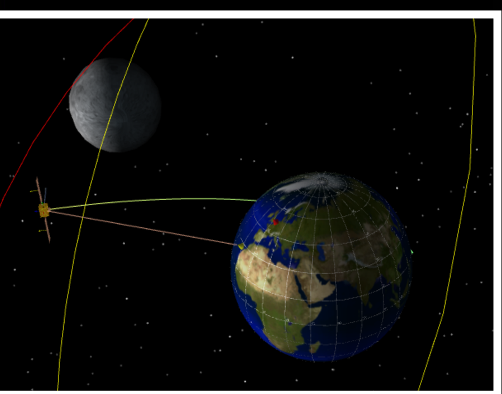
Solar Electric Propulsion to the Moon

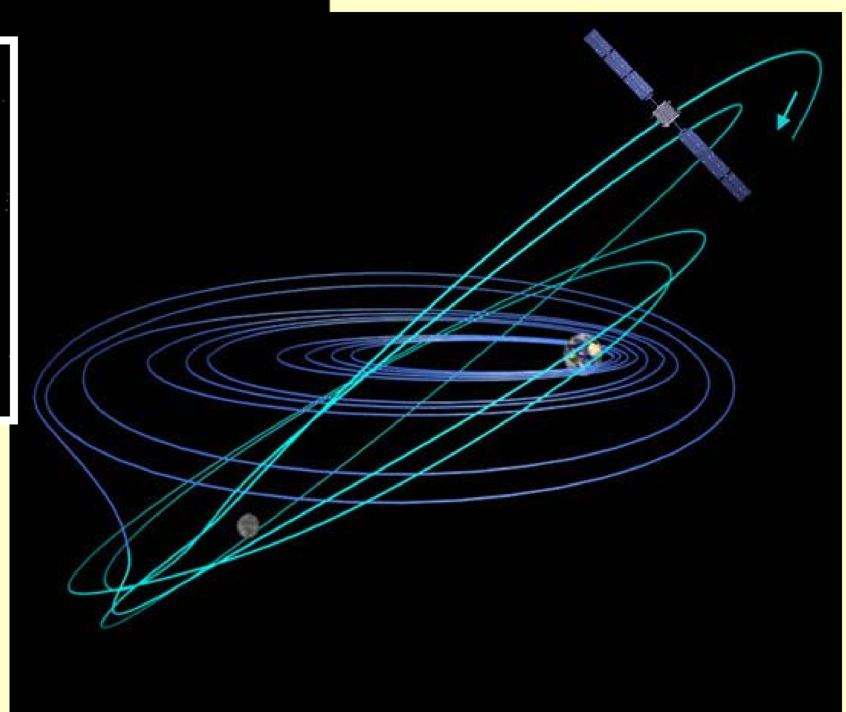


- Launched 27 Sept 2003 as Auxiliary passenger on Ariane 5 into Geostationary Transfer Orbit with INSAT3 E and e-Bird

  (a bargain hitchhike to space)

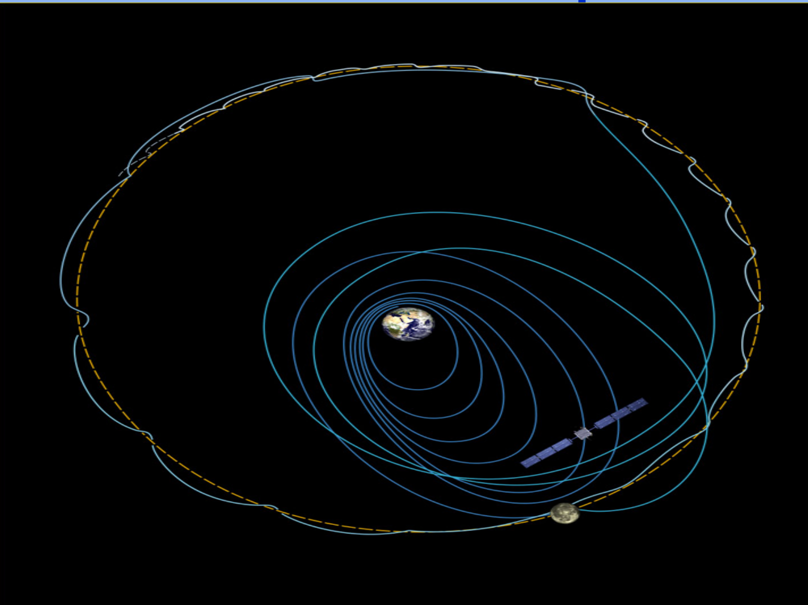
- Spiral out cruise (15-18 month), SPT/coast arcs, lunar resonance swingbys & capture





SMART-1

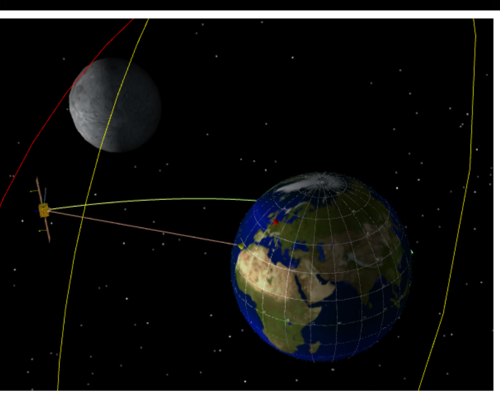
Solar Electric Propulsion to the Moon

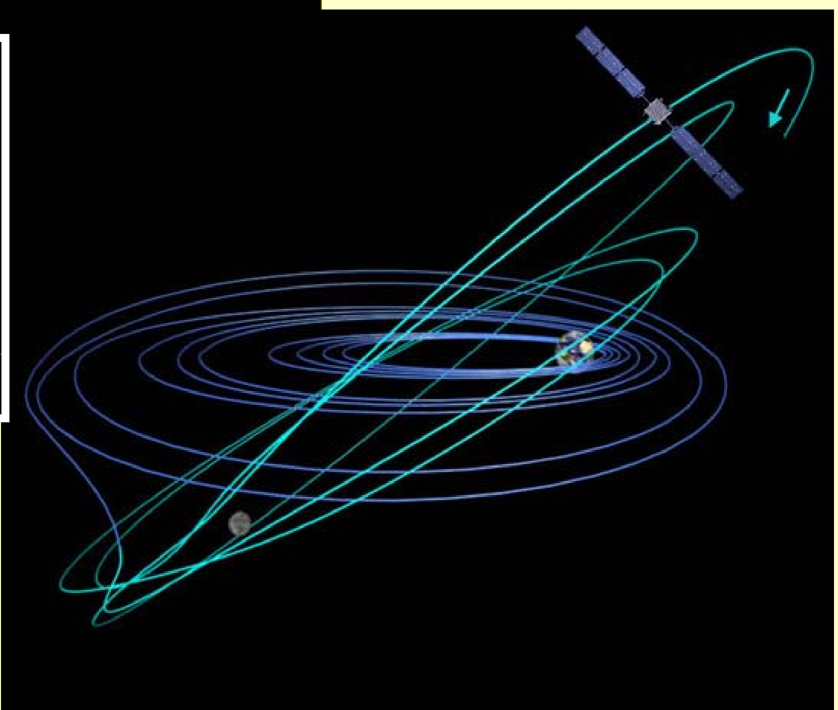


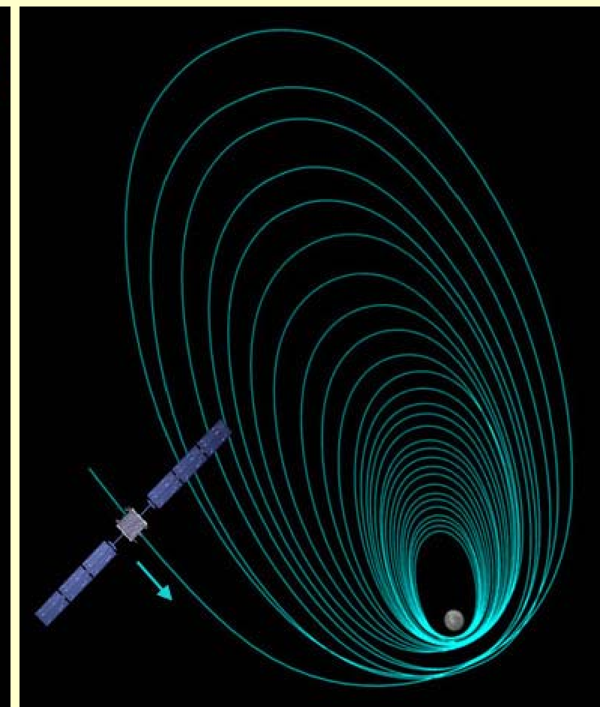
- Launched 27 Sept 2003 as Auxiliary passenger on Ariane 5 into Geostationary Transfer Orbit (a bargain hitchhike to space)
- Spiral out cruise (15-18 month), SPT/coast arcs, lunar resonance swingbys & capture**, and spiral in**
- **lunar science orbit**

(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

United Kingdom (UK)

Rutherford Appleton Laboratory: Compact imaging X-ray spectrometer (D-CIXS)

The Netherlands (NL)

Fokker Space: Solar Arrays
TNO/TPD: Sun acquisition sensors

Belgium (B)

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

France (F)

SAFT Division Defence et Espace: Batteries
Snecma Moteurs: Solar Array Mechanism, Electric Propulsion System (EPS)
ATERMES: Electric propulsion pressure regulation
Arianespace: Launcher (Ariane 5)

Spain (E)

Alcatel Espacio: S-band transponder
CRISA: Battery management electronics

Finland (FIN)

Finish Meteorological Institute: Space plasma electron and dust detection (SPEDE)

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

Denmark (DK)

Terma A/S: On-board Indepedent Software Validation
DTU Technical University of Denmark: Star tracker

Germany (D)

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

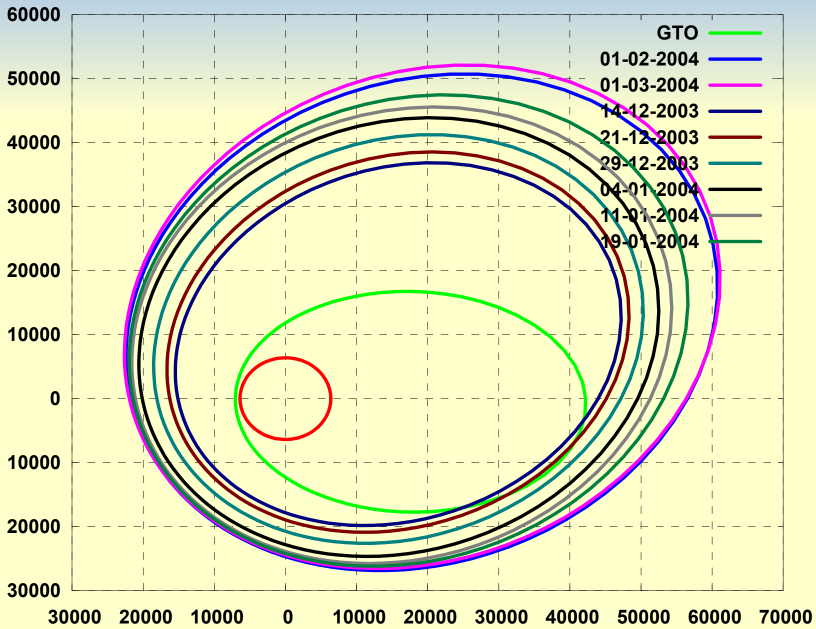
Switzerland (CH)

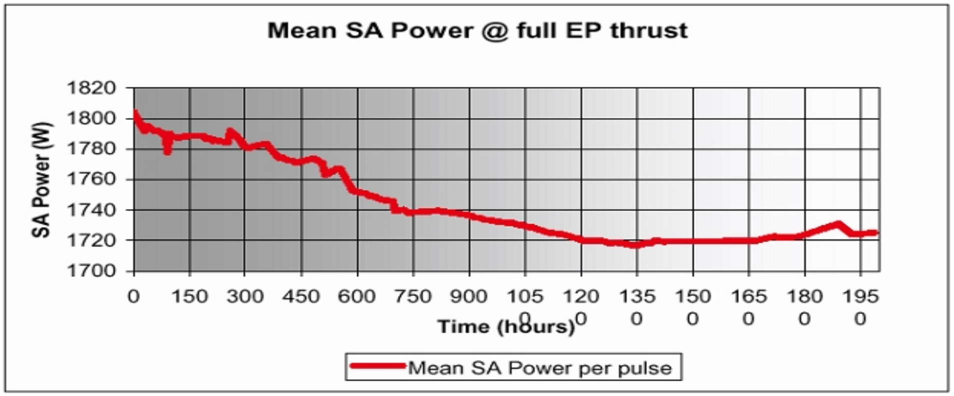
APCO Technologies SA: Structure and Mechanical Ground Support Equipment
Contraves Space AG: Electric propulsion mechanism
CSEM: Asteroid-moon micro imager (AMIE)

Italy (I)

LABEN SpA: Electric Propulsion Diagnostic (EPDP)
RSIS: Radio science investigation (RSIS)

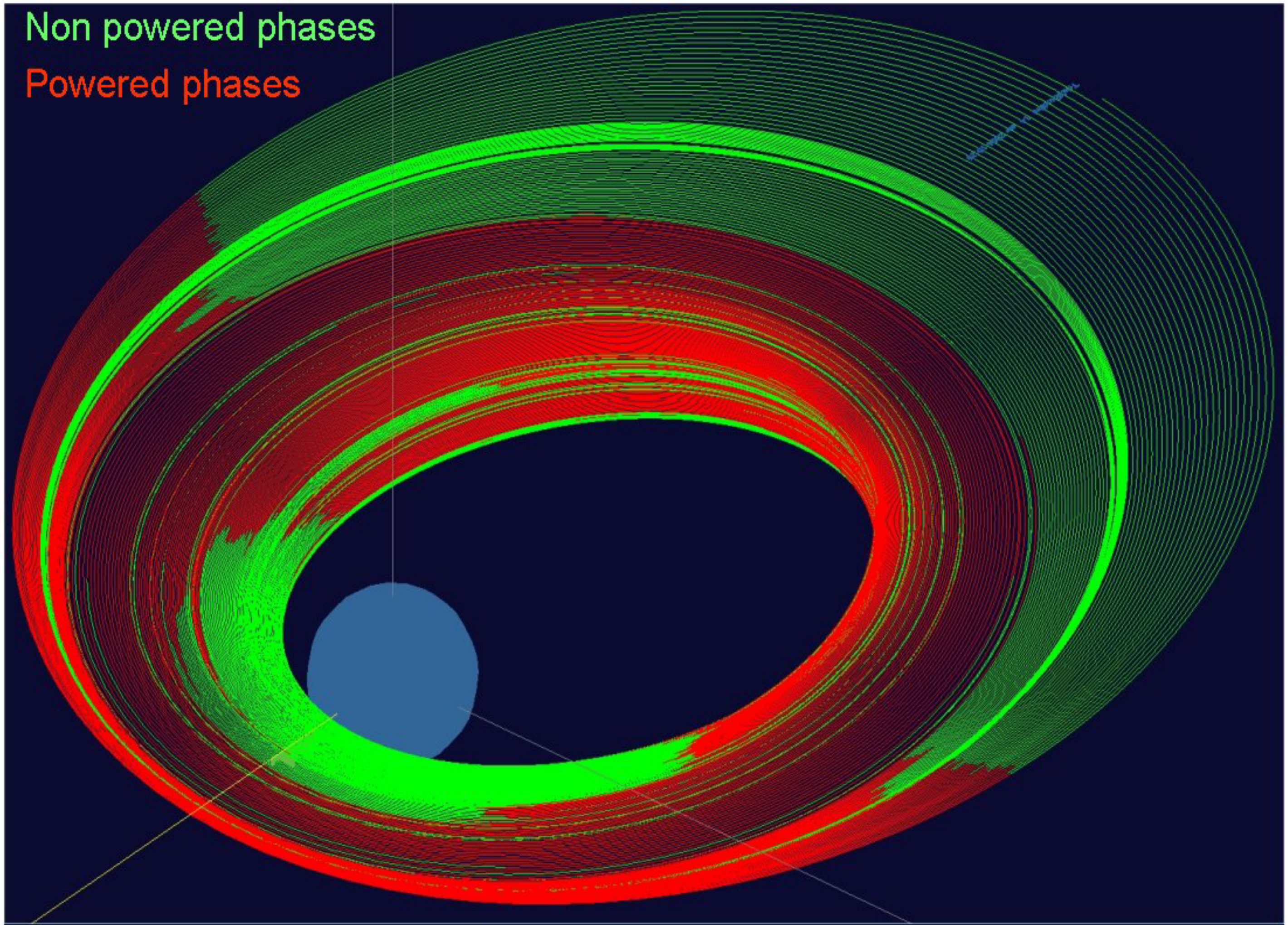
SMART-1


GTO
01-02-2004
01-03-2004
14-12-2003
21-12-2003
29-12-2003
04-01-2004
11-01-2004
19-01-2004
60000
50000
40000
30000
20000
10000
0
10000
20000
30000
30000 20000 10000 0 10000 20000 30000 40000 50000 60000 70000


Mean SA Power @ full EP thrust
SA Power (W)
1820
1800
1780
1760
1740
1720
1700
0 150 300 450 600 750 900 1050 1200 1350 1500 1650 1800 1950
Time (hours)
Mean SA Power per pulse

EN ROUTE TO THE MOON

SMART-1 - INCREASING ELLIPSES



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

Bernard H. Foing*,

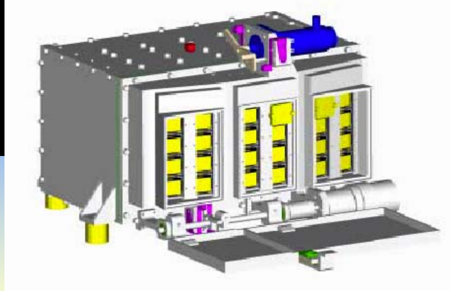
***Chief Scientist, ESTEC/SCI-SR, ESA Science Directorate, Bernard.Foing@esa.int**

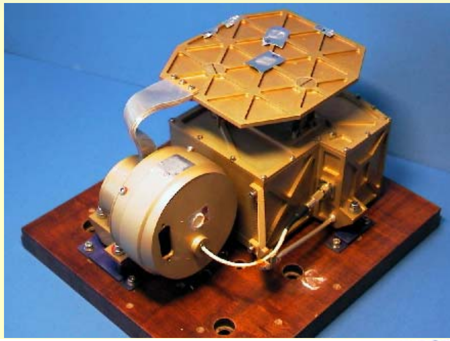
G.Racca, A. Marini, E. Evrard and SMART-1 Project team

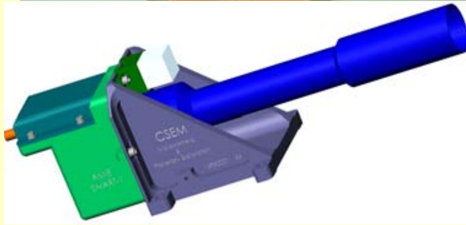
M. Grande, J. Huovelin, J.L. Josset, H. Keller, A. Nathues, D. Koschny, M. Almeida, J. Zender and SMART-1 Science & Technology team

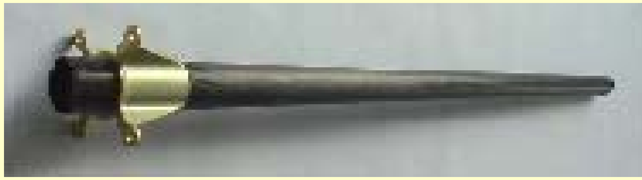
- *SMART-1 Technology Mission: Solar Electric Propulsion to the Moon*
- *Payload Technology and Science objectives*
- *Lunar and planetary science with SMART-1*
- *Performances, Status and first results data integration*
- *SMART-1 Contribution to preparing Future Planetary exploration*

Instrument Technology









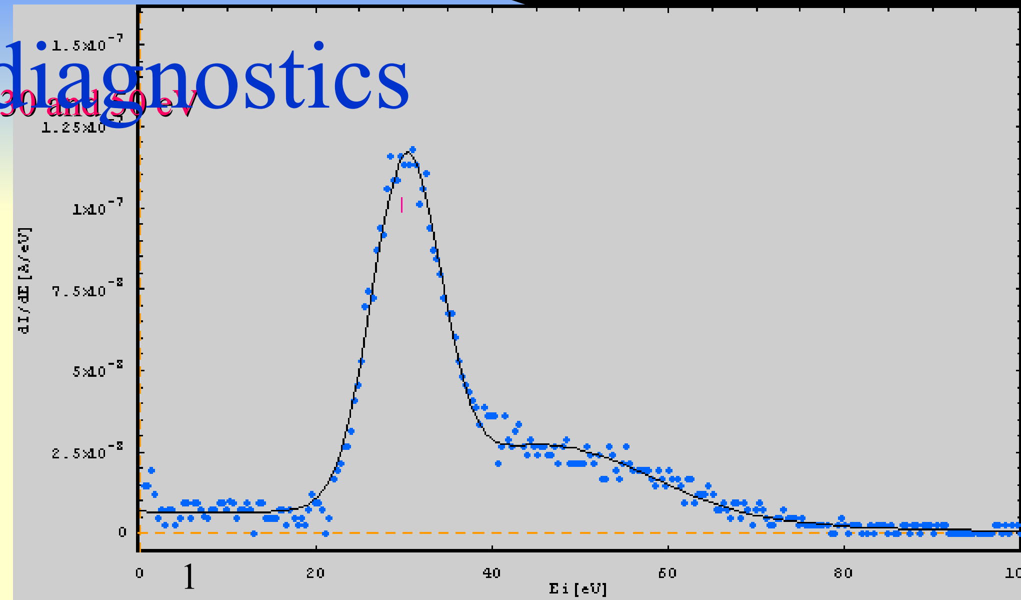
- D-CIXS (Compact Imaging X-ray Spectrometer)
  - Swept charge CCD, advanced micro structure collimator
- SIR (IR Spectrometer)
  - Monolithic quartz commercial grating spectrometer
- AMIE (High Resolution micro- Camera)
  - micro-camera, 3D electronics and integrated Data Processor
  - Multicolour imaging, 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

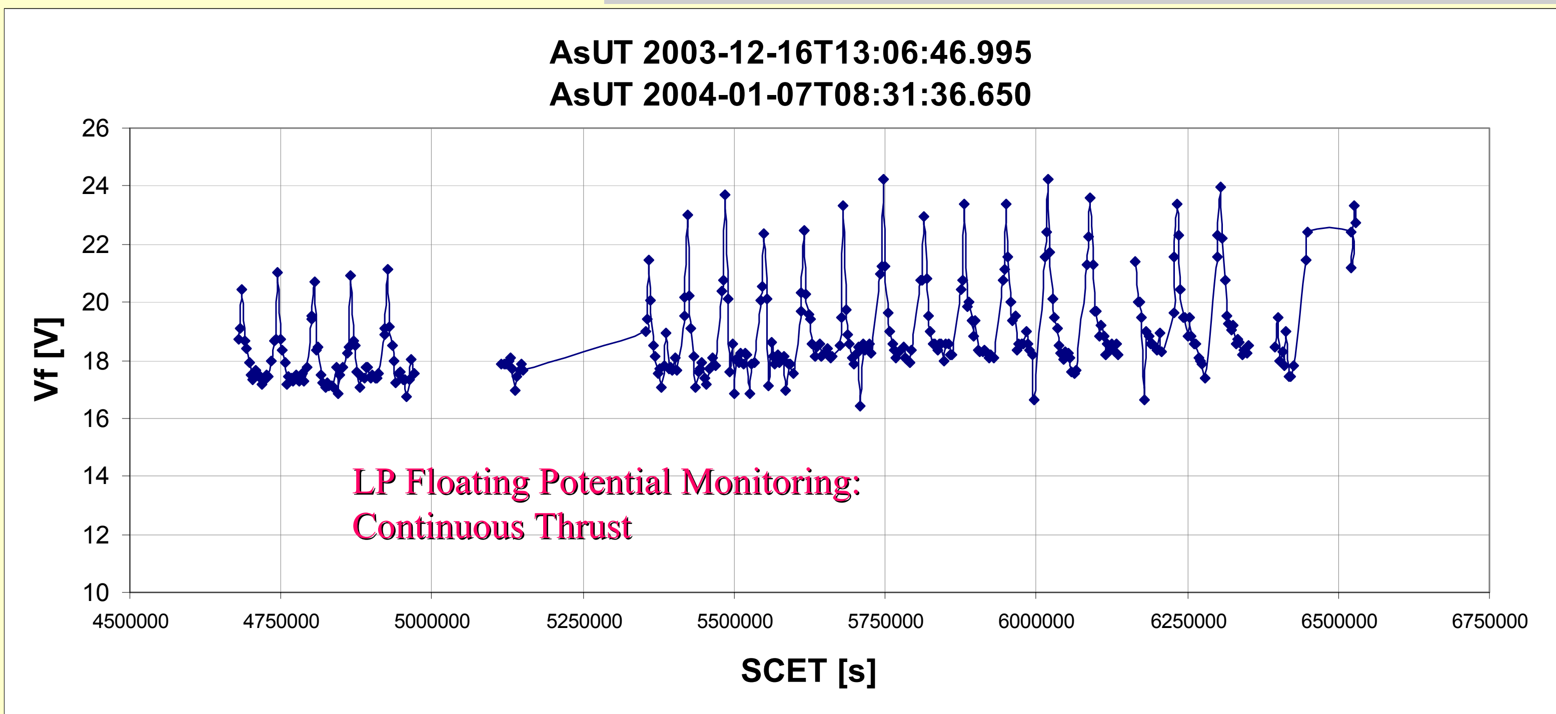
7 experiments and 10 investigations

		Mass (kg)	Power (W)	PI Investigator
EPDP	Electric Propulsion Diagnostic Package	2.4	18	G. Noci (I)
•**SPEDE**	Spacecraft Potential Electron and Dust Exp.	0.8	1.8	A. Malkki (SF)
•**KATE**	Ka-Band TT&C Experiment	6.2	2	R. Birkl (D)
•*RSIS*	Radio-Science Investigations for SMART-1	*(KATE/AMIE)*		L. Iess (I)
•**D-CIXS**	Demo Compact Imaging X-ray Spectrometer	5.2	18	M. Grande (UK)
•**XSM**	X-ray Solar Monitoring	(with D-CIXS)		J. Huovelin (SF)
•**SIR**	SMART-1 Infrared Spectrometer	2.3	4	H.U. Keller (D)
•**AMIE**	Advanced Moon micro-Imager Experiment	2.1	9	J.L. Josset (CH)
Laser	Experimental Deep-space Laser link	*(using AMIE)*		Z. Sodnik (ESA)
OBAN	On-Board Autonomous Navigation Exp.	*(using AMIE)*		F. Ankersen (ESA)

SMART-1 Startracker commissioning image
(J. Joergensen, DTU, DK)

SMART-1 plasma diagnostics

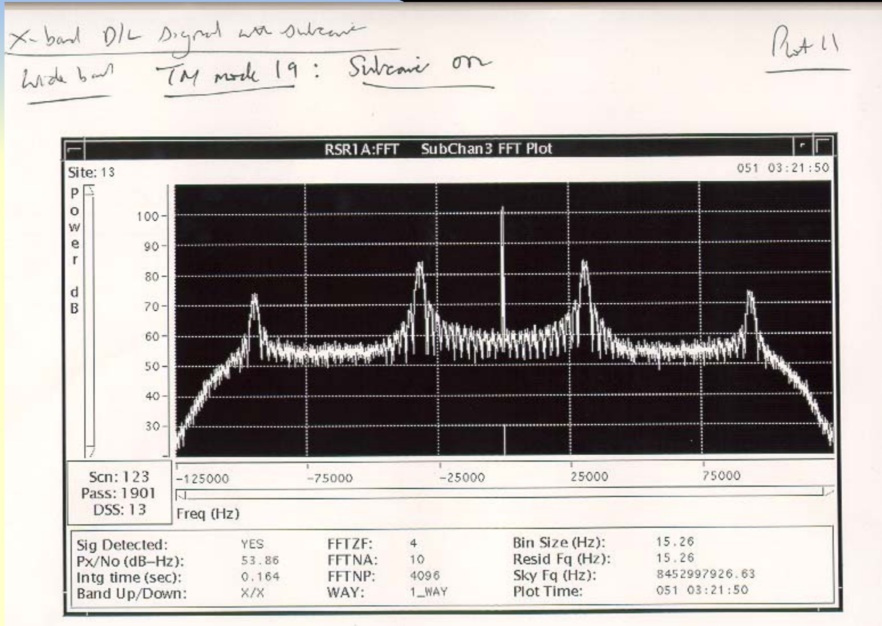




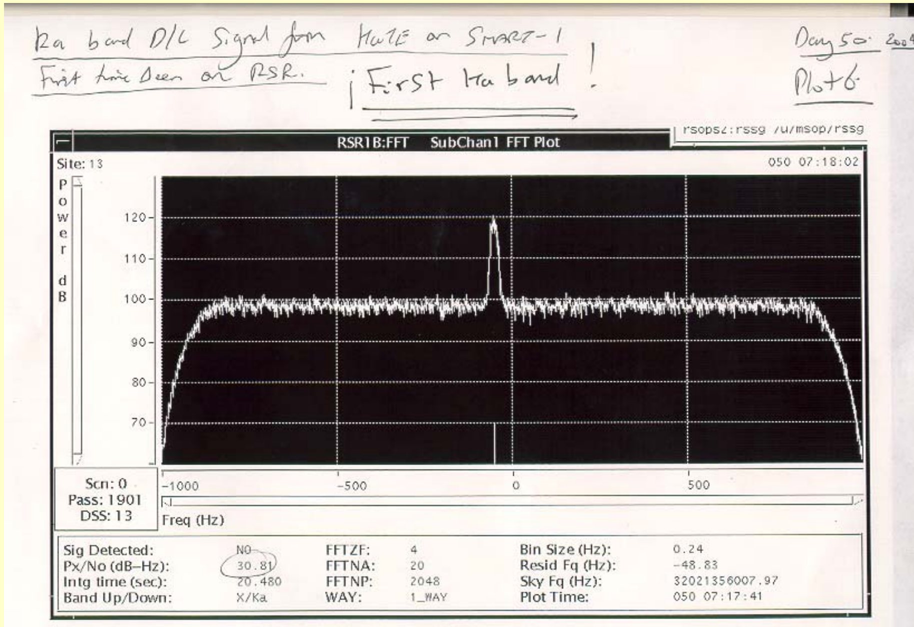
esa SCIENCE

SMART-1 KATE
Deep Space X Ka comm.

- X band experiment



- First European Ka experiment

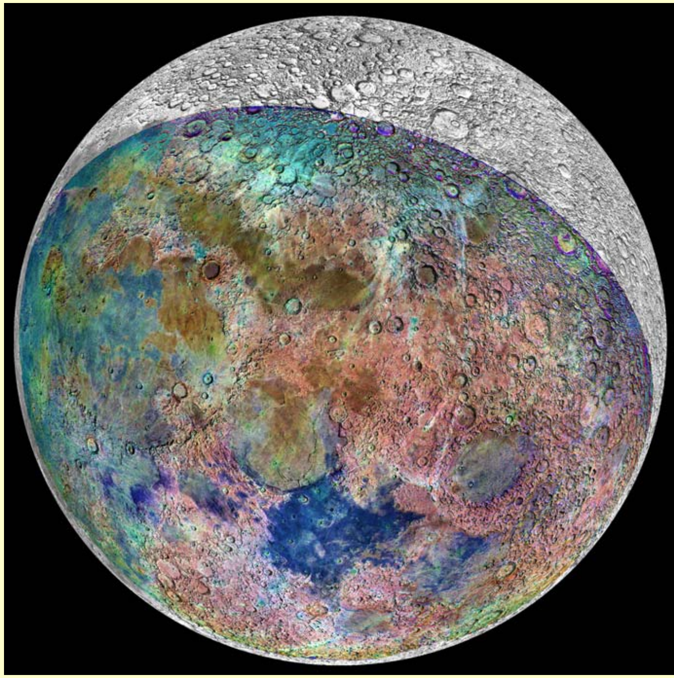


AMIE camera: multicolour eyes

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

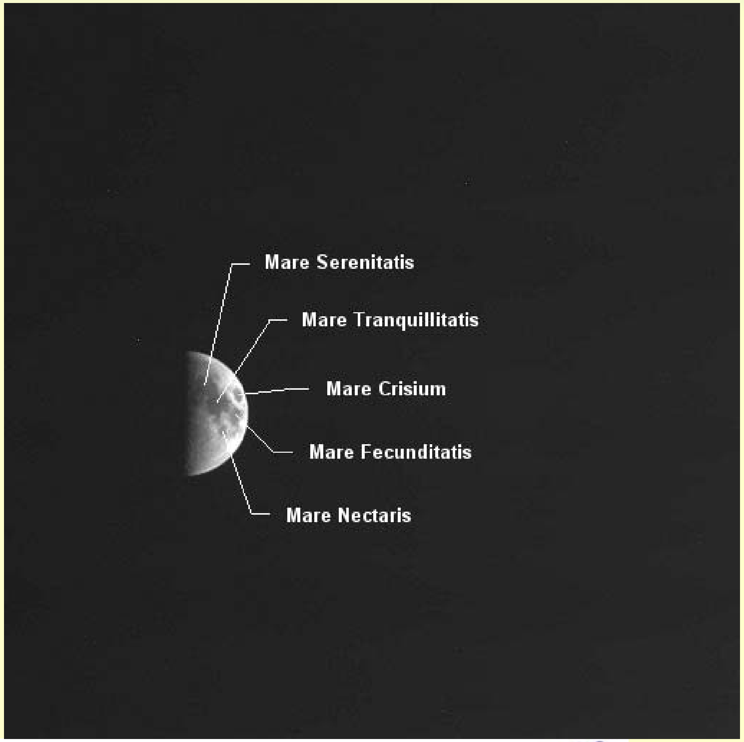


- 1st Moon quarter

Image from AMIE

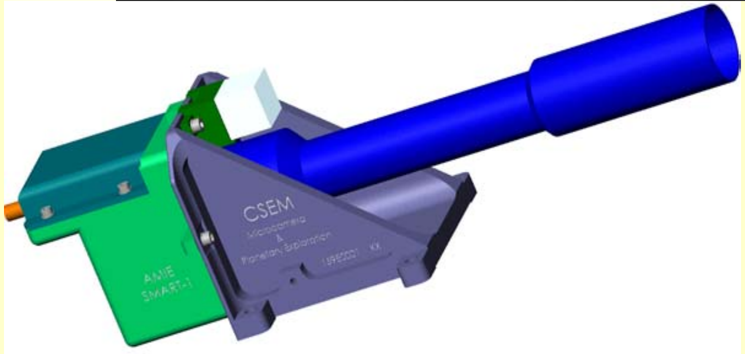
AMIE multicolour microcamera

PI:J.L.Josset (Space-X - CH); Co-I's from I,F,CH, Fin, NL, ESTEC



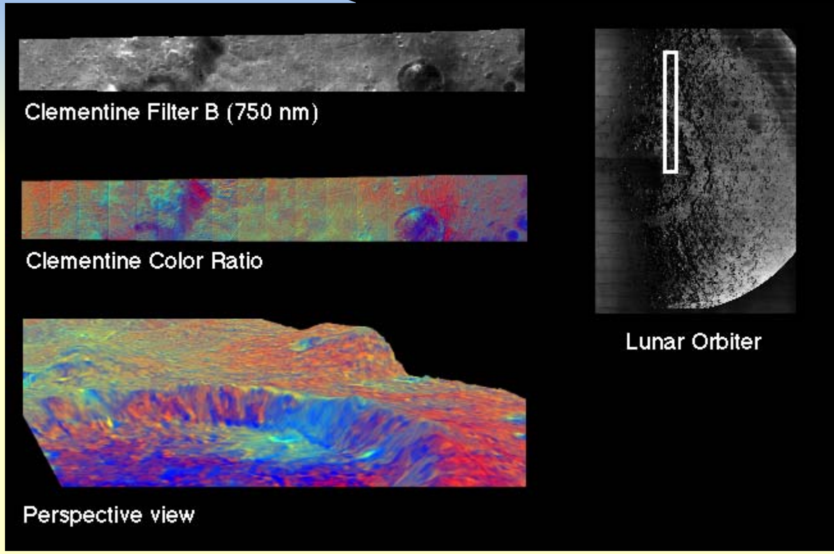
Main Experiment features:

- 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

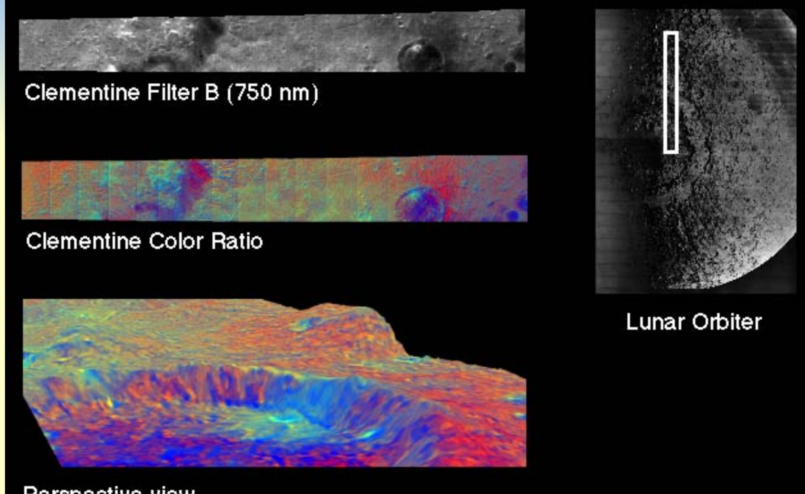
- **Multicolour:**
  - White light +3 filters 750, 900 and 950 nm
- **High Resolution Geology**
  - 40 m/pixel near perilune, 80 m average
  - Geological context for SIR & D-CIXS data
  - Multi-colour complement
  - Stereo/ multi-phase angle observations
  - Survey landing sites for sample return

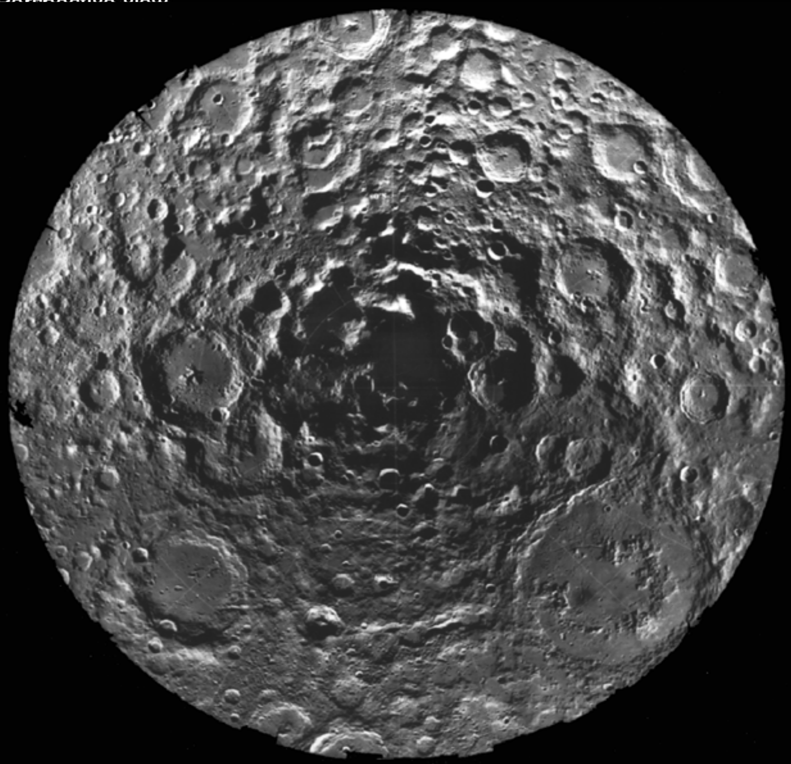


AMIE camera science

- 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
  - Multi-colour complement
  - Stereo/ multi-phase angle observations
  - Survey landing sites for sample return

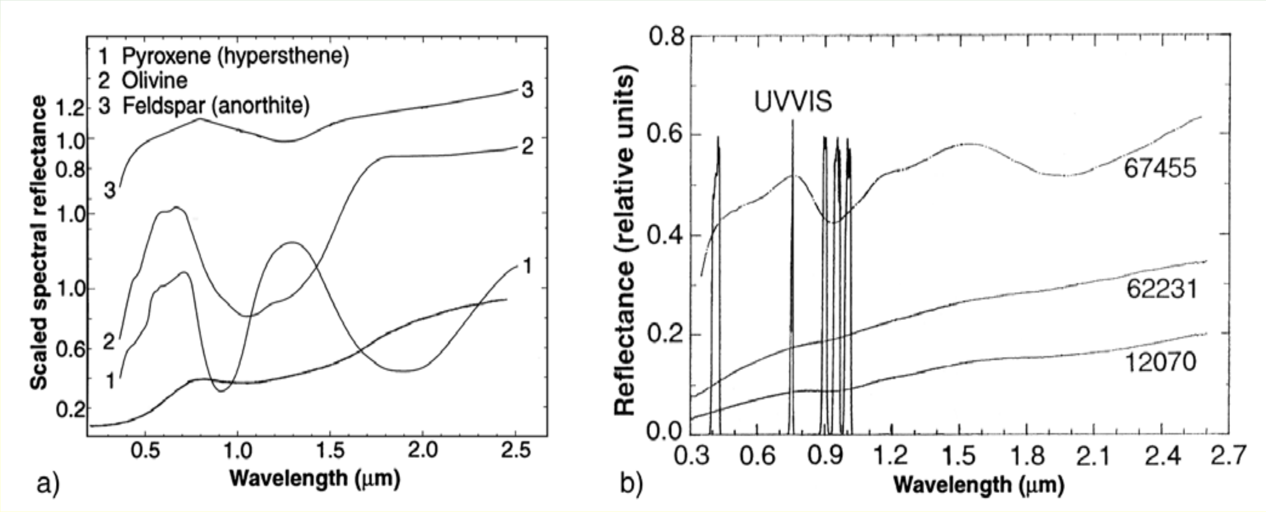
- **Repeated deep imaging of south pole**
  - **Mapping 'eternal light' and 'shadow'**
  - **Search for potential 'water ice traps'**
  - **Potential for lunar bases, power, resources**
  - **Preparation for future lunar exploration**





esa SCIENCE

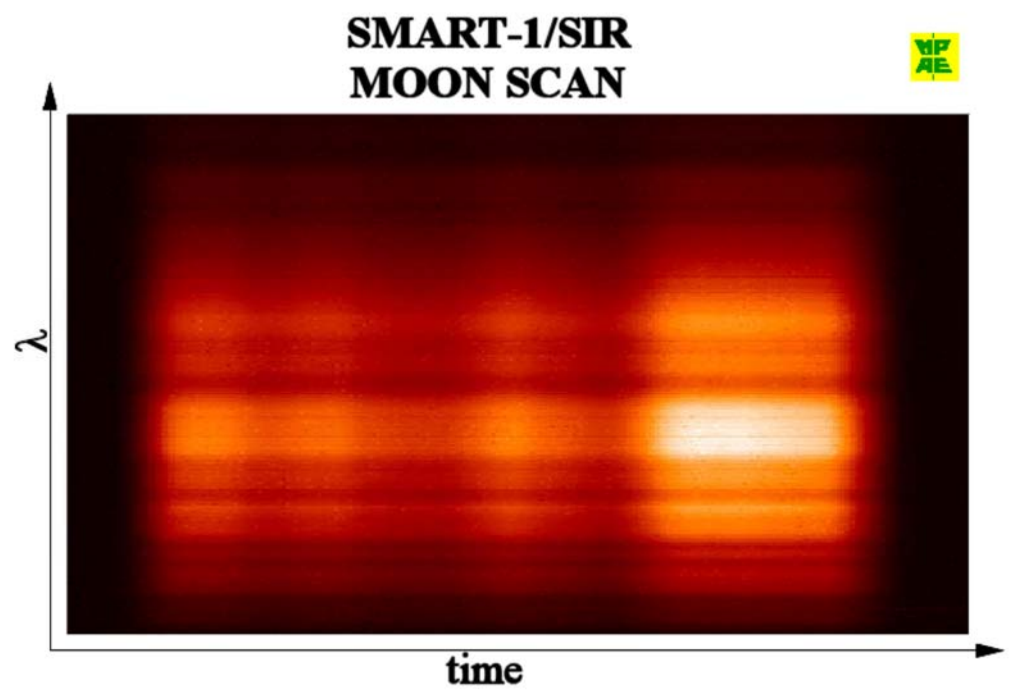
SIR IR spectrometer science



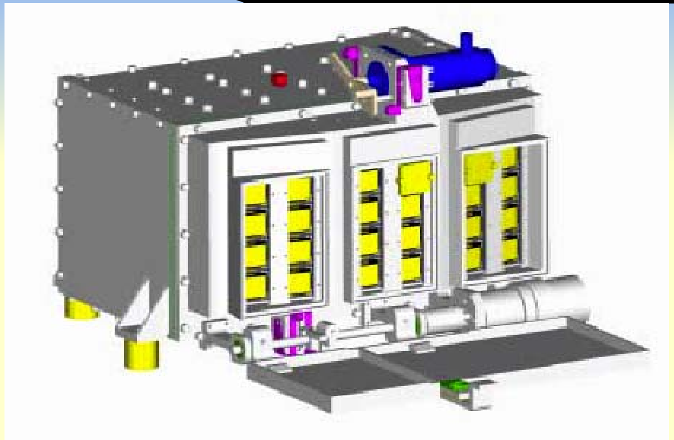
- 0.93 to 2.4μm, 256 channels, Lunar Spectral mapping
  - Discrimination of minerals: pyroxenes and olivine
  - Olivine from mantle : crustal differentiation/evolution
  - Basins exposed materials from mantle (e.g. South-Pole Aitken)
  - Deep spectra in permanent shadows (ice spectral features)
- SIR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

- 1st SMART-1 SIR infrared spectrometer Moon scan
- 6 Feb 04



D-CIXS spectrometer



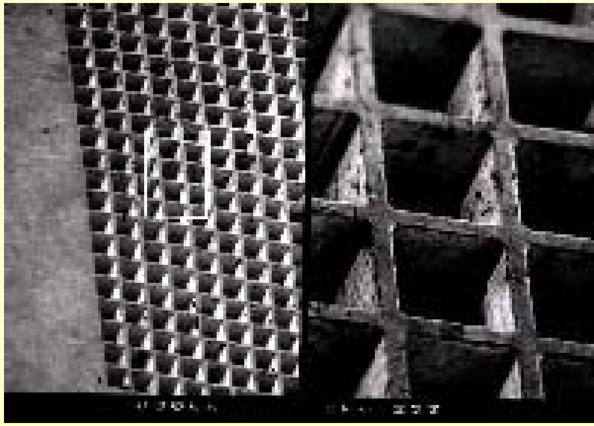
PI: M.Grande (RAL- UK), co-I's UK, Fin, F, E, S

Science and Technology Objectives

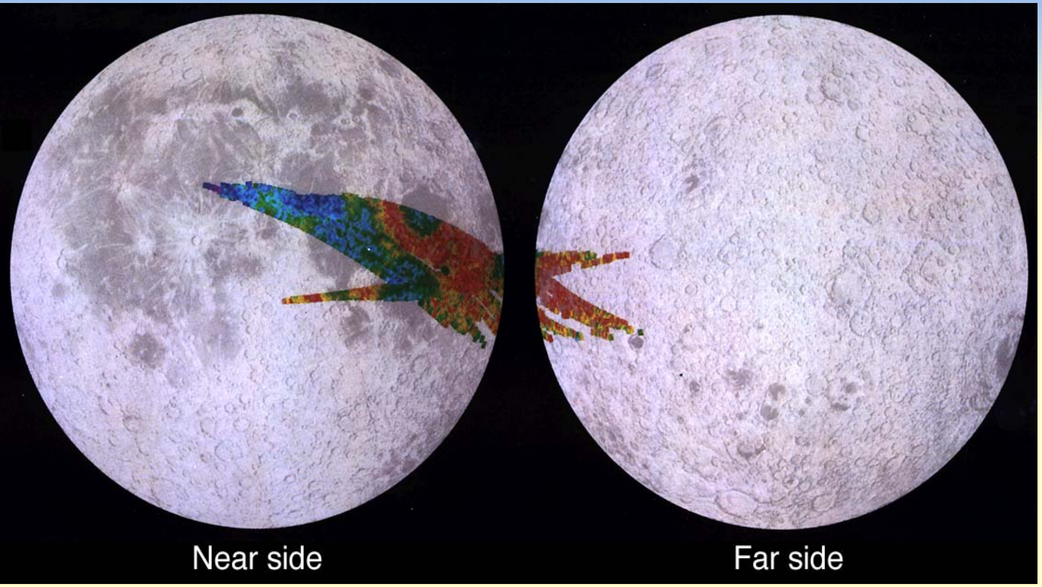
- Demonstrate compact X-ray imaging spectrometer
- Technologies: Swept Charge Devices (Detectors)
- Photo-lithographic Micro-structure collimator
- Global lunar elemental composition mapping of surface via X-ray fluorescence
- X-ray celestial sources, Earth aurora and magneto-tail during cruise

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)**

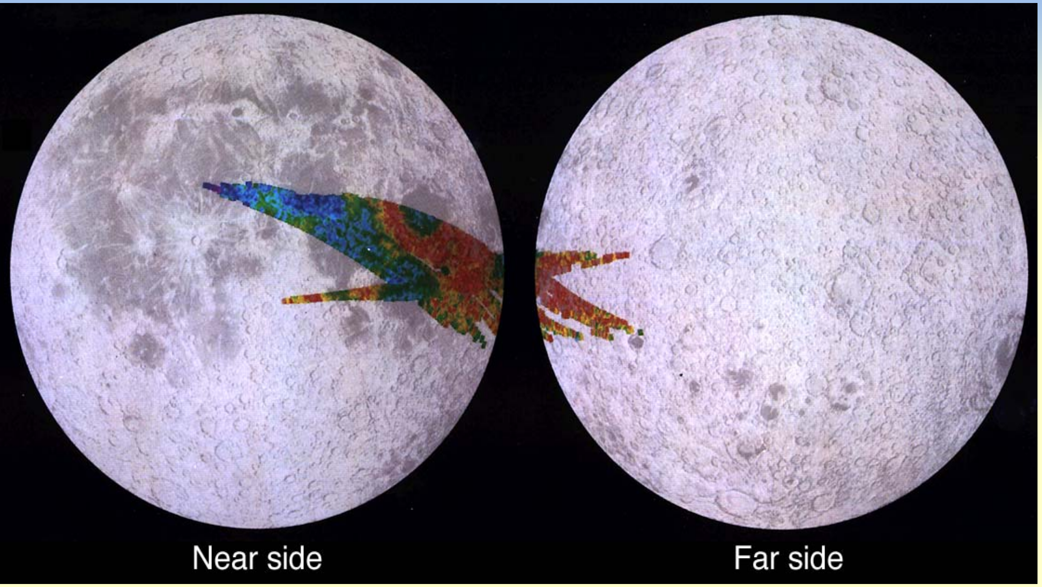


D-CIXS science



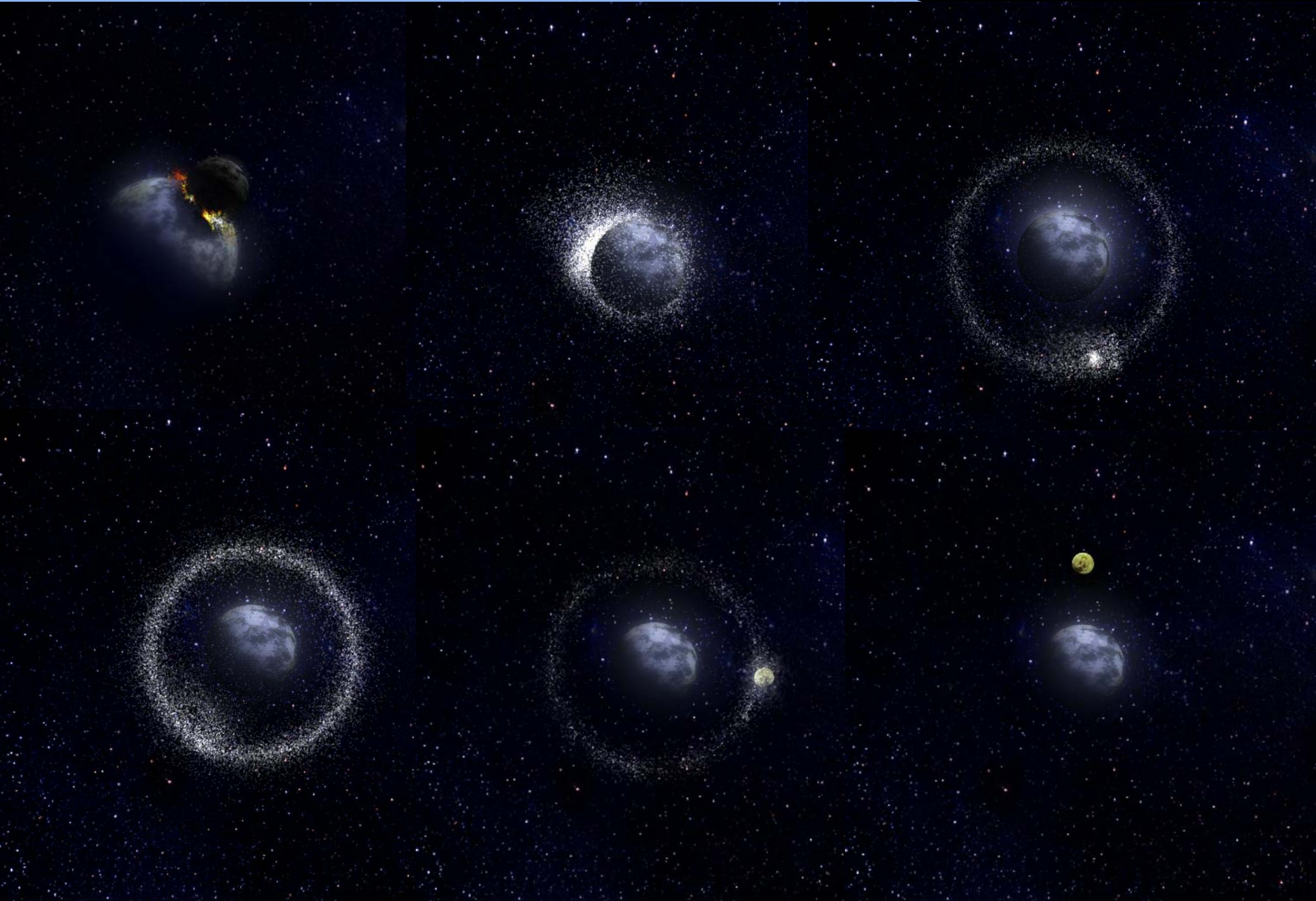
- D-CIXS map, 50 km resolution
- Absolute abundances Mg, Si, Al, (Fe)
- Bulk crustal composition

D-CIXS science



- 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?



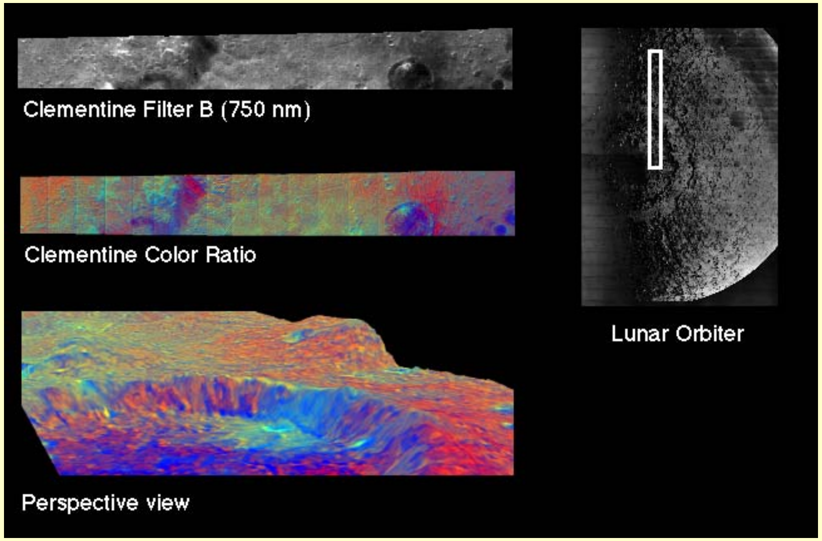
Resolution range vs previous lunar missions

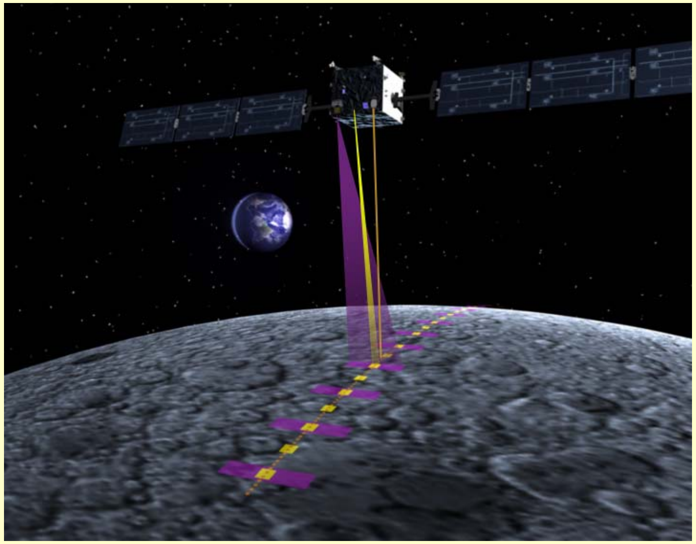
FOV/RES	AMIE	SIR	D-CIXS
Field of View (deg)	5.3	0.06	12x32
Resolution (mrad)	0.08	1	120
FOV in km	25	0.3	60x150
Res. Pixel	30 m	300 m	40 km
– from perilune 300 km			
Spectral channels	5	250	100
Spectral range	500-950 nm	0.9-2.4μm	.5-10kev

- 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

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

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, ..)
-

esa SCIENCE

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

- Muses-A Hiten Lunar Navigation (ISAS) 1990
- 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 19-23July 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