EUROPE TO THE MOON: HIGHLIGHTS OF SMART-1 MISSION

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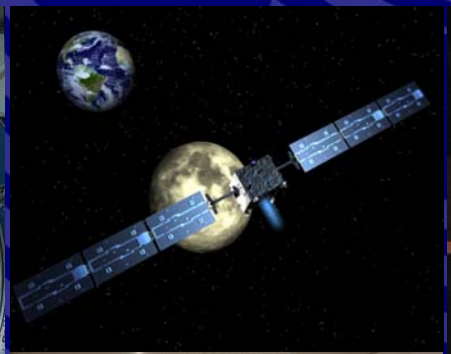
SMART-1 project team



Science Technology Working Team &
ESOC Flight Control Team

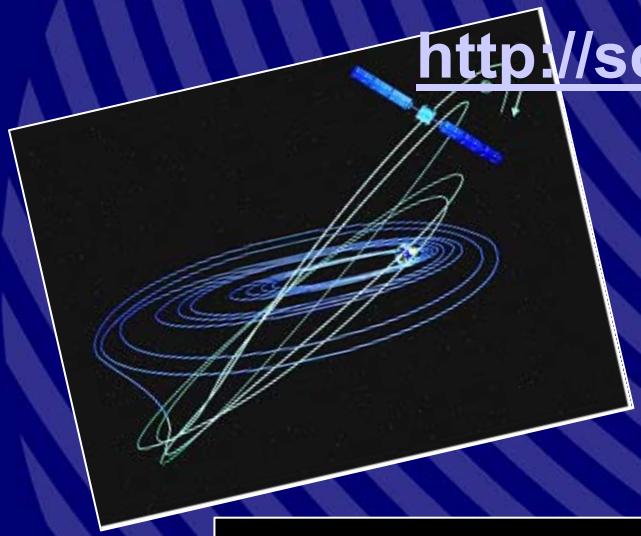
EUROPE TO THE MOON: HIGHLIGHTS OF SMART-1 MISSION

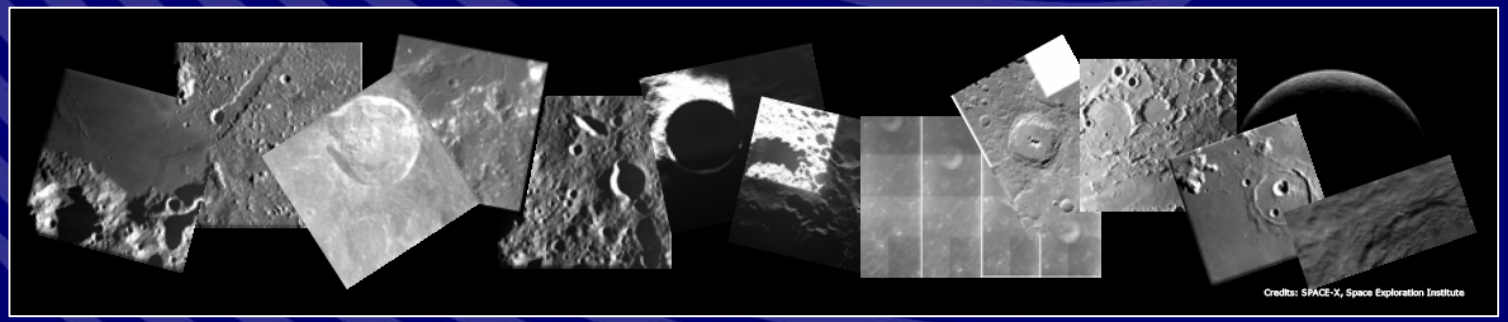
Bernard H. Foing

& SMART-1 Project & Operations team,

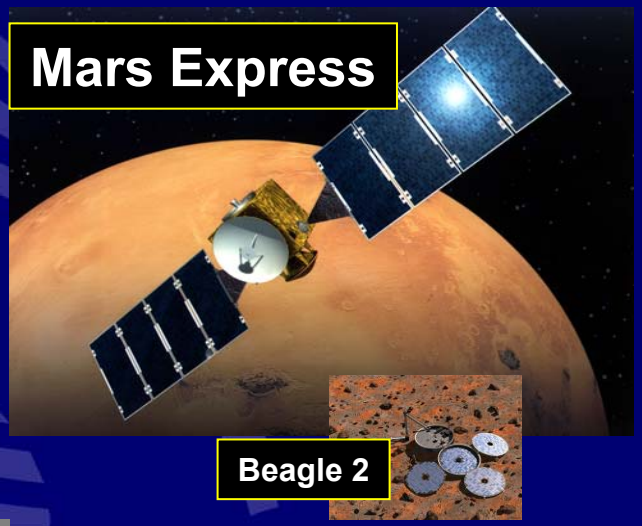
SMART-1 Science Technology Working Team,
SMART-1 Impact Campaign Team

http://sci.esa.int/smart-1/, www.esa.int





ESA Science programme

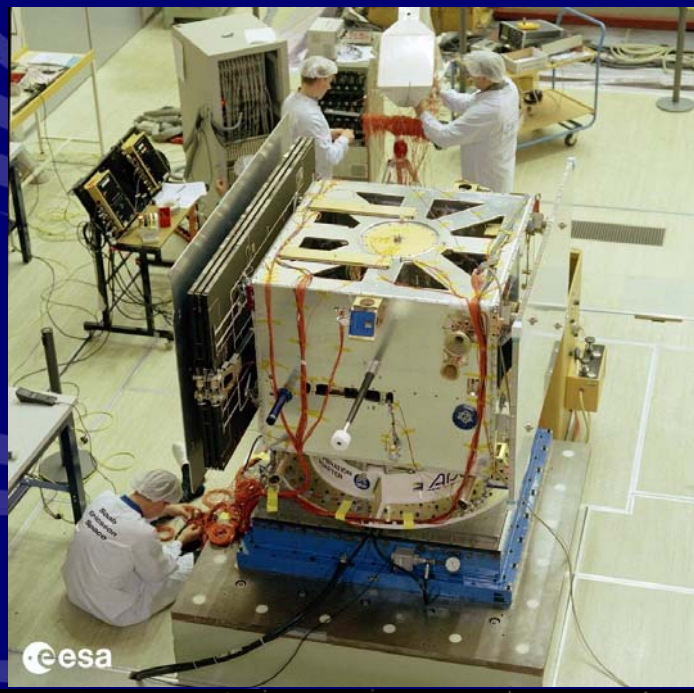


Solar System

Venus Express 05

esa

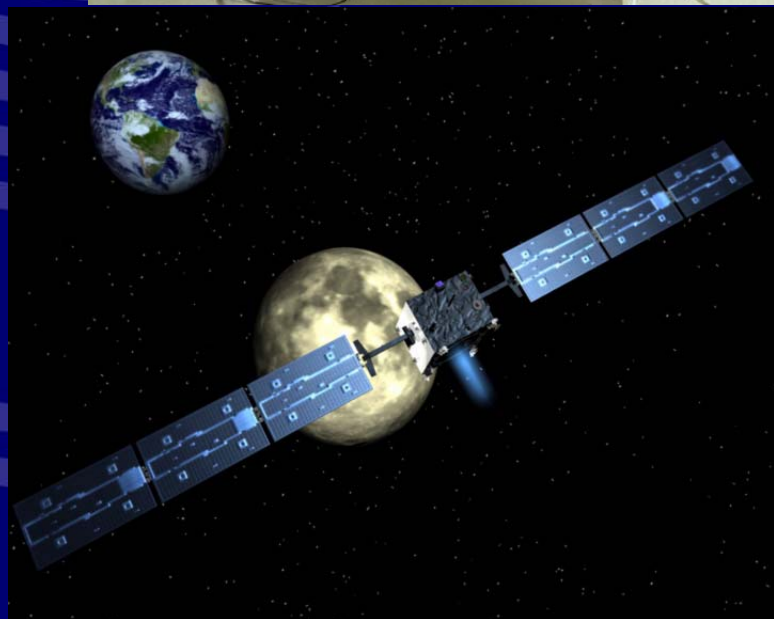
SMART-1 Mission SMART-1 web page (http://sci.esa.int/smart-1/)



- 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 Solar Electric Propulsion to the Moon

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



Europe to the Moon

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)

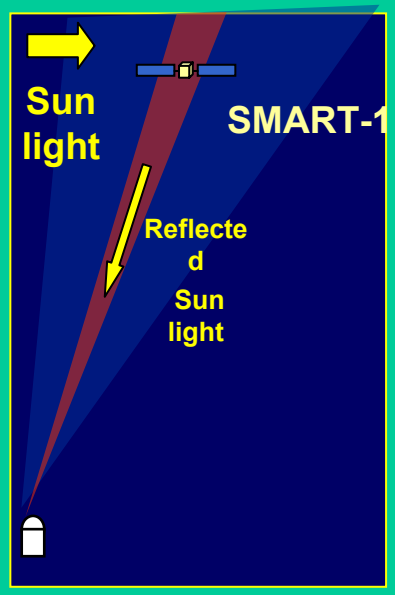
Switzerland (CH)

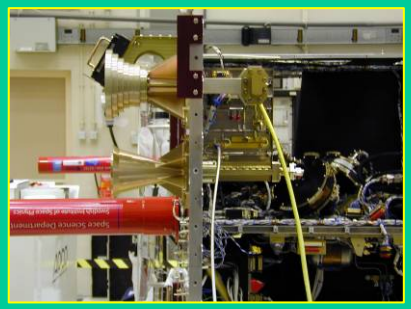
APCO Technologies SA: Structure and Mechanical Ground Support Equipment
Contraves Space AG: Electric propulsion mechanism
CSEM: Asteroid-moon micro imager (AMIE)

Italy (I)

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

Some of the Innovative Technologies on Smart-1

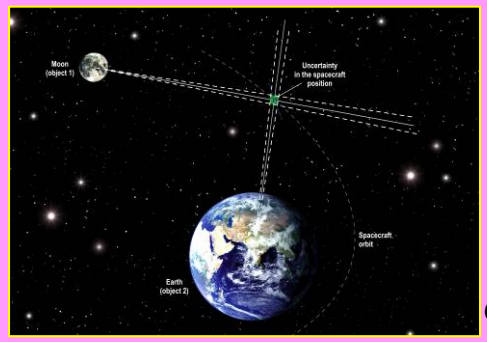


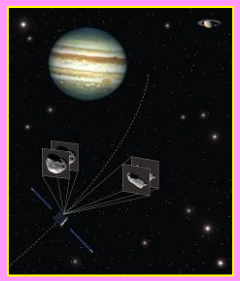


KA-band antenna

Laser Link

Communication





OBAN

Autonomy

Triple junction solar cells

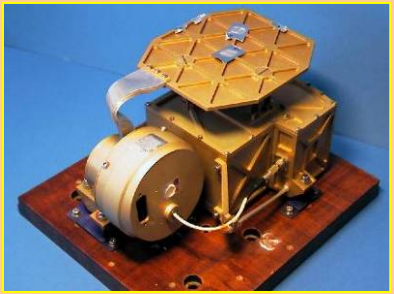
On-board computer

Lithium ion batteries

Platform Technologies

Multicolor microcamera

X-Ray Spectrometer

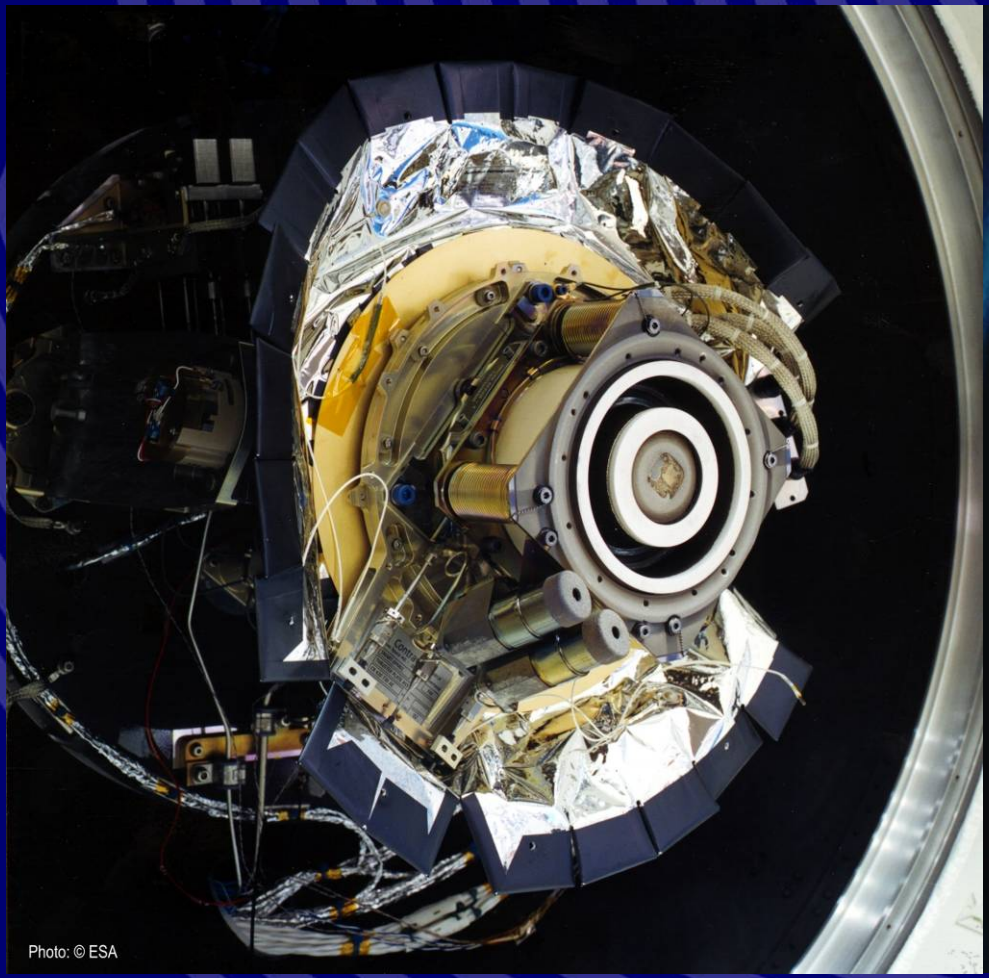


Infrared Spectrometer

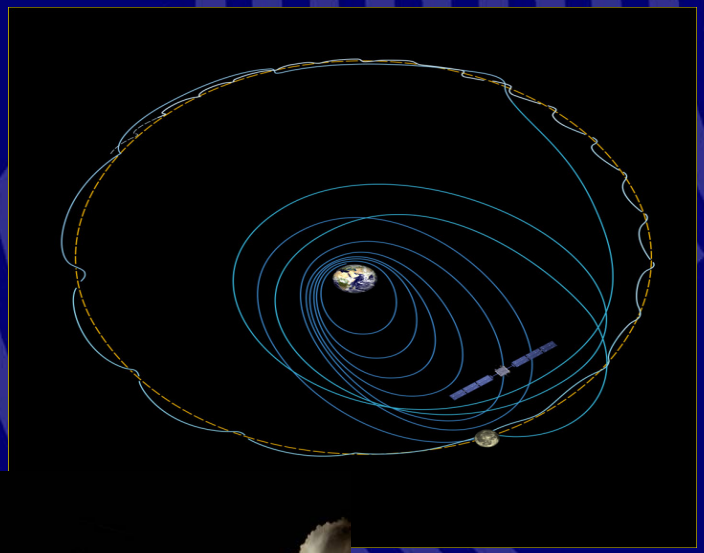
Miniaturisation

esa

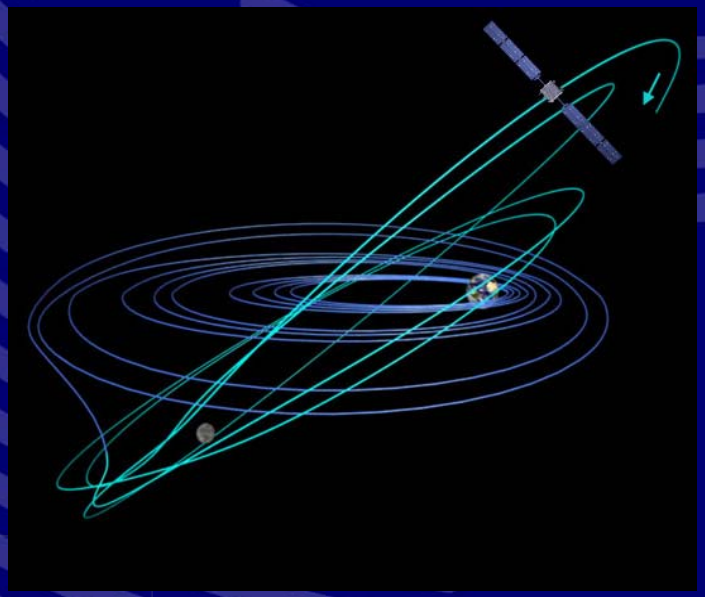
Electric Primary Propulsion:
7 g thrust, 60 liters Xenon fuel to the Moon

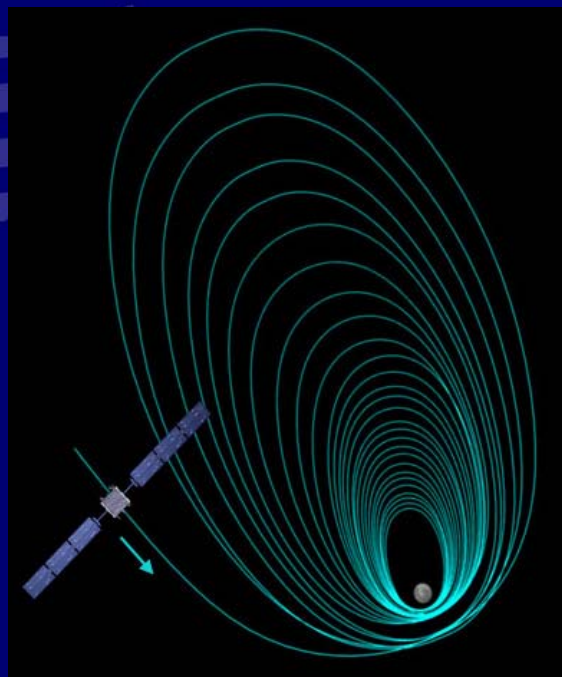


Solar Electric Propulsion to the Moon

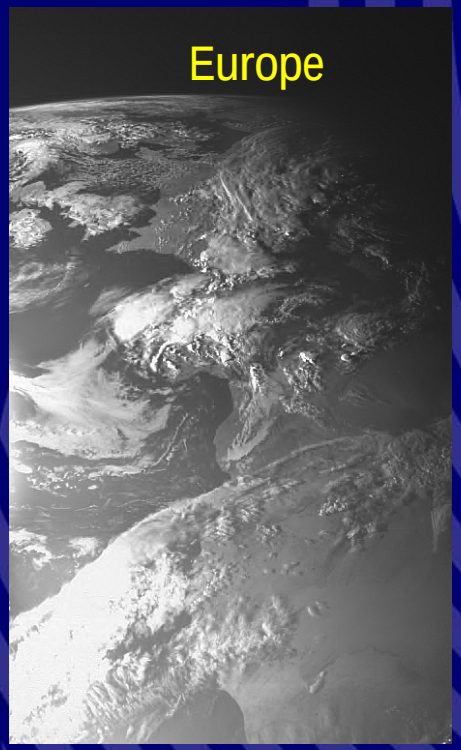


- Launched 27 Sept 2003 as Auxiliary passenger on Ariane 5 into Geostationary Transfer Orbit
- Spiral out cruise (13.5 month):
- lunar capture 15 November 2004, spiral down
- arrival 15 March 05 science(450 -2900 km): commissioned spacecraft/instruments at Moon, nominal science mission March-July 05
- *reboosting 2 aug-15 Sept 05 to increase orbit lifetime for extension phase* until Aug 2006





SMART-1 views planet Earth



1 year launch birthday

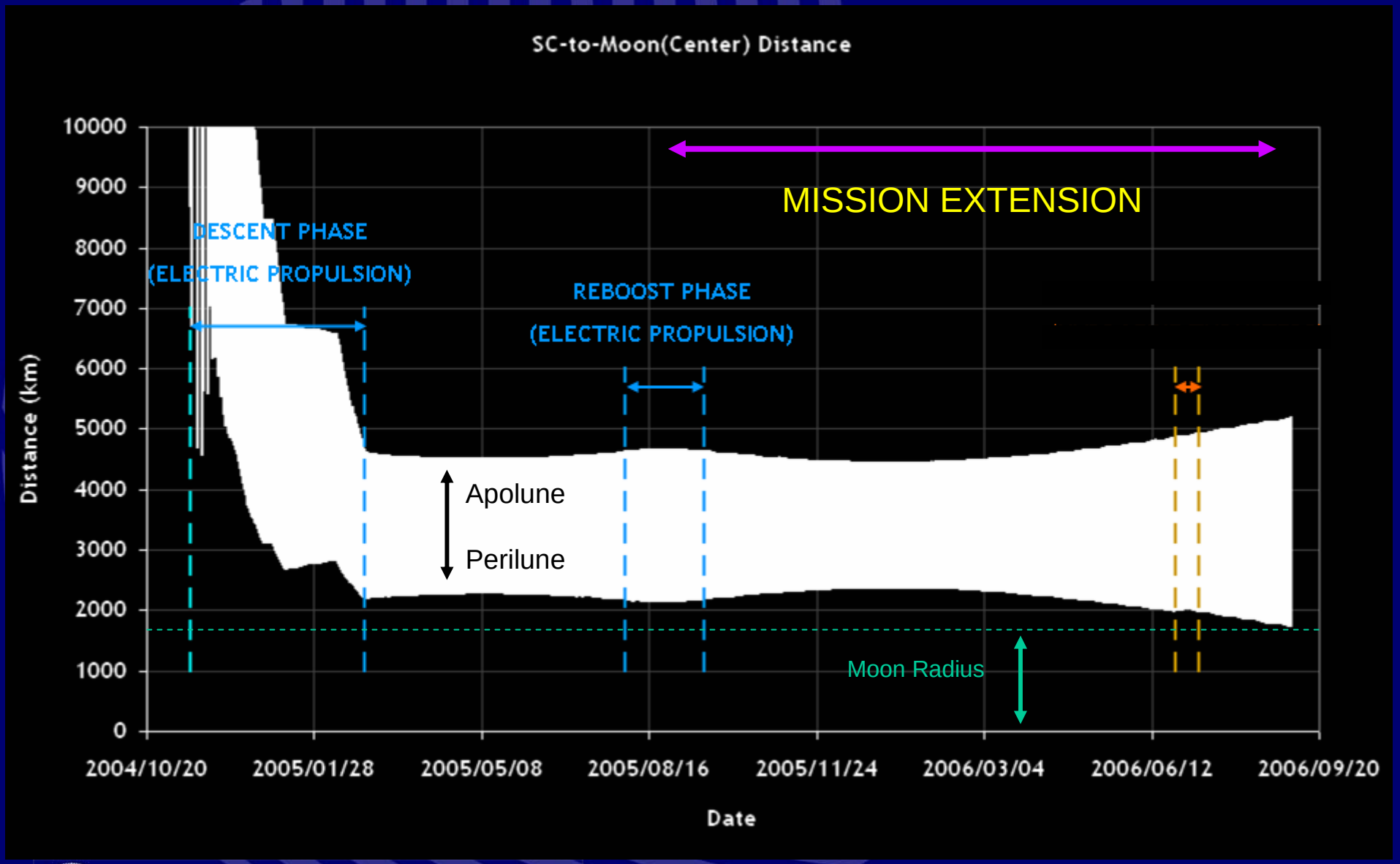
AMIE /SMART-1
May 21st, 2004

Earth view from
~70’000 km

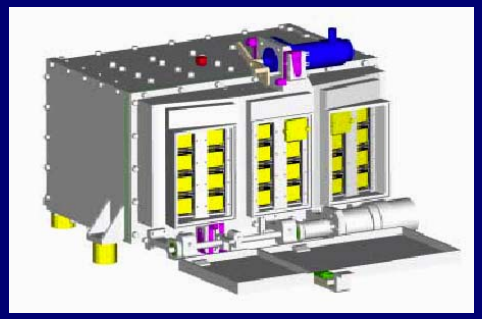
AMIE /SMART-1
End August 2006

Earth set & rise from
the Moon

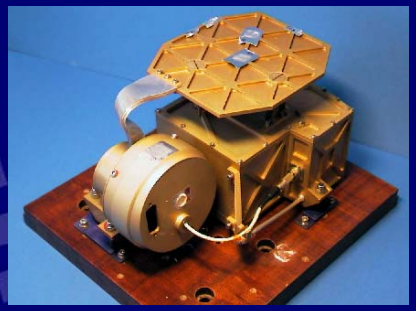
Moon Phase & Mission Extension



Mini-Instruments European Technologies (19 kg): eyes, nose and ears



- D-CIXS Spectrometer (UK, 5.2 kg)
- + XSM solar X-ray Monitor (SF)



- SIR Infrared Spectrometer (D, 2.3 kg)

- AMIE micro-Camera (CH, 2.1 kg)

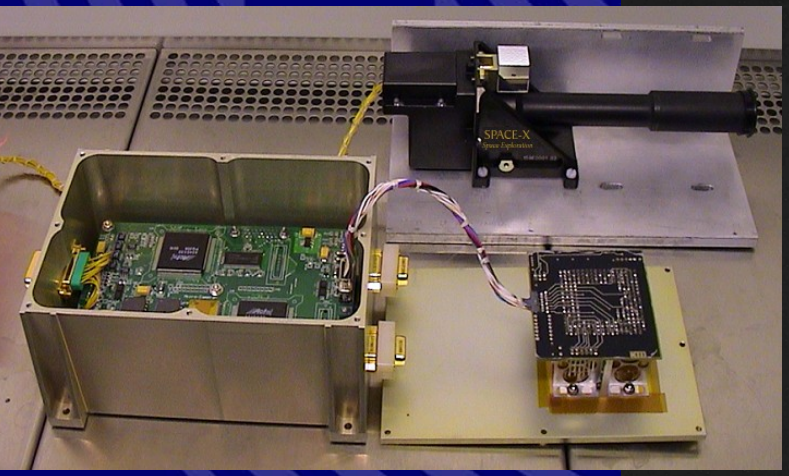
- SPEDE Spacecraft Potential Electron Dust (SF, 0.8 kg)
- EPDP Electric Propulsion Diagnostics Package (I, 2.4 kg)

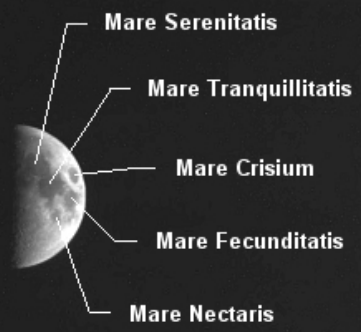
- KATE Deep Space Communications (D/ESA, 6.2 kg)
- RSIS radio science (I)

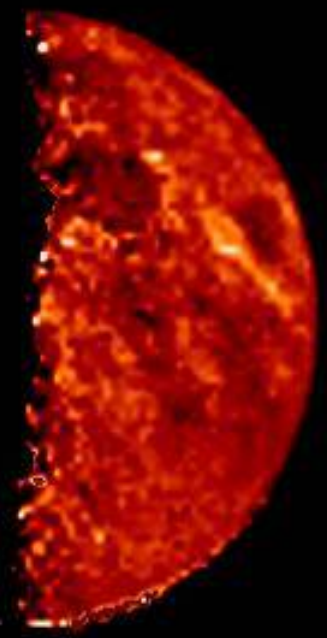
AMIE multicolour microcamera

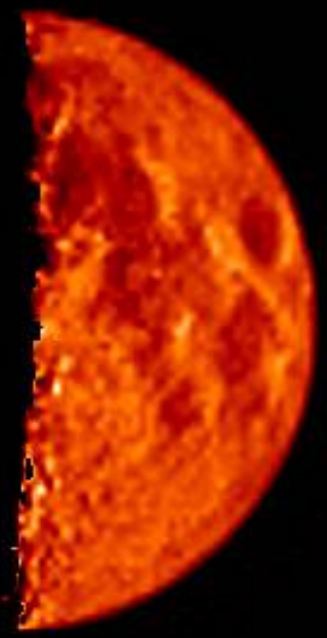
PI:SPACE-X, CH; Co-I's I,F,CH, Fin, NL, ESA

- CCD cam & micro-electronics packed in 3-D
- 4 colour filters (red to near infrared)
- Mass 2.1 kg , optics 400 g , 5.3° view
- Support laser-link, On Board Autonomy





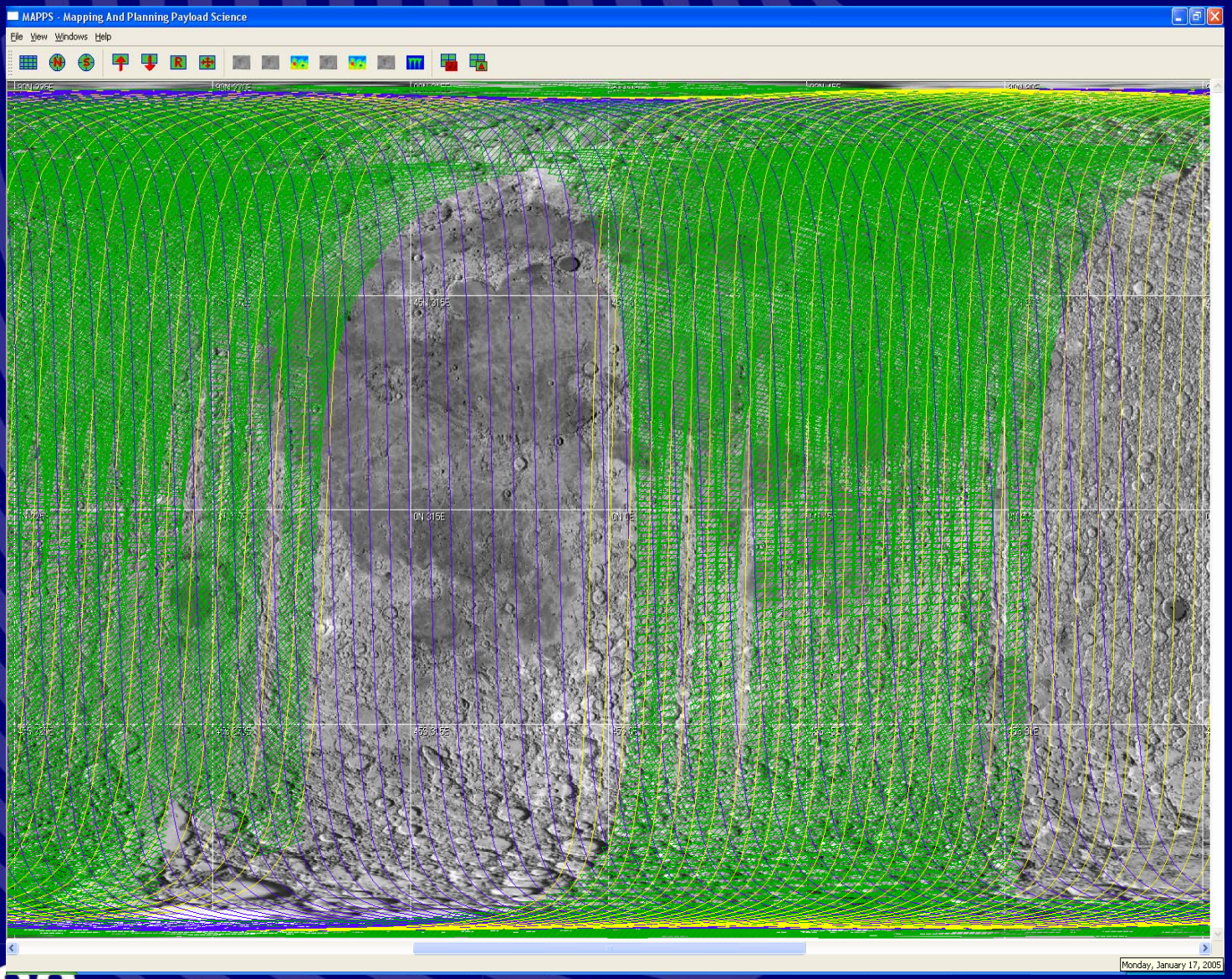




1st AMIE image of Moon from 300,000 km:

White, red (bottom) and near infrared (top)

Jan. 05 Low resolution Coverage from 1000 – 4700 km orbit

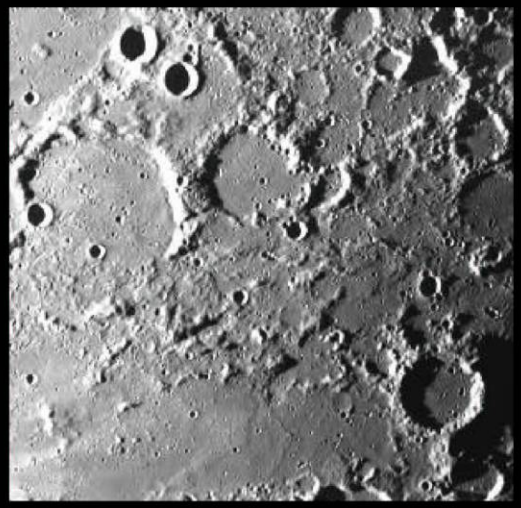


First Moon close-up images

First Moon close-up Images – 29 Dec. 2004

By AMIE/SMART-1

AMIE Instrument



Clear Filter

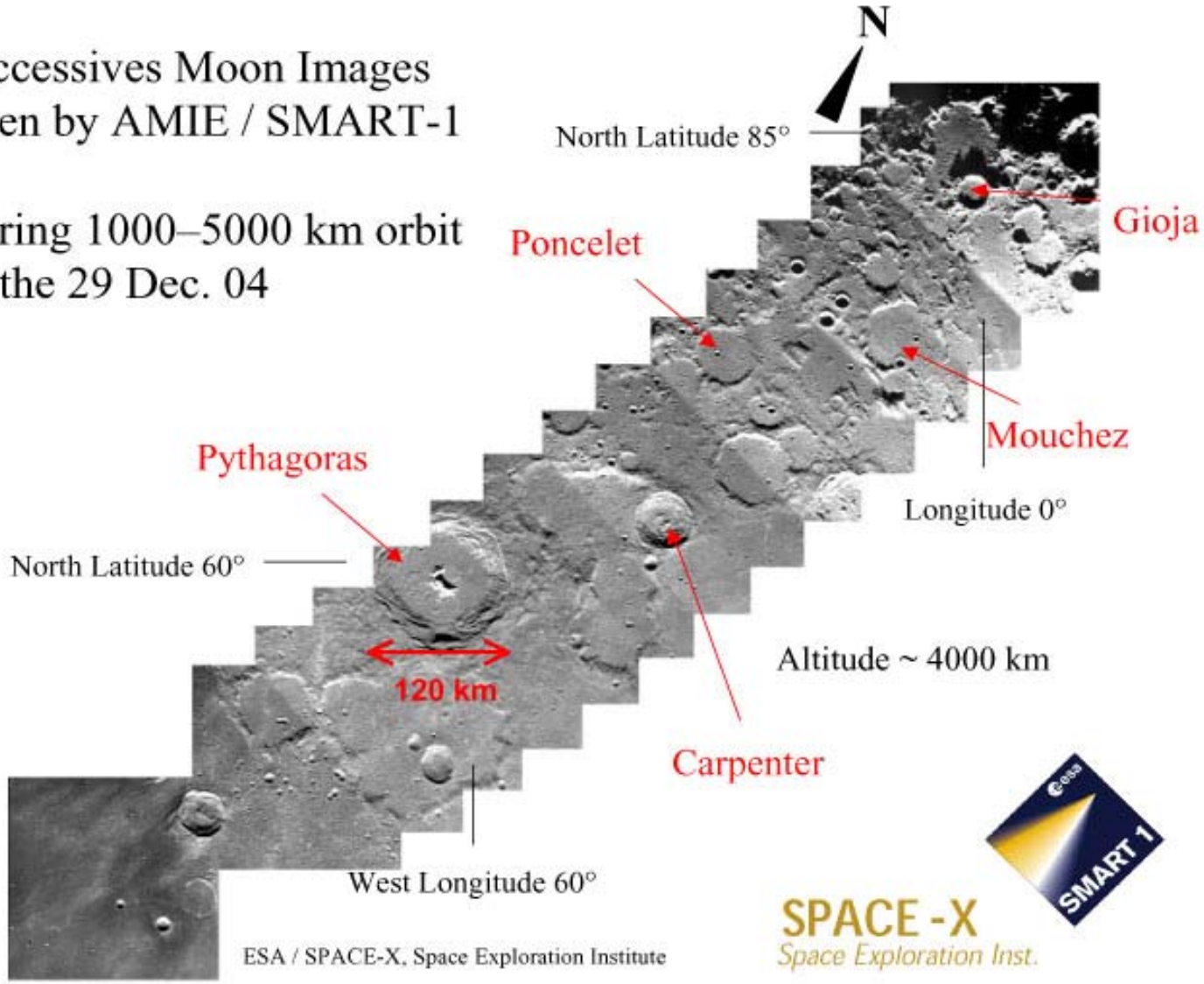
(~ 75° Lat. North)

Area covered by 3 Filters

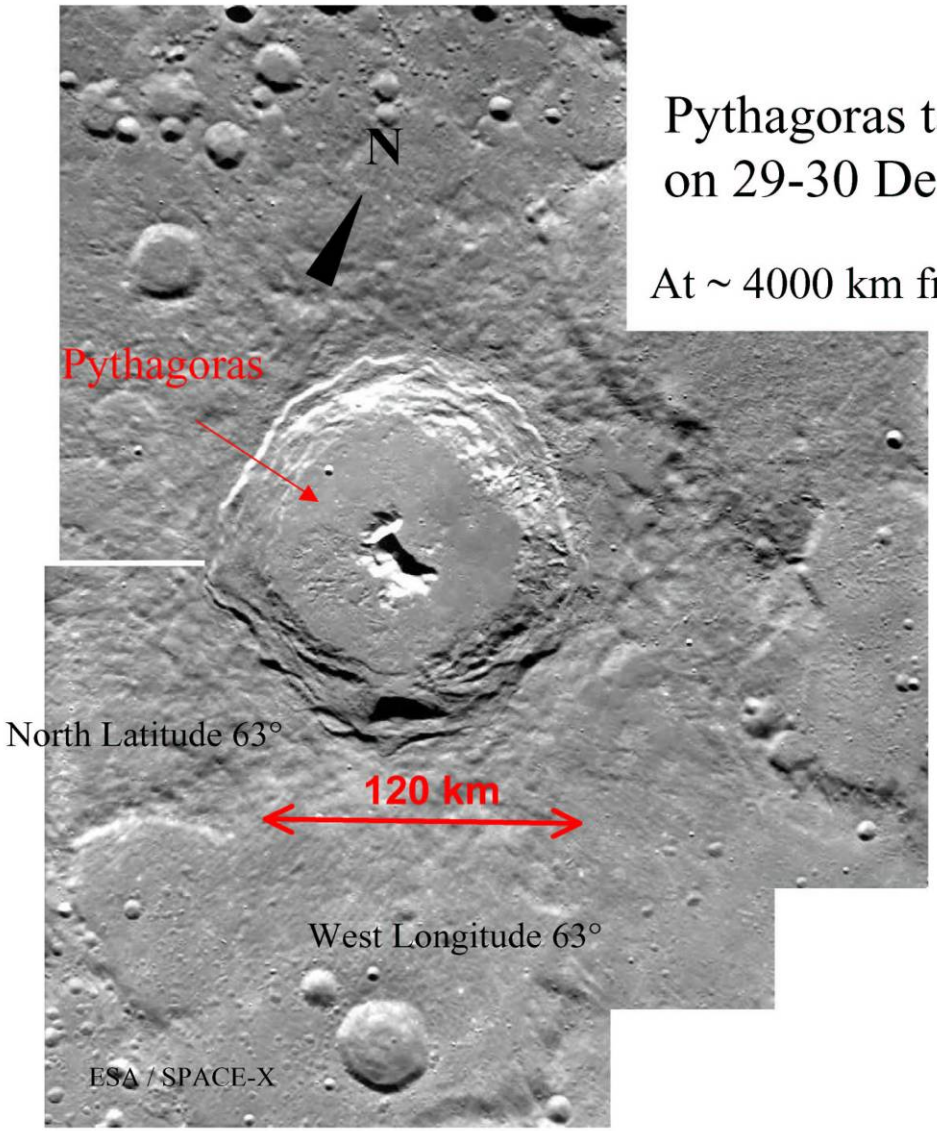
esa SPACE-X Space Exploration Inst.

Imaging sequence for one orbit

Mosaic of images along SMART-1 from orbit 1000-4500 km



Impact processes: Pythagoras crater



Pythagoras taken by AMIE / SMART-1 on 29-30 Dec. 04

At ~ 4000 km from the Moon Surface

This mosaic view of Pythagoras is composed of images taken during two successives orbits. Pythagoras is a 120 km diameter complex lunar crater characterized by a relatively flat crater floor, a central peak and terraced walls. The terraced walls height reaches 5000 m.

SPACE -X
Space Exploration Inst.

esa SMART 1

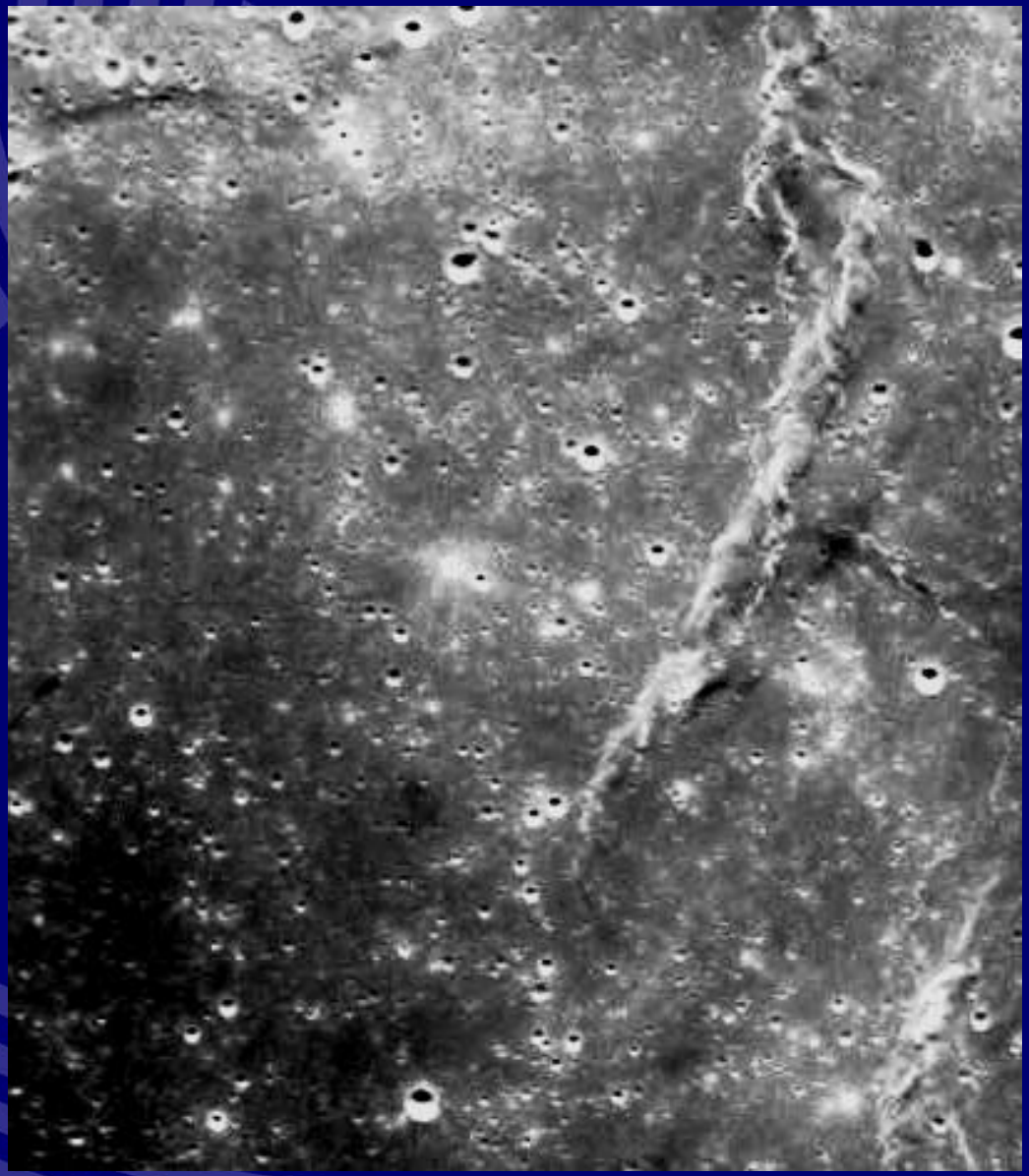
Impact cratering processes

- Glushko crater, a young impact caught after the act

- Fresh 43 km crater: wall, fresh rims, central peak and collapse, ejecta

Serenitatis

Crater counts and lunar chronology

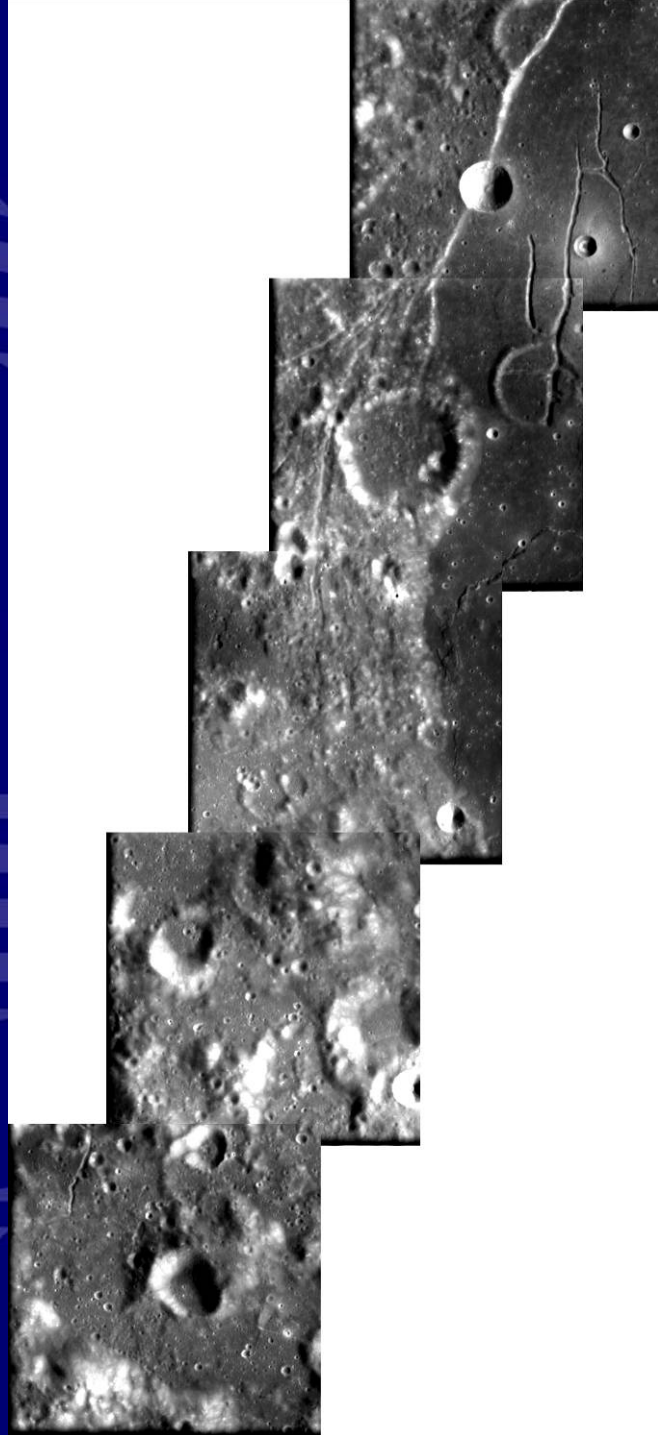


Crater de Gasparis

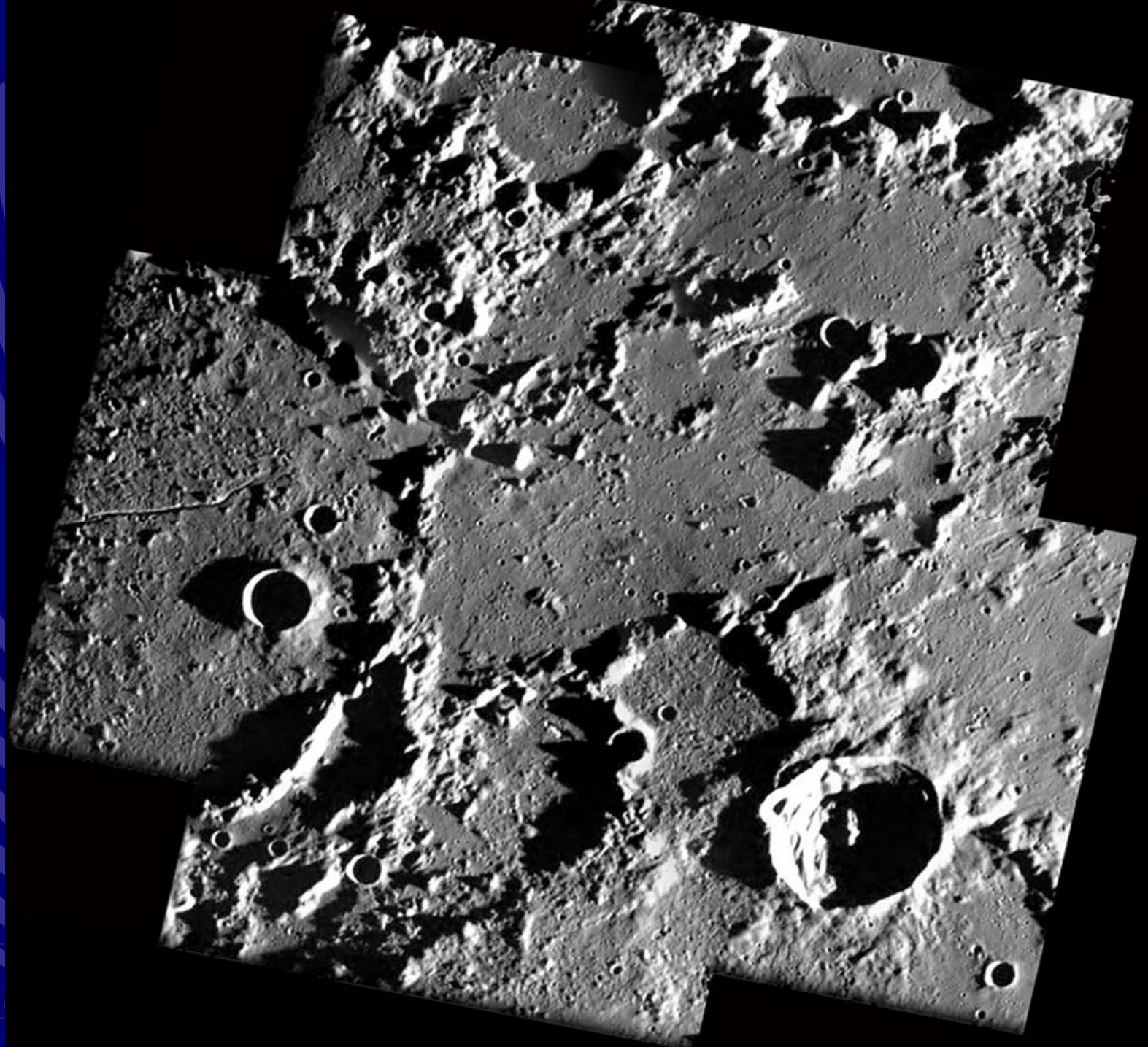
- Tectonic faults due to flooding of Procellarum post-dating crater

Mare Humorum edge

- Fresh craters in maria
- Ejected debris
- Tectonic faults due to impact and basin filling load
- Mare like deposits in fractured tectonic ring
- Highland craters



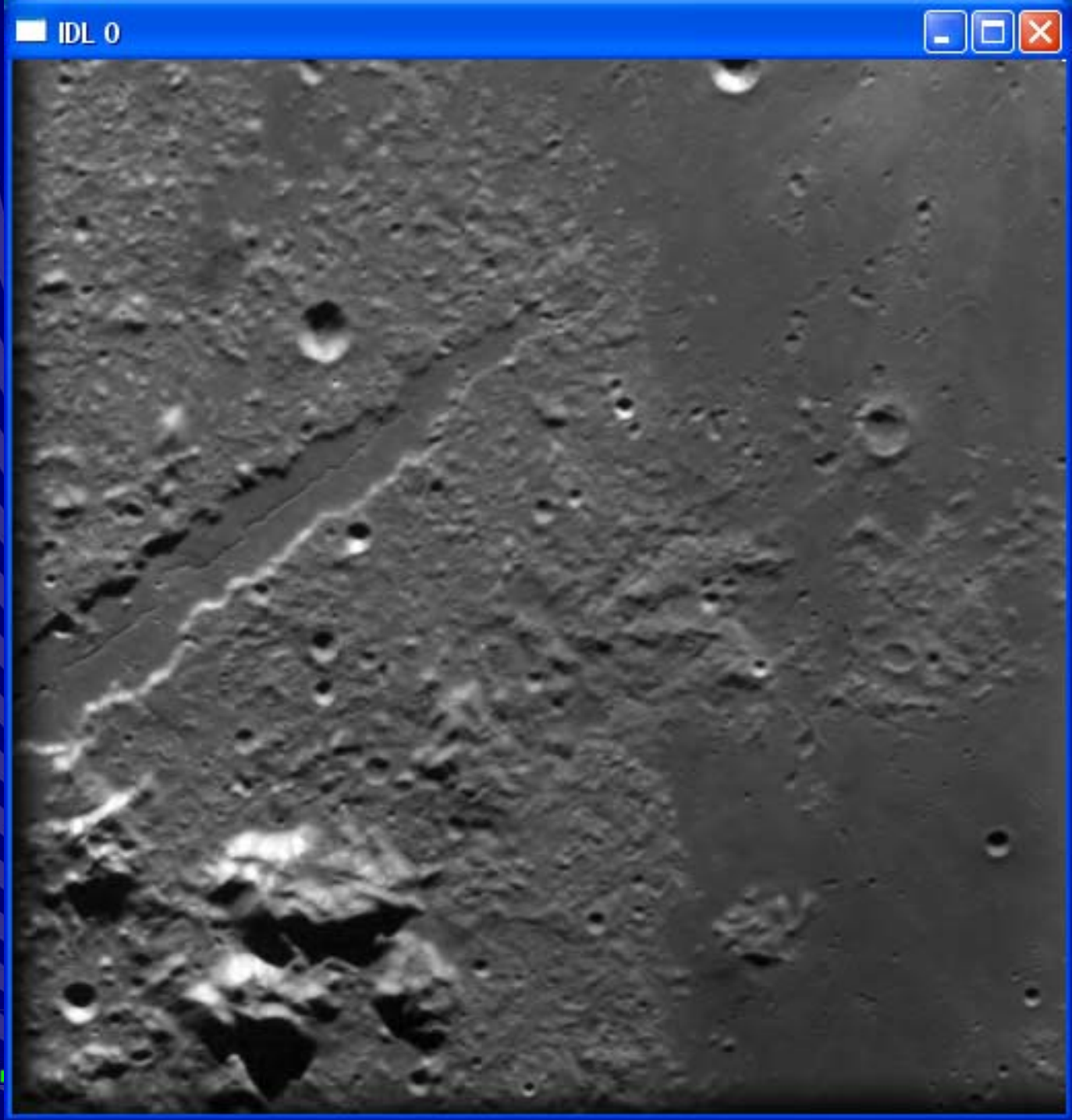
Meton: debris on the edge of Imbrium



Volcanism

Lunar Alps ridge

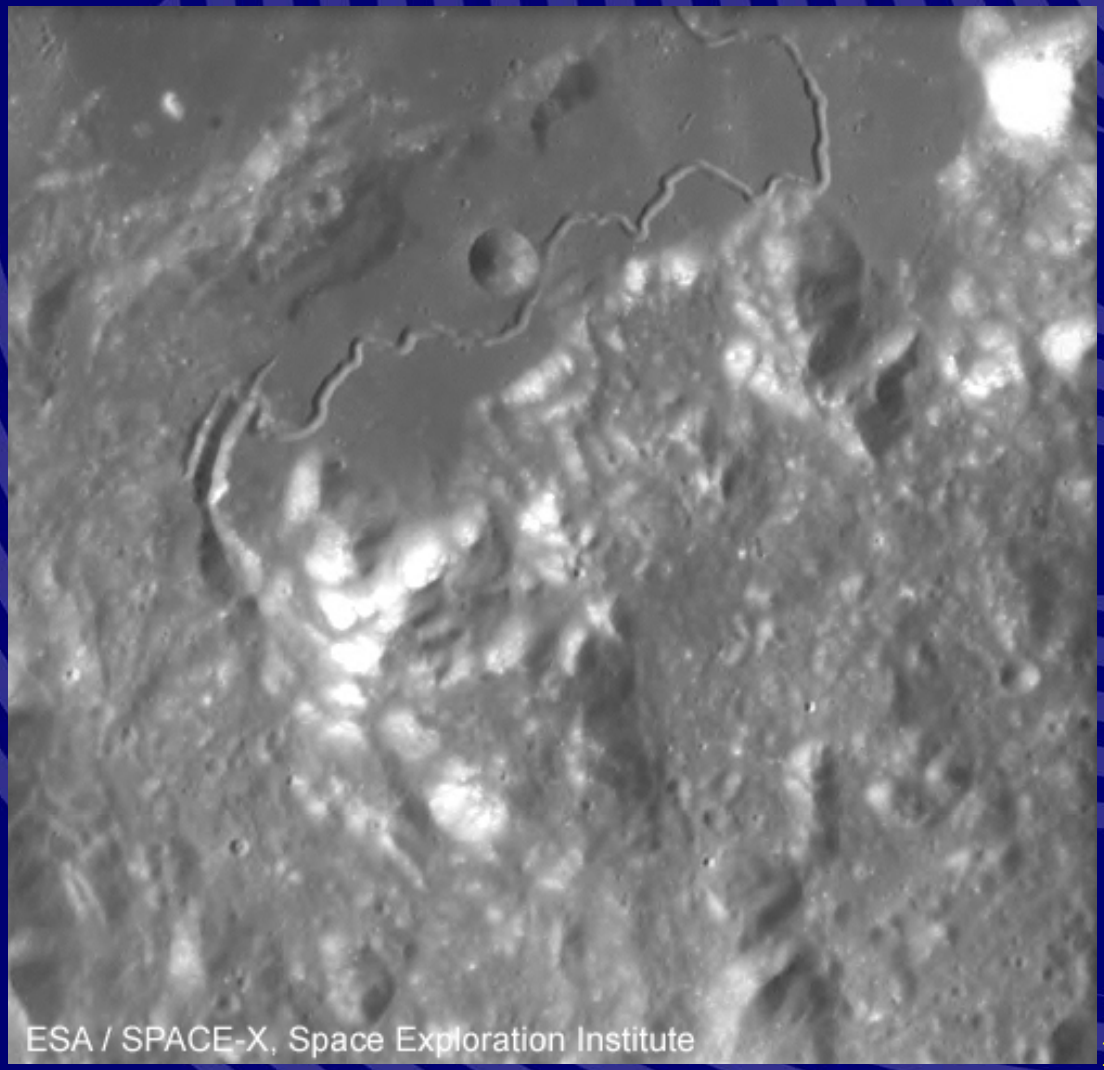
- **flooding**
- **Volcanic channel and late rille**

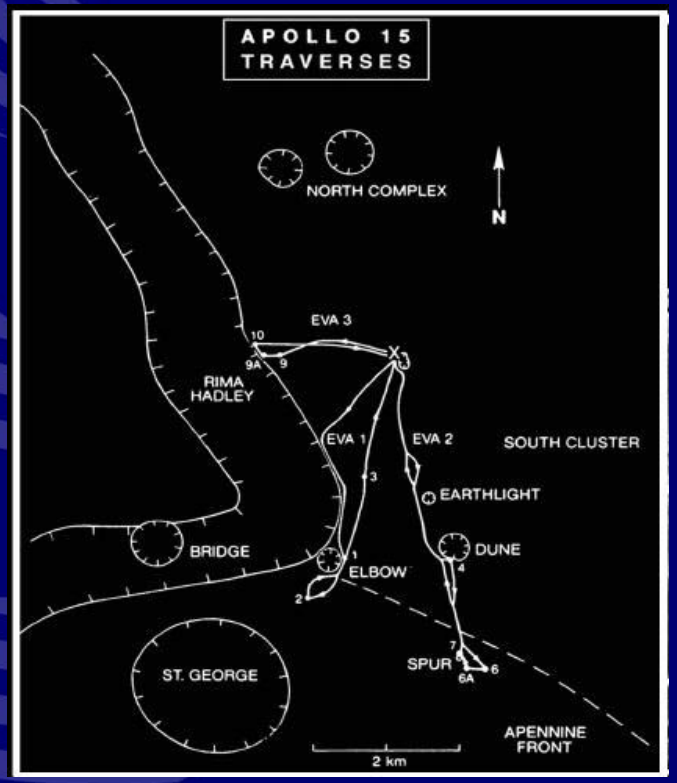


Cassini Crater flooded by lava in Imbrium mare

- Outer rim
- Small fresh crater exhuming deeper basement or debris?
- Volcanic center with rilles?

SMART-1 view of Hadley Rille near Apollo 15 landing site





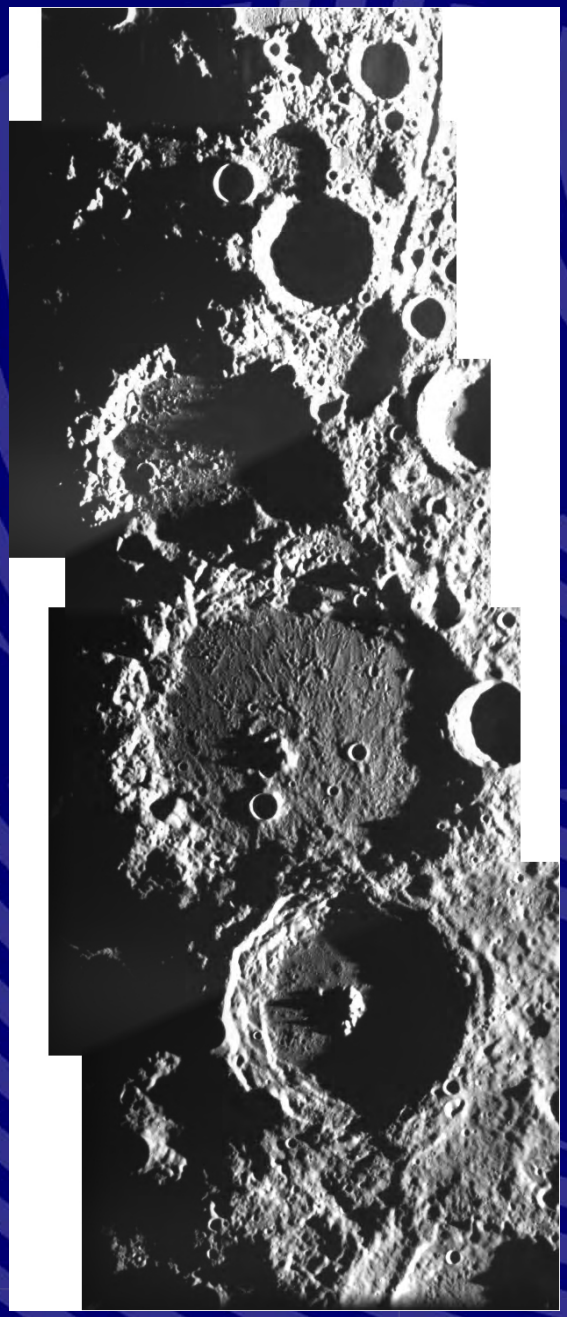
100 km field

Hermite

North Pole

Rozhdestvenskiy

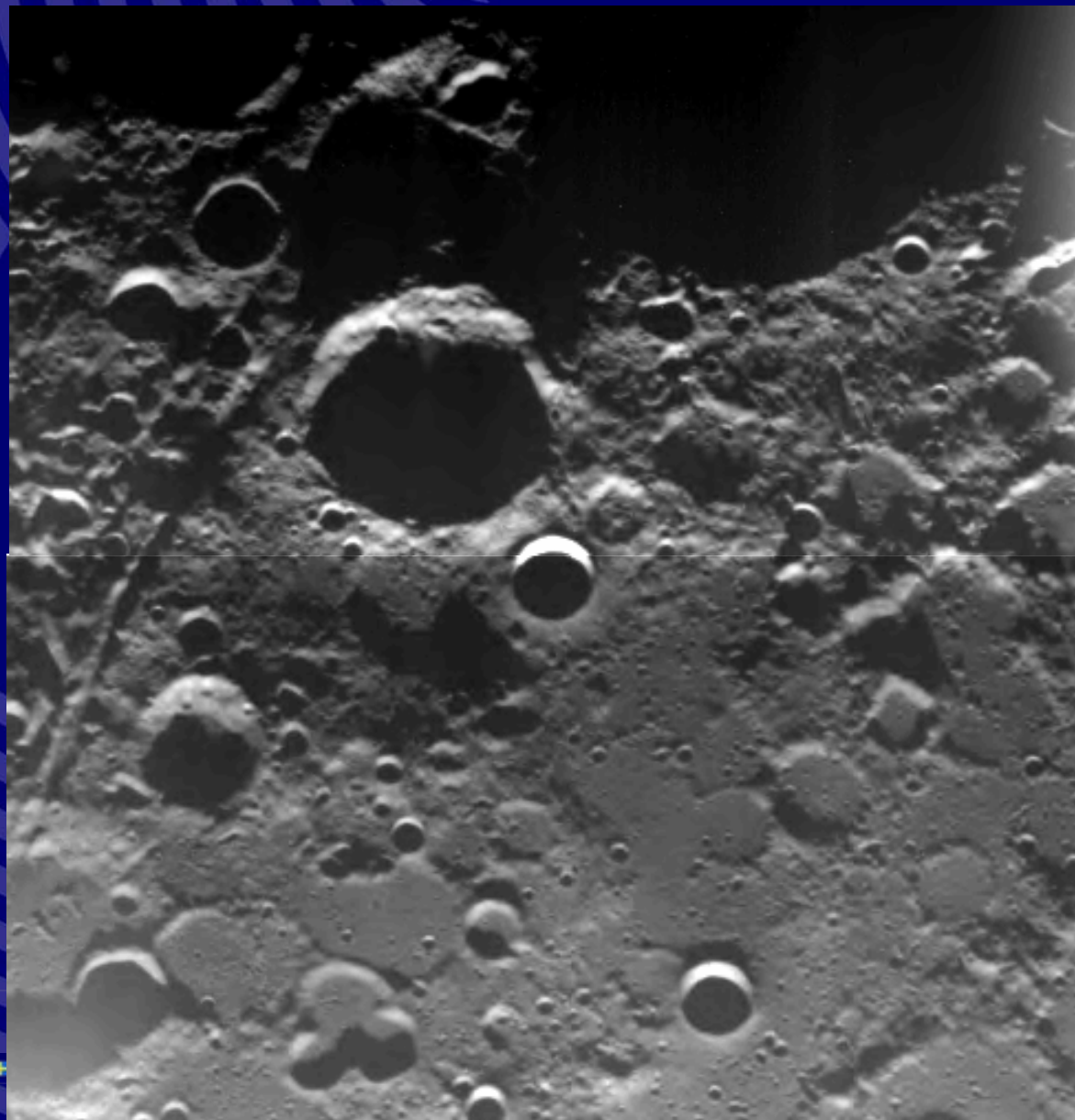
Plaskett



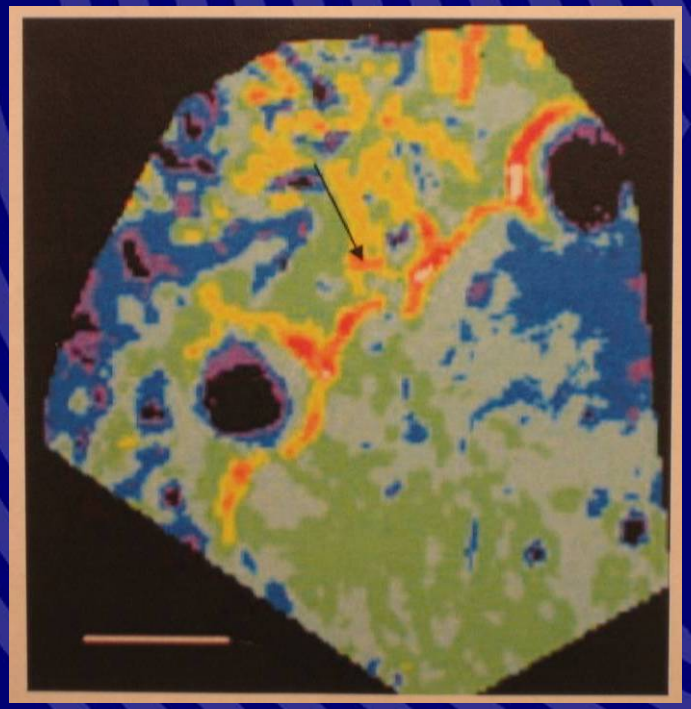
North polar highlands on West near side:

from saturated ancient cratered to flooded terrains
tectonic faults, feeding dykes/pit chains?

29 Dec, 200 km field
Filtered images



North pole peaks of light



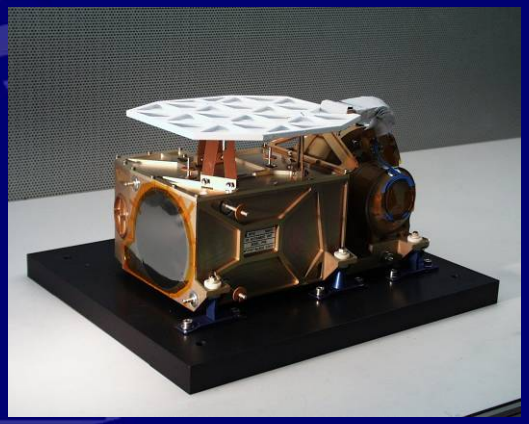
Summer average illumination
Clementine

Winter image
SMART-1

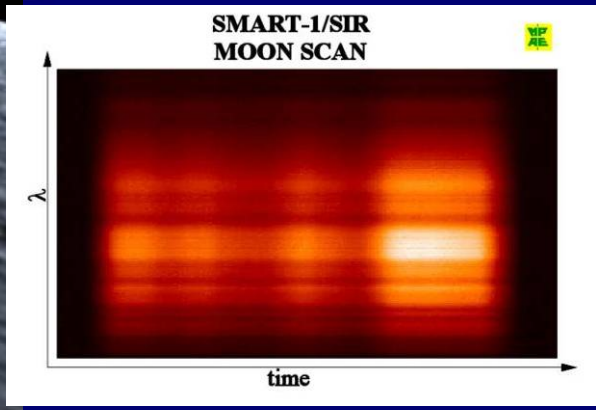
Minerals and ice:
Smart-1/SIR & the infrared Moon

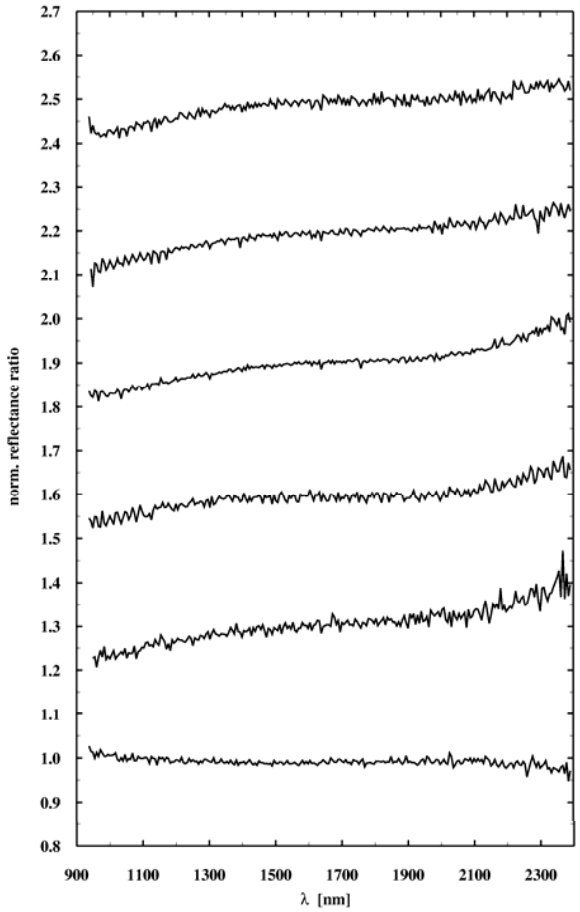
The SIR spectrometer 0.9-2.4 microns:

- to chart the Moon's minerals
- to find the signature of volcanism and impacts
- to search for the fingerprints of water- ice by peeking into dark craters

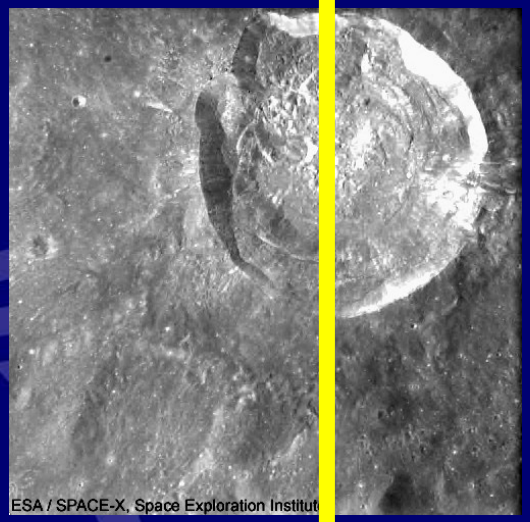


1st moon observations

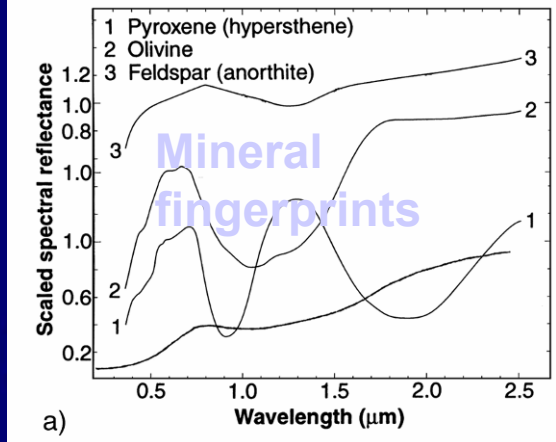


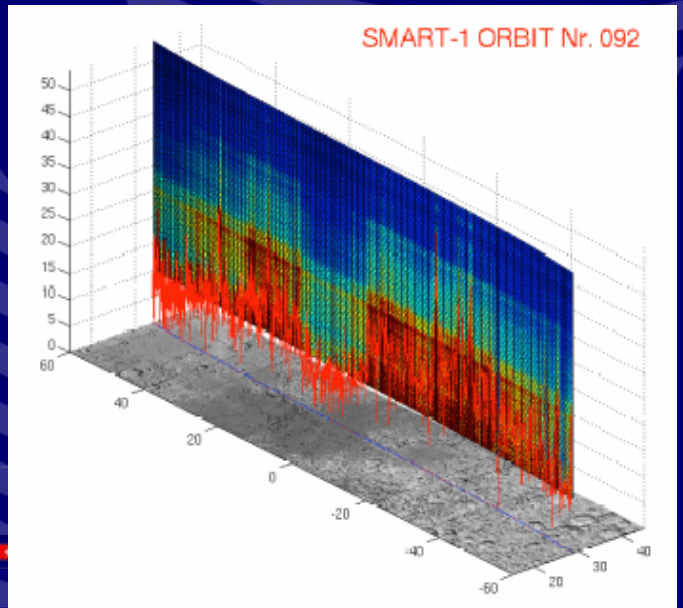


SIR infrared spectra across craters: a window to the subsurface

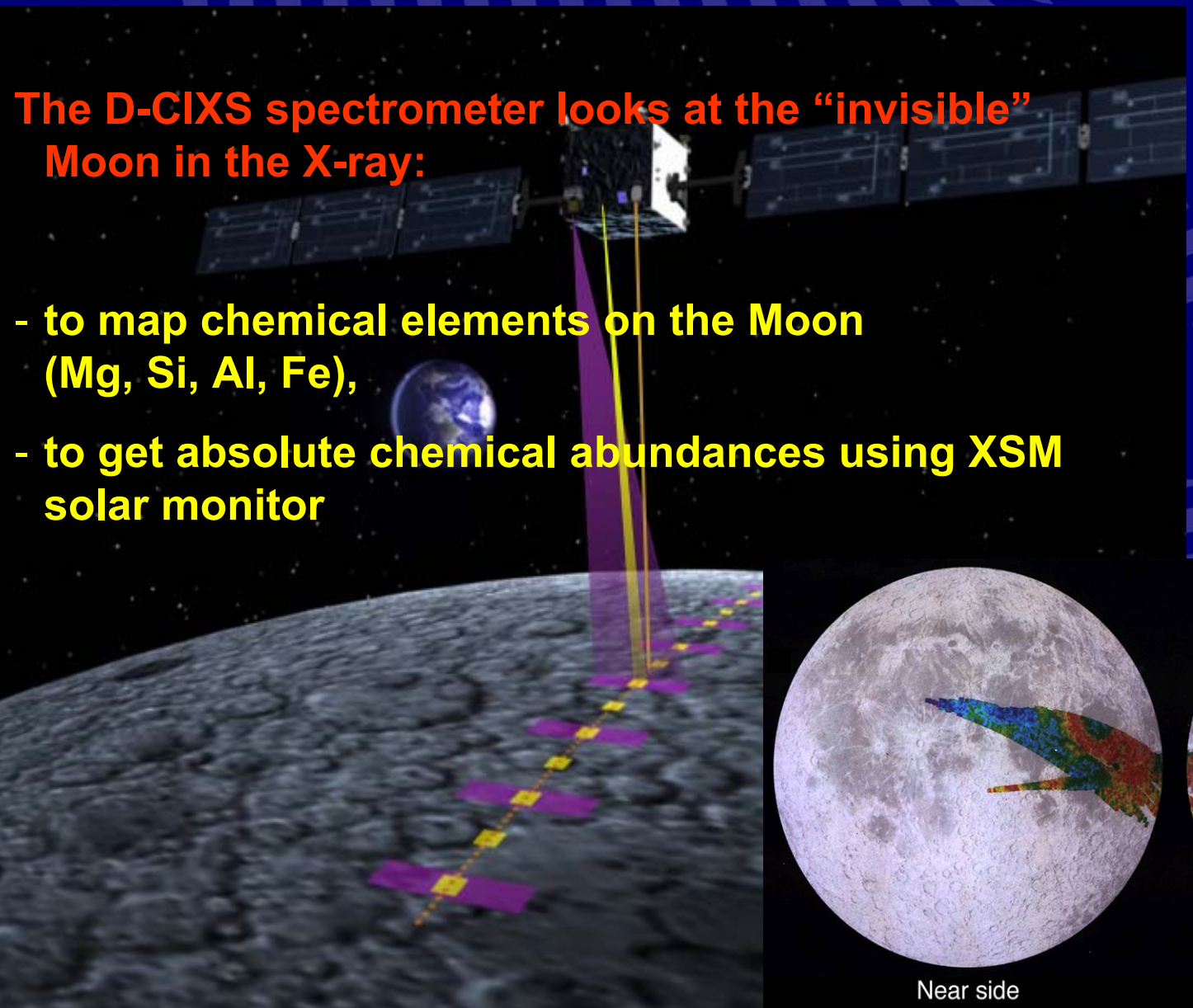


Mineral changes with SIR: from Highland to Mare



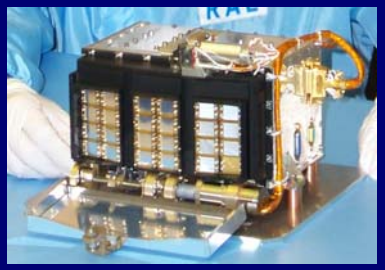


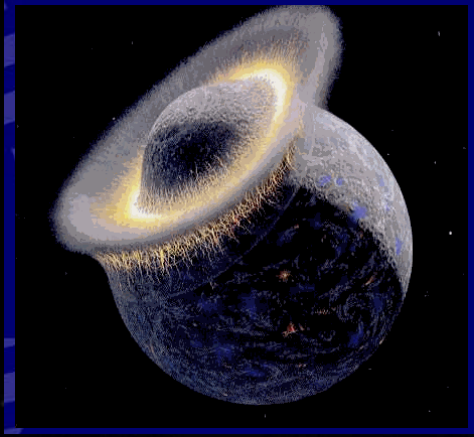
X-ray Moon with SMART-1 D-CIXS : tracing violent Earth-Moon beginnings

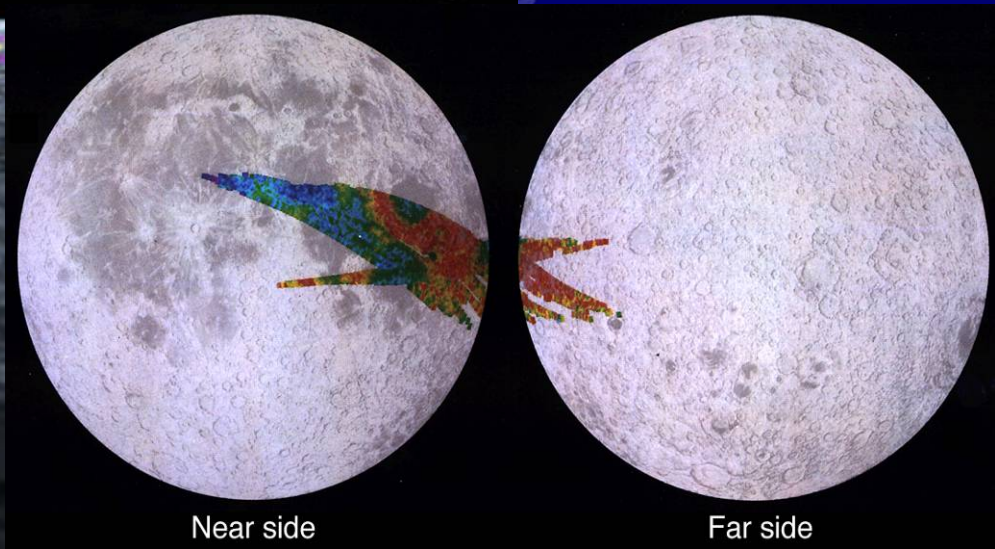


The D-CIXS spectrometer looks at the "invisible" Moon in the X-ray:

- to map chemical elements on the Moon (Mg, Si, Al, Fe),
- to get absolute chemical abundances using XSM solar monitor





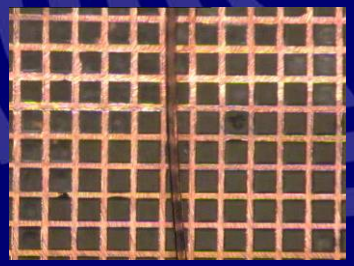


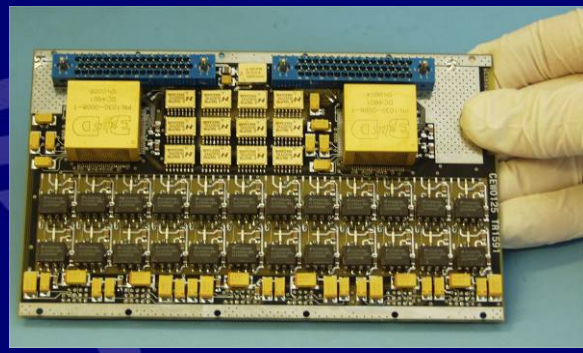
D-CIXS Compact X-ray Spectrometer

New X-ray Detector

Miniaturised electronics

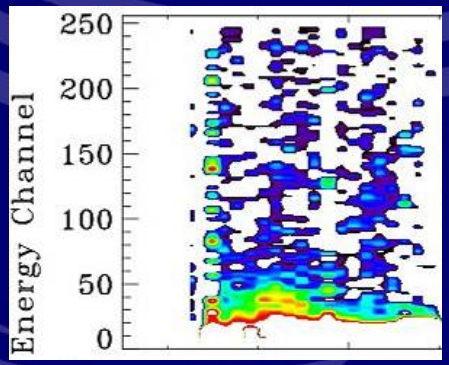
New X-ray micro-optics

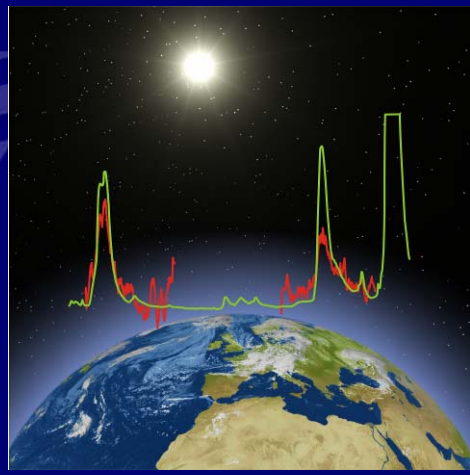




- Nominal performances,
- Cruise observations of cosmic X-ray sources

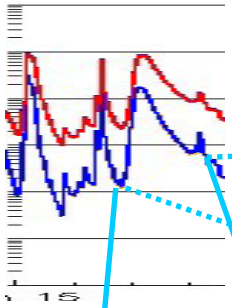
- Earth scans
- Detection of Earth X-ray fluorescence, Ar line

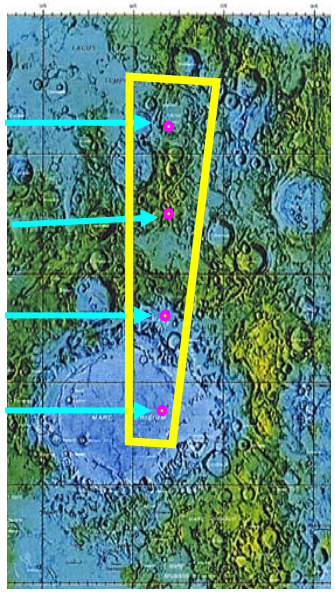




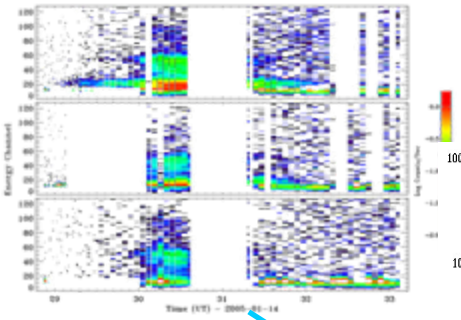
PI (RAL, UK), Co-Is (UK, F, SF, S, E, ESA, US, J, India)

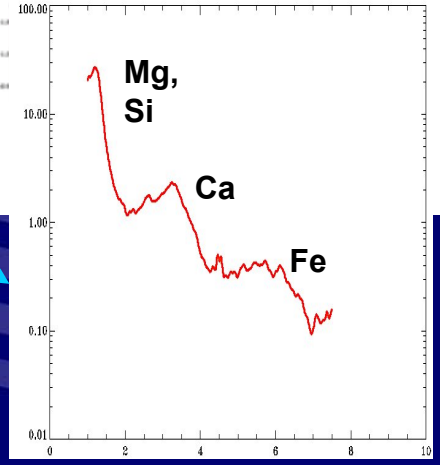
The Sun shines X-rays





The Moon glows → D-CIXS



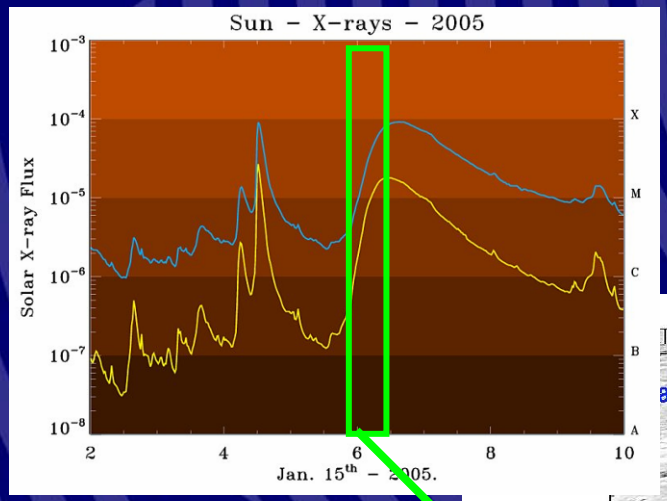


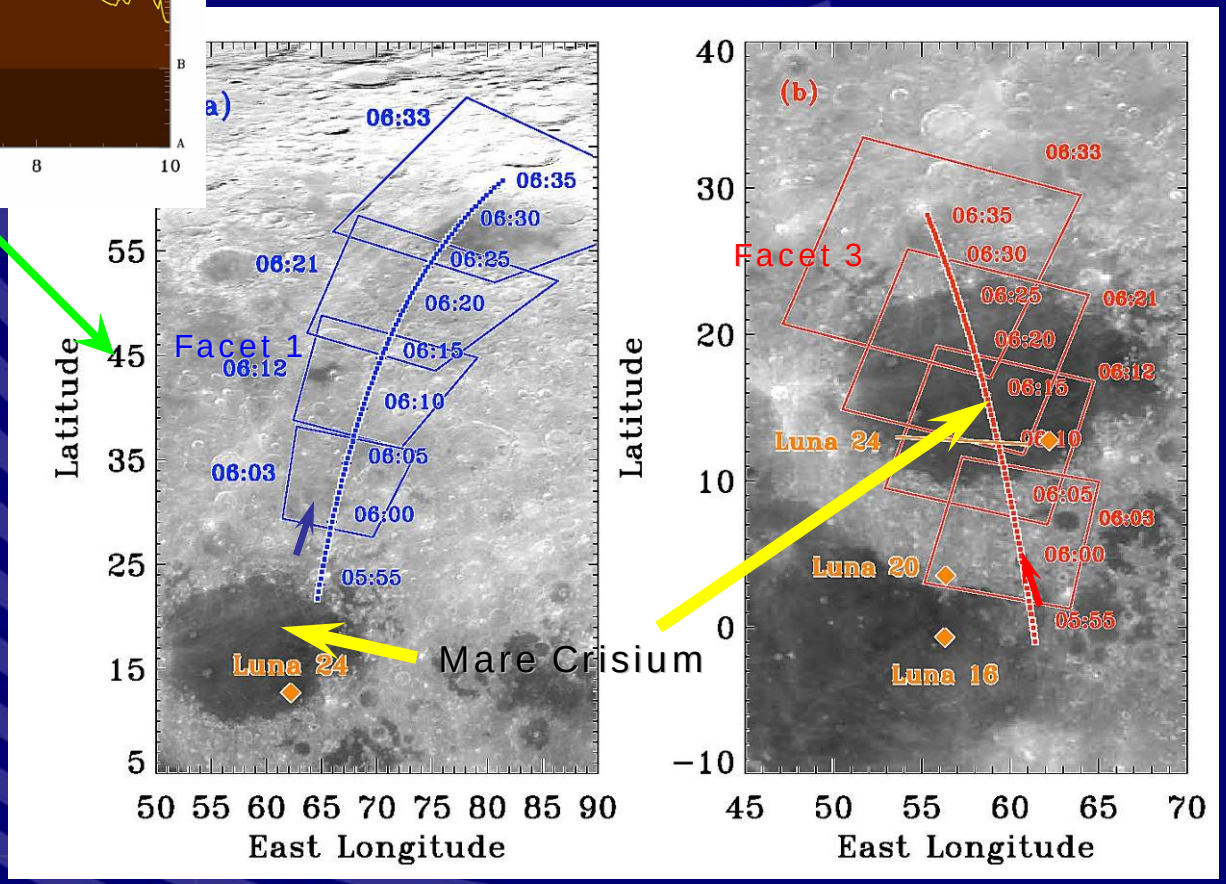
Derived elemental composition

1st detection of Calcium and Magnesium , comparison Luna 24 samples

(D-CIXS) Planetary Space Science, in press

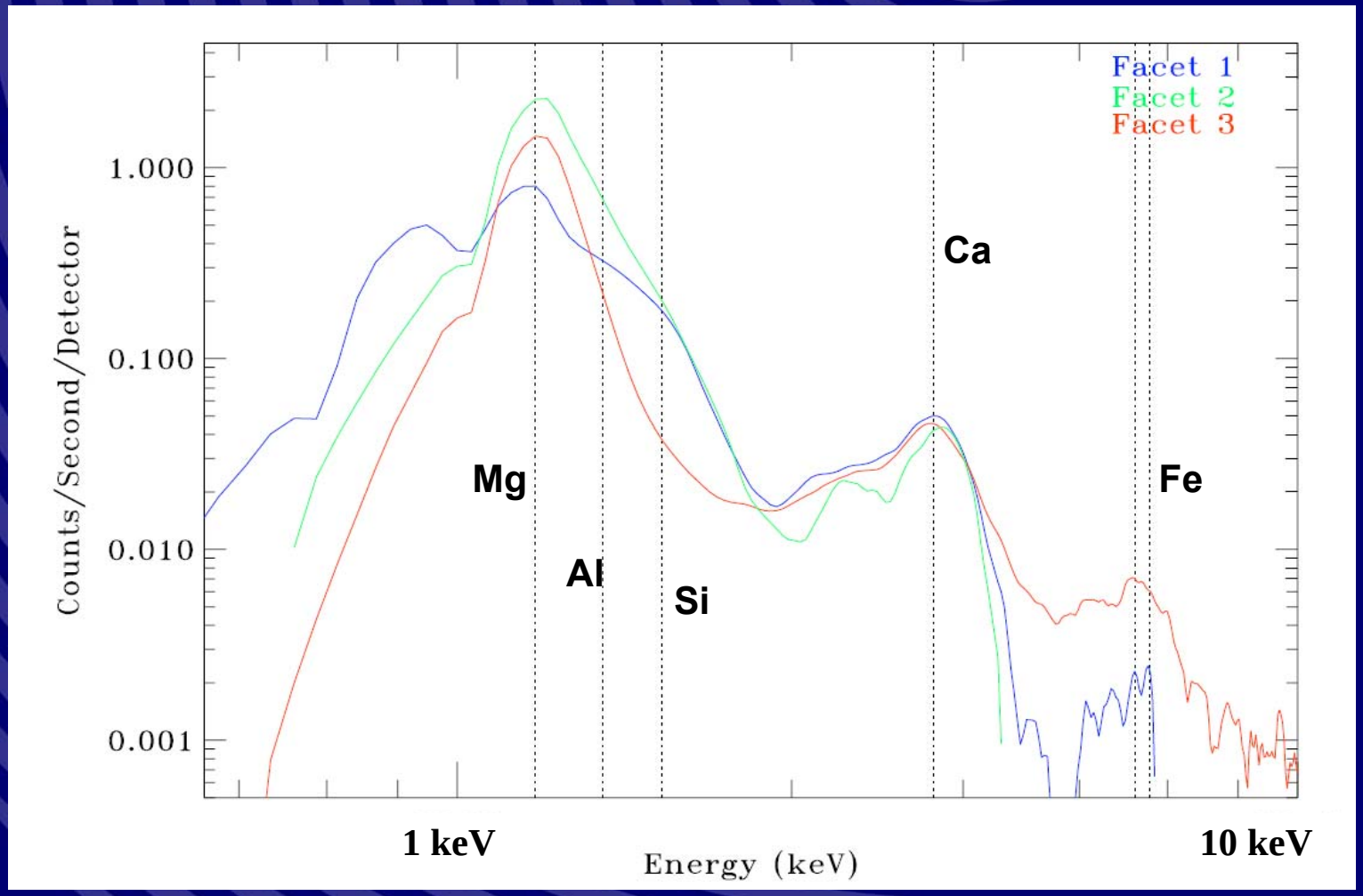
Solar Flare
15 Jan 2005

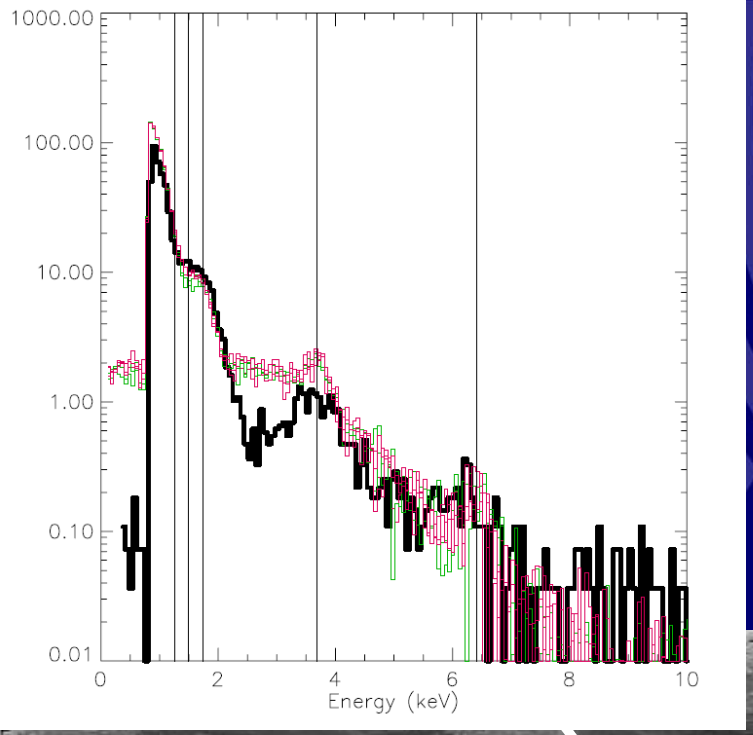


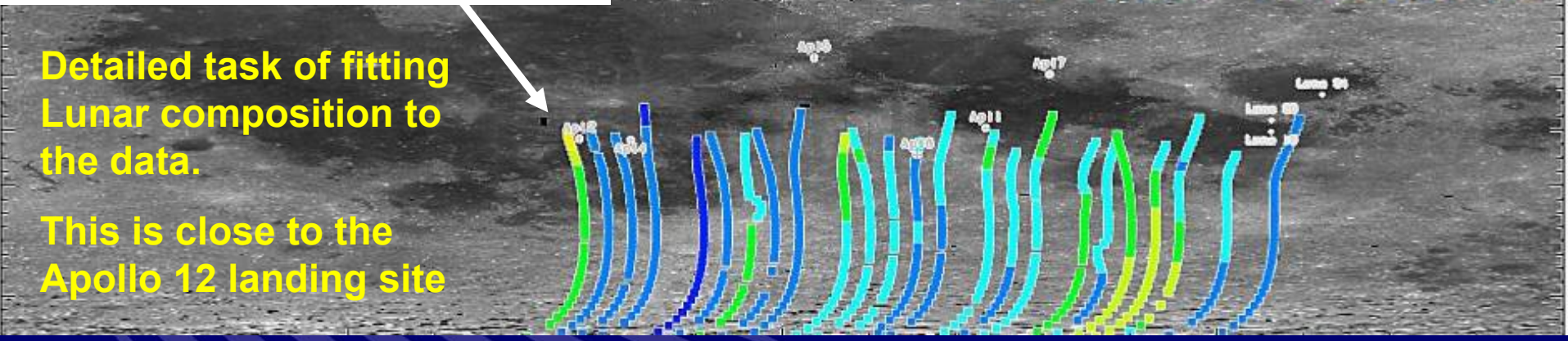


X-ray signatures of Chemical Elements

First ever remote sensing measurements of Ca at the Moon



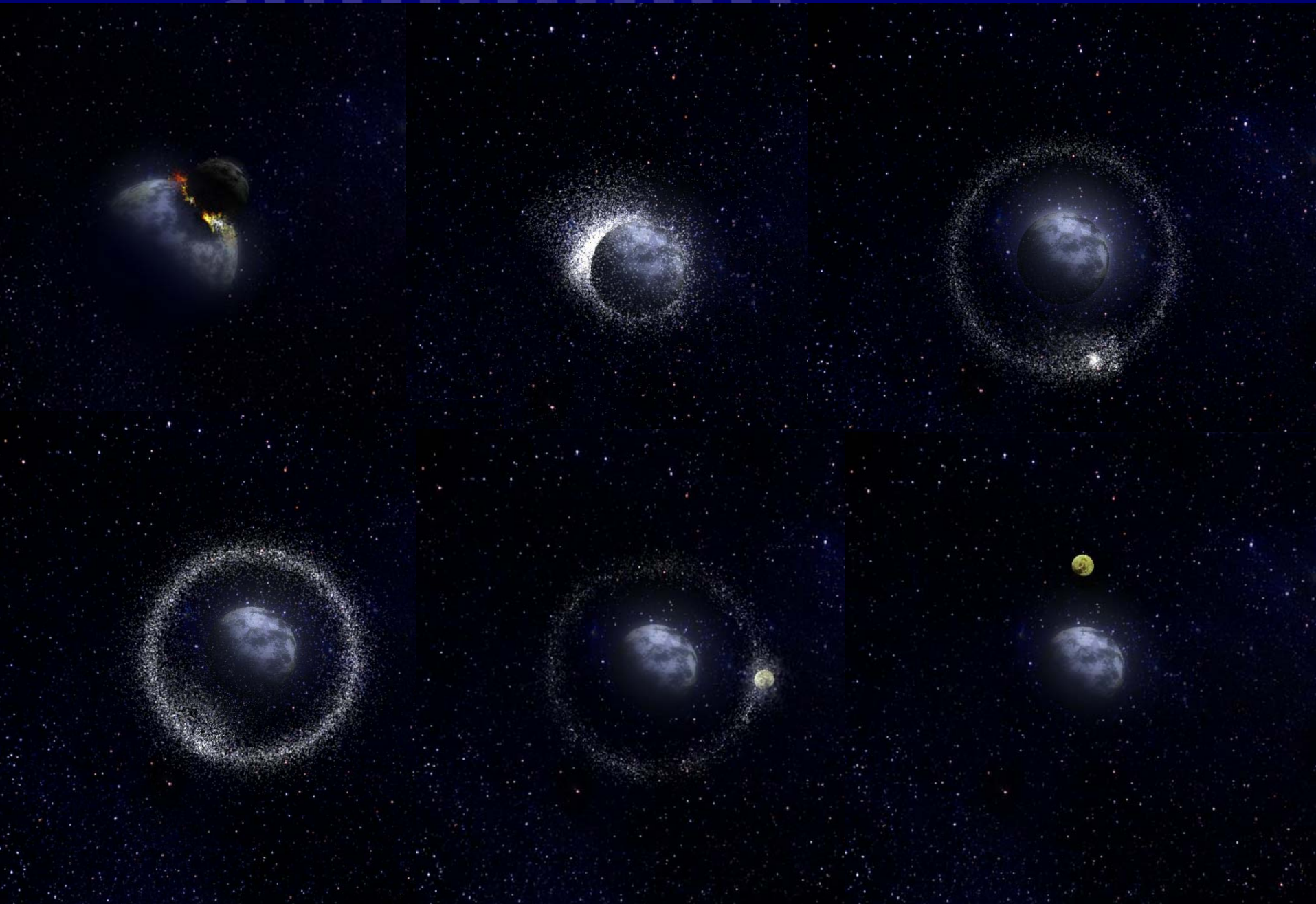




Detailed task of fitting Lunar composition to the data.

This is close to the Apollo 12 landing site

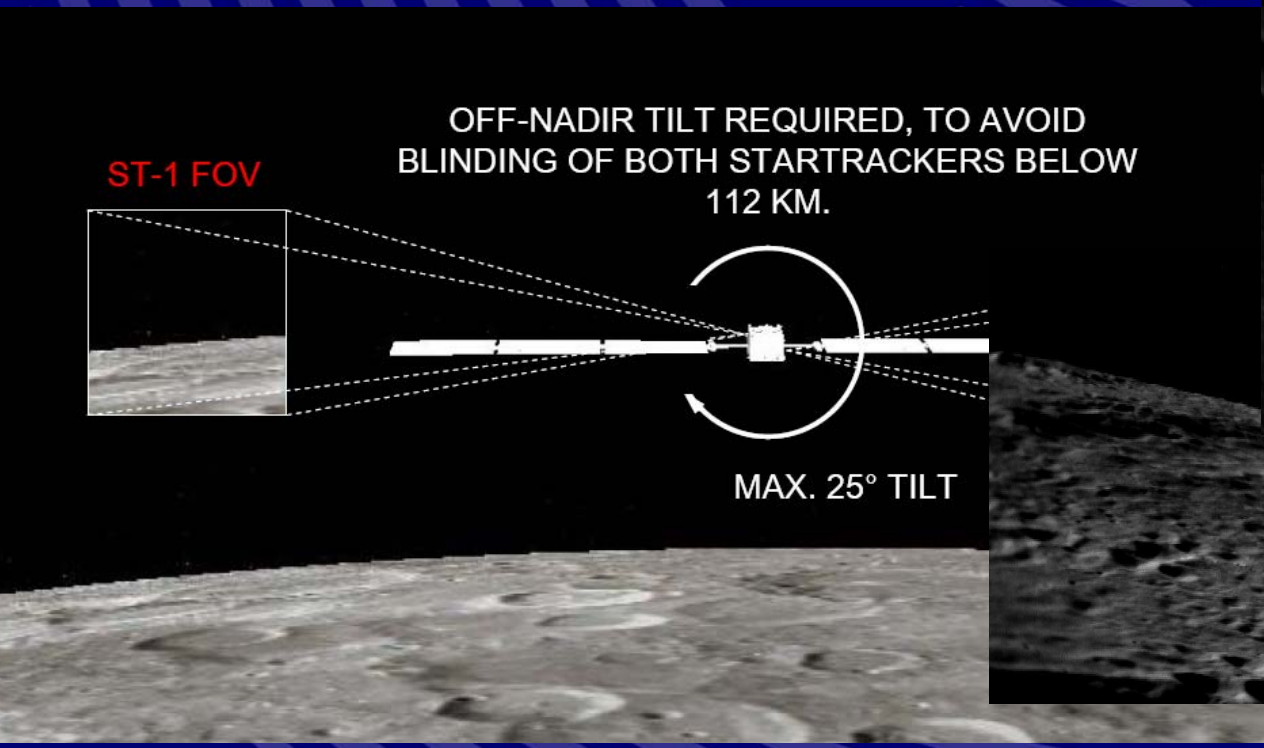
The Moon, daughter of the Earth , 4.5 billion years ago

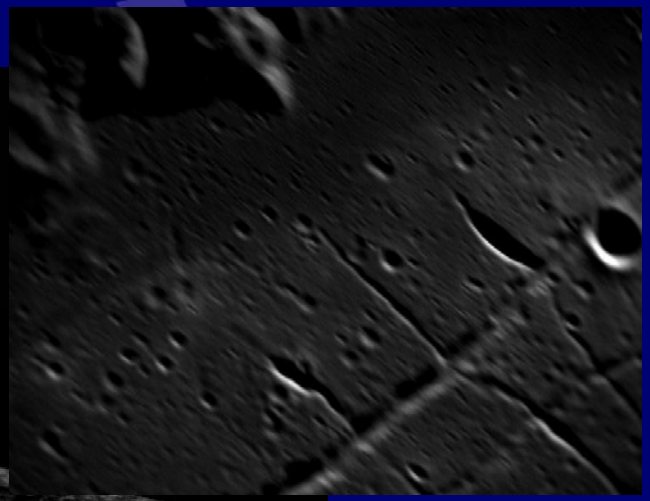


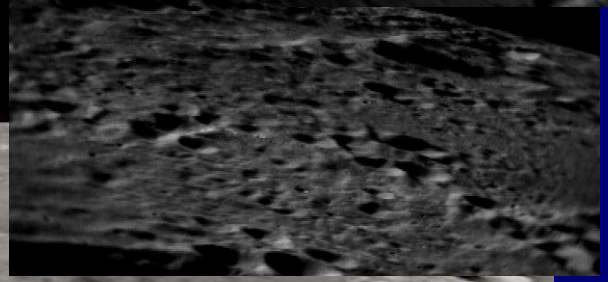
Star Cameras getting blinded…

Nadir pointing no longer possible at altitudes below 112 km:

- **Both star-trackers blinded by Moon in field-of-view → Pictures**
- **Below 112 km off-nadir tilt required, up to max. of 25° at 0 km altitude.**

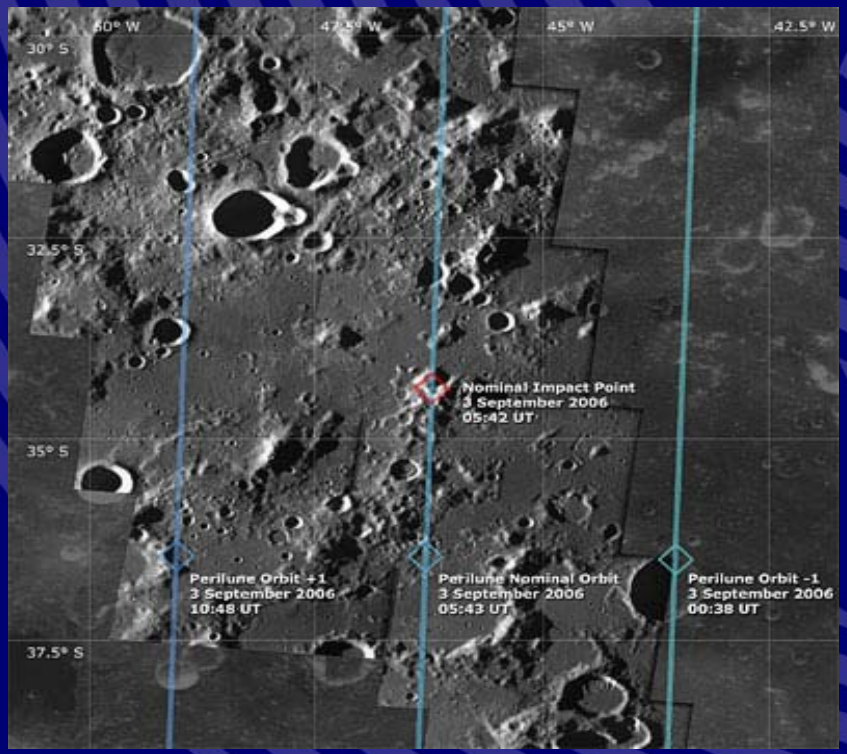






Preliminary results of the SMART-1 impact observing campaign

Bernard H. Foing, SMART-1 Project scientist, ESA
Pascale Ehrenfreund, Leiden University



Impact time: 3 sept 5h42:22 UT

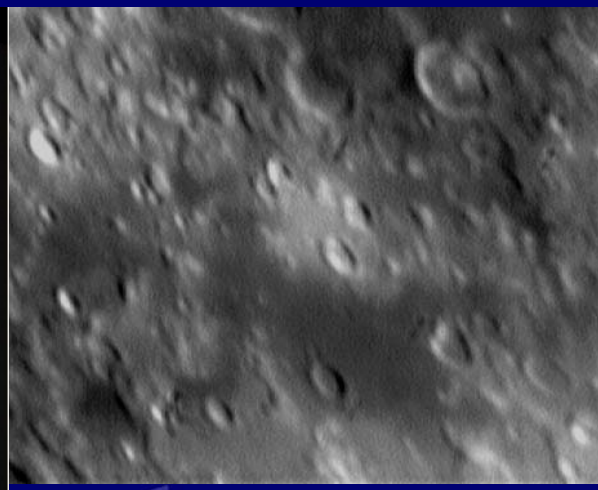
Low velocity impact: 2 km/s

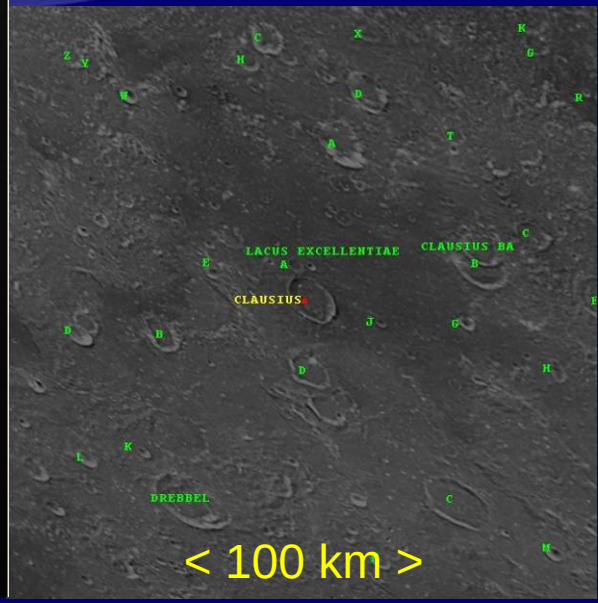
Kinetic energy: 600 MJ

Magnitude of thermal flash 9-17

Crater of 5-10 m

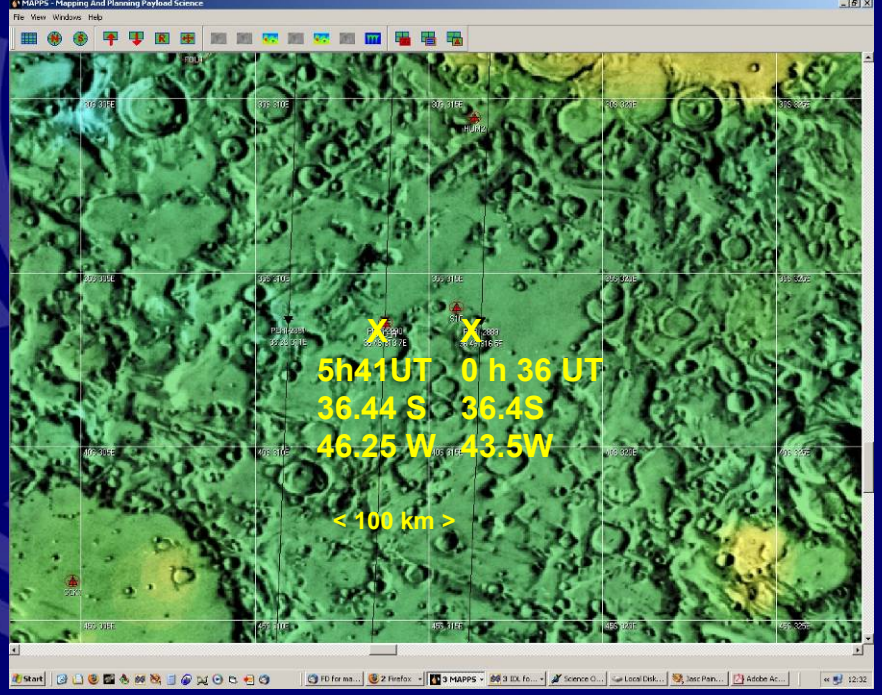
Observations of SMART-1 impact site



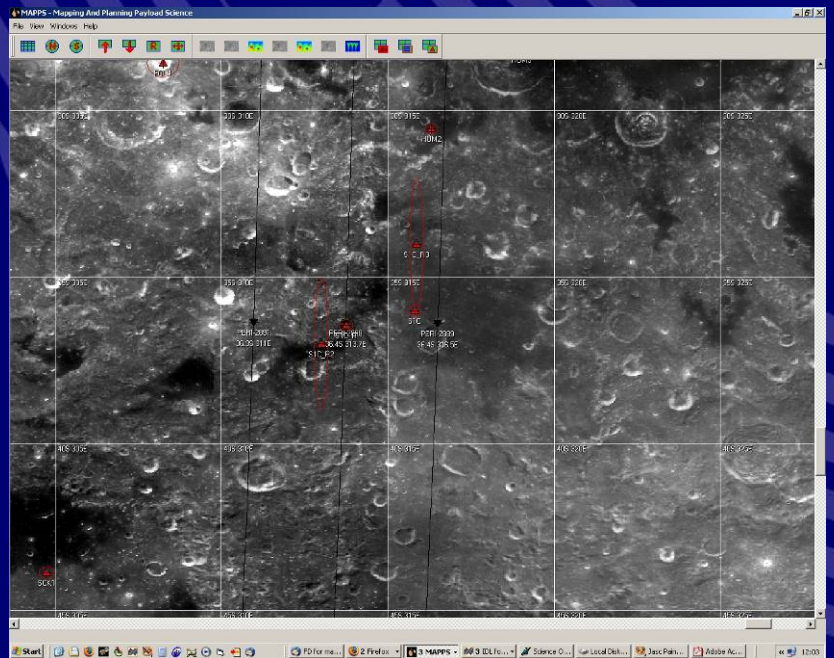


Topography

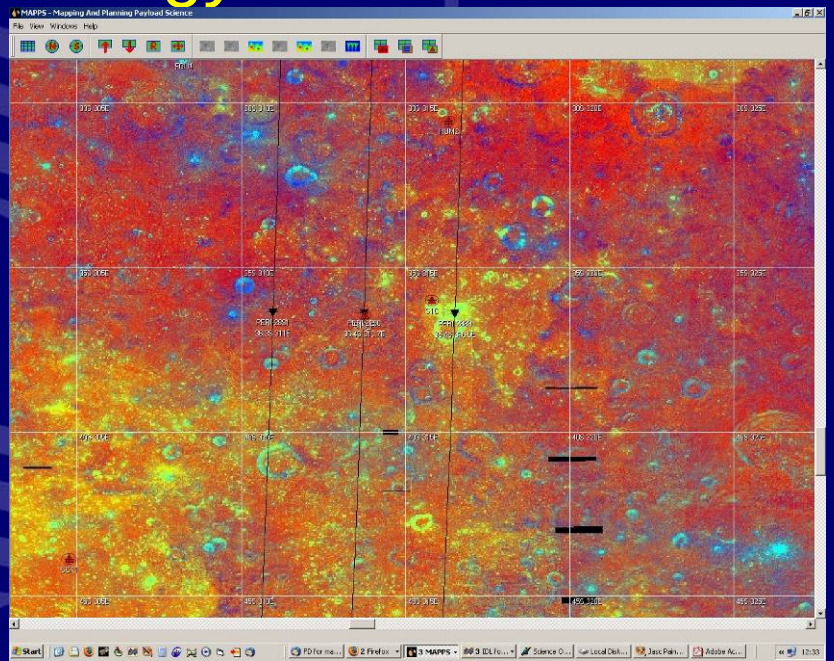
Lake of Excellence

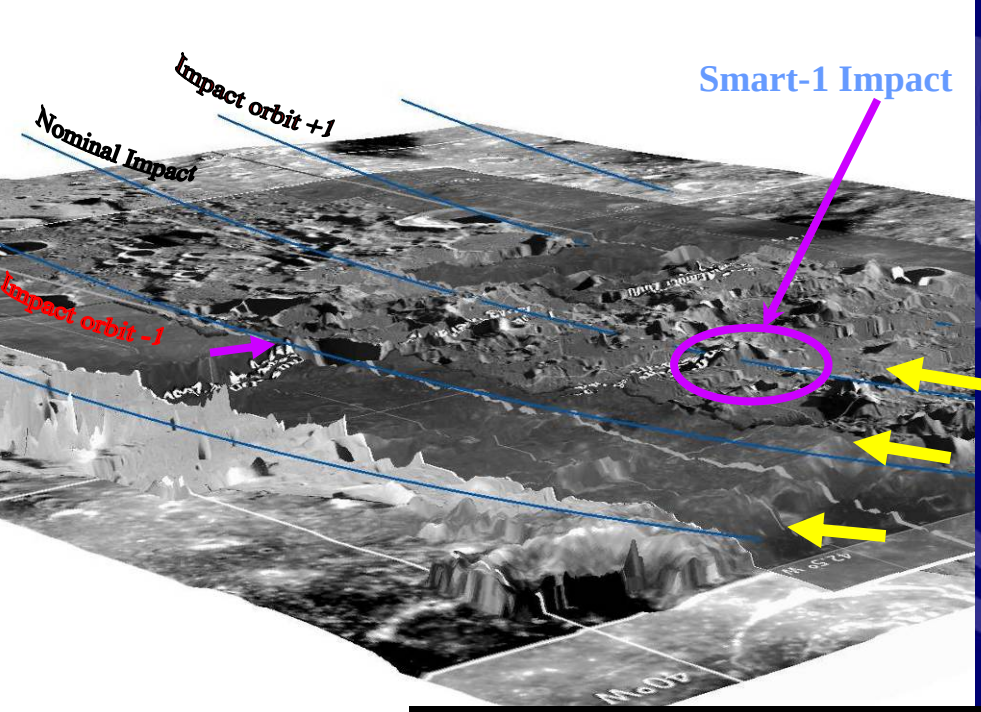


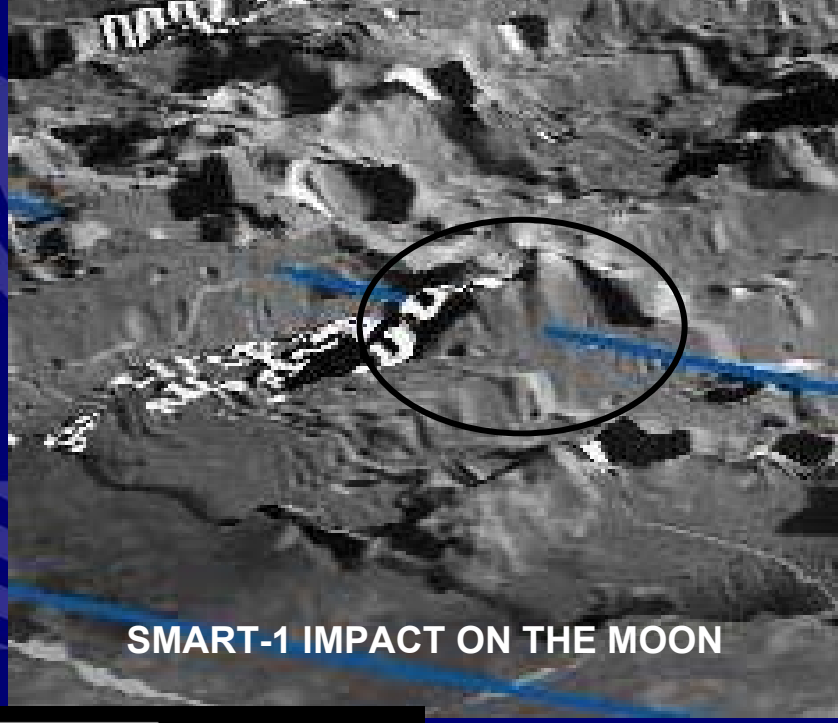
Albedo

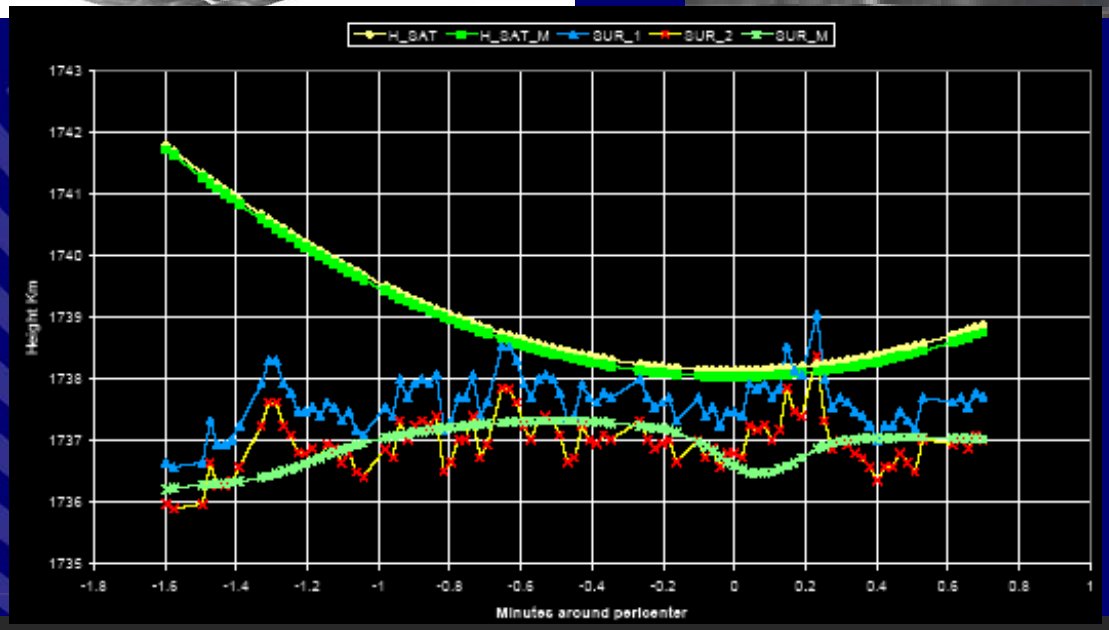


Mineralogy









Courtesy of Mark R Rosiek USGS Astrogeology Team, Planetary Geomatics Group and Dr Anthony C.Cook, School of Computer Science and IT, University of Nottingham,

Orbits

Our last Moon view

Science interest for SMART-1 impact observations…

Post-Observations
Crater Exosphere
0 - ~ days

Evolution of ejecta
Lunar Mineralogy
Optical & Infrared Imaging & Spectra

0-few min

Impact Dynamics
Properties of dust
Optical & Infrared imaging

Impact release of Spacecraft volatiles
Hydrazine N_2H_4 Spectroscopy

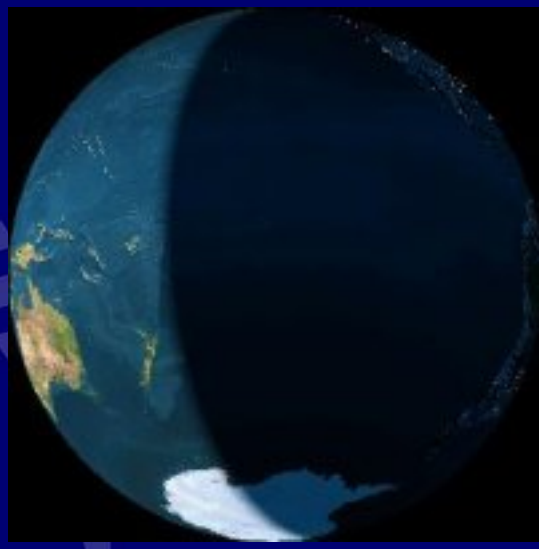
200ms

Impact Physics
Impact Flash
Thermal emission

Impact astronomical observations

- Infrared imaging of thermal flash
- Visible/infrared imaging of dynamics of ejected clouds
  - Earthshine illumination
  - Motions, plumes, curtains of ejected mass
  - Imaging of ejecta reaching sunlight
  - Mineralogy of ejecta
- Spectroscopy
  - Sputtering of lunar Na and neutral elements
  - Spacecraft emissions (N_2H_4, Al, C)
- Radio & VLBI observations
- Post-characterisation of ejecta, exospheric effects
- Follow up search for SMART-1 crater

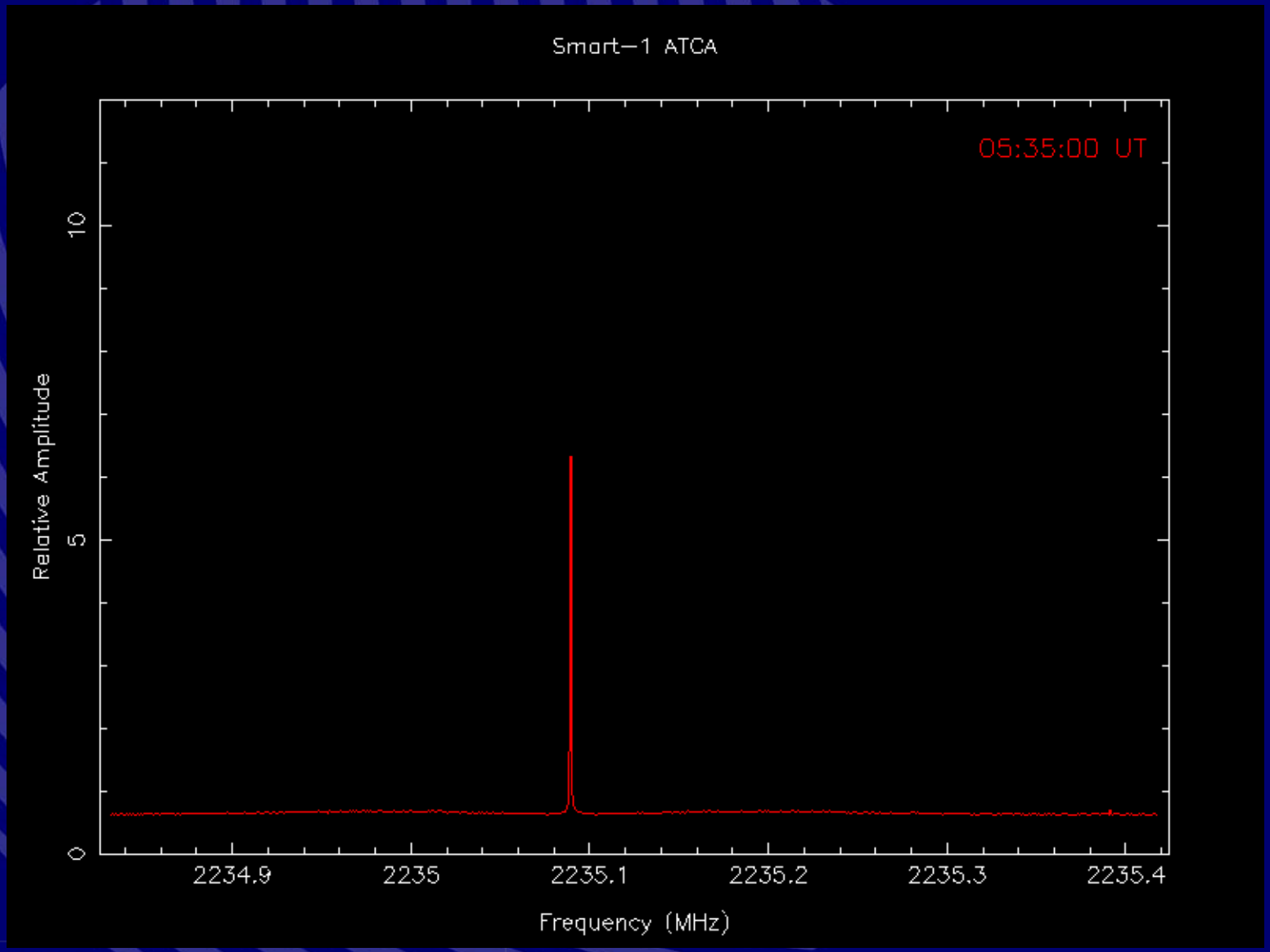
Observing Facilities



Radio observations JIVE VLBI
Calar Alto Spain on duty –2 orbits
Tenerife OGS telescope optical imaging
La Palma TNG
Brazil, Argentina observatories
US Kitt Peak
Big Bear Observatory California, Earthshine
Hawaii IRTF IR spectro/imaging
CFHT Canada France Hawaii IR imaging
Hawaii Subaru auxiliary telescope
ODIN space observatory

Amateur observations (worldwide)

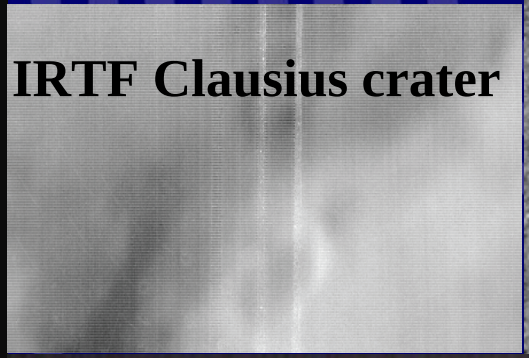
Echo from the heaven gate

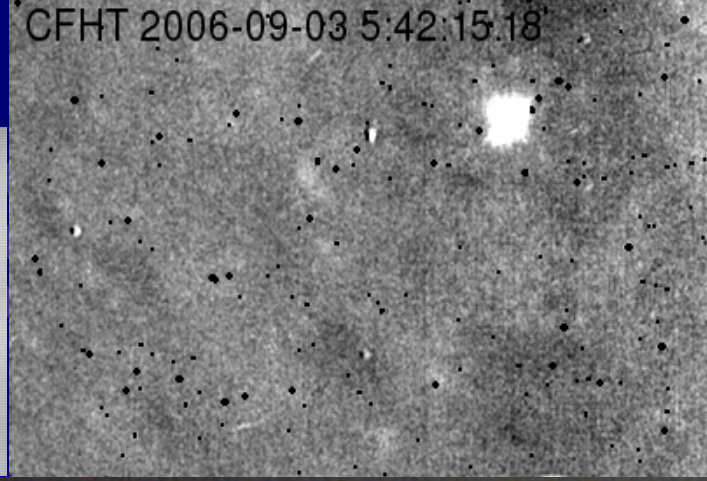


Data inflow….

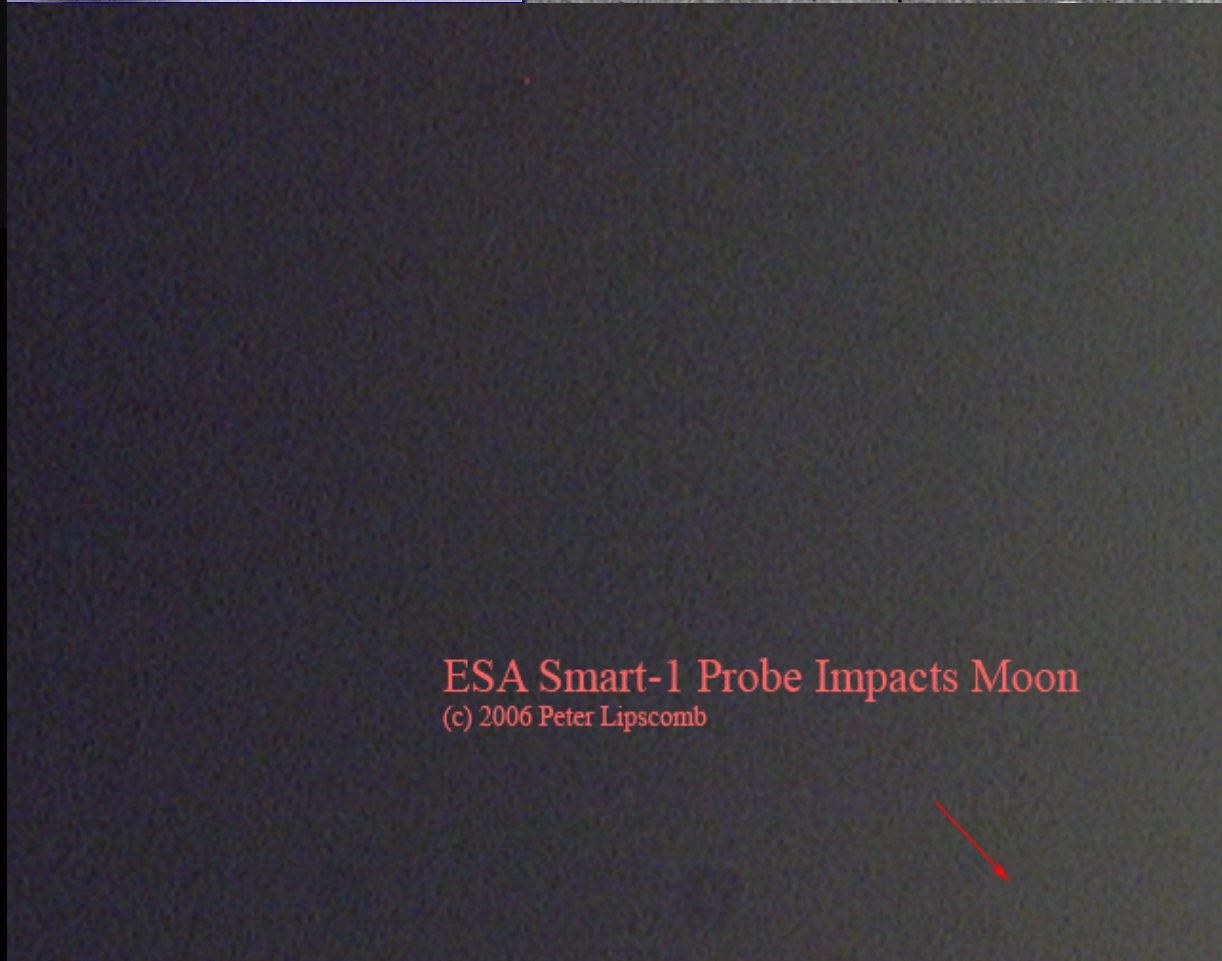
OGS, Teneriffe

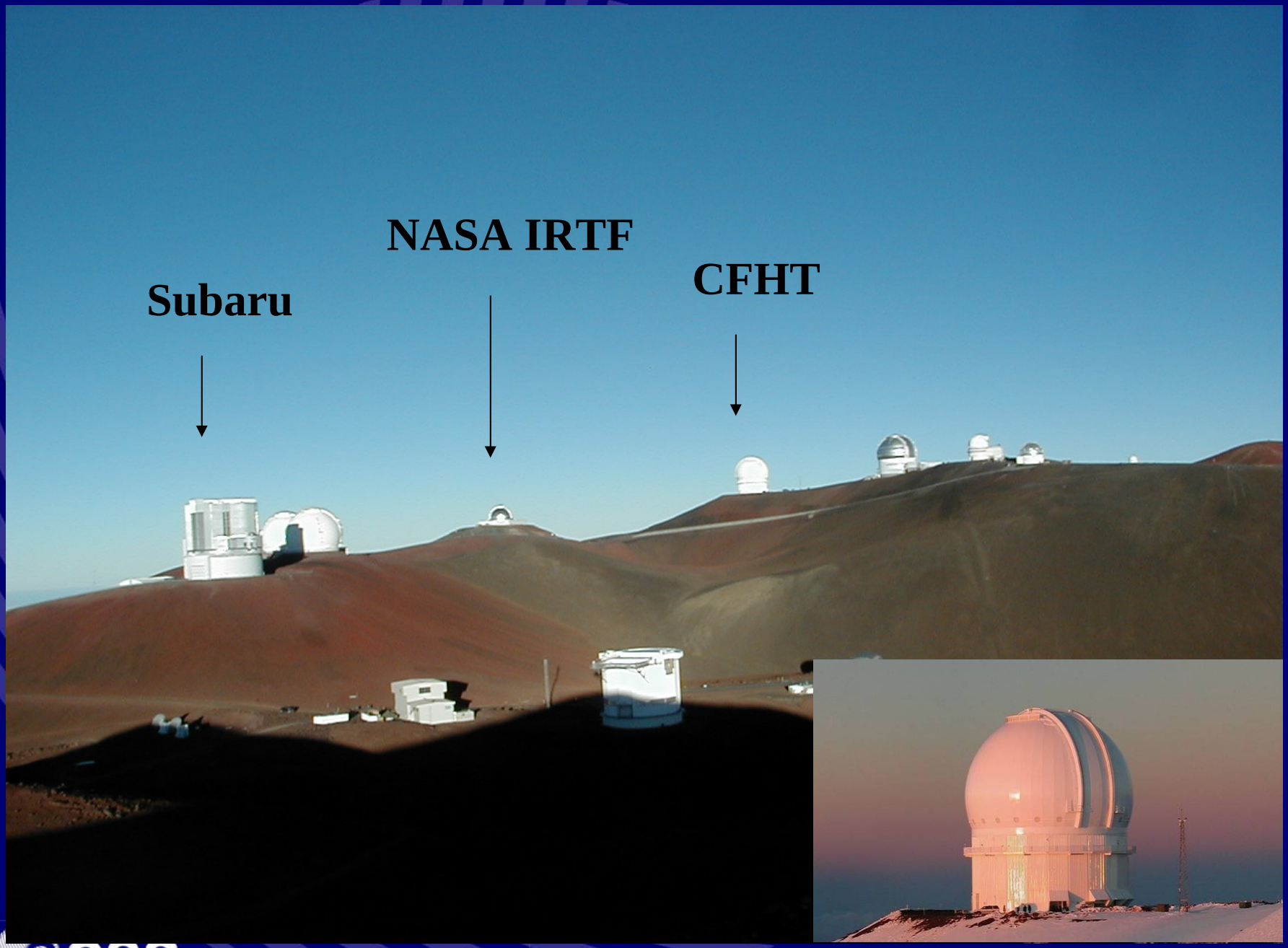
IRTF Clausius crater





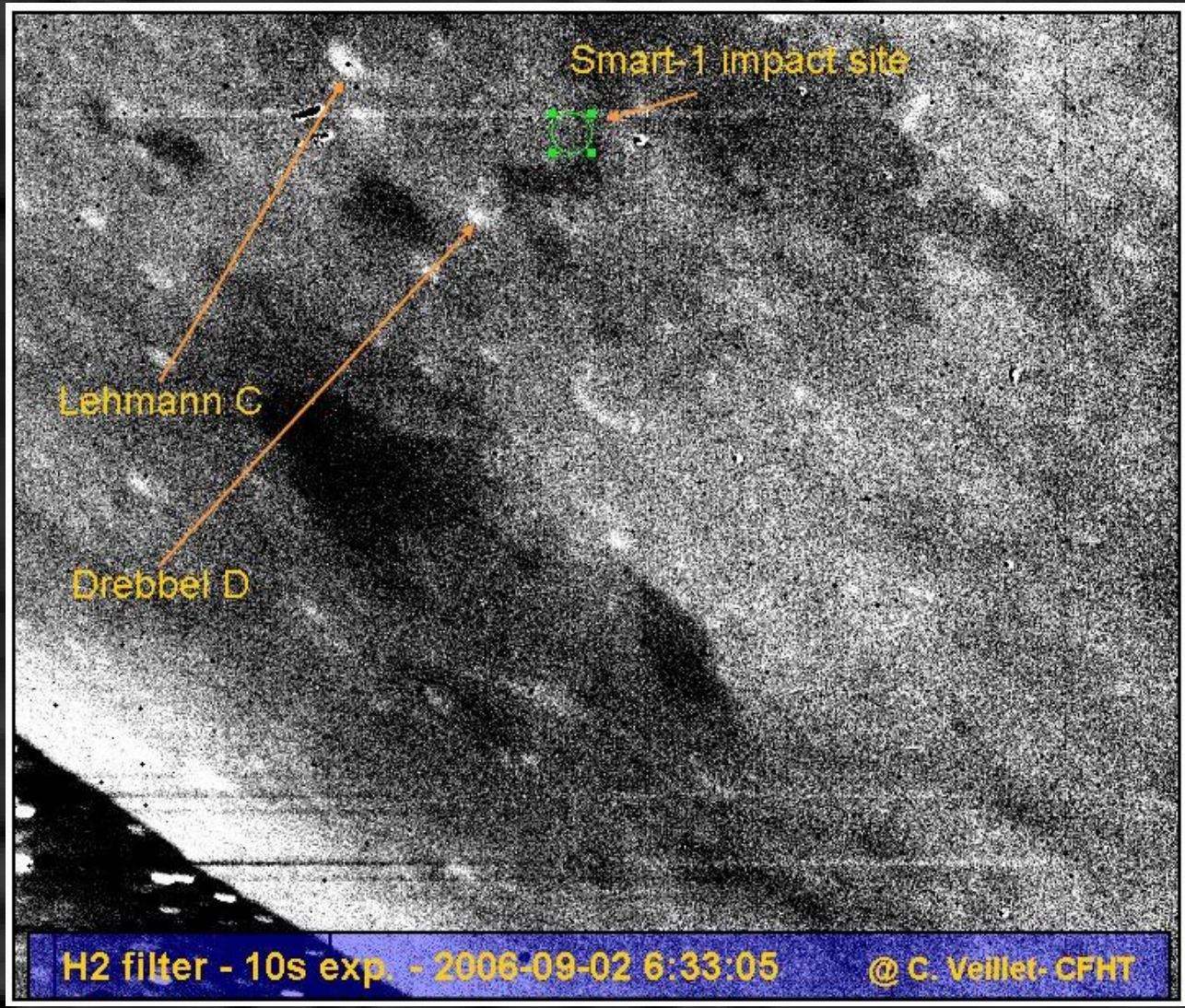
BBSO




NASA IRTF
Subaru
CFHT

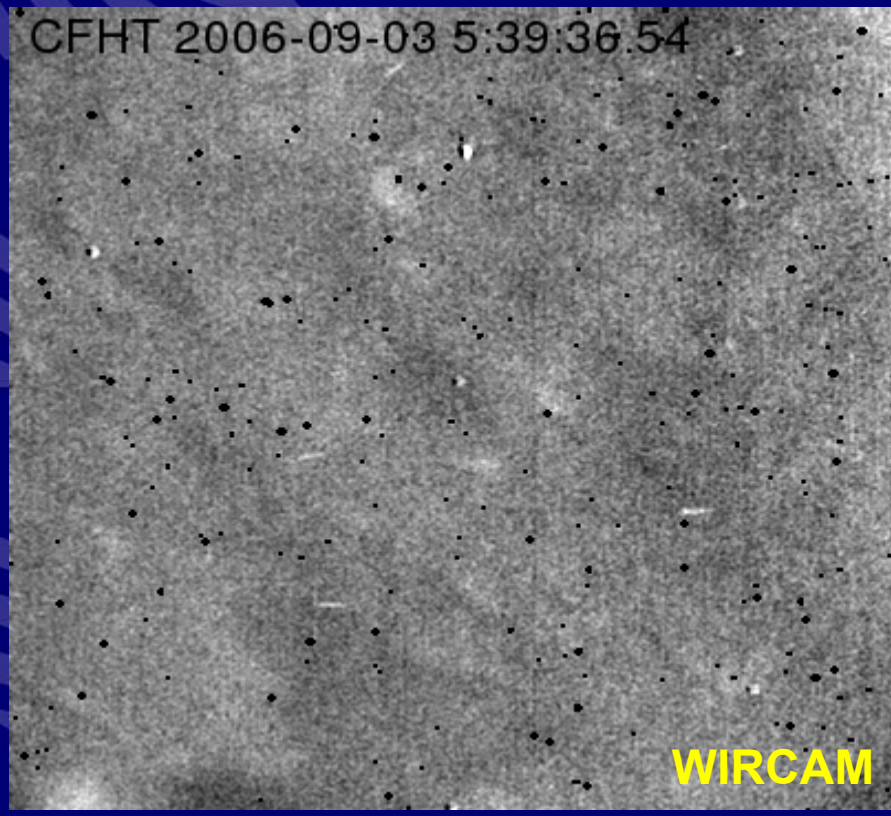
Pre-impact check

- 10s exposures
- one exposure every 15s
- 2/3rd probability of watching the impact



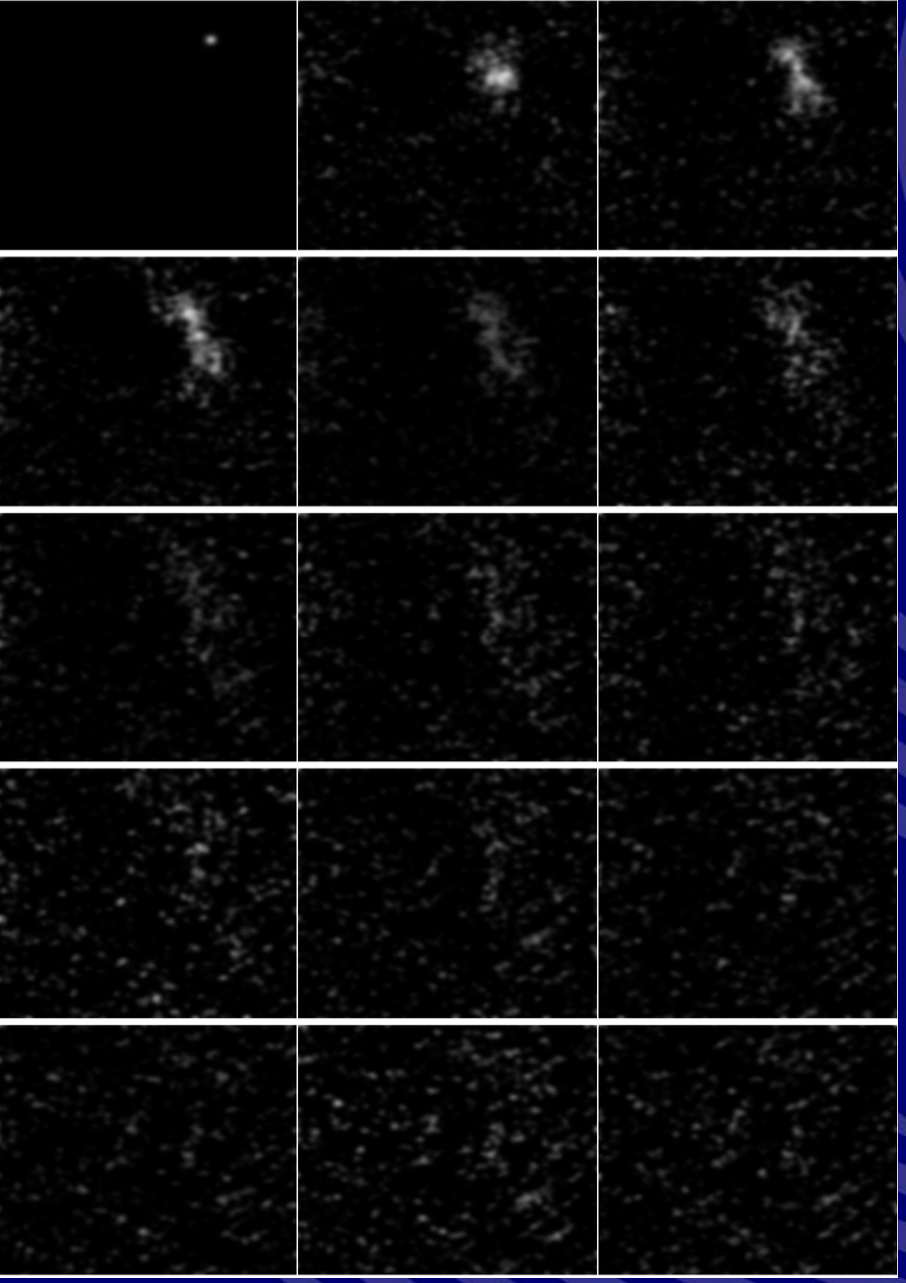
Observation of the SMART-1 Impact at CFHT

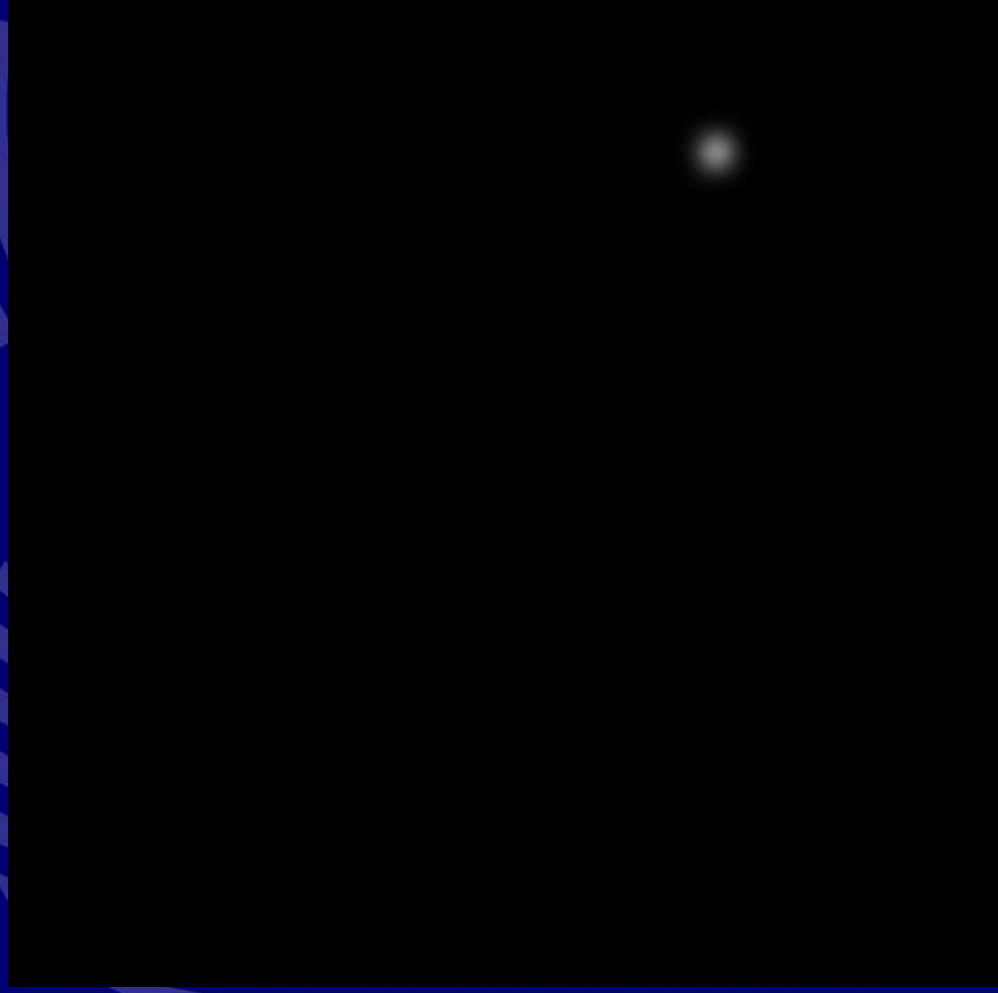
Christian Veillet et al

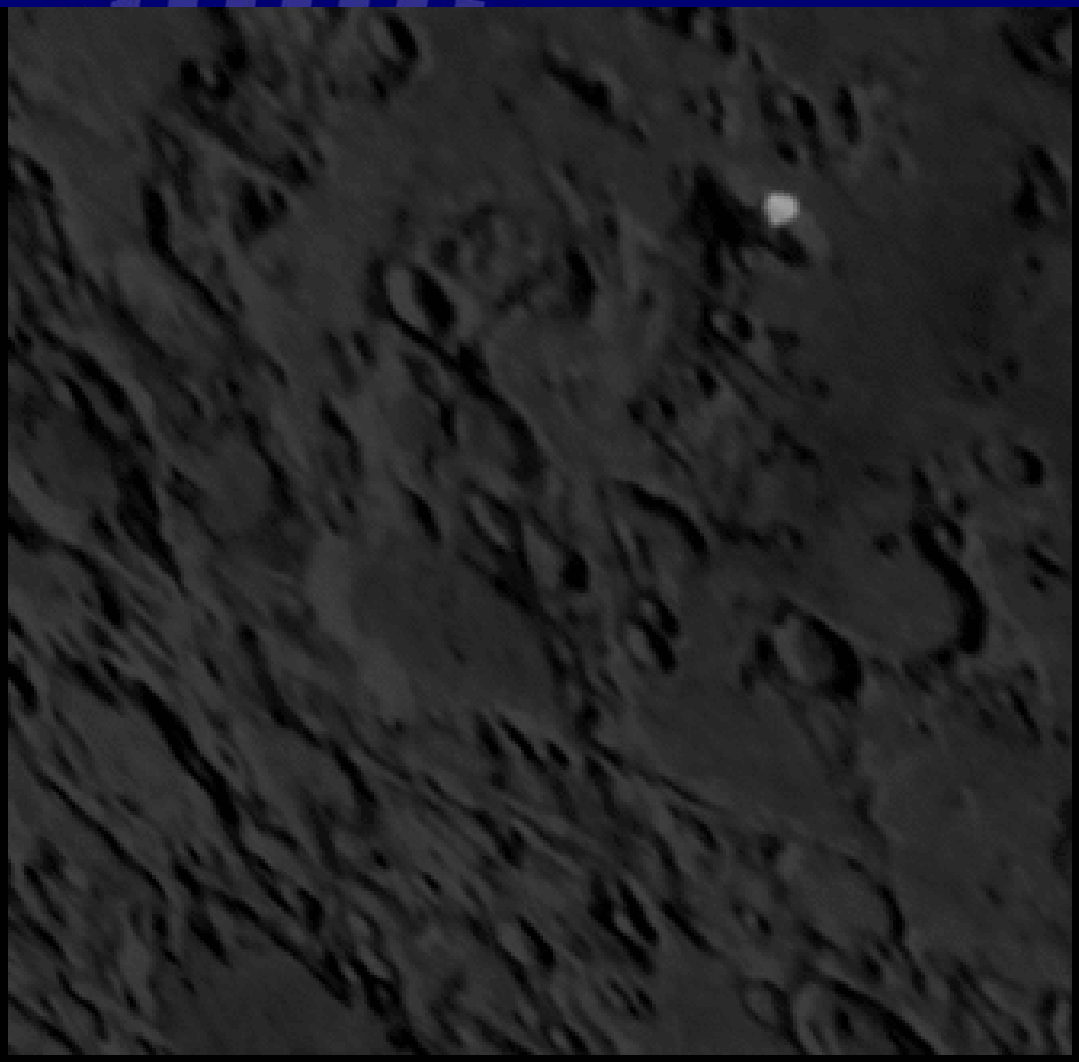


10 s exposure time
H2 narrow-band filter
at 2122 nm
with a 32 nm bandwidth
Image size: 2' x 2'
(or ~200km x 200km)

http://www.cfht.hawaii.edu/News/Smart1/

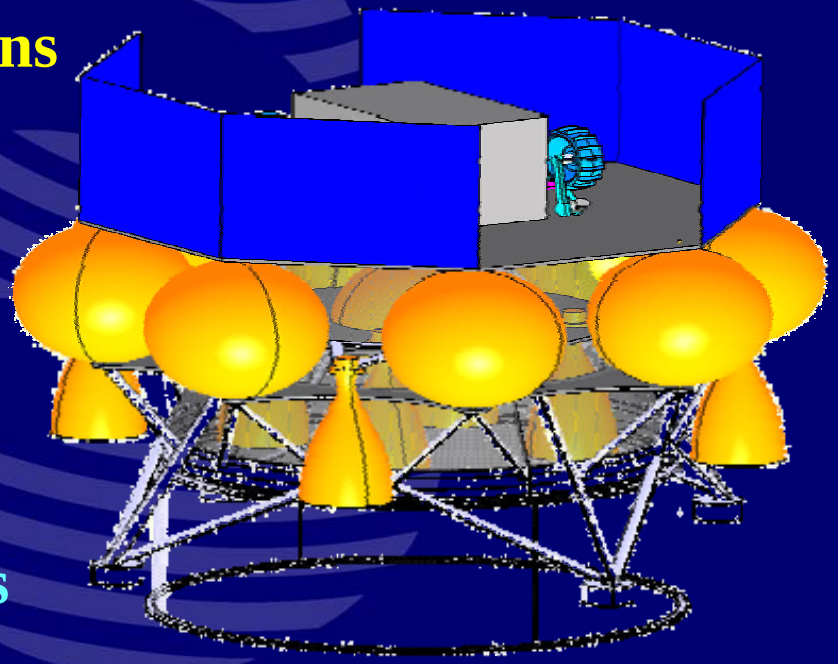






European Lunar Polar Lander

1) Precise Landing on the Moon
2) Preparation of future exploration
3) Geochemical study of polar regions
4) Ice Search/ characterisation



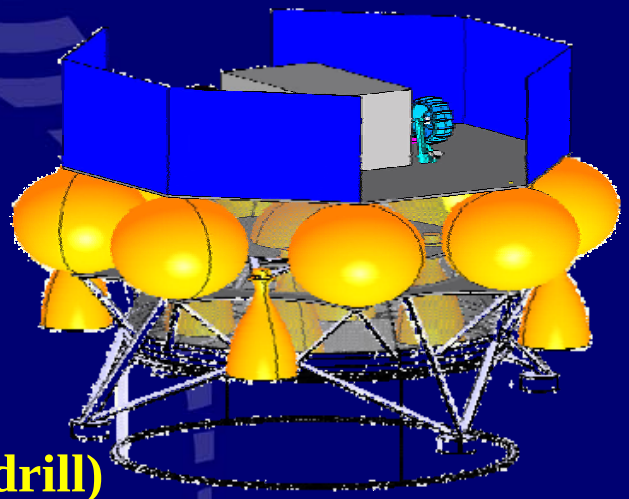
- Lander station element
- Rover element
- Robotic challenge
- Orbiter and relay infrastructures

- Opportunities for Students, education, outreach, cultural, artistic experiments

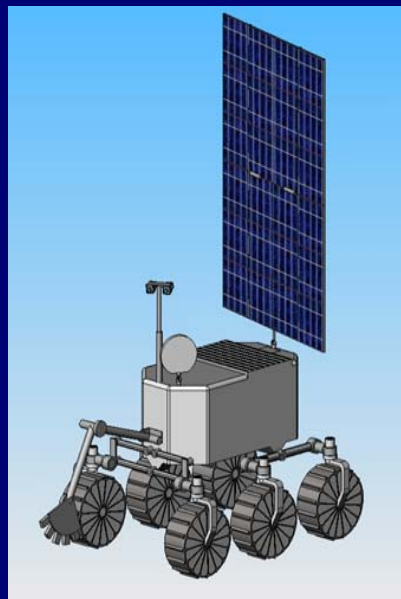
- Part of global robotic village with RLPE2, Chang-E2, Selene 2

European Lunar Polar Lander

- Lander station element
  - Technology survival, operations
  - Geophysical network
  - Life sciences/environment
- Rover element
  - Close range mobility 50 m: nanorover
  - Regional mobility 1-10 km: Exomoon rover
  - Vertical mobility (penetrating sensors, moles, drill)

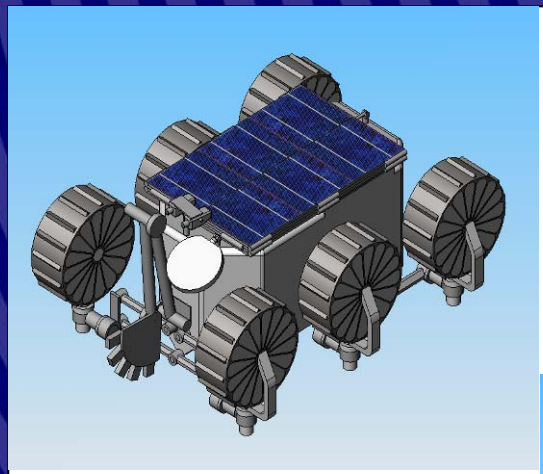


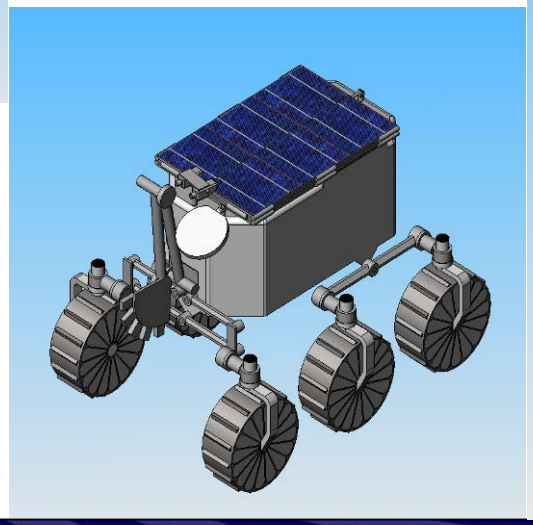
- Lunar Robotic Challenge
- Communication/navigation/survey infrastructure:
  - Small orbiter with HRSC camera and data relay
  - Exchange/support other international orbiters/landers

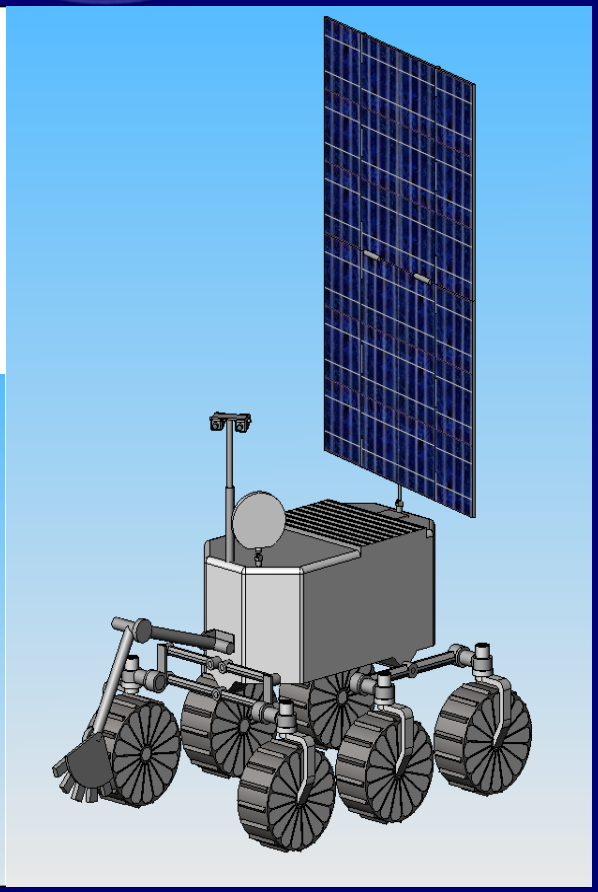


esa

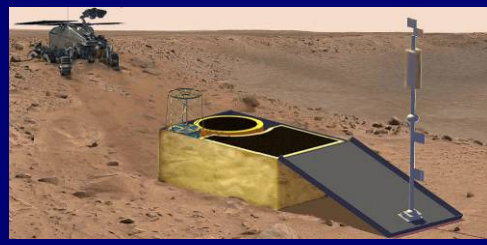
Preliminary Concept design 1



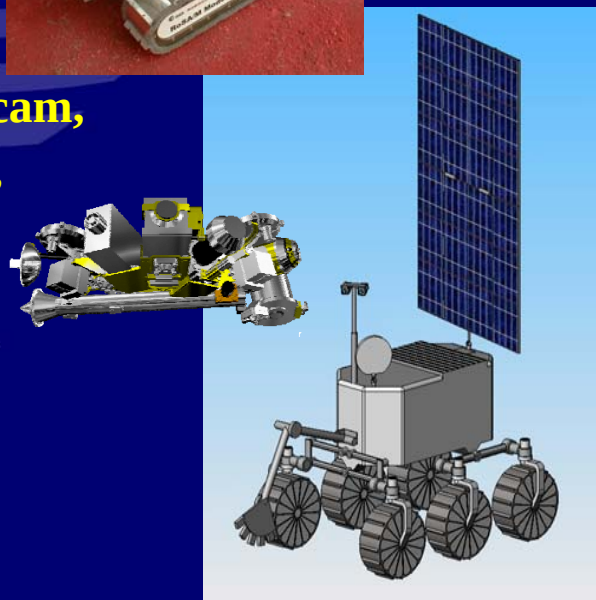


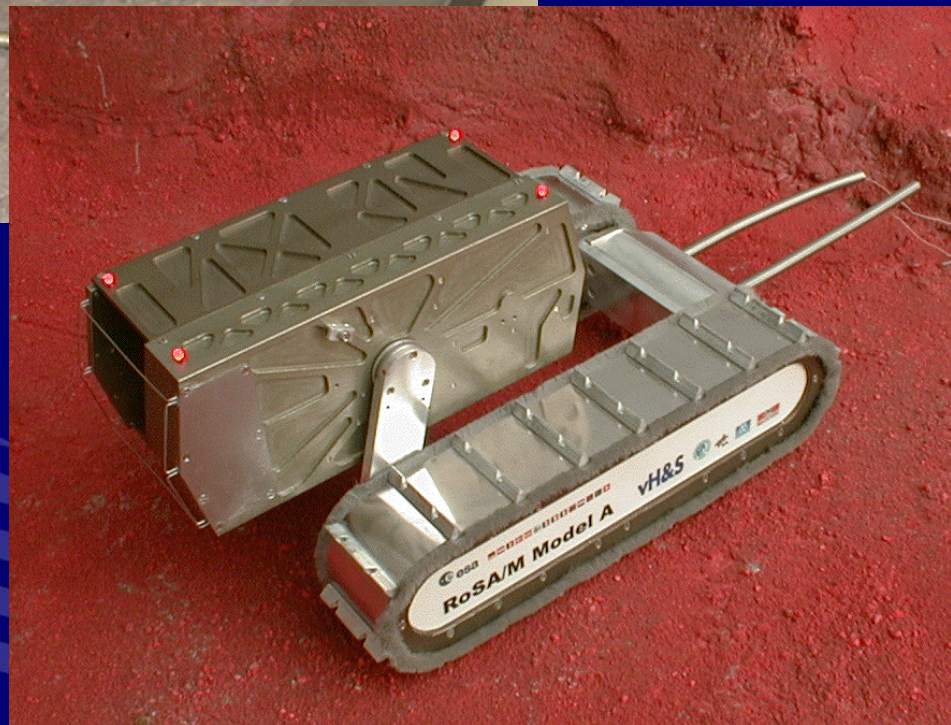


European Instruments for Moon landers (100-180 kg class):

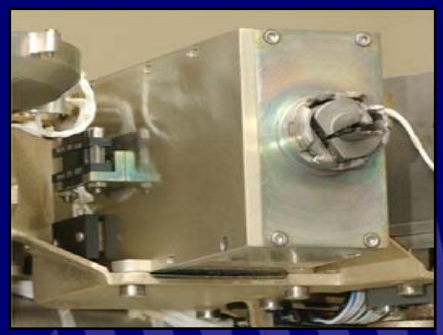


- ELP European Lunar Geophysics package: 15-20 kg
  - Seismometer, Geodesy and laser , Heat flux, Magnetometer
- Lander instruments: 10 kg
  - Cameras: Descent, Pan Cam, Stereo, SRC
  - Local sample analysis (GCMS), permittivity, susceptibility,
- Life science/environment experiments : 7 kg
  - Radiation/ environment/planetary protection studies
  - Melissa bacteria precursor, plants on the Moon
- Close proximity Rover: 5 kg
  - Neutron spectrometer, APX , Close up camera
  - Electromagnetic sounder, Ground penetrating radar
- Regional rover : 120 kg
  - Navigation and hazards avoidance, Nav and inspection cam,
  - Robotic arm (PAW like), drill and mole , Active seismic,
  - LIBS, Fluorescence, Thermal IR fluorescence
  - Dust lifting measurement device, QCM or cube piezo
- Lunar robotic challenge to access ice in dark: 15 kg
  - nanorover, harpoon, impactor, …

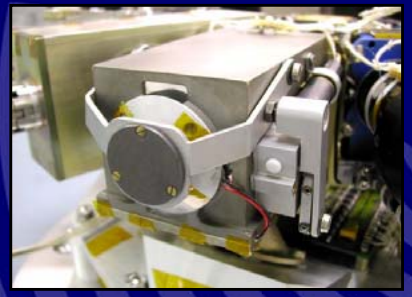




esa



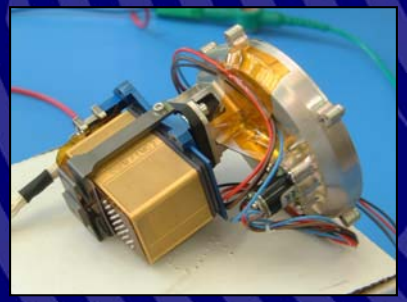
Rock Corer
Hong Kong Polytechniq

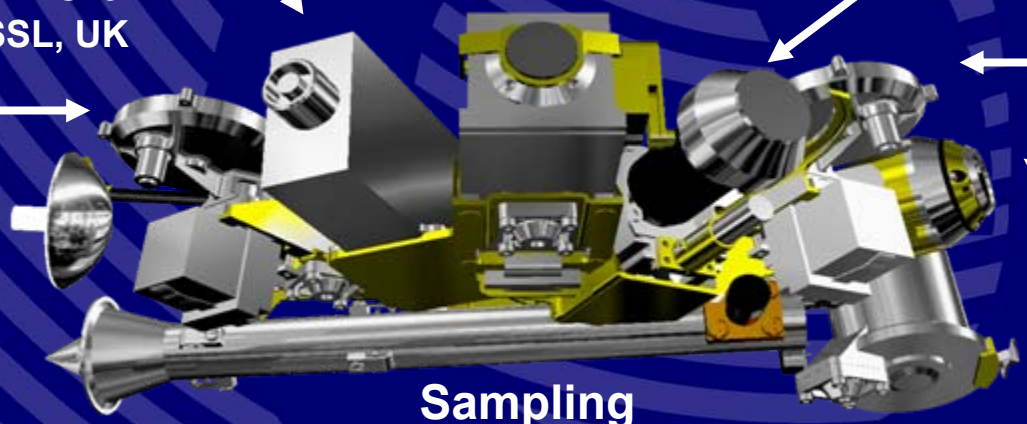


Mössbauer Spectrometer
University of Mainz, Germany

Microscope
Switzerland, MPEA Germany

Stereo Camera
MSSL, UK





Stereo Camera

X-Ray Spectrometer
University of Leicester, UK

Sampling Mole
DLR, Germany

esa

PAW Courtesy M. Sims Leicester U.

SMART-1 collaboration with upcoming lunar missions

- Science/exploration:
  - Earth-Moon formation & evolution
  - water ice and resources
  - conditions for future sciences & life
  - sites for future robots/humans

- SMART-1 precursor for future missions fleet

  2007 Chinese Chang'e 1 (science exchange & support)

  2007 JAXA Selene (science exchange & support)

  2008 Indian ISRO Chandrayaan-1 (3 ESA instruments

  2008 US Lunar Reconnaissance Orbiter/LCROSS

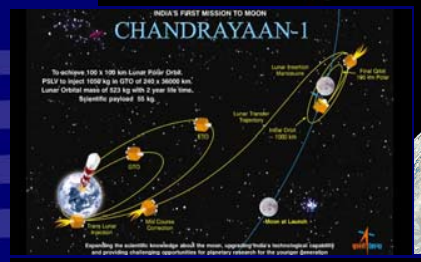
  2009 JAXA Lunar A penetrator

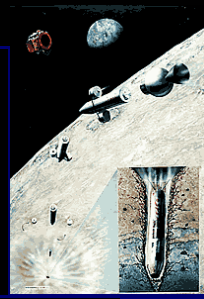
  2010-2012 landers, rovers, technology testbeds

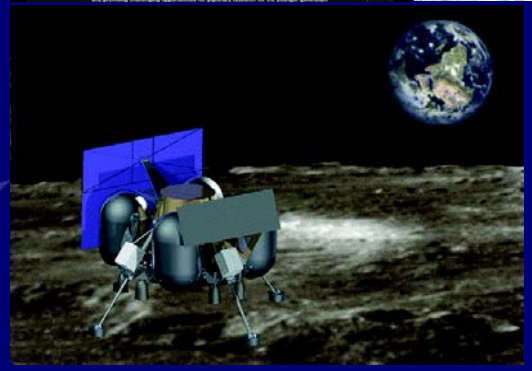
  (US, China, Japan, India, Europe)

  Sample return missions

  Preparation for human lunar missions







SMART-1 input to breakout sessions

- **Data archiving**
  - **ESA PSA Planetary Science Archive (PDS)**
  - **Ongoing data calibration and validation**
  - **Early access to data on collaborative basis**

- **Lunar mapping and data merging**
  - **Ongoing effort with space agencies and European Geological Surveys**

- **Lunar coordinates**
  - **Mismatch old Clementine reference (eg 4km W)**
  - **Insufficient lunar grid & topography model**
  - **Corrections to achieve SMART-1 impact within 1 s**
  - **Agree with LRO coordinates white paper**

SMART-1 *input to breakout sessions*

- **Calibration Targets**
  - **Observed for imaging, infrared and X-ray spectrometry**
  - **Instruments & space/ground intercalibration**
  - **Support Int'l Calibration targets effort (COSPAR, ILEWG)**
  - **Link with sample ground truth**

- **SMART-1 collaboration with upcoming missions**
  - **Feed forward, experience and data**

(www.esa.int & sci.esa.int/smart-1, sci.esa.int/ilewg)

Cooperative Scientific Opportunities

- Overall science and exploration goals
- Measurements objectives
- Observations conditions & SMART-1 planning tools
- Spacecraft and data download constraints
- Measurements modes
- Establish Targets lists and goals descriptors
- Specific actions on impacts (LCROSS, Selene, …)
- Specific actions and future landing sites

SMART-1: Science Exploration Themes & SubThemes

A) TECHNOLOGY DEMONSTRATION

B) CRUISE PHASE NAVIGATION, TECHNOLOGY AND SCIENCE

C) *HOW DO EARTH-LIKE PLANETS WORK?*

GEOPHYSICS: volcanism, tectonics, cratering, erosion, space weather , ices

D) *HOW DO ROCKY PLANETS FORM AND EVOLVE?*

GEOCHEMISTRY: chemical composition, Earth-Moon origin, Moon evolution

accretion and collisions, giant bombardment

E) PREPARING FUTURE LUNAR/PLANETARY EXPLORATION

LUNAR RESOURCES SURVEY (minerals, volatiles, illumination)

HIGH RESOLUTION MAPS for future landing sites and outposts

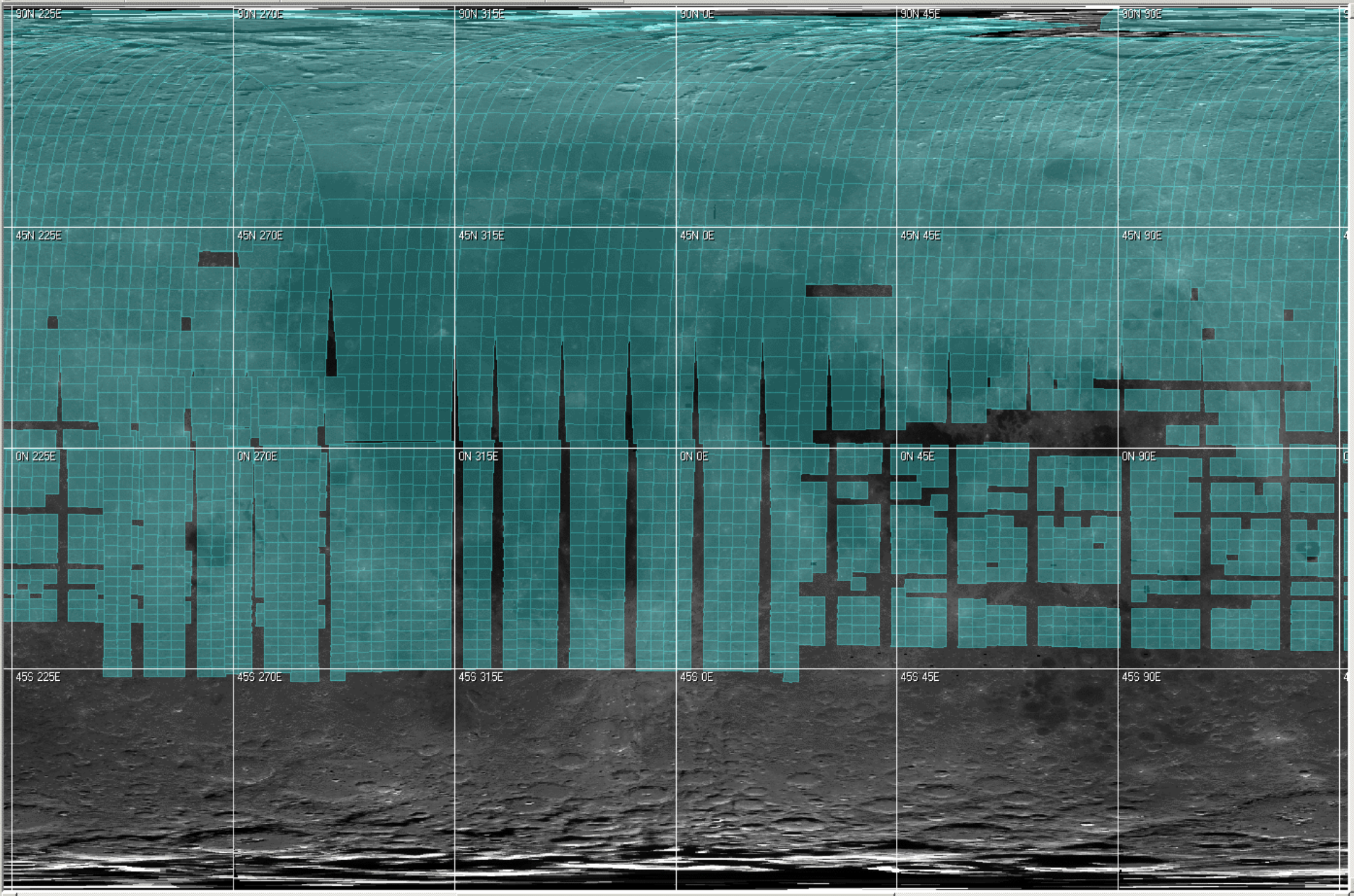
SUPPORT TO FUTURE EXPLORATION and coordination with other missions

F) PUBLIC OUTREACH, INSPIRATION AND EDUCATION

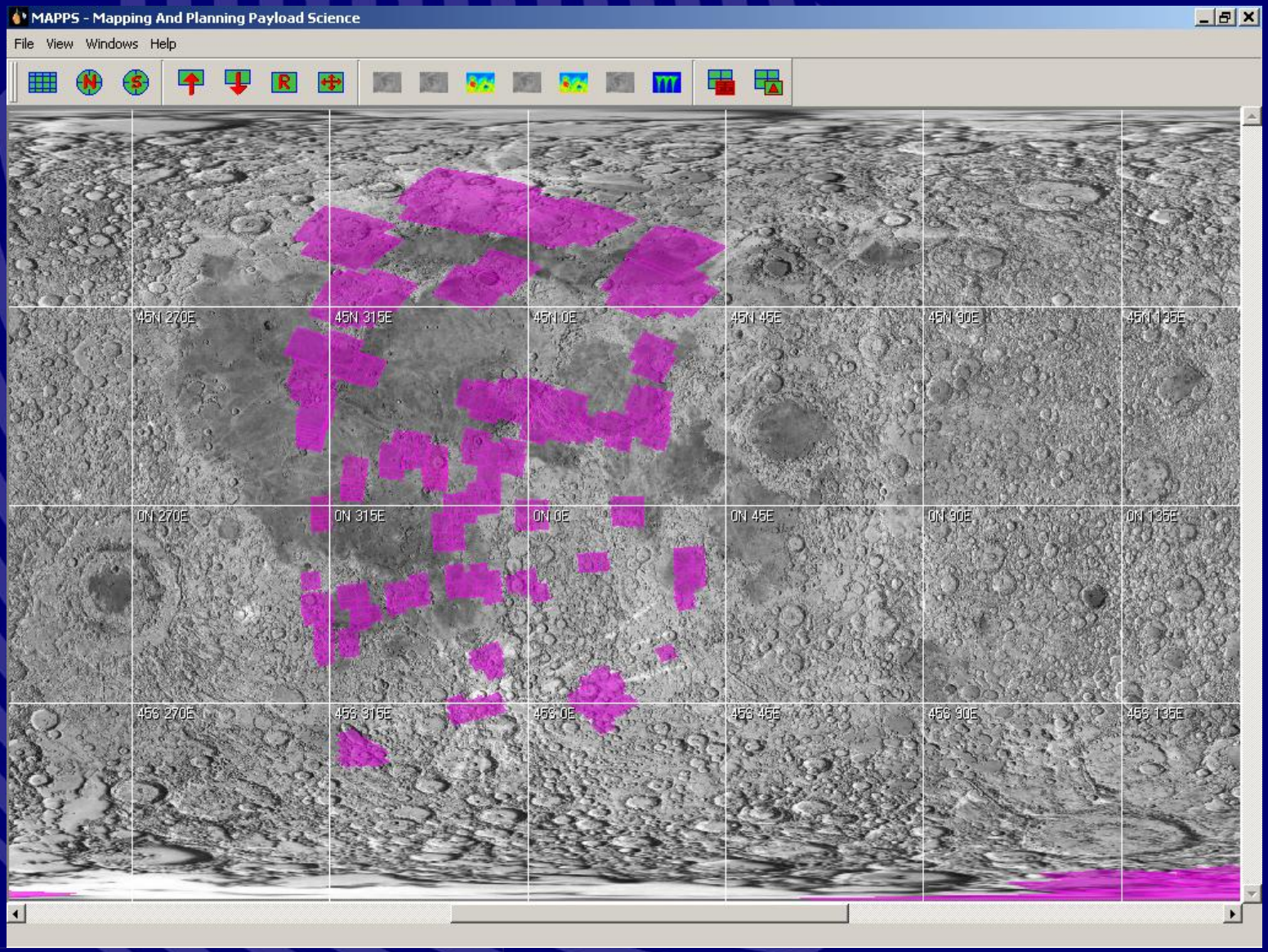
esa

MAPPS - Mapping And Planning Payload Science

File View Windows Help



SMART-1 AMIE Coverage Week 2, January 2006



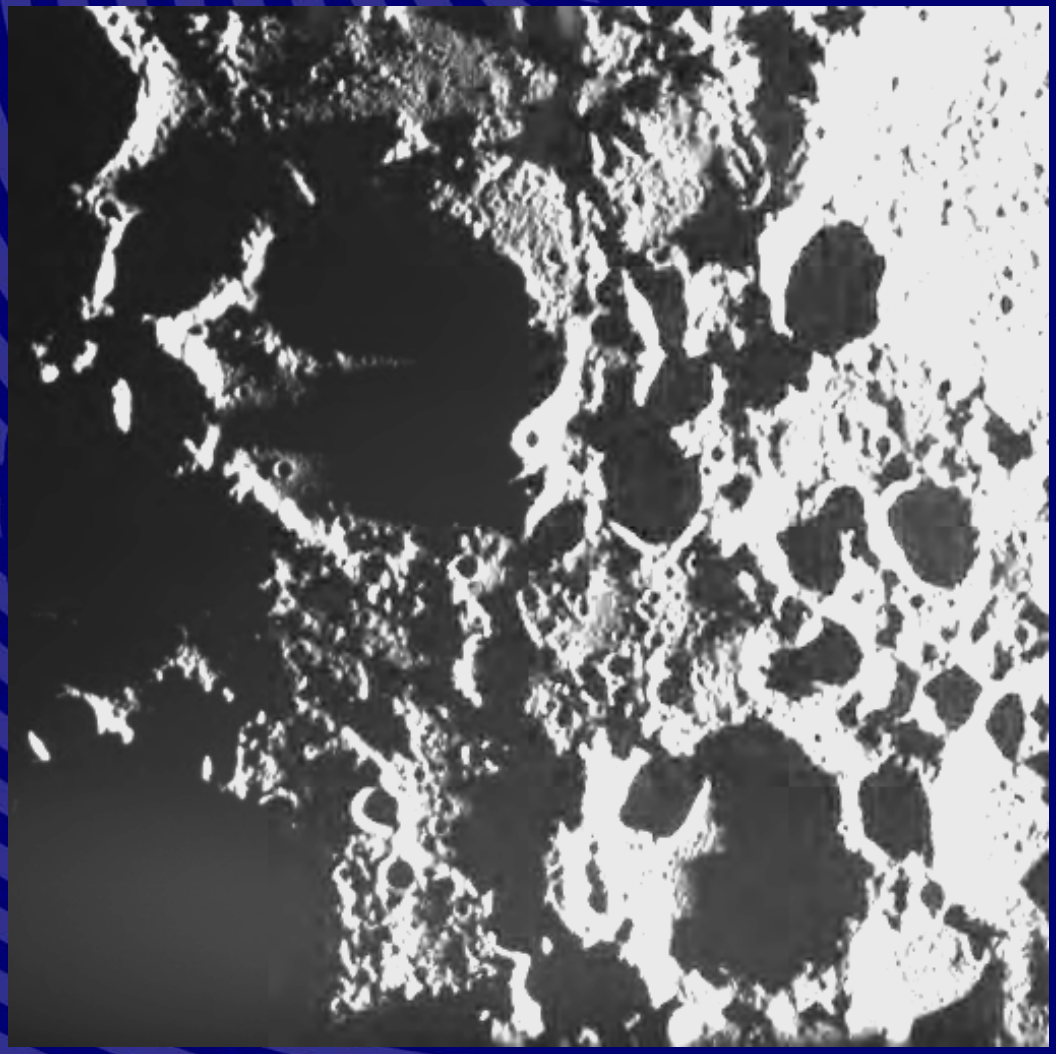
Peaks of eternal light in northern winter

200 km

Far side

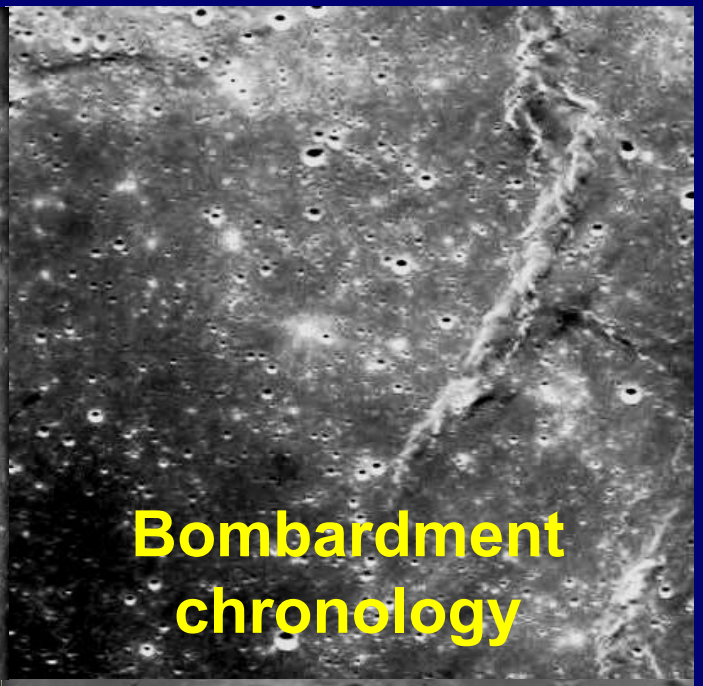
eternal peaks of light →
North pole →

Near side

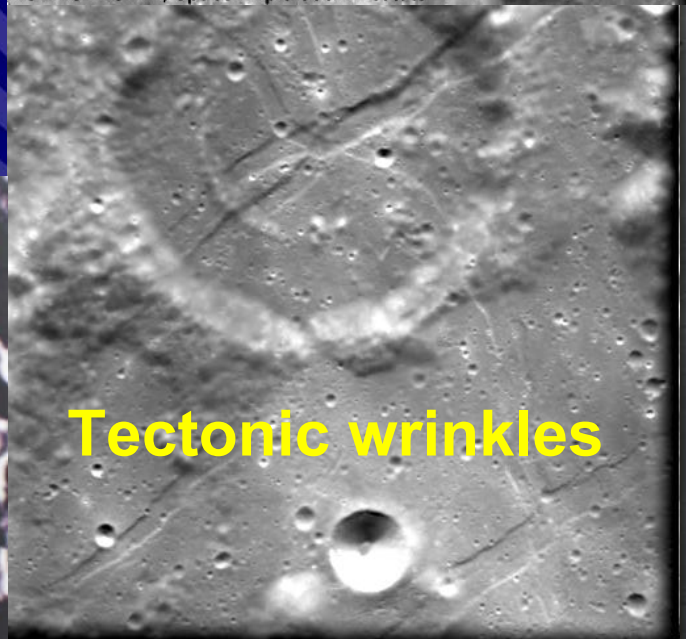


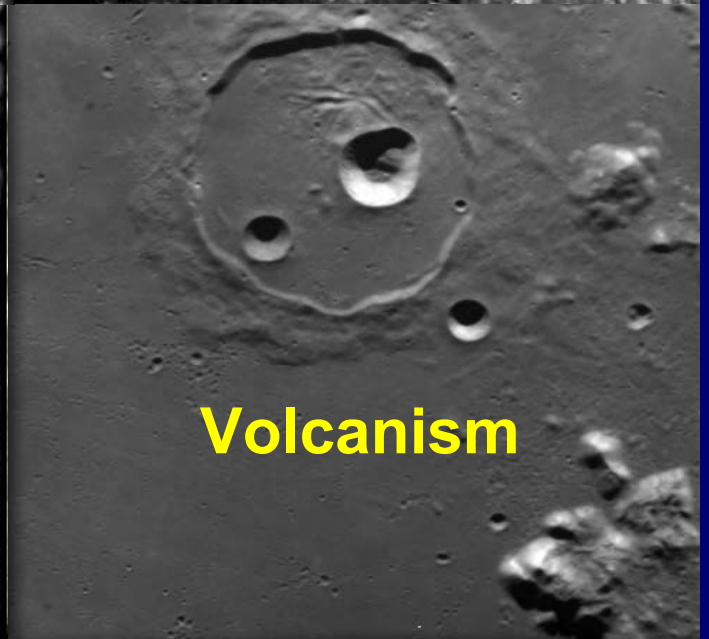
What shapes rocky planets?

Moon laboratory for Geophysics

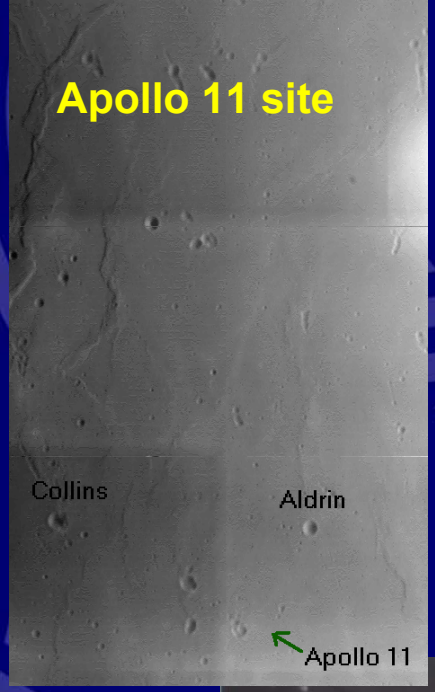


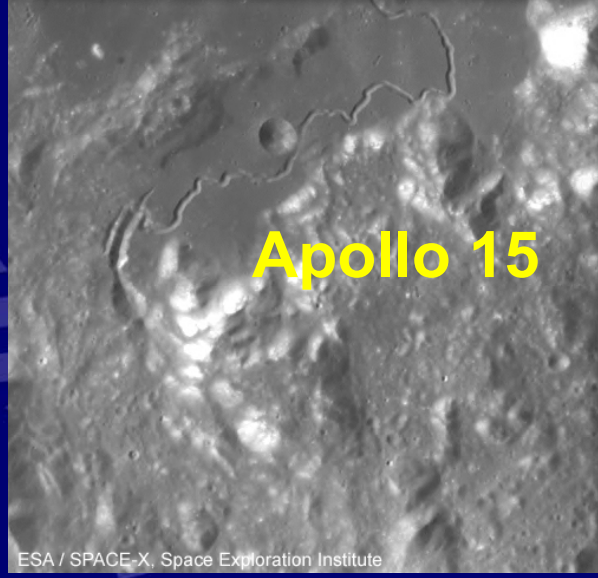
Erosion, Polar volatiles





Ground /Remote truth & Preparing for Future Exploration





Science data analysis and reconnaissance

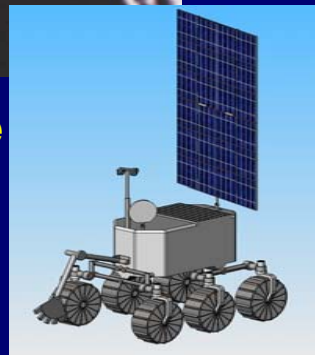
- **How do rocky planets work**
- **Earth-Moon formation**
- **Past and future landing sites**

Resources: minerals, light, ice

Peaks of eternal light, shadows & illumination monitoring every 5 hours

Maps for future landers, rovers, human bases

Peak of light near North pole



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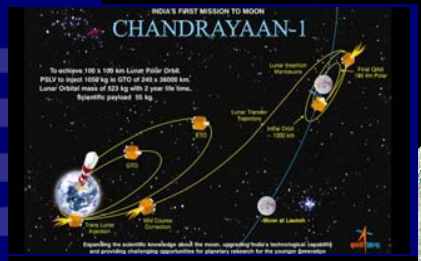
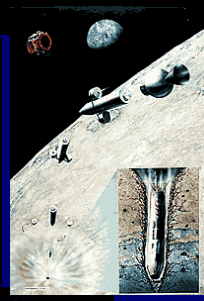
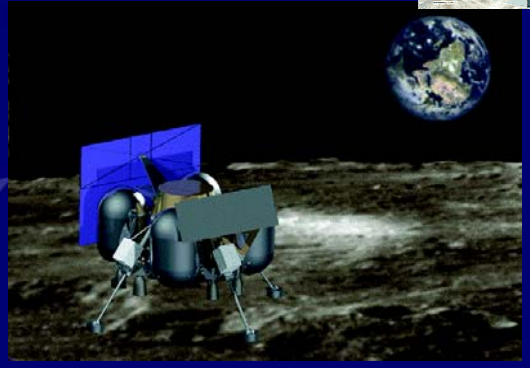






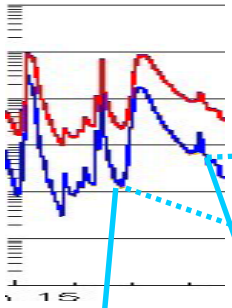
International Science Coordination/ Calibration targets

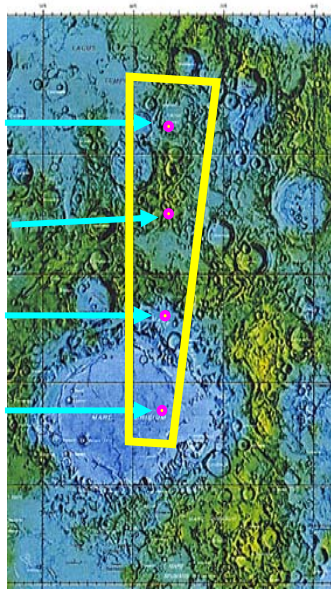
- Overall science and exploration goals
- Measurements objectives, modes & specific calibrations
  - Imaging
  - Spectrometry
  - Microwave
  - High energy (X Fluorescence, gamma Ray)
  - Time varying conditions
  - Solar and Space radiation standards
- Observations conditions, solar illumination angle
- Methods and procedures for calibration
- Ground based observations
  - multi wavelength, intercalibration
- Coordination Time critical Calibration Observations

International Science Coordination/ Calibration targets

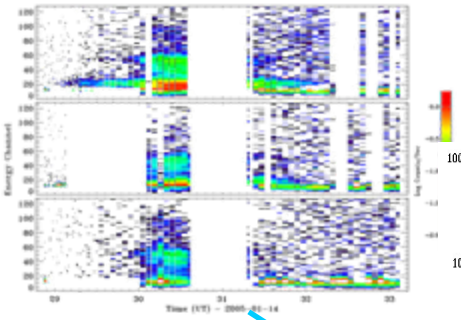
- Targets lists and descriptors
- Core calibration targets (agree with recommendation COSPAR/ILEWG)
- Specific calibration actions on past and future landing sites (ground truth)
- Secondary calibrations targets
  - Polar calibration repeated targets (straylight,)
  - Use of Sun, Earth, Standard Stars for Calibration
- Landing site candidates
  - science, exploration interests, safety, access
- Size of targets vs homogeneity and instruments FOV

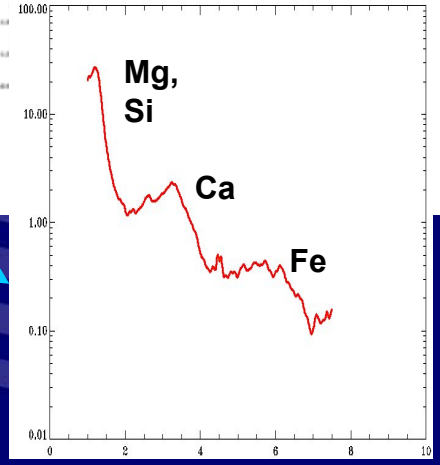
The Sun shines X-rays





The Moon glows → D-CIXS





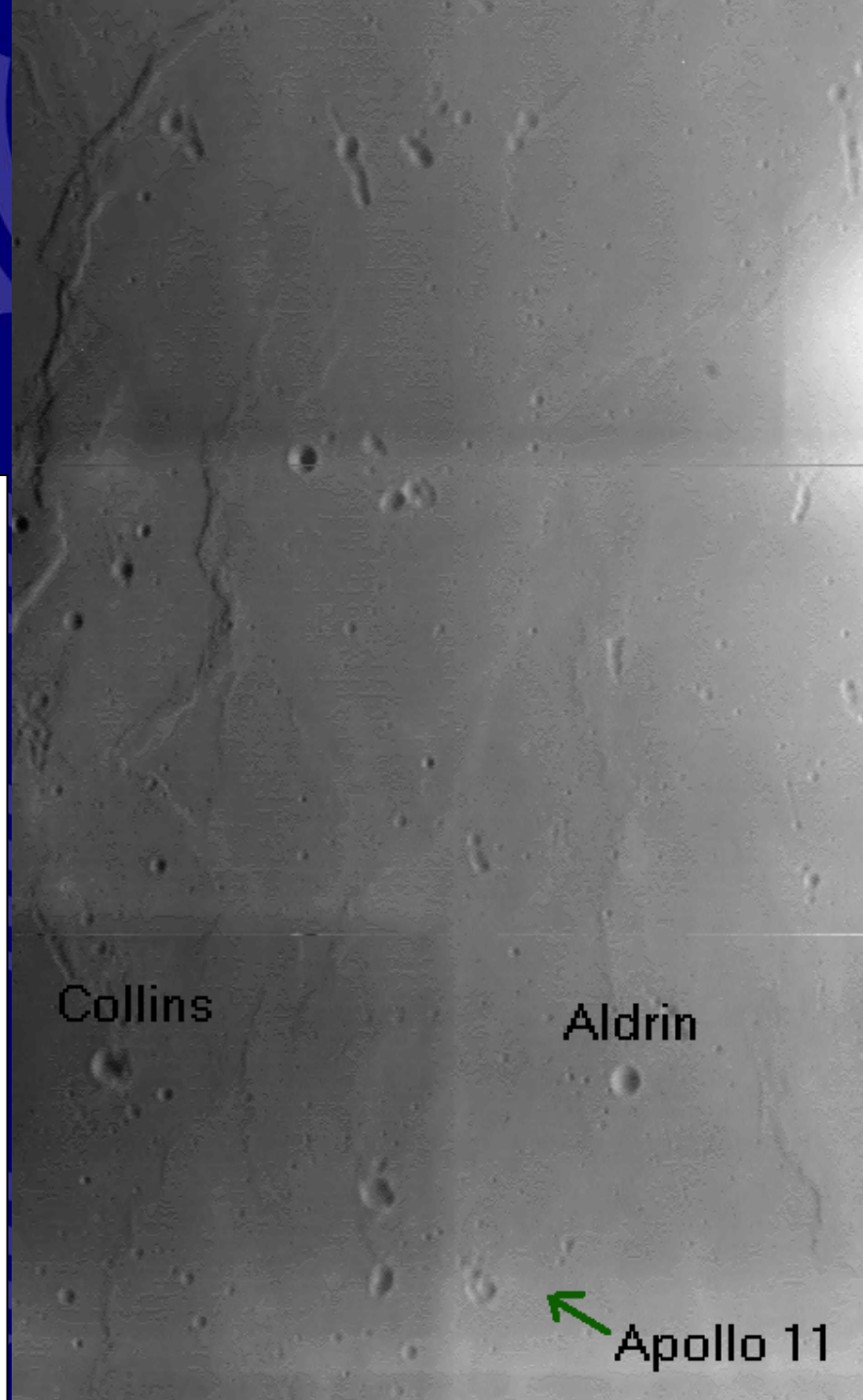
Derived elemental composition

1st detection of Calcium and Magnesium , comparison Luna 24 samples

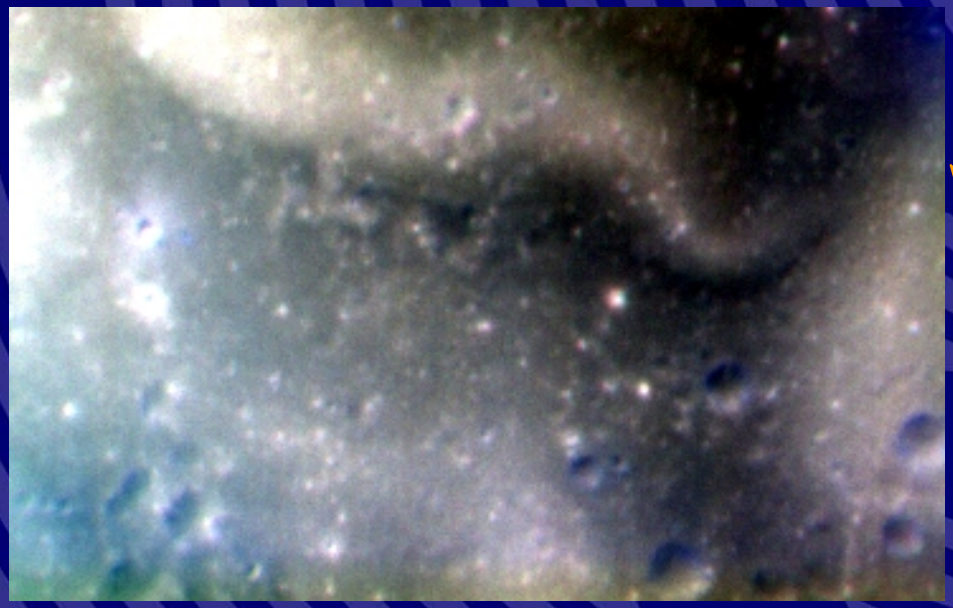
(D-CIXS) Planetary Space Science, in press

SMART-1 survey of Apollo 11 landing site 20 July 1969 37th birthday card release

- Apollo 11
- Long 23.9 lat 1.7
- Orbit 1888
- 5 Feb 2006
- Distance 1764 km
- FOV 80 x 120 km

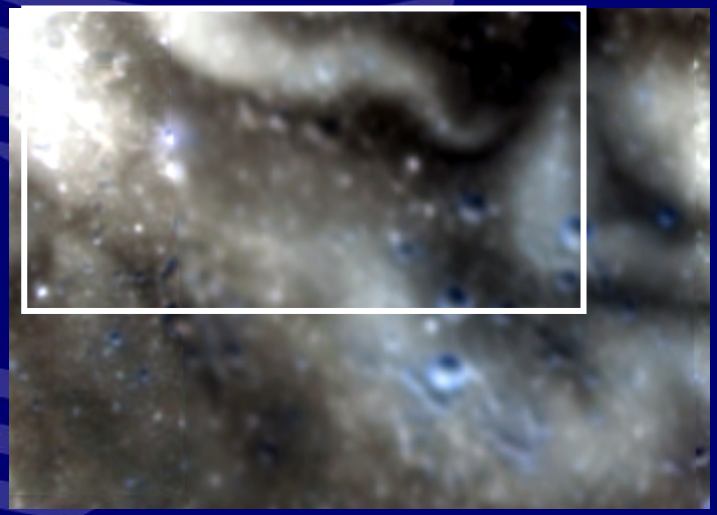


AMIE Colour results Orbit 1438



AMIE colour image

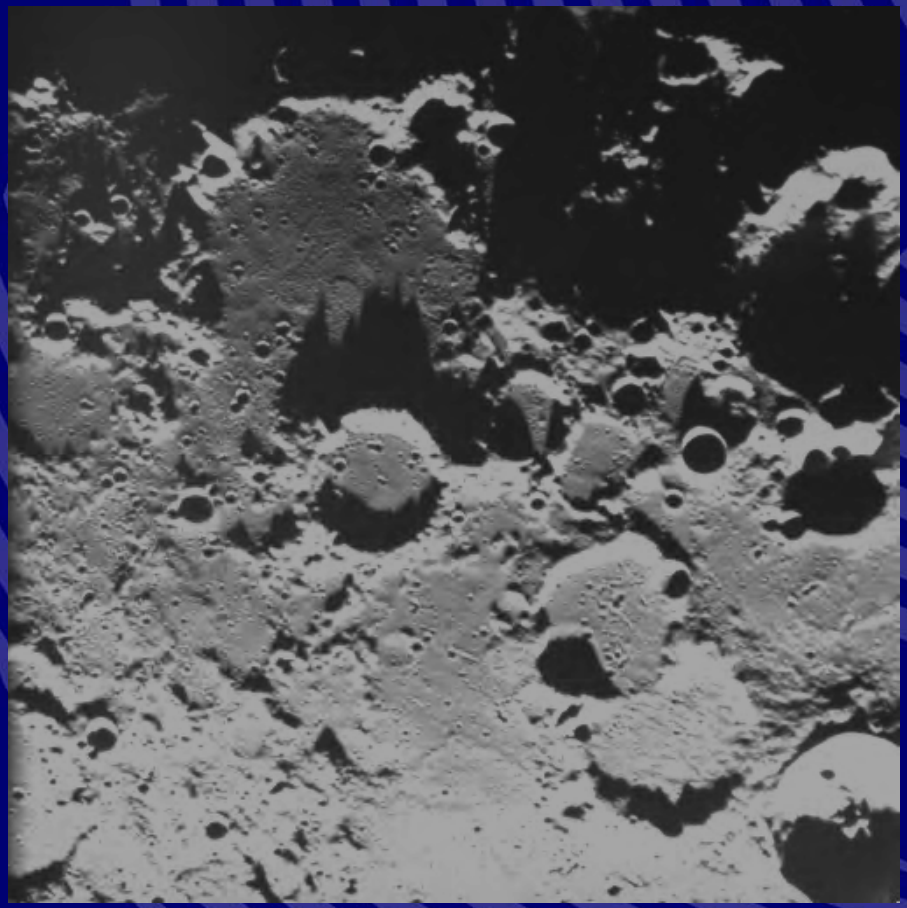
Clementine



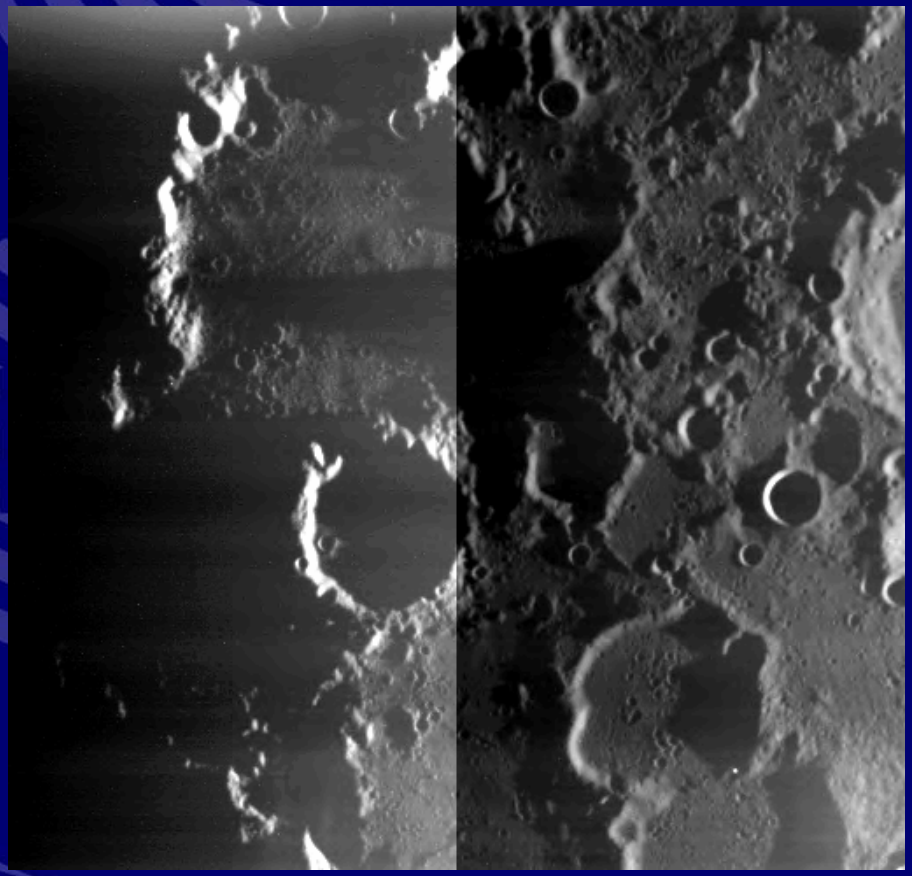
Reiner gamma

North polar winter shadows variations: near side around Byrd crater

29 Dec



19 Jan



Part of Hopmann crater at edge of South Pole Aitken Basin: search for anomalous composition material

SMART-1 Media and outreach

SMART-1 websites

- **ESA Public corporate PR www.esa.int**

  Google "SMART-1" 2.5 Mega-quotes

  PR multimedia products--> thousands of News articles,

- **SciTec SMART-1 website sci.esa.int/SMART-1/**

  60 webstories, image gallery (hundreds of images), publications , conferences, resources

- **ILEWG website http://sci.esa.int/ILEWG**

  lunar calendar, link lunar missions, lunar website resources, EPO task group and Young Lunar Explorers

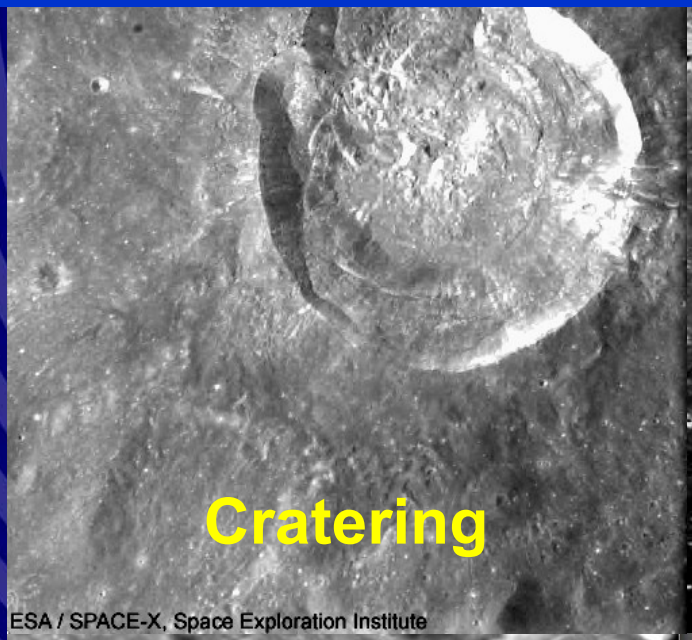
SMART-1 Media and outreach

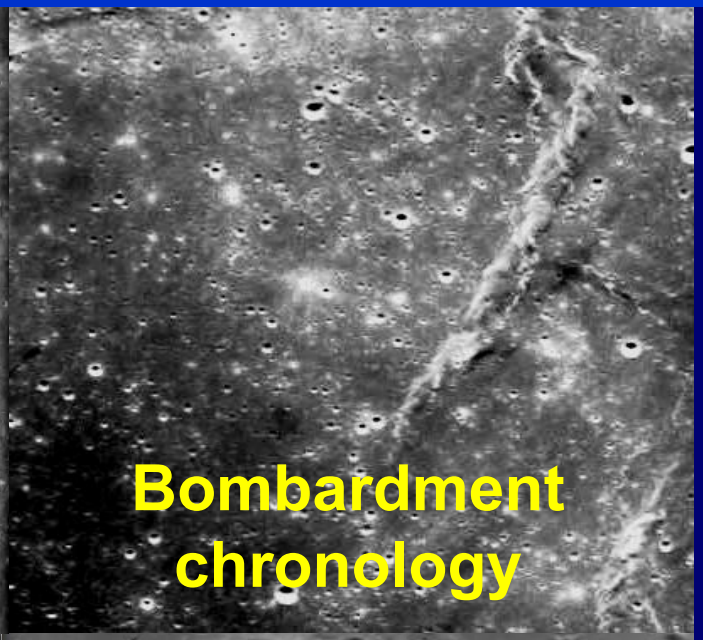
Messages:

- Smart Technology (electric propulsion, miniaturisation)
- Launch, Journey from Earth to Moon on 60 l fuel
- Why the Moon?
  Origins, Earth's daughter, planetary laboratory, future
- Engaging Public: Europe to the Moon
- Lunar results & achievements
- SMART-1 Precursor to future lunar exploration

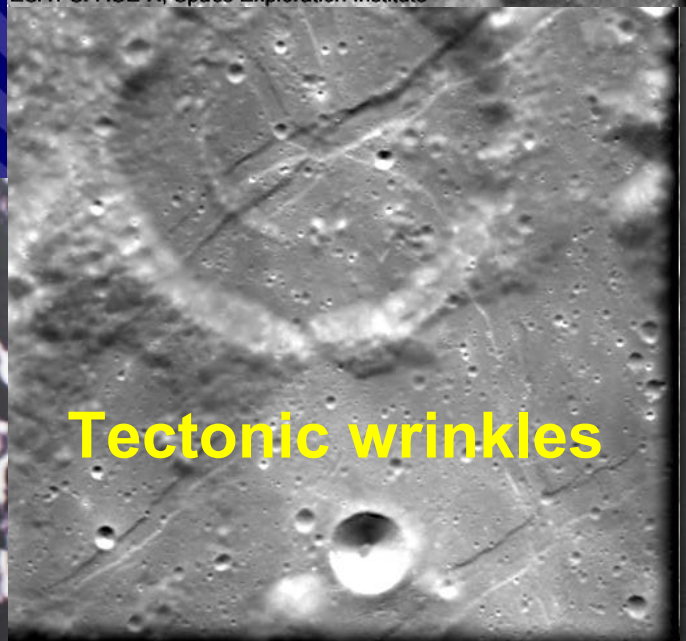
The Moon as a planetary education tool: What shapes rocky planets?

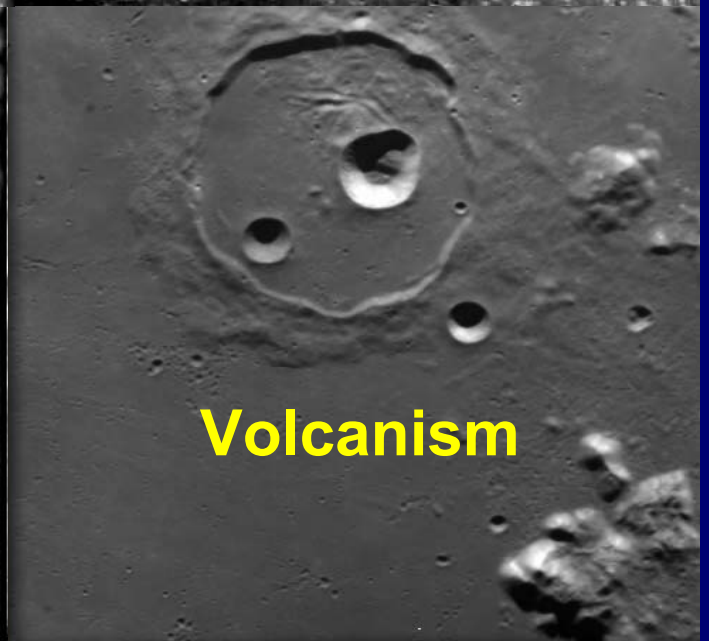
Moon laboratory for Geophysics





Erosion, Polar volatiles





SMART-1 last orbit

SMART-1 Media and outreach

Impact campaign

- Jan 06: call to astronomers, lunar & impact experts (resistance: nothing will be seen …)
- Low key low budget for media event
- Address issues on impact & lunar environment before,
- Call for amateur involvement
- 3 Month info campaign: 30 webstories, images/animations
- Intense last month briefings, daily stories on last week
- websites peaks 1 MHit on 3-4 Sept

Prime TV, survey 68 news for 100 M viewers in 7 states

- 191 news reports in 24 Hours broadcast
- 1500 multi-lingual News stories on Web
- > 300 million viewers over the world

SMART-1 Media and outreach

SMART-1 EPO

- EPO events, Exhibition material, SMART-1 /lunar content
- Use of SMART-1 EPO network
- Teacher's notes & Education material
- Earth views, Adopt a Crater
- Videos, Multi-lingual material
- Young Lunar Explorers (http://lunarexplorer.org),

ESA Education and Outreach

- ESA education division
  - Partnership with education national institutions
  - Hands on projects SSETI, Student Moon Orbiter