B.H. Foing et al (v.7, revised 29 August 2006)

SMART-1 IMPACT: PREDICTIONS AND OBSERVATION CAMPAIGN

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Background

ESA's SMART-1 mission launched to the Moon in September 2003, has reached lunar capture in November 2004. Since March 2005 three instruments have been operating from a 400-3000 km lunar science orbit: AMIE miniature high resolution multicolour camera AMIE for lunar geomorphology (down to 40 m per pixel), SIR infrared spectrometer (0.9-2.5 microns down to 400 m FOV) for mineralogy, and D-CIXS X-ray spectrometer for elemental composition (Foing et al 2001, 2006). Because of gravitational perturbations by the Earth and the Sun, the SMART-1 orbit will irremediably intersect the lunar surface, having exhausted its main Xe fuel. If we would have left the spacecraft on natural course, it would have impacted on the far side of the Moon on 17 August 2006. We have extended the mission at low altitude allowing an impact on the near side, in a dark part near the terminator, under good observation conditions for Earth telescopes. Using the hydrazine attitude thrusters to impulse an extra push of some 12 m/s on 23 June -3 July, the spacecraft impact has been changed from 17 August farside to 3 september on the near side. Note that the differences between these orbits is only of 1 km in perilune and the maneuver had to target this 1 km accuracy one month in advance (some 140 orbits or about 3 million km). The last small maneuver at the end of July has narrowed down the impact time on 3 September to two possible times UT 5h41, or 0h36 on the previous orbit due to topography uncertainties. For the current nominal ephemerides as of 28 August, the impact is expected at possible locations of impact:

Nominal impact: 3 sept 05:41:51 UTC, longitude 47.16 West, latitude 33.246 South

Perilune for impact orbit: 3 sept 05:42:38 UTC, longitude 46.27 West, latitude 36.44 South
Perilune for 1 orbits later: 3 sept 10:47:33 UTC, longitude 49.03 West, latitude 36.42 South
Perilune for 1 orbit earlier: 3 sept 00:37:43 UTC, longitude 43.50 West, latitude 36.46 South
Perilune for 2 orbits earlier: 2 sept 19:32:47 UTC, longitude 40.73 West, latitude 36.47 South

At nominal impact, the descending oblique angle is only 1 degree over a flat surface (with less than 1 degree general slope over kms). Note that according to available topography information from Clementine (only 1 km grid), there is now still a possibility that the impact could take place on the orbit before the nominal orbit. We have used images from SMART-1 to check the topography information. On orbit preceding impact the perilune is above Clausius crater rim.

The parameters of impact are:

- Low velocity grazing impact 2 km/s
- The probe is 290 kg, (200 kg from the Al), size of 1 m3
- with two solar panels in carbon fiber and AsGa solar cells of 6.5 m length each, oriented along the orbit near impact

Scientific rationale

Quantitative spectrometry of lunar dust mineralogy
Coordinated measurements from the ground allow to obtain spectrometric information constraining the mineralogy of key sites targeted by SMART-1. In particular the infrared range from 2 – 20 microns allows to constrain the present lunar minerals (pyroxene, olivine), complementary to SMART-1 diagnostics (AMIE camera colour ratio with 0.95 micron pyroxene band, and SIR 0.9 -2.5 micron spectrometry). The spectral energy distribution can provide quantitative characteristics such as mineralogical composition, porosity, crystallinity, size distribution and space weathering. The thin upper lunar surface layers have been exposed to cosmic rays and solar particles that modify the upper layers (space weathering) probed by remote sensing imaging and spectroscopy, and weaken the mineralogical signatures. Comparative observations of the ejected dust reflectance will allow to probe the soil properties of the one meter subsurface and their signature during the impact and ejecta.

Physics and diagnostics of impact at low velocity
Ground based and flyby observations of Deep Impact event (A Hearn et al., Meech et al., Harker et al., Sugita et al., 2005) have provided key measurements to constrain the subsurface properties of comet 9P/Tempel 1. Some of the modelling and observational methods can be adapted for the conditions of the SMART-1 low velocity lunar impact. The thermal and dynamic evolution of the thermal flash and ejecta can constrain the understanding of impact processes such as dust acceleration, gravity controlled excavation, and strength related effects. The monitoring of spacecraft volatiles released after impact can help to simulate and to understand processes occurring on volatile rich natural impactors. We should also monitor the speed and dynamics of ejecta and dust clouds that could be followed in the Earthshine or in sunlight, other transient changes, and the characteristics of impact crater and deposited ejecta. We asked modellers to predict ejecta morphology, total mass, speed distribution, fraction with vertical V > 200m/s reaching sunlight. These phenomena could be accessible to telescopes.

Modelling of the controlled SMART-1 impact

We have called on the numerical experts to model and predict what could be the impact flash magnitude in the visible or infrared, and ejecta dynamics. We expect the impact to be in the strength regime where the material of both the impactor and the regolith control the crater geometry, ejecta and plume properties. The kinetic energy is in the order of 600 MJ and the depth of penetration could be meters. The impact could give a 10-80 m3 excavation volume of which 80 % will be a cold ejecta plume. The thermal flash magnitude would be 7.4 if half of the kinetic energy was converted into heat. However, for a low velocity impact of 2 km/s some models predict only a very low efficiency (as low as 0.001) and an estimated magnitude between 16 (Koschny & Gruen 2001), and up to 11 magnitude (Jutzi, 2006 private comm.). The thermal flash duration could be as short as 200 milliseconds. Because of the very grazing angle of 1 degree, there is strong possibility of the probe to undergo ricochet. Laboratory experiments (Burchell and Cole 2006) using a two stage light gas gun and 2 mm sphere projectile indicate also a ricochet effect, as well as an elongated crater and ejecta.

Predicted effects of the impact and proposed observations:

- Thermal flash (bolometric magnitudes 7 –16 during 1s in infrared depending on efficiency 0.5-0.001)
- In addition to thermal effects, we expect the emission from volatile elements onboard N2H4 decomposing in NH3 and H compounds detectable in Paschen and Brackett (or even Balmer if the excitation temperature is sufficient). For the Hiten impact (300 kg, 2.7 km/s, 1 kg hydrazine) a flash signature detected in the K band was ascribed to Brackett gamma enission. Other probe signatures may be detectable (Al melting at 600 deg C, graphite)
- In probable case of ricochet there would be a possibility of SMART-1 spacecraft to create a fireball, while hydrazine would decompose and emit in hydrogen bands
- A crater size of 5-10 m is expected. The volume of material ejected will be essentially made of dust with dominant size around 15 microns (normalized per area) and the effective area of ejecta could be 25 km2. This will lead to obscuration of the underground soil in the first minute after impact, and partial obscuration later. The ejecta can be also traced in Earth shine reflected light giving a level of V=14.5 per arcsec2 (E. Palle, private communication) accessible to large telescopes (1500 photon per sec for a 2 m class telescope). Small telescopes are able to image the Earth shine on the Moon, even with modest resolution 1.5 arcsec they would be able to detect the excess brightness of the effective area of elongated ejecta with excess magnitude 13-14 due to their higher albedo
- The normal component of the velocity will be of order 130 m/s, therefore we may expect a tiny fraction of ejecta f that has enough vertical velocity above 280 m/s to reach sunlight. For the solar phase angle of 100 degree, a signal as bright as 11.5 magnitude is detectable by amateur astronomers even if only 1 % of ejecta reach this vertical speed
- The key interest of large telescopes will be their ability to collect enough photons and angular resolution down to 0.4 arcsec seeing or using adaptive optics to detect the flash impact, resolve the structure of the ejecta and their dynamics down to few hundred m resolution as well as trace the dynamics of the weak hydrazine gas plume
- Special care will have to be taken to limit and correct the straylight coming from the illuminated part of the half Moon beyond the terminator at 60 arcsec East from the impact.

Near infrared and thermal infrared spectroscopy can be used to diagnose some of the mineral properties from the expected cool ejecta (absorbed reflectance due to silicates and size distribution effects). Also Near IR spectroscopy will measure the Brackett emission lines due to H compounds released by hydrazine. Even after the short lived thermal flash, there can be a remnant excess temperature of several above the initial 100 K night time lunar soil temperature, their cooling can be monitored with infrared thermal imaging for a few hours.

- Some Exospheric effects are expected such as neutral emission production, that can be monitored with visible spectroscopy of species such as Na, K. It is expected that these effects will be weak, local and short lived
- Note that the kinetic velocity of SMART-1 is less than a 1 kg meteorite arriving at 40 km/s natural speed, or of previous more massive modules impacted during the Apollo era. The effects will be even more localized due to the smaller and oblique velocity
- Crater size (5-10 m) and morphology could be only accessed from the next lunar orbiters or from interferometric instruments. The morphology of ejecta may be elongated over several kms along the initial velocity, to be observed by high resolution or adaptive optics imaging

We conducted SMART-1 observations of previous impact sites (such as rangers, Apollo modules and Muses A Hiten) to characterize possible ejecta, and we made prior observations of the site area of impact. We have also identified a number of natural larger impact craters that we observed under different illumination, phase angle conditions to characterize the topography, roughness, colours and mineralogy of crater units and ejecta. Some lunar sites are also used for radiometric multiwavelength calibrations, see Annex. We propose to continue to observe some of these targets with ground based observations to extend the wavelength coverage enhancing the SMART-1 and spacecraft data interpretation.

Education /outreach

We are organizing a series of professional and public events related to SMART-1 results, legacy and end of mission. We expect to use these opportunities to promote ground based worldwide astronomy in coordination with space missions, and we plan to post some of the obtained results and images in near real time on our ESA and partners websites.

References:

SMART-1 scitech website http://sci.esa.int/ and ESA public site http://www.esa.int/SPECIALS/SMART-1/index.html

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Harker D.E. et al, *Science* 310, 278 (2005)

Koschny D. and Gruen E., Icarus 154, 402 (2001)

Meech K.J. et al, *Science* 310, 265 (2005)

Sugita S. et al , *Science* 310, 177 (2005)

Summary table of parameters relevant to SMART-1 impact observations

- Spacecraft Orbit inclination 90.6 deg, from North to South
- Maneuver on 23 June –8 July and 26 July (using 2.6 kg hydrazine, delta V 12 m/s) to move impact from farside to nearside in dark, near first quarter terminator, sun 10 deg below horizon, Moon 66%
- Current impact prediction 3 sept 2006: 5:42 UT or 00:36 UT
- Orbit perilune was < 200 km from 10 July, < 120 km from 7 aug
- Effect of topography (current altimetry, new observations)
- Impact speed 2 km/s, grazing 1 deg down over flat slope (<1 deg)
- SMART-1=Artificial comet: 290 kg including 1 m3 body, 200 kg Aluminum, 3 kg Hydrazine N2H4, 0.26 kg Xenon, epoxy, 2 x 6.5 m solar arrays (carbon fiber)
- Radio observations of S band carrier can be made for monitoring probe occultation and final impact
- Optical observations of the V=19 magnitude spacecraft can be done over non illuminated Moon after 27 August, and in particular up to 4 min before impact, or previous orbits
- Possible locations of impact in Lacus Excellentiae

Nominal impact: 3 sept 05:41:51 UTC, longitude 47.16 West, latitude 33.246 South
Perilune for impact orbit: 3 sept 05:42:38 UTC, longitude 46.27 West, latitude 36.44 South
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Table 1 science interest for observations

Science Motivations	Phenomena	Time duration of phenomena	VIS mode	VIS features to look for	IR/mode	IR features to look for
Impact Physics	Impact Flash	200 ms	VIS fast imaging	emission vs lambda (Temp)	imaging & spectra M_{bol}=11–16 ^{mag}	
Impact Physics and Dynamics	Ejecta Blanket Size, particle size	0-few minutes for ballistic trajectories, depending on height	VIS spectra VIS imaging	extinction vs lambda; transient "blurring" of lunar features by dynamic clouds		
Impact-release of remnant Hydrazine fuel N_2H_4	Impact Flash	200 ms	VIS spectroscopy	Hydrogen Balmer & Pachen Lines	NIR spectroscop y *NIR, MIR spectroscopy*	Brackett & Paschen NH_3
Lofted Lunar sub-surface Mineralogy	Evolution of Soil Plume	0-few minutes for dynamics; 0–400 sec 1% of ejecta reaches Sunlight?	VIS low spectral resolution imaging & spectra	albedo and color change (silicate mineralogy, particle size distribution)	NIR and MIR low spectral resolution imaging & spectra	silicate mineral absorption bands (mineralogy, particle size distribution)
Impact Crater size and properties	Re-Deposited Soil Blanket (post-impact minus pre-impact)	0–30 days before & after, in Sunlit Moon	VIS imaging; VIS low res. spectra	albedo change; reflectance color of fresh ejecta	NIR & MIR narrow band imaging & low res. spectra	silicate mineral absorption bands
Lunar soil grain sizes and minerals	Long time scale cooling of ejecta blanket	cooling over 0–4 hours			MIR imaging	thermal conductivity of new regolith
Lunar Surface Contamination from spacecraft	Spacecraft melting; new compounds?	0–20 sec	VIS spectroscopy	Al (396nm), C_2, C_3 (from graphite melting)	NIR, MIR	new carbon coating on dust?
Exosphere	lofted gas	0–3 days	VIS spectroscopy	neutral Na, K		
VIS=visual (300-900nm), NIR=near IR (1–5µm), MIR=mid IR (8–20µm)						

ANNEX

Timeline of specific observations : Chronology for coordinated observations:

- Until mid april : mid solar elevation studies and spot pointing
- Mid April- Mid June: SMART-1 push broom colour targeted observations
- 23 June – 4 July SMART-1 maneuver
- 6/7 July night same moon phase as impact date + other targets
- 10 & 11 July support to SMART-1 target overfly from 200 km, sun elevation 27 deg + other targets
- 3/4 or 4/5 Aug, close moon phase (within 0.5 day of impact date) + other targets
- 6 & 7 Aug support to SMART-1 target overfly (from 120 km , solar elevation 11 deg) + other targets
- 2 sept general rehearsal
- 3 sept (0:36 and) 05:41 UT 36 nominal impact window
- 4-17 sept possibility of detection of smart-1 impact illuminated ejecta blankets

Targets to be observed (lunar coordinates) for calibration and key coordinated studies:

Tycho	LC10	-43.40	348.90	East	Large crater; gabbroic plutons
Alphonsus	ALP1	-13.70	356.00		DMD, dark halo crater
Apollo 16	AP16	-9.00	15.50		Landing site, calibration check
Apollo 14	AP14	-3.70	342.50		Landing site, calibration check
Luna 16	LC34	-0.40	56.18		Luna 16 landing site
Apollo 11	PC4	0.67	23.47		Landing site
Reiner Gamma	REI4	4.95	298.70		swirl
Luna 24	LU24	12.50	62.25		Landing site area, calibration check
Apollo 17	PC9	20.19	30.77		Landing site
Aristarchus	ARI2	23.23	313.47		Aristarchus crater, Crustal mat.
Apollo 15	AP15	26.10	356.30		Landing site, calibration check
Gruithuisen	Delta1	35.90	320.45		Delta dome, early volcanism

Timing of impact and Moon visibility

	Perth	CapeT	Paris	CalarA	Tenerife	Brazil	LaSilla	KittPk	Hawaii
Sunset	10:03	17:13	18:38	18:38	19:27	21:34	22:25	01:52n	04:37n
End civil twilight	10:27	17:38	19:10	19:04	19:51	21:56	22:49	02:15n	04:59n
Moonset (2 to 3 sept)	20:02	22:55	22h49	00:08n	01:36n	6:50n	7:43	08:03n	11:42n

Moon Location or Crater	Description of Lunar location	additional notes	light	lunar long	lunar lat	lunar long E East	lunar lat
S1C-R 5:41UT S1C-OB0:36UT S1C-2OB 19:31 S1C-OA10:46	Smart-1 Crash Site Revised 6Aug Orbit Before 2 Orbits Before Orbit After	above U-shape lunar feature North rim Clausius 2 deg N Clausius D	E	46.25W 43.5W 41.8W 49.0W	36.44S 36.4S 36.4S 36.3S	313.74 316.5 319.2 311.0	-36.44 -36.4 -36.4 -36.3
Earthshine-lit Pointing Checks, Offsetting to S1C-R							
Clausius	med albedo circular crater E of S1C-R	fresh basalt ring, easily recognized at Full Moon	E	43.8W	36.9S	316.2	-36.9
Clausius E	tiny crater NE of U, NW of Clausius	tiny named crater closest to S1C-R	E	45.5W	36.4S	314.5	-36.4
Drebbel D	high albedo craterlet W of S1C-R	fresh highland	E	49.3W	37.9S	310.7	-37.9
Lehmann C	high albedo crater NW of S1C-R	fresh highland	E	50.1W	35.5S	309.9	-35.5
Bright Moon Pointing Checks							
Tycho CP	Tycho crater central peak (CP)		S	11.2W	43.3S	348.8	-43.3
Dunthorne	bright med size crater		S	31.6W	30.1S	328.4	-30.1
Dunthorne D	small crater close to terminator		S	34.0W	30.0S	326.0	-30.0
Hainzel A	N crater of group of 3, use central peak	shape different-crater has collapsed terraces	S	33.9W	40.3S	326.1	-40.3
Mineralogy Calibration Craters							
Campanus CP	med round crater with central peak		S	27.8W	28.0S	322.2	-28.0
Copernicus CP	med round crater with central peak	NIR pyroxene band (Warell et al .06)	S	20.0W	09.7N	340.0	09.7
Apollo 16	offset from Dollond	soil known	S	15.5E	09.0S	15.5	-09.0
Dollond	*circ crater near Apollo 16*	*offset to Apollo 16 from Dollond*	S	14.4E	10.4S	14.4	-10.4
Apollo 14		soil known	S	17.5W	03.7S	342.5	-03.7
Clausius	crater near S1C-R	fresh basalt	E	43.8W	36.9S	317.2	-36.9
Lehmann C	small high albedo crater NW of S1C-R	fresh highland	E	50.1W	35.5S	309.9	-35.5
Note: in this table "NW" in Lunar Coords equals NE in RA Right Ascension (+) and Declination (+) Note: Near S1C-R, pointing change of 0W, 0.1S equals RA, DEC = 0.12arc sec E, 1.0 arc sec S							

A lunar navigation itinerary towards SMART-1 impact sites

Please find herewith a possible draft roadmap to navigate along with your telescope. It takes into account sunlit features on 3 September but can be adapted to other times. It is useful to take images of the features on the way as they can be used for calibration as well.

AIDING PROCEDURE FOR POINTING (on 3 September):
To verify pointing to locations on Sunlit Moon
Tycho central peak -> Bullialdus central peak (follow the bright Tycho ray to RA,DEC=North, East towards terminator)
Tycho central peak -> Dunthorne -> Dunthorne D (now near terminator) [≥3m scope]

To go from Sunlit to Earthshine-lit Moon:
Dunthorne D -> Vitello B -> Clausius
Dunthorne D -> Vitello B -> Lehmann C (if Clausius' albedo is too low in Earthshine)
Dunthorne D -> Vitello B -> Drebbel D (if albedo of Clausius too low in Earthshine)

To check pointing accuracy in Earth-shine lit Moon:
Lehmann C -> Drebbel D -> Clausius -> S1C-R
Lehmann C -> Drebbel D -> Clausius -> Clausius E -> S1C-R
Lehmann C -> S1C-R

To calibrate images, use mineralogy calibration targets. Measurements through various filters are useful (for instance at 400, 450, 500, 550, 750, 900, 950, 1000 nm) or in infrared if you can.

To calibrate spectra, use locations of known or well studied mineralogy:

Reminder when looking at maps:
Clementine maps show S1C-R position, and VLO maps show relative crater locations and names in the region of S1C-R.
VMA/AVL maps are "as seen" in RA, DEC on the sky, lunar coords projected onto sky
Clementine maps are "as seen" in lunar coordinates
(a circular crater on Clementine map may look elongated with a Position Angle ≠ 0)
The lake of excellence is illuminated until 20 August, and then after impact from 4 September.

Use VMA (Virtual Moon Atlas/ Atlas Virtuel Lunaire– free software running on Windows http://www.astrosurf.com/avl)

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Diane Wooden NASA Ames Research Centre (impact observer at Hawaii IRTF)
Detlef Koschny (SMART-1 campaign amateur astronomer coordination)

Table: Core impact campaign observers and facilities for SMART-1 impact campaign

Observer	Institute	Location	Telescope	Instrument	Contribution
B.H. Foing	ESA	ESTEC/ESOC	SMART-1	Camera, spectro	Pre-impact observations
P. Ehrenfreund	Leiden	Leiden/ESOC	Ground -Based		Impact coordination
L. Gurvits	NL	worldwide	VLBI Radio	S,X receivers	Smart-1 carrier signal
D. Buckley	SAAO	S Africa	SALT/10m	CCD	20ms fast imaging optical
J. Ortiz	Calar Alto	Spain	2.2/3.5m	Magic/IRCAM	fast visible and IR imaging
Z. Sodnik	ESA	Teneriffe	OGS	CCD/Vidicon	Optical imaging visible & 1500 nm
D. Christian	Canarias	La Palma	3.5 m TNG	Spectrometer	Optical Na exosphere
R. Dantowitz	Clay Ctr Obs	US MA	25 "	FTS imager	Fast spectro-imaging
M. Wood	FloridaTech	US FL	robotic	CCDs	Optical imaging
B. Cooke	MSFC	US AL	robotic	Video CCD	Meteor fast imaging
M. di Martino	Torino, INAF	Argentina	25"	8.2 Mpx CCD	Optical imaging
N. Biver	Meudon, F	Space	Satellite	ODIN	Radio water lines
C. Veillet	CFHT	Hawaii	CFHT	WIRCAM	IR imaging
Kasuga/Sugita	Japan	Hawaii	Subaru Aux 10 "	CCD	Optical imaging
D. Wooden	NASA Ames	Hawaii	IRTF/4m	SpEX IR	IR imaging & Spectroscopy

Observatories/ Contact points:

General campaign coordination (P. Ehrenfreund, B.H. Foing)
Space observations: SMART-1 (B.H. Foing, before impact),
Radio signal and VLBI (Gurvits)
ODIN (Biver/Sandqvist)
SALT (Buckley)
Calar Alto (Ortiz/Lara)
OGS (Sodnik)
TNG SARG (D.Christian, C.Barbieri, G. Cremonese, F. Ferri, Mangano, P. Cerroni)
Argentina national Telescope (M. di Martino/P. Cerroni)
Florida Tech robotic telescope (M. Wood/ S. Vennes)
NASA MSFC Meteor telescope fast imaging (B. Cooke)
NASA IRTF (A.Tokunaga,D. Wooden, K. Meech, P. Lucey)
Canada France Hawaii Telescope WIR Cam (C. Veillet)
Subaru Auxiliary Telescope Hawaii fast imaging (S. Sugita/T.Kasuga/M.Kato)

Worldwide Robotic telescopes network (V. Reddy)
Coordination with Europlannet Ground Based Network: (M. Khodachenko)

Amateur coordination (D. Koschny, M.Talevi, S.Ansari, C.Lawton, G. Kosters at ESA)
- Cleveland Ohio (F. Graham)
- CEA Cariri Brazil 275 mm (Valmir de Morais)
- Nottingham UK lunar observers (A.C. Cook)
- Taiwan imaging (P. Maley)
- Yahoo Lunar Observing Group (C. Taylor)
- Eurastro (J.L. Dighaye)
- Planetary Society event (B. Betts, L. Friedman)
- List of other amateur observers to be updated on SMART-1 website