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Some design and applying aspects of Molecular Beam Epitaxy (MBE) machine Main Units in Ultra-Vacuum of Space

D.N. Pridachin (1), O.P. Pchelyakov (1,2), A.I. Nikiforov (1,2), L.V. Sokolov (1), V.V. Preobrazhenskii (1), V.V. Blinov(1)
(1) Rzhanov Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Science, Novosibirsk, Russia (dnp@isp.nsc.ru), (2) National Research Tomsk State University, Tomsk, Russia.

Abstract

Solar cell-assisted energy generation is believed to be the most attractive now. The technology does not require any regenerative energy sources (oil, coal, uranium, etc.). It is of low environmental pollution. MBE - the method of obtaining semiconductor films on single-crystal substrates - is, probably, the basic technological way to get the structures for solar cells [1].

More than twenty years Rzhanov Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences (ISP SB RAS), in co-operation with colleagues from Moscow and Krasnoyarsk, has been developing devices for MBE semiconductor film growth in Space. The device is to be mounted in the Russian segment of the International Space Station and, on Earth; operations are being carried out on the simulator-stand to work out the modes and testing [2].

The MBE machine scheme with a description of the main units and the principles of their operation are presented in the report. The growth chamber design, substrates heater, a cassette with the samples and a drive movement, also a unique design of molecular sources for elements III and V groups are specially focused on. The design of molecular sources has its peculiarities determined by using them under weightlessness [3]. Testing the source was realized using the "Katun-B" MBE machine. High-quality GaAs epitaxial films were grown.

Creation of hi-tech equipment, including the one that provides carrying out experiments in epitaxial semiconductor film growth in orbital flight conditions, requires a solution of non-standard tasks which are impossible to come across on Earth. The source of molecular flux that can be used in orbital flight conditions was developed, fabricated and successfully tested on ISP SB RAS.

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Asteroid Impact Mission: relevance to asteroid mining

P. Michel (1), M. Kueppers (2), I. Carnelli (3) for the Asteroid Impact Mission Team
(1) Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange Laboratory, Nice, France (2) ESA/ESAC, Madrid, Spain, (3) ESA Hq, Paris, France (michelp@oca.eu)

Abstract

The Asteroid Impact Mission (AIM) is the European (ESA) component of the Asteroid Impact & Deflection Assessment (AIDA) mission in collaboration with NASA. The objectives of AIDA are: (1) to perform a test of asteroid deflection using a kinetic impactor with the USA (NASA) component DART (Double Asteroid Redirection Test), and (2) with AIM, to investigate the binary near-Earth asteroid Didymos, in particular its secondary and target of DART, with data of high value for mining purposes.

1. Introduction

The Asteroid Impact Mission (AIM) is a small mission of opportunity whose objectives are to investigate a binary asteroid, to observe the outcome of a kinetic impactor test and thus, to provide extremely valuable information for mitigation, mining and science purposes [1, 2]. It is part of the Asteroid Impact & Deflection Assessment (AIDA) mission, in which the second component is the USA (NASA) Double Asteroid Redirection Test (DART) mission, which aims to send an artificial projectile to perform an asteroid deflection test and to observe the outcome from ground–based observatories [3] as well as from AIM. The AIM/AIDA target is the binary Near-Earth Asteroid (NEA) (65803) Didymos (1996 GT), in particular the secondary component and target of the DART mission, called hereafter Didymoon. A simplified version of AIM has been studied, called AIM-D^2 for AIM-Deflection Demonstration, which keeps the main objectives and is capable of providing crucial data for the interpretation of the DART impact. This modified mission concept provides the opportunity to reduce risk and cost by simplifying the spacecraft design and operational concept [2]. The payload is restricted to the AIM Framing Camera and the Cubesat ASPECT (Asteroid SPECTral Imaging), although optional payloads remain to be considered. They include a high-frame-rate camera to observe the plume generated by the DART impact, a hyperspectral camera for the analysis of the chemical composition and a LIDAR. A Radio Science Experiment (RSE) will also be performed. The mission will provide for the first time data from a new world, i.e., a binary asteroid and the smallest asteroid ever visited. In effect, the secondary is only 163 ± 18 meters in diameter. This size is actually among the most relevant ones to asteroid mining.

2. Relevance to asteroid mining

Asteroid mining, which needs appropriate tools for material extraction, relies currently on our poor knowledge of asteroid properties, in particular the mechanical properties at the surface and sub-surface, including regolith/dust properties. Moreover, a better understanding of the response of asteroid material to an external action in the appropriate low-gravity environment is strongly needed. Finally, a better knowledge of the composition of asteroids is needed, as it is not clear yet that meteorite material is representative of material in space, and spectral observations from the ground only provide disk-integrated information on the first microns of an asteroid surface. This prevents us from determining potential compositional heterogeneities within an asteroid. Extrapolating to an entire asteroid the abundance of rare materials in meteorites is unproven. AIM-D^2 is a crucial step in this ambitious adventure (see Table 1) that could eventually lead to successful asteroid mining. In effect, for the first time, AIM-D^2 will explore an asteroid of less than 200 hundred meters in diameter, sending us high-resolution images of its surface, telling us whether it is made of bare rock or granular material (including depth and grain size distribution down to the camera resolution limit), and measuring its global physical properties (shape, mass, density). All space missions that will allow us to obtain images and consequently access the detailed physical properties of an asteroid are very precious to enable us to cope with these bodies efficiently. Two sample-return missions underway, Hayabusa2 (JAXA) and OSIRIS-REx (NASA), will allow us to improve greatly our understanding of primitive asteroids in the size range 400–900 meters, in the coming years, and their preparation already showed how difficult it is to define the design of a proper sampling tool and the best sampling strategy when the knowledge of the target is still poor. The space mission Hayabusa (JAXA) showed us that getting back a sample is a real adventure and that we still have much to learn. The Rosetta space mission to a comet also showed how difficult it is to land in an unknown environment under low-gravity conditions. These experiences already allowed us to assess the difficulties associated with small-body investigations and to be better prepared for the next missions. AIM-D^2 will allow us to make another step performing measurements of the geophysical properties of the smallest asteroid ever visited. In addition, AIM-D^2 observations of the DART impact and outcome will provide fundamental information on the surface and subsurface mechanical properties and on the response of such a small body to an external action (here, an impact). Equipped with filters on the camera and with the Cubesat ASPECT, AIM-D^2 will also allow us to compare information on the compositional heterogeneity of the surface and ground truth for Earth-based observations. Another important aspect of AIM-D^2 is the size of Didymoon, which is very relevant for asteroid mining. In effect, asteroid mining relies on the abundance of targets to exploit. Big (km-size and larger) objects are rare, in particular if we account for their accessibility from Earth. Very small objects (below 100 meters in size) are very numerous, however they cause technical difficulties because of their extremely low gravity and their tendency to have a high spin rate, making it technically challenging to cope with them. Bodies of size of a few hundred meters are thus extremely interesting as they remain small enough to be numerous (some 10,000 are estimated to exist in the near-Earth space), but large enough to decrease the mentioned difficulties. Therefore, any data on bodies of this size, like AIM-D^2 will obtain, is of high value for asteroid mining. Moreover, as the target of the AIM-D^2 mission is a binary asteroid, we will have the opportunity to study two asteroids in the same mission! Although the investigations of the primary asteroid will likely not be as detailed as for the secondary, AIM-D2 will study the binary dynamical environment and should also be able to provide information about the morphology and surface properties of the primary. Given that almost one sixth of asteroids larger than 200 meters are expected to be binary, this information is very important for future asteroid exploration and resource utilization. Thus, all this information and the experience gained by AIM-D^2 on close proximity operations are precisely what is needed to make a big step towards actual asteroid mining.

Table 1: Mining Technology Demonstration and knowledge gained

Goals	Measurements
Close proximity operations around a 163 m-size asteroid	Mass Physical properties
Observing the response of a small asteroid to an external action (impact) and revealing the internal composition	Crater size/morphology Crater interior properties Ejecta properties
Deployment of and communication with the first interplanetary Cubesat at close proximity	Spectral properties In-situ charaterization

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Astronomical Prospecting of Asteroid Resources

M.Elvis (1), A. Stark (1) B. Stalder (1) and C. Desira (1,2)
(1) Harvard-Smithsonian Center for Astrophysics (melvis@cfa.harvard.edu); (2) University of Southampton, UK.

Abstract

Ore-bearing asteroids are not common among the known population. As a result, asteroid resource extraction requires that large numbers of asteroids be classified by their composition, and have precise orbits known. At present only near-Earth asteroids (NEAs) are accessible with massive (≥5mt) equipment that is likely needed for mining. Of the ~15,000 known NEAs, no more than 2000 have a taxonomic type. NEA discoveries are growing by ~2000/year, with most new discoveries being faint (V~20-21 at discovery). We have begun a program with the 6.5 m Magellan telescope and the PISCO 4-color imager to obtain precise colors and tracks for faint NEAs. This program can be scaled to characterize all NEAs as they are discovered. This "astronomical prospecting" can help close the business case for asteroid mining companies.

1. Introduction

Asteroids number in the millions and the total mass of industrially useful raw materials they contain is far vaster than the accessible materials in the Earth's crust [6]. This abundance has drawn great attention lately with a number of commercial companies developing ways to prospect for the most promising asteroids.

The mining industry term for commercially profitable concentrations of materials is *ore-bearing*. A rich vein of the desired material is not enough. A profit is essential. Ore-bearing is a technology dependent term. Improved methods can change material into being ore-bearing. It is also economics dependent, as a drop in price can render material non-ore-bearing, and vice versa.

There are a series of physical factors that reduce the number of asteroids that could be profitable to mine with current technology [3]. In total there remain many potentially ore-bearing asteroids, but as a fraction of the total among known NEAs they are quite rare, roughly 1 in 660, or 1 in 66 if low delta-v asteroids are preselected.

This fraction could rise if a thermal infrared survey of NEAs were undertaken, as the optically dark carbonaceous asteroids may well be far more common in such a survey [7]. Until at least the mid-2020s though we have only NEAs selected by their reflected optical light.

If a low delta-v NEA is selected at random some 100 must be visited to find one ore-bearing asteroid. Instead, if a rough classification into one of the 3 main type: stony (S), carbonaceous (C) or uncertain, and possibly metallic (X), then this number can be reduced to about 10 [4]. Cutting the number of spacecraft probes by an order-of-magnitude may be enabling for the closing of the business case.

Unfortunately, current investigations of NEAs, while highly successful at discovery, fall behind on the information gathering needed for prospecting [1]. Of the 2000 or so NEAs being discovered each year, almost half have ill-determined orbits in the sense that they will be almost impossible to re-acquire at their next close approach ("apparition"). An even greater fraction, ~90%, have no spectral information, and so have undetermined types.

Here we show that high quality optical imaging in 4 colors obtained from ground-based telescopes provide the most efficient method for obtaining the necessary orbit and type information that is basic to asteroid prospecting. To obtain this data needs large (>6m) telescopes with custom-built instrumentation and professional astronomers. We describe our pilot program at the 6.5m Magellan telescope in Chile using the PISCO 4-band imager.

2. Optical Colors and Astrometry

The standard method for obtaining asteroid types is to use near-infrared spectroscopy. However, the strong sky background in this band [2] sets a limit at V~19. As most new NEAs are discovered 1-2 magnitudes fainter, and then fade quite rapidly [1], a more sensitive method is needed if most NEAs need to be characterized.

The sky background in the optical band is much fainter, so that V=21-22 objects are quite accessible. However, NEAs are fast-moving, so spectral information must be collected rapidly, and this demands the use of large telescopes, with ≥6m diameter primary mirrors. Observing time on these large telescopes is currently scarce.

With measurements at ≤1% accuracy, just 4 of the optical bands of the Sloan Digital Sky Survey (SDSS) - g,r,i,z - are sufficient to make a reliable basic typing of asteroids (S,C,X) [5].

For orbit determination, accurate position determinations on the sky ("astrometry") are essential over as long an arc of the asteroid's orbit as possible [1]. Ground-based telescopes have image sizes ~0.5 arcsec due to the unstable atmosphere ("seeing"). Centroiding allows Pan-STARRS to obtain positions good to ~0.1 arcsec. However, with signal-to-noise of 100 it is possible to centroid an asteroid position to 1%, i.e. ~10 milli-arcsec (mas).
Until this year that accuracy was not useful, as the reference frame of stars was not defined to that level of accuracy for a dense enough grid of stars that any image would contain a sufficient number of them. With the release of the first *Gaia* catalog [Gaia2017] this is changed. We will report on our study of how well this newly accurate astrometry can improve orbit determination for NEAs.

To take advantage of the accurate color and astrometric information now obtainable for NEAs requires an instrument carefully designed to give this information. The Parallel Imager for Southern Cosmology Observation (PISCO, [8]) is a photometric camera that comprises four focal planes with a common shutter, capable of obtaining *simultaneous* images over a 9 arcminute field of view in the SDSS g, r, i and z optical passbands. PISCO is installed on the Magellan Clay telescope and is used for many astrophysics research projects. Simultaneous multi-band imaging removes uncertainties due to asteroid rotation. The large field enables accurate photometry by main sequence fitting, and accurate astrometry using ≥10 Gaia stars.

We report on our pilot project to test and optimize the abilities of PISCO/Magellan to produce the asteroid prospecting data needed for asteroid mining to be profitable.

3. Summary and Conclusions

Considerations of the rarity of ore-bearing near-Earth asteroids among the known population and the extreme faintness of the majority of newly discovered near-Earth asteroids, require the use of large aperture (>6 m) optical ground-based telescopes for the accurate determination of their orbits and a preliminary determination of their composition. This information can greatly reduce the need for in situ prospecting and so close the case for asteroid mining.

The 1% accuracy of the measurements requires: (1) high signal-to-noise in short observations, hence large apertures; (2) specialized instrumentation, such as PISCO; (3) professionally trained astronomers.
Our pilot program on Magellan will be used to validate and optimize this astronomical prospecting.

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How Many Ch-Class NEOs Do We Expect?

A. S. Rivkin (1), F. E. DeMeo (2) (1) JHU/APL, Columbia MD, USA, (andy.rivkin@jhuapl.edu) (2) MIT, Cambridge MA, USA

Abstract

The Ch asteroids are our best analogs to the hydroxyl-rich CM meteorites. Only a handful of Ch asteroids are known in the NEO population, though the discovery rate for NEOs has far outstripped the data needed to identify Ch asteroids in that population. Using models of delivery of objects from the main asteroid belt to near-Earth space and debiased models of the fraction of C-complex asteroids in the main asteroid belt and near-Earth space, we estimate that Ch asteroids should make up 3-12% of the NEO population, and that at least 20 Ch asteroids larger than 100 m and more accessible than the Moon should exist. Further work will be needed to identify such objects.

1. Introduction

Interest in the economic use of asteroidal materials has been increasing, with a particular focus on water. The CM and CI carbonaceous chondrites have hydroxylated minerals, with 5-10% water equivalent or more [1], and their parent bodies are natural targets for further investigation. Several different lines of evidence identify the Ch asteroid spectral group as the CM chondrite parent bodies [2-3]. Here we attempt to estimate the answer to a simple question: How many Ch asteroids should we expect to find in the NEO population?

2. Ch Asteroids in the Main Belt

The Ch asteroid class is defined by an absorption band near 0.7 μm. The subgroups within the C complex all have sufficiently similar albedos that comparisons to one another can be done without bias being a major concern.

Spectrophotometric [4] and spectroscopic [5] studies estimate that the Ch group makes up 30-50% of the C complex as a whole. Both studies also reported a size-dependent trend, with a smaller fraction of Ch asteroids as the size decreased. Rivkin reported a small variation in Ch fraction across the asteroid belt, from a low of 25% in the inner belt to a high of 55% in the outer asteroid belt.

3. Predicted Ch Asteroid Supply to NEO space

These numbers can be convolved with models of the supply of NEOs from various small body reservoirs [6]. Bottke et al. estimate 61% of the NEO population is derived from the inner main belt, with the central and outer main belt providing 24% and 8%, respectively. The remaining 6% is from the Jupiter Family Comet region, for which we set the Ch fraction at 0. The final necessary piece for this estimate is the fraction of asteroids belonging to the C complex in each reservoir. Bus and Binzel [7] provided a debiased estimate of the fraction of each spectral complex vs. semi-major axis in the main belt for objects > 20 km. The averages for the C complex in the inner, central, and outer belt are 37%, 47%, and 52%, respectively.

It is relatively straightforward to combine the numbers mentioned above [4,6,7] into an estimate for the expected fraction of Ch asteroids among the NEO population as a whole:

Ch fraction = (0.61)(0.37)(0.25) + (0.24)(0.47)(0.35) + (0.08)(0.52)(0.55) = 0.12.

By this estimate, 12% of all NEOs should be Ch asteroids. The C-complex should be 38% of NEOs via this same calculation. We note below that there are several implicit/explicit assumptions in this estimate.

4. Observed Ch Asteroids in NEO Space

The number of known Ch asteroids in NEO space is very small. In the nearly 2300 asteroids in the European Asteroid Research Node database [8], 740 of which have taxonomic types assigned at this writing, only 3 are identified as Ch asteroids: (285263) 1998 QE2, 2002 DH2, and 2012 EG5. This very small fraction is highly affected by biases, of course, among them the popularity of 0.8—2.5 µm observations of NEOs, which cannot be used to identify Ch asteroids, eclipsing the popularity of 0.5-1.0 µm observations, which can. The most recent large survey of NEOs in the visible-near IR [9] reported 1 Ch asteroid out of 23 C-complex NEOs, which is again much smaller than 12% but may be affected by the statistics of small numbers. Surveys of the NEO region specifically find C-complex fractions that are smaller than the 38% estimated above. Stuart and Binzel [10] report a C-complex fraction of 10% in the NEO population, while Carry et al. [11] used SDSS data to find 23% of 230 NEOs were C-complex asteroids. These two numbers suggest a Ch fraction of ~3-7% in the NEO population.

When we look to the meteorites, both the implied Ch and C-complex fractions are smaller still. The Meteoritical Bulletin database [12] reports 16 CM falls and 45 carbonaceous chondrite falls out of 1153 total falls of non-Mars meteorites. The CMs making up ~1/3 of all carbonaceous chondrites is consistent with the estimates above. However, taken at face value the fall statistics imply that less than 2% of NEOs are CM and only 4% of them are carbonaceous, both roughly an order of magnitude smaller than the estimates based on NEO delivery models.

5. A Ch Asteroid Problem?

The mismatch between the CM meteorites seen in the meteorite collection and what would be expected from NEO delivery models is puzzling, though it is perhaps too soon to consider this a "problem". Nevertheless, it is not obvious how best to reconcile the estimate with the observed CM fraction. Lowering the fraction of C-complex asteroids in the inner belt, where most NEOs are derived, is not consistent with existing data. Similarly, reducing the fraction of Ch asteroids within the C complex is inconsistent with the observed data and is also inconsistent with the CM fraction of carbonaceous chondrite falls.

The estimates in Section 3 assume that the various steps between residence in the asteroid belt and sample collection after a fall do not discriminate in favor or against particular asteroid classes. This is almost certainly not the case, nor is the C complex the only group affected: for instance, the X-complex asteroids are thought to represent 34% of the debiased NEO sample [10], but all meteorite falls from groups that could be associated with this complex total only ~6.5% of the total. It is also possible that the minerals responsible for the 0.7-µm band that distinguishes Ch asteroids have been destroyed on the surfaces of many/most NEOs that had them in the main belt. This could have happened during a low-perihelion period like those described by Marchi et al. [13]. Whether there are truly "too few" Ch asteroids in the NEO population requires additional observations in the 0.5-1.0 µm region. Happily, these are relatively easy to make, and there are a large number of known C-complex objects that can be targeted.

6. How many Ch NEOs do we expect?

If we disregard the meteorite fall statistics as unrepresentative of what we might find in space, the range of estimates for Ch fraction among NEOs ranges from 3-12%. With 900 or so NEOs larger than 1 km, that suggests anywhere from ~25-100 Ch asteroids larger than that size, with correspondingly more at smaller sizes.

Looking at delta-v, roughly 3200 known NEOs (of all sizes) are more accessible than the Moon (6 km/s). If thoroughly mixed, we might expect ~100-300 of them to be Ch asteroids. Roughly 670 of these NEOs have H<23.1, suggesting at least 20 Ch asteroids > 100 m diameter should be more accessible than the Moon (using the average C-complex NEO albedo:[10]). The trick is to find them.

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Figure of Merit for Asteroid Regolith Simulants

P. Metzger (1), D. Britt (1), S. Covey (2) and J.S. Lewis (2)
(1) University of Central Florida, USA (philip.metzger@ucf.edu), (2) Deep Space Industries, USA and Luxembourg.

Abstract

Asteroid regolith simulant is being developed for several asteroid classes. These simulants are shown to have very high fidelity to the reference meteorites in terms of mineral and elemental composition. Particle sizes and other characteristics are also being validated.

1. Introduction

Simulated asteroid regolith, or *asteroid simulant*, is needed for tests of space mining, propellant manufacturing, radiation shielding, and more. In 2015, NASA selected Deep Space Industries in partnership with the University of Central Florida to develop several asteroid simulants. Geological processes on asteroids are different than those operating on Earth so it is impractical to create simulants that replicate all characteristics of actual asteroids. Learning from the experiences of the lunar exploration community [1], we held a workshop October 6-7, 2015 to select the subset of those properties that would control the design of the simulants [2]. The workshop also chose which spectral class asteroids will be simulated: CI, CM, CR, C2, CV, and an L-Chondrite Ordinary. The CI simulant has now been developed and is reported here, while the others are in development [3].

It is important that members of the user community understand the limitations of any simulant. Here, we present a Figure of Merit (FoM) system based on NASA's lunar simulant program [4]. A simulant with a high FoM for mineralogical fidelity may be good for resource processing tests, while a simulant with a high FoM for geotechnical fidelity may be better for a mining mechanics test. The FoM is calculated by measuring particle size distribution, mineralogical composition, volatile inventory, and other properties of the simulant then mathematically comparing these results to the best available estimates of the same properties on asteroids.

2. Control Parameters

The workshop identified 65 properties of asteroid materials including grain properties, electrostatics and magnetics, geomechanics, optical properties, gas interactions, thermal and physical properties, chemical reactivity, texture, and volatile inventory. Of these, the following were chosen to be "control parameters" for simulant design: particle size distribution, magnetic susceptibility, tensile and compressive strength of cobbles, shear strength of regolith, bulk density and porosity of cobbles, mineralogical composition, water content, organic content, sulfur compounds, and volatile release patterns in temperature and pressure.

3. Mineral /Elemental Composition

The CI simulant is the first one developed. It is based on the mineralogy analysis of the Orgueil meteorite by Bland, et al [5]. It was made with minerals obtained from commercial suppliers and mines in various locales. In some cases, the minerals or volatiles in the actual meteorite are unstable (e.g., pyrrhotite and troilite) or unsafe for human exposure (polycyclic aromatic hydrocarbons in the insoluble organic material) so substitutions were made (pyrite for the iron sulfides, sub-bituminous coal for the organics). These substitutes were selected for reasonable chemical similarity and for elemental similarity. The olivine grains in Orgueil vary in Mg-Fe composition but are generally nearer the fayalite end member, so we have chosen Fo_{90} to match the bulk average composition. The phyllosilicates in Orgueil are a disordered serpentine-saponite mixture. We have chosen antigorite, vermiculite, and attapulgite clays for chemical similarity, to provide the correct volatile inventory, and to have realistic volatile thermal release patterns. We substituted the iron hydrate ferrihydrite with the magnesium hydrate epsomite since the former is commercially unavailable but the latter will approximate the water's thermal release pattern, and the net Mg and Fe abundances are still close to the targets.

Deep Space Industries is making the simulant available in several forms, including (1) regolith, (2) slabs and cobbles, (3) ready-to-prepare dry mix, and bagged un-mixed source materials. Here we discuss the completed regolith version. The minerals were crushed, mixed, wetted, and dried in a method described by Covey, at al [3] to create cobbles that are then re-crushed into multi-mineralic particles with the desired power law size distribution. The fidelity of the chemical composition is quantified by two FoMs, one for mineralogy and the other for elemental abundance.

4. Figure of Merit Calculations

We follow the FoM method developed by NASA for lunar soil simulants [4]. The method is to list in adjacent columns the mass percent of each component for the reference meteorite ("target") and the simulant and to take the lesser of these two values. These are summed. This calculates the "overlap" in compositional percentages. The Mineralogical FoM for the CI simulant is shown in Figure 1.

Mineral	Target	Simulant	FoM Score
Serpentine/Saponite Phyllosilicates	67.93%	62.00%	0.6200
Equivalent Fayalite $FeSiO_4$	1.20%	0.70%	0.0070
Equivalent Forsterite $MgSiO_4$	5.64%	6.30%	0.0564
Magnetite Fe_3O_4	9.22%	13.50%	0.0922
Equivalent FeS	5.80%	0.000%	0.0000
Equivalent FeS_2	0.48%	6.50%	0.0048
Ferrihydrite $(Fe3+)_2O_3$•$0.5H_2O$	4.75%	0.00%	0.0000
Epsomite $MgSO_4$*$7H_2O$	0.00%	6.00%	0.0000
Organics	5.00%	5.00%	0.0500
TOTAL			0.8303

Figure 1. Mineralogical FoM for CI simulant.

This compares very well with the scores for lunar simulants. The highest scoring, available lunar simulant, NU-LHT-2M, has a score of 0.55, while the widely used JSC-1A has a score of 0.35.

In addition to the mineralogical FoM, we have calculated an elemental FoM. Elemental composition is important for radiation shielding studies, for example. The results are shown in Figure 2.

Element	Target	Simulant	FoM Score
Fe	18.95%	16.24%	0.162438
Si	10.64%	11.18%	0.1064
Mg	9.62%	13.54%	0.0962
S	5.25%	4.19%	0.041944
C	3.22%	3.85%	0.03215
H	2.02%	1.67%	0.016743
Al	0.65%	1.14%	0.00645
Ni	1.00%	0.15%	0.001538
Ca	0.87%	1.50%	0.00865
Na	0.55%	0.04%	0.000355
N	0.12%	0.05%	0.000497
Cr	0.24%	0.03%	0.000273
Mn	0.17%	0.03%	0.000288
P	0.13%	0.04%	0.000375
O and traces	46.62%	46.34%	0.463426
Total Score			0.937727

Figure 1. Elemental FoM for CI simulant.

5. Additional Measurements

Particle size distribution, magnetic susceptibility, water release patterns, and other characteristics of the regolith are also being measured and will be reported. Simulants for the other asteroid classes are also in development.

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Asteroid Spectral Imaging Mission (ASPECT) CubeSat to characterize resources on asteroid surfaces

Tomas Kohout(1,2), Antti Näsilä(3), Tuomas Tikka(4), Mikael Granvik(1), Antti Kestilä(5), Antti Penttilä(1), Janne Kuhno(4), Karri Muinonen(1,6), Kai Viherkanto(3)
(1) Department of Physics, University of Helsinki, Finland, (2) Institute of Geology, The Czech Academy of Sciences, Prague, Czech Republic, (3) VTT Technical Research Centre of Finland, Espoo, Finland (4) Reaktor Space Lab, Helsinki, Finland, (5) Aalto University, Espoo, Finland (6) Finnish Geospatial Research Institute FGI, Masala, Finland

Introduction

Asteroid Spectral Imaging Mission (ASPECT) is a 3U CubeSat with a visible – near infrared (VIS-NIR) spectral imager payload. It can be deployed on an asteroid orbit to characterize the composition of its surface. It can work in tandem with its mothercraft or fleet of other CubeSats to provide complex insight into its target asteroid properties. It can contribute in search for surface resources and locate candidate areas for further sampling or utilization.

ASPECT concept

ASPECT (Asteroid Spectral Imaging Mission) is a 3U CubeSat designed for deep space exploration of small Solar System bodies. The payload, avionics, and cold gas propulsion units occupy each 1U space. The payload of ASPECT is a miniaturized spectral imager with primary scientific task of high resolution compositional mapping of target surface. The concept is originally developed for the ESA-NASA AIDA (Asteroid Impact & Deflection Assessment) project. In 2016 it underwent preliminary design study and was down selected as the only CubeSat payload for European AIDA component AIM-D^2 (Asteroid Impact Mission – Deflection Demonstration). ASPECT features autonomous navigation relying on inter-satellite link with the mothercraft, navigation camera, and Sun and star sensors. To assure desired spatial orientation reaction wheels are utilized while orbit is maintained using active cold gas propulsion.
Thanks to its modular design, ASPECT can be easily adopted to study other targets or to incorporate different payload of within 1U (10 cm × 10 cm × 10 cm) on the existing platform.

Spectral imager payload

The payload is a miniaturized spectral imager extending from the visible up to the shortwave infrared wavelengths. In contrast to more traditional spatial-scanning imaging spectrometers, the Asteroid Spectral Imager utilizes tunable Fabry-Perot Interferometers (FPI) to select the imaged wavelengths. When multiple snapshots are combined, a spectral datacube is formed, where the wavelength bands are separated in the time domain. The instrument is based on the space-qualified designs of the Aalto-1 Spectral Imager and Picasso VISION. The VIS and NIR channels are imaging spectrometers, while the SWIR channel only measures a single point. The target wavelength range is 500 - 900 nm for the VIS channel, 900 - 1600 nm for the NIR channel and 1600 - 2500 nm for the SWIR channel. All three channels have dedicated FPIs optimized for the desired wavelength range. The targeted spectral resolution is ca. 10 - 50 nm. All three channels can be operated simultaneously and are independent of each other. The main instrument parameters are listed in Table 1.

Table 1. The main Asteroid Spectral Imager parameters.

Parameter	VIS channel	NIR channel	SWIR channel	notes
Field of View [deg]	6° x 6°	5.3° x 5.3°	5° circular	
Spectral range [nm]	500 – 900	900 – 1600	1600 - 2500	
Image size [pixels]	614 x 614	256 x 256	1 pixel	
No. spectral bands	Ca. 14	Ca. 24	Ca. 30	Tunable in flight
Spectral resolution [nm]	< 20 nm	< 50 nm	< 25 nm	

ASPECT prospection

The prospecting objectives of ASPECT (Table 2) are based on the capabilities of the payload — the VIS-NIR imaging spectrometer. The payload allows for global compositional mapping and imaging of the target asteroid with sub-meter resolution. The spectral range of 500-2500 nm covers most common silicate mineral (olivine, pyroxene, and plagioclase) absorption bands related to Fe^{2+} ions in their structure. Additionally, ASPECT can also detect hydrated minerals as serpentine using ~700 nm Fe^{3+} absorption features. Direct presence of -OH an H_2O can be detected at 1400 and 1900 nm respectively. Additionally, observations at various phase angle allows for estimation of surface roughness. The payload design and constraints on ground resolution are shown in Fig. 1.

Table 2. ASPECT scientific objectives and expected results

ASPECT prospecting objectives and expected results	
Objective 1	Map the surface composition of the target
Result	Composition and homogeneity of the target surface
Result	Identification and distribution of volatiles
Objective 2	Photometric observations and modeling of the target
Result	Surface roughness / particle size distribution
Objective 3	Characterize possible landing sites
Result	Detailed composition and surface roughness information on potential landing sites
Objective 4	Evaluate surface areas and objects suitable for sample return or ISRU
Result	Identification of areas and objects with desired properties

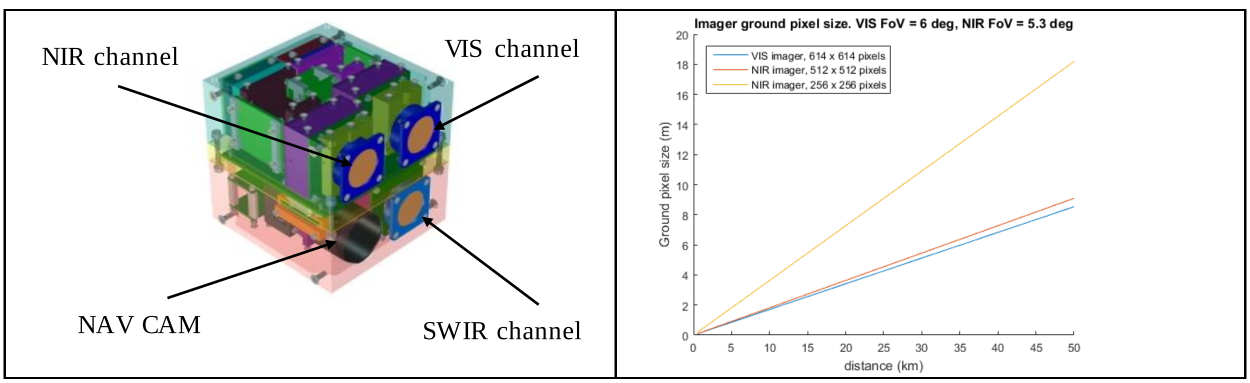

Figure. 1. Left: Payload concept showing three spectrometer channels and navigation camera. Right: Constrains on the imager resolution as a function of orbit distance.

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ASIME 2016 White Paper: Answers to Questions from the Asteroid Miners

JL Galache (1), A. Graps (2,3,4), and Thirty ASIME 2016 Contributors
(1) Aten Engineering, Portland, OR (jl@atenengineering.com) (2) University of Latvia, Institute of Astronomy, Riga, Latvia, (3) Planetary Science Institute, USA (graps@psi.edu) (4) Baltics in Space, Riga, Latvia, (4) Thirty ASIME 2016 Author Institutes.

Abstract

The aim of the Asteroid Science Intersections with In-Space Mine Engineering (ASIME) 2016 conference on September 21-22, 2016 in Luxembourg City was to provide an environment for the detailed discussion of the specific properties of asteroids, with the engineering needs of space missions that utilise asteroids. The ASIME 2016 Conference produced a layered record of discussions from the asteroid scientists and the asteroid miners to understand each other's key concerns and to address key scientific questions from the asteroid mining companies: Planetary Resources, Deep Space Industries and TransAstra. These Questions were the focus of the two-day conference, were addressed by scientists inside and outside of the ASIME 2016 Conference and are the focus of this White Paper.

The Questions from the asteroid mining companies have been sorted into the three asteroid science themes: 1) survey, 2) surface and 3) subsurface and 4) Other. The answers to those Questions have been provided by the scientists with their conference presentations or edited directly into an early open-access collaborative Google document (August 2016-October 2016), or inserted by A. Graps using additional reference materials. During the ASIME 2016 last two-hours, the scientists turned the Questions from the Asteroid Miners around by presenting their own key concerns: Questions from the Asteroid Scientists. The Questions and Answers form this field's first major reference document. These answers in this White Paper point to the Science Knowledge Gaps (SKGs) for advancing the asteroid in-space resource utilisation domain. The SKGs follow.

The thirty ASIME 2016 contributors to this White Paper are: JL Galache, Amara L. Graps (lead author), Philippe Blondel, Grant Bonin, Daniel Britt, Simone Centuori, Marco Delbo, Line Drube, Rene Duffard, Martin Elvis, Daniel Faber, Elizabeth Frank, Simon F. Green, Jan Thimo Grundmann, Henry Hsieh, Akos Kereszturi, Pauli Laine, Anny-Chantal Levasseur-Regourd, Philipp Maier, Philip Metzger, Patrick Michel, Migo Mueller, Thomas Mueller, Naomi Murdoch, Alex Parker, Petr Pravec, Vishnu Reddy, Joel Sercel, Andy Rivkin, Colin Snodgrass, and Paolo Tanga.

The White Paper can be found at: **https://arxiv.org/abs/1612.00709**

Science Knowledge Gaps for Advancing the Asteroid In-space Resource Utilisation Domain

1. **More studies are needed to map the classification of meteorites to asteroids. Presently the best-established link is between ordinary chondrites and S-type asteroids.** We need more useful published literature about the bulk composition of meteorites to help make more accurate simulants. **We need to understand the meteorite links to C-type asteroids.**

2. **Dedicated NEA discovery and follow-up instrumentation.** The best observability conditions for a given NEA are typically offered around the discovery time (brightest). Need to run observations to characterize NEAs quickly after discovery; best possible with dedicated telescope(s). What is needed: A photometric telescope of a 2-3m class (to reach V $\approx$ 21 with good S/N) available on short notice (for that the observations can be best taken right after discovery). To characterize one NEA, with full IR/vis spectral characterizations, but with 'proxies' or shortcuts to 'each NEO'.

3. **An understanding of granular material dynamics in low-gravity.** Before being sure that

we have a robust understanding of the asteroid regolith and to seriously start some systematic material extraction / utilisation programs, we must understand how this regolith with its properties responds to the envisage action, i.e. to understand granular material dynamics in low-gravity. Missions like AIM, Hayabusa 2 and OSIRIS-REx can help.

4. **Identifying the available low-delta-v (which are the objects with orbits similar to the Earth) targets are key.** What is needed is a map of low delta-v, low synodic period and low-albedo NEOs as a a first-cut to fine-tune the target possibilities.

5. **Determine if a NEO's dynamically predicted source regions is consistent with its actual physical characterisations.** Knowing the asteroid's source region, and hence, its orbital family characteristics, can enable a short-cut to characterize the small NEOs of that family which are difficult to measure spectroscopically.

6. **For making useful asteroid regolith simulants, immediate needs are: adequate data on the particle sizing of asteroid regolith and sub-asteroid- regolith surface. How does the asteroid regolith vary with depth?** If the NEOs have structure like comet nucleus 67P, then the NEO regolith is denser then the deep interior.

Acknowledgements

We (Galache and Graps) wish to acknowledge the tremendously thoughtful scientific conversations and inputs to this document during these days of the conference and online in the Google Docs White Paper. The mutual respect our community showed to each other lent to a very productive and fun experience to build our vision. It's here, in this White Paper. Thank you, all. Thank you, also, to the Luxembourg Ministry of the Economy to be the unifying view of in-space resource utilisation. Their multi-level commitment to bringing the asteroid scientists and asteroid mining companies together made the ASIME 2016 a historical meeting.

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Luxembourg Space Resources Initiative

M. Link (1) (1) Directorate of ICT and Space Affairs, Ministry of the Economy, the Government of the Grand Duchy of Luxembourg (Mathias.Link@eco.etat.lu)

Introduction

Luxembourg has started being active in space through the creation of the Société européenne des satellites (SES S.A.) in the middle of the eighties. With a significant commitment by the Government of the Grand Duchy of Luxembourg, SES launched its first publicly/privately owned Direct-to-Home communications satellite covering Europe. Since that date, Luxembourg has been actively making use of orbital resources in the form of geostationary orbital positions and satellite communication frequencies under the auspices of the International Telecommunications Union.

In 2005 Luxembourg became a Member of the European Space Agency and has since managed to develop a dynamic space sector consisting of some 30 different companies employing more than 800 people of diverse nationalities.

Luxembourg has also a long tradition in mining, dating back to 1850 with the birth of a major industrial basin. In 1913 the country was among the top ten producers of iron ore and pig iron in the world.

Luxembourg looks back at a compelling history of economic innovation and it is currently gearing up for a Third Industrial Revolution, part of which could once more occur in space. To that effect, Luxembourg is exploring the potential use of space resources, in coordination and collaboration with other states, the scientific community, as well as commercial partners.

1. Space Resources

Space resources, found on asteroids, the moon and other celestial bodies, hold a large potential for future technological innovation, economic activity and growth with a promise of ecologic and social benefits.

The vast majority of the asteroids can be found in the asteroid belt between Mars and Jupiter. Several of those asteroids are passing near our planet Earth. More than 14 000 Near Earth Asteroids have been identified. They are easily accessible and might contain more valuable resources than have been already found on Earth.

Water, respectively ice, is of particular interest. Water extracted from celestial bodies is an essential and highly valuable resource on long duration space missions and for future space colonizers. It could also be broken into oxygen and hydrogen for air and rocket or satellite propellant.

The metals could be used to build or repair spacecraft off Earth as well as to build other structures for a space colony, i.e. provide material for the construction of hardware in space.

2. Opportunities

Space resources utilization could open up a wealth of new resources, as well as new perspectives for humanity.

The space industry is currently held back by the high cost of launching equipment and supplies into orbit. Because of current launch costs of several million dollars per ton, the number of launched satellites is limited. Even more limited is the range of business activity, which is viable in light of that cost. Large quantities of raw material available directly in space at relatively low cost, can increase satellite capacities and lower the expenses of space missions. Satellite operators could improve services delivered to their customers on Earth. Once a supply chain of materials is established in orbit, it will encourage new applications and new business models as entrepreneurs attempt to introduce even more services useful for people on Earth find.

3. Objectives and Strategy

Luxembourg aims to contribute to the peaceful exploration and sustainable utilization of space resources for the benefit of humankind.

While respecting its international obligations, Luxembourg is working on an attractive and recognized legal and regulatory framework promoting investment and growth of private ventures in space resource utilization.

The strategy includes actions along 5 major pillars:

- Ensure national political support and promote international cooperation,

- Build a clear legal and regulatory framework,

- Promote long-term public support through research and education,

- Offer dedicated support for Research and Development activities,

- Provide long-term funding.

Drawing on its success and proven capabilities in the commercial satellite services industry, Luxembourg aims to develop into a global leader in the peaceful exploration and sustainable utilization of space resources.