Small satellites for big science: the challenges of high-density design in the DLR Kompaktsatellit AsteroidFinder/SSB


DLR German Aerospace Center
AsteroidFinder Mission & Instrument presentations given at the COSPAR 2010

- on the AsteroidFinder science mission
  - Stefano Mottola et al.  *The DLR AsteroidFinder for NEO*
  - Symposium P, Session SW2, Nr. 17 (COSPAR-10 PSW2-0017-10)
  - Sunday, 18 July 2010, 18:00-18:30, Hall 4.1 / Jupiter
    (solicited talk)

- on the AsteroidFinder Instrument payload (AFI)
  - Harald Michaelis et al.  *The AsteroidFinder Instrument*
  - Symposium P, Session SW2, Nr. 23 (COSPAR-10 PSW2-0023-10)
  - Tuesday, 20 July 2010, 16:00-17:30, Hall 3 / Poster Area; Tue-334
    (poster presentation)
AsteroidFinder in basic requirements

- Quickly find more Inner-Earth Objects, i.e. small solar system bodies orbiting the Sun completely Interior to Earth’s Orbit (IEO)
  - at least 10 IEOs to be found and tracked sufficiently to allow precise orbit determination, assuming a reference population equivalent to the long-term orbit evolution propagation model by Morbidelli and Bottke, simulated down to $H = 23$mag $\Leftrightarrow$ Ø $\sim 100$m @ albedo 0.15, and containing 1190 IEOs and $\sim 3300$ Atens, of a total of 57649 objects
  - so far, 10 found in total since 1998, the first one lost again, and only 1 “deep“ IEO known

- Re-use as much as possible of the earlier DLR missions BIRD & TET
  - BIRD – Bispectral InfraRed Detection small satellite, launched on October 22nd, 2001
  - TET – Technology Experiments Carrier small satellite, to be launched in December 2010
  - take advantage of local Concurrent Engineering Facility studies of other missions which have their first iterations based on AsteroidFinder/SSB itself, as “reverse re-use“

- Launch „piggy-back“ in 2013
  - take into account all launch vehicles presently announced or available on the market
  - be ready for every flight opportunity: no self-generated technical restrictions
  - robust design in terms of mechanical ruggedness and operational flexibility
How to get your scientific satellite into space
– Step 1: Decide…

Method (A) – or – Method (B)

(Note: not to scale)
**Satellite Size Matters**

**Cubesat**
- limited resources
- limited space
- limited mass
- no repeat pattern
- no LTAN control
- no altitude control
+ clearly defined design conditions
+ efficient solutions
+ up-to-date components and methods
+ changing coverage pattern
+ time-variable coverage
+ decay changes observing conditions

**Envisat**
- stable observing conditions
- predictable coverage cycles
- set data-take schedule
- space-qualified hardware & methods
- proven solutions
- design-to-mission flexibility
- fuel-related risks & hazards
- substantial analysis effort
- payload reliance on bus services
- no intrinsic hard growth limit
- voluminous platform-box structure
- resource sharing between payloads
Pros & Cons

Cubesat

- limited resources
- limited space
- limited mass
- no repeat pattern
- no LTAN control
- no altitude control

+ clearly defined design conditions
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Envisat

stable observing conditions +
predictable coverage cycles +
set data-take schedule +
space-qualified hardware & methods +
proven solutions +
design-to-mission flexibility +

- fuel-related risks & hazards -
- substantial analysis effort -
- payload reliance on bus services -
- no intrinsic hard growth limit -
- voluminous platform-box structure -
- resource sharing between payloads -
Satellite Size – Is there a best-of …?

from Cube:
- limited resources
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„Small Satellites“, the buzzword approach – or: How to Clash the Cultures

from Cube up:

± smart design-to-cost
± efficient hardware
± careful design
- no repeat pattern
- no LTAN control
- no altitude control
+ clearly defined design conditions
+ when new, efficient solutions
+ when needed, up-to-date design
+ orbit drift insensitivity
+ time-variable coverage
+ decay changes observing conditions

from Envisat down:

one full-scale instrument +
capable attitude control +
early mission analysis +
re-use of hardware & methods +
proven design concepts +
design-to-mission flexibility +
fuel-related risks & hazards -
substantial analysis effort ±
organic bus-payload integration ±
no intrinsic hard growth limit -
voluminous platform-box structure -
resource sharing between payloads -
“Small Satellites“, the buzzword approach – or: How to Clash the Cultures, Make It Work

from Cube up:

± smart design-to-cost
± efficient hardware
± careful design
  - no repeat pattern
  - no LTAN control
  - no altitude control

+ clearly defined design conditions
+ when new, efficient solutions
+ when needed, up-to-date design
+ orbit drift insensitivity
+ time-variable coverage
+ decay changes observing conditions

work & think harder!

from Envisat down:

one full-scale instrument +
capable attitude control +
early mission analysis +
re-use of hardware & methods +
proven design concepts +
design-to-mission flexibility +
fuel-related risks & hazards -
substantial analysis effort ±
organic bus-payload integration ±
no intrinsic hard growth limit -
 voluminous platform-box structure -
resource sharing between payloads -
capitalize benefits!

payload & bus: work & think together!

enforce initial decisions!

question basic requirements!
Convergence Matters!

from Cube up:
- ± smart design-to-cost
- ± efficient hardware
- ± careful design
  - no repeat pattern
  - no LTAN control
  - no altitude control
- + clearly defined design conditions
- + when new, efficient solutions
- + when needed, up-to-date design
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question basic requirements!
work & think harder!

multi-scenario mission analysis in cycles
multiple design options

from Envisat down:
- one full-scale instrument +
- capable attitude control +
- early mission analysis +
- re-use of hardware & methods +
- proven design concepts +
- design-to-mission flexibility +
- fuel-related risks & hazards -
- substantial analysis effort ±
- organic bus-payload integration ±
- no intrinsic hard growth limit -
- voluminous platform-box structure -
- resource sharing between payloads -

100³ cm³
200 kg
300 W

work & think harder!

payload & bus: work & think together!
integrated tech-team
one system-level design

enforce initial decisions!

capitalize benefits!
save fuel mass;
redistribute gains made;

system-level margin management
„Kompaktsatellit“ programmatic

- The „Kompaktsatellit“ programme has been created for scientific payloads from within DLR.

- „Kompaktsatellit“ spacecraft focus on one scientific mission and payload instrument.

- The AsteroidFinder instrument has been selected following an internal competition, to become the first payload in the „Kompaktsatellit“ programme.

- AsteroidFinder/SSB is the first satellite in a planned series of future satellites in the „Kompaktsatellit“ programme as part of the DLR research & development programmes.
AsteroidFinder requirements – first derivative: Rough-Order mag +18.5 V

- Region of Interest (RoI) defined relative to the Sun
  - 2 windows at ± (≤30° to 60°) ecliptic longitude, and ±40° ecliptic latitude

- extreme straylight suppression
  - Sun : asteroid \( \sim 10^{18} : 1 \)
  - planet : asteroid \( \sim 10^8 : 1 \)
  - asteroid : background \( \sim 5 : 1 \ldots 3 : 1 \)

- Ø25-cm-class telescope
  - convergence of astrometry, sensitivity, area coverage, and data volume

- passive cooling of the sensor
  - -80°C required for sensitivity & signal-to-noise ratio
  - ~3 W dissipation on focal plane array, mainly from fast-readout sensor itself
Geometry – Region of Interest vs Straylight
wedged in between constraints

- targets of observation are faint \textit{and} close to the brightest source of all
- the second-brightest source covers almost half of the sky all the time
- \textit{scattered} straylight from either source: observations become impossible
- the whole satellite shape is defined by RoI-Earth-Sun geometry, only
- RoI-Sun part of geometry is LTAN-independent, but RoI-Earth is not

\textit{cost of constraint:}
- >\(\frac{1}{4}\) of payload volume
- \(~\frac{3}{4}\) of deployable baffle volume
- scientific yield reduced when moving away from dawn-dusk Sun-synchronous orbit
Power – what goes in… must be radiated out

- 24/7 IEO survey observations
- operational satellite, not tech-dem
- 720 images & slews / day
- significant on-board processing

- ~275 W constant power consumption
- maximum solar panel area available in stowed & deployed configuration
- 'hot' solar panels very close to the 'cool' telescope bay at upper hinge
- 'cold' radiator well protected, but some leakage inevitable
- majority of satellite surface collects energy and/or radiates dissipation
  - energy flow ⇔ lower-limit satellite size
„piggy-back“ – optimized stowaway

- extensive survey of past and future launch activities, launch vehicles, and target orbits
  - all launched objects 2004 – today – 2015+

- analysis of lifting capabilities, payload envelopes, separation mechanisms, and interfaces

- TET-like Phase 0 initial design of AsteroidFinder determines „the smallest box we’re already in“

- satellite mass & volume limits determined by the size of this payload envelope
  - a synthesis of several small payload platforms and their options
  - used as a programmatically implemented hard constraint, equivalent to design-to-cost

\[
\begin{align*}
\text{BIRD} & \quad 550 \times 620 \times 647 \quad \text{of} \quad 600 \times 600 \times 800 \text{ mm}^3 \\
& \quad 92 \text{ of } 100 \text{ kg} \\
& \quad \text{defined by Kosmos-3M, actually flew with PSLV}
\end{align*}
\]

\[
\begin{align*}
\text{TET} & \quad 546 \times 639 \times 821 \quad \text{of} \quad 550 \times 650 \times 880 \text{ mm}^3 \\
& \quad 120 \text{ of } 120 \text{ kg} \\
& \quad \text{defined by „BIRD+P/L’s”, to fly with Soyuz-Fregat}
\end{align*}
\]

\[
\begin{align*}
\text{AsteroidFinder/SSB, Ph. 0 - } \Delta A & \quad 550 \times 650 \times 880 \text{ mm}^3 \\
& \quad 112\ldots135 \text{ of } 120 \text{ kg} \\
& \quad \text{defined by TET}
\end{align*}
\]

\[
\begin{align*}
\text{AsteroidFinder/SSB, Ph. } \Delta A & \text{ & B} & \quad 800 \times 800 \times 1000 \text{ mm}^3 \\
& \quad 160 \pm 20 \text{ of } 180 \text{ kg} \\
& \quad \text{defined by launch vehicles}
\end{align*}
\]
„piggy-back“ – wherever you end up

- extensive mission analysis to verify feasibility in all realistic Sun-synchronous, low Earth orbits (SSO)
- multiple campaigns of reference orbits covering 4 seasons in up to 12 LTAN’s (Local Time of Ascending Node, i.e. when crossing the equator)
  - target altitude range 650...850 km
  - complies with the majority of launch opportunities, past and future
  - tolerant to 600km perigee / 900 km apogee when due to injection errors and/or decay
- most popular SSO geometry configurations:
  - „dawn-dusk“ – LTAN ca. 06/18:00
    - Earth-observing radar, power-hungry, and solar science primary payloads
    - good scientific mission yield within ±02:00 LTAN, acceptable within ~±03:00
  - „late morning“ – LTAN ca. 10:30 ±02:00 and equivalents
    - optical Earth observation; surface photography, weather and atmosphere
    - scientific mission yield decreases rapidly beyond 09:00-LTAN-like geometry
In the Box – /SSB internal accommodation

- easy access to all units
- all bus & many payload units in one box
- avionics on Eurocards & backplanes
- extremely high volume utilization
- massive Al structure provides:
  - mechanical load handling
  - thermal conduction
  - thermal inertia
  - radiation shielding
  - $\Sigma$: lighter than dedicated subsystems!
- battery removable,
- separation mechanism exchangeable
- eases integration & reduces launch delay and launcher change impact
Out of the Box

**Cubesat Style**
- small team
- intense cross-training
- immediate communication
- single-site design, production, testing

**Envisat Style**
- large team
- highly specialized
- hierarchical communication
- many partners, distant sites, procedures
Synthesis

- design environment outlined by external as well as self-imposed constraints
- iterative evolution of the design solution towards full utilization of the design space
- strict application of structured requirements engineering within each iteration
- continuous budgeting of all resources using well-defined margin philosophy
- cyclic redefinition of the baseline design on all requirements levels by constraints
- baseline synchronized in regular concurrent engineering facility (CEF) sessions
the /SSB kit – a menu of options on unit level and subsystem level
options of dissimilar maturity can be combined in similar system
1st iteration in parallel CEF studies: current AsteroidFinder/SSB baseline
evolution of a payload-requirements-driven solution in ~1 CEF week
**Tech Progress & What a Difference the Way makes…**

<table>
<thead>
<tr>
<th><strong>Spacecraft C</strong></th>
<th>1996…2006 : 2007…2013 –</th>
<th><strong>Spacecraft A</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>14.5 mag @ SNR 1000:1</td>
<td>limiting magnitude @ SNR</td>
<td>18.5 mag @ SNR 3:1</td>
</tr>
<tr>
<td>2°.7 · 3°.05</td>
<td>Field of View</td>
<td>(2°)²</td>
</tr>
<tr>
<td>Ø27 cm</td>
<td>telescope aperture</td>
<td>22.8 · 23.0 cm², f/3.4</td>
</tr>
<tr>
<td>590 cm² (off-axis afocal)</td>
<td>telescope collecting area</td>
<td>474 cm² (Cook TMA)</td>
</tr>
<tr>
<td>4 CCDs 2048², (13.5µm)² pixel</td>
<td>focal plane array</td>
<td>4 EMCCDs 1024², (13µm)² pixel</td>
</tr>
<tr>
<td>2.32“/pixel</td>
<td>plate scale / IFOV</td>
<td>3.5“/pixel</td>
</tr>
<tr>
<td>-40°C</td>
<td>sensor operating temperature</td>
<td>-80°C</td>
</tr>
<tr>
<td>16“</td>
<td>pointing stability</td>
<td>100“</td>
</tr>
<tr>
<td>0“.5 (0“.15 rms)</td>
<td>payload-augmented stability</td>
<td>7“.5 /s (3σ)</td>
</tr>
<tr>
<td>4 .. 5 / year</td>
<td>fields visited</td>
<td>720 / day</td>
</tr>
<tr>
<td>2 GBit (EOL)</td>
<td>on-board storage</td>
<td>256 GBit (redundant)</td>
</tr>
<tr>
<td>1.5 Gbit/day</td>
<td>data transmission rate</td>
<td>224 Gbit/day</td>
</tr>
<tr>
<td>626 kg</td>
<td>satellite mass</td>
<td>180 kg</td>
</tr>
<tr>
<td>300 kg</td>
<td>payload mass</td>
<td>30 kg</td>
</tr>
<tr>
<td>4.10 m tall, Ø1.984 m</td>
<td>spacecraft size (launch)</td>
<td>1.00 m tall, □ (0.8 m)²</td>
</tr>
<tr>
<td>900 km, i = 90°</td>
<td>orbital altitude &amp; inclination</td>
<td>650…850 km, i ~ 98°</td>
</tr>
<tr>
<td>2 ½ years</td>
<td>design lifetime</td>
<td>2 years</td>
</tr>
</tbody>
</table>
… To Scale
Questions?

Asteroid 101: The Devil is in the Details

…named after the Ancient Egyptian Uncreator who dwells in the eternal darkness of the underworld. A close Earth flyby on Fri 13 Apr 2029 below geostationary altitude will gravity-assist Apophis for anything between a ~0.1 AU miss and a dead centre Earth impact on 13 Apr 2036, at 2.2E-5 estimated probability. Apophis spends most of its time inside the Earth’s orbit.
Small satellites for big science: challenges of high-density design in AsteroidFinder/SSB

**Asteroid 101: Space is not Unlimited**

- stars and nebulae form a distant diffuse background at any resolution ("Billions and Billions")
- interplanetary dust forms a local background that moves around the Sun (Zodiacal light, Lunar L4/5 dust clouds)
- the corona forms a variable background centered on the Sun, even beyond the area out to 32 solar radii covered by SOHO LASCO C-3

On camera, at any given pixel scale,…

…diffuse background, stellar background, or a passing asteroid may…  …READ EXACTLY THE SAME

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*background image: GRB990123 by HST STIS, cropped to (3".2)² FOV, 0".05 detector pixel, 0".025 drizzled — Difference Feb'99-Feb'00 — Feb'99 – Mar'99
HST FOC in hi-res mode: (3".6)² full FOV – VLT UT4 SINFONI in hi-res mode: (0".8)² full FOV*
Asteroid 101: $\Delta v$

IEO in 0.983 AU circular orbit

IEO in 0.005…0.983 AU elliptical orbit

Earth in 0.983…1.017 AU elliptical orbit with satellite in 650…850 km SSO

3.0 km/s
30.0 km/s
29.8 $\pm$ 0.5 km/s
$\pm$ 7.5 km/s

stellar background $\sim 1^\circ$/day
Asteroid 101: Δv projected

- Zero relative velocities and angular rates are possible, with a few to a few hundred arcseconds/minute being typical

- Impossible to catch all at any time

heliocentric velocity of the satellite = Earth's heliocentric velocity + SSO geocentric velocity

Range of heliocentric IEO velocity vectors

1°/day
Asteroid 101: IEOs, NEOs, Mitigation

FAQ resources

- Gerhard Hahn, DLR EARN asteroid database: http://earn.dlr.de/nea/ (provides population graph in slide #2)
- NEODyS Near Earth Objects Dynamic Site: http://newton.dm.unipi.it/cgi-bin/neodys/neoid
- David Vokrouhlický, Paolo Farinella and William F. Bottke, Jr.; The Depletion of the Putative Vulcanoid Population via the Yarkovsky Effect, Icarus Volume 148, Issue 1, Nov. 2000, p. 147-152 (google by title)
- Patrick Michel, Vincenzo Zappalà, Alberto Cellino, Paolo Tanga; Estimated Abundance of Atens and Asteroids Evolving on Orbits between Earth and Sun, Icarus Volume 143, Issue 2, Feb. 2000, p. 421-424 (google b.t.)
- Tunguska Home Page, University of Bologna: http://www-th.bo.infn.it/tunguska/ → Publications
- John S. Lewis, Rain of Iron and Ice, Addison-Wesley, 1997 (extended paperback ed.)
- Chrisian Gritzner, Kometen und Asteroiden – Bedrohung aus dem All, Aviatic Verlag (1999)