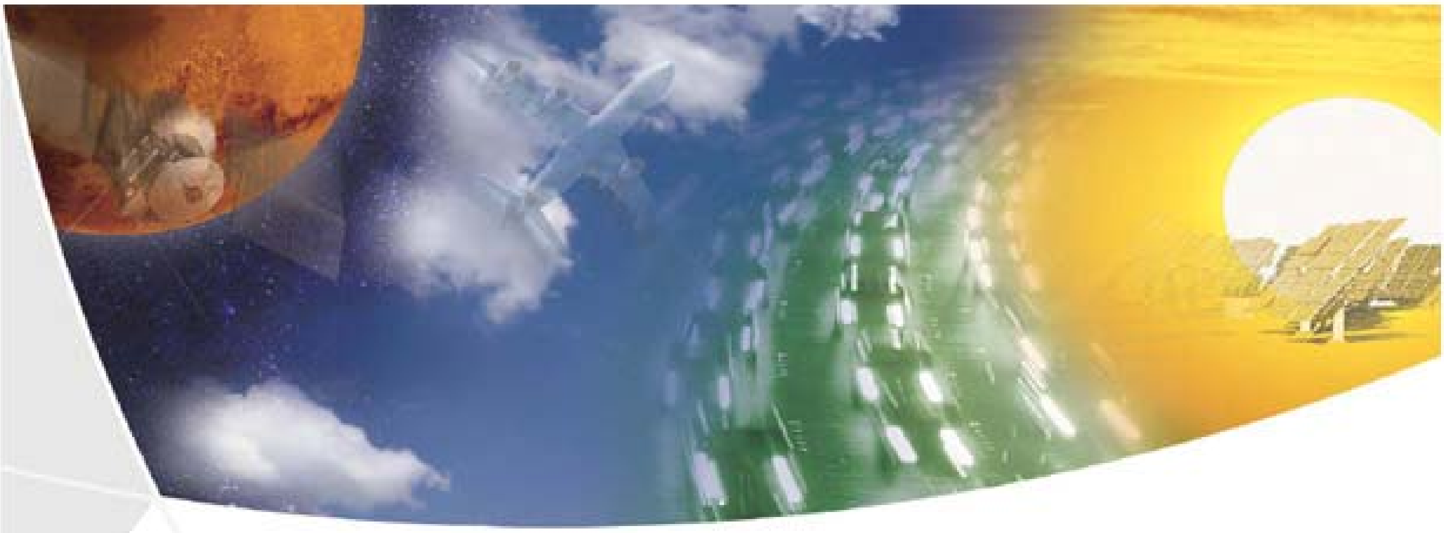

Study

"**Affordable Space Missions**"

Executive Summary

DLR

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Contents

1. Introduction

The study „Affordable Space Missions" (ASM) started with the kick-off meeting on October 13/2004 and was finished with the final presentation on August 16/2005. Its goal is the investigation of the cost reduction problem for micro-satellite missions. The starting point was the question "How can we reduce micro-satellite costs by one order of magnitude at constant performance".

Foundations for that investigation are the experiences with the successful micro-satellite project BIRD [1] of the German Aerospace Center (DLR), the literature ([2]-[5], the conferences ESA 4S Symposium: Small Satellites, Systems and Services (La Rochelle, 2004) and 5th IAA Symposium on Small Satellites for Earth Observation (Berlin, 2005), and a visit at AMSAT in Marburg/Germany (2005).

Because the funding was limited the study was concentrated on some general considerations and on the "Technologie-Erprobungs-Träger" (TET), a BIRD derivative, in the "On-Orbit Technology Verification" (OOV) program of the Space Agency of DLR.

The work was organized as a small project (see the Work Breakdown Structure, Appendix 1) with the four pillars System & Mission, Space Segment, Ground Segment, and Tests & Quality Assurance, which are presented in chapters 3 – 6, whereas in chapter 2 general low cost principles will be discussed.

2. General Considerations

Low cost principles for space missions already have been formulated in the past (see e.g. [2] – [4]). Some of these principles are shortly presented here again in order to show the possibilities left for cost reduction in the OOV-program and the road to the originally addressed one-order-of-magnitude reductions.

Apart from textbooks such as [2] and low cost studies ([3] and forerunners) much can be learned from the NASA program "Faster, Better, Cheaper" (FBC) and from the AMSAT approach. Some of the NASA problems (see [4]) are also problems of DLR and should be prevented in the future. Although the very successful approach of AMSAT is not applicable to DLR as a whole some methods applied there are of interest. They will be addressed shortly in the following and, more detailed, in chapter 3.

The low cost principles which will be addressed here refer to the fields of staff, systems engineering, politics/programmatics, technology, and miscellaneous. It will also be shown in which fields cost reduction must not happen.

2.1. Staff

To develop micro-satellite technology cost efficiently a small and motivated team of specialists is necessary. In case that this team works inside a big space center (such as NASA or DLR) the team and especially its leader needs far-reaching competences to allow fast decisions. If the work is done in a company, there must be a long-term contract to guarantee stability. To reduce cost the company should be small or medium sized. Big companies "burn" much money funding a big staff (often with very high wages) and big facilities.
A small team is good to minimize external interfaces and to have short ways (of course short ways lose importance because of increasing possibilities of electronic communications; AMSAT shows that). Unnecessary administrative burden must be avoided and the team should be given an incentive to reduce costs. Budget reduction after successful cost reductions is not motivating. The team should be small but not too small. A certain personal redundancy is necessary to prevent (expensive) time delays in case of illness or other reasons. Everything should be done to maintain the competence of the team. Brain drain from NASA off has led to severe consequences (e.g. reduced reliability leading to mission failures).

The employer or/and the funding agency should create an environment in which cost reduction is allowed and rewarded. This was not always the case in the past in NASA and other space centers. Very important is continuous funding. Piecewise funding leads to uncertainties and delays, which increase the overall costs. Important is also a basis of truth between the team and the administration. Otherwise, motivation is reduced leading to less working intensity.

The project leader must be given a high responsibility to decide alone after discussion in the team. External committees should only give advice!

It can be useful to include students and student assistants in the team because of personnel cost reduction. Of course, their work must be under supervision of experts which are the core of the team.

AMSAT relies on volunteer work which is one reason of the very low cost of AMSAT missions. But, of course, this approach is not applicable if contracts with customers have to be fulfilled.

2.2. Systems Engineering

From a cost reduction point of view it is useful to plan the complete mission, i. e. all phases of the live-cycle (conception, design, construction, manufacturing, tests, launch, operation, closure), or all missions of the same type from the very beginning as a *system*. The costs of the system must be considered and not the costs of the components alone. Minimization of the costs of one component (e. g. the launch) can lead to a severe enhancement of the costs of other components (which e. g. must be miniaturized).

There exist some cost models such as the Aerospace Corporation's Small Satellite Costing Model or TransCost for cost estimation of space transportation systems which can be used for preliminary, rough cost estimation. That gives a good foundation of a proposal and can be a guide in the process of cost considerations during the whole project.

"The main cost drivers are complexity and change" [2]. The more complex a system is the more faults can occur leading to higher costs. Therefore, it should be kept as simple as possible. Another point is modularity. Space-proven modules with standardized interfaces which can be used in more than one mission are a good basis for high reliability and low costs. The modules of a space bus should have certain margins of volume, power supply etc. giving the system a high flexibility. A variety of payloads can be adapted and later changes are alleviated (only absolutely necessary changes are allowed!). Only in that case standardizations are useful and feasible. Of course the margins lead to higher launch costs but the whole program becomes cheaper. Such an approach is not useful for unique missions where the complete mission should be optimized to solve one important (scientific) problem but it can be beneficial for operational missions (monitoring, communication networks, technology proving, servicing, …), and especially then when a series of satellites with similar objectives shall be launched.

To achieve low costs it is necessary that the customer accepts a certain risk. 95% reliability sometimes can be guaranteed for a low price but 99,9% can not. Again that cannot be expected for single important missions but for satellite networks or series or constellations of satellites it can. *„distribute risk by moving from single high-cost, long-development time missions to multiple low-cost, shorter development time missions"* [2]. Of course, the acceptance of a higher risk depends on the mission objectives. If only a low budget is available then the selection of adapted mission objectives is crucial. Then, science is not the mission driver, but the mission is driven by the budget. Often a mixture of both approaches is applied.

In systems engineering the role of software is increasing more and more. There are at least three aspects of that trend:

- The simulation of components, satellites and even complete missions is feasible or becomes feasible in near future. For instance, in thermal design existing thermal models allow to simulate the thermal behaviour of a micro-satellite with high precision. This is much cheaper than repeated experiments and tests during the development phase. In the thermal design area tests are needed more for the verification and improvement of thermal models than for hardware tests. The possibilities of simulation should be enhanced if one wants to reduce costs significantly. More generally, radical cost reduction relies on the use of high technology. Below this will be explained at another example again.
- Software reliability is crucial for the success of a mission, and this becomes true more and more with increasing complexity of missions. "*The study of the FBC failures does indicate that software failures, in particular their ability to tolerate "faults' during transient phenomena is one of the root causes of mission loss*" [4].
- The software vs. hardware approach: Sometimes expensive hardware can be substituted by cheaper hardware using error correcting or reducing software. An old example for that approach is the reduction of measurement errors provided by low-cost instruments using sophisticated estimation filters such as Kalman filters. Another example is the geometric correction of low-cost optics. Of course, that approach is not applicable universally; its applicability depends on the problem.

To be cost efficient, commercial tools should be used for software development. Software should be modular and re-usable.

Under the low-cost aspect the definition and analysis of the mission goals is very important. Often unrealistic goals are defined leading to high costs or even to non-feasibility. Needed is a priority list with primary and secondary mission goals. Then in case of exceeding the budget limit goals with low priority can be cancelled easier.

Furthermore, analysis of the requirements to the mission (which are derived to fulfil the mission goals) is necessary. "*Trading on requirements*" [2] is one of the most important means to reduce costs. Sometimes a minor reduction of the requirements can lead to a substantial cost reduction. As an example: It should be checked very carefully whether an instrument must have a good performance in a temperature range from -50° C to +50° C or not. The requirements must be fulfilled not as good as possible, but as good as necessary. In case of multiple mission objectives, one should choose such tasks which have similar requirements, if possible. If, for instance, there are ten experiments on a TET satellite and nine experiments need 20 watts each and only one experiment needs 200 watts then such a choice is counterproductive. In connection with the requirements it is also necessary to check carefully whether an orbit with high radiation doses can be avoided or not. Furthermore, the planned lifetime of the mission should be reduced as much as possible.

"The number of documents, meetings, analyses, tests, and reports determines the cost" [2]. What is needed are very few big meetings (such as critical design review) but more small ones inside the team. One should confine the number of documents to a necessary minimum. AMSAT has an ideal approach: Only one book per mission comprising the complete know-how which is necessary to repeat the mission. Email messages between team members also can be used as a part of the documentation. But no reports which no one reads!

One should not make use of big review boards which cost a lot of money. It is better to have close contact to few external experts whose messages are reliable.

Important are also well-kept in-house facilities such as space simulation and thermal chambers, shakers etc. They are needed very often during the development and manufacturing process and not only at the end to test the complete satellite. Cost-efficiency is only possible when such facilities exist and can be used always when they are needed. Of course, it is not cost-efficient to have every needed facility in house. Only facilities which are used often are meant here.

What is needed is a model-, redundancy- and test- philosophy which is well adapted to low-cost micro-satellite missions. The use of critical technologies should be avoided, and crucial hardware should be space qualified. Also crucial components/subsystems should have a redundancy. Of course, redundancy can be expensive and therefore AMSAT is doing without redundancy. But AMSAT has no external customers and can live with a higher risk. In most realistic cases a sophisticated redundancy concept is better. Components which are crucial for system failure should be used with a sufficient derating. Again, there must be a reasonable trade-off between costs and risk. Low-cost missions do not allow to apply many space-qualified or military standard (MIL) components. One can use such expensive components only for crucial subsystems. Otherwise, one has to rely on Commercial Of The Shelf components (COTS), which are sometimes very cheap. Especially, components which are used in (digital-electronic) consumer goods are applicable because they are tested millionfold. Of course, in most cases they have not to work under vacuum or radiation conditions. A special test program is necessary to space-qualify such components.

2.3. Technology

It is not always cost-efficient to use advanced technology. The newest technology which, of course, can be very powerful together with low volume and mass is often very expensive and sometimes not necessary to fulfil the mission objectives. Older space-proven components often can do the job with much lower price and risk. In most cases high technology is not space-qualified and not so robust as older "low-tech". The Soyus launchers demonstrate this convincingly. Of course, if it is otherwise not possible to fulfil the mission objectives old technology must be substituted by more powerful new technology. In the long term, radical cost reductions will become only possible if new technology with that goal is developed. An example: Remote sensing from space with 1m resolution or better needs telescopes with big focal length. Today such telescopes are big, heavy, and expensive and can only be operated on board of big and expensive satellites. Iconos and

Quickbird are examples with costs of more than 500 M$. If one would develop a light-weight foldable telescope with the possibility of on-board alignment than one could provide high resolution with a small satellite with substantial lower costs. But to do that a long-term technology program with the goal of radical cost reductions is needed.

Together with special technology developments (such as a foldable telescope) some other not so spectacular steps are necessary:

- Automation and autonomy on-board and on-ground reduces the ground station staff, but its implementation can also be very expensive. Therefore, a reasonable trade-off has to be found.
- On-board data processing with the goal to provide user-friendly data products in time directly from space is another promising field of research and development. User-friendly data products usually have a small data volume and need a low downlink bandwidth leading to a reduced telemetry system and a reduced ground segment. An example is the DLR FIRES project, the forerunner of the BIRD micro-satellite. In FIRES it was planned to evaluate detected fires and other high thermal events (HTE) such as volcanic eruptions on-board the satellite. The FIRES data product which is sufficient for the fire manager should contain only few HTE parameters (temperature, area, direction of propagation) together with time and coordinates. This is a very small amount of data which can be transmitted via cheap low frequency data links. Of course, the possibility for on-board processing depends on the mission objectives and is not always useful and feasible.
- Mission operations: Using standard interfaces, protocols, and procedures; re-using people, procedures, and software.
- Important is also the progress in software technology which was discussed already (section 2.2).
- If allowed by the mission objectives the satellite should be aligned to the sun direction all the time. Then only small batteries (or ideally no batteries) are needed. It is also helpful if sun-tracking and/or deployable arrays can be avoided. Of course, that is not often possible.
- In thermal design simple passive solutions should be used, if possible.

2.4. Administration / Miscellaneous

As it was already said in section 2.1 funding should be ensured until the mission end. This makes parallel work possible leading to a compressed schedule, and the team can be maintained better. Gaps in funding lead to delays which almost always result in a rise of costs.

It is necessary also to have decisive components and the system leadership in one hand. Other constructions lead to more interfaces and to a higher amount of interaction which costs money and creates error sources. Loss of competence at NASA seems to be responsible for some mission losses [4]. One should not imitate that.

The low-cost philosophy must be accepted by the administration. To pass the buck to the developers in case of failure is not fair. Joint efforts of administration and developing team are needed from the very beginning to the end of a low-cost mission. Otherwise the developing team will try to lower the risk and demand more money.

An efficient procurement scheme is necessary. When components cannot be delivered in time than the time schedule will be violated leading to higher costs. In particular, that means that the necessary components must be bought from reliable companies. Own development becomes necessary if that is not possible or too expensive. Especially, US government export licenses should be avoided.

It is useful to have the launch contract very early. Otherwise, time delays with higher costs can arise. Big disadvantages can occur when the launcher must be changed in a late state of development because then the satellite–launcher interface changes and special measures of adaptation become necessary.
The administration can also help to find sponsors and to establish cooperation agreements with universities (contributions from students, PhD students, post-docs etc.) or with space administrations of other countries. Of course, cooperation increases the number of interfaces leading to higher total costs, but the costs for each partner can be lowered considerably.

Existing infrastructure (test facilities, laboratories, ground station etc.) of the system leader should be used multiply because external use is more expensive in most cases.

It is crucial to optimize the time schedule. A too long schedule means more money but a too short one can also lead to more costs if time pressure causes more errors leading to re-design. Marginal system improvements should be avoided because they often lead to extensions of the schedule. Late changes of the design are prohibited at all.

"*To build or to buy that is the question*". Table 3.1-5 of [2] shows the advantages and drawbacks. One should check that very carefully to obtain a low-cost solution.

2.5. Where costs should not be reduced

Continuous research and development in the field of micro-satellite technology is needed to reduce the costs step by step maintaining good quality and low risk. That especially means that the R&D team needs good working conditions and should be strengthened in the course of time. The know-how of the team must be maintained by hiring young researchers in time. Furthermore, the team must be able to apply new technologies because only that way radical cost reductions become possible.

3. System & Mission

3.1. Preliminary Remarks

An important lesson learned from FBC was formulated in [4] as "managing and accepting risks" because extremely high assurance standards are a main cost driver. That principle has been applied also within the BIRD project as a typical low cost mission: *„Ein Projektziel war der Bau eines Satelliten, es einfacher und billiger zu realisieren als bei „ Groß "-Satelliten nach herkömmlichen Regeln der Raumfahrtindustrie. Ein höheres Risiko für den Missionserfolg wird dabei in Kauf genommen, wobei die Qualität durch extensive Redundanzstrategie und intensive Testphilosophie aufgefangen wird."* [10]
(*One of the project goals was a satellite to be constructed simpler and cheaper than big satellites which are constructed according to the traditional rules of the space industry. A higher risk for the success of the mission is taken into account, but a good quality is assured applying an extensive strategy of redundancy and an intensive test philosophy*).

Another lesson from FBC [4] also should be taken into account: "..*the time between missions must be short enough that careers span the complete life of more than a few missions. This process reduces risk and improves its efficiency due to increasing experience*". Long-time programs such as ORBCOM did put that into practice already. It should be hoped that the BIRD know-how can be transferred to the OOV program in a similar manner!

A further conclusion from FBC [4] is: *„The Aerospace Corporation report concluded that to achieve „faster" and „cheaper", the mission must give up „better" by reducing scope and science return on a per mission basis*"

Other solutions are possible too, but one cannot have faster, better, and cheaper together. In case of the BIRD payload it was decided for "better" taking into account higher costs as demonstrated in table 3.1. Choosing an infrared payload for the BIRD satellite the choice between a relatively cheep, but less sensitive Bolometer camera and the more expensive, but scientific more promising HSRS system was necessary.

	Bolometer camera	**Hot Spot Recognition Sensor (HSRS)**
Price	👍 200T$	👎 2M$
Demands to power, mass, volume	👍 low	👎 high (for micro-satellites)
Expenditure for development (man years)	👍 medium	👎 high
Technological risk 1995	👎 high	👍 medium
Scientific return	👎 low	👍 high

Table 3.1: Comparison of IR sensors

Without the decision for the HSRS system the usefulness and visibility of the BIRD project would have been extremely low. This example shows that one has to meet the requirements leading to a trade-off between faster, better, and cheaper.

3.2. Environmental Analysis / Benchmarking

In the following some micro-satellite missions are investigated to obtain direct comparisons with BIRD.

3.2.1. AMSAT

AMSAT is a worldwide group of Amateur Radio Operators who share an active interest in building, launching and then communicating with each other through non-commercial Amateur Radio satellites. It is a non-profit volunteer organization which designs, builds and operates experimental satellites and promotes space education [12]. It has constructed and launched worldwide more than 40 satellites successfully and is acknowledged as a very efficient organization from the low-cost point of view [2].

AMSAT-DL (Germany) states: „Die AMSAT-DL hat im Laufe ihrer über 30-jährigen Aktivitäten eigene Strategien und Arbeitsweisen entwickelt, um erfolgreich günstige Raumfahrtprojekte auf überwiegend ehrenamtlicher Basis durchführen zu können.“ [11] (During more than 30 years of activities AMSAT Germany has developed strategies and methods of operation to carry out low cost missions successively on a predominantly honorary basis).

That approach of volunteer work makes it difficult to compare costs of AMSAT and other missions and especially with BIRD and successors. Even the real costs for the materials are difficulty to estimate, because a part of them are private donations. Furthermore it has to be considered, that the requirements to the spacecraft caused by an AMSAT payload are quite different from those of a mission like BIRD.

„Die AMSAT-DL hat sich neben dem Bau und Betrieb von Satelliten besonders der gemeinnützigen Forschung und Entwicklung in Nachrichten- und Raumfahrttechnik sowie der Förderung des Technikverständnisses junger Menschen verschrieben“ [11].
(Besides the construction and manufacturing of satellites AMSAT promotes non-profit research, the development of communications engineering and space technology, and the technical understanding of young people).

This is a point, not considered sufficiently within the BIRD Project and the subordinated activities. Up to now the DLR did not succeed to sign a long-dated co-operation agreement with the Technical University of Berlin which would allow a continuous involvement of students.. OOV should use that possibility better.

„Entwurf, Aufbau und Betrieb der Projekte erfolgen von Anfang bis Ende quasi aus einer Hand: Benutzer, Entwickler und Betreiber der Satelliten bilden in der Regel eine gemeinsame Organisation.“ [11]
(Design, manufacturing, and operation of projects should be in one hand from the beginning up to the end. Users, developers, and operators of the satellites as a rule should belong to a common organization).

This basic principle was fulfilled in the BIRD project and was a guarantor to overcome all difficulties.

„AMSAT-DL- Projekte folgen weitestgehend dem "Open-Source"- Prinzip, jeder kann ein qualifiziertes Subsystem oder Experiment beisteuern, wenn es die Missionsziele voranbringt und vom Kernteam des Projekts akzeptiert wurde“ [11]
(AMSAT projects are open-source projects. Everyone can contribute a qualified subsystem or experiment if it promotes the mission goals and if it is accepted by the core team of the project).
This principle is connected to the honorary work approach and therefore is not applicable generally, and especially not for OOV.

An essential reason for its low cost products compared to commercial space projects AMSAT sees in the consequent usage of COTS [11].

BIRD, in a large scale, uses COTS too, and the possible use of COTS now is investigated by nearly all space agencies. In the Statement of Work of the currently running ESA project BIRD TECH is written: "*the BIRD mission has implemented new approaches in on-board processing technologies based on COTS*".

Other AMSAT statements to COTS:

- Complete mission consideration instead of component-wise approach
- Margins and back-up systems instead of redundancy
- Acceptance of higher risk
- Use of existing infrastructures and tools
- Use of mass-produced components instead of selected space proven components
- Own space qualification

Apart from redundancy, in the BIRD project all these principles have been applied too. Higher reliability requirements have led to another redundancy concept.

Apart from successful technological recipes AMSAT-DL also has defined own standards for complete missions, and especially has created the integrated mission teams [11]:

- The mission teams are small, concentrated, and interactive
- The core team is responsible for the most important mission elements
- The co-workers join the team early and stay with the project at least until the start of the commissioning phase
- There is an end-to-end mission development and management
- There are no barriers between the satellite people and the payload people

BIRD has used the same cost-efficient approach, and it is hoped that OOV will use it too.

3.2.2. ORBCOMM

ORBCOMM is a wireless telecommunications company that provides reliable, cost effective data communications services to customers around the world through its unique low-earth orbit (LEO) satellite network and global ground infrastructure. A diverse customer base uses ORBCOMM services to track, monitor and share information between mobile and fixed assets around the world. ORBCOMM data communications services are used by customers to track mobile assets including trucks, containers, barges, fishing vessels, locomotives and heavy machinery; to monitor fixed assets including pipelines, oil wells, energy meters, and storage tanks; and, to share information through data messaging services.

The network operates with 35 Microstar satellites which utilise the VHF band for communication with subscriber communicators. The Gateway Earth Station (GES) and Gateway Control Centre (GCC) act as the interface between the subscriber communicator, the satellites and the recipient by routing messages and data accordingly [13].

The ORBCOMM system has the following technical data [14]:

- Tracking solar arrays: 200 W peak
- Weight < 38kg
- budget < 130M$ (35 satellites) or 3,7 M$/satellite or 0,097 M$/kg satellite

To compare: BIRD parameters:

- Peak Power: 200W
- Weight: 94kg
- Costs up to 2001 (including launch and IR payload): 16M€ or 0,17 M€/kg satellite

3.2.3. Surrey Satellite Technology Limited

"Surrey Satellite Technology Limited is an enterprise company formed in 1985 by the University of Surrey to commercialise the results of its innovative small satellite engineering research. SSTL was the first professional organisation to offer low-cost small satellites with rapid response employing advanced terrestrial technologies". [15]

"The Disaster Monitoring Constellation (DMC) is the first earth observation constellation of 5-7 low cost small satellites providing daily images for applications including global disaster monitoring". [15]

Da Silva [14] gives cost estimations for some approximate satellite including launch costs (Table 3.2) for typical missions. There are assumed 8M US$ per satellite and 10M US$ per launch as fixed costs for comparison. The Payload is not included, but SSTL is investigating a low cost payload, for instance a

Bolometer camera for fire monitoring. This approach is criticised by different specialists.

Coverage	Revisit Time	Costs (mUSD)
Global	Daily	50
Global	3 hours	150
Global	1 hour	350
Global	20 mins	1000
Regional (600km Swath)	20 mins	360
Regional (2 x 600km Swath)	20 mins	520
Regional (600km Swath)*	20 mins	250

*Assuming enhanced propulsive capability, allowing 3 satellites to share each launch (see later in paper)

Table 3.2: Cost estimation for typical missions

That cost estimation is a little bit problematical because the costs for a launch are determined by the requirements of coverage. But one can compare the 8M$ per satellite with the estimated 6,9M€ for a BIRD duplicate (see below).

3.2.4. Myriade

“MYRIADE is the name of the CNES (french space agency) micro-satellite Line of Product which development started in 1998.
It was an answer to the scientific, application or technological missions needs, and also the opportunity to promote international cooperation, technical or technological innovation, new management techniques, new organisations …
MYRIADE has several objectives:
- provide <u>low</u> mission <u>cost</u> including launch
- provide <u>short</u> development <u>time</u>
- provide possibility to launch 2 missions/ year
- provide <u>high performances</u> together with great flexibility

The MYRIADE system is a multi-missions system, with a common ground segment and a specific flight segment for each mission.
This decision was an answer to the needs, mainly from the scientific community, to have low cost and quick access to space missions.
The recurring costs are also attractive, due to the series effect, the multi-missions ground segment and the launch philosophy.” (B. Tatry, [14])

MYRIADE is a strategic long term program which uses essential methods of cost reduction. With OOV Germany could make a first step into the same direction, of course with more modest goals.

A typical price for the DEMETER satellites of the MYRIADE program is 8M$ (without payload and launch) which is equivalent to DMC price of SSTL.

3.2.5. Small Satellites of German Universities

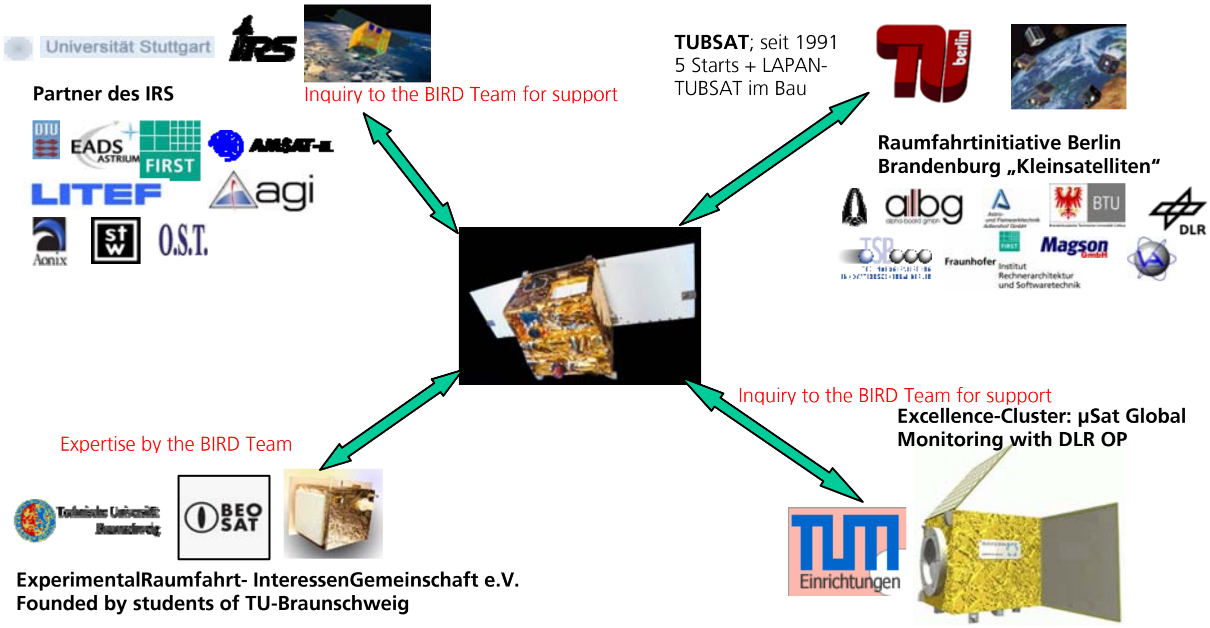

Fig. 3.1: Small satellite activities at German universities

Figure 3.1 shows the most important micro-satellite activities of German universities. Most of those teams want to use the BIRD know-how, and the connections between the teams are co-ordinated by the BIRD team. There is no higher level co-ordination by DLR. This is a deficiency with regard to the possible use of students and PhD students within related DLR projects.

3.2.6. Comparison of Specific Costs

Here and in the following sections costs of various satellites are given. It is obvious that big satellites are more expensive than smaller ones. Therefore, it is reasonable to use a specific price (M€ per satellite mass): For a comparison see Table 3.3:

Satellite	Specific costs M€/kg_satellite
ORBCOMM GLOBAL DATA & MESSAGING	0,10
SURREY SATELLITE TECHNOLOGY LTD	0,18
cnes	0,18
DLR BIRD	0,17

Table 3.3: Specific prices for micro-satellites

It can be seen that the currently flying BIRD is already cost efficient. The BIRD cost analysis (see below) shows that the envisaged duplication of BIRD for OOV will reduce the costs further.

3.2.7. On-Orbit Technology Verification (OOV)

Within the new DLR program OOV the launch of two satellites (TET) in 2008 and 2010 is planned. Their goal is the test of new developed space technologies. Now there are 60 needs for space-borne tests from 29 institutions (17 companies, 8 universities, 4 institutes). The Technology Test Carriers (Technologie-Erprobungs-Träger, TET) shall be developed in Germany on the basis of existing know-how, i.e. using a space verified platform. From reasons of costs and flexibility the class of micro- or mini-satellites is envisaged (total mass 100-150 kg, payload capacity 40-60 kg). In the first period 2005-2010 the TET 's will have a payload capacity of 40 kg with an one year verification period in LEO. DLR will contribute substantially to that program [16].

In contrast to MYRIADE the OOV program is limited to pure technological problems with a much smaller number of planned satellites. It was shown in a TET study [20] that a BIRD derivative is well suited.

3.3. Cost Estimation

3.3.1. BIRD Cost Analysis

To have an estimation for the OOV costs a BIRD cost analysis is useful (see Table 3.4).

Projekt BIRD:						
Man years (MY)	until	2001		107,0 MY		launch
		2002		14,5 MY		
		2003		10,6 MY		
		SUM		**132,1 MY**		
Material resources (MA)	until	2001		6,0 Mio €		launch
		2002		0,25 Mio €		
		2003		0,025 Mio €		
		SUM		**6,3 Mio €**		
Full cost (FC)						
	=	**19,4 Mio €**				

Table 3.4: BIRD cost analysis

3.3.2. Cost Estimation for Duplication of BIRD Satellite Bus

Table 3.5 gives an overview of the estimated costs for BIRD duplication:

	MA [k€]	**MY**	**MY [k€]**	**MA +MY [k€]**
Subsystems	2290	24	2928	5218
AIV & Tests	180	7	854	1034
Management	30	5	610	640
Satellite	2500	36	4392	6892
Reserve	400	4	488	888
Launch & Campaign	1200	1	122	1322
Total sum [k€]	**4100**	**41**	**5002**	**9102**

Table 3.5: Cost estimation for duplication of BIRD satellite bus

Table 3.6 analyses the cost structure of the satellite subsystem.

Components	**MA [k€]**	**MY**	**MY [in k€]**	**Total costs**
ACS & ONS	900	8	976	1876
On-board computer	240	5	610	850
TT&C	220	2	244	464
Power system	350	2	244	594
TCS	260	2	244	504
Structure & Mech.	320	5	610	930
Subsystem	**2290**	**24**	**2928**	**5218**

Table 3.6: Subsystem costs

3.4. Launching

The costs for launching depend very much on the chosen orbit. Up to now micro-satellites typically operate in LEO which is considered here. The launch option which is favoured from a costs point of view is piggy-back launch. A rule of thumb for piggy-back launch is 10-15 K€/kg. An example: Kosmos 3M (0.5 to 1.5M$) confirms the rule of thumb for a satellite of kg 100 [3].

BIRD, piggy-back launched from Shar (India) with PSLV-C3, is in the lower part of the price segment.

To compare these prices with those of a launch of a main payload the prices/kg for main satellites are given in table 3.7:

Launcher	LEO Payload	Launch Price	Price/kg US$
Ariane 5	18,000 kg	US $120 M	6667
Atlas IIA	3,066 kg	US $75 - $90 M	29354
Delta 7320	2,867 kg	US $40 M	13951
Dnepr 1	4,500 kg	US $10-13 M	2888
Rockot	1,850 kg	US $10-13 M	7027
GSLV	5,000 kg	US $35 - $45 M	9000
Kosmos 3M	1500 kg	US $12 M	8000
Pegasus XL	440 kg	US $14 M	31818
Proton D-1	20,860 kg	US $80 - $90 M	4314
Soyuz	7,000 kg	US $35 M	5000
Start - 1	632 kg	US $9 M	14240
Zenit 2	13,740 kg	US $60 M	4366

Table 3.7: Prices for main satellites

One can see that often the specific prices for main satellites are lower than for those which are piggy-back launched because of the higher co-ordination affords for multiple loads.

The Table 3.8 gives an overview over available launchers [17]:

Launcher	Manufact. Country	Launch site	Inclination range	PL Mass	Per/apo/incl	Price	Price small payload
			degrees	LEO	km x km, deg.	M$	M$
Pegasus XL	USA	ETR CCAFS	28 - 50.	440	200x200, 28.5	12 - 15.	
		WTR VAFB	70 - 130.	190	800x800, 98.	12 - 15.	
		NASA Wallops Island	30 - 65.	330	600x600, 38	12 - 15.	
Shavit-1	Israel	Palmachim	142 -144	225	366x1400, 143.4	10/15.	
Volna (R-29)	Russia	Barents Sea		50	600x600, 70?		
SHTIL-2 (R-29)	Russia	Barents Sea		265	200x200, 70	0.5?	
Start 1	Russia	Plesetsk	63 - 98.5	500	407x407, 51.6	5/10.	
VLS 1	Brazil	Alcantara	2 - 100	380	200x200, 5	8	
Falcon 1	USA	WTR VAFB	72 - 110.	420	700x700, 98	6 + launch fees	
		ETR CCAFS	28 - 50.	670	200x200, 28.5	6 + launch fees	
Kosmos 3M	Russia	Plesetsk	66 - 98.5	780	800x800, 98	10/14.	0.25 (50 kg)
		Kapustin-Yar	48 - 51	1400	400x400, 51.8		
Rockot	Russia	Plesetsk	63 - 98.5	1000	800x800, 98.1	12/15.	
		Baikonur	51.8 -95.4	1830	200x200, 63.		
Vega	Europe	Kourou ELA1	5.7 - 98.	1500	700x700, 90.	20	
Angara 1.1	Russia	Plesetsk	66 - 98.5	1400	900x900, 90	10/15.	
		Baikonur	51.8 -95.4	2000	200x200, 63.		
Tsiklon 3	Ukraine	Baikonur	51.8 -95.5	4100	200x200, 66	20/25	
		Plesetsk	63 - 98.5				
Dniepr	Russia / Ukraine	Baikonur	51.8 -95.5	650	700x700, 97.8	10 - 20.	
PSLV	India	Sriharikota		1200	?x?, 98.	15/25	0.5 (100 kg)
Molnya	Russia	Baikonur	51.8 -95.5	1800	2000x38464, 51.6	30/40	
	Russia	Plesetsk	63 - 98.5				
Soyuz	Russia	Baikonur	51.8 -95.4	5900	400x400, 51.8	30/50	
	Russia	Plesetsk	63 - 98.5	4300	800x800, 98.5		

Launcher	Manufact. Country	Launch site	Inclination range	PL Mass	Per/apo/incl	Price	Price small payload
SoyuzST 2-1b	Russia	Kourou ELS	5.7 - 98.	4900	660x660, 98.1	35	
Zenit-2M	Russia / Ukraine	Baikonur	51.8 -95.5	8000	1000x1000, 98.8	50?	
Ariane 5	Europe	Kourou ELA3	5.7 - 98.	9500	800x800, 98.1	120	1? (ASAP5)
Ariane 5 ECB	Europe	Kourou ELA3	5.7 - 98.	22000	450x450, 51.6	130	

Table 3.8: Available launchers

4. Space Segment

4.1. Structural Concepts

To define the structure of a micro-satellite bus one has two possibilities: light weight construction basing on carbon fiber composites (CFC) or the classical aluminium structure. The decision depends on the payload requirements and the launch costs. Of course, CFC reduces the weight of the satellite leading to lower launch costs but it also has certain disadvantages.
First, one must consider the thermal problems: CFC structures have a small heat capacity and low heat conductance whereas aluminium structures have big heat capacity and good heat conductance. Therefore, using aluminium the temperature variations inside the satellite are smaller than for CFC which reduces the effort and the costs for the thermal control system.
Secondly, the relation between mass and volume of the satellite must be considered: The light weight panel construction based on CFC leads to separate boxes with big harness and low available space. One needs a bigger volume than for the classical aluminium structure. This can lead to piggy-back launch problems with possibly higher costs. The classical structure with a backplane is simple and compact but heavier. E.g. the costs of 5 kg more mass of the structure are compensated by simpler fabrication, thermal regime, assembly, and qualification.

LAPAN TUBSAT is a good example for such a simple solution.

Fig. 4.1 LAPAN TUBSAT

To obtain a cost efficient solution the TET satellite will use the BIRD bus (service segment and electronics segment) substantially unchanged. The elaborate construction of the payload platform (sandwich structure and heat pipe) which was necessary for the infrared payload but which is not necessary for the TET payloads will be substituted by a simpler structure.

4.2. Power Supply

For the solar arrays which usually provide the primary power two technologies can be used: HighEtaSilicon (BIRD) and GaAs (table 4.1).

Parameter	High Eta Si	GaAs
Wirkungsgrad	15,8 %	26,8 %
Preis	40 €	270 €

Table 4.1: Parameters of solar array technologies

The much better efficiency of GaAs is connected with a much higher price. If one does not need much power and one is not forced to unfold the solar arrays then, of course, HighEtaSi-technology is the best. In other cases one must obtain a trade-off, e.g. between the expensive GaAs material on one side and the cheap HighEtaSi material with larger area and, possibly, a needed (expensive) mechanism for unfolding. The decision is only possible if one knows the requirements of the payload.

For secondary power supply batteries are used. Nickel-Hydrogen and Lithium-Ion technologies are available with the following advantages and disadvantages:

- Nickel-Hydrogen: very robust, discharging and overcharging is allowed, low energy density (37 Wh/kg)
- Lithium-Ion: Much higher energy density (136 Wh/kg), but must be protected against discharging and overcharging

Therefore, at equal energy storage, a Lithium-Ion battery needs much less mass than a Nickel-Hydrogen battery. Otherwise, it is more expensive. Taking into account the mission objectives and the payload requirements a trade-off must be found which guarantees low costs and satisfies the requirements acceptably.

4.3. Thermal Control System (TCS)

The TCS is determined by the payload and the orbit. If the energy consumption is low or one has continuous solar illumination (e.g. in GEO) and continuous payload operation then a passive TCS is adequate. Discontinuities and high peak energy consumption require an active TCS. Passive TCS 's need better thermal models and more expensive tests but active TCS 's require many radiators, many heaters, much energy, and large solar arrays. That, in most cases, is more expensive.

4.4. Telemetry & Telecommand

The costs of the T&T system are determined by the payload. If the payload data have a small data rate (or small bandwidth) then one needs small on-board transmission power. As already mentioned above, on-board real-time data processing can be helpful to reduce the bandwidth (and the costs) substantially. The ground station effort depends on that problem too (see chapter 5).

4.5. Attitude Control

Again, the payload determines the costs. E.g. a satellite with a payload which requires only a sun-orientated spinning satellite is much cheaper than a three-axis stabilized satellite with high pointing accuracy. One can use intelligent on-board algorithms to reduce hardware costs and to reduce ground station operation.

4.6. On-Board Data Handling

Most micro-satellites (e.g. AMSAT, TUBSAT) have no OBDH system. It is only necessary if the payload and auxiliary systems generate substantial amounts of data whose processing, storage, and transmission need special facilities such as mass data memory, buffers etc.. According to the payload requirements, TET needs an OBDH system which is planned as a payload-supply-system. It can be adapted to the changing needs of various payloads (up to 15 different components) on-board the satellite and provides all necessary interfaces (power, commands, data storage, uplink, and downlink).

5. Ground Segment

5.1. General Definitions for Ground Segments

For cost efficient missions flexible, modular, and low cost technologies are required which are compiled in a Cost Effective Ground Architecture (CEGA).

A satellite Ground Segment is comprised of the following components [3}:

- Satellite communications, TT&C, locate & track satellite
- Satellite command and control
- Mission planning
- Data Processing
- Data Archive & Inventory
- Data Dissemination

Some theses:

- The efficiency of ground station operation can only be assessed in connection with the operated satellite, e.g. an automated ground station is only possible if the satellite supports that by own autonomous functions.
- The efficiency of multi-mission operation is obvious, if standards are used.
- Standards are not fixed but are updated from time to time. There may arise problems if COTS implementations are used because COTS often span only a certain subset of the whole permitted standard set.
- Standards are necessary pre-conditions for the automation of ground station operations.

NASA has changed its communication standards starting in 2002:
"*Today, the primary National Aeronautical Space Administration (NASA) ground data communications (Nascom) architecture is based on Nascom Internet Protocol (IP) transition data format and protocol. ….*
The working group concluded that Consultative Committee for Space Data Systems (CCSDS) Space Link Extension (SLE) transfer services has become the predominant internationally accepted standard for interoperability between ground data service and mission user facilities" [18].

Now SLE is the NASA standard but a COTS version (Impact2000 — CCSDS Processing System, [19]) is on the market already. That may result in further changes which are expensive but sometimes necessary to enhance the competitive ability of a ground station. But during a series of low-cost missions (as OOV for instance) the standard should not be changed.

5.2. Multi-Mission Operation Center

Multi-Mission Operation Centers have the following low-cost capabilities:

- The staff can be used for more than one project.
- Know-how transfer between projects is possible.
- The work of the operation team can be optimized (7 days at 24 hours operation).

- The sequence of mission operations can be optimized using a multi-mission planning tool.
- The same hardware (including redundancy) can be used for several missions.
- High reliability and efficiency because of long-term experiences.
- Flexible adaptation to special tasks or upgrades
- Frictionless integration of new missions
- The basis software can be used for several missions.
- Often antennas for several frequency channels can be used (Weilheim)
- International compatibility by using communication standards (Neustrelitz: SLE already implemented, Weilheim: SLE in preparation)

A multi-mission ground station can be used as a data archive too. The advantages and disadvantages of multi-mission ground stations are presented in Table 5.1:

	Dedicated ground station	**Multi-Mission ground station**
Advantages	• Standard or special solutions: it makes no difference • (real-time) data reception at the user (without data transfers) • Exact adaptation to the link-budget possible	• Operational • Redundancy available • High operational standard (operation team / experts available • Using standards only small mission preparation is necessary • Reliability and reserve available • Costs are carried by several missions
Disadvantages	• Must be provided by and funded by a single project • All running costs must be carried by the project	• Received data have to be transferred to the users
Summary	Suitable for users with very special requirements and/or without sufficient data connections	In total more inexpensive and reliable

Table 5.1: Comparison of ground station types

5.3. Mobile Ground Stations

In DLR the PC-based mobile ground station software "Intelligent Compact Control Center" (IC3) has been developed. With IC3 a mission team can create an own ground station using the antennas of big receiving facilities. Such a ground station has the following properties:

- Small, mobile, generic ground system for smallsat missions
- Low cost implementation by integrating and supplementing (non-commercial) off-the-shelf components resulting in a complete off-the-shelf product
- Low cost operation by on-ground automation
- Synergy with 'classical' GSOC by maximum compatibility
- Validated by the BIRD mission

Synergies of IC3 with theGerman Space Operations Center (GSOC) and the German Remote Sensing Data Center (Deutsches Fernerkundungs-Datenzentrum, DFD) are shown in Table 5.2:

GSOC/DFD	IC3
All services	Basic services
Focus on missions with high customization needs	Focus on small sat missions, off the shelf configurable
All mission phases	Focus on routine operations
Site bound	No site constraints
Can take over from IC3 in critical phases	Backup functions for GSOC
24/7 operations	8/5 operations or below

Table 5.2: Comparison of IC3 with GSOC/DFD facilities

In case of high data rates users at other sites should take into account that, compared with the DFD possibilities, long waiting periods have to be expected because of the transfer of big amounts of data. This can be avoided by on-board data processing to obtain user-friendly data products with small data volumes (see e.g. the BIRD on-board classification experiment). Then one can use even smaller receiving facilities (which e.g. resemble GPS receivers).

5.4. Ground Segment and OOV

For OOV it seems not necessary to develop new solutions for ground segments for the following reasons:

- The operation of BIRD using the multi-mission ground segments of GSOC and DFD was efficient and can be used for OOV with a few minor improvements.
- There are no applications visible which would necessitate new developments
- New approaches would be not compatible with the OOV time schedule and low-cost principles.

Of course, it would be interesting to validate new ground segments (such as an IC3 based segment) inside OOV.

5.5. Comparison of Operation Concepts

BIRD operation concept:

- Early integration of the operating team in the development of the satellite
- Elimination of activities which were identified as non necessary
- Reduction of events which need fast reaction of the operating team
- Extensive use of existing components and software
- Use of automated modules of the existing multi-mission segment
- Automatic generation of standard command sequences
- Manual input of changed sequences
- Internet real-time availability of housekeeping data

AMSAT operation concept:

- KISS concept: Keep It Simple and Stupid; acceptance of a higher risk
- Mobile and de-centralized operation by volunteers
- Standards of radio amateurs

Proteus/Myriade operation concept:

- Early involvement of operation team during development
- getting rid of activities that are "not proved as necessary"
- decrease number of events, where quick reaction is required
- reduce training
- share staff with other control centers

Experiences of the operation team: Significant cost reduction because of:

- Integrated design between on-board and ground part of the system
- Extensive reuse of existing components
- Basic architecture principles
- Automation to allow staff reduction
- Share of operations staff between several missions
- Operations workload limited to the "strict necessary"

Drawbacks: Management of parallel mission developments more difficult, difficult to bring new missions in-line with existing system.

It is obvious that these concepts resemble each other very much. It follows that the BIRD operation concept is a good basis for OOV because it is already very cost efficient.

6. Tests & Quality Assurance

6.1. Preliminary Remarks

During the integration & test phase waste of money during all other project phases becomes apparent. Often the integration & test phase is blamed for that. But it is wrong and dangerous for the costs of the mission. A label of a good microsatellite project is a good organized test program comprising all project phases. Of course, tests of the system are most significant but tests of the components are important too.

6.2. Basic principles of quality assurance for BIRD follower projects

The lessons learned from the BIRD project are: Quality assurance (QA) must be realistic, plausible, and designed to meet the requirements. The highest priority has "design to cost". All procedures must be controlled by qualified experts, and the standard methodology should be adapted to the mission requirements. Furthermore, formalization of QA and especially the amount of produced paper must be reduced. Instead, the engineers should maximize the exchange of knowledge and information and should pay attention to the work of the colleagues. The errors should already be found during the development phase! Baseline should be the application of COTS together with qualification activities (screening, burn-in, and conditioning) which are adapted to the mission requirements. "Highrel" components are only used in critical areas (e.g. payload data handling, on board computer), but they must be tested too. To test is better than to belief.

6.3. Model Philosophy

Basic statements and definitions can be found in the publications [7] and [8] of the European Corporation for Space Standardization (ECSS).

The model philosophy is developed iteratively taking into account the constraints which are imposed by mission requirements and limited funding. Important drivers are the requirements for verification from the project which can lead to different model philosophies. Learned from BIRD, for TET an adapted ProtoFlight Philosophy (PFPh) is proposed. A pure PFPh needs only one model, the so-called ProtoFlight Model (PFM), which is used after refurbishment as the Flight Model (FM) too.

To apply the PFPh for OOV/TET the following criteria should be fulfilled:

- No critical technologies are used
- Widely qualified technology is applied
- There is redundancy for vital components/subsystems
- Vital components are used with sufficient derating
- Certain compromises concerning the risks and costs are accepted
- Development, manufacturing, integration, and tests are done only with experts

If one meets these criteria then low costs can be achieved. The risks also can be kept low if the reliability management combines systems integration with the development of modules and components. Parts delivered by subcontractors must be checked and audited (with tests at all levels). During the BIRD project that procedure was enforced consistently and successfully.

If the TET satellites will be simple BIRD duplicates then the pure PFPh can be applied. When, however, new subsystems which influence the design significantly become necessary then an adapted 2½ model philosophy is recommended. Depending on the strength of violation of the BIRD qualification status the PFM should be upgraded from a Structural Thermal Model (STM) or an Engineering Model (EM). An additional Qualification Model (QM, ½ model) should be used for necessary qualification tests. QM of that kind has only to simulate all interfaces correctly.

6.4. Test Concepts

Test concepts must be adapted to the mission requirements. It has to be determined which tests are necessary for which level of integration. Sometimes, suitability tests can become necessary already for materials or electronic components. However, test concepts are discussed here only for assemblies of components. The following scheme (Table 6.1) which is BIRD-proven can be used as a guideline:

System/ Subsystem	Development Tests Space Qualification	Q-Level	PF-Level	A-Level	Remarks
Payload		(X)	X	System Test	Q-Level only if new development
Elektronic Segment	C	C	C	System Test	Redundant C only Q-Level and System Test
Structure	C	C	C	System Test	
Thermal Control System (TCS)		C	C	System Test	
Attitude Control	C	C	C	System Test	If space qualified only PF-Level
Telemetry & Telecommand System		C as system	C as system	System Test	
Power Supply & Distribution		C only if not space qualified	C	System Test	
Complete System			Complete System only if PF-Status not achieved	System Test	Vibration Test (only resonance and random) with force limitation

A: Acceptance, C: Assembly of Components, Q: Qualification, PF: Proto-Flight

Table 6.1: Test scheme

6.5. Assembly, Integration, and Test (AIV) Principles & Inspection Mechanisms

The following AIV recommendations can be given:

- Inspection of the design concerning usefulness, tolerance, derating, producibility, consistency with instructions and standards, interface compatibility down to the level of components

- Inspection at delivery of critical components
- Inspection during manufacturing (observance of procedures, instructions, quality demands, operating and environmental conditions)
- Inspection and acceptance of test procedures (system level)
- Inspection before performance tests and inspections of performance tests on lowest system level (usefulness, meaningfulness, observance of instructions, status of test tools)
- Checking test reports starting with subsystem level; checking and release of quality test reports
- Final acceptance / clearance on the basis of tests of the complete system

6.6. Reliability Management

The management of reliability contains three important elements:

- Agreement on or determination of a reliability goal
- Implementation of the goal into the product or into the process
- Verification and validation of acquired reliability

The reliability is defined as the probability that a product or a process fulfils its task during a certain mission time. For a population of uniform products it is calculated from experiences with that product or from a certain model of that product. Therefore, in a population with certain reliability (between 0 and 1) there exist better and worse samples. The reliability also exists for more complex systems such that a whole microsatellite because it comprises components with certain reliabilities. For the protoflight philosophy holds the following: The FM benefits from the tests with the pre-models, the better the higher the functionality of those models is. It is useful to construct and to test the STM concerning structure, mechanisms and thermal system as a FM. For the test of the electrical functions an EM should be used but without the other functions of a complete satellite.

When a certain state of development of a subsystem is obtained and the manufacturing is finished and it is realized that there might be an error then the reliability cannot be enhanced arbitrarily by replacement of components. The replacement can lead to new problems with sometimes even worse results. An example: In the final phase of the BIRD project the team was forced to exchange some capacitors which, according to ESA, had not that high reliability which is necessary for a space mission, although the capacitors had been tested and were operated with sufficient derating. Such a procedure leads to an enhancement of costs and risk and should be avoided. Therefore replacement of components shall be realized only on the principle that the functionality is imperilled seriously.
Reliability is a property of a component or subsystem but only during the interaction with other components/subsystems it turns out how long it works without failure. The Mean Time Between Failure (MTBF [h]) is a used measure for that. Another measure is the failure rate which gives the mean number of components which fail during unit time. Both reliability indicators cannot be measured or calculated exactly. They can only be estimated using the knowledge from the past.

The reliability goal (which must be defined by the project team) is related to the necessary or accepted level of risk or safety. Because cost effectiveness and safety are closely connected and the connection can be complex it is difficult to define a goal of reliability. It is a trade-off which must be elaborated thoroughly by the project team and the customer.

Efficient management is needed to implement the reliability goal. One needs comparisons of nominal and actual values in all phases of the life cycle, and especially at the start of the commissioning phase. Iterations may become necessary.

Because of the low-cost approach, in the development of BIRD components with MIL standard could be used only exceptionally. To obtain, in spite of that, a sufficient reliability the management connected the system engineering and developers of components and modules closely. Partial reliability goals were defined and given to the subcontractors and the adherence of the goals was audited carefully. Extensive tests on all levels of development have been done. The same successful procedure is recommended to OOV/TET.

To proof the reliability of a system one estimates the reliability of the different levels (component, subsystem, system) bottom up, i. e. starting at the component level. Not only the actual state must be found out, but also factors of influence and weak points must be identified. Suggestions for improvement and their consequences for the reliability have to be pointed out. Comparisons of nominal and actual values then give the possibility to improve the system iteratively. During the first phases of the life cycle (concept, design, construction) the proof of reliability is carried out analytically using generic data. When a prototype is available then tests are used to verify the estimation. During system operation specific test data give more detailed reliability results. It becomes obvious that the proof of reliability is a process with stepwise better results.

A modern reliability management should try to map the "real world" in a model which can be used to answer all questions arising during the process. The tools for such a mapping are described in a manual ([9]).

7. Conclusions

The study has shown that many of the low-cost principles published in the literature (see below) have already been successful applied in the BIRD mission. Compared with other satellites (ORBCOMM, SSTL, MYRIADE) BIRD has already good specific costs (0.17 M€/ kg satellite) which can be reduced further if BIRD is duplicated for TET by a small company in co-operation with DLR. Therefore, the OOV program can be accomplished efficiently. Furthermore, the planned TET satellites can be a basis for other German missions, e.g. in earth observation or deep space applications.
Of course, radical cost reductions (e.g. one order of magnitude) can only be achieved by a long-term technological program.

8. References

[1] http://www.dlr.de/os/forschung/projekte/bird

[2] J.R. Wertz, W.J. Larson; Reducing Space Mission Cost; Space Technology Library; Kluwer Academic Publishers, Dordrecht 1996

[3] Position Paper on Cost Effective Earth Observation Missions; International Academy of Astronautics (IAA), in preparation

[4] L.J. Paxton; "Faster, better, and cheaper" at NASA: Lessons learned in managing and accepting risk; IAA-paper IAC-04-IAA.X.X.X

[5] B. Tatry; MYRIADE micro-satellite Line of Product, CNES, 2003

[6] H. Jahn, K. Briess (eds.); FIRES pre-phase A study, DLR, Berlin, 1994

[7] ECSS-E-10-02A

[8] ECSS-E-10-03A

[9] /VDI 85/ Verein Deutscher Ingenieure
Handbuch Technische Zuverlässigkeit
VDI, Beuth Verlag Berlin, 1985

[10] TN-BIRD-1400-WP/125 , Qualitätssicherung, 19.06.2002

[11] http://www.go-mars.de/

[12] http://www.amsat.org/

[13] http://www.orbcomm.de/

[14] ESA 4S Symposium: Small Satellites, Systems and Services; La Rochelle, France, 2004

[15] http://www.sstl.co.uk

[16] C. Nitzschke: OOV-Programm; 22. Juli 2005, DLR, Bonn-Oberkassel

[17] Table compiled by M. Sippel (DLR)

[18] Larry Muzny; CCSDS SPACE LINK EXTENSION PROPOSAL FOR A NASA WIDE GROUND DATA SERVICE STANDARD, Nascom Block Phase Out Working Group, Lockheed Martin Space Operations, Consolidation Space Operations Contract (CSOC), 2002

[19] http://www.tw.l-3com.com/telemetry_west/products/impact.htm

[20] BIRD-TET-Anpassungen
Untersuchung der möglichen und notwendigen BIRD-TET-Anpassungen zur Vorbereitung der Auslegung einer notwendigen Verifikationsplattform für die Programmlinie OOV
Astro- und Feinwerktechnik Adlershof GmbH, February 2005

Appendix 1: Work Breakdown Structure