TUBSAT-N, an experimental global communication satellite system, based on nanosatellites

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Abstract: In the framework of the research project TUBSAT-N (Technical University of Berlin SATellite-Nano) it should be demonstrated, that it is possible to realise ultra low cost space access very quickly. The Technical University of Berlin has launched two Nanosatellites as a satellite cluster in July 1998 with a convertible Russian military SS-23 SHTIL Rocket from a submarine. Both satellites has been separated together from the payload capsule of the rocket. In orbit TUBSAT-N has received a telecommand from the ground station to separate the smaller satellite TUBSAT-N1 with its own pyrocutter. This project should prove that nanosatellite technology can be a good solution for a commercial ultra-low cost project. The total costs of both nanosatellites TUBSAT-N and TUBSAT-N1, including material, manpower and the costs for a double launch, was less than 350.000 US$ per satellite.

1. INTRODUCTION

The main objective of most space agencies in the mid/long term is to reduce the costs of access to space. It means reducing spacecraft costs by at least one order of magnitude, without reducing the performance. For that reason the number of mini- and microsatellites was growing up in the last years. The logically consistent developments are nanosatellites. Nanosatellites are spacecraft's with a mass of less than 10 kg. TUBSAT-N has a total mass of only 8.5 kg and the main dimension's 320x320x104 mm³.

Four independent communication channels, two in the 2 m frequency band and two in the 70 cm frequency band, are available. All communication channels use FFSK (Fast Frequency Shift Keying) modulation with baudrates of 1200 and 2400 baud. Alternatively the user has the choice to transmit the messages with or without forward error correction. An additional downlink transmitter with 9600 baud GMSK (Gaussian Minimum Shift Keying) modulation will be used to transmit the collected messages to the ground station. The smaller satellite TUBSAT-N1 has a total mass of less than 3 kg and the main dimension's 320x320x34 mm³. It has two independent communication channels in the 70cm frequency band. Like TUBSAT-N, TUBSAT-N1 uses the same

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transceivers with FFSK modulation and 1200/2400 baud.

Both satellites will be used for mobile communication. The main purposes are:

- bi-directional data transfer between autonomous environmental stations and the satellite, e.g. drifting buoys in the ocean, arctic and antarctic meteorological stations, etc.,
- tracking of medium-sized and large mammals,
- world-wide location and deactivation of stolen cars,
- ultra mobile communication.

The first experiments with these services were made very successfully with the microsatellite TUBSAT-A. The satellites TUBSAT-N and TUBSAT-N1 (Fig. 1) are the consistent development. The on-board memory increased from some Kbytes to some Mbytes, the baudrate, transmitting power and receiver sensitivity increased by a factor of two, whereas the power consumption decreased by the same factor and the total mass and the main dimensions decreased by a factor of four to ten.

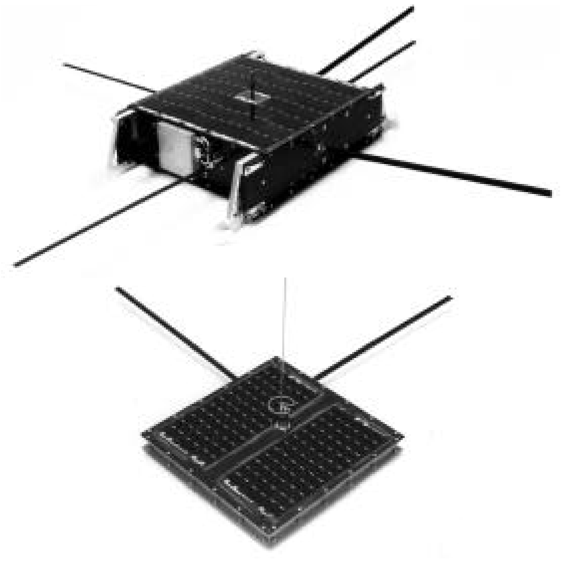

Fig. 1: TUBSAT-N (top) and TUBSAT-N1.

In addition to the mobile LEO satellite communication systems, which will use small satellites, there are several applications for micro- and nanosatellites for mobile communication. Especially the store-and-forward and the store-and-dump communication is very interesting for micro- and nanosatellites. Everybody who has time, relatively small data volume and restricted budget is a potential customer. Constellations of such nanosatellites for communication or Earth observation systems will increase the possibilities of access to space at lower cost for developing countries, industry, universities, environmental authorities, research departments and private persons. With a network of autonomous mobile or fixed environmental stations it will be better possible to foresee natural disasters, specially with meteorological, seismical and volcanical observation stations.

2. APPLICATION

A network of nanosatellites can be a good solution for special customers. In the following there are examples for three different applications for a nanosatellite communication system.

2.1 Satellite Telemetry on Red Deer

For that project, conducted from February to August 1995 [1] the spatial organisation of red deer in the northern German mountain range Harz was investigated using satellite telemetry. The respective locations of two males and one female were ascertained at regular intervals using a GPS receiver. These data were then transferred via the experimental microsatellite TUBSAT-A to the ground station in Berlin. The purpose of this study was twofold: to provide data on the size of the deer's home ranges and seasonal migrations in this area as well as to test the practical applicability of this technical advanced system for wildlife research purposes. The satellite telemetry proved to be a practical, ecologically sound, and cost effective method for investigating the spatial locations over time of red deer in difficult terrain. Figure 2 shows the satellite transceiver for TUBSAT-A with an integrating GPS receiver. The lifetime was one year with the integrated battery set.

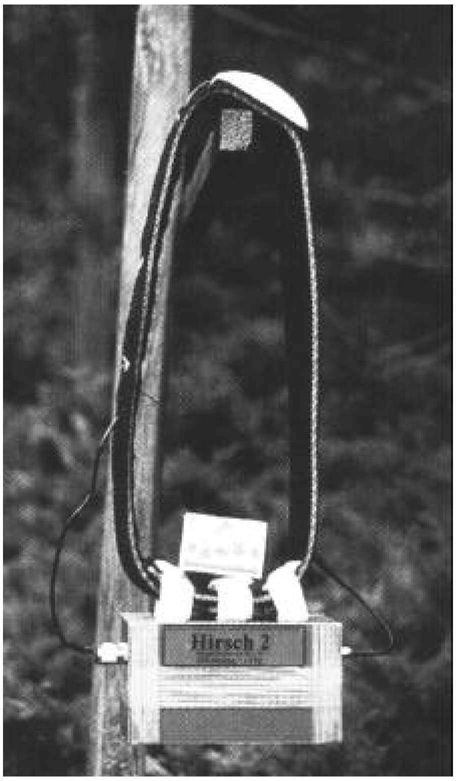

Fig. 2: TUBSAT-A Satellite transceiver with a 12 channel GPS receiver for deer tracking (in comparison with a matchbox).

2.2 Bi-directional Communication with Earth Environmental Observation Stations

The data exchange between observation stations and ground station is a predestine application for nanosatellites. The stations transmit the collected data to the satellites, whereas the satellite can transmit new commands from the ground station to the observation stations. Typical applications are buoys in the ocean (Fig. 3).

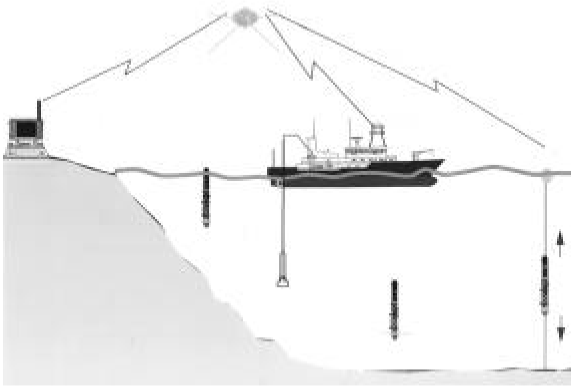

Fig. 3: Data exchange between ground station and Earth environmental observation stations (e.g. buoys) via TUBSAT-N.

2.3 Adventure Tourists

Another application for mobile communication are adventure tourists. The communication terminal should be lightweight and small. During the framework of TUBSAT-A, several small communication terminals for arctic and antarctic expedition, e.g. Weber/Malakhov, Icesail (A.Fuchs), have been developed (Fig. 4).

Fig. 4: Mobile TUBSAT-N communication terminal with integrated 12 channel GPS receiver.

3. GENERAL DESIGN PHILOSOPHY OF TUBSAT-N/N1

There are some general aspects in the design philosophy of Nanosatellites that will differ from the traditional policy.

- There is no physical separation between platform and payload.
- Subsystems are not independent and self contained.
- The model philosophy shall minimise the number of separate subsystems.
- All electronic components should be designed for the industrial temperature range from -40°C to +85°C.
- Components should have short delivery periods to minimise the costs.
- Extensive use of low power devices, but all electronic components should withstand a radiation of more than 20 kRad.

To minimise the costs, specially the operating costs, AOCS is not necessary, provided that the antenna radiation pattern is sufficiently omnidirectional to guarantee adequate link budget in any direction. More than 80% of the available communication time are below 30° of elevation angle at medium altitude for a polar LEO satellite. To avoid the path loss due to the ellipticity of the signal from the satellite with circularly polarised antennas, such as a canted turnstile antenna, two orthogonal linearly polarised antennas for each frequency band were used. Each pair of these orthogonal antennas will receive the signal from the mobile stations at the same time with independent receivers. The message from the satellite will transmit first over one antenna, than over the other orthogonal antenna. This communication concept is not very time efficient, but very robust in noisy environment. Usually linear polarised antennas like λ/4 antennas are ground sensitive and especially in the VHF frequency band nanosatellites do not have the size for a good groundplane. For that case a special matching unit has been developed to use these antennas as “radial-less“ antennas (ground insensitive).

4. ELECTRONIC DESIGN OF TUBSAT-N AND TUBSAT-N1

Due to the small size of nanosatellites there is only limited place for solar cells. For that reason it is extremely important to have electronic subsystems with low power consumption. A lot of low power semiconductors were radiation tested during the TUBSAT-N project, to find the best possible semiconductors for that project. Figure 5 shows examples of the radiation results for two Real Time Clocks. The RTC in Fig. 5a was the first choice in the beginning of the project. After the radiation test it was necessary to replace this RTC to another one (Fig. 5b).

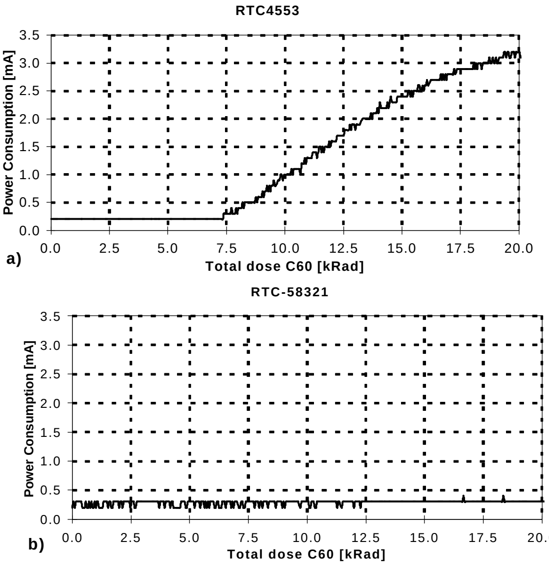

Fig. 5: Radiation test results for the RTC4553 (a) and the RTC58321 (b).

All power consumers have their own electronic fuse. In case of overcurrent the fuse will disconnect the consumer from the power bus in 2 µs with an accuracy of 1%. After 16 hours the consumer will be switched on again. An additional watchdog is implemented in this fuse, too. If the consumer does not trigger the fuse in regular intervals, the fuse will disconnect the consumer from the power bus again for 16 hours. A further detail is that the fuse will reset each 12 day the CPU from the communication unit.

Each device can communicate over the “Universal Communication Bus“ UCB with each other. Up to 255 devices are addressable. The radio protocol supports the UCB as well.

TUBSAT-N and N1 have solar cells on the top and on the bottom surface. The solar generator of TUBSAT-N consists of 34 serial cells on each side with the cell dimensions of 6 x 4 cm. The solar generator of TUBSAT-N1 consists of two parallel strings with 36 serial cells on each side with the cell dimensions of 4 x 2 cm. For the selection of batteries for nanosatellites it is very important to have a high energy density, low mass and high reliability. The battery string of TUBSAT-N consists of nine NiCd-cells from SANYO with a capacity of 5 Ah (KR-5000DEL), the battery string of TUBSAT-N1 consists of nine NiCd-cells from SANYO too, but with a capacity of 2,8 Ah (KR-2800CE). Both types of batteries were tested in orbit by the US Airforce.

The on-board electronics of TUBSAT-N are very modular and consist of the following main components:

- Electronic active fuse with integrated watchdog for each current consumer.
- Battery charging unit (BCU).
- TTC with integrated communication module 1 VHF, FFSK modulation, optional GMSK.
- TTC with integrated communication module 2 VHF, FFSK modulation, optional GMSK.
- TTC with integrated communication module 3 UHF, FFSK modulation, optional GMSK.

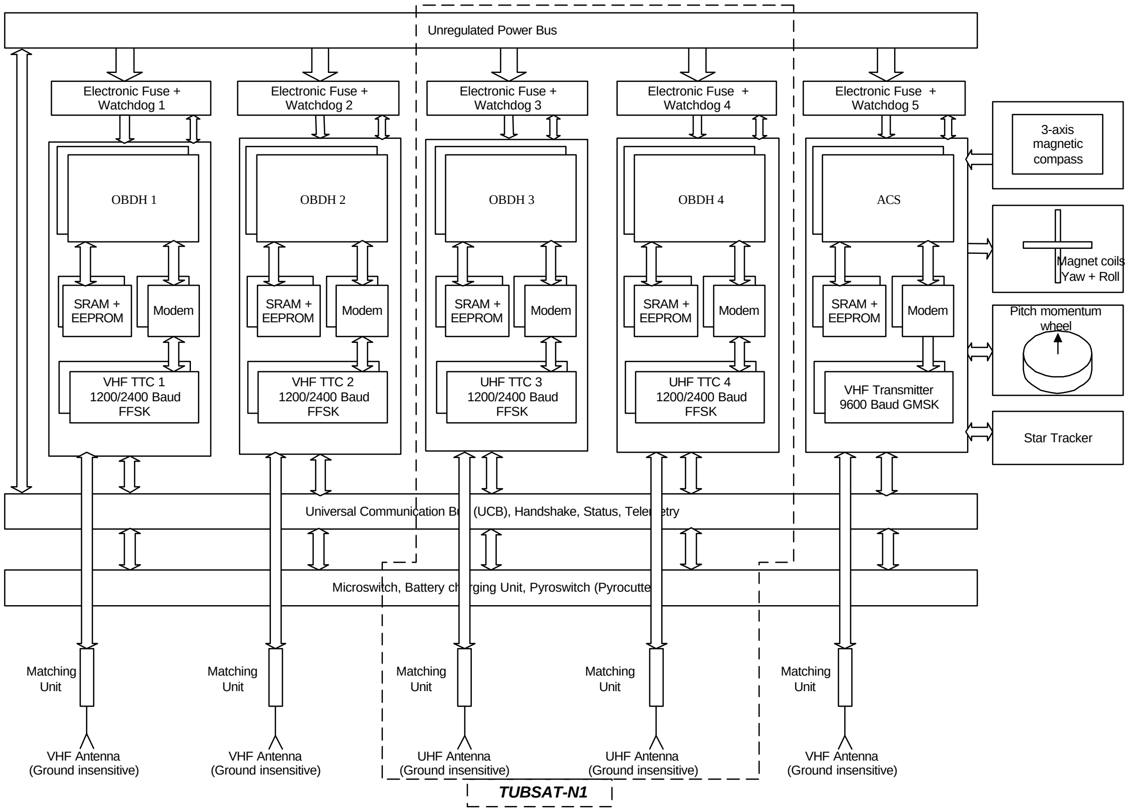

Fig. 6: Block diagram of the TUBSAT-N /N1 Bus.

- TTC with integrated communication module 4 UHF, FFSK modulation, optional GMSK.
- ACS with CCD star sensor, one reaction wheel, two magnetic coils, one three-dimensional magnetic compass and an additional 9600 Baud GMSK Transmitter.

TUBSAT-N1 consist of the following main components:

- Electronic active fuse with integrated watchdog for each current consumer.
- Battery charging unit (BCU).
- TTC with integrated communication module 1 UHF, FFSK modulation, optional GMSK.
- TTC with integrated communication module 2 UHF, FFSK modulation, optional GMSK.

The components of TUBSAT-N1 are exactly the same as of TUBSAT-N. Figure 6 gives an overview about the electronic design of TUBSAT-N and TUBSAT-N1.

To save space and electrical power, the TTC functions are implemented in the communication module. The main dimensions of the communication module are 8 x 16 x 2 cm³. The mass is less than 260 g. The Power consumption during receiving is less than 60 mA, during transmitting 1,5 A. In case that one or more modules will be have malfunctions, the other modules will take the communication service. Each communication module consists of:

- Electronic fuse with integrated watchdog.
- 16 Bit Hitachi H8/536 CPU.
- 512 Kbytes SRAM, 64 Kbytes ROM, 128 Kbytes EEPROM.
- Real Time Clock.
- 32 analogue Telemetry channels.
- FFSK (Fast Frequency Shift Keying) or GMSK (Gaussian Minimum Shift Keying) modulation.
- VHF or UHF Receiver with a sensitivity of better than -120dBm.
- VHF of UHF Transmitter, max. 10 Watt RF.

A detailed block diagram of the communication module is shown in Fig. 7.

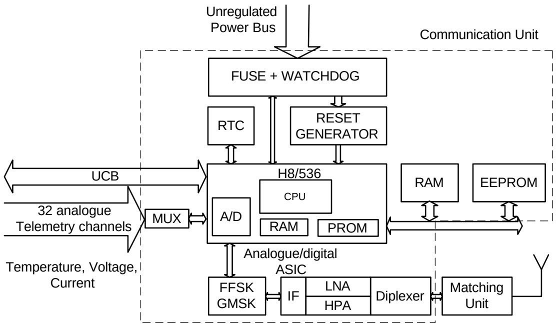

Fig. 7: Block diagram of the communication module.

5. MECHANICAL DESIGN OF TUBSAT-N AND TUBSAT-N1

The structure of both satellites is made out of carbon fibre. This design guarantees a lightweight, but very stiff structure. The solar generators are mounted on the upper and on the lower plate of each satellite. In case of TUBSAT-N, all components are screwed on the side walls (Fig. 8), in case of TUBSAT-N, all components are mounted on the lower carbon fibre plate (Fig. 9). The mass budget of both satellites is listed in table 1.

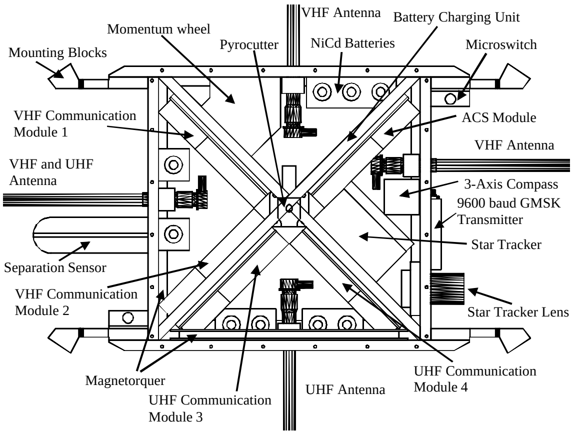

Fig. 8: Schematic view of TUBSAT-N with electronic components (view from top).

Table 1: Mass Budget of TUBSAT-N and TUBSAT-N1.

Components	TUBSAT-N	TUBSAT-N1
Structure, incl. Solar generator	2138	1179
Battery, incl. mounting blocks	1735	748
Communication modules	4x255=1020	2x255 = 510
Battery charging module	171	85
ACS CPU Module	247	
Star tracker	500	
3-Axis compass	96	
Momentum wheel	659	
Magnetorquer	335+377=732	
Pyrocutter	122	
9600 baud GMSK Transmitter	200	
Antennas with matching units	5x85= 425	2x85 = 170
Cables, screws, etc.	455	230
Total mass	8500 g	2922 g

The satellite design utilises passive thermal stabilisation to maintain the components within acceptable temperature limits. A 20 node thermal model was used to calculate the temperature of TUBSAT-N for an elliptical 750 x 400 km orbit (tumbling mode) [2]. The results of the calculated temperature ranges for a continuous dissipated power of 3 and 6 Watt and the real measured temperature values are displayed in Fig. 10.

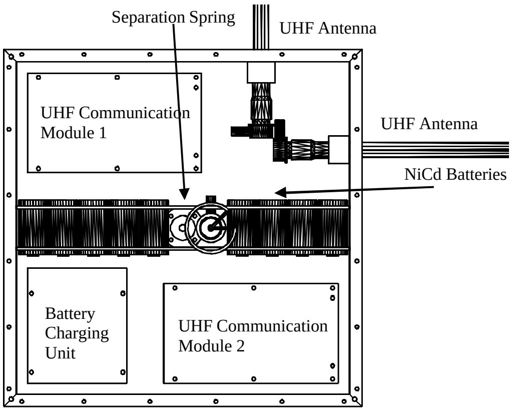

Fig. 9: Schematic view of TUBSAT-N1 with electronic components (view from top).

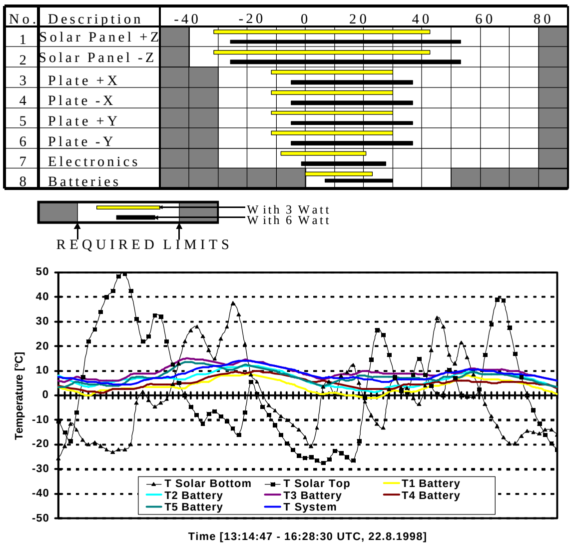

Fig. 10: Calculated temperature range for TUBSAT-N for an elliptical 750 x 400 km orbit (top) and real measured temperature values during two revolutions.

6. MOBILE COMMUNICATION UNITS

Each mobile communication terminal has the same main design. It consist of a 16 bit CPU, additional RAM, additional FLASH memory, Real Time Clock, high efficient (η=96%) DC/DC converter for the GPS receiver, FFSK or GMSK ASIC and an UHF/VHF transceiver, based on the YAESU chip sets. Several I/O pins, a serial communication interface and eight analogue channels make it possible to connect external devices, like LCD's, keyboards, measurement devices, etc. Figure 11 shows the block diagram of the mobile communication modules.

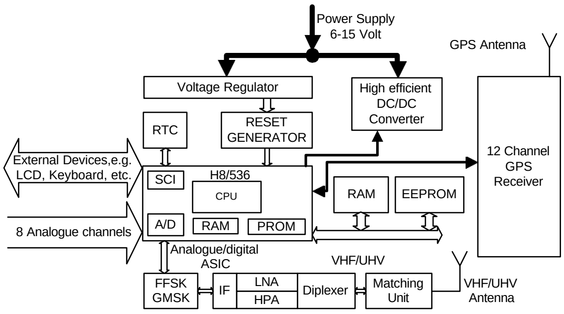

Fig. 11: Block diagram of a mobile communication unit.

7. COMMUNICATION ACCESS

With different SYNC words the satellite knows if this is a telemetry command or a user uplink. In case of user uplink there are several possibilities for the SYNC words:

- User uplink with 64 information bytes.
- User uplink with 128 information bytes.
- User uplink with 64 information bytes + 48 FEC (Forward Error Correction) bytes (interleaved).
- User uplink with 128 information bytes + 96 FEC (Forward Error Correction) bytes (interleaved).

The different SYNC words also contains the information about the user ID (Fig. 12).

120 Bit Preambel	32 Bit SYNC word + User ID	16 Bit CRC	64 Byte Information 128 Byte Information 64 Byte Information + 48 Byte FEC (interleaved) 128 Byte Information + 96 Byte FEC (interleaved)

Fig. 12: Data format depending on different SYNC words.

The access to the satellite is a Modified Preassignment Time Division Multiple Access (MP-TDMA). Each mobile communication terminal has a GPS receiver and knows the position and the time with an accuracy of better than 1 ms. With the knowledge of position, time and orbital parameters of the satellites the mobile terminal is able to calculate the contact time for elevations greater than 5°. Each terminal has an exactly defined time slot for transmitting messages, receiving messages and new orbital parameters. After the satellites rise above the horizon the terminal waits for the defined time slot, transmitting and receiving messages (Fig. 13). When all messages are transmitted or the elevation of the satellite is less than 5°, the terminal calculates the next contact time and enters a power stand by mode until the next crossing. The typically power consumption in stand by mode is less than 100µA. This concept has the advantage that a mobile terminal can work more than one year with a battery capacity of 10 Ah.

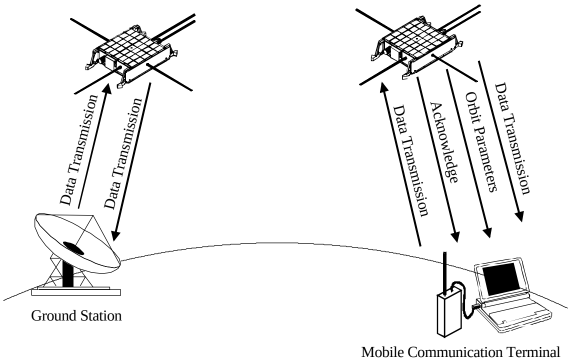

Fig. 13: Link sequence of TUBSAT-N/N1.

8. LAUNCH OPPORTUNITY

TUBSAT-N/N1 was designed to be launched with a convertible Russian military SS-23 SHTIL rocket. The advantage of the SHTIL rocket is that the micro- or nanosatellite is the prime payload, that means, that the customer has an influence on the orbit. The satellite is mounted in the payload bay representing a peripheral zone formed with the 3rd engine, 2nd stage upper bottom, 3rd stage lower bottom and stage adapter. The satellite is accommodated in the rocket within a protective capsule structurally consisting of a casing and a plane (Fig. 14).

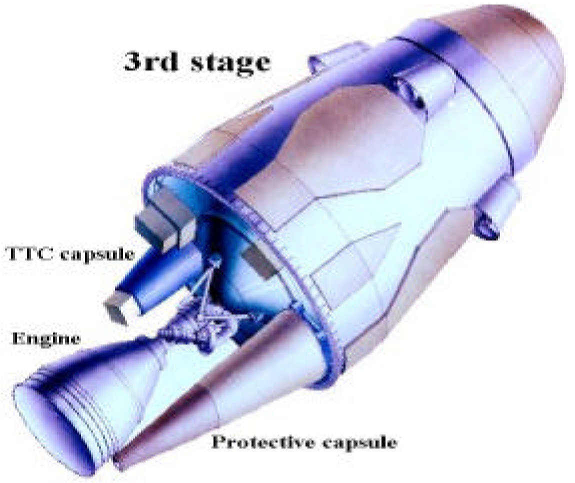

Fig. 14: Arrangement of the protective capsule within the 3rd stage of the SHTIL rocket.

The capsule casing represents a two-part elliptical cone made of fibre-glass plastics of uneven thickness. The external surface of the small cone is heat protected. It provides a case internal surface temperature of no more than 80°C at the moment of capsule-satellite separation. A small drainage hole evacuates the capsule slowly. TUBSAT-N was fixed within the capsule by clamping mounting flanges between mating areas on the capsule casing and the plate. When the rocket motion parameters were archived the capsule-platform mating fasteners opened. At the same time the final stage was drifted from the capsule. Within 36 s of the capsule-rocket separation the capsule casing-plate separation was performed by the spring pushers with simultaneous spacecraft release (Fig. 15).

The rocket is able to reach an elliptical 750 x 400 km orbit with a payload mass of 12 kg (i=78°), or a 400 km circular orbit with a payload mass of 70 kg (i=78°).

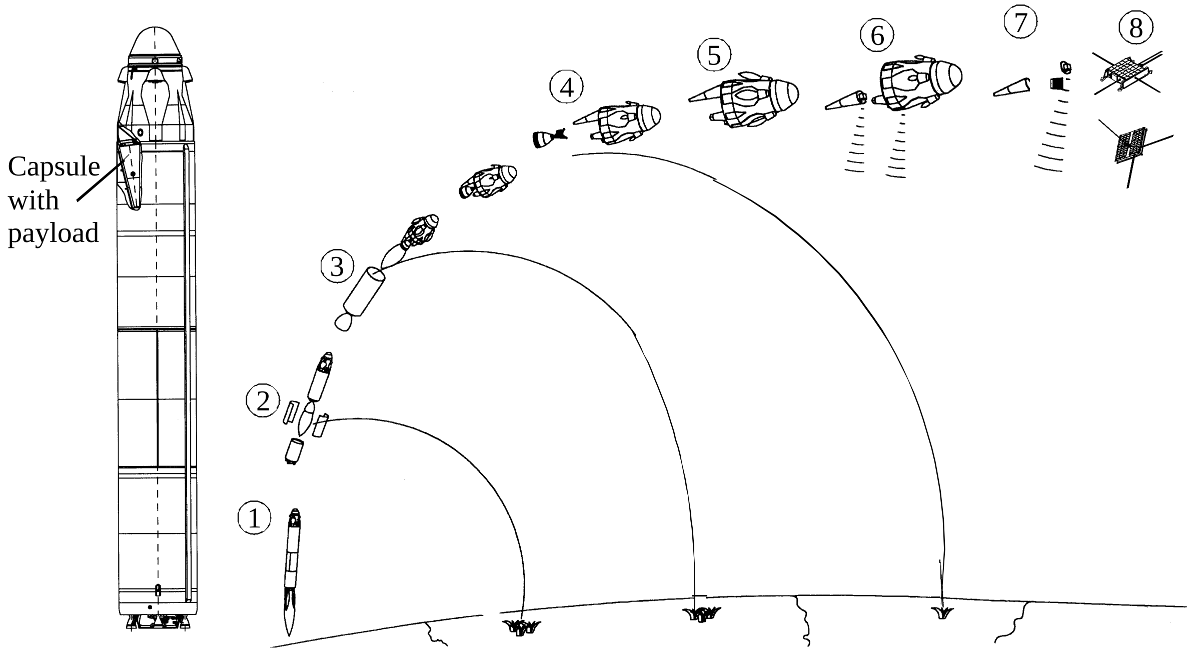

Fig. 15: Mission profile of spacecraft injection: (1) rocket takeoff, (2) separation of the first stage, (3) separation of the second stage, (4) separation of the main engine of the third stage, (5) Trajectory phase near apogee, (6) separation of the capsule with spacecraft, removal of the third stage away an orbit, (7) division of the capsule, spacecraft release, (8) spacecraft in orbit.

9. OVERALL COSTS, FUTURE STEPS AND CONCLUSION

The average costs per satellite were approximately 100.000 US$, including manpower. The commercial launch cost for the SHTIL rocket is 500.000 US$. In the case of TUBSAT-N/N1, two satellites were launched with one rocket, the overall costs were less than 700.000 US$, this means that the overall cost for one satellite was less than 350.000 US$.

The logical next steps in this project could be:

1. Use of GMSK modulation for the mobile communication terminals. This would increase the baudrate by a factor of 4 (4800 baud) with the same bandwidth requirements like 1200/2400 baud FFSK modulation.
2. Reducing the physical size and the power consumption of the PCB's by a factor of 2 to 3 (has been done, see table 2).
3. Use of smaller batteries.
4. Use of smaller solar cells.
5. Reducing the size of the satellite down to a cubic shape of 12 - 15 cm and a mass of only 1.5 to 2 kg.

With the above mentioned changes it would be possible to launch 8 to 16 nanosatellites as a satellite cluster for the same price like a microsatellite. Multiple launches of satellites with one rocket will dramatically reduce the costs for a nanosatellite communication network and will increase the communication time for the user. Figure 16 shows the average possible communication time, dependent of user latitude, for an open chain satellite network in the same orbit [4]. The overall cost will be reduced down to 150.000 US$ per satellite, including launch, when eight (or more) satellites will be launched together at the same rocket.

Table 2: Comparison of TUBSAT-N 1998 with TUBSAT-N 2000 (same Performance)

	TUBSAT-N 1998	TUBSAT-N 2000
No. of Resistors	> 2200	≈ 460
No. of Capacitors	> 1700	≈ 530
No. of semiconductors	> 750	≈ 216
No. of PCB's	26	5
Cable	> 110 m	< 3 m
Current Consumption (Rx)	280 mA	90 mA
Total mass	8.5 kg	1.5 - 2.0 kg

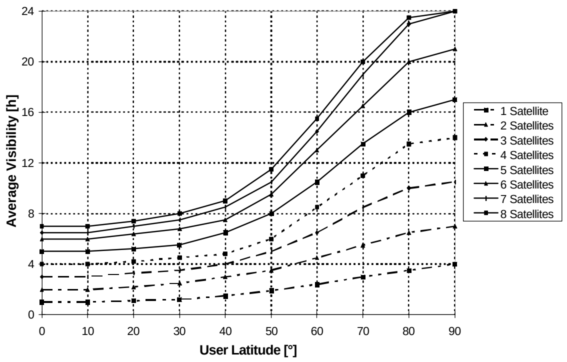

Fig. 16: Average visibility, dependent from user latitude, for an open chain satellite network (800 km orbit, i=98°).

ACKNOWLEDGEMENT

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