Seven-year Flight Testing of the Gurwin-Techsat Microsatellite

Moshe Guelman, Fred Ortenberg, Alexander Shiryaev, Roni Waler
Asher Space Research Institute, Technion, Haifa, 32000, Israel; 972-4-8293020
aerglmn@aerodyne.technion.ac.il, fred@tx.technion.ac.il, shiryaev@tx.technion.ac.il, waler@tx.technion.ac.il

ABSTRACT: A good example of an extended small satellite mission is that of Gurwin-Techsat, a small satellite developed and built in the Technion-Israel Institute of Technology, and launched in 1998 from Russia. Presented in the report is a review of the Gurwin-Techsat mission, and of some scientific and technological results obtained in the onboard experiments. Given also is a short analysis of the performance of its sub-systems and scientific payload. As was demonstrated by the mission, a substantial reduction of the satellite mass, size, and power consumption can be achieved without deterioration of its basic characteristics, such as mission lifetime, payload efficiency, precision of the measurements, etc. The platform itself, as well as the flight experience gained during the mission, may be used in designing and manufacturing similar microsatellites with new and different research payloads.

INTRODUCTION

The problem of small satellites' lifetime still remains of importance. As was pointed out at recent conferences on small satellites applications[1-3], most of the small launched satellites either did not operate at all, or lost performance within a few months after the launch. The university-class satellites proved to be in general less reliable than their industry counterparts. At the same time, the small satellites are dedicated mainly to short-term missions, the long-term ones being scarce, with their active lifetime never exceeding 3 years. Most of such long-term missions seem to be focused on non-research objectives, since no results of their flight performance have ever been published. Evidently thus, there is a necessity of results on small satellites' durability testing, collecting and distribute it to the scientific community. The main objective of this report is to sum up the test results obtained throughout 7-years in-orbit activity of both the Techsat platform and the on-board devices.

The Gurwin-Techsat microsatellite is a universal three-axis platform carrying devices for the space research and technological experiments. It was launched on July 10, 1998 from Baikonur launch pad by Zenith launch vehicle, as a piggyback onboard the Russian Resource-01 No.4 spacecraft. Besides Techsat, four more microsatellites were put in orbit by the same mother-spacecraft, viz.: Safir 2 (Germany-Belgium); Westpac (Australia); Fasat–Bravo (Chile-Great Britain); TMSat (Thailand-Great Britain).

Initial orbits of the satellite constellation were circular Sun-synchronous ones, with altitudes of ~820km, inclination of ~98.75°, period of orbit - ~101min, right ascension of the ascending node - ~262.1°, angle between normal to orbit plane and Sun direction - ~68°.

Stable radio contact with Techsat was established during the next revolution after its separation from Resource-01. The in-flight performance of the satellite and its payload, initialized after the separation, was maintained ever since without break. After seven years in space, the Techsat is still working and providing valuable information, showing no significant degradation. The results of the planned tests and technological and scientific experiments, performed onboard Techsat, were published elsewhere[4-14]. An updated account of the Techsat mission is also presented in the ASRI Web site[15]. This final report includes overall descriptions of the flight experiments and analysis of the space environment impact on the satellite mission.

LONG TERM FLIGHT TESTS

One of Techsat mission goals was to carry out long-term experiments, and to compare the actual in-flight parameters of the onboard equipment with those at the design stage. Such a comparison confirmed the effectiveness of the adopted scientific approaches and technical solutions. The power, attitude control, communication, computer, and thermal subsystems performed stably and provided the satellite's normal functioning in any of its possible operational modes. No substantial failures or malfunctions were noticed either in the housekeeping of the whole bus, or in its separate modules.

During the mission, the satellite operations were conducted on a daily basis. The satellite status was controlled twice a day (in the morning and in the evening), i.e. at least once during a revolution with good communication conditions. On-ground operational personnel conducted regular station equipment maintenance procedures, and improved the quality and reliability of the data reception. Many improvements in all ground software applications were made, and multiple faults in the command and control software were revealed. A long-term research implying continuous accumulation of the data, all the Techsat telemetry is stored on a regular basis; besides, the data of each thousand of revolutions are recorded on one separate CD-ROM disk. For the experimental telemetry data processing, a computational method was developed, enabling to determine the physical parameters from the onboard measurements. The algorithms involved take into account both onboard telemetry data, results of a pre-flight calibration, and the satellite in-orbit position. Some results obtained by the on-board measurements processing, which pertain to the space environment, the Earth's atmosphere, the properties of the materials under testing, and the satellite hardware, are presented below. Operational in-orbit status of Techsat subsystems and devices during the mission is presented in Table 1, an active status being marked by a dark bar.

Table 1. Duration of Techsat subsystems operation in orbit

Systems and devices	1998	1999	2000	2001	2002	2003	2004	2005
Attitude control	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—
Communication, computer	—	—	—	—	—	—	—	—
Detector of particles	—	—	—	—	—	—	—	—
Earth Imaging*	—	—	—	—	—	—	—	—
Laser Retroreflector*	—	—	—	—	—	—	—	—
X-ray detector**	—							
Super-conductivity***	—	—	—					
Ozone Meter	—	—						
Radio amateur community							—	—

* - Flight experiments carried out periodically for short duration.

** - X-ray experiment was stopped because no correct calibration of detector.

*** - After two years the tests were finished, because of the cooler degradation.

ORBIT EVOLUTION

The evolution of Techsat orbital elements over the mission is shown in Figure 1 (altitude), Figure 2 (eccentricity), and Figure 3 (inclination). The plots were obtained with SGP4 analytical orbit predictor, the initial conditions being taken from the NORAD two-line element (TLE) sets.

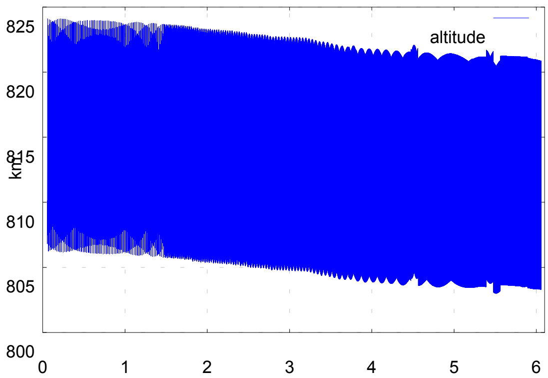

Figure 1. Semi-major axis evolution during the mission

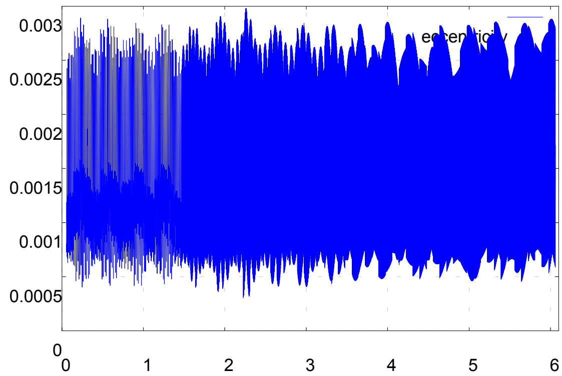

Figure 2. Eccentricity evolution during the mission

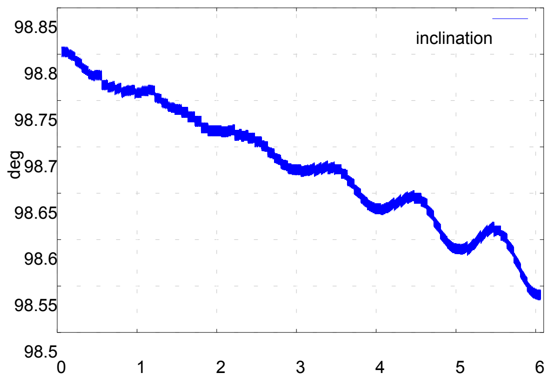

Figure 3. Orbit inclination evolution during the mission

Seen also are the secular trends in the altitude and the inclination, along with the periodic perturbations of the elements. The former trend of about -0.5 km per year is caused by the atmospheric drag, while the latter, -0.04º per year, is characteristic of Sun-synchronous orbits, as conditioned by the solar and lunar gravity.

ATTITUDE CONTROL SYSTEM

The satellite attitude history, based on the magnetometer telemetry processed both by the on-board and Ground Station Kalman filters, was statistically analyzed, to summarize the long-term performance of the attitude control system. The analysis made it evident, that throughout the most part of the flight, the magnetic control provided the 3-axis stabilization of the satellite with nadir-pointing accuracy of about 2°-2.5°. The attitude data, collected over July 2004 and reduced to the time interval between two successive passages of the ascending node, are plotted in Figure 4, together with their averaged values (solid lines), obtained by the following formulae,

$$\phi = 0.03 - 1.72\cos\left(\frac{2\pi}{T}t + 0.21\pi\right) \quad (1a)$$

$$\theta = 0.12 - 1.28\cos\left(\frac{2\pi}{T}t + 0.22\pi\right) \quad (1b)$$

$$\psi = -0.12 + 1.47\cos\left(\frac{2\pi}{T}t - 0.25\pi\right) \quad (1c)$$

where t = time reckoned from the ascending node passage; T = orbital period (≈6075^s). With these formulae, the satellite attitude can be predicted with a root-mean-square error of 0.5°.

In collaboration with Cornell University, a study was carried out of the attitude control algorithms, able to provide 3-axis stabilization of a satellite equipped with a magnetometer as the only sensor, and magnetic torques as the only actuators[13, 19]. Two different solutions to the problem were developed, namely *Linear Quadratic Regulator* and *No Wheel* controllers. The new algorithms were tested onboard the Techsat, nominally momentum-biased and stabilized within 2º–2.5º precision by the proportion-plus-derivative magnetic controller. In the flight tests of the new controllers, some valuable results were obtained, such as revealing the possibility to effectively maintain the satellite 3-axis stabilization even with a very small momentum bias.

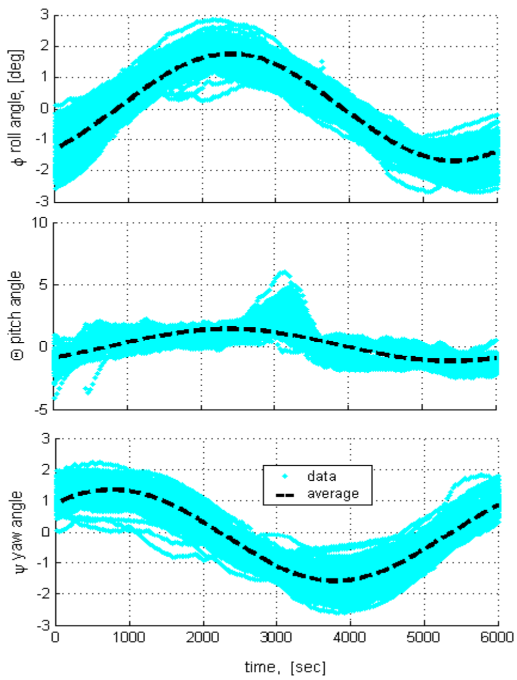

Figure 4. Attitude history of July 2004, reduced to one revolution

POWER SYSTEM

The need of the high-performance solar arrays for the small satellites is urgent. International efforts were launched, to develop and demonstrate the advanced solar array technologies, resulting in a lower cost, reduced weight, lesser risk, more reliability, and more power output[16]. The new technologies should be tested in flight, but unfortunately, the short duration of the most of small satellite missions do not permit to estimate the changes of the solar panels performance over a long time. Presented in this paragraph are the results obtained in the study of the long-term space environment impact on the Techsat solar panels[17].

The solar panels, mounted on the Techsat body, were produced in Russia by thin film photovoltaic cells technology. This advanced technology is a cost-performance- effective methodology; it was also used in manufacturing the solar panels for the International Space Station. The long-term Techsat flight enabled to estimate the parameters of the solar panels performance and reliability and, in particular, such very important properties, as conversion efficiency and hardness.

As followed from the analysis of the power supply functioning, the reduction of both the solar panels output and solar panel efficiency, caused by all possible factors (high-energy protons and electrons, ultraviolet radiation, highly active atomic oxygen, high- and low-temperature extremes, hard vacuum), did not exceed 2% per year. After the 6-years flight, the solar panels generated about 0.87 of their output at the Beginning of Life (BOL).

The degradation of the solar panels power was described by two-parameters (ξ and η) approximation formula, as follows:

$$P(t)/P_0 = \xi + (1-\xi)\exp(-t/\eta) \quad (2)$$

where P(t) is current solar panels power, and P_0 is its value at BOL.

The space radiation influence on the solar arrays characteristics during long-term (7-10 years) mission in a GEO orbit is plotted on Figure 5 by curve 2, with initial guess of ξ and η equal to 0.86 and 4.3, respectively[18]. Presented in these figures are also the Techsat solar panels output measurements during the whole operational period. The variations of the power data were processed by a standard statistical least-square procedure to the given nonlinear curve-fitting (2). The best-fit optimization of Techsat power system degradation in orbit was obtained with values of ξ and η of 0.827 and 3.95 (see curve 1 on Figure 5). The residual error for this approximation is equal to 0.03.

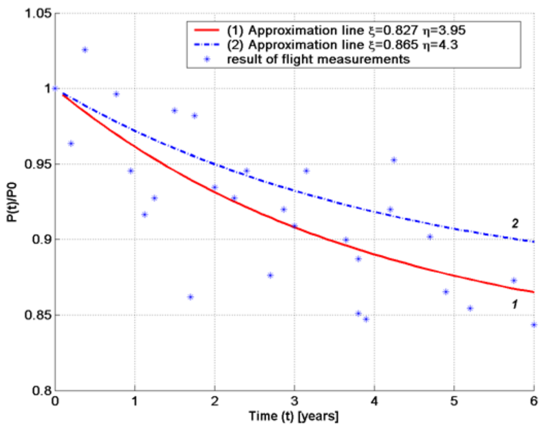

Figure 5. Solar Arrays of silicon cells degradation during long-term space tests (curve 1 – LEO Techsat, curve 2 – GEO)

THERMAL CONTROL

The Techsat thermal control was carried out on a non-stop basis, as shown in Figure 6. The temperature of the on-board devices was kept within -20ºC ÷ +10ºC, while that of the solar panels varied in the range of -35ºC ÷ +30ºC. Small changes in its average on-board temperature, registered during the Techsat flight, were brought about by the seasonal variations of the incident solar flux. The panel's optical properties can be deduced indirectly from temperature stability of the satellite external surfaces. Measurement processing indicated minimal changes in the panel thermal performance, caused by the exposure to the solar UV, relatively low charged-particle environment at the satellite altitude, and erosion of the materials by atomic oxygen during the flight. The surface thermal control experiment confirmed durability of the thermal and optical properties of the panels under both the long-term environment exposure and temperature cyclic effects. Furthermore, from the temperature telemetry, the thermo-stability of the satellite electric battery was derived. The time profile of all the curves is identical, and no essential distinctions in the temporal trend during the measurements time span were discovered. These results indicate minimal thermal degradation during the satellite lifetime.

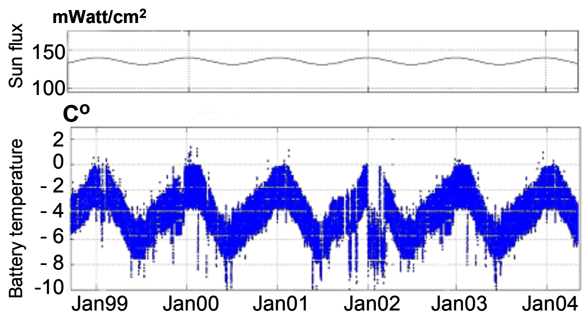

Figure 6. In orbit electric battery temperature measurements and Sun flux variation during 1998-2004.

COMMUNICATION SYSTEM AND ON BOARD COMPUTER

A stable radio-link with the Ground Station was maintained all along and provided up-linking of both the ground commands and the files with Fourier-approximated reference geomagnetic field vector for the attitude control system, and down-loading of the housekeeping telemetry and the experimental data. As for the on-board computer, no substantial failures were noticed in it thus far. The parameters of the on-board communication system were maintained during the operational time[21]. Sensitivity analysis of Techsat satellite 145 MHZ receiver under the flight conditions was measured in a special research, and these results confirmed the system stability.

Techsat satellite has a digital store-and-forward multi-user system, now utilized by the international amateur radio-electronic community. Thus communication system is compatible with existing store-and-forward facilities, already in use on AO-16, LO-19, UO-22 satellites, etc. The system could provide 6 uplinks (three 2-meter and three 23-cm), and one 70-cm downlink. The onboard computer is a part of this communication system, providing the functioning of a communication controller.

There were some difficulties with the amateur BBS program at the mission initial stages. After much effort, the necessary changes in the satellite software were inserted, in order to enable operation of the satellite by the radio amateur community. Techsat amateur BBS package tests were finished, and the system status was updated, so the Israeli GO-32 spacecraft (Techsat satellite) successfully provides a store-and-forward communications to the worldwide radio amateur community.

PAYLOAD PERFORMANCE

Being designed as a multi-purpose platform, suitable for the space research, Techsat was equipped with 6 different devices, to carry out the on-board scientific experiments. All of them were repeatedly run during the flight, according to their respective programs. Till recently, one of them was operating non-stop (Detector of the Particles), three were periodically turned on and off (Super-conductivity Experiment, Earth Imaging System, and X-Ray detector), one failed after 10-month successful operation (Ozone Meter), and one was used only in the early phase of the mission (Laser Retro-Reflector). On-board experiments and measurements were presented in the numerous publications[4-14]. We give here a brief description of their in-orbit performance, illustrated with some of the obtained results.

Earth Imaging System

CCD-camera with the frame dimensions of about 25 km×31 km, and resolution of 52m×60m, was aimed at taking panchromatic pictures of selected areas of the Earth surface and surrounding clouds. Unfortunately, it failed to operate stably, since the pictures taken at high Sun illumination level were overexposed, due to the signal saturation. As an example, the picture of the Sea of Galilee area (Israel-Jordan) is presented in Figure 7. The overexposure is obvious here too, but still some reference details can be clearly discerned.

This picture, as well as others, was used for the independent satellite attitude estimation. The core of the dedicated algorithm for the image processing was the least-square adjustment of a number of reference points, chosen both on the picture and on the map, to attach the picture frame to the Earth reference ellipsoid, and to derive the Field of View (FOV) parameters. An additional routine included comparison of the FOV observed position with that of an ideally stabilized satellite, with FOV center at the sub-satellite point. The attitude angles thus obtained were compared with the estimates from the magnetometer telemetry processing. The discrepancies between the two estimations might be caused by misalignment of the coordinate frames, inherent in the camera and the magnetometer. As a confirmation of this assumption, the misalignment angles found in most determinations proved to be fairly close.

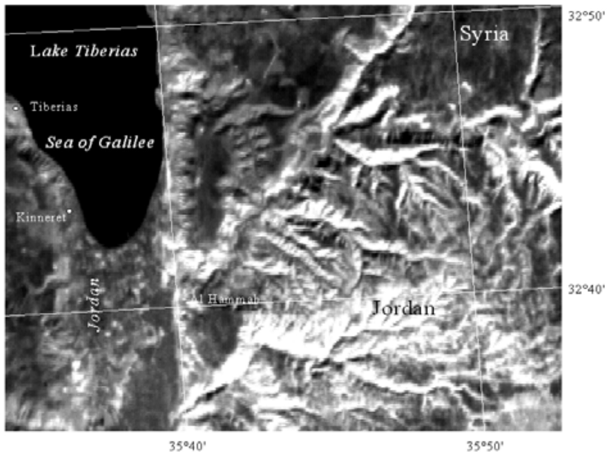

Figure 7. The Sea of Galilee Area (Israel-Jordan*)*

The Ozone Meter

The Ozone Meter (OM) is a filter photometer, measuring the solar backscattered ultra-violet (SBUV) radiation in nadir direction along the satellite orbit. These measurements were used to estimate the concentration of the atmospheric ozone. The dedicated correction, checking, and calibration algorithms were worked out, to process the raw data and put them into correspondence with specific satellite positions. In these algorithms, the global climate data were used, based on the measurements of preceding satellites, as well as on the monthly averages of ozone mixing ratio and total ozone data, provided via the Internet. The statistical processing of the measured radiation, together with *a priori* data, made it possible to accumulate a 10-month data set of global ozone profiles and total ozone values, as shown in Figure 8.

A number of OM ozone data sets had been compared with measurements performed by well-known satellite instruments SBUV and TOMS. Comparison of the OM data with results obtained by these instruments shows, that the estimated error in total ozone measurements is about 11%. The OM flight test has enhanced the prospect of developing reliable, low-cost instruments for small satellites, necessary for carrying out such vital tasks, as continuous ozone monitoring.

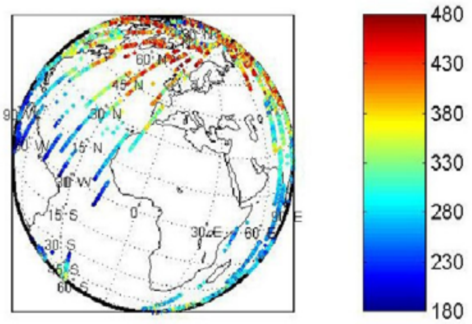

Figure 8. Total ozone distribution in the atmosphere collected during two days OM operation in orbit and measured in Dobson Units (color scale on the right).

Laser Retroreflector

Retroreflector (RR) array, attached to the Techsat Earth-facing panel, was intended for precise determination of the satellite position with the help of satellite laser ranging (SLR) technique. A number of laser ranging measurements were taken soon after its launch by many stations of the worldwide laser ranging network. Measurement processing was carried out by the Mission Control Center of the Russian Space Agency, and very precise orbital elements were derived, good enough for taking measurements in the automatic mode even in the daytime, with a prediction error of 10-20 m.

Backward propagation of the TechSat precise orbit thus derived in first days of its autonomous flight in orbit, together with that of the mother Resource spacecraft, enabled to specify the instant of their separation. At the separation moment, the relative velocity component in the along-track direction was equal to +0.319 m/s, in a good agreement with results obtained in the on-the-ground testing of the separation system.

The SLR station in Maidanak, Kazakhstan, had also carried out the photometric measurements of the sunlight, reflected from the Techsat. The Brightness curve, given in Figure 9, represents the record of one of such measurements. Clearly seen there are the reflections of the sunlight from 4 sides of the TechSat, the flashes with maximum intensity and minimum duration corresponding to the mirror reflection from the solar panels. These measurements also provided a reliable confirmation of the satellite attitude, in particular, the satellite's rotation with a period close to the period of the satellite's nutation about an axis, slightly tilted with respect to its axis of symmetry.

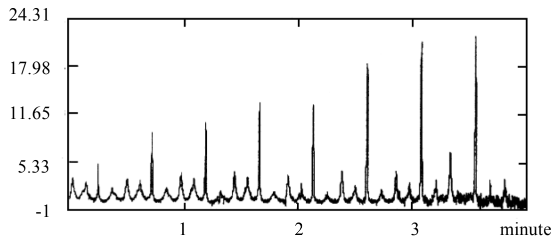

Figure 9. The Brightness Curve of TechSat satellite during an observation session (in stellar magnitudes).

Detector of Protons and Heavy Particles

The detector successfully operated over the most of the time since Techsat launch. The device was continuously turned on and performed in both the registration and the data accumulation modes.

The single event upsets and single event latch-ups were recorded, and their locations were determined with accuracy of 2°. The radiation event mapping, obtained with the detector, allowed to analyze the radiation environment along the track, and to study its impact on the satellite's electronics during the long mission. The map of the radiation events, that took place on June 2002 and February 2004, are given on Figures10 and 11. In these maps, the single event upsets are marked by "*" in black and by "+" in red; the single event latch-ups marked by "**o**" in green. The follows peculiarities of penetrating radiation were distinctly presented on pictures:

- High density of the single event upsets induced by the protons of the first radiation belt in the South Atlantic Anomaly region;
- Occurrence of the single event upsets originated from the heavy particles at the polar regions;
- Much smaller number of the observed single event latch-ups than of the single event upsets.

A good concordance (within an accuracy better than a factor of 2) between the measured and predicted numbers of events was marked.

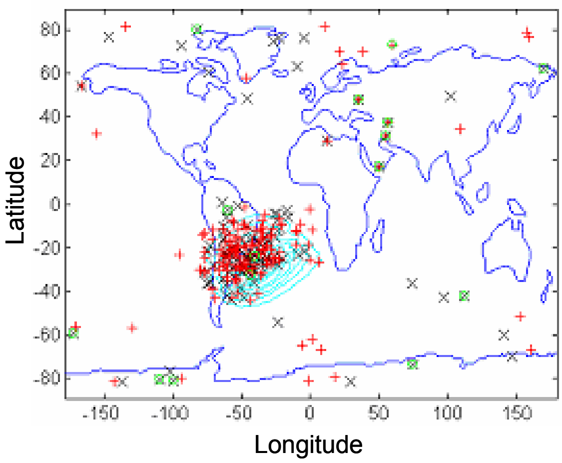

Figure 10. Results of particles measurements update in June 03, 2002.

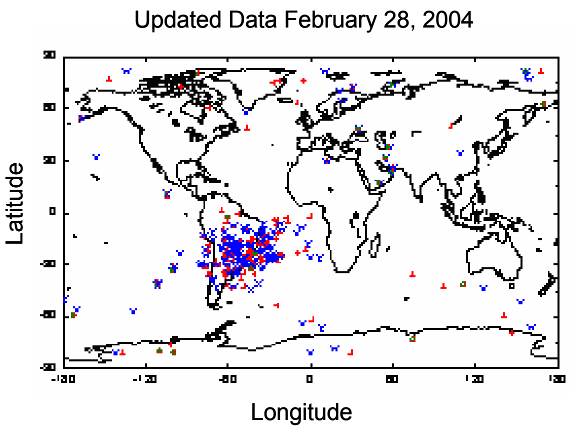

Figure 11. Results of particles measurements update in February 2004.

Superconductivity Experiment

This experiment is actually a technological research, aimed at testing the new High-Temperature Superconductive (HTSC) material and a miniature cryocooler in the space environment. It was anticipated, that after having been tested, such HTSC material could be used in the space communications systems, and, specifically, in the filters limiting frequency bands. Measuring periodically the resistance of the HTSC material, the critical temperature T_c and the critical current I_c were measured and recorded as functions of time, elapsed since the launch. These measurements enabled to discern a very slow decrease of the critical temperature (by about 0.5K/year). On the other hand, since the device had been put into an orbit, the temperature T***,** at which the critical current of the device amounted to 100 mA, remained constant, within scattering of the superconductive properties (Figure12). These data indicate that there is no fundamental problem concerning the survivability of HTSC thin films in space. After two years of satisfactory operation, either the cryocooler parameters degradation, or the thermal contact between the device and the cooler caused the latter deterioration to the point that the transition temperature to the superconducting state could not be reached any more. This event constituted in fact a termination of the experiment in its designed form. The only parameter, which can be still monitored, is the resistance of the device in its normal state.

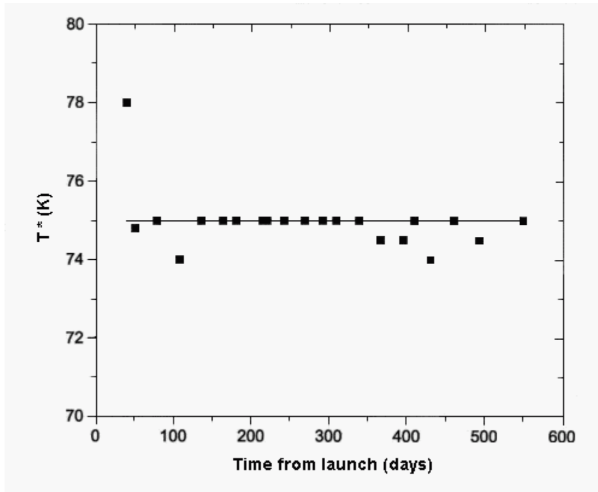

Figure 12. Critical temperature T* of superconductive materials as a function of time since launch.

X-Ray Detector

The experiment objective was development and in-orbit testing of the sensitive X-ray detector CdZnTe, dedicated to a future space X-ray telescope. The instrument consists of solid-state detectors, a preamplifier, a microcontroller, and a memory. After device switching on, the TM signals from detector were received on the Ground Station. Analysis of signals showed that instrument operated according to its nominal logic. Unfortunately, the pre-launch calibration of the detector was not fulfilled correctly, so it was impossible to transform the TM signals to real physical parameters of X-ray cosmic radiation (counts, energy and frequency) and the X-ray experiment was stopped.

SUMMARY AND CONCLUSIONS

The successful flight tests made it evident, that Gurwin-Techsat satellite is able to provide versatile opportunities for scientific experimenting. By all its basic characteristics it belongs to the microsatellite sub-class of small satellites, with mass of 50 kg and cost of about US$ 5M, including design, manufacturing, testing, ground station equipment, pre-launch and launch services, and ~7 years in-flight performance. Its manufacturing and ground tests took less than 30 months. Throughout the mission, the Techsat has orbited the Earth more than 35000 times, the guaranteed preflight endurance of 1 year being thus surpassed by seven times.

The Communications system enabled a stable radio-link with the Ground Station. During the whole period, satellite operations were conducted on a daily basis. This was accompanied by regular maintenance of the Ground station equipment. Full-scale tests of the satellite were routinely carried out ever since, and could be proceeded with in the foreseeable future. All the Techsat on-board systems were tested under different operational conditions. No considerable failures or malfunctions were noticed thus far, with regard to the satellite housekeeping as a whole, or its modules.

Today the satellite is revolving at a mean altitude of ~811 km. The secular variations of the mean altitude and inclination during the past 7 years were ~4 km and ~0.3°, respectively, with a mean eccentricity unchanged. The attitude control system, the camera, and the radiation testing equipment are still operational. The satellite attitude can be maintained within ±2°-2.5°. In all operational modes the energy consumption for housekeeping never exceeded 10 W. The power system retained the bus-bar voltage within 14.0±0.8 V. The solar panels system still supplies about 90% of the initial energy output. The reduction of the solar panel efficiency, caused by all possible factors (high-energy protons and electrons, ultraviolet radiation, highly active atomic oxygen, high- and low-temperature extremes, hard vacuum), did not exceed 2% per year. The temperature of the on-board devices was kept within -20° ÷ +10° C, and of the solar panels - within -35° ÷ +30° C. In-flight tests of some of the payload devices were completed with positive results. Not long ago, two of the 6 payload devices were periodically turned on, while three were not actuated, and one device inoperative. Nowadays, the satellite provides services for the radio amateur's community, which allocates the communication frequencies.

Review of the Techsat ~7-year mission gives evidence, that in the micro-satellites sub-class it belongs to the most cost-efficient ones, with low power consumption, stable hardware functioning, and reliable and simple attitude control. Six successfully performed onboard experiments provided data of scientific and technological value. In Techsat, compactness of a micro-satellite is combined with high performance, reliability, and versatility, proper to larger satellites. Techsat remained operational throughout its mission, and is still making overall platform service (power, attitude, communication, computer, thermal, etc.) for continuing experimental space activity.

In a review[1] of student-built spacecraft, general trends in satellite design were described. In consideration of university-class satellites low performance, the following reasons were mentioned:

- Lack of a sustainable spacecraft program;
- Production of only one satellite (for flight);
- Lack of space manufacturing and testing facilities;
- Impossibility to apply new and expensive space technologies;
- Lack of regular operational ground-orbit communication.

Techsat satellite development, tests, and in-orbit operation were free of these defects. Design of small satellites is one of continued ASRI research themes. During realization of the Techsat project, three modules of the satellite were manufactured and tested: flight module, destroyed in the unsuccessful 1995 launch by the Start rocket; qualification module; and final flight module, now in orbit. Techsat manufacturing and testing were fulfilled, using standard facilities of Israeli space industry. During Techsat design and integration, some radically new component and technical decisions were applied, e.g. solar panels ruggedization, which saved their efficiency to the present day, with minimum degradation. Communication with the Techsat was supported on a regular basis, and all the software faults were removed without delay. Thus, the Techsat satellite was built and operated by the ASRI team at the same level, as professional satellites.

References

1. Swartwout M., "University-Class Satellites: From Marginal Utility to 'Disruptive' Research Platforms", SSC04-II-5. 18th Annual AIAA/USU Conference on Small Satellites, Utah, 2004.
2. Teston F., Bernaerts D., Gantois K., "PROBA, an ESA technology demonstration mission, results after 3 years in orbit", The 4S Symposium Small satellites Systems and Services, September 2004, La Rochelle, France.
3. Frisk U.O., "ODIN – low cost and technically advanced – now 3.5 years in orbit", The 4S Symposium Small satellites Systems and Services, La Rochelle, France, September 2004.
4. Guelman M., Flohr I., Ortenberg F., Shachar M., Shiryaev A., Volfovsky A., Waler R., "The Israeli Microsatellite TechSat for Scientifical Research, Development and In-Orbit Testing", *Acta Astronautica*, Vol.46/2-6, pp.397-404, 2000.
5. Ortenberg F., Volfovsky A., "The TechSAT Satellite Separation System: Development, On-Ground and Flight Tests", Proceeding of the 39th Israel Annual Conference on Aerospace Sciences, pp.416-420, 1999.

6. Rozanov M., Shiryaev A., "Various Techniques for TechSat Attitude Assessment", Proceeding of the 41th Israel Annual Conference on Aerospace Sciences, pp.504-508, 2001.

7. Polturak E., Koren G., Ayalon M., Flohr I., Waller R., Guelman M., "Space Based High Temperature Superconductivity Experiment", Proceedings of the 14th AMSAT-UK colloquium SpaceComn-99, University of Surrey July 23rd-25th, pp.10-14, 1999.

8. Guelman M., Ortenberg F., Shiryaev A., Shargorodsky V. "TechSat Satellite Laser Ranging Retroreflector Flight Experiment", Proceeding of the 39th Israel Annual Conference on Aerospace Sciences, pp.406-410, 1999.

9. Barak J., Adler E., Murat M., Levinson J., Flohr I., Waller R., Lifshitz Y., 'The Soreq Radiation Monitor for Detecting Protons and Heavy Ions in Space and its Preliminary Flights Data on Gurwin II TechSAT", Proceedings of the 14th AMSAT-UK colloquium SpaceComn-99, University of Surrey July 23rd -25th, pp. 2-9, 1999.

10. Waller R., Flohr I., "Command & Control Software Techniques in TechSAT Microsatellite", Proceedings of the 14th AMSAT-UK colloquium SpaceComn-99, University of Surrey July 23rd -25th, pp. 58 – 70, 1999.

11. Guelman M., Ortenberg F., Wolfson B., "Flight Tests of the Novel TechSAT Satellite Ozone Meter", Algorithms and Measurement Processing Results. Proceeding of the 40th Israel Annual Conference on Aerospace Sciences, February, pp. 299- 309, 2000.

12. Guelman M., Ortenberg F., Shiryaev A., Waller R., "Microsatellites for Science and Technology: Gurwin-TechSat In-flight Experiments Results", 3rd International symposium of the IAA, Small Satellites for Earth Observation, Berlin, April, pp. 67-70, 2001.

13. Guelman M., Waller R., Shiryaev A., Psiaki M., "Design and Testing of Magnetic Controllers for Satellite Stabilization, Small Satellites for Earth Observation", Digest of the 4th International Symposium of the IAA, Berlin, April 7-11, pp.299-302, 2003.

14. Kramer H.J., "Observation of the Earth and Its Environment, Survey of Missions and Sensors", Springer, Berlin, 4-th edition, pp.1181-1184, 2002.

15. http://www.technion.ac.il/ASRI

16. Fosness E., Guerrero J., Mayberry C., Carpenter B., Goldstein D., "Next Generation Solar Array Technologies for Small Satellites", 16-th Annual AIAA/USU Conference on Small Satellites, SSC02-II-2, Utah, 2002.

17. Guelman M., Ortenberg F., Wolfson B., "Long Term Flight Tests of the Gurwin-TechSat Satellite Power System", Proceedings of the 43rd Israel Annual Conference on Aerospace Sciences, 12, 2003.

18. Shuvalov V.A., Kochubey G.S., .Priimak A.I., Reznichenko N.P., "Degradation of the Electric Power of Solar Arrays Under the Influence of the Near-Satellite Environment", Space Science and Technology, Ukraine, Kyiv, vol.8, N4, 2002.

19. Guelman M., Waller R., Shiryaev A., Psiaki M. "Design and Testing of Magnetic Controllers for Satellite Stabilization", Acta Astronautica, Vol.56, pp.231-239, 2005.