SUBMILLIMETER CRYOGENIC TELESCOPE WITH ANDREEV TYPE MICROBOLOMETER FOR THE INTERNATIONAL SPACE STATION. PROJECT SUBMILLIMETRON

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Abstract. The tasks of the celestial sphere observations in the Terahertz (500-3.000 GHz) frequency band are analyzed and the place of wideband microbolometers in these tasks is determined. Among such microbolometers the Andreev type is one of most promising. It is based on the heating electrons in the thin film of normal metal with superconducting electrodes (the S-LN-S structure, where "S" means the superconductor and "LN" means the long film of normal metal), cooled down to temperatures of order of 100 mK. Preliminary estimations and measurements [1, 2] show the possibility to reach the noise equivalent power of such bolometer down to 10^{-18} W/ $Hz^{1/2}$ at least in the part of the THz frequency band. The Astro Space Center of the P.N. Lebedev Institute of the Russian Academy of Sciences is developing the Submillimetron Project [3] that includes a submillimeter wave cryogenic telescope with the Andreev microbolometer as one of receiver candidates to be mounted at the International Space Station.

1. Introduction. One of the fundamental problems of the contemporary physics, in general, and the astrophysics, in particular, is the problem of the investigation of the electromagnetic radiation of the celestial sphere in the terahertz frequency region (0.5 - 3.0 THz), as a result of what they are expecting an abundant information which will bring us forward to the significant broadening of our ideas about the Universe and events taking place in it.

First of tasks on this way is the systematic observation of definite regions of the celestial sphere with the purpose to map the brightness of a distributed radiation and compile catalogues of discrete sources keeping in mind the finding objects unknown earlier as well as the obtaining the ranging of sources in accordance with their intensity and other characteristics what is necessary for the understanding the structure of the Galaxy and the Universe as a whole. The gap between the observation data of the celestial sphere radiation in the centimeter and infrared waveband regions is too big to permit at least slightly reliable oncoming extrapolation into the region of millimeter and submillimeter waves (or terahertz frequency band).
Next task is the investigation of the background radiation solving which, one may discover characteristics of as the distributed objects (the radiation of interstellar and interplanetary dust, initial background radiation) so the total radiation of spatially unresolved objects. Main goal

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here is the investigation of the initial background radiation (3 K) and its anisotropy on scales less than 10 angle degrees up to 5 angle minutes in Wien region of electromagnetic spectrum.

Further we have to indicate tasks of investigation of selected objects: spectra of discrete sources (stars, galaxies, quasars, active galaxy nuclei); radiation intensity time variations of quasars and active galaxy nuclei; the atmosphere radiation observation of planets and their satellites; the investigation of dust in the Solar System, the Galaxy and extragalactic formations.

Here we have indicated just some of tasks of the contemporary terahertz radio astronomy. One may find the impressive description of these and many other tasks in the said region of spectrum in the Proceedings of the European Space Agency Symposium named "The Far Infra-Red and Submillimetre Universe", taken place in Grenoble, France, on April 15-17, 1997 [4]

Geophysical tasks are adding to the astrophysical tasks in the terahertz frequency region [5]: the global monitoring of the Earth ozone sphere, including the study of the ozone content distribution in the Earth atmosphere and its variations; the global monitoring of the anthropogenic Earth atmosphere pollution etc.

To attack mentioned above tasks the receivers of the radiation in various bands of the terahertz frequency region, having highest sensitivity and different frequency resolution: high, medium and low, are necessary. To the present time three groups of such receivers have become clear as the result of the research and developments of many institutions. We are describing below these three groups after the example of the already formed groups of the receivers for multi-chanel ***FIRST*** telescope (Far InfraRed and Submillimeter Telescope) of the European Space Agency

1) The superheterodyne receivers based on SIS-mixers at frequencies 0.5-1.25 THz and on superconducting hot-electron bolometers at frequencies 1.25 - 2.5 THz. The achieved characteristic noise temperatures here are: 80 K at 0.5 THz, 750 K at 1.0 THz and 1900 K and 2500-3000 K at 1.3 and 2.5 THz correspondingly; the frequency resolution: $R = f/\Delta f = 1.2x10^7$; the operating temperature of these receivers - 4.2 - 2.0 K [6].

2) Direct detection receivers based on bolometers at frequences 0.5 - 1.5 THz. The characteristic noise equivalent powers estimated in accordance with measurements on dc (so-called electrical NEP) here are $\sim 2x10^{-18}$ $W/Hz^{1/2}$; the frequency resolution $R \sim 10^3$ when working together with grating or Fabry-Perot spectrometers; the time constant is 65 ms; the operating temperature of bolometers is ~0.1 K [7, 8].

3) Direct detection receivers based on photoconductors at frequencies 1.5 - 3.5 THz. The achieved characteristic noise equivalent powers (NEP) here are $\sim 4x10^{-18}$ $W/Hz^{1/2}$; the frequency resolution $R \sim 2\ x10^3 - 2\ x10^4$ when working together with Fabry-Perot spectrometer; operating temperature is ~1.7 K [9].

The direct detection receivers based on photoconductors are only ones being most sensitive of known now receivers at frequency region ~1.5 - 3.5 THz. The selection of two types of receivers for frequency region 0.5 - 1.5 THz, superheterodyne and direct detection types, is led mainly to the reason that when they are observing weak but broadband radiation sources it may occure that the integral sensitivity of narrowband superheterodyne receivers could be not enough and at the same time the bolometer owing to its very wide frequency band will detect this radiation. Besides as bolometers don't need heterodyne pumping it is much easier to construct on their basis multi-element receiving structures for an observation spatially inhomogeneous distributed radiation sources though having not too high frequency resolution.

The Earth-based operation of all considered receivers is limited by the atmosphere that is not enough transparent in 0.5 - 3.0 THz frequency region. At the same time all measures right up to cool receivers down to 0.1 K are taking as regards to achieve ultimate low noise equivalent power. Measures are taking also to cool antennae and radiation guided elements to reduce significantly their thermal noise coming

Thus it can be concluded that the receivers based on bolometers are playing among other receivers their own important part in the terahertz radio astronomy.

2. The Submillimetron Project. The Submillimetron Project [3] is dedicated to solve most of said above tasks of terahertz radio astronomy using the Cryogenic Telescope located on the Russian segment of the International Space Station (ISS). The Astro Space Center of the P.N. Lebedev Physical Institute of the Russian Academy of Sciences is responsible for developing the Submillimetron Project. The Project was selected by the Russian Academy of Sciences in 1997 along with seven other Russian experiments as candidates for scientific radioastronomical payloads on the Russian segment of the International Space Station (Fig. 1). Currently the Astro Space Center is carrying out pre-project study under the contract with Russian Space Agency. If the Project will succeed experiments with the onboard cryogenic telescope can be performed between the years 2001 and 2004. Besides said above tasks the secondary goal of the Submillimetron Project is to provide a test bed to perform the technological experiments needed to develop follow on projects.

The Submillimetron Project intends to fill the time gap between the IRAS, COBE and the follow on projects SIRTF, FIRST and PLANCK. If it succeeds it can provide information on research targets for these projects as well as test/resolve some technological issues needed to build these telescopes.

The uniqueness of the proposed telescope lies in the deep cooling of the entire telescope and even deeper cooling of the detectors (bolometers and photoconductors) to achieve a high sensitivity at terahertz frequency band. Comparative sensitivity performances of the telescopes of the flown project (IRAS and COBE) and projects under development (SIRTF. FIRST, PLANCK) and Submillimetron Telescope are given in Fig.Fig. 2 and 3.

Telescope concept. The telescope payload consists of the Cryogenic Telescope itself and the Data Registration and Processing Unit.

The telescope will be positioned on the Russian Segment of the International Space Station (Fig.4). The telescope assembly shall be oriented in such a way as to preclude interference from the thermal radiation of the station elements, and the Sun and Earth. The angle between the optical axis of the telescope and the directions to these objects shall be larger than 60 degrees in all possible telescope pointing positions.

The data registration and processing block will be located in one of the scientific modules of the Station and connected with the telescope assembly by a cable.

The Cryogenic Telescope parameters are:

Diameter: D = 0.6 m,
Focal length: F = 4 m,
Wavelengths:
- submillimeter band: 0.3, 0.4, 0.5, 0.6, 0.8, 1.0 and 1.5 mm,
- infrared band: 3, 10, 30, 100, 200 μm.

Cooling:
- telescope as a whole: 5 K,
- detectors (bolometers): down to 0.1 K,

Detectors:
- bolometer arrays.

Number of elements in the detector arrays:
- about 100 at wavelengths shorter than 0.5 mm,
- 7 elements at the wavelength 1.5 mm.

Angular resolution:
- submillimeter band: 5-20 min of arc,
- infrared band: 5 min of arc.

Sensitivity of the detectors:
- submillimeter band: 10^{-18} W/Hz$^{1/2}$,
- infrared band: 10^{-17}-$3 \cdot 10^{-16}$ W/Hz$^{1/2}$.

Sensitivity of the telescope (integration time = 1 s):
- submillimeter band: 3-12 mJy,
- infrared band: 6-40 mJy.

<u>Cryogenic Telescope</u> (see Fig. 5) includes following main units:

	Mass (kg)/Power (W)
- Optic Cryogenic Assembly (OCA)	300/40,
- Active Cooling System (ACS)	30/300,
- Telescope Electronics Assembly (TEA)	10/10,
- Telescope Pointing System (TPS)	90/80,
- Star Tracker (STR)	10/10,
Total	440/440.

<u>Technical Requirements on Active Cryogenic System (ACS):</u>

-The ACS system shall provide cooling of the internal screens of the Optic Cryogenic Assembly (OCA) from 300-350K to the screens operating temperature of 20K,
- Load temperature = 20 K,
- Minimum heat load = 1 W,
- Power consumption = 300 W,
- Maximum mass = 30 kg,
- Power voltage = 23-34 V.

<u>Technical Requirements on Star Tracker (STR):</u>

-The Star Tracker shall define the telescope optical axis pointing information (two perpendicular axes in the plane perpendicular to the optical axis and the rotation angle) and provide the correction signals to the Telescope Pointing System (TPS),
- Accuracy of the telescope pointing axes = ±10 arc sec,
- Accuracy of the telescope rotation angle axis = ±1 deg,

Telescope pointing data rate = 1 point per 10 sec,
- Power consumption = 10 W,
- Maximum mass = 10 kg.

Bolometric array concept. Scientific objectives connected with observation of extremely distant objects determines main features of the instruments and requirements for the detectors. In accordance to the main goal of the experiment - to achieve extremely high sensitivity in spectral density of continuum emission, this features includes: wide spectral bands and simultaneous observation in all spectral and spatial channels, maximum number of spatial elements in field of telescope, minimum instrumental thermal emission of cryogenic optics comparable with extraterrestrial background. Spectral region 0.3 -1.5 mm correspond to minimum in spectral density of this background. Corresponding requirements are the following:

- Wavelengths: 0.3, 0.4, 0.5, 0.6, 0.8, 1, 1.5 mm,
- Bandwidth: 10 - 30% of the observing frequency,
- Number of elements in the bolometer arrays:
  - about 100 at wavelengths 0.3 - 0.4 mm,
  - 7 elements at the wavelength 1.5 mm,
- Sensitivity of the bolometers: $\leq 10^{-18}$ W/Hz$^{1/2}$.

The last figure corresponds to measure of fluctuations in number of quanta in background radiation and can be achieved only with thermal detectors (bolometers). For phase sensitive receiver (heterodine mixer) in accordance to indefinity principle the noise temperature is restricted by a value about hf/k.

3. Normal-metal hot-electron microbolometer based on Andreev reflection effect. Taking into account the said above requirements to the bolometer receiver for the Terahertz Cryiogenic Telescope we have chosen one of most promissing bolometers - the normal-metal hot-electron microbolometer [1, 2] based on the Andreev reflection fenomenon [10] which is based on the heating electrons in the thin film of normal metal with electrodes of metal-superconductor (in the so-called S-LN-S structure (Fig. 6), where "S" means the superconductor and "LN" means the long film strip of normal metal), cooled down to extremely low temperatures of order of 100 - 200 mK. Briefly, the construction of the said microbolometer is the following: the comparatively simple structure consisted of normal metal strip (Cu, Cr or some other normal metal) with the dimensions: length - 3 - 12 μm, width - 0.1 - 0.3 μm and thikness - ~40-75 nm - with the Al or Pb superconducting electrodes at the ends and with S-I-N (superconductor-insulator-normal metal) tunnel junction at the central part of the strip - is evaporated under three angles onto the silicon substrate obtained by means of the usual electron-beam lithography using shadow evaporation technique. The radiation is absorbed by electrons in the strip of normal metal. Two circumstaces lead to the effective heating of electrons by the radiation: (a) the super low temperature (0.1 - 0.3 K) owing to what the interaction between electrons and substrate through electron-phonon collisions and therefore the energy transfer from electrons to the substrate lattice (low heat conductance G) is extremely low and (b) the phenomenon of Andreev reflection of electrons at the normal metal - superconductor boundary which takes place without the energy transfer of electrons to the superconducting electrodes at all [10]. At temperatures < 1 K the electrical resistance of the normal metal strip doesn't depend on temperature. By this reason the temperature increment of electrons in the strip is measuring by means of the mentioned above S-I-N tunnel junction. For the best matching of the bolometer with an incident radiation beam including the providing the maximum capture of the receiving radiation as in case of single so in case of multi-element receiver the log-periodic antenna (Fig.7) is integrated on the same substrate. The bolometer is placed in the center of the antenna.

The estimation of noise equivalent power (NEP) of the normal-metal hot-electron bolometer (NHEB). The shape of IV curve of the S-I-N tunnel junction depends on the electron temperature in the normal part, and by biasing the junction with a constant current and measuring voltage on it we can get a responce $\Delta V(T)$ linear in a rather wide range.

There are three major components contributing to the NEP of NHEB according to the expression:

$$NEP = \left[4k_B T_e^2 G + \frac{V_j^2}{S^2} + \frac{V_n^2}{S^2} \right]^{1/2}, \qquad (1)$$

where T_e is the temperature of electrons in the absorber (thin metal film), $G=dP/dT$ is the thermal conductance for the outflow of signal-induced heat, $S=dV/dP= dV/dT \cdot G^{-1}$ is the power responsivity of the bolometer, V is voltage noise of the SIN-junction and V_n is voltage noise of an amplifier. The first term describes the electron temperature fluctuations in the absorber and sets the fundamental noise limit for a given device at a given temperatire. It is clear from the expression above that it is mostly the small G that provides comparatively low NEP in this type of bolometer.

For an experimental verification of the NEP several test samples of the NHEB were fabricated. We performed measurements of IV curves of the SIN-junction at different temperatures and with different dissipated power from the signal current (Fig.8). The dependence of the voltage V at constant bias current through the junction on the signal current I_{ABS} in the absorber was measured at constant temperature for two devices with different absorber lengths. The corresponding curves $V(I)$ for the two devices are almost overlapped (Fig.9). The derivative dV/dI_{ABS} directly related to the form of the curve can be expressed via temperature responsivity, inverse thermal conductivity and dP/dI_{ABS}:

$$\frac{dV}{dI_{ABS}} = \frac{dV}{dP} \cdot \frac{dP}{dI_{ABS}} = \frac{dV}{dT} \cdot \left(\frac{dP}{dT}\right)^{-1} \cdot \frac{dP}{dI_{ABS}}.$$

One can find from the Joule law

$$P = P_{Joule} = I_{ABS}^2 R \Rightarrow \frac{dP}{dI_{ABS}} = 2RI_{ABS}..$$

The inverse thermal conductance can be found from the expression for the heat excange in case of the hot-electron effect:

$$P_{e \to ph} = \Sigma U \left(T_e^5 - T_{ph}^5\right) \Rightarrow \frac{dP}{dT} = 5\Sigma U T^4, \qquad (2)$$

where Σ is a material-specific parameter and we assume equilibrium, $P_{Joule}=P_{e \to ph}$. After substitution we get

$$\frac{dV}{dI_{ABS}} = \frac{dV}{dT} \cdot \left(\frac{2I_{ABS}R}{5\Sigma T^4 U}\right) \propto \frac{R}{U}. \qquad (3)$$

The overlapping of the curves means then, that increase of dissipated power (P) due to higher resistance (R) has been exactly compensated by increase of the heat conductance due to larger volume (U), i.e. no substantial thermal transport through the NS-contacts has been present. The dependence $V(I_{ABS})$ was then re-calculated to give $V(P)$. Maximal power responsivity at an optimal I_{bias} = 0.3 nA was found to be $S_{max}=|dV/dP|=3 \cdot 10^7$ V/W. Combining the data $V(I_{bias}, T)$ and $V(I_{bias}, P)$ the dependence $P(T_e)$ could be calculated (Fig.10).

From a fit to the expression (2) we could find the parameter $\Sigma = 3 \cdot 10^{-9}$ $nW \cdot K^{-5} \cdot \mu m^{-3}$ and consequently the thermal conductance $G = 6 \cdot 10^{-12}$ W/K at 300 mK. This value is twice as low as the one which can be calculated using the data from [1]. This decrease was due to the smaller volume of the absorber in our case. The thermal fluctuation component of the NEP (1) calculated for the value of G is about $5 \cdot 10^{-18}$ $W/Hz^{1/2}$. At 100 mK the thermal conductance was considerably decreased to $G = 7 \cdot 10^{-14}$ W/K. This value of G gives a thermal fluctuation noise component of the total NEP=$2 \cdot 10^{-19}$ $W/Hz^{1/2}$ which is well below the requirements for the Cryogenic Telescope (see the paragraph 2) as well as the ESA requirements for the total NEP for future spaceborn bolometers [11].

The thermal time constant can be computed as $\tau = C/G$ where C is the electron heat capacity. For the obtained value of Σ we get $\tau = 5T^3$ ns. At T=300 mK the time costant $\tau = 0.2$ μs and at T=100 mK the time costant $\tau = 5$ μs which is considerably shorter as what is typically required and much lower of 1 s what is the integration time of the Cryogenic Telescope (see the paragraph 2).

The recently measured sensitivity of the Andreev microbolometer about $5 \cdot 10^{-18}$ $W/Hz^{1/2}$ is presented in detail in separate paper at this Symposium [12].

REFERENCES

[1] **Ultrasensitive hot-electron microbolometer**, M. Nahum and John M. Martinis, Appl. Phys. Lett., **63** (22), 29 November 1993, pp. 3075-3077.

[2] **Andreev reflection based normal metal hot-electron bolometer for space applications,** A. Vystavkin, D. Chouvaev, L. Kuzmin, M. Tarasov, P. Sundquist, M. Willander and T. Claeson, Proc. of 4th International Conference on Millimeter and Submillimeter Waves and Applications, July 20-23, 1998, San Diego, USA, pp. 441-448.

[3] **Development of a Submillimeter Wave Criogenic Telescope for the Russian Segment of the International Space Station (ISS). Project Submillimeteron.** L. Kuzmin, N. Kardashev, V. Kurt, V. Gromov, A. Trubnikov, V. Altunin, M. Tarasov, D. Chouvaev, D. Golubev, A. Vystavkin, M. Willander, T. Claeson, The 2nd European Symposium on the Utilization of the International Space Station, ESTEC, Noordwijk, The Netherndls, November 16-18, 1998.

[4] **The Far InfraRed and Submillimetre Universe,** An ESA Symposium devoted to the Far InfraRed and Submillimetre Telescope (FIRST) mission, 15-17 April, 1997, Institut de Radio Astronomie Millimetrique (IRAM), Grenoble, France, complete volume.

[5] **The Choice of Main Spectral Characteristics of the Limb Spectrometer for Small Atmosphere Gas Components Measurements,** V.D. Gromov, E.N. Kadygrov, A.S. Kosov, M.G. Sorokin, I.A. Strukov, The Investigation of the Earth from the Space, 1991, N 5, pp. 16-21 (In Russian).

[6] **The HIFI Heterodyne Instrument for FIRST: Capabilities and Performance,** N.D. Whyborn, [4], pp. 19-24.

[7] **The Design of a Bolometer Instrument for FIRST**, M.J. Griffin, [4], pp. 31-35.

[8] **A Monolithic Bolometer Array Suitable for FIRST**, J.J. Bock, H.G. LeDuc, A.E. Lange, J. Zmuidzinas, [4], pp. 349-352.

[9] **An Optimised Photoconductor Instrument for FIRST**, A. Poglitsch, [4], pp. 25-30.

[10] **Thermal Conductivity of the Intermediate State of Superconductors**, A.F. Andreev, Sov. Phys. JETP, 1964, November, **19**, pp. 1228-1231.
[11] **ESA Tender AO3288 "Hot-electron Microbolometers Technology for IR and Sub-mmw Application",** Open Date: October 2, 1997.
[12] **Optimization of the normal metal hot-electron mictobolometer,** D. Chouvaev, D. Golubev, M. Tarasov, L. Kuzmin, T. Claeson, this Symposium, page ...

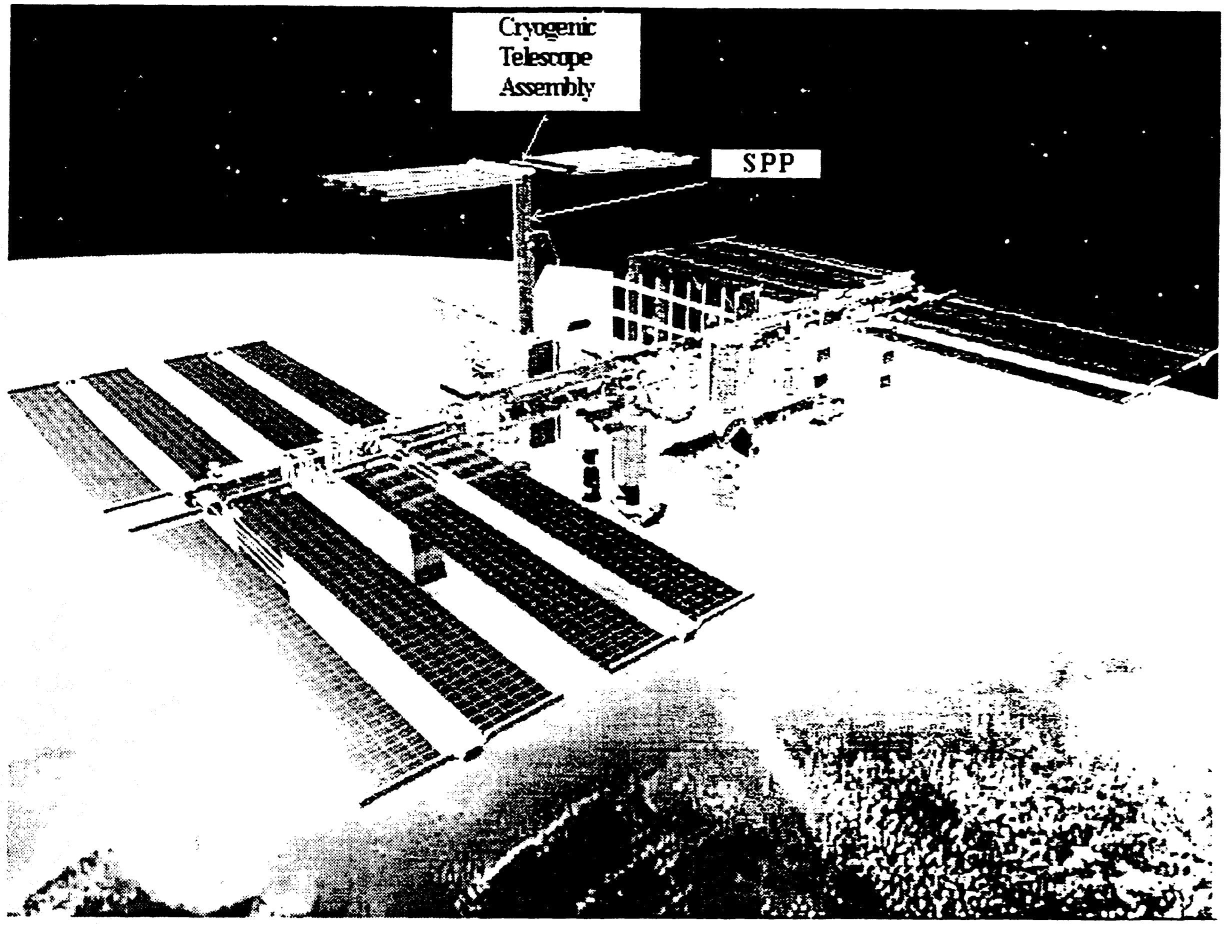

Figure 1. The International Space Station. General view shows a position of the Cryogenic Telescope Assembly and Science-Power Platform (SPP).

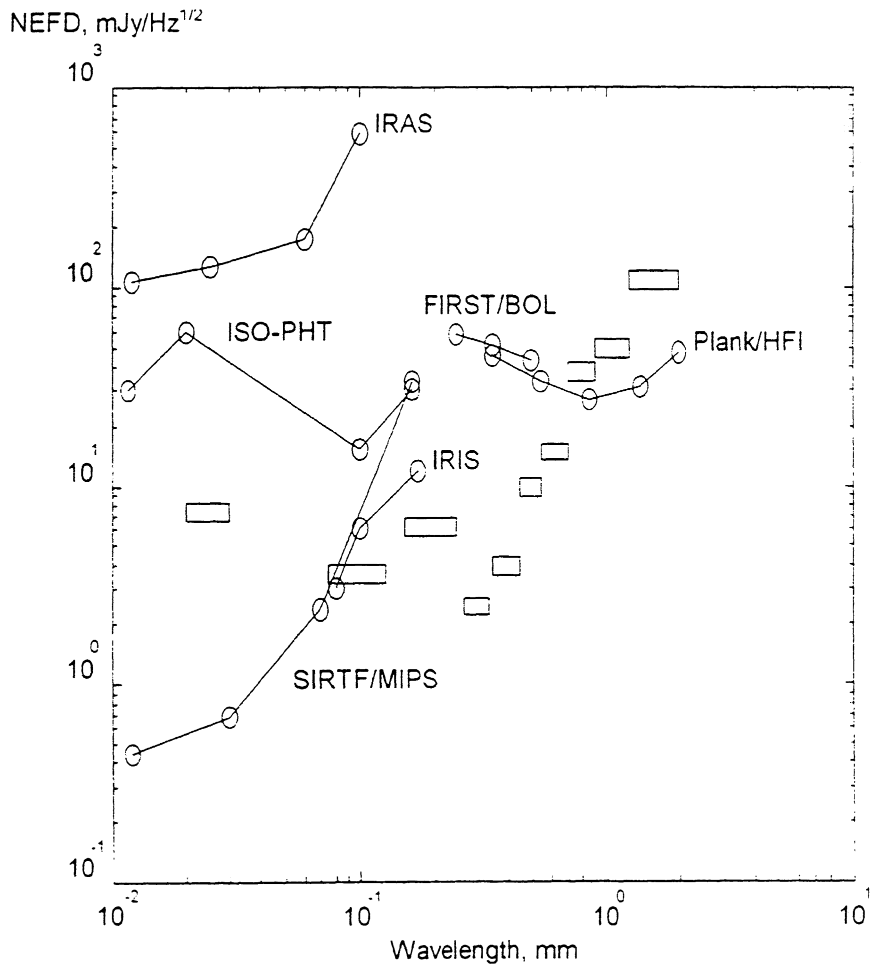

Figure 2. The sensitivity related to discrete sources. Rectangles - the Submillimeteron Project, circles - other projects. NEFD - noise equivalent flux density.

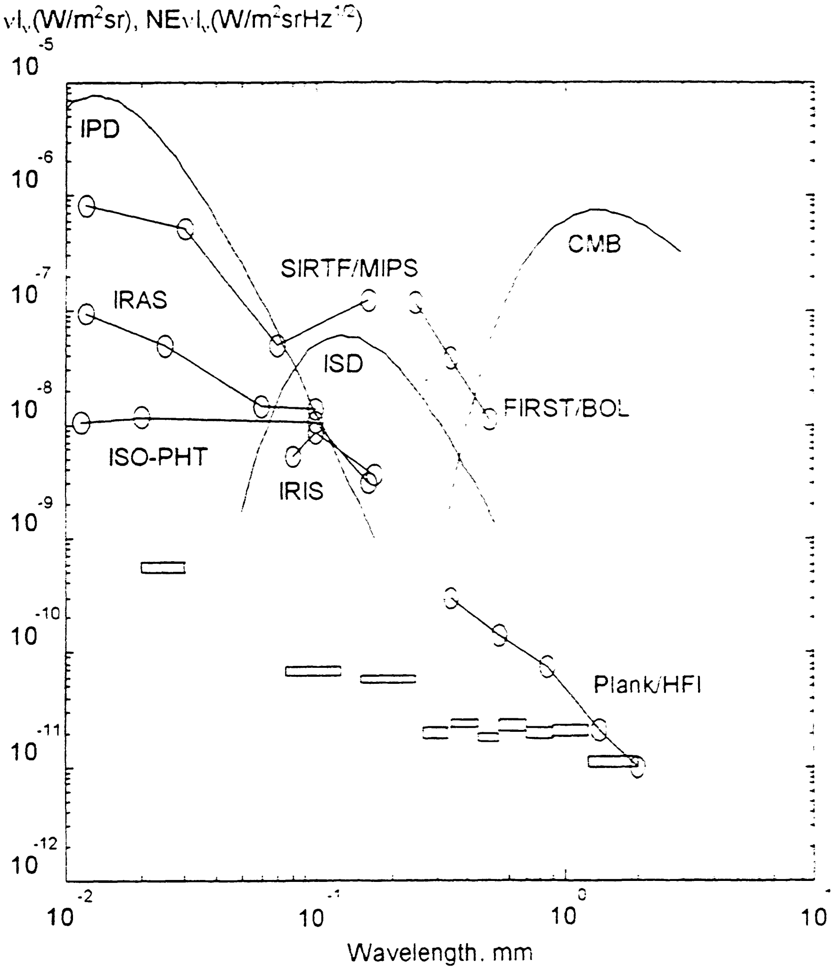

Figure 3. The sensitivity related to brightness of extended sources. Rectangles - the Submillimetron Project, circles - other projects. NE νI_{ν} - noise equivalent brightness with S/N=1. The brightness of sources given for comparison: CMB - cosmic microwave background, ISD - interstellar dust emission, IPD - interplanetary dust emission.

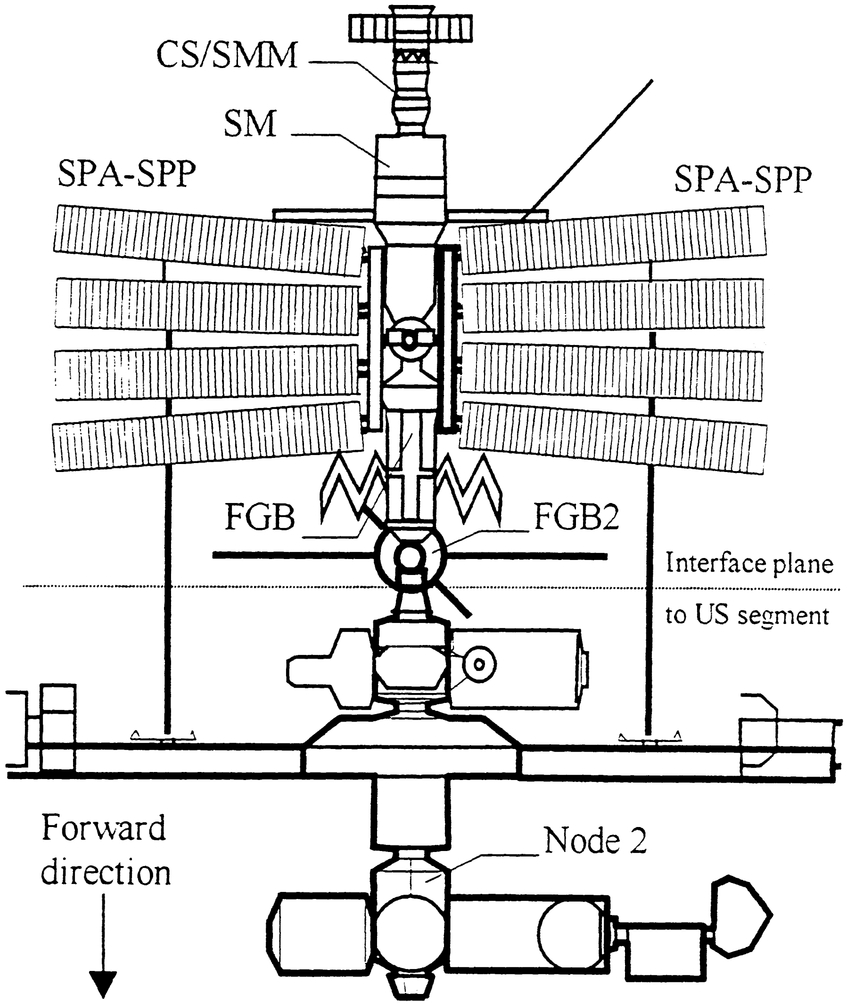

Figure 4. International Space Station. Top view. CS/SMM - Cargo Ship "Progress" (the Submillimetron telescope in the special transport bay); SM - Service Module with remote manipulator; SPA - Solar Power Array; SPP - Science-Power Platform. Large SPA's on both sides of US segment are not shown.

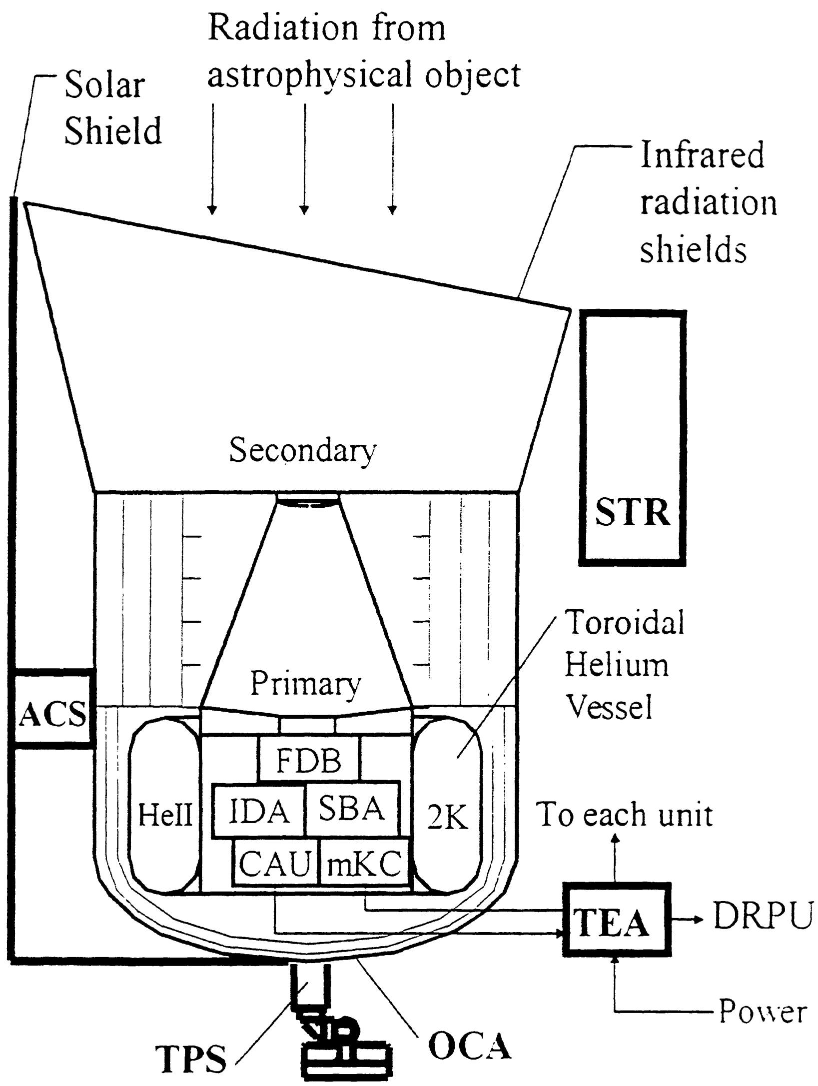

Figure 5. Block-diagram of the Cryogenic Telescope. FDB - Focal Dichroic Beam-splitters assembly; IDA - Infrared Detector Array; SBA - Submillimeter Bolometer Array; CAU - Cool Amplifiers Unit; mKC - milli-Kelvin Cooler (100-300 mK); DRPU - Data Registration and Processing Unit.

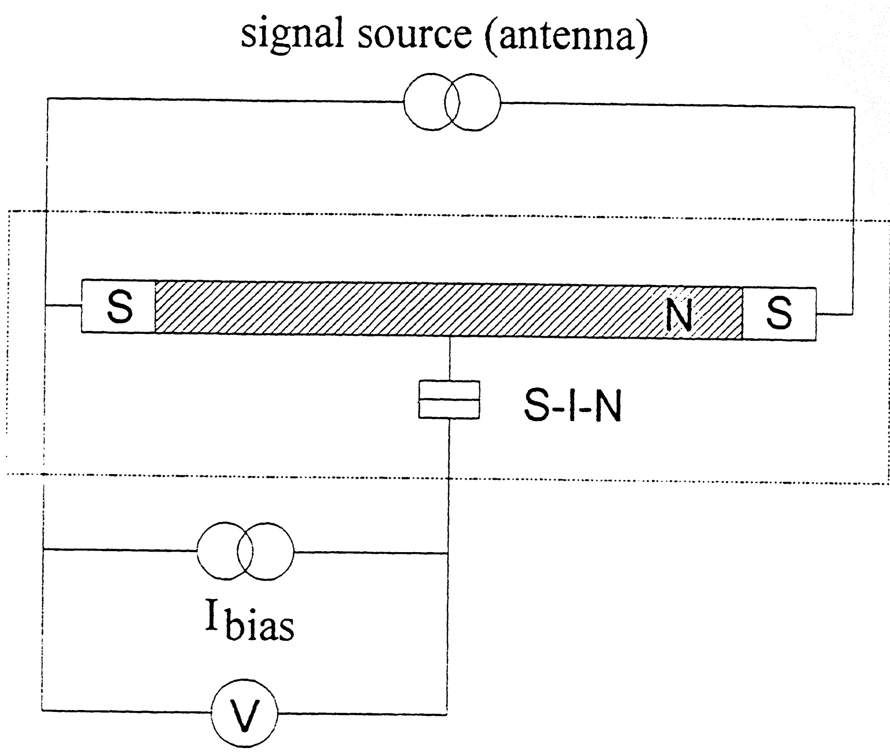

Figure 6. Schematic of the microbolometer: the SIN junction is biased at a small constant current. A junction voltage depends on the smearing of the IV-curve which is used to measure the electron temperature in the normal metal absorber (hatched).

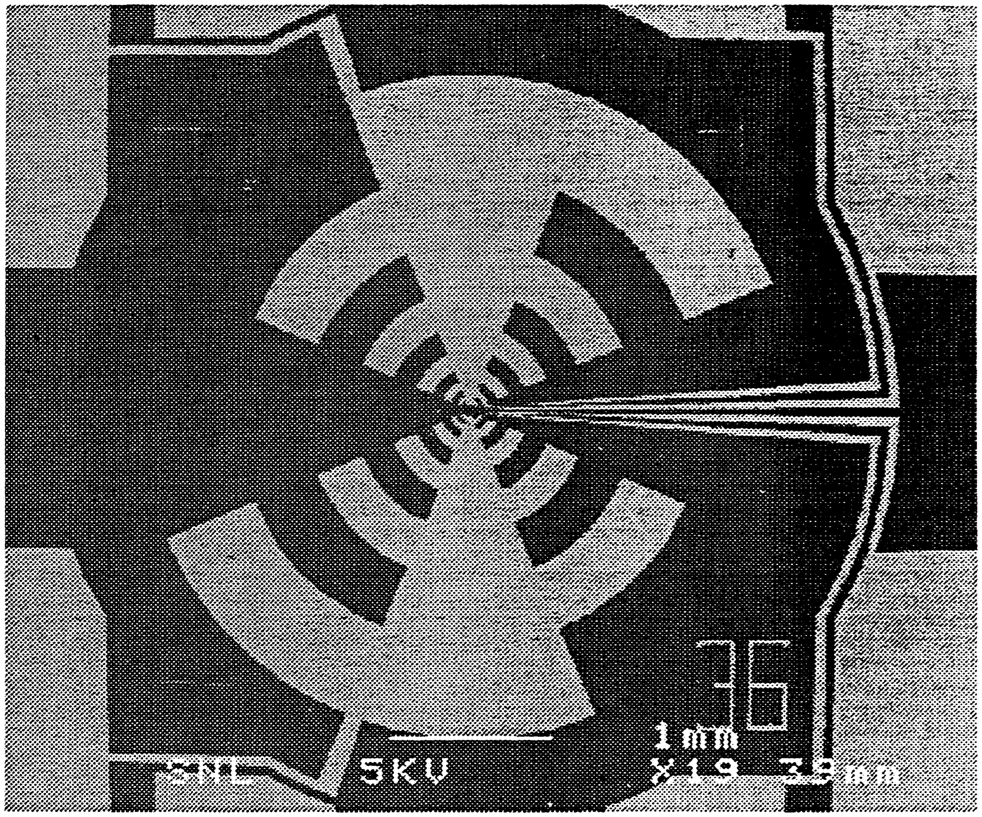

Figure 7. View of a chip with a planar log-periodic antenna and the microbolometer in the focus of the antenna designed for device tests at 100-1000 GHz.

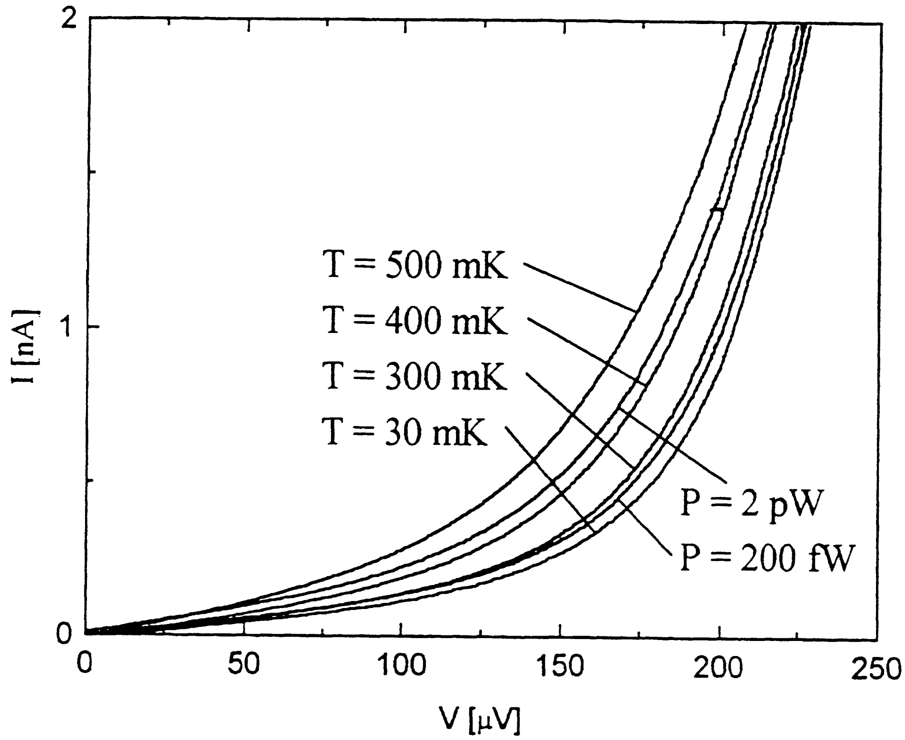

Figure 8. IV-curves of the SIN junction measured for different temperatures without any signal current and for two different powers dissipated by the signal current at the base temperature of 30 mK.

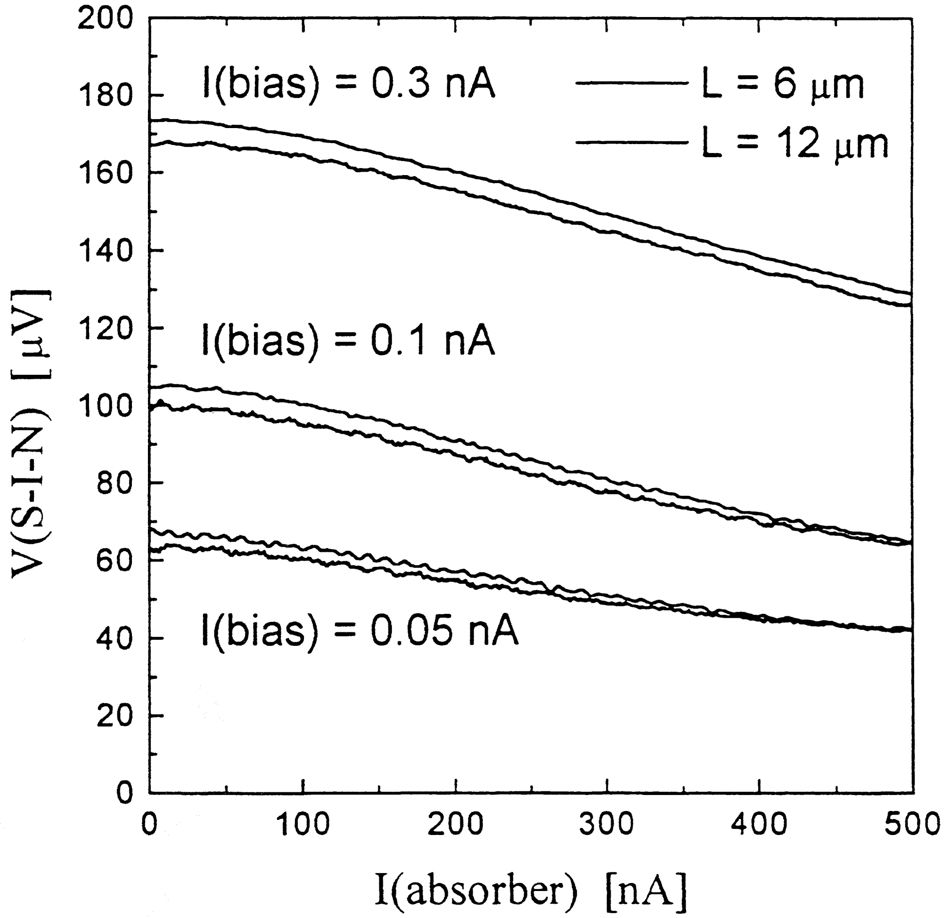

Figure 9. The junction voltage V at constant bias current I_{bias} through the junction as a function of the signal current I_{ABS} for two devices with different absorber lenght 6 μm and 12 μm at T=30mK.

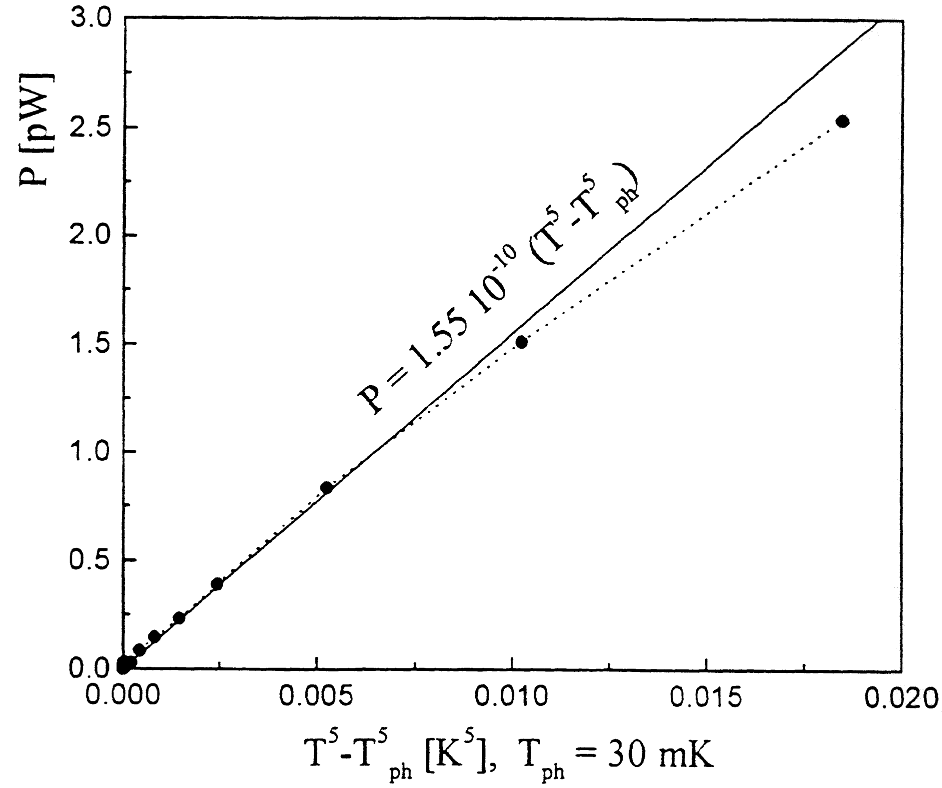

Figure 10. Power dissipated in the absorber vs. (T^5 -T^5_{ph}) where T is temperature of electronsdeduced from measurements $V(I_{bias}, T)$ and T_{ph}=30 mK is temperature of the lattice (measured temperature of the sample holder). Linear fit corresponds to the relation (2).