Submillimeter and millimeter wave sky mapping in the space project Submillimetron

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Abstract. Submillimetron is an international project of the space telescope for astronomical studies at submillimeter and millimeter wavelengths using free-flying spacecraft and facilities of the Russian segment of the International Space Station. The payload is the 60-cm telescope cooled to liquid helium temperature with arrays of a novel type detector, Normal-metal Hot-Electron Bolometer (NHEB). The angular resolution is 1-10 arcmin, field of view - about 1 degree, detectors sensitivity - about 10^{-18} W/Hz$^{1/2}$, spectral region - 0.2 - 2 mm. Parameters of the instrument and complementarity to other experiments including CMB measurements are discussed.

INTRODUCTION

A general aim of modern astrophysics and fundamental physics is to understand the processes by which the universe evolved from initial simplicity to complexity visible now in all scales. This evolutionary approach to astronomy was clear enough in early sixties along as understanding of importance of submillimeter waves. At that time our activity was initiated in this region for ground-based [1-3] and for air and space [4-6] observation. In 70's – 80's the perspective concepts of submillimeter space telescopes were determined: fully cryogenically cooled one similar to [7] and [6], radiatively-cooled like [8], and deployable reflector [9]. Last concept is more adapted for large mirrors but at cost of larger complexity. It is under development now in Millimetron project [10]. Radiative cooling was proposed for project POIROT and later for project EDISON [8] in combination with machine-cooling, lightweight mirror and very distant orbit (L2). The concept was finally accepted by ESA in 1993 for realization in 2007 in large projects Hershel (previously FIRST) [11, 12] and Planck (previously COBRAS/SAMBA) [13, 14]. As noted in review [15], the principles of space-suitable cryocoolers were defined in 60's [16, 17] and Planck already included close-loop refrigerators. Hershel uses a large ISO-like cryostat. Both systems maintain low-level temperature only for focal devices. Radiatively cooled mirrors have thermal emission greater than extraterrestrial background in submillimeter spectral region. A goal of background-limited sensitivity may be achieved by use of a cryogenically cooled telescope in project Submillimetron [18-21].

CONCEPT OF SUBMILLIMETRON PROJECT

Sensitivity of sensors is a main factor defining possibilities to observe faint distant objects. Fundamental limit of direct detector sensitivity δP depends on background power P_{bg} as $\delta P^2=n(n+1)m(h\nu)^2\Delta\nu$, where $\Delta\nu$ is spectral bandwith, $h\nu$ - energy of photons, $m=g(A\Omega)/\lambda^2$, $g=2$ (for one polarization $g=1$), $(A\Omega)$ – geometrical factor, λ - wavelength. A value of n is determined by $P_{bg}= nm(h\nu)\Delta\nu$. Here is an important difference with receivers using front-end mixers or amplifies, which noise limit is proportional to $(n+1/2)$ and can't be very small even at low background. $P_{bg}= \varepsilon(e^{h\nu/kT}-1)^{-1}m(h\nu)\Delta\nu$, where k is Boltzmann constant, T- temperature, ε - emissivity. Background with surface brightness νI_ν produces $P_{bg}=(\nu I_\nu)(A\Omega)(\Delta\nu/\nu)$. It was noted in [22] that previously used simplified evaluation $\delta P=\varepsilon^{1/2}\delta P_{\varepsilon=1}$ overestimated δP in submillimeter and mm regions where usually $n_{\varepsilon=1} > 1$.

Extraterrestrial background was measured by instruments on COBE satellite [23]. Submillimeter brightness spectra was determined in [24] and shown in Fig. 1 (left). Instrumental emission spectra are shown in Fig. 1 (right).

Even for low emissivity (ε=1%) of radiatively cooled mirrors (T > 10-40 K) their emission sufficiently exceeds that of the background. A cryogenically cooled telescope can reach background-limited sensitivity with detector "noise equivalent power" (*NEP*) of 10^{-19}-10^{-18} W/Hz$^{1/2}$ comparable with δP_{bg}. Principles of such devices were proposed in early 90's [25, 26] along as principles of electron cooling [27, 28]. In both cases, superconductor-insulator-normal metal (SIN) tunnel junctions were used. Novel detector technologies for extremely low astronomical backgrounds permit to reach unique observational sensitivity even for moderate size telescope.

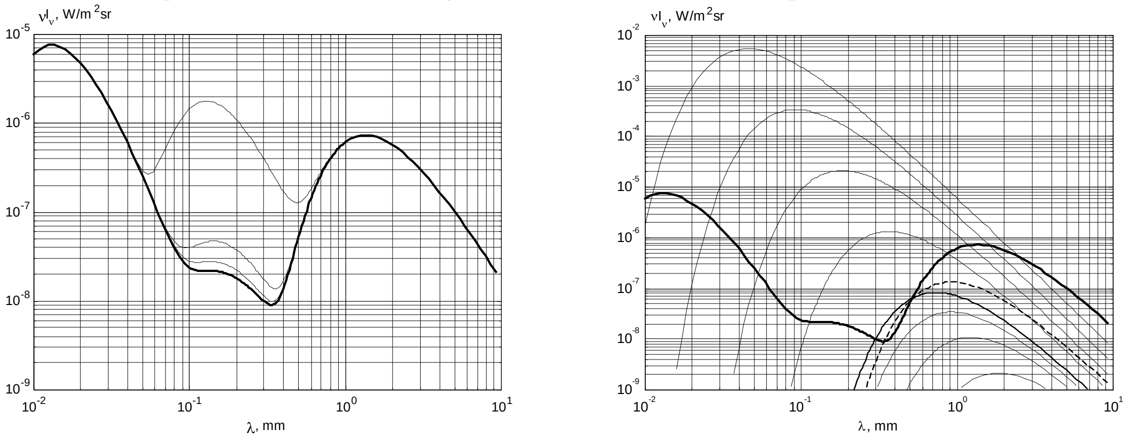

FIGURE 1. Spectra of background brightness νI_ν, W/m^{2}sr. Left panel: extraterrestrial background [24] in regions with galactic coordinates $b>60^o$, $30^o<b<60^o$, $10^o<b<30^o$, and $b=0$, $l=180^o$ corresponds to curves from bottom to top. Right panel: instrumental background for temperatures of telescope mirrors T = 80, 40, 20, 10, 5, 4, 3, and 2 K corresponding to thin curves from top to bottom, and emissivity ε=0.01; dashed curve - ε=0.04, T= 5 K. Thick solid curve shows extraterrestrial background for comparison.

International project Submillimetron [18-21] has been initiated by Astro Space Center of Lebedev Physical Institute. It uses a spacecraft with cryogenically cooled submillimeter telescope [20] flying separately from the International Space Station (ISS). The concept of a free-flying module with periodic docking to the ISS gives possibility to combine a low cost with reliability, refilling, repairment and maintenance. Main parameters of the instrument are given in Tables 1 for telescope of diameter 0.6 meters and with *NEP* of NHEB of 10^{-18} W/Hz$^{-1/2}$ [29-30]. The NHEB uses SIN tunnel junction as a temperature sensor. SQUID readout gives additional flexibility for combining the detectors in arrays providing opportunity for low noise multiplexing. Additional advantage of "built-in" electron cooling is compensation of background power load for bolometers [31]. As shown on Fig. 1, intensity of the background varies more than an order of magnitude depending on Galactic coordinates.

TABLE 1. Parameters of the submillimeter photometric instrument

λ_L, mm	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.5	2.0
λ_S, mm	0.15	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.5
θ, arcmin	1	1.4	2	2.6	3.2	4	5.2	7.2	10
P_{bg}, fW	0.09	0.2	0.54	1.7	4.4	24	54	244	300
δP_{bg}, W/Hz$^{-1/2}$	$3\cdot10^{-19}$	$4\cdot10^{-19}$	$5.5\cdot10^{-19}$	$8.7\cdot10^{-19}$	$1.3\cdot10^{-18}$	$2.6\cdot10^{-18}$	$3.4\cdot10^{-18}$	$6.3\cdot10^{-18}$	$6\cdot10^{-18}$
δP_{tot}, W/Hz$^{-1/2}$	$1\cdot10^{-18}$	$1.1\cdot10^{-18}$	$1.1\cdot10^{-18}$	$1.3\cdot10^{-18}$	$1.6\cdot10^{-18}$	$2.8\cdot10^{-18}$	$3.6\cdot10^{-18}$	$6.4\cdot10^{-18}$	$6.1\cdot10^{-18}$
NEFD, mJy/Hz$^{1/2}$	0.76	0.8	1.7	3.2	5.7	8.1	17	23	44
$NE\nu I_\nu$ $pW/m^2srHz^{1/2}$	120	43	33	29	29	20	20	10	6.9

Temperature of mirrors $T = 5$ K and total emissivity ε = 1% were used for estimations of P_{bg} and δP_{bg} in Table 1. Rise of ε to 4% leads to rise of δP_{tot} not greater than 35% in the worst case. The NHEB detector as an antenna-coupled microbolometer is optimal for high-resolution observations (diffraction limited, polarization sensitive) corresponding to $m=1$, $g=1$. The δP_{tot} includes noise of background and detector. For NHEB temperature of $T = 0.1$ K the used *NEP* is a "pessimistic" value. The wavelengths λ_L and λ_S are long-wave and short-wave boundaries of spectral bandwidths. Angular resolution $\theta=\lambda/D$. *NEFD* is noise equivalent of flux density for observations of point sources, $NE\nu I_\nu$ is noise equivalent of brightness for measurements of extended emission.

An orbit of Submillimetron is that of the ISS with period 90 min, very low eccentricity, 51.6 ^{o} inclination and altitude up to 425 km. During observation a large enough distance from the ISS is possible. Due to precession of the orbit ~5^o/day, any sky point is observable several times on neighborhood turns and ~10 times a year during repetition of sky survey. Multiple observations give tools for separation of moving bodies of Solar system and for investigation of flux variability. Each observation continues 0.2-2.5 s and total integration time increases as number of paths.

SCIENTIFIC OBJECTIVES AND COMPLEMENTARITY TO OTHER PROJECTS

Confusion-limited full-sky survey is a main goal of the Submillimetron experiment. It should reveal more than 10^6 individual sources in submillimeter spectral region. Information for these wavelengths has foremost importance for cosmology and problems of galaxies and stars formation. General interest should represent unbiased data on submillimeter spectral distributions and their variability in scale between an hour and a year. It shouldn't be underestimated the significance of massive data-sets on clusters of galaxies (SZ effect), active galactic nuclei (AGN), old and young stars (AGB, envelopes, protoplanetary disks). Catalog (database) of sources even with spectra and variability is relatively small extract from experimental data. Most of them should be in form of maps of brightness distribution for all spectral bands. These data contain information on relic background (CMB anisotropy), extragalactic IR background, unresolved faint sources, dust distribution in Galaxy and Solar system.

Figures 2, 3 shows sensitivity of Submillimetron (Table 1) in comparison with other space projects. Corresponding data are from the following publications: IRAS [32], ISO [33], IRIS (Astro-F) [34], SIRTF [35], Hershel [36, 37], Planck [13, 14]. Noise equivalent in units per $Hz^{1/2}$ corresponds to statistical error of 1σ for integration time of about 1 s.

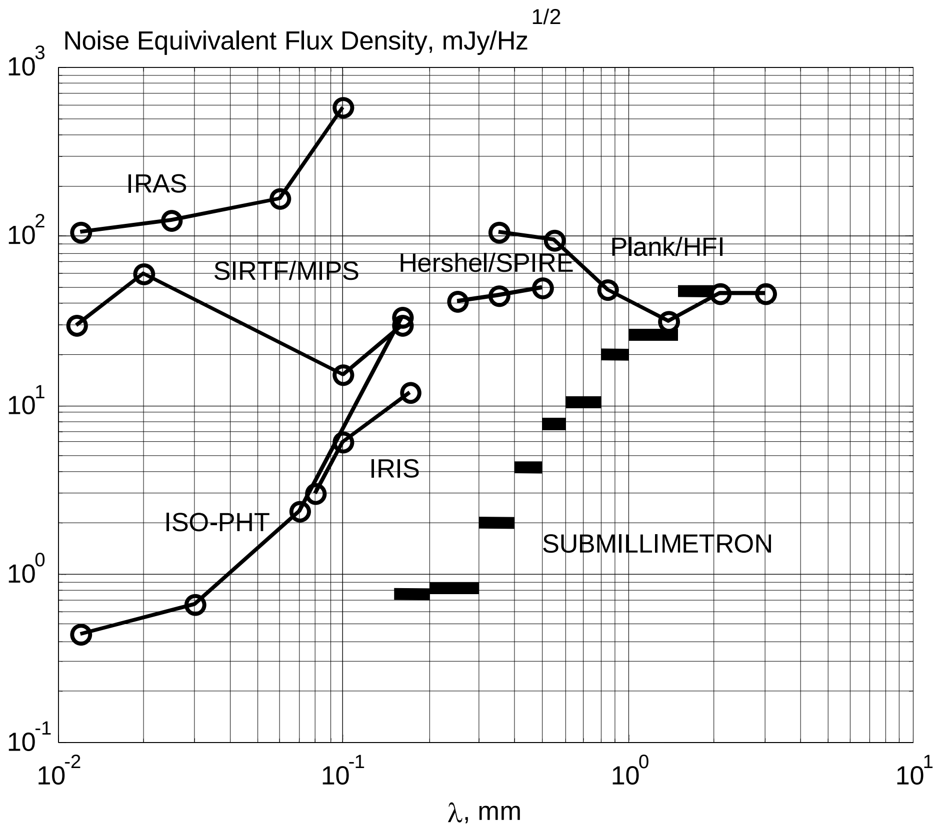

FIGURE 2. Sensitivity for point sources observation. Filled rectangles – Submillimetron project, open circles connected with lines – data for other projects (designations are given near corresponding lines).

Last decade of submillimeter (mainly ground-based) observations gives a lot of impressive results. They show particularly that up to 50-80 % energy of electromagnetic radiation from distant ($z \geq 1$) objects in Universe came in submillimeter region. Current decade is time of a number of infrared and submillimeter projects [13-14, 34-37]. Concurrent analysis of a totality of scientific data produces effect of synergy when final result is greater then sum of complementary component. It increases a value of each experiment. Due to high sensitivity, the Submillimetron should detect most targets of other space telescopes and has excellent complementarity to all these projects. Submillimeter spectra should expand infrared measurements (SIRTF and IRIS). Full sky survey in spectral regions of Hershel permits to generalize its investigation of individual objects and selected fields. Submillimetron data complement Planck experiments by data on foreground sources. Better angular resolution and sensitivity (in submillimeter channels) permit to reveal sources unresolvable in Planck maps. Their subtraction from millimeter-wave data should increase accuracy of measurements of CMB anisotropy.

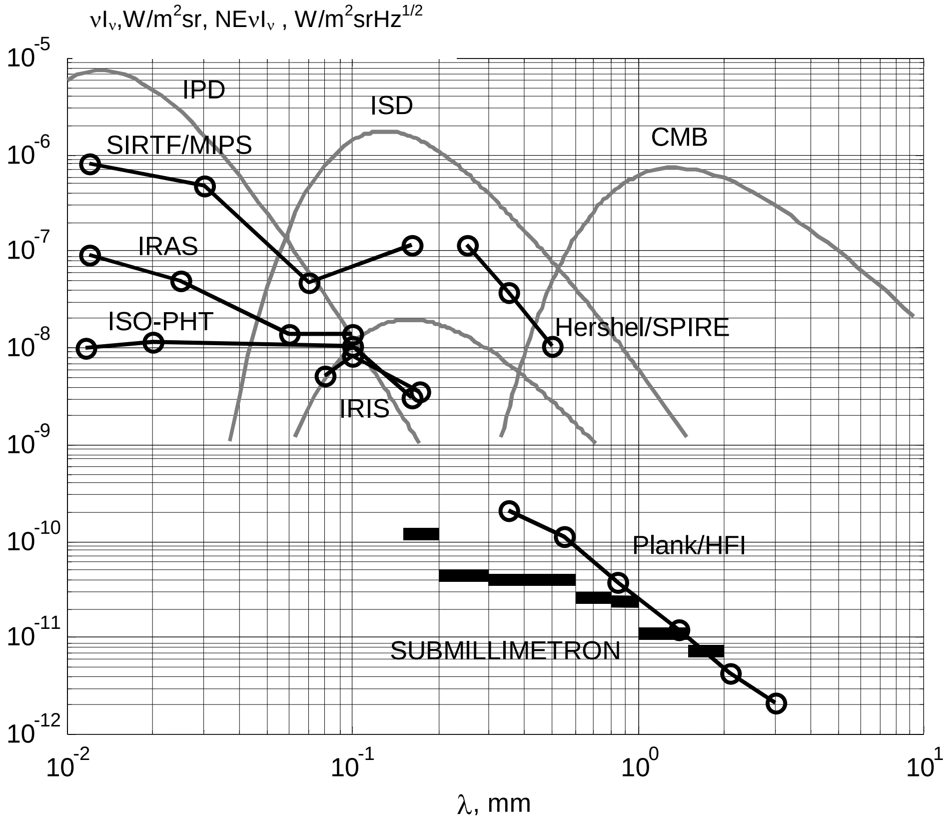

FIGURE 3. Sensitivity for extended emission observation. Filled rectangles – Submillimetron project, open circles connected by lines – data for other projects (designations are given near corresponding lines). Gray curves represent components of extraterrestrial background: left – interplanetary dust emission, right – CMB spectrum, upper curve in center - galactic emission near galactic plane, bottom one – near galactic poles.

CONCLUSIONS

Concept of the Submillimeron project is based on cryogenically cooled telescope and supersensitve antenna-coupled microbolomers. It permits to reach the high sensitivity in survey for catalogizing submillimeter sources and mapping a sky in sub-mm and mm-wave bands. This experiment offers an optimum solution for submillimeter full-sky survey and provides a good complementarity to other space projects.

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