Instrumentation for Millimetron - a large space antenna for THz astronomy

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Abstract— **Millimetron is a Russian-led 12m diameter submillimeter and far-infrared space observatory which is included in the Space Plan of the Russian Federation and funded for launch after 2015. With its large collecting area and state-of-the-art receivers, it will enable unique science and allow at least one order of magnitude improvement with respect to the Herschel Space Observatory. Millimetron is currently in a conceptual design phase carried out by the Astro Space Center in Moscow and SRON Netherlands Institute for Space Research. It will use a passively cooled deployable antenna with a high-precision central 3.5m diameter mirror and high-precision antenna petals. The antenna is specified for observations up to ~2 THz over the whole 12m diameter, and to higher frequencies using the central 3.5m solid mirror. Millimetron will be operated in two basic observing modes: as a single-dish observatory, and as an element of a ground-space VLBI system. As single-dish, angular resolutions on the order of 3 to 12 arcsec will be achieved and spectral resolutions of up to 10^6 employing heterodyne techniques. As VLBI antenna, the chosen elliptical orbit will provide extremely large VLBI baselines resulting in micro-arcsec angular resolution. The scientific payload will consist of heterodyne and direct detection instruments covering the most important sub-/millimeter spectral regions (including some ALMA bands) and will build on the Herschel and ALMA heritage.**

I. INTRODUCTION

Millimetron is a large (12m diameter) space observatory for millimeter, submillimeter and far-infrared observations. This Russian-led mission will enable astronomers to observe the universe with unprecedented sensitivity and angular resolution. The far-infrared and submillimeter spectral bands are crucial regimes for the study of the formation and evolution of stars, planets, and galaxies. In addition, extremely high-angular resolution imaging by VLBI allows exploration of ultra-compact radio sources including black holes.

Millimetron has two scientific observing modes each of which is unique and represents a major step forward in the investigation of the universe we are living in. Firstly, Millimetron will be used as a 12m diameter single-dish space observatory for high-sensitivity and high angular resolution observations of the submillimeter universe. Secondly, Millimetron will be used as a VLBI (Very Long Baseline Interferometry) antenna in millimeter and submillimeter wavelength bands providing extreme angular resolution of better than one micro-arcsecond. Observations in both observing modes will substantially contribute to solving questions as outlined in the Cosmic Vision themes.

Millimetron (Spectrum-M) is part of the Space Plan of the Russian Federation with a planned launch after 2015. The Russian Space Agency has approved the mission and has allocated funds for the development and implementation of Millimetron (Spectrum-M). At present, the Astro Space Center (ASC) in Moscow is carrying out studies for Millimetron which are funded by the Russian Space Agency. Concerning Millimetron, ASC has established contacts with ESA, ESO, and with SRON Netherlands Institute for Space Research with the aim to explore possibilities for European participation in the mission.

This paper gives a brief overview of the mission and its instrumentation. A more detailed description can be found in [1].

II. MISSION OVERVIEW

The main Millimetron characteristics are given in Table 1. They are driven by the objective to provide high sensitivity, high to extremely high angular resolution and high spectral resolution as well as far-infrared imaging and spectroscopic capabilities. High sensitivity and (extremely) high angular resolutions are achieved by using a 12m diameter space antenna, either in single-dish mode or as element of a space-ground VLBI system. High spectral resolution is obtained by using heterodyne receivers, and the far-infrared imaging/spectroscopy will be done by an imaging photometer/spectrometer. In order to achieve good u-v coverage in VLBI mode, an elliptical orbit is chosen. Figure 1 shows the satellite concept consisting of a 12m deployable antenna, several heat shields, and the satellite platform.

TABLE V
MAIN CHARACTERISTICS OF MILLIMETRON

Item	**Parameter**	**Value**
Primary mirror	Diameter	12m, deployable
	Physical temperature	≤ 50 K passively cooled
	Surface accuracy	≤ 10 µm rms
	Focal length	2800 mm
Secondary mirror	Diameter	600 mm
Total focal length		81550.7 mm
Orbit		Elliptical
	Apogee	300,000 to 370,000 km
	Perigee	30,000 to 70,000 km
	Period	~ 9.5 days
Space platform		Navigator
Launcher		Proton
Science instruments	VLBI receivers	18 and 26 GHz, ALMA bands
	Spectroscopy	~500 to 2000 GHz, 4700 GHz
	Imaging	Far-infrared
	Photometer	Far-infrared
Angular resolution	Single dish	3 … 12 arcsec
	VLBI	≤ 1 micro arcsec

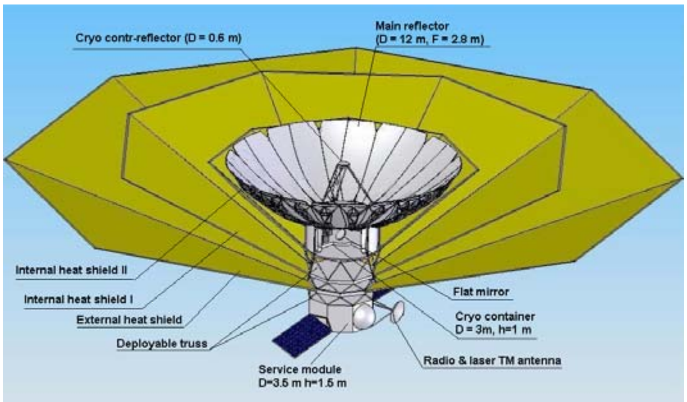

Fig. 1 Millimetron satellite concept with a 12m deployable antenna and several heat shields.

Millimetron will have two distinct scientific operational modes: (1) as a single-dish 12m diameter submillimeter space observatory, and (2) as space antenna of a sub-/millimeter space-ground VLBI interferometer. This will provide unreached angular resolutions in the millimeter to far-infrared regime of a few arcseconds in single-dish mode and micro-arcsconds in VLBI mode.

A number of technologies required for Millimetron, including the 12m diameter space antenna, are based on the Russian *RadioAstron* mission which is currently undergoing flight hardware integration and will fly a 10m deployable antenna in 2009 for ground-space VLBI. Figure 2 shows the 10m deployable antenna of RadioAstron. Millimetron will use a similar deployment strategy (Fig. 3).

The higher frequency range of Millimetron as compared to

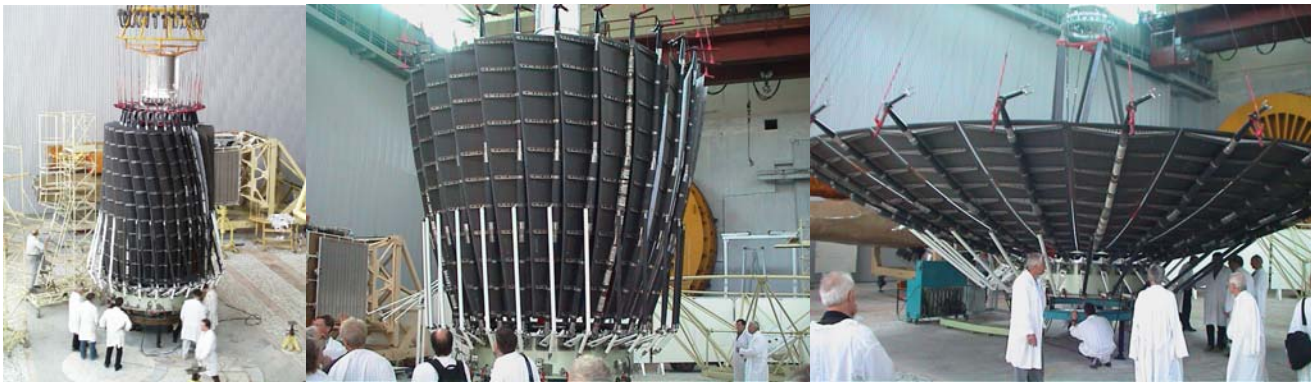

Fig. 2 Different stages of the “RadioAstron” 10m antenna deployment at Lavochkin Association (Moscow, Russia).

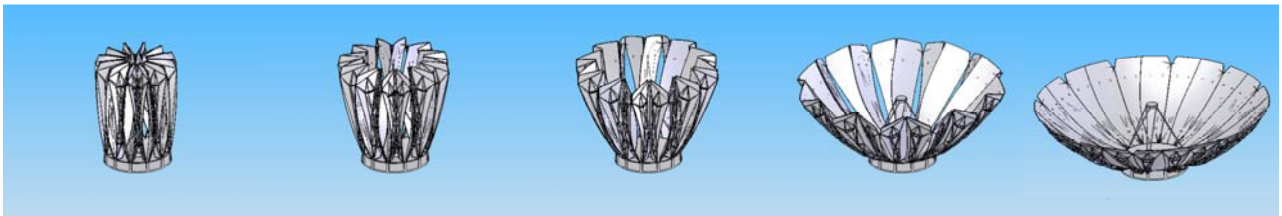

Fig 3 Stages of the Millimetron telescope deployment. Left: launch packaging, right: operational telescope.

RadioAstron means more demanding specifications in such areas as antenna surface precision, time reference system, phase stability etc. The instrumentation for Millimetron is based on the substantial investment into Herschel instruments and ALMA receivers and will build on developed (and largely space qualified) detector and instrument techniques.

III. SCIENTIFIC AIMS

The Far-Infrared (FIR) and submillimeter wavelength regime is one of the few areas were great progress can be expected in astrophysics as soon as high angular resolution and good sensitivity can be achieved. A passively cooled 12m dish optimized for the far-IR/submillimeter range, with an instrument suite building on Herschel heritage, provides this capability.

The spectral range with frequencies between 500 GHz and 5 THz (wavelengths between 600μm and 60μm) is of crucial importance for understanding how stars, planets and galaxies form and evolve. Furthermore, Very Long Baseline Interferometry (VLBI) in (sub-)millimeter waves allows micro-arcsecond access to compact sources such as black holes, neutron stars, and gamma-ray afterglows.

Millimetron will make unique contributions to the following areas of astrophysics (all of which are part of ESA's Cosmic Vision program) by combining high spatial and high spectral resolution as well as photometric and spectroscopic capabilities in the submillimeter/FIR regions. Millimetron will

- explore of the life cycle of gas and dust that leads to stars and planets (ESA Cosmic Vision theme 1),
- measure the deuterium content in the giant planets of solar system (ESA Cosmic Vision theme 2),
- investigate the physical parameters and processes near the event horizons of black holes and near the surfaces of neutron stars with sub-micro-arcsecond resolution (ESA Cosmic Vision theme 3), and
- trace the formation and evolution of black holes, trace the life cycles of matter in the Universe along its history, and resolve the far-infrared background (ESA Cosmic Vision theme 4).

IV. SCIENTIFIC INSTRUMENTATION

Millimetron will carry science instruments which will make optimal use of the large collecting area and high angular resolution. Basically, there will be two types of science instruments: those for single dish observations, and those for space-ground VLBI (SVLBI). Both types will build on earlier developments for space missions like RadioAstron, VSOP, and Herschel, as well as ground-based projects like ALMA.

Here we describe a baseline instrumentation plan for the two basic scientific modes of operation (single-dish and SVLBI). The final instrument suite will depend to a large degree on the available spacecraft resources with 4K cooling power probably being the most limiting parameter. Further study needs to refine the instrument technical requirements and evaluate various trade-off options.

V. SINGLE DISH INSTRUMENTATION

A. Overview

The baseline instrumentation for the single-dish observing mode consists of the two heterodyne instruments HET-1 and HET-2 and the far-infrared imaging photometer and spectrometer M-PACS. HET-1, a dual-frequency SIS array, will operate around the astrophysically important frequencies 557 and 1100 GHz, and HET-2, a three-channel HEB receiver, will cover 1.9, 2.7 and 4.7 THz (the latter using the central 3.5 m high-precision part of the antenna). M-PACS would be an adapted copy of Herschel-PACS with improved detectors covering the wavelength regime 60 to 210 μm. The instrument and detector technologies as well as operational modes and calibration schemes can build heavily on the developments done for Herschel.

Table 2 lists the key characteristics of the Millimetron baseline science instrumentation for single-dish observations.

TABLE II

MILLIMETRON SINGLE-DISH INSTRUMENTATION KEY CHARACTERISTICS.

Instrument	**Frequency or wavelength**	**Angular resolution (arcsec)**	**Spectral resolution**	**Detector technology**	**Sensitivity**
Heterodyne receivers					
HET-1	480 – 700 GHz	8…12	$\geq 10^6$	SIS 2x2 mixer array with multiplier LO	$T_{sys} < 100$ K
	1100 – 1400 GHz	5…6	$\geq 10^6$		$T_{sys} < 200$ K
HET-2	1650 – 2000 GHz	~3	$\geq 10^6$	HEB mixers with multiplier or QCL LO	$T_{sys} < 500$ K
	2600 – 2700 GHz	~2.5	$\geq 10^6$		$T_{sys} < 700$ K
	4700 – 4800 GHz	4 $^{(1)}$	$\geq 10^6$		$T_{sys} < 1000$ K
Far-Infrared imaging photometer/spectrometer					
M-PACS	60 – 210 μm	≥ 4	few 10^3 spectrometer	Photoconductor arrays	2×10^{-18} Wm^{-2}

B. Heterodyne Receivers

HET-1 and HET-2 are heterodyne receivers providing very high spectral resolution ($\geq 10^6$) in combination with a Fast-Fourier-Transform spectrometer (FFTS). The channels up to 2000 GHz can directly build on the successful developments for Herschel-HIFI, whereas the higher frequency channels of HET-2 around 2.7 and 4.7 THz, unique to Millimetron, have been demonstrated in the lab. For HET-1 it is planned to use 2x2 SIS waveguide mixer arrays with multiplier chain local oscillators (LO). This type of technology has been developed for many ground-based telescopes and as single mixers for Herschel-HIFI. The 2x2 mixer arrays for Millimetron would be a new development for space which could heavily build on ground-based developments. It is interesting to note that multiplier LOs up to 2000 GHz are now becoming available commercially and at much lower cost than for HIFI. HET-1 will make use of demonstrated SIS technology using Nb-AlN-Nb tunnel junctions in combination with Nb-SiO2-Nb on-chip tuning elements as used at all major submillimeter observatories and in Herschel-HIFI.

HET-2 will in principle employ hot electron bolometer mixers (HEBM) as used in HIFI. However, due to sensitivity and IF bandwidth limitations of HEBM, it is attractive to develop SIS junction technology up to 2000 GHz by utilizing high energy gap superconducting materials. If successful, this SIS technology will allow to achieve better sensitivity and IF frequency coverage. The best technology for the 1650 – 2000 GHz channel of HET-2 can be selected depending on development result. The 2.7 and 4.7 THz channels will in any case use HEB mixers. Local oscillators for HET-2 will be multiplier chains and quantum-cascade-lasers (QCL). QCLs have been used in the lab as THz LO source. Some development is required for the QCL to stabilize its frequency and reduce the dissipated power at the 30…70 K level.

Several developments of HEB mixers and mixer arrays are underway for frequencies beyond 2 THz. A heterodyne receiver at 2.8 THz using a quasi-optical HEB mixer and QCL local oscillator has been demonstrated with a noise temperature of 1400 K (DSB) by Gao et al. [2].

C. Heterodyne Backend

The heterodyne receivers will share a Fast Fourier Transform Spectrometer (FFTS) backend which is a digital spectrometer providing wide instantaneous bandwidth with high spectral resolution. In the case of a 2x2 pixel receiver (dual polarization) with an IF bandwidth of 4 GHz each, a total spectrometer bandwidth of 32 GHz is required. Current FFT technology, field-proven in several years of continuous operation at, e.g., the APEX submillimeter telescope, provides an instantaneous bandwidth of at least 1 GHz with 8-16 k channels. Under development at MPIfR (Germany) are single-board FFTs with 1.5 GHz bandwidth /16 k and, using the most recent ADC available, 2.5 GHz/8 k channels. With the latter implementation of a hybrid backend with 3 x 2.5 GHz to combine to a total of ~7 GHz (allowing for some overlap) bandwidth is within reach. The enormous increase of ADC bandwidth during the last years makes it very likely that FFTS can be pushed to instantaneous bandwidths wider than 3 GHz in the near future, thereby further reducing the complexity of the backend. The spectral resolution (the number of channels) that can be achieved is basically constrained by the on-board resources (power dissipation) and the level of complexity that appears acceptable for a space mission. FPGAs have quite a long space heritage. In any case, digital FFT spectrometers can provide the back-end capacities required by the Millimetron mission concept. Some development work will be needed to increase bandwidth, to optimize operation to minimum power dissipation, to adapt to particular constraints of a space observatory, and to comply with space qualification requirements.

D. Imaging Photometer and Spectrometer

The Far-infrared photometer and spectrometer M-PACS can be based on the successful development of the PACS instrument, as built for Herschel which offers photometric and spectroscopic capabilities in the wavelength band from 60μm − 210μm:

A) Imaging dual-band photometry (60 − 85μm or 85 − 130μm and 130 − 210μm) over a field of view of 1.75′ × 3.5′, with full sampling of the telescope point spread function.

B) Integral-field line spectroscopy between 57 and 210 μm with a resolution of 175 km/s and an instantaneous coverage of 1500 km/s, over a field of view of 47″ × 47″.

Both modes will allow spatially chopped observations by means of an instrument-internal chopper mirror with variable throw.

The focal plane unit provides these capabilities through five functional units:

1. Common input optics with the chopper, calibration sources and a focal plane splitter.
2. The photometer optical train with a di-chroic beam splitter and separate re-imaging optics for the two short wavelength bands (60 − 85μm / 85 − 130μm) and the long-wavelength band (130 − 210μm), respectively; band-defining filters on a wheel select one of the two short-wavelength bands at a time.
3. The spectrometer optical train with an image slicer unit for integral field spectroscopy, an anamorphic collimator, a diffraction grating in Littrow mount with associated actuator and position readout, anamorphic re-imaging optics, and a di-chroic beam splitter for separation of diffraction orders.
4. Two filled silicon bolometer arrays with 16 × 32 and 32 × 64 pixels, with cryogenic buffers/multiplexers and a common 0.3 K sorption cooler, for simultaneously imaging in two bands, 60−85μm or 85−130μm and 130−210μm over a field of view of 1.75′ × 3.5′ .
5. Two Ge:Ga photoconductor arrays (stressed and unstressed) with 16 × 25 pixels each, that allow to perform imaging line spectroscopy over a field of

50”×50”, resolved into 5×5 pixels, with an instantaneous spectral coverage of 1500 km/s and a spectral resolution of 175 km/s, with sensitivities (5σ in 1h) of 4 mJy or $3 - 20 \times 10^{-18}$ W/m^2.

VI. SPACE SEGMENT VLBI INSTRUMENTATION

A. *Overview*

Figure 4 describes in general terms what is needed for performing Space VLBI (SVLBI). The signal from the telescope is received by one of the SVLBI front ends and down converted to an intermediate frequency (IF) which is filtered and conditioned in the IF processor unit and then digitized. Currently quantization of two bits over a 4-8 GHz band with dual polarization is considered which would result in a data rate of 16 Gbit/s. The digital signals are recorded in a data storage unit which should have sufficient capacity to hold approx 40 min of SVLBI data (10 TB capacity). A high-speed down-link transfers the data to the ground.

B. *SVLBI Front-ends*

The front end instrumentation for the VLBI observing mode will consist of a low frequency (18-26 GHz) front-end very similar to the one which will be flown on the Russian RadioAstron mission in 2008/09. This receiver on Millimetron will greatly improve the u-v plane coverage achieved by RadioAstron and is required to ensure proper cross calibration. Unique to Millimetron will be the VLBI receivers at the ALMA frequency bands 1 (31.3-45 GHz), 3 (84-116 GHz), 6 (211-275 GHz) and 9 (600-720 GHz). Table 5 summarizes the key characteristics of the Millimetron VLBI instrumentation.

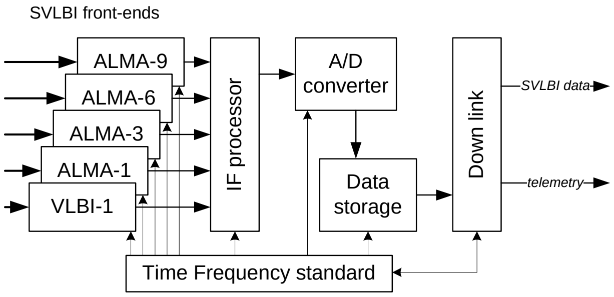

Fig. 4 Block diagram of the SVLBI instrumentation package

The VLBI-1 receiver will be based on previous developments as carried out for many radio telescopes and the RadioAstron or VSOP missions. The ALMA bands will follow technology developed within the ALMA project both for sideband separating SIS mixers, IF amplifiers and LOs. Adaptation of the ALMA technology for space use should not pose much difficulty as it is conceptually similar to the one used for Herschel (in fact ALMA uses some components that were developed for HIFI). Special attention will be paid to the polarization response of these instruments as observing polarization is one of the scientific goals. All ALMA band mixers require cooling to 4K like the HET-1 and HET-2 instruments.

C. *Additional Equipment for Space-Ground VLBI*

Space-ground VLBI requires special equipment onboard the Millimetron satellite.

1) On board time and frequency standard

There are two possibilities for onboard time synchronization. The first one is a hydrogen frequency standard developed in Russia which will be flown on the RadioAstron mission. The second one is an optical frequency standard with a stability of 3×10^{-16} in 5 minutes. This optical standard is under construction at the Lebedev Physical Institute.

2) A/D converter and data storage

The A/D converter technology will be the same as used for the FFTS backends. Adequate IF bandwidth can be covered by current technology already (ALMA). More weight/energy efficient solutions are expected to appear in the near future. On board data storage modules of up to several TBit are available commercially and space qualified from e.g. EADS-Astrium. It is anticipated that the maximum available capacity will only grow over the years. 10 TBytes would be sufficient for the mission but expanding on the capacity up to 30…40 TB will benefit the mission.

3) Down link

The high speed down link is a crucial part of the SVLBI system. Its speed will define the ground tracking station load for data transfer. The currently demonstrated radiolink data rate is two channels of 512 Mbit/s. It will take 22 hours to transmit 10 TBytes to Earth. A development towards improving data rates by using optical and other means would be of a great benefit for the Millimetron mission.

Telemetry and time synchronization data links can be common for the single dish and the SVLBI mode as they do not have high requirements concerning the data rate. Current state-of-the-art satellite communication equipment cold be used (similar to Herschel).

VII. INSTRUMENT COOLING

Both the heterodyne instruments HET-1/HET-2 and M-PACS need cooling to ~4 K from the spacecraft instrument cooling system (analogue to Herschel) with M-PACS having its own internal cooler to 0.3 K. The ALMA type receivers for SVLBI using SIS mixers need to be cooled to 4 K as well. The planned minimum mission life time of 5 years calls for a closed-cycle cryo-cooler to 4 K, also providing cooling to 20 K and 70…100 K levels. The temperatures below 1 K required for the M-PACS detectors will be generated within the M-PACS instrument (similar to the Herschel PACS scheme). A preliminary estimate of the required cooling powers for the scientific instrumentation gives: 40-50 mW at 4 K, 200 mW at 20 K, and 2 W at 70…100 K, with a temperature stability of 5 mK at 4 K, 10 mK at 20 K, and 0.2 K at 70…10 K. These values are first estimates based on the specifications and experience with Herschel and ALMA instruments and will have to be refined during a more detailed study phase. It is anticipated that the cooling requirements and associated mass and power needs for the cryocoolers place restrictions on the amount of instruments that can be carried on Millimetron.

VIII. REQUIRED DEVELOPMENTS

In some areas Millimetron can make direct use of existing technology as developed, e.g., for Herschel and ALMA. However, there are also areas which require further developments for Millimetron and other missions. These include:

- **SIS arrays around 650 GHz and up to 1400 GHz.** These arrays need to be space qualified, provide very low noise, and an IF bandwidth of 8 GHz. Using SIS up to 1400 GHz or even higher would be very beneficial but requires the use of new junction technology.
- **Multiplier Los for SIS arrays.** The SIS arrays need a local oscillator capable of pumping the SIS mixers. Current LO chains on Herschel-HIFI would not provide enough LO power.
- **HEB receivers at 2.6 and 4.7 THz.** Sensitive HEB mixers with a broad IF band (~ 8 GHz) are needed. Current state-of-the-art HEB mixers require further development to achieve quantum limited performance and a larger IF bandwidth.
- **THz local oscillator.** The HEB receivers at 2.6 THz and 4.7 THz require a suitable local oscillator, either multiplier based or QCLs. For the multiplier chains, output power will be a very challenging issue, and for the QCLs, frequency coverage (tuning) and phase-locking need further work and development.
- **Wideband backends.** The option of wideband FFTS for all receivers needs to be investigated, and space qualification needs to be achieved.
- **Space cryocoolers.** Ongoing developments by ESA, NASA, and JAXA may fulfil the Millimetron requirements. In any case, the available cooling capacity for the instrument suite will probably define the amount of possible instruments on Millimetron (along with mass and power needs). Reliability of the cryocoolers is a concern during the >5 yr mission lifetime.

CONCLUSION

The Russian Millimetron mission provides an exciting opportunity for far-infrared and submillimeter astronomy and advanced instrumentation. Unique mission characteristics include the large collecting area and angular resolution. The Millimetron mission is included in Russia’s Federal Space Program. It is currently in a conceptual design phase.

ACKNOWLEDGMENT

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