Cost Sensitive KA-band LNA using COTS MMIC devices and novel cooling

Morehead State University

Proposal to the ASTROBi

Proposal:

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1. TECHNICAL: SPACE and GROUND COMMUNICATIONS SYSTEMS ARCHITECTURES

The Space Science Center at Morehead State University (MSU) develops some of the world's most cutting-edge small satellite technology. MSU specializes in micro and nanosatellites, and in SmallSat communications systems and has evolved into an internationally recognized center for research in these "SmallSat" technologies. This work has culminated in the development of the Lunar IceCube satellite by MSU and NASA partners that will fly on the Artemis 1 mission to the Moon in 2022. Additionally, NASA has supported the upgrade of the MSU's 21-meter ground station to become the first non-NASA affiliated node on the NASA Deep Space Network and the instrument is now designated Deep Space Station 17 (DSS-17). mission success.

ASTROBi seeks to conduct ground station operations by building an array of dish antennas that can be used as a cross-correlated array to increase the total received signal to noise ratio. The objective is to use multiple lower cost antenna that will be simpler to build and maintain when contrasted against larger standard deep-space tracking stations such as the 34-meter NASA DSN stations.

To this end it is important that each dish be fitted with an exceptionally low noise receive feed and amplifier. Low noise amplifiers for RF work are normally cryo-cooled for the highest performance due to Johnson-Nyquist noise that is present in all devices above absolute zero temperature. Cryo-cooled devices however tend to be expensive and require control systems and/or a supply of liquid nitrogen or other cryo-materials to operate. This may be detrimental to the operations of a low-cost array since the maintenance and control required would increase operational costs significantly.

It is known that single stage thermoelectric cooling devices are low-cost alternatives to cryo-cooled apparatus. These devices operate using the Peltier Effect. When an electric current is passed through a circuit of a thermocouple, heat is evolved at one junction and absorbed at the other junction. The Peltier effect is the presence of heating or cooling at an electrified junction of two different conductors (or semiconductors). Thermo-Electric Cooling (TEC) devices are robust and can handle hot-cold side temperature deltas of up to 69C. However, these devices are not without a downside; they do not boast high efficiency. This is offset by the low cost and robust nature of the devices. Even at lower efficiency these devices are able to perform well for cooling small devices such as electronics and are used in –80C bio-freezer applications as well.

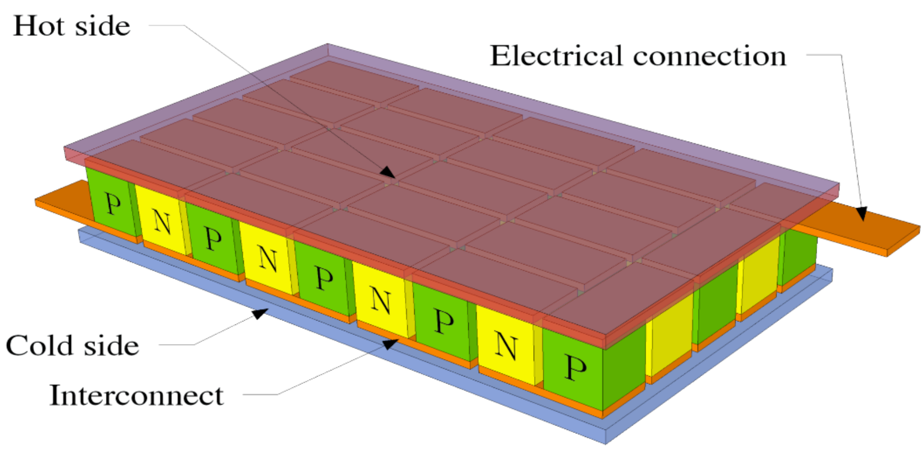


Figure 1: Principle construction of TEC device

With proper heatsinking Thermo-Electric cooling devices have been used to cool thermal (IR) imaging systems with little to no maintenance required. This allows the electron noise to be reduced to almost 1eRMS. Single stage Peltier devices however cannot achieve large temperature deltas. A solution therefore is to use 2 devices in series to increase the temperature delta. Careful design can allow large deltas up to 90C whereas a 3 stage can approach 110C delta.

Another technology that may be of use in this case is the Stirling engine. Below is a diagram of a helium-based Stirling cycle cooling device used to create a –80C biological freezer for a previous NASA project by the author. These devices are cost effective and allow for large temperature deltas and high (up to 10W) heat transfers at –110C. Such Stirling cooler technologies typically have system costs of under $4k in practice and approaching $1k in larger quantity. Cost however is related to system life, and this must be considered in any system design.

Stirling cycle based cryo-coolers are also very robust, with long lifetimes requiring minimal maintenance. They are typically used for storing biological material for experimentation with long service lifetimes of up to 15 years. If the system is well-balanced the device has very little wear and can thermal cycle 1000's of times. This is an advantage since very low noise measurements may not be taken continuously, rather they are taken at specific times. As long as the thermal control system allows for ramp control and does not thermally shock the displacer components, friction is kept very low, allowing for some systems to approach 120,000 hour continuous lifespans. A tradeoff must be made between cost and lifespan. For instance, if system A lasts 40,000 hours and system B lasts 20,000 hours, however system A costs more than 3x system B, it may be preferable to design the complete system in such a way that the cooling device can be easily exchanged. This is possible and is a technique used in many such systems.

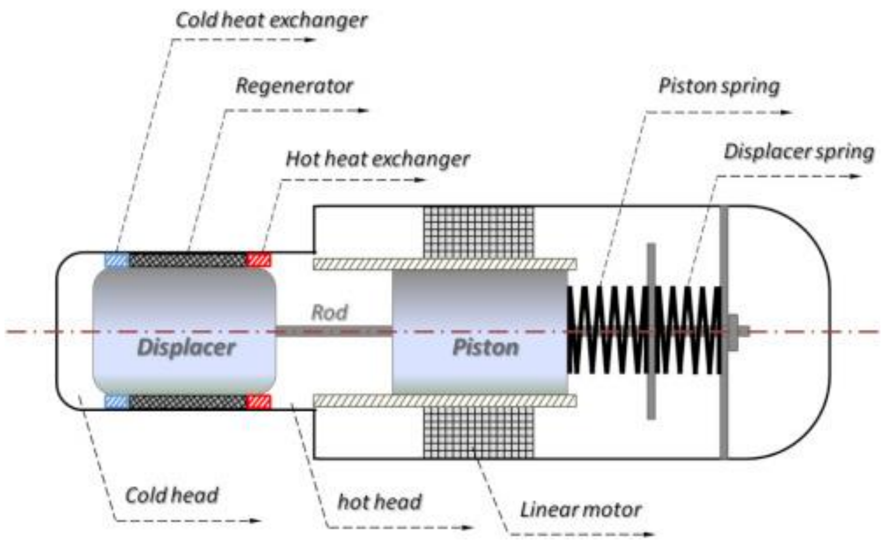


Figure 2: Stirling cooling device cross-section

Morehead State University Space Science Center proposes to investigate these concepts, and provide a solution/design along with simulation data to ASTROBi regarding several approaches to cooling LNA devices including but not limited to:

- 3 Stage Peltier device simulation
- Peltier with Sterling backing pump simulation

The best solution will be chosen from simulation data and used to create a small prototype system and verify the performance with our prototyping expertise and facilities.

Also needed for any LNA device is of course the amplifier itself. There are several options to choose from for a project with these specific objectives regarding both cost, loss, and frequency.

Figure 3: Standard LNA Amplifier module

The first of these solutions is a standard connectorized LNA module. These are available from several suppliers with varying noise performance and gain specifications. Figure 3 shows a KA band LNA available from Mini-Circuits with around a 1dB noise figure or 75K noise temperature. This noise figure can be reduced when cooled.

Figure 4: Die for MMIC device example to show integration of waveguide onto chip

Another solution and potentially a more cost-effective solution is the use of MMIC devices. Monolithic Microwave Integrated Circuits have become more abundant in recent years. Figure 4 is the die from an analog devices chip that can achieve sub 1dB noise figures (when cooled) at a price point of $100 per chip. An additional advantage to the MMIC device is that the cooled area can be reduced to the size of the chip. Reducing the amount of power (and thus heat) that must be use or removed from the system to ensure a low operational temperature and thus a low noise figure. An additional advantage to the MMIC device is that the cooled area can be reduced to the size of the chip. Reducing the amount of power (and thus heat) that must be used or removed from the system to ensure a low operational temperature and thus a low noise figure. These devices can be manufactured into a tightly integrated system that uses Rogers PC Board material, most likely bringing the large volume cost to around $300 per device. This cost, however, is dependent on amplifier frequency band and noise specifications and will vary. The performance metrics and unit economics must be taken into account when choosing the best design for the application in question.

Figure 5 shows a graph of the effect of package temperature on the noise figure. Note that even marginal cryogenic temperatures (-55C) are needed to reduce the noise figure to sub 1dB.

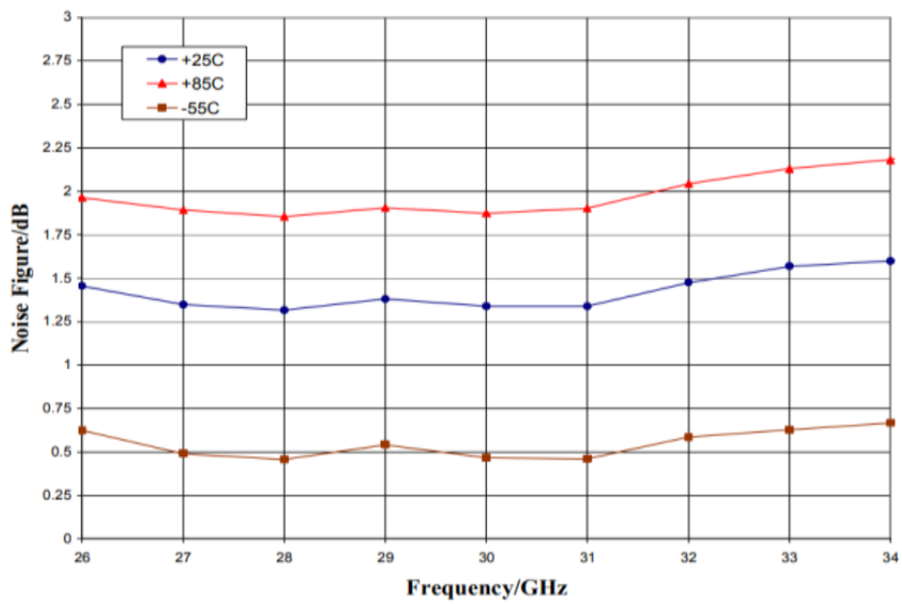


Figure 5:Frequency versus Noise as a function of T in MMIC devices.

We propose to conduct a trade study of various available MMIC devices as well as Connectorized versions and simulate combinations of cooling methods with the selected amplifier devices. This can give us the information needed to determine the efficacy of a low-cost KA band LNA capable of running without constant supervision and/or large amount of maintenance. A useful metric for system noise is a noise temperature under 50K (or 0.69dB) with preference given to systems that fall significantly below this value. We will therefore target our study for a noise temperature of 35K (0.5dB) which should be attainable based on the data shown above at –55C LNA temperature.

It is important to stay within manufacturing tolerance temperature ranges. Most MMIC devices can withstand –80C. However thermal cycling such a system can introduce microfractures in the traces and lead to system degradation and failure over time. Therefore, a ramped PID controller is necessary to be included in the thermal control system to slowly decrease the system temperature when turned on, and slowly increase the temperature when turned off. A backup power system will most likely be recommended to avoid hard resets of the thermal system. These costs are small compared with the total system cost, however they are metrics that will be included in the trade study and prototype design decisions.

2.0 STATEMENT OF WORK

Morehead State will:

- Conduct a trade study of currently available COTS hardware that could enable cost effective LNA designs.

- Conduct a trade study of available cost-effective thermal management and cooling solutions and design a cost-effective cooling system.

- Select from these components the "best" system wide design, taking into account both performance and cost. The cost will be weighed at the unit level taking into account total system units and economies of scale. The performance metric of sub-50K noise temperature will be used. A system for condensation/ice buildup mitigation will also be presented.

- Design and test a prototype system (1 LNA device) based on the principles and information gained from the trade study. This device will be used as an engineering model to build out multiple units for ASTROBi's demo array.

Period of performance 10 months from Authority to Proceed (ATP).

3.0 BUDGET

PERSONNEL	Salary	Effort	
Salaries & Wages			
Benjamin Malphrus			
Salary x Effort	175800	5%	7,325
Elijah Jensen			
Salary x Effort	79377	25%	16,537
RF/Communications Engineer TBD			
Salary x Effort	87700	25%	18,271
Nathan Fite			
Salary x Effort	78337	10%	6,528
Mike Combs			
Salary x Effort	77100	15%	9,638

Ryan Collins			
Salary x Effort	61688	15%	7,711
Subtotal Personnel			**66,010**
FRINGE BENEFITS	Flat	FICA/RET	
Malphrus	10752	23.52%	2,171
Jensen	10752	16.39%	4,950
RF/Comms Engineer TBD	10752	16.39%	5,235
Fite	10752	16.39%	1,966
Combs	10752	23.52%	3,611
Collins	10752	16.39%	2,608
Subtotal Fringe Benefits			**20,541**
SUPPLIES			
Supplies - Hardware, test equipment(specialized KA band devices and prototype system costs)			25,000
Subtotal Supplies			**25,000**
TOTAL DIRECT COST			**111,551**
INDIRECT COSTS @ 42% MTDC			46,851
TOTAL PROJECT COST			**158,402**

4.0 FACILITIES

MSU System Payload Integration Facility The team members at Morehead State have significant experience in assembling and integrating CubeSat and MicroSat systems, particularly communications systems. The team has integrated (and flown) 7 spacecraft developed in-house and has led or participated in integration activities for the NASA ELaNa program (California Polytechnical Institute), NPS, NASA WFF, Air Force, and US Space and Missile Defense Command and with the Italian GAUSS Company (Rome, Italy) for Kosmotras Dnepr launches. The Morehead State Space Science Center operates a Spacecraft Integration and Assembly Facility housed in four Class 10,000/100,000 Clean Rooms. Integration activities strictly adhere to the launch vehicle integration ICD provided by the launch services provider.

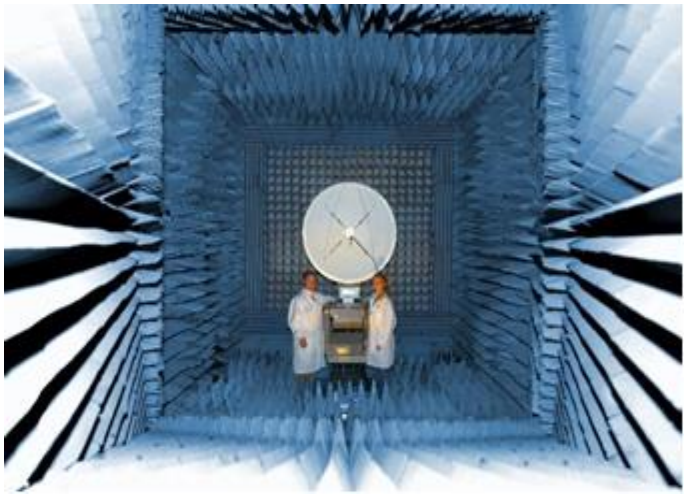
MSU Environmental Testing Facilities

The MSU staff has significant experience in communications systems and antenna design and in acceptance testing of the spacecraft buses and for the development of the Acceptance Test Procedures (ATPs). The MSU Spacecraft Verification Facility houses: 1.) a Vibration Analysis System, 2.) Thermal-vacuum chamber; 3.) Residual Gas Analysis System and 4.) a Large Anechoic Chamber for antenna and communications systems characterization. 5.) Screen room for EMI/EMC testing. Within these facilities, small spacecraft, up to 100 kg, can be tested and verified typically via hardware in the loop methods, and all subsystems flight verified. Environmental testing will include proto-qualification and qualification testing on subsystems and on the integrated system. The team will follow CubeSat standard practice and NASA NPR7123.1 and LSP Mission Assurance Requirements for nanosat missions. Testing processes adhere to NASA General Environmental Verification Standard (GEVS) GSFC-STD-7000 and EM-1 Environmental standards provided by the LF Launch Services Provider.

21-m Ground Station Overview

Figure: 21-meter dish seen here, also known as Deep Space Station-17 the only non-NASA affiliated node on the Deep Space Network

The MSU 21-m Space Tracking Antenna (Figure 3.0) currently provides telemetry, tracking, and command (TT&C) services for a wide variety of LEO missions but is particularly well-suited for supporting small satellites. In addition to being an operational ground station supporting NASA and university-based missions, the instrument is a unique research and educational tool that provides an active laboratory for students to have hands-on learning experiences with the intricacies of satellite telecommunications and radio astronomy. The 21-m supports undergraduate research in astrophysics, satellite telecommunications, Radio Frequency (RF) and communications system theory, and hardware/software development and testing. One of the primary uses of the 21-m system is to provide ground operations services for small satellite missions operated by Morehead State University and its partners. Ground support (telemetry, tracking and command services) are also provided for NASA and other missions. The 21-m has served as a ground station for JPL, Planet Labs, Cal-Poly, the University of Rome, the GAUSS Group, the LRO mission, and others. The 21-m station is currently the primary ground station for the JPL ASTERIA mission. In 2021, the 21-m station completed an upgrade to become the first non-NASA affiliated node on the NASA Deep Space Network, being designated NASA Deep Space Station -17 (DSS-17).



The anechoic chamber at MSU provides a great way to characterize the RF capabilities of spacecraft

4.0 BIOGRAPHICAL INFORMATION

PI – Dr. Elijah Jensen Ph.D.

Dr. Jensen has over 10 years of academic and professional experience working in the Engineering and Applied Physics fields. Dr. Jensen holds a PhD in Physics from the University of Louisville specializing in applied high dynamic range electronics and remote sensing. He has successfully developed state of the art electronics and mechatronics to support many SBIR and STTR projects for various agencies including NASA, USAF, ORL, DHS and others. Dr. Jensen has a demonstrated background in embedded microprocessor and FPGA based circuit design as well as extremely low noise analog and RF hardware design. Dr. Jensen has designed RF power transmission systems for space-based applications as part of a previous SBIR funded project. Dr. Jensen's research interests and background also include energy and high efficiency power systems design. Dr. Jensen's design experience focuses on robust hardware design for aerospace or military applications. Dr. Jensen has published several peer reviewed journal articles and has presented conference papers at various applied physics and engineering conferences.

Dr. Benjamin K. Malphrus is Professor of Space Science at Morehead State University where he also directs the University's Space Science Center. He serves as project director for the 21 M Space Tracking Antenna (Deep Space Station 17) operated by the Center. He has served on the scientific staff of the National Radio Astronomy Observatory, as visiting scientist at NASA's Wallops Flight Facility and on the faculty of the University of South Carolina and West Virginia University. He has served as PI or co-PI on several nanosatellite missions including Lunar IceCube, KySat-2, the Cosmic X-Ray Background Nanosatellite, CXBN-2, and TechSat-1 and has had roles on other microsatellite missions. He is currently PI on Lunar IceCube, a NASA mission to the Moon to investigate the transport physics of lunar volatiles including water ice. Lunar IceCube will launch on the maiden voyage (Artemis 1) of NASA's Space Launch System (SLS). He has published papers in scientific journals on topics ranging from extragalactic astrophysics to instrumentation in radio astronomy, to space systems engineering. Dr. Malphrus is co-editor of the recently released CubeSat Handbook (Elsevier). Dr. Malphrus has served as PI on over 100 grant programs totaling over $40 million R&D grant funding and led the design of a $16 million R&D center for space sciences. In the 1990s, he led a team that developed a theory of galaxy formation that has gained wide acceptance among the astronomical community.

Nathan Fite is Assistant Professor / Space Systems Engineer at the Morehead State University Space Science Center. Nate has served as AIT Team Lead at Tyvak Nanosatellite Systems Inc and as Graduate Assistants at Morehead State University and Montana State University. In these roles, Nate has worked on more than 30 satellite systems. Nate has deep expertise in mission assurance, Assembly Integration and Testing (AIT), Testing Architecture Development, End-to-End Hardware Design and Implementation, Failure Analysis and Remediation, Mission Planning and Analysis and R&D Infrastructure development. Nate has B.S. and M.S. Degrees from Morehead State University in Space Systems Engineering and an M.S. in Engineering Management in Electrical Engineering from Montana State University. Nate is the lead systems engineer on the $30M NASA Lunar IceCube mission.