National Aeronautics and Space Administration

FY24 Strategic Initiatives Research and Technology Development (SRTD)

All Solid-State Transmitter (ASTRAM) for Solar System Radar

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Strategic Focus Area: Cis-Lunar Space Situational Awareness | **Strategic Initiative Leader:** Joseph Lazio

Objectives: The objective of this effort is to develop an all-solid-state transmitter (ASTRAM) system operating at X-band frequency that can provide a reliable 4kW RF output power and degrade gracefully to minimize radar down times. The ASTRAM is to be developed with the ultimate goal in mind of eventually scaling the power of such a system for implementation in a solar system radar as a solid-state transmitter alternative to klystron tubes. This system builds on previous work, utilizing our low-loss spatial power combining amplifier (SPCA) technology [A], [B]. Each SPCA module combines sixteen 80W solid-state monolithic microwave integrated circuit (MMIC) devices using a radial spatial cavity combiner, delivering a >1.1kW output power at center frequency of 8.56 GHz with at least an 80 MHz 1 dB bandwidth. During the course of this effort, we intend to build and combine four of these SPCA modules into a complete >4kW X-band transmitter (TXR) unit using a 4-way radial waveguide combiner. The TXR system will include a graphical user interface (GUI) and bias control hardware for performance monitoring and control of the system. This will be accomplished through and interface with each individual MMIC device within the system.

Approach and Results: This task was a multistage development effort which began with design concept formation and ending with a completed operational prototype. Key stages of this effort includes RF architectural design, software architectural design, microwave and mixed signal board simulation and analysis, component and subsystem manufacture and testing, software implementation and testing, facilities infrastructure implementation, development of test procedures and data collection, and prototype testing and analysis. A diagram of the ASTRAM system architecture is shown in Figure 1. The design architecture is a layered hierarchy of parallel amplification units, wherein the combining for each unit is accomplished using a low-loss method of spatial combining. A matched phase and amplitude between all units within each layer is required for efficient combining, and this was achieved by digital control of the bias and phase of each MMIC within the system using custom software. Each of the SPCA modules serves as an individual amplifier unit within the larger ASTRAM system and combines the output of sixteen 80W MMIC solid-state amplifiers using a 16-way radial spatial cavity combiner. The 4kW ASTRAM system combines the outputs from four of these SPCA modules, each of which produces ~1200W RF output power, using a low-loss radial 4-way spatial cavity combiner. This is a flexible, power scalable design that allows for both an expandable number of hierarchical layers and an expandible number of parallel amplification units within each layer.

The effort concluded successfully with a fully operational 4kW solid-state transmitter prototype. Figure 2 shows the final ASTRAM prototype within the testbed during performance testing. Figure 3 shows the output power and gain over a 1hr 20min period of continuous operation. MMIC device gain is sensitive to temperature, wherein the gain is inversely correlated to localized heating within the transistor junction. The power peak observed at initial turn on is due to higher gain related to the initially cool junction temperature of the devices, which rapidly falls and stabilizes as the local junction temperature rises to a steady state temperature. This temperature sensitivity is also reflected in the observed output power ripple, which is directly inversely proportional to the supplied water-cooling temperature, as shown in Figure 4. Future solid-state transmitter systems will require consideration of the cooling system design to accommodate application specific power stability requirements. Some key system test performance characteristics are summarized in Figure 5. Of note is the 93% combining efficiency of the spatial combiner, and the overall DC to RF efficiency of 24%. The largest contribution to efficiency loss is the MMIC efficiency, which was independently measured to be around 27% during CW operation. The MMICs used for this effort were commercial Qorvo TGM2635 devices. These devices are designed to prioritize bandwidth over efficiency to satisfy a broad customer base. Future ASTRAM systems could in principle bring the efficiency into the range of 40% to 50% with the use of custom MMICs specifically designed to maximize efficiency, making such a system comparable to X-band tube amplifiers.

Significance/Benefits to JPL and NASA: With the successful development of the ASTRAM system, we have demonstrated the feasibility of implementing a scalable system architecture for low-loss coherent combining of many solid-state MMIC amplifiers in parallel. As a concept demonstration, this work has far-reaching implications for the communications and radar industry as a whole. The availability of a solid-state alternative to tube amplifiers provides a new high powered transmitter option available to NASA/JPL for both ground and flight-based communications and radar systems. Solid-state transmitters hold certain advantages over their tube counterparts in key areas such as lifetime, reliability, graceful degradation, reduced voltages, power conditioning, and size/weight/footprint among others. In addition, solid-state TXR technology lends itself well to active array-based antenna TXR systems. While not likely to completely replace tube transmitters in the future, as solid-state power amplifier (SSPA) technology continues to mature and advancements are made in MMIC output power and efficiency, the potential use cases for SSPA's continue to grow. This effort's prototype demonstration has played a critical role in advancing the Technology Readiness Level (TRL) of this technology from the theoretical towards practical implementation into a new set of instruments that will significantly impact future ground and flight mission capabilities.

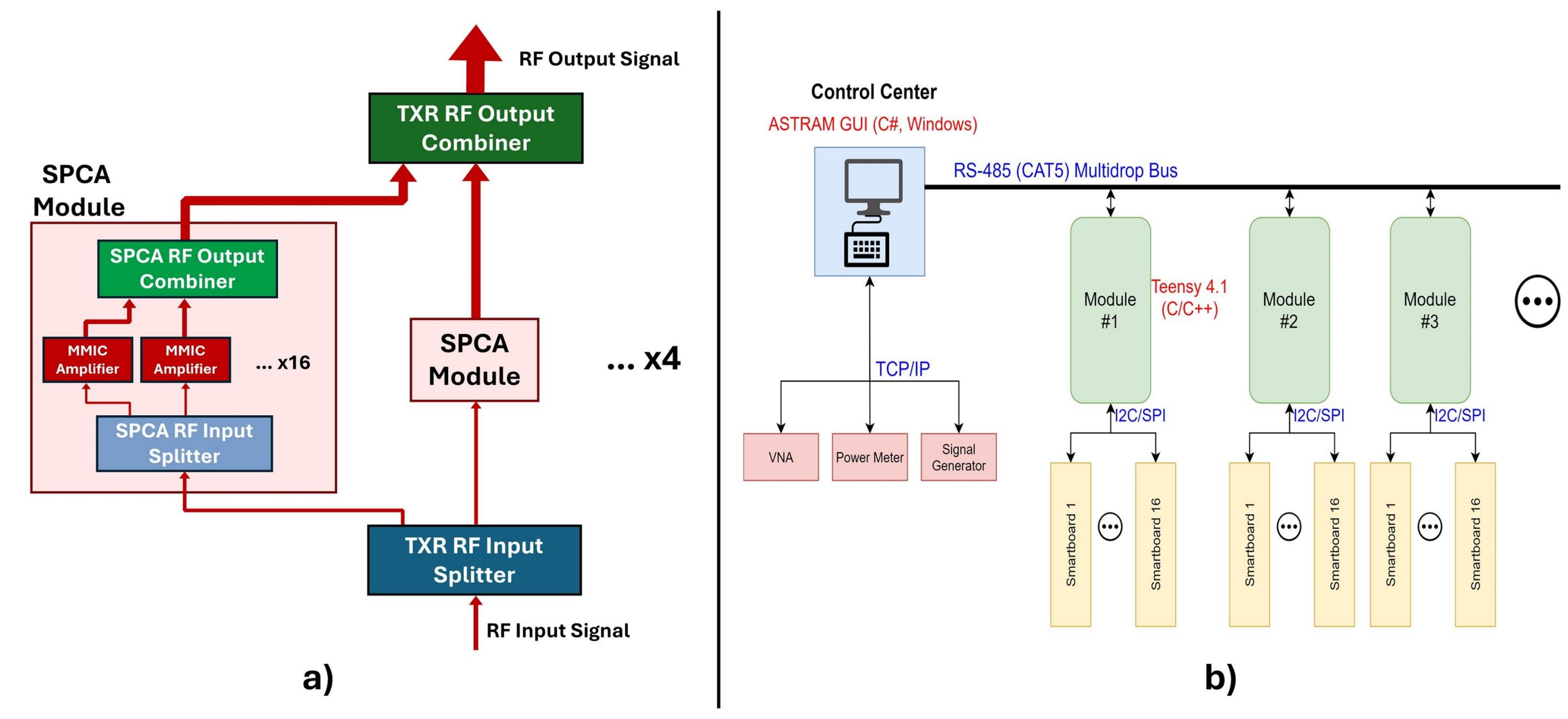

Figure 1. ASTRAM system a) RF combining architecture, and b) software monitor and control architecture.

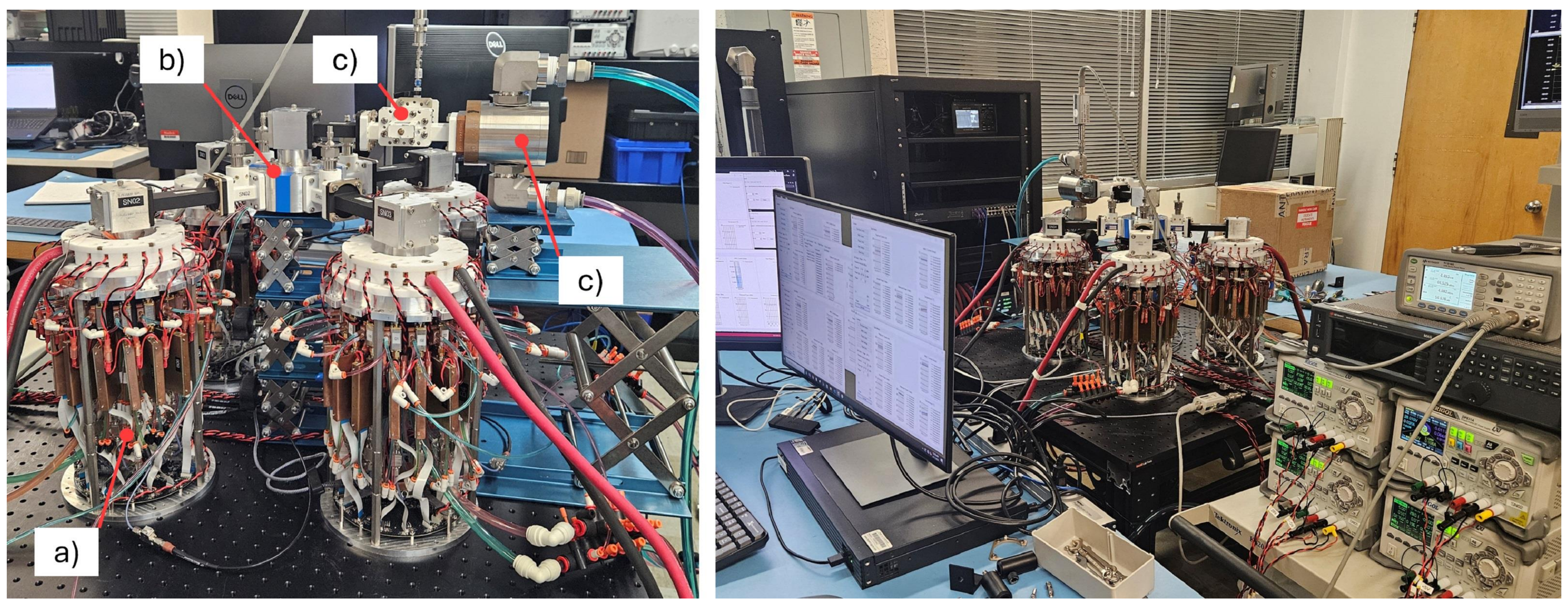

Figure 2. ASTRAM prototype in testbed, including: a) four SPCAs, b) 4-way cavity combiner, c) output waveguide coupler, d) high power RF load.

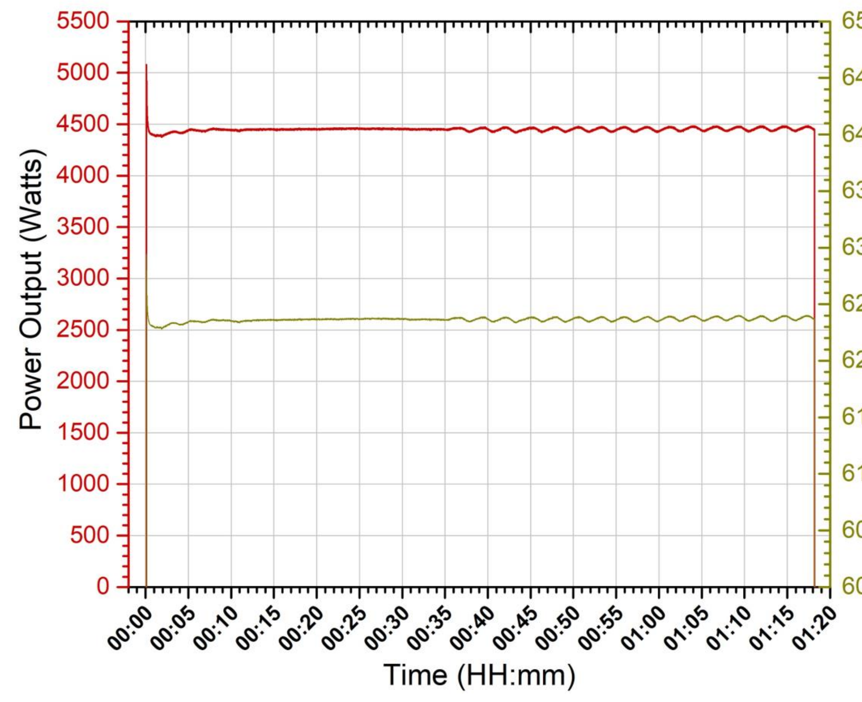

Figure 3. ASTRAM output power and gain.

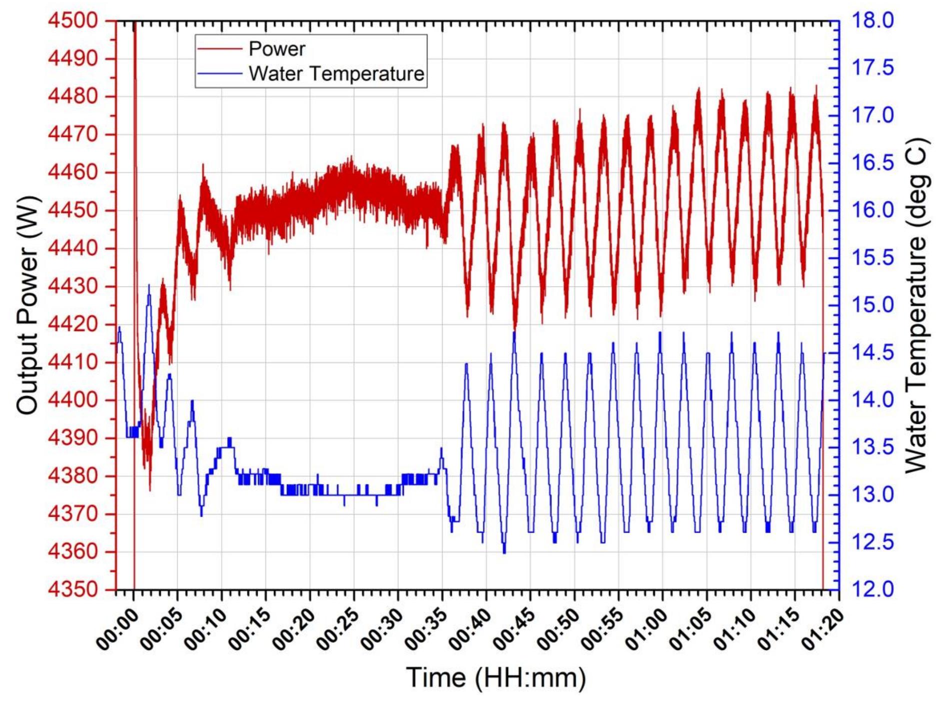

Figure 4. ASTRAM power output fluctuation with cooling water temperature.

Performance Parameter	Value	Units	Notes
Run time	1.25	Hr	
Center Frequency	8.56	GHz	
RF Output Power	4.45	kW	Average / Temperature dependent
Gain	62.37	dB	Average / Temperature dependent
DC Power Supplied	18.4	kW	Average / Temperature dependent
MMIC Efficiency	27	%	
ASTRAM Power Added Efficiency (PAE)	24.2	%	
ASTRAM Combining Efficiency	93	%	Through 4-way radial output combiner path
Output Power Variation with Water Temperature	25	W/°C	Inversely correlated
Measured Power Stability	1.1	%	
Intrinsic Output Power Stability (non-temperature related)	0.26	%	

Figure 5. ASTRAM performance results summary.

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RPD-21014 Clearance Number: CL#00-0000

Publications:

[A] M. Taylor, U. Escobar, A. Klaib, S. Rahimizadeh, S. Montanez, L. Ledezma, L. Yi, "All Solid-State Transmitter (ASTRAM) for Next-Generation Ground-Based Planetary Radar," 2024 IEEE Aerospace Conference , Big Sky, MT, USA, 2024, pp. 1-7, doi: 10.1109/AERO58975.2024.10521162.

[B] Mark Taylor, *et al.*, "All Solid-State Transmitter (ASTRAM) for Next-Generation Ground-Based Planetary Radar", U.S. Patent Pending, CIT-9192-P, July 30, 2024.

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