

# **New Generation Solid State Power Amplifier exceeds 1kW Output Power for Satellite Earth Stations**

Stephen D. Turner, M.Eng., PE  
VP Engineering  
Paradise Datacom LLC  
Boalsburg, PA, USA

Ahmed M. Zaghlol, PhD, PE  
Director Engineering  
R-Theta Inc.  
Mississauga, Ontario, Canada

## **ABSTRACT**

Careful thermal design coupled with innovative heat sink technologies have resulted in an industry benchmark in solid-state power amplifier technology. This paper presents thermal management, design concepts and reliability measures of a 1.1 kW C Band solid-state power amplifier. The RF chassis of the SSPA 1.1 kW C Band amplifier has been realized in a 6 ru chassis compared to 7ru for the TWTA amplifiers for the same RF power.

When both the semiconductor reliability and the system reliability is considered, the SSPA reliability is clearly far superior to the TWTA reliability.

## **Satcom Amplifier Technology**

Traveling Wave Tube Amplifiers (TWTAs) have long been the preferred amplifier in satellite earth stations. This is largely due to the high power density that the TWTA is capable of producing. TWTAs with output power capability of 2 kW have been commonplace in the satellite earth station

for years. These amplifiers are typically packaged in a separate RF and power supply rack drawers that combine to take up about 13 ru (22.75 inches) of cabinet space. Until recently, a Solid State Power Amplifier (SSPA) capable of this power level would occupy an entire equipment cabinet. This is largely due to the bulky heatsinks required to cool the microwave transistors that comprise the SSPA. Traveling Wave Tube Amplifiers have always had the advantage of being able to produce a large amount of microwave energy in a single electron tube. A TWTA is capable of producing power levels in excess of 1 kilowatt from a single tube. The tube can operate at power densities of approximately  $500\text{W}/\text{cm}^2$ . Additionally, the tube is capable of operating at anode temperatures of  $800\text{ }^\circ\text{C}$ . Contrast this to the typical gallium arsenide (GaAs) microwave transistor, which has power densities up to  $35\text{W}/\text{cm}^2$  and must not exceed a channel temperature of  $175\text{ }^\circ\text{C}$ .

At the present time, the highest RF output power achievable from a single gallium arsenide microwave device is 60W at 6 GHz. Therefore to produce satcom

amplifiers capable of output power levels greater than 100W, the output power from many devices must be combined. Microwave device DC to RF efficiencies range from 30 to 40%. This low efficiency along with the large device count means that a significant amount of power is lost to heat. Not only is the DC to RF efficiency a concern but the RF combining efficiency is also critical to the success of a solid state power amplifier. Much research has been done to develop novel, high efficiency microwave power combiners. One general result of all high efficiency combiners however is the requirement that the microwave transistors be mounted in very close proximity to one another. This results in a very complex, two-fold, heat-spreading problem. The first problem in spreading the heat from the microwave transistor involves transferring the heat from the microwave transistor chip to its mounting flange. The gallium arsenide chip must be mounted to a thermally stable metal such as kovar. The kovar carrier is then attached to a copper spreader, which is usually the mounting flange of the transistor.

With the extremely small size of the microwave transistor die, this results in a relatively inefficient heat spreader. This problem is the domain of the transistor manufacturer and there is little that the amplifier designer can do about this. The heat spreading resistance or thermal impedance from the channel to the flange of the microwave device is fairly large. Channel to flange thermal resistance is typically 0.6 °C/W for a 60W, 6 GHz device. This high thermal impedance of the transistor along with the high heat density created by the large number of devices creates a very difficult thermal management problem. The successful realization of high power solid state power amplifiers requires the unique combination of effective microwave combining techniques along with clever thermal design.

## **Size Disadvantage**

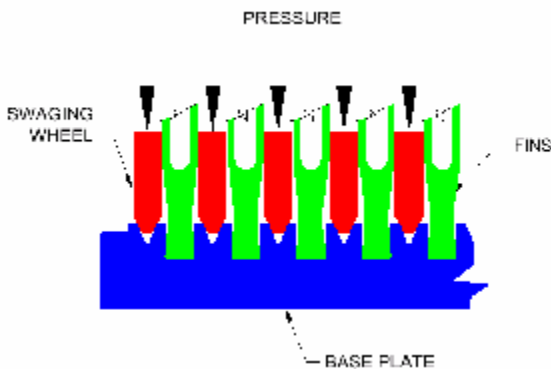
Historically, solid-state power amplifier designers have used brute force techniques to handle the thermal management problem. This involves very large heat sink extrusions and heavy heat spreading plates. The pressure drop and fin length of these heatsinks typically require large fans to produce the required volumetric airflow. This results in solid-state amplifiers that are usually 3 to 4 times larger and 4 to 5 times heavier than the TWTA equivalent. Even though it has been accepted that solid-state amplifiers are more reliable than TWTAs, the size and weight differential is a difficult hurdle for the SSPA. TWTA reliability has been improving in recent years, making it more difficult to sell SSPAs based on the reliability advantage alone. Additionally the reliability advantage of the SSPA can only be realized by careful observation of the maximum device operating temperatures. If the transistor is operated above its maximum channel temperature of 175 °C then the reliability decreases. This places the SSPA designer in a very difficult position when trying to reduce the size of high power amplifiers. In the past, the increased size and weight of the SSPA have completely eliminated their use in mobile and aeronautical applications. It is somewhat less critical in base station applications but along with the additional size and weight usually come higher initial cost. This higher cost has been yet another dilemma that has been associated with the SSPA.

## **High Performance Heatsink**

In an effort to reduce the size and weight of high power amplifiers, designers have looked toward using higher density finned heatsinks. There are some heat sink vendors offering high-density folded fin heatsink designs. While these designs achieve high fin density they are typically fabricated by epoxy glue attachment to a heat spreader

plate. This results in a heatsink that is unable to cope with the high heat density that is encountered in the SSPA. R-Theta, Inc of Mississauga Ontario has recognized this problem and developed a high density heatsink that uses a fin swaging process to dramatically increase the efficiency of high density finned heatsinks.

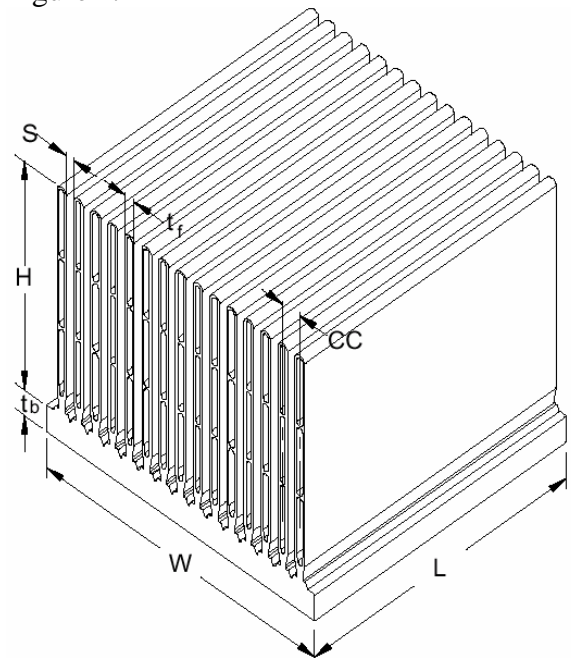
The heatsinks used in this SSPA application were bonded using a metal displacement process referred to as "Swaging". The Swaging process, depicted in Figure 1, can be described as a cold forming process, which is used in the fabrication of high fin density heatsinks. Currently, this process involves the placement of fins with a tapered base into a slotted base plate and then the application of a rolling pressure on the opposite sides of each fin. This results in vertical and lateral pressure of the base unit material, which tends to push the fin toward the bottom of the groove in the base. This secure connection provides very good thermal contact between the fins and base and also prevents air and moisture from entering the grooves, thereby preventing corrosion and allowing the heatsink to be anodized



**Figure 1:** Swaging process of tapered fins into the grooves of a baseplate with the application of rolling pressure on opposite sides of each fin.

The heatsink and fin geometry is defined in Figure 2. An aluminum Hollow fin heat sink was swaged with an average fin center-to-

center distance of 3.43mm. The individual Hollow fin is extruded with a wall thickness of 1 mm and an overall average thickness of 3.8mm. The Hollow fin is extruded with a tapered thick foot (see Figure 1). The thicker fin base helps to secure the connection between the fins and the baseplate and results in good thermal contact through the swaging process. The extrusion process used to produce the aluminum Hollow fins is flexible enough to allow for different fin body and fin base geometries as shown in Figure 2.



**Figure 2:** Heatsink geometry and dimensions

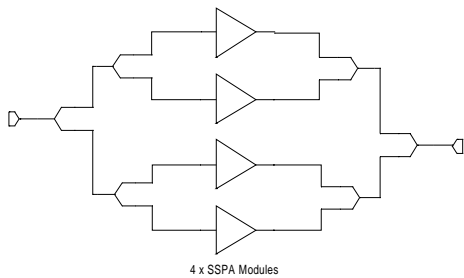
### Amplifier Distortion Primer

A 1.1 kW, C Band Solid State Power Amplifier is a very popular and useful output power level for satcom earth stations. This is due to the distortion characteristics of each amplifier technology. Generally the SSPA has superior distortion properties compared to the TWTA. Both the SSPA and TWTA must be operated below their maximum output power capacity in order to maintain distortion levels that meet satellite service criteria. This criterion is usually

defined as an operating level in which the distortion levels are at least -24 to -26 dB below the modulated signal. In an SSPA, the operating level is typically 2.5 to 3.0 dB below the maximum output power capability of the amplifier. The TWTA must be backed off 6.0 to 7.0 dB to result in similar distortion performance. Recent advances in predistortion linearization technology, however, allow the TWTA to operate more efficient. A linearized TWTA can typically be operated 4.0 to 5.0 dB backed off to achieve acceptable distortion levels. Therefore both a 2 kW linearized TWTA and 1.1 kW SSPA are capable of producing operating power levels in the 650 to 750 W range.

### 1.1 kW SSPA Architecture

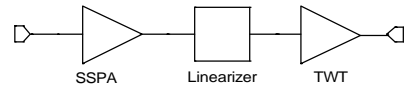
The basic RF architecture of the amplifier is based on a modular design approach. Four 300W C Band modules are combined to achieve 1.1 kW. The 300W SSPA module is a complete amplifier system of its own in that it is comprised of a high gain (75 dB) system complete with a communication bus, gain adjustment, and a microcontroller. A simplified block diagram of the amplifier is shown in Figure 3.



**Figure 3. Simplified SSPA Block Diagram**

The modular architecture gives the amplifier system a degree of soft-fail capability that does not exist in the TWTA. There exists no

single point of failure in any active component within the SSPA. If one module fails, the SSPA can continue to operate at reduced output power. The modules are also field replaceable, making system maintenance and repair possible. Contrast this to the TWTA which typically has architecture as shown in Figure 4. The TWTA is a single electron tube amplifier which is often in cascade with a small signal SSPA to boost the overall gain of the amplifier. The linearizer must also be in cascade with the TWTA, usually at the input. Therefore a failure in any one of the three major building blocks can result in the amplifier going off the air.



**Figure 4. Simplified TWTA Block Diagram**

The SSPA also has a decided advantage in operating voltage. An SSPA typically operates with a DC voltage input in the +12 to +50 VDC range. At these low DC voltages there exists a wide variety of reliable power supply options. Several power supply vendors are producing modular N+1 redundant power supplies that can be used to operate the SSPA. This results in a degree of built-in redundancy in the power supply as well as the RF amplifier section. Conversely the traveling wave tube requires supply voltages in the several thousand volt range. This requires more complexity in the power supply section. There are presently very few commercially available power supplies to choose from that produce these levels, much less provide the redundancy of a modular N+1 power supply. Therefore the basic architecture of the SSPA can provide significant reliability

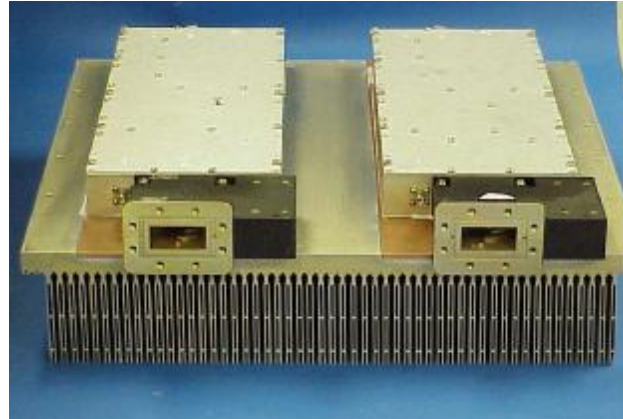
advantages. The remaining step in the design of a robust SSPA system involves innovative thermal design. Clever thermal design techniques can lead to SSPA systems that are no larger, and possibly smaller, than their TWTA counterparts. Proper thermal design that keeps microwave device temperatures well below their maximum rating, results in SSPA systems that have MTBF ratings that easily exceed 100,000 hours.

The 1.1 kW SSPA produces a heat load of approximately 4.5 kW. This becomes a considerable challenge for the thermal engineer to remove this heat while providing a compact and attractive enclosure for the amplifier assembly. The modular nature of the amplifier aids in the thermal design in that two modules can be attached to one heatsink. A second heatsink can then be stacked fin-tip to fin-tip to provide a compact assembly that can fit in a standard 19 inch rack chassis. The resulting hydraulic geometry of the heatsink presents a very good impedance to match with a set of parallel push pull fans. Each heatsink then must handle a heat load of 2.25 kW.

The size of the heatsink for the amplifier is 14 in. (355mm) wide by 15 in. (381 mm) long and is fabricated with the high efficiency fin structure developed by R-Theta. The output power from the modules is combined using a waveguide combiner to achieve the 1.1 kW output power level. Figure 5 shows the modules on the high efficiency heatsink. The design goal is to achieve less than 75 °C flange temperature on the RF output transistors.

A variety of software design tools exist for fast and reliable thermal design. The thermal design process can be a two step process of determining a basic size of a heatsink for the given heat load and a detailed analysis which includes all plate stacks between the heatsink fins and the

transistor flange. The basic heatsink size was determined using R-Tools (by R-Theta) while the detailed design was computed using Sauna (by Thermal Solutions Inc.).



**Figure 5.** Amplifier modules mounted to hollow fin heatsink.

### **Heatsink evaluation using R-Tools**

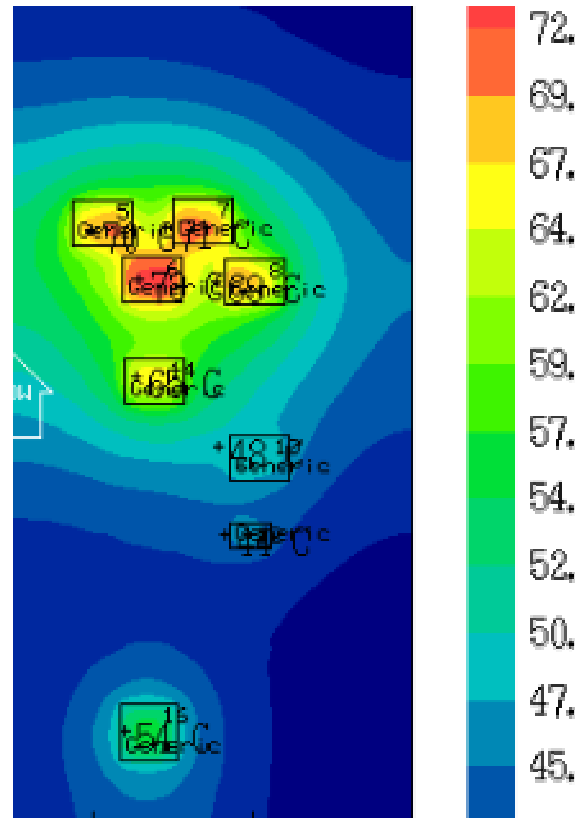
Power electronic designers require quick and accurate heat sink solutions. With the advent of the Internet, and realizing the potential of providing interactive design capability on the Web, R-Theta has introduced R-Tools®; a completely interactive on-line thermal design tool for heat sinks. The R-Tools mathematical engine is located on a web server at R-Theta Inc. R-Tools simulation can be run on an Internet browser, which is capable of utilizing Java Applets. R-Tools® thermal modeling is based on a set of analytical models for conduction heat transfer in the solid elements coupled with natural and forced convection heat transfer models in the cooling airflow. The conduction heat transfer model in the baseplate of the heat sink is based on the steady state solution of the Laplace equation for general rectangular geometry. The solution is based on a general three-dimensional Fourier series solution, which satisfies the conduction equation in the base plate. For the forced convection air-

cooled fins, an analytical model is used to predict the average heat transfer rate. The model used is a composite solution based on the limiting cases of fully developed and developing flow between parallel plates. Because the R-Tools<sup>®</sup> is analytically based, the solution is achieved within a few seconds, a very short time compared to the several hours required for a full CFD simulation. R-Tools<sup>®</sup> provides a method for quickly and accurately testing various heat sink configurations. The use of analytically based design tools allows the user to perform the thermal design of the heat sink concurrent with the optimization of the electrical and manufacturing elements prior to any prototype or testing. This approach results in reduction in design time and better reliability in the finished product.

Figure 6 shows the temperature map on the baseplate of the heat sink. The temperature shown in the Figure 6 is the maximum temperature on the heat sink baseplate under each individual power device. R-Tools provide hydraulic parameters for the heat sink performance such as the pressure drop and Reynolds number. The pressure drop can be used to determine the appropriate fan, which can deliver this volumetric flow rate for the system. Temperature of the device channel (junction) can be calculated using R-Tools. This can be achieved by providing interface thermal resistance  $R_{sc}$  and Channel to Case device thermal resistance  $R_{cc}$  (junction to case thermal resistance  $R_{jc}$ ). Those temperatures are based on the average temperature under the device. The average temperature under the hottest four devices is shown in Table 1.

**Table 1:** R-Tools temperature Results for heat sink, case and junction.

R-Tools	T <sub>1</sub>	T <sub>2</sub>	T <sub>case3</sub>	T <sub>case4</sub>
T <sub>heatsink</sub>	66	70	67	65
T <sub>case</sub>	70	74	71	68
T <sub>channel</sub>	145	149	146	143



**Figure 6:** R-Tools simulation results for an amplifier heat sink for velocity 5m/s (1000LFM) and ambient temperature of 25°C.

R-Tools results showed that the hollow fin heat sink would be capable of dissipation the heat out of the transistors. The case temperature under the hottest devices on the module is less than 75°C and the channel temperature is well below the maximum specified temperature of 175 °C.

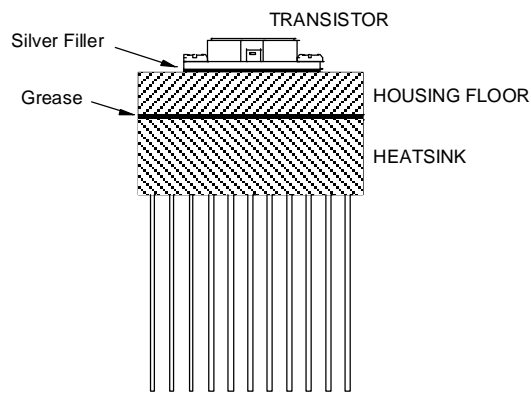
Table 2 shows a very remarkable agreement between R-Tools results and measured case temperature.

**Table 2:** R-Tools, Sauna results compared with measured case temperature.

	T <sub>case1</sub>	T <sub>case2</sub>	T <sub>case3</sub>	T <sub>case4</sub>
R-Tools	70	74	71	68
Measured	72	73	73	71
Sauna	69	72	70	69

## Detailed Heatsink Design using Sauna

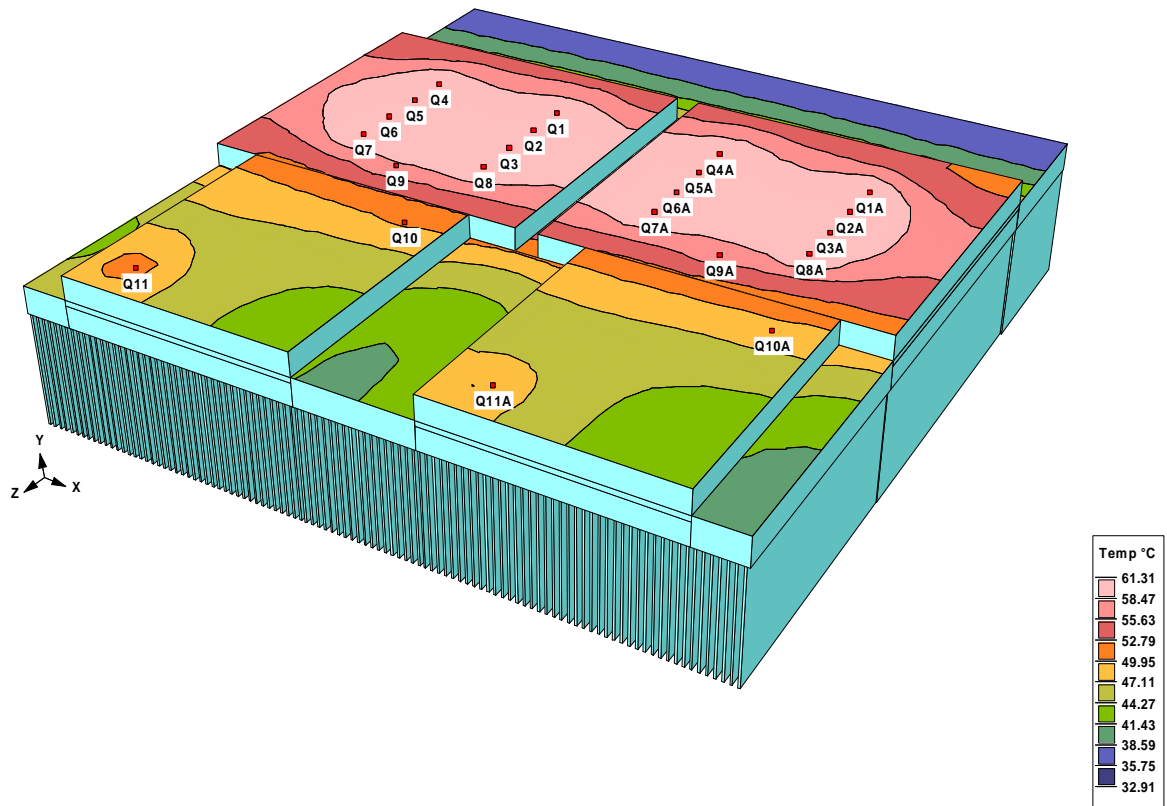
Once the basic heatsink configuration has been determined using R-Tools, the detailed heatsink design can proceed. The detailed heatsink design is implemented with Sauna. Sauna is a Windows based thermal design software by Thermal Solutions Inc. It is quite effective in heatsink designs that include a stack of interface materials or plates. The plate stack-up is a typical problem encountered in most RF amplifier designs. It is usually impractical to have the microwave transistors mounted directly to the heatsink. In each 300W amplifier module, the transistors are mounted to a heat spreader in the amplifier housing. The housing is then mounted to the heatsink. In each case there is a thermal interface material, which must be taken into account. A cross section of the thermal interfaces is shown in Figure 7.



**Figure 7.** Cross Section of Thermal Interfaces.

The completed Sauna thermal model is shown in Figure 8. The figure shows 22 transistors modeled as heat sources on the spreader plate. Sauna creates an electrically equivalent network of nodes and resistors throughout the plates. It uses the classic thermal network method of calculating the heat transfer throughout the plates and across the interfaces between plates. The program automatically calculates the resistor and node values based on the plate dimensions and material properties chosen.

The fin linear air velocity is then entered into the program along with the ambient temperature. The program quickly calculates the steady state temperatures throughout the heatsink assembly along with the channel temperature of the transistors. Sauna lends itself well to performing what-if analysis. Plate dimensions, heat source positions, and fin dimensions can be readily changed to determine the optimum heat transfer. Figure 8 shows the computed heat transfer contours for a single heatsink assembly. The difference between the measured flange temperatures and the simulated flange temperatures is no greater than 3 degrees Celsius. The program is able to achieve very good correlation with the measured results. This is particularly impressive considering the interface stack up and the high heat density created by the close proximity of the RF output transistors. In this case, the design goal of 75 °C maximum device flange temperature has been achieved (see Table 2).



**Figure 8.** Sauna CAD Model of (2) SSPA modules on a single high efficiency heatsink.

### Conclusions

The design of a 1.1 kW C Band Solid State Power Amplifier has been presented. Much has been written in recent years on the comparisons of solid state and traveling wave tube amplifiers for use in satellite earth stations. It has long been the opinion of engineers that solid state technology has had reliability and linearity advantages over TWTAs. However the cost and size of the SSPA have often disqualified its use as the preferred earth station high power amplifier. This fact combined with the use of TWTA linearizers and the increasing reliability of TWTA technology has continued to place the SSPA at a disadvantage. For the SSPA to become the preferred amplifier over the TWTA, three major goals had to be achieved.

1. Equivalent Size and Weight
2. Comparable cost
3. Superior overall reliability

The size and weight issue could only be solved by innovative thermal design and packaging techniques. Cost is closely tied to the amplifier package so once goal #1 has been achieved, the separation in cost has diminished. The RF chassis of the 1.1 kW C Band amplifier has been realized in a 6 ru (10.5 inch or 266.7 mm) chassis. The smallest 2 kW TWTA is enclosed in a 7 ru (12.25 inch or 310 mm) chassis. Thus a comparable SSPA has been realized that is actually smaller than a TWTA!

Reliability can further be subdivided into two categories.

1. Semiconductor Device Reliability
2. Modular System Reliability

Semiconductor device technology is more robust and reliable than electron tube technology only when the devices are permitted to operate at temperatures well below their maximum channel temperatures. If the devices are allowed to operate at elevated temperatures, the solid state reliability aspect rapidly diminishes. The thermal design techniques presented in this paper certainly show that the acceptable device temperature criteria have been met.

The second reliability advantage that must be considered is rooted in static reliability theory. The modular design architecture of the SSPA can be modeled as a parallel system. The TWTA must be modeled as a series system. This is a tremendous advantage to a satellite earth station carrying mission critical traffic. A failure of a single device or an entire module does not cause the entire system to fail. The same is true of the power supplies used with the SSPA. When both the semiconductor reliability and the system reliability is considered, the SSPA is clearly far superior to the TWTA.

This joint venture between Paradise Datacom and R-Theta has resulted in a true bench mark product. For the first time, the SSPA is truly superior to the TWTA in terms of reliability, size, and cost.

For more information on high efficiency heatsinks contact:

R-Theta Inc.  
6220 Kestrel Rd.  
Mississauga, ON. Canada L5T 1Y9  
905.795.0077

For more information on high power solid state power amplifiers contact:

Paradise Datacom LLC.  
1012 E Boal Avenue  
Boalsburg, PA. USA 16827  
814.466.6275

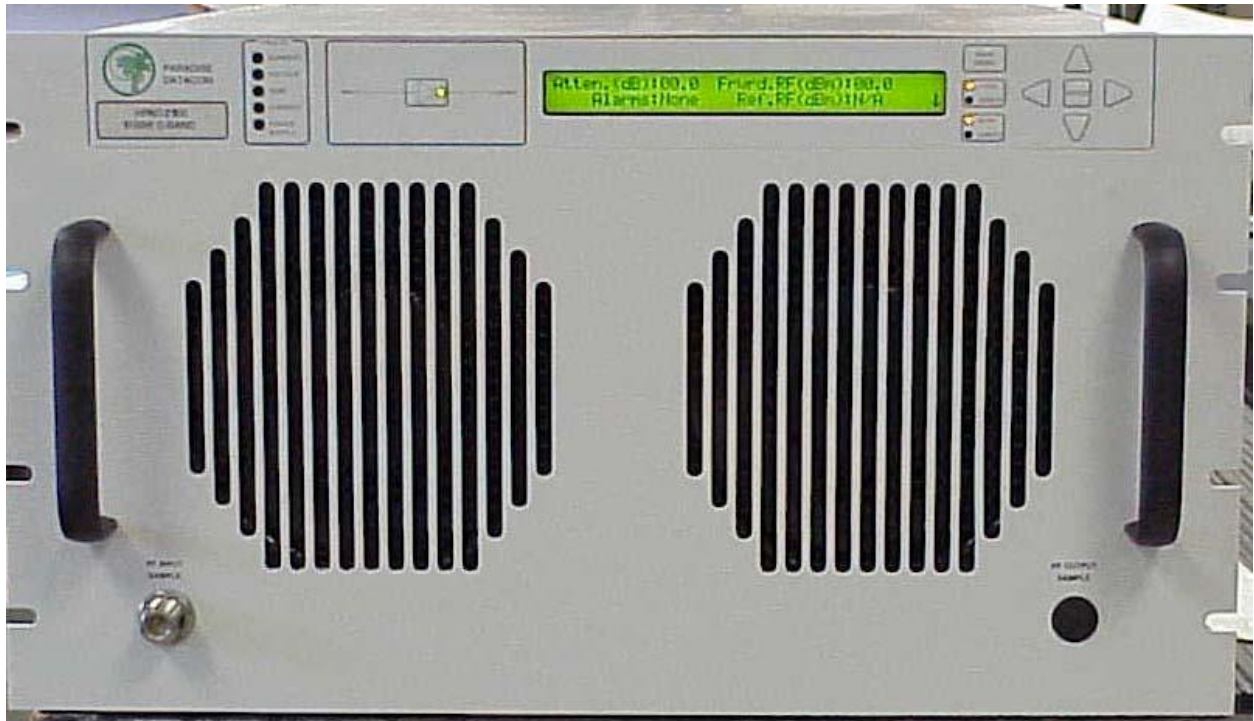


Figure 9. 1.1 kW C Band, Solid State Power in a 6 ru chassis.

## Author Bios

Dr. Ahmed M. Zaghlol received his B.S. and M.S. in Mechanical Engineering from Alexandria University in Egypt. After receiving his Ph.D. in Engineering Science from the University of Western Ontario, he joined the Microelectronic Heat Transfer Laboratory (MHTL) at the University of Waterloo as a post-doctoral Fellow. Currently, he is the Director of Engineering in R-Theta. Dr. Zaghlol published several papers and Articles on thermal performance of heat sinks for RF Amplifiers and Power Electronics. He manages R&D efforts for new products, development and implementation of R-Tools software. A registered Professional Engineer in Ontario (PEO), Dr. Zaghlol is a member of ASME, IEEE, and IMAPS. He can be reached at [azaghlol@r-theta.com](mailto:azaghlol@r-theta.com)

Stephen Turner received his B.S. degree in Electrical Engineering from the University of Pittsburgh and a Master of Engineering from the Pennsylvania State University. He has over 20 years of amplifier design experience including HF, VHF, and microwave frequency bands. A registered Professional Engineer (PE) in Pennsylvania, Stephen is a member of the IEEE Microwave Theory and Techniques society, Radio Amateur Satellite Corporation, and the Quarter Century Wireless Association (K3HPA). He is presently the Vice President of Engineering at Paradise Datacom LLC and can be reached at [sturner@paradisedata.com](mailto:sturner@paradisedata.com).