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A Conceptual Thermal Design Study of an Electronically Scanned Thinned Array Radiometer

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Summary

This report describes a conceptual thermal design study for an Electronically Scanned Thinned Array Radiometer (ESTAR). ESTAR is an instrument concept for the measurement of soil moisture from space using synthetic aperture radiometry. The thermal design goal is to minimize the orbital temperature variation of the radiometer receivers using established materials and techniques. Two design approaches have been investigated; the first uses the waveguide as a heat sink, and the second uses a nadir facing radiator on the receiver assembly. The second approach minimizes the receiver's impact on the waveguide temperatures. Predicted temperatures for all receivers are presented for the two cases indicating the transient thermal environments the receivers would experience during an orbit. In addition, the effects of the receiver heat dissipation on the waveguide temperatures are shown.

Introduction

Since 1990, a number of conceptual design studies for a mission to measure soil moisture from space have been conducted at Langley Research Center (LaRC) in collaboration with the Goddard Space Flight Center. Microwave radiometry at 1.4 GHz is the proposed measurement method for the soil moisture mission. A primary science requirement for the mission is 10 km of spatial resolution, which translates to the need for a large aperture instrument at this electromagnetic wavelength. Aperture synthesis in the radiometric measurement offers the opportunity to minimize the mass and volume of the instrument while maintaining the necessary large aperture. The Electronically Scanned Thinned Array Radiometer (ESTAR) is an instrument concept that implements aperture synthesis to meet the soil moisture mission requirements. The LaRC mission design studies have been based around the ESTAR instrument.

The objective of this work was to extend prior ESTAR studies to better estimate instrument performance and to define instrument calibration requirements. A thermal design was developed for the instrument that minimized the temperature variation of the receiver electronics while maintaining a viable thermal environment. Ideally, the receivers would all run at the same temperature, and that temperature would stay constant throughout the spacecraft's lifetime. In reality, each box will operate at slightly different temperatures and the temperatures will vary throughout the orbit and throughout the season. This study investigated orbital temperature variations, seasonal temperature variations, as well as spatial temperature variations.

Background and Assumptions

A 400 km Sun Synchronous orbit with 10:00 a.m. nodal crossing was used to determine the thermal environment for the spacecraft. A 1997 launch date and a three-year mission lifetime were also used in the analysis. Figure 1 shows the spacecraft concept which consists of 14 aluminum waveguides, 14 receiver assemblies, a 1 m^3 spacecraft bus, and two 1 m^2 solar arrays. The waveguides are 6.9 cm wide, 13.8 cm high, and 9.1 m long. They are assembled into a 9 m wide array so that the deployed spacecraft is 9.1 m long and 9.0 m wide. The waveguides are oriented with their narrow dimension facing toward the earth and the receivers wrap around one end of the waveguide as shown in figure 2. Figure 3 gives the dimensions and layout of the receivers which were estimated to dissipate 6 watts of power apiece based on the receiver design of reference 1.

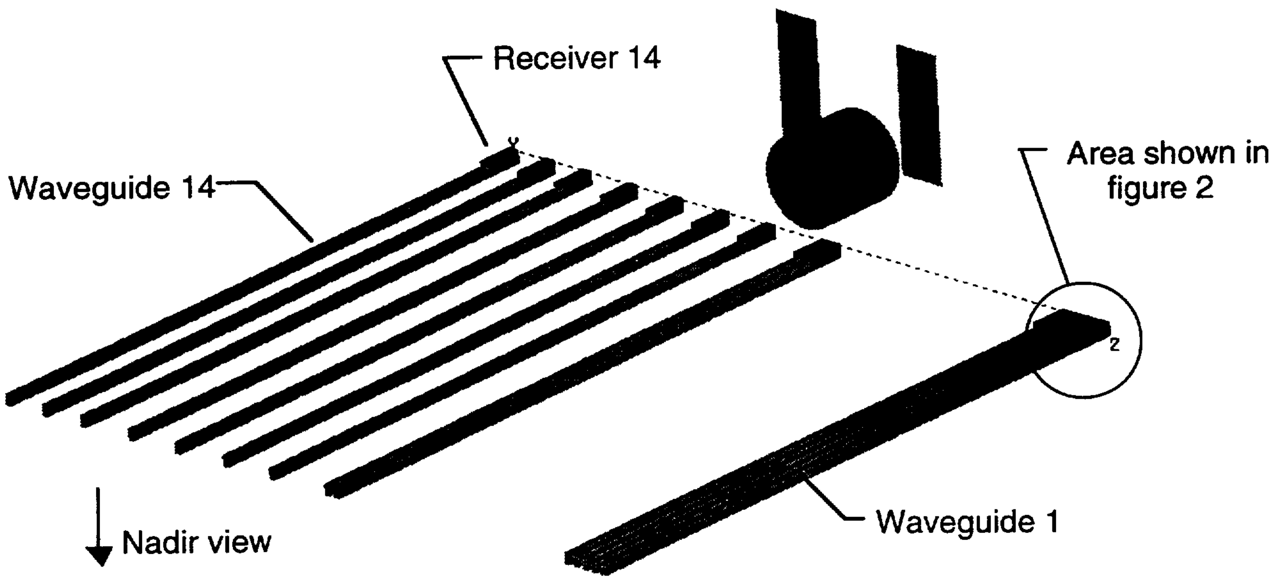

Figure 1. ESTAR Concept.

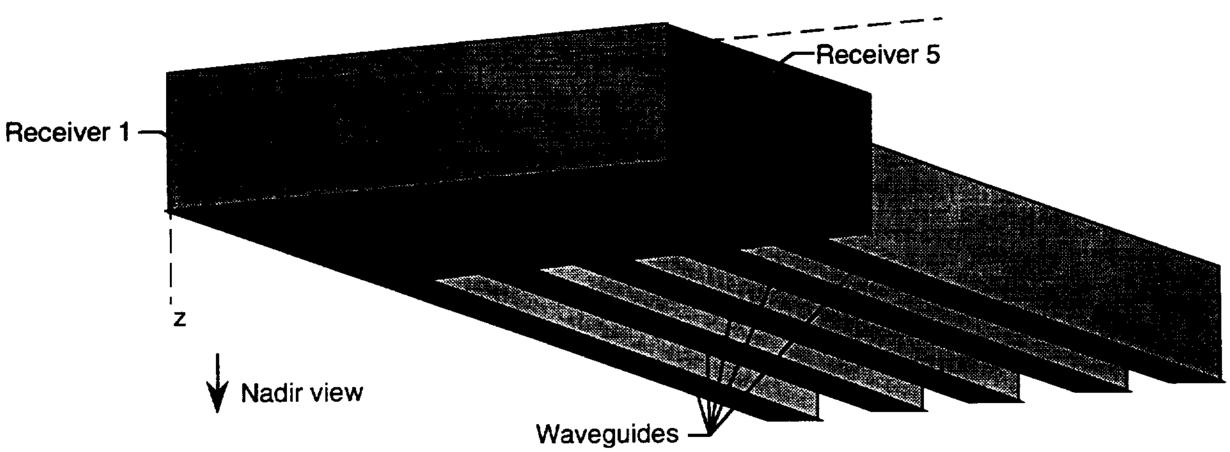

Figure 2. ESTAR Receiver mounting.

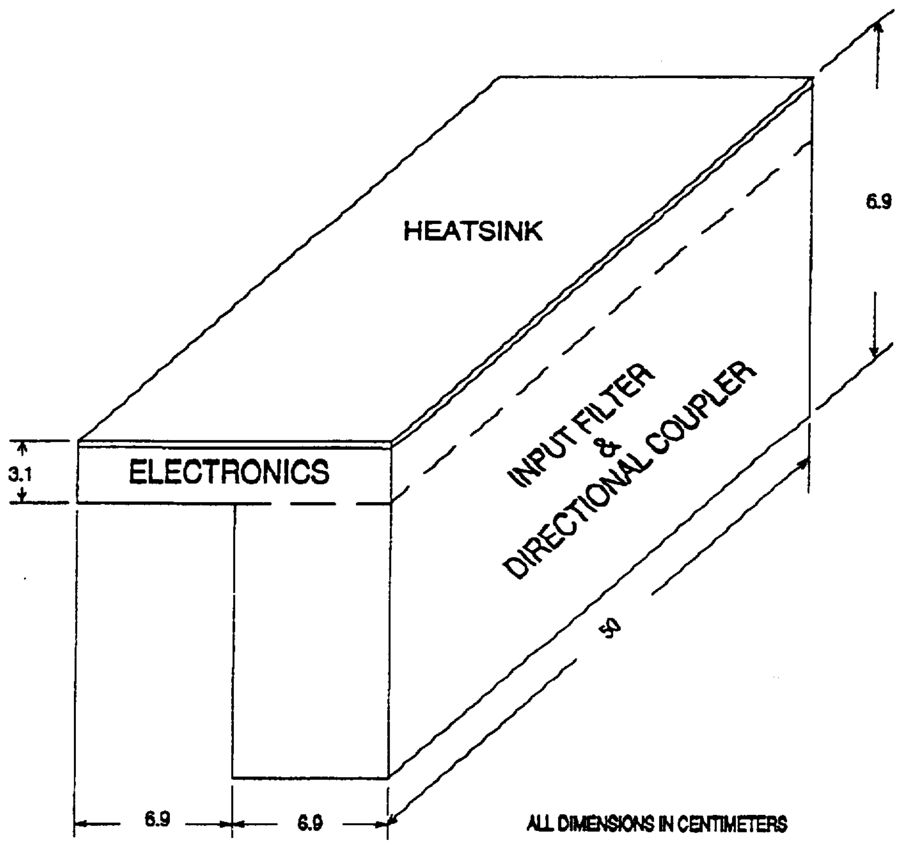

Figure 3. Receiver Characteristics.

Tools and Models

The Thermal Radiation Analyzer System (TRASYS) was used to generate the orbital boundary conditions and thermal radiation model for the analysis. This model contains approximately 1200 surfaces consisting of the antenna, receivers, spacecraft bus, and solar arrays. The orbital heat fluxes and radiation network generated by TRASYS were used in a Systems Improved Numerical Difference Analyzer (SINDA) model. This model is a finite difference model that calculates structural temperatures. The SINDA model contains approximately 650 nodes and 2300 conductors.

Conceptual Design Results

The main goal of the ESTAR thermal design is to dissipate the receiver electronics heat while maintaining the receivers at a constant temperature. A second goal is that the thermal design of the receiver boxes should be as similar to each other as possible. Since each receiver will experience a slightly different environment, the thermal control system must be flexible enough to allow all receivers to operate at approximately the same temperature.

Waveguides as Heat Sinks

Two approaches for dissipating the heat from the receiver electronics were investigated. The first approach maximized the conduction of the heat from the receiver box to the waveguide where it was radiated to space. This approach allowed all surfaces of the receiver box to be covered with multilayer insulation (MLI) thus reducing the effects of the transient thermal environment. The waveguides were also covered with MLI except for the nadir sides which contained the receiving slots. Since the slots cannot be blocked, MLI is not a viable option for these surfaces. In addition, the nadir surfaces of the spacecraft experience the most constant environmental heat flux making them good candidates for radiator surfaces. The slots were assumed to cover 15% of the nadir side surface area, but since the thermal coating could not be applied all the way up to the edge of the slots, some of the aluminum waveguide will be exposed. The amount of exposed aluminum was estimated to be 25% which left 60% of the surface area to be covered with silver Teflon. The material properties used in the calculations are listed in Table 1. Applying these properties and their corresponding surface area percentages yields an effective solar absorptivity of 0.34 and effective emissivity of 0.765 for the nadir surfaces of the waveguides.

Table 1. Thermal Properties

Material	Solar Absorptivity	Thermal Emissivity	Thermal Conductivity	Specific Heat	Density
MLI		0.03*			
Silver Teflon	0.07	0.63			
Beta Cloth	0.34	0.765			
Aluminum	0.50	0.13	1.7123 W/cm-K	0.962 J/gm-K	2.713 gm/cm^3

*Effective emissivity of MLI blanket

The beta angle varies between 21.6° and 31.8° for this orbit and there is very little difference in predicted temperatures for the two cases. The results for the 21.6° beta angle case will be presented since this case gave a slightly larger variation in receiver temperature. Figure 4 shows this temperature variation for each receiver during one orbit. The receiver temperatures all follow the same curve with a slightly different offset or average temperature. Each receiver has a minimum to maximum temperature change of less than 2°C over the orbit. Receivers 1 through 5 run about 20°C, or 4°C hotter than the rest of the receivers. This is because they are adjacent to each other and block each other's view to space. This also applies to waveguides 6 and 7 but to a lesser extent since only two waveguides are involved there.

One of the design goals is to have all of the receivers operate at the same temperature. In order to achieve this, the insulation on the first seven waveguides was reduced. By reducing the size of the MLI blanket on these waveguides, their operating temperatures can be brought in line with the other waveguides. Analytically, this was done by using a higher effective emittance to account for the smaller MLI blanket. Figure 5 shows results for a case with effective MLI properties given in Table 2:

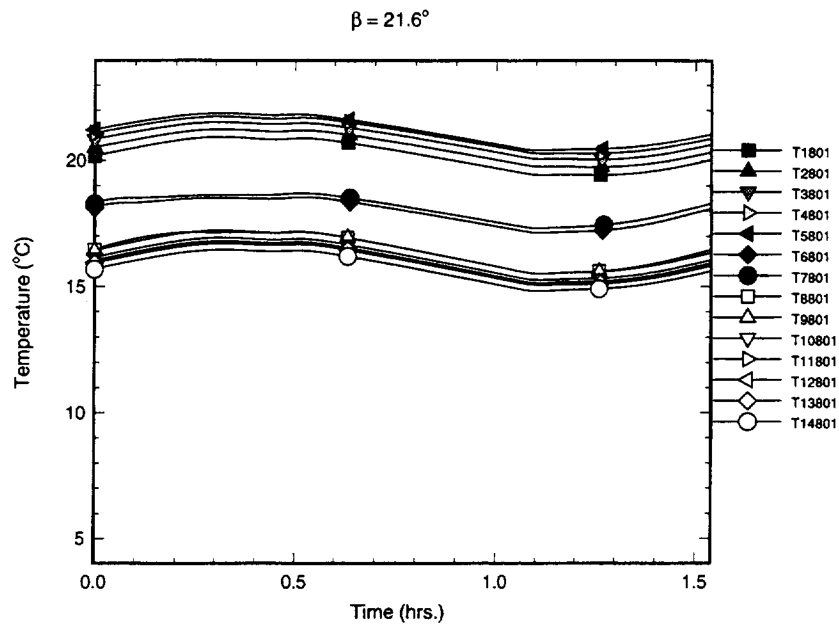

Figure 4. Receiver temperatures.

Table 2. Effective MLI properties

Waveguides	Effective emittance
1–5	.07
6, 7	.04
8 –14	.03

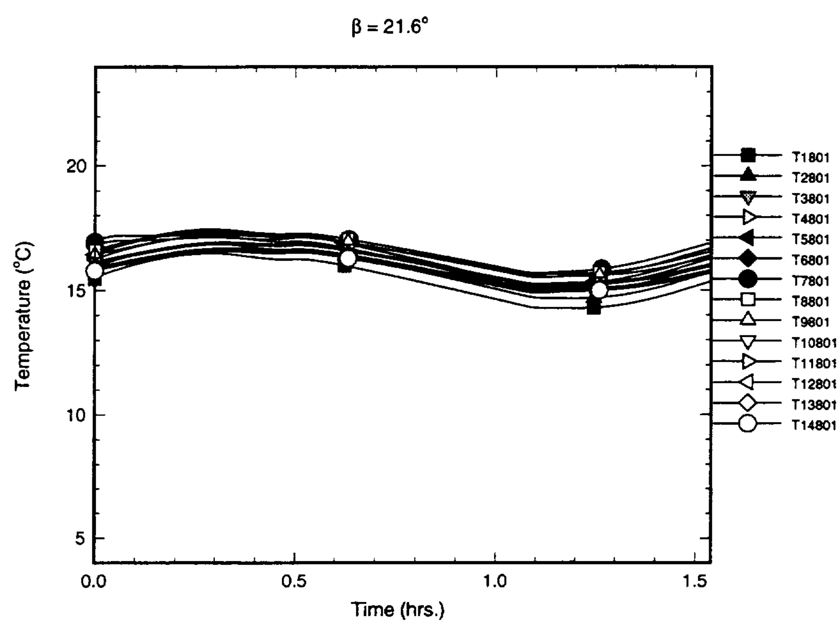

Figure 5. Receiver temperatures with reduced MLI effective emittance.

A consequence of using a smaller blanket is that the temperature variation over an orbit of a receiver with a smaller MLI blanket will increase due to the reduction in insulation. Although hard to see in the figures, the orbital temperature variation of the first five waveguides went from 1.5°C with a full blanket to 2.5°C with the smaller blanket. Note also the tradeoff between average operating temperature and orbital temperature variation—the better the insulation, the smaller the orbital temperature variation but the higher the average temperature.

Figure 4 indicates that receiver 5 will run the hottest with a peak temperature of 21.9°C, and receiver 14 will run the coolest with a minimum temperature of 14.8°C. This gives a peak to valley maximum temperature difference among all the receivers of 7.1°C. This number includes the effects of both the temperature variation due to transient orbit conditions as well as the temperature variation due to spacecraft location. The corresponding number for the second case, shown in figure 5, is 3.2°C. So, by reducing the size of the blanket over receivers 1 through 7, the maximum to minimum temperature difference over all the receivers has been cut in half.

The drawback to conducting the heat from the receiver to the waveguide is shown in figure 6, which is a plot of the temperature distribution along waveguide number 8. The horizontal axis corresponds to the distance along the waveguide with the receiver located at the left end of the graph. The figure shows that by conducting the heat from the receiver box to the waveguide, a temperature difference of nearly 30°C is developed from one end of the waveguide to the other. This temperature difference may lead to unacceptable thermal distortions.

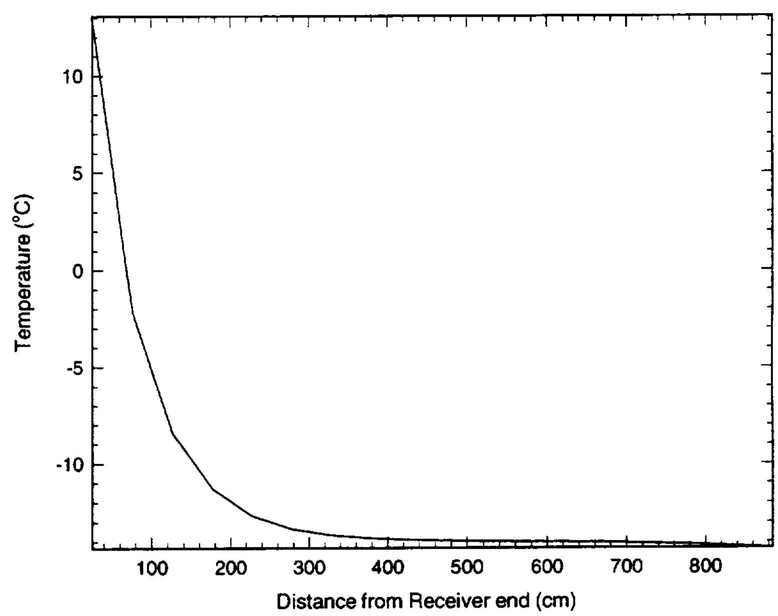

Figure 6. Temperature distribution along waveguide 8.

Receiver Radiator

To avoid this potential problem a second approach to dissipating the receiver electronics heat was investigated. By adding a radiator to the receiver box, the receiver heat can be dissipated from the box directly and the receiver and waveguide can be thermally isolated. The nadir side of the receiver box was chosen for the radiator surface for two reasons: first, was the desire to have the design of all the receiver boxes the same; and second, was the desire to minimize the orbital temperature variation. In order to keep the design of each box the same, only sides which were not affected by receiver location were acceptable—the nadir, zenith, and antivelocity sides. The nadir surface was chosen because it had the most stable heat flux environment and therefore the smallest orbital temperature variation.

Optical Solar Reflector properties (solar absorptivity of 0.1, thermal emissivity of 0.78) were used for the radiator. Figure 7 shows the orbital temperature variation of the receivers for the radiator case. The most obvious result is that the average receiver temperature has been reduced about 10°C to approximately 7°C . These results assume no effort is made to isolate the receivers from the antenna. Several cases with various amounts of thermal isolation between the receiver and antenna were run to try and minimize the waveguide temperature gradient. Figure 8 shows the temperature distribution of waveguide 8 for some of the cases. With no effort to isolate the two components, a 17°C temperature difference along the waveguide exists. If it were possible to totally isolate them, the temperature difference would drop to 4°C. Note that it is not possible to eliminate this temperature difference totally because the receivers wrap around the end of the waveguide and block its view of space. In essence, the receiver becomes a perfect MLI blanket ($\varepsilon^*=0$) and the heat loss to space through it is eliminated. Figure 8 shows that using thermal isolation to get a significant reduction in the waveguide temperature difference may not be practical. There is essentially no difference in the results between the 100% conduction case and the 25% conduction case (25% case not shown because the curves coincide). In fact, to cut the temperature difference in half requires cutting the conduction path by 99.5%! This would be extremely hard to do, if not impossible. A more reasonable approach would be to have the antenna and the receivers running at nearly the same temperature so that the heat transfer between them is minimized. This can be accomplished by either raising the antenna temperature, lowering the receiver temperature, or a combination of both. For example, the antenna temperature could be increased by using a lower emissivity material on the surface of the antenna and the receiver temperature could be decreased by increasing the size of its radiator.

Since only a rough estimate of the electronics heat dissipation was possible, a contingency case was run to see how the system would respond to a larger heat dissipation. The receiver electronics dissipation was raised from 6 watts to 10 watts for this case and there was no thermal isolation between the receiver and antenna. The results are shown in figure 9, and once again we see only a shift in the curves from an average temperature of 7°C (figure 7) to approximately 20°C.

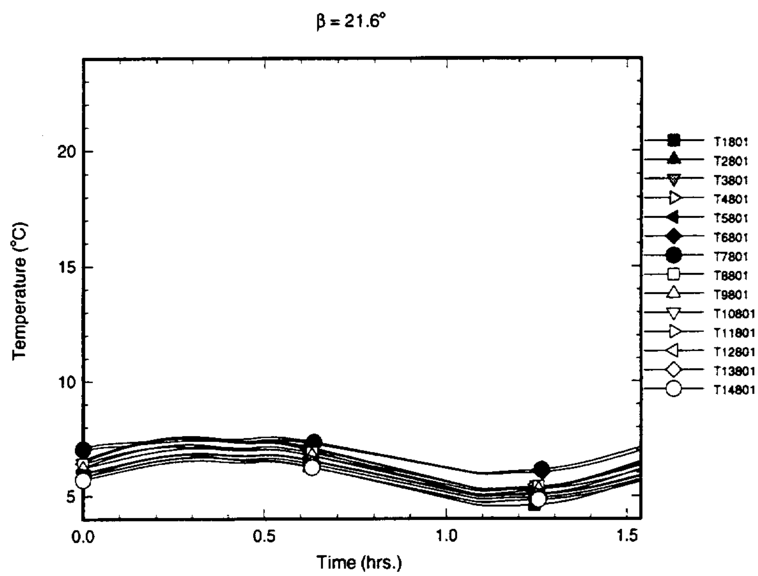

Figure 7. Receiver temperatures with radiator configuration.

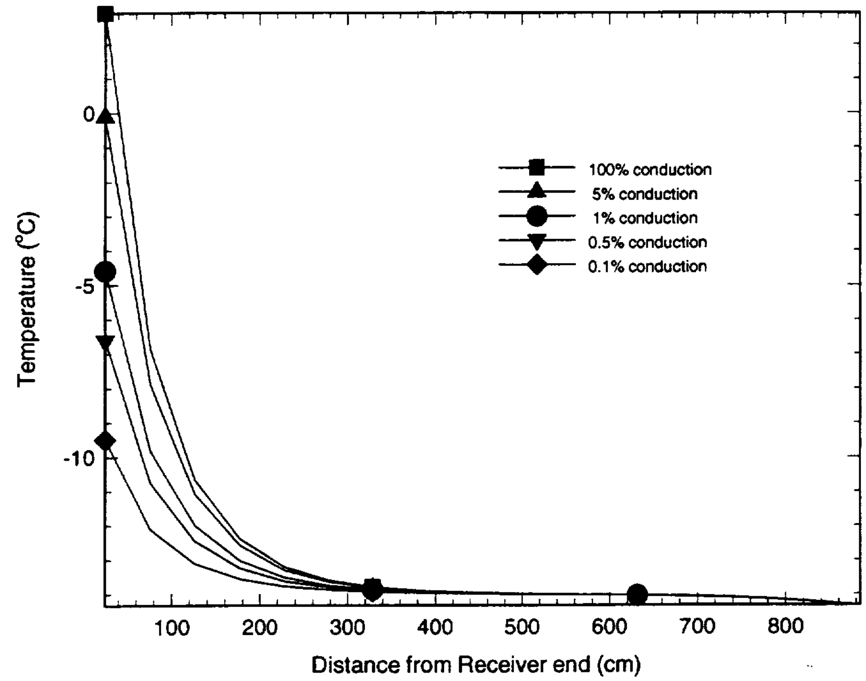

Figure 8. Waveguide temperature for various degrees of receiver isolation.

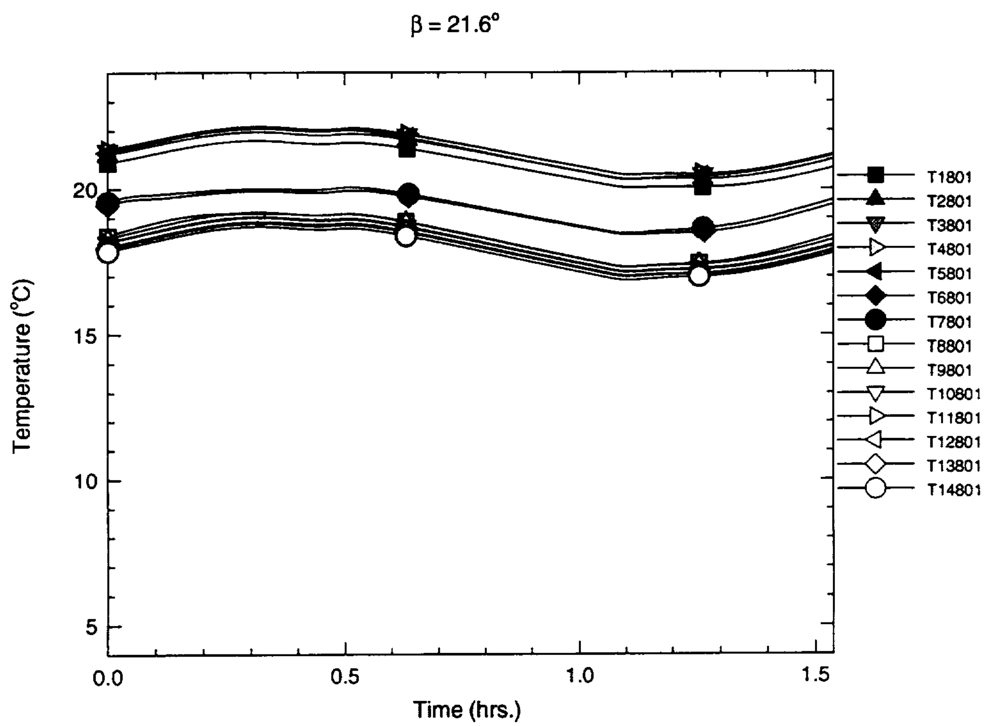

Figure 9. Receiver temperatures for 10 watt receiver dissipation case.

Graphite Epoxy Waveguide

A final analysis was performed to determine the effect of changing the waveguide material from aluminum to graphite epoxy. A graphite epoxy waveguide would reduce thermally induced deformations and improve the performance of the system. The thermal conductivity of the aluminum is 70 times that of the graphite epoxy, so a graphite epoxy waveguide would have the effect of isolating the receiver. This effect is shown in figure 10, where the graphite epoxy waveguide is at a nearly constant temperature outside of the receiver. The receiver temperatures are shown in figure 11. The average temperature is approximately 13°C, slightly hotter than the corresponding aluminum waveguide case (figure 7) since graphite epoxy has reduced the heat conduction to the waveguide.

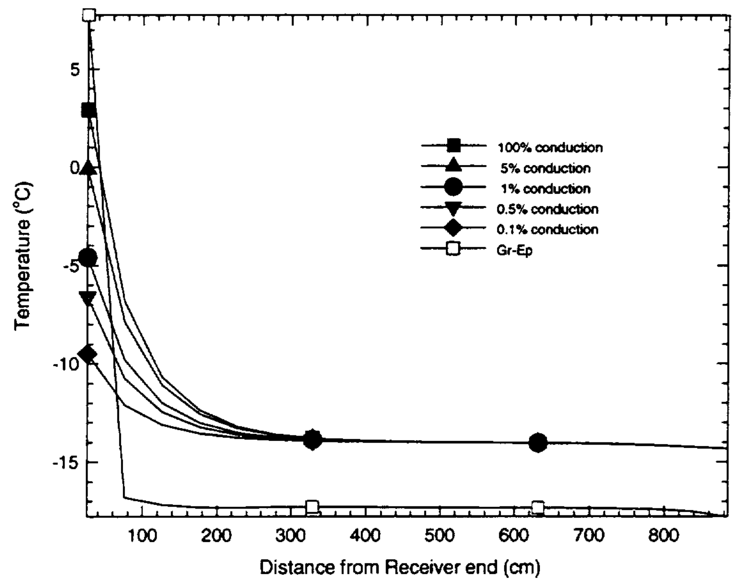

Figure 10. Graphite-epoxy waveguide temperature distribution comparison.

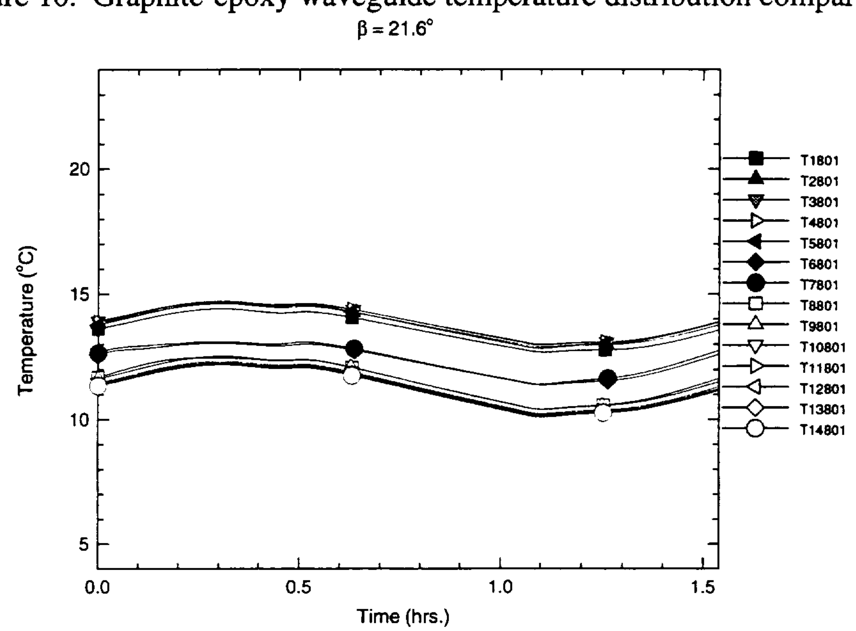

Figure 11. Receiver temperatures for graphite-epoxy waveguides.

Concluding Remarks

Two thermal design approaches were developed and analyzed for an Electronically Scanned Thinned Array Radiometer with intent to minimize orbital temperature variations of the receiver electronics. The first approach used the waveguide as a heat sink, and the second used a nadir facing radiator on the receiver assembly. Using the waveguides as heat sinks resulted in receiver temperature variations of approximately 2°C over one orbit. The analysis also indicated that the receivers that were closely spaced (1–5, 6 & 7) operated at a higher temperature than the other receivers. By reducing the size of the receiver MLI blankets on the hottest receivers, their temperatures were brought in line with the other receivers; however, the smaller MLI blankets resulted in a slightly larger orbital temperature variation (2.5 °C) for these receivers. A plot of the predicted waveguide temperature indicated that the receiver end of the waveguide was nearly 30 °C warmer than the opposite end of the waveguide. Since it is not clear how this large temperature difference would affect antenna performance, a second thermal design was investigated which would reduce this temperature variation. This design used a radiator on the receiver assembly to dissipate the receiver electronics heat. In addition, various amounts of thermal isolation between the receiver and the waveguide were studied. These analyses showed that even a very small conductive path between the waveguide and the receiver would lead to a large end-to-end temperature difference along the waveguide. One way to avoid this is to have the waveguides and receivers operate at nearly the same temperature. This could be accomplished by varying the size of the radiators or MLI blankets on either the waveguides or receivers (much like was done to bring the receivers operating temperatures in line for the first approach). A final case was run to study the effects of using a waveguide made of graphite epoxy. The low thermal conductivity of graphite epoxy reduced the heat transfer between the receiver and the waveguide resulting in a higher operating temperature for the receiver. It also resulted in a nearly constant waveguide temperature outside of the receiver area. Thus, if the portion of the waveguide adjacent to the receiver is excluded from the active antenna area, the end-to-end temperature difference along the antenna would be very small. Finally, it should be noted that the designs use established materials and techniques so that no new technologies are required.

Acknowledgments

The author would like to acknowledge the contributions of Dr. Richard F. Harrington of the Research Triangle Institute for his support in defining the design requirements for a synthetic aperture radiometer receiver, and James W. Johnson of NASA Langley Research Center for his guidance in conducting this study.

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