MINIATURIZED RF REMOTE SENSING INSTRUMENTS

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Abstract

Until recently, miniaturization of RF remote sensing instruments has not been cost effective. Aperture size has governed launch vehicle selection and spacecraft mass has been well within margins. However, as technologies improve for miniature spacecraft, multiple spacecraft can fit within small launch vehicle shrouds. Down-sizing payloads is now advantageous. E-Systems is applying state-of-the-art technologies to significantly reduce the size and weight of RF remote sensing payload electronics. Current activities include the development of MMIC modules; the application of advanced materials; the development of multi-band feeds; and the development of micromachined filters and other RF components. These technologies will be combined with Multi-chip Modules (MCMs) and application-specific integrated circuits (ASICs) to yield a new generation of instruments. Further miniaturization is planned using emerging mixed-mode technologies that will allow these MMICs and MCMs to be combined onto common substrates, and new high-efficiency solid state power amplifiers to replace the current traveling wave tube amplifiers (TWTAs) in active sensors. With these advances, it becomes feasible to integrate the RF components with the feed and mount the sensor electronics virtually on the back of the antenna, thereby reducing cabling losses and permitting integrated testing and acceptance of the electronics and antenna as a complete system before integration on the spacecraft. This reduces cost, complexity, and facilities required for integrating small spacecraft missions.

Nomenclature

Abbreviation	Definition
JPL	Jet Propulsion Lab
LNA	Low Noise Amplifier
MIC	Microwave Integrated Circuit
MMIC	Monolithic Microwave Integrated Circuit
MMW	Millimeter Wave
RF	Radio Frequency
SSPA	Solid State Power Amplifier
TWT	Traveling Wave Tube
TWTA	Traveling Wave Tube Amplifier

Introduction

Remote sensing instruments that operate at RF provide high priority data including water vapor, rain intensity, snow, atmospheric absorption, ocean temperature, sea ice, ocean surface winds, and sea height sensing. RF instruments suffer significant geometry penalties compared to their optical counterparts. Aperture diameters of a meter or more are common for imaging radiometer subsystems, scatterometers, and altimeters. Synthetic aperture applications including side-looking imaging radar require large arrays to achieve the desired resolution. Deployable structures are often considered for these applications, but these bring a host of accuracy and repeatability problems making calibration nearly impossible. Thus, in the quest for smaller, more affordable spacecraft, aperture size for RF remote sensing instruments will continue to drive spacecraft size and launch vehicle selection. Using current spacecraft technology, reducing the payload mass through technology infusion sometimes will allow selection of a slightly less robust launch vehicle within the same class, but the launch vehicle cost savings do not justify the expense required.

However, with the continuing reduction in size of spacecraft support systems, miniaturizing the instrument electronics becomes practical. Launch vehicle class reductions are now possible, provided fairing sizes can accommodate the antenna aperture. If not, multiple spacecraft of the same or different types, can be stacked in the larger diameter fairing.

E-Systems ECI Division, a wholly-owned subsidiary of Raytheon, is transforming its existing RF remote sensing business to meet these new requirements through a structured technology development and insertion process. E-Systems is completing the development of a next generation Ku-band Radar Altimeter (RA) for the Geosat Follow-on (GFO) program that is one third the weight and half the power of the previous Geosat RA. At the same time, we are developing the SeaWinds Scatterometer Electronics Subsystem (SES) for the Jet Propulsion Lab (JPL) using similar technologies. By leveraging knowledge gained from these and other programs, key technologies have been identified for insertion within the next five years including:

- Monolithic Microwave Integrated Circuit (MMIC) receiver modules to reduce circuit complexity, improve thermal stability, and improve performance
- Advanced materials to reduce weight and improve thermal stability and performance
- Multi-band dual-polarization feed with an optimized corrugated horn to improve pattern efficiency
- Micro-machined filters to replace larger stripline and waveguide filter technologies

These technologies are being developed and integrated into a multi-band dual-polarization microwave radiometer receiver testbed operating at 19 GHz, 22.5 GHz, and 37 GHz as shown in *Figure 1*. The direct-detect receivers are integrated with the feed to improve efficiency and dramatically reduce instrument complexity and over-all size and weight. *Figure 2* shows how the integrated feed/receiver fits into a scanning multi-band radiometer.

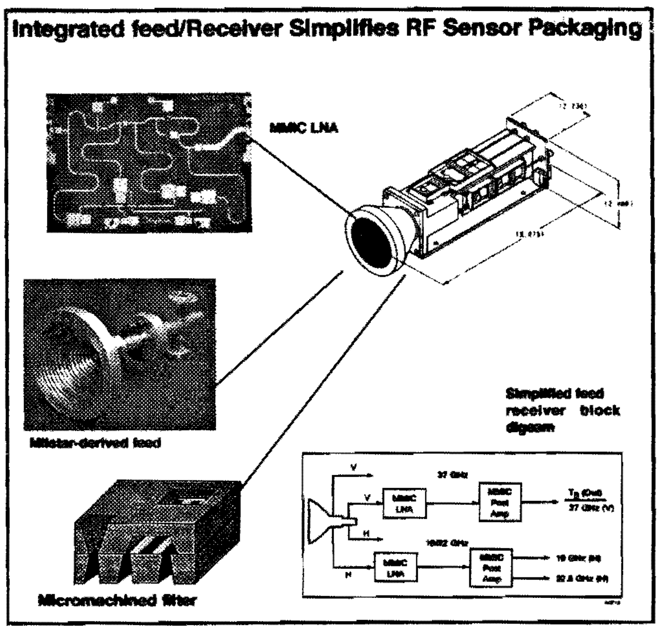

Figure 1. Advanced technologies combine into an integrated feed/receiver subsystem

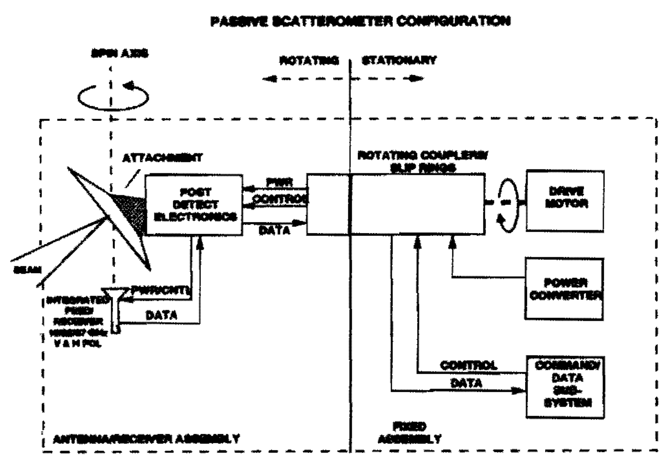

Figure 2. Integrated feed/receiver simplifies instrument design

Current Technology Efforts

MMIC Receivers

The driving requirements for RF remote sensing receivers are noise figure and stability over temperature and aging. Calibration of the instrument requires detailed knowledge of the receiver gain and noise figure as functions of time and temperature. Once established during initial instrument calibration, these models flow into the compensation algorithms applied to the resulting data and determine the over all accuracy of the instrument. MMIC receiver channels reduce electronics module size and weight by a factor of 3 or more over conventional packaging technologies. MMIC receivers provide more stable performance over temperature and aging than standard discrete designs. In addition, the smaller form-factor reduces thermal variations across the circuit and allows multiple receivers to be thermally connected, thereby simplifying calibration between multiple channels. MMIC receivers have been developed by government and commercial communications programs at or near frequency bands of interest to RF remote sensing. Most of these circuits require some improvements either in noise figure or frequency range for application in science instruments. We have identified MMICs from several sources for application to the multi-band radiometer testbed and further evaluations of the impact and cost of required modifications are on-going.

Advanced Materials

Temperature control of the RF assembly and the MMIC receivers are critical to the performance of the radiometer system. Structural strength, mass, and moment of inertia of the rotating sensor assembly are competing, often conflicting requirements. Without accurate thermal control, numerous additional temperature sensors are required to assess the impact of parasitic system thermal noise on the measured noise power of the instrument, significantly complicating the calibration and data correction processes.

Traditional 'black box' instrument packaging uses waveguide (or coax at appropriate frequencies) to transfer received RF from the antenna feed to the receiver. These systems require extensive temperature monitoring to properly correct for thermal differences along the receive path. Integrating the MMIC receivers directly onto the feed assembly virtually eliminates this problem. There is only a short connecting probe from the feed launcher waveguide to the electronics module. Additionally, the weight and complexity penalties of waveguide assemblies and a separately-located receiver are eliminated.

Materials for the feed, circuit modules, and structural elements are selected primarily to provide thermal control of the integrated feed/receiver assembly and to minimize scanning mass and inertia. Non-metal matrix composites such as graphite or carbon filled epoxy are used to provide low mass and high stiffness properties of the spinning assembly. Metal-matrix composites such as Aluminum-filled Silicon Carbide and Aluminum Nitride are used to provide thermal conductivity and thermal expansion matching to the MMIC and micromachined filter components. These materials are space qualified and are compatible with low earth orbit environments.

Further temperature control is achieved by decoupling the metal orbit-exposed horn from the electronics by design and materials selected for the composite feed waveguide/housing. The smaller thermal mass of the integrated subsystem reduces instrument warm-up time and reduces requirements for active temperature control. Operational thermal stability of ±0.5° K provides the simplest calibration requirements. This capability can only be achieved through the combination of MMIC receivers and advanced materials.

Passive thermal control materials include multilayer insulation blankets using outer surfaces of carbon filled Kapton compatible with atomic oxygen and total dose degradation as well as providing a ground path. High emittance second surface silver-Teflon radiators provide passive temperature stability independent of the platform. This material has selectable solar absorptivity as a function of metalization choice and infrared emittance values depending on Teflon thickness and is applied as a reflective tape. The advantage is that it reflects 90 percent solar and emits 85 percent IR making it a material of choice for low Earth orbit thermal control.

Active thermal control using heatpipes, micro-louvers, and other active devices can be implemented as required by the instrument and the specific mission to meet thermal stability requirements and maintain instrument calibration.

These materials have proven spaceflight heritage and can be tailored to reduce the complexity of internal temperature control. Structural response of the compact subsystem is fully manageable. Moreover, low mass, small size and high stiffness allow maximum flexibility for integrating antenna dish, cold/hot sources and other instrument components.

Multi-band Feeds

For radiometer applications, high beam efficiency, low outboard side lobes, and beam symmetry are key performance parameters. Corrugations, or baffles, are typically employed to tune the feed for optimum performance. However, achieving good performance with a multi-band feed traditionally involves compromises at one or more of the feed frequencies. Separate feeds are sometimes used when the performance penalties outweigh the additional complexity of closely packaging, aligning, and calibrating multiple feeds at the reflector focal point. Raytheon has patented an optimized baffle design for dual frequency feeds. Work is underway to extend this concept to multiple frequencies. For the testbed application, the 19 and 22.5 GHz bands are close enough that the Raytheon dual-frequency design can be applied with one band centered at 20.5 GHz and the other at 37 GHz.

The Aluminum feed horn transitions into a two-piece waveguide launcher that incorporates probes for horizontal and vertical polarizations at each frequency band. Waveguide concentricity between the two launcher segments is provided by thin-wall tubing pressed into the aft segment and oriented via gage tooling at assembly. Mounting surfaces are provided for the RF circuit modules for each polarization and frequency. A mechanical adjustment is provided in each waveguide cavity using separate end-caps. Space has been allowed in the testbed design to transition the analog-to-digital converter networks into the integrated assembly in the future.

The integrated feed/receiver subsystem, consisting of the corrugated horn attached to the launcher, measures less than 6 cm square by 23 cm in length and has an estimated mass of less than 1 KG. The aft segment of the two piece feed housing is bolted to the forward segment. Fabrication of the launcher using composites offers weight savings, thermal isolation from the horn, thermal control for the RF circuit modules, and the possibility of lower-cost advanced manufacturing techniques including injection molding. For the testbed, the forward and aft segments are lightweight graphite-epoxy composite and each has three drilled holes, wave guide cavity and orthogonal coax transitions. Circuit module housings are silicon carbide aluminum or graphite/aluminum containing GaAs substrates with MMIC chips and micro-machined elements wire-bonded to the substrates.

Feed-throughs are incorporated in the module walls for power, coax transitions, and Gilbert-type blind-mate connectors. Design and arrangement of the modules around the feed anticipates growth or shrinkage consistent with technology evolution by modifying feed housing length and adding or subtracting standardized modules or custom snap-in elements as required.

Micromachined Components

Like any filter, bandwidth, roll-off, and insertion loss are driving requirements. Traditional stripline and waveguide filters are large, even at the millimeter wave frequencies. Evolution of semiconductor etching processes over the last few years has yielded a host of micromachined components ranging from electro-mechanical actuators to simple filters. Micromachined filters provide performance comparable to traditional counterparts with reduced production cost and dramatic reductions in size and weight. Filter parameters are tightly controlled by the masking and etching process, so variations in critical performance parameters over time and between filters of a given design should be minimal. This stability enables automated production and test with minimal tuning. Micromachined filters use proven silicon etching and deposition techniques to reduce microwave filter size by up to 75%, resulting in smaller electronics packages.

A typical micromachined filter is shown in *Figure 3*. The planar structure combines standard silicon etching and metal deposition techniques with emerging membrane technology to produce filters with integral shielding cavities etched into the two laminated substrates. The center silicon wafer is etched through. The resulting sandwich resembles a waveguide filter in performance at 25% of the volume.

Other micromachined components are possible including magic-T's, couplers, dividers, and phase-shifters. These components are combined with the MMIC receiver components on GaAs substrates using either flip-chip or conventional wire bonding techniques.

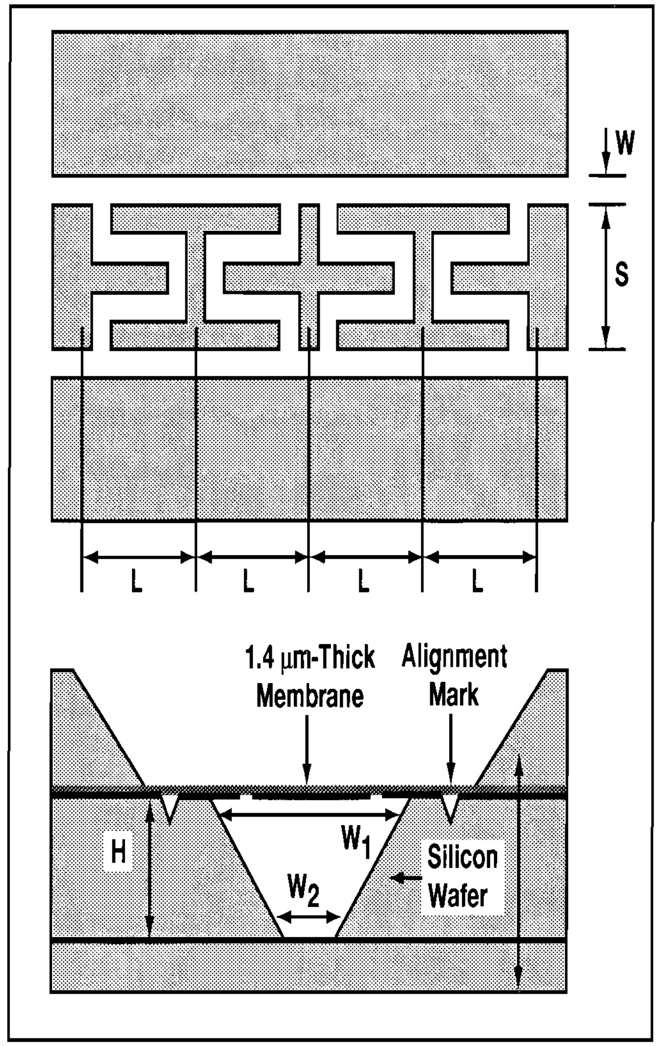

Figure 3. Micromachined Filters

Application to Ocean Surface Winds

The SeaWinds scatterometer is an example of current-generation wind sensing instruments. As shown in *Figure 4*, the SeaWinds instrument is mounted on a nadir-facing panel of the ADEOS II spacecraft and consists of a rotating antenna subsystem, the Scatterometer Electronics (SES) and a Command and Data System (CDS). The complete instrument weighs in at 176.8 KG and draws 234 Watts of prime power. Thermal control components make up nearly a third of the instrument mass, while the TWTA accounts for half of the power consumption.

Recent work by JPL, Marshall Space Flight Center, and others, has shown that wind vectors can be derived from a passive scatterometer. The passive scatterometer uses dual-channel radiometers operating at selected frequency bands to derive the required Stokes parameters for ocean thermal emission. Processing of this data along the circular scan of the instrument

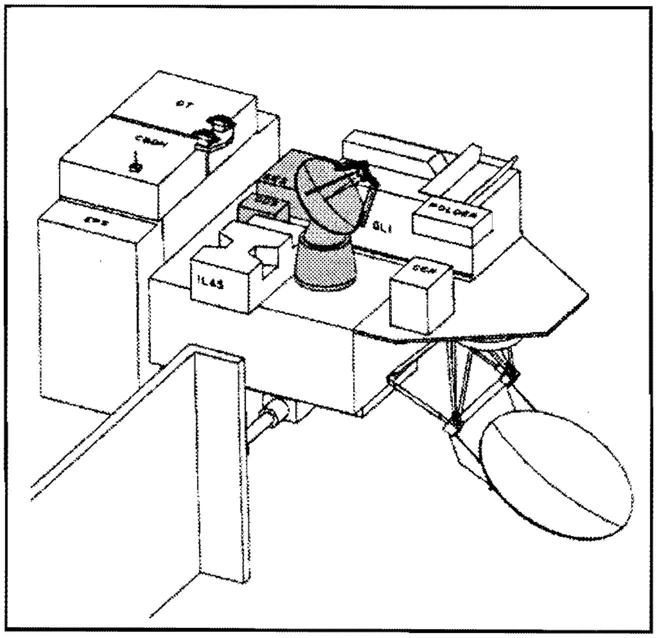

Figure 4. The SeaWinds backscatter radar wind vector sensor

yields the wind direction and velocity. Frequency bands of interest for this instrument are 19 and 37 GHz. Some extraction algorithms under study use 22.5 GHz as well. Including this band is beneficial because it allows measurement of water vapor.

For 800 km altitude scanning at an incidence of 54 degrees, a reasonable reflector mechanical assembly is possible that produces a 2500 km swath at 25 km resolution. A projected reflector diameter of 86 cm results for the 19 GHz band. The Integrated Feed/Receiver is small enough to be integrated into the scanning antenna subsystem without adverse impact on the mass properties. Sampling and control functions are performed in the post-detect electronics. This allows the data to be transferred through slip rings or roller contacts, rather than transferring RF through a rotating waveguide joint as is done on the SeaWinds instrument. *Figure 5* summarizes the weight and power advantages of the miniaturized wind vector radiometer over just the SeaWinds SES component. This assessment assumes SeaWinds-like digital components and does <u>not</u> include weight or power advantages of integrating other instrument components into MCMs.

Power Comparison (Watts)		
Module	SeaWinds (SES)	Proposed PS
TWTA	140	N/A
Tx Chain	17	N/A
Rx Chain	9	< 8
Processor	10	< 10
	176 Watts	< 18

Weight Comparison (Kg)		
Hardware	SeaWinds (SES)	Proposed PS
TWTA	40	N/A
RF Group	12	< 3
Digital Group	7	< 7
Thermal Control Subsystem	31	≤ 3
	90 Kg	< 13 Kg

Figure 5. Advantages of an Integrated Passive Scatterometer over SeaWinds

Other radiometer applications including ocean surface temperature measurement and atmospheric moisture sounding also benefit from the reduced size and weight of the Integrated Feed/Receiver subsystem.

Application to Altimetry

Future extension of the technology to include transmit/receive isolation will enable significant reductions in size and weight of active RF instruments like radar altimeters for sea height sensing and backscatter cross section measurements. Similar application of these technologies will also enable significant size and weight reductions of microwave and millimeter wave communications systems.

The GFO instrument consists of a fixed-aperture Ku-band radar altimeter and a 2-frequency, 4-channel water vapor radiometer to allow correction of the radar data. Incorporating integrated feed/receiver technologies would allow the current feed and waveguide assemblies to be replaced with a single assembly incorporating the radiometer and radar receiver front-ends. A simpler transmit-only waveguide would connect the SSPA to the feed. Application of MIC and MCM technologies to the SSPA could allow migration of the final drive stage to the integrated feed and further simplification of the instrument.

Demonstration Plans

The packaging and component technologies described herein are being integrated into a multi-band radiometer testbed. Testbed components will be tested individually to verify performance prior to integration. Calibration of the radiometer channels will be achieved either in-house or at an outside lab using standard targets. Environmental screening tests will be performed on the Testbed to assess the mechanical and thermal designs. The Testbed integrated feed/receiver will be married to an available reflector for further evaluation. The Testbed will also be available for field testing of radiometer applications. Results of this integration and test program will enable insertion of these technologies into future programs at NASA Technology Readiness Level 5.

Conclusion

The miniaturization of RF remote sensing instruments must be approached on two fronts: 1) the application of current and emerging packaging technologies to reduce the physical space required for the necessary functions, and 2) the development of new passive alternatives to high-power active instruments. Even with these, aperture size is often the limiting factor and deployable real and synthetic apertures are required. The primary concern with deployable antennas is surface shape and tolerances, and their effect on beam uniformity and calibration. Deployables offer no advantage if calibration of the instrument on-orbit is impossible.

Miniaturized RF instruments are possible for near-term missions as close as two years away using currently available miniaturization technologies such as MMIC. Further integration of emerging technologies provides a path to even smaller, cost-effective instruments. These technologies lend themselves to mass production and lead to affordable synthetic aperture instruments for soil moisture surveys and SAR surface imaging.

The miniaturization of RF remote sensing instruments will enhance future planetary missions by enabling atmospheric monitoring of Venus, Mars, and selected moons; ice-cap formation and dynamics monitoring on Mars and ice sheet monitoring on the frozen moons of the outer planets at a fraction of the current mass penalty cost.

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Mr. Brady has been involved in advanced technology development for sensor and communications equipment for over five years. Mr. Brady came to E-Systems ECI division in 1992 and works in the Space Systems Engineering group where he leads technology development and business development projects for space communications and RF remote sensing systems. Mr. Brady previously worked at Lockheed Missiles and Space Co., Inc. in Sunnyvale Ca. where he developed advanced technologies for communications and instrument systems. Mr. Brady holds Bachelor's degrees in Electrical and Computer Engineering and Physics.

Greg G. McEachron, Mechanical Engineering, E-Systems ECI Division

Mr. McEachron leads the mechanical design team for the SeaWinds Scatterometer Electronics Subsystem payload currently under development for JPL. Mr. McEachron came to E-Systems ECI Division 6 years ago and has been involved with packaging advanced space instrument and communications system designs throughout this time. Mr. McEachron leads the in-house advanced packaging IR&D program for space hardware. Previously, Mr. McEachron worked at Honeywell where he designed and qualified hardware for flight on the Space Shuttle and other programs. Mr. McEachron holds a BS in Engineering Mechanics and an MS in Mechanical Engineering.