Microwave Radiometers from 0.6 to 22 GHz for Juno, A Polar Orbiter around Jupiter

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Abstract— A compact radiometer instrument is under development at JPL for Juno, the next NASA New Frontiers mission, scheduled to launch in 2011. This instrument is called the MWR (MicroWave Radiometer), and its purpose is to measure the thermal emission from Jupiter's atmosphere at selected frequencies from 0.6 to 22 GHz. The objective is to measure the distributions and abundances of water and ammonia in Jupiter's atmosphere, with the goal of understanding the previously unobserved dynamics of the subcloud atmosphere, and to discriminate among models for planetary formation in our solar system.

The MWR instrument is currently being developed to address these science questions for the Juno mission. As part of a deep space mission aboard a solar-powered spacecraft, MWR is designed to be compact, lightweight, and low power. The entire MWR instrument consists of six individual radiometer channels with approximately 4% bandwidth at 0.6, 1.25, 2.6, 5.2, 10, 22 GHz operating in direct detection mode. Each radiometer channel has up to 80 dB of gain with a noise figure of several dB. The highest frequency channel uses a corrugated feedhorn and waveguide transmission lines, whereas all other channels use highly phase stable coaxial cables and either patch array or waveguide slot array antennas. Slot waveguide array antennas were chosen for the low loss at the next three highest frequencies and patch array antennas were implemented due to the mass constraint at the two lowest frequencies. The six radiometer channels receive their voltage supplies and control lines from an electronics unit that also provides the instrument communication interface to the Juno spacecraft.

For calibration purposes each receiver has integrated noise diodes, a Dicke switch, and temperature sensors near each component that contributes to the noise figure. In addition, multiple sensors will be placed along the RF transmission lines and the antennas in order to measure temperature gradients. All antennas and RF transmission lines must withstand low temperatures and the harsh radiation environment surrounding Jupiter; the receivers and control electronics are protected by a radiation-shielding enclosure on the Juno spacecraft that also provides for a benign and stable operating temperature environment.

This paper will focus on the concept of the MWR instrument and will present results of one breadboard receiver channel.

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1 INTRODUCTION

The Microwave Radiometer (MWR) is one of a suite of instruments on NASA's New Frontiers Mission Juno, scheduled for launch to Jupiter in 2011. The Juno mission has the overall goal of answering the outstanding questions about Jupiter's structure and origin, with four main scientific objectives:

Origin: Determine the O/H ratio (water abundance) and constrain the core mass to decide among alternative theories of Jupiter's origin.

Interior: Understand Jupiter's interior structure and dynamical properties through mapping of its gravitational and magnetic fields, including internal convection and the size and mass of its core.

Atmosphere: Map variations in atmospheric composition, temperature, cloud opacity and dynamics to depths greater than 100 bars at all latitudes.

Magnetosphere: Characterize and explore the three-dimensional structure of Jupiter's polar magnetosphere and auroras.

The MWR specifically addresses the questions of water abundance and atmospheric structure, which are the major parts of two of these objectives. Given that oxygen is the third most abundant element in the universe, and recognizing that icy planetesimals were the dominant carriers of heavy elements in the solar nebula, this measurement is pivotal in understanding giant planet formation and the delivery of volatiles throughout the solar system. Also, how deep Jupiter's zones, belts, and other features penetrate is one of the most outstanding fundamental questions in Jovian atmospheric dynamics. By mapping variations in atmospheric composition, temperature, cloud opacity and dynamics to depths much greater than 100 bars at all latitudes, Juno determines the global structure and dynamics of Jupiter's atmosphere below the cloud tops for the first time.

The measurement of thermal emission from an atmosphere has been the basis used by many instruments for the determination of atmospheric properties, and the specific approaches used in the microwave region are described in Janssen, 1993. Thermal emission from an atmosphere arises because of the presence of absorbing constituents in the atmosphere, and the measured emission contains information on both the concentration and temperature of these constituents. The information content changes with frequency, and the determination of the spectrum of atmospheric thermal emission can be used to infer both its temperature and compositional structure. Water and ammonia are the only significant sources of microwave opacity in Jupiter's atmosphere, so their concentrations are the target of any microwave sounding approach. Figure 1 shows the contribution functions for thermal emission from the atmosphere as a function of depth for the six MWR wavelengths. The measurement of the brightness spectrum of Jupiter using radio-astronomical techniques has been our principal source of information about Jupiter's sub-cloud atmosphere, for example.

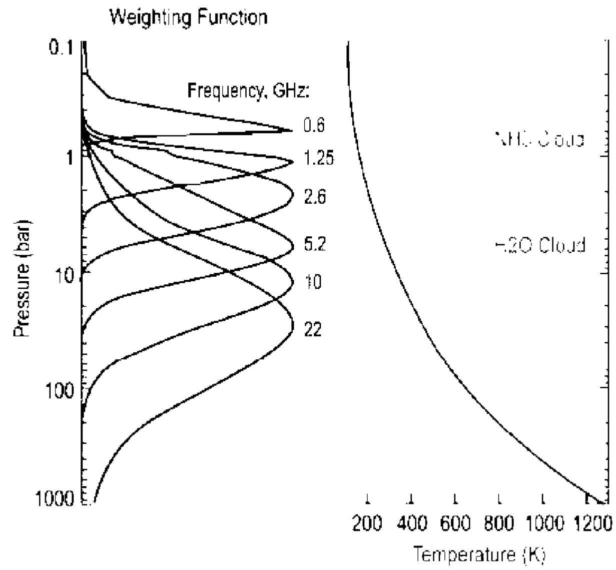

Figure 1: Contribution functions for the emission from Jupiter's atmosphere at nominal MWR frequencies. The ammonia cloud tops lie above the 1-bar pressure altitude, and all we know about Jupiter's atmosphere below the clouds has come from Earth-based microwave measurements. The lowest frequency of the MWR is sensitive to atmospheric temperature and water content to depths below 100 bars.

The approach used by the MWR for sounding Jupiter's atmosphere is described by Janssen et al., 2005, where it is shown that much more precision is obtained by measuring the emission angle dependence of the brightness at specific frequencies, rather than the spectrum at a fixed emission angle. Juno's polar orbit and spinning platform provide views at multiple emission angles and frequencies at all latitudes. The MWR footprints for a 12-degree beam are shown superimposed on a Cassini image of Jupiter in Figure 2.

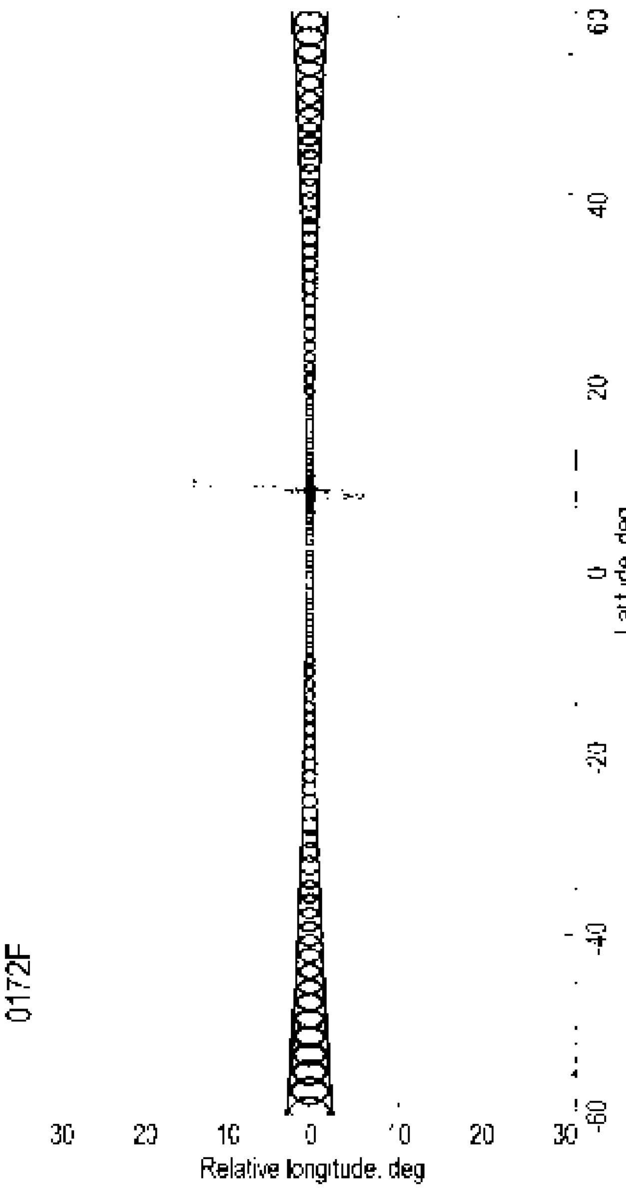

Figure 2. MWR footprints for a 12° beam are shown superimposed on a Cassini image of Jupiter for a typical MWR orbit and demonstrate that the instrument will resolve the major dynamical features of Jupiter's atmosphere. The actual density of measurement footprints is much greater than shown.

The advantage of this approach lies in the fact that the spectral measurement must rely on absolutely calibrated receivers at each frequency, since the information content of a spectrum is in the inter-comparison of brightness among frequencies. The absolute calibration of microwave radiometers is difficult and uncertainties of 2% or more must be expected. In the MWR approach the information lies in the inter-comparison of the emission at different angles at the same frequencies, and is independent of the absolute calibration. We have studied the sources of error for such a measurement for a Jupiter orbiter and have determined that a relative error in the measurement of brightness of 0.1 % is achievable, and have used this as our driving requirement for the MWR. Figure 3 shows the ability of the relative emission angle dependence to discriminate among cases for different water content in Jupiter's atmosphere.

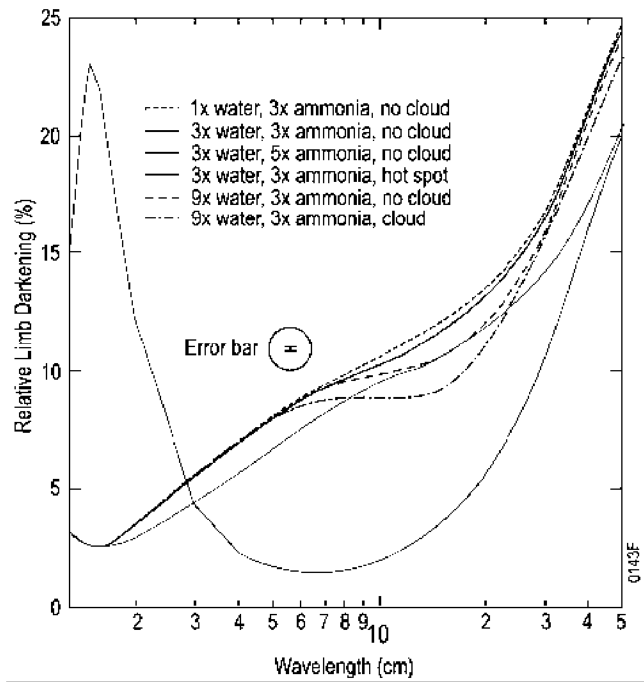

Figure 3: The relative brightness of Jupiter at an angle of 60° relative to the nadir emission, in percent. The curves show possible frequency dependencies for atmospheres with different water and ammonia content. The ability to distinguish among cases for water content differing by differences by factors of three is sufficient to achieve the primary goal of Juno to identify the origin of the water and distinguish among possible cases for the origin of Jupiter and the solar system.

2 THE MWR INSTRUMENT DESIGN

The MWR instrument accomplishes the experiment objectives by providing radiometric brightness temperature measurements at six distinct frequencies such that the weighting functions are approximately evenly spaced from approximately 1 to 100 bars. MWR is designed to operate at center frequencies of 0.6, 1.25, 2.6, 5.2, 10.0 and 22.0 GHz. The radiometers utilize direct-detect, Dicke-style receivers with approximately 4% bandwidth. The receivers are fed by a combination of patch array, slot array, and horn antennas (each with different advantages of mass, size and/or performance depending on the various operating wavelengths). The electronics unit that controls the instrument and communicates with the spacecraft is derived from designs developed for the Advanced Microwave Radiometer (AMR) instrument to be deployed on the Ocean Surface Topography (OSTM) mission scheduled to launch in 2008.

The Juno mission imposes several challenges on the implementation of the MWR instrument. As an interplanetary mission, mass is a premium resource. The majority of mass of MWR is in the antennas that are physically large due to the long wavelengths involved (especially for the 0.6, 1.25 and 2.6 GHz channels). The antenna designs utilize compact structures such as patch arrays and waveguide slot arrays to minimize the volume and mass impacts of the instrument, while at 22 GHz a scalar horn is used because its size is not a driver and it easily achieves desirable sidelobe and loss performance.

In addition, Juno is a deep space mission with a solar powered spacecraft making DC power a critical resource. The MWR instrument uses custom designed power distribution circuits to optimize the use of DC power.

The radiation environment at Jupiter is a harsh one for the exterior of the spacecraft and over the course of all the orbits the exterior of the spacecraft will accumulate a very large (greater than 10 MRad-Si TID) amount of radiation. To simplify the implementation, the MWR receivers and the electronics are located inside a radiation-shielded "vault" in the middle of the spacecraft so that during the course of its operational lifetime, MWR receivers and electronics accumulate less than 6 kRad-Si TID (less severe than many Earth-orbiting instruments). Since the antennas are exposed to the external environment, they are assembled from materials that are tolerant to high levels of radiation and that can dissipate any charge that may build up.

In orbit, the spacecraft is subjected to low temperatures, typically below -140 °C on the exterior. The antennas are designed to operate at extremely low temperatures. Inside the radiation vault where the receivers and control electronics are located, the temperatures are maintained at a relatively benign range of 0 to +40 degrees C.

Finally, since the antennas are attached to the periphery of the spacecraft, they are physically located 2-3 meters from the receivers where the front-end low noise amplifiers (LNAs) are located. Therefore, it becomes critical that the temperature-dependent losses and phase changes in the antenna-to-receiver transmission lines be characterized and modeled as part of the instrument data calibration. As such a large quantity of temperature sensors are placed on the cables (and also on the antennas) that are read out by housekeeping circuitry in the Electronics unit and are used in the calibration algorithm.

2.1 MWR Calibration

The MWR is operationally calibrated using stable internal references. Many Earth observing radiometers utilize a scanning platform to image both the Earth and scan across external calibration targets, such as a warm black body target and cold space. The external calibration approach calibrates the entire radiometer system with the exception of the reflector. Design constraints for the MWR prohibit such a calibration scheme and require internal calibration. In this way, the calibration scheme for MWR is similar to that of the water vapor radiometers on NASA precision ocean altimetry satellites such as Topex/Poseidon, Jason-1 and Jason-2, which use internal calibration due to their fixed viewing geometry (Ruf et al, 1995; Brown et al, 2004).

The MWR internal calibration system (integrated in each receiver front-end) consists of precision noise diodes and an internal Dicke switch, which is used to switch between the antenna and a 50-ohm ambient load. The noise diodes are used to inject a stable noise signal that provides an estimate of the radiometer gain. It is necessary to reference the internal calibration sources (i.e. the coupled noise diode brightness and reference load brightness) to the input of the antenna. This requires a correction for the losses and reflections in the radiometer front end between the antenna and internal references. The references are calibrated to the input of the radiometer during pre-launch thermal-vacuum calibration testing. An external calibration source is used to calibrate the system at the input. This external calibration is then transferred to the internal calibration references using a parametric model for the radiometer front end. This front end path loss correction requires knowledge of the distributed temperatures along the front end, distributed component losses and reflections between components.

The required temperature knowledge of the front-end components is proportional to the magnitude of their losses. Because of the harsh radiation environment at Jupiter, the sensitive MWR receivers are kept in the spacecraft vault, roughly 2-3 meters from the MWR antennas. This requires long RF transmission lines that contribute 1-2 dB of front-end loss. The matter is complicated because of the large thermal gradient (roughly 160°C) that exists between the antennas and the receiver. The thermal design of the RF transmission lines includes several thermal breaks, to constrain the gradients over a short length, producing long, nearly isothermal sections in between. This design complements the parametric model for the radiometer front end, which is formed by breaking the path to the front end into several sections with a single effective temperature and loss.

The MWR noise diode placement is unique, compared to previous instruments that have used noise diodes. The Jason Microwave Radiometer (JMR) was the first spaceborne radiometer to use noise diodes for calibration, and the follow-on instrument, the AMR (launch no earlier than June 2008), will be the second. Both of these radiometers use three redundant noise diodes per channel, which are injected between the antenna and the switch. Having three redundant noise diodes allows one to look for relative changes between them; however, a study of the long term noise diode stability of the JMR came to the conclusion that the coupling circuit, common to all three noise diodes, was the most likely source of observed instability (Brown et al, 2006). Therefore, to truly make an assessment of the relative stability between the diodes, independent coupling circuits are required. The MWR design takes this one step further and distributes the noise diodes between the front-end components. The MWR couples one noise diode between the antenna and the Dicke switch, one between the Dicke switch and the isolator, and the last between the isolator and the LNA. The distributed nature of the MWR noise diodes allows one to assess changes in the front end and also provides information that can be used to associate the changes to a single component.

The stability of the internal references and the radiometer front-end components is imperative. Any changes in component losses or reflections, or changes in the noise diode brightness between the pre-launch calibration and the science measurements will bias the absolute calibration of the MWR. Fortunately, the nature of the MWR science measurement only requires relative stability over a 2-hour period. The MWR retrieves the deep water abundance in the Jovian atmosphere using the limb darkening ratio, which is the brightness temperature difference between the nadir direction and some off nadir direction, normalized by the brightness in the nadir direction. Approximately two hours prior to perijove, the MWR has a view of cold space that is not contaminated by the planet or the strong synchrotron emission around Jupiter. This cold space look is used as a zero-level reference to make the limb darkening measurement. Therefore, the MWR measurement only requires that the calibration be stable between the zero measurement and the science measurements, and stable between the nadir measurement and the off-nadir measurement. Examples of the spin-correlated error sources include beam pattern corrections and magnetic field effects on the isolator. Examples of long-term (i.e., time scales greater than 2 hour duration) error sources include errors in the knowledge of time variable front-end temperature gradients, noise diode drifts and front end drifts.

2.2 MWR Systems Engineering

2.2.1 Key Requirements

Beyond the usual mass, power and volume key requirements commonly heavily constrained on all space missions, the Juno MWR faces requirements on the frequencies and precision imposed by the science to be addressed. The key high-level science requirement that drives most subsystem performance requirements is the requirement to measure brightness temperatures of Jupiter with a precision of 0.1% 1-sigma relative to the nadir brightness temperature. The rationale for this requirement is discussed in the introduction of this paper. This requirement drives for example, antenna and antenna cable physical temperature knowledge, return losses, gain stability, magnetic field sensitivity, and receiver noise temperature (Table I). A computational model of the instrument performance was developed to aid in balancing the error budget.

	R1	R2	R3	R4	R5	R6
Ideal NEDT (%)	0.026	0.03	0.026	0.026	0.02	0.03
NEDT including calibration (%)	0.03	0.03	0.03	0.03	0.03	0.04
Front-End Path Loss Correction Requirements (In units of R [%])						
Antenna Physical Temperature Tracking over 2 hours (%)	0.02	0.02	0.01	0.02	0.02	0.02
Antenna Physical Temperature Tracking over [2] minutes (%)	0.02	0.02	0.02	0.02	0.02	0.02
RF Transmission Line Physical Temperature Tracking over [2] minutes [%]	0.02	0.02	0.02	0.02	0.02	0.02
Antenna Loss Knowledge (%)	0.02	0.02	0.02	0.02	0.02	0.02
RF Transmission Line Loss Knowledge [%)	0.02	0.02	0.02	0.02	0.02	0.02
RF Transmission Line Physical Temperature Tracking over 2 hours (%)	0.02	0.02	0.02	0.02	0.02	0.02
Antenna Return Loss Knowledge (%)	0.005	0.005	0.005	0.005	0.005	0.005
Radiometer Return Loss Knowledge (%)	0.005	0.005	0.005	0.005	0.005	0.005
RSS of FPL Errors [%] (units of R)	**0.049**	**0.049**	**0.046**	**0.049**	**0.049**	**0.049**

TABLE I. ANTENNA TEMPERATURE CALIBRATION ERROR BUDGET (IN UNITS OF R [%]).

2.2.2 System Allocations

MWR is designed to weigh less than 46 kg and to operate on less than 32W. MWR requires a very small data rate and volume (especially in comparison to imagers and spectrometers). Typically, MWR generates a data rate of about 3 kbps and during a normal Juno orbit, generates about 100 Mbits.

2.2.3 The Benefits of "Heritage"

The initial design concepts for Juno MWR were heavily influenced by recent experience at JPL of building the AMR instrument for OSTM. MWR was able to avail itself of the experience base built up with the AMR project. A few design concepts have survived with minimal changes (especially in some of the circuits within the Electronics Unit and the bias circuitry for the RF circuits in the receivers). However, many other aspects of the AMR design have proven inapplicable to the MWR experiment are being specifically designed, analyzed, and implemented for this application.

2.3 MWR Antennas

The MWR antenna subsystem consists of six antennas. Each antenna is designed to operate at one of the six frequency bands (0.6, 1.25, 2.6, 5.2, 10 and 22 GHz) and are referred to as A1-A6 respectively. The antennas are located on the outside of the spacecraft and occupy two of the open bays of the hexagon-shaped body (Figure 4). A1, at 600 MHz, occupies one entire side of the hexagon and is directly mounted on the spacecraft. A3, A4 and A5 are integrated on a separate support panel and then mounted to another side of the spacecraft along with A2. Finally, A6 is mounted on the upper deck of the spacecraft. Each antenna is connected to the receiver either via coaxial cables (A1-A4) or rectangular waveguides (A5-A6).

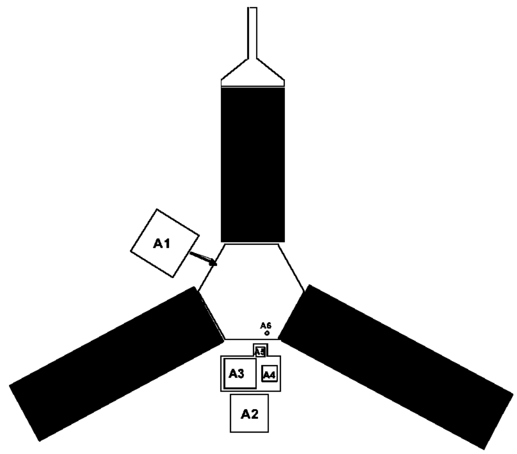

Figure 4. Juno Spacecraft with MWR Antenna locations shown.

2.3.1 Antenna Key Driving Requirements

Since MWR is an instrument on a spacecraft to Jupiter, the MWR antennas are required to function and perform under the Juno environment such as high radiation and operating temperatures in the range of –120 to –140 °C. All selected materials need to survive temperatures as low as –190 °C (the coldest expected temperature during inter-planetary cruise to Jupiter). The resonant frequency shift due to the wide temperature range encountered must be taken into consideration in the antenna design.

The antennas must be designed to prevent electric static discharge (ESD) as the spacecraft orbits Jupiter. The synchrotron radiation from Jupiter has the potential to interfere with the operation of the radiometer, and dictates low antenna sidelobes and backlobes (20 to 150 degrees). For appropriate impedance matching to the receivers, the antennas need to have a low insertion loss and wide return loss bandwidth. Low mass is desired and a compact volume is required given that the antennas are located far from the spacecraft's spin axis.

2.3.2 Antenna Design

Three types of antenna designs are selected for MWR, one profiled corrugated feed-horn (A6), three waveguide slot arrays (A3, A4, A5), and two patch array antennas (A1, A2)

2.3.2.1 Profiled corrugated horn (22 GHz)

A profiled corrugated horn with a simple circular-to-rectangular transition is used as the 22 GHz MWR antenna. The corrugated horn is known to have low sidelobe performance. The horn is profiled in order to reduce the overall length. Since the horn is made of solid aluminum there are no ESD issues with this antenna. Figure 5 illustrates the concept for the MWR profiled corrugate horn.

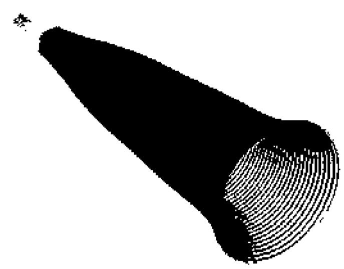

Figure 5. Concept drawing of A6 profiled corrugated horn.

2.3.2.2 Waveguide slot array (2.6, 5.2 and 10 GHz)

Three waveguide slot array antennas will be used for the 10, 5.2 and 2.6 GHz bands. A corrugated horn would be too long and massive in these frequency bands, but the slot array offers a thin volume and low mass. Each slot array antenna has 8x8 slots and is subdivided into four 4x4 sub-arrays. The slot waveguide array consists of slots radiating from the top layer, with series angled feeder slots in the second layer. A 4-way power divider network (Figures 6 and 7) lies below the feeder and connects to the four sub-arrays.

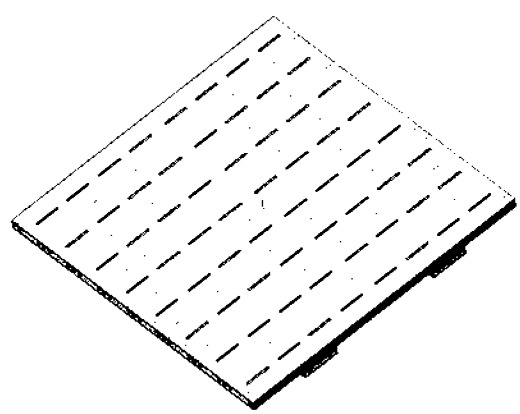

Figure 6. Concept drawing of 8x8 slot array power network.

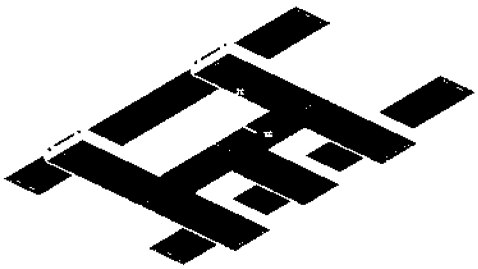

Figure 7. Concept drawing of 8x8 slot array power network.

2.3.2.3 5x5 patch array (0.6 and 1.25 GHz)

Mass and volume are the main challenges in the low frequency bands. The size of the 600 MHz antenna is limited by the size of the spacecraft body width of ~1.7 m. Aluminum waveguide slot arrays at 600 MHz and 1.25 GHz exceed the mass allocated by the project to the antennas; therefore, 5x5 patch array antennas are chosen for these frequency bands. However, ESD in the dielectric material in the radiation environment of Jupiter is a concern. The ESD issue is overcome by using carbon-doped dielectric material and a metal post under the patch to prevent bulk charge from accumulating. Six 5-way air-stripline power dividers are used to form a 25-way network (Figures 8 and 9).

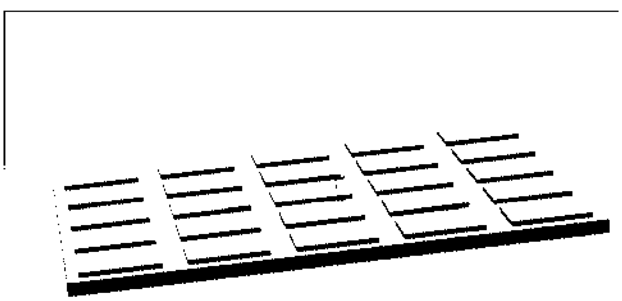

Figure 8. Concept drawing of a 5x5 patch array.

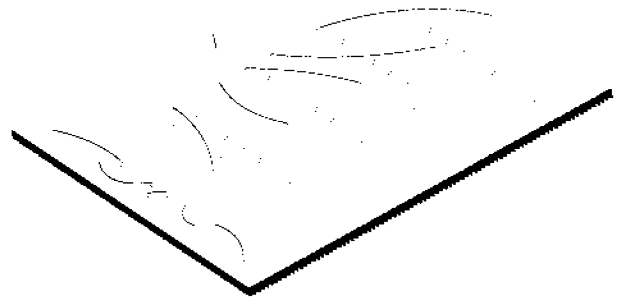

Figure 9. Concept drawing of a 5x5 patch array.

2.3.3 Antenna Scale Model Test

To understand the spacecraft's impact on the antenna patterns, a scale model spacecraft including the A1 antenna was built and tested. The chosen scale factor was 22:1. The scale model A1 antenna was a 5x5 patch array at 13.85 GHz, which simulated the pattern of the full scale 600 MHz antenna. The scale model spacecraft was constructed using a STEP file provided by Lockheed. First the pattern of scale model antenna alone was measured in a near field chamber. Next the pattern measurement was repeated after the antenna was integrated on the scale model spacecraft (Figure 10). While individual sidelobes were slightly affected by the spacecraft's presence the azimuthally averaged sidelobe level was relatively unchanged (Figure 11). Since the averaged sidelobe level is the key antenna requirement for the radiometer, we conclude that the spacecraft's presence has a minimum impact on the antenna pattern and hence on the radiometer performance.

Figure 10. Scale model spacecraft mockup test in antenna chamber.

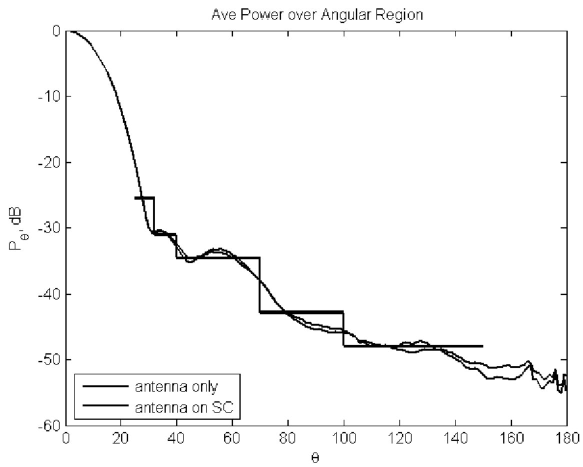

Figure 11. Measured integrated sidelobes over theta for scale model antenna only and scale model antenna on scale model S/C mockup.

2.4 MWR Receivers

The six receivers R1-R6 of the MWR instrument have an individual package and form one compact unit when bolted together as seen in Figure 12. This package is located inside a radiation-shielded vault of the Juno spacecraft. Only the RF transmission lines from the receivers to the antennas need to withstand the high radiation. For R1—R4 coaxial cables made of radiation-tolerant materials are used while rectangular waveguides are used for R5 and R6. Both the coaxial cables (by their design) and the waveguides are phase-stable over the broad temperature range in order to support accurate calibration of the front-end. Figure 12 shows an early concept of the receiver and electronics package.

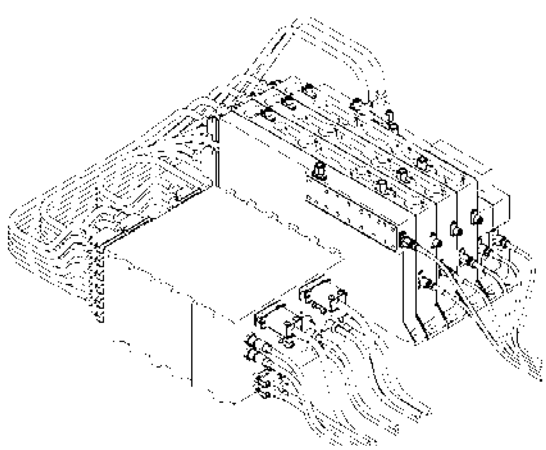

Figure 12: Early concept of receiver and electronics package. Waveguide for R6 not shown.

The packaging design for each receiver uses multiple connectors to separate LNA bias signals from the digital control and sensor read-out signals in order to reduce the introduction of noise into the sensitive RF electronics of the receiver. Figure 13 shows a block diagram representation of the receiver subsystem.

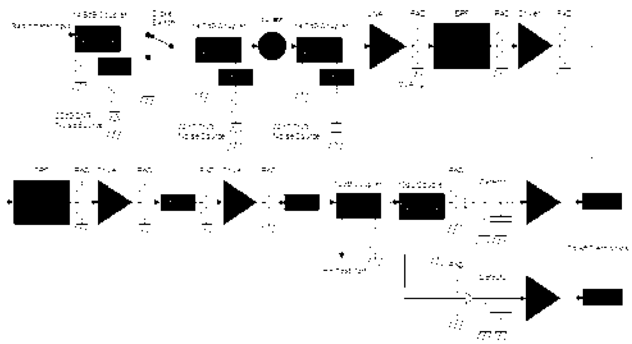

Figure 13: Receiver Block Diagram.

Each receiver is based on the Dicke principle [3] that allows for compensation of gain fluctuations by switching between a 50-Ohm load at a defined temperature from -20 to 50C and the antenna which points to the object to be measured. For gain calibration and diagnostic purposes three noise diodes with brightness temperatures in the range 100-300K are placed strategically in the receiver's front-end: one between the antenna and the Dicke switch, one between the Dicke switch and an isolator, and the last between the isolator and the first LNA. The noise diodes are biased by a constant-current bias circuit that provides conditioned power with low noise.

Up to 5 LNA stages are integrated in each receiver to provide sufficient gain to process the observed signal. Low noise figure, high gain, and good stability in addition to overall DC power consumption are all important factors in selecting the amplifiers. An LNA bias circuit has been designed with built-in temperature compensation and better than 0.001 dB/C has been achieved from -15 to +50 degrees C. Attenuators are used between the amplifier stages to optimize matching and suppress interaction between the gain stages.

The required 4% science passband is formed by multiple stages of bandpass filters that also guarantee sufficient out-of-band rejection. The RF signal is converted to a DC signal by a diode detector followed by a video-amplifier before the signal is converted to a train of pulses by a voltage-to-frequency converter. The resulting signal is then read-out, packaged, and sent to the spacecraft computer system by the MWR Electronics Unit.

2.5 MWR Electronics Unit

The MWR Electronics Unit (EU) is a five-slice assembly consisting of the Power Distribution Unit (PDU), the Command & Data Unit (CDU) and the HouseKeeping Unit (HKU). The PDU is two slices designated PDU-R for the slice that provides power distribution to the Receivers and PDU-D for the slice that distributes power to the "Digital" or other EU slices. The HKU is two identical slices designated HKU1 & HKU2. Figure 14 shows the current EU assembly with CBE[1] dimensions noted.

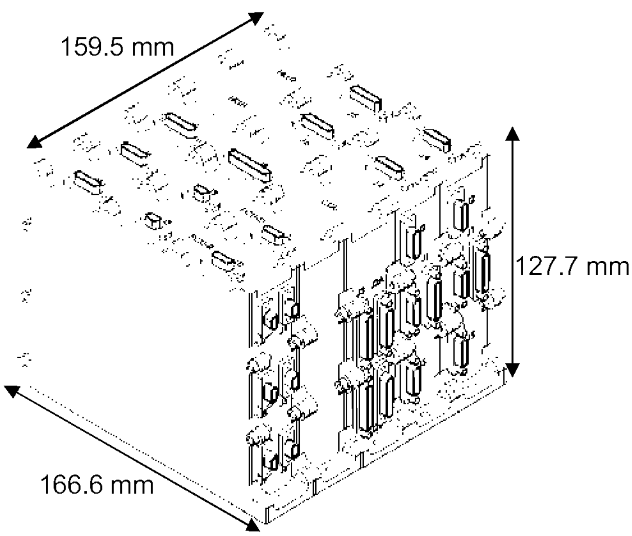

Figure 14. MWR EU Assembly with CBE Dimensions.

2.5.1 Power Distribution Unit (PDU)

The Juno spacecraft (S/C) provides +28V power to the MWR PDU. In order to operate the MWR instrument, a minimum of six different DC-DC converters are necessary to produce the voltages required in the digital and RF circuits as shown in Table II.

Converter	Interface	Function
+5V	CDU	Digital
+/-15V	HKU	Digital
+/-12V	R1-R6	Analog & Digital; 6 x VFC
+7V	R1-R6	RF on/off; Dicke switch
-5V	R1-R6	RF
+15V	R1-R6	RF; Noise Diode on/off

TABLE II. PDU CONVERTERS

The initial MWR PDU design was based on COTS[2] converters; however, the +7V needed for the receivers is not a standard COTS voltage. In addition, the inefficiency of the COTS converters did not provide a design solution that could meet the MWR power allocation. Therefore, JPL is designing a custom PDU that will provide 84% efficiency in all converted voltages and will provide fault isolation for the 6 receivers.

2.5.2 Command & Data Unit (CDU)

The CDU is an 8051 microcontroller-based system that includes circuitry, logic and software to 1) service and execute spacecraft commands and telemetry, 2) retrieve, integrate, assemble and control MWR science and housekeeping data, and 3) interface to ground support equipment (GSE) for control, command and telemetry functions. The CDU also has an FPGA that integrates CDU sub-module functions. A photo of the breadboard CDU is shown in Figure 15.

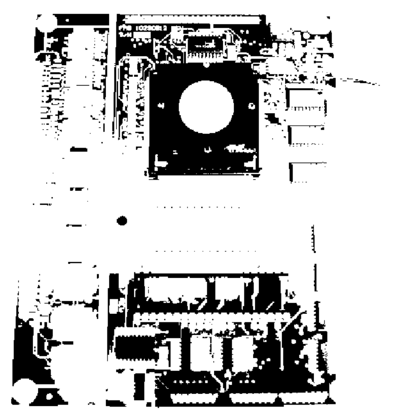

Figure 15. MWR Breadboard CDU. The FPGA and socket for the 8051 are visible. The dimensions of the board are 5.44" x 4.44" and these are the expected dimensions of the flight board.

Spacecraft communication with the CDU is through dual, redundant RS-422 interfaces with a transfer rate of 57.6 Kbps. Two FIFOs buffer incoming and outgoing data. Flight software developed for the 8051 μcontroller may be uploaded through either the S/C or GSE interfaces. All of the FPGA and 8051 clocking is derived from a master crystal oscillator. Power to all CDU circuitry, is derived from the PDU +5V supply.

[1] CBE = Current Best Estimate

[2] COTS = Commercial Off-The-Shelf

The CDU includes circuitry and logic to interface with two separate housekeeping voltage-to-frequency converters (VFCs) and the receiver VFCs. Counters are implemented inside the FPGA and mapped into 8051 memory space. The CDU also includes six Dicke switch control signals, six RF control signals to turn the LNAs in the receivers on or off, and eighteen noise diode control signals. All of these signals are optically isolated, settable through FPGA registers and mapped into 8051 memory space.

2.5.3 *HouseKeeping Unit (HKU)*

Two identical MWR housekeeping units, HKU1 and HKU2, acquire temperature measurements for radiometric calibration and instrument health monitoring, and voltage measurements for PDU health monitoring. There are a total of 128 multiplexed channels (64 per board) with 112 allocated to temperatures and 16 to voltages (including calibration channels). Because of the radiation environment and predicted sensor temperature ranges, thermistors will be used for temperature measurements within the vault while platinum resistive thermometers (PRTs) will be used for external temperature measurements.

The CDU selects the temperature channel via HKU multiplexer (MUX) addressing. The corresponding sensor is excited by a current source and the resulting voltage is channeled to a single-ended amplifier. The conditioned signal is routed to a VFC and the resulting frequency is then routed to the CDU for transfer to the S/C for downlink.

The HKU similarly monitors the PDU voltages with the CDU providing MUX address selection and also receiving the resulting VFC output.

3 INITIAL RECEIVER (R2) VALIDATION

3.1 *Breadboard Receiver Development Phase*

The breadboard phase was used to build three receivers R1, R2, and R4 to evaluate the selected commercially available components and to determine which assembly technology for the device package to use. The available technologies were based on SMT[3] for R1-R3 and chip-and-wire for R5-R6. The R4 radiometer was selected to be SMT but due to limitations on the selection of available LNAs and findings on the RF performance the decision was made to use the same technology utilized for R5 and R6. Particularly the limited selection of LNAs made the trade-off on noise performance, low power consumption, gain, and utilization for flight applications challenging. The R1 and R2 receivers are designed to cover a wide dynamic range that make the implementation of a second detector circuit for R1 necessary. All receivers are designed into an H-frame chassis that allows separation of the DC electronics and RF. This approach provides maximum rejection of noise.

During the breadboard phase, the mass and power consumption was iteratively reduced by phasing the designs of the three receivers. Therefore the lessons learned with the built package could be utilized for the design of the next receiver. The initial estimates on power consumption could be reduced when measured values were available.

The predicted performance of gain, noise figure, and the 1-dB compression point of the R1 and R2 receivers based on the manufacture data was confirmed during the initial measurements. Extended tests on evaluating the radiometric performance revealed that the stability was within expectations. Furthermore, the gain stability of the receivers meets the science requirements.

3.2 *Measured R2 Performance*

A 1.2 GHz breadboard radiometer was developed and tested at JPL. A coaxial-based calibration system developed by the University of Michigan was used as the external calibration source. The system consists of an active cold load (ACL) and an ambient termination that can be switched. The system also employs a mixer to up-convert the signal from an Arbitrary Waveform Generator (AWG) at baseband to the RF band. The AWG can generate white noise at arbitrary magnitudes between 0 to 5000 K. This signal is coupled with either the signal from the ACL or the ambient termination. In this way, the calibration system can generate any brightness temperature from about 100 to 5000 and programmable output sequences are possible.

The main objectives of breadboard validation were to test the inherent gain stability and stability over temperature, the radiometer linearity, and to assess the calibration potentialof the radiometer. The inherent gain stability of the radiometer is tested by stabilizing the physical temperature of the radiometer and keeping the output of the calibrator at a constant, stable value. A long duration dataset was collected, and a plot of the NEDT vs. integration time generated. In the absence of 1/f noise, the NEDT decreases as the inverse of the integration time. The deviation from this curve in an RSS sense is the inherent gain stability of the radiometer as a function of time. A plot of the computed R2 breadboard gain stability is shown in Figure 16. As can be seen from this plot, the inherent gain stability of the R2 radiometer is excellent, 2e-5 at 30 seconds and 9e-5 at 2 hours. The variation of the gain with temperature is also very small due to the compensation near ambient. The temperature coefficient of the gain is less than 0.03%/C over a 10 to 40 C temperature range (Figure 17).

[3] SMT = Surface Mount Technology

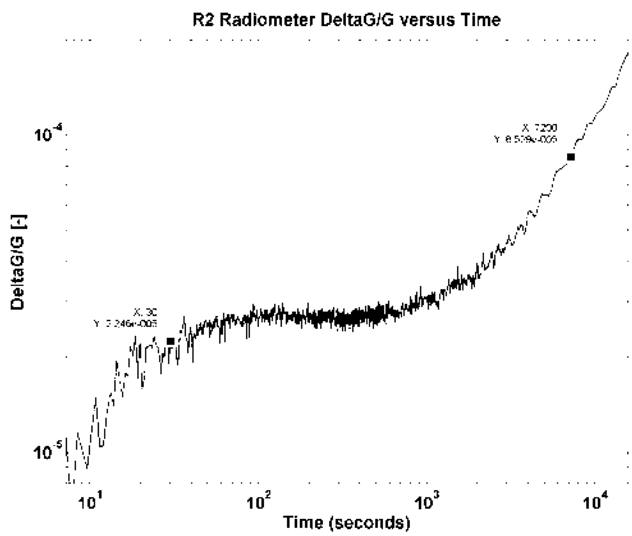

Figure 16. Radiometer deltaG/G versus time.

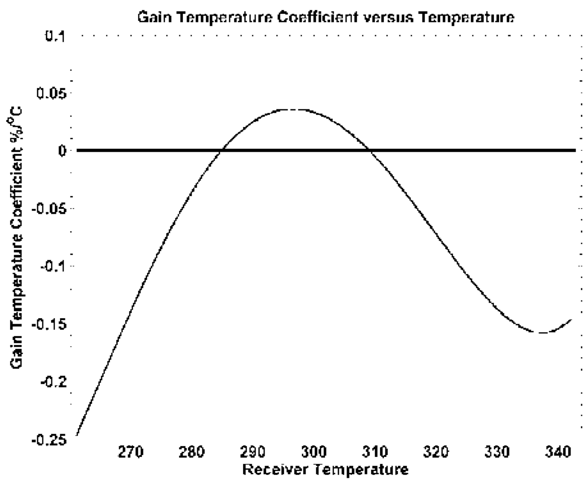

Figure 17. Temperature coefficient of R2 radiometer gain.

The MWR radiometers must be able to measure the strong synchrotron emission from Jupiters radiation belts. The magnitude of this emission can be thousands of Kelvin at 600 MHz and 1.2 GHz. Therefore, it is important for the radiometer non-linearity be low over a wide dynamic range. The linearity of the R2 radiometer is tested by stepping the output brightness of the calibrator from 100 to 5000 K in discrete steps. The non-linearity can be directly computed and is shown in Figure 18. As is illustrated from the lower panel of this plot, the non-linearity is less than 0.1% below 800 K and is less than 1.5 % up to 5000 K.

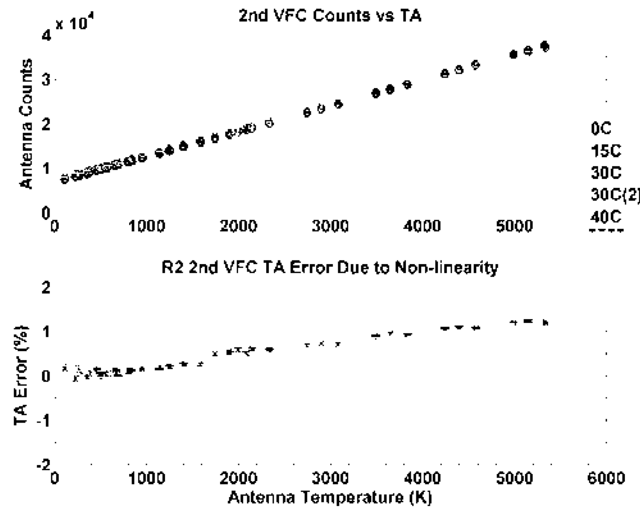

Figure 18. Linearity of the R2 radiometer from 100 to 5000 K. The top panel shows the counts/K response of the radiometer and the bottom panel shows the deviation from linear.

The system noise temperature of the R2 radiometer was computed to be about 350 K at ambient, giving a NEDT of 0.25 K for an input brightness of 300 K. Overall, the performance of the R2 radiometer was excellent.

4 FUTURE PLANS

Each of the MWR subsystems will be developed in two phases. First, engineering models (EM) will be designed and fabricated by the first half of 2008. The EMs will serve to validate the technical designs, mitigate risks, and to identify issues related to the flight qualification. The EM subsystems will be integrated together in the summer of 2008 for use as an instrument test bed. The EM test bed will be used to develop and test early versions of the flight software and to validate instrument test and calibration plans. This will also be the first opportunity to perform limited end-to-end system testing and to validate the performance error budget.

Using lessons learned during the EM phase of the development, the hardware design will be updated and flight models (FM) will be built by the Spring of 2009. Each of the subsystems will be qualified for the flight environment and tested over the range of temperatures prior to integration together as the complete MWR instrument. The subsystems will be assembled into a complete instrument in the summer of 2009. The system will undergo extensive performance testing in the lab as well as in a more realistic (thermal-vacuum) environment to verify the instrument performance. In addition, the instrument will be subjected to Electro-

Magnetic Interference and Electro-Magnetic Compatibility (EMI/EMC) testing to ensure that the instrument can perform as required in an environment with RF noise (e.g., as generated and radiated or conducted by other instruments or spacecraft avionics).

The MWR instrument will be delivered to Assembly, Test and Launch Operations (ATLO) at Lockheed Martin in Denver, CO by summer of 2010 where it will be integrated onto the Juno spacecraft along with the other science instruments. During ATLO, numerous functional checkouts will ensure that the instrument continues to function properly and environmental testing such as thermal-vac and EMI/EMC will allow assessment of the instrument performance in an environment that attempts to closely mimic what will be seen in orbit around Jupiter.

After the functional and environmental testing at the spacecraft level are completed at Lockheed Martin, Juno will be delivered to Cape Canaveral where the spacecraft will be integrated onto a <soon to be announced> launch vehicle. In August 2011, Juno will begin its 6-year journey to Jupiter. During this cruise stage prior to Jupiter Orbit Insertion (JOI), MWR will remain powered off most of the time for thermal and power reasons as well as to preserve the instrument lifetime, especially that of the sensitive RF parts. However, approximately twice per year the instrument will be turned on for about one day to acquire data such as measurements of the brightness temperature of the cosmic microwave background that is used as a calibration reference for tracking the instrument performance drifts.

After JOI, Juno will eventually stabilize into an 11-day, highly-elliptical polar orbit around Jupiter. While the mission is planned for 32 <Check this number> science orbits, MWR is only operated for 5 of the first 8 orbits. In fact, the vast majority of the data required for a successful MWR experiment is acquired in a single orbit; the additional orbits allow for additional opportunities to acquire the data and may allow for observation of the Great Red Spot (a goal, but not a requirement, of the mission) if it should fall under the sub-spacecraft footprint during one of these early orbits. During one of the orbits that MWR is operating, observations of Jupiter will be made when the spacecraft is at apojove (approximately 40 Jovian radii away). At this distance, Jupiter is nominally a point source relative to the large beamwidths of the MWR antennas. As such, these observations allow for an important opportunity to verify the beam patterns of the antennas, including any and all effects of the spacecraft structure (at least for one cut of the beam pattern).

After completion of all the MWR orbits, the instrument will nominally be powered off for the remainder of the mission, and the Juno spacecraft will be placed in an attitude that is not favorable for MWR observations.

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7 BIOGRAPHY

Paula Pingree is a Senior Engineer in the Instruments and Science Data Systems Division at JPL. She has been involved in the design, integration, test and operation of several JPL flight projects, the most recent being Deep Impact (DI) where she was Test Bench Manager pre-launch and Co-Lead of the Impactor Comet Encounter activity post-launch. She is presently the Electronics CogE for Juno's Microwave Radiometer (MWR) instrument. Paula has received a BE degree in Electrical Engineering from Stevens Institute of Technology in Hoboken, NJ, and an MSEE degree from California State University Northridge. She is a member of IEEE.

Dr. Michael Janssen has over thirty years of experience in radio astronomy and has specialized in the microwave remote sensing of the Earth and solar system, observational astrophysics and cosmology, and the development and application of microwave instrumentation for astrophysics and remote sensing. In addition serving as lead for the Juno Microwave Radiometer, he is currently the lead for the Cassini Radar radiometer. He was a member of the Science Working Group for the Cosmic Background Explorer (COBE) and played a major role in implementing the COBE Differential Microwave Radiometer experiment on COBE, for which work he was awarded the NASA Exceptional Scientific Achievement Medal in 1992 and was a co-recipient of the 2006 Cosmology Prize from the Gruber Foundation.

John Oswald is a member of the Instruments and Science Data Systems Division staff at JPL. He has been involved in the development and implementation of microwave, millimeter and sub-millimeter wave technologies, component and subsystems for nearly 20 years. He was the Cognizant Engineer for the 640 GHz receiver for the Aura-MLS instrument launched in 2004 and currently operating in Earth orbit. He is presently the Instrument Manager for the Microwave Radiometer (MWR) instrument. John has received SB and SM degrees in Electrical Engineering from the Massachusetts Institute of Technology in Cambridge, MA.

Shannon T. Brown joined the NASA Jet Propulsion Laboratory in Pasadena, CA in 2005 as a member of the engineering staff in the Microwave Advanced Systems section. He received a B.S degree in Meteorology from the Pennsylvania State University and a M.S. from the University of Michigan. He received a Ph.D. in 2005, also from the University of Michigan. His research interests include microwave radiometer calibration, geophysical algorithm development for both passive and active sensors and cloud and precipitation science. He has been involved with the spaceborne Topex and Jason Microwave Radiometers, WindSat Polarimetric Radiometer and the Jason follow-on Advanced Microwave Radiometer. He received a NASA Group Achievement Award in 2004 for his contribution to the UMich/GSFC Lightweight Rainfall Radiometer.

Jacqueline Chen is a senior engineer in the Communication, Tracking and Radar Division at JPL. She was a Cognizant Engineer for Wide Swath Ocean Altimeter antenna and Contract Technical Manager for MSL TDS antennas. She is presently the Project Element Manager for Juno Microwave Radiometer antenna. From 1996 to 2004, Jackie became an Associate Technical Fellow at Boeing Satellite System in El Segundo. She worked on a variety of spacecraft projects and tasks including Tracking Data Relay Satellite (TDRS) Single Access (SA) reflector antennas, TDRS tracking feed system, and Spaceway 1500-element active array re-configurable antenna algorithm. Prior to Boeing, from 1987-1996 Jackie worked at JPL where she was responsible for engineering and technology development tasks of the Deep Space Network, including frequency selective surfaces (dichroic plates), X/X/Ka-band ring-loaded-slot feeds and contributed to the design of the DSS13 Beam Waveguide Antenna. She holds one U.S. patent. Jackie graduated with a B.S. in Physics from National Taiwan Normal University, M.S. Physics from the University of California, Los Angeles and MSEE from University of Southern California.

Kenneth Hurst is a Senior Engineer and Scientist in the Instruments and Science Data Systems Division at JPL. He is presently the Systems Engineer for the Microwave Radiometer on the Juno mission. While investigating crustal deformation due to earthquakes, he has worked with data from microwave radiometers to correct GPS signals for water vapor delays. Ken did his undergraduate work in Geology and Physics at Earlham

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Ami Kitiyakara received co-terminal BS and MS degrees in Electrical Engineering from Stanford University, Stanford, CA, in 1992. He joined JPL in 1993 where he is currently Instrument Manager for the Ocean Surface Topography Mission (OSTM) Advanced Microwave Radiometer (AMR). Past projects include the Airborne Rain Mapping Radar (ARMAR); WINDRAD polarimetric radiometer for passive sensing of ocean surface winds; Passive/Active L and S-band (PALS) Radar and Radiometer for measuring sea salinity and soil moisture; and the Jason-1 Microwave Radiometer (JMR), a spaceborne radiometer providing a wet troposphere path delay correction for radar altimeter ocean topography measurements.

Frank Maiwald (M'95) received the M.A.Sc. Diploma degree and Ph.D. degree in applied physics from the I. Physikalische Institut der Universität zu Köln, Cologne, Germany, in 1995 and 1999, respectively. In April 1999, he joined the Jet Propulsion Laboratory (JPL), Pasadena, CA, as a Post-Doctoral Fellow, where he developed a 2.7-THz solid-state frequency-tripler source for the heterodyne instrument on the Herschel Space Observatory (HSO). He was responsible for delivering space qualified frequency multiplier chains with more than 30uWatts output power from 1100 to 1250 GHz (120K) for two of the 14 channels implemented in HSO. Currently he is a Senior Member of the Technical Staff with the JPL, where he is project element manager for the development and delivery of six direct detection receivers in the frequency range from 0.6 to 22GHz for the MicroWave Radiometer instrument on the polar orbiter for Jupiter, called Juno. Dr. Maiwald is a member of the Institute of Electrical and Electronics Engineers (IEEE) Microwave Theory and Techniques Society (MTT-S).

Stephen Smith is currently the President and Chief Design Engineer for MMW Technology, Inc. He has been providing engineering design and support to JPL for almost 10 years, including designs for MMW phase locked oscillators for the Aura-MLS instrument, 18GHz, 24GHz and 34GHz radiometer and noise source designs for the Advanced Microwave Radiometers for the Ocean Surface Topology Mission, electronics designs for the Quiet Telescope and various Deep Space Network projects. He received a BS in Electronics Engineering from Cal Poly San Luis Obispo in 1977 with emphasis in the field for electromagnetics.

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