Next-Generation Spaceborne Precipitation Radar (PR-2) Instrument and Technology

E. Im, S. L. Durden, G. Sadowy, A. Berkun, J. Huang, M. Lou, B. C. Lopez
Jet Propulsion Laboratory
California Institute of Technology, Pasadena, CA 91109

Y. Rahmat-Samii
University of California, Los Angeles
Los Angeles, CA 90095-1594

S. Rengarajan
California State University, Northridge
Northridge, CA 91330

Abstract - The Global Precipitation Mission (GPM) is currently being developed as a follow-on to the Tropical Rainfall Measuring Mission (TRMM). One of the key components of the GPM science instrumentation is an advanced, dual-frequency rain mapping radar. In this paper, we present a potential system concept for this second-generation spaceborne precipitation radar. This proposed design incorporates several advanced technology features, including 13.6/35-GHz dual frequency radar channels; a dual-frequency, wide-swath scanning, deployable antenna; digital chirp generation and the corresponding on-board pulse compression scheme; and adaptive antenna scanning.

I. INTRODUCTION

Atmospheric latent heating field is fundamental to all modes of atmospheric circulation and upper mixed layer circulations of the ocean. The key to understanding the atmospheric heating process is understanding how and where precipitation occurs. It is well known that surface and near-surface rainfall are two of the key forcing functions on a number of geophysical parameters at the surface-air interface, including the water salinity, sea surface temperature, fresh water supply, and marine biology and eco-system, rainforest ecology and chemistry, land hydrology and surface runoff. Precipitation has also been closely linked to a number of atmospheric anomalies and natural hazards that occur at various time scales, including hurricanes, cyclones, tropical depressions, flash floods, droughts, and most noticeable of all, the El Ninos.

These and many other science applications require the knowledge of, on a global basis, the vertical rain structures, including vertical motion, rain intensity, differentiation of the hydrometeors' phase state, and the classification of mesoscale physical structure of the rain systems. The launch of the Tropical Rainfall Measuring Mission (TRMM) satellite [1] in late 1997 has made a great stride towards this ultimate goal. The Precipitation Radar (PR) aboard the satellite is the first-ever spaceborne radar dedicated to three-dimensional, global precipitation measurements over the tropics and the subtropics. The measurements collected by the PR, together with those collected by other science instruments abroad the satellite, have provided unprecedented insights into the rainfall process.

Because of the TRMM success, a follow-on mission, called the Global Precipitation Mission (GPM), is currently being developed to extend the TRMM's instrument capability in such a way to fully address the key science questions from microphysical to climatic time scale. The baseline GPM configuration consists of a constellation of 8 micro-satellites each carries a 3-frequency scanning radiometer, and a core satellite which carries a 5-frequency scanning radiometer, and a high-resolution, Doppler-enabled, wide-swath scanning, dual-frequency radar. In this paper, a potential system concept for this second-generation precipitation radar (PR-2) will be described.

II. SYSTEM CONCEPT

The current plan calls for the PR-2 to operate at an orbital altitude of 400 km. PR-2 will operate in two modes: Wide-Swath Mode and Nadir Doppler Mode. During Wide-Swath mode operations, the antenna will scan ±37° cross-track with the corresponding ground swaths of 600 km. The Nadir Doppler mode will acquire the "vertical" Doppler profiles of precipitation at nadir if precipitation is detected in such regions. The radar antenna is planned to be 5.3 m in size, and will be fully illuminated at 13.6 GHz and under-illuminated at 35 GHz in order to obtain the matched beams at 2-km horizontal resolution. The vertical resolution will be set at 250 m at all altitudes of operation, but the chirp bandwidth will be 5 MHz to allow an 8-fold increase in the number of independent samples.

Wide Swath Mode: In this mode, rain reflectivity profiles will be measured over a 600-km cross-track swath using the so-called 'adaptive scan' scheme. As shown in the GATE and other experimental results (e.g., [2]), the probability of rain occurrence over a specific location is < 20%. For this reason, and to effectively utilize the limited observation time, each PR-2 observation sequence will be divided into two periods: a Quick-Scan Period to determine the location and vertical extent of the rain cells within the entire swath, and a Dwell Period at which detailed precipitation measurements of the identified rain cells will be made. At an altitude of 400 km, a nominal observation sequence will last ~0.3 sec, the Quick-Scan Period will occupy the first 0.1 sec and the Dwell Period will use the remaining available time (0.2 sec). During the Quick-Scan Period the radar will make a complete cross-track scan through the entire swath, transmit and receive only 1 pulse at each 2-km ground resolution cell at a nominal pulse repetition frequency (PRF) of 2700. The radar backscatter measurements at each resolution cell will be averaged on-board over a vertical column of 2 km (~64 samples) and will be compared with a set of thresholds and ranked according to their respective backscatter strength. The ranked results will then be used to develop the subsequent antenna scan pattern for the Dwell Period. In the Dwell Period, the radar will measure the detailed rain backscatter profile over areas with significant rainfall. The nominal swath covered in the Dwell Period is ~200 km, which should be sufficient to cover most of the rain areas within the swath. In the event that there is pervasive rainfall covering areas >200 km across the track, our proposed dwell pattern would allow observations over cells with the most intense rainfall, thus covering a significant portion of the total rainfall in those areas.

Nadir Doppler Mode: When the Quick-Scan results indicate rain occurrence at or near nadir, the Nadir Doppler Mode will be exercised. In this mode, the radar antenna will be pointed at this small region for a total time of ~0.05 sec. A higher pulse repetition frequency (~5000) will be used to accommodate the anticipated Doppler spread. Multiple rain echoes obtained in each resolution cell will be used to estimate the Doppler shift caused by the mean rainfall motion. Conventional pulse-pair technique to estimate the mean Doppler will work well only in uniform rain. However, a new algorithm recently developed [3] has shown satisfactory vertical rain velocity even with the highly inhomogeneous rain cells. With the PR-2's operating parameters, the vertical rainfall velocity can be measured to an accuracy of between 1 and 1.5 m/s.

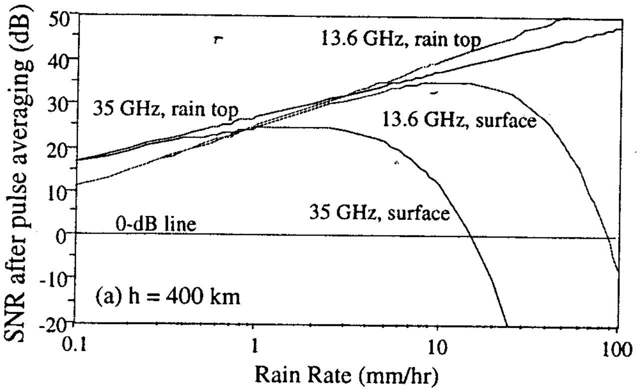

Fig. 1. Expected signal-to-noise ratios for the PR-2 system at 400-km altitude.

Detection Sensitivity: Figure 1 shows the signal-to-noise ratios (SNRs) of the rain echoes as a function of the rain rate for the PR-2 system. Notice the significant sensitivity improvement, as compared to the TRMM PR, in detecting both very light rain (< 0.1 mm/hr) and very intense rain (~90 mm/hr) systems. At rain rates below ~15 mm/hr, measurements from both frequencies can be combined to measure the entire rain rate profile. At rain rates between 15 and 35 mm/hr, the dual-frequency measurements can be used to retrieve at least the upper half of the rain clouds.

III. RADAR TECHNOLOGY

Radar Antenna: The large swath coverage and fine horizontal resolution desired for detailed rain profiling lead to the use of a large, dual-frequency, scanning antenna. While the TRMM PR's slotted waveguide antenna design can be extended to a larger scan range and to two frequencies, it is heavy and can only be accommodated by large, and often more expensive, satellite buses and launch vehicles. The PR-2 antenna, therefore, is designed to achieve the goals of low mass and small stowage volume. Our proposed design is a 5.3m x 5.3m, one-dimensionally curved cylindrical/parabolic inflatable antenna offset-fed by a linear array with T/R modules (see Figure 2). In order to achieve the required matched beams for the two frequencies, the 35-GHz feed will under-illuminate the reflector and will be less than half the length of the 13.6-GHz feed. Representative antenna patterns, together with the required sidelobe levels (green curves) are given in Figure 3.

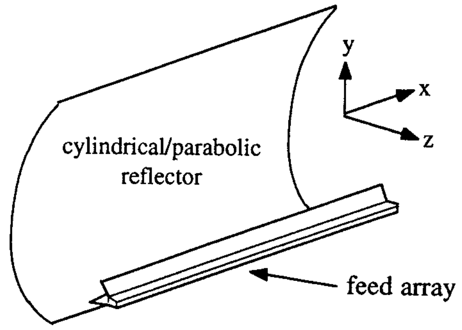

Fig. 2. Configuration of a cylindrical/parabolic reflector illuminated by a linear array.

The mechanical design of the PR-2 antenna comprises a reflective membrane surface. The parabola has a linear (projected) span of 5.3 m originating at the apex, and a focal location at 1.89 m from the apex. A set of two inflatable and rigidizable tubes will be used to deploy, pre-tension, and maintain the desired parabolic-cylindrical shape of the reflective membrane. These space-rigidizable tubes are cantilevered from the spacecraft interface and interconnected at their free ends by a rigid cross-member. At launch, each inflatable tube is rolled up around a rigid mandrel, and the thin-film reflective membrane in turn, around the rigid cross-member; thus forming a cylindrical bundle with a launch volume no greater than a square cross section of 1.3m x

1.3m and 5.5 m in length. This antenna design is expected to have a mass density of less than 2.0 kg/m^2. In order to meet the low sidelobe requirement, the antenna's RMS surface accuracy should be better than 0.17 mm. To maintain such accuracy, the inflatable tube must be rigidized, and the reflective membrane must be dimensionally stable in the expected space environment. Preliminary analyses have been performed which indicate that these goals are achievable.

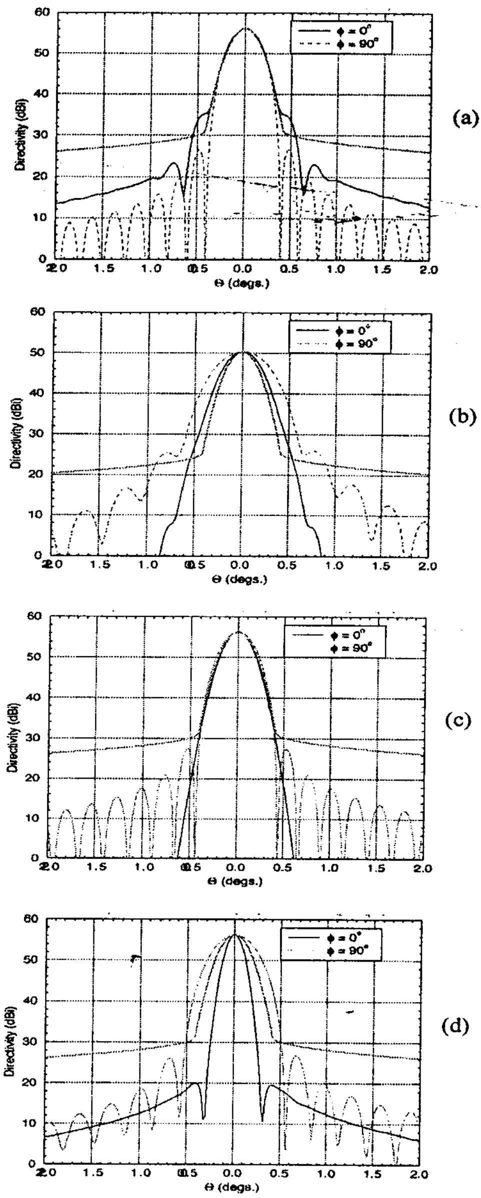

Fig. 3. Far-field antenna patterns: (a) 13.6 GHz, beam at boresight. (b) 13.6 GHz, beam tilt to 37°. (c) 35 GHz, beam at boresight. (d) 35 GHz, beam tilt to 37°. The desired sidelobe envelope template is also shown in green curves.

T/R Module Design: Overall system requirements and the results of antenna configuration studies determined the requirements T/R modules. A preliminary design for this module has been created and development of a prototype is currently underway.

The 35-GHz T/R module is composed of a transmitter channel and two identical receiver channels. One of the receive channels is duplexed with the transmitter channel using MMIC switches. Each channel contains a mixer for up or downconversion, an image filter, a phase-shifter and a suitable amount of amplification. Use of up and downconversion within the module while increasing complexity has two main advantages: it allows lower frequency phase shifters to be used and it reduces losses in the divider/combiner networks, permitting simple stripline and microstrip dividers rather than complex, bulky and expensive waveguide manifolds.

The 384-element array is divided into 48 subarrays of 8 elements each. Each subarray contains signal divider/combiner networks for both polarization channels and for the local oscillator (LO). These will be implemented as 8-way corporate dividers in a multilayer microwave substrate. The center layer will contain the LO divider, implemented in stripline while the top and bottom surface will contain the V and H channel dividers, which will be implemented in microstrip.

Each subarray will share a common control and bias module (CBM). The CBM will receive DC power from the spacecraft bus and will generate all operating voltages required by the T/R modules. The CBM will also receive commands from the array controller and will command the phase shifters and switches within each module. By sharing the bias generation and control functions between eight modules, the complexity of the module electronics is drastically reduced.

The circuitry within each module has been designed to employ currently available MMICs and relatively mature technologies. The X-band IF within the module permits the use of a wide range of components available of that frequency range, including high-precision phase shifters. Subharmonically pumped mixers are used for both up and down conversion, thereby eliminating the need to generate and distribute a 25 GHz LO signal.

The major design challenge in implementing the T/R modules is thermal management and compensation. Each module will generate 1 W output power with a duty cycle of up to 25%. Due to the efficiency of the power amplifiers and other amplifier MMICs the overall power dissipation for each module will be several watts. The bias voltages and circuitry will be optimized to minimize power consumption while yielding adequate performance.

In addition to the problem of managing waste heat, there is the problem of thermal compensation. Due to changing solar illumination the array can experience large temperature swings over an orbit. The gain of amplifier MMICs in both the receiver and transmitter channels is strongly affected by temperature. In order to insure that the transmitter power and the receiver gain are sufficiently stabilized, some form of compensation is required. Our initial approach to this problem includes both active and passive gain compensation methods. The passive approach uses Thermopads, which are constant impedance attenuators that change insertion loss with temperature. These devices are simple, rugged and require no DC power. However, to achieve the required compensation range, large values of attenuation are required. Large attenuation values require inclusion of additional amplifier stages which increases module complexity and power consumption. Automatic gain control (AGC) amplifiers can be used to supplement the passive compensation. A temperature sensing circuit controls the gain of these amplifiers, according the measured temperature/gain characteristics of the whole signal chain. This circuit can be tailored to remove and mismatch between the temperature coefficient of the Thermopad and signal chain gain drift characteristics.

Digital Signal Processor: To achieve the required resolution and sensitivity without using impractical peak power levels, a linear frequency modulated (LFM) chirp waveform is used. LFM chirps have been used successfully for decades in various radar systems but their use in down-looking atmospheric radar presents special challenges.

In chirped radar system, a long LFM is transmitted. The echo signal is then correlated with the original pulse waveform, yielding temporal resolution approximately equal to the reciprocal of the pulse bandwidth. However, in addition to the main correlation peak, spurious correlations occur. These are referred to as time or range sidelobes and are analogous to antenna sidelobes. These sidelobes are particularly troublesome for a down-looking precipitation radar because the surface echo power can be as much as 60 dB larger the echoes from precipitation very close to the surface. Thus, the range sidelobes need to be suppressed 60 dB with respect to main correlation peak. Digital pulse compression techniques permit compensation for non-ideal characteristics of the system (provided that they are well characterized) and can provide substantially better sidelobe suppression. Experiments with JPL's Airborne Rain Mapping Radar (ARMAR) demonstrated sidelobe suppression of up to 60 dB [4]. However, this was achieved by recording all radar echoes on a high speed tape recorder and processing them later. While this technique has been used for spaceborne synthetic aperture radars (SARs), SAR systems only collect data intermittently while a precipitation radar collects data continuously. Since continuous operation is required, and it is not practical to downlink large volumes of raw echo data, a real time processing solution is required.

The first step in the development of the real-time digital pulse compression system is the development of an airborne breadboard system. Such a system is being developed using a combination of custom and commercial-off-the-shelf (COTS) VME hardware. The system has three main components, a two channel (one for Ku-band, one of Ka-band) arbitrary waveform generator (AWG), a four channel (two received polarizations by two frequencies), acquisition board and a programmable digital signal processor board which uses Xilinx field programmable gate arrays (FPGAs).

The PR-2 airborne breadboard uses a custom 12 bit analog-to-digital converter (ADC) board based on an Analog Devices 14 bit converter, which provides four simultaneously sampled and processed channels (Ku and Ka, H and V receive channels). Data is oversampled a factor of 2 above Nyquist limit (20 MHz) and then digitally low-pass filtered and decimated by a factor of two. Using a digital filter as the main video filter, allows more precise control of the filter characteristics and eases the requirements on the analog antialiasing filter.

The transmit waveform is generated by a custom two channel AWG which yields 14 bits resolution at a sample rate of 40 Samples/s. Using AWGs instead of a traditional numerically controlled oscillator has two major advantages. The AWG can be used to implement amplitude weighting of the pulse which substantially reduces range sidelobes at the expense of slightly degrading range resolution. Secondly, the AWG allows a predistortion to be applied to the transmit waveform in order to partially compensate for nonideal characteristic of the system. While, in a perfectly linear system, it is mathematically equivalent to compensate for these effects in the receive processing, dividing the distortion compensation between transmit side and receive side reduces quantization noise. Also, by producing a chirp which is spectrally flat at the transmitter output, it is easier to see small changes during test and calibration. The compensation calibration technique uses a closed loop algorithm which incrementally changes the transmit pulse to get the desired results at its feedback point.

The real-time signal processor card is a COTS VME card made by Annapolis Microsystems. The board contains three large Xilinx Vertex FPGAs; reprogrammable parts which can be configured as almost any kind of digital logic. With four channels, the system performs 20 billion multiplications and 20 billion additions per second. This processing throughput would be difficult to achieve with microprocessors. FPGAs enable implementation of efficient algorithm specific, circuitry without the nonrecurring costs and development time associated with application specific integrated circuits (ASICs). The highly parallel implementations possible with FPGAs allow realization of the entire real-time processor in only two chips.

The front-end of the processor is four 64-tap, 16-bit finite impulse response (FIR) filters implemented with bit serial multipliers clocking at 133 MHz. The filter receives 20 MHz offset video, and selects 4 MHz flat bandwidth centered around 5 MHz, with 70 dB suppression of the 4 MHz band centered around DC. Following the filter is a downsampling and digital IQ demodulation yielding in-phase and quadrature baseband signals. The output data is complex and clocked at 5 MHz.

Following the video filter is a matched filter stage. This is a 256 tap complex FIR filter (actually 4 real integer FIR filters) loaded with a 12 bit reference function clocking at 5 MHz. The reference function we use is a Kaiser window (K=6) squared envelope modulated on an ideal chirp which has be modified slightly to tune out system distortion.

For every range sample the co- and cross-polarized echo power is computed. The pulse pair technique is used to calculate the Doppler velocity and the Doppler spectral width. The power and pulse-pair estimates from 64 pulses are then averaged, yielding a 64-fold reduction the output data rate. Any echo containing a saturated ADC value is dropped from the averages because even a single clipped ADC sample creates large sidelobes which can obscure much of the useful data near the oceans surface. The averaging and resulting reduction in data rate is only possible only after pulse compression and calculation of power and pulse-pair estimates has been performed.

An FPGA processor implementation has been developed and tested successfully in both laboratory environment and through airborne demonstration. Figure 4 show the domain response of individual pulses through the entire PR-2 system, including the non-ideal characteristics of the transmitter. These measurements were made during a NASA DC-8 airborne flight in early July, 2001. These plots demonstrate sidelobe suppression of greater than 55 dB for each of the individual pulses. By averaging over 80 to 100 pulses, the compression sidelobes can indeed be suppressed to the 60 to 65 dB level as required.

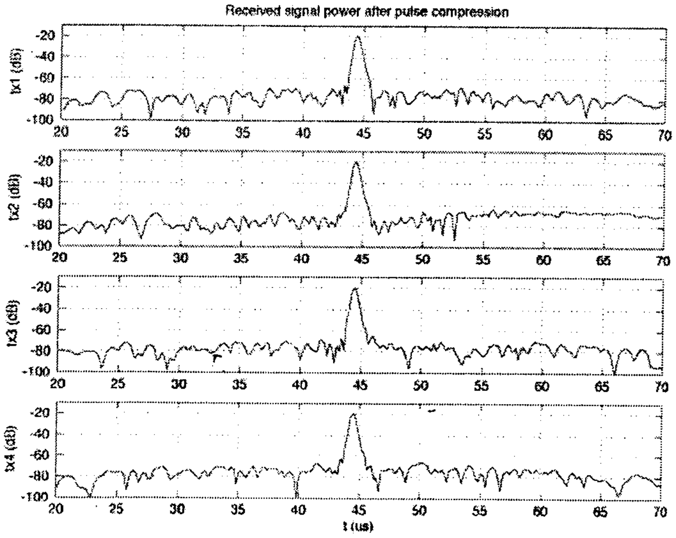

Fig. 4. The single-pulse time-domain response at 13.6 GHz channel of the PR-2 radar measured during the NASA DC-8 airborne flight in July, 2001.

IV. SUMMARY AND REMARKS

A system architecture of the associated technologies for the second-generation spaceborne precipitation radars was presented in this paper. In this design, several innovative features are being incorporated to enhance the rain measurement capability. These include: 13.6/35-GHz dual-frequency operations, a large, shared-aperture, deployable, scanning antenna, nadir Doppler measurements, and pulse compression. It is anticipated that such instrument concept can provide significant data for advancing our understanding on rain processes, latent heating, climate variability, and atmospheric anomalies.

Both the electrical and mechanical designs of the reflector have been carefully studied. Study results indicate that is antenna would yield acceptable performance and can be implemented using current membrane and inflatable rigidizable structure technology. The next step is to build a breadboard model of this reflector and demonstrate its mechanical stability.

A design for a scanning feed system has also been created and analyzed and development of the Ka-band subarray prototype is underway. Production of a Ka-band T/R module with integrated miniature OMT will take place next year with integration and testing of an 8-element subarray to follow.

We have also developed a real-time digital signal processing system for the PR-2 airborne breadboard. This system is being used to capture real precipitation data from an airborne platform and to demonstrate the real-time signal processing algorithms. In a separate, parallel, effort a custom FPGA processor board is being developed. This board will be a space flight compatible design and will incorporate additional circuitry to mitigate the effects of radiation induced single-event upsets.

The entire airborne PR-2 breadboard is completed and has undergone successful laboratory testing and airborne test demonstration. This airborne PR-2 system, in additional to provide a means to demonstrate the advanced technologies, is also being used for science applications. Indeed, PR-2 is scheduled to participate in the NASA DC-8 airborne field campaign during the Fourth Convection and Moisture Experiment (CAMEX-4) in August-September, 2001, and the planned NASA P-3 airborne experiment over the Sea of Japan in early 2003.

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