FINAL REPORT:

Development of a UAV-Mounted 95 GHz Radar System to Conduct Scientific Studies of Clouds

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1. INTRODUCTION

This report describes the development and testing of the Compact Millimeter-Wave Radar (CMR). CMR is a solid-state W-band radar designed for integration on the Department of Engergy's (DOE's) Atmospheric Radiation Measurement (ARM) Unmanned Aerial Vehicle (UAV) platforms. One of the primary scientific objectives of the DOE ARM-UAV program was to investigate the role of clouds in the Earth's atmospheric radiation balance. W-band radars have the ability to profile a wide variety of clouds, including ones with high optical extinction. The DOE ARM-UAV program funded UMass to investigate whether the size, weight and power consumption of typical airborne W-band radars could be reduce to meet the constraints imposed by the UAV payload capacity, and based on the results of this study, funded UMass to build the CMR. In the sections to follow, the design and development of the CMR will be described, results from comparisons between CMR and the UMass Cloud Profiling Radar System (CPRS) presented and upgrades that will enhance the sensitivity of CMR by 20 dB discussed.

2. Publications

Based on the work performed for this grant, Dr. Ray Bambha received his PhD from UMass in 1999. Publications describing this work are listed below:

- Bambha, R.P, "A Compact Millimeter-wave Radar for Studies of Clouds and Precipitation", PhD Thesis, University of Massachusetts, 1999.

- Bambha, R.P., J.R. Carswell, J.B. Mead, and R.E. McIntosh,"A Compact Millimeter Wave Radar for Airborne Studies of Clouds and Precipitation", IEEE Geoscience and Remote Sensing Symposium, Seattle, WA, 1998.

Table 1: UAV radar specifications compared with conventional systems

radar system parameter	UAV	Conventional
power	150 W	1.0 kW
volume	1.8 ft^3	9 ft^3
weight	40 kg	110 kg

3. CMR Design

The CMR was designed to meet the power, size and weight constraints imposed by the DOE ARM Altus UAV platform. The original requirements were that the radar should consume less than 100 Watts, weigh under 30 lbs and occupy no more than 1 cubic feet. The power and size constraints were later relaxed to 150 Watts and 1.5 cubic feet so that Doppler capability could be added to the CMR. A picture of the CMR system is shown in figure 1. Table 1 lists the size, weight, and power of the CMR compared to values typical of earlier airborne 95 GHz radars. The values in the table do not include contributions from computer monitors, cables, or equipment racks required for the conventional radar. A portion of the size and weight savings in the UAV radar comes from the use of DC-DC converting power supplies. This power supply also allows the radar to run efficiently off the 28 VDC supply available on the UAV.

During the Phase I study of this grant, we considered several different radar designs: a FMCW radar, a linear FM chirp radar and a conventional pulsed radar. A FMCW radar offers the highest sensitivity given a fixed peak transmit power. This is accomplished by transmitting a long linear frequency modulated waveform while simultaneously recording returns with the receiver. Range information is contained in the frequency domain. By Fourier transforming the return signal, the range information can be extracted. Since the radar is operating continuously, the average power is equal to the peak transmit power. With only 300 milliwatts average power, the sensitivity of the FMCW radar would be comparable

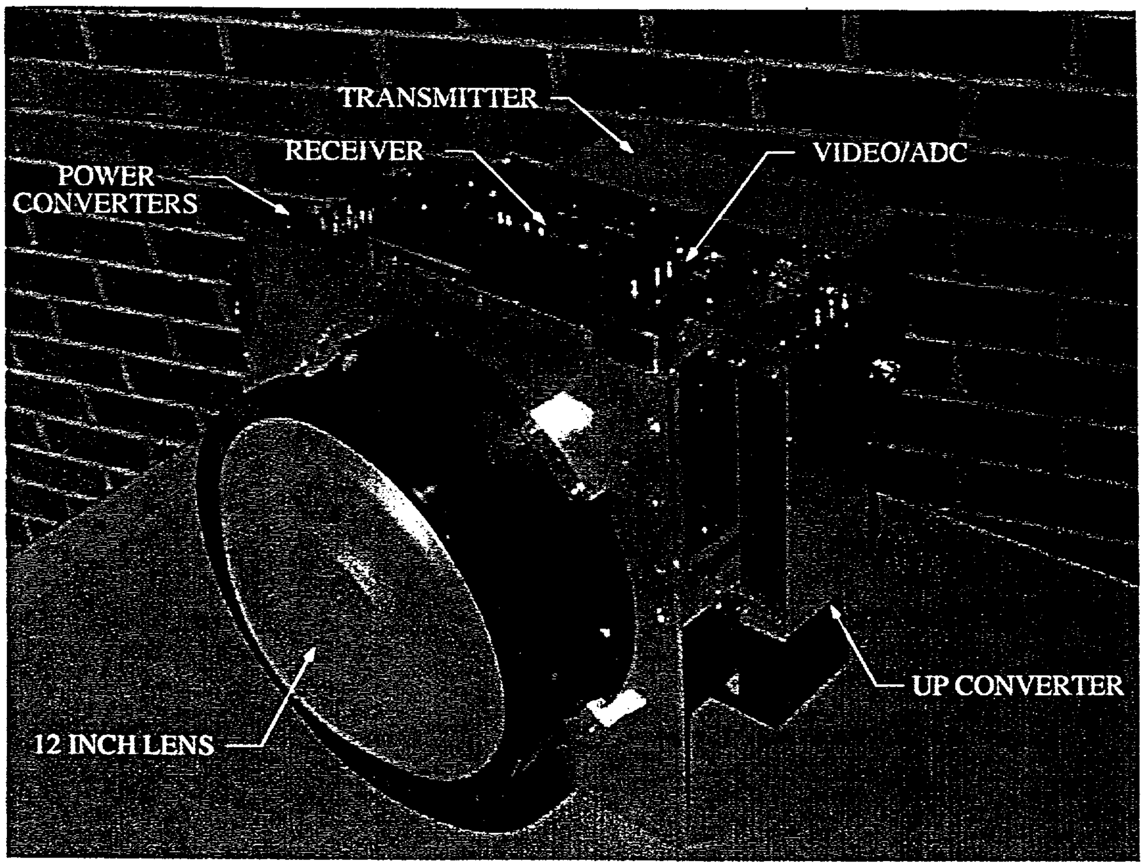


Figure 1: Picture of the CMR with its 12 inch compact lens antenna.

to conventional W-band airborne radar systems. Unfortunately, a FMCW system operates under the assumption that the round trip time to the farthest range extent of interest is an order of magnitude smaller than the integration time. Since the UAV is expected to operate at altitudes greater than 15 km (a roundtrip time of 100 usec) and the decorrelation time of clouds at W-band is less than 500 usec, this requirement could not be satisfied.

A linear FM chirp design also provides another method for obtaining high sensitivity with low peak power. Like the FMCW system, the transmit waveform is frequency modulated allowing the pulse length to be extended. The received signal can be compressed by using a matched filter. The range resolution is related to the bandwidth of the frequency modulation and not the transmit pulse length. The average power is increased since much longer pulses can be transmitted compared to that transmitted with a conventional pulsed radar. To implement a the transmit chirp waveform and matched filter receiver, we consider using a pair of surface acoustic wave (SAW) devices. However, these devices are difficult to matched, and result in less than 30 dB range sidelobe performance. This is not be adequate for clouds applications where the dynamic range can exceed 60 dB at W-band. Higher range resolution performance on the order of 50 to 60 dB had been demonstrated using a direct digital synthesizer to generate the chirp waveform and a digital matched filter receiver to compress the received signal. Unfortunately, the power and size of the data acquisition system required to do these operations far exceeded our power and size budget. For these reasons, we determined that a conventional pulsed radar was the only design that could be used. At that time, Millitech Corporation was developing a 38 Watt peak power W-band transmitter and a W-band low noise amplifier (LNA) that would allow us to build a compact W-band radar with reasonable sensitivity, approximately -20 dBZ at 1 kilometer. This was deemed acceptable, and UMass designed and built this radar.

Figure 2 presents the CMR system block diagram, and Table 2 lists the specifications. Due to the uncertainty in location where CMR would be installed, a modular design was used to allow for the most flexibility in integrating the CMR into the UAV payload. The transmitter, receiver, power-supply, and analog-to-digital converter (ADC) were all designed

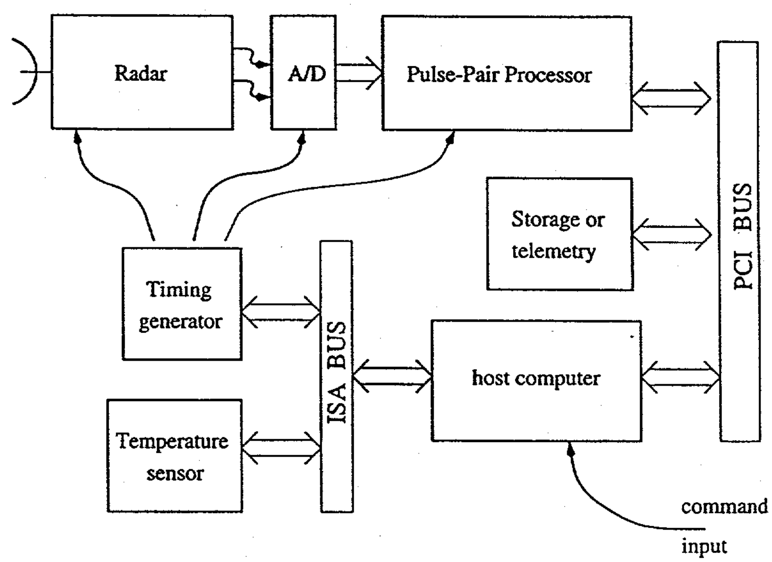


Figure 2: Block diagram of the radar system

specifically for this radar and housed in separate enclosures. Below, the CMR transmitter, receiver and data processor modules are described.

3.1 Transmitter

The CMR utilizes a solid-state transmitter operating at 95.04 GHz. The majority of W-band cloud radars are pulsed-Doppler systems employing either an extended interaction klystron amplifier (EIA) or an extended interaction oscillator (EIO) as the transmitter. EIA and EIO transmitters can provide up to 1.5 kWatts peak power with duty cycles as high as 1%. However, they weigh approximately 25 kg and occupy over .025 m^3. EIA's and EIO's also have high voltage modulators that draw in excess of 600 watts. In addition the EIA modulators have internal voltages of 17 kV and are not specified for operation above 1500 meters altitude due to concerns over arcing.

By comparison, the CMR amplifier has a peak power of 38 watts with a fixed pulse duration of 100 ns., but its volume and weight are 0.009 m^3 and 9.3 kg. The CMR transmitter was built by Millitech Corporation in Deerfield, Massachusetts. Figure 3 shows a picture of this device. It has seven IMPATT amplifiers with four IMPATT diodes combining their

Table 2: **95 GHz UAV solid-state radar specifications**

parameter	value
Transmit Frequency:	95.04 GHz
Peak Power:	38 W
Pulse Duration:	100 ns
Pulse Repetition Frequency:	7 - 20 kHz
Antenna Diameter:	.3 m
Antenna Gain:	44 dB
Beam width:	$.67^o$
Receiver Noise Figure:	8.3 dB
Receiver Bandwidth:	10 MHz

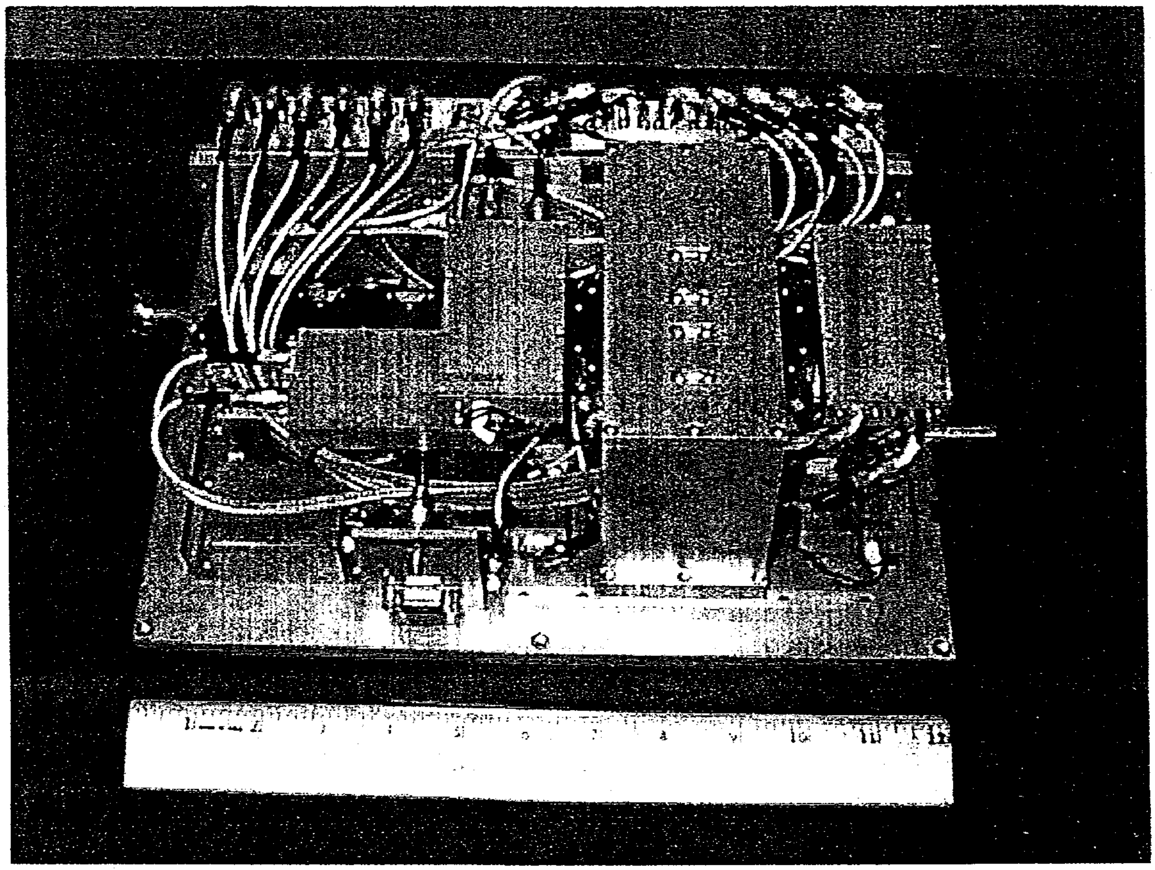


Figure 3: W-band solid-state 38 watt transmitter.

power at the output. Each diode has a separate driver that forms the required current pulse, and the driver characteristics are tuned to the individual diode. The highest voltage used in the drivers is 36 V, and there is no anticipated altitude restriction.

The short pulse width gives CMR range resolution as fine as 15 m., which is desirable for accurate location of cloud edges and thin cloud layers. However, in order to achieve this resolution we must have high-speed signal processing and 10MHz receiver bandwidth. The custom high-speed signal processor is described in section 3.4.

3.2 Receiver

A superheterodyne design is employed in the receiver with intermediate frequencies (IFs) at 4.32 GHz and 120 MHz. The components of the receiver are included in figure 4. Gain is distributed approximately evenly through the receiver chain in a fashion that avoids the need for mixers with high LO drives. The W-band LNA has a gain of 22.5 dB at 95.04 GHz and a noise figure specification of 7 dB. A high-pass filter follows the LNA to reject noise at the image frequency of the W-band mixer. The 95.04 GHz RF signal is mixed down to the 4.32 GHz IF using a double-balanced mixer. The LO for the W-band mixer is generated using a 15.12 GHz DRO and a 6× multiplier. A C-band IF was chosen in favor of one at a lower frequency to avoid a sharp cutoff requirement for the W-band image-rejection filter. This allowed the use of a low insertion-loss filter that would have no measurable effect on the receiver noise figure. The 4.32 GHz IF amplifier has a gain of 25 dB and .1 dB output compression for an input of -16 dBm, which approximately matches the .1 dB compression level of the components that precede it. A demodulator with an LO of 120 MHz converts CMR's 120 MHz IF to baseband in-phase (I) and quadrature (Q) components. The amplification at 120 MHz is set so that the maximum signal levels entering the IQ demodulator are within its linear region approximately 10 dB below its 1dB compression point. Figure 5 is a photograph of the receiver with its cover off and the connector panel in place.

The I and Q channels are amplified and digitized at 10 Msamples/sec. Since the channels are DC-coupled, they will include DC offsets introduced by the amplifiers and the I/Q demodulator. The DC offsets are measured by acquiring eight samples of the I and Q channel voltages prior to each transmit pulse during which time there is no coherent signal in the receiver. Following 1×10^5 averages of the pre-transmit I and Q samples, accurate measurements are obtained of the DC offsets in each of the channels. Using the measurements of the DC offsets, an analog voltage correction is applied to each channel using 12-bit D/A converters to correct the DC-offset.

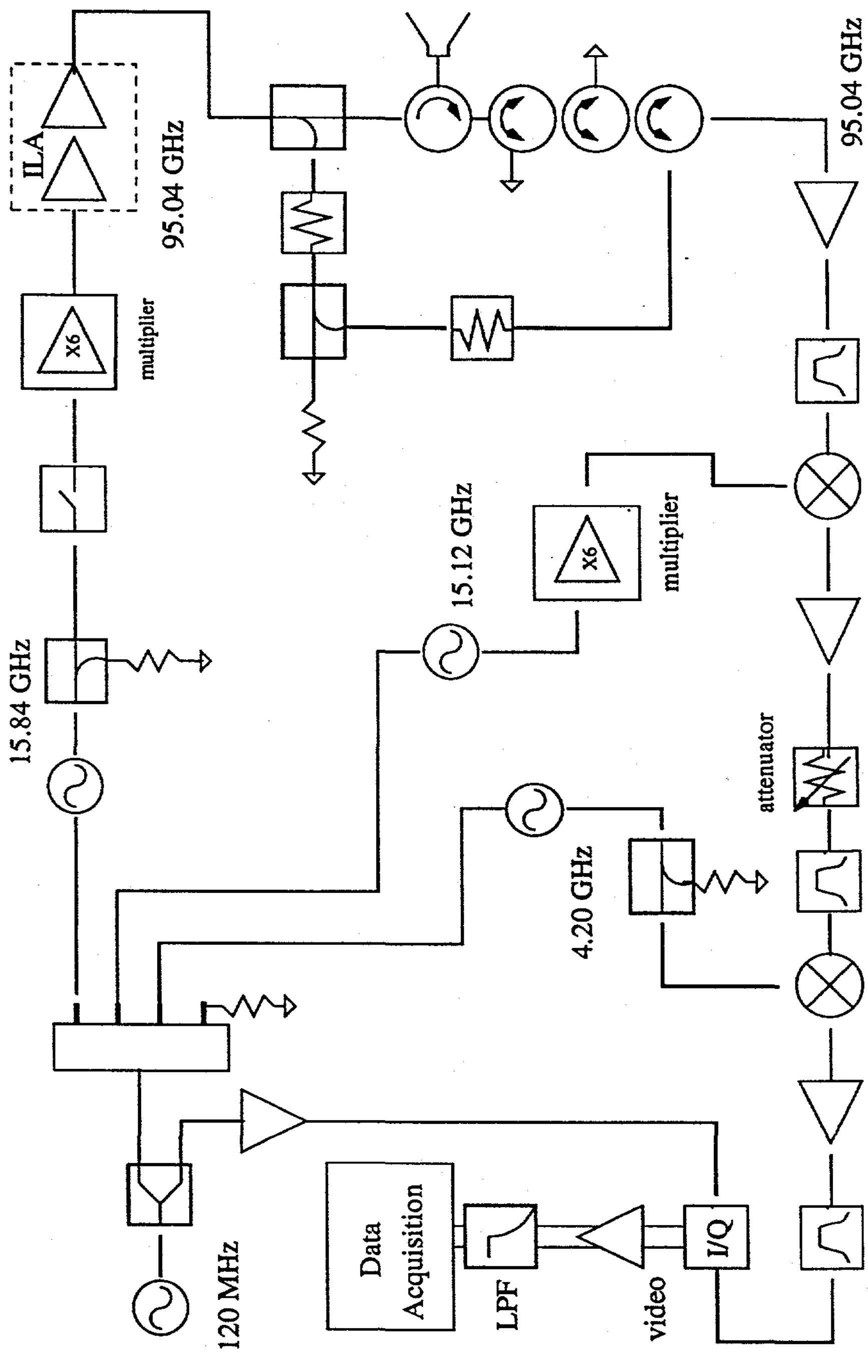
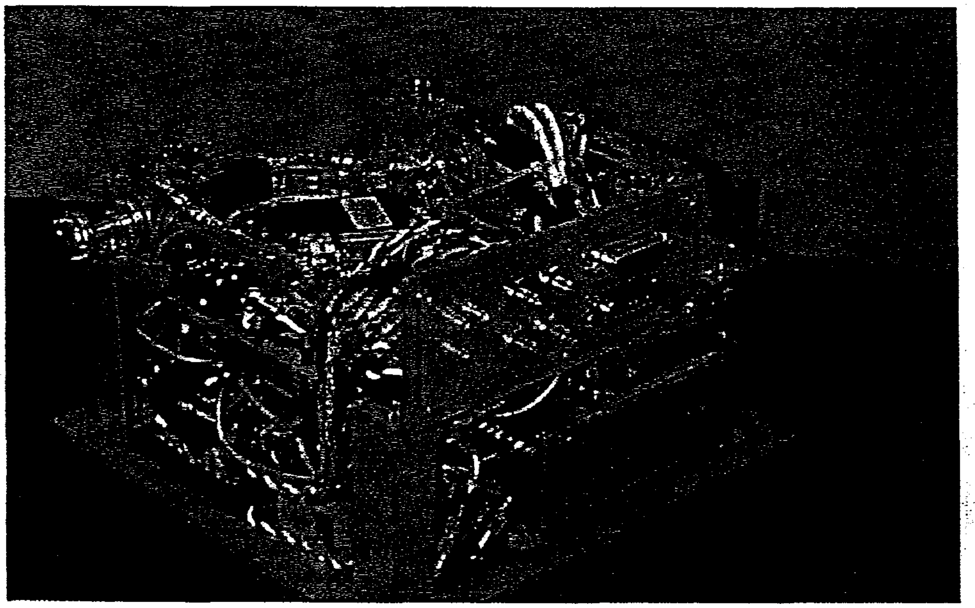


Figure 4: Block diagram of the RF design.



6 inches

Figure 5: Photograph of the CMR receiver.

3.3 Transmitter-receiver isolation, and internal calibration

The transmitted and received signals are duplexed by a fixed circulator. Approximately 107 dB isolation is provided by the combination of a series of latching circulators and the fixed circulator. The three latching circulators are contained within a single assembly with two states, a high isolation state and a low insertion-loss state. During transmit, the latching circulator assembly is set to a state giving 87 dB isolation, and on receive the insertion loss is 1.5 dB.

A portion of each transmit pulse is coupled into the receiver through a set of attenuators and couplers with stable insertion loss. The power in this coupled pulse gives a measure of the combined gain of the transmitter and receiver. This signal is digitized and used to remove gain fluctuations during calibration. (Insertion loss through the latching circulators has been observed to be stable. However, this loss is measured in combination with the antenna gain during internal calibrations.)

3.4 Data acquisition

The goal for the CMR signal processing system was to achieve the greatest possible sensitivity improvement available through sample averaging. This is accomplished by transmitting pulses at the maximum repetition rate suitable for the required unambiguous range and averaging all the profiles within a given period of time. In previous cloud radars it was necessary to restrict the number of range gates processed or to process only a subset of pulses that could be transmitted in a given period or to restrict both. Since the potential applications of CMR include monitoring cloud coverage, it was deemed important to process all the data within the unambiguous range. The A/D sample rate of the I and Q video channels was set to 10 MHz to match the available range resolution dictated by the 100 ns pulse width. Using 12 bit A/D samples, the resulting input data rate is 240 Mbit/second, which is too high to be stored practically over long periods of time. Computations of reflected power and autocovariance must be performed in real-time, and the results averaged prior to output to reduce the data rate.

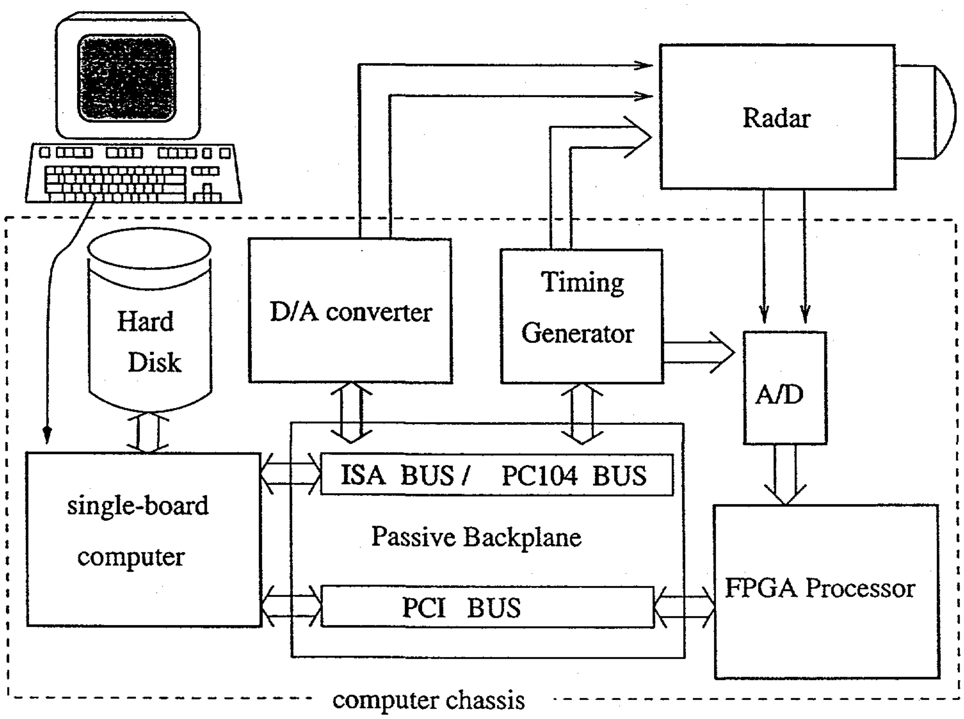


Figure 6: Diagram of the signal processing and control system for CMR.

A diagram of CMR's signal processing and control system is shown in figure 6. A PC-compatible passive backplane system connects the single-board computer, pulse-pair processor, timing generator, and D/A converter board. The timing generator and D/A board are connected through the PC-104 bus. The cards are mounted in a small rugged chassis with a separate 120VAC power supply.

Previous cloud radars used programmable digital signal processing (DSP) chips for real-time processing [1]. Such DSP's run software programs and hence expend clock cycles and power loading instructions. Ideally, one would use a custom Application Specific Integrated Circuit (ASIC) in order to reduce power and size to an absolute minimum, but this would be completely inflexible to future design changes. Field Programmable Gate Array (FPGA) processors offer an attractive compromise between a general-purpose DSP system and a custom ASIC. Calculations can be performed at hardware speed in an FPGA while retaining the ability to reconfigure the device. FPGA also take advantage of parallelization of

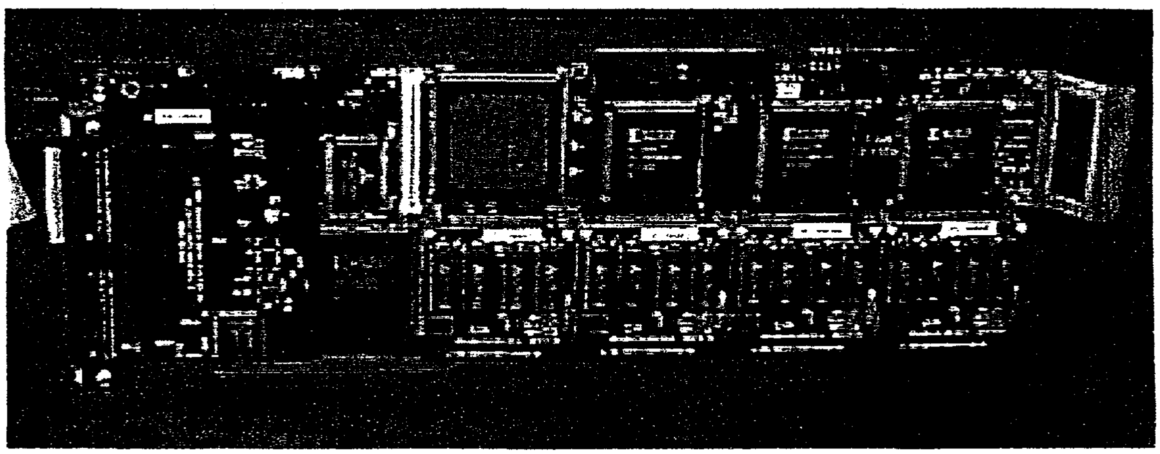


Figure 7: Picture of the FPGA-based Pulse-Pair processor.

the calculations by dividing each calculation into multiple simultaneous operations that are multiplexed into a single output data stream. The processing for the CMR is done on a single 13"x5" computer board containing four Xilinx 4013E FPGA's. Figure 7 shows a picture of the FPGA processor. The power consumption of the FPGA processors by themselves is estimated to be less than 3 W. By comparison, the same processing using TMS320C40 DSP's would require at least four processors with an estimated power consumption of 1.75 W each [2] for a total of 7 W dissipated in the processors alone. Although our primary motivation for choosing the FPGA approach was power savings, the design is potentially valuable for other radars requiring continuous pulse-pair processing.

The FPGA board requires a single PCI slot, and to get a PCI bus we needed to use a Pentium class computer. CMR's computer has a 200 MHz Pentium which is convenient in the development stage. However, for normal operation the computer only serves as a controller for the radar while the FPGA board does all the high speed computations. A future version of the instrument would not necessarily incorporate as sophisticated and high-speed CPU and bus.

4. CMR Performance

Experiments were performed at the University of Massachusetts, Amherst in fall, 1998 and winter, 1999 to determine the performance of the CMR. During these experiments, the dual-frequency Cloud Profiling Radar System (CPRS)[3] was operated within 60 meters of the CMR. CPRS is a truck-mounted instrument built at the University of Massachusetts [4]. It contains two radars, one operating at 94 92 GHz and another at 33 GHz., although only the 94.92 GHz radar was available during the experiment. It has participated in numerous field campaigns, and its performance is recognized as a standard in the meteorological community.

Table 3 gives the CPRS specifications relevant to the comparison. The transmitter used by CPRS is an extended interaction klystron that provides 1.3 kWatt peak power and pulses of 500 ns duration. Prior to averaging CPRS has almost 27 dB greater sensitivity than CMR. Additionally, the radars are mounted on a positioner that facilitates external calibration with a corner reflector.

The CPRS radar has heaters and temperature control, but lacks an internal calibration, so changes in the transmitter and receiver gain directly impact the reflectivity values it measures. This was a particular concern during the winter experiments because CPRS was stored outdoors, where temperatures were near freezing. Prior to taking data, CPRS was operated for an hour to allow its temperature to stabilize.

4.1 Experiment - Weather Conditions

The clouds observed on 24 September, 1998 were non-precipitating and multilayered with a base heights near 4 km. The prevailing winds were approximately along the direction from CPRS to CMR. Heavy snowfall occurred on the 13th and 14th of January, 1999. Both radars were covered with nylon tarpaulins, which may have produced some loss, but since they were made of the same material, we expect that both radars experienced nearly the same loss. The snow was removed from the antennas frequently to reduce uncertainties due to accumulation. The snow made the direction of clouds motion less obvious than on 24

Table 3: CPRS 94.92 GHz radar specifications.

radar system parameter	CPRS	CMR
peak transmitter power	1.3kW	30.5W
noise figure (dB)	13.0	10.7
receiver bandwidth (MHz)	2	10

September, 1998.

4.2 Measurements

Figure 8 shows images of one minute averaged reflectivity profiles of the clouds measured by CMR and CPRS on 24 September, 1998. Two layers are visible in both images. Although the CMR does not demonstrate the same sensitivity as CPRS, it is still able to image both layers. In this case, the CMR would have been a nice complement to the Cloud Detection Ladir (CDL). It is likely that much of upper layer would have been opaque to the CDL, and only a single layer would have been reported when that occurred. From 12 km a down-looking CMR would have detected both layers at all times, which could have been a valuable detail given the large height difference and therefore temperature difference between the layers.

Figure 9 and figure 10 are images of the clouds and precipitation observed during the winter experiment. The precipitation came in the form of snow consisting of short needles, graupel and stellar crystals. The data collected on 13 January, 1999 for both radars were averaged for ten seconds. The plot of CPRS data clearly shows a system artifact at the cloud top. Rather than displaying a sharp cloud edge as seen in the CMR image, the data shows a persistent feature. This was caused by the time-domain response of the logarithmic detector. Specifically, at range-times corresponding to the cloud top the output of the logarithmic detector still had a significant response to the strongly reflecting cloud beneath.

The data displayed for CPRS for 14 January, 1999 were averaged for two seconds, so that this effect would not be as apparent in the image, and the data for CMR were averaged for ten seconds.

4.3 CMR Sensitivity

A detection threshold corresponding to a SNR equal two (3 dB) was used when processing the data in figures 8 - 10, and this level is plotted as a dotted curve along with the profiles of reflectivity in figures 11, 12, 13. To illustrate the level of signal processing gain achieved we have also included a plot of the signal level corresponding to an input SNR of two prior to averaging, which appears as the upper dashed curve.

An important figure of merit for the performance of a cloud radar is the minimum detectable reflectivity factor, which is directly related to the calibration factor. The minimum detectable reflectivity factor, $dBZ_{e,min}$, is defined as the dBZ_e value that results in unity signal-to-noise ratio at a given range [5], which is usually taken to be 1 km. for cloud radars. With a measurement of the standard deviation of the receiver noise, σ_n, the $dBZ_{e,min}$ at 1 km is given by

$$dBZ_{e,min} = 10log_{10}(C\sigma_n). \tag{1}$$

The value of σ_n depends on the receiver noise figure as well as the number of averages performed. Table 4 lists $dBZ_{e,min}$ at 1 km for CMR assuming 5×10^5 averages, and figure 14 plots $dBZ_{e,min}$ as a function of range for the winter instrument configuration. The difference between measured and predicted $dBZ_{e,min}$ results directly from the discrepancy in the measured and predicted calibration constants.

5. CMR Upgrades

Currently CMR has a sensitivity of approximately -20 dBZ at 1 km. This does not meet the needs of all ARM-UAV science team members. There are a few hardware upgrades that

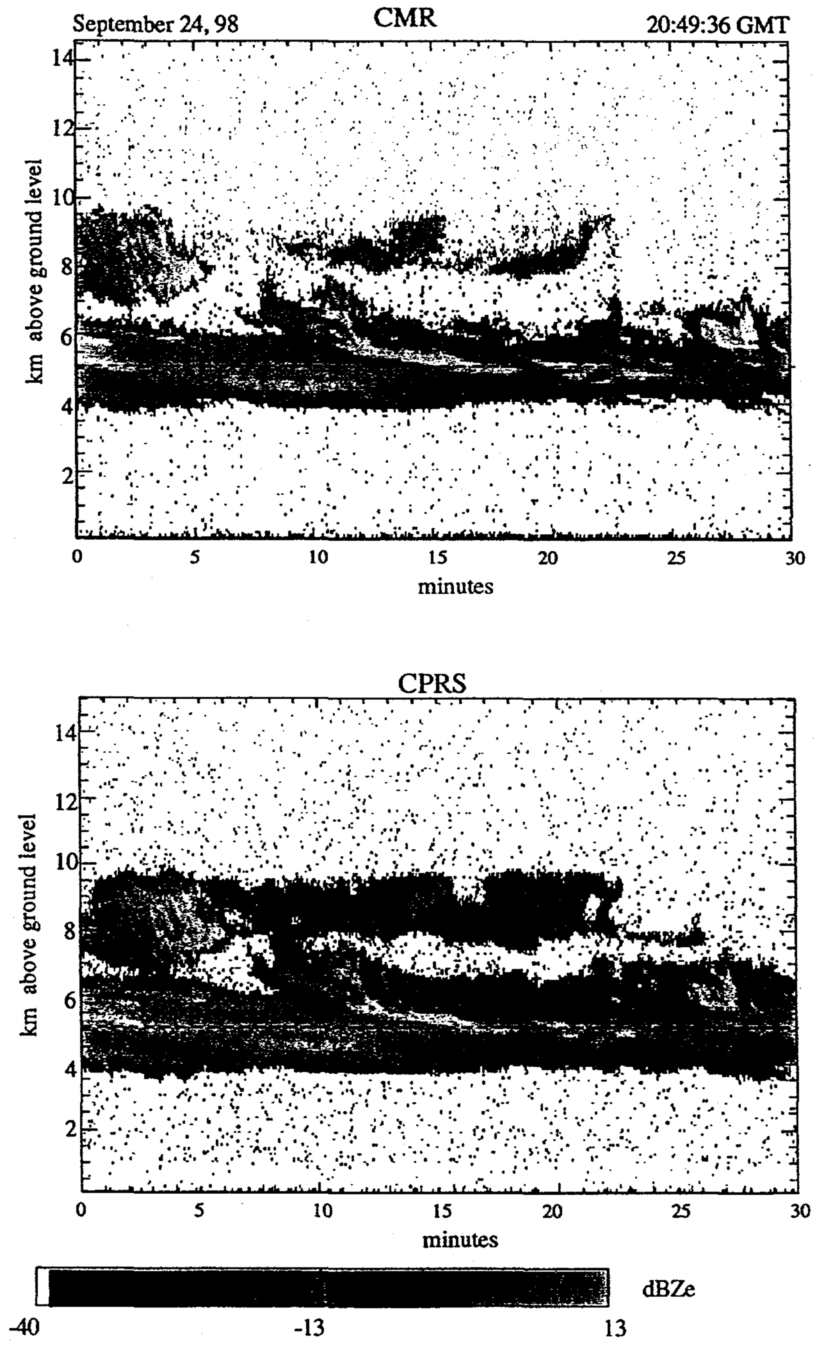


Figure 8: Images of clouds taken with CMR and CPRS on Sept. 24, 1998.

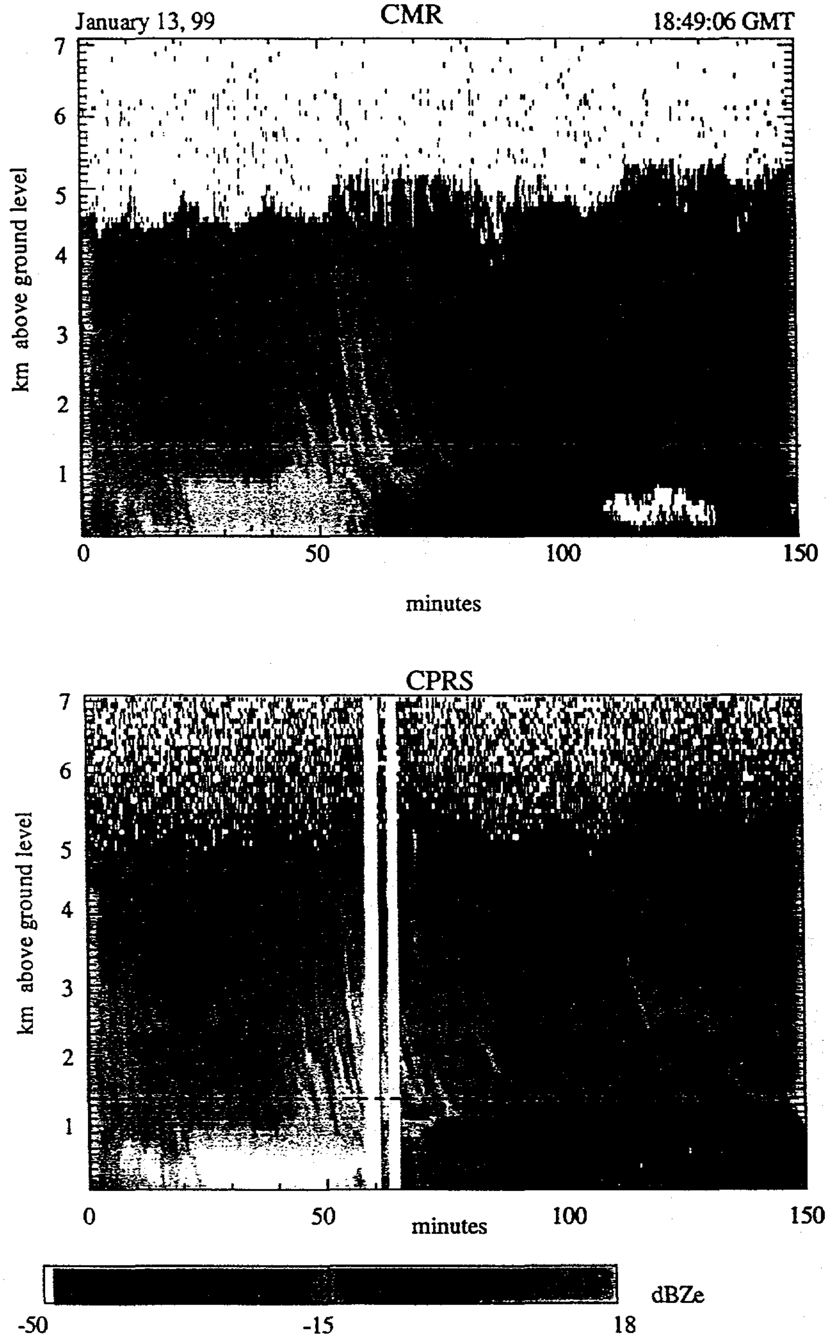


Figure 9: Images of clouds taken with CMR and CPRS on Jan. 13, 1999.

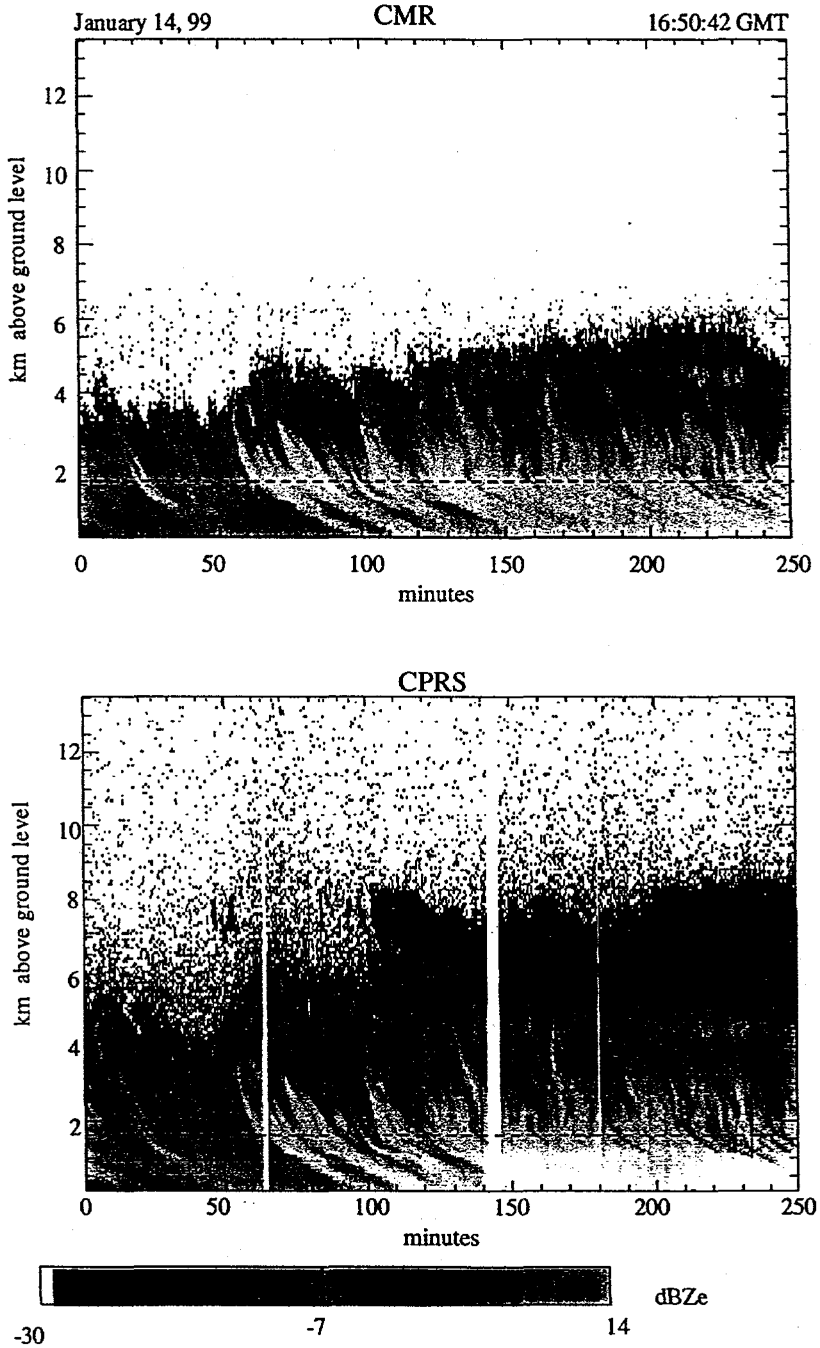


Figure 10: Images of clouds taken with CMR and CPRS on Jan. 14, 1999.

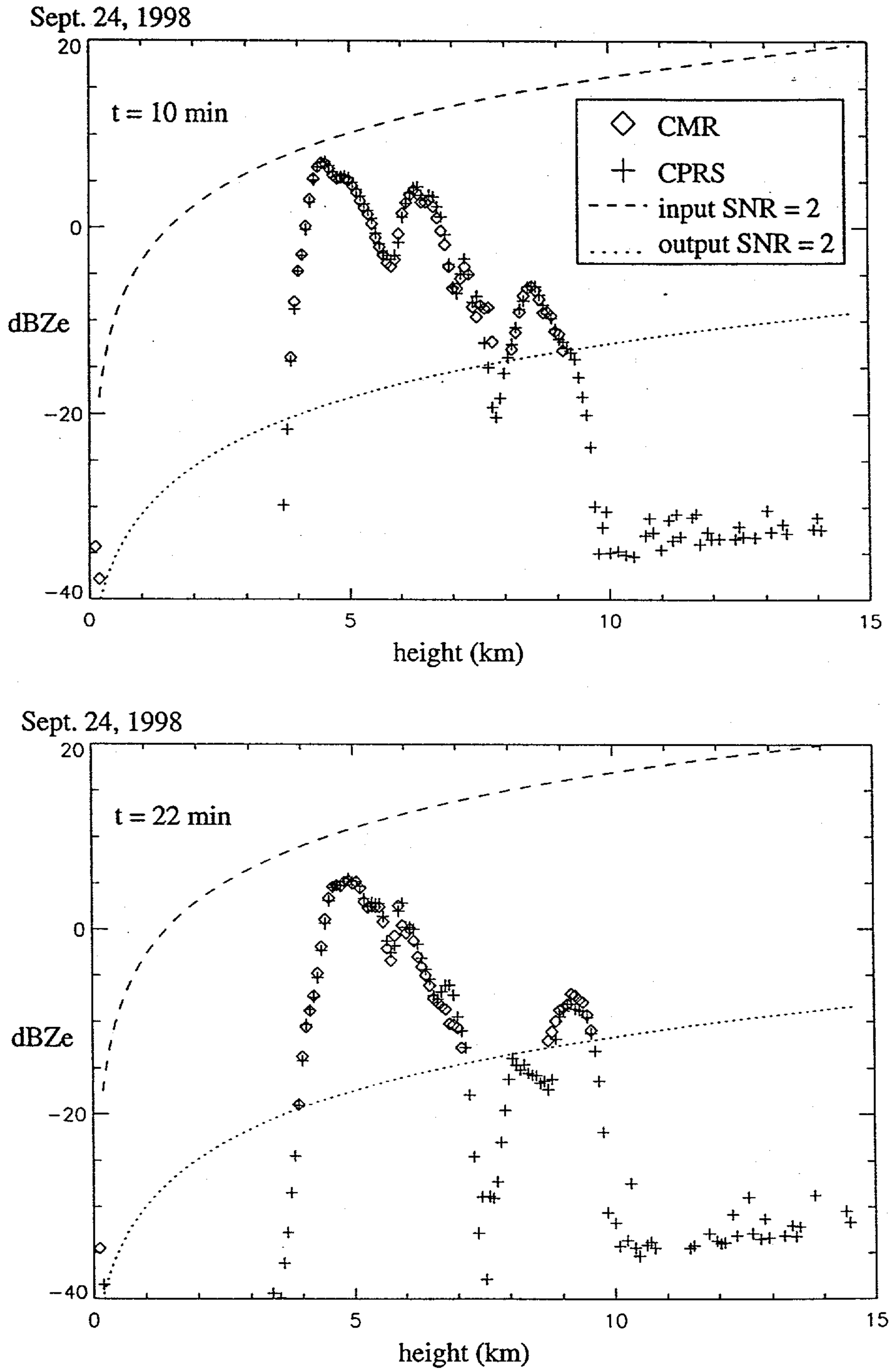


Figure 11: Examples of reflectivity *vs.* height taken on Sept. 24, 1998.

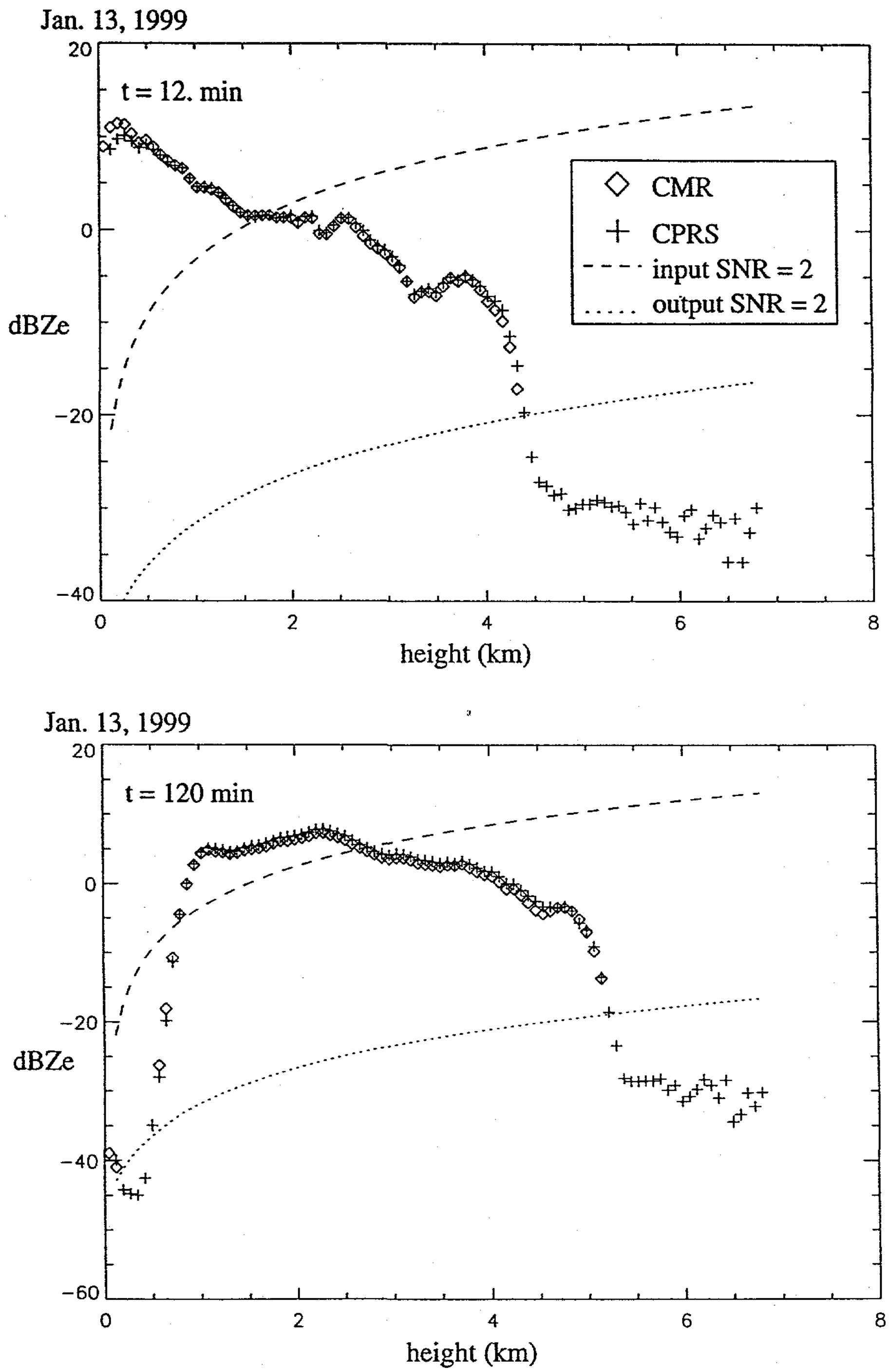


Figure 12: Examples of reflectivity *vs.* height taken on Jan. 13, 1999.

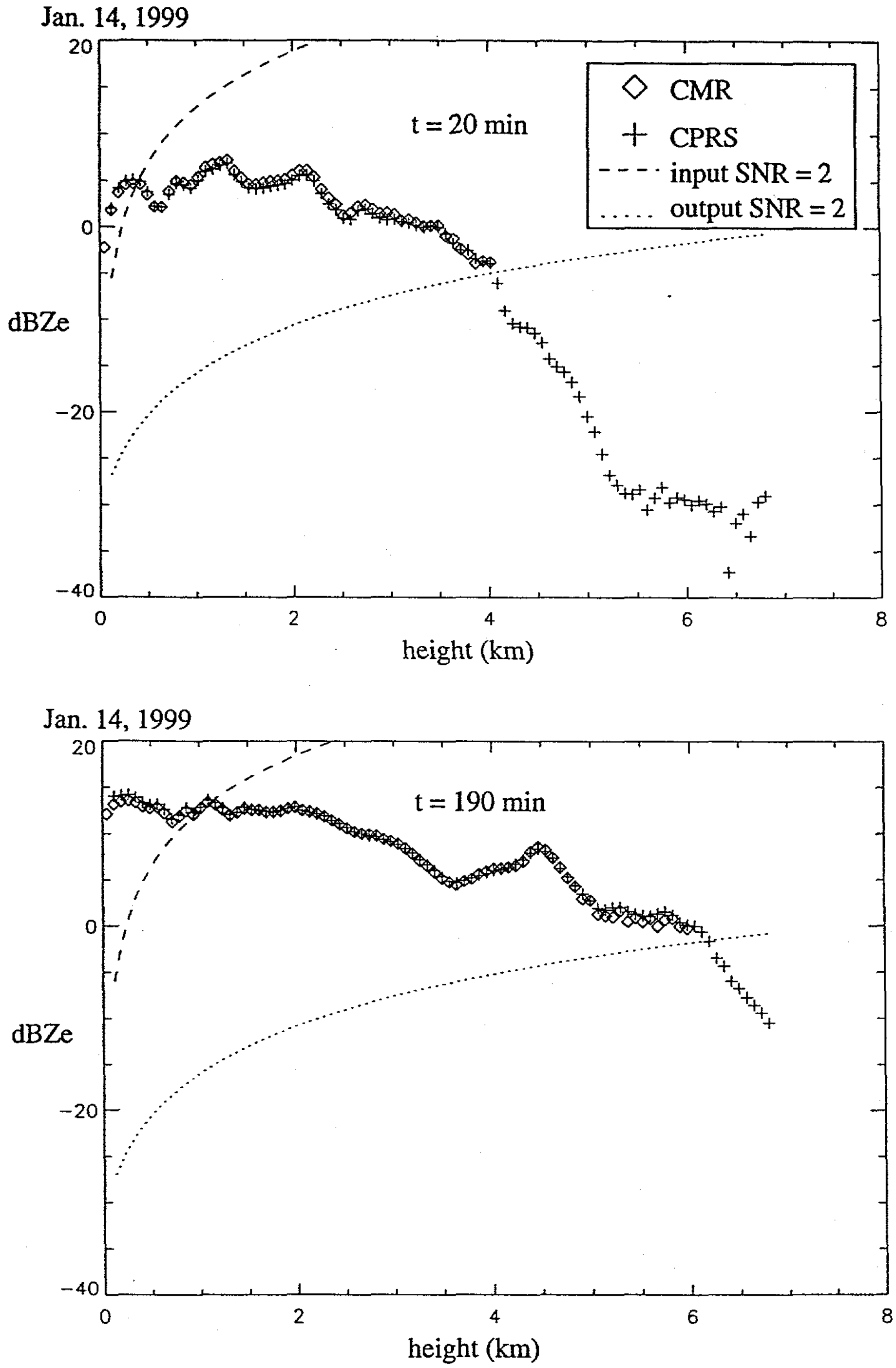


Figure 13: Examples of reflectivity *vs.* height taken on Jan. 14, 1999.

Table 4: Minimum detectable signal for CMR.

day	calfactor	samples averaged	$dBZ_{min} measured$	$dBZ_{min} predicted$
09-24-98	46.2	5×10^5	-34.2	-36.09
01-13-99	53.1	5×10^5	-35.2	-38.2
01-14-99	68.9	5×10^5	-19.46	-22.5

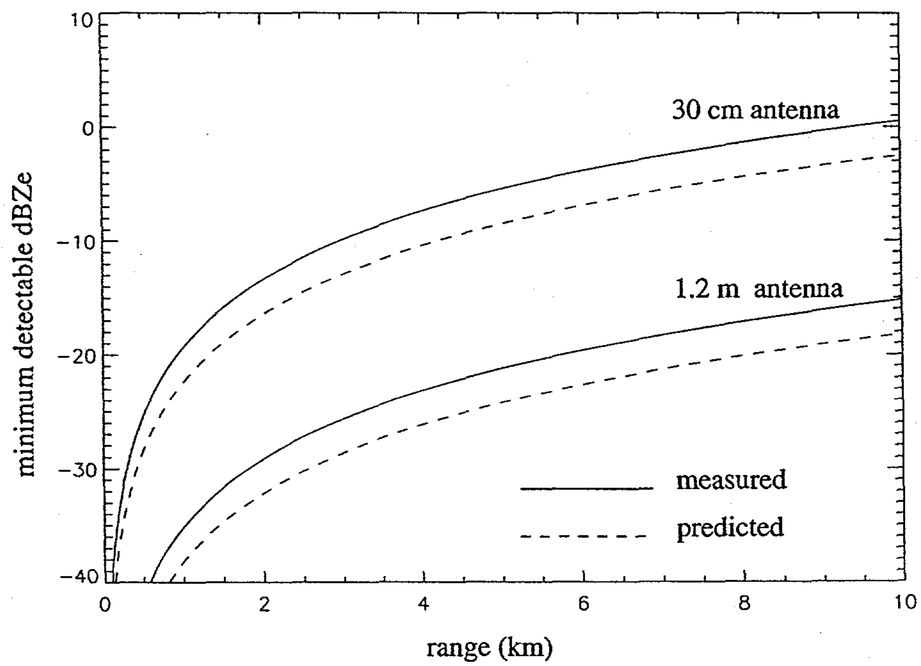


Figure 14: Minimum detectable Z for the winter experiment.

will dramatically improve CMR's sensitivity, while still keeping CMR within the size, weight and power constraints imposed by the Altus platform. The sections below summarize the upgrades, list their costs and show their impact on CMR's sensitivity. If all upgrades are implemented, the CMR sensitivity will improve to -42 dBz at 1 kilometer which meets the requirements of all science team members.

There are three main modifications to increase CMR's sensitivity without negatively impacting the weight, size and power budget for the instrument: reduce transmitter/receiver bandwidth, install a more efficient compact antenna and improve the receiver noise figure. These can be broken into four options. Each option is described below. Note that each option builds off the previous by including all components in the previous option. Figure 15 plots the minimum detectable Z as a function of range for each upgrade option.

5.1 Option 1: Antenna Upgrade

A three-fold compact lens antenna was chosen for the original CMR in order to meet the volume constraints imposed by the UAV platform. Although small, this type of antenna has additional loss compared with more conventional lens antennas. Unfortunately, the UAV platform cannot support a conventional lens antenna due to its large size and shape. However, W-band cassegrain antennas with integrated radomes can now be purchased. These antennas will have a gain of 46 dB rather than 44 dB given a twelve inch diameter and occupy slightly less volume than our compact lens antenna. By using this antenna, a 4 dB improvement in the sensitivity will be realized. The cost for the antenna will be no more than $12K. This includes some NRE costs to customize the antenna for our application.

5.2 Option (2): LNA Upgrade

Recent advancements in W-band low noise amplifiers have resulted in LNA's with 4 dB noise figures. CMR's LNA has a noise figure of 7 dB. By installing the new antenna and LNA, a 7 dB improvement will be realized.

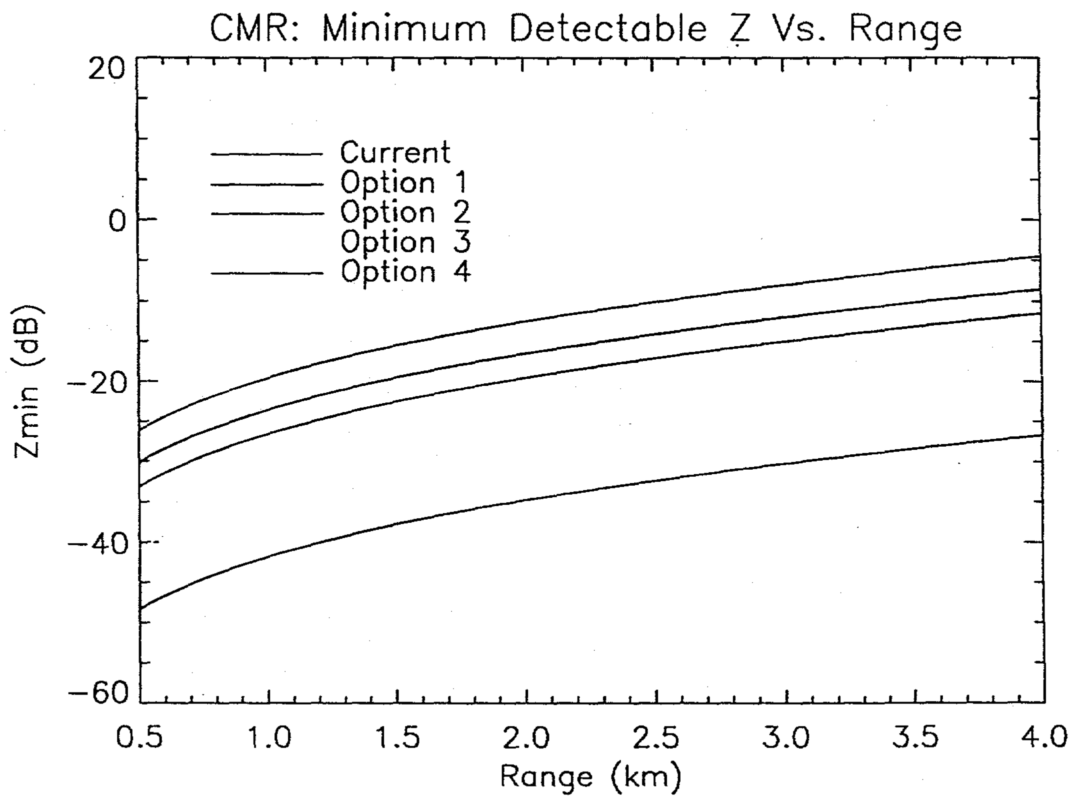


Figure 15: Minimum detectable Z plotted versus range for the current CMR configuration and four possible upgrade configurations.

5.3 Option (3): Transmitter Upgrade

The solid state transmitter used by CMR can only produce 100 nsec pulses. This results in a 15-m range resolution which is finer than required. If the resolution could be reduced to 75 m, the required transmitter/receiver bandwidth would be reduce by a factor of 5 and the volume illuminated would increase by a factor of 5. This would result in a 10 dB improvement in sensitivity compared to just averaging the five 15-m range cells to get 75 m resolution. Unfortunately, current W-band technology cannot produce a pulse longer than 100 nsec at power levels above 1 watt. However, four 300 milliwatt continuous-wave amplifiers can be power combined to produce a 1 watt W-band amplifier capable of pulse lengths from 100 nsec to continuous-wave (CW). Using this type of amplifier in the CMR transmitter and a 10 usec linear FM chirp transmit waveform (2 MHz bandwidth), the loss in peak power can be overcome and a 10 dB improvement in sensitivity realized. Combining this with the LNA and cassegrain antenna, a total improvement of 17 dB is obtained. Note that originally we chose not to use a chirp waveform because the data acquisition technology was not adequate to perform match filtering and Pulse-Pair processing in real-time while staying within the require power limits. However, recent advancements in FPGA technology will enable us to perform digital I/Q demodulation, implement a match filter and perform Pulse-Pair processing with very low power consumption. Furthermore, the 1 watt CW amplifier will much be more reliable than the 30 Watt 100 nsec transmitter that we currently use in CMR. In the case that an amplifier fails, the total transmit power will only reduce by 1.3 dB. Replacement diodes only cost $4K and can be installed quickly.

5.4 Option (4): System Upgrade

This is the same as option 3 except that two antennas are used. By adding one latching circulator to the receiver, an antenna can be connected directly to the receiver. Note that Option (3) suffers from a minimum range/sensitivity tradeoff. As the pulse length is increase to improve sensitivity, the minimum range is also increased. For a 10 usec chirp, the closest observable range will be greater than 1.5 km. However, with separate transmit and receive antennas, this problem is overcome because the receiver can be on simultaneously with the transmitter. Due to the low transmit powers for CMR, we can obtain enough isolation between the transmitter and receiver so that we can operate both simultaneously. This will allow us to transmit much longer pulses, and therefore obtain higher sensitivities without compromising the minimum range. Furthermore, some of the loss in the receiver can also be removed. Note that a 40 usec 2 MHz digital matched filter receiver has already been implemented on a FPGA processor. In the future, we may be able to extend to even longer pulses (ie. higher compression gains). It should also be noted that we plan to use a latching circulator to connect the second antenna directly to the receiver so that CMR can be electronically switched between a single and a dual antenna mode. This will allow us to compare both modes in the field and directly measure any errors in the antenna alignments. The antennas are only 12 inches and we will be integrated into a single structure so that we don't expect problems with the alignment. Nevertheless, we will be able to measure how well the antennas are aligned by comparing the two modes. Mike Ferrario has sent us ProEngineering drawings of the Altus payload. We have determined that a two antenna system will not negatively impact any of the other payloads on the aircraft. In fact, the two antenna system will ultimately require less volume than CMR's current configuration due to the large size of the 30 watt solid-state transmitter that will be replaced with the 1 watt CW transmitter.

References

[1] A. L. Pazmany, R. E. McIntosh, R. Kelly, and G. Vali, "An Airborne 95 GHz Dual Polarization Radar for Cloud Studies", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 1, 1994.

[2] J. Hong, "Calculation of TMS320C40 power dissipation application report", Tech. Rep. SPRA032, Texas Instruments, November 1993.

[3] S.M. Sekelsky and R.E. McIntosh, "Cloud observations with a polarimetrc 33 GHz and 95 GHz radar", *Meteorology and Atmospheric Physics*, vol. 58, pp. 123–140, 1996.

[4] S. M. Sekelsky, *A 33 GHz and 95 GHz Cloud Profiling Radar System (CPRS): Preliminary estimates of particle size in precipitation and clouds.*, PhD thesis, University of Massachusetts, 1995.

[5] R.J. Doviak and D.S. Zrnić, *Doppler Radar and Weather Observations*, Academic Press, Inc., 1984.