GROUND-BASED AND AIRBORNE WEATHER RADARS AND LIDAR FOR OBSERVING THE ATMOSPHERE

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1. INTRODUCTION

The Earth Observing Laboratory (EOL) at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado develops and deploys state-of-the-art radar and lidar instruments for both ground and airborne operation, to advance scientific understanding of the atmosphere. This paper describes the capabilities of current and planned developments of the following remote sensing instruments: (i) S-band dual-polarization Doppler radar (S-Pol); (ii) Electra Doppler Radar (ELDORA); (iii) HIAPER cloud radar (HCR); and (iv) high spectral resolution lidar (HSRL).

The S-Pol and ELDORA have been deployed in a number of field projects over the past decade. Recently these instruments have been upgraded with new signal processors, data format and display. The EOL continues to improve data quality procedures for S-Pol and ELDORA and to derive value-added products from measurements as per users' needs. Two other instruments, HCR and HSRL are being developed and they will be operational in less than a year.

2. S-BAND DUAL POLARIZATION DOPPLER RADAR (S-POL)

The ground-based S-band dual-polarization radar (S-Pol) is equipped with dual-wavelength capability (S-band and Ka-band) (Lutz et al., 1997). The two radars record simultaneous dual-polarimetric measurements. Dual-polarization measurements are used for identifying rain, snow, hail (Vivekanandan et al., 1999) and quantifying amounts of the precipitation.

The entire S-Pol radar system, including power generators and operations control is packaged into six standard-size sea containers for transport (Fig. 1). S-Pol is the only S-band radar that is relatively easy to transport for deployments in the continental US and overseas. Its agile radar control software makes it easily configurable to meet the individual scientific needs of researchers. In fact, many scientific users design radar scan strategies and actually operate the radar during field experiments.

2.1 DATA PROCESSING

A new digitizer and signal processor have replaced the legacy radar signal processing system in the S-Pol. Pulse-pair and dual-polarization processing is performed by the NCAR-designed HAWK data processing system. The In-phase and Quadrature (I and Q) time series are transmitted from a Sigmet RVP8 receiver to a high power PC via Ethernet. The data are first processed by a newly-developed fuzzy logic ground clutter recognition algorithm. The identified clutter- contaminated radar data are then filtered with an adaptive, spectral-based clutter filter, which has better than 50 dB clutter rejection. This effectively eliminates the problem of anomalous propagation (AP) and normal propagation (NP) ground clutter without attenuation of zero-velocity weather echoes Hubbert et al., 2009).

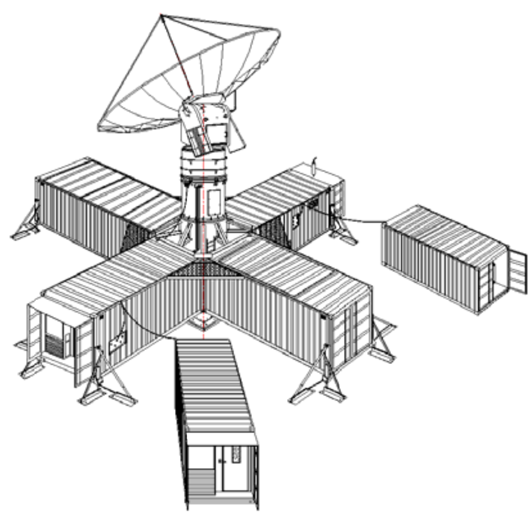

Figure 1. NCAR S-band polarization radar (S-Pol).

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Recent hardware upgrades now enable researchers to quickly switch the S-Pol transmitter between fast alternating of horizontal and vertical polarizations and simultaneous transmit modes. Also, previously unavailable I and Q time series data can now be recorded for signal processing research, algorithm development and verification. S-Pol uses an advanced suite of real-time algorithms to create value-added products, including estimates of particle type, precipitation accumulation, and moisture fields from both absolute phase measurements and dual-wavelength observations.

3. ELECTRA DOPPLER RADAR (ELDORA)

ELDORA captures faster moving weather events such as tornadoes, records observations of clouds and precipitation systems over rugged mountainous terrain and observes detailed kinematics of eyewalls in hurricane rainbands over the ocean. The Electra Doppler Radar (ELDORA) is an airborne, dual beam, meteorological research radar developed jointly by NCAR and France's Centre de Recherches en Physique de L'Environnement Terrestre et Planetaire (CRPE) (Hildebrand et al., 1997). ELDORA mounts on a Lockheed P-3 aircraft, operated by the Naval Research Lab (NRL). ELDORA's two antennas extend back from the tail of the aircraft and spin about the longitudinal axis of the aircraft. One antenna points slightly ahead (~16°) and one slightly aft (~-16°) of the aircraft. As the aircraft translates the antennas through space, ELDORA traces two conical helixes through the atmosphere within 50-100 km of the aircraft, essentially observing the entire atmosphere with two separate looks several minutes apart (Fig. 2).

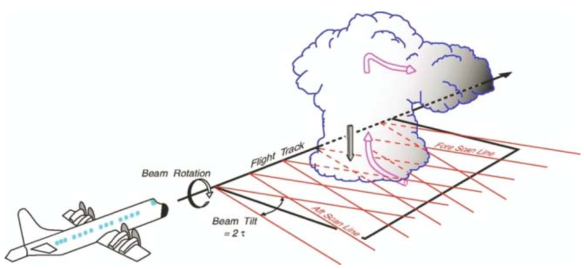


Figure 2. Schematic shows dual-Doppler observations of a thunderstorm using aft and fore radars of ELDORA.

ELDORA has been used to observe detailed kinematics of tropical convection, mid-latitude frontal circulation, convection and gravity waves over complex terrain, lake-effect, snow, convection initiation, hurricane eyewalls and rainbands, damaging winds emanating from squall lines, and tornadoes at higher spatial and temporal resolutions than previously possible. It is the only airborne Doppler meteorological radar that is able to detect motions in the clear air.

3.1. DATA PROCESSING

The research flight speed of the P-3 aircraft is approximately 130 m s^{-1}. At this flight speed the scientific requirement for samples every 300-500 m dictates an antenna rotation rate of approximately 24 RPM. This resolution also dictates at least one integration period (dwell time) to be completed every degree of rotation, which gives dwell times the order of 8 msec. Since the phenomena to be studied have a time to independence of 3-7 msec, only two or three independent samples can be taken in a dwell time with a simple radar pulse. Meeting the velocity accuracy of 1 m s^{-1} requires about 10 independent samples per dwell time. As a result, a complex transmit waveform is therefore necessary.

The waveform chosen was a 4-element stepped chirp. Physically, a complex waveform consists of a pulse of RF energy, within which are sub-pulses or chips that are coded in some way. For ELDORA these chips are distinguished by discrete shifts in transmit frequency which enable the received signals to be processed individually, thus improving the sampling statistics of the radar measurements. The resulting transmitted waveform consists of these composite pulses.

The frequencies must be close enough together that the unambiguous velocity and the beam squint angle for each frequency are similar but far enough to maintain required independence. A typical frequency separation is 9 MHz. At X-band and typical pulse repetition frequencies (PRFs), the unambiguous velocity is relatively small and the velocity data are frequently folded. ELDORA has solved this problem by operating in a staggered PRT mode (Loew and Walther, 1995). The two PRTs have a ratio of 4/5 and extend the unambiguous velocity to 110 m s^{-1}.

4. HIAPER CLOUD RADAR (HCR)

Precipitation or cm radars are not sensitive enough to detect cloud droplets. One of the attractive features of a millimeter wave radar system is its ability to detect micron-sized particles that constitute clouds with lower than 0.1 g m^{-3} liquid or ice water content.

The engineering specifications of such a radar are mainly driven by climate, Earth's radiation budget, and cloud initiation studies.

Scanning or vertically-pointing, ground-based millimeter wavelength radars have been used to study stratocumulus fair-weather cumulus (e.g., Kollias et al., 2001) and fog properties. Airborne millimeter wavelength radar systems, such as the University of Wyoming King Air Cloud Radar (WCR) and the NASA ER-2 Cloud Profiling System (CRS), have added mobility to observe clouds in remote regions and over the oceans.

The Earth Observing Laboratory (EOL) of NCAR is in the process of building the first phase of a three phase dual wavelength W/Ka-band airborne cloud radar to be called the HIAPER Cloud Radar (HCR), Farquharson et al., 2007) This phase is a pod-based W-band radar system with scanning capability (Fig. 3). The second phase will add pulse compression and polarimetric capability to the W-band system, while the third phase will add a complementary Ka-band radar. The pod-based radar is primarily designed to fly on NSF/NCAR's Gulfstream V (GV) and possibly C-130 aircraft. It is a part of the HIAPER (High-performance Instrumented Airborne Platform) Aircraft Instrumentation Solicitation (HAIS).

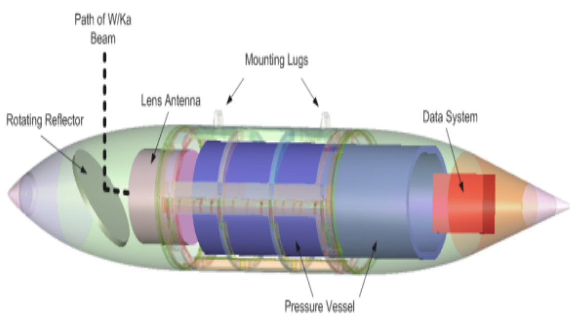


Figure 3. Layout of W-band cloud radar in NCAR pod. The pod will be mounted on NCAR's GV wing.

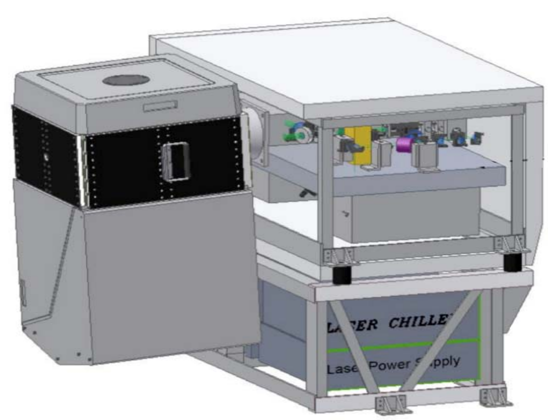
The majority of the radar system will be housed in GV's 20" wing pod, designated the NCAR pod. The HIAPER instrumentation philosophy dictates that only power and a high-speed network connection will be available to equipment located in the wing pods. For this reason it is necessary that nearly the entire radar system be located within the pod; the exception being the radar control and data display/archive computer(s). The pod will be attached to the mid-wing hardpoint. The instrument will be flight tested on board GV in Summer 2010.

5. HIGH-SPECTRAL RESOLUTION LIDAR (HSRL)

One of the largest remaining uncertainties in assessing the future trajectory of the earth's climate is the proper treatment of cloud processes and, in particular, the interactions between aerosols and clouds in models (Houghton et al., 2001). Aerosols affect cloud formation and evolution and hence have strong indirect effects on the radiative forcing of clouds, and even on the timing and magnitude of precipitation.

Cloud properties are available from several recent instruments, including the Moderate Resolution Imaging Spectoradiometer (MODIS) and GOES-R. However, there are large uncertainties in retrieving optical properties such as the sizes of cloud particles. This is particularly true for ice clouds because variations in crystal habit result in an ill-constrained retrieval problem.

The envisioned capability of a millimeter wave radar system on GV in characterizing cloud properties is enhanced by coordination with microwave radiometer, in situ probes, and especially with the NCAR GV High-Spectral Resolution Lidar (HSRL) (Razenkov et al., 2008). The lidar, designed and built by the University of Wisconsin, provides unique measurements of optical depth of clear air, clouds and precipitation (Fig. 4). At present the ground-based version of the HSRL is operational at the University of Wisconsin and it is being upgraded for airborne deployment. The instrument will be flight tested on board GV in late 2010. When it is not deployed for airborne measurements, it will be operational in a ground-based mode. In a ground-based configuration, HSRL and HCR will be housed in a common seatainer. This setup would enable collocated observations of lidar and cloud radar.



4. Configuration of high spectral resolution lidar (HSRL). It is an aircraft cabin based system and a lidar beam can be pointed either zenith or nadir through 45-cm optical port.

One of the challenges in lidar observation is independent estimation of scattering and optical depth, i.e., extinction. Despite backscattered signals from aerosol and air molecules being superimposed, the HSRL separates the scattering from air molecules from aerosol with an ultra-narrow spectral filter. This separation is possible because the Doppler spectrum of air molecules is considerably broadened by thermal motion compared to the Doppler spectrum of aerosols.

Since atmospheric density is linearly proportional to concentration of air molecules, the return from molecular scattering is used as a reference calibration target. The backscatter from air molecules is used for calibrating the scattering signals from aerosol at all ranges. Also, the reference aerosol scattering is used for retrieving extinction profile and optical depth.

The combination of the lidar and cloud radar will be used for estimating cloud fraction, particle size, precipitation rate, and scattering cross sections (Donovan and van Lammeren: 2001). Furthermore, estimates of particle size coupled with Doppler velocity provide information on particle shape and density.

6. SUMMARY

The combination of scientific measurement requirements and engineering specifications of key components in an instrument dictate sensitivity, spatial and temporal resolutions of observations. Table 1 summarizes sensitivity and temporal and spatial resolution characteristics for each of the instruments presented in this paper. As expected lidar is the most sensitive and collects the highest spatial resolution measurement but its range and penetration into cloud is limited. HCR has superior ground clutter rejection than S-Pol since the Rayleigh scattering cross-section of a cloud particle at W-band is larger than the corresponding value at S-band while the sensitivity to ground clutter is the same at S and W-bands. The sensitivity of the ELDORA is limited by antenna gain and peak transmit power.

Reflectivity and radial wind measurements are calibrated using various techniques. In the case of S-Pol reflectivity and differential reflectivity, measurements are calibrated within 1.0 dB and 0.1 dB, respectively. Radial wind measurements of S-Pol and ELDORA are calibrated to within 1 m sec^{-1}. Reflectivity measurements from HCR and HSRL will be calibrated to better than 1.0 dB and wind measurements from HCR will be calibrated to better than 1 m sec^{-1}.

Table 1. Resolution and sensitivity of radars and lidar

Instrument t	Temporal resolution	Spatial resolution (m)	Sensitivity at 10 km (dBZ)
S-Pol	3 minutes	200 m	-32
ELDORA	1 minute	350 m	-12
HCR	0.5 sec	120 m	-22
HSRL	0.5 sec	100 m (horizontal) 15 m (vertical)	-36

Numerical prediction models have evolved from single discipline (e.g., weather, cloud, chemistry and biogeosciences) into multi-disciplinary models that require simultaneous measurement of the atmosphere for initialization and validation. Simultaneous and collocated observations from aircraft as well as ground-based platforms are valuable not only for process studies to improve parameterization schemes but also to improve the accuracy and reliability of data for assimilation and refinement of numerical models. For example, simultaneous observations of clouds and aerosol are used for parameterization schemes of cloud droplet distributions as a function of aerosol concentrations**.**

Instruments described in this paper provide a range of measurements and derived microphysical and dynamical products. At present, simultaneous measurements using the above described instruments can only be achieved by combining observations from aircraft and ground-based instruments and by assuming simultaneity in time and collocation in space.

7. **ACKNOWLEDGEMENTS**. The National Center for Atmospheric Research is sponsored by the National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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