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DEVELOPMENT OF ADVANCED RADAR AND LIDAR PLATFORM SUITE FOR INTERDISCIPLINARY AIRBORNE AND GROUND-BASED REMOTE-SENSING RESEARCH

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1. INTRODUCTION

The NCAR Earth Observing Laboratory (EOL) is embarking on a cutting edge facility development to take the potential synergy of simultaneous radar and lidar observations to the research community. The Community Airborne Platform Remote-Sensing Interdisciplinary Suite (CAPRIS), will provide the geosciences community the capability for measuring key components of clouds, precipitation, aerosols and chemistry to advance basic understanding of related processes in a warming planetary environment. Many airborne platforms and active remote sensors exist through out the world, but thus far it has been rare for multiple radar and lidars to be operated simultaneously from a single aircraft or on the ground. Furthermore, it is widely recognized that a fusion of microwave and optical data can provide new insights into atmospheric processes. The suite will work in conjunction with existing in-situ sensors on NSF/NCAR C-130 and NSF/NCAR Gulfstream V (GV) aircraft by providing an unprecedented combination of coincident observations of precipitation, winds, cloud microphysics, water vapor, ozone, and aerosol at a wide range of temporal and spatial scales. More detailed information on CAPRIS may be found at the project web-page: http://www.eol.ucar.edu/development/capris

Radars and lidars at multiple wavelengths/frequencies [clear air (lidars), cloud (MM-wave radar), and precipitation (CM-wave radar)] are necessary in order to sense variables in both clear and cloudy regions and over the several orders of magnitude of particle size range that is required to link microscale and mesoscale processes and for data assimilation. For example, by operating cloud and precipitation radars simultaneously with water vapor and Doppler lidars, investigators could gain a more comprehensive view of how conveyor belts of boundary layer moisture are transformed into heavy precipitation storms. Similarly, by using radars and lidars simultaneously to probe clouds, investigators can deduce microphysical properties such as particle size distribution. This type of measurement is necessary in order to reduce the uncertainty on estimates of indirect radiative forcing caused by aerosols. The uncertainty of the indirect effect projects the largest component of uncertainty in to the net anthropogenic radiative forcing IPCC AR4, (2007).

2. TECHNICAL DESIGN SPECIFICATIONS

The CAPRIS suite includes (i) a flat antenna-aircraft fairing mounted, dual-polarization, dual-Doppler precipitation radar; (ii) a pod-based dual-wavelength, dual-polarization, Doppler cloud radar; (iii) a water vapor differential absorption lidar (DIAL)/aerosol lidar; (iv) a UV ozone DIAL; (v) a UV molecular clear air Doppler wind lidar; (vi) a heterodyne boundary layer Doppler wind lidar; and (vii) pod-based vegetation canopy lidar. These instruments will be mounted on the NSF/NCAR C130 and GV (HIAPER) (except the precipitation radar). We also propose a design that can be deployed in a ground-based mode to maximize lifetime, utility and flexibility.

A consortium of scientists and engineers, led by the NCAR Earth Observing Laboratory, present here a strategy to develop and deploy the CAPRIS. The design of this system considers the needs expressed above, current thinking in the community about measurement priorities and new engineering capabilities now available for use in geosciences research. CAPRIS satisfies the following criteria for supporting multidisciplinary research:

- Measurement capability in clear air, cloudy, and precipitating conditions;
- Observations at nested spatial and time scales; providing both in-situ and remote sensing measurement techniques.

The proposed suite of instruments making up CAPRIS along with key science topics that can be addressed with each sensor are shown in Table 1.

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** National Center for Atmospheric Research is sponsored by the National Science Foundation.

Table 1: Proposed CAPRIS instruments and their corresponding potential scientific applications.

Instruments	Science
Polarimetric airborne centimeter Doppler radar – C and/or X-bands	Hurricane, severe storms, convection initiation, tropical meteorology. Kinematics and microphysical processes.
Pod-based dual-wavelength, dual-polarization, millimeter wave Doppler radar – W, Ka-bands	Cloud and drizzle microphysics, ice microphysics, and cloud radiation properties
H_2O differential absorption lidar (DIAL), O_3 DIAL, Doppler wind lidar (UT/LS and PBL systems) CO_2 DIAL, vegetation canopy lidar	Climate change, fluxes and transport of water vapor, ozone, and pollutants from boundary layer to UT/LS, gravity waves, volume extinction coefficient

CAPRIS deployed on long-range aircraft or in ground facilities will allow investigation of weather systems worldwide such as monsoons, tropical cyclones, severe convection over continents, orographic precipitation, convection over the oceans, and polar and upper atmosphere chemistry. The potential scientific advancements from CAPRIS in four research areas include: weather, chemistry and transport, effect of clouds and aerosol on earth’s radiation budget, and transport of fluxes in boundary layer.

With the exception of the centimeter radar, all systems can be deployed on either the HIAPER or C130 aircraft. Possible radar and lidar configurations on the C130 are given in Figure 1. Existing optical apertures on HIAPER are sufficient to allow for simultaneous operation of multiple lidar systems depending on aperture lens material requirements. The C130 fuselage must be modified slightly to incorporate a horizontal optical aperture and an external fairing. In addition, a rotating “turret” will be added to the existing up-looking aperture. With these modifications, the C130 will also support simultaneous operation of multiple lidars plus both radars. In the basic CAPRIS configuration for the C130, a combination of lidars such as the ozone DIAL and UV Doppler lidars share the rear apertures, while the water vapor DIAL occupies the forward aperture. Due to practical design limitations, both systems are constrained to look either up, down or horizontal. HIAPER presents similar constraints. For example, the ozone DIAL and UV Doppler lidars could share the forward apertures, while the water vapor DIAL would use the rear. In this case, the ozone/Doppler system will look either up/down or horizontal, while the water vapor DIAL will be down looking only. The final configuration and position of the instruments on either aircraft will be determined once the suite of lidars is finally determined.

2.1 CENTIMETER DUAL POLARIZA-TION DOPPLER RADAR

The centimeter wavelength dual polarization Doppler radar is intended to replace the aging ELDORA and provide new research capabilities as well. It should provide twice the along-track resolution of ELDORA to yield higher resolution wind fields, while dual-polarization capability will provide microphysical information and aide in QPE.

The proposed system consists of four active electronically scanned array antennas (AESAs) strategically mounted on the fuselage of the NSF/NCAR C130 turboprop aircraft. Figure 1 shows the proposed configuration on the C130. Four flat AESAs (shown in blue) will be mounted on the fuselage using aerodynamic fairings. Two will be mounted on either side of the fuselage behind the rear doors, the third will be mounted on the top of the fuselage and the fourth on the upper portion of the tail ramp. Each AESA measures approximately 1.5 m x 1.9 m. Unfortunately, due to the required size of the four AESAs and aerodynamic limitations, operation of this antenna system on HIAPER would not be possible. However, this technology would lend itself to a ground-based application. A more detailed description of the AESA technology is provided in a companion paper in this Conference Loew, et. al., (2007).

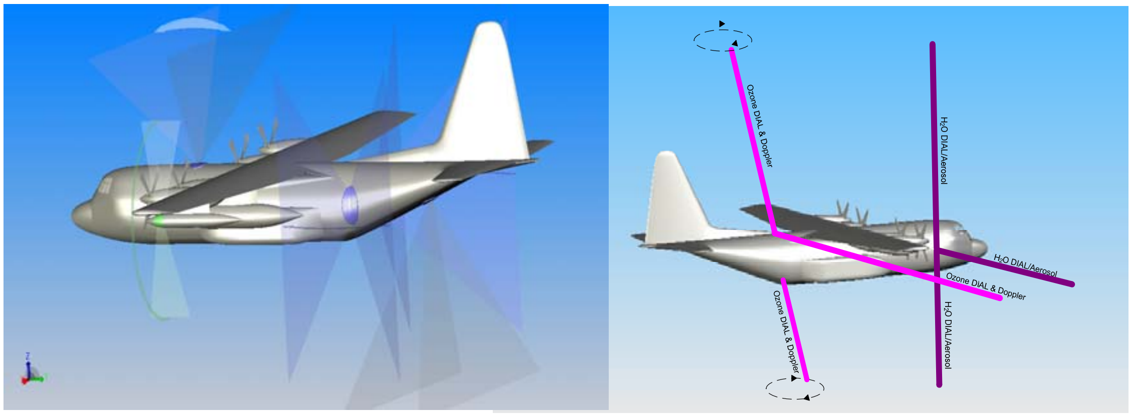

Figure 1: Left panel showing location of two of four AESAs (blue), plus beam envelopes (depicted as blue fans) of all four radars (one each port and starboard, one top, and one on the rear cargo door). The HIAPER Cloud Radar is depicted in green. Right panel showing possible lidar scanning beams on C130.

There are three possible options considered for CAPRIS based on physical constraints, performance and cost. These three options are:

- X-band dual-pol, alternating H,V transmit/receive
- C-band dual-pol, simultaneous H,V transmit/receive
- Wide-band (X,C) dual-pol, simultaneous H,V transmit/receive

All three options are based on custom designed monolithic microwave integrated circuit (MMIC) transmit/receive (T/R) modules. It should be noted that the wide-band AESA cannot operate simultaneously at X and C bands, but can operate at either wavelength. The user can switch between wavelengths (~1 minute) during a mission, but not pulse to pulse. A detailed comparison of these options is given in Loew, et. al. (2007). It takes over 10,000 T/R modules to populate each AESA, but together they replace the antenna, transmitter, pedestal and RF receiver of a conventional radar such as ELDORA. The associated benefit is that most of the heat associated with radar operation is dissipated outside the aircraft in the externally mounted array.

2.2 MILLIMETER (W AND KA-BAND) DUAL WAVELENGTH, DUAL POLARIZATION DOPPLER CLOUD RADAR

NCAR's EOL is currently developing a wing pod based 94 GHz (W-band) Doppler radar for HIAPER. We proposed to enhance the capability of this HIAPER cloud radar (HCR) via system upgrades to achieve dual-wavelength, dual-polarization capability. The addition of the second wavelength at Ka-band (35 GHz) transforms the HCR into an airborne radar with unique capabilities having the potential of using differential absorption between wavelengths to better estimate the liquid water content (LWC) and ice water content (IWC) of clouds. Figure 2 shows the HCR as configured for left wing operation on HIAPER.

The radar beam(s) can be rotated about the longitudinal axis of the pod with the use of a rotating reflector plate mounted in the front of the pod ahead of the wing. This allows the radar to look clockwise from zenith through nadir, and then nearly 90° until fuselage blockage occurs (see inset in Figure 2). Narrow sector scans (e.g. cross-track) could also be performed. Scan rates are limited to ~30 deg/sec to maintain velocity accuracy.

2.3 Water Vapor DIAL/Aerosol Lidar

The proposed water vapor DIAL/aerosol lidar will be designed for in-cabin operation in both HIAPER and the C130, using appropriate apertures for scanning as described above. It will also be capable of hemispherical scanning operations as a ground-based instrument. To operate in this diverse way, the water vapor DIAL must be eye-safe. We therefore propose to operate in the 1.4-1.5 micron eyesafe wavelength region. Figure 3 shows six water vapor absorption band heads, each of which contains hundreds of individual water vapor absorption lines. The blue horizontal lines in Figure 3 indicate optimal line strength for maximum DIAL performance in the lower troposphere and lower stratosphere, respectively. The red curve in Figure 3 shows the maximum permissible laser energy as a function of wavelength for the eye-safety. It is clear that the

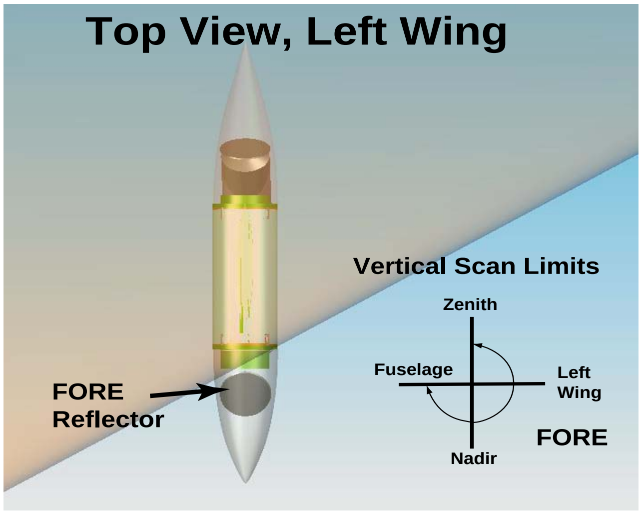

Figure 2: HIAPER Cloud Radar (HCR) Left Wing Position on NSF/NCAR GV aircraft.

1.4–1.5 micron region offers both superior eye-safety (more allowable transmit energy) and the strong water vapor absorption lines required for the DIAL technique.

Based on our knowledge of the present state of the art in optical receivers and transmitters operating in the 1.4–1.5 micron wavelength region, estimated water vapor DIAL performance is shown in Table 2. The range of the CAPRIS lidars is also compared with proven, existing systems (NASA LASE and DLR) operating at non-eye safe wavelengths.

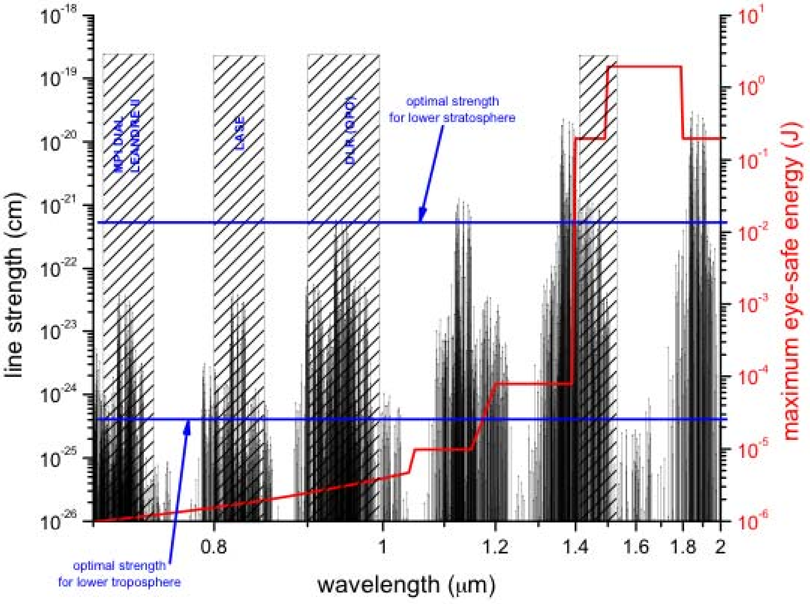

Figure 3: Water vapor absorption line strength and eye-safety as a function of wavelength between 700 nanometers and 2 microns.

Table 2: Estimated CAPRIS water vapor DIAL performance with the following assumptions: 25,000 ft. flight altitude, 300 m range resolution and 60 second averaging.

Instrument	Wavelength (nm)	Range, up-looking (km)	Range, down-looking (km)	Nominal Ocular Hazard Distance (km)	Horizontal pointing?
NASA LASE	815	2.6	6.9	7.7	No
DLR	840	3.7	4.6	2.4	No
CAPRIS (air)	1420	3.5	4.4	0.0 (eye-safe)	Yes
CAPRIS (ground)	1420	7.0	N/A	0.0 (eye-safe)	Yes

To our knowledge, a water vapor DIAL has not been constructed in the 1.4–1.5 micron region. This has been due primarily to the high cost of lasers with sufficient power, spectral purity, beam divergence, and frequency agility. Technologies that allow this new implementation in CAPRIS are: diode pumped solid state 1.064 micron Nd:YAG pump lasers and solid-state converter modules (second and/or third order nonlinear processes) to shift the wavelength to the desired 1.4–1.5 micron range. These technologies are well understood and exist, but the components must be combined in an improved instrument design for CAPRIS.

2.4 ULTRAVIOLET OZONE DIAL LIDAR

Unlike water vapor DIAL which can be used at several different band heads over a broad range of wavelengths in the near-IR, ozone DIAL operates exclusively in the ultra-violet at wavelengths between 240 nm and 300 nm. The proposed ozone DIAL will be designed for in-cabin operation in both the HIAPER and the C130, sharing apertures with the UV Doppler lidar. It will also be capable of hemispherical scanning operations as a ground-based instrument (see Section 6). Estimated performance is given in Table 3.

Table 3: Estimated CAPRIS Ozone DIAL Performance

Instrument	Wavelength (nm)	Range, up-looking (km)	Range, down-looking (km)	Nominal Ocular Hazard Distance (km)	Scanning
NASA	280 - 300	5.0	6.2	0.5	No
NOAA/SESI	280 - 300	4.2	5.2	0.0 (eye-safe)	No
CAPRIS	280 - 300	4.2	5.3	0.0 (eye-safe)	Yes

The ozone DIAL must be eye-safe to operate in this manner. We propose to operate the ozone DIAL in a high pulse repetition frequency mode to ensure eye safety. By transmitting at kilohertz pulse repetition rates, we can reduce the pulse energy below the approximately 6 mJ level required for eye-safety, and maintain sufficient average transmit power to measure ozone for at least 4 – 5 km range. The ozone DIAL technique is mature and practiced by several other lidar groups (e.g., NASA Langley, NOAA). We are proposing to build a compact high-rep rate system, similar to that being developed by the lidar group at NOAA; however with increased performance similar to the larger the NASA system.

2.5 ULTRAVIOLET MOLECULAR DOPPLER LIDAR (UT/LS DOPPLER WIND LIDAR)

All Doppler lidars fall into one of two broad categories: heterodyne (Coherent) and direct detection. We propose to construct a direct-detection Doppler lidar operating at a 355 nm wavelength (ultra-violet). Doppler lidar operation at this wavelength has been successfully demonstrated by several groups Gentry et al. (2000); Imaki and Kobayaski (2005). In fact, the technique is sufficiently mature that the European Space Agency is presently constructing a polar orbiting 355-nm Doppler lidar for global wind measurement (Stoffelen et al., 2005). NASA Goddard operates the GLOW (Goddard Lidar Observatory for Winds) system from a van (http://glow.gsfc.nasa.gov/). The distinct advantage of a direct-detection UV Doppler lidar is its ability to obtain backscatter in “clean” regions of the atmosphere exhibiting low aerosol (Mie) scattering. UV Doppler lidars measure the frequency shift of the molecular (Rayleigh) scattering. This lidar would operate in-cabin, using apertures for sensing on both the HIAPER and the C-130. It will also be capable of hemispherical scanning operations as a ground-based instrument These operational scenarios also necessitate eye-safe operation.

2.6 IR HETERODYNE DOPPLER LIDAR (BOUNDARY LAYER DOPPLER WIND LIDAR)

Resolving the turbulent wind perturbations responsible for boundary layer fluxes of heat, momentum and trace gases requires a Doppler lidar with high temporal and spatial resolution. This capability is best accomplished by using the heterodyne technique in the 1.5 to 2.0 micron wavelength region. The heterodyne Doppler lidar technique has been around for a long time and was first practiced at long wavelengths Post et al. (1981); Bilbro et al. (1984); Mayor et al.)1997). Long wavelength Doppler lidars were physically large and tended to be high maintenance due to the laser requirements. With the advent of solid-state lasers at shorter wavelengths, Doppler lidars became more compact and reliable. Grund et al. (2001) describe the NOAA High-Resolution Doppler Lidar that operates at 2.0-microns wavelength. This system was later reduced in size to fly in the main cabin of the DLR Falcon during IHOP. Ground-based heterodyne Doppler lidars are also commercially available. The CTI *Wind Tracer* is presently used to detect wind-shear at airports around the world, and at least two universities own *Wind Tracers* for micro-meteorological research.

2.7 CO2 LIDAR

Active remote sensing of CO_2 is presently an area of active focused research and development at a number of labs in the world institutions worldwide. Six papers addressed such work in progress at the July 2006 International Laser Radar Conference. To our knowledge, no group has yet succeeded in making a range-resolved measurement of CO_2 by lidar. In theory, the measurement should be achievable by the differential absorption lidar (DIAL) technique. Suitably strong CO_2 absorption lines exist in the 1.6 and 2.0 micron wavelength regions. What makes CO_2 more challenging to measure by DIAL than other trace gases such as ozone and water vapor is the very small amount of variation (1 ppm) that must be detected to be useful in a relatively high background (380 ppm) environment. The detection of these small variations is necessary for process studies of CO_2. This presents a formidable challenge with measurement technology now available.

The CAPRIS team met with individuals from the biogeosciences community at NCAR on 8 January 2007. The option of creating a lidar capable of measuring *column-content* instead of *range-resolved* CO_2 was presented and discussed. Their conclusion was that measurement of range-resolved CO_2 was critical to addressing key science questions related to budgets and transport mechanisms in the boundary layer and higher troposphere.

2.8 VEGETATION CANOPY LIDAR

Thirty percent of the Earth’s surface is land and much of it is covered by some form of vegetation. Knowledge of the 3-D vegetation structure provides much needed scientific insight into carbon dynamics studies at various scales; contribution of evapotranspiration to hydrologic budgets; effects of biomass on erosion and non-point-source pollution transport; wind speed effects of canopy aerodynamic roughness; habitat features associated with particular species including those that are rare, endangered or invasive; and identification of forest areas susceptible to large, especially damaging, fires. As data availability increases, it is anticipated that even more applications related to Earth science, land use management, and risk mitigation will emerge and/or directly benefit. Unfortunately, conventional sensors for mapping vegetation are limited in both sensitivity and accuracy, especially for dense canopies, and provide only 2-D data, i.e. no vertical structural information. However, medium to large footprint scanning lidar systems can rapidly map three-dimensional canopy structure over a large forested area that is important to understanding flux dynamics and carbon sequestration.

3. CAPRIS GROUND-BASED IMPLEMENTATION

This section describes how the CAPRIS radars and lidars can be reconfigured for use as easily transportable ground-based remote sensors. Simultaneous measurements of wind, ozone, water vapor and precipitation could be made over a full hemisphere using the scanning techniques described below.

3.1 MOBILE DUAL-POLARIZATION CENTIMETER RADAR

The ground-based centimeter wavelength radar concept is a combination of two AESAs into a single antenna, thereby halving the radar's horizontal beamwidth and increasing the radar's sensitivity by 6 dB over the values anticipated in the airborne configuration. This antenna will then be attached to a pedestal to achieve hemispherical coverage. Mobility will be enhanced by mounting the pedestal on a diesel powered truck. This configuration could be duplicated for the other two AESAs as well. This approach gives the research community two highly mobile, rapidly scanning, dual polarization Doppler radars. This concept would also make dual-Doppler measurements possible if both radars were used in concert.

3.2 PORTABLE MILLIMETER RADAR

The dual wavelength HCR also lends itself well to mobile ground-based operation. The concept is to house the radar in a "mini" 8-ft. sea container with an aperture cut in the roof to allow for scanning. The radar would be mounted vertically in the container utilizing the same "pallet-like" mounting structure used in the 20-in. G-V pod. A new radome/beam-steering unit would attach to the roof to allow full hemispherical scanning. The mini sea container could then be deployed on the back of a diesel powered truck for maximum mobility or transported to a stationary site for longer duration operations.

3.3 LIDARS ON A TRANSPORTABLE PLATFORM

All CAPRIS lidars are capable of hemispherical scanning on the ground without endangering the public. The concept is to use two standard 20-ft. sea containers as the platform. Each sea container will be fit with a beamsteering unit to enable hemispherical scanning. A similar beam steering unit is now operational in EOL. As with the airborne configuration, both the ozone DIAL and UV Doppler lidars will share the same aperture and hence the same container. The water vapor DIAL system will be housed in the other container. We recommend the DIAL ground-based configuration be enhanced by increasing the telescope size to 1m. This would allow water vapor measurements to be made with 300 m resolution over 7 km vertical range averaging for only one second. The lidars can be transported to the field site on an existing flatbed trailer. This lidar must remain in a single fixed location during a field deployment (i.e. they are not movable within the project domain) to assure maintenance of the precise optical alignment critical to high quality instrument performance. By contrast, airborne turbulence, which is generally much less severe in magnitude, does not pose the same problem.

3.4 POSSIBLE AUTONOMOUS OPERATIONS

The design goal of the ground-based CAPRIS instruments is to be able to operate them unattended for significant periods of time, to lower both deployment costs and staffing requirements. This entails significant up-front planning in the design of these instruments in the following areas: fault tolerance, self-monitoring, and command/status telemetry.

4. OVERALL PROJECT TECHNOLOGY READINESS ASSESSMENT

The CAPRIS development has some identifiable risks. They must be carefully considered along with reasonable mitigation measures. Proper utilization of this risk assessment will allow us to institute risk mitigation strategies in advance to help assure the success of the instrument development and long term operational stability of the sensor suite. We provide an evaluation of technological readiness using an established NASA evaluation tool. Additional risk factors related to implementation are also evaluated.

Table 4 shows the centimeter and millimeter radars and lidars under consideration for CAPRIS along with an assessment of technological readiness, a summary score and comments on their application in CAPRIS. The final instrument choices for the CAPRIS suite will be made based on this information, community input discussed in Section 11 and guidance from the NSF. We are showing all major modules that were considered and why they are or are not included in the final system configuration.

Technology Readiness Levels (TRL) are a systematic metric/measurement system that rates the maturity of a particular technology with a score from 1 to 9, with 9 being the most mature (Mankins, 1995). This tool was developed by NASA and considers basic research, focused technology development, technology demonstration, prototype fabrication and system integration and operations as a typical "maturation process" for an instrument or large facility. Even though the TRLs have been developed to measure component readiness for space flight, we believe this is a valuable metric to gauge development and implementation of CAPRIS instrumentation. The single number assigned in

Table 3 is our summarized instrument readiness using the NASA TRL guidelines and is our best estimate given all information on each instrument. We also comment on the readiness of a particular instrument for the CAPRIS application. Primary distinction is related to ground versus airborne implementation.

NASA TRL Categories:

1. Basic principles observed and reported
2. Technology concept and/or application formulated
3. Analytical and experimental critical function and/or characteristic proof-of concept
4. Component and/or breadboard validation in laboratory environment
5. Component and/or breadboard validation in relevant environment
6. System/subsystem model or prototype demonstration in a relevant environment (ground, airborne, or space)
7. System prototype demonstration in a space “ground or airborne” environment
8. Actual system completed and “flight qualified” through test and demonstration (ground, airborne or space)
9. Actual system “flight proven” through successful mission operations

Table 4: Instrument categories with technological readiness assessment, scores and other comments. Green covers TRL summary ratings of 8 or higher, yellow from 5-7, and red from 1-4.

Instrument Type	Technological Readiness Comments and Cost Considerations	TRL Score	Overall Readiness for CAPRIS Implementation
RADARS			
Centimeter Radar X-band dual-pol	MIT/LL has designed, built, and tested many of the integrated silicon-based MMIC devices and radiators required for the CAPRIS AESAs. Wide bandwidth, passive cooling, and ultra-low cross polarization dual-pol elements pose some challenges.	**6**	Ground implementation is tractable. Airborne implementation requires major development.
C-band dual-pol		**6**	
Wide-band (X/C) dual-pol		**4**	
Millimeter Cloud Radar Ka-band	Known technology, pod based application poses environmental and size challenges	**7**	HCR design includes required modifications to add this frequency. Not so easily adaptable to ground-based implementation.
W-band (for comparison purposes only, development is already underway)	Known technology, pod based application poses environmental challenges	**8**	Airborne application already under development for HCR.
LIDARS			
IR Heterodyne Doppler Lidar (BL wind lidar)	Mature, proven, commercially available technology at 2.0 microns wavelength and presently emerging at 1.5 microns.	**7**	Proposed 1.5 microns approach for advantages of size, weight, availability of components, and promise of future growth. However, proposal costs have large uncertainty and could be financially risky.
Water Vapor DIAL	Airborne water vapor DIAL has previously been demonstrated—but not in the eye-safe wavelength region of 1450 nm.	**7**	Strive for 1450 nm wavelength water vapor DIAL, but have fall back to non-eye-safe 940 nm lasers if 1450 nm laser challenges can’t be overcome.
Ozone DIAL	Airborne ozone DIAL has previously been built using mature bulk laser technology (i.e. NASA LLAG). We wish to use a state-of-the-art all-solid-state laser and newly available wavelength converter technology to reduce size and weight. We also strive for higher pulse energy for better performance.	**6**	Some concern that suitable high pulse repetition pump lasers for these frequency converters are still in developmental stages. These introduce some risk, but there a fall back position with lower energy, and performance. (e.g., similar to NOAA’s new airborne ozone DIAL).
UV Molecular Doppler Lidar (UT/LS wind lidar)	Main risks associated with receiver frequency shift detection in airborne environment	**6**	Proposed systems may not meet random error measurement requirement during flight.
Vegetation Canopy Lidar	Demonstrated technology. Most risk associated with making it unattended from wing-pod. Also, highly desirable to operate in eye-safe 1.5 micron wavelength region.	**6**	Low risk and highly attractive proposal in hand for 1.5 micron system, but cost is quite high. Eye safety is a key goal for the VCL design
Carbon Dioxide DIAL	Not yet demonstrated. Too risky and costly to take on for CAPRIS.	**3**	Not recommended for CAPRIS since technology is unable to achieve range resolved measurements with required precision

The centimeter and millimeter radar options have been described in Section 2. The decision of which centimeter radar configurations should be considered is based on both technological and scientific considerations. All three options share a similar level of technical readiness.

Airborne AESA technology has reached a mature status (Hommel and Feldle, 2004) – at least for military applications. AESA radars are in service in the F15C and are currently being installed in the nose cones of the F35, F22 and F18/18a fighter aircraft, as well as European tactical aircraft. MIT/LL also has an operational X-band AESA which it deploys on a Boeing 707 for research purposes. The biggest challenge for the CAPRIS application is the ability to adequately remove heat from the elements of the array without resorting to active cooling measures. The ability to effectively remove heat is critical if we are to produce the transmit power necessary for our application. Therefore, we have been conservative in estimating the power handling capabilities of each element. Another challenge is obtaining sufficient bandwidth from the T/R and radiating elements to allow operation over both C and X frequency bands, as is required for the Wide-band (X/C) dual-pol radar. It is for this reason that it is rated at TRL 4 rather than 6.

The W-band millimeter radar is already under development as the principle frequency used in the HCR. As discussed previously, the addition of the Ka-band frequency and the dual polarization capability is a logical step with no major new development required.

Ground based dual wavelength Ka/W-band radars have been successfully built by the University of Massachusetts (Sekelsky and McIntosh (1996); Majurec et al. (2004). An airborne system has also been developed by ProSensing, Inc. in Amherst, MA. Millimeter wave technology is now routinely available for research applications. The major technical challenges facing the HCR are the dual wavelength feed horn/antenna and attempting to achieve greater sensitivity through the use of pulse compression. Several dual wavelength antennas (Ka/W-band) have been developed by the University of Massachusetts, but there is some risk in achieving the desired range sidelobe suppression and cross-pol isolation. Although pulse compression has been used extensively in military radars and some weather radars, to our knowledge it has not been proven using the extended interaction klystron (EIK) transmitters available at millimeter wave frequencies. The fallback position would be to forego pulse compression and accept a loss in sensitivity.

The group of proposed lidar instruments is made of six systems that are described in Section 2. The technical readiness shown in Table 4 represents a combination of community expertise/experience with the systems augmented from information contained within the Phase I proposals received from industry. TRL values consider the demonstrated expertise of the industry partners that submitted proposals. It is noted that the disciplinary communities (e.g. air chemistry, biogeosciences, boundary layer meteorology) naturally have different priorities of which lidars are required to answer key science questions of interest to them. There are some common threads across several disciplines regarding lidar measurements of interest.

The IR heterodyne Doppler lidar, the water vapor and ozone DIAL lidars, the UT/LS wind lidar, and the vegetation canopy are all at a similar levels of development and deployment readiness with TRL scores of 6-7. These lidars require similar amounts of instrument development and implementation before the systems can be deployed as reliable observation tools. It is notable that meeting one of the high-priority technology requirements of CAPRIS has proven to be a challenge for some of these systems. It was important to the CDT that the lidars all operate in the eye-safe region of the electromagnetic spectrum, if at all possible

EOL issued Request For Proposals (RFP)s to develop and build the lidars and is awaiting industry proposals. The evaluation of the preliminary proposals received in response to the RFPs, community and EOL experience, and priorities suggest that the water vapor DIAL lidar offers a high probability of success. There is a clear message from the several disciplines (e.g. meteorology, atmospheric chemistry, biogeosciences) in the science community that a high resolution measurement of water vapor in the troposphere and lower stratosphere is important. There are several water vapor DIAL systems that our now operational but they are not eye-safe. There is a clear path to develop an eye-safe water vapor DIAL system.

Development of a CO_2 DIAL system that will be reliable and meet CAPRIS measurement requirements is a major challenge at this time. In particular, there will be a significant and costly development effort to make range resolved measurements of CO_2. This challenge is compounded by the need to measure variations in CO_2 concentrations of 1 ppm in a background concentration of about 380 ppm. NASA does operate a CO_2 lidar that can measure a total integrated path. Most of community comments received during the last six months have emphasized the need for range resolved measurements.

4.1 OTHER RISK FACTORS

In addition to the technical readiness of the CAPRIS instruments, we also believe it is important to assess related risk factors for meeting the overall scientific needs of CAPRIS as described in several previous sections. We have attempted to gauge the overall impact of operations and maintenance (O&M) as a risk factor for these instruments. This takes into account personnel resources, spare parts requirements and cost as well as reliability of components or sub-components to the extent they are known. With the one exception for the millimeter radar, O&M costs for these systems are non-trivial and must be considered in their long term support.

In general, the MM radar has the lowest overall risk to implement considering related factors of airborne and ground based implementation, overall scientific and technical requirements and O&M costs. The CM radar presents moderate risk in most other areas that were considered. The implementation of advanced AESA technology for weather radar application will be challenging. The development and integration of multiple exciters and receivers to four independent antennas will also present moderate challenges. The five lidars have varying degrees of risk in the CAPRIS application, typically dependent on the ability of the technology to meet the eye-safe criteria and instrument stability in vibration rich environments.

5. SOFTWARE DEVELOPMENT AND DATA MANAGEMENT

NCAR/EOL will maintain the CAPRIS instruments over their ten-year expected life. To ensure that NCAR/EOL can maintain the software and high quality datasets for the long-term, NCAR/EOL will enforce some common requirements on all CAPRIS instruments.

5.1 SOFTWARE REQUIREMENTS

CAPRIS instrument software should be written in C++/C, JAVA or Labview. By limiting the language choices for CAPRIS software, NCAR/EOL staff can more easily maintain multiple systems. The computers provided with instruments or embedded in instruments should use Linux or RTLinux, with Windows as a less desirable alternative. Requiring common operating systems among instruments will also reduce engineering staff support requirements. CAPRIS instrument vendors need to provide data using common data format, since this will enable common display and analysis tools. Data files will be written using netCDF3 or HDF5 using a format that NCAR/EOL will provide. NCAR/EOL will provide a description of the netCDF “convention” for lidar data along with a sample program that writes data in that format. NCAR/EOL will provide a web page that documents the netCDF convention and contains links to associated software.

5.2 DATA MANAGEMENT SUPPORT

EOL emphasizes the collection of high-quality data and supports rapid data dissemination to the user community. EOL has a well-established record of field project data support, including quality assurance, metadata creation, archival, and distribution. Data management and quality assurance from the new CAPRIS sensors will be integrated into the already existing EOL data management framework. The framework is flexible and will allow necessary modifications to support the high volume of CAPRIS data, and to adjust for unexpected issues associated with this cutting-edge sensor array.

CAPRIS will add a significant amount of data to the EOL archive. EOL currently supports several platforms with high data rates: S-PolKa produces .8 to 1.2 GB/hour for field projects of ~1000 hours; ELDORA produces 1.0 to 2.0 GB/hour for field projects of ~100 hours; and satellite data ingest produces 12 GB/day, 365 days per year. Without considering timeseries data, CAPRIS has the potential to add 50% to 100% to the yearly increase in the EOL archive (assumes ~300 hours of flight data collection per component).

6. EDUCATION AND TRAINING OPPORTUNITIES

The CAPRIS project will offer some remarkable opportunities for young scientists and engineers to participate in instrument development as well as the subsequent system deployment on aircraft or the ground to answer important scientific questions. NCAR, including EOL, offer several programs that CAPRIS will take advantage of to entrain students, scientists and engineers into this activity. This includes the Significant Opportunity in Atmospheric Research and Science (SOARS) Program, the EOL Summer Engineering Internships, Advanced Studies Program Graduate Fellowships and Post-Doctorate Fellows, and the EOL Field Campaign Student Assistants effort. We will take advantage of these programs to bring on interested interns, advanced students and young Ph.Ds well matched to the challenges offered by CAPRIS. These avenues have proven effective to entrain and educate the next generation observational scientists. Projects of benefit to CAPRIS could include software engineering tasks, component design, data management and later on, field deployment support and scientific data analysis. We hope that longer term collaborations can be developed through the visiting scientists and engineers programs that have worked very well for EOL and the partnering institution. This will include support in the area of data analysis and data quality from the new measurements we anticipate to come from the CAPRIS suite.

7. COMMUNITY OUTREACH

It became apparent to us that the community is very interested in the potential of the suite of CAPRIS sensors to make valuable contributions in several disciplinary areas. Over the last 12 months the

CAPRIS has engaged a variety of national and international institutions to provide advice, criticism and options for the proposed development of CAPRIS. There have been more than a dozen gatherings to receive questions and comment on CAPRIS. We estimate that the number of non-EOL participants in these meetings exceeded 220.

8. FUTURE WORK

The CAPRIS Project has reached a critical point in its design preparations. A formal white paper has been written that describes the complete development and implementation strategy for CAPRIS including budgets, project management, and development timelines. The document is now ready for submission to the U.S. National Science Foundation. We are hopeful this will result in approval to develop one or more of the radar and lidar components described herein. The project is also working toward strategic partnerships with institutions and private companies to respond effectively to an approval for development and instrument construction to begin. We would anticipate updating the community on our progress and continuing to engage all interested parties in discussions for improving the instruments capabilities to address community needs.

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