RESEARCH & RELATED PERSONAL DATA
Project Director/Principal Investigator and Co-Project Director(s)/Co-Principal Investigator(s)

The Federal Government has a continuing commitment to monitor the operation of its review and award processes to identify and address any inequities based on gender, race, ethnicity, or disability of its proposed PDs/PIs and co-PDs/PIs. To gather information needed for this important task, the applicant should submit the requested information for each identified PD/PI and co-PDs/PIs with each proposal. Submission of the requested information is voluntary and is not a precondition of award. However, information not submitted will seriously undermine the statistical validity, and therefore the usefulness, of information received from others. Any individual not wishing to submit some or all the information should check the box provided for this purpose. Upon receipt of the application, this form will be separated from the application. This form will not be duplicated, and it will not be a part of the review process. Data will be confidential.

Project Director/Principal Investigator

Prefix:	* First Name:	Middle Name:	* Last Name:	Suffix:
	Harindra	J.	Fernando	

Gender: Male

Race (check all that apply):
- ❍ American Indian or Alaska Native
- ● Asian
- ❍ Black or African American
- ❍ Native Hawaiian or Other Pacific Islander
- ❍ White
- ❍ Do Not Wish to Provide

Ethnicity:
Not Hispanic or Latino

Disability Status (check all that apply):
- ❍ Hearing
- ❍ Visual
- ❍ Mobility/Orthopedic Impairment
- ❍ Other
- ❍ None
- ● Do Not Wish to Provide

Citizenship:
Permanent Resident

RESEARCH & RELATED PERSONAL DATA
Project Director/Principal Investigator and Co-Project Director(s)/Co-Principal Investigator(s)

The Federal Government has a continuing commitment to monitor the operation of its review and award processes to identify and address any inequities based on gender, race, ethnicity, or disability of its proposed PDs/PIs and co-PDs/PIs. To gather information needed for this important task, the applicant should submit the requested information for each identified PD/PI and co-PDs/PIs with each proposal. Submission of the requested information is voluntary and is not a precondition of award. However, information not submitted will seriously undermine the statistical validity, and therefore the usefulness, of information received from others. Any individual not wishing to submit some or all the information should check the box provided for this purpose. Upon receipt of the application, this form will be separated from the application. This form will not be duplicated, and it will not be a part of the review process. Data will be confidential.

Co-Project Director/co-Principal Investigator 1

Prefix:	*** First Name:**	**Middle Name:**	*** Last Name:**	**Suffix:**
	Raghavendra		Krishnamurthy	

Gender: Male

Race (check all that apply):
- ❍ American Indian or Alaska Native
- ❍ Asian
- ❍ Black or African American
- ❍ Native Hawaiian or Other Pacific Islander
- ❍ White
- ● Do Not Wish to Provide

Ethnicity:
Do Not Wish To Provide

Disability Status (check all that apply):
- ❍ Hearing
- ❍ Visual
- ❍ Mobility/Orthopedic Impairment
- ❍ Other
- ❍ None
- ● Do Not Wish to Provide

Citizenship:
Do Not Wish to Provide

APPLICATION FOR FEDERAL ASSISTANCE
SF 424 R&R

3. DATE RECEIVED BY STATE

State Application Identifier

1. TYPE OF SUBMISSION

❍Pre-application ●Application ❍Changed/Corrected Application

4. a. Federal Identifier N00014

b. Agency Routing Identifier 322 [Eleuterio, Daniel]

c. Previous Grants.gov Tracking ID

2. DATE SUBMITTED
07/02/2018

Applicant Identifier

5. APPLICANT INFORMATION **Organizational DUNS:** 824910376

Legal Name: University of Notre Dame

Department: Division:

Street1: 940 Grace Hall Street2:

City: Notre Dame County/Parish: St. Joseph State: IN: Indiana

Province: Country: USA: UNITED STATES ZIP / Postal Code: 46556-5708

Person to be contacted on matters involving this application

Prefix: First Name: Mark Middle Name: W. Last Name: DeVore Suffix:

Position/Title: Pre-Award Program Manager

Street1: 926 Grace Hall Street2:

City: Notre Dame County/Parish: St. Joseph State: IN: Indiana

Province: Country: USA: UNITED STATES ZIP / Postal Code: 46556-5612

Phone Number: 5746317973 Fax Number: Email: devore.1@nd.edu

6. EMPLOYER IDENTIFICATION NUMBER_(EIN) or (TIN)_: 350868188

7. TYPE OF APPLICANT: O: Private Institution of Higher Education

Other (Specify):

Small Business Organization Type ❍Women Owned ❍Socially and Economically Disadvantaged

8. TYPE OF APPLICATION:

●New ❍Resubmission

❍Renewal ❍Continuation ❍Revision

If Revision, mark appropriate box(es).

❍A. Increase Award ❍B. Decrease Award ❍C. Increase Duration

❍D. Decrease Duration ❍E. Other_(specify)_:

Is this application being submitted to other agencies?❍ Yes ● No What other Agencies?

9. NAME OF FEDERAL AGENCY:
Office of Naval Research

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER:
12.300
TITLE: Basic and Applied Scientific Research

11. DESCRIPTIVE TITLE OF APPLICANT'S PROJECT:
A Scanning FMCW W-Band Radar for Cloud and Fog Research

12. PROPOSED PROJECT:

Start Date	Ending Date
06/15/2019	06/14/2020

13. CONGRESSIONAL DISTRICT OF THE APPLICANT:
IN-002

14. PROJECT DIRECTOR/PRINCIPAL INVESTIGATOR CONTACT INFORMATION

Prefix: First Name: Harindra Middle Name: J. Last Name: Fernando Suffix:
Position/Title: Professor, Civil & Env Engr & Earth Sci
Organization Name: University of Notre Dame
Department: Civil & Env Engr & Earth Sci
Division: College of Engineering
Street1: 311-D Cushing
Street2:
City: Notre Dame
County/Parish: St. Joseph
State: IN: Indiana
Province:
Country: USA: UNITED STATES
ZIP / Postal Code: 465565612
Phone Number: 5746319346
Fax Number:
Email: fernando.10@nd.edu

15. ESTIMATED PROJECT FUNDING

a. Total Federal Funds Requested	$480,445.00
b. Total Non-Federal Funds	$0.00
c. Total Federal & Non-Federal Funds	$480,445.00
d. Estimated Program Income	$0.00

16. IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCESS?

a. YES ❍ THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON:

DATE:

b. NO ● PROGRAM IS NOT COVERED BY E.O. 12372; OR

❍ PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. By signing this application, I certify (1) to the statements contained in the list of certifications* and (2) that the statements herein are true, complete and accurate to the best of my knowledge. I also provide the required assurances * and agree to comply with any resulting terms if I accept an award. I am aware that any false, fictitious, or fraudulent statements or claims may subject me to criminal, civil, or administrative penalties. (U.S. Code, Title 18, Section 1001)

● I agree

The list of certifications and assurances, or an Internet site where you may obtain this list, is contained in the announcement or agency specific instructions.

18. SFLLL or other Explanatory Documentation. File Name: Representation_for_Tax_Delinquency_Criminal_Violation_and_Internal_Confidentiality_Agreements1015555596.pdf Mime Type: application/pdf

19. Authorized Representative

Prefix: First Name: David Middle Name: Last Name: Ross Suffix:
Position/Title: Senior Director, Pre-Award Administration
Organization Name: University of Notre Dame
Department: Notre Dame Research
Division: Office of the VP for Research
Street1: 940 Grace Hall
Street2:
City: Notre Dame
County/Parish: St. Joseph
State: IN: Indiana
Province:
Country: USA: UNITED STATES
ZIP / Postal Code: 46556-5708
Phone Number: 574-631-7432
Fax Number:
Email: dross5@nd.edu

Signature of Authorized Representative	**Date Signed**
David Ross	07/02/2018

20. Pre-application File Name: Mime Type:

21. Cover Letter Attachment File Name: Mime Type:

Proposal Title A Scanning FMCW W-Band Radar for Cloud and Fog Research

Proposal Number and/or Date 18-1258 7/6/2018

Representation Regarding an Unpaid Delinquent Tax Liability or a Felony Conviction under Any Federal Law – DoD Appropriations

(1) The applicant represents that it is ☐ is not ☑ a corporation that has any unpaid Federal tax liability that has been assessed, for which all judicial and administrative remedies have been exhausted or have lapsed, and that is not being paid in timely manner pursuant to an agreement with the authority responsible for collecting the tax liability.

(2) The applicant represents that it is ☐ is not ☑ a corporation that was convicted of a felony criminal violation under any Federal law within the preceding 24 months.

NOTE: If an applicant responds in the affirmative to either of the above representations, the applicant is ineligible to receive an award unless a Federal agency suspension and debarment official (SDO) has considered suspension or debarment and determined that further action is not required to protect the Government's interests. The applicant therefore should provide information about its tax liability or conviction to the agency's SDO as soon as it can do so, to facilitate completion of the required consideration before award decisions are made.

OMB Control Number: 0704-0494
OMB Expiration Date: 11/30/2019

AGENCY DISCLOSURE NOTICE

The public reporting burden for this collection of information is estimated to average 5 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewed the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Washington Headquarters Services, Executive Services Directorate, Directives Divisions, 4800 Mark Center Drive, East Tower, Suites 02G09, Alexandria, VA 22350-3100 [0704-0494]. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

Representation Regarding the Prohibition on Using Funds under Grants and Cooperative Agreements with Entities that Require Certain Internal Confidentiality Agreements

By submission of its proposal or application, the applicant represents that it does not require any of its employees, contractors, or subrecipients seeking to report fraud, waste, or abuse to sign or comply with internal confidentiality agreements or statements prohibiting or otherwise restricting those employees, contractors, or subrecipients from lawfully reporting that waste, fraud, or abuse to a designated investigative or law enforcement representative of a Federal department or agency authorized to receive such information. Note that, as applicable, the bases for this representation are the prohibition(s) as follow:

a. Section 743 of the Financial Services and General Government Appropriation Act, 2015 (Division E of the Consolidated and Further Continuing Appropriations Act, 2015, Pub. L. 113-235)
b. Section 101(a) of the Continuing Appropriation Act, 2016 (Pub. L. 114-53) and any subsequent FY2016 appropriations act that extends to FY2016 the same restrictions as are contained in section 743 of Division E, title VII of the Consolidated and Further Continuing Appropriations Act, 2015 (Pub L. 113-235)
c. Pub. L. 114-223, Continuing Appropriations Act, 2017, or any other Act that extends to fiscal year 2017 funds the same prohibitions as contained in section 743, Division E, title VII, of the Consolidated Appropriations Act, 2016 (Pub. L. 114-113).
d. Any successor provision of law on making funds available through grants and cooperative agreements to entities with certain internal confidentiality agreements or statements

The prohibitions stated above do not contravene requirements applicable to Standard Form 312, Form 4414, or any other form issued by a Federal department or agency governing the nondisclosure of classified information.

Project/Performance Site Location(s)

Project/Performance Site Primary Location

Organization Name: University of Notre Dame		
* Street1: 940 Grace Hall		Street2: N/A
* City: Notre Dame	County: St. Joseph	* State: IN: Indiana
Province:	* Country: USA: UNITED STATES	* Zip / Postal Code: 46556-5612
DUNS Number: 824910376	* Project/Performance Site Congressional District: IN-002	

File Name	Mime Type

Additional Location(s)

RESEARCH & RELATED Other Project Information

1. * Are Human Subjects Involved? ❍ Yes ● No

1.a. If YES to Human Subjects

Is the Project Exempt from Federal regulations? ❍ Yes ❍ No

If yes, check appropriate exemption number

Exemption Number: _ 1 _ 2 _ 3 _ 4 _ 5 _ 6 _ 7 _ 8

If no, is the IRB review Pending? ❍ Yes ❍ No

IRB Approval Date:

Human Subject Assurance Number

2. * Are Vertebrate Animals Used? ❍ Yes ● No

2.a. If YES to Vertebrate Animals

Is the IACUC review Pending? ❍ Yes ❍ No

IACUC Approval Date:

Animal Welfare Assurance Number

3. * Is proprietary/privileged information included in the application? ❍ Yes ● No

4.a.* Does the Project have an Actual or Perceived Impact – positive or negative – on the environment? ❍ Yes ● No

4.b. If yes, please explain:

4.c. If this project has an actual or potential impact on the environment, has an exemption been authorized or an environmental assessment (EA) or environmental impact statement (EIS) been performed? ❍ Yes ❍ No

4.d. If yes, please explain:

5.a.* Is the research performance site designated, or eligible to be designated, as a historic place? ❍ Yes ● No

5.b. If yes, please explain:

6.a.* Does this project involve activities outside the U.S. or partnership with International Collaborators? ● Yes ❍ No

6.b. If yes, identify countries: Bay of Bengal

6.c. Optional Explanation:

7. Project Summary/Abstract	Abstract1015555594.pdf	Mime Type: application/pdf
8. Project Narrative	Project_Narrative1015555607.pdf	Mime Type: application/pdf
9. Bibliography & References Cited	Bibliography1015555608.pdf	Mime Type: application/pdf
10. Facilities & Other Resources		
11. Equipment		

Publicly Releasable

Abstract:

This proposal seeks DURIP funding to acquire a Frequency Modulated Continuous Wave (FMCW) W-band radar for research involving atmospheric water droplets (hydrometeors; e.g., fog, clouds and rain). Hydrometeors cover a range of sizes, and radars operating at different frequency bands are used for their observations. For instance, Ka (~35 GHz) and W (~94 GHz) band radars operating at millimeter-wavelength are employed to observe cloud microphysical processes, measure the velocity structure, estimate rain rates, obtain distribution of small cloud particles from non-precipitating or weakly precipitating clouds, and retrieve information on in-cloud turbulence. Where higher sensitivity is needed and the size and weight of the instrument are not a factor, Ka band radars that require larger antennas are used. Where instrument compactness and weight are a limiting factor, such as deployment on a research vessel with the radar resting on a motion compensated platform, W-band is the radar of choice for hydrometeor research. Recent advent of a new generation of user-friendly commercial FMCW W-band radars has enabled researchers and observatories to engage in hygrometric research without facing onerous infrastructure and maintenance challenges. The radar requested in this proposal, the FMCW W-band cloud Doppler radar (model RPG-FMCW-94-DP-G1/S) manufactured by Radiometer Physics GmbH (RPG), is of this type. It is a dual polarization, single frequency turnkey system provided with an elevation/azimuth scanner designed for cloud and fog research. These radars measure small water droplets of millimeter and submillimeter scales ($\geq 10\ \mu m$) enabling retrieval of useful quantities such as reflectivity, mean radial velocity, spectrum width, skewness and kurtosis for characterization of atmospheric water droplets. Its compactness, low power (several Watts), agility, and high space-time resolution (~ 1m spatial and integration times of seconds) allow characterization of small cloud drops and ice particles, fog, liquid and solid precipitation, and even non-meteorological scatterers such as insects and pollen. This off-the-shelf instrument comes with a comprehensive, adaptive software interface. The versatility of the instrument can be significantly enhanced by operating it alongside other available instruments to the PI such as Doppler lidars and microwave radiometers. It is the pioneering commercial W-band radar of its kind, extensively field tested, and currently used by several European observatories. It will greatly add to the atmospheric instrumentation capabilities of University of Notre Dame, thus enhancing PIs ability to characterize fog and clouds in two Office of Naval Research funded large international projects and in other existing and future federally funded projects. Close collaboration with Department of Defense (DOD) and non-DOD laboratories and universities is a hallmark of the PIs projects, and thus a wider scientific constituency will benefit from the acquisition of proposed instrument.

Project Narrative

A Scanning FMCW W-Band Radar for Cloud and Fog Research

1. Introduction

Atmospheric water appears in various forms, as clouds, fog, mist, ice crystals and rain droplets (Stevens and Bony 2013), and it plays a major role in Earth's hydrological cycle and radiation budget (Boucher et al. 2013) on multiple scales. Thus, it is important to characterize atmospheric water with high accuracy and spatial resolution. Reliable and robust ground-based Doppler radars and radiometers are key instruments for detailed observations of atmospheric hygrometric processes, long-term data collection, and model and satellite evaluations. Atmospheric water droplets (hydrometeors) cover a range of space scales, and thus radars operating in different frequency bands are used for different size ranges. For example, Ka (35 GHz) and W (94 GHz) band radars operating at millimeter-wavelength have been conventionally used for observing cloud microphysical processes (e.g., Kollias et al. 2007a; Kneifel et al. 2011; Acquistapace et al. 2017; Tridon and Battaglia 2015), to estimate rain rates (Maahn et al. 2015), to measure the velocity structure and distribution of small cloud particles from non-precipitating and weakly precipitating (drizzle) clouds (Frisch et al. 1995; Vali et al. 1998) or to obtain information on in-cloud turbulence (e.g., Kollias et al. 2002; Borque et al. 2016). For sensitivity needed for land-based cloud observing sites, where radar's size and weight are not a factor, Ka-band radars with large antenna diameters (2–4m) and integration times of several seconds are typically used (Ackerman and Stokes 2003). On the other hand, for mobile platforms such as ships and aircraft, the requirements for carefully engineered miniaturization as well as motion-compensation place a stringent demand on the size and weight of the radar (Pazmany et al. 1994; Li et al. 2004). The smaller size and weight of W-band cloud radars make them better suited for shipboard as well as aircraft deployments. The wavelength (λ) dependence (λ^{-4}) of the radar cross-section offers a factor of 50 advantage in sensitivity to a W-band radar over a similar Ka-band design (Moran et al. 2012). This has been capitalized in designing W-band radars for mobile-platform applications without sacrificing the sensitivity of the radar. Smaller antennae at the W-band with less weight make the task of beam steering more manageable. For mobile platforms, short dwell times are often used (<1 s) to reduce the effects of platform motion, the influence of which is further reduced customarily by using motion stabilized platforms. Accelerometers on stabilizing platforms monitor the platform motion and stabilize the instrument against the pitch, yaw and possibly heave of ship platforms.

Since the pioneering studies of Lhermitte (1987, 1988, 1990), high frequency radars operating at W-band have become an instrument of choice for studying thin liquid or ice clouds, fog and their microphysical processes. The disadvantage of using high frequencies is increasing signal attenuation as a result of dry gases, water vapor, and frozen and liquid hydrometeors. As such, the W-band radars have been mostly used for research applications, and thus are custom produced, requiring specialized maintenance. Combining Ka-band and W-band radars, the community of cloud researchers are starting to use radar clusters with two wavelengths, providing greater insights on cloud microphysics (Sekelsky and McIntosh 1996; Sekelsky et al. 1999; Kollias et al. 2007a),

Radars can be combined with remote sensors to enhance the sensitivity and accuracy of the derived cloud properties. Frisch et al. (1998) used microwave radiometer (MWR) and radar data to retrieve the liquid water content (LWC) profile of a cloud. The vertically integrated amount of liquid water and liquid water path (LWP) were constrained by the MWR, and the range-resolved radar signal was used to reconstruct the vertical distribution of liquid water. Illingworth et al.

(2007) exploited the synergy of collocated radar, microwave radiometer, and lidar observations to further refine the retrieval of cloud properties, such as the hydrometeor phase, type, and position in the vertical column (Küchler et. al., 2017).

Currently, the majority of cloud radars, especially those used at comprehensive observatories, are pulsed systems (e.g., Löhnert et al. 2015; Kollias et al. 2007b; Haeffelin et al. 2005). Illingworth et al. (2015) pointed out that Frequency Modulated Continuous Wave (FMCW) radars are a more economical solution, opening avenues for a larger number of observatories to conduct comprehensive hydrometeor studies. FMCW radar requires two antennas, however, which could increase system costs, especially when considering low-frequency radars where larger antenna diameters are required (Heijnen et al. 2000). Another disadvantage of FMCW technology is that it requires a large bandwidth at great distance to sustain vertical and temporal resolution, which increases the background noise. Notwithstanding, several studies have shown that FMCW W-band radars are suitable for ground-based (Yamaguchi et al. 2009; Huggard et al. 2008; Bennett et al. 2009; Thies et al. 2010; Delanoë et al. 2016), ship-based, and airborne fog and cloud studies (Pazmany et al. 1994; Mead et al. 2003). FMCW radars allow greater flexibility of varying vertical resolution on the order of 5 m or finer. Such enhanced resolutions are beneficial for evaluating high-resolution model simulations such as large-eddy simulations LES (e.g., van der Dussen et al. 2013) or for investigating processes with strong vertical gradients (e.g., melting layer, fog). The increased time on target, because of continuous transmission, provides similar average output powers as pulsed systems and leads to comparable sensitivities. In general, FMCW systems are cheaper to build in view of simpler electronic design and lack of high-voltage components (Ligthart and Nieuwkerk 1980), which further leads to better long-term stability and easier calibration. The smaller instrument dimensions and lower transmitter power facilitate their installation in diverse environments.

In 2016, Radiometer Physics GmbH (RPG) of Meckenheim, Germany unveiled an innovative and cost-effective FMCW W-band cloud radar for the detection and analysis of scatterers of any type above 10µm in size (Figure 1a,b). Since its introduction, RPG FMCW W-band radars have been tested and used for research (Küchler et. al., 2017), and several radars are already purchased by observatories. According to RPG, the attributes of this new generation of radars are:

(i) Higher sensitivity with a smaller form factor than X and Ka-band radars.
(ii) Observation capabilities of small cloud drops and ice particles, fog, liquid and solid precipitation, and even non-meteorological scatterers such as insects and pollen of size above 10 μm. Scanning units (optional) can sweep both in azimuth and elevation for three-dimensional fog, cloud and precipitation observations.
(iii) Small size and low weight make them suitable for airborne and shipborne measurement platforms (with suitable motion compensation).
(iv) Unlike traditional pulsed radars, FMCW radars do not require a concentrated high power (~ 1 kW peak) transmission. Instead, the power is emitted continuously, but with linearly varying frequency, thus requiring only a few Watts. No high power magnetron tubes and high voltage power supplies are required, reducing the overall radar power consumption.
(v) Calibration of FMCW radars is more accurate compared to pulsed radars, because the transmitter power can be determined more accurately.
(vi) High flexibility of range/Doppler resolution variation along the ranging path

(vii) It can measure atmospheric profiles with the spatial resolution down to 1 m, which is often not accessible with pulsed cloud radars.

(viii) Minimum observable range of 50 m and very high range resolution enables detailed observations of boundary layer and fog.

(ix) Transmitter can be realized in solid state technology, leading to long lifetime and low cost

(x) 100% integration duty cycle

(xi) A sophisticated data level concept to ensure compatibility with satellite radiometers. Detailed housekeeping of data, and sanity/quality flags are provided.

(xii) Delivery with a complete set of accessories to operate it in an outdoor environment and to perform regular instrument calibrations. This includes a stand with rain mitigation system, radome blowers and air heater modules, power and data cables, a signal converter, an external calibration target and target frame, a weather station plus GPS receiver, a complete software package for the radar PC (R-PC) and external host PC (H-PC) and several tools to assemble the system. An elevation/azimuth scanner can be added for zenith observations.

(xiii) High sensitivity to tiny particles (-60 dBZe at 500 m with 5 m resolution and 3 s time sampling rate). Distinct linear dependence of signal attenuation on liquid water content provides a good reference for validation of fog predicting models and radar-based estimates of visibility.

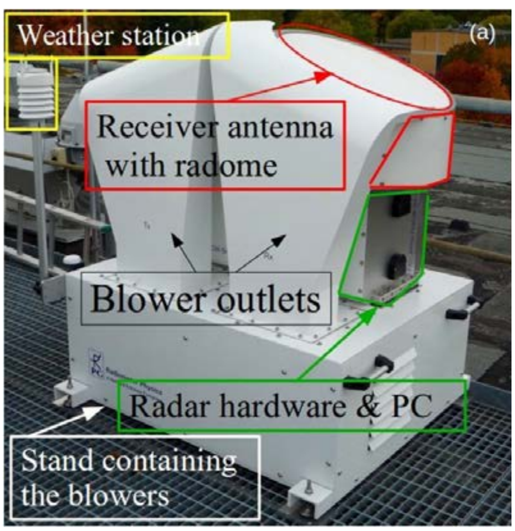

Figure 1a: A W-band radar system for accurate and continuous monitoring of clouds and precipitation (courtesy: RPG)

Figure 1b: The RPG W-band cloud radar with the base scanning unit (courtesy: RPG)

This proposal seeks funding to acquire a RPG FMCW W-band Cloud Doppler Radar (model: RPG-FMCW-94-DP-G1/S) with an elevation/azimuth scanner for cloud and fog research based on land or a research vessel. This dual polarization, single frequency *turn-key* system (94 GHz, ± 100 MHz) comes with a comprehensive user-friendly software interface that allows seamless integration into real-time networks. These radars measure small water droplets of millimeter and submillimeter scales, enabling retrieval of useful quantities such as reflectivity, mean radial velocity, spectrum width, skewness, Kurtosis for characterization of atmospheric water. It will greatly add to the instrumentation capabilities of the proposing institution (University of Notre Dame), thus enhancing the PIs ability to characterize fog and clouds in two funded large ONR projects (See section 11) and other federally funded projects.

Several RPG FMCW W-band radars are already in operation. Model RPG-FMCW-94-SP, purchased by University of Cologne, Germany is now located in Ny-Alesund, Spitzbergen, Norway. It has been deployed since June 2016. Model RPG-FMCW-94-SP was purchased by École polytechnique fédérale de Lausanne (EPFL), Switzerland. It is now located in Verbier, Switzerland.

2. Rationale for the Request (Special Circumstances Regarding Acquisition)

In 2018 and 2019, PI Fernando's group at University of Notre Dame is scheduled to participate in two comprehensive collaborative field projects funded by the Office of Naval Research (ONR). The first project deals with Monsoon Intraseasonal Oscillations (MISO) in the Bay of Bengal (BOB), dubbed MISO-BOB. The pilot experiment for MISO-BOB is currently underway with two cruise legs between 04 June to 24 July, 2018 and C-130J aircraft observations over a two-week period 10-24 June, 2018. The full scale field study is scheduled for 2019 summer with land, aircraft and ship based observations. The second project, named C-FOG, investigates the formation, evolution and dissipation of fog in coastal areas via experiments during September-October 2018 and September 2019. Both projects have sizable numerical weather prediction and forecasting components, including delving into microscale process (~ 1-10 m) using research grade numerical studies (LES and Direct Numerical Simulations DNS). During the MISO-BOB Pilot study, remote sensing of cloud clusters was performed using a W-Band radar borrowed from the Environmental Sensing Research Laboratory at NOAA (courtesy of Dr. Chris Fairall); Figure 2a. It is an in-house built pulsed radar with high power consumption, and it needs acute maintenance. Wherever possible, comparisons are being made between measurements of W band radar, MWR and radiosondes (Figure 2b).

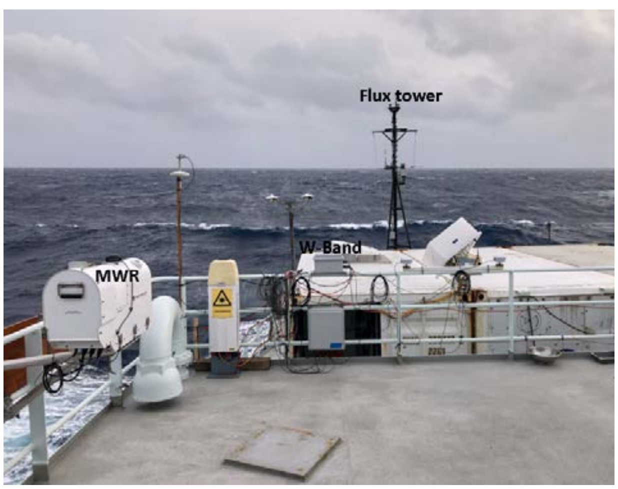

Figure 2a: Deployment of the NOAA/ESRL W-band radar alongside the flux tower and microwave radiometer (MWR) during the MISO-BOB Pilot experiment by the Notre Dame Group. Photo date: June 08, 2018 courtesy of Byron Blomquist. Research Vessel: Tommy G. Thompson

Figure 2b: A large cloud system conceivably belonging to the Monsoon Intraseasonal Oscillations (MISO) in Bay of Bengal. Notre Dame group released ~ 90 radiosondes during MISO-BOB Pilot (Photo date: June 04, 2018). Courtesy: Gualtiero SpiroJaeger.

Because of a scheduling conflict, NOAA W-Band radar may not be available for the C-FOG experiment in 2018, and its availability in 2019 is not guaranteed because of aging parts of the current instrument and concerns regarding its repairs owing to attrition of expertise within ESRL/NOAA. This is unfortunate, since in the 2019 MISO-BOB cruise a Ka band radar on the vessel will be deployed by the NRL-Monterey group (Dr. Jerry Schmidt), thus enabling two wave-length studies if a W-band is available. Alongside the radar(s), there will be a MWR, ceilometer, tethered lifting system, radio soundings and dropsondes (WC-130J), thus promising a comprehensive study on clouds. Instrumentation deployment on R/V Hugh G. Sharp during C-FOG will be similar, sans Ka-band radar.

As such, acquisition of a FMCW W-Band radar will greatly benefit the two ongoing ONR projects of the PI. When available, other groups at Notre Dame will be able to use the proposed radar. Other US institutions and national laboratories will also have access to it upon formulating a suitable entente with University of Notre Dame.

3. Description of the Instrument

The requested RPG FMCW W-band radar differs from conventional meteorological radars that use high-power vacuum tubes and estimate the distance to the target from the time delay between the transmitted pulse and reflected signals. Instead, RPG uses the frequency modulated, continuous wave (FMCW) concept, meaning that the radar emits an uninterrupted microwave signal. The frequency of the signal is changed linearly over time in saw-tooth steps, known as chirps. The signal is formed digitally and amplified by a solid-state transmitter. The radar receiver compares frequencies of the transmitted and the returned signals. The frequency difference is proportional to the distance to atmospheric scatterers. An embedded 89-GHz direct-detection channel provides the functionality of a passive microwave radiometer within the antenna pattern of the radar's main beam. This is the first cloud radar that can measure the integrated liquid water signal with the same field-of-view as the radar reflectivity. Digital signal formation and processing give the instrument spatial resolution down to a few meters, which is important for the analysis of small-scale hydrometeor microphysics and cloud dynamics. Its high transmission power and state-of-the-art receiver components also provide great sensitivity. The radar easily detects even the thinnest ice clouds at a height of 12km (Figure 3). Low peak power meets the electromagnetic compatibility requirements critical for applications in urban areas.

Accurate absolute calibration is crucial in the quantitative characterization of cloud particles and precipitation. The RPG FMCW W-band has been designed to provide precise characterization of all components in the transmission and reception parts of the system. A common issue with radar systems is that wet antennas reduce sensitivity. A wet radome could also spoil the quality of cloud radar's passive channel. As a remedy, RPG has implemented dry antennas during operation, by covering the transmit and receiver antennas with radomes featuring a hydrophobic coating. Strong fans provide airflow of $1m^3s^{-1}$ to prevent water from accumulating on the antenna radomes. This is the first radar to benefit from dry antennas in all weather conditions, even strong rain. The RPG radar uses internal monitoring of transmitter power, absolute receiver calibration with liquid nitrogen reference, and Dicke-switch stabilized radiometric receivers to calculate calibration parameters. The design of RPG W-Band is a step toward 0.5dB accuracy (10-15%) in radar reflectivity. With a digitally controlled synthesizer as a chirp generator, this radar makes use of a variety of chirp sequences optimized for typical standard observation modes. These observation modes can be selected according to the target of interest. For example, low-level fog measurements require different chirps from observations targeting high-level ice clouds. The chirp sequences are reprogrammable during operation and can be optimized by the user.

On the data processing front, RPG FMCW radar combines all advanced observational techniques such as Doppler processing, comprehensive scan pattern analysis, and radar polarimetry. The data output of the RPG FMCW radar contains Doppler velocity distributions and additionally derived parameters such as spectral width, skewness and kurtosis. Owing to the very low system noise, complex features of the Doppler spectra are clearly identifiable. Modern meteorological radars are polarimetric. In general, cloud particles are non-spherical and aligned nearly horizontally. Therefore, scattering of the horizontal polarization is often more intense than the vertical one. The scattering differences between the two polarizations depend on the particle's phase, liquid or ice, air inclusions, shape and orientation.

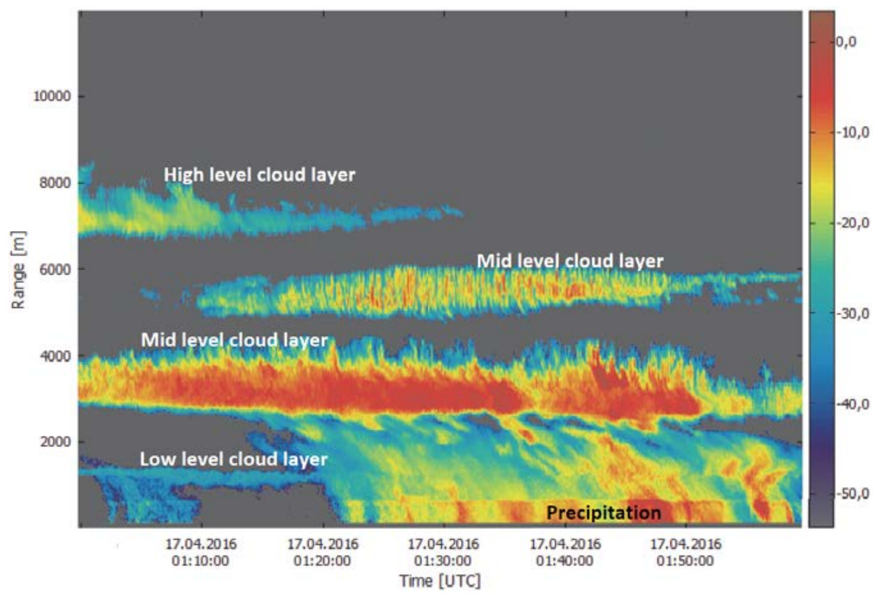

Figure 3: The time-range cross section of the radar reflectivity factor. The measurements have been taken on 17 Apr 2016 at a site in Meckenheim, Germany by the manufacturer RPG. The RPG FMCW W-band radar is capable of detecting thin ice clouds at a height of ~ 12km.

Radar polarimetry has been widely used by the precipitation radar community for improved detection of weather phenomena as well as for efficient classification and quantitative characterization of precipitation. Nevertheless, the polarimetric approach is not intensively employed in cloud radars. To this end, RPG FMCW radar provides a set of products similar to that used in weather radar networks. Its data processing technique is novel, and involves a combination of Doppler and polarimetric measurements. This allows for a precise estimation of liquid precipitation intensity. The RPG FMCW radar can measure the drop-size distribution for conversion into rain rate. Based on polarimetric observations, it can provide a detailed classification of atmospheric scatterers into several classes, including liquid precipitation, melting particles, dendrites, hail, ice columns and aggregates. Cloud radar polarimetry is also suitable for removing non-meteorological scatterers. Atmospheric plankton, such as insects and pollen, may often hamper reliable detection of low-level clouds and fog, which are characterized by low reflectivity values.

Applications

- Given its accuracy, the RPG FMCW W-band radar system can be used for the calibration of other radar systems, such as pulsed magnetron based radars, where hardware performance depends on environmental conditions and ageing components. Operating nearly the same frequency as many satellite-based cloud radars, the RPG radar is a good reference for data evaluation.
- It detects the areas of limited visibility by providing vertical profiles of clouds continuously. The scanning unit can deliver vertical profiles of wind direction and velocity to indicate windshears that are a risk to aviation safety.
- Its Doppler capabilities allows quantitative characterization of turbulence in the atmosphere.
- It can identify areas in the atmosphere featuring tiny liquid drops at temperatures below 0°C. These drops freeze when they come into contact with surfaces. In aviation, this leads to accumulation of ice, and the resulting increase of mass and change of aerodynamics characteristics negatively impact aircraft performance
- Its high sensitivity and scanning capabilities make the radar suitable for fog research and fog nowcasting. Performing continuous azimuthal scans, the radar can be used for local short-term forecasts of clouds and precipitation for early warning systems and disaster prevention. Catching the early stages of convection will help improve forecast quality.
- The FMCW W-band radar can also be combined with a profiling microwave radiometer (MWR) to provide temperature and humidity profiles for research and practical (e.g. weather modification by seeding) applications.
- It offers the highest-quality insights into cloud structure and evolution.

4. Specifications for RPG-FMCW-94-DP-G1/S

- FMCW Cloud Radar, dual polarization
- Solid-state / low power source
- RF at 94 GHz (W-band)
- Very High Sensitivity (down to -60 dBz)
- High Dynamic Range (-60 to +20 dBz)
- Complete Rain Mitigation System
- Full Networking Capability (TCP/IP)
- Positioner system for moving the radar in azimuth and elevation
- Built-in weather station to monitor weather conditions at ground level
- Passive channel for absolute calibration
- Includes embedded 89 GHz passive channel for measurements of integrated liquid water path (LWP)
- Easy adaption of operating modes, allowing the researchers to focus on certain parameters by re-coding the chirps
- Compact and easily transportable

The specifications of the system are given below based on the RPG datasheet.

Parameter	Specification
Centre Frequency	94 GHz (λ=3.19 mm) ± 100 MHz typical, (adjustable by software between 92.3 and 95.7 GHz)
IF range	350 kHz to 3 MHz
Transmitter power	2 W typical (solid state amplifier) Lower transmitter powers are available for reduced priced
Antenna type	Bi-static Cassegrain with 500 mm aperture
Antenna gain	51.5 dB
Beam width	0.48° FWHM
Polarisation	V (optional V & H)
Rx System Noise Figure	4 dB (400 K system noise temperature)
Typical Dynamic range (sensitivity) with 2 W transmitter	-60 dBz to +20 dBz (at 500 m height / 5 m resolution) -50 dBz to +20 dBz (at 2 km height / 10 m resolution) -47 dBz to +20 dBz (at 4 km height / 30 m resolution) -36 dBz to +20 dBz (at 10 km height / 30 m resolution)
Ranging	100 m to 12 km typical, 16 km maximum
Maximum vertical resolution	1 m (range: 0.1 km – 0.6 km), 2 m (range: 0.6 km – 1.0 km), 4 m (range: 1.0 km – 2.5 km), 8 m (range: 2.5 km – 5.0 km), 16 m (range: 5.0 km – 12.0 km)
Calibrations (automatic)	Power monitoring of the transmitter, plus receiver Dicke-switch for gain drift compensation (radar and passive channel)
Calibrations (maintenance)	Liquid nitrogen receiver calibration, external reference sphere
A/D Sampling rate	8.2 MHz (data processing between 0.35 and 3 MHz)
Data processing system	High-Performance embedded PC
Sampling rate (full profiles)	Adjustable: ≥1 second
Doppler range	± 9 m/s unambiguous velocity range (0-2500 m), ± 4.2 m/s above
Doppler resolution	± 1.5 cm/s or higher
Chirp variations	3 typical, 10 possible, re-programmable
Passive channels	89 GHz for integral LWP detection
Control connection	TCP/IP connectivity via fibre optics data cable to internal PC
Operation software	Real time visualization, real time data extraction, real time control (adaptive observation modes depending on context)
Data products (available as files)	Reflectivity, Doppler spectra (including calculated moments), LWC profiles. Data levels: L1: calibrated dBZ, L2: retrieved data
Data formats	netCDF (CF convention), proprietary binary, ASCII
Mitigation system for rain/fog/dew	Strong dew blower (approx. 2000 m³/h), radomes with hydrophobic coating ,optional heater (additional 2-4 kW)
Additional sensors	Automatic weather station with P, T, RH, RR, Snow, WS, WD
Scanning / mounting	Baseline: mounted on a fixed stand of 0.5 m height Optional: scanner unit for full sky scanning capability
Dimensions	115×56×82 cm³ (with antennas),(80×40×40 cm³ (box only)
Weight	Approx. 280 kg/80 kg with/without stand & blower (w/o scanner)

5. Selection and Comparison with Other Available Products

Until recently, most of the W-band radars in operation were of pulse type, and were produced in house by skilled engineers and technicians. However, the introduction of FMCW W-band radars by RPG as a new product line has revolutionized the Radar community, providing unique opportunities to measure small water particles in the atmosphere and educe new information of cloud and fog dynamics. Since its introduction, it has been used in several research projects. As evident from the attachment to the budget justification, they are produced *sui generis*, and hence no fair comparison with a competitor radar could be made.

An exhaustive search indicates the availability of two other commercial radar systems with W-band capabilities. One is the French small BASTA radar system produced by Metro Modem (http://www.meteomodem.com/cloud-radar.html), which is compact and operated at 95 GHz. A prototype of BASTA has being tested (Delanoë et al. 2016), but it does not have scanning capabilities nor is it available commercially at present. The other is the Pro-Sensing system (https://www.prosensing.com/crb-product/wcr/), which is an airborne Cloud Radar operating in the W-band at 95 GHz that uses 1.8kW klystron (vacuum tube type) amplifiers. The power consumption of this system is excessively large for our applications.

As a research tool the RPG FMCW concept offers the advantages of low power, compactness and the possibility to adapt RF operation frequency for fast and easy adaption of modus operandi (focusing on certain parameters by re-coding the chirps "on the fly"). It has a definite potential for better range resolution (~ 2 m is possible) over pulse radars. In addition, the FMCW power level eases the cost of maintenance (solid-state amplifier versus pulse-power). The passive channel and the rain mitigation system that RPG FMCW offers are unique attributes.

As such, the proposed instrument is sole sourced to RPG (also see the letter from RPG attached to the budget justification).

6. Budget (also see the budget justification)

RPG-FMCW-94-DP-G1/S, Positioner System for RPG-FMCW 94 GHz, Host PC, Factory Training, Radar Warranty Extension and Shipping **– US$ 480,445.00**

RPG-FMCW-94-DP-G1/S has a channel for LWP measurements, and it delivers LWP retrievals at no additional cost. RPG also has added the software synergy with temperature/humidity profiling radiometers, which is a specific advantage for expanding capabilities at a later time.

Useful life of the equipment: 7 years

Contact point:

Mr. Larry Malenfant
Vice President, Business Development
ATS Services (North American Distributor for RPG)
35 Auriga Drive, Unit 213
Ottawa, ON, CA K2E 887
Telephone: 902-860-1556
Fax: 902-860-1556

7. Timeline

Considering pending field campaigns in 2019 summer and fall, and expecting the DURIP award announcement in April 2019 (with grant start date of June 15, 2019), the PI has negotiated the following with the manufacturer, which was approved by the RPG management on June 13, 2018. In October 2018, the sales team will inform the production department of a pending order to secure a favorable position in the production queue. RPG expects a tentative order immediately after DURIP awards are announced, roughly by April 15th. If funding does not come through, RPG will cancel the project and simply realign their production queue. If awarded, the project will start and by June 15th a firm confirmation with a 75% deposit is necessary to expedite the production and ensure delivery in July 2019.

8. The Role of Proposed Instrumentation in the Existing Equipment Pool

The equipment arsenal at Notre Dame consists of a Flat Array Sodar (MFAS) with RASS interface (heated), Triple Lidar (extended range), single Lidar (ND/ARL) motion stabilized for RV operations, profiling microwave radiometer (PMWR, Radiometrics), sonic anemometers (30), 4x20 m towers (3), fine-wire thermocouples, RH sensors, Kipp & Zonen net radiometers (4), pygeometers (2), pyranometers (2), LiCORS® (water vapor fluxes, 2), Vaisala CL 31 ceilometers (2), boat flux tower, Remote Ocean Surface Radiometer (ROSR), energy balance station (1), Vaisala tethersonde system (1), vertical microstructure profiler/CTD (VMP) for upper-ocean characterization (1), FLIR Infrared camera model A6260Sc (1), and a 449 MHz Radar Wind Profiler (1). The proposed radar will aptly complement this equipment array by enabling the measurement of small water droplets (< 3mm) contained in clouds and fog.

The existing equipment at Notre Dame adds value to the proposed acquisition. For example, the FMCW radar can be combined with the profiling MWR to retrieve the liquid water content (LWC) profile of a cloud or in fog (Frisch et al. 1998). The vertically integrated amount of liquid water and liquid water path (LWP) are constrained by the MWR, and the range-resolved radar signal can be used to reconstruct the vertical distribution of LWC. As mentioned, collocated radar, microwave radiometer, and lidar observations can be combined to obtain cloud properties such as the hydrometeor phase, type, and position in the vertical column (Küchler et. al., 2017). As such, we will be able to enhance the versatility of the proposed radar.

9. Maintenance and Personnel

The senior person involved in this request is Dr. Raghu Krishnamurthy, who is an expert in Lidar measurements and in-charge of the triple Lidar system purchased under a 2105 DURIP award. Dr. Krishnamurthy is funded by a combination of external grants and internal resources such as the Wayne and Diana Murdy fund of University of Notre Dame. The university also will provide the services of a dedicated research engineer, Mr. Scott Coppersmith, to maintain the system. His position is internally funded to provide research support for the PI's Environmental Fluid Dynamics laboratory. Mr. Coppersmith has been a key resource for past DOD funded projects. In addition, through a combination of internal and external funds, a new post-doctoral fellow will be hired for at least one year to support the research enterprise surrounding the acquisition of RPG FMCW W-band Radar.

PI Fernando will broadly oversee the instrument maintenance. Currently the PI is closely working with ARL (White Sands) and NRL (Monterrey, DC and Stennis) in DOD sponsored projects, and loaning of equipment and personnel among the groups has been customary. As such, RPG FMCW W-band Radar will essentially be a collaborative tool. The availability of technical and post-doctoral support at no cost to DURIP grant will enhance the vitality of proposed instrument for DOD-related research.

10. Role in Enhancing Research and Research-Related Education

The proposed equipment will be used for DOD and non-DOD funded research as well as training graduate students for careers in academia, research and development and industry. Hands on experience with advanced measurement techniques such as lidars, microwave radiometers and ceilometers is a part of graduate courses offered at University of Notre Dame (Environmental Fluid Dynamics, Wind Energy, Turbulence), and the proposed FMCW W-band radar will be used for such activities. Students usually take data in the field setting, and the data are then used for calculating mean and turbulence quantities as well as fluxes of momentum and temperature. In the future, atmospheric water will be included in measurements. Engineering students are particularly interested in thermodynamic calculations, and the two departments where the PI has regular appointments are catering to engineers. Therefore, the proposed instrumentation is expected to be a favorite amongst students. Currently the PI has seven PhD students, and his regular courses have 10-15 graduate students. The senior personnel, Raghu Krishnamurthy, teaches a wind energy course with about 15 students. As mentioned, faculty of the PI's institution will have access to the proposed equipment when not in use for committed projects.

Research projects that the proposed equipment is of direct utility and with pending field campaigns are as follows:

Title of the Project: Toward Improving Coastal Fog Prediction (C-FOG)
Organization: Office of Naval Research, Code 322 Marine Meteorology
Contract/Grant Number: N00014-18-1-2472
Project Period: 2018-2020 (two years + possibly one year no cost extension)
Program Manager: Dr. Daniel Eleuterio
Amount: $3,000,000
Notre Dame Principal Investigator: H.J.S. Fernando (Main PI), co-PIs: Clive Dorman (Scripps), Ismail Gultepe (Notre Dame and Environment Canada), Eric Pardyjak (University of Utah), David Richter (Notre Dame), Qing Wang (NPS)
Research Thrust:

Fog consists of suspended water droplets and ice crystals in the atmospheric boundary layer, formed by a favorable collusion of dynamic, microphysical and thermodynamic processes. Socio-economic and defense implications of fog abound, including impacts on ecosystems and agriculture, visibility impairment, disruption of air, marine and ground transportation as well as debasement of electromagnetic propagation, with particular relevance to infrared-based detection and tracking as well as directed energy technologies. A myriad of classifications is used for fog, based on either formation mechanisms, thermodynamic conditions, geographical location, microphysical properties or a mix thereof. This project concerns fog in coastal areas (or *coastal fog*) controlled by the interactions of land, marine and atmospheric processes. Given the inherent complexity of coastal-fog dynamics, previous literature has mostly dealt with case studies with limited microphysical observations, and there is a critical need for research that integrates across fundamental processes (fog life cycle), dynamics (energetics, two-phase flow and turbulence), microphysics (droplet characterization, nucleation) and thermodynamics (radiative mechanisms, cooling, phase changes) through a symbiosis of well-designed field campaigns and modeling. Thus, at the heart of C-FOG will be a field study in eastern Canada at two supersites (in Nova Scotia and Newfoundland) rich in fog climatology and conducive to disparate fog types. An unprecedented array of in situ, path integrating and remote sensing instruments, profilers, and a UAV will be deployed, allowing measurements across a swath of space-time scales relevant to fog formation. Instrumentation platforms will be located over both land and the coastal ocean. Satellite products, mesoscale numerical weather prediction (NWP) model outputs, microscale (direct-numerical and large-eddy) simulations and phenomenological modeling will help interpret fog observations in a multi-scale framework, identify physical mechanisms, test hypotheses, and develop physics-based parameterizations. NWP models (WRF and WRF-CHEM) will be validated vis-à-vis fog observations, and model deficiencies will be identified. Newly developed parameterizations will be implemented in the NWP models and tested. The comprehensive scope of the C-FOG program calls for melding of expertise from a multidisciplinary group of researchers, which are to be drawn from four universities with track records in fog research.

The proposed instrument will help characterize fog (drop sizes < 50 μm) by measuring or retrieving reflectivity, mean radial velocity, spectrum width, skewness and liquid water path in a scanning mode, thus allowing to obtain information on fog lifecycle. With simultaneous Lidar and MWR measurements, the scope of the project will be expanded to include spatial distribution of small water droplets.

Title of the Project: Air-Sea Coupling in Monsoon Intraseasonal Oscillations (MISO)
Organization: Office of Naval Research, Code 322, Physical Oceanography
Contract/Grant Number: N00014-17-1-2334
Project Period: 2017-2022 (five years)
Program Manager: Dr. Theresa Paluszkiewicz
Amount: $2,839,118
Notre Dame Principal Investigator: H.J.S. Fernando, co-PIs – Dr. Peter Sullivan (NCAR), Mr. Priyantha Jinadasa (NARA, Sri Lanka), Ö. Gustafsson (Maldives Climate Observatory, Hanimadoo), Vincent Amelie (Seychelles Meteorological Authority, Arjun Balasuriya, Charles River Analytics

Research Thrust: In this project, a multidisciplinary research team associated with MISO-BOB DRI of ONR seeks to address critical science questions underlying MISO dynamics in Bay of Bengal (BOB). Of particular interest are the physical mechanisms responsible for heat, momentum and mass transfer across the air-sea interface, feedbacks between atmospheric and oceanic boundary layers, lead-lag relationships between the sea-surface temperature, net heat flux and precipitation as well as sustaining and dissolving MISO convective clouds. Collectively, a suite of high-end atmospheric and oceanic instrumentation will be deployed in the Indian Ocean, on the land over multiple countries and on research vessels, to collect data of high granularity. The 53rd Weather Reconnaissance Squadron of the US Airforce are in Sri Lanka at the time of writing this proposal to conduct flights through MISO events (June 15-26), with onboard meteorological instruments, radar, and dropsondes.

Ultra-high resolution coupled numerical simulations will be used to guide field experimental designs and data interpretation. Novel autonomous measurement platforms and large eddy simulation (LES) technologies will be developed to study relevant air-sea processes. Satellite and reanalysis products will be used to augment in situ data, allowing integration of observations across sub-meso to seasonal scales. In unison, the proposed research will contribute immensely to improve forecasts of MISO, and Monsoons in general, via discovery of physical mechanisms, understanding their linkages, development of parameterizations, and providing a robust dataset for modelers. Collaboration with government agencies from the US and partnering countries will help transition research to forecasting products. The project also includes capacity building of partnering countries.

The proposed FMCW W-band radar will help the 2019 summer MISO-BOB measurement campaign. The measurement quantities are as before. The emphasis will be on MISO convective cloud clusters, characteristics of which can be recorded by the proposed FMCW W-band radar.

Ongoing projects with a completed field component but can be benefited from data taken from future field campaigns are as follow:

Title of the Project: Coupled Air-Sea Processes and EM Ducting Research (CASPER)
(Notre Dame Title: Toward Improving Similarity Theories for Marine Surface Layer)
Organization: Office of Naval Research, Code 322 Marine Meteorology
Contract/Grant Number: N00014-17-1-3195
Project Period: 2014-2015 (five years)
Program Manager: Dr. Daniel Eleuterio
Amount: $1,044,220 (Total MURI budget - $7,437,924**)**
Notre Dame Principal Investigator: H.J.S. Fernando, co-PI (Main PI - Professor Qing Wang, NPS)
Research Thrust:

This is a collaborative research effort between the Naval Postgraduate School, University of Notre Dame, Ohio State University, Oregon State University and University of California, Irvine, to address overarching knowledge gaps related to electromagnetic (EM) wave propagation in coastal Marine Atmospheric Boundary Layers (MABL). The objective is to fully characterize the MABL as an EM propagation environment. The emphases will be on spatial heterogeneities and surface wave/swell effects, both of which contravene the underlying assumptions of Monin-Obukhov Similarity Theory (MOST) used in coupled environmental forecast models and evaporative duct models. Furthermore, coastal variability in the elevated trapping layer atop the MABL presents challenges to forecast models, and causes practical issues in trapping-layer interpolation in EM prediction models, which will be addressed in the project. The approach includes theoretical analyses, field measurements, and numerical modeling. Theoretical analyses will guide the field experimental design and data analyses. The field component of this project was completed with two main campaigns: CASPER-East (Duck, NC, October, 2015) and CASPER-West (Southern California, October-November 2017). These two campaigns captured ducting along developing internal boundary layers over inhomogeneous regions near the Gulf Stream, evaporative ducts over warm water and affected by wave/swells, and surface-based and elevated ducts near the MABL top under coastal influence. Unique to this project was an optimal combination of platforms and sensors for high-resolution measurements on either side of the air-sea interface away from regions of ship influence, as well as in the higher atmosphere. Also unique was the concurrent measurements of MABL turbulence, scalar mixing and detailed range-dependent propagation measurements. The data analyses continue to address scientific questions related to three hypotheses dealing with spatial heterogeneity, waves and swells and to develop novel approaches to EM propagation modeling and signal characterization. CASPER modeling efforts utilize high-resolution models such as large-eddy-simulations of dynamically coupled air, surface waves and upper ocean, single column and mesoscale models and various propagation modeling approaches.

The data obtained from the proposed instrument in C-FOG project in the coast of eastern Canada will help understand coastal MABL development and the structure and extent of evaporative ducts required for CASPER research. Lacking of a scanning instrument for moisture detection, the evaporative duct had to be investigated using MWR data, which is of low resolution near the surface.

Title of the Project: Collaborative Research: Perdigao: Multiscale Flow Interactions in Complex Terrain
Organization: National Science Foundation (Physical Meteorology Division)
Contract/Grant Number: AGS-1565535
Project Period: 2016-2019
Program Manager: Dr. Nicolas Anderson
Amount: $ 1.3M (Total budget - $3.4M**)**
Notre Dame Principal Investigator: H.J.S. Fernando, Co PIs: Petra Kline (University of Oklahoma) and Rebecca Barthelme (Cornell University)
Research Thrust:

Atmospheric flow in complex terrain is found in numerous applications, including air pollution, contaminant dispersion, aviation, Alpine warfare and wind energy harvesting. Much of the past work in complex-terrain meteorology has been on improved weather prediction at the mesoscale (resolution on the order of km), but wind energy and dispersion applications demand predictions at the microscale (tens to hundreds of meters). To this end, ERANET+, a European Union (EU) funding instrument, has granted a consortium of EU scientists a megaproject to provide the wind energy sector with more detailed and accurate wind resource mapping capabilities. The project deliverables include creation and publication of a new digital EU wind atlas (NEWA) based on new or improved models for wind energy physics and forecasting. NEWA conducted a major land-based experiment during 2016-2017 in a valley (Vale Cobrão) nestled within a double ridge, southeast of Porto, Portugal. In recognition of the closest city, the field campaign was dubbed Perdigão. EU deployed state-of-the-art core instrumentation (remote sensors, tall instrumented towers, unmanned aerial systems), which was augmented by flux towers, profilers and remote sensors by the Lower Atmospheric Observing Facilities (LAOF) of NCAR.

In a collaborative project, research groups from the University of Notre Dame (Lead), Cornell University and University of Oklahoma deployed high-end platforms to augment the core instrumentation, with the goal of measuring both mean and turbulent quantities at an unprecedented resolution (~100 to 500m) to study interactions between flows of different scales, effects of topographic and diurnal thermal forcing, valley/slope boundary layers and turbine wakes. Included also were algorithm development for instrument control and data handling and inter-comparison of instruments. Coordinated theoretical and numerical studies undergird the interpretation of data.

Measurements of complex-terrain mean flow, turbulence and fluxes with cutting-edge stationary, profiling, aerial and scanning platforms, including triple-Lidar technology formally debuted at a major field study, permitted investigations of multi-scale physical processes in complex terrain and interactions thereof at the highest resolutions ever attempted. The project outcomes include improved wind energy and microscale physics in complex terrain, new model-usable parameterizations, and data resources for high-fidelity microscale simulations and forecasting. The nominally two dimensional (2D) topography at Perdigão with isolated gaps allowed regions of nominally 'clean 2D' and 'distorted' conditions, which will be analyzed under different stability and synoptic flow conditions. Ensuing flow structures and their transitions under different forcing will be identified, and whenever possible presented in regime diagrams based on dimensionless governing parameters. The Perdigão data set will be the gold standard of benchmark data for two-hill configurations, which is opportune as a sequel to the well-known microscale Askervein data set taken decades ago for a single hill and mesoscale MATERHORN studies during 2012-2015.

The Perdigão campaign encountered several days of fog, and the use of triple Lidars, MWR, flux towers and a differential absorption lidar (DIAL) allowed studies of fog formation and advection mechanism. Although it is removed from coastal fog, the fog observed some days was formed in a nearby river valley and advected to the campaign area. Other fog days were characterized by radiative fog formed during local cooling. Analysis of these fog events continue, and general understanding so gained will be useful in studies of fog cycle under different environmental conditions, and hence for futures studies of fog and low-level clouds.

In summary, the proposed instrument is directly relevant to the research interests of ONR Ocean, Atmosphere and Space Research Division, Marine Meteorology and Atmospheric Effects Program (322MM). It is also closely relevant to ONR 322PO (Physical Oceanography). The former emphasizes topics in global, mesoscale and on-scene modeling of the marine atmosphere and coastal zone whereas the latter emphasizes submesoscale ocean processes, air-sea interactions and new ocean observing technologies. The proposed instrument will also help many other federal projects such as those from the US National Science Foundation and Department of Energy.

11. Relation to research-related education currently proposed to the DoD

There are no pending proposals to DOD at present, since current projects continue for a few more years. A proposal will be submitted to NSF to study 'Sundowner' phenomena, a hydraulic and non-linear wave phenomenon in the coast of southern California with large vertical velocities, subsidence, updraft regions and thermodynamic activity. It is associated with stably stratified conditions. Measurement of atmospheric moisture by the proposed instrument during Sundowner will provide information on the role of moisture advected into the area.

12. Current and Pending Support:

PI:	H.J.S. Fernando
Title:	Experimental investigation of thermally driven anabatic flow separation
Awarding Agency:	US-Israeli Binational Science Foundation
Contract Number:	BSF:2014075
Performance Period:	09/16/2015 – 09/15/2018
Total award amount:	$54,359 (Notre Dame portion)
Person months/year:	- none
Status:	Current
No cost extension:	NA

PI:	H.J.S. Fernando (Co-PI)
Title:	Coupled Air-Sea Processes and EM Ducting Research (CASPER)
Awarding Agency:	Office of Naval Research
Contract Number:	N00014-17-1-3195
Performance Period:	07/01/14 to 06/30/2019
Total award amount:	$1,044,220 (Notre Dame portion)

Person months/year:	1
Status:	Current
No cost extension:	NA

PI:	H.J.S. Fernando
Title:	Air-Sea Coupling in Monsoon Intraseasonal Oscillations
Awarding Agency:	Office of Naval Research
Contract Number:	N00014-17-1-2334
Performance Period:	03/01/17to 03/01/22
Total award amount:	$2.9M (multi-investigator funding)
Person months/year:	0.75
Status:	Current
No cost extension:	NA

PI:	H.J.S. Fernando
Title:	Toward Improving Coastal Fog Prediction (C-FOG)
Awarding Agency:	Office of Naval Research, Code 322 Marine Meteorology
Contract Number:	N00014-18-1-2472
Performance Period:	05/01/2018 to 04/30/2030
Total award amount:	$ 3M
Person months/year:	1
Status:	Current
No cost extension:	Yes, will seek

PI:	H.J.S. Fernando
Title:	Perdigão: Multiscale Flow Interactions in Complex Terrain
Awarding Agency:	National Science Foundation
Contract Number:	AGS-1565535
Performance Period:	03/01/2016 -2/28/2019
Total award amount:	$ 531,260 (Notre Dame share); Total 1.3M
Person months/year:	1.00
Status:	Current
No cost extension:	NA

PI:	H.J.S. Fernando
Title:	Wind Measurements in Colombia River Gorge in Support of Forecast Improvements
Awarding Agency:	3-TIER, a Vaisala Company (DOE Prime)
Contract Number:	DOE-WFIFP2-SUB-001
Performance Period:	03/01/15 to 06/30/2018
Total award amount:	$286,067 (Notre Dame share)
Person months/year:	0.25
Status:	Current
No cost extension:	NA

13. Bibliography

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RESEARCH & RELATED Senior/Key Person Profile (Expanded)

PROFILE - Project Director/Principal Investigator

Prefix: First Name*: Harindra Middle Name J. Last Name*: Fernando Suffix:

Position/Title*: Professor, Civil & Env Engr & Earth Sci
Organization Name*: University of Notre Dame
Department: Civil & Env Engr & Earth Sci
Division: College of Engineering
Street1*: 311-D Cushing
Street2:
City*: Notre Dame
County: St. Joseph
State*: IN: Indiana
Province:
Country*: USA: UNITED STATES
Zip / Postal Code*: 465565612

Phone Number*: 5746319346 Fax Number: E-Mail*: fernando.10@nd.edu

Credential, e.g., agency login:

Project Role*: PD/PI Other Project Role Category:

Degree Type: Degree Year:

	File Name
Attach Biographical Sketch*:	Fernando___Biosketch1015555598.pdf
Attach Current & Pending Support:	

PROFILE - Senior/Key Person

Prefix: First Name*: Raghavendra Middle Name Last Name*: Krishnamurthy Suffix:

Position/Title*: Research Scientist
Organization Name*: University of Notre Dame
Department: Civil & Env Engr & Earth Sci
Division: College of Engineering
Street1*: 318 Cushing Hall Of Engineering
Street2:
City*: Notre Dame
County: St. Joseph
State*: IN: Indiana
Province:
Country*: USA: UNITED STATES
Zip / Postal Code*: 46556-5708

Phone Number*: 574-631-3467 Fax Number: E-Mail*: rkrishn1@nd.edu

Credential, e.g., agency login:

Project Role*: Co-PD/PI Other Project Role Category:

Degree Type: Degree Year:

	File Name
Attach Biographical Sketch*:	Krishnamurthy___Biosketch1015555597.pdf
Attach Current & Pending Support:	

13. Key Personnel: **HARINDRA JOSEPH S. FERNANDO (PRINCIPAL INVESTIGATOR)**

Education:	Post-Doctoral	(Fluid mechanics) California Institute of Technology, 1983-84
	Ph.D.	(Fluid mechanics) The Johns Hopkins University, 1983
	M.A.	(Fluid mechanics) The Johns Hopkins University, 1982
	B.Sc.	(Mechanical engineering: 1st Class Honors) University of Sri Lanka, 1979

Academic Experience:

2010-	Wayne and Diana Murdy Endowed Professor of Engineering and Geosciences, University of Notre Dame
1994-2009	Director, Center for Environmental Fluid Dynamics Program, Arizona State University (2010- Professor Emeritus)
1992-	Professor, Department of Mechanical and Aerospace Engineering, Arizona State University (also, Professor, Global Institute of Sustainability, 2008-2009)
1988-1992	Associate Professor, Department of Mechanical and Aerospace Engineering, Arizona State University
1990	Senior visitor, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, U.K.
1984-1988	Assistant Professor, Department of Mechanical and Aerospace Engineering, Arizona State University
1983-84	Research Fellow, Division of Engineering and Applied Sciences, California Institute of Technology

Awards, Scholarships and Honor Societies (Selected):
1997 – ASU Alumni Distinguished Research Award; 2001 – Rieger Foundation Distinguish Scholar Award in Environmental Sciences; 2004 - Walter Mong Award (University of Hong Kong); 2009 – Elected to *Academia Europaea*; 2012 - Telford Premium Prize – Society of Civil Engineers, UK; 2015 Enrico Marchi Award Lecture, Italian Hydraulics Association; *2014 - Docteur Honoris Causa, University of Grenoble*; *2016 - Doctor of Laws Honoris Causa, University of Dundee, Scotland, UK.*

Professional Societies and Activities:
Fellow: American Society of Mechanical Engineers, American Physical Society; American Meteorological Society, American Association for Advancement of Science (AAAS)

Editor-in-Chief – *Journal of Environmental Fluid Mechanics* Editor *-Theoretical and Computational Fluid Mechanics; Nonlinear Processes in Geophysics* Editorial Board - *IAHR Journal of Hydro Environment; Physical Reviews Fluids, Proceedings of the Royal Society A*

Selected Relevant Publications:

Kit, E., Hocut, C.M., Liberzon, D., and Fernando, H.J.S. Fine-Scale Turbulent Bursts in Stable Atmospheric Boundary Layer in Complex Terrain, *Journal of Fluid Mechanics*, 833, 745-772, 2016. doi:10.1017/jfm.2017.717, 2017.

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Bhat, G.S. and Fernando, H.J.S., Remotely Driven Anomalous Sea-air Heat flux over the North Indian Ocean during the Summer Monsoon season. *Oceanography* 29(2), 232-241, 2016, http://dx.doi.org/10.5670/ oceanog.2016.

Wijesekera, H.W., Shroyer, E., Tandon, A., Ravichandran, M., Debasis, D., Jinadasa, P., Fernando, H.J.S., et al., ASIRI Ocean-Atmosphere Initiatives on Bay of Bengal, *Bulletin of the American Meteorological Society*, 97 (10) October, 1859-1884, 2016.

Wang, Y., Creegan, E., Felton M., Huynh, G., Hocut, C., Fernando, H.J.S., Hoch, S., Whiteman, C.D., Triple Doppler wind lidar observations during the MATERHORN field project, *Journal of Applied Remote Sensing*, 10(2), 026015, 2016.

Lozovatsky, I., Jinadasa, S.P., Fernando, H.J.S., Lee, J.-H. and Hon, C. S., The Wall-Layer Dynamics in a Weakly Stratified Tidal Bottom Boundary Layer, *Journal of Marine Research*, 73(6), 207–232, 2015.

Fernando, H. J. S., E. R. Pardyjak, S. Di Sabatino, F. K. Chow, S. F. J. DeWekker, S. W. Hoch, et al.: The MATERHORN – Unraveling the intricacies of mountain weather, *Bulletin of the American Meteorological Society,* 96 (11), 2015. doi: http://dx.doi.org/10.1175/BAMS-D-13-00131.1

Lozovatsky, I. and Fernando, H.J.S., Mixing efficiency in natural flows, *Philosophical Transactions, Proceedings of the Royal Society (Lond) A*, 371: 20120213, 2012. http://dx.doi.org/10.1098/rsta.2012.0213.

Baklanov, A., Grisogono, B., Bornstein, R., Mahrt, L., Zilitinkevich, S., Taylor, P., Larsen, S., Rotach, M. and Fernando, H.J.S., On the nature, theory, and modeling of atmospheric planetary boundary layers, *Bulletin of the American Meteorological Society***,** *92,* 123- 128 (DOI:10.1175/2010BAMS2797.1), 2011.

Raghavendra Krishnamurthy (Senior Personnel)
Department of Civil & Earth Sciences Engineering, University of Notre-Dame, Indiana
Phone : 574-631-3467, Email : rkrishn1@nd.edu

PROFESSIONAL PREPARATION

Arizona State University, Mechanical & Aerospace Engineering	Ph.D., 2013
Arizona State University, Mechanical & Aerospace Engineering	M.S., 2008
Jawaharlal Nehru Technological University, Mechanical Engineering	B.S., 2006

APPOINTMENTS

Research Scientist, University of Notre-Dame, USA	2016 – Present
Senior Scientific R&D Engineer & Application Expert, LEOSPHERE, Paris, France	2013 – 2016
Doctoral Candidate, Arizona State University, USA	2010 – 2013
Faculty Associate, Mechanical Engineering Department, A	2011 – 2012
Teaching Assistant, Mechanical Engineering Department, ASU	2010
Environmental Consultant, Trinity Consultants, Inc., Texas, USA	2008 - 2009
Research Assistant, Arizona State University, USA	2006 - 2008

RELEVANT PUBLICATIONS

1. Offshore wind turbine wake characteristics using scanning Doppler lidar (2017), R Krishnamurthy, HJS Fernando, B Sarvadal, J Reuder, J Jakobsen, Energy Procedia, 137C, pp. 428-442
2. 3D winds and turbulence characteristics of the atmospheric boundary layer (2014), R Barthelmie, P Crippa, H Wang, CM Smith, R Krishnamurthy, A Choukulkar, R Calhoun, D Valyou, P Marzocca, D Matthiesen, G Brown. Bulletin of Atmospheric and Meteorological Sciences. 95(5), 743-756.
3. Coherent Doppler lidar for wind farm characterization (2013), R Krishnamurthy, A Choukulkar, R Calhoun, J Fine, A Oliver, K Barr (2013), Wind Energy, 16(2), 189-206. DOI: 10.1002/we.539
4. Wind turbulence estimates in a valley by coherent Doppler lidar, R Krishnamurthy, R Calhoun, B Billings, J Doyle (2011), Meteorological Applications, 18(3), 361-371. DOI: 10.1002/met.263
5. Large-eddy simulation based retrieval of dissipation rate from coherent Doppler Lidar, R Krishnamurthy, R Calhoun, & HJS Fernando (2010), Boundary-Layer Meteorology, 136(1), 45-57.

PROFESSIONAL SERVICE

1. Member of the IEC 61400-15 standard committee on Assessment of Wind Resource, Energy Yield and Site Suitability input conditions for wind power plants 2014 – 2016
2. Interim-member of the IEC 61400-12 standard on Power Performance Testing 2013 - 2014

COLLABORATIVE PROJECTS

I. *MISO-BOB (2018)*: Monsoon Inter-seasonal oscillations in Bay of Bengal
II. *Perdigão (2017)*: Study of microscale complex flows for wind energy applications in Portugal
III. *CASPER (2017)*: Coupled Air Sea Processes and Electromagnetic ducting Research
IV. *WFIP2 (2016)*: Wind Forecasting Improvement Project II
V. *OBLEX-F1 (2015)*: Offshore Boundary Layer Experiment at FINO1 platform
VI. *CHATS (2007)*: Canopy Horizontal Array Turbulence Study
VII. *T-REX (2006)*: Terrain-Induced Rotor Experiment

RESEARCH & RELATED BUDGET - SECTION A & B, BUDGET PERIOD 1

*** ORGANIZATIONAL DUNS:** 824910376

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Notre Dame

*** Start Date:** 06-15-2019 *** End Date:** 06-14-2020 **Budget Period: 1**

A. Senior/Key Person

	Prefix	* First Name	Middle Name	* Last Name	Suffix	* Project Role	Base Salary ($)	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits ($)	* Funds Requested ($)
1.		Harindra	J.	Fernando		PD/PI	363,314.00				0.00	0.00	0.00
2.		Raghavendra		Krishnamurthy		Co-PD/PI					0.00	0.00	0.00

Total Funds Requested for all Senior Key Persons in the attached file

Additional Senior Key Persons: File Name: Mime Type: **Total Senior/Key Person** **0.00**

B. Other Personnel

* Number of Personnel	* Project Role	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits	* Funds Requested ($)

Total Number Other Personnel **Total Other Personnel**

Total Salary, Wages and Fringe Benefits (A+B) **0.00**

RESEARCH & RELATED Budget {A-B} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTION C, D, & E, BUDGET PERIOD 1

*** ORGANIZATIONAL DUNS:** 824910376

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Notre Dame

*** Start Date:** 06-15-2019 *** End Date:** 06-14-2020 **Budget Period: 1**

C. Equipment Description

List items and dollar amount for each item exceeding $5,000

Equipment Item	* Funds Requested ($)
1. RPG FMCW W-band scanning radar	480,445.00
Total funds requested for all equipment listed in the attached file	
Total Equipment	**480,445.00**

Additional Equipment: File Name: Mime Type:

D. Travel	Funds Requested ($)
1. Domestic Travel Costs (Incl. Canada, Mexico, and U.S. Possessions)	
2. Foreign Travel Costs	
Total Travel Cost	

E. Participant/Trainee Support Costs	Funds Requested ($)
1. Tuition/Fees/Health Insurance	
2. Stipends	
3. Travel	
4. Subsistence	
5. Other:	
Number of Participants/Trainees **Total Participant/Trainee Support Costs**	

RESEARCH & RELATED Budget {C-E} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTIONS F-L, BUDGET PERIOD 1

*** ORGANIZATIONAL DUNS:** 824910376

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Notre Dame

*** Start Date:** 06-15-2019 *** End Date:** 06-14-2020 **Budget Period: 1**

F. Other Direct Costs	**Funds Requested ($)**
1. Materials and Supplies	
2. Publication Costs	
3. Consultant Services	
4. ADP/Computer Services	
5. Subawards/Consortium/Contractual Costs	
6. Equipment or Facility Rental/User Fees	
7. Alterations and Renovations	
Total Other Direct Costs	**0.00**

G. Direct Costs	**Funds Requested ($)**
Total Direct Costs (A thru F)	**480,445.00**

H. Indirect Costs

Indirect Cost Type	**Indirect Cost Rate (%)**	**Indirect Cost Base ($)**	*** Funds Requested ($)**
		Total Indirect Costs	

Cognizant Federal Agency DHHS, Arif Karim, 214-767-3261

(Agency Name, POC Name, and POC Phone Number)

I. Total Direct and Indirect Costs	**Funds Requested ($)**
Total Direct and Indirect Institutional Costs (G + H)	**480,445.00**

J. Fee	**Funds Requested ($)**

K. Total Costs and Fee	**Funds Requested ($)**
Total Costs and Fee (I + J)	**480,445.00**

L. * Budget Justification File Name: Budget_Justification_6_28_181015555609.pdf Mime Type: application/pdf

(Only attach one file.)

RESEARCH & RELATED Budget {F-L} (Funds Requested)

RESEARCH & RELATED BUDGET - Cumulative Budget

	Totals ($)
Section A, Senior/Key Person	**0.00**
Section B, Other Personnel	
Total Number Other Personnel	
Total Salary, Wages and Fringe Benefits (A+B)	**0.00**
Section C, Equipment	**480,445.00**
Section D, Travel	
1. Domestic	
2. Foreign	
Section E, Participant/Trainee Support Costs	
1. Tuition/Fees/Health Insurance	
2. Stipends	
3. Travel	
4. Subsistence	
5. Other	
6. Number of Participants/Trainees	
Section F, Other Direct Costs	
1. Materials and Supplies	
2. Publication Costs	
3. Consultant Services	
4. ADP/Computer Services	
5. Subawards/Consortium/Contractual Costs	
6. Equipment or Facility Rental/User Fees	
7. Alterations and Renovations	
8. Other 1	
9. Other 2	
10. Other 3	
Section G, Direct Costs (A thru F)	**480,445.00**
Section H, Indirect Costs	
Section I, Total Direct and Indirect Costs (G + H)	**480,445.00**
Section J, Fee	
Section K, Total Costs and Fee (I + J)	**480,445.00**

University of Notre Dame

Budget Justification

Equipment

The total amount of $480,445 is requested for the purchase of a RPG FMCW W-band scanning radar.

The DURIP funding will be solely used for the purchase of the proposed RPG FMCW W-band scanning radar. The radar will be immediately deployed for two existing field projects, one dealing with Monsoon Intra-Seasonal Oscillations in the Bay of Bengal (summer 2019) and the other on the thermodynamic processes underlying the life cycle of fog, both funded by the ONR (Fall 2019). A dedicated motion stabilizing platform is available for the radar for mobile platform applications. The maintenance of the radar will be covered by the internal funds. The maintenance of the radar falls under the purview of Mr. Scott Coppersmith (an electrical engineer), and his time is covered by University of Notre Dame Dean's funds provided to the PI as a part of research support services. Mr. Coppersmith maintains the two previous pieces of DURIP equipment, Microwave Radiometer (2013 DURIP) and the Triple Lidar system (2015 DURIP). The service of the equipment beyond the warranty period will be covered by research grants. The price quotation from the manufacturer and a letter supporting the sole sourcing of the instrument follow.

ATS Services Ltd.
35 Auriga Drive, Unit 213
Ottawa, ON Canada K2E 8B7

Phone: 1-888-845-4913
Fax: 1-613-221-9815

Quotation: ATSTECH 181406-1
Date: June 15, 2018
Valid until 31/10/2018

NCAGE code: L0DG0
DUNS: 209545966

To: Professor H.J.S. Fernando
Departments of Civil and Environmental
Engineering and Earth Sciences
University of Notre Dame, Notre Dame, IN 46556

Email: *hfernand@nd.edu*
Phone: 574-631-9346

Price Quotation for
RPG FMCW 94 GHz (W-band) Cloud Radar

Item	Item no.	Description	Quantity	Unit Price	Total Amount
1	47009006	**RPG-FMCW-94-DP-G1 /S** 94 GHz (W-band) FMCW cloud radar, including: - STSR mode, prepared for scanning operation - Providing reflectivity and Doppler profiles - Dual polarisation configuration (V & H) - TCP/IP connectivity for control and data extraction - Passive channel at 89 GHz for integrated LWP measurements - High performance embedded PC - Integrated weather station with P, T, RH, RR, Snow, WS, WD - Precipitation mitigation system with powerful dew blower - External liquid nitrogen (LN2) target with stand, for absolute calibration - Complete software package for radar internal PC and external host PC - LWP retrievals and software synergy (data exchange) with profiling radiometer - Including all cables (power, fibre-optic data)	1 Pcs.	346,500.00	346,500.00
2	47009007	**Positioner System** for RPG-FMCW 94 GHz For moving the RPG-FMCW 94 GHz Radar in Azimuth and Elevation	1 Pcs.	78,750.00	78,750.00
3	41000002	**Host PC** Laptop for remote control via Ethernet/LAN interface with software loaded and tested	1 Pcs.	2,815.00	2,815.00
4	40000005	**Factory Training** (2 days) Comprehensive training at RPG premises for setup and operation of the instrument	1 Pcs.	3,780.00	3,780.00
5	40000069	**Radar Warranty Extension** An RPG cloud radar still in warranty will receive an extension of the initial warranty conditions by 12 months.	1 Pcs	42,750.00	42,750.00
7	40000055	**Shipping FOB Destination** Airfreight, handling, in-transit insurance, customs clearance	1 Pcs.	5,850.00	5,850.00
Plus applicable local taxes. (0.00% with Government exemption tax code)				**Total USD**	**480,445.00**

ATS Services Ltd 35 Auriga Drive, Unit 213, Ottawa, ON, Canada K2E 8B7
Email: jmalenfant@atstechnology.ca Ph.1-888-845-4913 or 1-613-288-9139 Ext. 203

Radiometer Physics
A Rohde & Schwarz Company

RPG Radiometer Physics GmbH
Werner-von-Siemens-Str. 4
D-53340 Meckenheim
Telefon 02225-99981-0
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35 Auriga Dr, Unit 213
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Dr. Harald Czekala
1RP-RS

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Harald.czekala@radiometer-physics.de

Meckenheim, 18.06.2018

Letter of sole source

Ladies/Gentlemen:

Per request from Professor H.J.S. Fernando, University of Notre Dame, Department of Civil and Environmental Engineering and Earth Sciences, Notre Dame, IN 46556, USA, we wish to confirm that to the best of our knowledge the following radar system, including its specific combination of advanced features, is basically not being offered by any other manufacturers.

The RPG-FMCW 94 GHz (W-band) radars are delivered with a complete set of accessories to operate the radar in an outdoor environment and to perform regular instrument calibrations. This includes (in addition to the radar itself) a radar stand with a rain mitigation system, a set of power and data cables, a signal converter, an external liquid nitrogen calibration target , a weather station plus GPS receiver, a complete software package for the radar internal PC and external host PC (optional) and several tools to assemble the system.

As optional hardware, an elevation / azimuth scanner is also being offered to replace the radar stand and to complete Professor Fernando's technical requirements for his fog study and other future research activities. Incidently RPG FMCW W-band Cloud Radar can also measure the same polarimetric parameters as polarimetric weather radars (including differential reflectivity, correlation coefficient, and differential phase shift). Its unique advantage is that it can measure spectrally resolved polarimetric parameters (Doppler polarimetry). This is not widely known at the moment and it has a great potential for researchers.

Our special offer consists of:

- 94 GHz (W-band) FMCW Cloud Radar (STSR mode, thus prepared for scanning operation)
- Solid-State Technology / Low Power Source / Low Maintenance Cost
- Dual Polarized Configuration for horizontal linear and vertical linear

HC
GM

RPG Radiometer Physics GmbH | Sitz Meckenheim | Geschäftsführer: Dr. Thomas Rose, Achim Walber | HRB 10291 Bonn
UST-IDNr./VAT/CEE no: DE 123 377 395 | Deutsche Bank AG München I BLZ 700 700 10 | Kto-Nr. 202 399200
BIC (SWIFT-Code): DEUTDEMMXXX | IBAN: DE02 70070010 0202399200

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Telefon 02225-99981-0
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- Very High Sensitivity (down to -55 dBz)
- High Dynamic Range (-55 to +20 dBz)
- Complete Rain Mitigation System
- Full Networking Capability (TCP/IP)
- Passive channel for absolute calibration with liquid nitrogen (LN2)
- Built-in weather station to monitor weather conditions at ground level
- Embedded 89 GHz channel for measurements of integrated liquid water path (LWP). The LWP retrievals are part of the radar software package included in the delivery.
- Positioner system for moving the radar in azimuth and elevation
- Special adaption of process modes, allowing the researchers to focus on certain parameters, permitting re-coding of the chirps while radar is in operation
- Compact and easily transportable
- Implemented software synergy (data exchange) with profiling radiometer

These particular Cloud Radar systems are the result of a recent product development that RPG technology established through their laborious and continuous R & D.

With RPG radar high sensitivity to tiny particles (-55 dBZe at 500 m with 5 m resolution and 3 s time sampling rate) and range resolution down to 1 m, it makes our scanning radar to be an important tool for investigation of fog layers. Well-pronounced linear dependence of the signal attenuation on liquid water content provides a good reference for a validation of fog predicting models and radar-based estimates of visibility.

For the high precision of our radar systems, we recognised that the radar receiver and its direct detection channel need to be calibrated by two absolute temperature standards, namely a target at ambient temperature and another one at liquid nitrogen (LN2) temperature.

A major progress has been achieved in radar calibration accuracy (±0.5 dBz). We have developed a novel liquid nitrogen (LN2) cooled precision calibration target for the radar. In addition, the RPG radars can be calibrated with the same precision by operating a RPG-HATPRO radiometer side by side. Such a configuration has the additional benefit of easy software integration, so that the radar software uses humidity and temperature profiles from the radiometer in a perfect synergy.

Currently we have FMCW (W-band) Cloud Radar systems in use at various sites, operated by different agencies. Two of which are:

Ny-Ålesund, Spitzbergen, Norway
Purchased by University of Cologne, Germany

Radar model RPG-FMCW-94-SP

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www.radiometer-physics.de

- Deployed since June 2016
- Observations of clouds in the Arctic

Verbier, Switzerland

Purchased by École polytechnique fédérale de Lausanne (EPFL), Switzerland

Radar model RPG-FMCW-94-SP

- Delivered at the end of 2016
- Deployed at a ski resort for ice particles investigation (2370 m above sea level)
- At a later time: Campaign deployment in PyeongChang (South Korea) at the Olympic games 2018

The latest deployments have been made to the University of Helsinki (Hyytiala measurement site, Finland) and to the University of Granada (Spain).

If you have any questions about the above mentioned radar system, please do not hesitate to contact us again.

Sincerely,

Dr. Harald Czekala
Manager
Remote Sensing 1RP-RS

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Fax: +49 (0) 2225 999 81-99

Dr. Gerrit Maschwitz
Product Manager
Remote Sensing 1RP-RS

Project Abstract

The Project Abstract must not exceed one page and must contain a summary of the proposed activity suitable for dissemination to the public. It should be a self-contained description of the project and should contain a statement of objectives and methods to be employed. It should be informative to other persons working in the same or related fields and insofar as possible understandable to a technically literate lay reader. This Abstract must not include any proprietary/confidential information.

* Please click the add attachment button to complete this entry.

Abstract1015555593.pdf

Attachments

ProjectAbstractAddAttachment

File Name	Mime Type
Abstract1015555593.pdf	application/pdf

Publicly Releasable

Abstract:

This proposal seeks DURIP funding to acquire a Frequency Modulated Continuous Wave (FMCW) W-band radar for research involving atmospheric water droplets (hydrometeors; e.g., fog, clouds and rain). Hydrometeors cover a range of sizes, and radars operating at different frequency bands are used for their observations. For instance, Ka (~35 GHz) and W (~94 GHz) band radars operating at millimeter-wavelength are employed to observe cloud microphysical processes, measure the velocity structure, estimate rain rates, obtain distribution of small cloud particles from non-precipitating or weakly precipitating clouds, and retrieve information on in-cloud turbulence. Where higher sensitivity is needed and the size and weight of the instrument are not a factor, Ka band radars that require larger antennas are used. Where instrument compactness and weight are a limiting factor, such as deployment on a research vessel with the radar resting on a motion compensated platform, W-band is the radar of choice for hydrometeor research. Recent advent of a new generation of user-friendly commercial FMCW W-band radars has enabled researchers and observatories to engage in hygrometric research without facing onerous infrastructure and maintenance challenges. The radar requested in this proposal, the FMCW W-band cloud Doppler radar (model RPG-FMCW-94-DP-G1/S) manufactured by Radiometer Physics GmbH (RPG), is of this type. It is a dual polarization, single frequency turnkey system provided with an elevation/azimuth scanner designed for cloud and fog research. These radars measure small water droplets of millimeter and submillimeter scales ($\geq 10\ \mu m$) enabling retrieval of useful quantities such as reflectivity, mean radial velocity, spectrum width, skewness and kurtosis for characterization of atmospheric water droplets. Its compactness, low power (several Watts), agility, and high space-time resolution (~ 1m spatial and integration times of seconds) allow characterization of small cloud drops and ice particles, fog, liquid and solid precipitation, and even non-meteorological scatterers such as insects and pollen. This off-the-shelf instrument comes with a comprehensive, adaptive software interface. The versatility of the instrument can be significantly enhanced by operating it alongside other available instruments to the PI such as Doppler lidars and microwave radiometers. It is the pioneering commercial W-band radar of its kind, extensively field tested, and currently used by several European observatories. It will greatly add to the atmospheric instrumentation capabilities of University of Notre Dame, thus enhancing PIs ability to characterize fog and clouds in two Office of Naval Research funded large international projects and in other existing and future federally funded projects. Close collaboration with Department of Defense (DOD) and non-DOD laboratories and universities is a hallmark of the PIs projects, and thus a wider scientific constituency will benefit from the acquisition of proposed instrument.