Wind Farms and Radar

Study Leader:
Michael Brenner

Contributors Include:
Shelly Cazares (IDA Intern)
Michael J. Cornwall
Freeman Dyson
Douglas Eardley
Paul Horowitz
Darrell Long
Jeremiah Sullivan
John Vesecky
Peter J. Weinberger

January 2008

JSR-08-125

JASON
The MITRE Corporation
7515 Colshire Drive
McLean, Virginia 22102-7508
(703) 983-6997

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
January 2008

2. REPORT TYPE
Technical

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Wind Farms and Radar

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
M. Brenner et al.

5d. PROJECT NUMBER
13089022

5e. TASK NUMBER
PS

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The MITRE Corporation
JASON Program Office
7515 Colshire Drive
McLean, Virginia 22102

8. PERFORMING ORGANIZATION REPORT NUMBER
JSR-08-126

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

US Department of Homeland Security
Science and Technology Directorate
Washington, DC 20528

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; Distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

As part of its 2008 Winter Study, JASON was asked by the Department of Homeland Security (DHS) to review the current status of the conflict between the ever-growing number of wind-turbine farms and air-security radars that are located within some tens of miles of a turbine farm.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Mr. Kevin “Spanky” Kirsch
a. REPORT	b. ABSTRACT	c. THIS PAGE			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	UL		202-254-6425

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Contents

1 EXECUTIVE SUMMARY

Wind farms interfere with radar. This interference has led the FAA, the DHS, and the DOD to contest many proposed wind turbines in the line of sight of radar, stalling development of several thousands of MW of wind energy. A large number of such denials is a serious impediment to the nation's mandated growth of sustainable energy.

There is no fundamental physical constraint that prohibits the accurate detection of aircraft and weather patterns around wind farms. On the other hand, the nation's aging long range radar infrastructure significantly increases the challenge of distinguishing wind farm signatures from airplanes or weather.

Progress forward requires the development of mitigation measures, and quantitative evaluation tools and metrics to determine when a wind farm poses a sufficient threat to a radar installation for corrective action to be taken. Mitigation measures may include modifications to wind farms (such as methods to reduce radar cross section; and telemetry from wind farms to radar), as well as modifications to radar (such as improvements in processing; radar design modifications; radar replacement; and the use of gap fillers in radar coverage).

There is great potential for the mitigation procedures, though there is currently no source of funding to test how proposed mitigations work in practice. In general, the government and industry should cooperate to find methods for funding studies of technical mitigations. NOAA has an excellent research plan, but no adequate funding to carry it out.

Once the potential for different mitigations are understood, we see no scientific hurdle for constructing regulations that are technically based and simple to understand and implement, with a single government entity taking responsibility for overseeing the process. In individual cases, the best solution might be to replace the aging radar station with modern and flexible equipment that is more able to separate wind farm clutter from aircraft. This is a win-win situation for national security, both improving our radar infrastructure and promoting the growth of sustainable energy.

Regulatory changes for air traffic could make considerable impact on the problem. For example, the government could consider mandating that the air space up to some reasonable altitude above an air-security radar with potential turbine interference be a controlled space, with transponders required for all aircraft flying in that space. This would both solve the problem of radar interference over critical wind farms and would provide a direct way to identify bad actors, flying without transponders.

Current circumstances provide an interesting opportunity for improving the aging radar infrastructure of the United States, by replacing radar that inhibits the growth of wind farms with new, more flexible and more capable systems, especially digital radar hardware and modern computing power. Such improvements could significantly increase the security of U.S. airspace.

2 INTRODUCTION

As part of its 2008 Winter Study, JASON was asked by the Department of Homeland Security (DHS) to review the current status of the conflict between the ever-growing number of wind-turbine farms and air-security radars that are located within some tens of miles of a turbine farm.

In studying this topic, we were very fortunate to have briefings from talented scientists and engineers from the DOE, FAA, DOD and industry. We would like to thank Gary Seifert (Idaho National Laboratory); Mark Carmouche (FAA); Peter Markus (FAA); Jim Perry (Sensis); Geoff Blackman (Regulus); Shawn Jordan (84 Rades); Tim Crum (NOAA); Karl Dahlhauser (DOD); and Stu Webster (Clipper Wind). Special thanks to Spanky Kirsch (DHS) for both his help in teaching us about this problem, as well as identifying such an excellent list of speakers.

Wind turbines, with tip speeds of 6-7 times the wind speed, can create clutter interference and possibly significant Doppler interference with the very sensitive radars fielded by the FAA, DOD, NOAA, and other agencies. Aircraft targets and, to some extent, weather features seen by NOAA radars, can be temporarily lost, fail to be located, shadowed by the radar signature of the turbine farm, or misidentified, and the wind turbines may also lead to false detection of aircraft. These problems have led the FAA to issue a number of Notices of Presumed Hazard, stalling further work on the installation of several thousand MW of wind turbine power, and the DHS has issued an interim policy calling for contesting any wind-turbine installations that are in line of sight of the impacted radars. In a number of cases the military has claimed that the wind-turbine farms are an encroachment on military radar facilities, and have stalled construction on the turbine farm. Similar problems have arisen in other countries where wind power is expanding.

As a result, the 2006 National Defense Authorization Act required the DoD to prepare a report both on the effect of wind-turbine interference on military readiness, and on possible mitigation measures. The report, which was briefed to us by Karl Dahlhauser from DDR&E, concluded that there was indeed significant impact from wind turbines, and that the best solution is, in their words, "non-technical mitigation". By this they mean that the preferred solution is to declare encroachment and block the installation of offending turbines, rather than to attempt to find technical means of ameliorating the turbine impact.

We favor a different approach, based on mitigation approaches that will be developed cooperatively by the government stake-holders in the radar operations and the wind-turbine farm developers. This approach will involve:

- Move to a *technically based* rule system for determining the severity of the interference. Quantitative metrics for when turbine farm interference has an unacceptable impact on air security should be developed and consistently applied. The evaluation system should include include requirements that the cost and efficacy of potential mitigation approaches be included as part of the decision process.

- Study in some detail a number of promising technical approaches that we outline later on, to determine whether –and in what combination– they can reduce interference to acceptable levels.

- Provide for, possibly in cooperation with the American Wind Energy Association (AWEA) or similar turbine-developer organizations, an appropriately-funded research and development effort on technical mitigation strategies.

- Consider the mitigation potential of regulatory changes for air traffic, such as making the air space up to some reasonable altitude above an air-security radar with potential turbine interference a controlled space, with transponders required for all aircraft flying in that space.

The rest of our report provides more detail.

3 FINDINGS

Wind farms interfere with the radar tracking of airplanes and weather. The velocity of the blade tips can reach 170 mph, causing significant Doppler clutter. This creates problems and issues for several stake holders, including DHS, DOD, FAA and NOAA. Examples of issues include: a wind farm located close to a border might create a dead zone for detecting intruding aircraft; current weather radar software could misinterpret the high apparent shear between blade tips as a tornado; current air traffic control software could temporarily lose the tracks of aircraft flying over wind farms.

Despite these difficulties, there is no fundamental physical constraint preventing detection and mitigation of windmill clutter. The technologies of wind turbines and radar can coexist. On the other hand, the nation's aging long range radar infrastructure increases the challenge of distinguishing wind farm signatures from airplanes or weather; this is especially so since many promising mitigation measures (discussed below) are based on digital processing capabilities. The challenge is to evolve the current system, and to design future sytems to effectively distinguish and mitigate a source of clutter that was not anticipated in the original design specifications for either radar or wind farms.

Progress forward requires the development of not only mitigation measures, but also of quantitative evaluation tools and metrics to determine when a wind farm poses a sufficient threat to a radar installation for corrective action to be taken.

3.1 Mitigation Measures

There are a variety of mitigating measures that could be employed to alleviate the problem. In practical circumstances mitigation will likely consist of a collection of techniques; these may vary on a site-to-site basis. Mitigation measures can be divided into modifications of the wind farm, and modifications of the radar. *Wind farm* modifications include:

1. *Reduced Radar Signature* Several groups have suggested modifications to the turbine blades that would modify or reduce their radar signature. One proposal is to put an active layer on the outside of the turbine blades to modulate dynamically the blade Doppler signature. These modulations, it is claimed, could shift the Doppler frequency spectrum from the blades to lie outside the range of frequencies processed by the radar. It is not known, to us at least, whether such modifications to the outside of the blades would produce unacceptable changes to their aerodynamic properties or whether they would last the lifetime of the blades. Another proposal, from QinetiQ, is to modify the *inside* of the blades (which are hollow and made of dielectric materials that are almost transparent to the radar beam) with layers of circuits and reflectors that would reduce the strength of the radar return from the blades. Any such reduction is highly frequency-specific. It is a research project to show that these measures would be effective at the relatively long (L-band) radar wavelengths typical of US air-security radars, whose size is in the range of the sizes of the tips of the turbine blades. This is the regime where radar signature reduction measures are typically the most difficult. The potential for signature reduction is considerable; QinetiQ has carried out tests with shorter-wavelength radars on sections of wind turbine blades that are larger than the tips and claims a factor of 100 reduction in signature. They also claim that the cost penalty for such treatment is of the order of 10% of the total blade cost.

2. *Telemetry from turbines to radars* Although it may be possible to use sophisticated radar data processing to blank out turbine radar returns while preserving returns from objects of interest, such as aircraft, it would seem much easier to do so if the actual configuration of the turbines were known at every instant. Data about the instantaneous state

of every turbine (angular velocity, phase, azimuthal orientation of the turbine axis, and pitch angle) could be telemetered to the radar processors and electronics. The data stream is quite small, probably no more than 50 to 100 bits per second per turbine, and the turbine-mounted sensors needed for the four quantities listed above are straightforward and not expensive (although not necessarily available without retrofits). Armed with this information, the processor, with the aid of a relatively simple model of the turbine radar cross section, could make a near real-time calculation of the time-varying amplitude expected from each turbine in the farm and subtract it coherently from the radar input signal. The potential of this technology is promising, although unproven; we believe it is worth investigating. Significant networking, data processing, and implementation challenges might exist, to be investigated in a research project.

Radar system modifications can be further subdivided into modifications of radar hardware and of radar software. Useful radar software modifications presuppose a radar with digital output and the capability to mount sufficiently powerful processing power. Although it remains to be shown how much processing power will be enough, a good basis of comparison for a radar with modern and flexible processing is NOAA's NEXRAD weather radar. In contrast to older radars, the most modern NOAA radar can stream raw data into an external laptop, which furnishes it with plenty of computing power for its data processing needs. Unfortunately, many long-range air-security radars cannot take advantage of modern processing power because their processor approaches are hardwired and changes in processing software require changing hardware. (See however, item 3 below.)

1. *Processing* For *long-range* radar, we were shown only processed and filtered data, from which primary aircraft tracks were sometimes lost over wind farms. Secondary (i.e., transponder, or "beacon") tracks were rarely affected. While it is clear that the filtered data loses aircraft over wind farms, the extent to which there is significant infor-

mation loss in the raw data is completely unclear: The question is whether aircraft can be detected near wind farms, in the raw, unprocessed data. Although we were not shown raw data for aircraft, we were shown the evolution of range and doppler signals for a large weather front passing near a wind farm in the NEXRAD weather radar. There was a clear distinction between the signals for the weather front and the wind farm, strongly suggesting that automated methods could be designed for discriminating between the two. It is evident to the eye that the completely stationary wind farm could be distinguished from the moving weather in dynamic (movie-like) imagery, and this must be kept in mind for processing improvements. As a caution, without access to raw data for aircraft, we cannot say whether the distinction between aircraft and wind farm signatures will be as clear to the eye.

2. *Radar Design Modifications* The radar could be modified to have shorter pulses, a higher pulse repetition frequency (PRF), local oscillators coherent over a turbine blade period, or multiple elevation beams to avoid ground scraping. The higher PRF allows for painting a given turbine blade with more pulses before the blade rotates significantly. The design of the entire radar signature (including side lobes) needs to take into account the presence of wind farms. For example we were briefed about an incident where the interference with a wind farm occurred in a side lobe.

3. *Radar Replacement* Radars which don't have the capabilities to mitigate wind farm interference could simply be replaced, in a phased upgrade of the aging radar infrastructure. The new radar would incorporate multidimensional detection, with greatly enhanced processing, with pulse shapes designed to optimally distinguish between aircraft and wind farms. The cost of a single radar installation was said to be in the range of \$3–8M, to be compared with the \$2–4M cost of a *single* wind turbine, and the roughly \$0.5M annual electric production of a single turbine (5×10^6 kWh, at \$0.10/kWh retail). A wind farm can

have hundreds of turbines.

4. *Gap Fillers* When a wind farm has caused an unacceptable loss of coverage, a supplementary gap filler radar could be installed,with appropriate data fusion. The gap filler, by allowing a second view of the wind farm radar interference, makes it considerably easier to process this interference out through data fusion.

We believe there is great potential for these mitigation procedures. However, we were shown relatively little effort aimed at understanding how each would work in practice. According to our briefers, there is no source of research funding to study the efficacy of the various mitigation procedures. Neither the wind farm manufacturers (AWEA) nor government entities support significant research activies. NOAA has an excellent research plan, but no adequate funding to carry it out.

3.2 Evaluation Tools

Although wind farm interference with radar is well documented, it is important to have quantitative metrics to determine in *particular* situations the impact of this interference on the required radar performance. Such metrics would depend on the particular situation: for example the metric used by the FAA to evaluate radar needs over low population density airspace would be quite different than those used by DHS for border security.

The evaluation of the potential impact of wind farms on specific radars in specific situations would be greatly aided with software tools. Such evaluation tools were not discussed during our briefings, and, to our knowledge, do not currently exist. The development of such software tools requires gathering enough experimental data to allow formulation of a model for the radar signatures of wind turbine generators at least as a function of type, rotation rate, aspect angle, and blade angle. Such a model must be validated by testing against different experimental configurations. It could be determined whether wind farm signatures could be separated from those of aircraft on a particular radar, in terms of signal to noise, probability of detection, false alarm rate, etc. Particularly important is the gathering of I (in-phase) and Q (quadrature) radar data, rather than simply radar-return intensities. The extra phase information of the combined I and Q data make it possible to test coherent-processing software algorithms. Fortunately, a fair amount of useful I and Q data already exists, and more could be gathered, for example by use of the AFRL Mobile Radar Laboratory.

3.3 Other Findings

The United States' long range radar infrastructure is aging and inflexible. Perimeter radar systems are typically the ARSR-4, which was designed in the early 1990's. The radars in the interior of the United States are much older. Approximately 80% of the radars are a late 1950's design that was upgraded in the early 1980's; the rest were designed in the early 1970's. In contrast, computing speed has increased 600 fold since the early 1990s. We were told by an independent radar expert (M. Tuley, private communication) that even if the radar beam were physically modified to prevent direct line of site with a wind farm, the processing is often hard wired, and unchangeable for older systems. Unfortunately, some air-security radars are stuck with outdated and inflexible processing capabilities, far less than those of a current laptop computer. Any radar update program should strive to enable the radar to connect to modern computing power, with processors that are easily replaced as computing power continues on its exponential growth curve. Such development will allow flexible evolution of backend signal processing and mitigation algorithms. The limited capability and lack of flexibility in long range primary radar is a national security issue.

Current circumstances therefore lead to an interesting opportunity for improving the aging radar infrastructure of the United States, by replacing radar that inhibits the growth of wind farms with new, more flexible and more capable systems, especially digital radar hardware and modern computing power. Such improvements could significantly increase the security of U.S. airspace. Designing radars to be more robust in wind farm clutter environments is likely to be useful for future military or civilian radars used in foreign countries, with their significant wind farm densities.

3.4 Recommendations

1. We recommend that the Government move beyond a policy of unilaterally blocking turbine farms on the basis of any observable impact on existing radars, and move to a technically based rule system for determining the severity of the interference. The evaluation system should include a cost benefit analysis of mitigation strategies as outlined below. Once the potential for different mitigations are understood, we see no scientific hurdle for constructing regulations that are simple to understand and simple to implement, with a single government entity taking responsibility for overseeing the process.

2. The Government and developers should consider as an alternative giving developers the option of furnishing gap-filler radars, or contributing to the cost of replacement long-range radars, as part of the price for constructing turbine farms that would otherwise encroach. This way, the US not only eases the way to increased renewable energy supplies but improves an aging air-security radar infrastructure. The amount of developers' contributions should be established cooperatively through negotiations, not unilaterally by the Government, and will probably lie in the range of one to a few percent of the turbine farm construction costs.

3. A research program on technical mitigations needs to be started. This program should

(a) Gather I and Q data and use this as a test bed for software processing. The tests should be carried out under two sets of assumptions:

    i. Assume no real-time knowledge of turbines

    ii. Assume real-time knowledge of turbine motions, e.g. through telemetry.

(b) Make a full scale test of radar signature reduction techniques at the wavelengths used in FAA and US Radars.

(c) Gather data with something like the AFRL mobile lab to (i) characterize turbines and (ii) determine the needed characteristics of a gap filler radar.

4. We recommend that some combination of the Government and the turbine-farm industry fund and carry out research on the technical mitigation measures we have discussed. Currently neither the government nor the wind farm manufacturers are making significant investments in research on mitigation measures. There is presently little incentive for the industry to sponsor research, and while the incentive may emerge in the future, for now we recommend that the Government jump-start the research process. Ultimately the wind farm manufacturers (the AWEA, or a similar organization) could need an EPRI (electric power research institute) equivalent, or alternatively could connect directly with EPRI.

5. The Government should evaluate as a mitigation strategy the impact of controlling air space over wind farms. An example is to require all traffic over a wind farm in a specified box of altitude and lateral extent to have transponders. This would not only help to identify potentially hostile flights (not transponding) but also might also come close to solving the interference problem for transponding aircraft.

DISTRIBUTION LIST

Assistant Secretary of the Navy
(Research, Development & Acquisition)
1000 Navy Pentagon
Washington, DC 20350-1000

Assistant Deputy Administrator for
Military Application [5]
NA-12
National Nuclear Security Administration
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

DARPA Library
3701 North Fairfax Drive
Arlington, VA 22203-1714

Director of Space and SDI Programs
SAF/AQSC
1060 Air Force Pentagon
Washington, DC 20330-1060

Deputy Under Secretary of
Defense Science & Technology
3040 Defense Pentagon
Washington, DC 20301-3040

Headquarters Air Force XON
4A870 1480 Air Force Pentagon
Washington, DC 20330-1480

IC JASON Program [2]
Chief Technical Officer/OCS
2P0104 NHB
Central Intelligence Agency
Washington, DC 20505-0001

JASON Library [5]
The MITRE Corporation
3550 General Atomics Court
Building 29
San Diego, CA 92121-1122

Records Resource
The MITRE Corporation
Mail Stop D460
202 Burlington Road, Rte 62
Bedford, MA 01730-1420

Reports Collection
Los Alamos National Laboratory
Mail Station 5000
MS A150
PO Box 1663
Los Alamos, NM 87545

Superintendent
Code 1424
Attn: Documents Librarian
Naval Postgraduate School
Monterey, CA 93943

U. S. Department of Energy
Chicago Operations Office Acquisition and
Assistance Group
9800 South Cass Avenue
Argonne, IL 60439

U S Army Space & Missile Defense Command
Attn: SMDC-ZD (Dr. Swinson)
PO Box 1500
Huntsville, AL 35807-38017

Dr. Albert Brandenstein
Chief Scientist
Office of Nat'l Drug Control Policy Executive
Office of the President
Washington, DC 20500

Mr. Thomas D’Agostino
U.S. Dept of Energy
National Nuclear Security Administration
1000 Independence Avenue, SW
NA-10 FORS Bldg
Washington, DC 20585

Dr. James F. Decker
Principal Deputy Director
Office of Science, SC-2/Forrestal Building
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Ms. Shirley A. Derflinger
Management Analysis
Office of Science for Biological &
Environmental Research
SC-23/Germantown Building
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585-1290

Dr. Jerry Elwood
Acting Associate Director of Science for
Biological and Environmental Research
Germantown Building / SC-23
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585-1290

Mr. Dan Flynn
Program Manager
DI/OTI/SAG
5S49 OHB
Washington, DC 20505

Dr. Paris Genalis
Deputy Director
OUSD(A&T)/S&TS/NW
The Pentagon, Room 3D1048
Washington, DC 20301

Mr. Bradley E. Gernand
Institute for Defense Analyses
Technical Information Services
Room 8701
4850 Mark Center Drive
Alexandria, VA 22311-1882

Dr. Lawrence K. Gershwin
NIC/NIO/S&T
2E42, OHB
Washington, DC 20505

Dr. Alfred Grasso
President & CEO
The MITRE Corporation
Mail Stop N640
7515 Colshire Drive
McLean, VA 22102-7508

Dr. Barry Hannah
Reentry Systems Branch Head, Navy Strategic
Systems Programs
Strategic Systems Programs (Attn: SP28)
2521 Clark Street, Suite 1000
Arlington, VA 22202-3930

Mr. Hal Hagemeir
Operations Manager
National Security Space Office (NSSO)
PO Box 222310
Chantilly, VA 20153-2310

Dr. Robert G. Henderson
Staff Director
The MITRE Corporation
Mailstop MDA/ Rm 5H305
7515 Colshire Drive
McLean, VA 22102-7508

Dr. Bobby R. Junker
Office of Naval Research
Code 31
800 North Quincy Street
Arlington, VA 22217-5660

Dr. Andrew F. Kirby
DO/IOC/FO
6Q32 NHB
Central Intelligence Agency
Washington, DC 20505-0001

Mr. Kevin “Spanky” Kirsch [5]
Director, Special Programs
US Department of Homeland Security
Science and Technology Directorate
Washington, DC 20528

Dr. Anne Matsuura
Air Force Office of Scientific Research (AFOSR)
Program Manager, Atomic & Molecular Physics
875 N. Randolph Street
Suite 235, Room 3112
Arlington, VA 22204

Dr. Daniel J. McMorrow
Director, JASON Program Office
The MITRE Corporation
Mailstop T130
7515 Colshire Drive
McLean, VA 22102-7508

Dr. Julian C. Nall
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA 22311-1882

Mr. William Ostendorff
Principal Deputy Administrator for
Nuclear Security
1000 Independence Avenue, SW
NA-1, Room 7A-049
Washington, DC 20585

Mr. Thomas A. Pagan
Deputy Chief Scientist
U.S. Army Space & Missile Defense Command
PO Box 15280
Arlington, VA 22215-0280

Dr. John R. Phillips
Chief Scientist, DST/CS
2P0104 NHB
Central Intelligence Agency
Washington, DC 20505-0001

Dr. William S. Rees, Jr.
OSD/DDR&E
Deputy Under Secretary of Defense for
Laboratories and Basic Sciences
3030 Defense Pentagon
Room 3C913A
Washington, DC 20301-3030

Dr. John Schuster
Submarine Warfare Division
Submarine, Security & Tech Head (N775)
2000 Navy Pentagon, Room 4D534
Washington, DC 20350-2000

Dr. Alan R. Shaffer
Office of the Defense Research and Engineering
Director, Plans and Program
3040 Defense Pentagon, Room 3D108
Washington, DC 20301-3040

Dr. Frank Spagnolo
Advanced Systems & Technology
National Reconnaissance Office
14675 Lee Road
Chantilly, VA 20151

Mr. Anthony J. Tether
DIRO/DARPA
3701 N. Fairfax Drive
Arlington, VA 22203-1714

Dr. Bruce J. West
FAPS - Senior Research Scientist
Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. Linda Zall
Central Intelligence Agency
DS&T/OTS
3Q14, NHB
Washington, DC 20505-00