

**AFRL-AFOSR-UK-TR-2012-0014**



## **The Energy Spectrum of Accelerated Electrons from Wave-plasma Interactions in the Ionosphere**

**Mike J. Kosch**

**Lancaster University  
Physics Department  
Bailrigg  
Lancaster, United Kingdom LA1 4YB**

**EOARD Grant 10-3036**

**Report Date: June 2012**

**Final Report for 10 March 2010 to 31 December 2011**

**Distribution Statement A: Approved for public release distribution is unlimited.**

**Air Force Research Laboratory  
Air Force Office of Scientific Research  
European Office of Aerospace Research and Development  
Unit 4515 Box 14, APO AE 09421**

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                       |                                |                                       | Form Approved OMB No. 0704-0188                                      |                                                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|--------------------------------|---------------------------------------|----------------------------------------------------------------------|-----------------------------------------------------------------|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing 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 Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. 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.<br><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                      |                       |                                |                                       |                                                                      |                                                                 |
| 1. REPORT DATE (DD-MM-YYYY)<br>29-06-2012                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                       | 2. REPORT TYPE<br>Final Report |                                       | 3. DATES COVERED (From – To)<br>10 March 2010 – 31 December 2011     |                                                                 |
| 4. TITLE AND SUBTITLE<br><br>The Energy Spectrum of Accelerated Electrons from Wave-plasma Interactions in the Ionosphere                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                       |                                |                                       | 5a. CONTRACT NUMBER<br>FA8655-10-1-3036                              |                                                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                       |                                |                                       | 5b. GRANT NUMBER<br>Grant 10-3036                                    |                                                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                       |                                |                                       | 5c. PROGRAM ELEMENT NUMBER<br>61102F                                 |                                                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                       |                                |                                       | 5d. PROJECT NUMBER                                                   |                                                                 |
| 6. AUTHOR(S)<br><br>Professor Michael J. Kosch                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                       |                                |                                       | 5d. TASK NUMBER                                                      |                                                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                       |                                |                                       | 5e. WORK UNIT NUMBER                                                 |                                                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                       |                                |                                       |                                                                      |                                                                 |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>Lancaster University<br>Physics Department<br>Bailrigg<br>Lancaster, United Kingdom LA1 4WA                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                       |                                |                                       | 8. PERFORMING ORGANIZATION REPORT NUMBER<br><br>N/A                  |                                                                 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>EOARD<br>Unit 4515 BOX 14<br>APO AE 09421                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                       |                                |                                       | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>AFRL/AFOSR/RSW (EOARD)           |                                                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                       |                                |                                       | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)<br>AFRL-AFOSR-UK-TR-2012-0014 |                                                                 |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><br>Distribution A: Approved for public release; distribution is unlimited.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                       |                                |                                       |                                                                      |                                                                 |
| 13. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                       |                                |                                       |                                                                      |                                                                 |
| 14. ABSTRACT<br><br>A HAARP campaign was executed 1-15 April 2010. Dr. Bjorn Gustavsson attended from the UK with optical equipment from Sweden and the UK. Unfortunately, no useful data was obtained. It was therefore necessary to find the resources to repeat the campaign effort (see budget below). A HAARP campaign was executed 21 March – 5 April 2011. Dr. Bjorn Gustavsson (3/21 – 4/5) and Prof. Mike Kosch (3/21 – 3/25) attended from the UK with optical equipment from Sweden and the UK. Very good optical data was obtained at multiple wavelengths (427.8, 557.7, 630.0, 7320.0, 777.4 and 844.6 nm). However, the emissions were highly structured in space and time. This fact, and the lack of electron temperature data at HAARP, made data analysis difficult. It became necessary to develop a quantitative model of the pump-wave self-absorption in the ionospheric D-region (publication 1), a quantitative model of electron heating in the ionospheric F-region (publication 2) taking into account D-region absorption, and an empirical model of electron temperature and optical emission intensity enhancements (publication 3) as a function pump wave power. These tasks have been completed now (see publications 1-3) using the EISCAT facility with its incoherent scatter radar, so progress on the originally specified task at HAARP can now be made. |                       |                                |                                       |                                                                      |                                                                 |
| 15. SUBJECT TERMS<br><br>EOARD, Space Environment, Space Weather, Ionosphere, Ionospheric Heating, Radio Frequency Plasmas                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                       |                                |                                       |                                                                      |                                                                 |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                       |                                | 17. LIMITATION OF ABSTRACT<br><br>SAR | 18. NUMBER OF PAGES<br><br>5                                         | 19a. NAME OF RESPONSIBLE PERSON<br>SCOTT DUDLEY, Lt Col, USAF   |
| a. REPORT<br>UNCLAS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | b. ABSTRACT<br>UNCLAS | c. THIS PAGE<br>UNCLAS         |                                       |                                                                      | 19b. TELEPHONE NUMBER (Include area code)<br>+44 (0)1895 616162 |

## **Performance Report**

The energy spectrum of accelerated electrons from wave-plasma interactions in the ionosphere

Contract FA8655-10-1-3036

Prof. Mike Kosch (Lancaster University, UK)

### **Activities:**

A HAARP campaign was executed 1-15 April 2010. Dr. Bjorn Gustavsson attended from the UK with optical equipment from Sweden and the UK. Unfortunately, no useful data was obtained. It was therefore necessary to find the resources to repeat the campaign effort (see budget below).

A HAARP campaign was executed 21 March – 5 April 2011. Dr. Bjorn Gustavsson (3/21 – 4/5) and Prof. Mike Kosch (3/21 – 3/25) attended from the UK with optical equipment from Sweden and the UK. Very good optical data was obtained at multiple wavelengths (427.8, 557.7, 630.0, 7320.0, 777.4 and 844.6 nm). However, the emissions were highly structured in space and time. This fact, and the lack of electron temperature data at HAARP, made data analysis difficult. It became necessary to develop a quantitative model of the pump-wave self-absorption in the ionospheric D-region (publication 1), a quantitative model of electron heating in the ionospheric F-region (publication 2) taking into account D-region absorption, and an empirical model of electron temperature and optical emission intensity enhancements (publication 3) as a function pump wave power. These tasks have been completed now (see publications 1-3) using the EISCAT facility with its incoherent scatter radar, so progress on the originally specified task at HAARP can now be made.

### **Publications:**

1) A. Senior, M.T. Rietveld, F. Honary, W. Singer, and M.J. Kosch. Measurements and modelling of cosmic noise absorption changes due to radio heating of the D-region ionosphere. J. Geophys. Res., 116, A04310, doi:10.1029/2010JA016189, 2011.

2) A. Senior, M.T. Rietveld, T.K. Yeoman and M. J. Kosch. The dependence of F-region electron heating on HF radio pump power: measurements at EISCAT Tromsø. J. Geophys. Res., 117, A04309, doi:10.1029/2011JA017267, 2012.

3) C. J. Bryers, M. J. Kosch, A. Senior, M. T. Rietveld and T. K. Yeoman. EISCAT observations of pump-enhanced plasma temperature and optical emission excitation rate as a function of power flux. Accepted J. Geophys. Res., doi:10.1029/2012JA017897, 2012.

### **Budget:**

Purchases are round to the nearest Dollar, and an exchange rate of 1 GBP = 1.6 USD has been assumed.

### **Equipment:**

Filters (427.8, 777.4 & 844.6 nm), field-widening mirror, and lens: 1,340-

### **HAARP campaigns:**

2010 (1 person, including flights, accommodation, shipping and consumables): 4,638-

2011 (2 persons, including flights, rental car, accommodation, shipping and consumables): 9,482-

**Total:** 15,460-

The original budget (\$8580-) was exceeded by \$6880- and this was resourced from elsewhere.

### **Collaborations:**

The HAARP activity supported by EOARD has resulted in multiple collaborations between US scientists and the EISCAT facility in Norway, which is part-owned by the UK:

- 1) A proposal with Dr. Todd Pedersen (AFRL, Albuquerque) entitled “Heater-induced Artificial Ionisation Layers” (HAIL) was awarded 22 running hours on EISCAT (worth \$52,800-) and the campaign was successfully executed in July and November 2011. Another similar experiment is expected in 2012.
- 2) Two third-party EISCAT proposals involving Dr. Paul Bernhardt (NRL, Washington) entitled “Stimulated electromagnetic emissions and ionospheric temperature” and “Stimulated electromagnetic emissions and field-aligned irregularities” were awarded 18 and 24 hours (worth \$43,200- and \$57,600-), respectively. These will be executed in July 2012.
- 3) Dr. Paul Bernhardt (NRL, Washington) visited Lancaster University in the UK 21-22 March 2012 for the purpose of coordinating our EISCAT support for the CARE-2 rocket launch from Andoya Rocket Range in Norway, scheduled for August/September 2013.
- 4) Prof. Wayne Scales (Virginia Tech) was awarded 20 running hours on EISCAT (worth \$48,000-) for a proposal entitled “Radiowave heating of mesospheric dusty plasma”, which was executed in July 2009. This work was before the period of the EOARD grant. However, following our conversion of the EISCAT Heater into an HF-radar, collaboration will continue with an experiment entitled “PMSE actively charged dust”, which has been awarded 24 running runs on EISCAT (worth \$57,600-), scheduled for July 2012.
- 5) I anticipate a new collaboration with Prof. Bill Bristow (Geophysical Institute, Alaska) to support his discovery at HAARP that the growth of ionospheric irregularities depends on plasma temperature. The incoherent scatter radar at the EISCAT facility will be used to observe the electron temperature whilst generating artificial field-aligned irregularities.



Prof. M. J. Kosch  
Physics dept.  
Lancaster University  
Lancaster LA1 4YB  
UK  
[m.kosch@lancaster.ac.uk](mailto:m.kosch@lancaster.ac.uk)  
+44-(0)1524-510404