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14. ABSTRACT

This report results from a contract tasking University of Crete as follows: The contractor will investigate the ionosphere's ability to reflect radio waves (backscatter) using the Sporadic E SCATter experiment (SESCAT). SESCAT is an ionospheric radio Doppler system on the island of Crete, Greece (a fixed, ground-based facility). The contractor will evaluate bulk motions and spatial structuring within unstable sporadic E layers. The objective of this research is to experimentally validate theoretical models proposed to explain strong backscatter periodicities associated with mid-latitude sporadic E layer plasma. Contract hardware supports other USAF funded experiments in Crete.

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SESCAT investigations of 50 MHz coherent backscatter phenomena in the midlatitude E-region Ionosphere

Final Progress Report

C. Haldoupis
Iraklion, December 2, 2002

An ionospheric science proposal entitled "SESCAT investigations of 50 MHz coherent backscatter phenomena in the midlatitude *E* region ionosphere" received a special contract (SPC) award by the European Office of Aerospace Research and Development (EOARD). The contract was signed end of January 2001 and its duration was set to 22 months, that is, end of November 2002. The annual report was sent in March 2002. Following is the final report which summarizes the experimental and scientific progress made during the whole period of the project.

Summary of objectives. The main scope was to use SESCAT, that is, the Sporadic E Scatter Doppler radar experiment, which is operated by the University of Crete in the island of Crete, to pursue basic ionospheric research on problems relating to plasma instabilities and irregularities associated with nighttime midlatitude sporadic E layers, and on the formation and morphology of sporadic E layers. A major goal of the contract was to upgrade SESCAT into a dual (azimuthal and vertical) radio interferometer. This required the construction of a phase-coherent, 3-channel receiver and a data acquisition unit for real time high resolution spectral and cross-spectral data processing. The upgraded system could then be deployed in an experimental campaign for dual interferometric measurements. The scientific objective was to use existing SESCAT observations and high resolution interferometry measurements to study midlatitude coherent backscatter in an effort to enhance our knowledge of midlatitude sporadic E layers, their electrodynamics and unstable plasma state (research topics included the study of the Farley-Buneman plasma instability at midlatitude, and the newly discovered relationship between sporadic E layers and planetary waves). Also, it was suggested to use backscatter measurements to study bulk motions of unstable plasma structures across the radar beam. The idea was to test experimentally models and physical mechanisms proposed the last few years in order to explain prominent periodicities in backscatter and quasi-periodic sporadic E layer structuring. In more general terms, the present contract was aiming in supporting the basic ionospheric science research carried out at the of Ionospheric Physics Lab in the Department of Physics, University of Crete.

<u>Experimental progress.</u> Using EOARD funding we have accomplished during the contract period the following tasks:

1) ***<u>Construction of a new 50 MHz triple, phase-coherent, receiver</u>***. The receiver was designed and built by Prof. J. A. Koehler in full accordance with the requirements set by the project. Its construction was completed in January 2002 and the receiver, with several spare modules, was shipped to the University of Crete end of February 2002. The receiver is designed to be used with three separate antennas in order to observe ionospheric echoes from a 50.521 MHz transmitter. The three antennas allow one to measure phase differences between the arriving signals at each antenna, and hence to make inferences about the spatial dimensions and motions of the scattering targets in two dimensions. The basic requirements for this triple receiver were: a) excellent frequency stability, b) exact phase-coherence between all three receivers, c) good rejection between receivers, and d) good linearity. All these requirements were fulfilled through genuine design and the use of last generation, state-of-the-art, electronic components (details can be found in the receiver manual written by J. A. Koehler). Seeing below is a photograph of the receiver unit plus some spare parts.

View of the new 50 MHz triple, phasecoherent SESCAT receiver with spare parts

2) ***<u>A DSP-based data acquisition system.</u>*** A DSP (digital signal processor) real time data acquisition system was developed in the University of Crete for real time dual interferometric measurements. This was based on the existing SESCAT acquisition system (used in the past for single interferometer measurements) which applies two identical DSP cards and specialized software in order to perform power spectrum and cross-spectrum calculations in real time. This has now been expanded by adding an identical 3rd DSP card and by modifying the existing software extensively. The new unit is now capable of performing full Doppler spectrum calculations simultaneously for each of the three receiver signals and cross spectral analysis between two different receiver (signal) pairs, all done in real time (including data transfer and storage) using a modest pentium personal computer.

3) ***A LABVIEW-based data acquisition system.*** In the framework of a 4th year physics student project, an alternative, real time data acquisition system was designed and developed which can perform the same task as the DSP-based system just described. It can perform spectral and cross spectral calculations for 3 signals, but now this will be done by means of using a 4 channel A/D (analog to digital) PC card and the LABVIEW software package of National Instruments. The implementation of this system has been completed but needs more testing and evaluation before it can be used as an alternative, to the DSP based one, data acquisition system for the SESCAT radio interferometer measurements.

4) ***Software for specrtral and cross spectral analysis.*** Over the years we have developed and integrated and rather versatile software package for the analysis of SESCAT observations. This system, which has become our indispensable analysis tool, needed to be expanded and include options for interferometry data analysis. This task has been implemented to a large extend and the software package is used in the analysis of the last summer (2002) radio interferometric observations.

5) ***Repair and conditioning of the dual SESCAT receiver.*** The existing SESCAT receiver equipment, that has been used briefly in the past for azimuthal interferometry measurements and which was out of function for sometime, was shipped to France (Radio- Communications Lab, Universite de Rennes) for repair and conditioning. This was implemented and the receiver was shipped back to Crete May 2001 and used for extensive measurements during the summer of 2001.

6) ***Summer 2001 SESCAT data collection campaign.*** A long and continuous data collection campaign was undertaken with success from the beginning of June to the end of September, 2001. The system was run as a horizontal interferometer virtually without interruption which led to establishing a large data base. Part of these observations were used to produce a paper that has been submitted recently for publication in Annales Geophysicae, whereas the rest of the data are presently under analysis and study.

7) ***Antenna installation for vertical interferometer.*** An array of two 7-element Yagis was installed at about 75 meters in front of the existing 4-Yagi SESCAT array. This antenna was used for vertical interferometry observations.

8) ***Pulsation Magnetometer.*** We have managed to keep on continuous operation over the last two years a sensitive pulsation magnetometer in Crete, a project in collaboration with the University of Oulu, Finland.

9) ***Summer 2002 observational campaign.*** With help from Prof. J. A. Koehler who visited the University of Crete in June 2002, we have completed the SESCAT site preparation, as well as the installation and testing of the new equipment and software (triple coherent receiver and DSP data acquisition system). Then, an interferometer experiment was run continuously for several periods between July 1st and September 31, 2002 which allowed, in spite of some technical problems, the collection of many E region coherent backscatter observations. These SESCAT observations were accompanied by magnetic pulsation measurements in Crete and by optical airglow measurements made with the Cornell All Sky Imager (CASI), which was shipped in Crete by Prof. Mike Kelley of Cornell University,

for simultaneous measurements with SESCAT. The objective of these joint measurements was to test the electrical coupling through the magnetic field lines of the *F* region and the unstable *E* region. The installation and operation of CASI , first under the SESCAT observing area in the island of Milos and then in Crete, was conducted by M. Nichols a young American student from Cornell who came in Crete for this purpose from June 20 to July 20, 2002 (e.g., see following picture). The 2002 experimental campaign was made possible thanks to EOARD.

Installation of the Cornell University All Sky Imager in Milos, July 2002

10) ***Data analysis and interpetation.*** Further software development and preliminary analysis of the 2002 SESCAT interferometer and CASI observations started September 2002 and continues to date. This effort was reinforced by the presence and contribution of Prof. M. C. Kelley, who visited Crete for 3 months as a Fulbright Fellow, and Dr. S. Shalimov from the Moscow Institute of Physics of the Earth who was also a visitor for 2 months.

Scientific progress and Publications. Most of the EOARD contract funds were used to upgrade the SESCAT intereferometer and run the summer 2002 experimental campaign. In addition to this, however, the present EOARD science contract provided small but crucial support for the unobstructed continuation over the last 20 months of our research and collaborative work. This effort, resulted to 4 papers that have been already published and to 4 more papers that have been submitted for publication over the last 2 months. All papers were published/submitted in well known scientific journals, and EOARD support is acknowledged in all of them.

Next we provide a list of publications followed by a summary of their contribution, whose materialization was assisted by the EOARD contract. More details can be found in the complete copies attached in the present report. Also, one more paper is presently under preparation which relates to the SESCAT radio interferometer and CASI optical imager simultaneous measurements made during the joint (University of Crete and University of Cornell) 2002 campaign. Since the paper is nearing completion a draft is also attached to the present report.

1) ***Haldoupis C., and D. Pancheva, Planetary waves and midlatitude sporadic E layers. Strong experimental evidence for a close relationship, Journal of Geophysical Research, Vol., 107, No A10, doi: 10.1029/2001JA00212, June 2002.***

Following recent suggestions that planetary waves might play a role in the formation of midlatitude sporadic *E* layers (*Es*), we have obtained and analyzed, for the period from August 1 to September 30, 1993, the sporadic *E* critical frequency (*foEs*) time series from 8 midlatitude ionosonde stations covering a large longitudinal zone from about 58 deg. E to 157 deg. W. The analysis revealed that all 8 station *foEs* data showed a strong 7-day periodicity, occurring concurrently with the 7-day planetary wave reported elsewhere. Our findings here provide the first direct evidence, proving that planetary waves play an important role in the physics of midlatitude sporadic *E* region layers. In addition, our results include an important implication, that the *Es* parameters measured routinely and rather reliably with a dense global network of digital ionosondes, as well as the enormous ionogram data bases existing in World Data Centers, may be used as an alternative means of studying large scale neutral atmospheric dynamics in the 100-120 km MLT region.

2) ***Shalimov, S. and C. Haldoupis, A model of midlatitude plasma convergence inside a planetary wave cyclonic vortex, Annales Geophysicae, Vol., 20, 1193, 2002.***

Recently, a new mechanism was proposed for large-scale accumulation of long-lived metallic ions in the midlatitude ionosphere driven by planetary waves in the lower thermosphere. In this mechanism, the combined action of frictional and horizontal magnetic field forces at E region altitudes causes the plasma to converge and accumulate in large areas of positive neutral wind vorticity within a propagating planetary wave. The present paper provides a theoretical formulation for this mechanism by modelling both horizontal and vertical plasma transport effects within a planetary wave vortex of cyclonic neutral wind using non steady state numerical solutions of the ion continuity equation. We have concluded that, for shorter times, vertical plasma transport may act constructively to the horizontal gathering process to produce considerable E region plasma accumulation over large sectors of a planetary wave vortex of cyclonic winds.

3) ***C. Haldoupis, K. Schlegel, G. Hussey, and J. A. Koehler, Radar Observation of kinetic effects at meter scales for Farley-Buneman plasma waves, Journal of Geophysical Research, Vol., 107, No A10, doi: 10.1029/2001JA009193, October 2002.***

Coherent backscatter Doppler measurements, made simultaneously at 144 MHz and 50 MHz from a common volume in the midlatitude E region ionosphere, were analyzed in order to study the phase velocity ratio of type 1 plasma irregularities at 1-m and 3-m wavelengths. The simultaneous spectrogram signatures of type 1 echoes suggested a somewhat higher threshold for instability excitation at 144 MHz than at 50 MHz. Statistically, the measured 144 MHz to 50 MHz velocity ratios attain values above unity, mostly in the range from 1.05 to 1.14 with an overall average of 1.10. It was found that the theoretical predictions for gradient-free Farley-Buneman waves agreed well with the observations, under the suppositions that the strongest type 1 echoes come from E region altitudes where conditions for instability are optimal, and that type 1 waves have their phase velocities limited at threshold values equal to the plasma ion acoustic speed. The present study has confirmed the accuracy of the kinetic theory of the Farley-Buneman instability, a fact that strengthens its validity and suitability for meter-scale E region irregularity studies.

4) ***Bössinger, T., C. Haldoupis, P. P. Belyaev, M.N. Yakumin, N. V. Semenova, A. G. Demerkov, and V. Angelopoulos, Spectral properties of the ionospheric Alfven resonator at a low-latitude station (L=1.3), Journal of Geophysical Research, Vol., 107, No A10, doi: 10.1029/2001JA005076, October 2002.***

Measurements for a half year of operation of a sensitive search coil magnetometer at a remote site in the island of Crete, Greece, was used to investigate for first time the properties of the spectral resonance structure (SRS) of the ionospheric Alfven resonator (IAR) at L=1.3. In contrast to high latitudes, SRS signatures were detected every night but never during daytime. In summaty, the observations in L=1.3 exhibit most of the properties known from higher-latitude studies, but also there are certain distinct differences which to our knowledge make the Crete (L=1.3) observations rather unique and suggest a need for more research.

5) ***Haldoupis C., A. Bourdillon, A. Kamburepis, G. C. Hussey, and J. A. Koehler, 50 MHz continuous wave interferometer observations of the unstable midlatitude E region ionosphere, Annales Geophysicae, submitted October 2002***

This paper describes the conversion of SESCAT, the bistatic 50 MHz CW Doppler radar located in Crete, Greece, to a single (east-west) baseline interferometer. The first results show that SESCAT has its measurement capabilities enhanced significantly when operated as an interferometer, as it can also study short term dynamics of localized scattering regions within midlatitude sporadic E layers. The interferometer observations detected that the viewed by the radar area contains a few zonally confined scatter regions, presumably blobs or patches of unstable metallic ion plasma, which drift across the field-of-view with the neutral wind. Also found is that Farley-Buneman (type 1) echoes occur much more frequently than it has been previously assumed and that they originate in single and rather localized areas of elevated electric field. On the other hand, type 2 echoes are often found to result form two adjacent regions in azimuth undergoing the same bulk motion westwards but producing scatter of opposite Doppler polarity, a fact that contradicts the ideas of isotropic turbulence to which type 2 echoes are attributed. Further, we found that quasi-periodic (QP) echoes are observed to be sequential unstable plasma patches which transverse across the radar field-of-view, sometimes in a wave like fashion.

6) ***D. Pancheva, C. Haldoupis, C. E. Meek, A. H. Manson, and N. J. Mitchels, Evidence of a role for modulated atmospheric tides in the dependence of sporadic E layers on planetary waves, Journal of Geophysical Research, submitted, November 2002.***

Recent evidence by Haldoupis and Pancheva, J. Geophys. Res., 107, 2002, showed that planetary waves (PW) indeed play a role in the formation of midlatitude sporadic E layers (Es). In the present paper we investigate further this role by considering the same PW event and correlating the 7-day periodicity in the sporadic E critical frequencies foEs directly with concurrent variations in the mesospheric neutral wind measured with atmospheric radars in Canada and in UK. Our analysis shows clearly that Es are affected indirectly by the PW through the action of the diurnal and semidiurnal tides which are strongly modulated by the same PW, apparently through a nonlinear interaction process at altitudes below 100 km. This 7-day PW modulation was found to be clearly present simultaneously in the amplitude of the 12-hour and 24-hour tidal winds, and in both, the 12-hour and 24-hour periodicities which existed in the foEs time series. The results here provide a new physical explanation for the observed relation between sporadic E layers and planetary waves.

7) ***Kelley, M. C., S. Shalimov, and C. Haldoupis, On a possible role of image formation in creating 150 km Echoes over the magnetic equator, Geophysical Research Letters, submitted, November 2002.***

Reasonably strong ionospheric plasma instabilities, including quasi-periodic echoes, have been reported to be rather common during the daytime at a location 5 deg. off the magnetic equator at Gadanki, India (e.g., see Patra et al. 2002). We argue here that the electric fields associated with these instabilities may map up the field lines to create weak irregularities in the 140-160 km height range at the magnetic equator without the need for a zero order density gradient. The gathering of plasma is by a process known as image formation which operates best in the region of greatest Pedersen drift. Although not directly capable of generating 3 m irregularities associated with the so-called 150 km echoes, this work suggested that the images may play a role in their generation by providing weak plasma density gradients.

8) ***Shalimov, S., C. Haldoupis, and M. C. Kelley, Plasma destabilization in the equatorial upper E region and 150 km echoes. Geophysical Research Letters, submitted, November 2002.***

This paper introduces a new instability mechanism which appears to be capable of producing intermediate scale plasma waves in the upper equatorial E-region, that is, in altitudes from about 130 to 170 km. The free energy for the instability is provided by an electron-ion drift along the magnetic field, associated with the field-aligned current which is known to exist in the upper E region just outside the magnetic dip equator. In addition, downward plasma density gradients with scale lengths near 20 km are necessary. It is argued that these can be non-zero order plasma gradients caused by passing gravity or tidal waves, and/or vertical plasma structuring created by an image formation process that maps up the field lines electrostatic fields from the unstable E region at very low latitudes. Under these conditions, it is shown that large scale plasma waves with wavelengths in the range from several hundred meters to a few kilometers can grow and propagate along the zonal direction, slightly off perpendicular to the magnetic field. Finally, it is postulated that these waves could be seeding vertically propagating meter scale irregularities which can be responsible for the equatorial 150-km echoes, the origin of which remains a mystery.

9) ***Kelley, M. C., C. Haldoupis, M. N. Nicolls, J. J. Makela, A. Belehaki, S. Shalimov, and V. K. Wong, A midlatitude study of correlation between F region TIDs and E-region scatter using coherent scatter radar and allsky imaging techniques, draft, to be completed and then submitted in the Journal of Geophysical Research.***

This is a detailed study of F-region / E-region electrical coupling during times when the E region becomes unstable under the action of locally produced polarization fields. These fields may map along the magnetic field lines in the F-region causing vertical plasma transport and thus F region ionization distortions, possibly relating to spread-F conditions. This study is based solely on data obtained during our joint summer 2002 campaign when the SESCAT interferometer operated simultaneously with the Cornell all sky imager. For more details see attached draft of the paper which is to be completed soon and submitted for publication in the Journal of Geophysical Research.