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PRINCIPAL COMPONENT ANALYSIS OF SIMULTANEOUS IRIS AND TV OBSERVATIONS OF PULSATING PATCHES

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Abstract. Observations of aurora by highly sensitive television (TV) cameras and of riometric absorption by IRIS imaging riometer allows one to study spatial-temporal dynamics of precipitated particles. The dissipation of energetic particles in the atmosphere is accompanied by excitation of auroral emissions at altitudes of 100-200 km, which is observed by optical instruments. If the precipitated particles are rather energetic to penetrate to altitudes below than 90 km, then their ionizing the atmospheric gases leads to effective absorption of radiowaves, which is observed by riometers. Pulsating electron precipitations are usually believed to be a consequence of wave-particle interactions in the magnetosphere. Such pulsating forms in the morning sector are usual for recovery phase of a substorm. However, one-to-one correspondence between the optical and riometric variations is usually not obvious. Here we apply the principal component analysis (also known as proper orthogonal decomposition) to find the correlated spatial structures in simultaneous two-dimensional observations by IRIS (Kilpisjärvi, 69.05° N, 20.79° E) and TV all-sky camera (Porojarvi, 69.17° N, 21.47° E). Results of several case studies are discussed.

Introduction

The pulsating electron precipitation are detected usually in the recovery phase of substorm in the morning sector of the auroral zone [Trefall at al., 1975]. It is generally accepted that cyclotron wave-particle interaction is responsible for these electron precipitation [Trakhtengerts, 1984, Davidson, 1979]. VLF waves caused pitch angle scattering of energetic electrons close to the equatorial plane in the magnetosphere and this is followed by precipitation into the ionosphere. The dissipation of energetic electrons in the atmosphere is accompanied by excitation of auroral emissions at altitudes of 100-200 km, that is observed by optical instruments. An increase of ionization in the region of particle precipitation leads to increasing of cosmic radio noise absorption (CNA). The CNA is generally attributed to energetic particle precipitation in the D-region and the bays of absorption are observed by riometers. Thus, the electrons of different energies are the most effective to produce the optical aurora and CNA. Therefore, one-to-one spatial correspondence between the optical and riometric variations is not obvious. However, these events are usually observed in the same region of the auroral oval.

TV observations are used during a long time for the analysis of aurora fine structure for pulsating patch especially because of their having greater temporal and spatial resolution: a fraction of a second and several kilometer respectively [Scourfield et al., 1972, Kosch and Scourfield, 1992]. The aurora is produced basically by the electrons with energy 1-10 keV while CNA is produced effectively by electrons with energy more 30 keV. However the resolution of ordinary riometer is very low (several minutes in time and a hundred kilometers in space). The Imaging Riometer for Ionospheric Studies (IRIS) is suitable to analyze details of particle precipitation with higher time and spatial resolution, 15-30 km, and 1 second respectively. Thus simultaneous IRIS and TV observations permits to control a wide range of precipitating electrons 1-100 keV with good temporal and spatial resolution. In this paper we analyze the results of simultaneous IRIS/TV registrations obtained in auroral region in northern Finland. The main subject is to find a correspondence between spatial structures of optical aurora and CNA.

Data set

The Imaging Riometer for Ionospheric Studies (IRIS) [Browne et al., 1995] is based at Kilpisjärvi in northern Finland, (69.05° N, 20.79° E). It records the absorption of cosmic radio noise at 38.2 MHz with time resolution 1s. IRIS consists of 49 (7×7) narrow imaging beams with widths between 13° and 16°, which covers an area of 240 x 240 km from L shell 5.5 to 6.5. The techniques and uses of imaging riometers have been summarized by Stauning [1996]. The beams with scintillation due to radiowave sources in Cassiopeia and Cygnus have been excluded from the considered arrays of IRIS.

VLF waves and aurora observations were based at Porojarvi (69.16° N, 21.47° E). The television all-sky camera (TVASC) observed the aurora in "white" light with a broad maximum at blue-green wavelengths. The TV data were recorded by a VHS recorder in a PAL video system, at 25 images per second. The TV data were digitized using a TV-Capture plate with an output resolution of 5 images per second, 160×144 pixels, 8 bits per pixel.

Here we consider the simultaneous observations of the CNA and aurora which were carried out from 7 to 12 January 1997. These events were taking place in the morning hours in close with substorms of magnitude <600γ. Previously the relation of CNA and pulsing aurora with appearance of discrete ELF/VLF chorus emissions have been discussed in [Kozelov et al., 2005]. A typical event under consideration is shown in Fig.1. One can see the latitudinal variation of the CNA during the event and development of the pulsing auroral structures. To simplify the comparison of the localization of spatial structures observed by IRIS and TVASC, a set of 'virtual photometers' were defined in the TVASC field of view. The position of each virtual photometer corresponds to the mapping of an individual IRIS beam to 100 km altitude, see Fig.2. Thus the data set under consideration is a sequence of 7×7 values of CNA with 1 s temporal resolution, and the same arrays of non-calibrated auroral intensity, but with 0.2 s resolution.

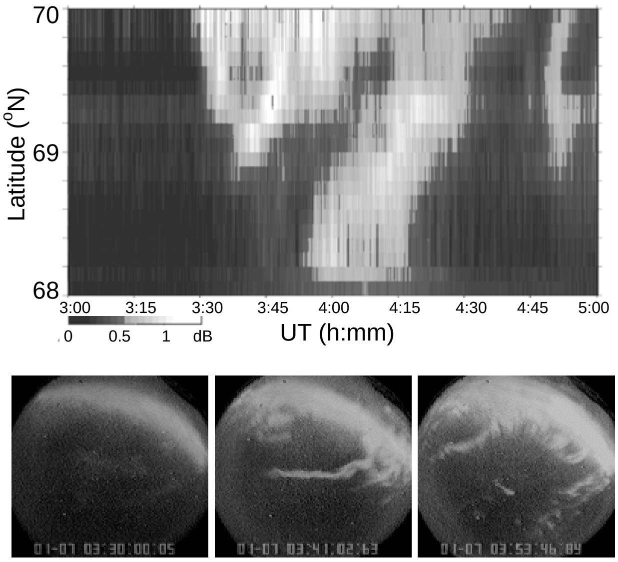

Fig.1. Top: IRIS absorption keogram, 1997-01-07, 03:00-05:00 UT; bottom: TVASC images for 03:30:00, 03:41:02, and 03:53:46 UT.

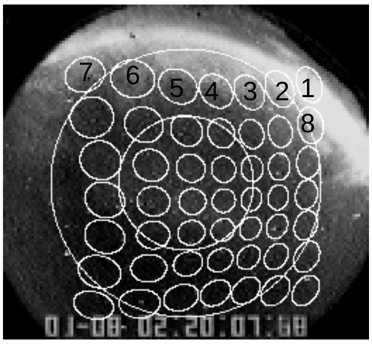

Fig.2. Mapping of the IRIS beams to the TV image.

Numerical method

The principal component analysis, also known as the Proper Orthogonal Decomposition (POD) [Holmes et al., 1996], decomposes a field $u(\mathbf{r},t)$ as

$$u(\mathbf{r},t)=\sum_{j=0}^{\infty}a_j(t)\psi_j(\mathbf{r}) \qquad (1)$$

The eigenfunctions ψ_j are constructed by maximizing the average projection of the field onto ψ_j, constrained to the unitary norm.

Averaging leads an optimization problem

$$\int_\Omega \langle u(\mathbf{r},t),u(\mathbf{r}',t')\rangle\,\psi(\mathbf{r}')\,d\mathbf{r}'=\lambda\,\psi(\mathbf{r}) \qquad (2)$$

where Ω represents the spatial domain and brackets represent time averages. The integral equation provides the eigenfunctions ψ_j and a set of ordered eigenvalues $\lambda_j \geq \lambda_{j+1}$,each representing the 'kinetic energy' of the j-th mode. The method builds up the basis functions, which are not given a priori, but rather obtained from observations. The time coefficients $a_j(t)$ are then computed from the projection of the data on the corresponding basis functions $\psi_j(\mathbf{r})$. Thus, a result of the POD contains a spectrum of eigenvalues λ_j, spatial eigenfunctions ψ_j (in our case each eigenfunction is an array 7×7), and time variations of each eigenfunction $a_j(t)$.

The POD in this formulation was applied to study the spatial structure of solar photospheric motions [Vecchio et al., 2005]. Several applications of more refined version of the method were discussed in [General components of the time series: 'caterpillar' method, St.-Petersburg State University, 1997.]

Results of signal decomposition

The results of POD for in interval 03:30-03:45 UT, 1997-01-07 are shown in Fig.3 and 4 for IRIS and TVASC data, correspondingly. In both cases the spectra of eigenvalues sharply decrease with the increase of j, therefore only the first several eigenvalues are the most important. Typically, only a few eigenfunctions for IRIS as well as for TV data is possible to interpret and compare.

The eigenfunction for j=0 corresponds to a spatial structure which is common for all images in an interval under consideration. One can see that for TVASC images the ψ_0 clearly demonstrates an increase of the observed intensity at the array boundaries in our case due to increasing of the square of virtual photometers. For IRIS data there is a central spot in the ψ_0 image. Note that 4 beams in top raw of the IRIS images have been set to zero to decrease the effect of scintillation. Surprisingly, the time variations $a_0(t)$ of the ψ_0 eigenfunctions are very similar in both cases.

Next eigenfunction, ψ_1, contains the east-west arc structure which is the most interesting feature during this time interval, see central image in Fig.1. However, for TV eigenfinction ψ_1 this structure is not such pronounced as in IRIS case. The time variation of this structure in IRIS and TV signals are correlated. Simultaneously, northward from this arc in the same eigenfunctions there are patches which are strongly anti-correlated (the black patches in IRIS eigenfunction correspond to the white ones in TV one).

The ψ_2 eigenfunctions describe the large-scale evolution of the structure in south-west to north-east direction. The time variations $a(t)$ of the ψ_1 and ψ_2 eigenfunctions are very similar for CNA and TV.

Such a comparison is complicated for higher eignfunctions due to increasing of their noisy structure with the increasing number.

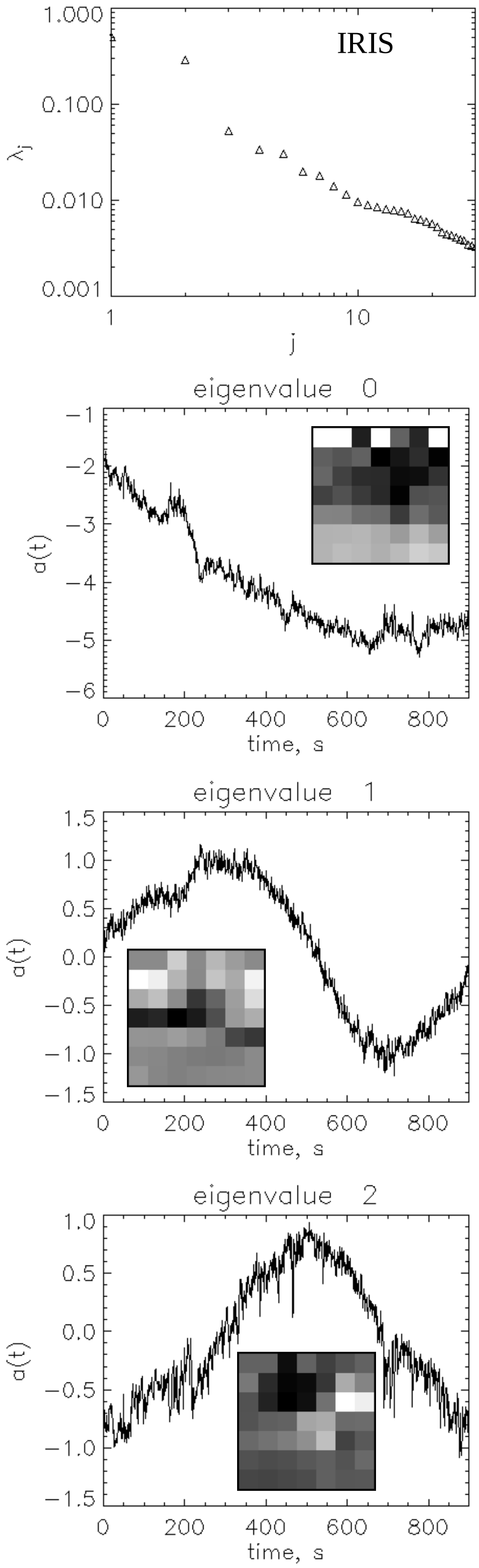

Fig.3. Top panel: POD spectrum of eigenvalues for IRIS observations, 1997-01-07, 03:30-03:45 UT (value for j=0 is not shown). Other panels: time evolution of POD coefficients $a_j(t)$ for first three modes. Insets - the corresponding eigenfunctions ψ_j.

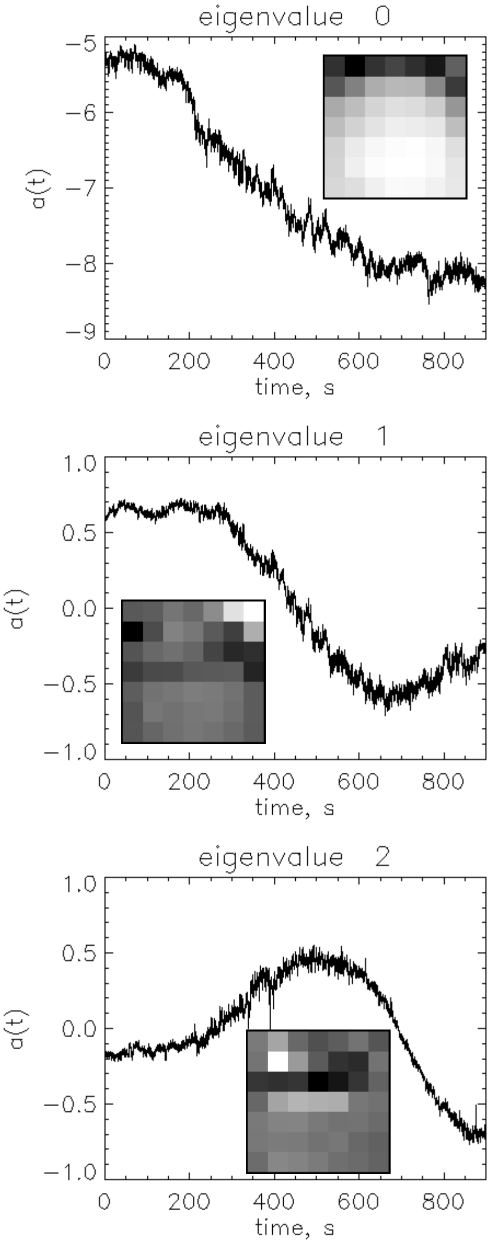

Fig.4. The same as Fig.4, but for TV ASC observations during the same time interval.

We should note that some spatial structures are observed only by IRIS or TV. For example, Fig.5 shows a manifestation of the pseudo-periodical optical pulsation observed by TVASC only. These pulsations are separated by POD and well seen as a peak in the Fourier spectra of the time variations $a(t)$ of the corresponding eigenfunction.

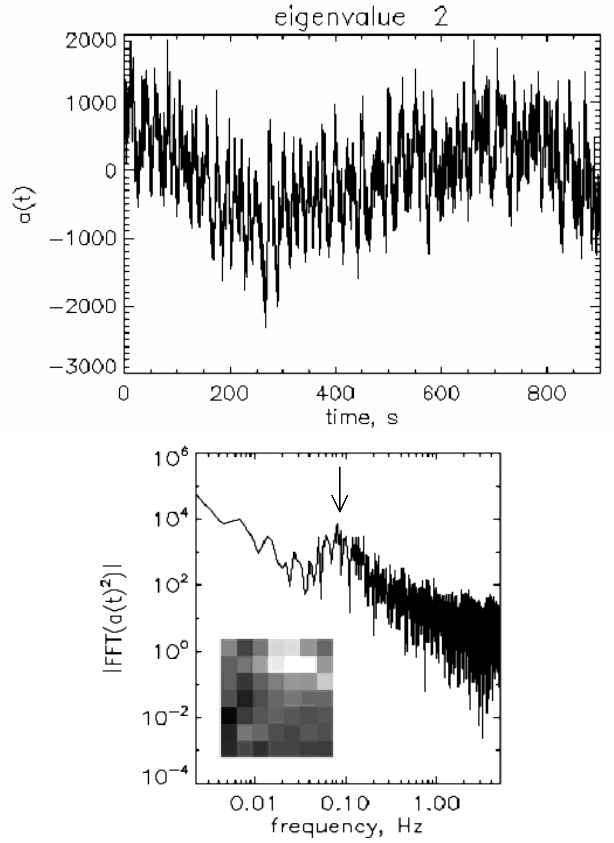

Fig.5. Example of an event observed by TV ASC only during the time interval of 05:35-05:50, 1997-01-12. Top: time evolution of POD coefficients $a_2(t)$. Bottom: Fourier spectrum of $a_2(t)$. Inset is the corresponding eigenfunction ψ_2.

Conclusions

1. Principal component analysis, also known as proper orthogonal decomposition (POD), has been applied with data of simultaneous two-dimensional observations by IRIS riometer and TV all-sky camera. The decomposition of the data set on the orthogonal eigenfunctions gives a possibility of finding the correlated spatial structures observed by both devices.

2. During the considered morning-time events there was found a correspondence between pairs of eigenfunctions (two-dimensional spatial structures) obtained from IRIS and TV data that have similar large-scale time variations. The eigenvalues in the pair have a similar but usually not the same spatial structure. The structures in the IRIS data tend to be shifted in south and east direction relative to the optical.

3. The time variation of this structures tends to be correlated at the south boundary of the particle precipitation zone, but anti-correlated a little northward.

4. We have not found any sufficient correspondence for events with riometer absorptions less than 0.2 dB.

5. There were phenomena observed by only one device.

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