Proc. NIPR Symp. Upper Atmos. Phys., **6**, 1–14, 1993

AURORA STEREO OBSERVATION IN ICELAND

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Abstract: Aurora stereoscopic observation for the monochromatic regime has been carried out in Iceland in November and December, 1991. A distance between two observation sites, Husafell and Efri-Brunna, is about 90 km in the magnetic meridian plane. The aim is to obtain stereo image data with longer baseline for the detailed study of inverse algorithm and to clarify three-dimensional luminous structures of aurora at typical wavelengths. This paper gives a brief description of the observation and some provisional results of data analysis.

1. Introduction

For several years, we have been analyzing image data of the aurora stereo observations in Antarctica to reconstruct three dimensional spatial structure of luminous aurora (Aso *et al.*, 1990a). Tomographic approach to this inverse problem has been used which relies on the nonlinear parameter optimization of the assumed luminosity model function. Retrieval of luminosity structure for some of the stable arc and pulsating auroras either gives profiles consistent with stable arc generated by electrons with energy of some tens of keV or brings about some evidence for the controversial issue on the vertical extent of pulsating auroras (Stenbaek-Nielsen and Hallinan, 1979; Aso *et al.*, 1990b). These observations have a distance of 20–30 km as a baseline for stereopsis, and it is not at times long enough relative to the vertical extent and thickness of some types of auroral illuminating region. Numerical calculation of case studies indicates degradation of optimization minimum in identifying vertical extent for either larger horizontal thickness of aurora or shorter site distance, when a model aurora with vertical extent of 20 km is assumed (Aso *et al.*, 1991).

A new expedition was carried out in Iceland so as to realize longer baseline stereo observation more easily, as a part of the study of geomagnetic conjugate characteristics of aurora and related magnetospheric phenomena between Syowa Station and Iceland. Siting is based on the studies mentioned above, and also on the accessibility, local weather condition and logistics. A holiday farm house at Efri-Brunna (65°23.4′N, 21°52.5′W) is selected by the courtesy of Profs. N. Sato of National Institute of Polar Research and Th. Saemundsson of University of Iceland, along with existing facility at Husafell (Augastadir) (64°40.4′N, 21°1.5′W) as indicated in Fig. 1. These two sites

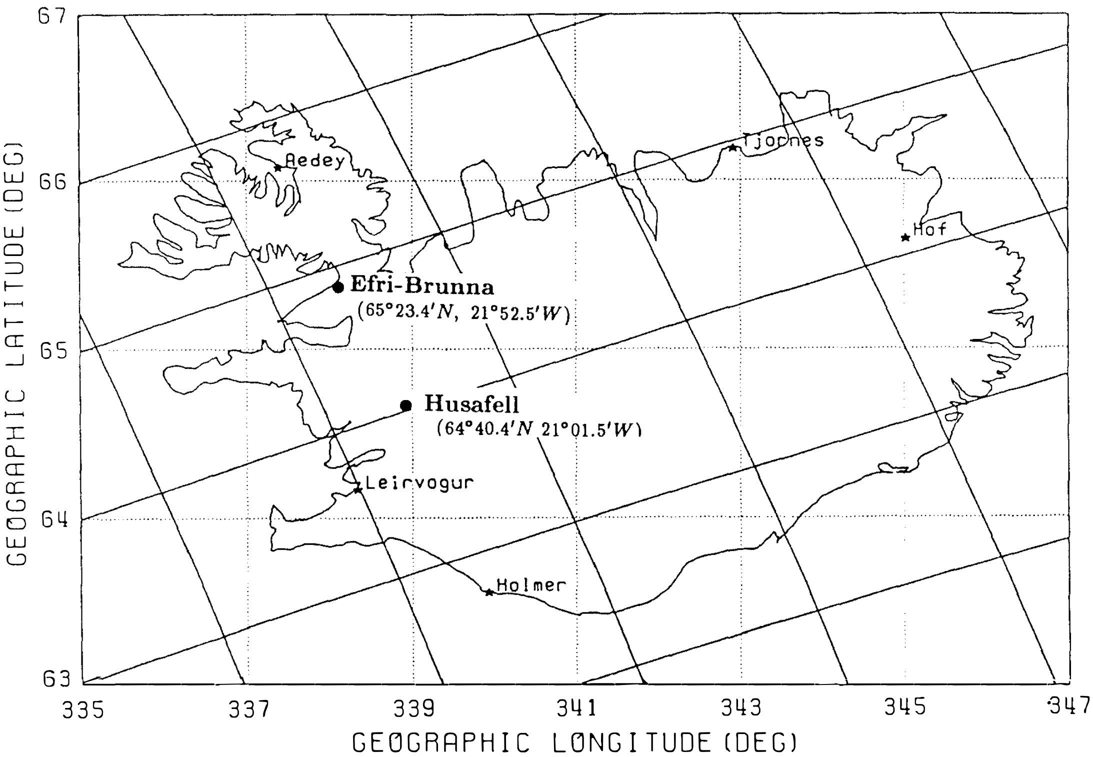


Fig. 1. Locations of stereo observation sites in Iceland. Oblique lines indicate geomagnetic longitude and latitude.

are about 90 km apart and almost in the same geomagnetic meridian plane. Geomagnetic vector at 100 km height above Efri-Brunna has its declination of -21.7°, inclination of 76.5°, and above Husafell -20.7° and 76.1°, respectively. Telephone link was available between two sites for synchronous observations, and a GPS receiver and a quartz standard time base generator give position and time at each site.

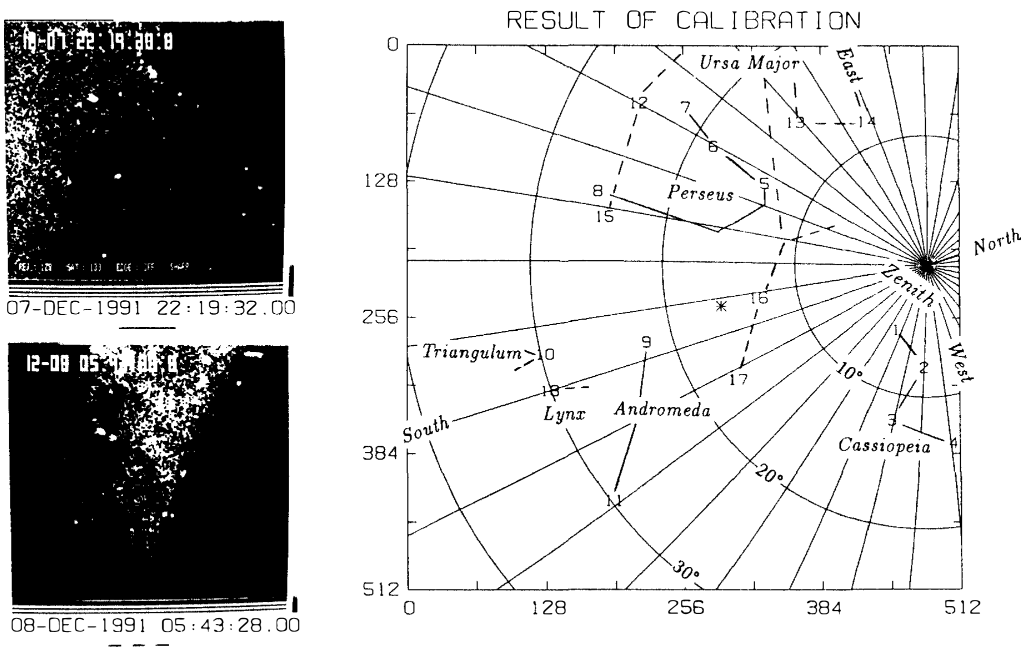
2. Observation

High sensitivity ICCD (CCD with Image Intensifier C4206-01, Hamamatsu) imaging system was installed at two sites with analog Hi-8 (EV-S900, SONY) video recording system. Digital quick-look data was also available through personal computer (PC9801, NEC) after integrating 30 images (1 s) by an ImageΣ (Nippon Avionics). Interference filter (Andover Corp) subsystem (SK-ITV-020, Shinwa) equipped with collimating relay lens gives monochromatic 5577 Å images mostly along with 6300 and 4278 Å ones occasionally with bandwidth of 30 Å. Object lens is a Nikkor $f=8$ mm/F2.8 fisheye and overall field of view is about $40\times55^\circ$. Camera pointing direction is adjustable to the zenith angle of 0–25° in 5° step by the platform (SK-ITV-010, Shinwa). ICCD unit was kept in the cooling box (NS Elecool-Box, Shin-Nittetsu). Calibrations of relative sensitivity of two camera systems were made at Efri-Brunna after the observation run using indoor scenes. Parameters are temperature of ICCD unit and monitor voltage of MCP (micro-channel plate) high tension voltage. A gray level ratio or sensitivity of Husafell to Efri-Brunna ranges from 1.5 to 2 for the same monitor voltage at the temperature of 0°C. A temperature control was not automatic in the observation and at present, relative sensitivity correction is still under way. So in the following analyses, the sensitivity ratio is also a parameter to be determined by nonlinear minimization procedures. Other instruments as SIT all-sky and Night viewer (C3100, Hamamatsu) cameras (both panchromatic) and a scanning photometer supported stereo observations.

Observation was carried out for about two weeks from late November to early December, 1991 around the new moon period. The weather at the observation sites was such that satisfactory stereo observation was only possible during three or four nights. In the following, two specimen stereo pairs of 5577 Å image taken at 2104:53 on December 7 and 0306:10 on November 30, 1991 are analyzed.

3. Some Results of Analysis

Figure 2 illustrates the result of camera calibration at Efri-Brunna using background stars for the analysis of stereo images on December 7. The result gives the direction of line-of-sight for a particular pixel point in the image. Total of 18 stars with magnitude greater than 5.0 at two times are used for the calibration. These include Andromeda, Cassiopeia and Perseus for the former image and Ursa Major for the latter image. Calibration result shows that star positions are on an average retrieved by the estimated polynomial formula between image plane and pinhole projected plane within the accuracy of some 0.5 pixels. A lens characteristic here is assumed to be $2\sin(\theta/2)$ and optical axis is also determined so as to minimize residual rms errors. Field of view



(a) (b)

Fig. 2. (a) Star images at Efri-Brunna at two different times and (b) the result of calibration for analyzing December 7 stereo images.

is about 45° since we take the central square region of the TV image plane with an aspect ratio of 1 : 1. Upper side refers to geomagnetic east and right-hand side is to geomagnetic north. In this case Efri-Brunna camera was pointing southward by 15° from the zenith, while Husafell camera was pointing northward by 15° in the magnetic meridian plane, and overlapping region at around 100 km height is about 60 km in horizontal extent. When we digitize the whole image area as in the analysis for the November 30 aurora, the field of view in the geomagnetic north-south direction is about 55° and overlapping region extends to 90 km.

To obtain a rough estimate of the spatial extent of aurora we use the conventional triangulation method for the height determination. For the stereoscopic point of view, correspondence or stereo matching problem is a major concern as in machine vision applications. The epipolar constraint states that the corresponding point of a feature point in one image lies on the epipolar line which is an image of the line of sight in the other image plane. A plane determined by two lens centers and the image point is called as an epipolar plane.

Figure 3 shows stereo images which were observed in the course of auroral breakup at 2104:53 on December 7, 1991 and superimposed seven epipolar lines. Correspondence for smooth surface is difficult to identify because of the so called occluding edge as shown in the inset in Table 1 where the intersection of both lines of sight, A or C is not

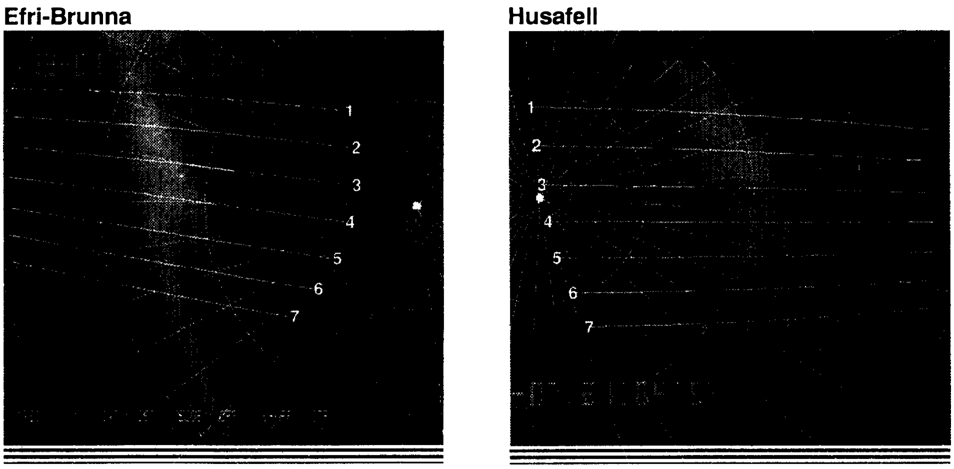
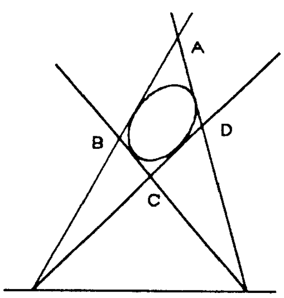


Fig. 3. Stereo images at 2104:53 on December 7, 1991 with superimposed seven epipolar lines numbered 1–7.

Table 1. Height (km) determined by triangulation along epipolar lines 1–7.

Epipolar plane	A	B	C	D	Center1	Center2
1	185	111	88	127	108	
2	184	111	88	127	108	
3	189	114	89	130	107	
4	187	112	85	129	107	
5	189	113	88	130	109	111
6	187	113	87	127	108	113
7	189	112	88	129	109	111



strictly identical to the upper or lower boundary edge of aurora. Table 1 shows the height estimated from triangulation using epipolar constraints. A and C are uppermost and lowermost height inferred from occluding edge and B and D are north-south boundaries. These values are fairly acceptable height ranges of usual auroral arc.

In the following analysis, we solve the inverse problem of computed auroral tomography by a revised Marquardt method, a nonlinear least squares minimization scheme (ASO *et al.*, 1990a). In this method, we determine model parameters of volume emission rate or luminosity function which minimize the square sum of the differences between observed gray levels and reconstructed projection values for interested parts of stereo images. Unambiguous determination of a minimum in the residual depends on

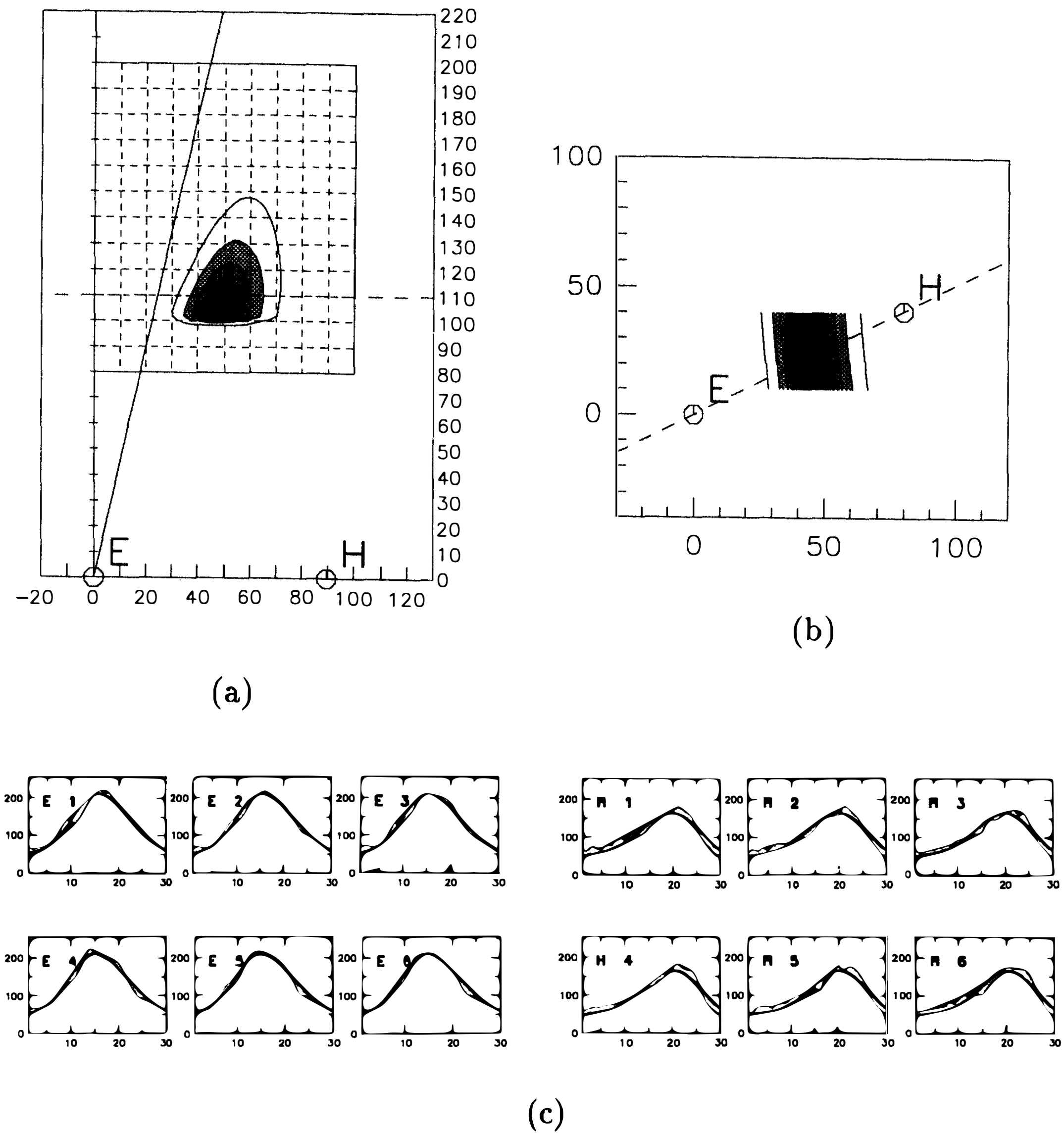


Fig. 4. The result of analysis for overlaid portion of the stereo image observed at 2104:53 on December 7 in Fig. 3. (a) Vertical profile, (b) plan at 110 km of the reconstructed structure, and (c) comparison of gray level profiles between observed (thin lines) and reconstructed (thick, smooth lines) aurora. E and H stand for Efri-Brunna and Husafell, respectively.

the form, size and position of aurora relative to observing sites and, for ill condition case, unique reconstruction becomes rather difficult. Pre-processing of image data includes averaging over 7×7 or 9×9 neighbors, and subtraction of background gray levels is also a requisite to extract the aurora luminosity from the effect of atmospheric scattering of other luminous obstacle. In the present analysis, a constant background value is determined as a baseline of gray level.

Curtain-like aurora illuminating region is assumed aligned with the geomagnetic line of force. Luminosity model function L is approximated by the product of Chapman function or its modified form in altitude z, and Gaussian, box-car, spline functions or its modified form or cellular structure in horizontal thickness y, which is assumed to be (piece-wise) uniform or in some case undulant in elongated direction x, viz.,

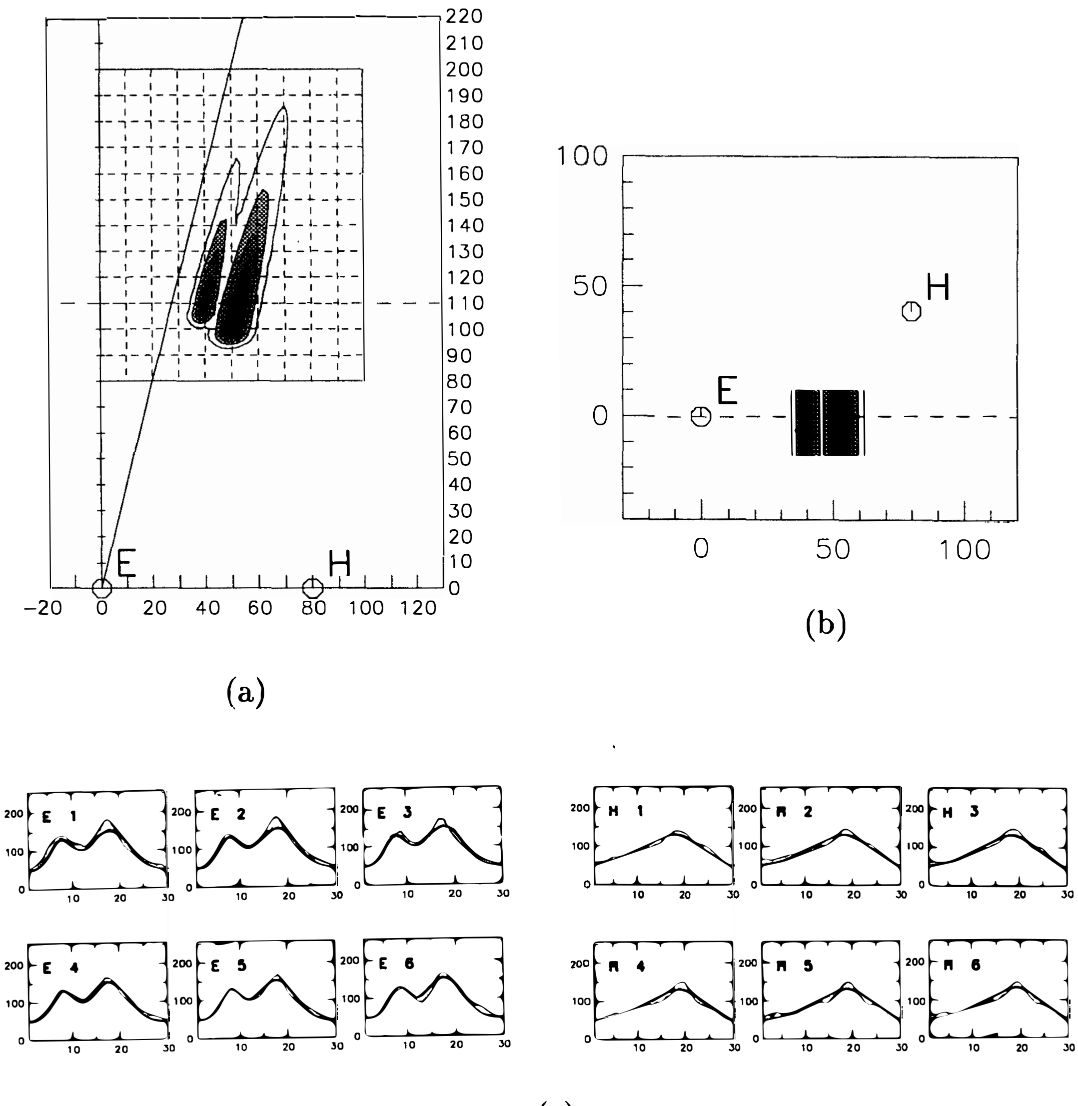


Fig. 5. The result of analysis for bifurcated portion of the stereo image observed at 2104:53 on December 7. Details are as in Fig. 4.

$$L(x,y,z)=A\cdot L_{\text{altitude}}(z)\cdot L_{\text{horizon}}(x,y)\ , \tag{1}$$

where

$$L_{\text{altitude}}(z)=\exp[1-\eta-\exp(-\eta)]\ ,$$
$$\eta=B(z-C)\quad \text{for } z>C\ ,\quad B'(z-C)\quad \text{for } z<C\ ,$$
$$L_{\text{horizon}}(x,y)=\exp[-(y-D)^2/2E^2]\ ,\ \text{box-car, spline etc.,}$$
$$D=D(x)\ ,\ \text{uniform or undulant (polynomial, spline)}\ ,$$
$$(A, B, B', C, \cdots \text{ parameters to be determined})\ .$$

If we focus on some limited portion of luminous aurora image, rather simple function is sufficient to describe the structure. When, however, we analyze a wider range of image as a whole, description in terms of more sophisticated model function is required to conform to complicated auroral structure.

Figures 4a–4c show the result of analysis for one-layer or overlaid portion (upper part) of the stereo image in Fig. 3 observed at 2104:53 on December 7. In the figure, possible reconstruction of aurora structure is shown in the Fig. 4a vertical and Fig. 4b horizontal plane. E and H stand for Efri-Brunna and Husafell, respectively. It is seen that the arc is seemingly thick or of composite-type with its peak around 105 km. Vertical extent is about 25 km and horizontal thickness of composite layer is about 20 km. The arc is rotated a little bit clockwise from magnetic east-west direction. In Fig. 4c, comparison of gray level profiles almost along epipolar lines is exemplified. Six

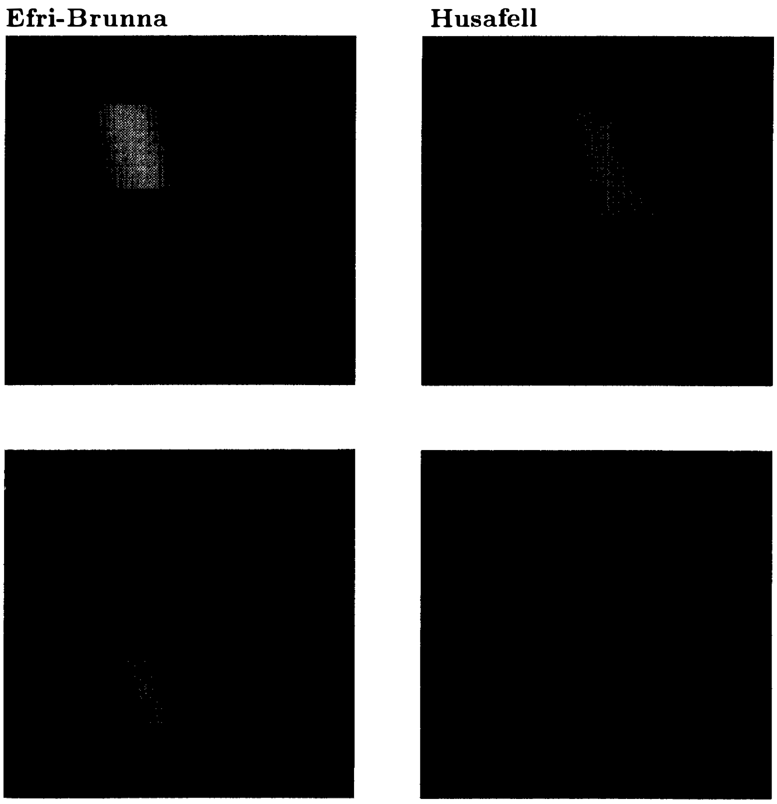


Fig. 6. Retrieved stereo images for the separate analysis of overlaid (top) and bifurcated (lower) portions at Efri-Brunna (left) and Husafell (right). Compare with Fig. 3.

epipolar lines (not shown) lie in the analyzed region (indicated by Fig. 6). Observed and reconstructed profiles are indicated by thin rugged and thick smoother lines, respectively. The reconstruction is seen to conform more reasonably to Efri-Brunna projection data.

The result of analysis for bifurcated portion, *i.e.* the lower portion of the same stereo image as in Fig. 4 is shown in Figs. 5a–5c. Figures 5a and 5b show reconstructed bifurcated structure which has its peak at around 100–110 km. Vertical extent for south-side layer is about 45 km, and horizontal thickness is about 10 km for both layers. In Fig. 5c, gray level profiles are compared between observed thin line profiles and reconstructed smoother thick lines as in Fig. 4c. The reconstructed structure is reasonably consistent with two-peak characteristics at Efri-Brunna and almost single peak at Husafell.

Retrieved stereo images based on the three-dimensional reconstruction in Figs. 4

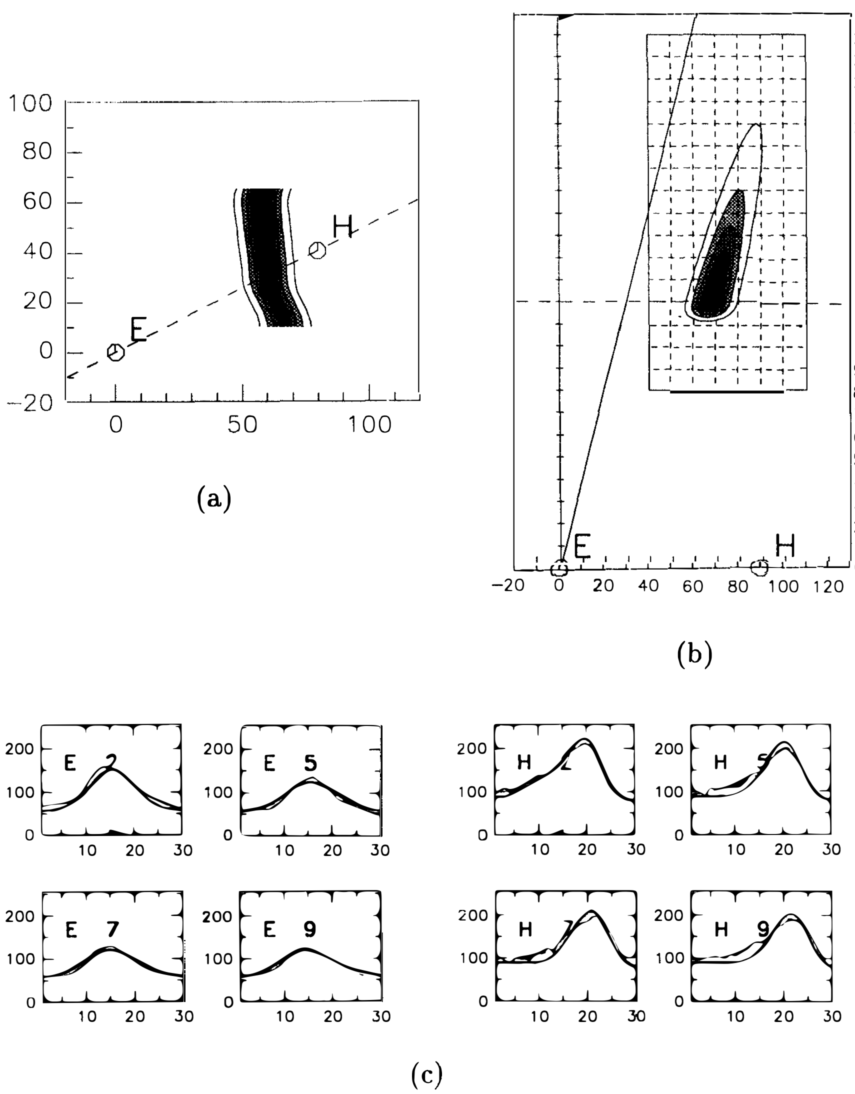


Fig. 7. The result of analysis for the aurora at 0306:10 on November 30, 1991. (a) Horizontal and (b) vertical structures and (c) comparison of observed gray levels as in Fig. 4.

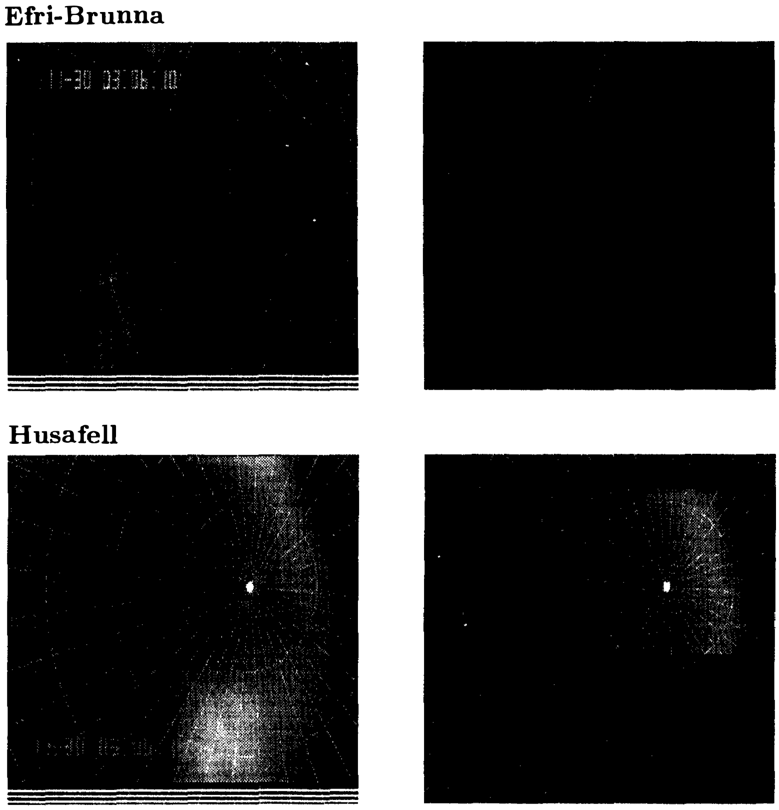


Fig. 8. Comparison of observed (left) and reconstructed stereo images for "spline-interpolated" elongated model in Fig. 7.

and 5 are shown in Fig. 6. Those at Efri-Brunna are on the left, and Husafell on the right. Upper figure is a retrieval for overlaid or one-layer portion, and lower one is shown for bifurcated portion. If we compare the images with observed stereo images in Fig. 3, the reconstruction is by and large fairly acceptable, and compatible with ground-based stereo image observation.

Figures 7a and 7b illustrate analysis for the thin layer (upper) part of aurora at 0306:10 on November 30 shown in Fig. 8. In this analysis, spline description of undulating east-west structure is interwoven to the Gaussian peak position, and horizontal structure in Fig. 7a is expressed by 9 knots spline function. The knots have been decided referring to triangulation results. It is seen the spline description helps to have reasonable agreement to observed gray level profile as shown in Fig. 7c in case arc is undulated in the elongated direction.

Figure 8 compares observed and reconstructed stereo images for "spline-interpolated" elongated model. It should be realized again that the analysis is relatively limited to local area and acceptable reconstruction is obtained by this complex luminosity model.

More comprehensive analysis based on the sophisticated luminosity model function describing structure as a whole for the same aurora at 0306:10 on November 30 is given in Figs. 9a–9d. In the model, polynomial undulation of Gaussian-type thickness together with two-dimensional Gaussian structure at its edge in the horizontal plane is assumed. Horizontal structure at 120 km is shown in Fig. 9a in which two layers of

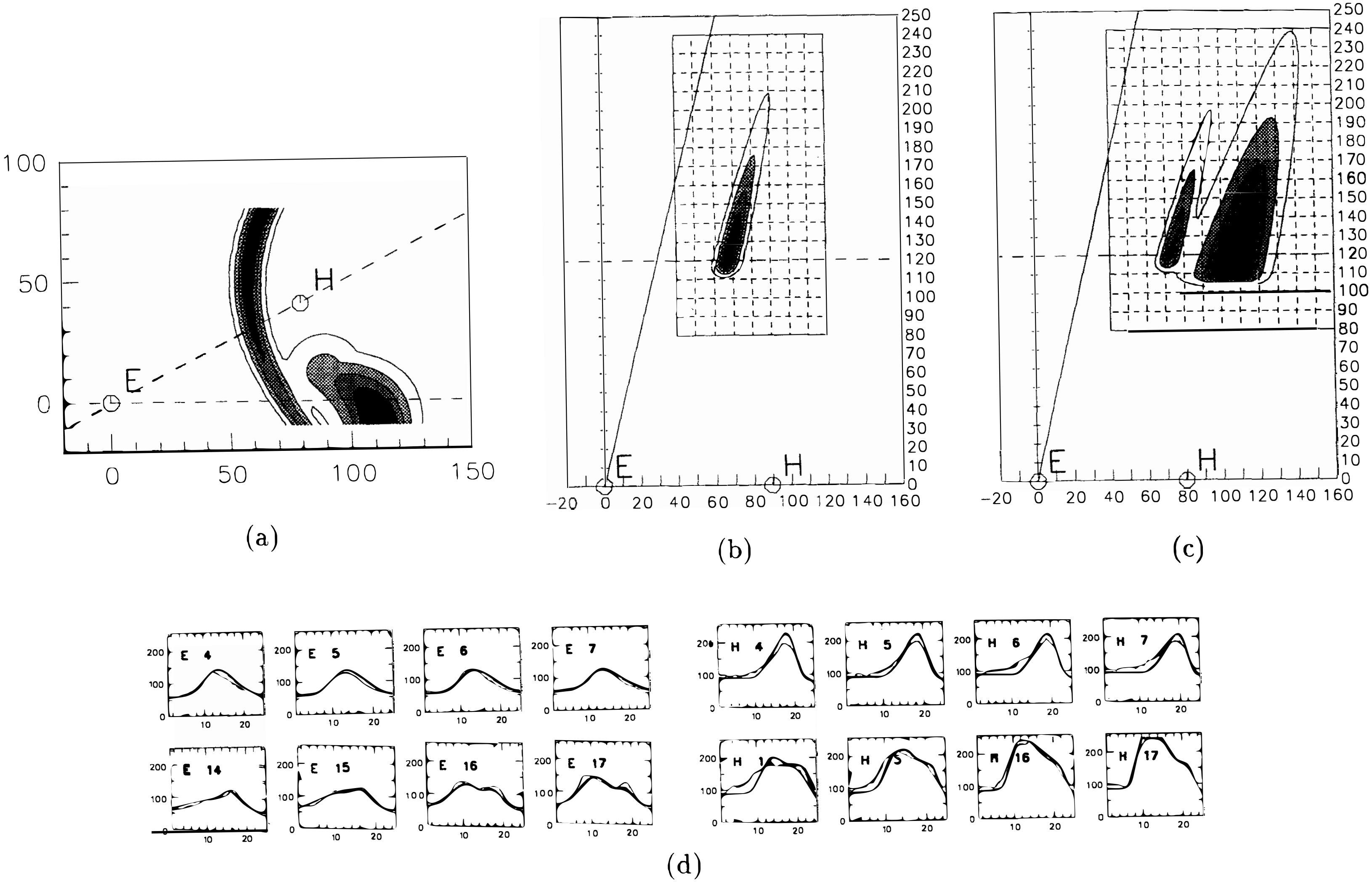


Fig. 9. The result of analysis for the same aurora at 0306:10 on November 30 with (a) horizontal structure, (b) and (c) vertical structures at two sections indicated by dashed lines in (a), and (d) comparison of gray level profiles.

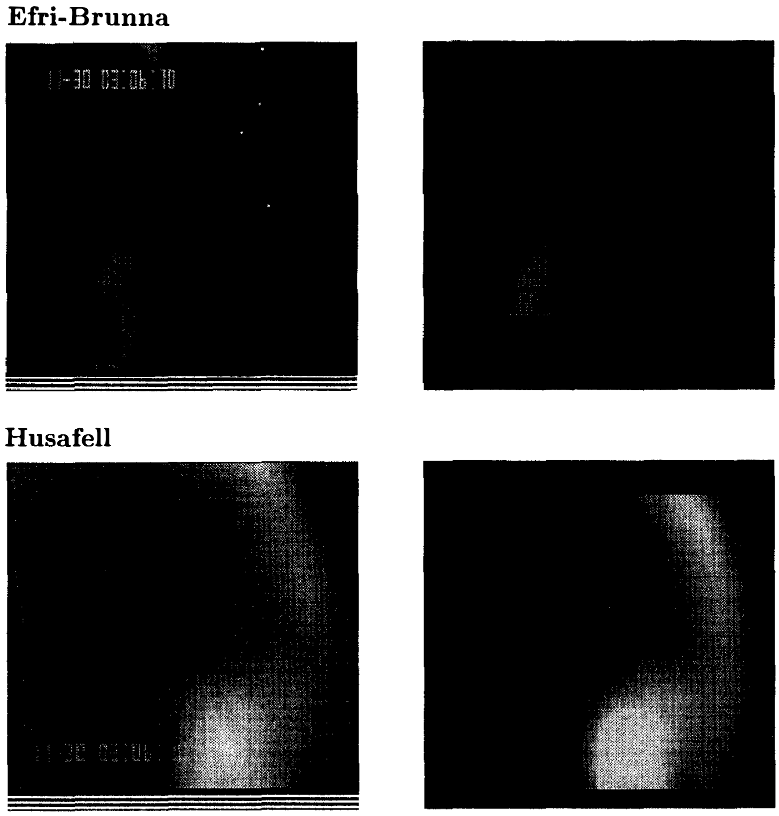


Fig. 10. Comparison of observed (left) and reconstructed stereo images for the analysis in Fig. 9.

these, simple arc-type in the east and composite or blob-type in the west, are assumed. Reconstructions in the vertical plane are shown in Figs. 9b and 9c along two dashed lines in Fig. 9a and comparison of gray level profiles are shown in Fig. 9d. Image restoration in Fig. 10 by this model is found to be reasonable, retrieving the whole image structures.

Figures 11a–11d likewise show the comprehensive analysis to those done separately in Figs. 4 and 5. In this case, larger area of images are simultaneously taken into account and overlaid and bifurcated portions are analyzed together by a sophisticated three-layer model description of the same undulant-Gaussian plus two-dimensional Gaussian edge arc. In the gray level comparison indicated in Fig. 11d, profiles in this case are along a set of line segments not aligned with epipolar lines to cover as wide area as possible for the reconstruction. The results are mostly consistent with separate analysis. Image restoration in Fig. 12 by this wide-scopic analysis gives also satisfactory gray level structures. These results indicate the possibility for the reconstruction of a more distorted type of auroral arcs than a stable, linear arc.

4. Conclusion

Stereo observation using longer baseline was recently realized in Iceland and some interesting monochromatic stereo image pairs at 5577 Å were obtained. In reconstructing appropriate luminosity model functions, we tentatively determine gray level ratio and uniform background values to correct for imaging characteristics and background luminosity, respectively. From the analyses of CAT–computed auroral tomography–it

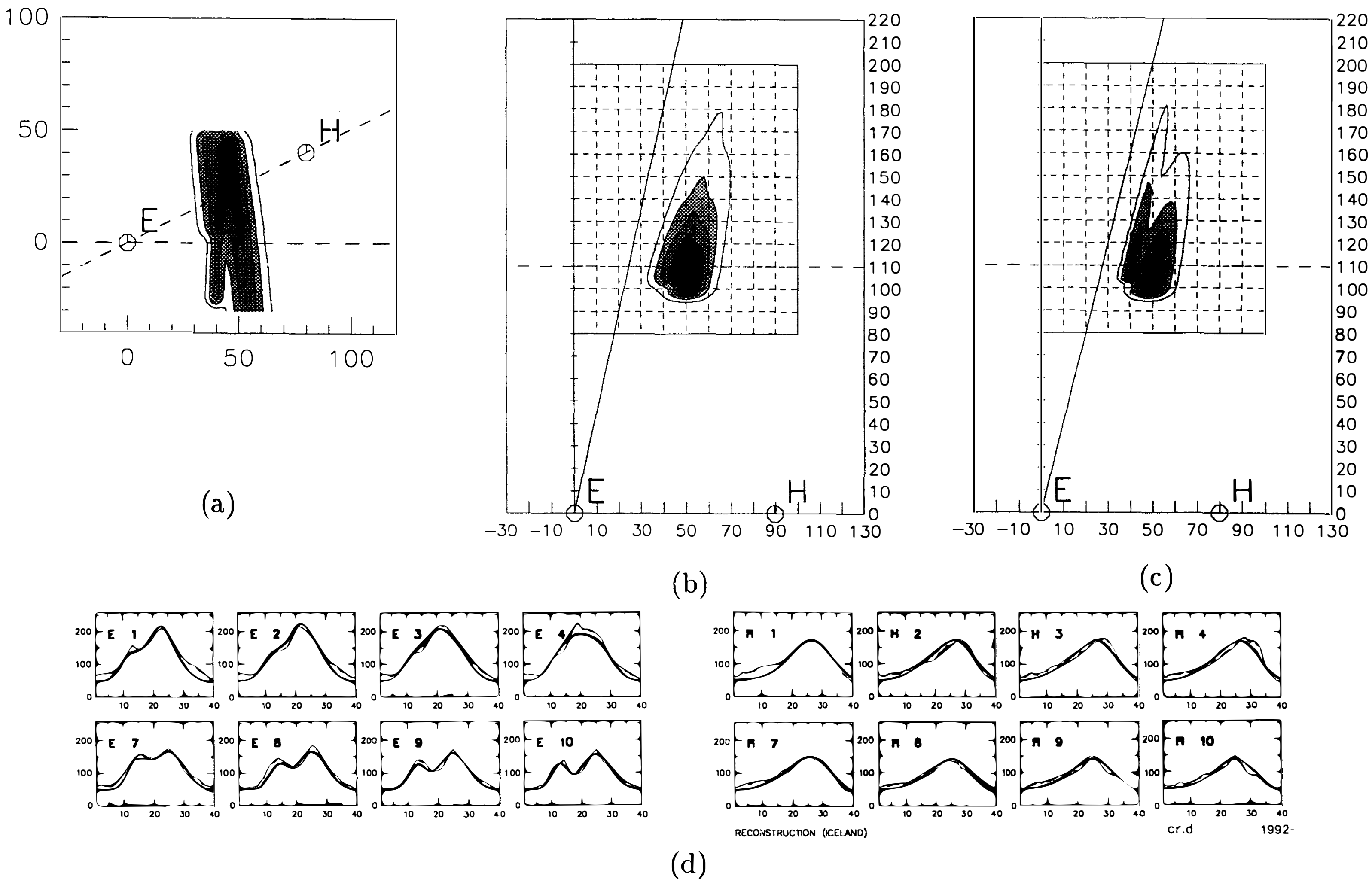


Fig. 11. The result of overall analysis for the stereo images at 2104:53 on December 7. Details are as in Fig. 9.

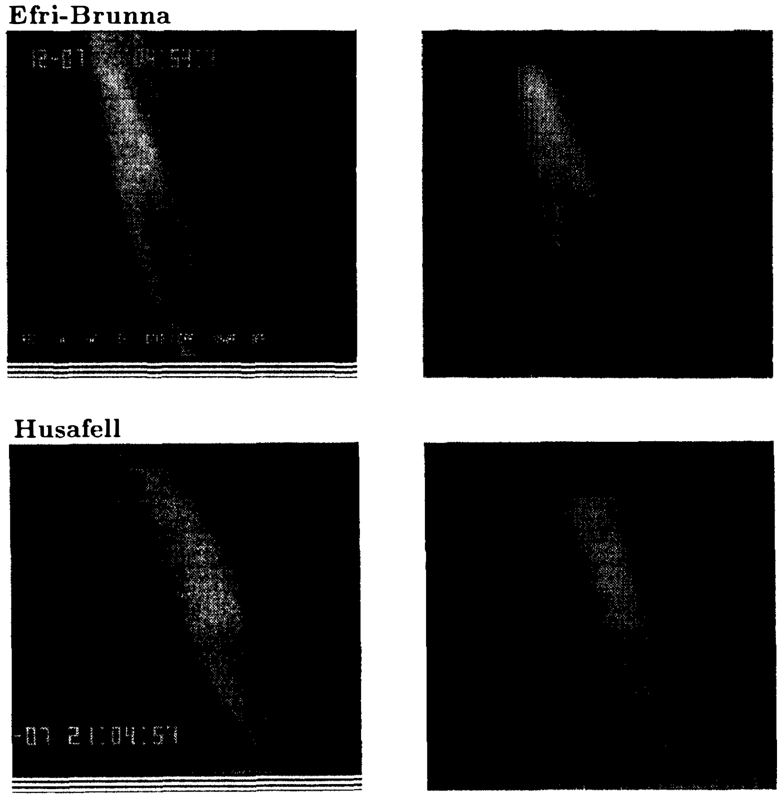


Fig. 12. Comparison of observed (left) and reconstructed stereo images for the analysis in Fig. 11.

is envisaged that limited portion of aurora luminosity structure can well be approximated by a linear elongation with Gaussian description of horizontal thickness, while for an undulant and layered structure, more realistic multi-layered modelling based on spline or polynomial descriptions in the elongated direction is required. A possible reconstruction of the three-dimensional aurora illuminating region is expected to bring about important information on the energy and acceleration of incoming high energy particles related to the magnetospheric activity.

Acknowledgments

The authors are grateful to Profs. T. HIRASAWA, N. SATO, TH. SAEMUNDSSON, and Dr. H. YAMAGISHI for their interests in the present observation campaign. They also appreciate kind help from Mr. S. H. JOHANESSON and Dr. T. OGAWA during the campaign and some of the computer work by Mr. K. MUGURUMA. Financial support for the observation was provided by the Grant-in-Aid for Scientific Research No. 01044143 of the Ministry of Education, Science and Culture, Japan. Image analysis has been carried out at the Integrated Media Environment Experimental Laboratory, Kyoto University.

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(Received September 16, 1992)