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Stellar Speckle Spectroscopy for High Spatial Resolution
and
its Observational Data Analysis

Susumu Kawamura

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Susumu Kuwamura

Department of Applied Physics, Faculty of Engineering,

Hokkaido University, Sapporo 060, Japan

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Chapter 1. Introduction

Atmospheric turbulence on the earth has prevented us from achieving stellar observations with a diffraction-limited spatial resolution of an optical telescope settled on the ground. Many techniques have been proposed to attain intrinsic high spatial-resolution of ground-based large telescopes. The stellar speckle interferometry is one of these techniques. In this method, a diffraction-limited image of a stellar object can be reconstructed by using speckle interferograms, or specklegrams.

Currently, constructions of large telescopes of 8-10m class are in progress over the world and importance of such high spatial-resolution techniques is increased. The movement to consider a larger telescope as an ultimate mean to gain available photons was motivated by recent achievement of nearly full detectability of photons with a detector. Furthermore, a large telescope possesses not only a highly collecting power but also an intrinsic high resolving power. Thus, toward completions of the large telescopes, development of the high spatial resolution techniques and related instrumentations becomes to be urgent to draw the intrinsic high resolving power of the large telescopes. The stellar speckle interferometry is believed to be one of the most powerful methods in the new age of large telescopes.

The stellar speckle spectroscopy is an extension of the speckle interferometry to attain a high spatial-resolution spectroscopy. Purpose of the speckle spectroscopy is to reconstruct a stellar spectrum with the diffraction-limited spatial resolution of a telescope by using dispersed specklegrams. Such a high spatial-resolution spectroscopic technique offers more information about a stellar object than that obtained by a high spatial-resolution imaging technique.

The present thesis concerns an instrumentation of the speckle spectroscopy for optical astronomy. Several methods to realize the speckle spectroscopy have been proposed and demonstrated with simulated data. However, any demonstrations with observational data have not been reported. Thus, the present thesis is devoted to show observational results of the speckle spectroscopy and to demonstrate its feasibility. The present thesis is based on an instrumentation proposed by Baba et al.(1988a,b). The instrumentation comprises a data acquisition system and a data reduction system, and the present thesis mainly

contributes the development of the computational data reduction algorithms.

Since the stellar speckle spectroscopy is based on the stellar speckle interferometry, the first section is devoted to a brief description of the stellar speckle interferometry as one of high spatial resolution techniques in astronomical observation. In Section 1.1., historical backgrounds of the speckle interferometry are reviewed, dating back to the Fizeau's suggestion in 1868. In Section 1.2., development of the speckle spectroscopic methods is reviewed. Competitive methods of the speckle spectroscopy are also mentioned in this section. In Section 1.3., outline of the thesis is given.

1.1. Historical Background of Stellar Speckle Interferometry

Under ideal conditions, the spatial resolution of an optical telescope is limited by diffraction. The diffraction-limited resolution is determined by a ratio of wavelength to diameter of a telescope's aperture so that larger telescopes intrinsically possess higher resolving power. However, in practice, a random aberration induced by the atmospheric turbulence severely limits the spatial resolution of ground-based telescopes. The atmospheric turbulence causes wavefront fluctuation with a typical coherence size of 10 cm and a typical coherence time of 10 msec in the visible region. A stellar image is then observed as an extended and randomly changing pattern. In conventional observations for stellar objects, the exposure time required to gain a sufficient signal to noise ratio (SNR) is far longer than the atmospheric coherence time. The spatial resolution is then what can be achieved by only a 10cm telescope, even if a larger telescope is used. The angular resolution limited by the atmospheric turbulence (seeing) is typically 1 arcsecond, otherwise, several ten times higher diffraction-limited resolution is expected for telescopes with aperture size of a few or several meters.

Many efforts have been made to overcome such seeing limitation and to attain a higher spatial resolution. In 1868, Fizeau suggested to observe the Young's fringes produced by star light passing through an aperture with two holes (Fizeau 1868). When the size of the holes is less than seeing-cell size (the coherence size of the disturbed wavefront for which the phase of optical wave is considered to be uniform), atmospheric effect appears as random translations of a fringe system. The fringe visibility which includes high spatial resolution

information can then be observed by eyes more easily than observing the randomly changing patterns. The Young's fringe produced by using an aperture mask with two holes was observed by Michelson (Michelson 1891).

The Fizeau's suggestion was developed into the Michelson's stellar interferometry (Born & Wolf 1988) and the apparent diameters of several bright stars were measured (Michelson 1920; Michelson & Pease 1921). The Michelson's stellar interferometry originated the so-called synthetic aperture technique in which the higher spatial resolution beyond that restricted by each aperture can be obtained by increasing the distance between the apertures. However, further developments of this technique in the optical astronomy were hampered by the problems of instrumental stability and the atmospheric turbulence (Tango & Twiss 1980). Those problems limit the accuracies of the fringe contrast evaluated from the measurement. Meanwhile, the synthetic aperture technique has been developed in radio astronomy, because longer wavelengths are less affected by the atmospheric turbulence.

Hanbury Brown and Twiss invented the intensity interferometry (Hanbury Brown & Twiss 1957a,b). In this method, a correlation between two intensity fluctuations collected by two apertures is measured, whereas the Michelson's stellar interferometry measures the correlation of amplitudes. The intensity interferometry is not affected by the phase fluctuation induced by the atmospheric turbulence. By this technique, the angular diameters of some bright stars were measured with the accuracy of $0.001''$ (Hanbury Brown et al. 1974). However, the intensity interferometry has a problem of its intrinsic low SNR (Twiss 1969) and measurable magnitude is considerably limited.

The optical synthetic aperture method was recalled in 1965 to obtain higher spatial resolution. This is mainly due to the developments of laser metrology and artificial detectors which replace human eyes. The optical synthetic aperture technique is currently in progress toward optical long baseline interferometry (Léna 1989; Labeyrie 1986; Mourard et al. 1992; Mourard et al. 1989) and optical very large array (Labeyrie 1989).

In 1970, Labeyrie proposed the stellar speckle interferometry as another extension of the Fizeau's interferometry (Labeyrie 1970). While the latter uses the interferogram from two small parts of a telescope's aperture, the former

uses that from the full aperture so that the available flux is increased. The Labeyrie's proposition is as follows. A telescope aperture can be regarded as that covered by many seeing-cells with random phases. Wave fronts from all the seeing-cells interfere on the focal plane to form a random two dimensional (2-D) interferogram, or specklegram, for every moment. A quasi-monochromatic specklegram of a point star features a random distribution of speckles, the size of which is comparable to that of Airy's disc. Such a fine structure in a specklegram suggests that the combined optical transfer function (OTF) of the atmosphere and the telescope allows to transmit the spatial frequency content up to the diffraction-limit cutoff. The object's information up to the diffraction-limited cutoff frequency is then preserved in a short exposure image formed during a frozen atmospheric fluctuation. By processing many short exposure images, the diffraction-limited image of an object can be reconstructed.

While the Michelson's stellar interferometry or the synthetic aperture technique allows to attain arbitrarily higher spatial resolution by extending the baseline between apertures, the speckle interferometry is an interferometric method using a single aperture and the spatial resolution is limited by the aperture size. However, one of the advantages of the stellar speckle interferometry is the simultaneous reconstruction of all the spatial frequencies within the cutoff of a telescope, while in the synthetic aperture technique the reconstruction are attained at discrete points in the Fourier space at a time. Further, the synthetic aperture system requires frequent adjustments to equalize the optical path-lengths of the beams from all the apertures with accuracy of a few wavelengths. The adjusting equipment then makes the system complicated. In contrast, the speckle interferometry does not need such an adjustment, since a primary mirror of a telescope usually has a surface with accuracy of about $\lambda/8$ (Kitchin 1991). The speckle interferometry can be achieved by comparatively simple devices, a magnifying optics with a high speed shutter and a high-sensitive detector. The stellar speckle interferometry has progressed with supports of developments of detectors and computers. As the result, the limiting visual magnitude in the stellar speckle interferometry has reached to around 17 (Foy 1992).

As other methods of the single aperture interferometry, the aperture masking and the pupil plane interferometry are known. The aperture masking

method (Rogstat 1968; Rhodes & Goodman 1973) is an application of radio array interferometry to the visible region. In the aperture masking method, interference patterns are observed by setting a mask with several holes in a reduced pupil plane. Each hole has a size comparable to that of the seeing cell. An interferogram taken with a short exposure contains many fringes related to different pairs of any two holes, each of which corresponds to a 2-D spatial frequency determined by a vector between two holes. Respective fringes have random components in their phases due to the atmospheric disturbance. However, when a sum of three fringe phases related to three holes forming a triangle is taken, the random components are canceled out, provided that the arrangement of the holes on the aperture mask is made so that the vectors with different hole pairs never coincide (non-redundant condition). To attain the full coverage in the 2-D spatial frequency domain, rearrangements of the aperture mask are needed.

While the interferometries described so far use interferences occurring on the imaging plane of a telescope, the pupil plane interferometry (Rodier et al. 1979) produces an interferogram between the wavefront on the pupil plane and its sheared version. In this approach, a coherence interferometer or shearing interferometer is needed and the instrumentation is rather complicated.

In contrast to the passive interferometric methods described so far, the adaptive optics (Babcock 1953; Merkle 1988) is known as an active method to overcome the atmospheric turbulence. The adaptive optics corrects fluctuated wavefronts in real time by using a deformable mirror which is controlled in a servo system. The servo control is performed by referring the wavefront from a point source which is located within the isoplanatic region over which the atmospheric point-spread-function (PSF) can be regarded as constant. The adaptive system has been successfully applied in the near infrared region (Rousset et al. 1990), but in the visible region, some technical problems still remain, because the atmospheric coherency and isoplanaticity decrease in shorter wavelengths.

At present, there are three typical ways to achieve high spatial resolution, namely, synthetic aperture optics, speckle interferometry and adaptive optics. The stellar speckle interferometry appears to be the most established method in optical astronomy for its simplicity, and many astronomical results have been

reported. The higher spatial resolution is promised by combining this method with the 8-10 m class telescopes which are being constructed in the world (Enard 1991).

1.2. Stellar Speckle Spectroscopy

The stellar speckle spectroscopy is an application of the stellar speckle interferometry to obtain spectra with high spatial resolutions (Weigelt et al. 1986). In this method, dispersed specklegrams are processed and point by point spectra on an object can be reconstructed in a diffraction-limited resolution. The spectral resolution is also enhanced as the spatial resolution of the dispersed image is increased, while in the conventional slit spectroscopy a slit must be used to improve the spectral resolution and accordingly losses of the optical throughput are unavoidable. Thus, the speckle spectroscopy serves as a slitless spectroscopy. The speckle spectroscopy supplies more astrophysical information than that obtained from the non-dispersed image and several methods to realize the speckle spectroscopy have been proposed.

Weigelt et al. proposed a speckle spectroscopic method based on the speckle masking, presenting some results with laboratory simulated data (Weigelt et al. 1986; Grieger et al. 1988). Weigelt et al. have assumed that dispersed specklegrams can be described by a convolution of the diffraction-limited spectrum of an object and the atmospheric PSF. However, because of the spectral dependence of the PSF, this assumption is satisfied only when the spectral band concerned is narrower than several tens nano-meters in wavelength. Thus, the Weigelt's method gives a reasonable result only for narrow band data.

A group of the Steward Observatory, University of Arizona, envisioned a speckle spectroscopy in the original design of their differential speckle camera (SO/DSC) (Beckers et al. 1983) to study a variation of stellar size over a wavelength region. In the early envision, a slit was still employed. The concept of slitless speckle spectroscopy occurred several years later but was not published. In the scheme of the slitless spectroscopy, a conventional narrowband specklegram and a spectrally dispersed specklegram are simultaneously detected. The conventional specklegram contains the instantaneous atmospheric PSF by which the dispersed specklegram is degraded. By using the conventional specklegram

as the deconvolution key, the diffraction limited spectrum can be recovered from the dispersed specklegrams.

In 1988, Baba et al. proposed method based on the shift-and-add(SAA) algorithm to reconstruct wideband objective prism-spectra with a diffraction-limited resolution and reported some results with simulated data in laboratory (Baba et al. 1988a,b; Baba 1989). The advantages of this method are its simplicity for the computational processing and its insensitivity to the spectral bandwidth. In the SAA scheme, the simultaneous recording of a dispersed specklegram and the corresponding nondispersed reference specklegram is needed, and hence the instrument has two optical channels. The instrumental scheme is coincidentally the same as what developed for the slitless speckle spectroscopy in the Steward Observatory, except the dispersion schemes. The SAA process applied on nondispersed reference specklegrams to reconstruct a diffraction-limited image also recovers a diffraction-limited spectrum from dispersed specklegrams. It can be considered that the spectrum is recovered with referring to the instantaneous atmospheric PSF included in the nondispersed reference specklegrams. Following the Baba's proposition, the speckle spectroscopic camera No.1 (SSC1) was constructed, and the first observation with the SSC1 was conducted using the 188 cm telescope in Okayama Astrophysical Observatory (OAO) on November, 1988.

The speckle spectroscopic methods as described above have been demonstrated with simulated data, but any demonstrations with observational data have not been given. Thus, the present thesis aims to demonstrate feasibility of the speckle spectroscopy using observational data. Series of the studies in this thesis follows the first observation using the SSC1.

1.3. Outline of the Thesis

In Chapter 2, underlying theories are briefly reviewed. In Section 2.1., the statistical properties of the stellar specklegram are explained. The Kolmogorov's model of the atmospheric turbulence is then introduced to describe the statistics of the refractive index fluctuation. In Section 2.2., several speckle imaging techniques associated with the present studies are introduced. Labeyrie's speckle interferometric method and the shift-and-add (SAA) method are mainly

described. In Section 2.3., brief descriptions on the dispersed specklegram are given.

In Chapter 3, speckle spectroscopy with wideband and low dispersion is demonstrated using the data obtained by the SSC1. In Sec. 3.2., a description of SSC1 is given. The SSC1 is designed to take a white light specklegram and a low dispersion specklegram on the same frame, simultaneously, through two optical channels, reference channel and spectral channel, respectively. Data acquisition and data reduction algorithm are described in Sec. 3.3. The image taken by SSC1 is digitized into many frames. The computational SAA imaging-algorithm (Bates & Cady 1980) is applied on the white light specklegrams so as to reconstruct a diffraction-limited image of an object. The SAA process equally works on the dispersed specklegrams and then a diffraction-limited spectrum results. However, the raw SAA frame is attended by a strong background component. To remove the background component, a background-subtraction algorithm with use of a pseudo-long-exposure frame (Kuwamura et al. 1992a) was developed. Since an imaging process performed in the reference channel is critical for a reasonable reconstruction in the spectral channel, preliminary experiments for examining performances of the SAA imaging-algorithm and the background-subtraction algorithm are presented in Sec. 3.4.1. The experiments were carried out with simulated data and observational data obtained by a conventional speckle camera. The SAA imaging results with the observational data are compared with results obtained by iterative blind deconvolution method (Miura et al. 1993). In Sec. 3.4.2., speckle spectroscopic results with SSC1 data are given. As a notable result in this section, two separated spectra of a double star with angular separation of about $0.5''$ was reconstructed, otherwise those spectra are not distinguishable because of the seeing (Kuwamura et al. 1992a,b; Kuwamura et al. 1993a).

In Chapter 4, speckle spectroscopy with narrow band and medium dispersion is demonstrated. In Sec. 4.2., the data-reduction algorithm developed with the SSC1 was applied to a data set supplied by E.K. Hege of the Steward Observatory. The data set was obtained by a differential speckle camera (SO/DSC) (Beckers et al. 1983) in the Steward Observatory and the 4 m telescope at the Kitt Peak National Observatory (KPNO). The SO/DSC data are narrow

band and medium dispersion. In Section 4.2., processed results of the SO/DSC data are shown. It will be demonstrated that spectra of two single stars can be reconstructed with the diffraction-limited resolution of the 4m telescope. The reconstructed spectra show clearly resolved $H\beta$ -absorption line and $H\beta$ -emission line (Kuwamura et al. 1992b, Kuwamura et al. 1993a). Sections 4.3. and 4.5. are concentrated onto the data obtained by speckle spectroscopic camera No.2 (SSC2). The SSC2 was developed by Baba et al. (1993) to obtain augmented performances. A brief description on the SSC2 is given in Sec.4.3. The SSC2 has also two optical channels and is designed to simultaneously take a bandwidth-limited specklegram and a medium dispersion specklegram on the same frame. Data obtained by the SSC2 with the 188cm telescope were processed by the SAA algorithm. Since the spectral bandwidth of the SSC2 data is narrow, the cross-correlation technique was newly introduced. Detailed descriptions on the data-reduction algorithms are given in Sec.4.4. The processed results of data of single stars are presented in Sec. 4.5.1. The data sets of two single stars have been processed using the two methods (Kuwamura et al. 1993b), SAA and cross-correlation technique. Comparative considerations are made between the results obtained by two different methods. The profile of the reconstructed spectrum of α Per is compared with Procyon's profile which is obtained with a slit spectroscopy by Griffin et al.(1979). Processed results for a double star, of which separation is closer than the seeing limit, are shown in Sec. 4.5.2. In the results, two separated spectra around the $H\alpha$ lines are clearly reconstructed in response to the reconstructed image in the reference channel.

In Chapter 5, an instrumentation toward the speckle spectroscopy with high dispersion is proposed. In this system, the SAA is performed in real time by using a tip-tilt mirror controlled by a servo system. The image stabilized by the real-time SAA is fed to a spectrograph and the spectrogram with the diffraction-limited resolution is integrated on a detector in a long-exposure mode. This long-exposure is advantageous to high dispersion spectroscopy. The other advantages in the proposed system are also discussed. The new system will overcome drawbacks in the previous systems, SSC1 and SSC2, and improved performances can be expected. In Sec.5.3., the possibility to realize this new system is discussed.

Chapter 6 gives conclusions to close the thesis.

1. Stable Spectra

1.1. Stable and Unstable Spectra

The electromagnetic spectrum is divided into regions according to wavelength λ , calculated in a vacuum, like we treat the earth as a plane wave. Such an idealization can be applied to such practical situations that the spatial extension of the field is larger than the wavelength, and the temporal extension is longer than the maximum path difference. During the transmission through the earth's atmosphere, each electromagnetic field undergoes spatial and temporal variations in random manner by stochastic fluctuations. This can be due to the fact that the spectrum is a function of time and space. The temporal scale of about 10^{-10} s, and the spatial scale of about 10^{-10} m, are much smaller than the wavelength of the field.

Photons as particles of the electromagnetic field cause the stochastic fluctuations. The stochastic spectrum $S(\omega)$ of the perturbed field in the plane plane (the electric field is represented by

$$E(t) = \psi_1(z) \cos(\omega t) \quad (1.1)$$

where $\psi_1(z)$ is the unperturbed wave (plane wave) and $\psi_2(z)$ is the wave perturbation (a random function). Then the disturbance of the unperturbed field at the point z is $\psi_2(z)$ which is related to the refractive index fluctuation $\delta n(z)$ (Tatarski 1961, Sridhar 1965)

$$\psi_2(z) = \frac{1}{2} \int_0^z \delta n(z') dz' = \frac{2\pi}{\lambda} \left(\frac{1}{2} \int_0^z \delta n(z') dz' \right) \quad (1.2)$$

where

$$\delta n = \frac{\delta \epsilon}{2\epsilon_0}$$

$\delta \epsilon$ is the dielectric constant fluctuation, and ϵ_0 is the permittivity of free space.

$\delta n(z)$ is the refractive index fluctuation, and λ is the wavelength.

The refractive index fluctuation $\delta n(z)$ is related to the density fluctuation $\delta \rho(z)$ by

$\delta n(z) = \frac{1}{2} \left(\frac{\delta \rho(z)}{\rho_0} \right) \left(\frac{1}{n_0} \right)$ where ρ_0 is the density of the medium, and n_0 is the refractive index of the medium.

Chapter 2. Principles

2.1. Stellar Specklegram

2.1.1. Statistical Models of the Wavefront Fluctuation

The monochromatic electro-magnetic field at wavelength λ_0 radiated from a point like star reaches the earth as a plane wave. Such an idealization can be applied to such practical situations that the spatial coherency size of the field is larger than telescope's diameter and the temporal coherency length is larger than the maximum path difference. During the transmission through the earth's atmosphere, such a coherent field undergoes spatial and temporal modulation in random manner by atmospheric fluctuations. This reduces the field's coherency to a spatial scale of about 10cm and a temporal scale of about 10msec, both determined by the atmospheric seeing conditions.

Fluctuation of refractive index of the atmosphere mainly causes the wavefront distortion. The complex amplitude $\psi(x)$ of the perturbed field on the pupil plane of the telescope can be represented by

$$\psi(x) = \psi_1(x)\psi_0(x), \quad (2.1.1)$$

where ψ_0 is the unperturbed wave (plane wave) and $\psi_1(x)$ represents the modulation factor (a random function). Then, the disturbance of the wavefront from the point star in the zenith is related to the refractive index fluctuation by (Tatarski 1961; Goodman 1985)

$$\ln \psi_1(x) = \frac{k_0^2}{2\pi} \int_0^h \Delta n(x; z) * \frac{\exp\left(ik_0 \frac{|x|^2}{2z}\right)}{z} dz, \quad (2.1.2)$$

where

$$k_0 = 2\pi/\lambda_0;$$

h : total distance for which the wave propagates through the atmosphere;

$\Delta n(x; z)$: refractive index fluctuation around the average, $n(x; z) - \bar{n}$;

x, z : transverse and altitudinal coordinates, respectively;

and $*$ indicates the convolution operation. The real part and the imaginary part

of $\ln \psi_1(x)$ are equal to the log-amplitude fluctuation and the phase fluctuation, respectively. If the disturbed and undisturbed wavefronts are represented by

$$\begin{aligned}\psi(x) &= A(x) \exp[i\phi(x)], \\ \psi_0 &= A_0 \exp[i\phi_0],\end{aligned}\tag{2.1.3}$$

then the log-amplitude fluctuation χ and the phase fluctuation $\Delta\phi$ are given by

$$\begin{aligned}\chi &= \ln \frac{A}{A_0}, \\ \Delta\phi &= \phi - \phi_0.\end{aligned}\tag{2.1.4}$$

Equation (2.1.2) is derived from the wave equation under the Rytov approximation (Tatarski 1961) in which the refractive index fluctuations $\Delta n(x; z)$ are small ($\Delta n \ll n_0$) and the wave perturbations $\Delta\psi(x) = \psi(x) - \psi_0(x)$ are then weak ($|\Delta\psi(x)| \ll \psi_0$). This equation means that the wave disturbance on the pupil plane of a telescope is a superposition of the contributions of the Fresnel diffractions from all the altitudes.

The distribution of the refractive index fluctuation has correlation scales ranging from the inner scale (l_0) with typical values of 2-3mm to the outer scale (L_0) with typical values of 1-100m (Goodman 1985; Roddier 1981). Such statistics can be characterized by Kolmogorov's power spectral density with the statistical homogeneity and isotropy in local,

$$\Phi_n(\kappa) = 0.033 C_n^2 \kappa^{-11/3},\tag{2.1.5}$$

(Tatarski 1961; Roddier 1981), where κ is the spatial wavenumber, the reciprocal representation of the correlation scale, and C_n^2 is called the structure constant for scaling the amplitudes of the refractive index variations. This expression is meaningful for range $1/L_0 \leq \kappa \leq 1/l_0$, and the power spectrum density is cut off for $> 1/l_0$ or saturated for $< 1/L_0$ (Goodman 1985). If the atmosphere is divided into many layers with thickness of about L_0 , the contributions from those layers to χ and $\Delta\phi$ are considered to be statistically independent. By employing the central limit theorem, the log-amplitude fluctuation χ and the phase fluctuation $\Delta\phi$ can be considered to obey the Gaussian statistics. Such statistical model for the wavefront fluctuations is called log-normal model. The log-normal model (Korff 1973) fairly represents the reality, provided that the fluctuations are sufficiently weak.

There is another statistical model known as the normal model (Dainty 1973). In this model, the real part and the imaginary part of the complex amplitude $\psi(\mathbf{x})$ of the disturbed wavefront, obey the circular Gaussian statistics. This model have been used to describe the far field produced by scattering from a rough surface, i.e., the model describing the statistics of the sum of large number of random phasors (Dainty 1977; Goodman 1975; Goodman 1985). This may correspond to the case that a strong turbulent layer is assumed to exist in a very high altitude. When the complex amplitude obeys the circular Gaussian statistics, its intensity I takes the negative exponential probability density function (Dainty 1977; Goodman 1975; Goodman 1985)

$$p(I) = \begin{cases} \frac{1}{I} \exp\left(-\frac{I}{I}\right) ; & I \geq 0 \\ 0 ; & \text{otherwise} \end{cases} \quad (2.1.6)$$

and its phase uniformly distributes over $[-\pi, \pi]$. Those statistics predict that the strong intensity fluctuations (scintillation) and phase fluctuation would occur. However, such phenomena, in which the intensities of the incident waves are allowed to be zero at some points, rarely occur. Although the normal model is less realistic than the log-normal model, the former can give reasonable results for the most problems without labored calculations.

From the statistical homogeneity of the refractive index perturbations, the wavefront fluctuations can be considered to be a stationary random process with respect to the spatial coordinate $\mathbf{x}$. The statistics of the stationary Gaussian random process with zero mean is fully characterized by the statistical autocorrelation function $\Gamma(\Delta\mathbf{x})$. In the log-normal model, $\Gamma(\Delta\mathbf{x})$ of the perturbed wavefront is represented by

$$\Gamma(r) = \exp\left[-\frac{1}{2}\{D_\chi(r) + D_{\Delta\phi}(r)\}\right]; \quad r = |\mathbf{x}|^2 \quad (2.1.7)$$

(Fried 1966), where $D_\chi(r)$ and $D_{\Delta\phi}(r)$ are the structure functions of χ and $\Delta\phi$, in which the statistical isotropy has been assumed. When the refractive index fluctuations obey the Kolmogorov's power spectral density Eq.(2.1.5), the wave structure function $D(r) = D_\chi(r) + D_{\Delta\phi}(r)$ is given by

$$D(r) = 2.91k_0^2 h C_n^2 r^{5/3} \quad (2.1.8)$$

(Tatarski 1961) and the autocorrelation function is

$$\Gamma(r) = \exp\left[-\frac{1}{2}(2.91k_0^2 h C_n^2 r^{5/3})\right] \quad (2.1.9)$$

(Fried 1966). This expression can be derived from Eq.(2.1.2) and Eq.(2.1.5) with several approximations. The shape of this function is similar to the Gaussian and the spatial coherence size of the atmospherically disturbed incident wavefront is defined from the autocorrelation function. In 1966, Fried introduced an atmospheric coherence size (Fried's parameter) r_0 (Fried 1966) defined by

$$r_0 = 0.185 \left[\frac{\lambda_0^2}{h C_n^2} \right]^{3/5} \quad (2.1.10)$$

which corresponds to a diameter for which the $\Gamma(r)$ is larger than about 0.34. The Fried's parameter is proportional to $\lambda_0^{6/5}$ and the stronger fluctuation (larger C_n^2) results in the smaller r_0 . Under the moderate seeing conditions, 10cm is usually quoted for the value of r_0 .

2.1.2 Formation of Stellar Specklegram

The disturbed wavefront from the point source enters a telescope's aperture of circle of diameter D , and is diffracted by the aperture to form an interference pattern or specklegram on the focal plane of the telescope. A short exposure specklegram taken within the coherence time Δt_a associated with atmospheric turbulence manifests fine features of randomly distributed speckles, whereas such features disappear in the long exposure image for which the statistically independent speckle patterns are superimposed.

The monochromatic specklegram $s(x)$ of the point source, or instantaneous atmosphere-telescope PSF, observed within Δt_a is described as a square modulus of the Fourier transform of the atmospherically aberrated (instantaneous) pupil function $\psi(\xi)P(\xi)$:

$$s(x) = \left| \int \int \psi(\xi)P(\xi) \exp \left[-\frac{2\pi i}{\lambda_0 f} x \cdot \xi \right] d^2 \xi \right|^2, \quad (2.1.11)$$

(Goodman 1968; Mariotti 1989) where

x : 2-D coordinate on the focal plane of the telescope;

ξ : 2-D coordinate on the pupil plane;

$P(\xi)$: telescope's pupil function;

f : focal length of the telescope;

and $\cdot$ indicates the inner product. The averaged angular size of respective speckles is then comparable to that of the telescope's diffraction limited Airy disc (Born & Wolf 1980), about λ_0/D . Thus, the respective speckles are considered to be distorted versions of the diffraction-limited image of the point source (Bates & Cady, 1980). On the other hand, the specklegram extends by $\sim \lambda_0/r_0$, where r_0 is the Fried's coherence diameter within which the phase of the wavefront can be regarded as constant.

Under assumption of the ergodicity of the atmospheric random process, the long exposure PSF $l(x)$ or seeing disc can be found by calculating an ensemble average $\langle s(x) \rangle$. Taking the ensemble average of Eq.(2.1.11) and interchanging the integration and the ensemble average leads to

$$l(x) = FT[\Gamma(\Delta\xi)]_{u=x/\lambda_0 f} * a(x) \quad (2.1.12)$$

or equivalently, representing in the plane of spatial frequency u as the long exposure OTF,

$$L(u) = \Gamma(-\lambda_0 f u) T(-\lambda_0 f u) \quad (2.1.13)$$

where

$$FT[f(\xi)] = \int \int [f(\xi)] \exp(-2\pi i \xi \cdot u) d^2 \xi, \quad (2.1.14)$$

$a(x)$ is the atmosphere-free PSF and $T(u)$ is the telescope's OTF. Since $\Gamma(\Delta\xi)$ has a shape similar to the Gaussian, the long exposure PSF is represented by a convolution of a broad Gaussian function and the far narrower function $a(x)$. Using Eq.(2.1.9) and Eq.(2.1.10), the atmospheric long-exposure OTF $H_L(u)$ is rewritten as

$$H_L(u) = \Gamma(-\lambda_0 f u) = \exp \left[-3.44 \left(\frac{\lambda_0 f |u|}{r_0} \right)^{5/3} \right] \quad (2.1.15)$$

(Fried 1966). Thus, the angular size of the long-exposure PSF ($= FT^{-1}[H_L(u)]$) is proportional to λ_0/r_0 , and consequently depends on the wavelength as $\lambda_0^{-1/5}$ (Rodier 1981).

The random translations (wandering or dancing) of the instantaneous speckled PSFs broaden the long-exposure PSF. The extent of the long-exposure PSF

is then larger than those of the instantaneous PSFs. The average extent of the instantaneous PSF can be found from the ensemble average of the centroided versions of the instantaneous PSFs. The average of the centroided instantaneous PSFs is usually referred to as short exposure PSF. To correct the image dancing, the statistics of the tip-tilt of the incident wavefront should be known. Fried derived from the Kolmogorov's spectrum that the isotropic tip-tilt b [radian/meter] of the wavefront is randomly shifting by (Fried 1965; Fried 1966)

$$\langle b^2 \rangle \simeq 6.88\alpha \left(\frac{1}{r_0} \right)^{5/3} \left(\frac{1}{D} \right)^{1/3}, \quad (2.1.16)$$

where α takes unity or $1/2$ according to the near-field propagation or the far-field propagation (Goodman 1985). The short exposure PSF $sh(u)$ is then related to the long-exposure PSF by

$$l(x) = sh(x) * \exp \left[-2\pi^2 \frac{|x|^2}{\lambda_0^2 f^2 \langle b^2 \rangle} \right], \quad (2.1.17)$$

where the Gaussian function represents the extension by the image dancing. The angular extension amounts to

$$\frac{\lambda_0}{D^{1/6} r_0^{5/6}} \quad [radian], \quad (2.1.18)$$

and its dependency on the wavelength is canceled out because r_0 is proportional to $\lambda_0^{6/5}$.

In the statistical sense, the stellar specklegram of a point star is different from the normal speckle pattern. The highly coherent light (laser light) scattered by a rough surface produces a normal speckle pattern in the far field. In this case, any point on the speckle pattern is a result of sum of the random phasors from large number of scatterers within the illuminated area on the rough surface. The roughness is sufficient to have the phase of each phasor be uniformly distributed for $[-\pi, \pi]$. On the other hand, each point on the stellar specklegram is a result of the random phasor sum [see Eq.(2.1.11)] from all the seeing cells within the aperture. The differences between the stellar specklegrams and the laser speckle patterns are that, (1) while the laser speckle pattern obeys the circular Gaussian statistics because of the conditions mentioned above, a stellar specklegram is not necessarily so, for the weak fluctuations are

the most cases and the number of the seeing cells within the aperture is rather small $[(D/r_0)^2]$ because of the definite size of the cells, (2) while the correlation size of the rough surface is considered to be indefinitely small to the illumination area so that the normal speckle pattern can be assumed to be stationary random process, the seeing cell size is not so (thus the stellar specklegram is localized for extent λ_0/r_0), and (3) while the contrast of the laser speckle pattern is uniform all over, the contrast of stellar specklegram can be slightly reduced in the marginal parts because of quasi-monochromaticity. However, when the wavefront fluctuations are strong and $D \gg r_0$, the stellar specklegram of a point star can be regarded as similar to a laser speckle pattern. In this case, the intensity $I = s(x)$ of the specklegram obeys the negative exponential statistics [Eq.(2.1.6)]. Further, the second order statistics of I is completely characterized by an statistical autocorrelation function

$$\langle I(x + \Delta x)I(x) \rangle = \langle I \rangle^2 + \langle I \rangle^2 a(x) \quad (2.1.19)$$

(Dainty 1977; Goodman 1975), where $a(x)$ is the Airy's disc with $a(0) = 1$. This equation explains the fact that a specklegram shows a granular structure with a scale comparable to the Airy disc.

2.1.3. Wideband Specklegram

The expressions for describing the atmospherically degraded images shown so far are derived in context of the frozen atmosphere and monochromatic radiation. The actual specklegrams, however, are taken with finite spectral bandwidth and exposure time. In this case, the specklegram is considered to be a superposition of less correlated specklegrams due to the spectral and time dependencies of the speckle pattern. The contrast of the specklegram taken with the finite spectral band and the finite exposure time is then reduced. Reduction of the contrast results in depressing the modulation transfer function (MTF, which is averaged modulus of the Fourier spectrum of the instantaneous PSF) in higher spatial frequencies. The restrictions on the spectral band $\Delta\lambda$ and on the exposure time Δt compete with requirement to collect sufficient photons. Thus, it is important to investigate the maximum amount of the spectral bandwidth and the exposure time in which the speckle interferometric methods

are applicable. The effects of the finite spectral band and exposure time on the MTF have been theoretically or experimentally investigated by several authors (Karo et al. 1978; Ohtsubo 1985). The theoretical studies on the dichromatic speckle cross spectrum were made by Borgnino et al.(1989). Karo et al.(1978) experimentally found that the MTF depression at higher spatial frequencies is negligible up to $\Delta\lambda = 30nm$ and not severe even at $\Delta\lambda = 70nm$ under conditions of $D = 1.6m$, $D/\lambda_0 \sim 14$, $\lambda_0 = 500nm$ and $\Delta t = 5msec$. With the same conditions except $\Delta\lambda = 40nm$, they also found that the exposure time shorter than 50msec is allowable.

In 1980, Bates and Cady pointed out that the several compact and intensive speckles can be recognized in wideband (white light) specklegram. This suggests that the diffraction-limited resolution is retained even in the white light specklegrams. They simulated the white light specklegrams ($\Delta\lambda \sim 100nm$) and reconstructed the diffraction-limited image from the whitelight specklegrams (Bates & Cady 1980). The reconstruction was achieved by averaging only the most intensive speckles in individual frames (i.e., by the shift-and-add method). A specklegram is an interference pattern produced by contributions from $(D/r_0)^2$ seeing cells. By an analogy with the Young's fringe of a white light (Born & Wolf 1980), it may be said that the brightest speckle in a white light specklegram is located at a position such that a significant number of contributions from many seeing cells interfere in phase with optical path differences of zero (i.e., this point lies on an instantaneous "optical axis"). Hence the brightest speckle most resembles the diffraction-limited image of the point source which is formed by all the contributions from the aperture in phase (Lynds et al. 1976). At the other points, optical rays meet with different optical path lengths and they interact constructively for some wavelengths but destructively for the others. It causes the chromatic elongated wideband speckle and such a distortion becomes serious for the outer speckles from the optical axis. In other words, the contrast of the specklegram begins to be reduced as the optical path differences are larger than the coherence length of the light. The whitelight specklegram can be considered to be an integration of many monochromatic specklegrams with different wavelengths. The location of the brightest speckle is where significant number of monochromatic speckles overlap so as to form the

most compact and intensive wideband speckle. However, the spectral dependence of the fine structure in a specklegram causes the chromatic elongations of the outer speckles. The chromatic distortion of a wideband speckle affects the dispersed speckle as its direction of elongation may deviate from the dispersion direction of the disperser used.

2.1.4 Specklegram of General Object

As described in preceding sections, a specklegram of a point-like star (unresolved star) are comprised by more or less distorted versions of the Airy's disc and some of them are compact speckles with comparable size of the Airy's disc. A specklegram of any extended object is considered to be the incoherent superposition of respective speckle patterns originating from respective points on the object. This implies that a specklegram of an extended object can be represented as a random distribution of more or less distorted replicas of the diffraction limited image of the object, provided that the angular size of the object is enough small to form correlated speckle patterns for respective points on the object. If the object has one isolated intensive point, the brightest speckle in the specklegram is related to the brightest point on the object and is the least distorted replica of that point. If the object includes several isolated and intensive points, the brightest set of speckles with the original disposition is found in the specklegram as the least distorted replica. Therefore, for such an object including isolated dominant points, at least one replica of the object hidden in its specklegram corresponding to the brightest part can be found. This gives an insight to reconstruct the diffraction-limited image. Descriptions on this subject are given in the later section.

A monochromatic specklegram $i(x; \lambda_0)$ of an object at some instant is generally represented by

$$i(x; \lambda_0) = \int \int o(\zeta; \lambda_0) s(x, \zeta; \lambda_0) d^2\zeta \quad (2.1.20)$$

where

- x, ζ : 2-D coordinates on the imaging plane;
- $o(\zeta; \lambda_0)$: geometric image of an object at λ_0 ;
- $s(x, \zeta; \lambda_0)$: instantaneous PSF related to respective object's point at ζ ;

and the integration is carried out over the object's support. If the isoplanatic condition holds, i.e., the object's support is sufficiently small so that the PSF is regarded to be constant, then the above integral is reduced to a convolution integral;

$$i(x; \lambda_0) = o(x; \lambda_0) * s(x; \lambda_0), \quad (2.1.21)$$

or equivalently

$$I(u; \lambda_0) = O(u; \lambda_0) S(u; \lambda_0), \quad (2.1.22)$$

where the upper case letter denotes the Fourier transform of the corresponding lower case letter. Practically, the convolution relation holds in the cases of the quasi-monochromatic and narrow spectral band width ($\Delta\lambda < \sim 50nm$). Those expressions shown above are for noise-free cases. Usually, the noise is taken into account in some additive term.

2.2. Stellar Speckle Imaging Techniques

2.2.1 Labeyrie's Speckle Interferometry

In 1970, Labeyrie invented a method to recover object's information up to the diffraction-limited spatial resolution from atmospherically degraded specklegrams (Labeyrie 1970). In this method, the power spectra of many short exposure specklegrams with narrow spectral band are averaged. According to Eq.(2.1.22), the averaged power spectrum is represented by

$$\langle |I(u)|^2 \rangle = |O(u)|^2 \langle |S(u)|^2 \rangle, \quad (2.2.1)$$

where λ_0 has been dropped. For a particular spatial frequency u , the instantaneous OTF $S(u)$ of the atmosphere-telescope system represents a complex visibility of the fringe formed from all the pairs of the seeing cells with a spacing of $\lambda f u$. The seeing cells can form such pairs with spacings up to the aperture size D of a telescope. Then, the ensemble average of the square modulus of the OTF or energy transfer function $\langle |S(u)|^2 \rangle$ has the definite positive values up to the diffraction-limited cutoff frequency $D/\lambda f$ so that the averaged power spectrum contains the high spatial resolution information of the object.

By using Eq.(2.1.11), the energy transfer function is related to the fourth order moment of the perturbed wavefront $\psi(\xi)$ (Dainty 1973; Dainty 1975). The log-normal model complicates the calculation of the fourth order moment (Korff 1973; Roddier 1981; Borgnino et al. 1989). If the normal model of the incident wavefront and a large telescope $D \ll r_0$ are assumed, then an analytical expression for $\langle |S(u)|^2 \rangle$ are obtained more easily (Korff et al. 1972; Dainty 1973):

$$\langle |S(u)|^2 \rangle = |\langle S(u) \rangle|^2 + \left(\frac{r_0}{D}\right)^2 T(u) \quad (2.2.2)$$

which also indicates that an attenuated version of diffraction-limited OTF is included in the energy transfer function. Considering in the imaging plane, it is equivalent to that the averaged autocorrelation of the instantaneous speckled PSFs is a sum of the Airy's disc and the autocorrelation of long-exposure PSF. In Labeyrie's speckle interferometric method, only a power spectrum of an object or an autocorrelation of the object can be obtained and the phase information of the Fourier spectrum of the object are dropped. According to Eq.(2.2.1), the object's power spectrum $|O(u)|^2$ is obtained by dividing $\langle |I(u)|^2 \rangle$ by the energy transfer function $\langle |S(u)|^2 \rangle$ which can be estimated from a nearby point source. Thus, the modulus of the Fourier spectrum of the object is readily obtained by taking the square root. The Labeyrie's power spectrum analysis has been applied to binaries and resolved supergiants (Gezari et al. 1972; Bonneau et al. 1973; Labeyrie et al. 1974; McAlister 1977; McAlister et al. 1979; Isobe et al. 1990).

To reconstruct object's image completely, the phase information of the object must be appended. Several algorithms are proposed to solve such a phase retrieval problem. In 1973, the speckle holography technique was proposed by Liu et al. and Bates et al. to obtain an object's image (Liu et al. 1973; Bates et al. 1973). In this method, an unresolved star (reference star) within the isoplanatic region of the object is recorded simultaneously. Many specklegrams of the total object(object + reference star) are taken and the Labeyrie's method is applied to those specklegrams:

$$\langle |I_T(u)|^2 \rangle = \langle |I(u) + S_r(u)|^2 \rangle \quad (2.2.3)$$

where $I_T(u)$ is the Fourier spectrum of the specklegram of the total object, and $I(u)$ and $S_r(u)$ are those of the concerned object and the reference star,

respectively. The averaged power spectrum of the total object can be written with four terms:

$$\langle |I_T(u)|^2 \rangle = \langle |I(u)|^2 \rangle + \langle |S_r(u)|^2 \rangle + \langle I(u)S_r^*(u) \rangle + \langle I^*(u)S_r(u) \rangle. \quad (2.2.4)$$

After calibrating by the energy transfer function estimate $\langle |S_r(u)|^2 \rangle$, the autocorrelation of the total object $o(x) + \delta(x - x_r)$ is finally obtained:

$$o_T(x) \star o_T(x) = \delta(x) + o(x) \star o(x) + o(-x + x_r) + o(x + x_r). \quad (2.2.5)$$

If the object's support size is sufficiently smaller than x_r , the object image can be extracted from the autocorrelation of the total object. The speckle holographic estimation of the object corresponds to

$$\frac{\langle I(u)S_r^*(u) \rangle}{\langle |S_r(u)|^2 \rangle} \quad (2.2.6)$$

in Fourier space. The first application of the speckle holography to the observational data was presented by Weigelt(1978). However, the speckle holographic technique is useful only when a point-like star exists in the isoplanatic region.

In 1974, Knox and Thompson proposed a method in which an ensemble average of a cross-spectrum $\langle I(u)I^*(u + \Delta u) \rangle$ is calculated instead of calculating the power spectrum $\langle I(u)I^*(u) \rangle$ where $\Delta u = 0$ (Knox & Thompson 1974). In 1977, Weigelt proposed the speckle masking method (Weigelt 1977; Lohmann et al. 1983; Weigelt 1991) in which the bispectrum or equivalently the triple correlation of the speckle images is calculated. The bispectrum $B(u, v)$ is written by

$$B(u, v) = \langle I(u)I(v)I^*(u + v) \rangle, \quad (2.2.7)$$

where u and v are 2-D vectors in the plane of the spatial frequency. After the calibration with nearby point source, the phase of the calibrated bispectrum gives the closure phase $\beta(u + v)$ (Weigelt 1991) of the object

$$\beta(u + v) = \varphi(u) + \varphi(v) - \varphi(u + v) \quad (2.2.8)$$

where $\varphi(u)$ is the phase of the Fourier spectrum of the object. From this relationship, the object's phase is recursively reconstructed. The recursive calculations are very sophisticated and time-consuming. Many speckle masking

reconstructions for double star, multiple star and the Seyfert galaxy have been reported (Weigelt et al. 1983; Neri et al. 1988; Hofmann et al. 1989).

2.2.2 Shift-And-Add (SAA) Method

In 1976, Lynds, Worden and Harvey (hereafter LWH) invented a deconvolution method to obtain a diffraction-limited image (Lynds, Worden & Harvey 1976; Worden et al. 1976). From an inspection to the feature of a specklegram, LWH supposed that a specklegram $s(x)$ of an unresolvable star can be represented by a convolution of the Airy's disc and a set of impulse functions $imp(x)$:

$$s(x) = a(x) * imp(x) \quad (2.2.9)$$

where respective impulse functions in $imp(x)$ are positioned and weighted randomly corresponding to the respective speckles. The $imp(x)$ has some physical basis (Hege 1989). The disturbed wavefront $\psi_P(\xi)$ on the telescope's pupil plane can be represented within the aperture region by an infinite series of the plane waves

$$\psi_P(\xi) = \sum_{j=1}^{\infty} A_j \exp(i k_j \cdot \xi), \quad (2.2.10)$$

where A_j is a complex constant and k_j is the j th wave number vector of the j th plane wave component. The square modulus of the Fourier transform of $\psi_P(\xi)$ gives the impulse feature of the specklegram

$$\sum_{j=1}^{\infty} w_j \delta(x - x_j), \quad (2.2.11)$$

where w_j represents the weight of each impulse function. The practically obtained impulse set is a truncated version of the infinite set of the impulses. A specklegram of an object $o(x)$ is then given by

$$i(x) = o(x) * a(x) * imp(x) \quad (2.2.12)$$

where each impulse function in $imp(x)$ generates the corresponding replica of the object's diffraction-limited image in the specklegram. Correlating the object's specklegram $i(x)$ with $imp(x)$ and averaging over the many frames results

in the reconstruction of the diffraction-limited object's image. This calculation is written by

$$\langle i(x) \star imp(x) \rangle = o(x) \star a(x) \star \langle imp(x) \star imp(x) \rangle, \quad (2.2.13)$$

where $\star$ indicates the correlation operation. The ensemble averaged autocorrelation of the impulse set is comprised by a dominant delta function at the origin and side lobes. The former is a result of correlating the respective impulse functions with themselves, and the latter is a result of correlation between different impulses. Since there exists the convolution with the dominant delta-function, the diffraction-limited image $o(x) \star a(x)$ appears to be emphasized. The convolution with the residual side lobes results in the background noise. With this method, LWH obtained a profile of the diffraction-limited image (resolution of a 4m telescope) of Betelgeuse. To correlate a specklegram with the impulse set can be interpreted as shifting all speckles (or diffraction-limited object's replicas) to be coadded. Thus, the LWH's algorithm works as if all the related replicas are averaged. It is critical in the LWH's method that the discrete bright speckles can be clearly identified for respective short exposure specklegrams (Worden et al. 1976). The allowable spectral band, magnitude and object's extent are then limited.

In 1980, Bates and Cady proposed shift-and-add (SAA) method (Bates & Cady 1980) as an extension of the LWH's method. In the SAA method, only the brightest speckle of a specklegram is designated. The designated speckles in individual specklegrams are coadded by properly shifting the individual speckle frames. The advantage to use the SAA method is that the object may be as faint as only the brightest speckle is detectable. Bates and Cady pointed out that the SAA method can be applied to white light specklegrams. By an analogy with the white light Young's fringe, the brightest speckle in a white light specklegram shows the highest contrast. In other words, the brightest part in a specklegram most resembles the wideband diffraction-limited image of an object. The limiting magnitude is augmented by using white light specklegrams. In 1983, Hunt et al. analyzed the SAA method statistically in the monochromatic case (Hunt et al. 1983). In this analysis, it is assumed that a stellar specklegram can be described as an normal specklegram. From such an

approximated analysis, the SAA image $s_{sa}(x)$ of an unresolvable object (SAA PSF) is given by

$$s_{sa}(x) = (\ln N - 1)\langle I \rangle a(x) + \langle I \rangle, \quad (2.2.14)$$

where N is the number of speckles in a specklegram. This result suggests that the SAA's PSF is a sum of the Airy's disc (diffraction-limited image) and the background $\langle I \rangle$. The background level is obtained by averaging the specklegrams, i.e., long exposing. By subtracting the background, the diffraction-limited image can be obtained. Though there has not been a rigorous theory on the SAA process, the SAA is reliable from empirical evidence (Hege 1989) and comparative studies (Christou 1991a; Davey et al. 1989).

Another extension of the LWH's method is weighted shift-and-add (WSAA) method (Christou et al. 1986a,b; Hege 1988; Sinton et al. 1986; Ribak 1986). The Fourier space representation of the LWH's method is written as a form of weighted averaging by

$$\langle I(u)IMP^*(u) \rangle. \quad (2.2.15)$$

By introducing a normalization to the weighted averaging, the representation of the WSAA method is obtained:

$$\frac{\langle I(u)IMP^*(u) \rangle}{\langle |IMP(u)|^2 \rangle}. \quad (2.2.16)$$

The expression can be rewritten as

$$\frac{\left\langle \frac{I(u)}{|IMP(u)|} |IMP(u)|^2 \right\rangle}{\langle |IMP(u)|^2 \rangle}. \quad (2.2.17)$$

The $IMP(u)$ can be considered as the atmospheric OTF (not including the telescope's OTF) and the WSAA can be interpreted as a process of frame by frame deconvolution, i.e., the individual specklegrams are deconvolved with the instantaneous atmospheric PSF, $imp(x)$, and the diffraction-limited estimates individually obtained are averaged. The WSAA algorithm also relies on proper production of the impulse set. However, the WSAA is superior to the LWH and the SAA because the result of WSAA process is background-free. The analysis for the WSAA is given in Ribak et al.(1986). Several astrophysical results with WSAA have been reported (Christou et al. 1988; Hebden et al. 1986b).

2.3. Dispersed Specklegrams

It is clear by a similar argument to that in the Section 2.1.4 that a dispersed specklegram includes many replicas of diffraction-limited dispersed image. In general, a dispersed specklegram $d(x)$ can be regarded as integration of monochromatic specklegram $i(x; \lambda)$ shifted by $\epsilon(\lambda)$ (i.e., dispersion shift at wavelength λ) over a spectral band Λ :

$$d(x) = \int_{\Lambda} i(x; \lambda) * \delta(x - \epsilon(\lambda)) d\lambda, \quad (2.3.1.)$$

where $*$ denotes a convolution operation, x represents the 2-D coordinate in the image plane and $\delta(x)$ is the delta function. For $\epsilon(\lambda) = 0$, Eq.(2.3.1.) represents a non-dispersed specklegram of any spectral band. Under the isoplanatic and the noise-free assumptions, the monochromatic specklegram $i(x; \lambda)$ can be represented by Eq.(2.1.21). Substitution of Eq.(2.1.21) into Eq.(2.3.1) results in

$$d(x) = \int_{\Lambda} o(x; \lambda) * s(x; \lambda) * \delta(x - \epsilon(\lambda)) d\lambda. \quad (2.3.2)$$

If the spectral region concerned is narrow enough, the λ -dependence of $s(x; \lambda)$ is negligible and $s(x; \lambda)$ is represented by $s_0(x) = s(x; \lambda_0)$ where λ_0 indicates the central wavelength. Thus, Eq.(2.3.2) reduces to

$$d(x) \simeq s_0(x) * \int_{\Lambda} o(x; \lambda) * \delta(x - \epsilon(\lambda)) d\lambda = s_0(x) * sp(x). \quad (2.3.3)$$

This is a convolution of the atmospheric-telescope PSF and the object's spectrum or the dispersed object $sp(x)$. A non-dispersed specklegram with narrow spectral bandpass is given by

$$i_0(x) = s_0(x) * \int_{\Lambda} o(x; \lambda) d\lambda \simeq s_0(x) * o_0(x), \quad (2.3.4)$$

where it is assumed that the object seen in a definite bandpass can be represented by the monochromatic object $o_0(x) = o(x; \lambda_0)$. The fact that a dispersed specklegram can be expressed by a convolution integral is used in the speckle spectroscopy with narrow band width as described in Chapter 4.

3.1. Introduction

The concept of the speckle spectroscopy was first suggested by Weigelt et al. (Weigelt et al. 1986). They proposed a technique based on the speckle masking method. However, the simultaneous spectral coverage in the speckle spectroscopy based on the speckle masking is restricted to several tens nanometers, because in this method the dispersed specklegram is assumed to be representable by a convolution integral (see Chapter 2). To obtain the spectrum for wider spectral range, it is necessary to divide this range into narrow ones and apply the speckle masking to them, separately. In 1988, Weigelt et al. proposed a wideband projection speckle spectroscopy method to this end. In this method, a specklegram is reduced to the one-dimensional (1-D) specklegram by taking a projection optically. The 1-D specklegram is then dispersed to produce a 2-D projection speckle spectrogram in which each line represents a 1-D speckle spectrogram with a narrow spectral bandwidth. The 1-D speckle masking method is applied to each line separately. The advantages to take the projection are that (1) the narrow band specklegrams does not overlap each other, and (2) time-consuming process of the speckle masking for 2-D specklegrams is relaxed by using the 1-D specklegrams.

On the other hand, the SAA method reasonably reconstructs the diffraction-limited image even from the wideband specklegrams. This led to employ the SAA method for the wideband speckle spectroscopy (Baba et al. 1988a,b; Baba 1989). However, it is not easy to apply the SAA process directly to the dispersed specklegrams because a compact speckle can not be defined in the dispersed specklegram even though the object is a point source. In the speckle spectroscopy based on the SAA, it is needed to simultaneously record nondispersed specklegrams(reference specklegrams) to which the SAA process is applied so as to reconstruct the diffraction-limited object's image. Since the SAA process is accomplished only by shifting and adding, this process also works on the dispersed specklegrams and results in the reconstruction of the diffraction-limited spectrum. The features of the speckle spectroscopy based on SAA are simplicity and flexibility. Those features enable to implement a system including the

real-time SAA mechanism from which the great advantages will be obtained. The proposition of the real-time system is given in Chapter 5.

For the purpose of the wideband speckle spectroscopy based on the SAA, a dedicated camera, speckle spectroscopic camera of version I (SSC1), was constructed. The SSC1 is designed to obtain the speckle spectroscopic data in the wideband (400nm - 800nm) and low dispersion mode. The spectral resolution attainable with the data obtained by SSC1 amounts to 4nm - 7nm. In this chapter, a speckle spectroscopic implementation with the SSC1 and its results are described. In the following section, the features of the SSC1 are described. The processes of the data acquisition by SSC1 and the frame digitization are briefly mentioned in Sec.3.3. After that, the detailed descriptions on the data reduction algorithm are described. The data reduction algorithm comprised by the matched filter SAA (Ribak et al. 1985; Christou et al. 1986b) and the background subtraction. To remove the background effectively, a technique which employs a pseudo-long-exposure image is newly introduced (Kuwamura et al. 1992a; Kuwamura et al. 1993a). In Sec.3.4., results of the data reduction are presented. Before presenting the spectroscopic results with data obtained by SSC1, some preliminary results with respect to the SAA speckle imaging are shown. In the SAA speckle spectroscopic system, it is critical to reasonably reconstruct the diffraction-limited image from the reference specklegrams by the SAA algorithm. To demonstrate the validity of the SAA algorithm, simulations were performed using the computationally generated (non-dispersed) specklegrams. Further, the SAA algorithm was applied to the observational data obtained by the conventional speckle camera with 212cm telescope at the San Pedro Martir Observatory and compared with the results obtained by the iterative blind deconvolution technique (Miura et al. 1993). The results for these data confirm that the SAA algorithm exhibits a satisfactory performance to reconstruct the diffraction-limited images.

3.2. Speckle Spectroscopic Camera I (SSC1)

The SSC1 is designed to take a reference specklegram and the dispersed specklegram on the same frame simultaneously. The observation is carried out with this camera attached at the focus of a telescope. Figure 3.1 illustrates the

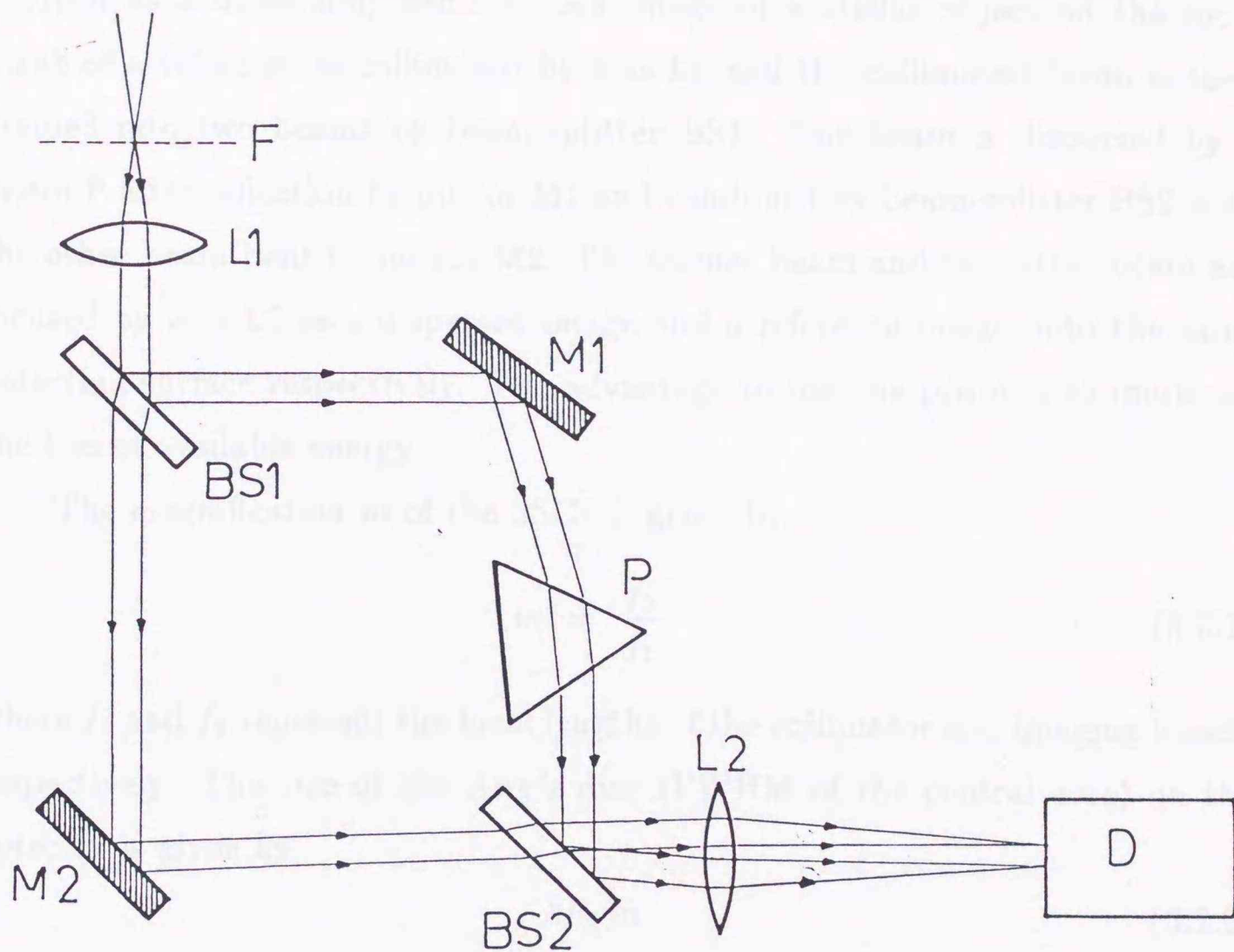


Fig. 3.1 : Configuration of the optical part of the speckle spectroscopic camera No.1(SSC1). The focal plane of a telescope is indicated by F , and a detector by D .

principal configuration of the optical part of SSC1. The SSC1 has an optical part similar to the Mach-Zehnder interferometer (Born & Wolf 1980) including a prism as a dispersing element. An image of a stellar object on the focal plane of a telescope is collimated by lens L1 and the collimated beam is then divided into two beams by beam-splitter BS1. One beam is dispersed by a prism P after reflection by mirror M1 and combined by beam-splitter BS2 with the other beam bent by mirror M2. The former beam and the latter beam are focused by lens L2 as a dispersed image and a reference image onto the same detecting surface respectively. The advantage to use the prism is to minimize the loss of available energy.

The magnification m of the SSC1 is given by

$$m = \frac{f_2}{f_1}, \quad (3.2.1)$$

where f_1 and f_2 represent the focal lengths of the collimator and imaging lenses, respectively. The size of the Airy's disc (FWHM of the central core) on the detector is given by

$$\lambda F_T m \quad (3.2.2)$$

where F_T is f-number of the telescope. The achievable spectral resolution defined by the wavelength width corresponding to the Airy size in a dispersed image is then given by

$$\frac{\lambda F_T}{f_1} \frac{d\beta}{d\lambda} \quad (3.2.3)$$

where β is the angle of emanating ray from the disperser as a function of the wavelength so that $d\beta/d\lambda$ gives the angular dispersion, and f_1/F_T gives the diameter of the collimated beam. When the values of F_T and the angular dispersion are specified, the lower limits of the optical magnification f_2/f_1 and the focal length of the collimator lens f_1 are determined by the pixel size of a detector. The SSC1 is designed to be optimized with respect to the image sampling and the spectral resolution.

A CCD TV camera coupled with an image intensifier (I.I.) is used as a detector. The I.I. is built in a micro channel plate which has the amplification of $\sim 10^5$ and the significant sensitivities for $\lambda = 450nm \sim 850nm$. The relative position between the reference and the dispersed images is determined by the

optical alignment and must be fixed during the observation. For the computational data reduction, the data observed by the SSC1 is digitized frame by frame. The SSC1 is designed such that the achievable spectral resolution by the data reduction is comparable with that of the objective prism spectra obtained with the Kiso Schmidt telescope.

3.3. Data Acquisition and Data Reduction

Observations with the SSC1 were conducted on the Cassegrain focus (Kitchin 1991) of the 188cm telescope (F/18) at the Okayama Astrophysical Observatory (OAO). The observed images taken with SSC1 are once recorded into S-VHS video tape, and later digitized frame by frame at the video rate of 1/30 sec. Finally, the equivalent exposure time is reduced to 1/60 sec by computational interlacing for each frame. Figures 3.9(a) and 3.10(a) show examples of the speckle frames thus obtained, in which a white light reference specklegram is displayed in the upper side and the dispersed speckle image in the lower side. For both the channels, the spectral bandwidth spans from 450nm to 850nm which is mainly due to the detector sensitivity.

Let us assume that N digitized short exposure frames are prepared, each of which includes reference specklegram and its dispersed specklegram. The relative position of the two images formed through the two different optical channels is fixed over all the frames. The SAA method is applied to the reference specklegrams to reconstruct the diffraction-limited object's image. Since the SAA process is accomplished only by linear shifting and adding, this process also works on the dispersed specklegrams and results in the reconstruction of the diffraction-limited spectrum.

To reconstruct a diffraction-limited image from the reference specklegrams, 1) the brightest speckle is found for each specklegram, 2) then the whole frame is correspondingly shifted and, 3) added to register the brightest speckle with those of other frames similarly shifted (Bates & Cady 1980). Thus the designated speckles in all the frames are averaged. Since the brightest speckle is keenly related to the brightest point on the object, and is regarded as a statistically distorted replica of a diffraction-limited image of that point, such averaging emphasizes the diffraction-limited image of the object, assuming the statistical

distortions are random with zero mean, and similarly emphasizes the dispersed image. The SAA process with a single speckle detection acts correctly provided that an object has a dominant point.

If the object contains some isolated points with comparable intensities, ghost peaks (Sinton et al. 1986) may appear in the resultant frame because locating the brightest speckle, which is statistically distorted, frequently does not uniformly correlate to the brightest point on the object. To avoid the ghost peaks effectively, it is convenient to use a matched filter (Ribak et al. 1985; Christou et al. 1986b) to detect a set of speckles corresponding to some isolated object's peaks and to perform the SAA again. The matched filter must have a distribution equal to that of the object, especially with respect to the configuration of the peaks. A suitable matched filter can be estimated from the reconstructed image obtained in the preceding process. General objects including diffuse objects are possible to be reconstructed by matched filter SAA(MF/SAA), provided that the object's estimates are properly obtained in advance by other methods. It is crucial that the SAA operation detects the least distorted object replicas hidden in the specklegrams.

The SAA process produces as its intrinsic nature a strong background component (Sinton et al. 1986; Hege 1989) on which the emphasized images of the reference and the spectrum are superimposed. This background is the result of averaging the residual parts other than the emphasized part in the specklegrams and has low spatial frequency components similar to those of a long exposure image in which the speckle-like structures disappear. Hunt et al.(1983) showed that the raw SAA image of a point source is a sum of the diffraction-limited image (Airy disc) and a background level which is consistent with the averaged specklegram. In this analysis, a stationary assumption is invoked and the stellar specklegram is assumed to be a normal specklegram, so that the background component is calculated to be constant. However, actually the SAA background has a shape like a hump rather than constant. Here arises a question whether the long-exposure image, which is derived by averaging the specklegrams, serve as an estimate of the SAA background. As presented in Chapter 2, the long-exposure PSF $l(x)$ can be represented by a short exposure

PSF $sh(x)$ convolved with a some Gaussian function:

$$l(x) = sh(x) * \exp \left[-2\pi^2 \frac{|x|^2}{\lambda^2 f^2 \langle b^2 \rangle} \right] \quad (3.3.1)$$

where $\langle b^2 \rangle$ represents the centroid fluctuation from the frame center in the guiding error-free case. The short exposure PSF is given by

$$sh(x) = \langle s(x + x_g) \rangle = \langle s(x) * \delta(x + x_g) \rangle \quad (3.3.2)$$

where x_g represents the position of the centroid in an instantaneous specklegram. Christou(1991b) showed with the simulated speckle data that the rms difference between the centroid and the location of the brightest speckle depends on the seeing condition and amounts to roughly $7 \times (\lambda/D)$ for $D/r_0 \sim 20$. Thus, the SAA background $bg(x)$ of a point star is not equal to either the long-exposure PSF or the short-exposure PSF, but should be represented by

$$bg(x) = sh(x) * \exp \left[-2\pi^2 \frac{|x|^2}{\lambda^2 f^2 \langle b_m^2 \rangle} \right] \quad (3.3.3)$$

where $\langle b_m^2 \rangle$ is associated with the relative fluctuation of the brightest speckle location to the centroid. It should be noted that the long-exposure PSF calculated by taking the ensemble average never be identical to the sum of the real specklegrams of a point star, because the guiding error of the telescope further extends the averaged image.

The background component attended with the SAA algorithm can be interpreted as the sum of the low spatial frequency components contained in the individual shifted specklegrams. To identify the background component, a pseudo-long-exposure frame is constructed as an averaged low spatial frequency component for all the data frames. The process to estimate the background components is as follows:

(1) Pseudo-long-exposure frame is produced; respective frames are shifted in order to arrange the centroids of the reference specklegrams and then all the shifted frames are averaged. The frame thus obtained consists with an averaged low spatial frequency components of the speckle images. As the reference specklegram in j th frame is denoted by $i_j(x)$, the pseudo-long-exposure image $i_l(x)$ obtained in the reference channel is written by

$$i_l(x) = \sum_{j=1}^N i_j(x + x_{g_j}) \quad (3.3.4)$$

where xg_j represents the image centroid of $i_j(x)$.

(2) The pseudo-long-exposure frame is shifted according to the shifts carried out in the SAA operation, and all the shifted frames are averaged to produce background components for both the reference side and the dispersion side. The background component $i_{bg}(x)$ thus obtained can be written by

$$i_{bg}(x) = \sum_{j=1}^N \sum_{i=1}^{M_j} i_i(x + xm_{ji} - xg_j), \quad (3.3.5)$$

where M_j is the number of object's replicas to be coadded in the j th frame and xm_{ji} is the location of the centroid of the i th object's replica included in the j th frame. Note that the centroid of the object's replica can be estimated iteratively.

Subtracting the background frame from the SAA frame leaves the spectrum and the reference image with diffraction-limited resolution. The pseudo-long-exposure image in the reference channel is the same as the short-exposure PSF, provided that the object is a point star. To avoid the confusion with the instantaneous image, calling the pseudo-long-exposure image as "short-exposure image" is avoided. It should be noted that actually the low spatial frequency components vary with the frames, while in the background estimating procedure these components are assumed to be all equal to the pseudo-long-exposure. This is a good statistical approximation, however, and gives a good estimate for the background, provided that sufficient number of data frames are available. The method of the background estimation described here is different from one used by Baba(1989), where the median filtering(Pratt 1978) is applied to find background components for respective frames. The latter is rather reasonable in the sense of reflecting the mechanism of generating the background, but it takes much processing time. Furthermore, in the latter method, overestimations of the background component for the dispersed specklegrams can occur, particularly because the dispersed background is estimated with a certain size of the window. Such overestimations cause losses of object information in low spatial frequencies. In the former method described here, neither filtering processes nor considerations for optimum window size are needed. In Fig. 3.2, the data reduction algorithm is summarized.

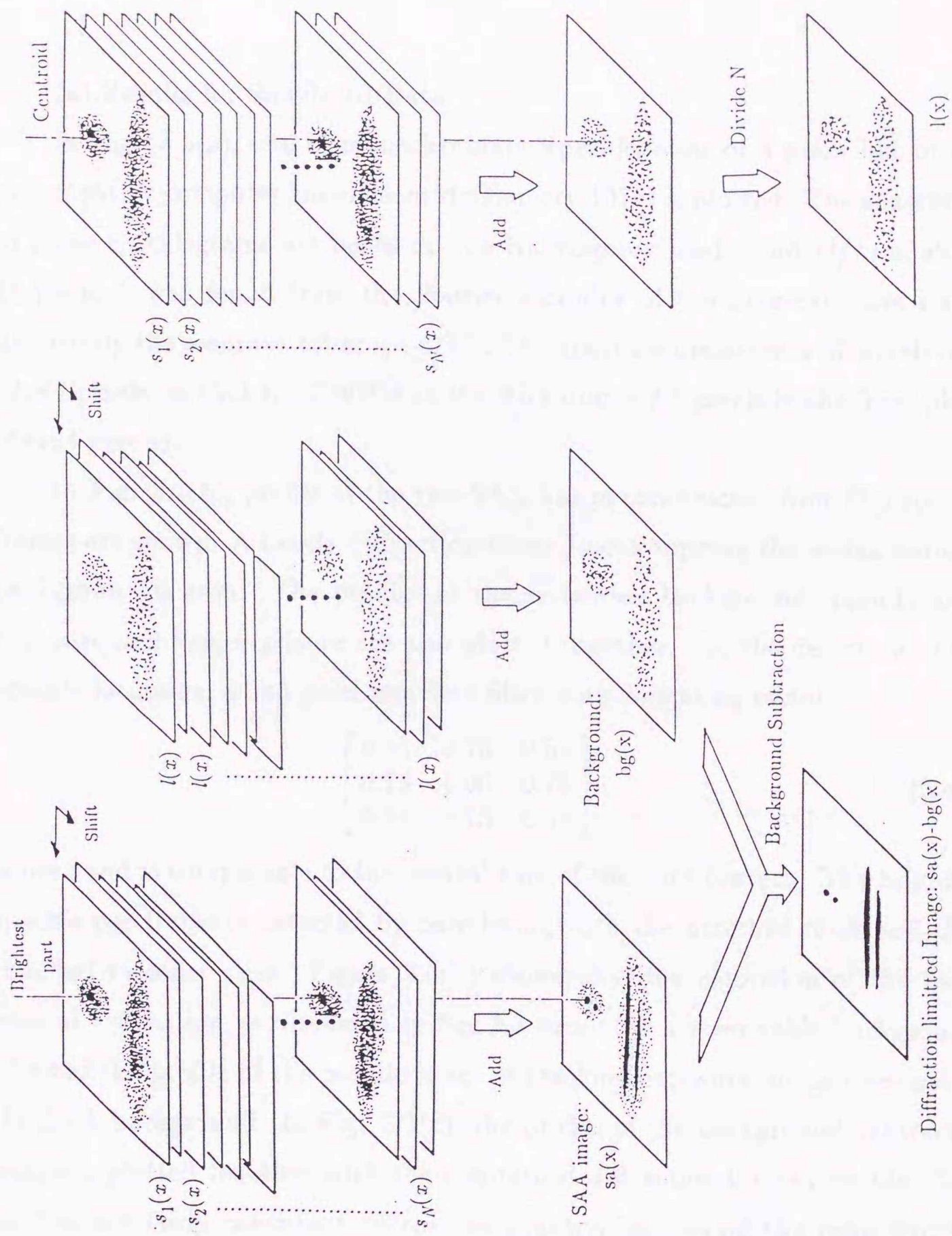


Fig. 3.2 : Schema for SAA and background subtraction algorithm. N frames are represented by $s_1(x), s_2(x), \dots, s_N(x)$, where x indicates a position vector in the frame. $l(x)$ represents pseudo-long-exposure frame.

3.4. Results of Data Reduction

3.4.1 Preliminary Results for SAA Imaging

(a) Results for Simulated Data

In Fig. 3.3(a), one of monochromatic specklegrams of a point-like object generated by computer simulation (McGlamery 1976) is plotted. The generation of those specklegrams are based on the Kolmogorov model and D/r_0 is about 16.7 which was found from the Fourier modulus of the long-exposure image divided by the assumed telescope OTF. The aperture diameter is 50 pixels over 64x64 pixels, so that the FWHM of the Airy disc is 2.6 pixels in the focal plane (64x64 pixels).

In Fig. 3.3(b), profile of the raw SAA image constructed from 500 speckle frames are shown. A nearly diffraction-limited peak topping the seeing induced background is seen. The profiles of the estimated background, pseudo-long-exposure and long-exposure are also plotted together. For the detection of the speckle locations, a 3x3 pixel matched filter with weighting factor

$$\begin{bmatrix} 0.54 & 0.73 & 0.54 \\ 0.73 & 1.00 & 0.73 \\ 0.54 & 0.73 & 0.54 \end{bmatrix}, \quad (3.4.1)$$

is used and is comparable to the central core of the Airy pattern. The brightest speckle per frame is detected by correlating with the matched filter and then coadded to other ones. Figure 3.3(b) shows that the algorithm of the background estimation as discussed in Sec.3.3 produces a reasonable background, whereas the profile of the pseudo-long- or the long-exposure image does not fit the SAA background. In Fig. 3.3(c), the profile of the background subtracted image is plotted together with the theoretical diffraction-limited profile. Two profiles are fairly consistent except the negativities around the reconstructed image which is due to overestimation of the background.

It is possible to detect multiple speckles per frame and coadd them, especially in the case of a point-like star. Figure 3.4(a) shows the profile of the raw SAA image produced by the process with multiple speckle detection using the same data set as mentioned above. A few or several speckles are detected per

(a)

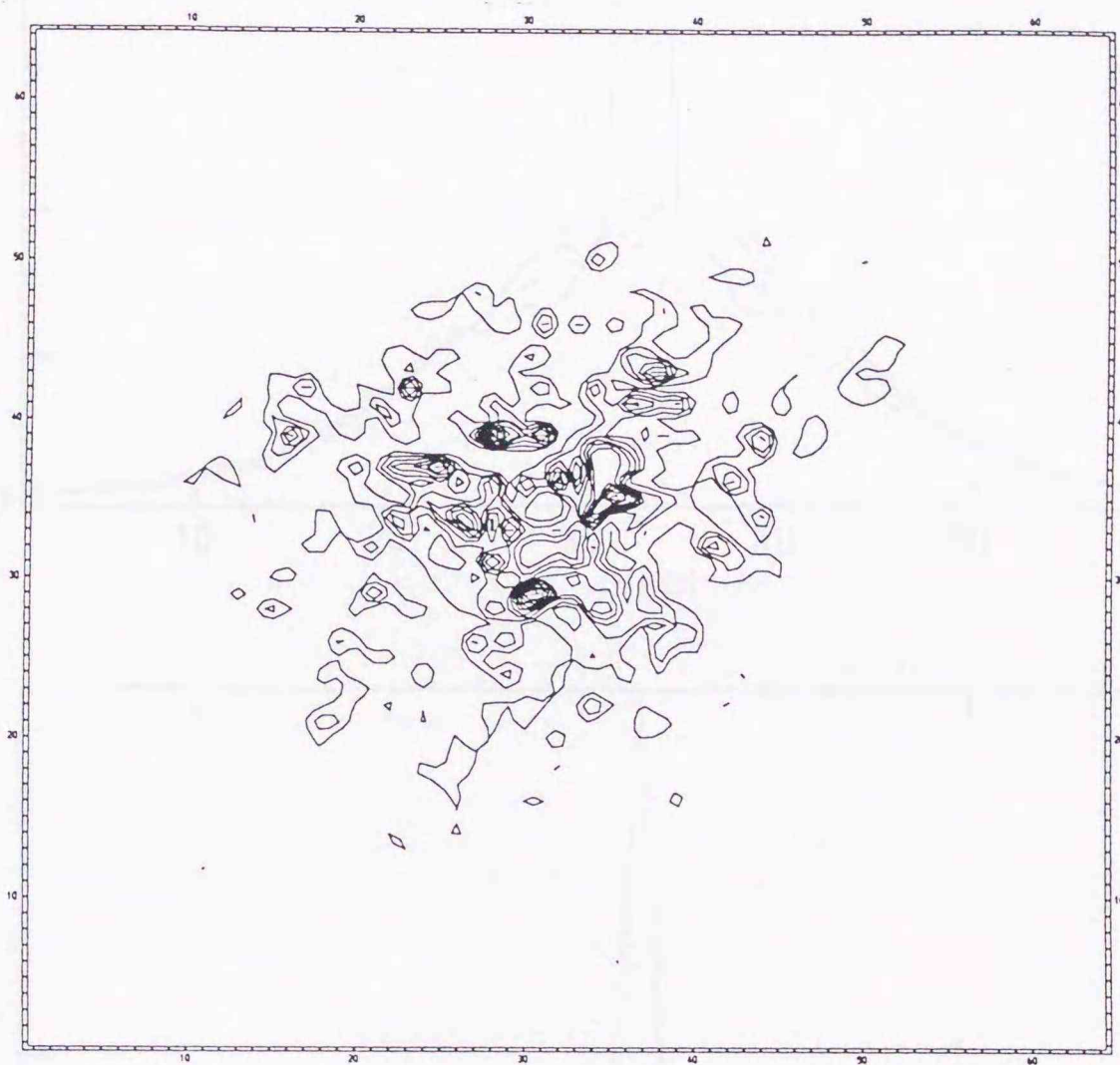


Fig. 3.3 : Experiment with computer generated speckle data of a point-like star. Results are obtained by SAA process with a single speckle detection per frame. (a) Contour plot of one of the computer simulated speckle data.

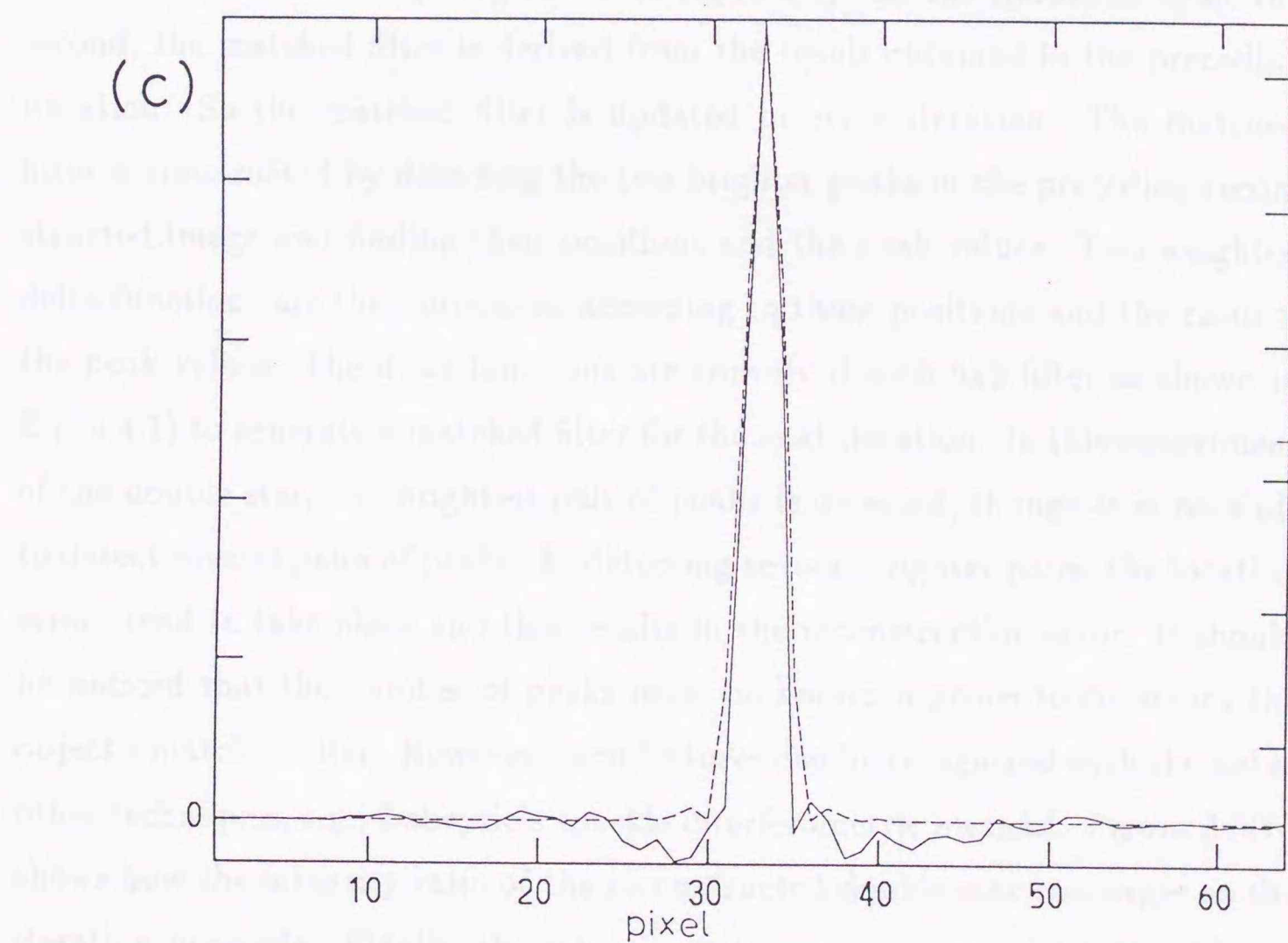
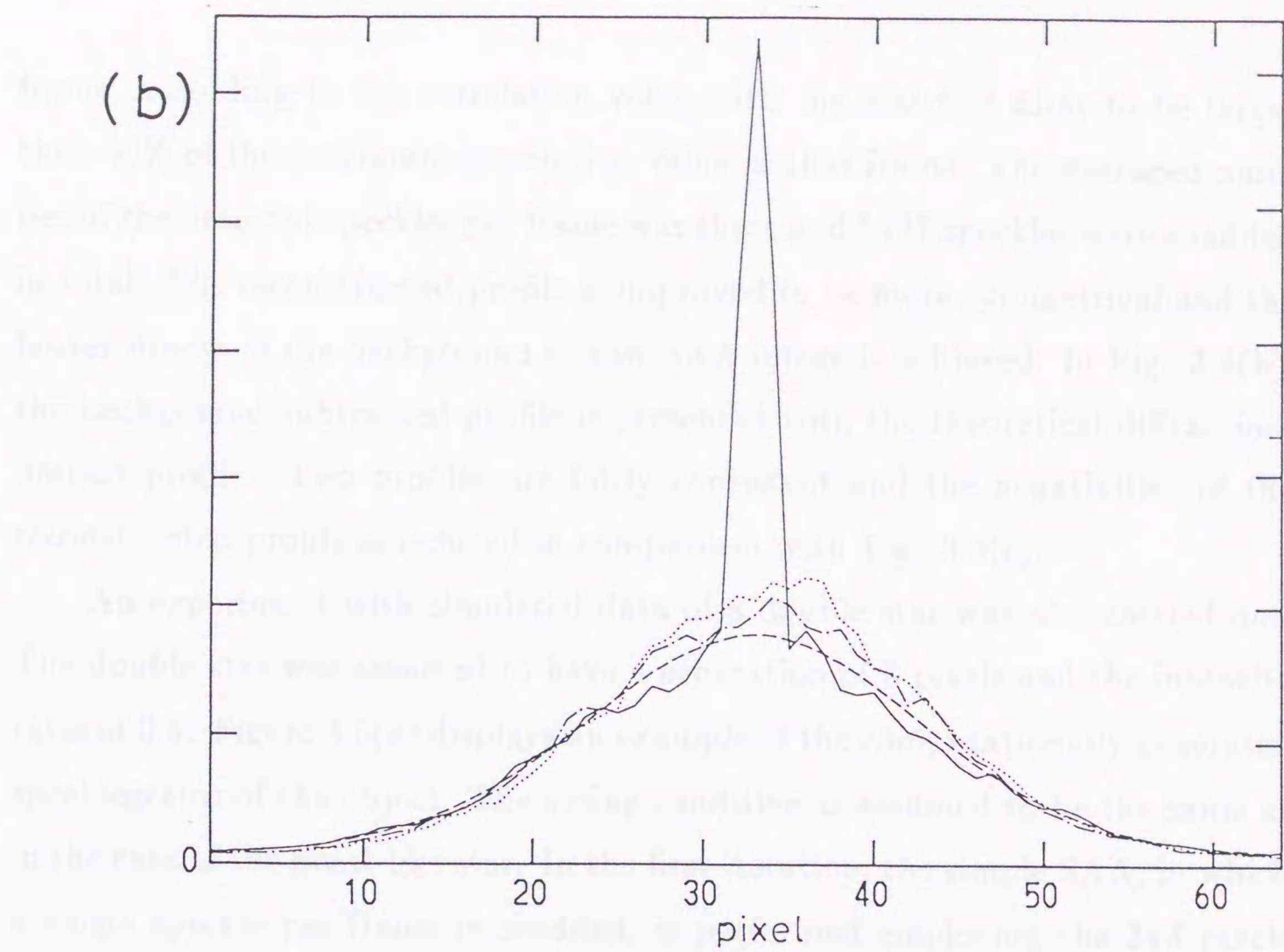


Fig. 3.3 (continued) : (b) Profiles of the raw SAA image(solid line), the estimated background component(dashed line), the pseudo-long exposure image(dotted line) and the long-exposure image(dot-dashed line). (c) Profiles of the background subtracted image(solid line) and the diffraction-limited image of the assumed object(dashed line).

frame, according to the correlation value with the matched filter to be larger than 80% of the maximum correlation value in that frame. The averaged number of the detected speckles per frame was three and 1427 speckles were coadded in total. The reconstructed profile is improved to be more symmetrical and the better fitness of the background to raw SAA image is achieved. In Fig. 3.4(b), the background subtracted profile is presented with the theoretical diffraction-limited profile. Two profiles are fairly consistent and the negativities of the reconstructed profile is reduced in comparison with Fig. 3.3(c).

An experiment with simulated data of a double star was also carried out. The double star was assumed to have a separation of 6 pixels and the intensity ratio of 0.5. Figure 3.5(a) displays an example of the computationally generated specklegrams of the object. The seeing condition is assumed to be the same as in the case of the point-like star. In the first iteration, the simple SAA, in which a single speckle per frame is coadded, is performed employing the 3x3 pixels matched filter with weighting factor of Eq.(3.4.1). In the iterations after the second, the matched filter is derived from the result obtained in the preceding iteration. So the matched filter is updated in every iteration. The matched filter is constructed by detecting the two brighter peaks in the preceding reconstructed image and finding their positions and the peak values. Two weighted delta functions are then produced according to those positions and the ratio of the peak values. The delta functions are convolved with 3x3 filter as shown in Eq.(3.4.1) to generate a matched filter for the next iteration. In this experiment of the double star, one brightest pair of peaks is detected, though it is possible to detect several pairs of peaks. In detecting several brighter pairs, the locating errors tend to take place and this results in the reconstruction error. It should be noticed that the number of peaks must be known *a priori* to construct the object's matched filter. However, such features can be recognized with the aid of other techniques, e.g., Labeyrie's speckle interferometric method. Figure 3.5(b) shows how the intensity ratio of the reconstructed double star converges as the iteration proceeds. Finally, the intensity ratio is estimated to 1:0.62 which is overestimated than the assumed one. In Fig. 3.5(c), a profile of the raw SAA image is shown together with the profiles of the estimated background, pseudo-long-exposure and the long-exposure. The estimated background appears as

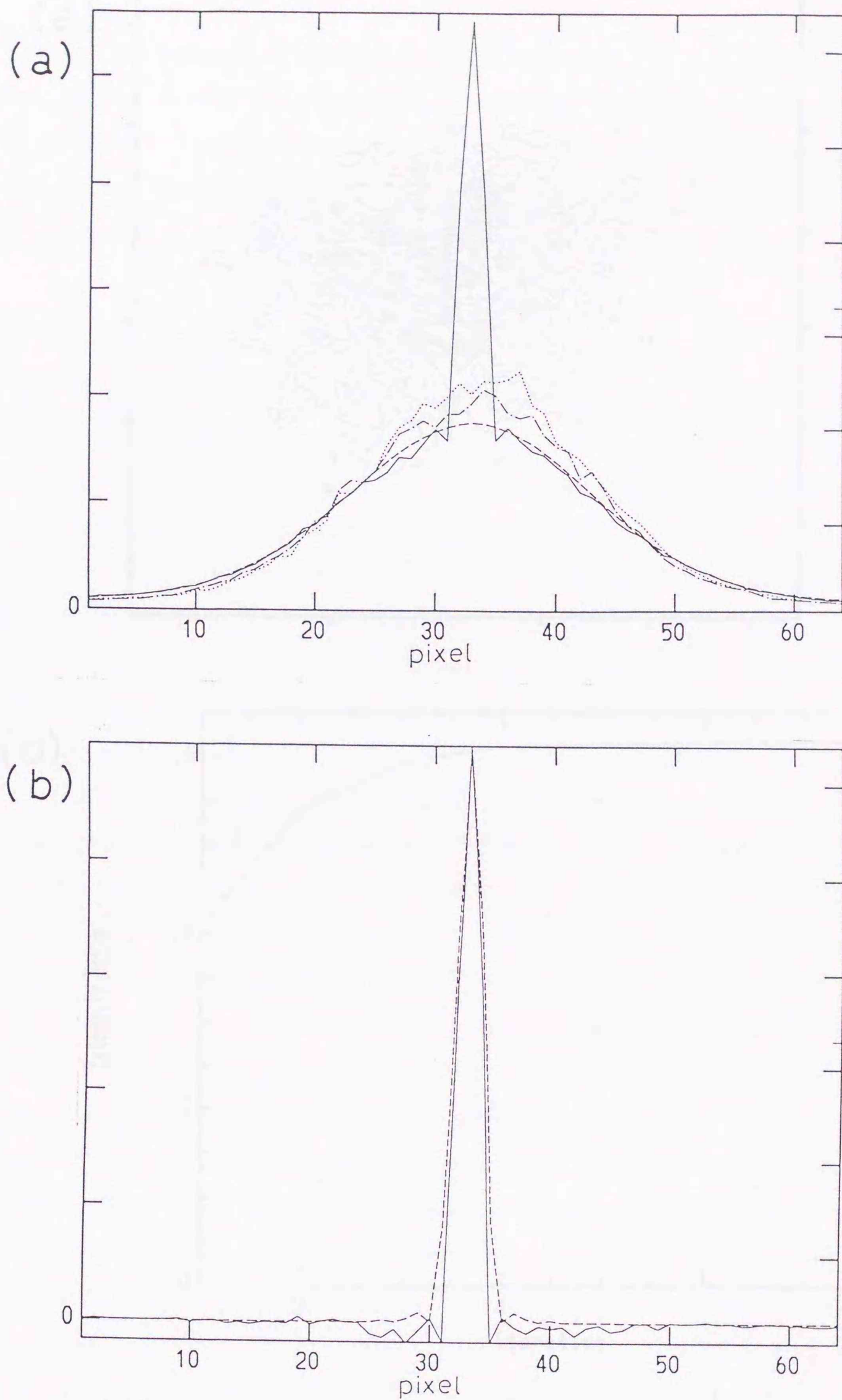


Fig. 3.4 : Experiment with computer generated speckle data of a point-like star. Results are obtained by SAA process with multiple speckle detection per frame. (a) Profiles of the raw SAA image (solid line), the estimated background component (dashed line), the pseudo-long exposure image (dotted line) and the long-exposure image (dot-dashed line). (b) Profiles of the background subtracted image (solid line) and the diffraction-limited image of the assumed object (dashed line).

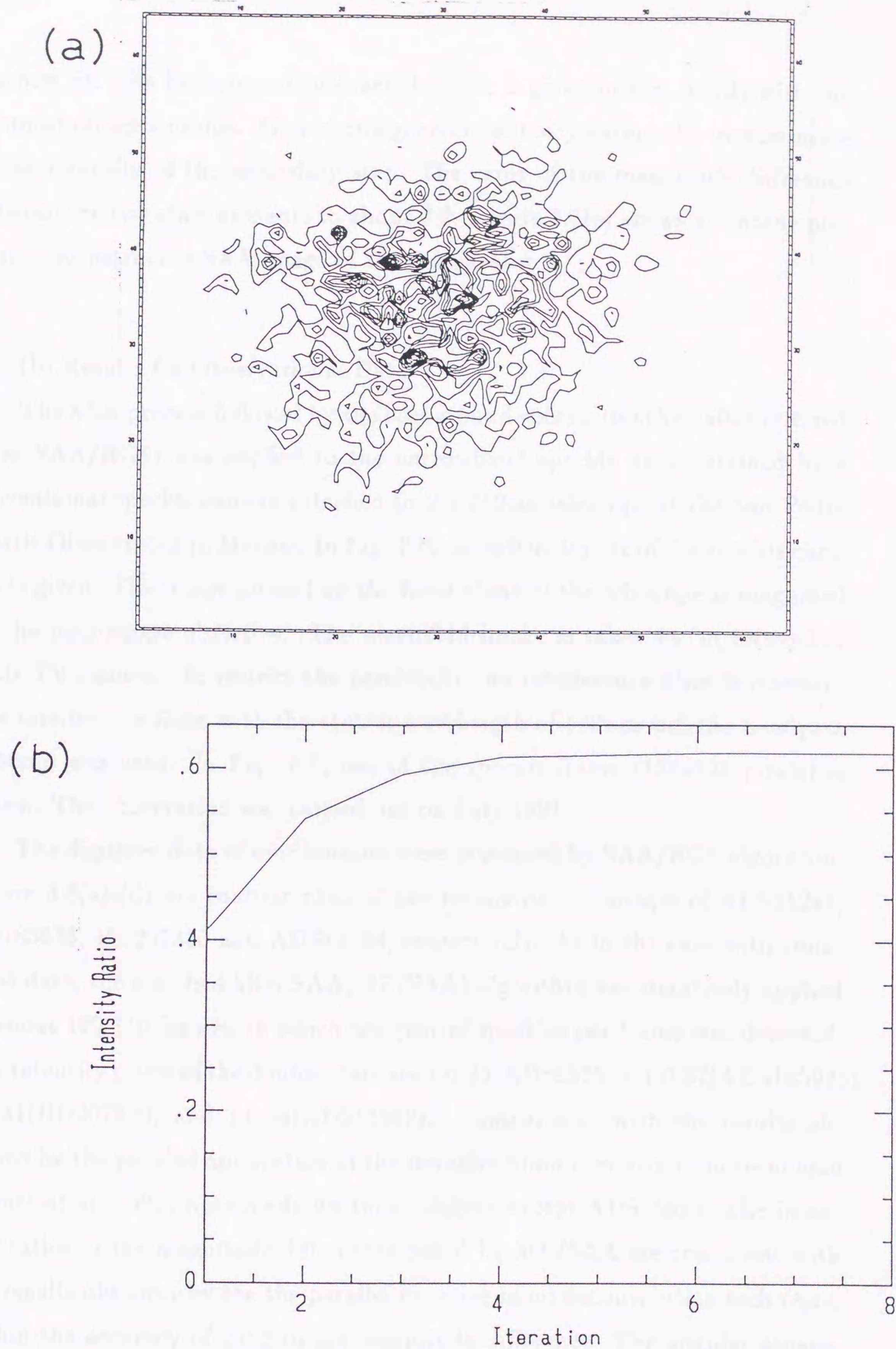


Fig. 3.5 : Experiment with computer generated speckle data of a double star. (a) Contour plot of one of the computer simulated speckle data. (b) Convergence of the estimated intensity ratio of the double star in each iteration.

the best fit. The background subtracted profile is given in Fig. 3.5(d) with the assumed object's profile. They show good consistency except the overestimate of the intensity of the secondary star. The error of the magnitude difference between the two stars amounts to about 0.2. Figure 3.5(e) shows a contour plot of the reconstructed SAA image of the double star.

(b) Results for Observational Data

The SAA process followed by the background subtraction (hereafter referred to as SAA/BGS) was applied to the narrowband speckle data obtained by a conventional speckle camera attached to the 212cm telescope at the San Pedro Martir Observatory in Mexico. In Fig. 3.6, an optical layout of the speckle camera is given. The image formed on the focal plane of the telescope is magnified by the microscope objective. The magnified image is taken by an intensified CCD TV camera. To restrict the bandwidth, an interference filter is inserted. The interference filter with the central wavelength of 630nm and the bandpass of 30nm was used. In Fig. 3.7, one of the speckle frame (128x128 pixels) is shown. The observation was carried out on July 1991.

The digitized data of four binaries were processed by SAA/BGS algorithm. Figure 3.8(a)-(d) are contour plots of the reconstructed images of ADS15281, HD185936, HD207330 and ADS15988, respectively. As in the case with simulated data, the matched filter SAA(MF/SAA) algorithm was iteratively applied to about 100-110 frames, in which one pair of speckles per frame was detected. The intensity ratios of the double stars are 1:0.95(ADS15281), 1:0.97(ADS185936), 1:0.31(HD207330) and 1:0.58(ADS15988). Comparisons with the results obtained by the parallel application of the iterative blind deconvolution technique (Miura et al. 1993) were made for those objects except ADS15988. The intensity ratios or the magnitude differences found by MF/SAA are consistent with the results obtained by the parallel iterative blind deconvolution technique, within the accuracy of ± 0.2 in the magnitude difference. The angular separations and the position angles found by two techniques are completely consistent. For details of those measurements, refer to Miura et al.(1993).

A notable pattern in the background consistently appears in Figs. 3.8(a) and (b). This pattern is likely to be the telescope's aberration. The existence of

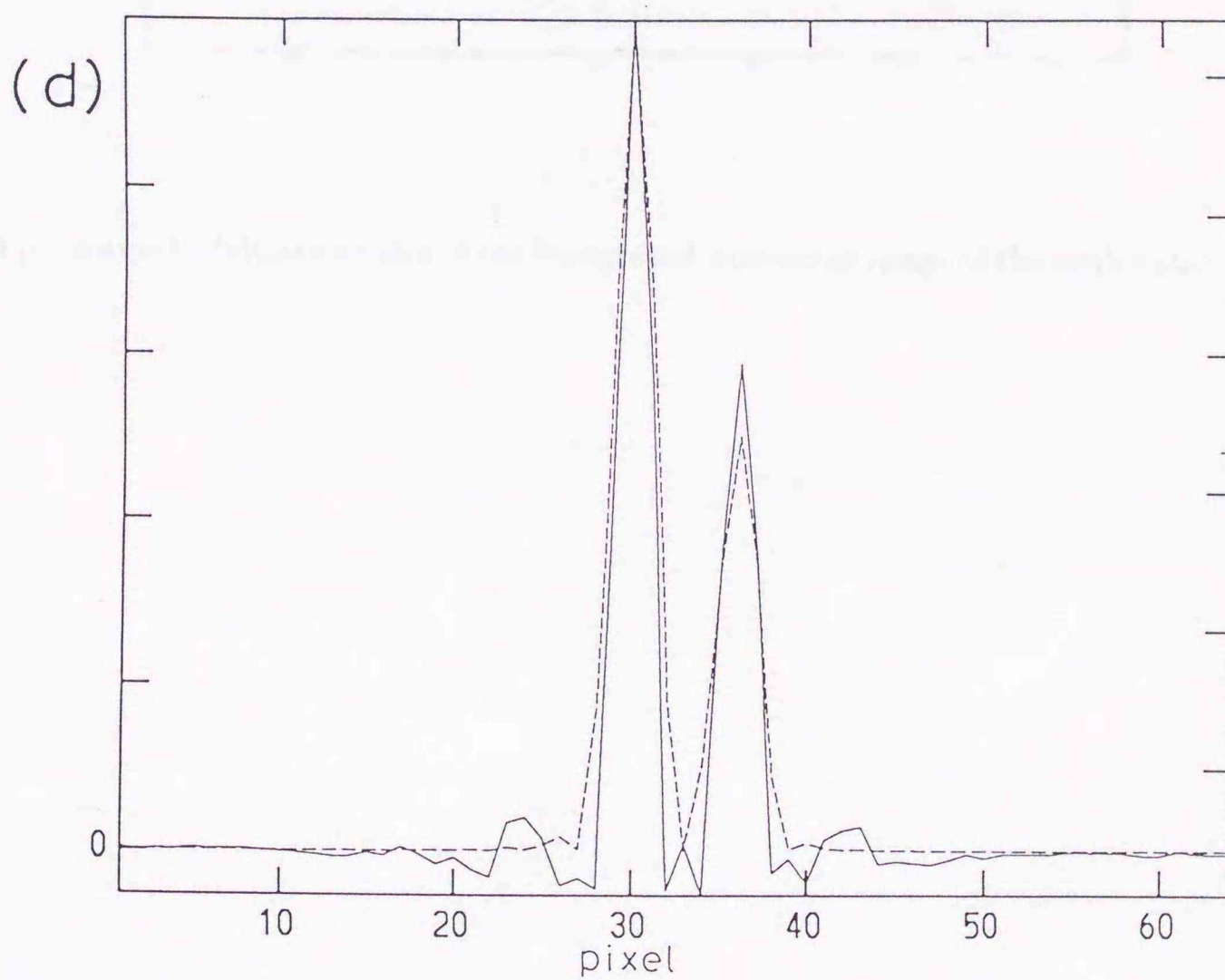
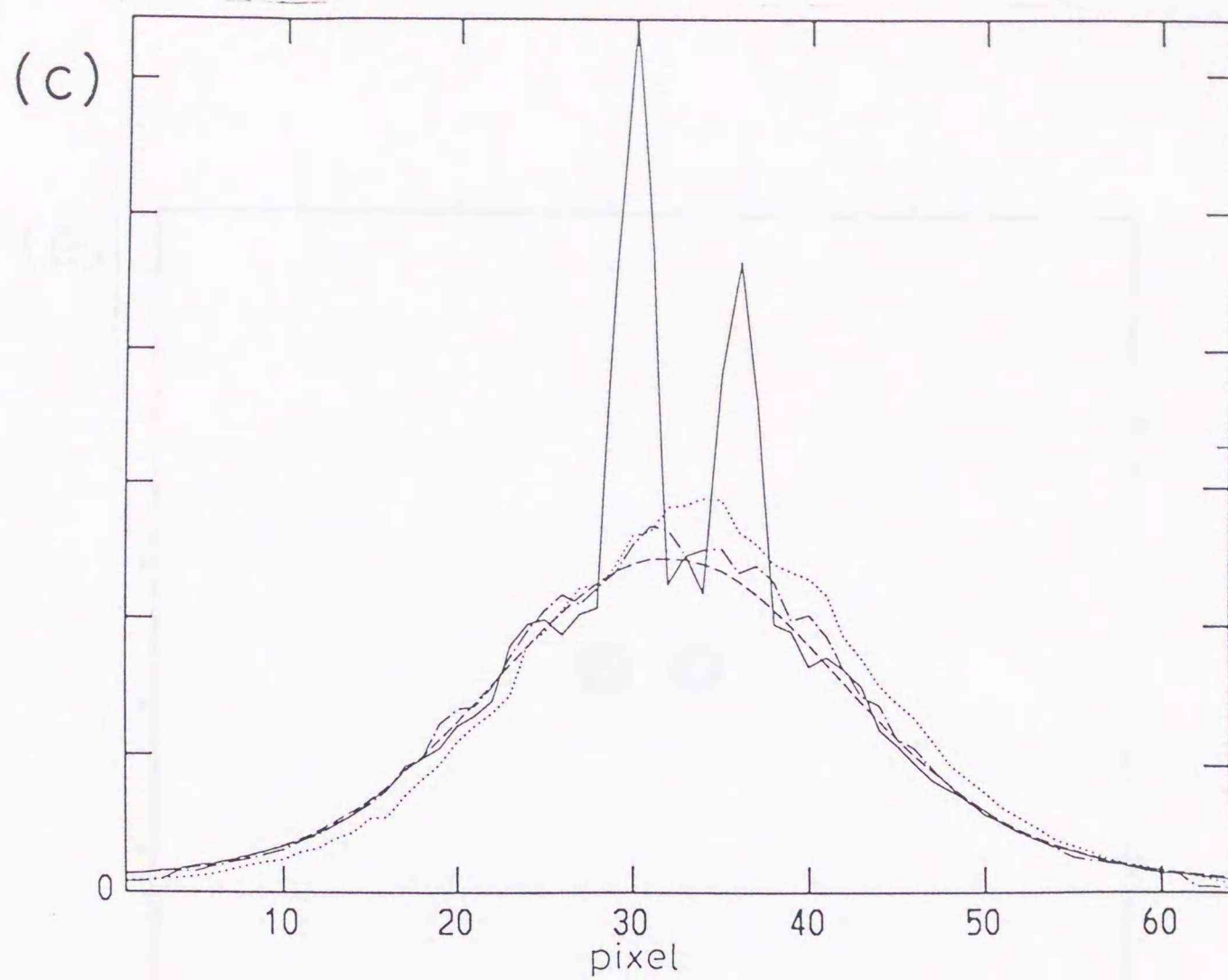


Fig. 3.5 (continued) : (c) Profiles of the raw SAA image(solid line), the estimated background component(dashed line), the pseudo-long exposure image(dotted line) and the long-exposure image(dot-dashed line). (d) Profiles of the background subtracted image(solid line) and the diffraction-limited image of the assumed object(dashed line).

(e)

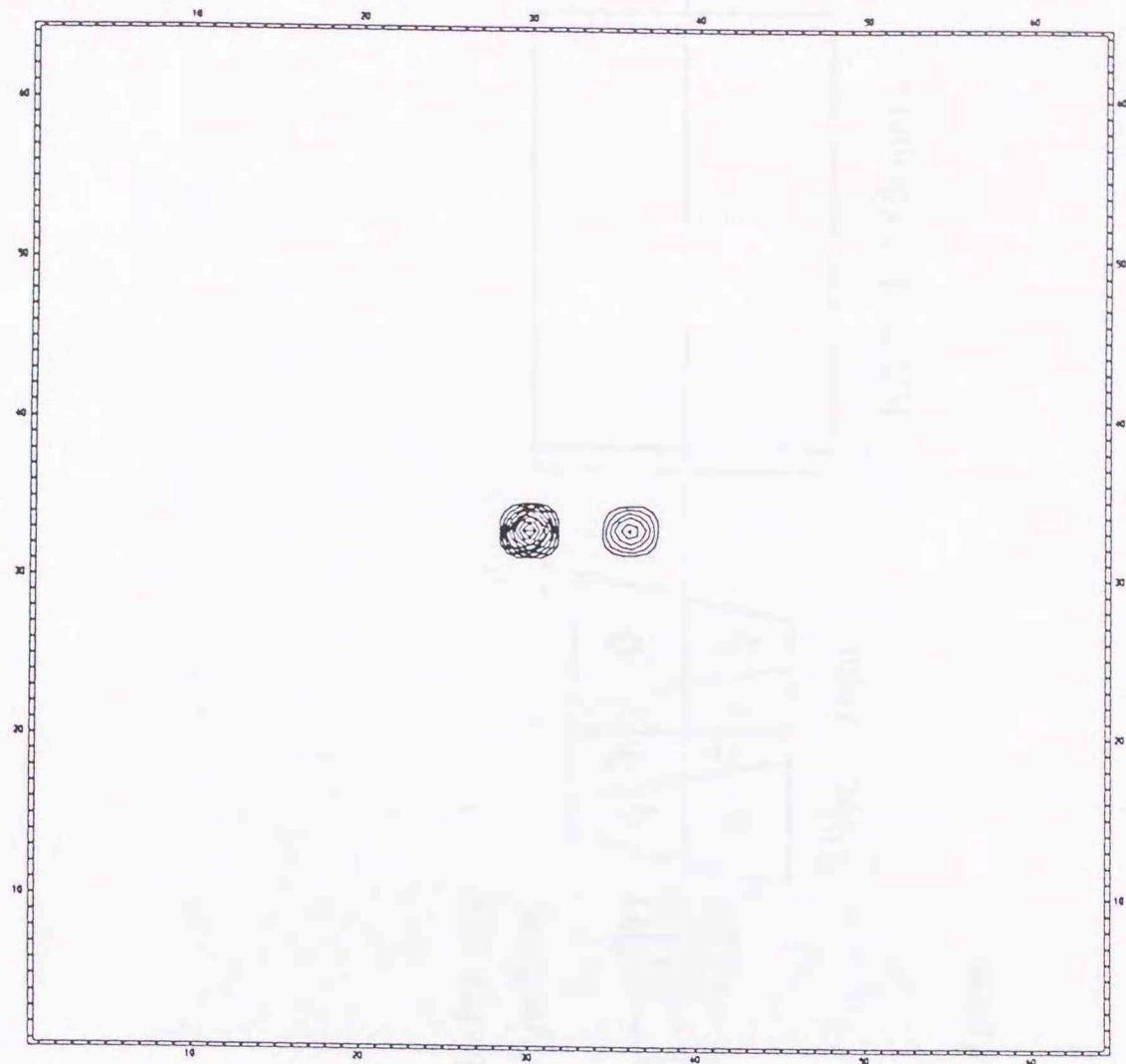


Fig. 3.5 (continued) : (e) Contour plot of the background subtracted image of the double star.

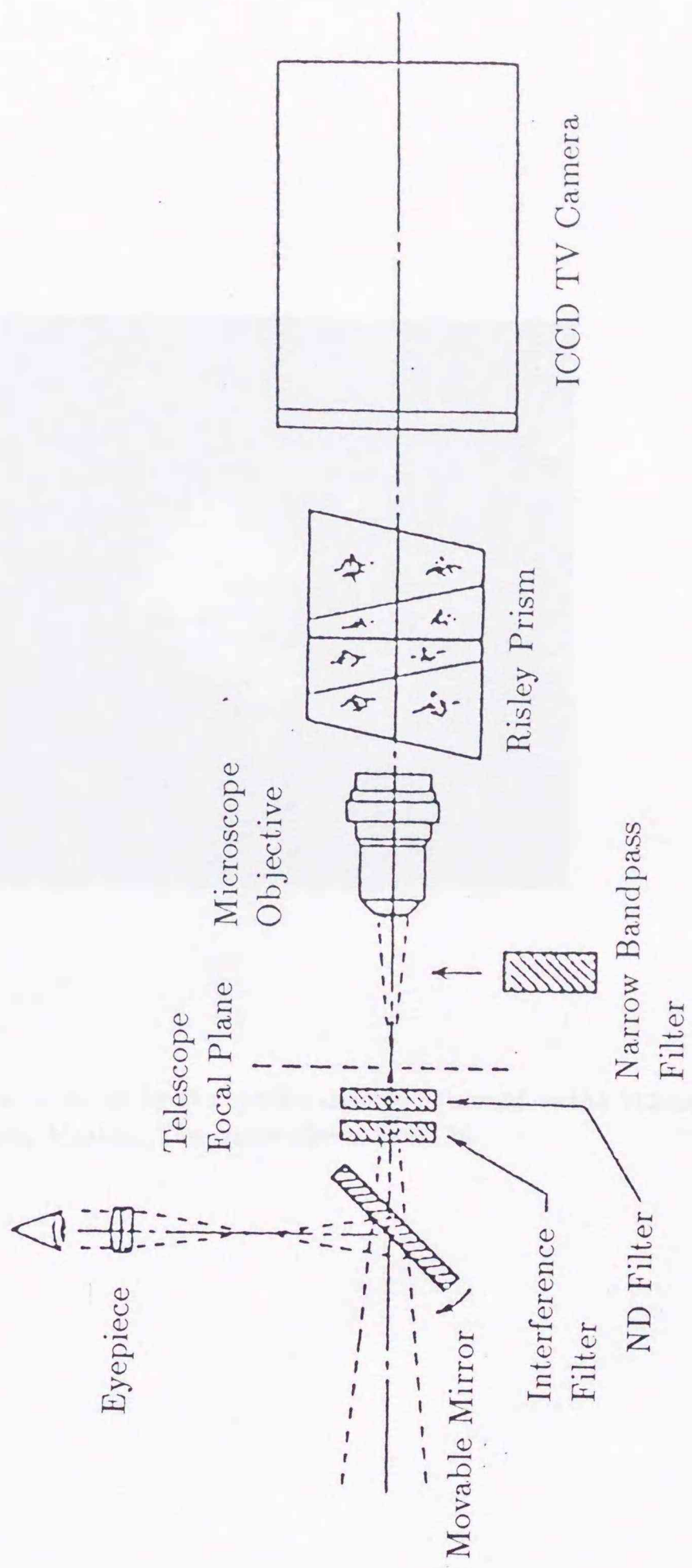


Fig. 3.6 : Optical layout of speckle camera.

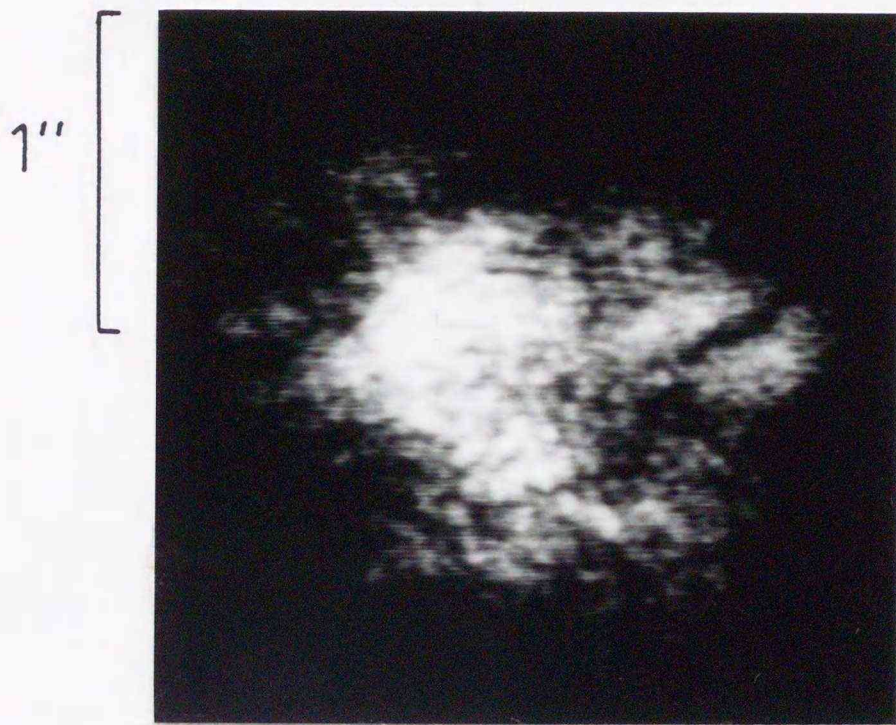
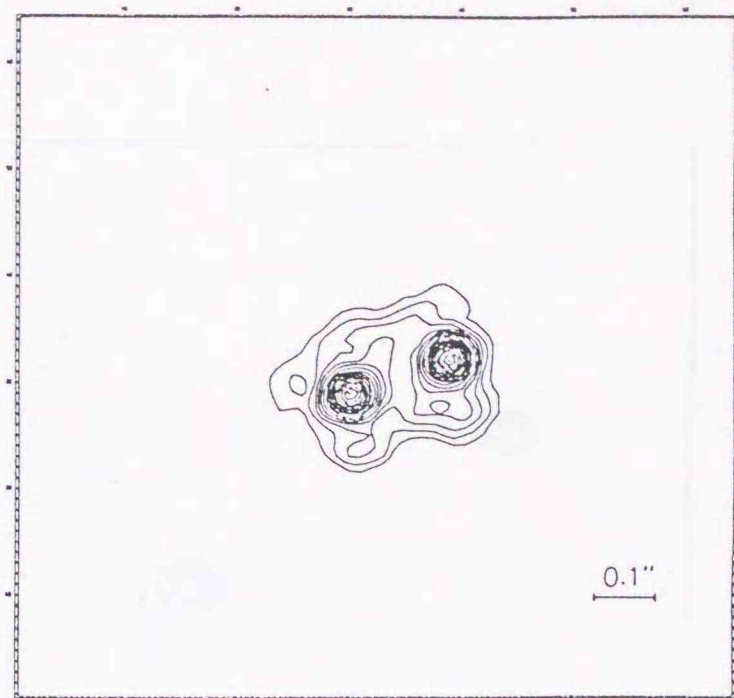
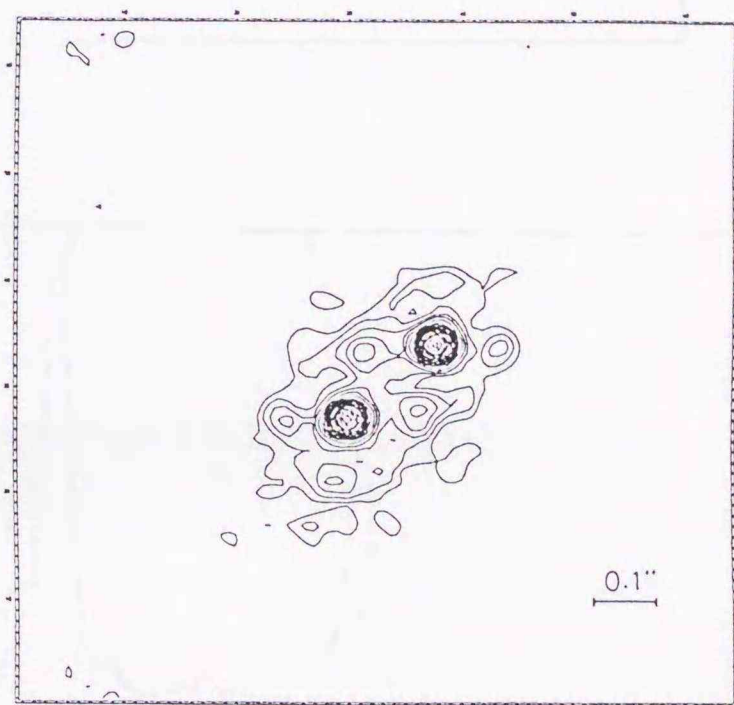


Fig. 3.7 : One of data frames obtained by the speckle camera attached to the 212cm telescope at the San Pedro Martir Observatory, Mexico. The frame size is 128x128.

(a)



(b)



(c)

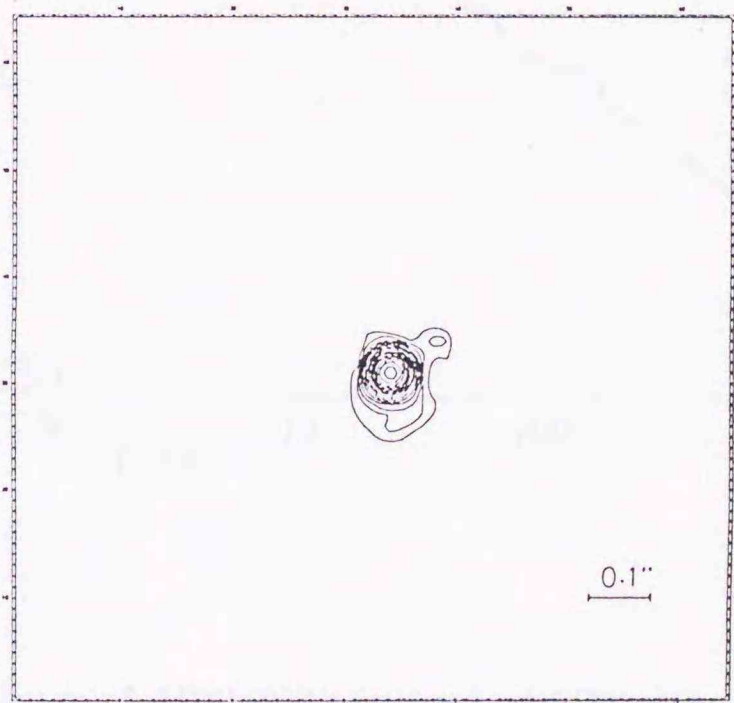
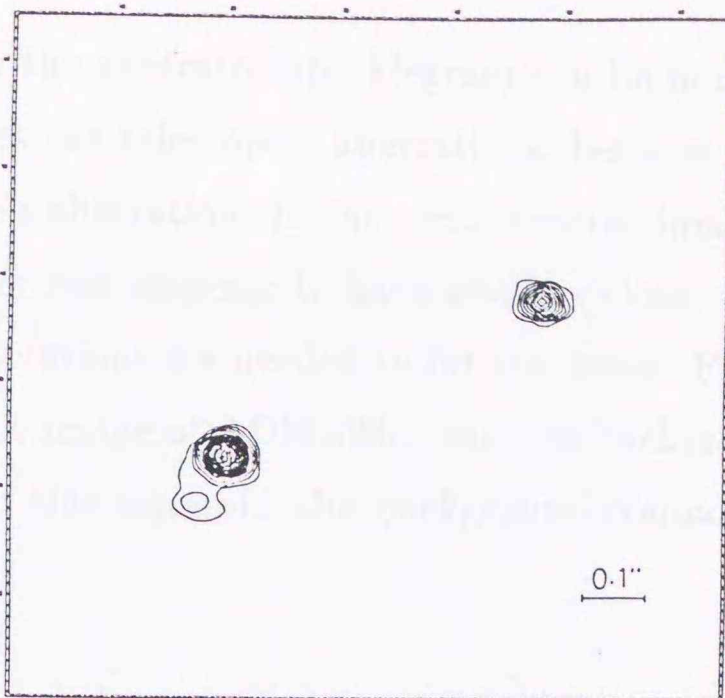


Fig. 3.8 : Results of the background subtracted SAA applied to the speckle data with the 212cm telescope. The reconstructed images of (a)ADS15281, (b)HD185936, (c)HD207330 and (d)ADS15988 are shown with contour plots. The contour levels of each plot are optimized to display the binary structure clearly. (a) is contoured with 16 steps down to about 20% level of the peak value, (b) contoured with 16 steps down to about 10% level, and (c) contoured down to about 30% level with logarithmic scale. The number of contours in (c) is 13. The logarithmic contouring in (c) is due to large difference of the magnitudes of two component stars.

(d)



(e)

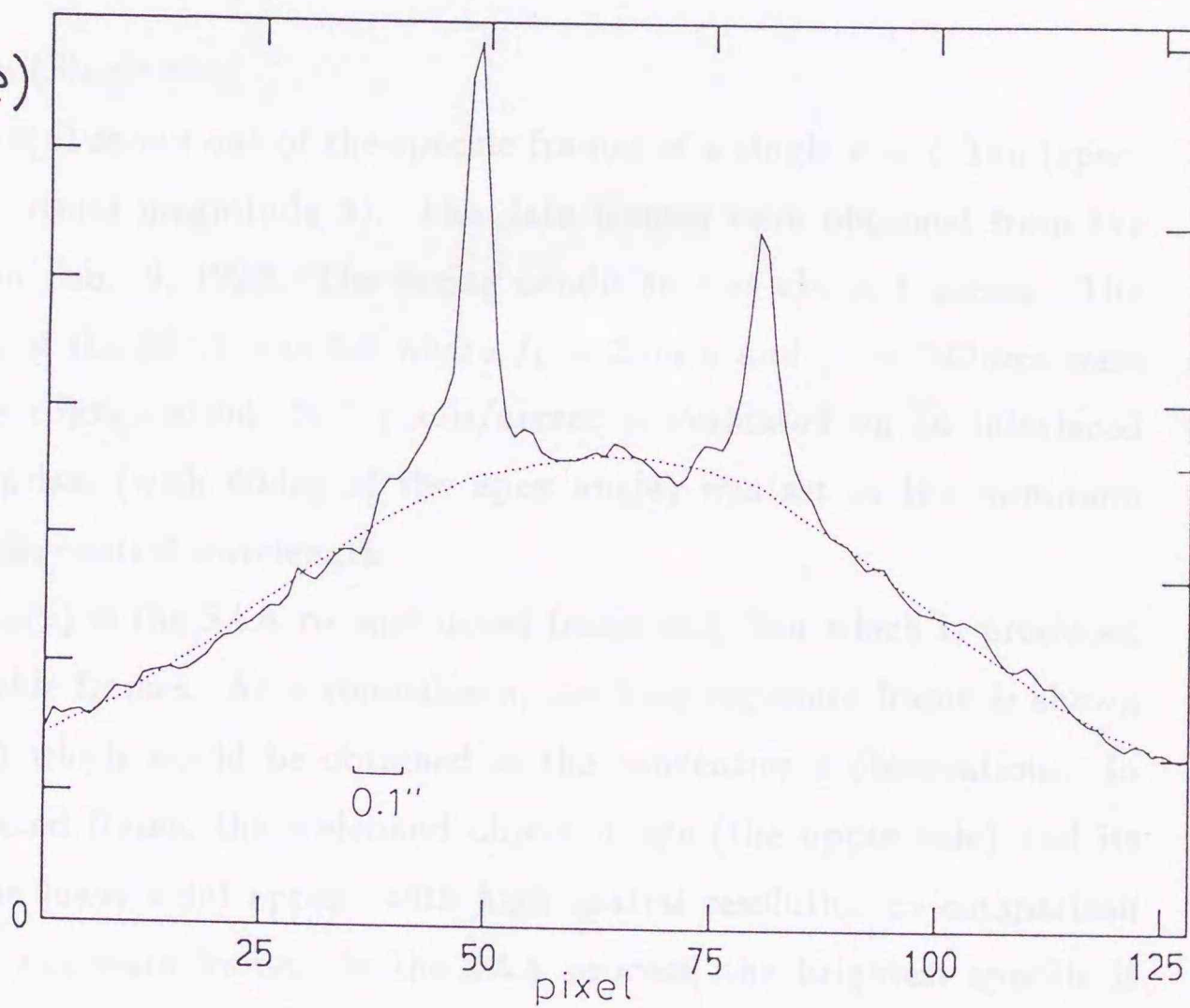


Fig. 3.8 (continued) : (d)The SAA/BGS image of ADS15988 contoured with 18 steps down to about 15% level. (e)Profiles of the raw SAA image(solid line) and the estimated background component(dotted line) of ADS15988.

the aberration has been known, for the aberrated specklegram can be noticed. The SAA image practically includes the telescope's aberrations, because each speckle is degraded by the telescope's aberration. In the reconstructed image of ADS15988 [Fig. 3.8(d)], the primary star appears to have another closer companion and the astronomical considerations are needed to for this issue. Figure 3.8(e) shows the profiles of raw SAA image of ADS15988, with its background component estimated. As shown in this example, the background component is reasonably estimated.

3.4.2 Observational results with SSC1 Data

(a) ζ Tau (Single Star)

Figure 3.9(a) shows one of the speckle frames of a single star ζ Tau (spectral type B2, visual magnitude 3). The data frames were obtained from the observation on Feb. 9, 1990. The seeing condition was about 1 arcsec. The magnification of the SSC1 was 6.8 where $f_1 = 35mm$ and $f_2 = 240mm$ were used. In this configuration, 38.7 pixels/arcsec is evaluated on an interlaced frame. The prism (with 60deg of the apex angle) was set in the minimum deviation at the central wavelength.

Figure 3.9(b) is the SAA reconstructed frame of ζ Tau which is produced from 900 speckle frames. As a comparison, the long exposure frame is shown in Fig. 3.9(c) which would be obtained in the conventional observations. In the reconstructed frame, the wideband object image (the upper side) and its dispersion (the lower side) appear with high spatial resolution in comparison with the long exposure frame. In the SAA process, the brightest speckle is located by correlated with a 3x3 pixels weighting filter

$$\begin{bmatrix} 0.30 & 0.57 & 0.30 \\ 0.57 & 1.00 & 0.57 \\ 0.30 & 0.57 & 0.30 \end{bmatrix}. \quad (3.4.2)$$

The filter has comparable shape with the telescope's PSF and it suppresses higher spatial frequency components mainly due to Poisson noise, beyond the telescope's cutoff frequency.

Figure 3.9(d) shows a contour plot of the reconstructed wideband object

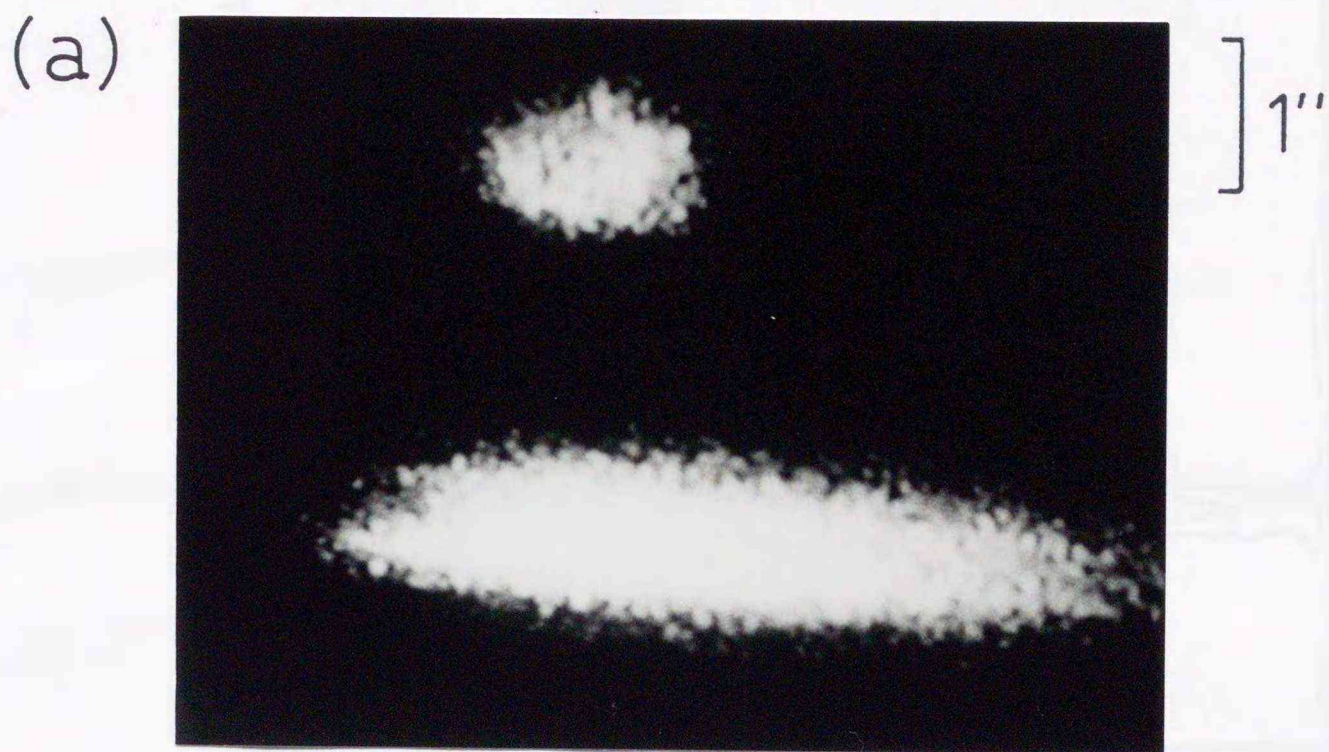


Fig. 3.9 : Data reduction for the SSC1 data of single star ζ Tau. (a) One of the speckle spectroscopic data, where the wideband specklegram (upper) and the dispersed specklegram (lower) are shown.

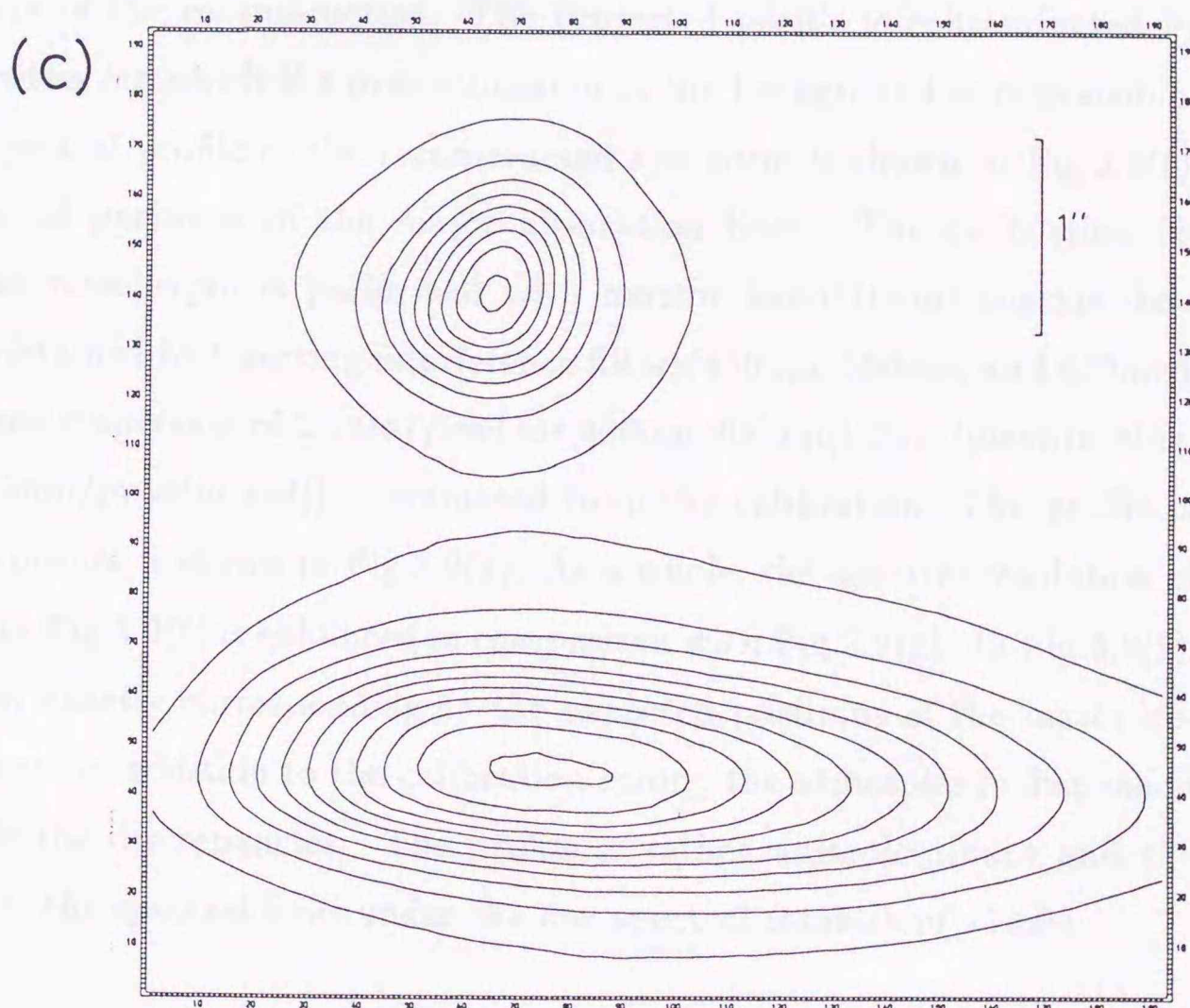
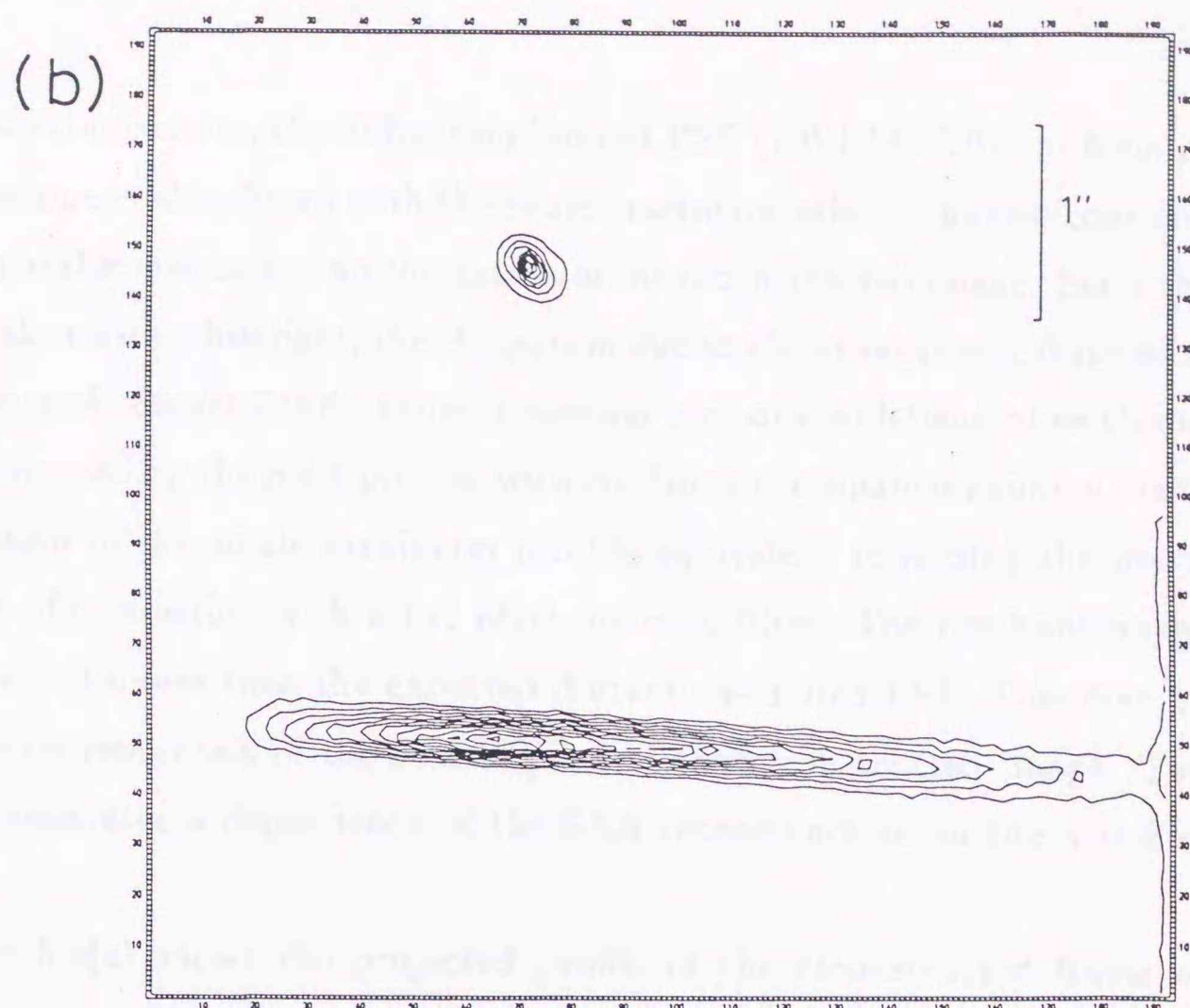


Fig. 3.9 (continued) : (b)SAA reconstructed frame from 900 speckle spectroscopic frames, where the wideband object's image(upper) and its spectrum(lower) are shown. Both are normalized with respect to each maximum value. (c)Long-exposure frame produced by averaging the data frames without any shifting.

image. As a comparison, the diffraction-limited PSF (FWHM=0.07" at 650nm) of the telescope is also shown with the same maximum value. The two contours show comparable size except an elongation in the reconstructed image. Since the data are taken with whitelight, the elongation due to the atmospheric dispersion can not ignored. Figure 3.9(d') shows a contour plot of a wideband object's image reconstructed by the SAA process with coadding the single maximum pixel. The detection of the single maximum pixel is equivalent to finding the maximum peak of correlation with a 1x1 pixel matched filter. The resultant image appears to be thinner than the expected diffraction-limited PSF. This may be due to the overemphasis of the central pixel of the reconstructed image. The result demonstrates a dependency of the SAA reconstruction on the matched filter size.

Figure 3.9(e) shows the projected profile of the reconstructed frame of Fig.3.9(b), where the projection is taken in the direction of the dispersion. As expected, the profiles in both the channels are similar, which supports the reasonability of the reconstruction. The projected profile is contaminated by the negativities for which the overestimation of the background is responsible.

The spectral profile of the reconstructed spectrum is shown in Fig.3.9(f), with expected positions of the major absorption lines. The calibration for the scale of wavelength is performed with narrow band(10nm) speckle data which are obtained by inserting interference filters(450nm, 550nm, and 650nm). The averaged dispersion of 2.7nm/pixel for 400nm-900nm[1.3nm/pixel(in blue) through 6.3nm/pixel(in red)] is evaluated from the calibration. The profile of the long exposure is shown in Fig.3.9(g). As a whole, the spectral resolution of the profile in Fig.3.9(f) is enhanced in comparison with Fig.3.9(g). In Fig.3.9(f), dips are not exactly corresponding to the expected positions of the major absorption lines. In addition to the calibration errors, the atmospheric dispersion causes such the discrepancies. The profile is rather noise-dominant and the noise smears the spectral lines under the low spectral resolution(>7nm).

(b) ADS16836 (Binary Star)

Figure 3.10(a) shows one of the speckle frames of a binary star ADS16836 (spectral type K3IIb, visual magnitude 5.0). The data frames were obtained

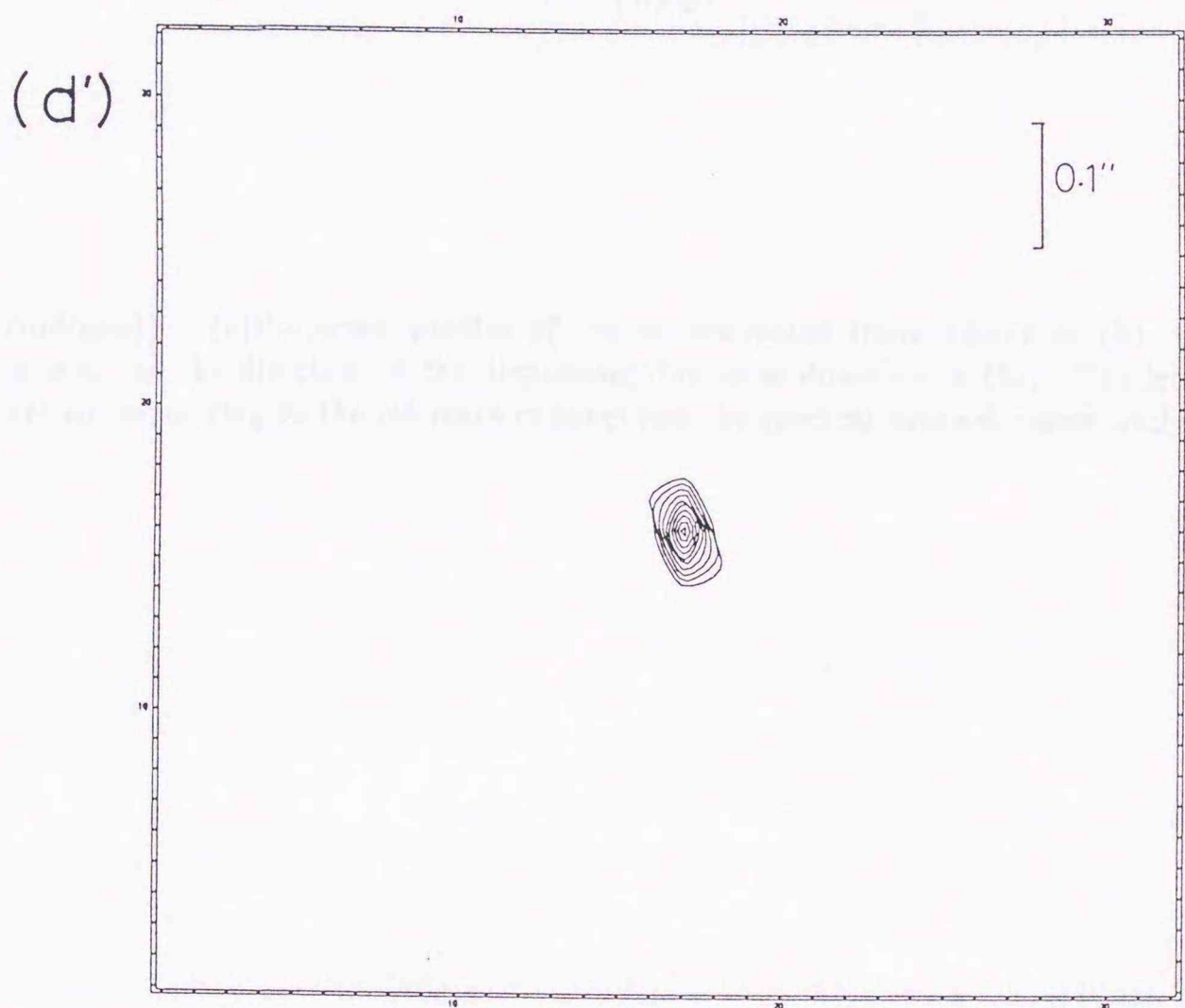
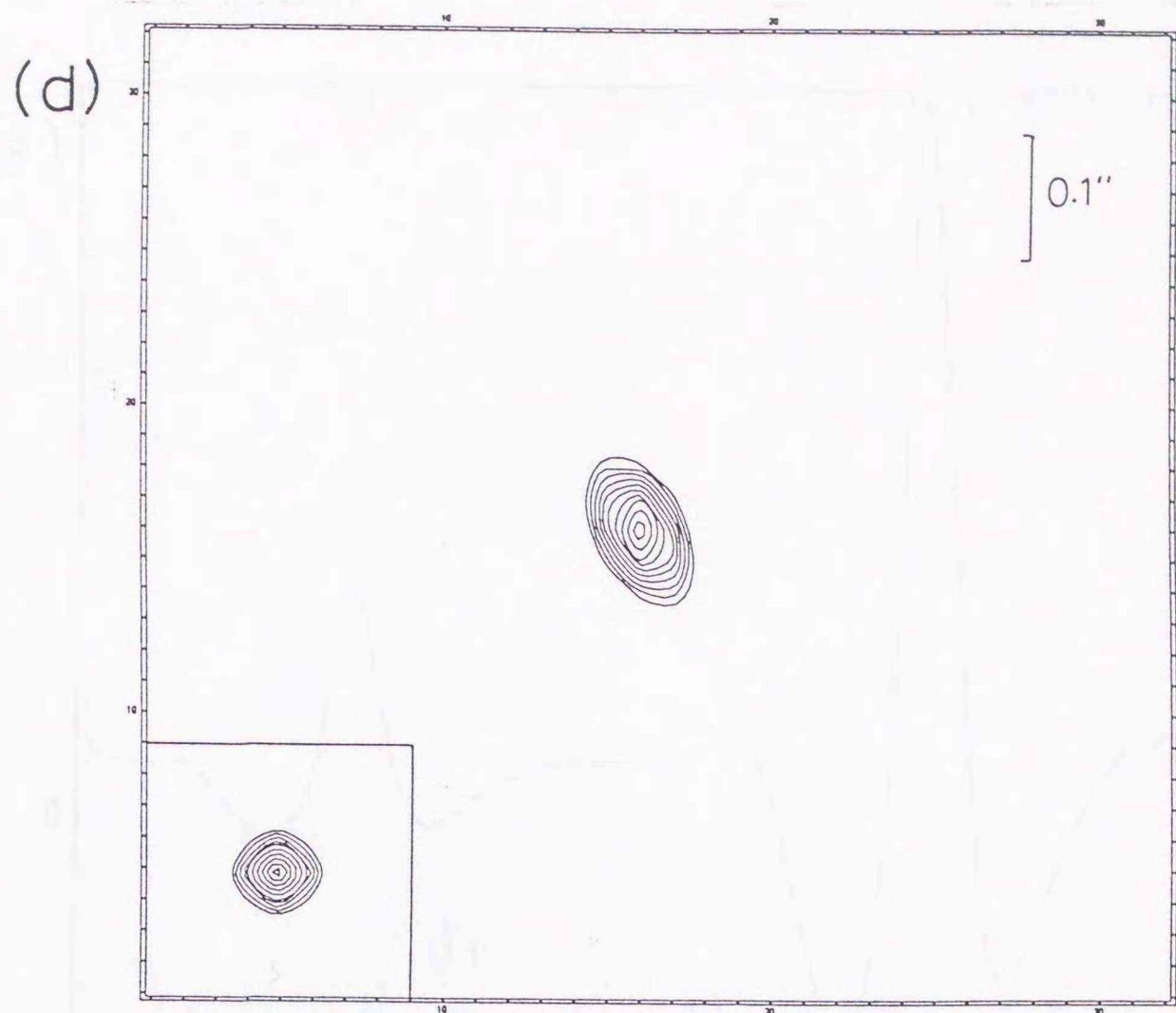


Fig. 3.9 (continued) : (d) A close-up of the reconstructed wideband object's image. The calculated diffraction-limited PSF of the 188cm telescope at $\lambda = 650\text{nm}$ is also plotted with the same peak value as that of the reconstructed image. The frame is plotted with 10 steps down to 50% level of the peak value. (d') A close-up of the wideband object's image reconstructed by SAA with coadding maximum pixels. The frame is plotted with 10 steps down to 50% level of the peak value.

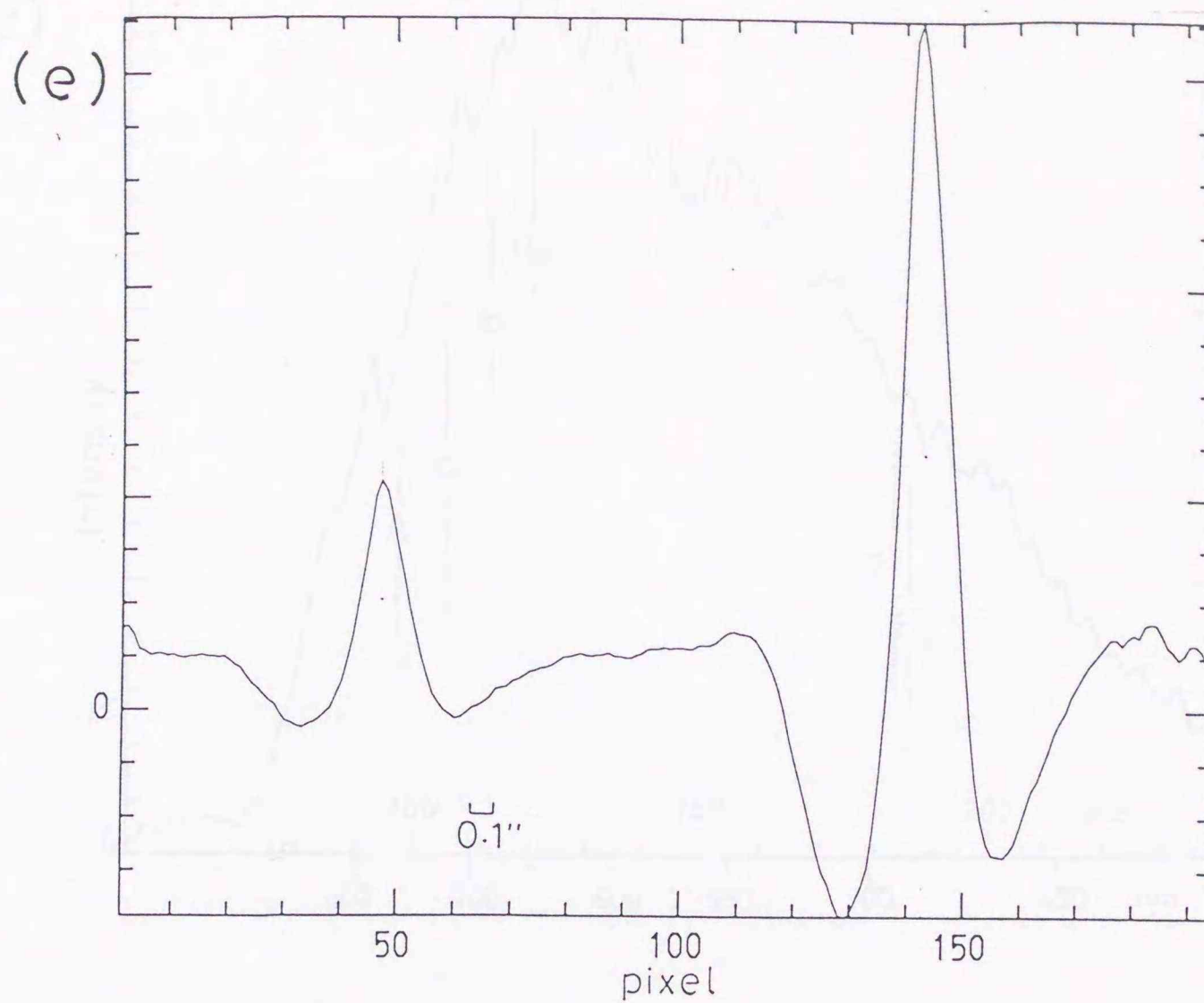


Fig. 3.9 (continued) : (e) Projected profiles of the reconstructed frame shown in (b), where the projection is taken in the direction of the dispersion (horizontal direction in (b)). The left and the right sides are corresponding to the reference channel and the spectral channel, respectively.

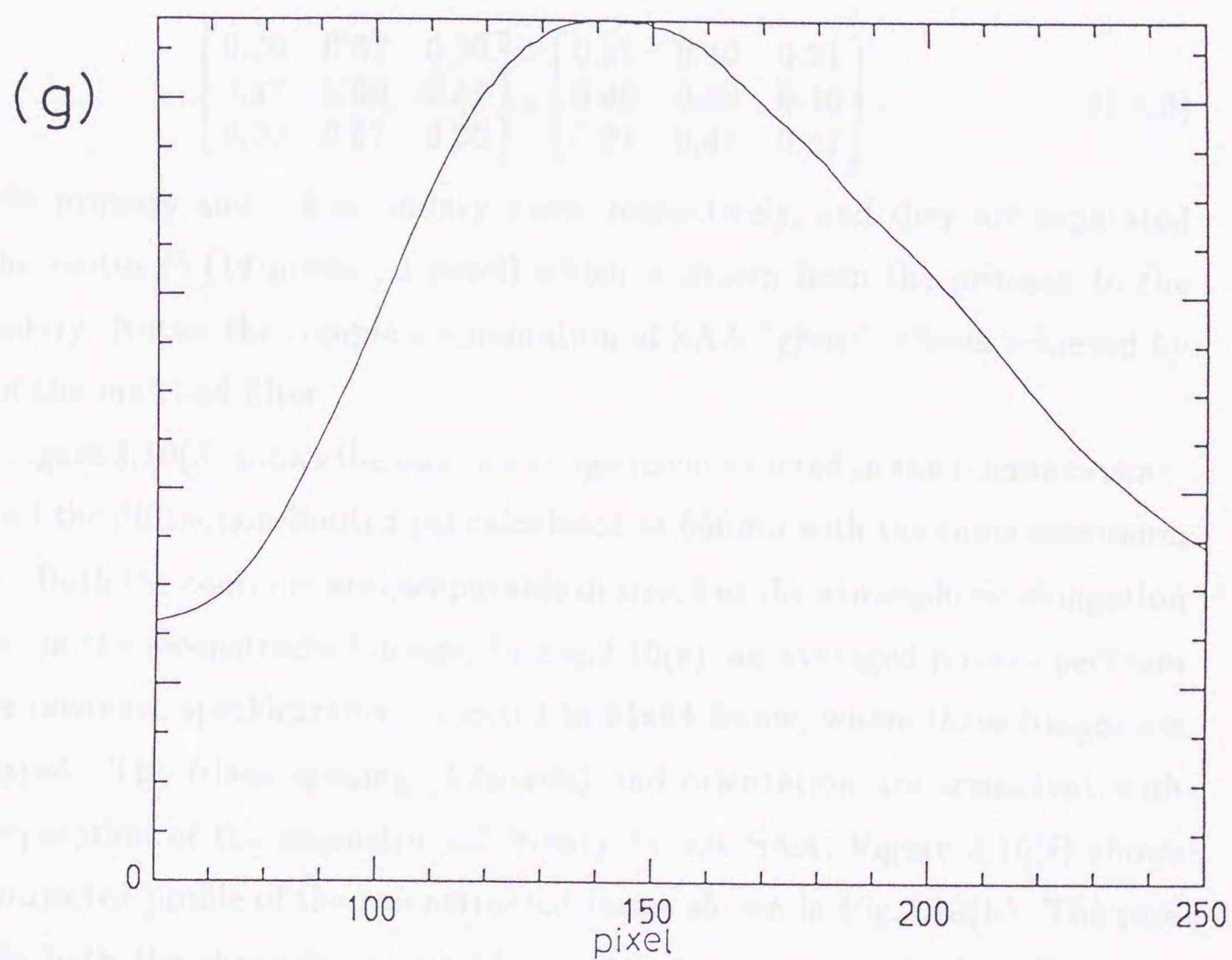
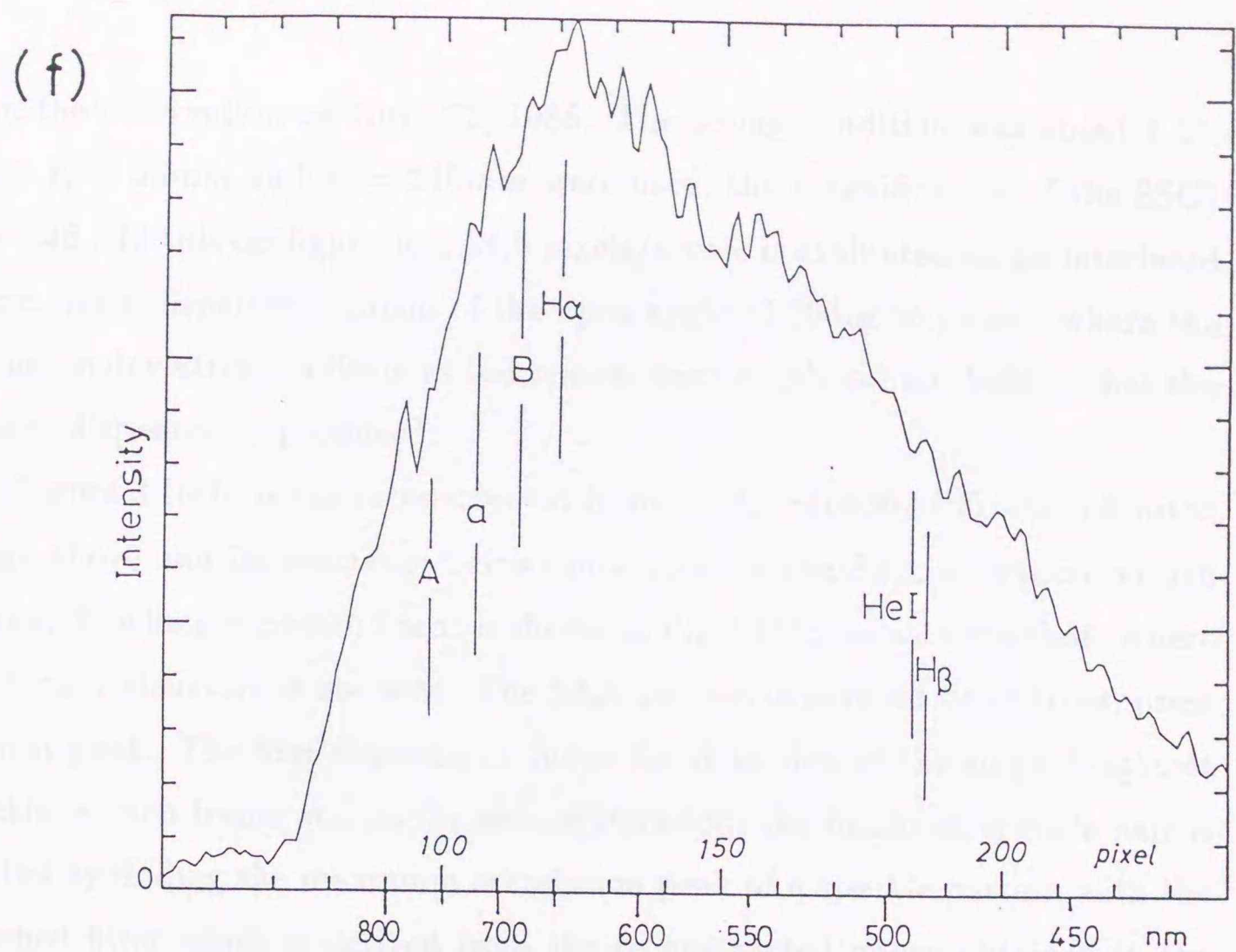


Fig. 3.9 (continued) : (f) Spectral profile of the SAA reconstructed spectrum shown in the lower side of (b). The profile is obtained by taking the projection on the spectral side in the vertical direction of the frame. The expected positions of the major absorption lines are also indicated. The abscissa is converted into the wavelength[nm]. (g) Spectral profile of the long-exposure spectrum shown in the lower side of (c).

from the observation on Nov. 22, 1988. The seeing condition was about 1.5". Since $f_1 = 55mm$ and $f_2 = 240mm$ were used, the magnification of the SSC1 was 4.36. In this configuration, 24.8 pixels/arcsec is evaluated on an interlaced frame. As a disperser, a prism of the apex angle of 30deg was used, where the minimum deviative condition at the central wavelength did not hold so that the desired dispersion is produced.

Figure 3.10(b) is the reconstructed frame of ADS16836 (diffraction-limited image above and its spectrum below) produced by the SAA operation on 376 frames. The long exposure frame is shown in Fig.3.10(c) as a comparison, where any binary structure is not seen. The SAA process is iterated twice to suppress a ghost peak. The first iteration includes the detection of the single brightest speckle in each frame and in the second iteration, the brightest speckle pair is located by finding the maximum correlation peak of a speckle pattern with the matched filter which is derived from the reconstructed image obtained in the first iteration. The matched filter pair derived is

$$\begin{bmatrix} 0.30 & 0.57 & 0.30 \\ 0.57 & 1.00 & 0.57 \\ 0.30 & 0.57 & 0.30 \end{bmatrix}, \begin{bmatrix} 0.21 & 0.40 & 0.21 \\ 0.40 & 0.70 & 0.40 \\ 0.21 & 0.40 & 0.21 \end{bmatrix}, \quad (3.4.3)$$

for the primary and the secondary stars, respectively, and they are separated by the vector of (14 pixels, 1 pixel) which is drawn from the primary to the secondary. Notice the complete elimination of SAA "ghost" effects achieved by use of the matched filter.

Figure 3.10(d) shows the object's image reconstructed in the reference channel and the diffraction-limited psf calculated at 650nm with the same maximum value. Both the contours are comparable in size, but the atmospheric elongation is seen in the reconstructed image. In Fig.3.10(e), an averaged power-spectrum of the reference specklegrams is plotted in 64x64 frame, where three fringes are displayed. The fringe spacing (4.5pixels) and orientation are consistent with the separation of the reconstructed binary by the SAA. Figure 3.10(f) shows the projected profile of the reconstructed frame shown in Fig.3.10(b). The profiles in both the channels show a binary structure and are similar. From the projected profile, the intensity ratio between two stars is evaluated to 1:0.66.

It is noteworthy that in the reconstructed frame of ADS16836, the primary's spectrum and the secondary's spectrum are spatially separated with the

(a)



] 1"

Fig. 3.10 : Data reduction for the SSC1 data of binary star ADS16836. (a) One of speckle spectroscopic frames obtained by SSC1.

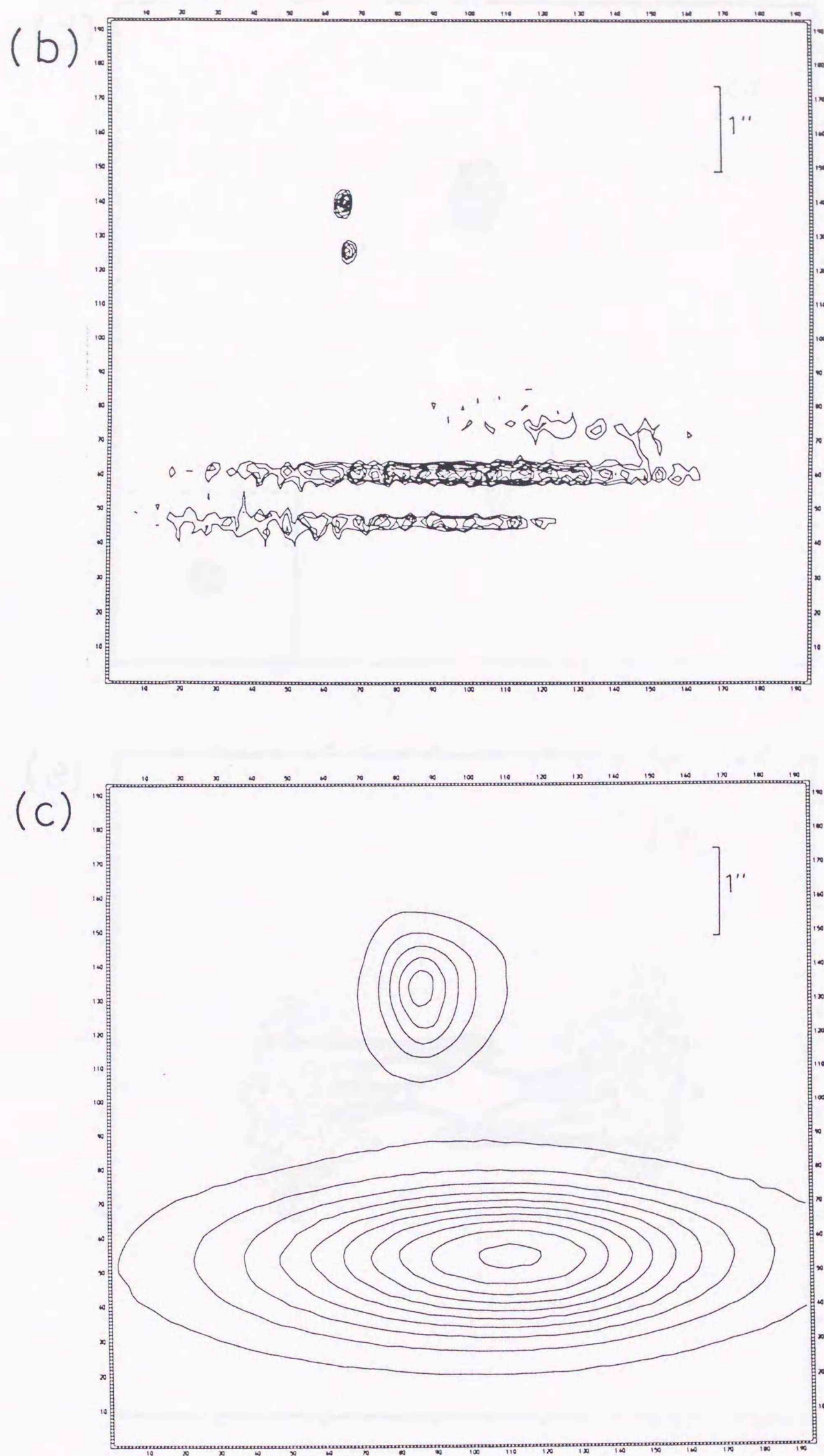


Fig. 3.10 (continued) : (b)SAA reconstructed frame from 376 speckle spectroscopic frames, where the wideband object's image(upper) and its spectrum(lower) have a binary structure. Both are normalized with respect to each maximum value. (c)Long-exposure frame produced by averaging the data frames without any shifting. No binary structure is recognized.

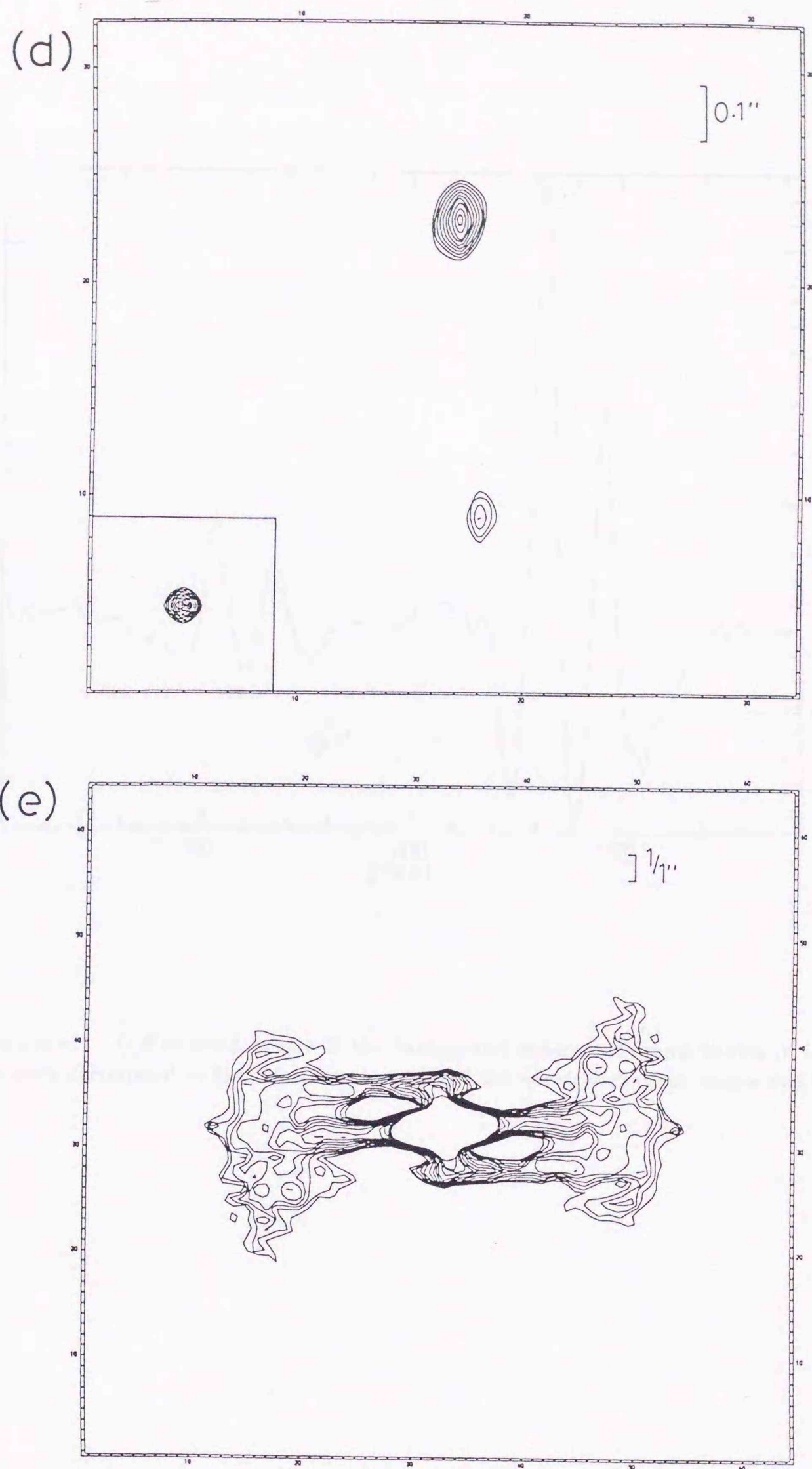


Fig. 3.10 (continued) : (d) A close-up of the reconstructed wideband object's image. The calculated diffraction-limited PSF of the 188cm telescope at $\lambda = 650\text{nm}$ is also plotted with the same peak value as that of the reconstructed image. The frame is plotted with 10 steps down to 50% level of the peak value. (e) Averaged power spectrum of the reference specklegrams with logarithmic grayscale. The frame size is 64×64 pixels and the central peak is clipped. Three fringes are seen.

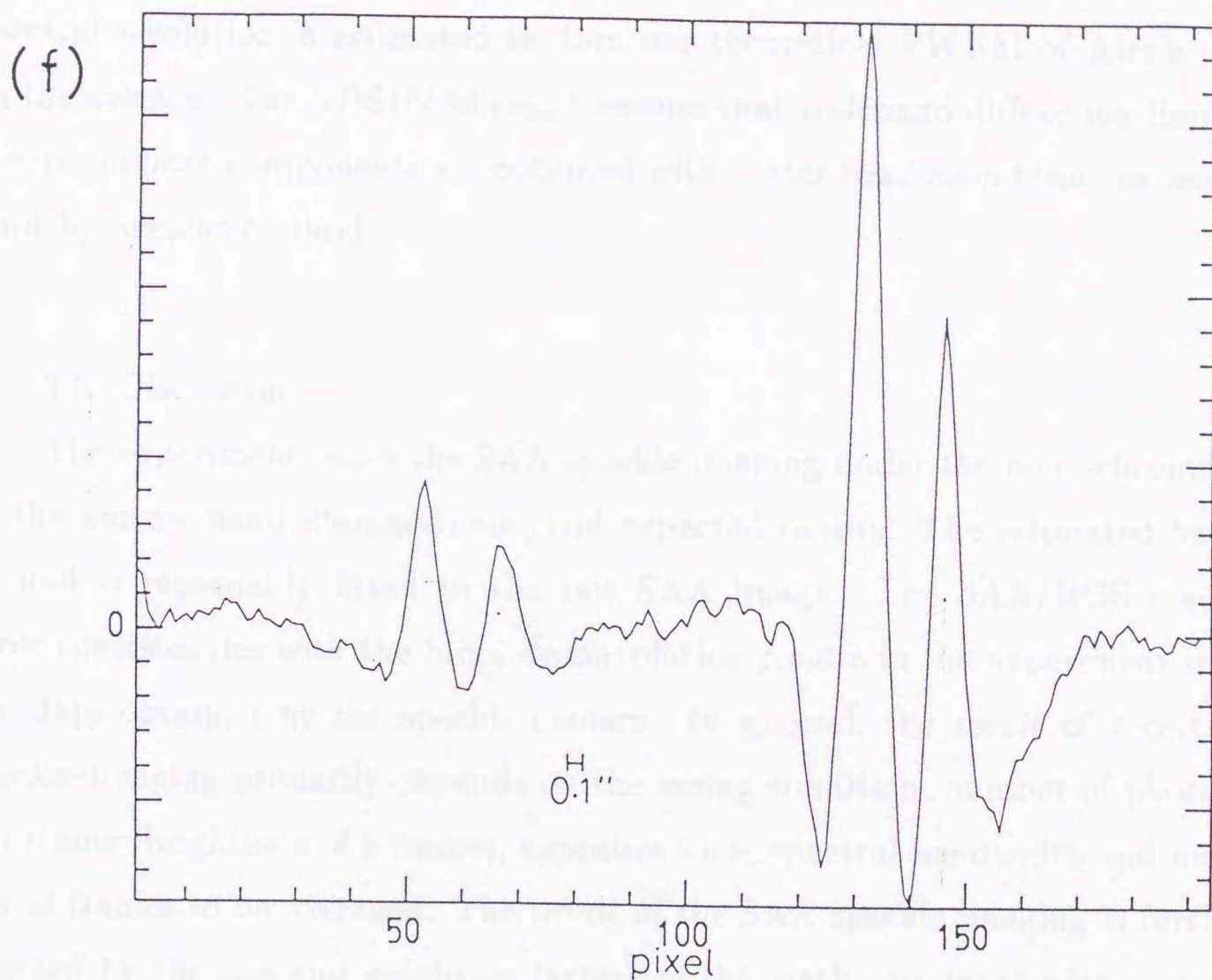


Fig. 3.10 (continued) : (f) Projected profile of the background subtracted frame shown in (b). The left and right sides correspond to the reference channel and the spectral channel, respectively.

angular separation of approximately $0.56''$, which is closer than the seeing limit and corresponds precisely to the separation of the binary components. The spectral resolution is estimated to 4nm per theoretical FWHM of Airy's disc on the average. The ADS16836 result verifies that wideband diffraction-limited spectra of both components are obtained with better resolution than the seeing limit by present method.

3.5. Discussion

The experiments with the SAA speckle imaging under the monochromatic or the narrow band illuminations yield expected results. The estimated background is reasonably fitted to the raw SAA image. The SAA/BGS results show consistencies with the blind deconvolution results in the experiment with the data obtained by the speckle camera. In general, the result of a certain speckle imaging primarily depends on the seeing condition, number of photons per frame (brightness of a frame), exposure time, spectral bandwidth and number of frames to be averaged. The result of the SAA speckle imaging is further affected by the size and weighting factors of the mask correlated with a single speckle, and the number of detected speckles per frame. The optimum FWHM of the weighted mask is comparable with the Airy's disc. Smaller FWHM can cause the reconstructed point-image to be narrower than that of the expected Airy's disc because the photon noise and spike noise are recognized as single speckle. The larger FWHM of the weighting of the mask can cause the reconstructed point-image to broaden than the size of the Airy's disc. It is important that the compact and intense speckles are selected. Thus, the number of the detected speckles per frame depends on the contrast of individual specklegram. For the wider spectral band and/or more complex objects, the careful selection for the detected speckles are needed, otherwise the resultant image is rather degraded even though a larger number of speckles coadded.

The results with SSC1 in the previous section prove that the present method has an ability to reasonably reconstruct the wideband spectra of stellar objects with the diffraction-limited spatial resolution of the telescope. The nearly diffraction-limited wideband images are also reasonably reconstructed. However, there are less evidences for the spectral profiles reasonably recon-

structed.

For the speckle spectroscopic data, it is required that the imaging character of the speckle spectroscopic camera is shift invariant, i.e. the dispersion and the relative position of the two images, the reference and the dispersed images, are constant in spite of the presence of image dancing at the telescope's focal plane due to the atmospheric turbulence and the fluctuation of the telescope guiding. Actually, the instabilities of the imaging character exist, especially due to the shifting of the incident ray on the prism. In general, the $d\beta/d\alpha$ is not unity for all the wavelengths and depends on α , e and λ (Kingslake 1969), where α and β are the incident and the emergent angles projected into the meridian plane of the prism, respectively, and e represents an angle inclined to the meridian plane (Fig.3.11). These dependencies result in the instabilities. Such instabilities occur only in the direction of the dispersion and affect the reconstructed spectral profiles. For the configuration in which the ζ Tau were observed, the variation of the relative position between the two images amounts to ± 5 pixels as the reference specklegram moves by full detector size (8.8mmx6.6mm). The variation nonlinearly depends on the wavelength, which makes the full correction difficult. The instabilities of the optics cause lowering of the spectral resolution of the reconstructed spectra. The reconstructed spectral profile with low spectral resolution is blurred by noise, which results in the loss of the spectral fine structures.

The reconstruction algorithm consists of matched filter recognition of object figures hidden in the speckle pattern, averaging them and subtracting the seeing induced background. Only the part of the speckle image proximate to the white-light speckle, where object distortion is less dependent on wavelength, is referred in the SAA process. Thus, the reconstruction algorithm is applicable to data of any spectral bandwidth, with any dispersion in principle, provided that an adequate set of data is supplied.

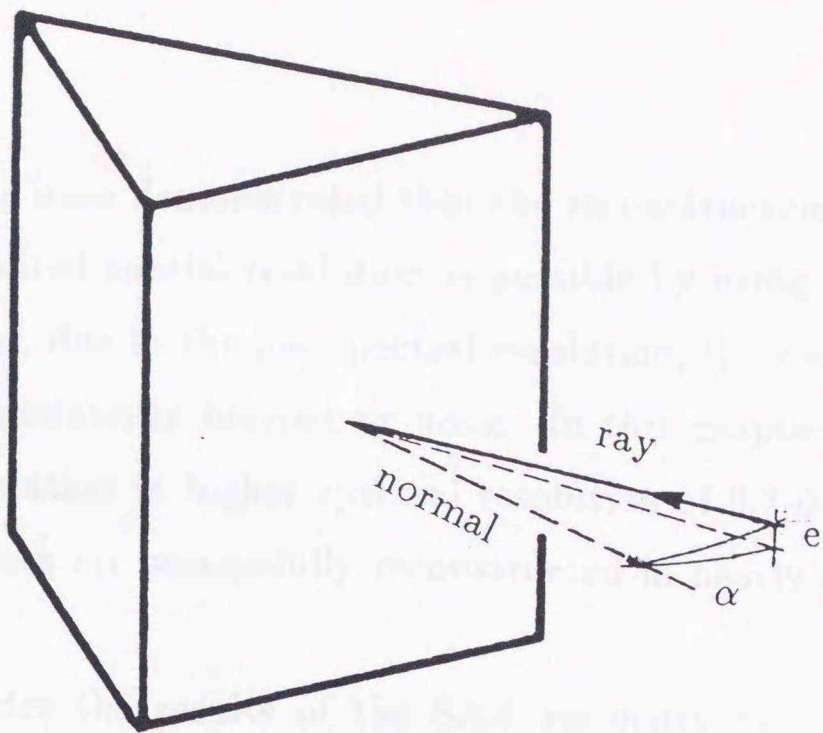


Fig. 3.11 : Illustration of incident angles to a prism.

Chapter 4. Speckle Spectroscopy in Narrowband and Medium Dispersion Mode

4.1. Introduction

In Chapter 3, it has been demonstrated that the reconstruction of spectra up to the diffraction-limited spatial resolution is possible by using the system with the SSC1. However, due to the low spectral resolution, the reconstructed spectral profiles were dominantly blurred by noise. In this chapter, a speckle spectroscopic instrumentation in higher spectral resolution of 0.3-0.6nm is described. The spectral lines are successfully reconstructed in nearly diffraction-limited resolution.

Section 4.2. includes the results of the SAA reconstruction applied to the data supplied by E.K.Hege of the Steward Observatory, which were obtained with the differential speckle camera, SO/DSC (Beckers et al. 1983). The SO/DSC was developed for the purpose to detect an object's difference at two slightly different wavelengths with the diffraction-limited resolution. Thus, the SO/DSC also has two optical channels corresponding to the two wavelengths. If a disperser [a grism(Nelles et al. 1981; Walker 1987; Traub 1990) was used in the SO/DSC] is inserted into either of the channels, the data can have the same format as those obtained by the SSC1. The 0.6nm spectral resolution is attainable from the SO/DSC data and the result for single stars showed resolved spectral line, $H\beta$. The SO/DSC results suggested that the spectral features of an object can be restored in the diffraction-limited angular resolution when the dispersion is large enough.

The revised camera SSC2 was constructed to acquire the narrow band medium dispersion data (Baba et al. 1993). The SSC2 is designed to restore a medium dispersion spectrum with spectral resolution of 0.3nm and is devised to enhance the optical throughput. Since the data are narrowband ($\sim 50\text{nm}$), some deconvolution techniques are available for the data reduction. Besides the SAA technique, the cross-correlation technique is newly introduced to reduce the data obtained with SSC2. In sections 4.3.~4.5., the speckle spectroscopy with SSC2 and its observational results are described.

The spectra of single stars, γ Cas and α Per are reconstructed in nearly

diffraction-limited angular resolution with the resolved $H\alpha$ emission and absorption lines, respectively (Kuwamura et al. 1993b). It is shown that the cross-correlation method is superior to the shift-and-add method in the narrow bandwidth region. Especially, the results of α Per are compared with the slit spectrogram of Procyon (Griffin et al. 1979) which has the similar spectral type as α Per and they are shown to be fairly consistent. It is demonstrated that the new system exhibits a sufficient performance to enable us to make the quantitative spectral analysis. Spectra of a binary star with the separation closer than the seeing limit are also reconstructed in nearly diffraction-limited resolution. The reconstructed spectrum shows a binary structure. The $H\alpha$ lines for both of the primary and the secondary stars are clearly resolved in the separated spectra.

4.2. Data Reduction for the SO/DSC Data and its Results

The data supplied by E.K.Hege were acquired by employing a speckle spectroscopy module of the SO/DSC with the 4m telescope of the Kitt Peak National Observatory (KPNO). In Fig.4.1, the layout of the SO/DSC with the speckle spectroscopy module is depicted. Its optical part is similar to SSC1 in configuration but in some details two cameras are different

In the Steward Observatory speckle spectroscopy module, the collimated beam is divided by a polarizing beam splitter into two orthogonally polarized beams. One beam is dispersed by a grism and the other is made narrow bandwidth by an interference filter. The two beams are combined again by a second polarizing beam splitter. The differential speckle camera's Wollaston prism (Kitchin 1991) serves to give the combined beams a relative shift according to their polarizations and the overlap of two images is avoided. A Pulnix CCD video camera with a four-stage electrostatic image intensifier is used as the detector. The observed image is recorded by U-matic video recorder. The digitized speckle frames suffer from severe pincushion distortion due to the image intensifier preceding the CCD imager. The distortion is corrected by remapping the frames with reference to a grid image taken by the same detector. Figure 4.2 shows one of the speckle frames after remapping. In the right side, the reference specklegram is imaged with the spectral bandpass of about 30nm centered at

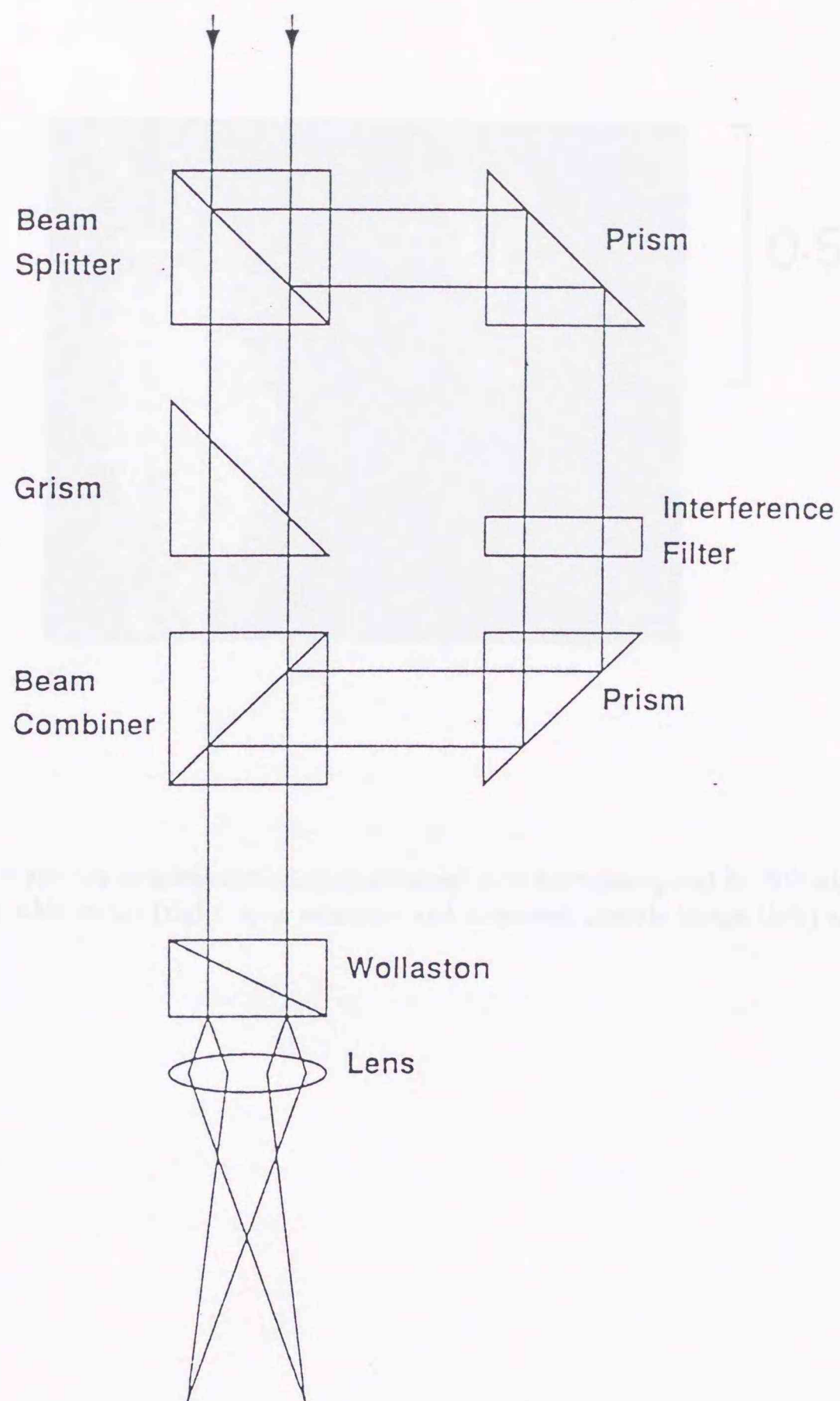


Fig. 4.1 : Optical setup of speckle spectroscopy module in the Steward Observatory's differential speckle camera(SO/DSC).

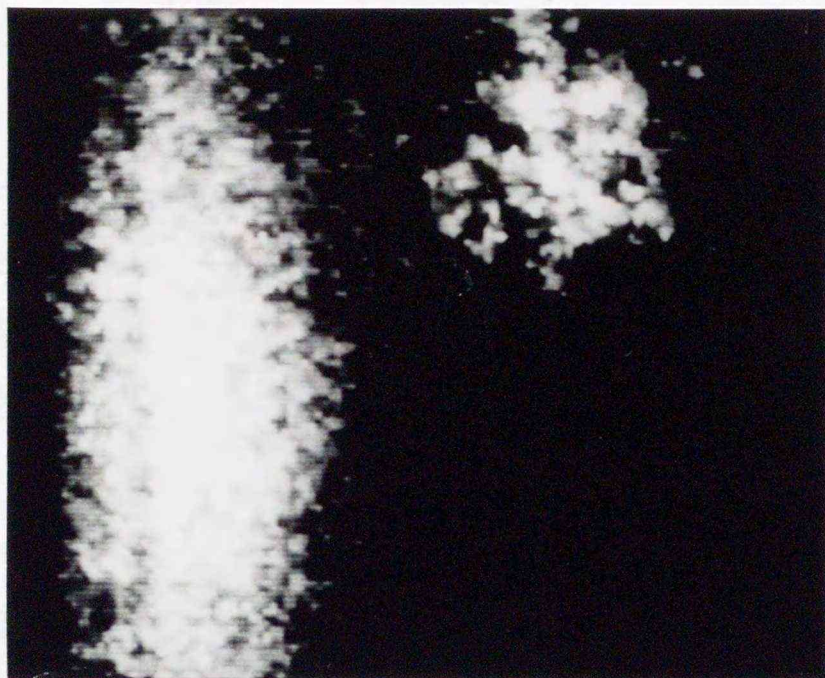


Fig. 4.2: One of speckle spectroscopic frames obtained with 4m telescope at KPNO with the SO/DSC. Narrowband speckle image (right) as a reference and dispersed speckle image (left) are displayed.

550nm. On the left side, a dispersed speckle image with the spectral range of about 24nm around the $H\beta$ line is displayed. Note that the spectral regions in two channels does not overlap. Since the bandwidth of the reference speckle image is narrow enough to minimize the chromatic effect on the speckles, several brighter speckles can be selected for SAA averaging unlike the wideband case.

The dispersed specklegram obtained by SO/DSC extends up to the edges of the frame. In such a case, a mismatch between the raw SAA frame and the background frame occurring at the marginal region makes the resultant (background subtracted) frame degrade. The number of pixels coadded is not uniform over the frame, especially at the marginal parts the number of coadded pixels being reduced. Such a non-uniformity is different between the raw SAA frame and the background frame. To normalize such a mismatch, the integrated frame is divided by the number of coadded pixels at each position.

Figure 4.3(a) presents a contour plot of the reconstructed frame of ϵ Her by the SAA process with 3203 speckle frames which were obtained from the observation on August 28, 1987. The details of the SAA process used here are described in Chapter 3. In Fig.4.3(b), the profile of the reconstructed spectrum is plotted. The spectral resolution of the reconstructed spectrum is approximately 0.6nm per theoretical FWHM of Airy's disc. For the data reduction, several brighter speckles are detected per frame and about 11000 speckles were coadded. To find the speckle positions, each reference speckle image is correlated with the 3x3 pixels weighted filter

$$\begin{bmatrix} 0.54 & 0.73 & 0.54 \\ 0.73 & 1.00 & 0.73 \\ 0.54 & 0.73 & 0.54 \end{bmatrix}, \quad (4.2.1)$$

and several higher correlation peaks are detected. The correlation filter is comparable to the PSF of the telescope. In the resolved spectrum of ϵ Her, the absorption line of $H\beta$ is seen with diffraction-limited resolution, which is indicated in the profile. Figure 4.3(c) shows a crosscut profile of the raw SAA frame together with the corresponding background profile. The figure shows that the background is fairly estimated to the raw SAA frame and the weak signal in the spectral channel can be effectively extracted. Figure 4.3(d) shows the projected profile of the resultant frame taken in the direction of the dispersion. The width of the projected profile for the reconstructed spectrum is slightly broader than

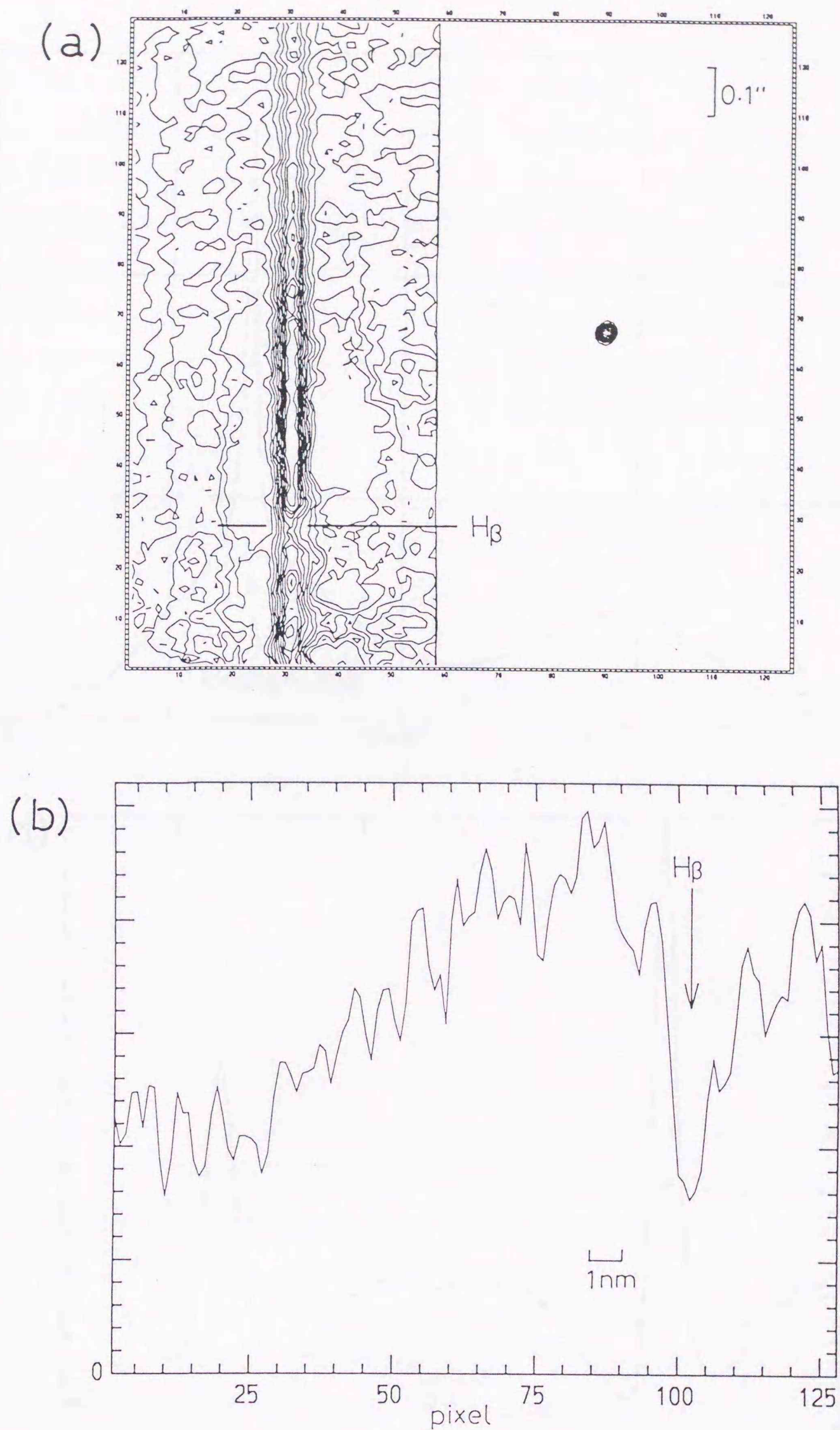


Fig. 4.3 : Result for ϵ Her. (a) The reconstructed diffraction-limited image (right) and its spectrum (left) are shown with contour lines, and the absorption line of $H\beta$ is indicated. Both are normalized with respect to each maximum value. (b) Profile of the reconstructed spectrum. Four columns of the spectrum in (a) are averaged to obtain the profile.

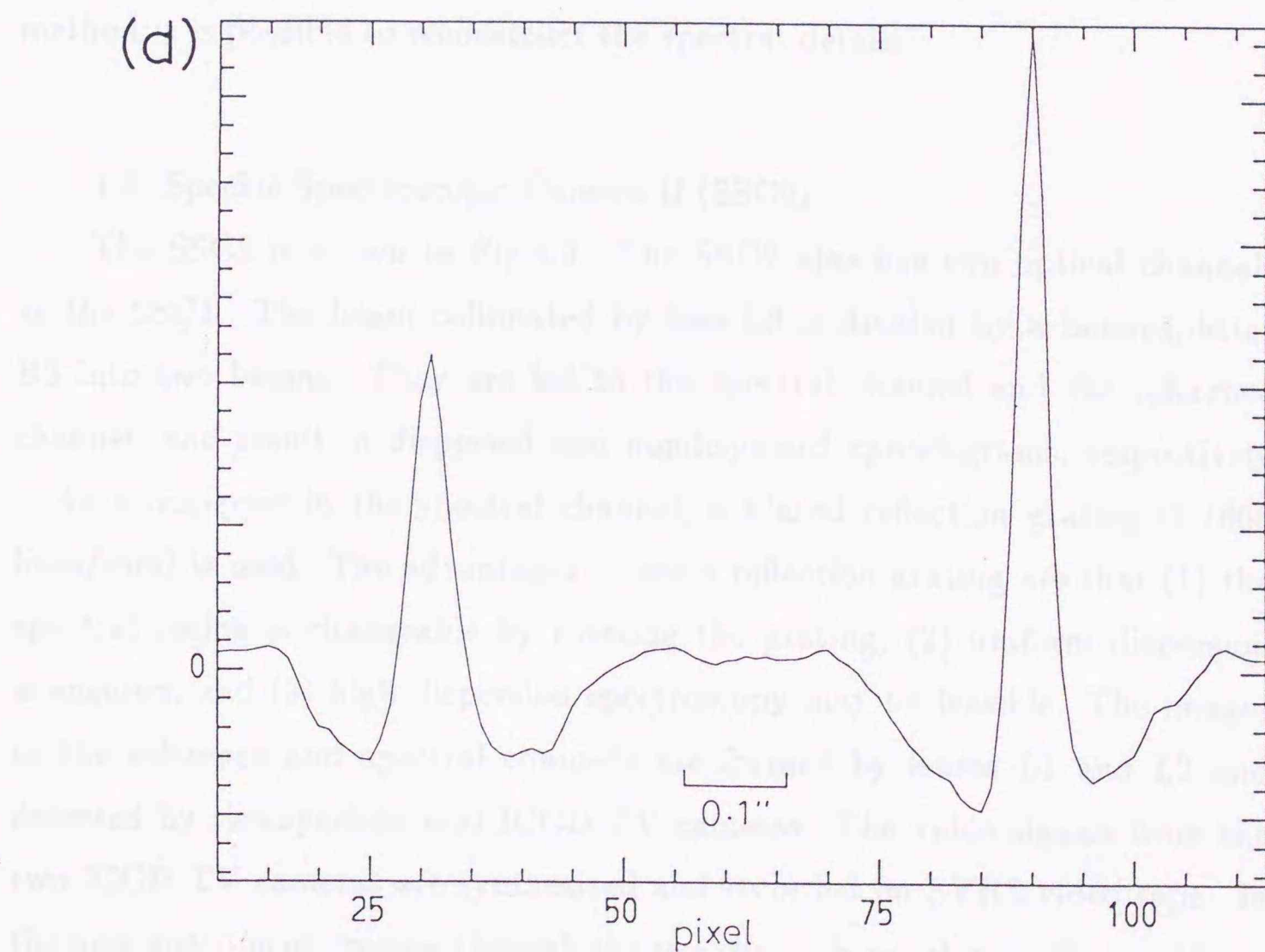
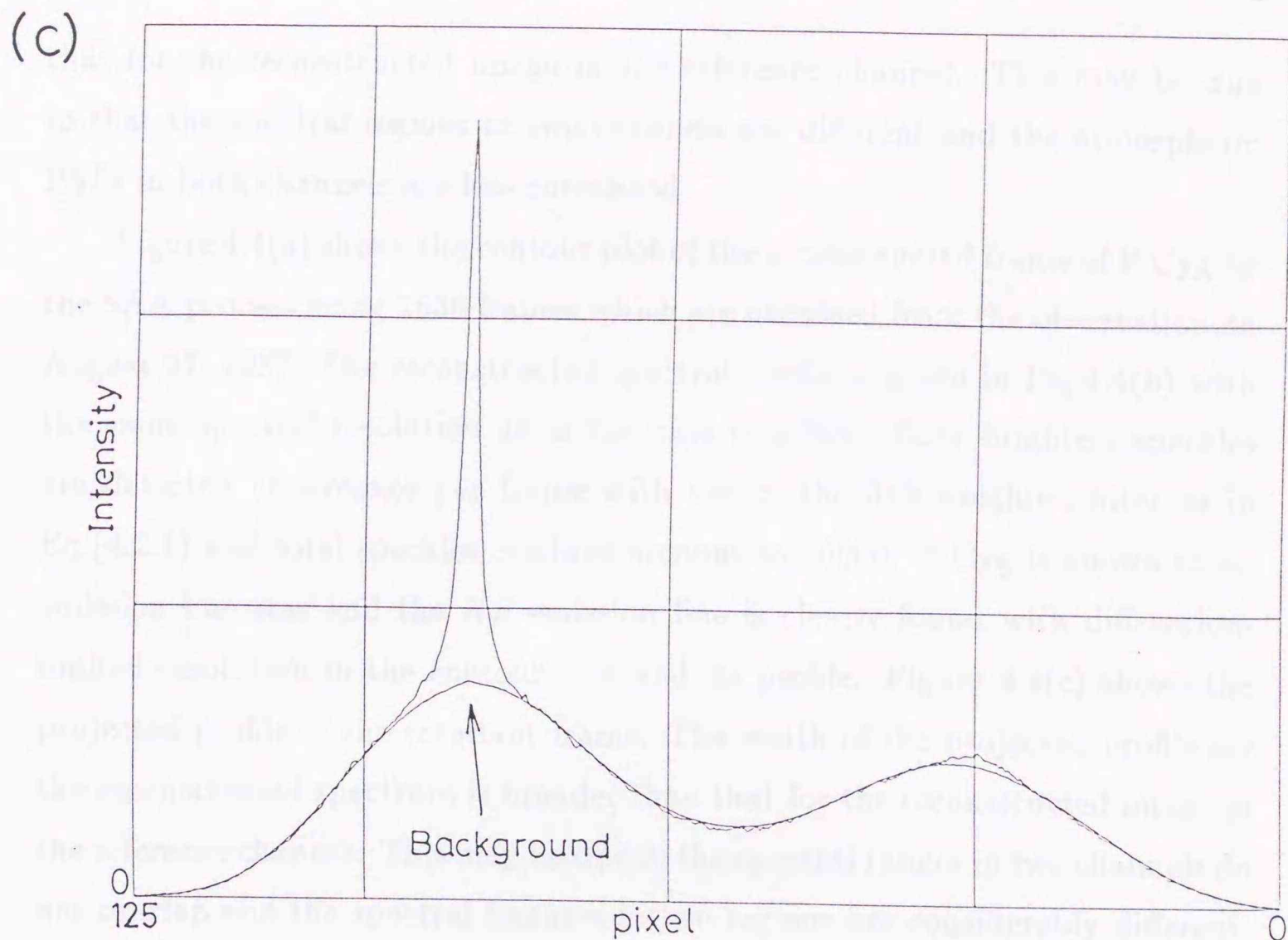


Fig. 4.3 (continued) : (c) Crosscut profile of the raw SAA frame. The left and right sides correspond to the reference channel and the spectral channel, respectively. The profile of the estimated background is also plotted. (d) Projected profile of the background subtracted frame shown in (a). The right and left sides correspond to the reference channel and the spectral channel, respectively.

that for the reconstructed image in the reference channel. This may be due to that the spectral regions in two channels are different and the atmospheric PSFs in both channels are less correlated.

Figure 4.4(a) shows the contour plot of the reconstructed frame of P Cyg by the SAA process using 2636 frames which are obtained from the observation on August 27, 1987. The reconstructed spectral profile is given in Fig.4.4(b) with the same spectral resolution as in the case of ϵ Her. Four brightest speckles are detected on average per frame with use of the 3x3 weighted filter as in Eq.(4.2.1) and total speckles coadded amount to 10000. P Cyg is known as an emission line star and the $H\beta$ emission line is clearly found with diffraction-limited resolution in the contour plot and its profile. Figure 4.4(c) shows the projected profile of the resultant frame. The width of the projected profile for the reconstructed spectrum is broader than that for the reconstructed image in the reference channel. This may be due to the spectral ranges in two channels do not overlap and the spectral features in two regions are considerably different. Those results with the 4m telescope shown so far demonstrate that by present method it is possible to reconstruct the spectral details.

4.3. Speckle Spectroscopic Camera II (SSC2)

The SSC2 is shown in Fig.4.5. The SSC2 also has two optical channels as the SSC1. The beam collimated by lens L0 is divided by a beam-splitter BS into two beams. They are led to the spectral channel and the reference channel, and result in dispersed and nondispersed specklegrams, respectively. As a disperser in the spectral channel, a blazed reflection grating G (600 lines/mm) is used. The advantages to use a reflection grating are that (1) the spectral region is changeable by rotating the grating, (2) uniform dispersion is ensured, and (3) high dispersion spectroscopy may be feasible. The images in the reference and spectral channels are formed by lenses L1 and L2 and detected by two synchronized ICCD TV cameras. The video signals from the two ICCD TV cameras are synthesized and recorded on SVHS video tape. In the new instrument, images through the two channels are electrically combined, while in the former SSC1 the two beams were combined by beam-splitter where energy losses were not avoidable. Moreover, in the new camera, both the ICCD

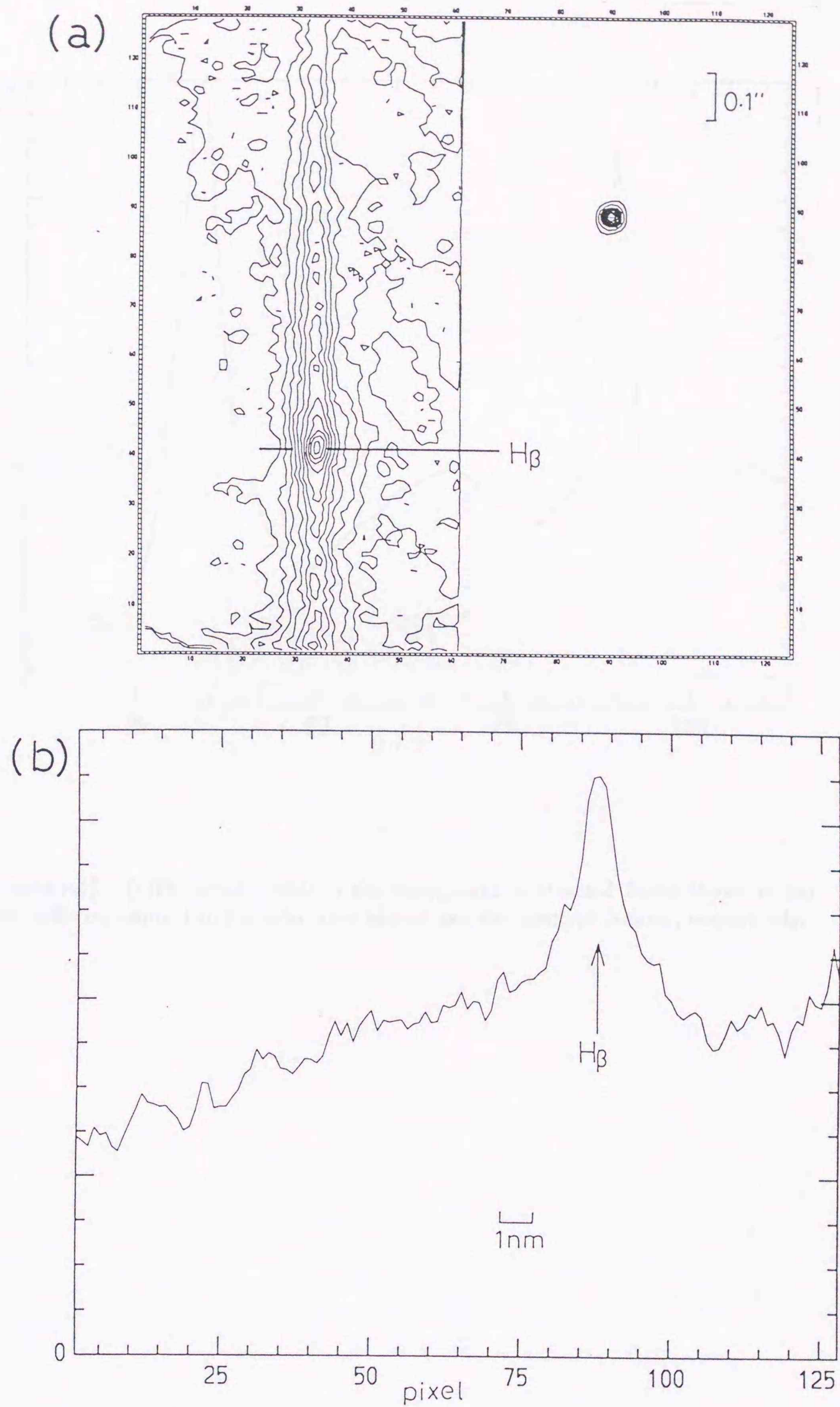


Fig. 4.4 : Result for P Cyg. (a) The reconstructed diffraction-limited image (right) and its spectrum (left) are shown with contour lines, and the emission line of $H\beta$ is indicated. Both are normalized with respect to each maximum value. (b) Profile of the reconstructed spectrum. Four columns of the spectrum in (a) are averaged to obtain the profile.

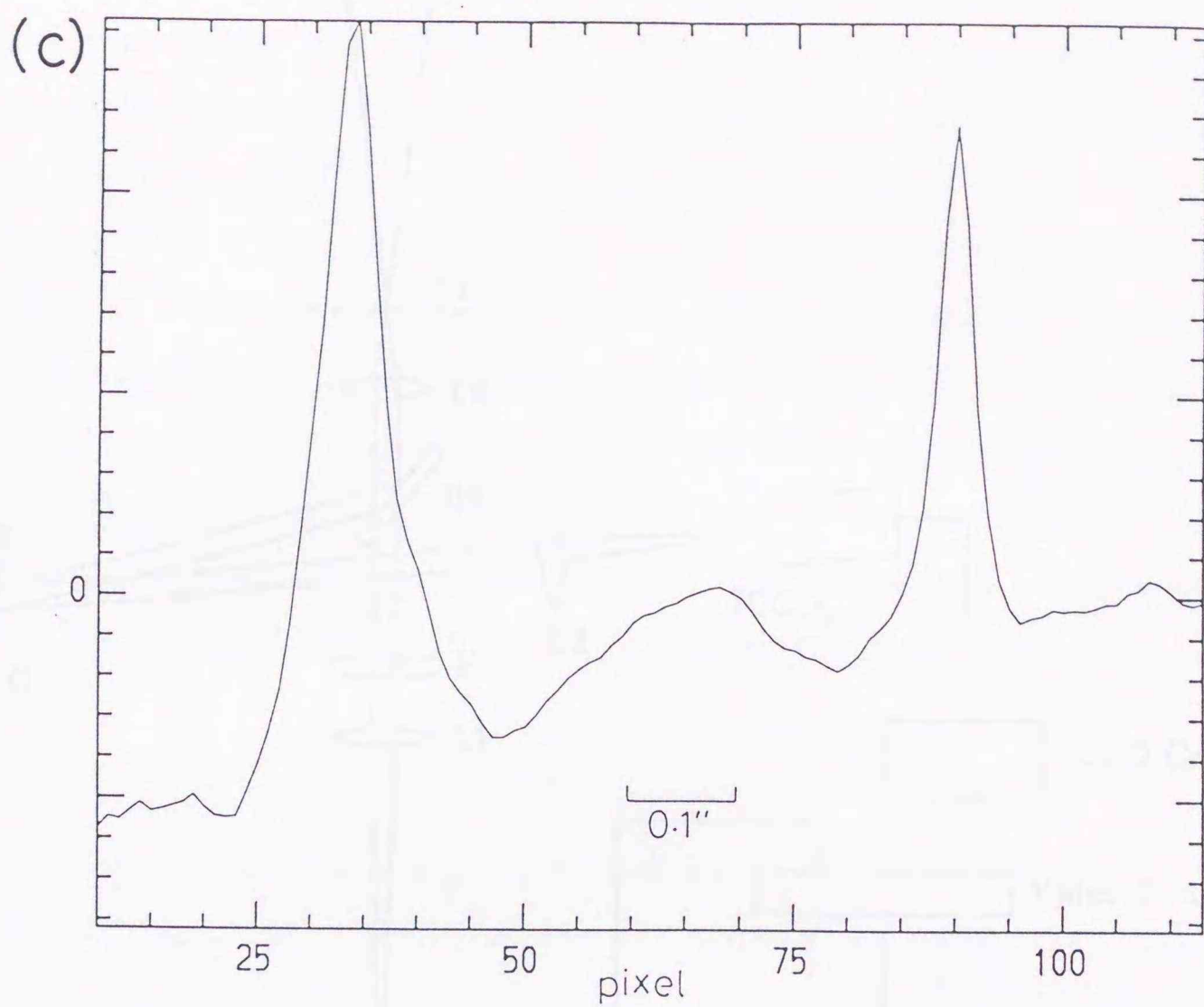


Fig. 4.4 (continued) : (c) Projected profile of the background subtracted frame shown in (a). The right and left sides correspond to the reference channel and the spectral channel, respectively.

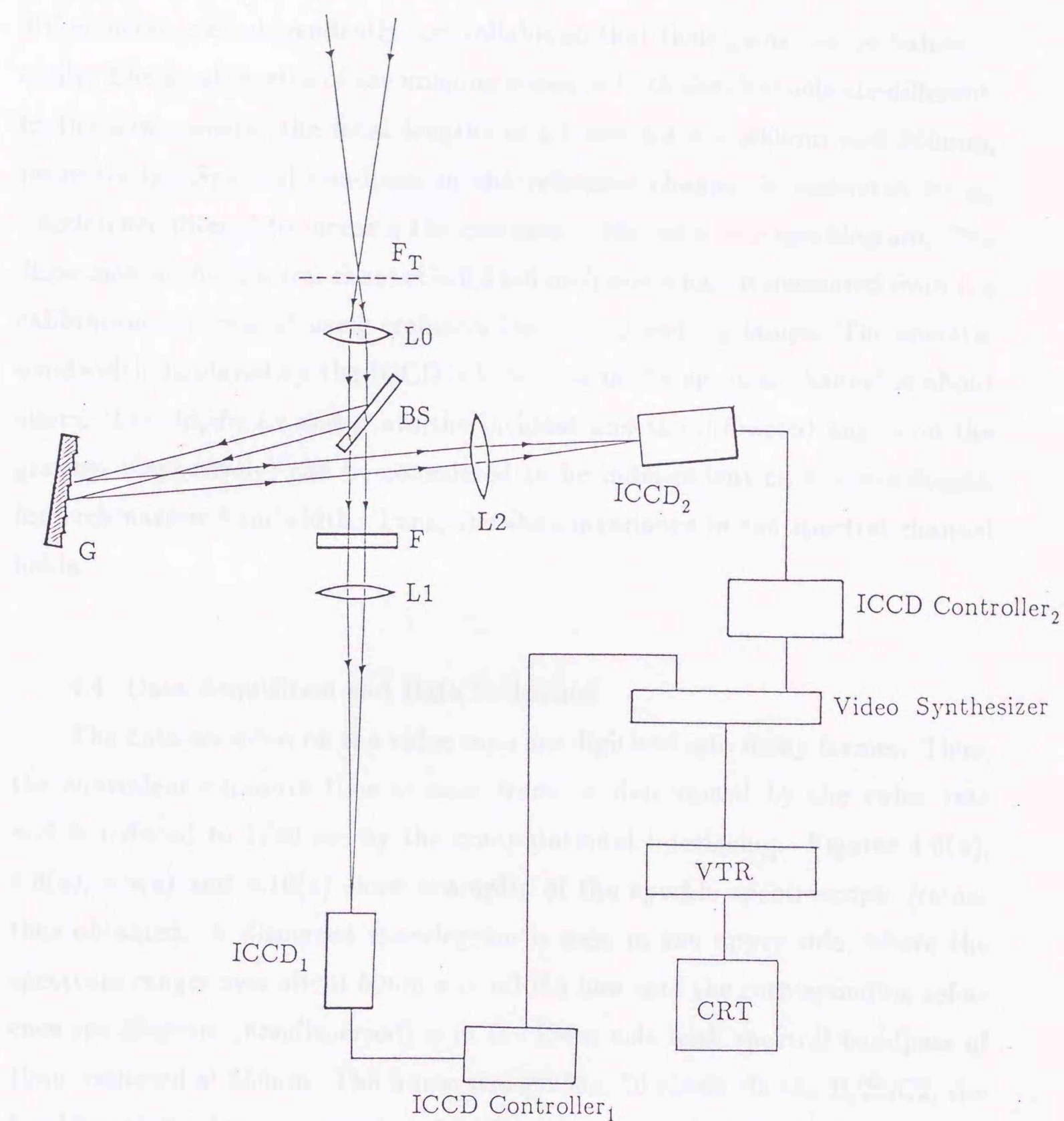


Fig. 4.5 : Layout of revised speckle spectroscopic camera (SSC2). Abbreviations stand for the focal plane of the telescope(F_T), collimator lens(L_0), beam-splitter(BS), grating(G), interference filter(F), imaging lenses(L_1 , L_2). The focal lengths of the lenses L_0 , L_1 and L_2 are 55mm, 300mm and 200mm, respectively. A blazed reflection grating of 600 lines/mm is used as a disperser. The gains of two ICCDs are adjustable separately. The video signals are sent to the video synthesizer. The synthesized signal is recorded by VTR.

TV cameras are independently controllable so that their gains can be balanced easily. The focal lengths of the imaging lenses in both the channels are different. In the new camera, the focal lengths of L1 and L2 are 300mm and 200mm, respectively. Spectral bandpass in the reference channel is restricted by an interference filter F to increase the contrast of the reference specklegram. The dispersion in the spectral channel is 0.2146nm/pixel which is measured from the calibration experiment using emission lines of Cd and Hg lamps. The spectral bandwidth displayed by the ICCD TV camera in the spectral channel is about 50nm. The $d\beta/d\alpha$ (α and β are the incident and the diffracted angles on the grating, respectively) can be considered to be independent on the wavelength for such narrow bandwidth. Thus, the shift invariance in the spectral channel holds.

4.4. Data Acquisition and Data Reduction

The data recorded on the video tape are digitized into many frames. Thus, the equivalent exposure time of each frame is determined by the video rate and is reduced to 1/60 sec by the computational interlacing. Figures 4.6(a), 4.8(a), 4.9(a) and 4.10(a) show examples of the speckle spectroscopic frames thus obtained. A dispersed specklegram is seen in the upper side, where the spectrum ranges over about 50nm around $H\alpha$ line, and the corresponding reference specklegram (nondispersed) is in the lower side with spectral bandpass of 10nm centered at 650nm. The frame size is 256x239 pixels. In the H/SSC2, the focal length f_1 of the imaging lens L1 (Fig.4.5) in the reference channel is longer than that in the spectral channel f_2 because it is critical in the SAA process to locate the speckles accurately and a sufficient magnification is needed for reference specklegrams. The SSC2 is designed so that the α and β are enough small that $d\beta/d\alpha (= \cos \alpha / \cos \beta)$ is nearly constant when the image shifts within the detector size. Since $d\beta/d\alpha$ is not unity, an anamorphic magnification occurs in the spectral channel by $1 : \cos \alpha / \cos \beta$. Such disagreements between the two channels should be corrected when the SAA process is performed. The shifting vector in the spectral channel is related to the one in the reference channel as

$$\begin{bmatrix} \Delta x_s \\ \Delta y_s \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} \Delta x_r \\ \Delta y_r \end{bmatrix}, \quad (4.4.1)$$

where $[\Delta x_s, \Delta y_s]$ and $[\Delta x_r, \Delta y_r]$ are shifting vectors on the spectral and the reference channels, respectively, and the 2x2 matrix represents the magnifying and rotational disalignment. In the cross-correlation method, the image in either channel is remapped according to Eq.(4.4.1) before the cross-correlation is taken between the two channels. The parameters in the matrix were theoretically evaluated from the optical specifications.

As described in Chapter 2, under the isoplanatic and the noise-free assumptions, the reference specklegram and the corresponding dispersed specklegram are properly represented by convolution integrals, provided that the spectral region is sufficiently narrow, e.g., less than 50nm. Thus, the reference specklegram $i_0(x)$ and the dispersed specklegram $d(x)$ are formalized by

$$\begin{aligned} i_0(x) &= o_0(x) * s_0(x), \\ d(x) &= sp(x) * s_0(x) \end{aligned} \quad (4.4.2)$$

or equivalently in terms of the Fourier spectra denoted by the corresponding upper case letters

$$\begin{aligned} I_0(u) &= O_0(u)S_0(u), \\ D(u) &= SP(u)S_0(u), \end{aligned} \quad (4.4.3)$$

where u denotes the 2-D spatial frequency. It is assumed here that the instantaneous PSFs in both the channels are identical except the instrumental disalignments (Eq.(4.4.1)) and the disalignments are corrected. These assumptions are retained in the next two subsections.

4.4.1. SAA Method

The SAA algorithm as described in Chapter 3 is applicable to the data obtained by the SSC2. Then, the diffraction-limited frame can be obtained by subtracting the background frame from the raw SAA frame. In the context of a narrow spectral region centered at λ_0 , the diffraction-limited spectrum can also be derived by a deconvolution from the raw SAA images. When the reference specklegram and the dispersed specklegram in the j th frame are represented by convolutions as Eq.(4.4.2), the raw SAA images $i_{s,a}(x)$ in the reference channel

and $d_{sa}(x)$ in the spectral channel can be described by

$$\begin{aligned} i_{sa}(x) &= \sum_{j=1}^N \sum_{i=1}^{M_j} s_{0j}(x + x_{ji}) * o_0(x), \\ d_{sa}(x) &= \sum_{j=1}^N \sum_{i=1}^{M_j} s_{0j}(x + x_{ji}) * sp(x), \end{aligned} \quad (4.4.4)$$

where N and M_j are the total number of frames and the number of object's replicas to be coadded in the j th frame, respectively, $s_{0j}(x)$ represents the atmosphere-telescope PSF in the j th frame, x_{ji} denotes the location of the i th object's replica in the j th frame and the other notations are the same as Eq.(4.4.2). By the definition of the SAA-PSF

$$s_{sa}(x) = \sum_{j=1}^N \sum_{i=1}^{M_j} s_{0j}(x + x_{ji}), \quad (4.4.5)$$

Eq.(4.4.4) is rewritten as

$$\begin{aligned} i_{sa}(x) &= s_{sa}(x) * o_0(x), \\ d_{sa}(x) &= s_{sa}(x) * sp(x). \end{aligned} \quad (4.4.6)$$

Deconvolution between the raw SAA images $i_{sa}(x)$ and $d_{sa}(x)$ is

$$FT^{-1} \left[\frac{D_{sa}(u)}{I_{sa}(u)} \right], \quad (4.4.7)$$

where $FT^{-1}[\cdot]$ indicates to perform the inverse Fourier transformation. From Eq.(4.4.6), the deconvolution is reduced to

$$FT^{-1} \left[\frac{SP(u)}{O_0(u)} \frac{S_{sa}(u)}{S_{sa}(u)} \right]. \quad (4.4.8)$$

A statistical analysis (Hunt et al. 1983) reveals that the SAA-PSF $s_{sa}(x)$ is governed by the autocorrelation function of the ensemble of specklegrams, of which the Fourier spectrum equals the speckle interferometric modulation transfer function (MTF). The speckle interferometric MTF [i.e., the ensemble average of the power spectra of $s_{0j}(x)$] is known to have definite positive values up to the cutoff frequency of a telescope (Dainty 1975). Thus the deconvolution in Eq.(4.4.8) gives a differential image convolved with the besinc function $J_1(2\pi\rho)/(2\pi\rho)$, namely,

$$FT^{-1} \left[\frac{SP(u)}{O_0(u)} \right] * \frac{J_1(2\pi\rho)}{2\pi\rho}, \quad (4.4.9)$$

where J_1 is the Bessel function of the first kind and the first order (Bracewell 1986), and ρ is the radial distance in the image plane normalized by $\Delta\rho/0.61$ ($\Delta\rho$ is the radius of the first dark ring of the Airy's disc) (Born & Wolf 1980). The besinc function is a result of forcing to be zero outside the cutoff frequency of a telescope. If the diffraction-limited object's image at λ_0

$$o_D(x) = o_0(x) * a_0(x) \quad (4.4.10)$$

has been obtained by another method, where $a_0(x)$ represents the Airy's disc, the diffraction-limited spectrum can be derived by convolving the differential image Eq.(4.4.9) with $o_D(x)$.

4.4.2 Cross-Correlation Technique

The cross-correlation technique employed here has been used in the differential speckle interferometry (DSI) (Beckers 1983; Aime et al. 1986; Hebden et al. 1986a,b; Petrov et al. 1986). In the DSI method, two images of an object $i_1(x)$ and $i_2(x)$, which are observed simultaneously but with slightly different wavelengths (λ_1 and λ_2), are compared by taking a correlation between them. Since the comparison is performed in the speckle mode, the output includes information up to the diffraction-limit of the telescope. The DSI output is represented as

$$FT^{-1} \left[\frac{\langle I_1(u) \bar{I}_2(u) \rangle}{\langle |I_2(u)|^2 \rangle} \right], \quad (4.4.11)$$

where $\bar{}$ and $\langle \rangle$ mean taking complex conjugate and an average with respect to the atmospheric random process, respectively. As $o_1(x)$ and $o_2(x)$ denote the object's appearances at the wavelengths λ_1 and λ_2 , respectively, $i_1(x)$ and $i_2(x)$ are representable by

$$\begin{aligned} i_1(x) &= o_1(x) * s(x), \\ i_2(x) &= o_2(x) * s(x) \end{aligned} \quad (4.4.12)$$

or equivalently

$$\begin{aligned} I_1(u) &= O_1(u)S(u), \\ I_2(u) &= O_2(u)S(u), \end{aligned} \quad (4.4.13)$$

where the atmosphere-telescope PSF $s(x)$ is considered to be identical in both the wavelengths if they are close enough. Substitution of Eq.(4.4.13) into

Eq.(4.4.11) yields

$$FT^{-1} \left[\frac{O_1(u)}{O_2(u)} \frac{\langle |S(u)|^2 \rangle}{\langle |S(u)|^2 \rangle} \right]. \quad (4.4.14)$$

The $\langle |S(u)|^2 \rangle$ is speckle interferometric MTF and is definite inside the cutoff frequency of the telescope. Thus the DSI gives the differential image between two object's appearances convolved with the besinc function

$$FT^{-1} \left[\frac{O_1(u)}{O_2(u)} \right] * \frac{J_1(2\pi\rho)}{2\pi\rho}. \quad (4.4.15)$$

The diffraction-limited image of $o_1(x)$ can be obtained by convolving the differential image with an estimate of the diffraction-limited image of $o_2(x)$ which may be derived by another method. If the one appearance $o_2(x)$ is point-like, the DSI image would be the same as another object's appearance $o_1(x)$ convolved with the besinc function. The astrophysical results with use of the DSI have been reported (e.g., Hebden et al. 1986b). The application of the DSI on the solar polarimetry was made by Kellar et al.(1992a,b) in which narrow band images($S \cdot O_1$) are simultaneously taken with the broader band images ($S \cdot O_2$) and the estimate of the diffraction-limited image of O_2 is obtained by the Labeyrie's technique combined with the Knox-Thompson algorithm.

Those ideas shown above can be applicable to SSC2 data by replacing $I_1(u)$ and $I_2(u)$ with $D(u)$ and $I_0(u)$, respectively. Under the ideal condition such that Eq.(4.4.2) or Eq.(4.4.3) holds, calculation of the deconvolved cross-correlation between the two channels

$$FT^{-1} \left[\frac{\langle D(u) \bar{I}_0(u) \rangle}{\langle |I_0(u)|^2 \rangle} \right] \quad (4.4.16)$$

again yields the differential image as Eq.(4.4.9)

$$FT^{-1} \left[\frac{SP(u)}{O_0(u)} \right] * \frac{J_1(2\pi\rho)}{2\pi\rho}. \quad (4.4.17)$$

If the diffraction-limited object image $o_D(x)$ has been obtained, the diffraction-limited spectrum can be derived by convolving the differential image with $o_D(x)$.

In the analysis with real data, the noise bias appearing in the power spectrum is a dominant error source. Under the assumption that the noises in both the channels are (1)additive, (2)zero mean, (3)uncorrelated each other,

(4) uncorrelated with the object and the atmospheric process, the calculation Eq.(4.4.16) is modified to a filtered version of the differential image [Eq.(4.4.17)]

$$FT^{-1} \left[\frac{SP(u)}{O_0(u)} W(u) \right] * \frac{J_1(2\pi\rho)}{2\pi\rho}, \quad (4.4.18)$$

(Hebden et al. 1986a), in which $W(u)$ has a form

$$W(u) = \frac{|O_0(u)|^2 \langle |S_0(u)|^2 \rangle}{|O_0(u)|^2 \langle |S_0(u)|^2 \rangle + \langle |N(u)|^2 \rangle}, \quad (4.4.19)$$

where $\langle |N(u)|^2 \rangle$ is the noise bias in the reference channel, and $W(u)$ works as a noise suppressing filter (Bates & McDonnell 1986).

4.5. Results of Data Reduction

4.5.1. Single Stars

The speckle spectroscopic data with SSC2 were acquired at the Cassegrain focus of the 188cm telescope in OAO. The digitized data are processed by (1) SAA followed by the background subtraction (SAA/BGS), (2) SAA followed by the deconvolution with the raw SAA image in the reference channel (SAA/DCV), and (3) the cross-correlation method (XC). The SAA/BGS image produced in the reference channel was used as an estimate of the diffraction-limited object's image. In the higher spatial frequencies, the differential image generated by XC or SAA/DCV is unnecessarily emphasized. The convolution with the SAA/BGS object's image suppresses such a high-pass filter effect and ensures the diffraction-limited resolution. In this section, results of two single stars α Per and γ Cas are shown.

(a) α Per

The observation for this object was carried out on Oct. 20, 1992, under the seeing of about 1.7". In Fig.4.6(a), one of the data frames of α Per is shown. The visual magnitude of α Per is about 1.8. The spectral features of α Per (spectral type of F5Ib) reconstructed from 1133 data frames by SAA/BGS, SAA/DCV and XC followed by the convolution with the diffraction-limited object's estimate (XC/CV) are shown in Figs.4.6(b),(c) and (d), respectively. Figures

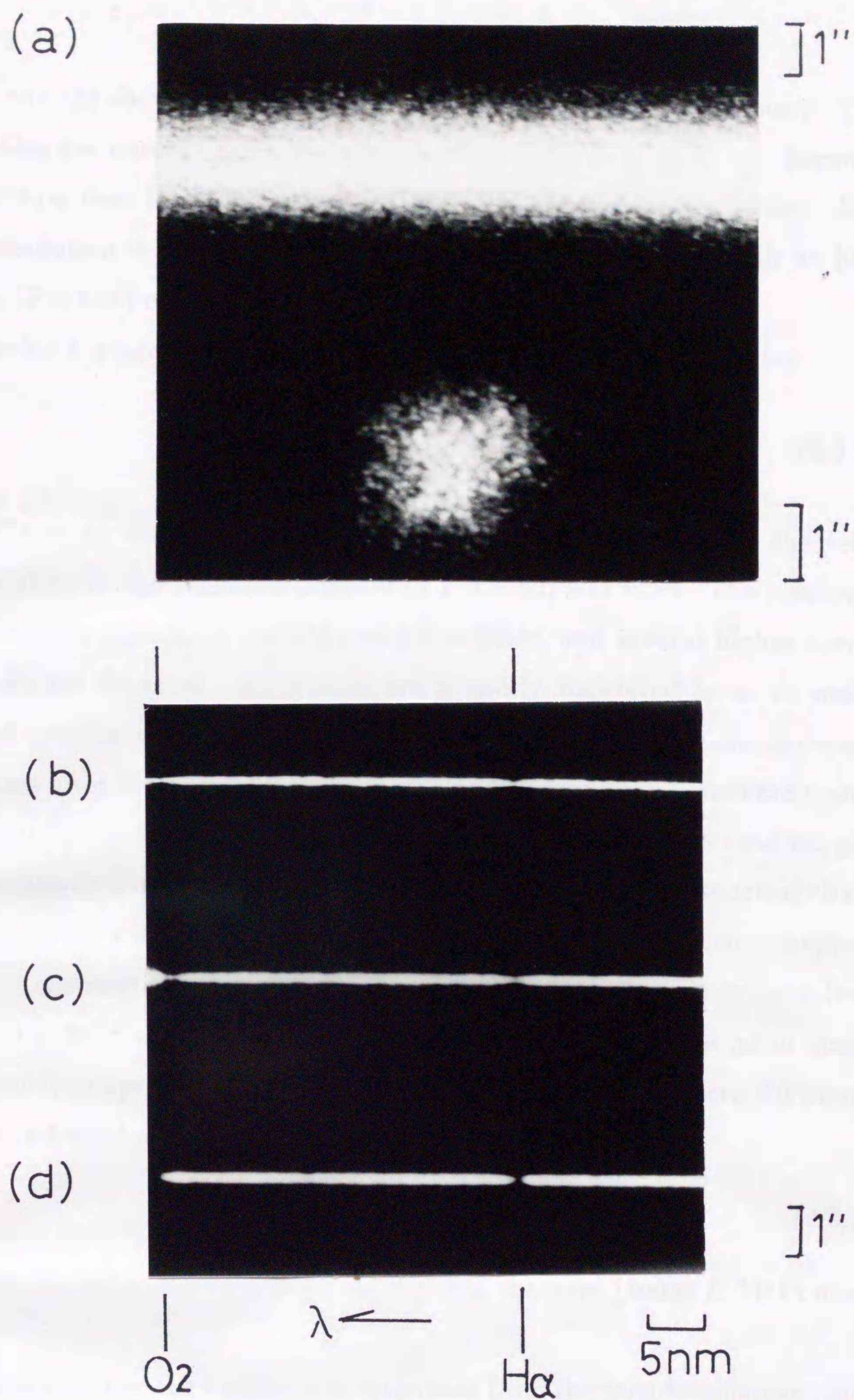


Fig. 4.6 : Results for α Per. (a) One of the SSC2 speckle spectroscopic frames, where the dispersed specklegram (upper) and the narrowband reference specklegram (lower) are displayed. The reference specklegram is imaged with the magnification of 5.5 and the spectral bandwidth of 10nm centered at 650nm. The dispersed specklegram shows the spectral region of about 50nm around H α and the magnification is about 3.6 in the direction perpendicular to the dispersion. The anamorphosis in the spectral channel is 1:0.975 in perpendicular:parallel to the dispersion. (b), (c) and (d) are the spectra reconstructed by SAA/BGS, SAA/DCV with filtering by Eq.(4.5.2), and XC/CV, respectively.

4.6(e),(f) and (g) show the corresponding profiles (averaged over 3 lines). The three profiles are normalized with respect to the $H\alpha$ absorption flux, because the integration over the line profile is insensitive to a convolution noise. The spectral resolution is approximately 0.3nm per theoretical full width at half maximum (FWHM) of the telescope PSF.

In the SAA process, 3x3 pixels matched filter with weighting factor

$$\begin{bmatrix} 0.25 & 0.50 & 0.25 \\ 0.50 & 1.00 & 0.50 \\ 0.25 & 0.50 & 0.25 \end{bmatrix}, \quad (4.5.1)$$

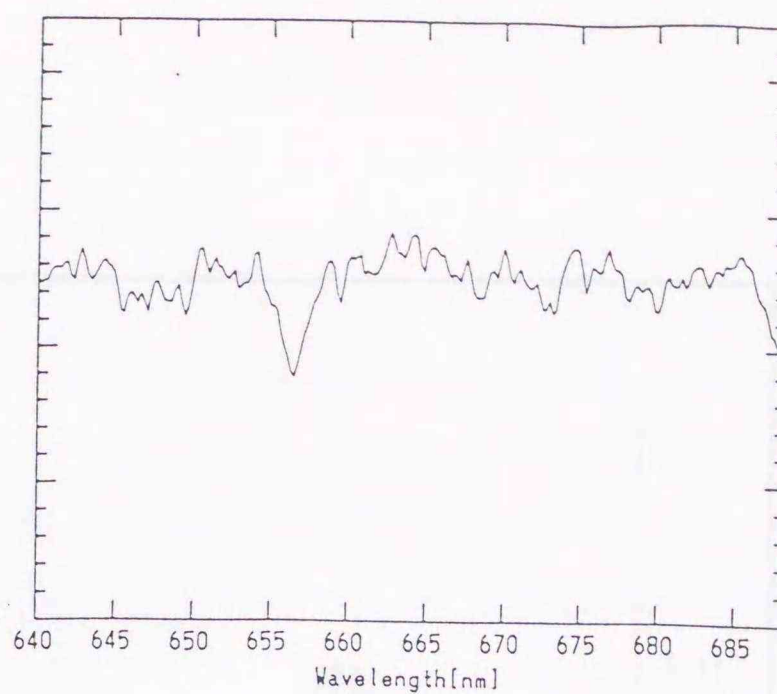
which is Gaussian with the same FWHM as the theoretical PSF of the telescope at 650nm in the reference channel (2.2 pixels), was used. The reference specklegrams are correlated with the matched filter, and several higher correlation peaks are detected. All frames are properly registered so as to make the located speckles coadd. Those operations are also applied on the dispersed specklegrams after the shifting vectors found in the reference channel are transformed according to Eq.(4.4.1) in Sec.4.4. The number of speckles coadded per frame was nine on average. The raw SAA image obtained in the spectral channel is deconvolved with that in the reference channel which has been remapped according to the relation of Eq.(4.4.1). The SAA/DCV result was not convolved with the SAA/BGS object's image, because the filtering with the latter could not sufficiently suppress the several poles produced by nearly zero divisions. Instead, we adopted a filter

$$\frac{|I_{sa}(u)|^2}{|I_{sa}(u)|^2 + \Phi} \quad (4.5.2)$$

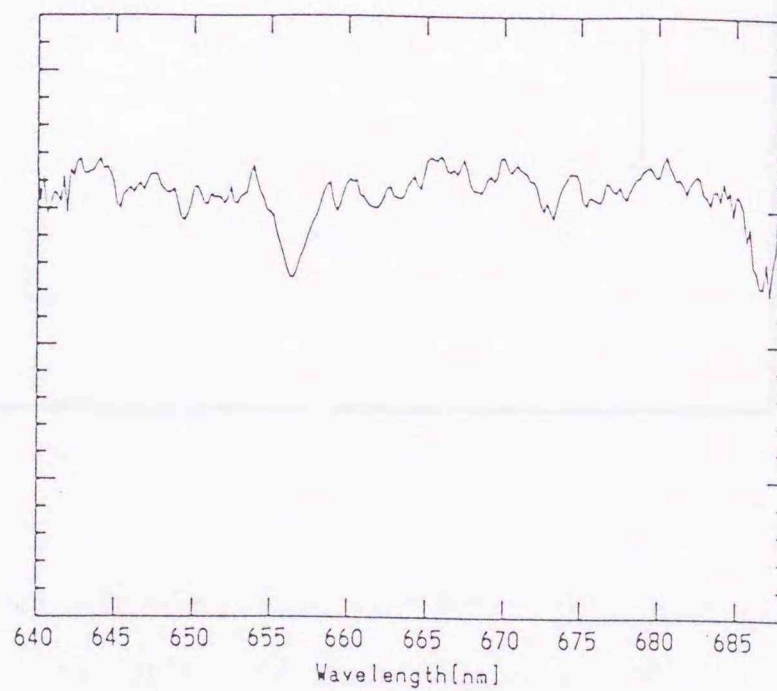
to eliminate the poles, where Φ is an appropriate constant (Bates & McDonnell 1986).

At the same time, the background estimated from the pseudo-long-exposure frame is subtracted from the raw SAA image in the respective channels. Figure 4.6(h) shows the SAA/BGS image in the reference channel and its FWHM is comparable to the theoretical one of 0.07" at the wavelength of 650nm. On the other hand, the cross-correlation is taken between the spectral specklegrams and the remapped versions of the reference specklegrams to generate a XC image. The subsequent convolution with the SAA/BGS image in Fig.4.6(h) suppresses the noisy structures seen in the XC image.

(e)



(f)



(g)

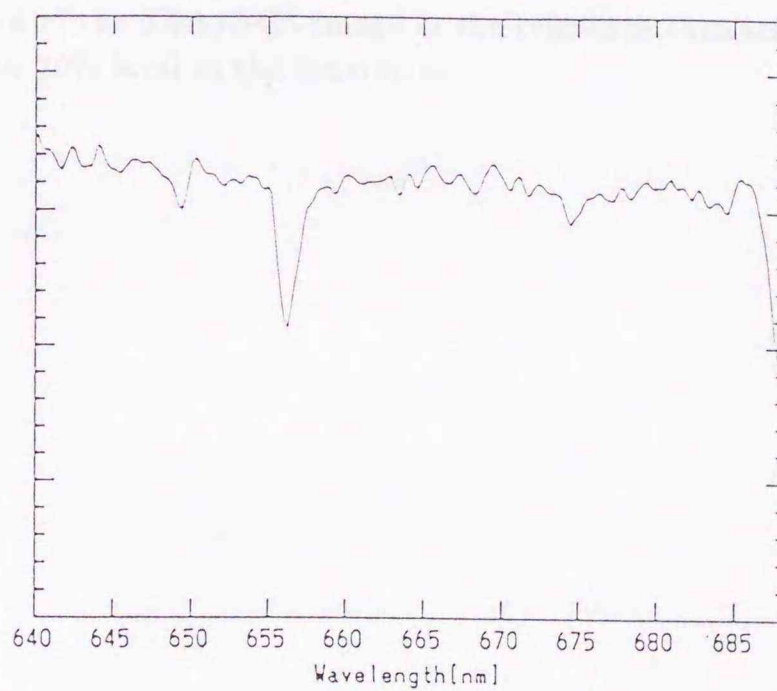


Fig. 4.6 (continued) : The profiles(averaged over 3 lines) corresponding to (b)-(d) are shown in (e)-(g), respectively. In (e)-(g), the abscissa is converted into the wavelength[nm].

(h)

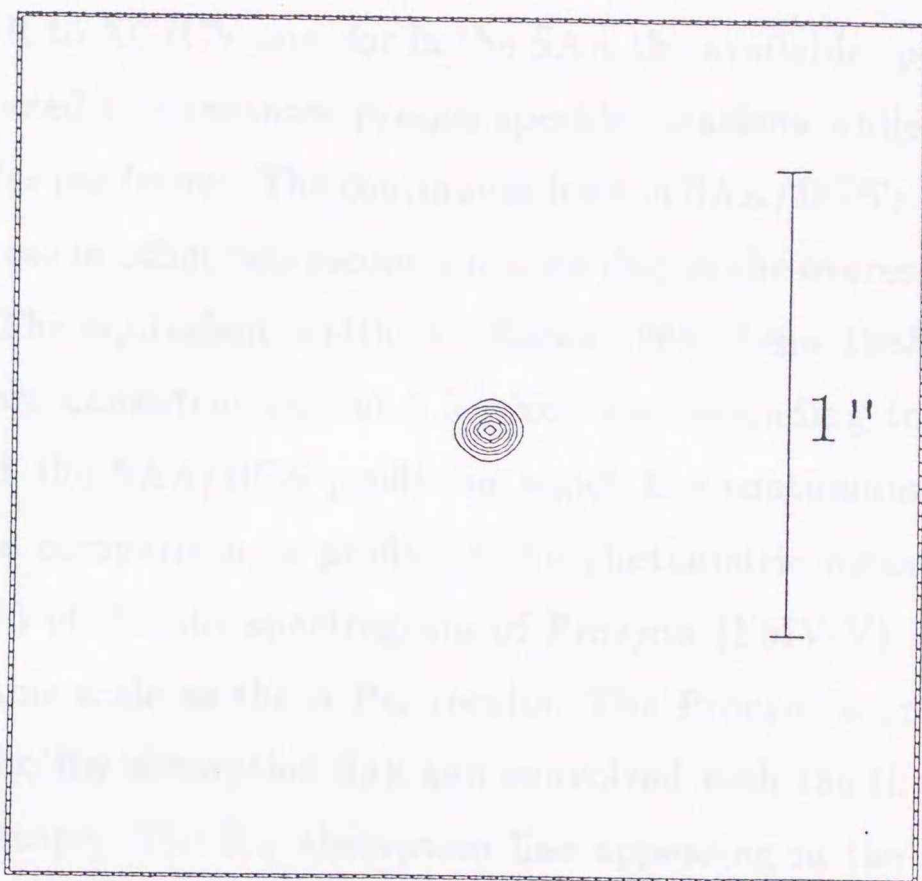


Fig. 4.6 (continued) : A contour plot of the SAA/BGS image in the reference channel is shown in (h) with 6 contour lines plotted down to 20% level of the maximum.

As expected in the spectral profiles shown in Figs.4.6(e)-(g), $H\alpha$ absorption line is clearly resolved in all the three reconstructions. The SAA reconstructions appear inferior in SNR to XC/CV one, for in the SAA the available speckles to be coadded are restricted to guarantee precise speckle locations while the XC includes all the speckles per frame. The continuum level in SAA/BGS's profile is slightly lower than those in other two reconstructions due to the overestimation of the background. The equivalent widths (Jefferies 1968; Léna 1988) of the $H\alpha$ absorption line are consistent (about 2.5 pixels corresponding to 0.5nm) in two profiles except the SAA/BGS profile in which the continuum level is underestimated. As a comparison, a profile of the photometric measurement (R. & R. Griffin 1979) of the slit spectrogram of Procyon (F5IV-V) is shown in Fig.4.7 with the same scale as the α Per results. The Procyon's profile has been normalized by the $H\alpha$ absorption flux and convolved with the theoretical PSF of the 1.8m telescope. The $H\alpha$ absorption line appearing in the XC/CV profile is shown to be fairly consistent with that in the Procyon's profile. The FeI+BaII blended absorption (Swensson 1946) around 649.6nm seen in Fig.4.7 is consistently reconstructed in Figs.4.6(e)-(g). The large dip which is evident for all the profiles in the marginal part corresponding to $\lambda > 686.7\text{nm}$ is the O_2 (oxygen) absorption by the earth's atmosphere, though such a marginal part of a frame is degraded due to a break of the convolution relationship and/or the fewer number of pixels integrated by the SAA process. In Fig.4.6(g), a dip for $674.5 \pm 0.5\text{nm}$ is seen, but that is not consistent in the Procyon's profile and the other reconstructed profiles.

The reconstructed spectra are affected by low pass filtering so that they are slightly spread. Such a low pass filtering effect can be caused by the noise bias as mentioned in Sec.4.4, the residual scale discrepancy between two channels, and the convolution with the SAA object image which may contain the residual background.

(b) γ Cas

The observation for this object was carried out on the same date as α Per. In Fig.4.8(a), one of the data frames of γ Cas is shown. The reconstructed spectra by SAA/BGS, SAA/DCV followed by the filtering of Eq.(4.5.2), and

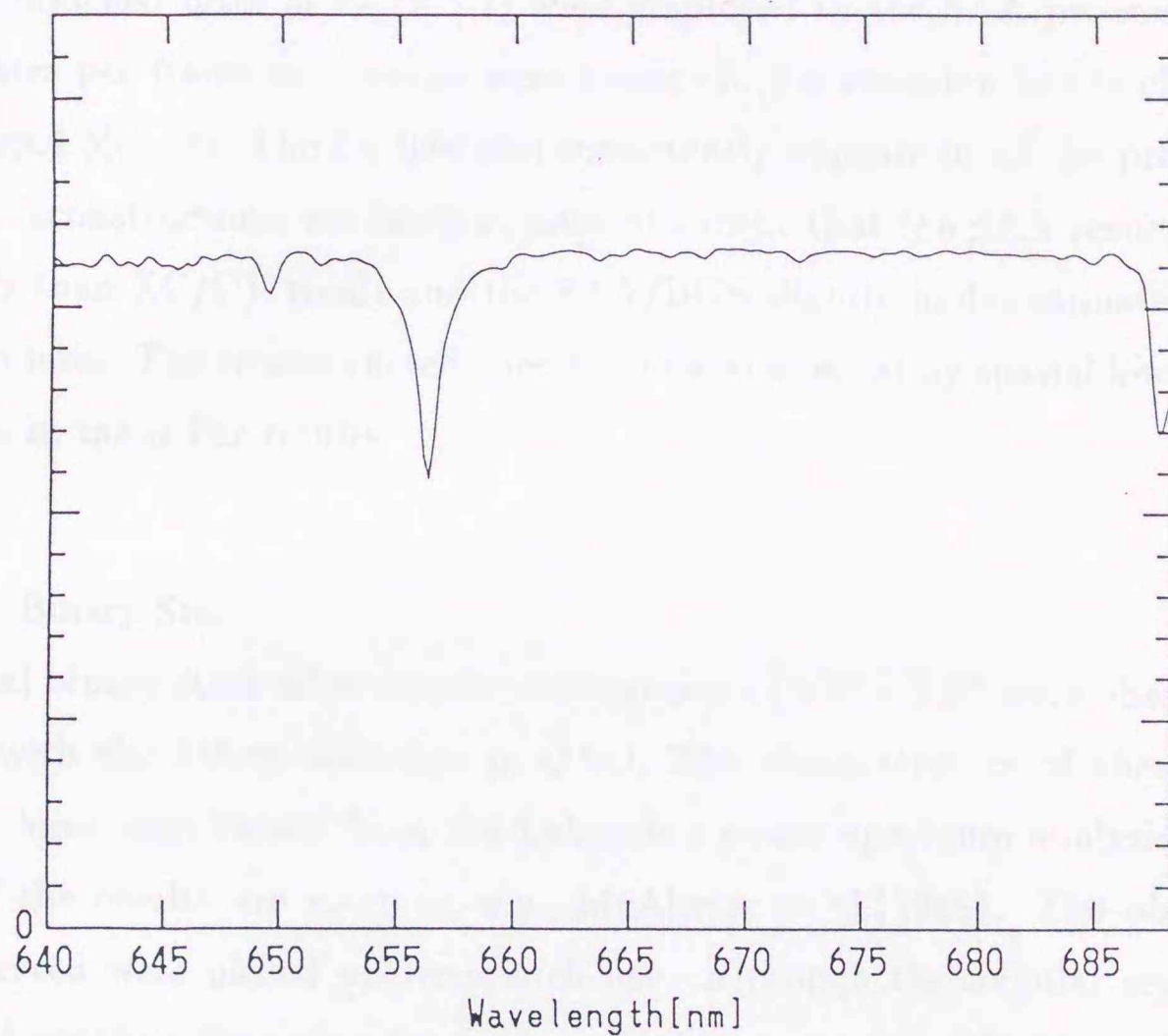


Fig. 4.7 : Profile of Procyon's spectrum based on the photometric measurement by R. & R. Griffin(1979). The wavelength scale is adjusted to α Per data and the theoretical PSF of the telescope is convolved.

XC/CV are shown in Figs.4.8(b), (c) and (d) with their profiles in Figs.4.8(e),(f) and (g), respectively. They are obtained from 1049 frames. The profiles in Figs.4.8(e)-(g) are normalized with respect to the intensity of the $H\alpha$ emission line. The matched filter of Eq.(4.5.1) were employed in the SAA process and nine speckles per frame on average were coadded. $H\alpha$ emission line is clearly seen in Figs.4.8(e)-(g). The O_2 line also consistently appears in all the profiles. The three reconstructions are fairly consistent except that the SAA results are more noisy than XC/CV result and the SAA/BGS slightly underestimates the continuum level. The reconstructed spectra are also affected by spatial low pass filtering as in the α Per results.

4.5.2. Binary Star

Several binary stars with angular separations of $0.3'' - 0.8''$ were observed by SSC2 with the 188cm-telescope in OAO. The characteristics of these binary stars have been known from the Labeyrie's power spectrum analysis and the list of the results are given in, e.g., McAlister et al.(1988). The objects to be observed were picked up from such list. Although the angular separations are closer than the seeing-limit, those double stars are resolvable with the diffraction-limited resolution of the 188cm telescope($0.07''$). The visual magnitudes of the observed double stars were rather faint, more than 4. To gain the sufficient SNR, several thousands frames are needed. The SAA/BGS, XC/CV and SAA/DCV/CV scheme are employed in the data processing. The objects which are characterized by the position angle and the intensity ratio between the two stars were estimated from the SAA/BGS image produced in the reference channel. In this section, results for a binary star ADS12973 are given. The data are taken in two different position angles of the instrument and the results are presented for two cases, respectively.

ADS12973

The observation was conducted on Aug. 31, 1993, with the seeing condition of about $1''$. The composite visual magnitude of this binary is 5.04. Fig.4.9(a) shows one of the digitized data frame obtained in that observa-

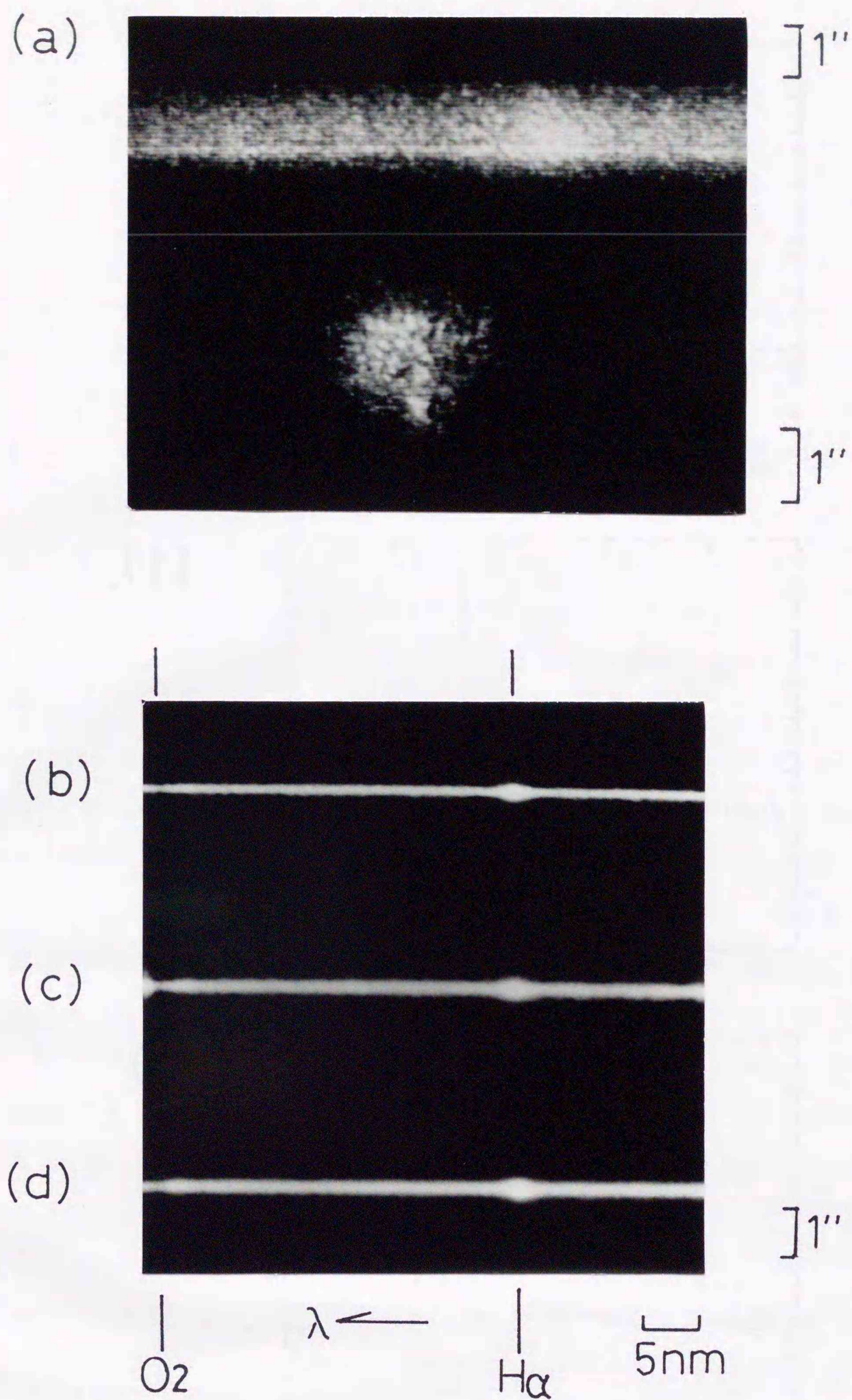
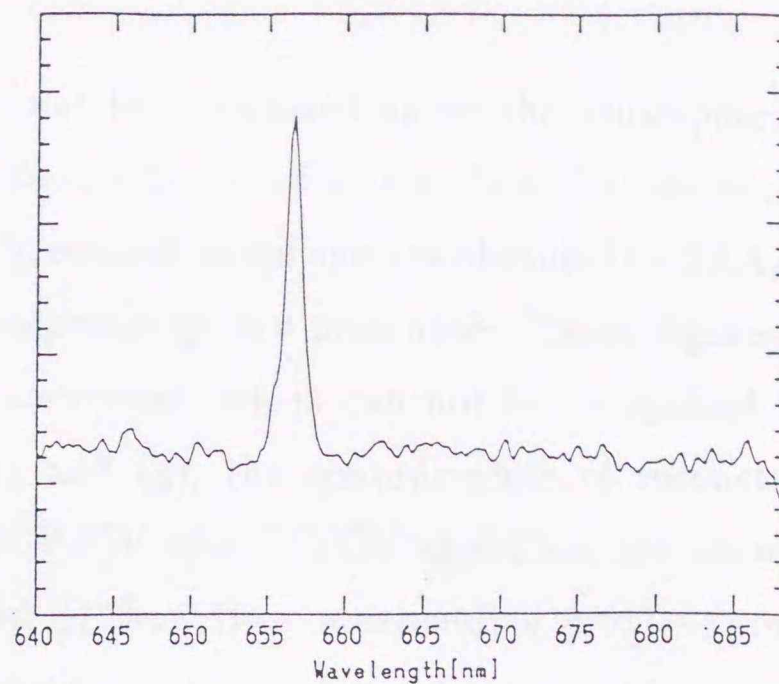
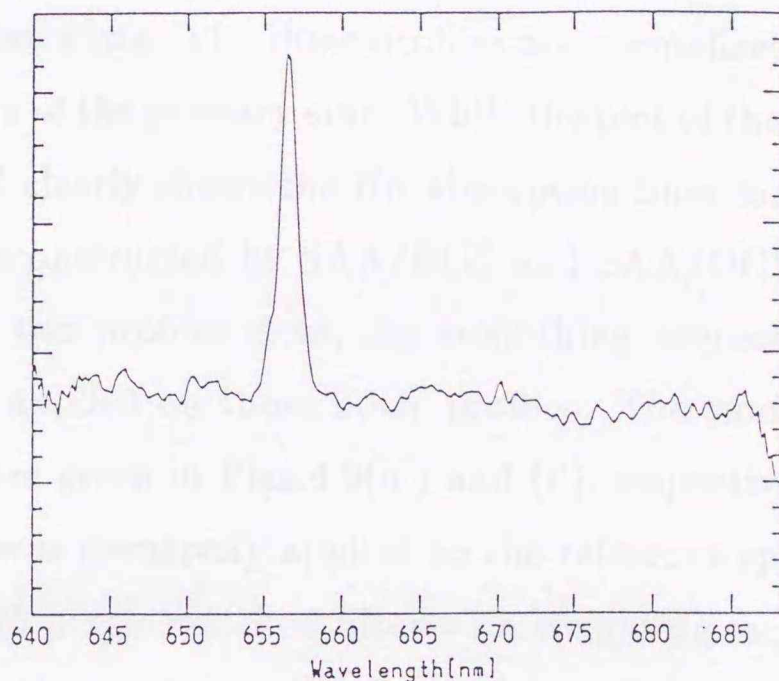


Fig. 4.8 : Results for γ Cas. (a) One of the SSC2 speckle spectroscopic frames, where the dispersed specklegram (upper) and the narrowband reference specklegram (lower) are displayed. (b), (c) and (d) are the spectra reconstructed by SAA/BGS, SAA/DCV with filtering by Eq.(4.5.2), and XC/CV, respectively.

(e)



(f)



(g)

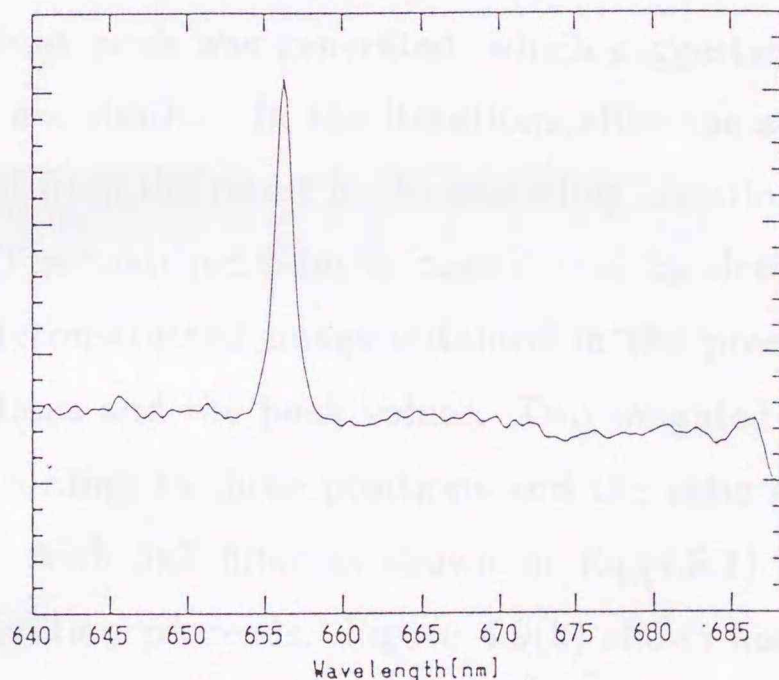


Fig. 4.8 (continued) : The profiles(averaged over 3 lines) corresponding to (b)-(d) are shown in (e)-(g), respectively. In (e)-(g), the abscissa is converted into the wavelength[nm].

tion. The double structure can not be recognized under the atmospheric turbulence. To reconstruct the diffraction-limited frame, 5130 frames were processed. In Figs.4.9(b),(c) and (d), reconstructed spectra obtained by SAA/BGS, SAA/DCV/CV and XC/CV, respectively, are presented. Those figures show that the $H\alpha$ line is clearly reconstructed, which can not be recognized in the speckle data. In Figs.4.9(e),(f) and (g), the contour plots of reconstructed spectra by SAA/BGS, SAA/DCV/CV and XC/CV algorithm are shown, respectively. Figures 4.9(h),(i) and (j) show the corresponding profiles (averaged over 3 lines) to the respective algorithms. On each graph, two profiles are drawn for the primary and the secondary stars. The three profiles are normalized with respect to the $H\alpha$ absorption flux of the primary star. While the plot of the spectral profile obtained by XC/CV clearly shows the $H\alpha$ absorption lines for both component stars, the profiles reconstructed by SAA/BGS and SAA/DCV/CV are very noisy. To make those two profiles clear, the smoothing process with the window size of 10 pixels is applied on those noisy profiles. The smoothed profiles for Figs.4.9(h) and (i) are given in Figs.4.9(h') and (i'), respectively.

The SAA/BGS algorithm was iteratively applied to the reference specklegrams. As the first iteration, 3×3 pixels matched filter with weighting factor of Eq.(4.5.1) is used for detecting the single brightest speckle per frame. In the result of the first iteration, a ghost peak was generated, which suggested that the intensities of the two stars are similar. In the iterations after the second one, the matched filter is derived from the result in the preceding iteration and is updated in every iteration. The matched filter is constructed by detecting the two brighter peaks in the reconstructed image obtained in the preceding iteration and finding their positions and the peak values. Two weighted delta functions are then produced according to those positions and the ratio of the peak values, and are convolved with 3×3 filter as shown in Eq.(4.5.1). The SAA image converges as the iteration proceeds. Figure 4.9(k) shows how the intensity ratio of the reconstructed double star converges as the iteration proceeds. The convergence is smooth and the intensity ratio reaches an estimate of 1:0.73. In Fig. 4.9(l), the final reconstructed image by the iterative SAA/BGS is shown. The dispersion is taken in the horizontal direction. A binary image is clearly obtained with nearly diffraction-limited resolution. As a reference for

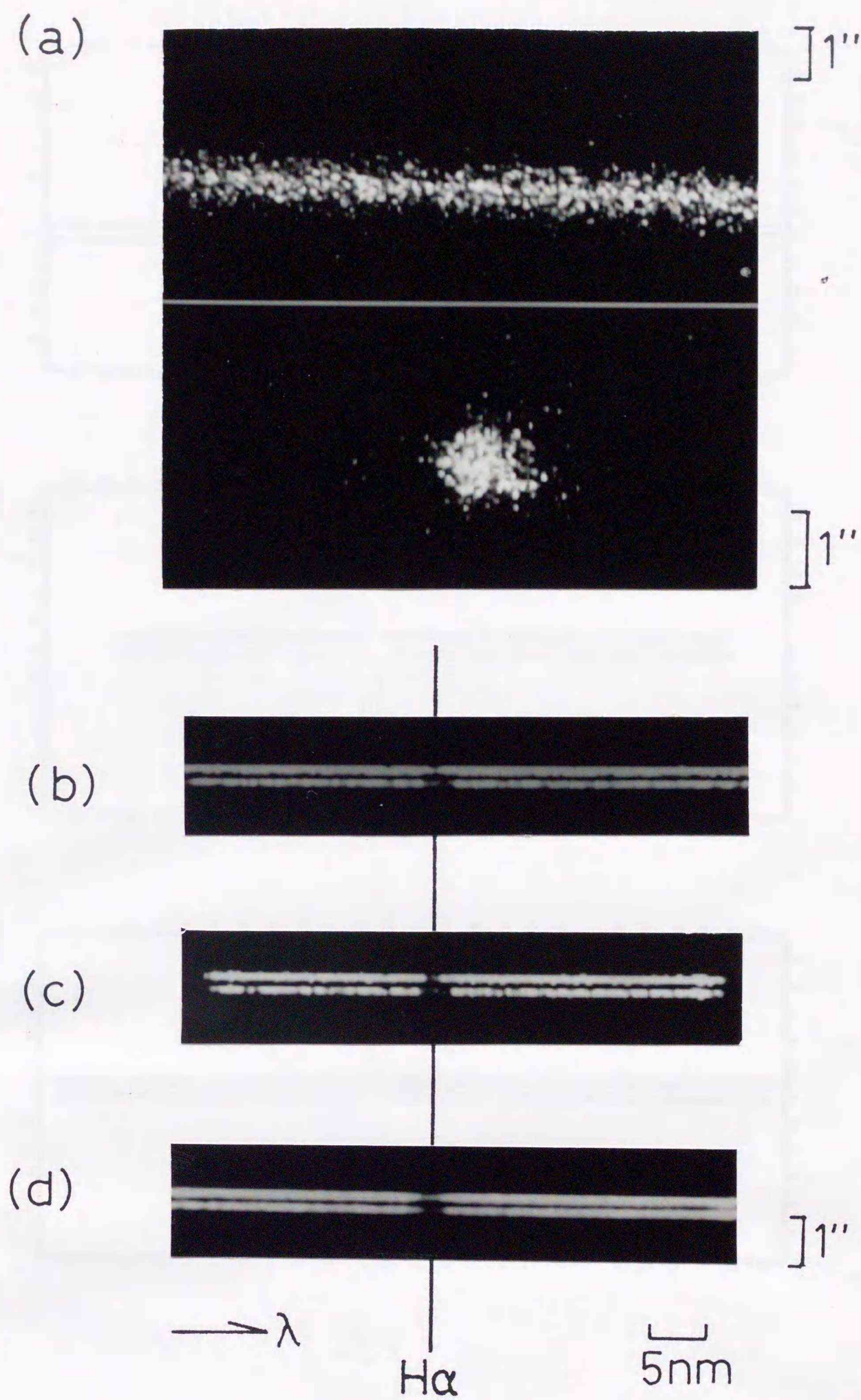


Fig. 4.9 : Results for ADS12973. In (a), one of the SSC2 speckle spectroscopic frames is shown, where the dispersed specklegram(upper) and the narrowband reference specklegram(lower) are displayed. (b),(c) and (d) are the spectra reconstructed by SAA/BGS, SAA/DCV/CV and XC/CV, respectively.

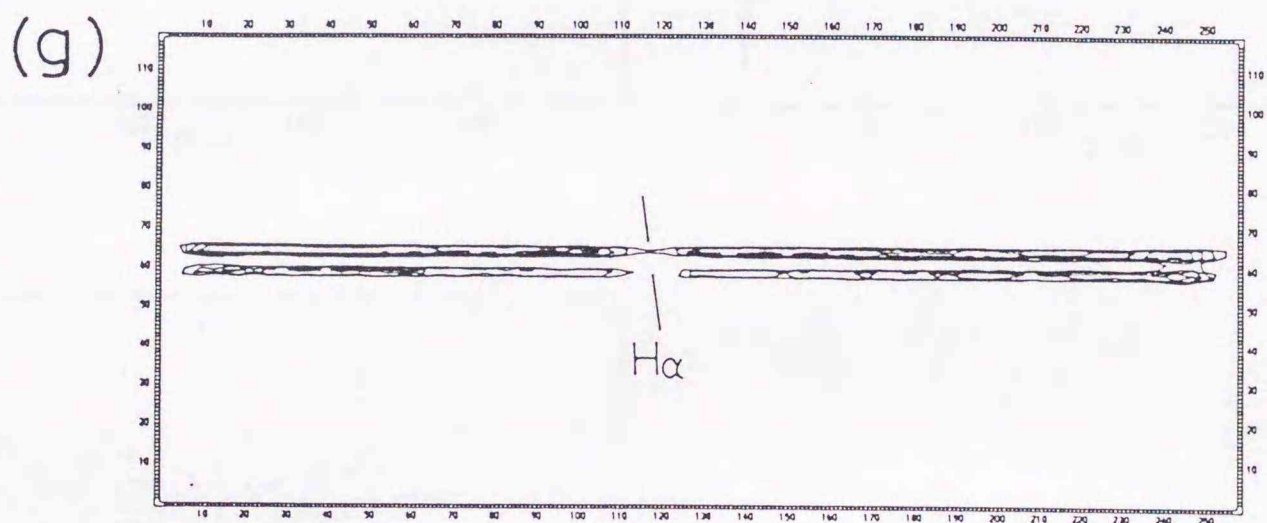
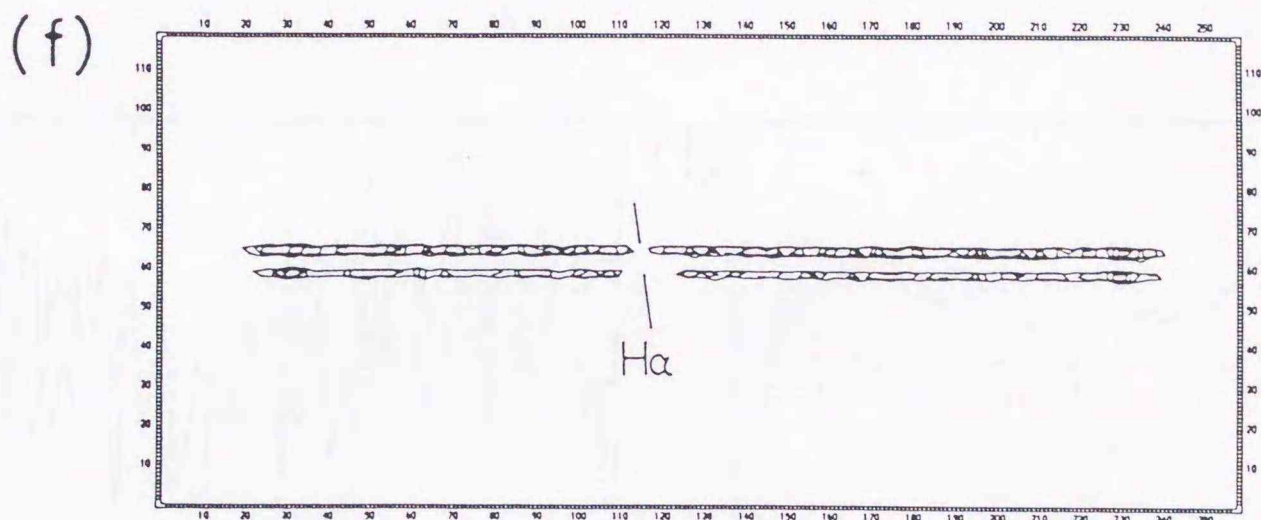
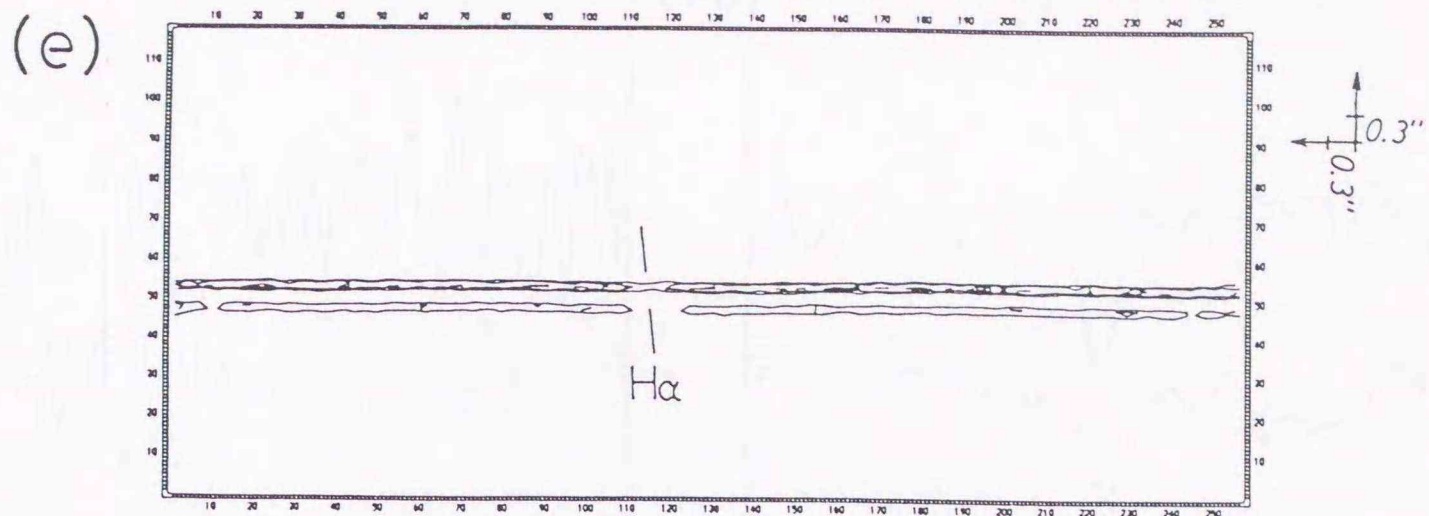


Fig. 4.9 (continued) : (e)-(g) are contour plots corresponding to (b)-(d). The truncation seen in the SAA/DCV/CV spectrum (f) is a trace of the apodization carried out in the deconvolution process.

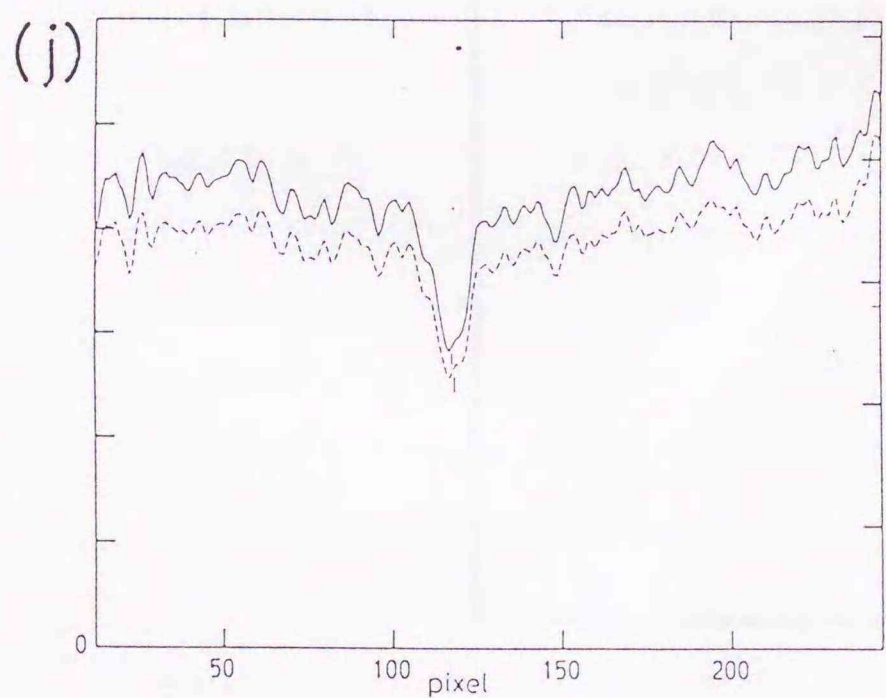
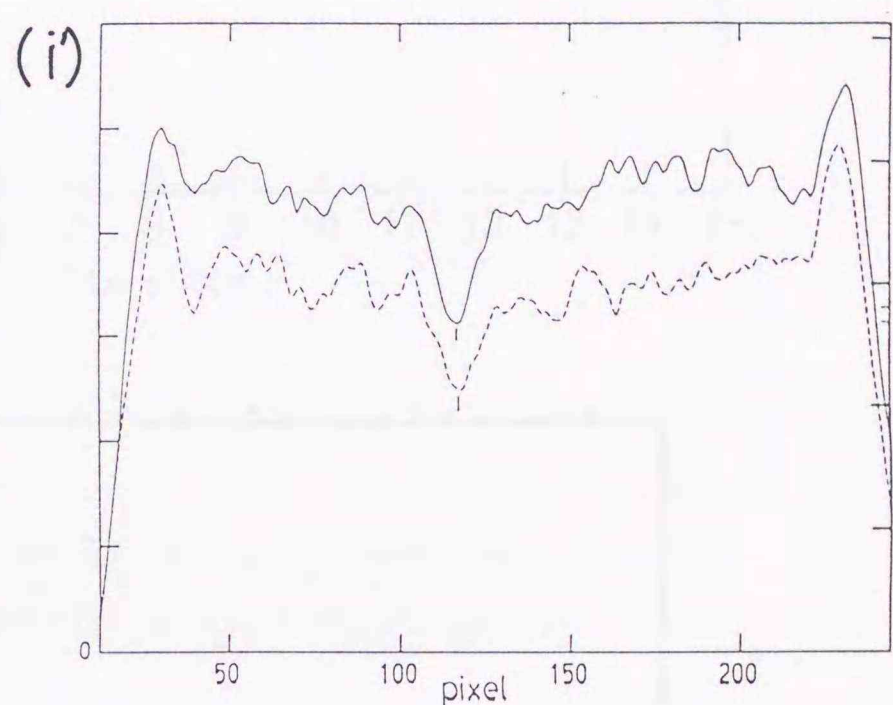
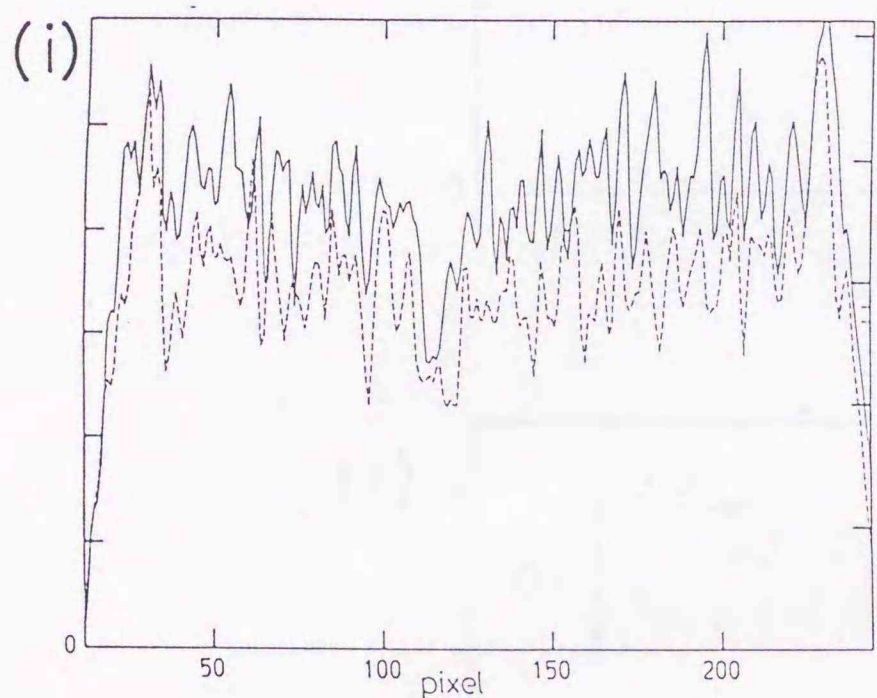
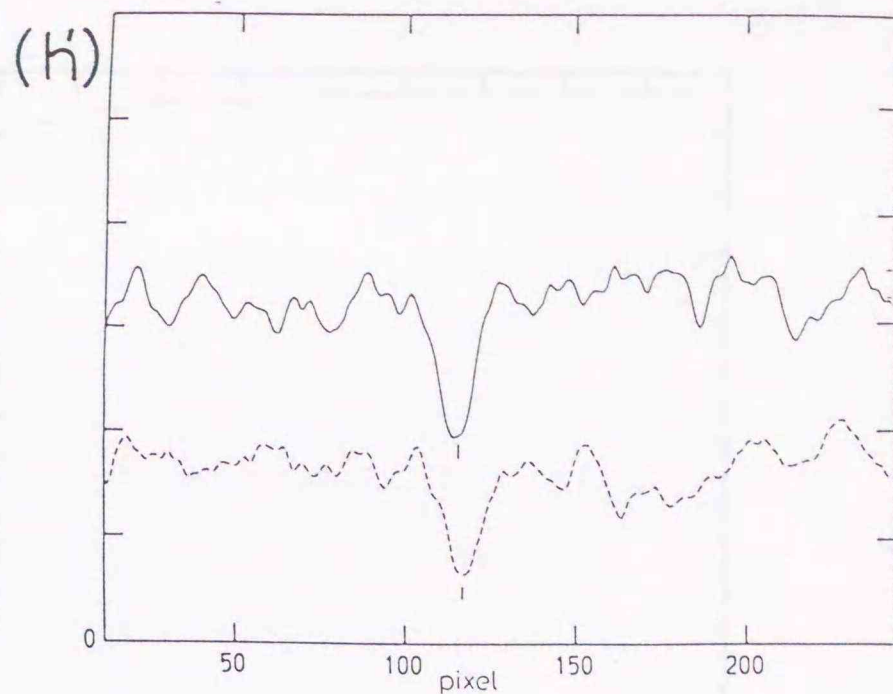
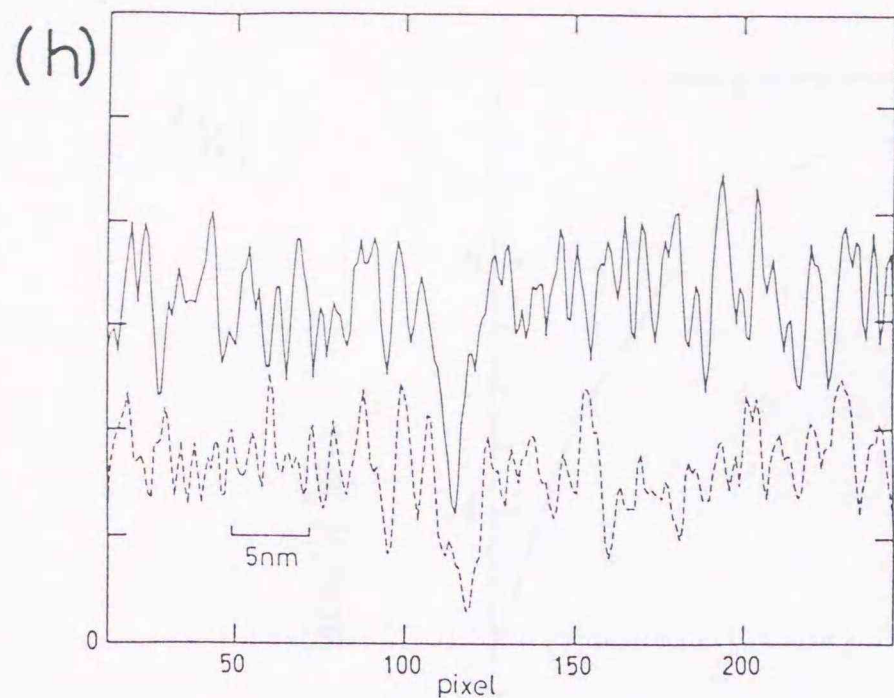


Fig. 4.9 (continued) : The spectral profiles(averaged over 3 lines) reconstructed by SAA/BGS, SAA/DCV/CV and XC/CV, respectively, are shown in (h)-(j). In each of (h)-(j), two profiles for the primary star(solid line) and the secondary star(dashed line) are plotted. The noisy profiles on (h) and (i) are smoothed by 10-pixels window to produce clear profile (h') and (i'), respectively.

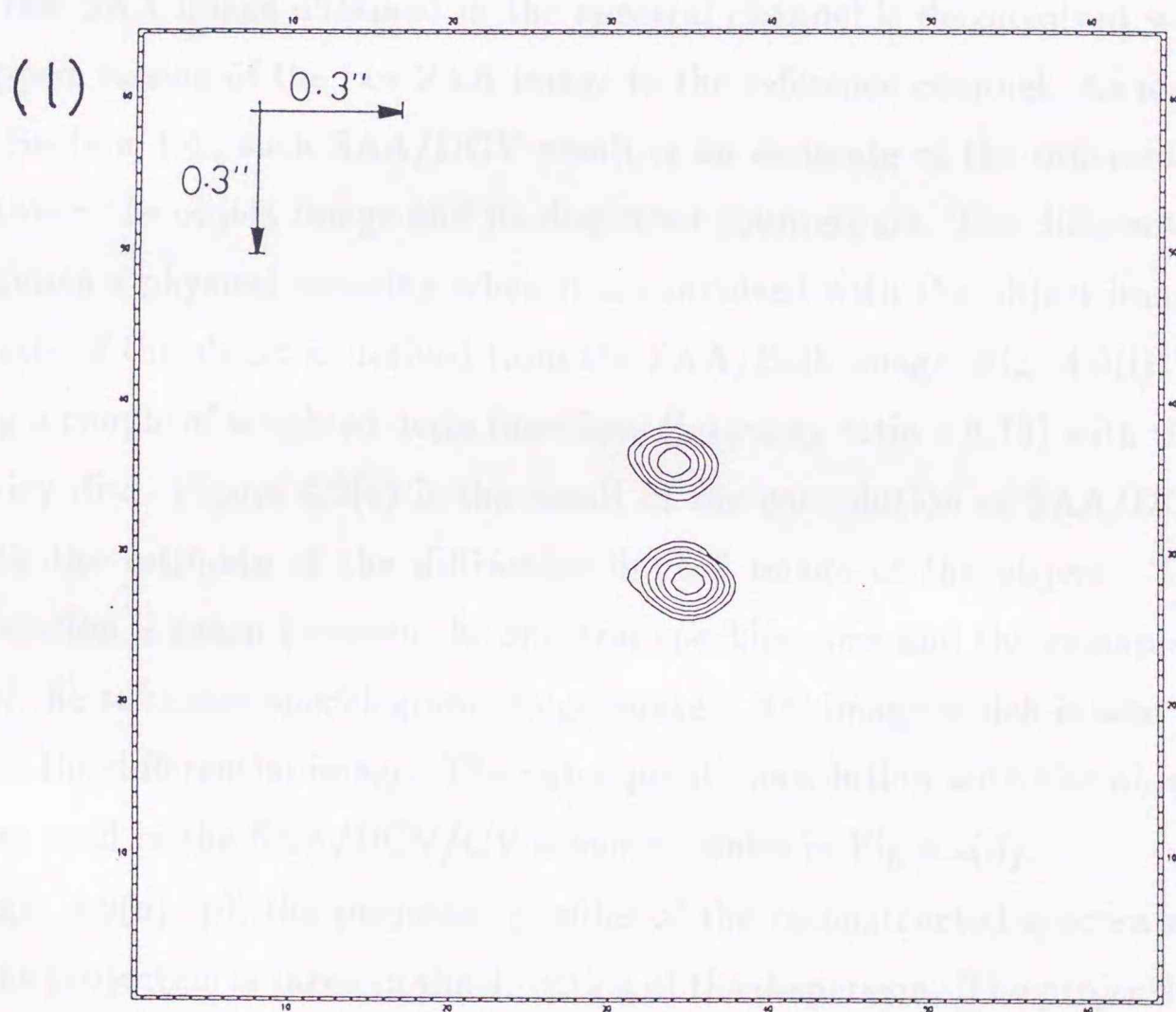
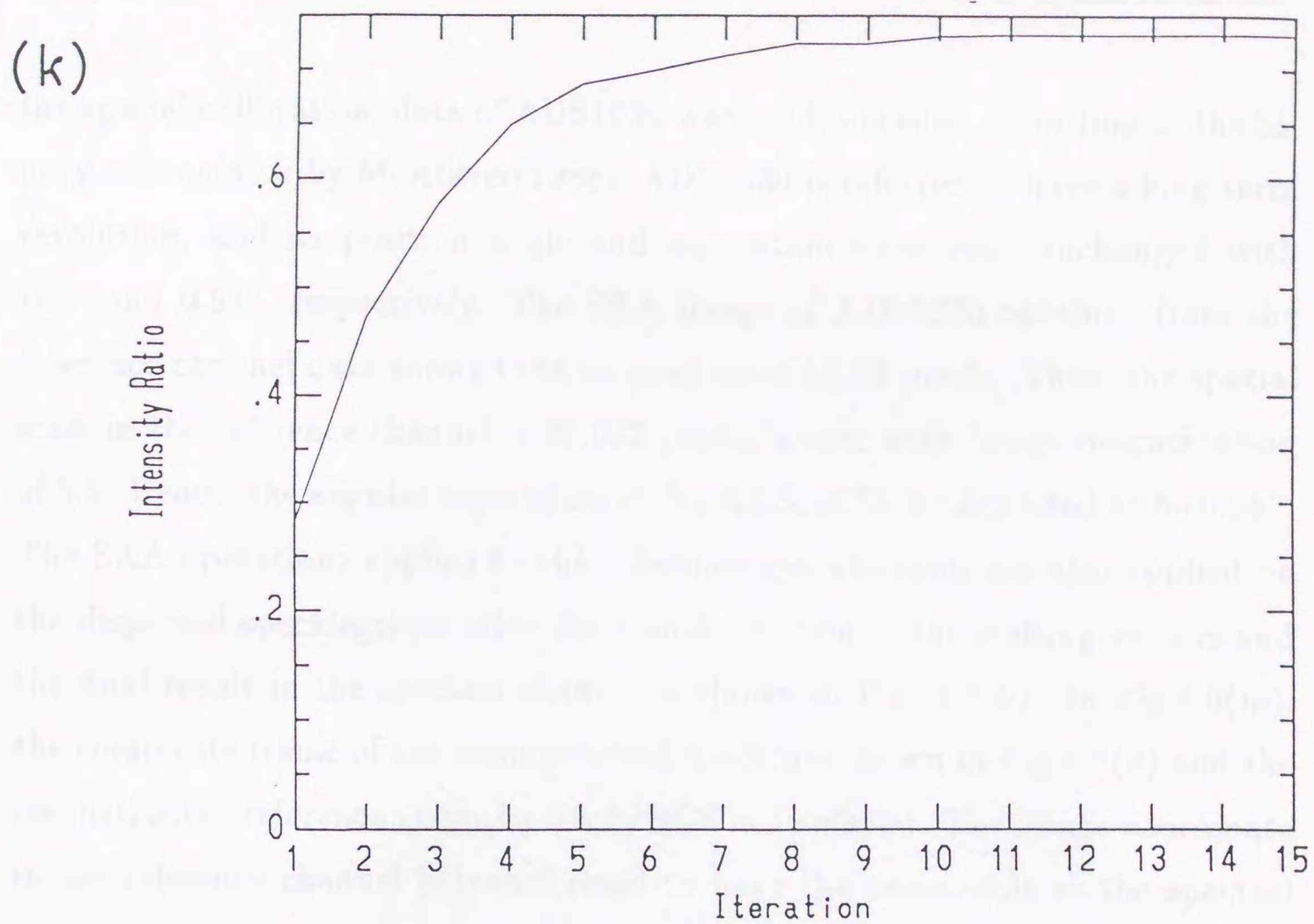


Fig. 4.9 (continued) : In (k), convergency of the estimated intensity ratio of the binary star is plotted as a function of the iteration. The SAA/BGS image reconstructed in the reference channel is drawn in (l) with $2^{-0.5}$, 2^{-1} , $2^{-1.5}$, ..., 2^{-3} contour levels of the peak value of the primary star.

the spatial calibration, data of ADS1630 was used, because, according to the binary star catalog by McAlister(1988), ADS1630 is inferred to have a long term revolution, and its position angle and separation have been unchanged with 108° and $0.58''$, respectively. The SAA image of ADS1630 obtained from the reference channel data showed the separation of 18.03 pixels. Thus, the spatial scale in the reference channel is 31.083 pixels/arcsec with image magnification of 5.5. Hence, the angular separation of the ADS12973 is calculated to be $0.26''$. The SAA operations applied to the reference specklegrams are also applied on the dispersed specklegrams after the transformation of the shifting vectors and the final result in the spectral channel is shown in Figs.4.9(b). In Fig.4.9(m), the composite frame of the reconstructed spectrum shown in Fig.4.9(d) and the reconstructed reference image by SAA/BGS is displayed. The image coordinate in the reference channel is transformed to have the same scale as the spectral channel.

The raw SAA image obtained in the spectral channel is deconvolved with the remapped version of the raw SAA image in the reference channel. As mentioned in Section 4.4., such SAA/DCV result is an estimate of the differential image between the object image and its dispersed counterpart. The differential image acquires a physical meaning when it is convolved with the object image. The estimate of the object is derived from the SAA/BGS image [Fig. 4.9(l)] by convolving a couple of weighted delta functions (intensity ratio 1:0.73) with theoretical Airy disc. Figure 4.9(c) is the result of the convolution of SAA/DCV image with the estimate of the diffraction-limited image of the object. The cross-correlation is taken between the spectral specklegrams and the remapped versions of the reference specklegrams to generate a XC image which is also an estimate of the differential image. The subsequent convolution with the object estimate as used in the SAA/DCV/CV scheme results in Fig.4.9(d).

In Figs. 4.9(n)-(p), the projected profiles of the reconstructed spectra are shown. The projection is taken in the direction of the dispersion. The projecting plots indicate the two spectra well separated. The intensity of the secondary peaks in those plots are about 0.7 ± 0.1 which corresponds to an uncertainty of 0.2 in the magnitude. Such uncertainty is due to some residual bias noise (including negativities) in the reconstructed spectrum. The width of the peak

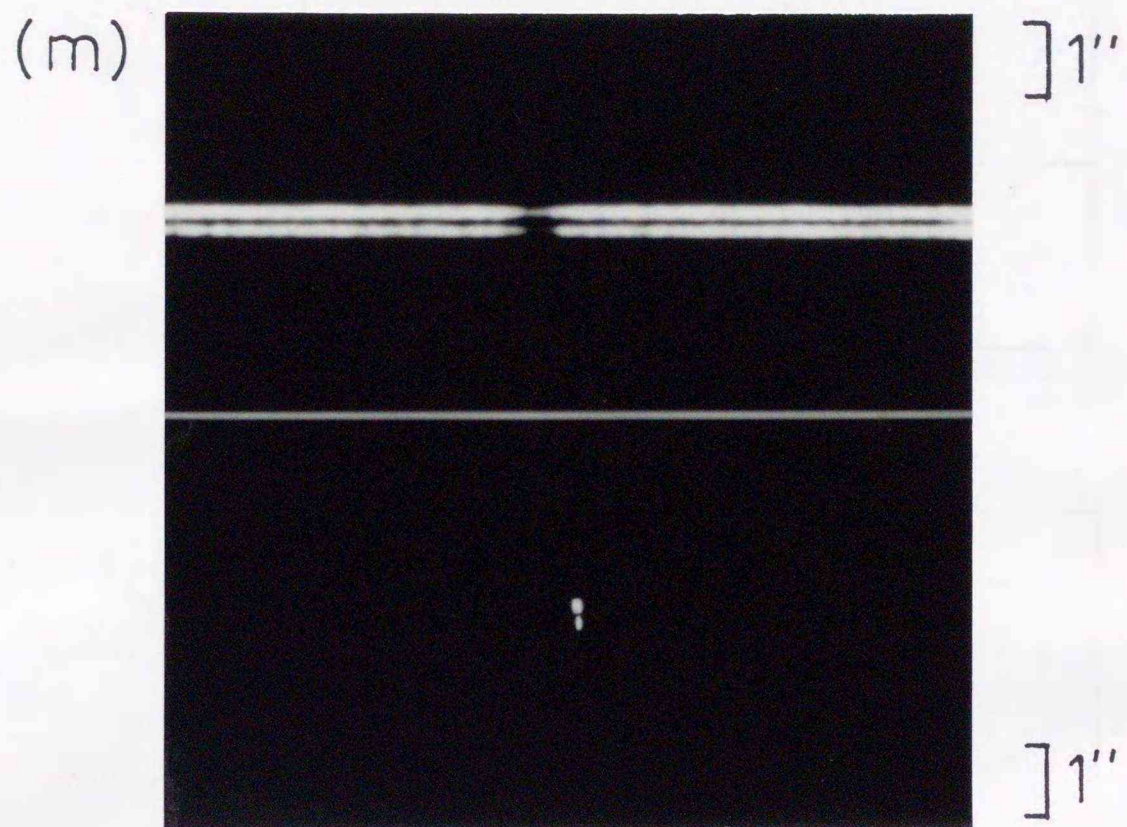
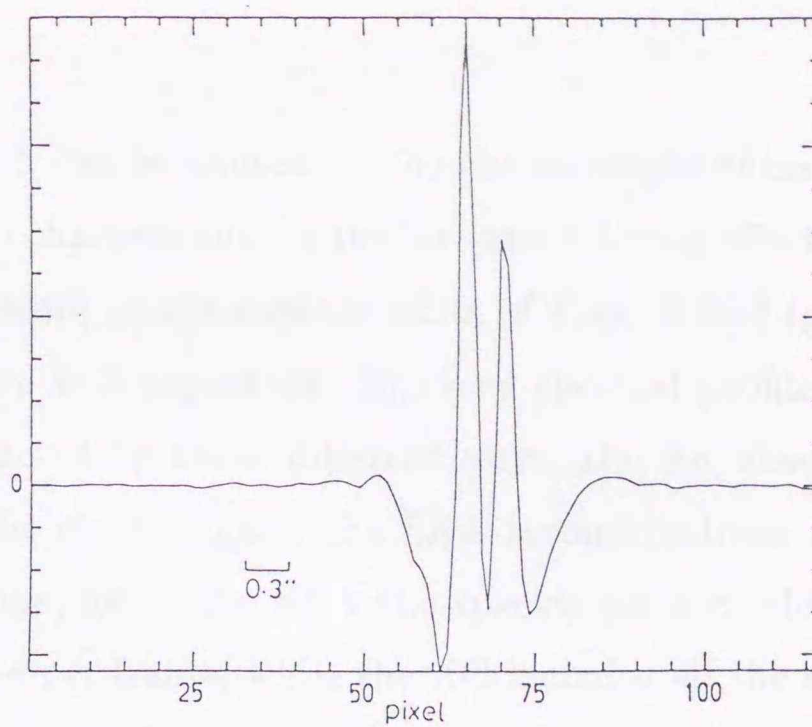
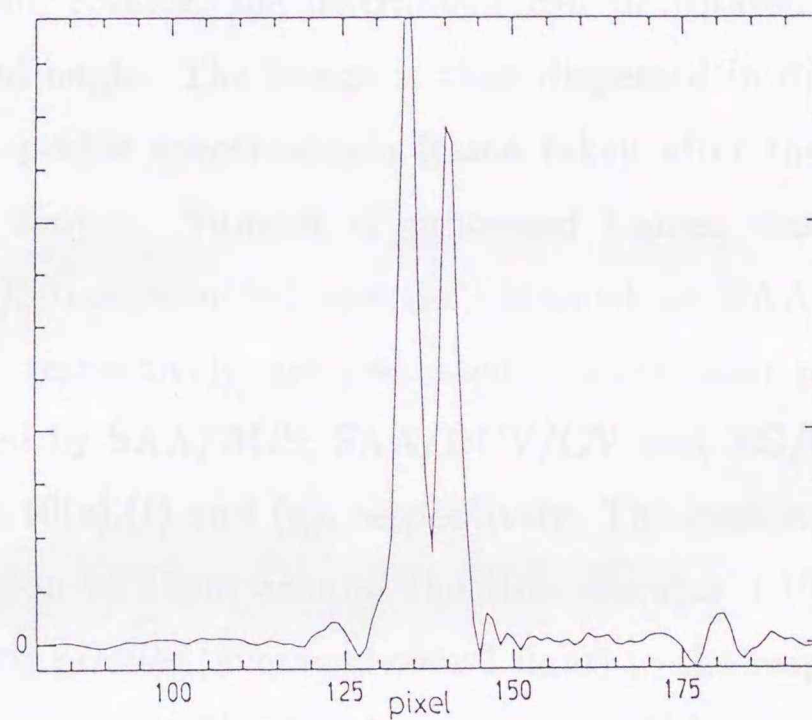


Fig. 4.9 (continued) : In (m), composite frame of (d) and the remapped version of the SAA/BGS image in the reference channel is shown.

(n)



(o)



(p)

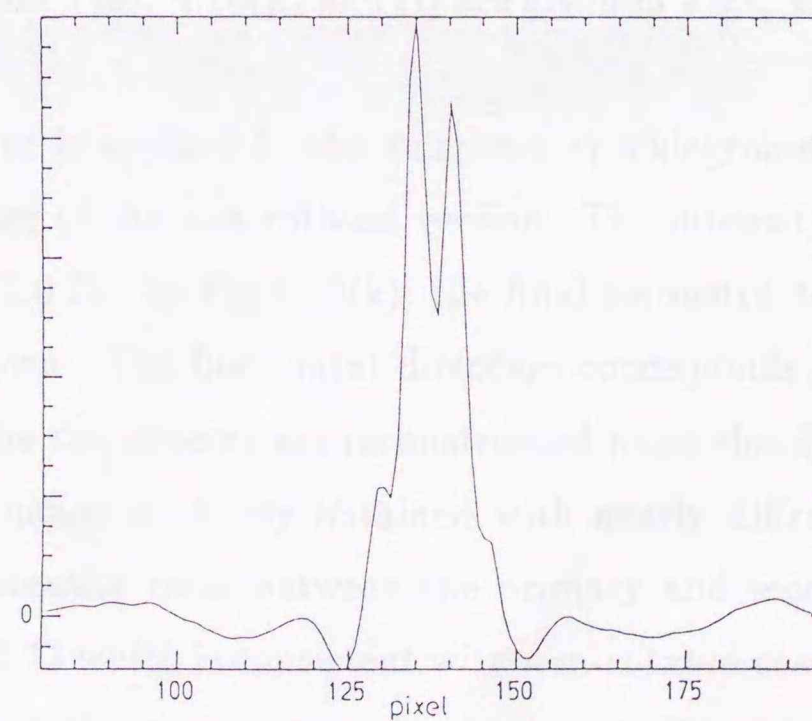


Fig. 4.9 (continued) : The projected profiles of the reconstructed spectra shown in (e)-(g) are plotted in (n)-(p).

is somewhat broadened, which can be caused by the incompleteness of the scale adjustment between two channels and/or the low pass filtering effect in the deconvolution process. As shown in the contour plots of Figs. 4.9(e)-(g), two spectra of the double star are well separated. In every spectral profile [Figs. 4.9(h'),(i') and (j)] reconstructed by three different ways, the $H\alpha$ absorption lines are resolved for both the stars. Again, the SAA reconstructions appear inferior in SNR to XC/CV one, for in the SAA the speckle pairs coadded are restricted to the brightest one per frame, while the XC includes all the speckle pairs per frame.

By driving the Cassegrain rotator, the instrument can be rotated about the optical axis with specified angle. The image is then dispersed in different direction. In Fig.4.10(a), a speckle spectroscopic frame taken after the rotation of about 45 degrees is shown. Number of processed frames was 5150. In Figs. 4.10(b),(c) and (d), reconstructed spectra obtained by SAA/BGS, SAA/DCV/CV and XC/CV, respectively, are presented. The contour plots of resolved spectra reconstructed by SAA/BGS, SAA/DCV/CV and XC/CV algorithm are shown in Figs. 4.10(e),(f) and (g), respectively. The contour plots display only the spectral region of 14nm around the $H\alpha$. Figures 4.10(h),(i) and (j) show the corresponding profiles (averaged over 3 lines) to the respective algorithms. Each plot displays two profiles for the primary and the secondary stars. The smoothed profiles for Figs. 4.10(h) and (i) are given in Figs. 4.10(h') and (i'), respectively.

The SAA/BGS algorithm is applied to the reference specklegrams iteratively as performed in the case of the non-rotated version. The intensity ratio reaches an estimate of about 1:0.73. In Fig.4.10(k), the final reconstructed image after 20 iterations is shown. The horizontal direction corresponds to the dispersion direction so that the two spectra are reconstructed more closely than non-rotated case. A binary image is clearly obtained with nearly diffraction-limited resolution and the intensity ratio between the primary and secondary stars is evaluated to about 1:0.73 which is consistent with non-rotated case. The orientation of the reconstructed binary appears to be consistent with the instrument rotation angle. In Fig.4.10(l), the composite frame of Fig.4.10(d) and the remapped version of the SAA/BGS image as shown in Fig.4.10(k) is displayed.

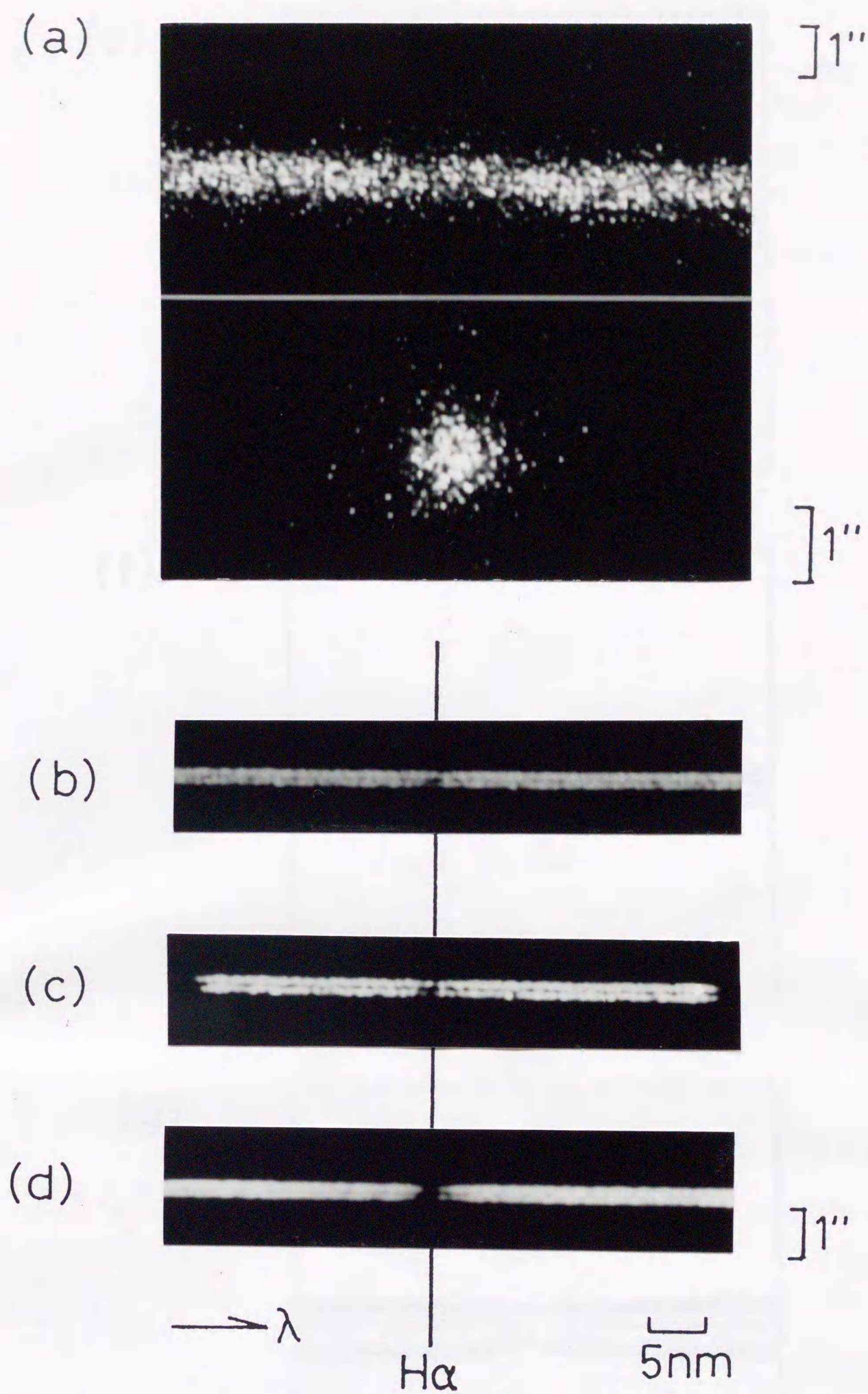
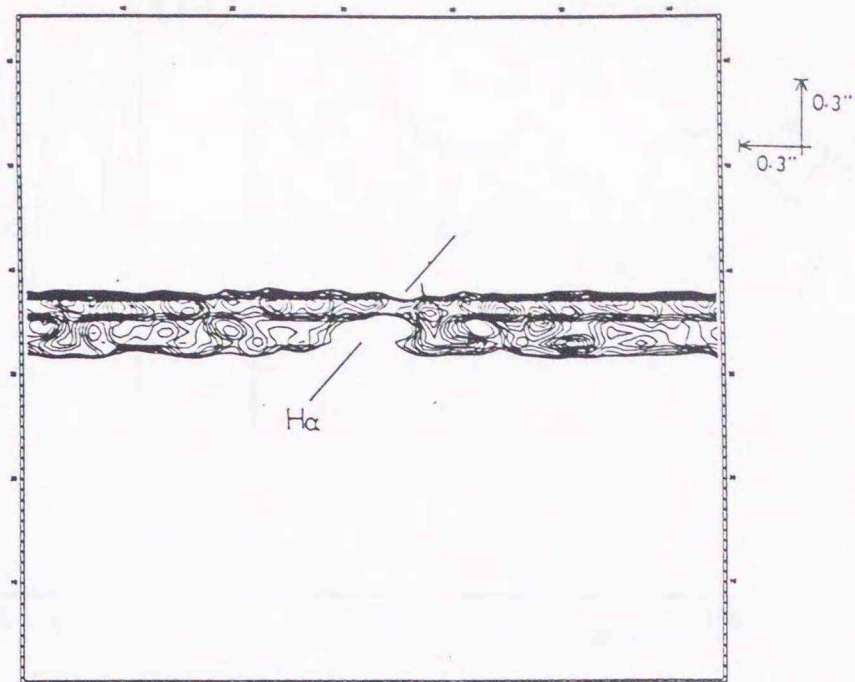
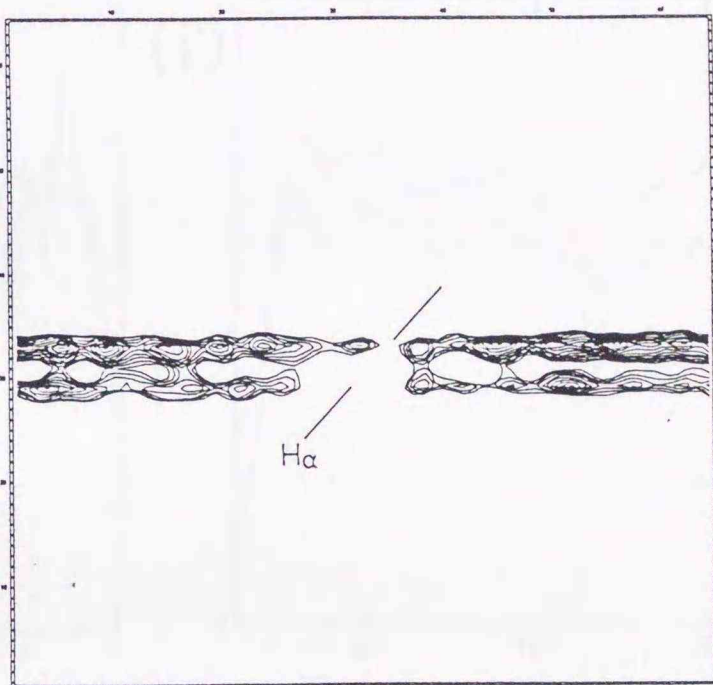


Fig. 4.10 : Results for ADS12973 observed after 45° rotation of SSC2. In (a), one of the SSC2 speckle spectroscopic frames is shown, where the dispersed specklegram(upper) and the narrowband reference specklegram(lower) are displayed. (b),(c) and (d) are the spectra reconstructed by SAA/BGS, SAA/DCV/CV and XC/CV, respectively.

(e)



(f)



(g)

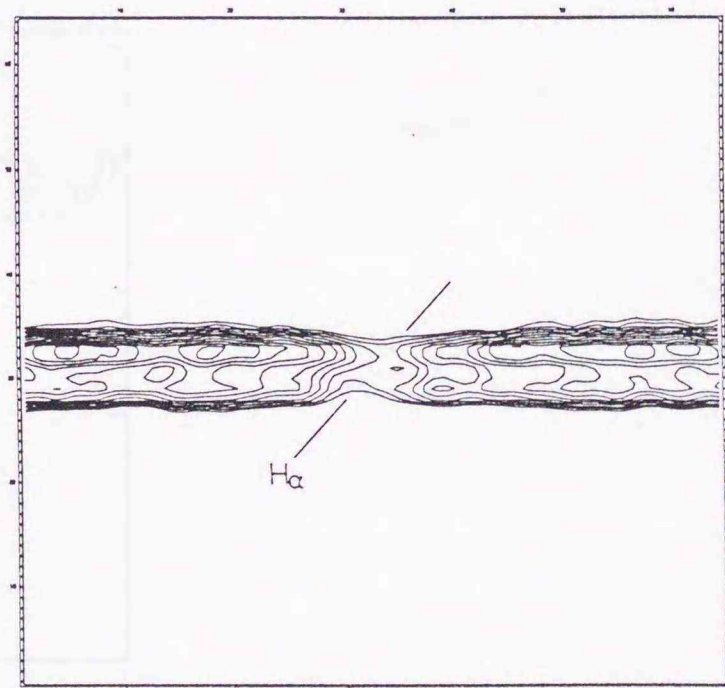


Fig. 4.10 (continued) : (e)-(g) are contour plots corresponding to (b)-(d). The spectral region displayed is 14 nm around the H α .

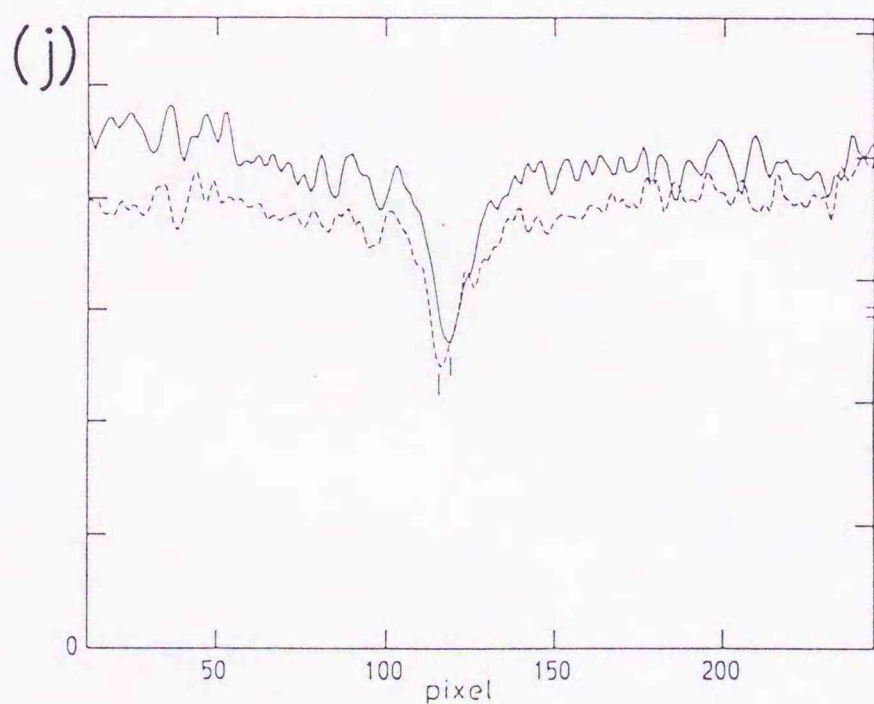
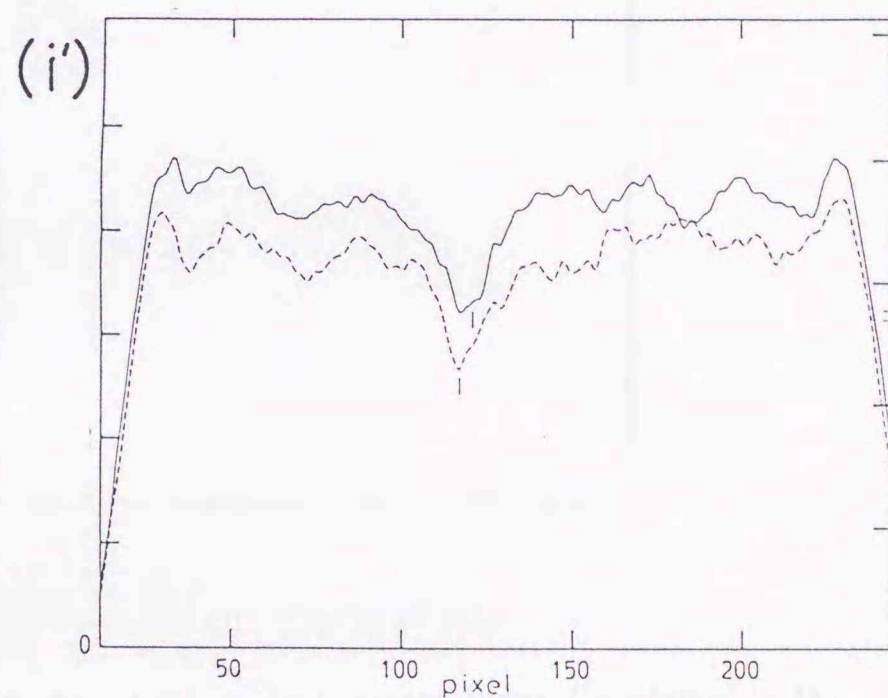
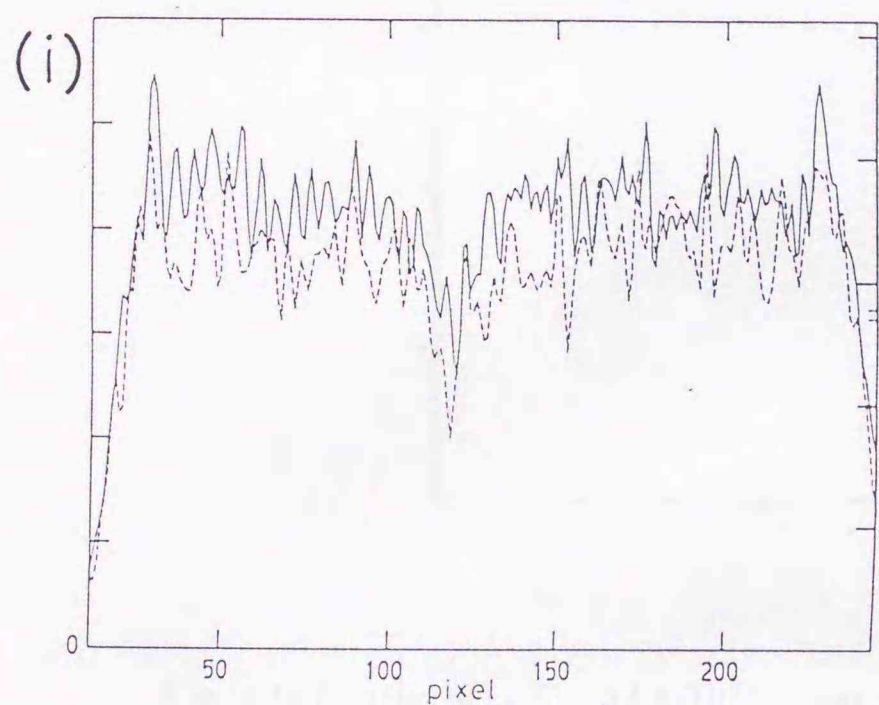
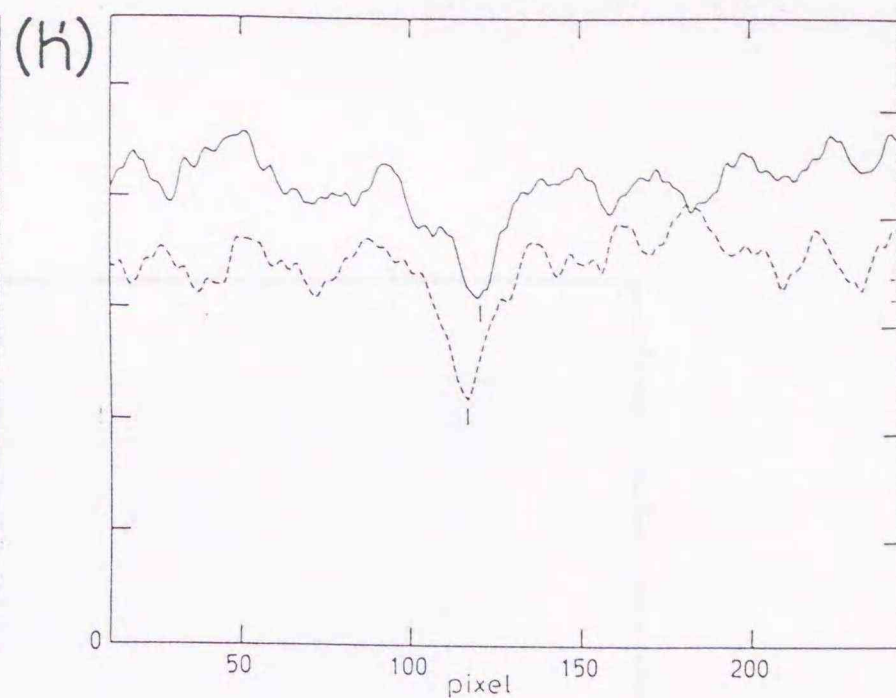
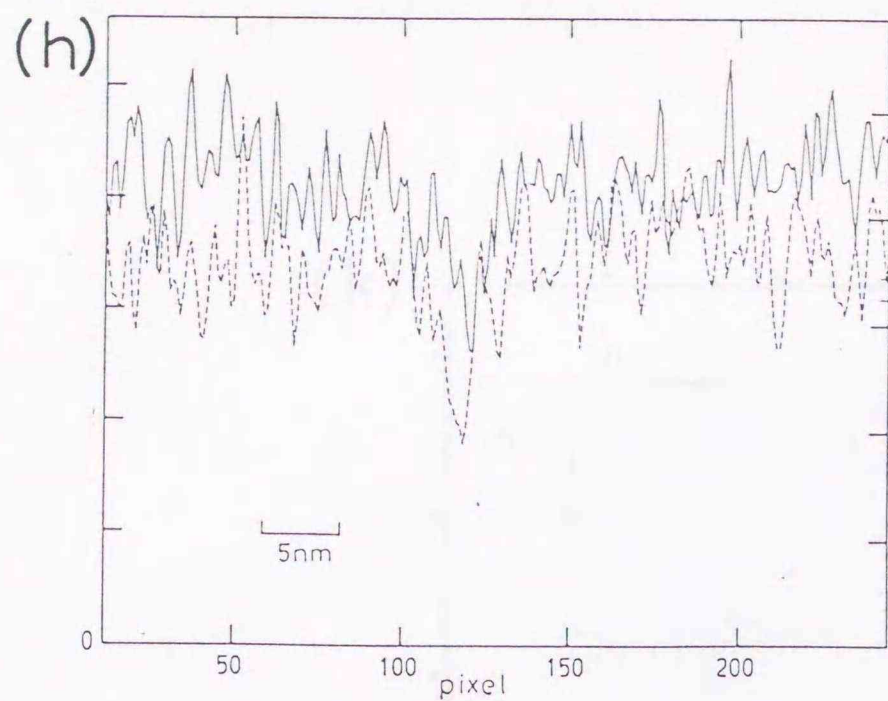


Fig. 4.10 (continued) : The spectral profiles (averaged over 3 lines) reconstructed by SAA/BGS, SAA/DCV/CV and XC/CV, respectively, are shown in (h)-(j). In each of (h)-(j), two profiles for the primary star(solid line) and the secondary star(dashed line) are plotted. The noisy profiles on (h) and (i) are smoothed by 10-pixels window to produce clear profile (h') and (i'), respectively.

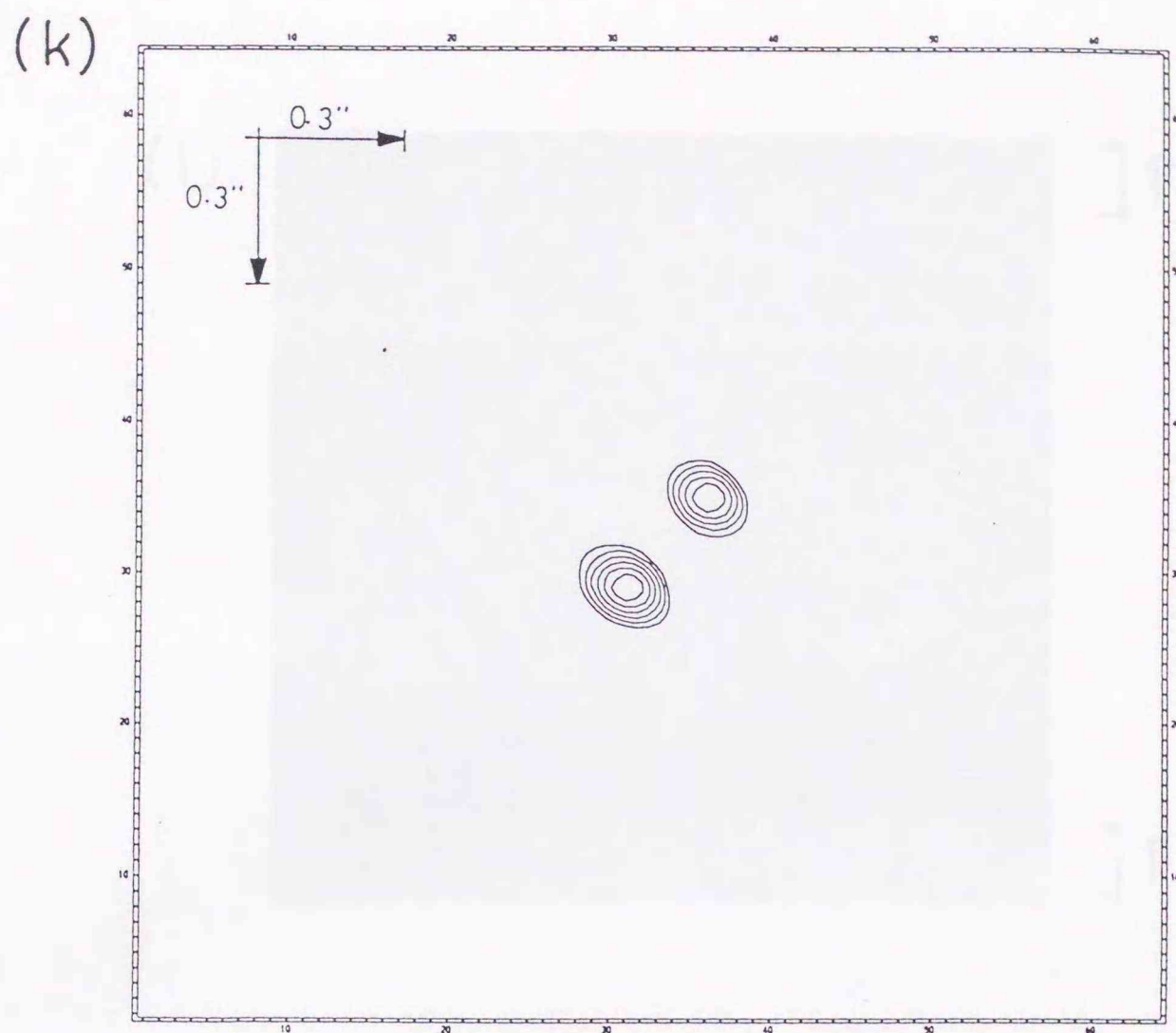


Fig. 4.10 (continued) : The SAA/BGS image reconstructed in the reference channel is plotted in (k) with $2^{-0.5}$, 2^{-1} , $2^{-1.5}$, ..., 2^{-3} contour levels of the peak value of the primary star.

By comparing with Fig. 4.9, the effect of the instrumental error on the image is evident.

In Fig. 4.10, the effect of the instrumental error on the image is shown. (1)

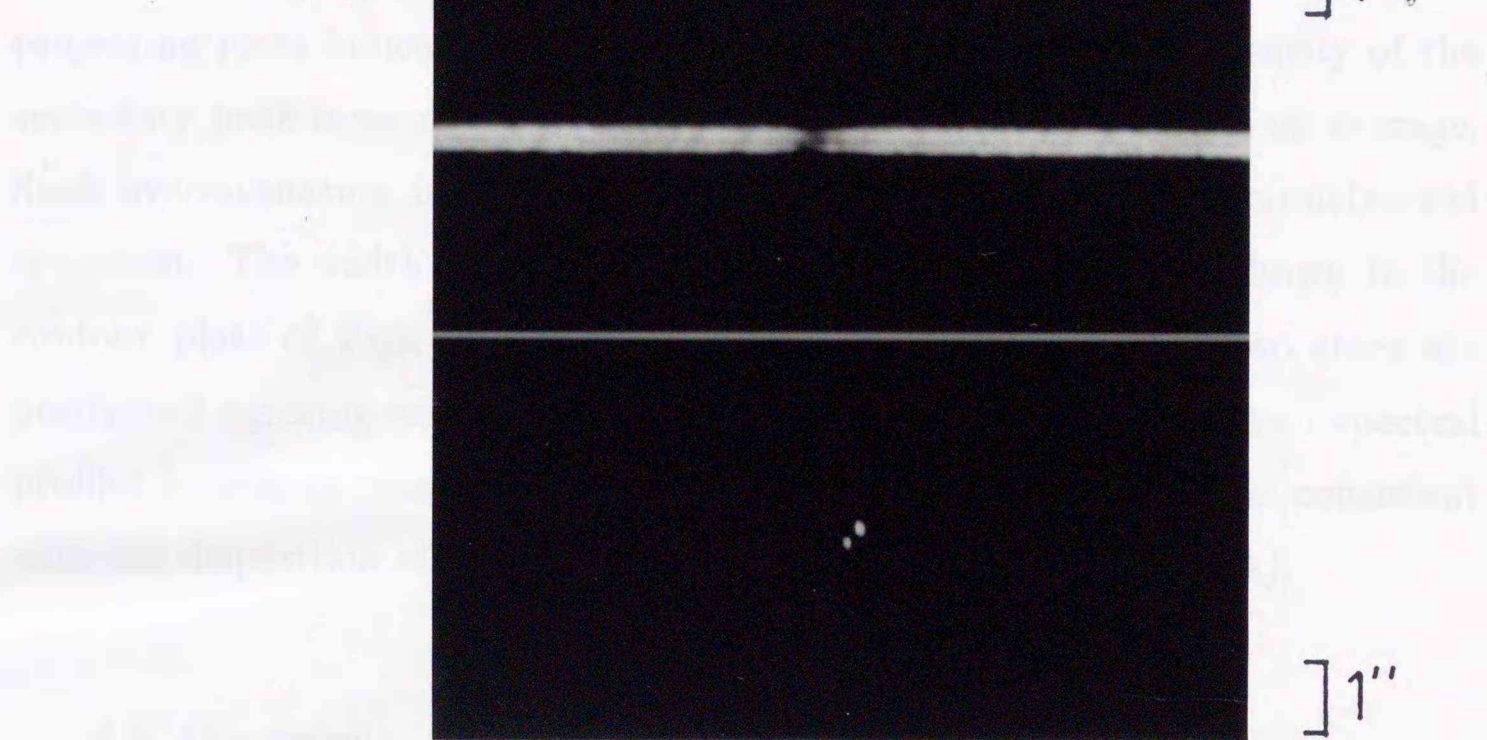


Fig. 4.10 (continued) : In (1), composite frame of (d) and the remapped version of the SAA/BGS image in the reference channel is shown.

By comparing with Fig.4.9(m), the effect of the instrumental rotation on the reconstructed image is evident.

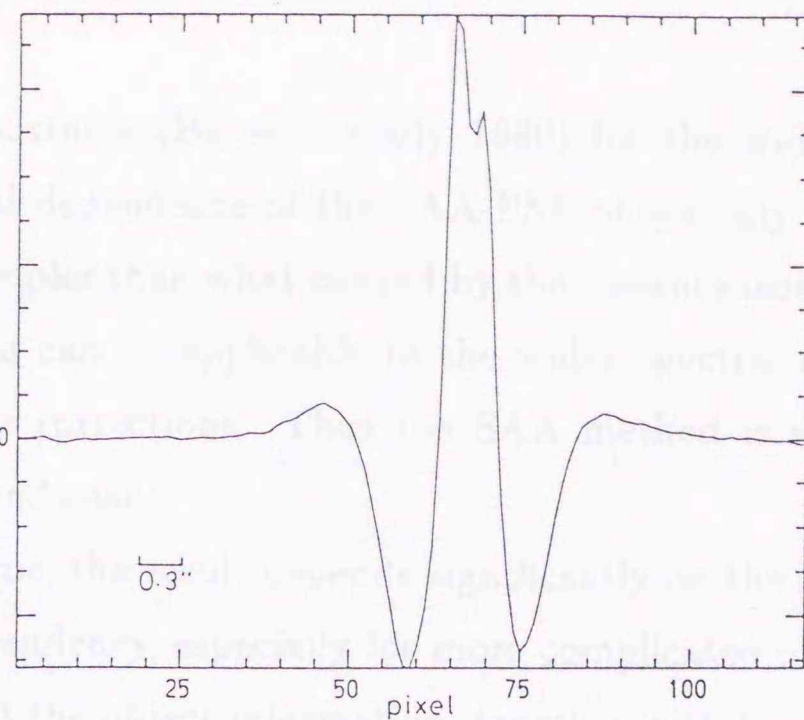
In Figs. 4.10(m)-(o), the projected profiles of the reconstructed spectra are shown. The projection is taken in the direction of the dispersion. The projecting plots indicate the two spectra well separated. The intensity of the secondary peak in every plot is larger than 0.73 and is around 0.85 on average. Such overestimation is due to some residual bias noise in the reconstructed spectrum. The width of the peak is somewhat broadened. As shown in the contour plots of Figs. 4.10(e)-(g), the $H\alpha$ absorption lines of two stars are positioned agreeing with Fig.4.10(k). The relative shift between two spectral profiles is seen in every profile of Figs. 4.10(h'),(i') and (j) and is consistent with the disposition of two component stars as shown in Fig.4.10(k).

4.6. Discussion

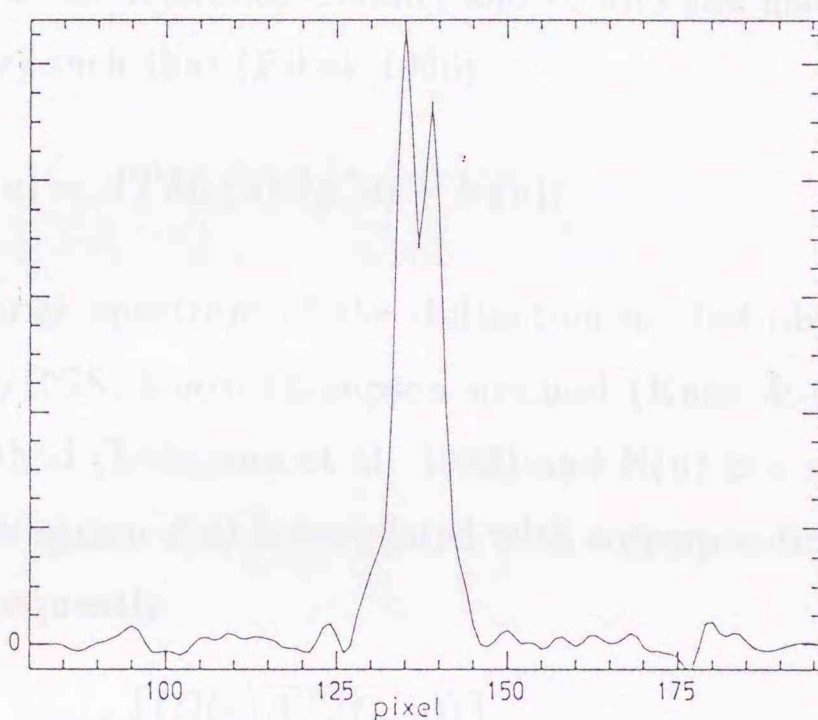
The consistency between the α Per result and the Procyon's photometric measurement leads to the conclusion that the SSC2 system has sufficient performance to enable us to make the quantitative spectral analysis in speckle spectroscopy. The results for double star demonstrate that the spectral features can be reconstructed separately for two stars: otherwise they are blended due to the atmospheric turbulence. In this Chapter, the reconstruction results around the $H\alpha$ line are shown, which is mainly due to the maximum sensitivity of the I.I. around 650nm. However, by rotating the grating and changing the interference filter, the information of the other spectral region can be obtained in the same way.

The cross-correlation method shows a superior performance in SNR to the SAA method. Since all the speckles included in the reference specklegram correlates to the respective counterparts in the dispersed specklegram on the same frame, the effective throughput is augmented in comparison to that with the SAA. Thus, the cross-correlation method is an optimum selection as data reduction algorithm in the narrow band system. It should be noticed that the cross-correlation method gives a reasonable estimate only for the spectral region of less than several ten nano-meters around the reference channel's bandpass which must be also sufficiently narrow. On the other hand, the advantage of

(m)



(n)



(o)

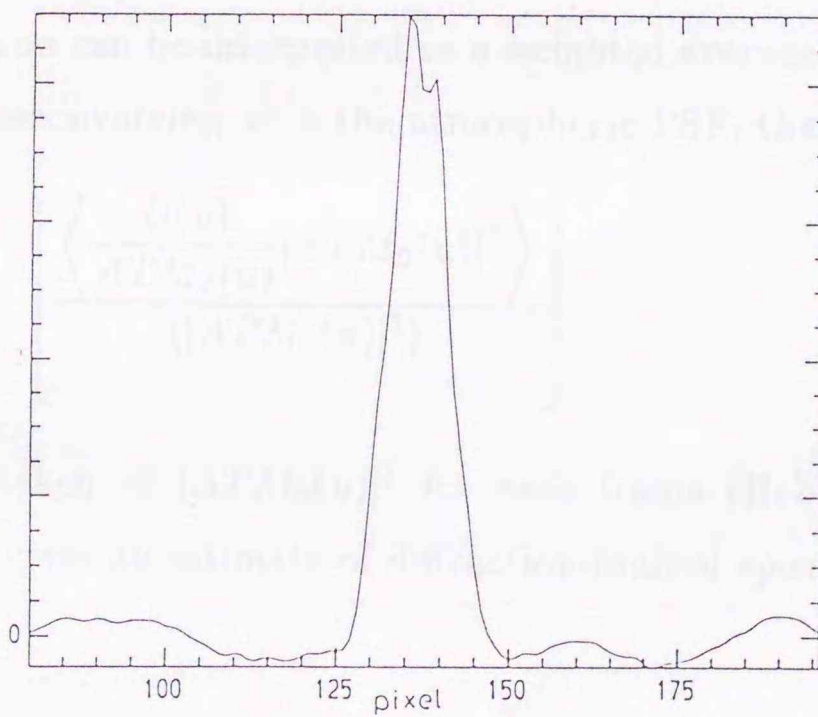


Fig. 4.10 (continued) : The projected profiles of the reconstructed spectra shown in (e)-(g) are plotted in (m)-(o).

the SAA method is robustness (Bates & Cady 1980) for the wider spectral range. Since the spectral dependence of the SAA-PSF obeys only the scaling law ($\propto \lambda^{-1/5}$) which is simpler than what obeyed by the instantaneous PSF, the subsequent deconvolution can be applicable to the wider spectral region only with the additional scale corrections. Thus the SAA method is still a good candidate for the wideband case.

In the XC/CV scheme, the result depends significantly on the object's estimate. To relax the dependency, especially for more complicated objects, it is advantageous to filter out the object information, together with the noise component, frame by frame in the reference channel and to find the instantaneous atmospheric PSF $atm_0(x)$ such that (Ribak 1986)

$$I_0(u) = ATM_0(u)O_D(u) + N(u), \quad (4.6.1)$$

where $O_D(u)$ is the Fourier spectrum of the diffraction-limited object image estimated by, e.g., SAA/BGS, Knox-Thompson method (Knox & Thompson 1974) or bispectrum method (Lohmann et al. 1983) and $N(u)$ is a noise term. Then, the dispersed specklegram $d(x)$ is correlated with corresponding $atm_0(x)$ instead of $i_0(x)$ and consequently

$$FT^{-1} \left[\frac{\langle D(u) \overline{ATM_0(u)} \rangle}{\langle |ATM_0(u)|^2 \rangle} \right] \quad (4.6.2)$$

is obtained. This expression can be interpreted as a weighted average of spectra found in each frame by deconvolving with the atmospheric PSF, that is

$$FT^{-1} \left[\frac{\left\langle \frac{D(u)}{ATM_0(u)} |ATM_0(u)|^2 \right\rangle}{\langle |ATM_0(u)|^2 \rangle} \right], \quad (4.6.3)$$

in which the weight is taken as $|ATM_0(u)|^2$ for each frame (Hebden et al. 1986a). This calculation gives an estimate of diffraction-limited spectrum with noise-bias suppressed.

Chapter 5. Speckle Spectroscopic System toward High Spectral Resolution

5.1. Introduction

In Chapters 3 and 4, a speckle spectroscopic scheme with two optical channels are demonstrated. In this scheme, dispersed specklegrams and non-dispersed reference specklegrams are simultaneously recorded on, e.g., a video tapes. The observational data are computationally processed by referring to the information of the atmospheric turbulence included in the reference specklegrams. In other words, the speckle spectroscopic systems described so far are rather passive and post-processing type. In such an approach, the spatially degraded specklegrams are dispersed objectively and the dispersed specklegrams so obtained are quadratically detected. The reconstructed result is then an objective spectrum with the diffraction-limited spatial resolution. However, the diffraction-limited spectrum reconstructed from the dispersed specklegrams is not equivalent to what would be obtained by averaging the dispersed versions of the isolated speckles. The former would be far inferior to the latter in SNR. Actually, the dispersed versions of the respective speckles overlap each other in the dispersed specklegram, which hampers the smooth enhancement of SNR in the reconstructed spectrum.

Thus, it is advantageous to isolate the single speckle before dispersing. A slit can be employed for this purpose. For the random displacement of the single speckle due to the atmospheric turbulence, a certain active mechanism is needed to stabilize the single speckle on the slit. It is just to perform the SAA process in real time. By introducing the real-time SAA mechanism, some other advantages are generated. First, a long exposure on a spectroscopic detector is possible without any degradation of spatial resolution due to the atmospheric turbulence, and the desired amount of photons can be collected by taking longer exposure. It is advantageous especially for the high spectral resolution speckle spectroscopy in which the speckles are largely dispersed. Second, since a slit is available, the spectra on an extended object are separately extracted for every point. In this Chapter, a speckle spectroscopic system including a real-time SAA mechanism is proposed. In this scheme, the SAA is performed in real time by using a tip-tilt mirror to stabilize the brightest part in the image. Thus,

the system is augmented toward the high spatial and high spectral resolution spectroscopy.

5.2. Scheme of the New System

The speckle spectroscopic system with real-time SAA mechanism is schematically shown in Fig.5.1. The light from the telescope is collimated and divided by a beam-splitter(BS) into two beams. One beam is led to a spectroscope through a tip-tilt mirror and the other is provided for imaging of the short exposure specklegrams(reference specklegrams) on ICCD TV camera. The reference speckle image taken by the ICCD is digitized into a frame memory and correlated with a matched filter of the object which has been obtained by a speckle imaging technique. The correlation is calculated by a microprocessor. According to the position of the correlation peak, the tip-tilt mirror is controlled for an object's replica to be stabilized in the entrance of the spectroscope. The stabilized image is then fed to a spectroscope and the spectrogram is detected by a CCD detector. Since the diffraction-limited resolution is attained by the stabilization prior to feeding the spectroscope, a long time exposure of the spectrogram on the detector is permitted to gain the SNR. This is an advantage for high dispersion spectroscopy because the sufficient flux per wavelength is intrinsically required there. Furthermore, a slit on the entrance of the spectroscope is allowed without loss of the diffraction-limited resolution. The advantage to use the slit is that point by point spectra on an extended object can be isolated, whereas the previous systems produce an objective spectrum in which the spectra at different points overlap. In order to get two dimensional spectra of an object, the instrument should be rotated with a specified angular increment. Instead of the slit, an optical fiber bundle can be used. By using a fiber bundle, point by point spectra on the whole object can be extracted simultaneously. Thus, the proposed system overcomes the drawbacks in the previous systems and improved performances are expected.

5.3. Discussion toward the Realization

The tip-tilt mirror is controlled by a servo system including a digital com-

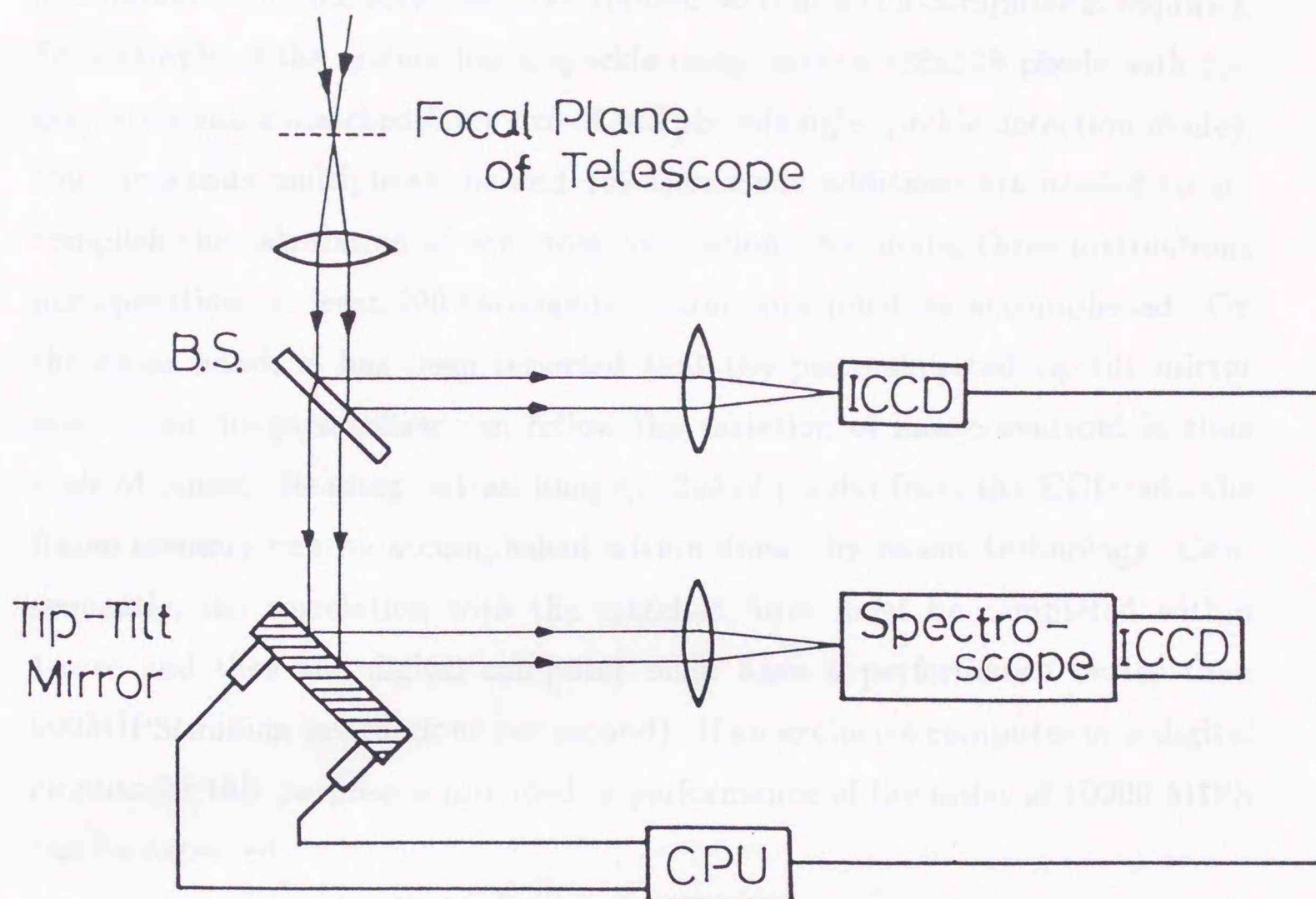


Fig. 5.1 : Speckle spectroscopic system with real-time SAA mechanism. Tip-tilt mirror is movable around two orthogonal axes.

puter. It is critical to perform the servo control as rapidly as the atmospheric fluctuation with time scale less than 10msec, so that a fast computer is required. For example, if the system has a speckle image size of 128x128 pixels with 256 graylevels and a matched filter size of 3x3 pixels(single speckle detection mode), 150 'thousands multiplications and 150 thousands additions are needed to accomplish the calculation of the cross-correlation. Assuming three instructions per operation, at least 900 thousands instructions must be accomplished. On the other hand, it has been reported that the piezo-actuated tip-tilt mirror used in an image stablizer can follow the variation of image centroid in time scale of 5msec. Reading out an image(512x512 pixels) from the CCD into the frame memory can be accomplished within 4msec by recent technology. Consequently, the correlation with the matched filter must be completed within 1msec and then the digital computer must have a performance better than 900MIPS(million instructions per second). If an exclusive computer or a digital circuits for this purpose is provided, a performance of the order of 10000 MIPS can be expected.

The spectrogram obtained from the slit spectroscope also contains a background, on which the diffraction-limited slit spectrum is superimposed. To obtain the final result, the background component must be estimated and subtracted from the slit spectrogram. A strategy is that the servo loop is implemented to work with two modes, peak tracking mode(SAA mode) and centroid tracking mode. The two modes are switched during the observation for a object. Two integrated spectrograms obtained under the two tracking modes are separately recorded. From the spectrogram obtained under the centroid tracking mode, the background can be estimated. The estimated background is subtracted from the slit spectrogram obtained under SAA(peak tracking) mode.

Some active techniques to improve the spatial resolution of images through a telescope have been studied. The image stablizer is one of them, in which the image centroid is stablized so that the resolution is considerably improved to the seeing-limited resolution. This technique aims at correcting only the tip-tilt component of the wavefront distortions. The adaptive optics aims at full correction to the wave front distortions and formation of the diffraction-limited image. This technique has been successfully applied to the infrared observation,

but some technical problems remain in application to the visible region due to system's complexity. The real-time SAA mechanism in the proposed system corrects only one plane wave component of the randomly distorted wavefront by registering the single speckle and driving the tip-tilt mirror. In spite of such simplicity, the real-time SAA is expected to reconstruct the diffraction-limited resolution, provided that the background is effectively removed. Christou(1991b) suggested the use of active peak tracking system to improve the resolution of image of large telescope in the near-infrared. The proposed speckle spectroscopic system including the real-time SAA mechanism is expected to be applicable in the visible region. If the proposed system is combined with the adaptive optics which partially compensates the optical image, then augmented performances are expected.

Chapter 6. Conclusions

The spatial resolution of a large telescope is severely limited by the atmospheric turbulence on the earth. The stellar speckle interferometry is one of high spatial resolution techniques to overcome such a limitation. This method restores a diffraction-limited image of a stellar object by post-processing speckle interferograms. At present, the stellar speckle interferometry appears to be the most established method in optical astronomy.

Recently, constructions of telescopes with larger aperture-size become to be considered as an ultimate way to increase available photons. This movement is mainly due to the remarkable advance of detectors. To augment the collecting power of photons, constructions of larger telescopes have been planned over last two decades. The constructions of 8-10m class telescopes are now in progress, particularly by Europe, U.S.A. and Japan (Enard 1991). The large telescopes have not only highly collecting powers of photons but also intrinsic high resolving powers. Thus, developments of high spatial resolution techniques and instrumentations are now urgent problems.

There are two main approaches to draw the intrinsic resolving power of a large telescope. One approach is to employ the adaptive optics which may be regarded as an active method and the other typical one is the speckle interferometry as a passive method. When 8-10 m telescopes are available in the future, those two approaches will be complementarily employed.

The stellar speckle spectroscopy demonstrated in this thesis is an application of the stellar speckle interferometry. This method restores the diffraction-limited spectrum by processing the speckle spectrograms. The stellar speckle spectroscopy has a possibility to offer astrophysical information of an stellar object with fine spatial resolution, if this method is combined with large telescopes.

The purpose of the present thesis is to demonstrate feasibility of the speckle spectroscopy with use of observational data. The studies in this thesis are based on the scheme proposed by Baba et al.(1988a,b), in which two images with the same atmospheric degradation are simultaneously taken through two optical channels. The author believes that this thesis has contributed to the development of computational processing algorithm for the data obtained by

speckle spectroscopic cameras.

In Chapter 1, a historical review of the stellar speckle interferometry is made to show that the speckle interferometry has played an important role as a high spatial-resolution technique for optical astronomy. A historical transition of the speckle spectroscopy is also described. Purposes of the present thesis are given in this chapter.

In Chapter 2, theoretical backgrounds of the imaging through the atmospheric turbulence have been reviewed. Several methods of speckle imaging are also introduced.

In Chapter 3, the wideband speckle spectroscopy has been demonstrated using data obtained by the speckle spectroscopic camera No.1 (SSC1). In this system, the achievable spectral resolution is about 5 nm with the spectral span of 400 nm. The shift-and-add (SAA) method is employed as the data processing algorithm. The SAA process is applied to white-light reference-specklegrams so as to reconstruct a diffraction-limited image. To avoid the SAA systematics, "ghost peak", an iterative matched-filter SAA is used. The background component attending with the raw SAA image is feasibly identified by applying the SAA process to the pseudo-long-exposure image. The reconstruction of a diffraction-limited spectrum relies on the process of speckle imaging in the reference channel. To examine the performance of the speckle imaging algorithm, a preliminary demonstration is carried out by using the simulated and observational data sets, which is presented in the the first half of section 3.4. The results with the simulated data show the verification of the algorithm: the reconstructed images are found to be consistent with the original images within a few percent residual noise, and the intensity ratio of a binary star can be reproduced with the uncertainty of ~ 0.2 in the magnitude. It is seen that the background subtraction (BGS) causes a negativity in the final image amounting to around 5 percent to the peak value. The processed results by the SAA/BGS with observational data of binary stars are compared with the results obtained by the iterative blind deconvolution (IBD) method. Both the results are consistent within the accuracy of ± 0.2 in the magnitude difference between the two component stars. The orientations and the angular separations of the reconstructed binary obtained by the SAA/BGS are completely agreed

those obtained by the IBD.

Speckle spectroscopic results of the SSC1 are given in the latter half of Section 3.4. Wideband data of a single star ζ Tau are processed by the SAA/BGS algorithm. The size of a wideband image reconstructed in the reference channel is found to be comparable to the theoretical Airy's disc. However, the reconstructed image noticeably shows a directional elongation, which is thought to be an effect of the atmospheric dispersion because of its directionality. The reconstructed wideband-spectrum of ζ Tau shows nearly diffraction-limited resolution, which can be verified by taking the projected profile. However, the spectral profile shows less reasonable features, i.e., all dips appearing in the profile do not correspond to the expected absorption lines. Wideband data of a binary star ADS16836 are also processed by the SAA/BGS. Nearly diffraction-limited image can be reconstructed in the reference channel. The reconstructed wideband-image shows a binary structure as expected. The binary structure is also restored in the spectral channel, i.e., spectra of the two component stars closer than the seeing limit have been separated. The projected profile demonstrates that the spatial resolution of the reconstructed spectrum is nearly diffraction-limited. However, both of the separated spectral profiles are too noisy to identify spectral lines. From the results of the two objects, it is concluded that the spatially resolved wideband-spectra can be reconstructed in nearly diffraction-limited resolution. However, it can not be confirmed whether the spectral features can be resolved in wideband mode.

In Chapter 4, the narrow-band speckle spectroscopy have been demonstrated. The SAA/BGS algorithm developed in the experiments using the SSC1 data is applied to the data obtained by the Steward Observatory differential speckle camera (SO/DSC). The spectral region of the SO/DSC data is 24nm and the achievable spectral resolution is 0.6nm. SAA/BGS data reductions for two single stars are carried out, and the $H\beta$ absorption and emission lines are reconstructed in nearly diffraction-limited resolution. From the results with the SO/DSC data, it is confirmed that the SAA/BGS algorithm can be feasibly applied to narrow-band data and that the spectral features (spectral lines) can be resolved far beyond the seeing limit.

Narrow-band speckle spectroscopic data are also obtained by speckle spec-

troscopic camera No.2 (SSC2). The spectral region of the SSC2 data is 50nm and the achievable spectral resolution is 0.3nm. The spectral region of the SSC2 data are sufficiently narrow so that the spectral dependence of the atmospheric point-spread-function (PSF) is negligible. Thus, a diffraction-limited spectrum can be reconstructed not only by the SAA/BGS method but also by a deconvolution method applied to the raw SAA image (SAA/DCV). The cross-correlation (XC) method is also introduced as another deconvolution approach. Two data sets of two single stars are individually processed by the three approaches, i.e., SAA/BGS, SAA/DCV and XC. For each object, the three methods can clearly reconstruct the $H\alpha$ spectral line. The results of α Per obtained by the SAA/DCV and XC methods are fairly consistent with respect to the equivalent width of the $H\alpha$ absorption line. The reconstructed spectral profile of α Per is compared with a photometric measurement of a slit spectrogram of Procyon. Both the profiles show a comparable spectral resolution. The $H\alpha$ emission lines of γ Cas reconstructed by the three methods are fairly consistent with respect to the line shape. For both the objects, the continuum level in SAA/BGS results is underestimated. The XC results are superior to the other reconstructions in SNR because the whole speckles per frame contribute to the signal. From the SSC2 results of the single stars, it is confirmed that it is possible to perform a quantitative spectral analysis to the diffraction-limited spectrum. In the narrow band cases, the XC method has advantages for this purpose.

The SSC2 data sets of a binary star (0.3") with two different instrumental position-angles are also analyzed by the three methods described above. For all the reconstructions, two spectra of the primary and the secondary stars are well resolved and the $H\alpha$ absorption line appears in the spectra of the two stars. The reconstructed spectra obtained by the XC method are superior in SNR to those obtained by other two methods, SAA/BGS and SAA/DCV. For either the instrumental position-angle, the $H\alpha$ lines of two stars are reconstructed in response to the binary image reconstructed in the reference channel. This illustrates that, in the present scheme, wavelength calibration for respective stars can be achieved by referring disposition in the image reconstructed in the reference channel. From the SSC2 results of the binary star, it is confirmed

that spatially-resolved spectra can be reconstructed in nearly diffraction-limited resolution, and such an enhancement of the spatial resolution results in an improvement of spectral resolution. The SSC2 results of the binary star have clearly illustrated that it is possible to resolve point by point spectra on a stellar object with high spatial resolution.

In Chapter 5, a proposition of a speckle spectroscopic system for high-dispersion speckle-spectroscopy has been made. The proposed system includes an active SAA mechanism using a tip-tilt mirror. By introducing the active SAA mechanism, a long exposure of spectrograms becomes possible, with retaining a high spatial resolution. The long-exposure of spectrograms allowed is advantageous to higher dispersion spectroscopy. Furthermore, in the proposed system, a slit can be employed to avoid an overlap of spectra at different points on an object. This construction is advantageous to apply the speckle spectroscopy to an extended object. For the active SAA, it is crucial to perform rapid detection of the brightest speckle in a snapshot. It is concluded that if an exclusive computer is employed for this purpose, the new system will be realized.

In the present thesis, the stellar objects are restricted to single and binary stars. However, the speckle spectroscopic method developed in the present thesis also can be applied to general objects other than single and double stars, provided that a proper estimate of the diffraction-limited image is provided. Such an estimation is possible by applying a proper speckle imaging technique on the specklegrams obtained in the reference channel of the speckle spectroscopic cameras.

The speckle spectroscopic method combined with large telescopes will realize a high spatial-resolution spectroscopy with various degrees of dispersions. It will make possible to study fine structures of stellar objects.

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