Evaluation of Error Propagation in Profilometry using Stitching

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It is necessary for realizing next-generation linear collider studied in ILC project aiming TeV of acceleration energy to evaluate straightness of accelerator structure with high accuracy for overall structure length. Stitching is a technique which enables longer measurement length of profilometry from several partially measured profiles and is promising for highly precise profilometry with long measurement length. We had analytically expressed error in the stitched profile as a function of several dimensionless parameters considering error propagating model. Here, error estimated through the analysis was compared to the error in actual stitched profiles

1. INTRODUCTION

In order to realize TeV class energy of experiments, construction of linear collider having approximately 50 km of total length is considered in International Linear Collider (ILC) project. [1] Here, two main linacs are expected to be aligned with 100 micro-meter order of accuracy for several 100 to several 1000 m of running length for accelerator structure in primary alignment, that is mechanical alignment. However, the requirements for this alignment can hardly satisfied by using conventional measurement method.

We had analytically shown that tilt-corrected autocollimation and tilt-corrected 2 point method with stitching have a potential to satisfy the requirements.[2] Stitching is a technique which enables longer measurement length of profilometry from several partially overlapped profiles. With our analysis error propagation in case using stitching can be expressed by combination of 3 dimensionless parameters which characterize measurement conditions.[3]

In this paper error in stitched profile analytically estimated considering error propagation was compared with experimental value obtained by stitching for evaluation of our analysis.

2. STRAIGHTNESS MEASUREMENT WITH LONG MEASUREMENT LENGTH

Figure 1 shows measurement error as a function of measurement length for several conventional straightness measurement methods. In this figure, deviation of 2-sigma is used for expressing measurement error or accuracy. As shown in figure 1, it’s difficult to satisfy measurement accuracy for main linacs in ILC project by using conventional method.

On the other hand, tilt-corrected autocollimation and tilt-corrected 2 point method are promising for accurate profilometry having long measurement length.[2] They cancel scanning fluctuations by principle of autocollimation or 2 point method and correct angular fluctuation by monitoring anglemeter as shown in Figure 2. However, in these methods, measurement length is limited by limitation for measurement length of the monitoring anglemeter. Stitching which realize longer measurement length by connecting several measured profiles is applied in various fields to overcame such limitation.

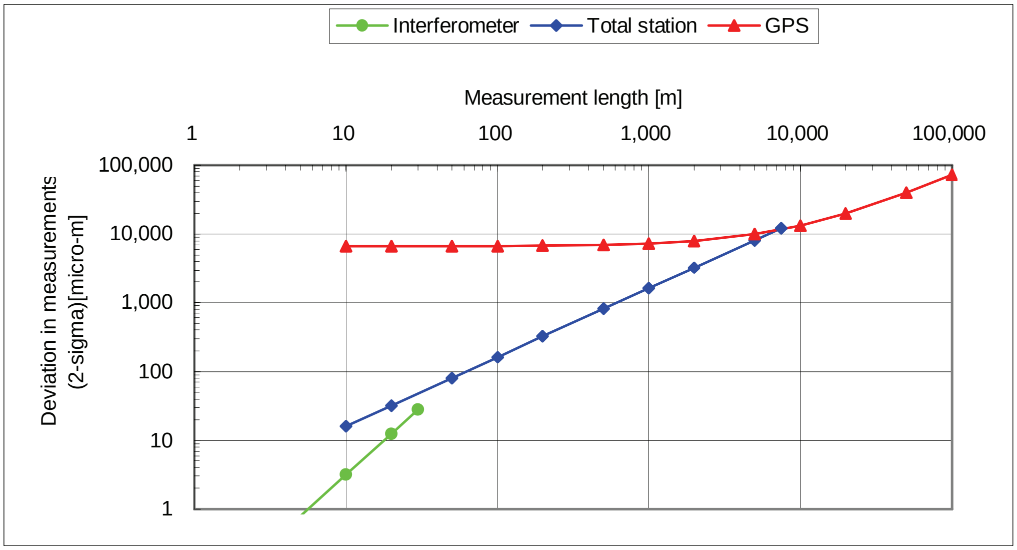

Fig. 1. Measurement error as a function of measurement distance for conventional straightness measurement methods

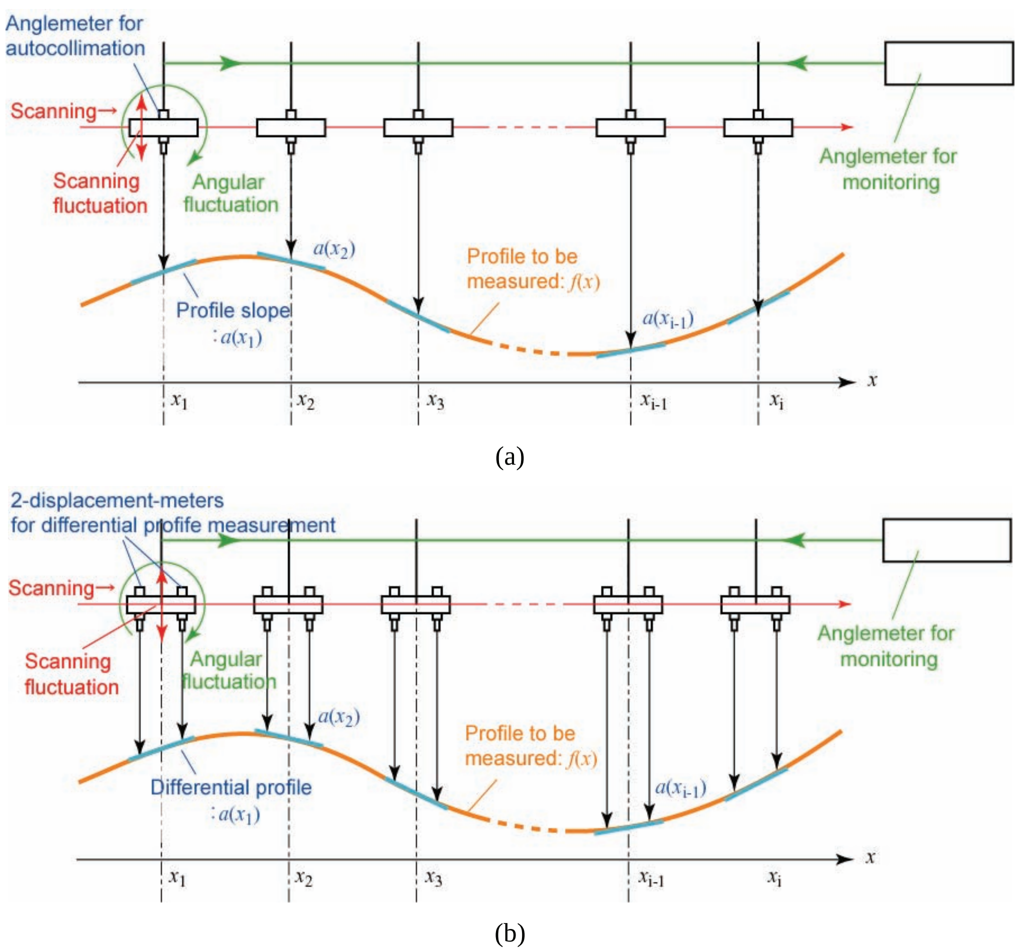

Fig. 2. Schematics of (a) tilt-corrected autocollimation and (b) tilt-corrected 2 point method.

Figure 3 shows schematics of stitching, where f(x) and l express total profile to be measured and its length, $f_i(x)$s and Ls express partly measured profiles from the total profile and their length called unit measurement length, and k*Ls express overlaps of the measurement range. A dimensionless parameter k is defined as an overlapping ratio against the unit measurement length L. In this figure, σ_d and σ_e express error in each measurement and error of the stitched profile at the end of measurement, respectively.

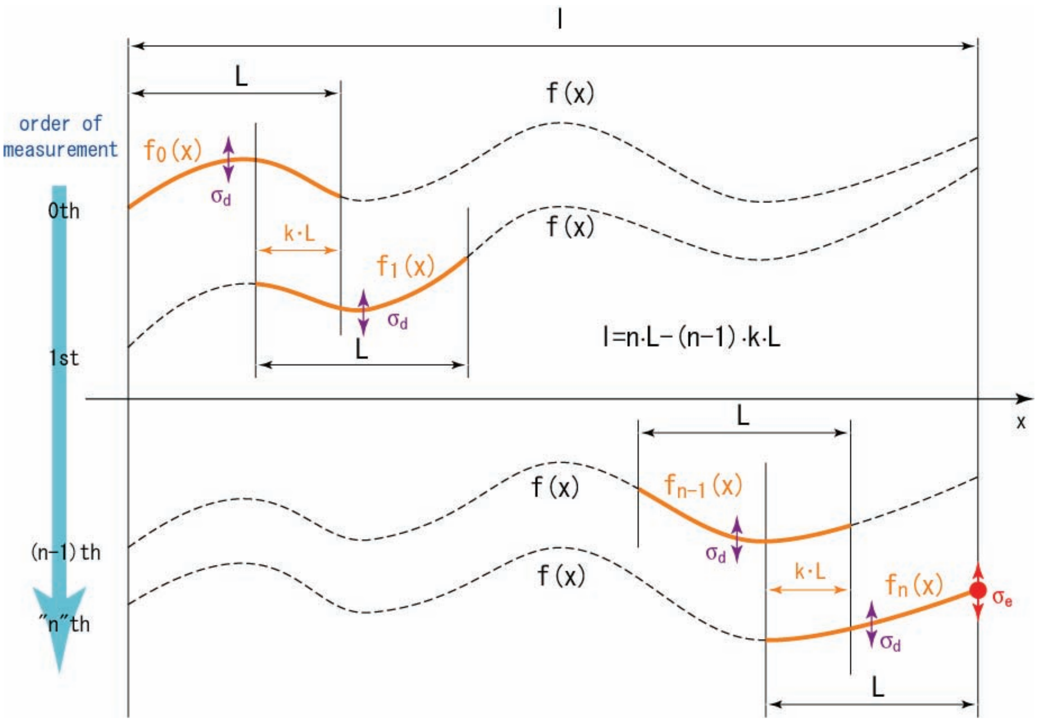

Fig. 3. Schematics of stitching.

Figure 4 shows analytically predicted error as a function of measurement length for tilt-corrected autocollimation with stitching, where unit measurement length L=1[km], sampling interval s=10[mm], overlapping ratio k=0.5, error for each autocollimation σ_{da}=0.13[sec], error for each monitoring anglemeter σ_{dp}=0.33[sec]. The relationship for tilt-corrected 2 point method is expressed similarly. As shown in figure 4, tilt-corrected autocollimation is promising for accurate profilometry having long measurement length expected for primary alignment of accelerator structure in ILC. Parameters used here are based on the specifications for conventional measurement instruments. The relationship for the tilt-corrected 2 point method can be considered similarly to that of the tilt-corrected autocollimation.

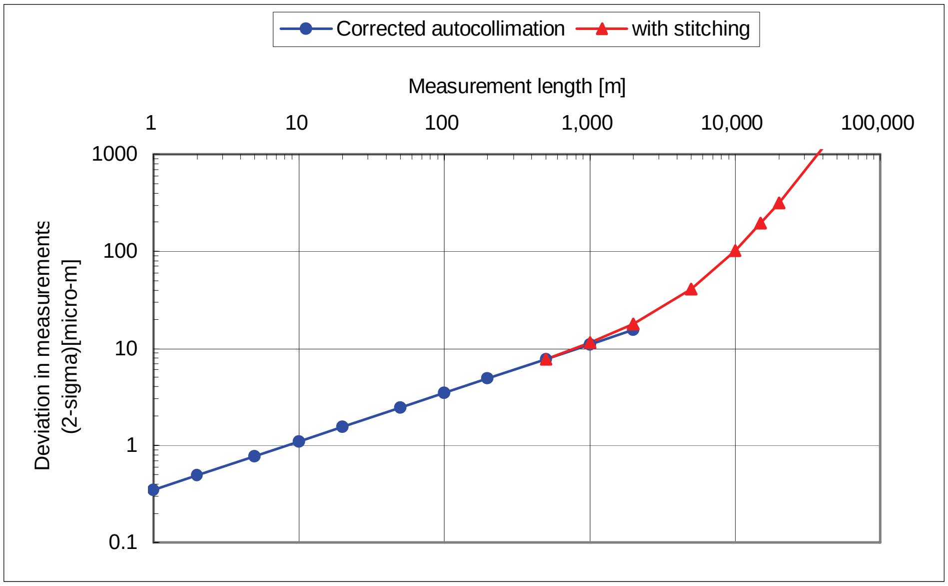

Fig. 4. Measurement error as a function of measurement length for tilt-corrected autocollimation.

3. ERROR ESTIMATION IN STITCHING CONSIDERING ERROR PROPAGATION

Assuming that measured profiles next to each other $f_{i-1}(x)$ and $f_i(x)$ are connected as their least square approximation lines match at their overlap as shown in figure 5, propagated error to the profile connected by stitching σ_e is expressed as

$$\sigma_e = \sqrt{1 + \frac{4(v-k)}{(1-k)\cdot(1+uk)\cdot(2+uk)} \cdot \left(\sqrt{\frac{6uv^2}{k}} + \sqrt{2uk+1}\right)^2} \cdot \sigma_d = K_e \cdot \sigma_d \qquad (1)$$

considering error propagating rule, where dimensionless coefficients u and v are defined as

$$u = \frac{L}{s}, \qquad (2)$$

$$v = \frac{l}{L}, \qquad (3)$$

respectively.[3] Here, u named sampling coefficient stands for number of sampling point within the unit measurement length, v named measurement length expansion coefficient stands for expansion ratio for measurement length by stitching. As shown in equation 1, error propagation toward stitched profile can be expressed as product of error for each measurement unit σ_d and error propagating coefficient K_e. Here, K_e is expressed by 3 dimensionless parameters u, v and k.

Figure 6 shows estimated error propagation coefficient K_e as a function of overlapping ratio k, using sampling coefficient u as a parameter. It predicts existence of the optimum “k” s which make K_es minimum.

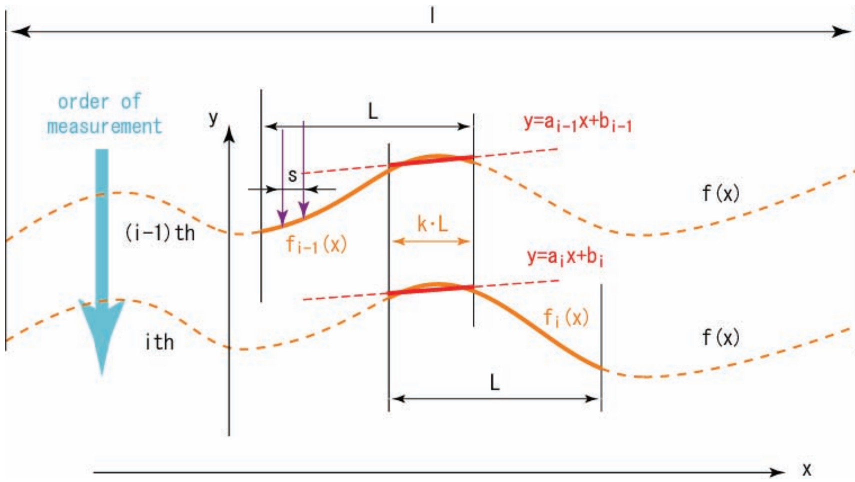

Fig. 5. Profiles next to each other $f_{i-1}(x)$ and $f_i(x)$ are stitched as their least square approximation lines , $y=a_{i-1}x+b_{i-1}$ and $y=a_ix+b_i$ match at overlap, where s stands for sampling interval.

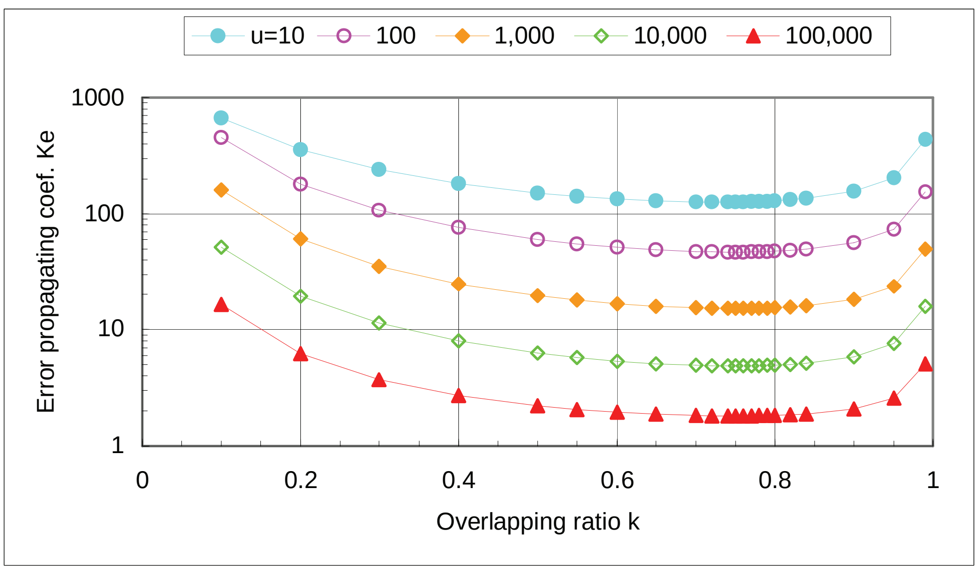

Fig. 6. Estimated error magnification K_e as a function of overlapping ratio k for sampling coefficient u as a parameter.

4. EVALUATION OF THE ERROR ESTIMATION USING EXPERIMANTAL VALUE

As error propagation by stitching can be expressed by using several dimensionless parameters, error in the stitched profile can be estimated indepen

dently of scale. It means that the relationship expressed by Eq. 1 can be applied for any scale of stitching and that the relationship can be evaluated by using arbitrary size of experimental set up, not necessarily using real size of setup.

We used data obtained by straightness measurement system shown in figure 7 for evaluation. It was made to measure straightness of single accelerator structure, using laser displacementmeters and can measure up to 1.5 m of length with repeatability of 0.2 micro-meters (σ) by using inverse method.

Measured profiles were divided into virtual units having unit measurement length of L and overlapping ratio of k. Then, the units cut from different measurements with each other were connected to realize virtual stitching. Figure 8 shows examples of the 10-times of measured profiles by using the system shown in Fig. 7. Figure 9 shows 10 profiles obtained through 9-times of stitching with overlapping ratio of k=0.5 by using virtually divided profiles from the measured profiles shown in figure 8.

Fig. 7. Straightness measurement system for single accelerator structure, whose measurements were used in virtual stitching for experimental evaluation of error estimation in stitched profile. Left: Overview (2.5 m of system height), Right: Enlarged picture of the system around laser displacementmeters. It is set in thermostatic chamber (20±1℃), Measured sample was turned oxygen free cupper rod with 1.5m-length and 60mm-diameter, Measurement time: 50min for 2 orthogonal profiles with each other by inversion method (needs 4-times of full-length scanning), in case using sampling interval: s=4mm.

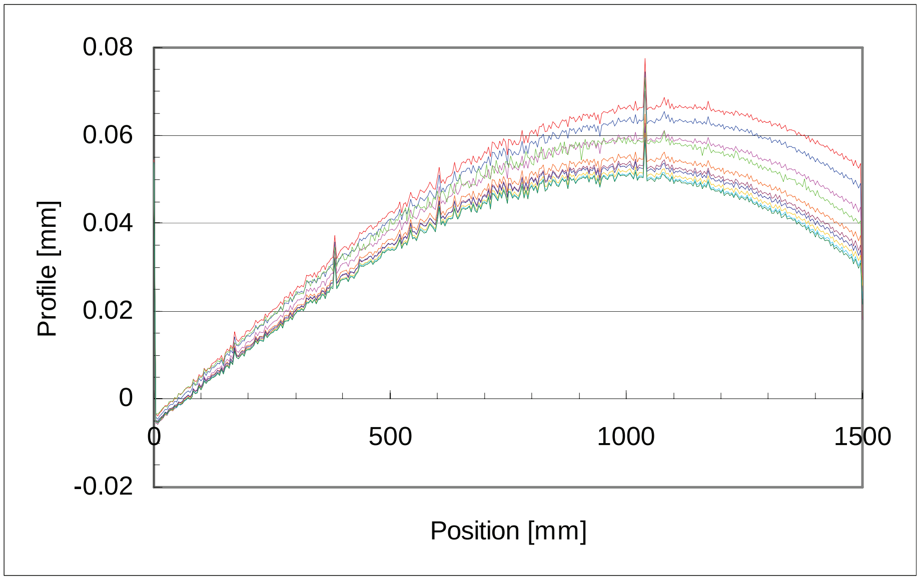

Fig. 8. Examples of the 10-times of measured profiles using straight measurement system shown in figure 7. They are divided into shorter profiles having certain unit measurement length L and overlapping ratio k for virtual stitching.

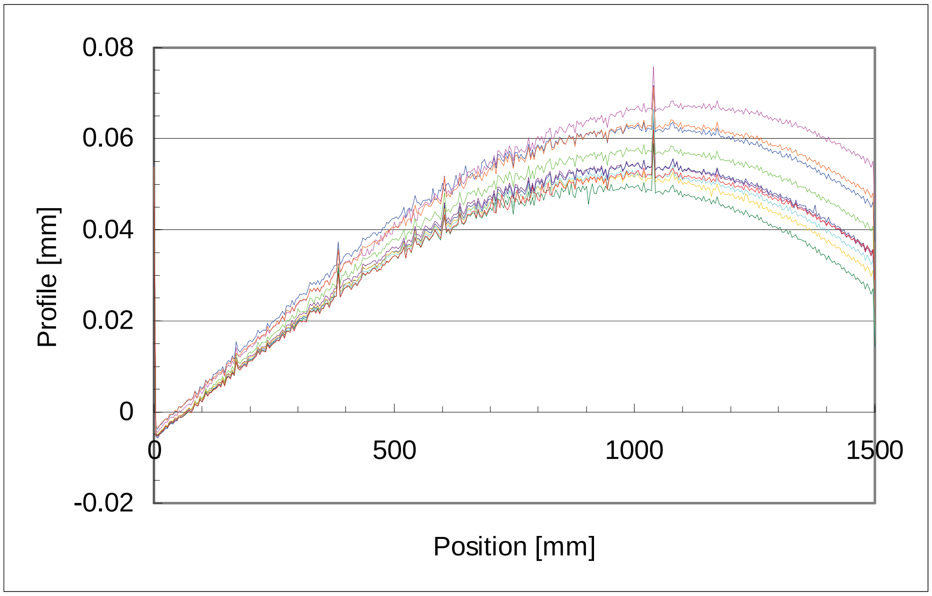

Fig. 9. 10 profiles obtained through 9-times of stitching with overlapping ratio of k=0.5 by using virtually divided profiles shown figure 8.

We made experiments for 3 combinations of u and v, and experimentally obtained relationship between overlapping ratio k and error propagating coefficient K_e in figure 10. As shown in figure 10, existence of the optimum “k” s had not clearly shown by experiments; however, experimental values tend to be smaller than predicted values. We have not yet analyzed the reason; however, it suggests that our estimation tents to show pessimistically, that is more safely.

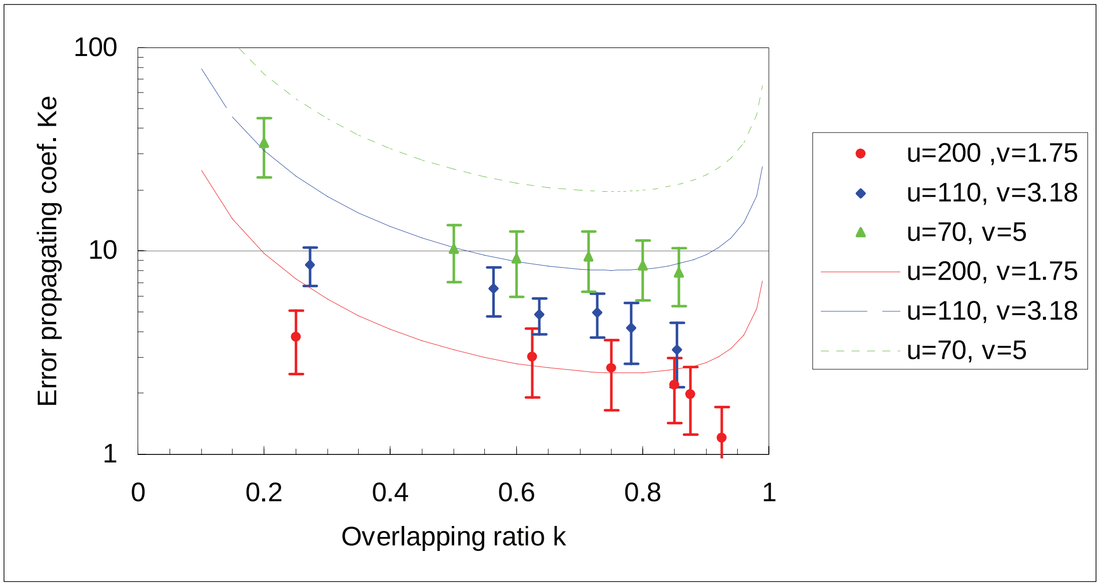

Fig. 10. Error propagating coefficient K_e as a function of overlapping ratio k with 3 combinations of sampling coefficient u and measurement length expansion coefficient v as parameters. 3 lines express analytically estimated relations. Prot points and error bars express average values and deviations for 20 times of measurements, respectively.

5. CONCLUSIONS

Error propagation toward stitched profile was estimated considering error propagation rule and compared to the virtually stitched value through experiment for the relationship between k and K_e.

As a result, existence of the optimum "k" s predicted by analysis had not clearly shown by experiments; however, experimental values tend to be smaller than predicted values it suggests that our estimation tents to show pessimistically, that is more safely..

We are planning to compare in more various measurement conditions, evaluate by using real stitching data, and if need, reconsider analysis model and more accurately estimate error. On the other hand, it's necessary to experimentally confirm validity of tilt-corrected autocollimation and tilt-corrected 2 point method for applying to initial alignment of ILC collider.

References

[1] http://www.linearcollider.org/cms/.

[2] T. Kume, et. al., 2006 spring JSPE biannual meeting N15 (in Japanese).

[3] T. Kume, et. al., "Analysis of error propagation in profile measurement by using stitching", presented on MEDSI2006 (May 24-26, 2006), http://medsi2006.spring8.or.jp/