CAN THE KERN ME5000 MEKOMETER REPLACE INVAR MEASUREMENTS?

RESULTS OF TEST MEASUREMENTS WITH THREE MACHINES

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ABSTRACT

The use of the Kern Me5000 as a 'stand alone' instrument is restricted to a minimum measurement distance of approximately 20m (Kern internal 'low range' program), with 2 display readout to the nearest 100µm. Using an external program, it is possible to extend both, the display resolution to 10µm, 2nd the range down to distances well below 20m. This paper attempts to explain Kern's reasoning behind the original limitation of approximately 20m, and presents the results from testing three Mekometer Me5000 instruments. Their similarities, differences, and accuracies are assessed for distances below 25m providing a comparison against the use of invar wires.

INTRODUCTION

For most of the accelerator research centres, the primary range of distance measurement is less than 200m. Below 50m invar wires are used to determine the required networks within the accelerator tunnels for installation and verification of the accelerator components. With the advent of the Kern Mekometer Me5000 an alternative solution to the measurement of quasi-linear (machine and transfer lines) or three-dimensional (experimental areas) networks using invar wires is offered.

The use of the Kern Me5000 as a ‘stand alone’ instrument is restricted to a minimum measurement distance of approximately 20m (Kern internal ‘low range’ program), with a display readout to the nearest 100µm. Using an external program, it is possible to extend both, the display resolution to 10µm, and the range down to distances well below 20m.

This paper attempts to explain Kern’s reasoning behind the original limitation of approximately 20m, and presents the results from testing three Mekometer Me5000 instruments. Their similarities, differences, and accuracies are assessed for distances below 25m providing a comparison against the use of invar wires.

Starting with the basic equation for distance measurement :

$$\mathbf{D} = (\mathbf{N} \times \mathbf{L}) + \mathbf{A} \qquad (t)$$

Where

N x L = the number of Standard Wavelengths.
A = fractional part of **L.**

The standard-length is a light wave modulated with constant frequency **F.** The half wavelength **L** of the modulation is :

$$L = \frac{c}{2 \times F}$$

So with the light velocity in a vacuum C :

$$c = \frac{C}{n}$$

Where

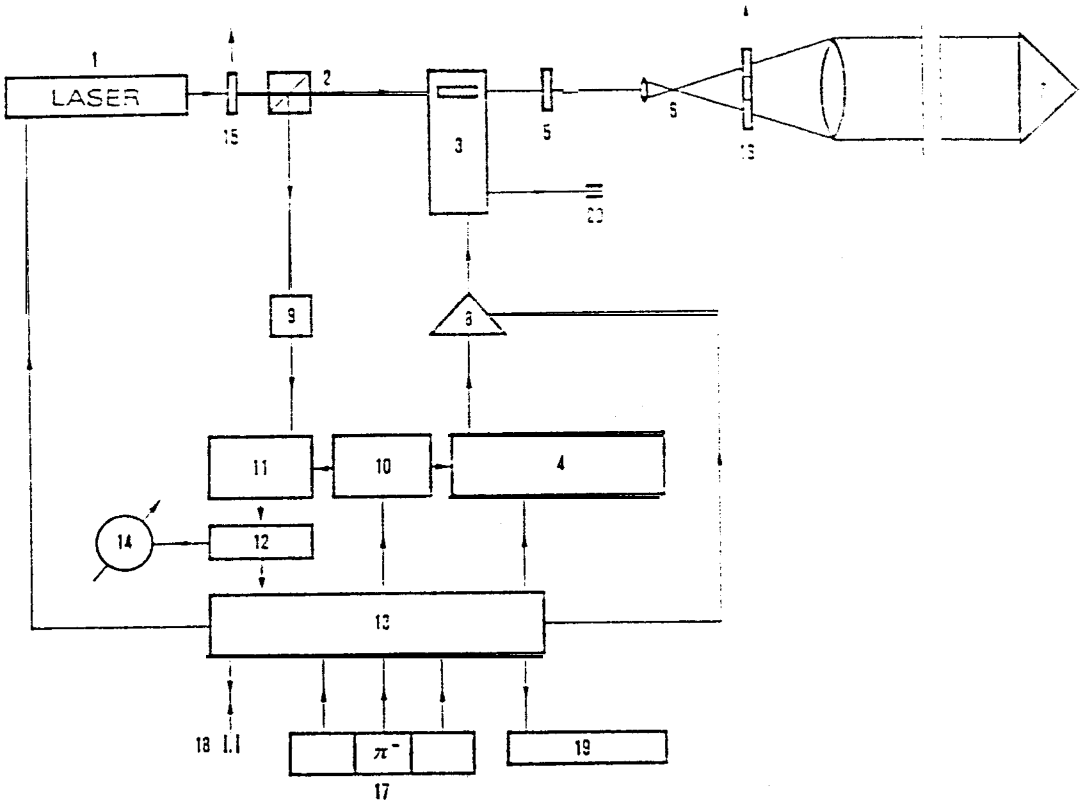
c = light velocity in the medium (ie. air).
n = index of refraction of the medium which is a function of temperature, pressure, humidity, etc...

To improve the resolution of the fractional part of **L,** the modulation is applied on the polarization of the light beam. Schematically (see figure 1), the optical path is : from the source, the light passes through the modulator and is sent to the reflector, returning to a phase detector which compares the polarization with the internal reference beam. The difference of phase is then transformed into a fraction of **L**. In relation (1) above, the unknowns are **N** and **D.** All electro-optical distance meters use two or more frequencies to find **N** but can be separated into two distinct groups due to their method of measuring the fractional part of **L**, namely, **A**.

The first group of instruments which include the Kern Dm502, AGA Geodimeters, Mekometer 3000, and Wild Di2000, use discrete, fixed frequencies to measure the phase difference between the reference and return beams via an electro-optical process.

An alternative method, adopted by the second group, is to vary the frequency until the fractional part is effectively nulled. The Terra Technology Terrameter and Mekometer Me5000 (see figure 1) belong to this group and have the advantage that they are not affected by cyclic errors.

For the Me5000, which uses a Helium-Neon laser (approximate wavelength 0.6m), Kern designed a system incorporating a quartz oscillator coupled together with a light modulator. This produces a working frequency range of 460MHz-510 MHz.



1	Laser	11	Lock-in amplifier
2	Polarization beam splitter	12	A/D converter
3	Modulator	13	Controller
4	Frequency synthesizer	14	Indicator
5	$\lambda/4$ plate	15	Attenuator
6	Telescope	16	Aperture
7	Reflector	17	Control switches
8	RF-amplifier	18	Data I/O
9	Light detector	19	Display
10	Sweeper (Wobbler)	20	Frequency output

FIGURE 1 Schematic diagram of the Me5000 (from [l]). A Helium-Neon laser (1) emits continuous linear polarized light of wavelength, 632.8nm. The light ray passes unaffected, through a polarized beam splitter (2) into the modulator (3) to give a polarized modulated frequency of approximately 500Mhz, the frequency being set by the synthesizer (4). The beam continues to the $\lambda/4$ plate (5), which serves as the temperature compensation for the modulation crystal, and through the telescope (6). The telescope widens the beam before it travels over the measurement path and returns from the reflector (7). In the reverse direction, the contracted beam passes back through the $\lambda/4$ plate, where now, the electro-optical crystal acts in reverse to demodulate the light wave. If at the entry and exit points, given by the amplifier (8), the phaselag of the modulated signal is balanced, then the original linear polarization is restored. In the case no light passes onto the light detector (9), the zero point always occurring when the distance is a multiple of 1/2 the modulation wavelength (approximately 30cm).

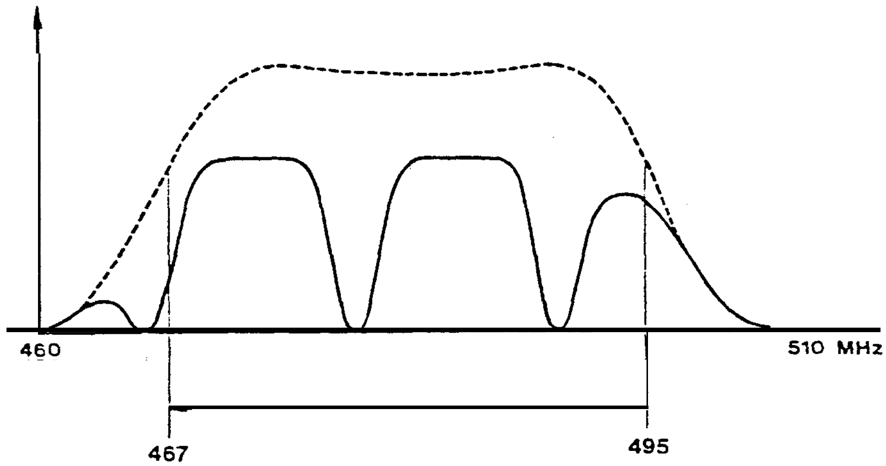


FIGURE 2 Frequencies and minimums (from [1]). The dashed line represents the modulation frequency curve throughout the working range of the instrument obtained during internal calibration of the crystal (plotted against the intensity). The solid line shows an example of how this curve is affected during the measurement process (the minimums occurring where the phase difference between the reference and return beams approaches zero). Although three minimums are shown, the first one is outside the usable range, having a low definition due to the modulation efficiency. The other two are within the optimum band width and would exhibit a good result (notice that both of these appear where the modulation frequency intensity is at a maximum: as the intensity decreases the definition of the minimum is reduced).

However, the actual frequency range used for measuring is reduced from this to an optimum band-width of 470MHz-490MHz; this range varying slightly between instruments due to the uniqueness of each crystal used (see figure 2).

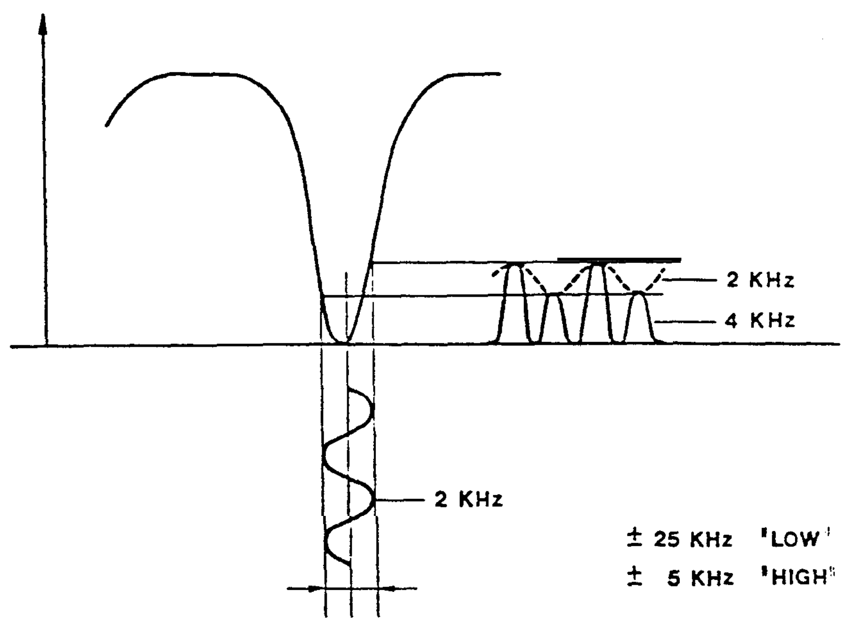


FIGURE 3 Search of a minimum (from [1]). To determine more accurately a frequency at the zero point, the modulation signal is changed by a wobbler, (10) in figure 1, with a sine wave of 2Khz and a shift of either ±5Khz or ±25Kz (dictated by the selection of ‘low’ or ‘high’ range). In the case of zero phase difference, the detector diode actually receives a frequency of 4Khz. Additionally, the amplitude difference, with a frequency of 2Khz, is measured in the look-in amplifier, (11) in figure 1, and sent to the computer via an A / D converter. The zero point is found by changing the synthesizer frequency in steps of 0.3ppm.

In order to measure a distance, the Me5000 varies the modulation frequency to search for minimums within the optimized band-width (ie. where the superimposition of the returned and internal reference beams are exactly in opposite phase. see figure 3). These places are referred to as minimums because residual background prevents the complete suppression of light.

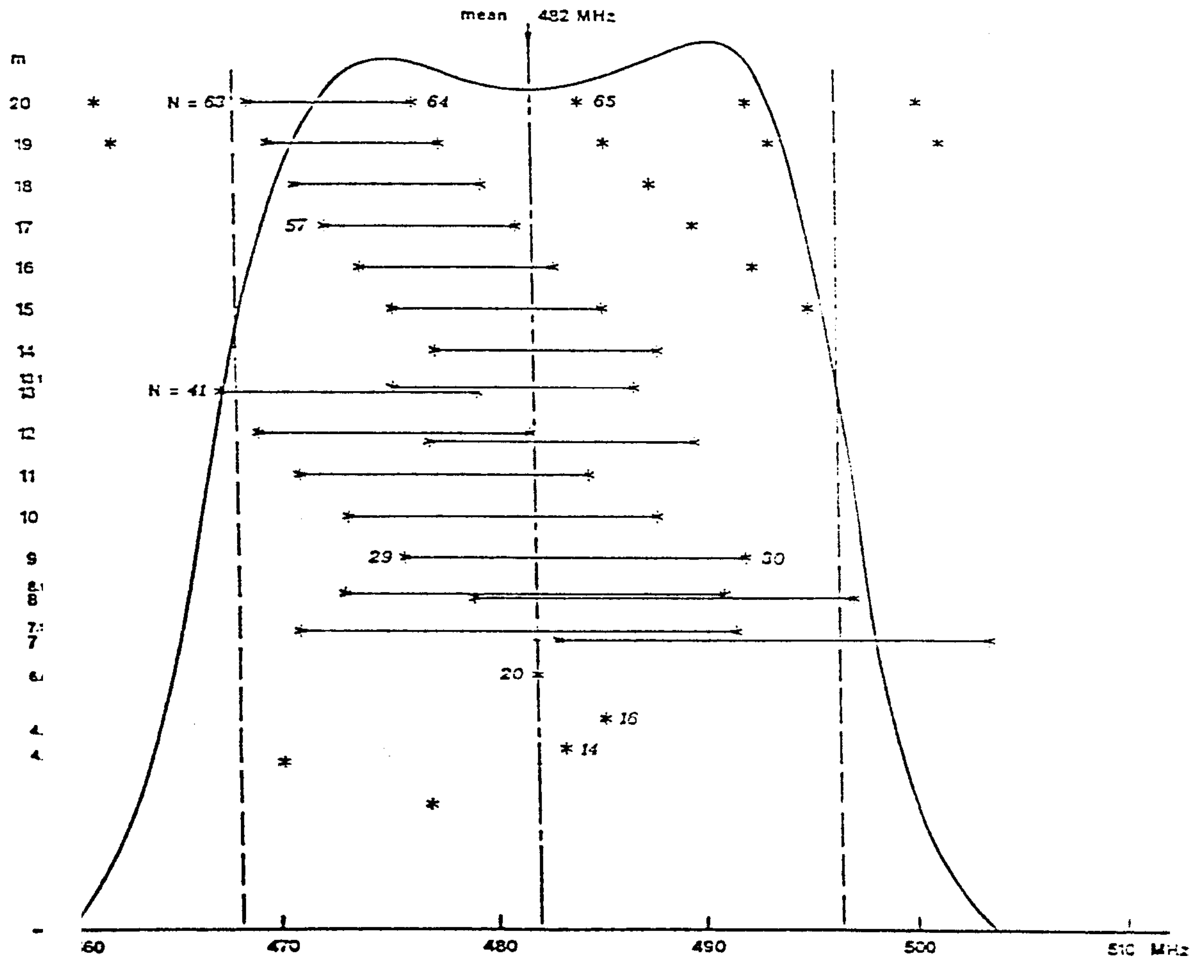


FIGURE 4 Distances, frequencies, modulation efficiency and minimums. This figure illustrates several characteristics of the Mekometer 5000. As in figure 2, the frequency curve is displayed with the extended band-width limits of 467Mhz-495Mhz. Following a horizontal line across from the distance axis the location of minimums (number and spacing) is depicted, each asterisk corresponding to a minimum. The general trend can be seen; the spacing of the minimums increase as the distance decrease, but the difference, in Mhz, between adjacent minimums, for any given distance, remains identical (e.g. if the second minimum is 5Mhz higher than the first, the third will be 5Mhz higher than the second). Therefore, knowing two frequencies, it is a simple computation to determine if any others exist within the extended range of the instrument without any further searching. This leads to the logic, that for distances greater than 25m, where more than four minimums exist, the minimums used for the distance calculation are chosen to be the first, last and median ones (the median minimum being the closest to the centre of the band-width). The cut off point between finding two frequencies, or only one frequency, within the range is not precise (e.g. only one frequency is found at 8m, but two occur at 7m).

Depending on the distance measured and the available frequency band-width, there are a varying number of possible minimums for the determination of D. This number increases from 4 frequencies at 20m as the distance is extended (in its normal mode as a stand alone instrument). When the distance is reduced below 20m, the number of frequencies decrease until only one

Before a calibration was conducted using an HP interferometer as the reference standard, the position of the windows present for each machine were calculated from the extended modulator range. The distances set during the tests included positions at the edge of windows as well as the centre, from table 2 we can see that due to the smaller range of machine B, there is approximately a 30% reduction in the size of the measurement windows between 4 and 5 metres and hence an approximate distance is required sooner than for the other instruments (notice the reduction in window size as the distance is decreased with all of the instruments).

Instruments A and C				Instrument B			
Position of Measurement Windows (metres)		Percentage of measurable distances per metre		Position of Measurement Windows (metres)		Percentage of measurable distances per metre	
lower limit	upper limit	Distance (metres)	(%)	lower limit	upper limit	Distance (metres)	(%)
2.984	3.083	0 - 1	11	2.904	3.033	0 - 1	8
3.197	3.405	1 - 2	30	3.208	3.350	1 - 2	20
3.501	3.728	2 - 3	54	3.513	3.668	2 - 3	40
3.804	4.050	3 - 4	71	3.817	4.985	3 - 4	50
4.108	4.373	4 - 5	88	4.122	4.303	4 - 5	58
4.412	4.695	5 - 8000	100	4.427	4.620	5 - 6	75
4.715	8000			4.731	4.938	6 - 7	90
				5.036	5.255	7 - 8000	100
				5.340	5.573		
				5.645	5.890		
				5.949	6.208		
				6.254	6.525		
				6.559	6.843		
				6.863	8000		

TABLE 2 The range of distances measurable (in metres) translates into the given percentages per metre. it was found that machines A and C exhibited virtually the same windows, instrument B losing a large percentage of measurable distances. This affects the performance of B in two ways; namely, a need to enter the approximate distance at longer distances due to only one frequency being available, and a greater restriction to the distances possible to measure.

CALIBRATION SETUP

Prior to calibration of the instruments, a series of tests were conducted to compare the dispersion characteristics of the standard Kern Me5000 reflector against the HP interferometer prism. Although a slight increase in dispersion was observed the overall differences when using the mean of three measurements were considered insignificant.

Using a 30m calibration bench, a Mekometer was positioned just off the end of the bench on a separate rigid stand at the interferometer beam height. By using two HP interferometer prisms ‘back to back’ on the bench, the following observational errors were eliminated:

1) all measurements were taken at the same height eliminating the need to apply height reductions later,

2) by not using the standard Kern prism, problems due to height differences between the Interferometer and Mekometer laser beams were avoided.

Therefore, all measurements recorded led to the calibration the instruments for relative distances (ie. the absolute distances were not compared).

minimum can be found in the optimized band-width, here an approximate distance is required to compute N in the above equation. However, minimums may also occur outside the optimized band-width and still within the modulator limits of 460MHz-510MHz. Where this situation occurs, it is still possible to obtain a distance but the reduced efficiency of the modulator can lead to a loss in definition of the minimum, causing a drop in the attainable accuracy. Eventually, as the distance is shortened even further, the only minimum found occurs outside the optimized range of the modulator so that the resulting distance may be less accurate or even wrong (e.g. it locates a point of inflexion rather than a minimum). Finally, where the only (theoretically) possible minimums occur outside the working range of 460MHz-510MHz, no measurement is possible. This situation is referred to as outside the measurement window (see figure 4).

With this design, the primary operating range from 20m to 8000m was chosen by Kern so that no approximate distances would be required (as at least 2 minimums are locatable in the optimum range of the modulator). incidentally, the problem of finding the minimums is reversed at very long distances (greater than 8000m) as the minimums get closer and closer it becomes difficult to change the frequency by small enough steps so that a minimum is not missed.

SHORT DISTANCES

For distances less than 18m it is necessary to have a separate measurement procedure via an external program in order to initialize the parameters of the instrument prior to any measurement. This is required to optimize the instruments sensitivity for minimum detection, the primary influences being the frequency sweep range and the signal interruption characteristics. In fact, the design range of 20m to 8000m is also split into high and low range, selectable via a switch on the instrument display, to give optimum frequency sweep band-widths from approximately 20m to 1000m and above 1000m.

The original versions of the Me5000 provided a short distance capability by using only the optimized band-width. In an attempt to further extend the measurement range at short distances the band-width used was increased to 3/4 of the light intensity (465MHz-495MHz corresponding to a maximum and minimum half wavelengths of 320.9mm and 302.7mm respectively). This effectively extended the window size and so reduced the need for approximate values until much shorter distances (ie. two frequencies are found at shorter distances). However, a trade-off in accuracy can be noticed when using a frequency not within the optimal band-width.

The first indication of a difference between the three machines was noticed by looking at the variance of the modulator working range when the instruments are warm. Table 1 shows the ranges for the three instruments (instruments warm), giving an indication that their capabilities are related directly to the uniqueness of the quartz crystal used.

Variance of Modulator Working Range (MHz)			
Instrument Range	A	B	C
Normal	472.8-487.6	474.8-489.6	472.1-486.2
Extended	464.7-493.6	472.1-492.3	464.0-493.0

TABLE 1 Variance of the modulator working range (Mhz). This table clearly shows the basis of the difference between the three machines. Instrument B has a much steeper slope on the left hand side of the modulator curve (unlike the curve shown in figure 2), resulting a restriction of measurement possibilities in comparison to A and C.

The modulator band-width actually shifts very slightly as the instrument warms up. This change does not influence the results obtained in the normal use of the instrument, but there is a corresponding shift in the measurable windows implying a small variation in distances measurable below approximately 10m.

OBSERVATIONS

Starting at a distance of approximately 25m, a series of three measurements were recorded and corrected for meteorological influences, the mean being used for the Least Squares regression fit. The distance was then reduced by regular intervals until 10m, below which, each distance measured corresponded to either, a minimum located within the centre of the band-width, or a minimum at the lower edge of the extended band-width. To obtain the required distances measured by the Mekometer, the correct distance change using the Interferometer was pre-calculated and implemented. The range selected for each measurement was chosen as specified within the program; for example, below 20m, the selection chosen used the 'very short' distance option parameters, and above 20m the normal distance parameters were implemented.

The time taken for a particular measurement varies depending on whether one or two zeros are present and the location of the point within the band-width. It is also dependent on the distance; experience has shown that the definition of the zero becomes worse as the distance decreases.

Using the short distance modes, below approximately 16m, the final distance is computed from either two frequencies obtained or a single frequency plus an approximate distance given by the operator. This coarse distance must be known to an accuracy of ±0.1 m in order to compute the number of nodal points, (N). Experience has shown that, if entering the approximate distance prior to the search, it is always better to err on the higher side of the actual distance (i.e. ±0.1m) so as not to initiate the search after position of the minimum (the starting position is pre-calculated from the median frequency within the band-width). Should the coarse distance be greater than ±0.1m, an incorrect result will be calculated as the wrong nodal number will have been computed. Within the range where measurement windows are present, the required approximate distance must be determined to greater accuracy for the search to detect a minimum (to 2mm depending on the location of the frequency). The necessity for mm accuracy stems from the change in frequency due to a change in distance; the longer the distance the smaller the change in frequency.

In addition to the variance of measurement windows for each instrument, it was noted at very short distances, usually less than 5m, that two frequencies (minimums) may be located, in contradiction to the theory stated previously. This anomaly is possible because as the distance measured decreases, the definition of the minimums also reduces until the instrument mistakes a point of inflexion for a minimum. Should this incorrect frequency not be rejected, the ensuing reductions to obtain the distance will yield the wrong result. Usually, the incorrect frequency can be disregarded by verification of each frequency with the coarse distance measured to an accuracy of lmm.

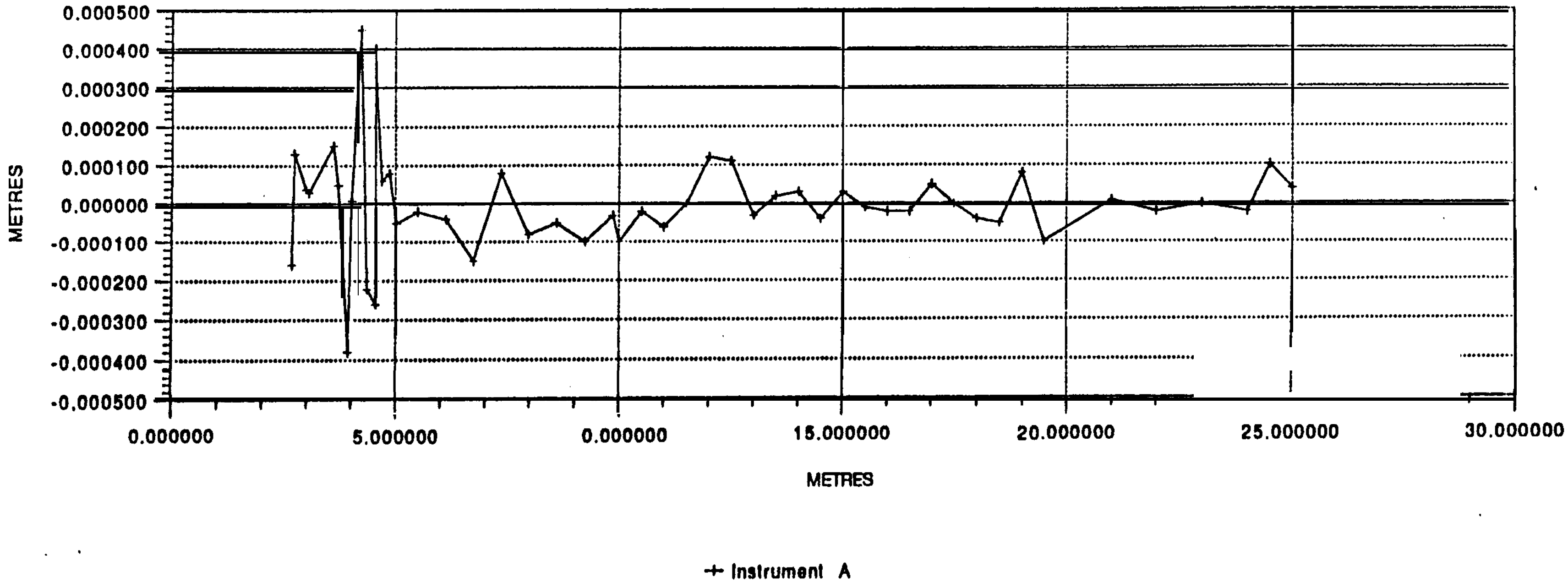
Another observation which affects the instruments only within the range of the measurement windows (below 6m), is the variance of the working frequency range of the modulator. As the machine warms up there is a noticeable shift in the frequency band-width downwards by usually 0.5MHz, which corresponds to a shift in the position of the measurement windows. Although this always occurs during the warm up, it is transparent at distances above the measurement windows and can be ignored.

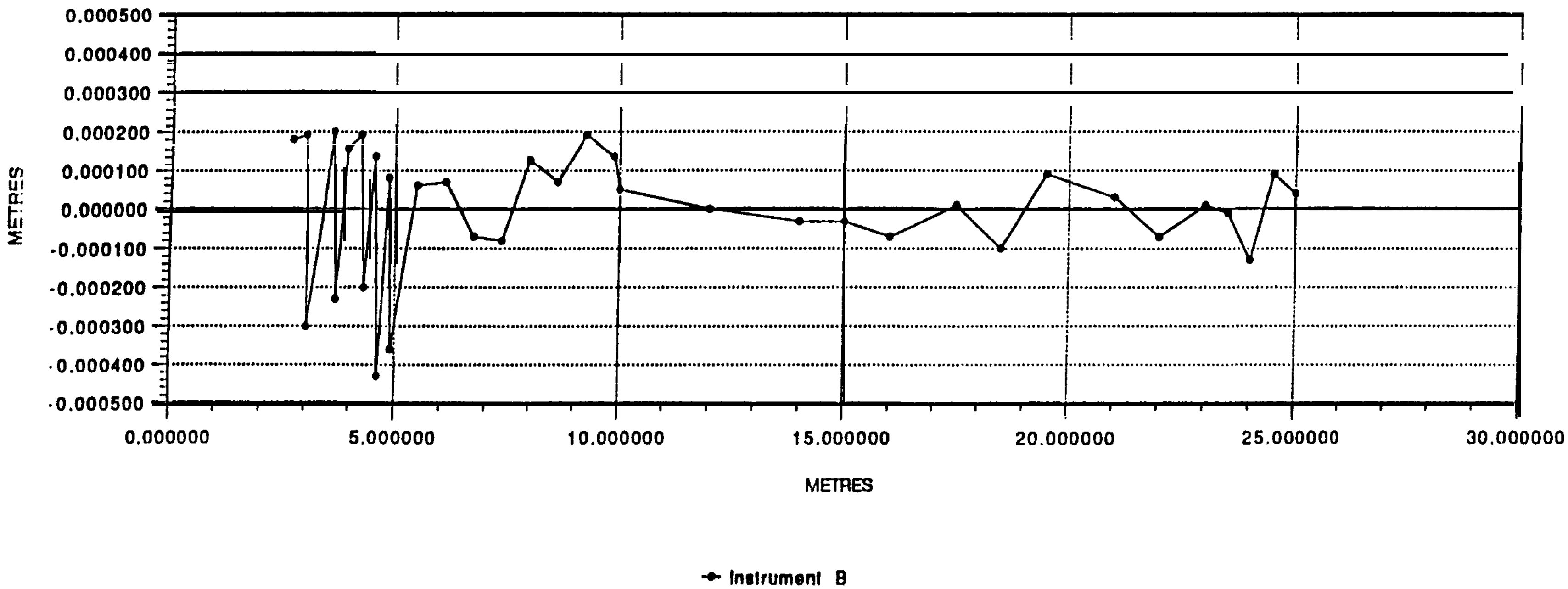
For all distances measured, the final distance determined by the Mekometer was the mean of a series of three individual measurements. In virtually all cases, from the experienced gained, the dispersion of individual measurements should not exceed 120μm. The exception to this occurs at extremely short distances where poor minimum definition leads to an increase in dispersion.

RESULTS

Based from this theory, the results, shown in the individual graphs, were obtained for machines A and B and C. For the these graphs, the regression line parameters and overall standard errors can be seen in table 3. The overall standard errors, in the worse case (160μm-instrument B), are still within Kern's quoted accuracy of ±200μm. The measurement range was taken from 25m down to the minimum feasible distance for each instrument This minimum feasible distance being defined as the point where windows account for less than 50% of the distances per metre.

RESIDUALS FROM LEAST SQUARES REGRESSION FIT





Although the measurements were not made exactly at distances which were an integral number of 1/2 wavelengths (approx 30cm), in general it appears that the distance is more accurate when this condition has been met (this usually does not apply in the normal range as other influences become of greater concern).

Regression fit for a line **aX + bY = r**			
Instrument	A	B	C
	Metres	Metres	Metres
a	0.000018	0.000129	0.000393
b	1.000002	1.000016	0.999994
r	1.000	1.000	1.000
Qverall Standard Errors			
	Metres	Metres	Metres
σ_o	0.000100	0.000160	0.000134
σ_a	0.000024	0.000048	0.000037
σ_b	0.000002	0.000004	0.000003

TABLE 3 **The overall standard errors and regression line parameters obtained for the three machines.** The measurement range was taken from 25m down to the minimum feasible distance for each instrument. This minimum feasible distance was defined as the point where windows account for less than 50% of the distances per metre.

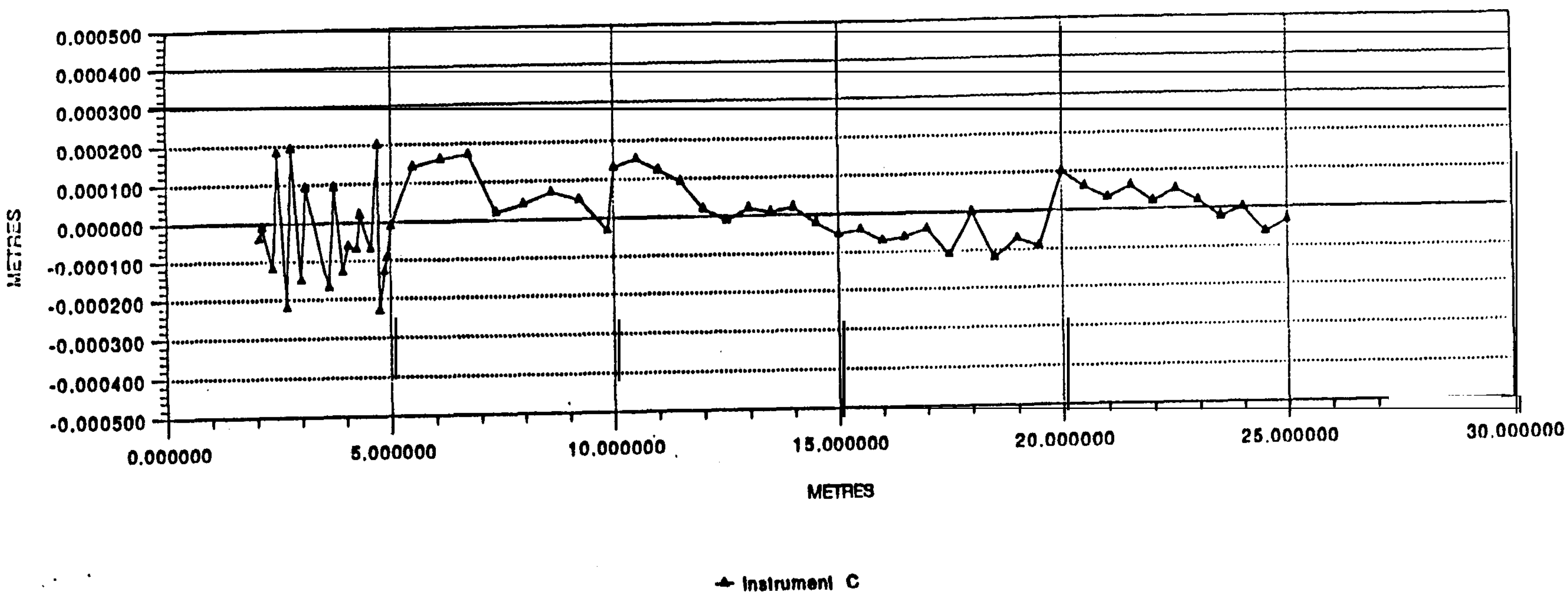
However, there may well be a basis for optimization of the short distances when in the initial planning stages of a survey. As can be seen from these individual graphs, the residuals increase noticeably below 5m for all three instruments.

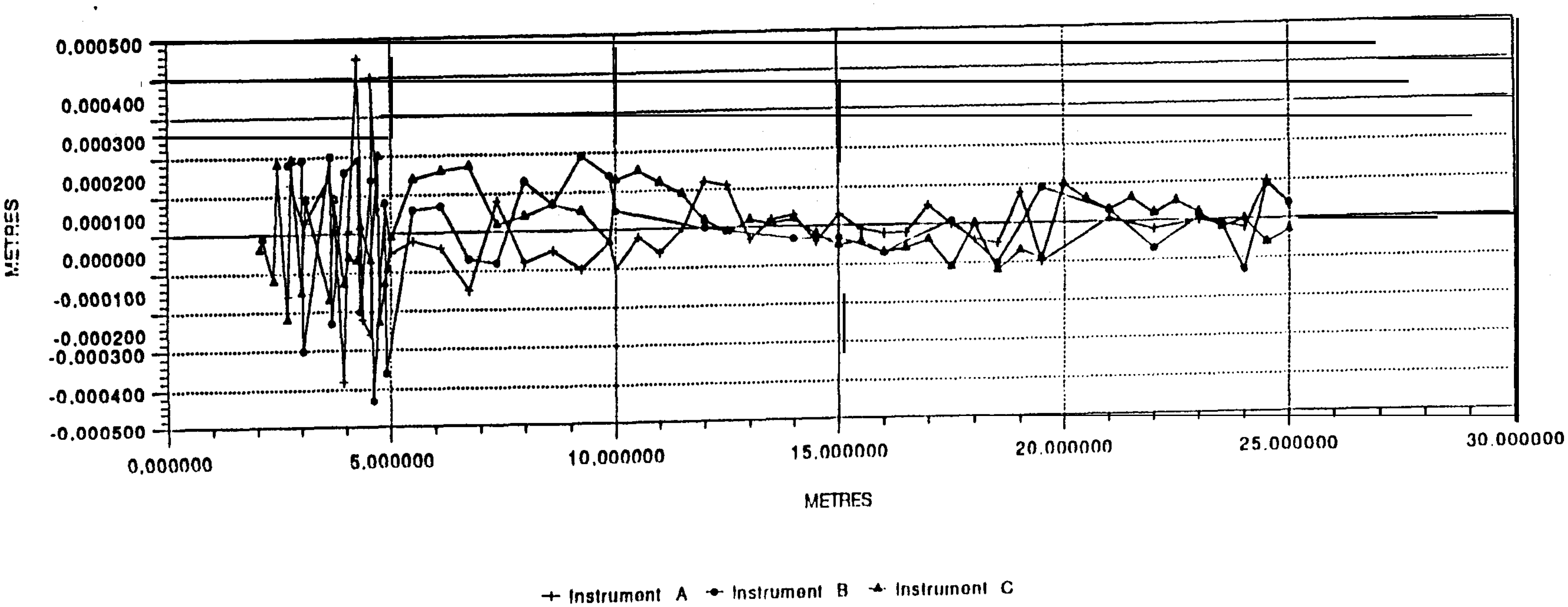
Regression fit for a line **aX + bY = r**			
Instrument	A	B	C
	Metres	Metres	Metres
a	0.000126	0.000202	0.000330
b	0.999996	1.000012	0.999997
r	1.000	1.000	1.000
Amended Standard Errors			
	Metres	Metres	Metres
σ_o	0.000066	0.00080	0.00059
σ_a	0.000029	0.000041	0.000027
σ_b	0.000002	0.000003	0.000002

TABLE 4 **The amended standard errors and regression line parameters obtained for the three machines.** The measurement range was taken from 25m down to 5m.

Table 4 indicates the significant reduction in the standard errors when the cut off point is raised to 5m. Combining the three graphs together shows further the various consistencies between the three instruments. Effectively, the graph may be subdivided into 4 sections in order to explain the variations:

RESIDUALS FROM LEAST SQUARES REGRESSION FIT





1) **Below 5m.** Only one frequency is located and, as a small change in the distance will correspond to a large change in the frequency, the resolution of the minimum will be reduced leading to a decrease in accuracy.

2) **5m to 12.5m.** Here, two frequencies are found, with a strong possibility that one of them occurs outside the optimum band-width. Although, the accuracy is less than at longer distances, because the final distance is a reduction from two zero points, the accuracy remains greater than when below 5m.

3) **12.5m to 20m.** In this region, most of the time, the minimums will be within the optimized band-width coupled with the correct initial parameter set for the range (for example the low and high range selector for 'normal' distances).

4) **Above 20m.** This gives a good indication that the instrument is reaching the limit when the low range initial setup parameters are used. As the region is an overlap between the very short distance and the lower end of the low range settings, perhaps an increase in accuracy may result in using the same option as with the section 12.5 to 20m.

It should also be noted that the HP interferometer prisms are much smaller than the standard Kern Prism and therefore may exhibit slightly different results. However, within the restrictive tunnel environment, it becomes preferential to employ a smaller prism due to limited lines of sight.

CONCLUSION

With the Mekometer Me5000, Kern has produced an excellent instrument of sound design and construction incorporating the best possible choice of crystal modulation range, plus an ability to access the internal Eprom, via special commands, for utilization with a portable computer. In fact within its usual working range the limiting factor tends to be the instruments sensitivity to atmospheric conditions. Additionally, to extend the instruments normal working limits it is essential to have good software. To this end, a complete software package has been developed at SLAC to directly incorporate measurements into the GEONET environment.

In order to make a direct comparison against invar measurements a 3-dimensional trilateration network consisting of 33 distances (8 less than 5m, 16 between 5m and 10m, and 8 more than 10m) was measured at SLAC (in the collider hall of the SLC) using both the Me5000 and Distinvar. The ease of using the Me5000, especially as these distances varied from 3.3m to 13.9m, was clearly demonstrated against the use of invar wires. However, as the original network was setup primarily for invar measurements two distances within the network could not be measured by the Me5000 due to line of sight difficulties. Therefore, the two corresponding invar distances were appropriately weighted and added to compensate the Me5000 network After reduction via least squares, the final results for the Mekometer and Distinvar measurements yielded standard errors of 0.178mm and 0.143mm respectively, in a 95% confidence limit. However, from the calibration results presented in this paper, the accuracy of the Mekometer drops significantly when measuring distances below 5m, indicating that the results would probably be closer to the adjustment via invar if distances below 5m were avoided.

Another illustration of the results attainable can be seen from a three-dimensional 'ring' traverse typical of the type required for small accelerator rings. The network was measured entirely by trilateration using the Me5000 together with geodetic levelling and consisted of 38 distances varying from a minimum of 2.6m to a maximum of 13.4m (the majority lying within the range 5m-9.2m). The final standard error computed via least squares was 0.18mm in a 95% confidence limit.

Although the Distinvar is not commercially available in its automated form, it is still used extensively for network measurements at accelerator research centres. This system requires a prior knowledge of distances to within 5cm so that the invar wires may be cut and calibrated both before and after the survey. Certain distances may not be measurable with the Distinvar such as, steep slopes or where access to enable suspension of the wire between points is difficult. For longer distances, such as a linear traverse, typical within a tunnel environment, the Me5000 has be used to compliment the use of the Distinvar, for example, to check for propagation of errors.

‘Can the Kern Me5000 Mekometer replace invar measurements’ does not yield a straight forward answer. For short distances below 5m the Distinvar will give better results. However, the Mekometer does offer a viable alternative for measurement between 5m and 25m, as indicated by table 4, against the usual standard error of 70µm for the Distinvar. Above 25m, the Me5000 would be the instrument of choice, a distinct advantage being its ease of use over a larger measurement range. Full application of this range, from a minimum feasible distance to 8000m, would enable surface and tunnel networks to be measured using the same distance measurement system.

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