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Forschungsberichte des
Instituts für Phonetik und
Sprachliche Kommunikation
der Universität München
(FIPKM) 31 (1993) 91 -104.

MAGNETOMETRY IN SPEECH ARTICULATION RESEARCH:

Some misadventures on the road to enlightenment

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Abstract:

With the loss of x-ray microbeam technology (at least in the United States) as a tool for tracking speech articulatory motion, electromagnetic transduction of the lips, jaw, and tongue may soon become a widely used alternative. The technique involves the generation of three alternating magnetic fields and measurement of the three voltages induced in a number of small transducer coils attached to flesh points in the mid-sagittal plane of the device. These voltages are then converted to transducer positions in a two dimensional Cartesian coordinate plane. While the principles of electromagnetic transduction are well known, the application of magnetometry to speech articulation is new and brings with it a number of potential problems. Perkell and colleagues have recently reported on the sensitivity and reliability of one such device (Perkell, Cohen, Svirsky, Mathies, Garabieta and Jackson, 1992). This presentation focuses on some practical problems encountered during the introduction of a new version of the Perkell instrument at Haskins Laboratories. The Haskins system uses similar transducers, and head mounted transmitter coils. However, the physical environment, electronic components and system software differed sufficiently to necessitate the independent evaluation of several performance dimensions. We conclude that a magnetometer can be a reliable and sensitive instrument for measuring two-dimensional midsagittal articulatory motion if certain procedures are adopted to avoid potential artifacts.

Introduction:

This paper reports on the practical experience gained by one group of investigators during the course of installing, calibrating and using one particular model of articulatory magnetometer. The object in question is the Electromagnetic Midsagittal Articulometer or EMMA developed by Dr. Joseph Perkell and his colleagues at the Massachusetts Institute of Technology (Perkell, Cohen, Svirsky, Matthies, Garabieta and Jackson, 1992).

Model number 9004, which we believe to be the first commercially manufactured version of the MIT instrument, was delivered to Haskins Laboratories in the fall of 1991. During the first year of use we experienced several alarms and misadventures caused by the appearance of, what were to us at the time, unexpected or inexplicable artifacts. Therefore, we undertook a series of precautionary tests and discovered a number of facts about our articulometer. In retrospect, we now think that few of these facts may be worthy of more than passing attention, nevertheless, the work of uncovering them did enlighten us about the level of precision that our magnetometer could achieve, and about the pitfalls that must be avoided if magnetometry is to become firmly established as a practical scientific tool. Therefore, we would now like to briefly pass on these observations.

1 Computational Errors:

Because of incompatibilities between the MIT and Haskins computer systems, we were unable to use the MIT software, and one of our first jobs was to write the programs to acquire transducer voltages, and to calibrate, and operate the EMMA system. At the heart of those programs is a routine that converts the three voltages, induced in each transducer coil by the three transmitter coils, into distances from those transmitters. That conversion employs a relationship between voltage and distance (known as the V-to-D function) which is nonlinear and shown in Figure 1.

V-to-D Function


$V = \frac{K}{d(Ad^2 + Bd + C)}$
Alternative form

$\text{Log}(V) = \text{Log}(K) - (Ad^2 + Bd + C) * \text{Log}(d)$

Figure 1

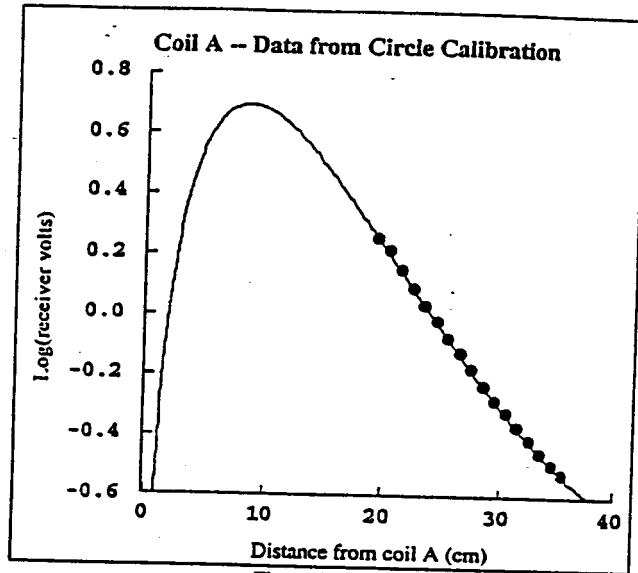


Figure 2

The calibration procedure involves two steps -- calibration of the magnetic field followed by the calibration of each transducer. The first step requires the collection of data from a special transducer that traces seven or eight concentric circles in the midsagittal plane followed by the calculation of the four field coefficients K, A, B and C that appear in Figure 1. The second step involves, for each transducer in use, the calculation of a set of linear coefficients based on data obtained at two known locations in the field. However, given a transducer voltage, the form of the V-to-D function necessitates the use of an iterative rather than an algebraic method for finding the corresponding distance.

Our first problem became apparent when we observed that the distances emerging from the V-to-D conversion procedure were too small. The coefficients were examined and appeared to fit the calibration data as shown in Figure 2. However, an evaluation of the V-to-D function down to $d=0\text{cm}$ as shown, revealed that, within the range of transducer voltages, the inverse of the function is not single valued. Hence, starting at zero, the iteration returned the first solution, a physically unrealistic distance that nevertheless satisfied the V-to-D function. Consequently, to fix the problem, we added instructions that now limit all V-to-D solutions to the realistic range.

2 Electromagnetic Noise:

Eventually, we found that not all V-to-D functions had this dual solution property and that such anomalous V-to-D functions were linked to the presence of noise in the calibration data -- specifically, two kinds of noise.

The first source of noise was a disturbing 50 millivolt, six Hertz oscillation that was superimposed on the EMMA output voltage corresponding to excitation induced by coil A (the first of the three transmitter coils). The same frequency of oscillation was observed in each one of the 10 channels. Initially, a failure or misadjustment of the circuitry that regulates the power output of coil A was suspected but eventually ruled out. It was at that point that the laboratory environment first came under suspicion and "to cut a long story short," the source of the problem turned out to be the horizontal deflection coil of a nearby computer terminal. This terminal, which was used to operate the computer during data input, radiated a 50kHz electromagnetic signal that, upon being picked up by the transducer coils, became inter modulated with the 50kHz output frequency received from transmitter coil A. Because we needed to have a terminal located closeby, we decided to select three new higher frequencies at which to operate the EMMA transmitter coils. Following that adjustment, the low frequency oscillation disappeared completely.

Evidence of a second noise source became apparent when we permanently wired all thirty of the EMMA outputs (corresponding to 10 transducer channels) to the input channels of an analog-to-digital (A/D) converter. Initially, we attempted to avoid ground loops by installing only one ground path between our EMMA and the A/D converter and providing each of the thirty cables with a metallic shield connected to a single ground on the chassis of the magnetometer. However, approximately 60 millivolts of high frequency noise persisted on all thirty cables, and we discovered that, to eliminate it, the shields of each of the cables had to be grounded at *both* ends. For reasons which may have something to do with the impedance of the output lines, the electrical noise picked up by the metallic shielding appear to be transferred by capacitance to those outputs and the A/D converter.

When these sources of noise were eliminated, all that remained was the intrinsic noise of the system. With only this noise present, the residual error of the calibration data with respect to the computed V-to-D function was found to be significantly reduced. So much so that, using data which had been low pass filtered with a 17Hz bandpass, the value of the statistic F frequently exceeded 8.0×10^6 over a circular area in the midsagittal plane whose diameter was 14.0cm. As with all physical systems, the magnitude of EMMA's intrinsic noise is related to the signal bandwidth and Figure 3 shows that the Standard Deviation of a measurement is approximately proportional to the logarithm of the bandwidth. Clearly, intrinsic noise limits measurement precision as well as the quality of the V-to-D function and, as we shall later show, there are also other factors that play a part.

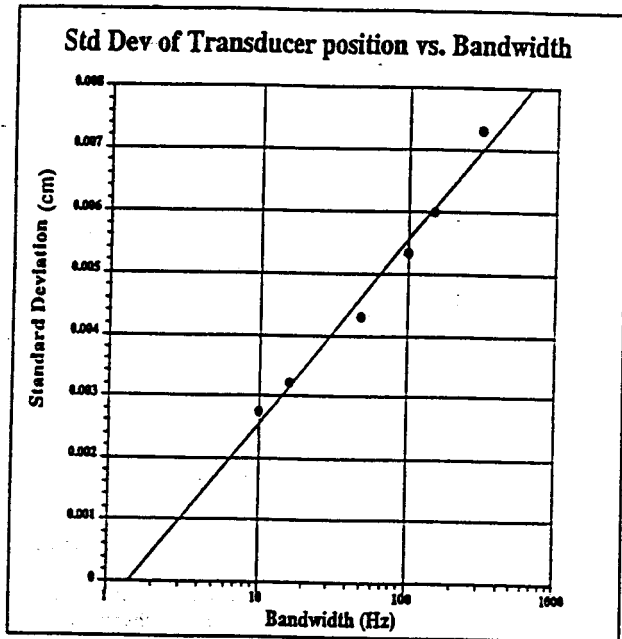


Figure 3

3 Other Environmental Interference:

Having learned the lesson that one should be wary of the effects of the environment, we began to look at other objects in the immediate neighborhood of the magnetometer -- in this case, the subject and the experimenter.

In the subject's case, for example, we attached a transducer to the helmet assembly about 1mm in front of the bridge of a subject's nose. Data were then collected from the transducer with, and without, the subject's head inside the helmet. Our results showed that the presence of a subject's head differentially attenuates the voltages induced in the transducer, the largest attenuation being found for the signal received from the posterior coil which must pass from back to front through the subject's head. However, after the voltages are converted to Cartesian coordinates, the apparent displacement due to the subject's head amounts to only 0.3mm along a roughly horizontal line in the anterior direction -- clearly, not an alarming error.

In the experimenter's case, we were disturbed by the discovery that care must be taken to avoid placing hands in the immediate neighborhood of the two anterior transmitter coils. As a hand approaches any one of the three transmitter coils along its principal axis, the signal from the corresponding EMMA output undergoes a deflection that can be as large as plus or minus 0.2 volts. Hand approach-

es made along a line orthogonal to the principal axis usually result in an elevation of the output voltage. The largest of these deflections is associated with the transmitter coil that operates at the highest frequency; in our case, the third coil located in front of, and below, the subject's mandible. An explanation of the deflection has been offered by Domnitz, 1993. He has pointed out that each transmitter coil is operated with its center point at virtual ground. The proximity of the experimenter's hand and body provide a capacitive connection to ground through which a proportion of the current passing through one side of the transmitter coil will leak. This, in turn, causes an imbalance in the output of the coil which, when demodulated, causes the signal voltage to change. The plausibility of this explanation is enhanced by the fact that the polarity of the deflection changes when the experimenter's hand approaches (and, therefore, partially shorts to ground) the left or the right side of the transmitter coil.

The risk of such experimenter-induced signal deviations is not particularly high under most experimental conditions because no part of the experimenter's body needs to remain close enough to any of the transmitter coils while data are being collected. However, to obtain such data as tracings of the subject's face and palate profiles using a transducer coil attached to a short wand, the placing of a hand or wrist in close proximity to one of the transmitter coils can be difficult to avoid. We found that, in the worst-case, the deflections that can be expected due a contact of the experimenter's hand with one of the transmitter coils is 1.5mm. However, we also discovered that when the experimenter grasps the shielding around the transducer leads at the same time as his other hand approaches a transmitter coil, the resulting output voltage deflection is substantially reduced.

4 Component Interactions:

Pre amplification and phase discrimination circuitry in the EMMA system is housed in a small self-contained chassis called the remote unit. Leads from the transducer coils are plugged directly into this unit. One day we were alarmed to find that, if one of these leads is allowed to stray too close to any one of the transmitter coils, the computed position of the transducer can be shifted by as much as 2.0cm in a direction toward that coil. Thus, for example, the presence of a transducer lead in the vicinity of transmitter coil C, which in our system is located in the most exposed position below the mandible, causes that transducer and its lead to convey a stronger signal from coil C and give the appearance that the transducer is closer to coil C than it actually is. Obviously, this is a serious error.

The lesson we have learned from this discovery is to avoid trouble by routing the leads from the subject and transmitter assembly along the magnetically neutral path lying parallel to the axes of the transmitter coils and passing through the center of the measurement field. A miniature cable tray, made from a plastic material, is now attached to the side of the subject's helmet to hold the leads in the correct location. This cable tray serves to remind the experimenter of the importance of proper transducer lead routing.

5 Thermal Stability:

Another line of inquiry was provoked by a recommendation of a government mandated committee, that reviews the ethical and safety issues arising from experiments performed on human subjects. The committee stated that our subjects' exposure to electromagnetic fields should be kept to a minimum by the practice of energizing the transmitter coils only during periods of actual data collection. This

raised the question in our minds as to whether any thermal instability in the transmitter coils or their drivers would be evident immediately after switch-on since, if this were so, its presence could undermine the accuracy of the data being collected. To answer this, and the broader question of the stability of the EMMA circuitry as a whole, we sampled a group of output voltages at a slow rate under a set of three conditions.

In condition 1, a full cold start, the main power supply and the transmitter drivers were both turned on at the same time and the output voltage sampled over a period of 90min. In condition 2, a partially-cold start, the main power supply was turned on at least 60min before the transmitter drivers were switched on and sampling for a 60min period was begun. In condition 3, the fully warmed up condition, both the main power supply and the transmitter coils and drivers were given at least 60min to reach thermal equilibrium before the 60min sampling period was initiated.

The results of both test condition 1, shown in Figure 4, and the 60min duration of test condition 2 looked identical. The figure clearly indicates that the EMMA electronics require at least 60min to reach equilibrium. That equilibrium was found to be in effect throughout condition 3. However, because a rotation correction algorithm is used, any effects of thermal drift on the accuracy of the Cartesian output coordinates largely depends on whether there are any differences, or imbalances, in the rates of change of voltage output as a function of time. For if it can also be assumed that the three V-

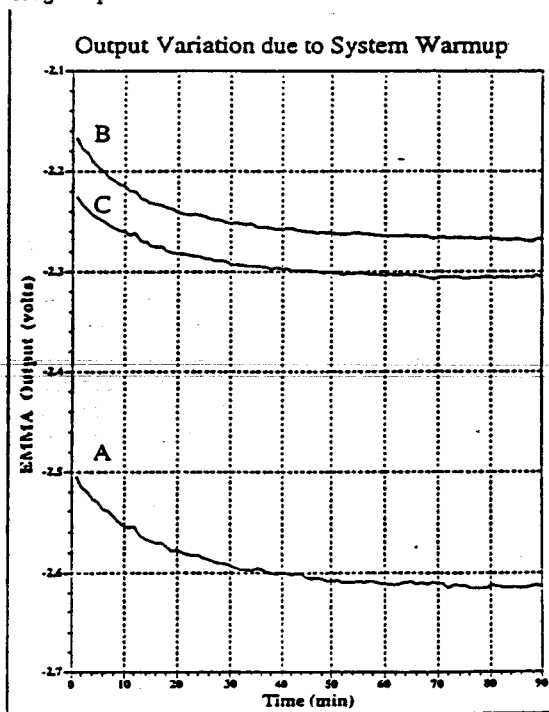


Figure 4

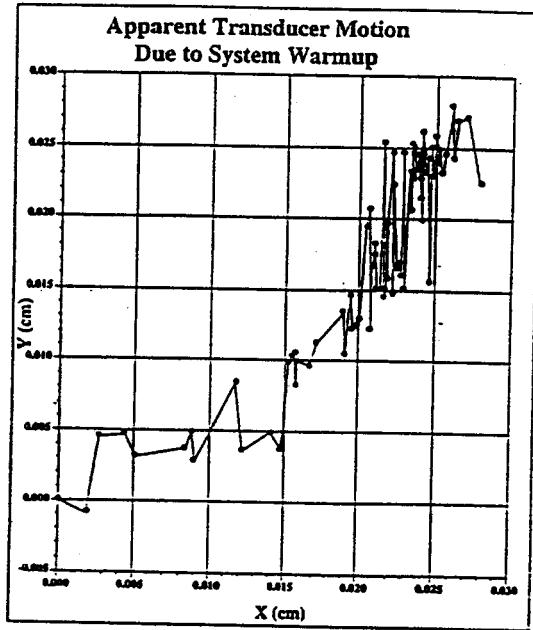


Figure 5

to-D calibration functions are very similar, then the three changing output voltages should give rise to distances that retain the same relative magnitudes and, therefore, result in no change in the apparent position of the transducer. If, however, the three voltages do change differentially with time, then an apparent change in the position of a physically stationary transducer can be expected to occur.

In fact, Figure 4 does provide evidence of differential behavior and the effect that such a variation has on the apparent location of a single transducer is shown in Figure 5. It is evident that a displacement artifact occurs which traverses over 75% of its range in the first 30 minutes. However, the maximum deviation amounts to only 0.25mm measured at the center of the field and 0.8mm when measured at point 4.5cm from the center. Again clearly, we do not have a serious problem here, at least, that is, during normal data collecting activities.

During calibration procedures, however, the voltage drift is potentially of greater concern. If the EMMA system is not fully warmed up during the 20min per channel periods required for calibration data collection, progressive voltage drift can undermine the quality of the data and the precision with which a V-to-D function can be found to fit those data. For example, we have examined the F-statistics of V-to-D functions obtained from data collected as rapidly as possible with those based on data collected over a period which was approximately 8 times longer. In both cases the magnetometer was fully warmed up. The results, shown in Figure 6, indicate that a substantially higher average F statistic is obtained if the data collection period is kept as short as possible.

F values vs. Time Taken to Collect Calibration Data
(EMMA fully warmed up)

Calib. Function	F Values x 10 ⁶	
	<u>Fast Cal</u>	<u>Slow Cal</u>
Funct. A	3.5	18.0
	17.0	8.4
	9.7	9.4
Funct. B	14.0	5.3
	18.0	4.0
	27.0	6.2
Funct. C	31.0	1.4
	6.2	0.9
	2.4	0.9
<u>Averages</u>	<u>14.31</u>	<u>6.05</u>

Figure 6

In an effort to obtain a better understanding of the performance limits of our EMMA, we have also examined a number of other potential sources of error. For example, we have looked at the cumulative position error for transducer motion over a roughly 9cm range, and we have explored the errors due to transducer coil rotation (or tilt) and off-axis misalignment with respect to the midsagittal plane: two conditions that are difficult, if not impossible, to avoid to some degree in practice. The remainder of this paper will address these issues.

6 Cumulative Displacement Error:

We used a rack and pinion driven assembly fitted with a digital micrometer gauge and a 60cm long shaft made from non magnetic materials to precisely control the motion of a transducer in EMMA's midsagittal measurement plane. The transducer, attached to the distal end of the shaft, traversed a distance of almost 9cm in increments of 1.0mm. Samples were collected in each position at the rate of 625 per sec for periods of 320msec each, and the transducer was pre calibrated along the path of motion. The x and y coordinates were then derived from averages of the repeated samples obtained at each successive location and applied in the formula shown in Figure 7 where the suffixes c and p indicate the current and previous values of the associated coordinate variables.

Thus the errors in successive x and y samples were made a cumulative factor of the total distance traversed. Figure 7 shows the reading from the micrometer gauge plotted against the total distance obtained from receivers which had been calibrated with data obtained from two positions located in line with, or *along*, the path of motion (upper) and two positions located on either side of, or *across*, the path of motion (lower). It is evident that, in the first case, cumulative error in the EMMA data gave rise to an overestimate of 1.2mm in a distance of 8cm traveled by the rack and pinion device and in the second case the error was 2.1mm over the same distance. Thus, in the best of conditions

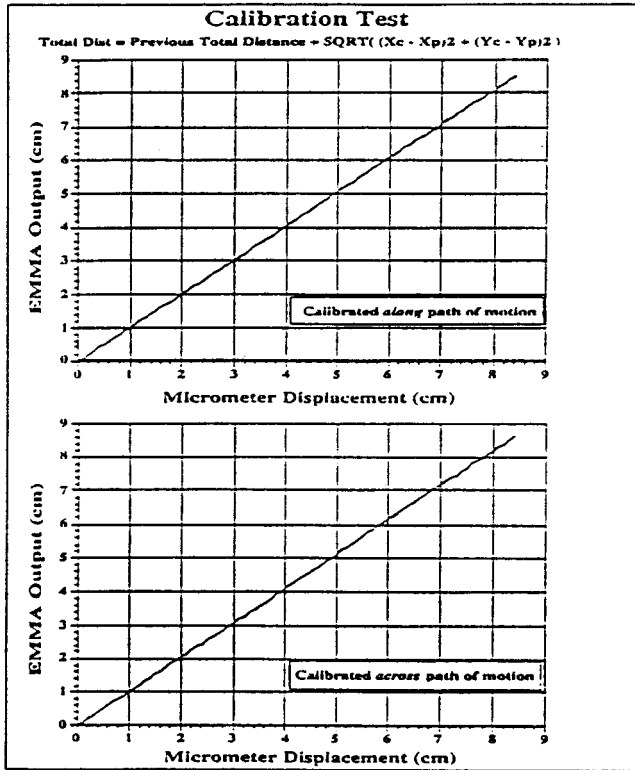


Figure 7

in which the transducer is calibrated to operate along the path in question, cumulative displacement errors can be kept to insignificant levels of the kind shown here (i.e., barely two tenths of a mm per cm).

7 Transducer Rotation:

We have examined the position error due to rotation about an axis lying in the measurement plane. The effect of rotation is to reduce the magnetic flux through the transducer, lower the induced voltages at the three transmitter frequencies and, make the transducer behave as if its distance from the three transmitter coils has increased. By employing an algorithm that proportionally rescales the three distances to values that are consistent with the physical locations of the transmitter coils, a correction for rotation is achieved. Our aim was to test the ability of that algorithm to accurately compute

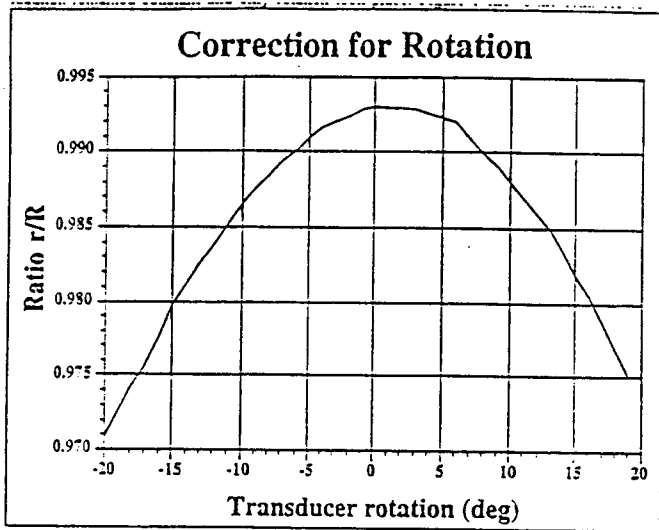


Figure 8

transducer position under conditions in which the physical location remained constant and only rotation took place. Figure 8 shows the behavior of the scaling factor r/R (the apparent radius vs. the ac-

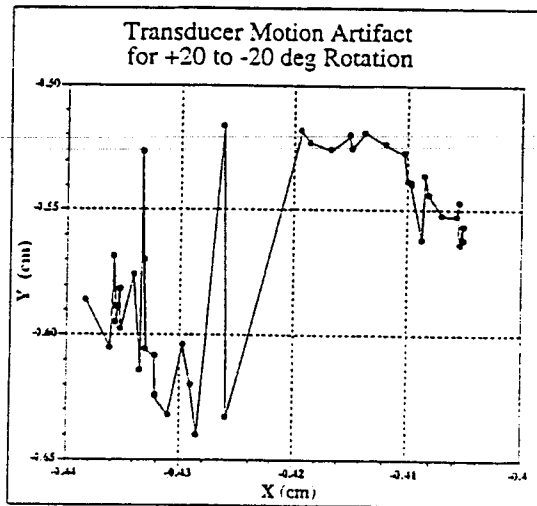


Figure 9

tual radius of a circle that intersects the centers of the three transmitter coils) as a function of angle over a rotation range of +20 to -20 deg.

The corresponding x and y coordinates of the transducer over the same range of rotation is shown in Figure 9. The apparent variation in position, which, in the data available here, is approximately 0.35mm along the x axis and 1.3mm along the y axis, is agreeably small and clearly of little consequence in comparison with other sources of error.

8 Midline Misalignment:

The errors due to transducer misalignment with the midsagittal plane vary with position. At the origin of EMMA's Cartesian coordinate system, a point which is equidistant from all three transmitter coils, one might expect the flux fields generated by the three transmitter coils to be identical in shape and to give rise to little or no appreciable error for displacements orthogonal to the midsagittal plane or midline. However, Figure 10 shows that for a constant transducer displacement of 1.55cm from the

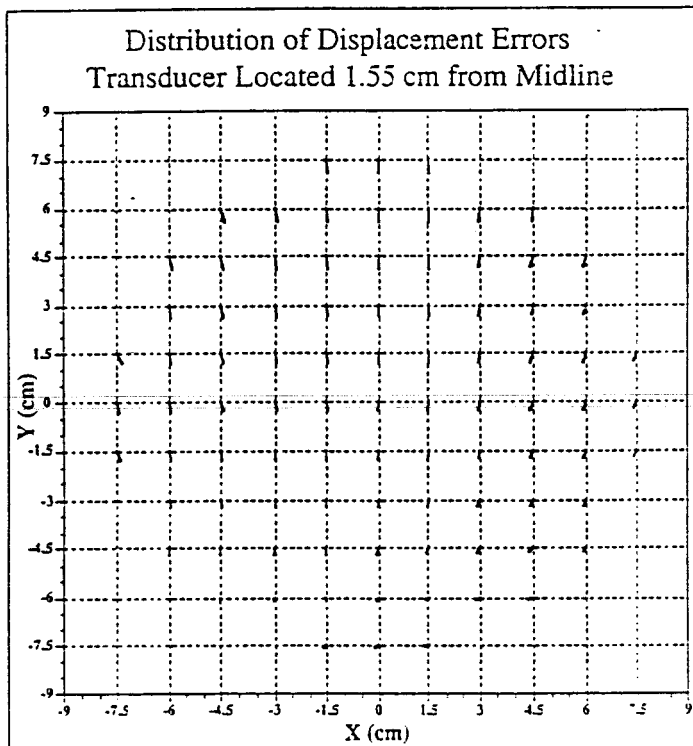


Figure 10

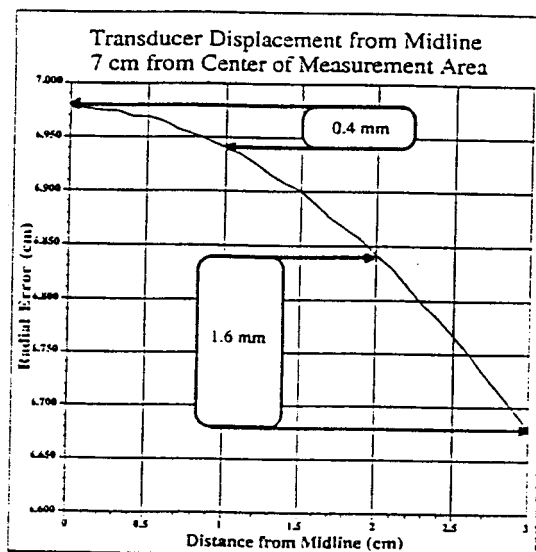


Figure 11

midsagittal plane, the error vectors range in length from 1.2 to 5.0mm and the distribution of those vectors is not symmetrical about the origin.

Further, if the displacement of a transducer from a point in the midsagittal plane physically located 7cm from the origin is plotted as a function of the transducer's apparent distance from the origin, then the result can take the form shown in Figure 11.

In this example, for a 1.0cm displacement from the midline, the distance from the origin has an error of only 0.4mm -- in most instances, not a serious problem. When the displacement increases from 2.0 to 3.0cm, however, the error increases by a further 1.6mm. Thus, the error grows more rapidly with increasing distance from the midline. However, it should be noted that similar measurements made on other channels can be expected to differ due to individual differences in transducers and the relative precision of the coefficients of the three V-to-D functions applicable to that channel. Thus, the error could be larger (or smaller) than shown here. The only reliable way to find the potential error due to a misalignment of the transducer coil is to collect data of the kind used to generate Figure 10 from each data channel and to directly measure the vector magnitude of the error in the region of interest.

9 Conclusions:

There are two principal conclusions that have emerged from our examination of the new EMMA system. The first is that provided a number of precautions are followed, the precision that can be achieved by an electromagnetic articulometer can be kept sufficiently high to qualify it as a valid competitor of x-ray microbeam systems. The second conclusion is that the effort to respond to the

alarms, misadventures and peculiar artifacts we have experienced has been worthwhile inasmuch as it has enabled us to separate the potentially serious problems from the much less serious, and has given us an added confidence in the use of magnetometry as a tool in the study of speech articulation.

Acknowledgements

The research reported here was supported by grants DC-00594 and DC 00121 from the National Institute on Deafness and Other Communication Disorders. The authors would also like to express their gratitude to Anders Löqvist who drew their attention to several of the technical issues and to Michael D'Angelo who provided software and assisted with data collection.

REFERENCES

- Perkell, J.S., Cohen, M.H., Svirsky, M.A., Matthies, M.L., Garabieta, I and Jackson, M.T.T. (1992) Electromagnetic midsagittal articulometer systems for transducing speech articulatory movements. *J. Acoust. Soc. Amer* 92(6) 3078-3096.
- Domnitz, R. (1993) Personal communication. See also circuit data supplied with the users manual for the EMMA system published by Technical Collaborative Inc., 14 Oakland Street, Lexington, Massachusetts 02173, USA.