NBSIR 81-2360

Analysis of the Calibration of Metering CCVTs in A Utility Substation

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Washington, DC 20234

October 1981

Final Report

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This report contains results from a limited study. The data and analysis presented here will be combined with additional measurements to produce a report of a full and complete investigation which is to be published at a later date.

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
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ANALYSIS OF THE CALIBRATION OF METERING CCVTs IN A UTILITY SUBSTATION

David L. Hillhouse and David A. Leep

This report presents the results of an investigation of unexpected variations in nine 500 kV metering CCVTs, tested for Gulf States Utilities at Baton Rouge, LA. These measurements were performed on three occasions - May 1979, March 1980, and December 1980.

On the first two occasions, six out of nine CCVTs were out of tolerance; on the third, four out of nine. More important, the changes between the first two occasions seemed to be correlated by phase, i.e., most of the devices on a given phase shifted in the same general direction and by similar amounts. When analysis failed to provide an explanation for this, the third set of measurements was undertaken.

Analysis of the three sets of data produced some evidence of a bias voltage in the 1979 data. Investigation of all plausible known sources of error in the NBS system, the substation, and the CCVTs themselves failed to produce a probable source for such a bias voltage.

No evidence of consistent malfunction of the NBS system was found. Even allowing for a possible bias in one set of data, a majority of the CCVTs were still outside of metering tolerance. Continuous monitoring of a statistically significant number of operating CCVTs should be considered.

Key words: calibration; CCVT; EHV substations; error sources; high voltage measurements; revenue metering.

1. INTRODUCTION

This report documents an investigation of some peculiar results obtained during measurements of metering coupling capacitor voltage transformers (CCVTs) at Gulf States Utilities' (GSU) Willow Glen Substation, near Baton Rouge, LA. The work was an extension of EPRI Project RP-134-1. The measurements under discussion were performed using the field calibration system for CCVTs developed during the above research project. This system is described in [1][1] and documented in detail in [2].

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[1] Numbers in brackets refer to the literature references listed at the end of this report.

Willow Glen is a typical low profile substation, situated next to a generating station on the bank of the Mississippi River, about 15 miles below Baton Rouge. These measurements were performed in the 500 kV section of the substation. Three lines (Franklin, Gypsy, and Webre) meet at this substation. Each line has three metering class CCVTs connected to it, for a total of nine for the substation. Measurements were performed on the metering tap (X1X3) and two relaying taps (X2X3, Y2Y3) of each CCVT, for a total of 27 per calibration trip.

A total of three sets of measurements were performed at Willow Glen on three occasions - May 1979, March 1980, and December 1980. Summarizing:

May 1979 - Referring to metering values only[2] (X1X3 tap), six out of nine devices were found to be out of tolerance to within NBS measurement uncertainty, the worst being >1 percent in ratio and >9 mrad in phase angle from nominal. These values were measured in the control house for the connected burdens.

March 1980 - In view of the very poor showing of the CCVTs in May 1979, and because of the large dollar value of the energy passing through the substation, GSU invited NBS to repeat the measurements, in order to see how stable the CCVTs were, and whether any more had drifted out of tolerance. Once again, six devices were out of tolerance, including two out of the three which had been in tolerance in May, 1979. More important, it was noted during the measurements, and confirmed by preliminary analysis immediately afterward, that the changes from May 1979 to March 1980 appeared to be correlated by phase (A, B, C). Rain, which continued for the remainder of the available time at GSU, prevented repeating the measurements. Detailed analysis after returning to NBS confirmed the initial observations, but yielded no explanation for them.

December 1980 - These measurements were made in an attempt to find an explanation for the peculiarities discussed above. A much more detailed and comprehensive series of measurements was made than for the first two trips. For example, whereas the earlier measurements were performed only in the control house and on the normal working (connected) burdens, and used only the NBS prototype system's current comparator bridge, this third set used both the prototype and a new simplified system [1,2], and included zero-burden and connected-burden measurements at the CCVT makeup boxes (MUBs) and numerous intercomparisons both between CCVTs on the same phase, and between taps

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[2] Refers to ANSI accuracy requirements for the X1X3 output tap of a revenue metering device -- 0.3 percent for ratio correction factor (RCF) and 4.6 milliradians (mrad) for phase angle (γ). See reference [3], p. 21.

on the same CCVT. Results for connected burden at the control house showed five CCVTs to be within metering tolerance (two from 1979, two from March 1980) and four out of tolerance.

The results from all three measurement sets are compared and analyzed in detail in the following sections. All plausible sources of error known to us are reviewed in a search for possible explanations for the observed results.

2. DETAILED REVIEW OF RESULTS

2.1 History

The history of the metering tap (X1X3) results from May 1979 to March 1980 is shown in figure 1. The ratio correction factor (RCF)[3] and phase angle (γ) values are plotted in x-y coordinates for each CCVT in conformance with the conventional presentation in ANSI Standard C56.13-78 [3]. In that standard, RCF is defined as the quantity by which the nominal ratio (e.g., 300 kV:120 V, or 2500:1) of the test piece must be multiplied to give the true ratio. The phase angle, γ, is defined as the angle by which the output voltage of the test piece leads the input voltage. The ANSI parallelogram, which delineates the error limits of the metering device, is superimposed on the graph, as is the estimated NBS measurement uncertainty.

In this figure and in figures 2-5 and 15, A-, B-, and C-phase values are shown as solid, long-dashed and short-dashed lines, respectively. Open and solid circles represent May 1979 and March 1980 data, respectively. Arrows on the lines connecting the data points indicate the progression of time. Only one CCVT is connected to each phase of each line. Therefore, the simple legends unambiguously identify each CCVT by phase and line. For example, "AF" designates the CCVT on A-phase, Franklin Line, "CW" the CCVT on C-phase, Webre Line, etc.

Expanding upon the brief summary in the Introduction, figure 1 shows that in May 1979 three devices (AG, BW, and CF) were in tolerance (inside the parallelogram). In March 1980, only two (BF, BW) were in, and one (AW) was marginal, i.e., out only by approximately our uncertainty of ±0.1 percent and ±0.3 mrad. The 1979 extremes were BG, at $F = 0.9892$, and CW, at $\gamma = +9.2$ mrad. It should be noted that in 1979 GSU adjusted[4] AF, AW, and CW. Figure 1 results for these devices were obtained after these adjustments. Adjustment improved the accuracy of AW, degraded that of CW, and left AF neither better nor worse. It did not bring any of them into tolerance.

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[3] In this report, RCF ≡ F in equations, for conciseness.

[4] Values for AF, AW, and CW before adjustment were (1.0073, -0.4 mrad), (1.0043, +9.5 mrad), and (0.9947, +5.9 mrad), respectively.

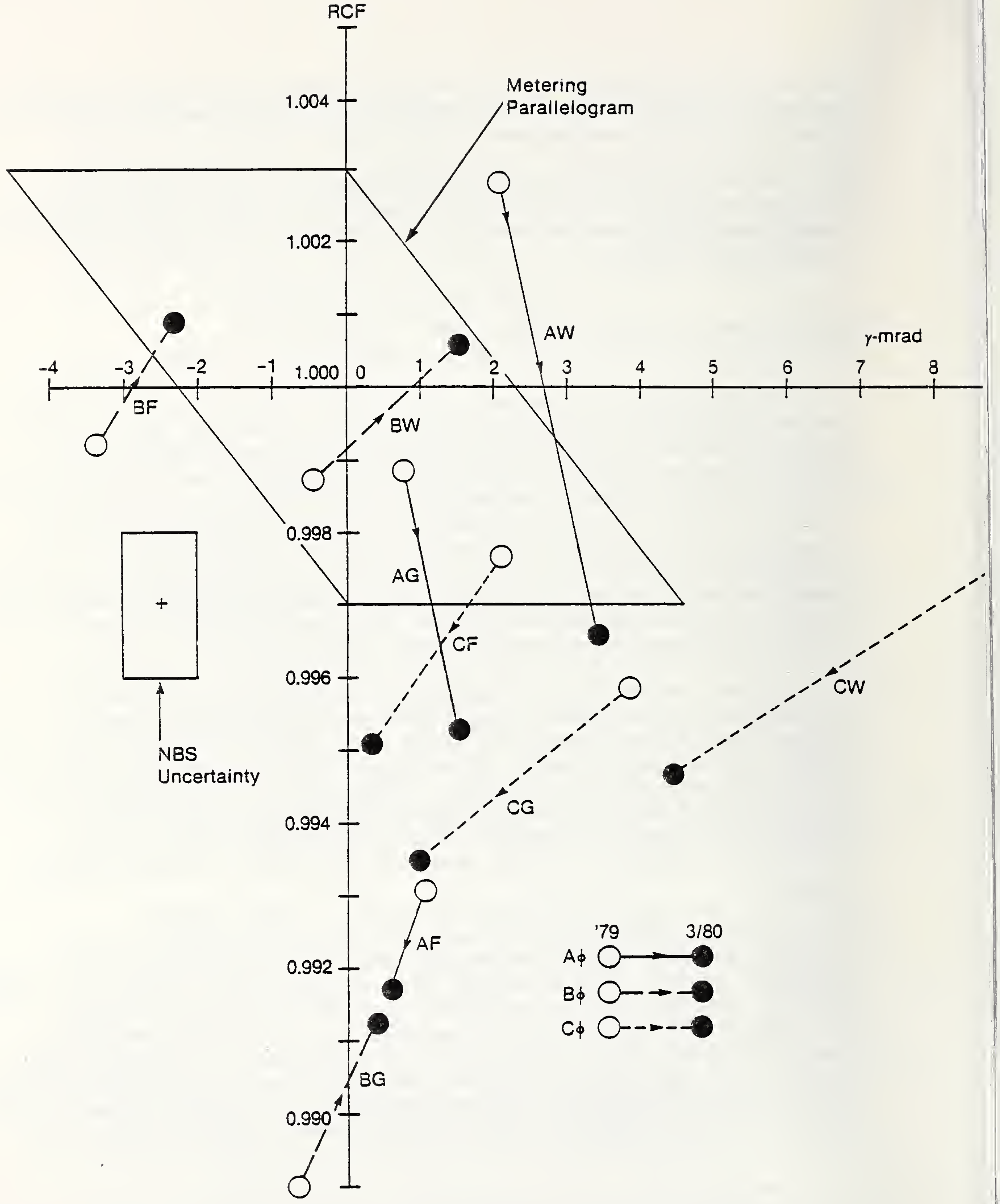

Figure 1. History of X1X3 RCF and γ, May 1979 to March 1980

Figure 1 shows the apparent phase-by-phase correlation of the May 1979 - March 1980 changes, i.e., all A-phase and C-phase values moved generally downward, and all B-phase values generally upward. Phase angle changes were somewhat less correlated. It was this appearance of correlated changes which generated the investigation reported here.

Figure 2 extends the metering tap history by having the December 1980 results added to the figure 1 plot (closed squares represent December 1980 data). The only notable changes are the apparent reversal of some of the earlier trends. This will be discussed in more detail later. As mentioned earlier, five devices were in tolerance, four were out.

2.2 December 1980 - More Detailed Results

Because these measurements were planned specifically to look for explanations for the seemingly unusual differences in earlier data, they were considerably more extensive in their scope and in the equipment and personnel applied to them. Earlier measurements had been performed only for connected burdens in the control house, using the NBS-EPRI prototype system and its current comparator bridge. These latest measurements included the above, plus connected burden measurements and zero burden measurements at the makeup boxes (MUBs) at the base of the CCVTs. They also included the use of a voltage comparator of comparable accuracy (see "Simplified System," section 9, ref. [2]) for numerous intercomparisons of ratios between CCVTs on the same phase, intercomparisons between taps on the same CCVT, and for spot checking some of the ratio measurements made by the current comparator bridge. Most of the intercomparisons were performed in the control house.[5] In almost all cases, these intercomparisons were also closely correlated in time with ratio measurements on the same phase using the bridge.

CCVTs are adjusted and calibrated initially by the manufacturer at zero burden (open circuit). They are installed on the substation bus at the end of leads from the control house which may be 200 or more meters long. From there the CCVTs may drive burdens of 100 VA (volt-amperes) or more. Because of voltage drops due to the internal impedance of the CCVT and to lead impedance, the ratio in the control house will be significantly different from the zero burden ratio of the CCVT if the connected burden exceeds a few volt-amperes.

In order to obtain information on the effects of burden and of lead impedance, zero burden and connected burden measurements were performed at the MUBs and the results compared with connected burden

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[5] With short cable runs, and a minimum of ground voltage and other interference problems.

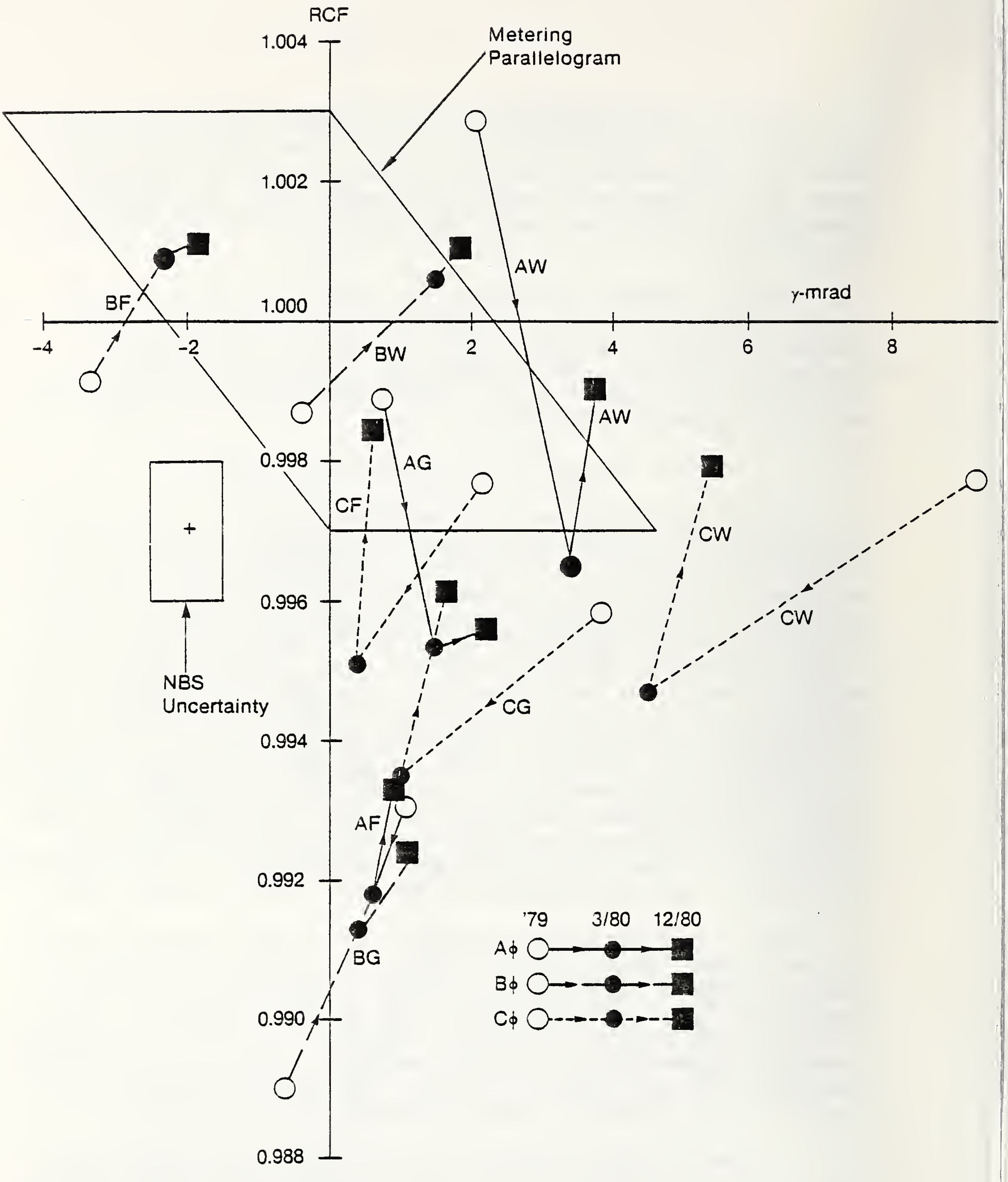

Figure 2. History of X1X3 RCF and γ, May 1979 to Dec. 1980

values in the control house. Figure 3 shows the results of these measurements. Nomenclature is the same as for earlier figures. The lines connecting points on the graph show the progression from zero burden-MUB to connected burden-MUB to connected burden-control house. In all cases, the connected burden referred to was the total burden for all windings.

Most of the results show the trends toward increasing RCF which would be expected for predominantly resistive, lagging power-factor burdens, as these were. The two exceptions (BF, CW) can be at least partially accounted for by neutral currents due to unbalanced burdens.

The extremely large change in AW is probably due to high device impedance, caused by detuning. The CCVT is a tuned device, in which the high equivalent impedance of its capacitor stack (magnitude approximately 16 000 Ω for a 500 kV CCVT, or 2.5 Ω referred to the CCVT output terminals) is approximately tuned out by a series inductor. This reduces the output impedance for a properly adjusted CCVT to a small value (typically of the order 0.3-0.5 Ω at 40-50°, inductive, referred to the CCVT output). During final adjustment, the desired phase angle (γ) is obtained by small changes in the tuning inductor. If a large change in γ is required, the circuit becomes detuned, significantly increasing its impedance. Burden current flowing through this larger impedance produces a greater than normal change in output voltage.

Now recall from the discussion of figure 1 that AW was adjusted in 1979, with a resultant large change in γ. This means that large changes were made in the tuning reactor during this adjustment. To test the detuning hypothesis, an equivalent circuit was drawn up, containing the impedance values typical for a CCVT of the AW type. This circuit was assumed to be connected to lead resistance and connected burden impedance approximating that of the actual CCVT. Values of tuning inductance were assumed, and the resultant voltage drop calculated and compared with the magnitude of the actual AW voltage drop in figure 3, inferred as follows: $\Delta V = 120\ \Delta F = 120\ (0.9990-0.9825) \cong 1.98$ volts. This calculation showed that inductance values well within the range of tuning can produce voltage drops of the size encountered here.

Note also that eight out of nine CCVTs are outside metering tolerance, even at zero burden. The usual factory practice is to set them at approximately (F = 0.997, V = +2.0 mrad) for zero burden.

Figures 4 and 5 show, for the relaying taps (X2X3, Y2Y3), the same data as figure 3 showed for the metering taps. They display the same general trends as figure 3.

In figure 6 are summarized the results of intercomparisons among the metering taps of the CCVTs on each phase in December 1980. Coding is the same as for previous figures. The nomenclature is to

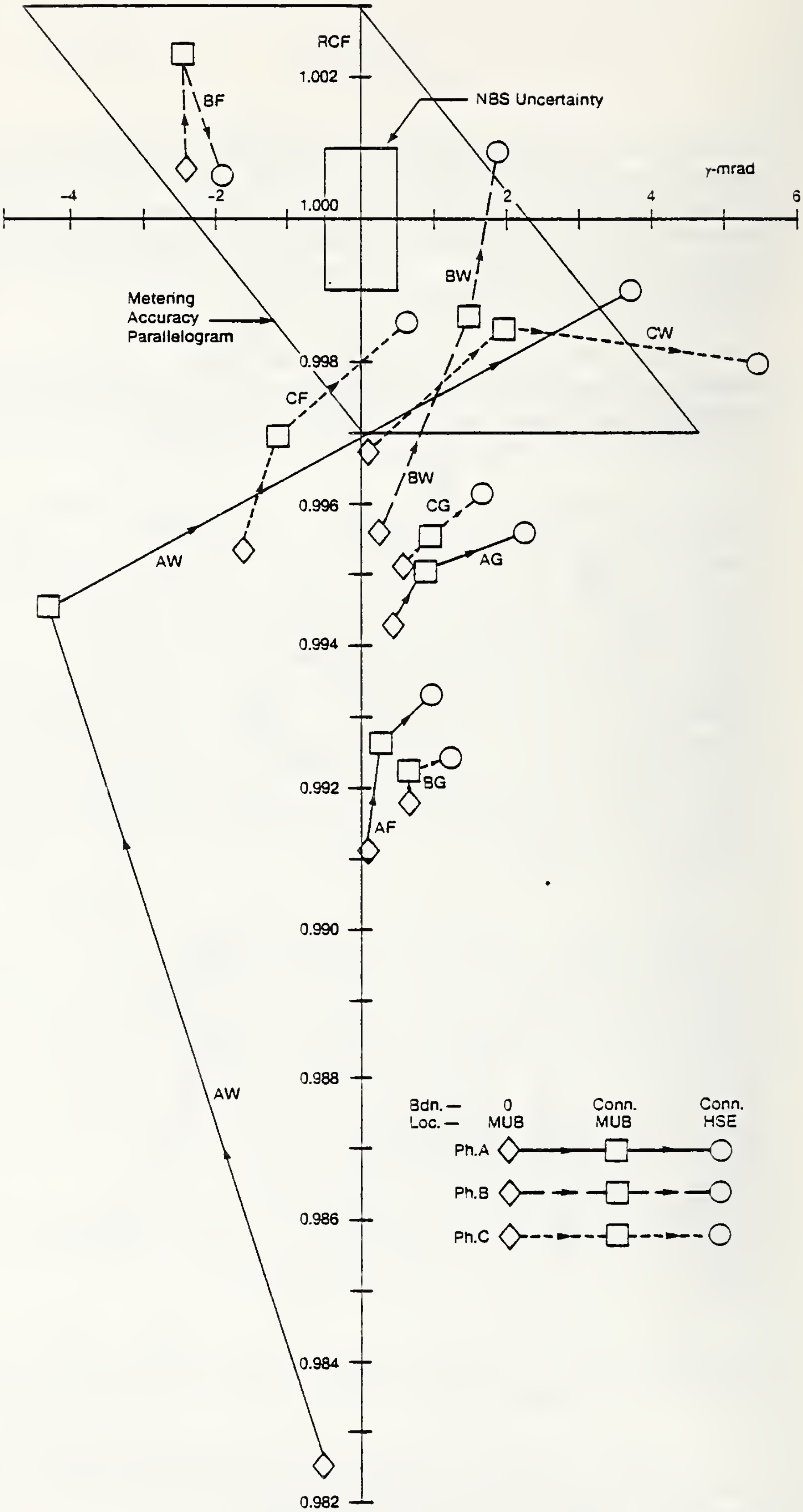

Figure 3. Effect of burdens on X1X3 RCF and γ, Dec. 1980

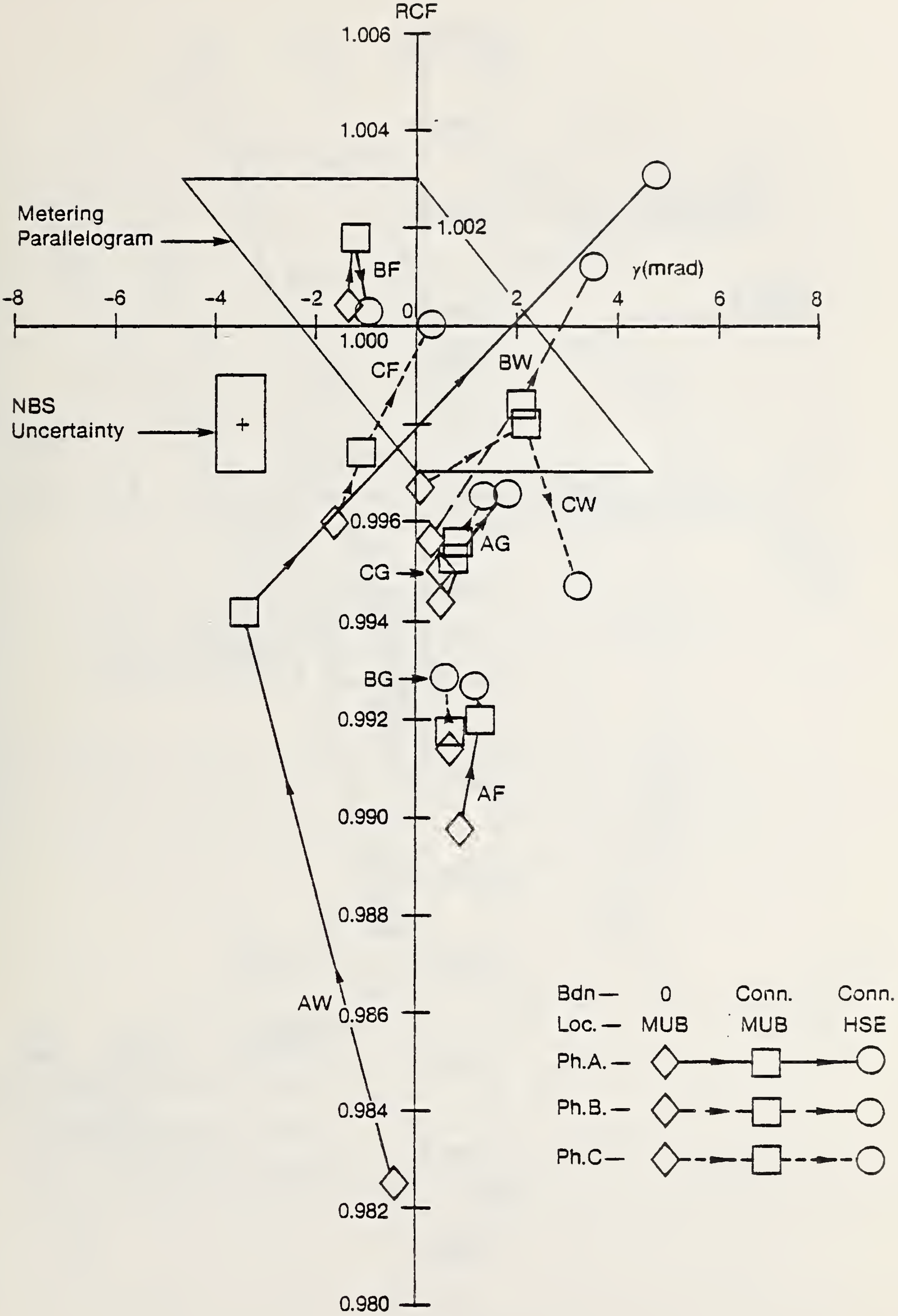

Figure 4. Effect of burdens on X2X3 RCF and γ, Dec. 1980

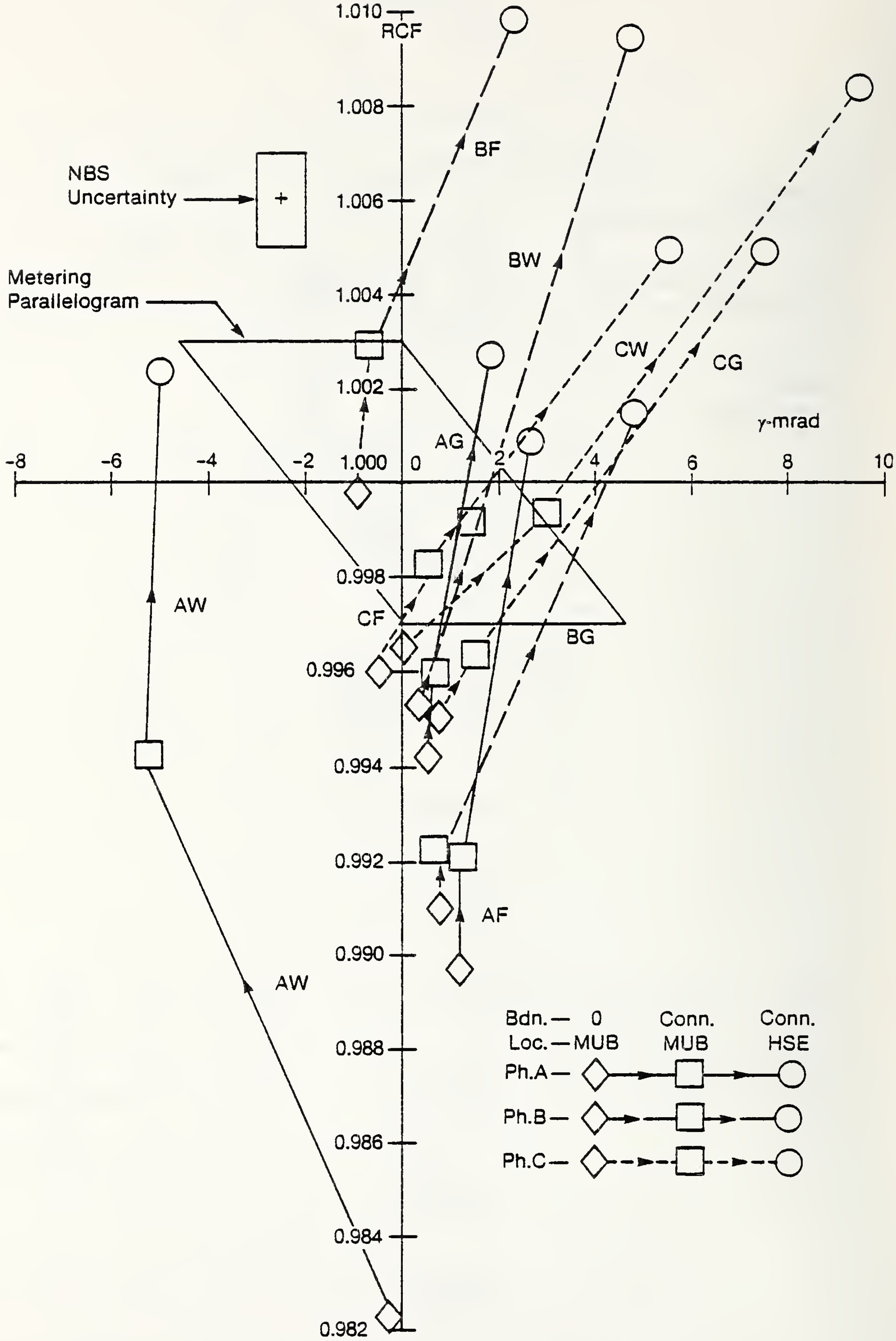

Figure 5. Effect of burdens on Y2Y3 RCF and γ, Dec. 1980

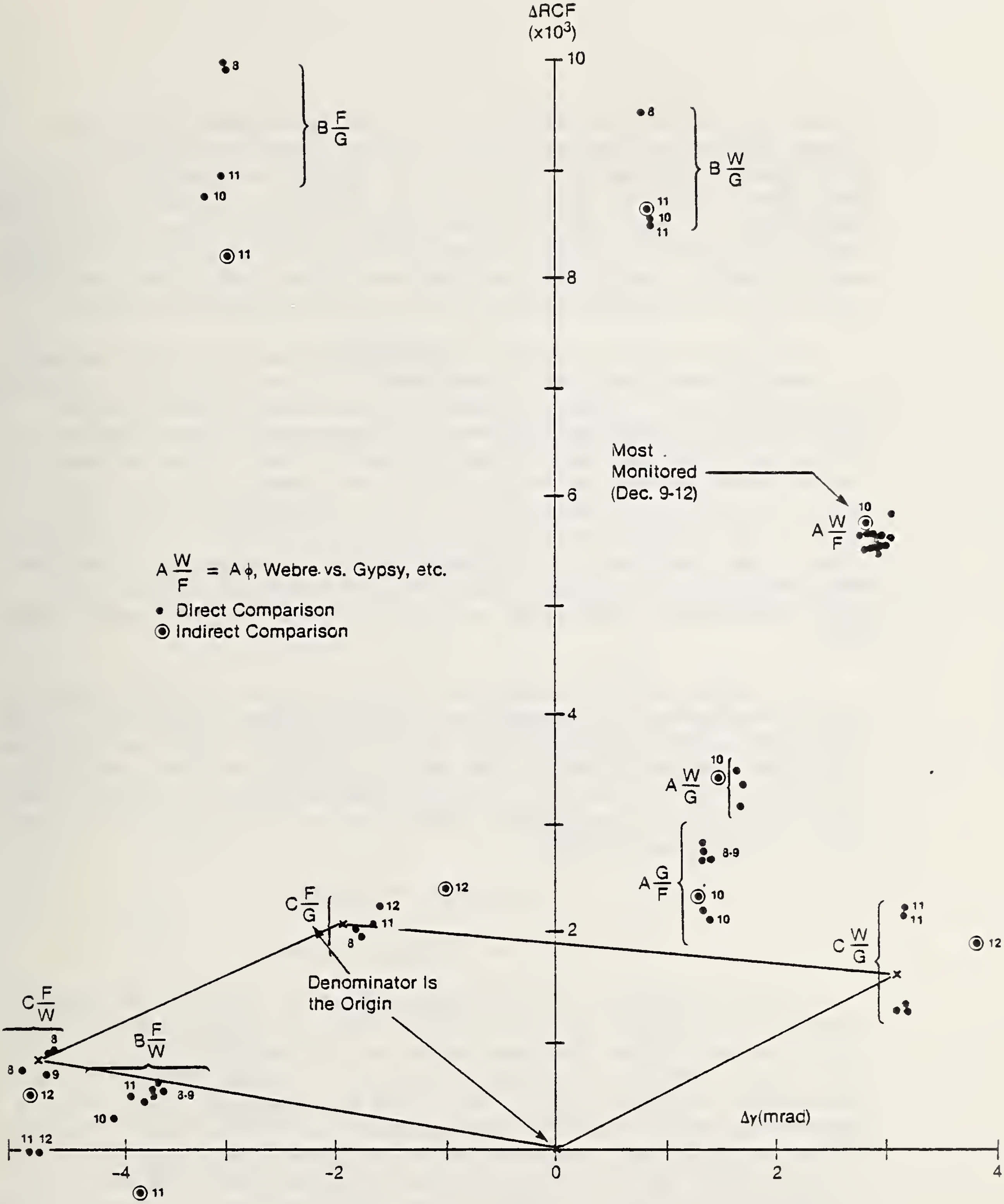

Figure 6. Intercomparison of the X1X3 RCF and γ of pairs of CCVTs on the same phase, Dec. 1980

be read as follows: A(W/F), e.g., is the intercomparison of the A-phase devices on the Webre and Franklin lines, with Franklin (the denominator) as the reference, or origin, on the graph. Thus AW differs from AF in RCF and γ by approximately +0.0057 and +3.0 mrad, respectively. Where small numbers appear alongside the data, they indicate the date (December 8 through 12, 1980) on which the measurement occurred. The circled dots represent the same values derived from two ratio measurements with the current comparator bridge.

The quality of closure of three intercomparisons (two degrees of freedom--therefore, one is redundant) can be grasped by inspecting the quadrilateral formed by connecting the means of each of the three sets of values and the origin. This quadrilateral should form a parallelogram, as is demonstrated for the C-phase values. Perhaps more significant are the ratio measurement results (circled dots), all but one of which fall in with intercomparisons on the same date to well within our measurement uncertainty. Since each of these values required two ratio measurements, independent from the intercomparisons in several ways, they give confidence that the ratio measurements themselves were not subject to significant random error.

The spread of intercomparison points taken on different days can be interpreted as a measure of the short-term instability of the CCVTs due to temperature changes or other causes. Most such families are grouped rather tightly. The most notable exceptions are B(F/G) and B(W/G), which show shifts of RCF greater than 0.1 percent in two days (combining the two results indicates the shift was in G, since B(F/W) is tightly grouped).

3. ANALYSIS OF RESULTS

3.1 The "Triangle Effect"

In the discussion of the changes shown in figure 1, an apparent correlation by phase was pointed out. This is brought out much more clearly by replotting the same values as differences (fig. 7). In this figure, the May 1979 metering RCF and γ values (the first, or open-circle values in fig. 1) are taken as reference, i.e., 1979 becomes the origin, and the changes from May 1979 to March 1980 the plotted points. Here the correlation by phase shows up quite plainly in the segregation of values, particularly for B and C phases. If the means of the sets of phase values are connected, a figure approaching an isosceles triangle is generated. A plot of the same kind for the May 1979 to December 1980 differences (fig. 8) shows a similar triangle. However, in a March to December 1980 difference plot (fig. 9), the triangle has disappeared. There is almost no phase angle discrepancy in figure 9. With the exception of phase C, the segregation by phase is much less, and the changes are smaller. In figure 10, the

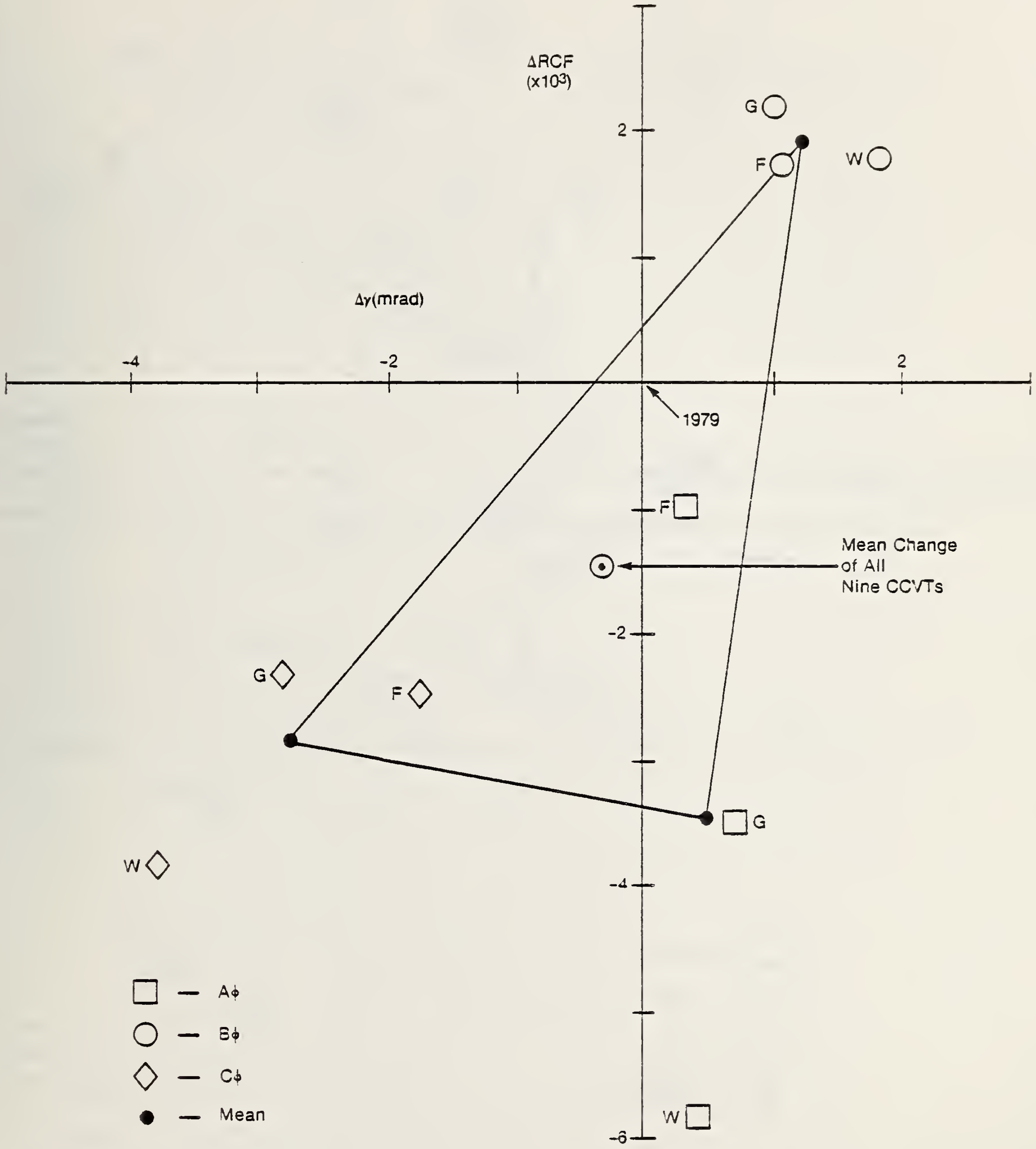

Figure 7. Changes of control house metering RCF and γ, May 1979 to March 1980

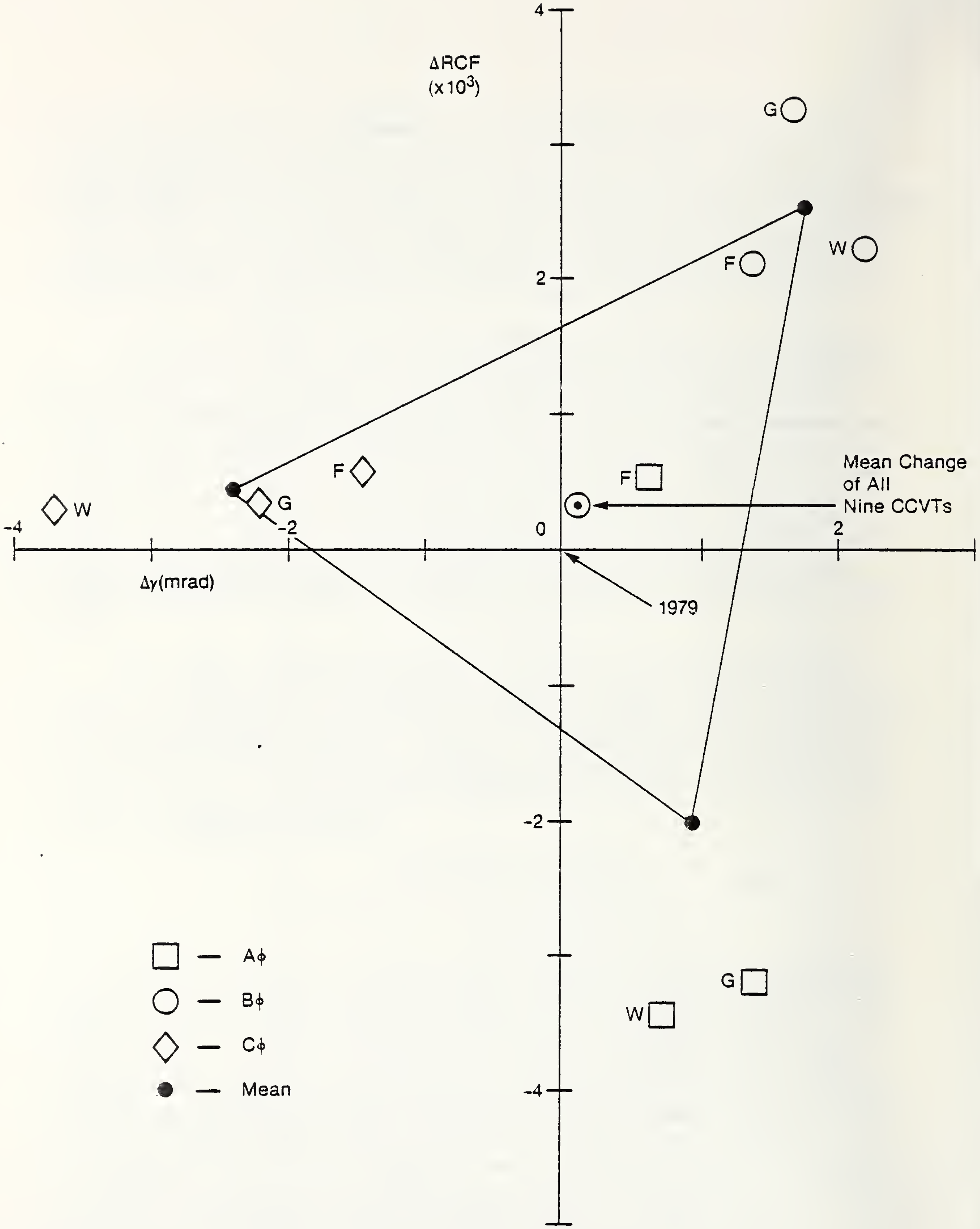

Figure 8. Changes of control house metering RCF and γ, May 1979 to Dec. 1980

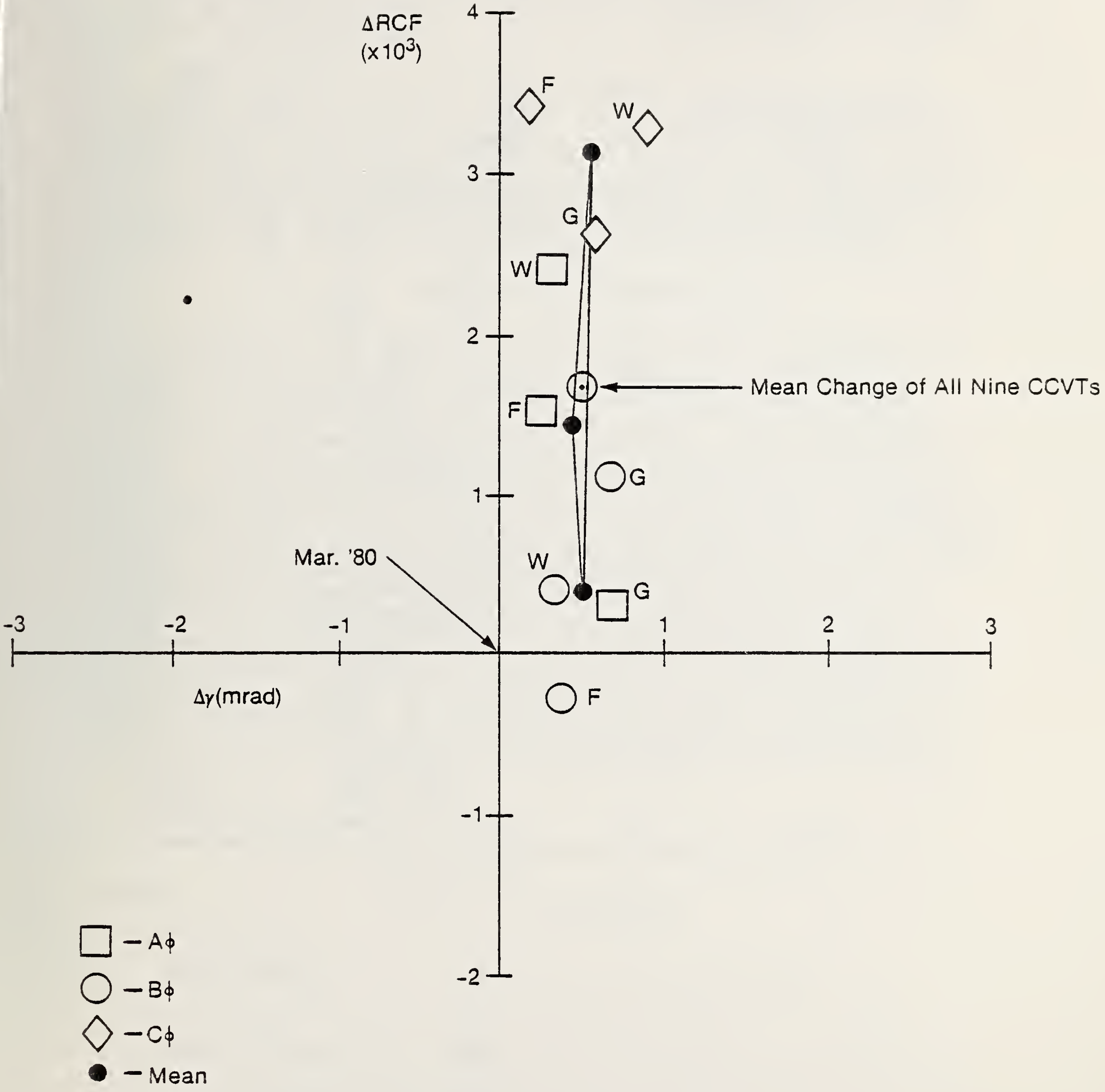

Figure 9. Changes of control house metering RCF and γ, March 1980 to Dec. 1980

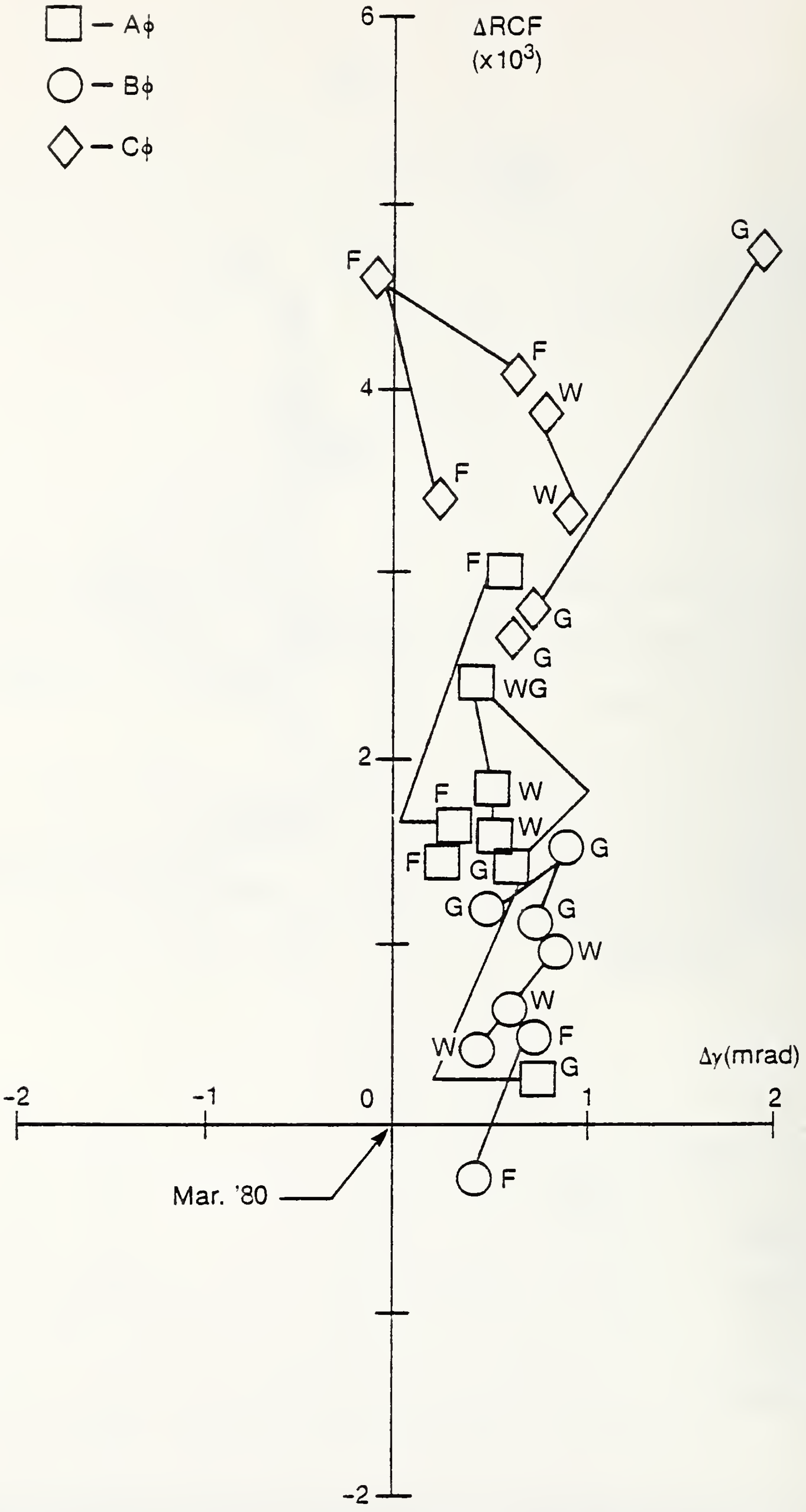

Figure 10. Changes of control house metering and relaying RCF and γ, March 1980 to Dec. 1980

changes for the relaying taps from March to December 1980 have been added to figure 9. They reinforce the inference that the "triangle effect" has disappeared.

The presence of the "triangle effect" in both sets of data involving May 1979 (figs. 7 and 8), and its absence in the March to December 1980 set (fig. 9) suggests a bias in the 1979 data, i.e., the presence throughout that test of a voltage or voltages, affecting all three phases, not present in the other two tests. Fortunately, the available data provide a tool for estimating the required magnitude and phase of such a voltage, as discussed in section 3.2.

3.2 Estimating the Unknown Voltage

In most of the measurements, the X1X3, X2X3, and Y2Y3 taps of the CCVT were calibrated. For ratio changes due to the CCVT's capacitive divider (e.g., temperature, shorted roll) and tuning reactor or anything else on the primary side of the intermediate voltage transformer, the relaying taps should "track" the metering taps. In particular, the X2X3 tap should "track" the X1X3 tap to within a few hundredths of a percent. On the other hand, changes due to common effects on the output, or secondary side (e.g., burden or lead impedance changes, a spurious voltage in the CCVT or test system ground circuits) will affect the relaying and metering taps differently, because of the difference in ratio, hence in voltage levels. For example, an in-phase 1-volt change applied to the metering tap changes its ratio (or RCF) by 1/120, whereas the same voltage changes the ratio of the relaying tap on the same phase by approximately 1.8/120, or by a factor of 1.8 more.[6] With this in mind, the differences in the changes of the X1X3 and X2X3 tap ratio correction factors from May 1979 to March 1980 were determined as

$$\Delta F_{12} = \Delta F_2 - \Delta F_1 \qquad (1)$$

where

$$\Delta F_2 = (RCF_{80}, \gamma_{80}) - (RCF_{79}, \gamma_{79}) \text{ for the X2X3 tap}$$

$$\Delta F_1 = (RCF_{80}, \gamma_{80}) - (RCF_{79}, \gamma_{79}) \text{ for the X1X3 tap,}$$

and (F, γ) are the coordinates on an "x-y" plane.

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[6] 1.8 is based on 4500:1 for relaying, 2500:1 for metering.

The results are plotted in figure 11, using the data in table 1. When this is done, e.g., using the A-phase, Gypsy data, it is found that $\Delta F_2 = (-6.9 \times 10^{-3}, +1.8 \text{ mrad})$, $\Delta F_1 = (-3.5 \times 10^{-3}, +0.7 \text{ mrad})$. ΔF_{12} is then calculated as $(-3.4 \times 10^{-3}, +1.1 \text{ mrad})$, and plotted as G-square, figure 11.

Connecting the means of the sets of phase quantities forms a near-perfect three-phase vector system (all vectors within ±5° of 120° separation). Two possible hypotheses are suggested: (1) a more or less fixed voltage (e.g., a voltage due to a ground loop, commonly referred to as a ground voltage) approximately in phase with A-phase; and (2) a voltage drop produced by approximately the same burden change in each A-phase device. These hypotheses will be dealt with when sources of error are discussed (section 4).

Figure 12 shows the results of the same analysis for changes from March to December 1980. They show almost perfect agreement between the X1X3 and X2X3 values (within measurement uncertainty). This indicates that if a spurious effect was present at any time, it should be assigned to the 1979 measurements. Assuming for the moment that the March 1980 values are correct, the data in figure 11 can be used to extract the "true" metering tap values for the 1979 measurements. This is accomplished by simple application of analytic geometry to the ratio of the tap-to-tap differences. If ΔF_1 and ΔF_2 as calculated above are plotted on a $(\Delta F, \Delta\gamma)$ graph, they define a straight line, which also passes through the "perfect tracking" point, i.e., the point representing the change in both the metering and the relaying ratios from May 1979 to March 1980 if the postulated extraneous voltage is removed. Furthermore, relative to the "perfect tracking" point, $|\Delta F_2| = 1.8|\Delta F_1|$ along this straight line. Since the coordinates of ΔF_1 and ΔF_2 are known, the distance ΔF_1 to the "perfect tracking" point can be found by simple proportions as $(\Delta F_1 - \Delta F_2)/(1.8 - 1)$, or $\Delta F_{12}/0.8$. When this is done using the A-Gypsy values for ΔF_1 and ΔF_2 calculated above, the "perfect tracking" point is found to lie at $(0.75 \times 10^{-3}, -0.7 \text{ mrad})$. This point is A-Gypsy (G-square) in figure 13.

Figure 13 shows the results obtained when this process is applied to all the May 1979 data in figure 7. The changes are smaller and the "triangle effect" has essentially disappeared. There are still sizeable RCF changes and evidence of segregation by phase (especially C-phase). The pattern is now quite similar to that for March to December 1980 (fig. 9), i.e., sizeable RCF shifts, very small phase angle shifts. Furthermore, these patterns (figs. 9 and 13) are generally similar to those found at another utility's twice-calibrated substation. Compare figure 14 with figures 9 and 13. Figure 14 shows changes in X2X3 tap ratios (X1X3 taps were not measured in that substation) from November 1979 to May 1980. Evidence for phase segregation, especially A-phase, is strong (statistical analysis has indicated that the probability for random scatter of figure 14 data is less than 5%). As at GSU, this apparent segregation has yet to be explained.

Table 1. Comparable Values From the Three Willow Glen Calibrations

Line	Phase	Tap	May 1979		March 1980		Dec. 1980	
			RCF[6]	γ	RCF	γ	RCF	γ
Franklin	A	X_1	0.9930	+1.0	0.9918	0.6	0.9932	+0.9
Franklin	A	X_2	0.9940	+0.2	0.9909	0.9	0.9924	1.0
Franklin	A	Y_2	1.0019	+1.9	0.9978	2.0	1.0005	2.5
Franklin	B	X_1	0.9992	-3.3	1.0009	-2.3	1.0010	-1.9
Franklin	B	X_2	0.9969	-3.3	0.9999	-1.7	1.0003	-1.0
Franklin	B	Y_2	1.0068	-0.4	1.0101	+1.8	1.0097	2.2
Franklin	C	X_1	0.9976	2.1	0.9951	0.4	0.9981	0.4
Franklin	C	X_2	0.9973	3.5	0.9953	0.4	0.9996	0.3
Franklin	C	Y_2	1.0026	8.2	1.0009	4.8	1.0045	5.5
Gypsy	A	X_1	0.9988	+0.8	0.9953	1.5	0.9954	2.2
Gypsy	A	X_2	1.0018	-0.6	0.9949	1.2	0.9962	1.7
Gypsy	A	Y_2	1.0087	-1.2	1.0012	1.2	1.0023	1.8
Gypsy	B	X_1	0.9891	-0.6	0.9913	0.4	0.9925	1.0
Gypsy	B	X_2	0.9876	-2.4[7]	0.9911	-0.3	0.9925	0.6
Gypsy	B	Y_2	-	-	1.0000	4.2	1.0012	4.7
Gypsy	C	X_1	0.9958	3.8	0.9935	1.0	0.9959	1.7
Gypsy	C	X_2	0.9951	4.4	0.9935	0.6	0.9959	1.3
Gypsy	C	Y_2	1.0018	9.2	1.0002	5.4	1.0045	7.4
Webre	A	X_1	1.0028	2.1	0.9966	3.4	0.9988	3.8
Webre	A	X_2	1.0097	2.2	1.0006	4.3	1.0027	4.7
Webre	A	Y_2	1.0081	-8.2	1.0004	-5.5	1.0019	-5.0
Webre	B	X_1	0.9988	-0.3	1.0006	1.5	1.0012	1.9
Webre	B	X_2	0.9975	+0.2	1.0005	2.9	1.0010	3.5
Webre	B	Y_2	1.0054	+1.4	1.0084	3.9	1.0092	4.7
Webre	C	X_1	0.9977	9.1	0.9947	4.5	0.9977	5.4
Webre	C	X_2	0.9944	9.0	-	-	0.9946	3.2
Webre	C	Y_2	1.0063	13.8	1.0044	8.5	1.0079	9.3

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[7] The AF, AW, and CW CCVTs were adjusted after initial measurement. However, only the metering taps (X1) were measured after adjustment. The adjusted metering values and the initial relaying values (X2 and Y2), appropriately noted, were reported. For purposes of this analysis, the relaying values were adjusted by the same amounts as the reported differences in the initial and adjusted values for the corresponding metering windings. For this reason, the six values will not agree with those reported for the 1979 tests.

[8] Reported as +3.4 mrad. Error discovered during this analysis.

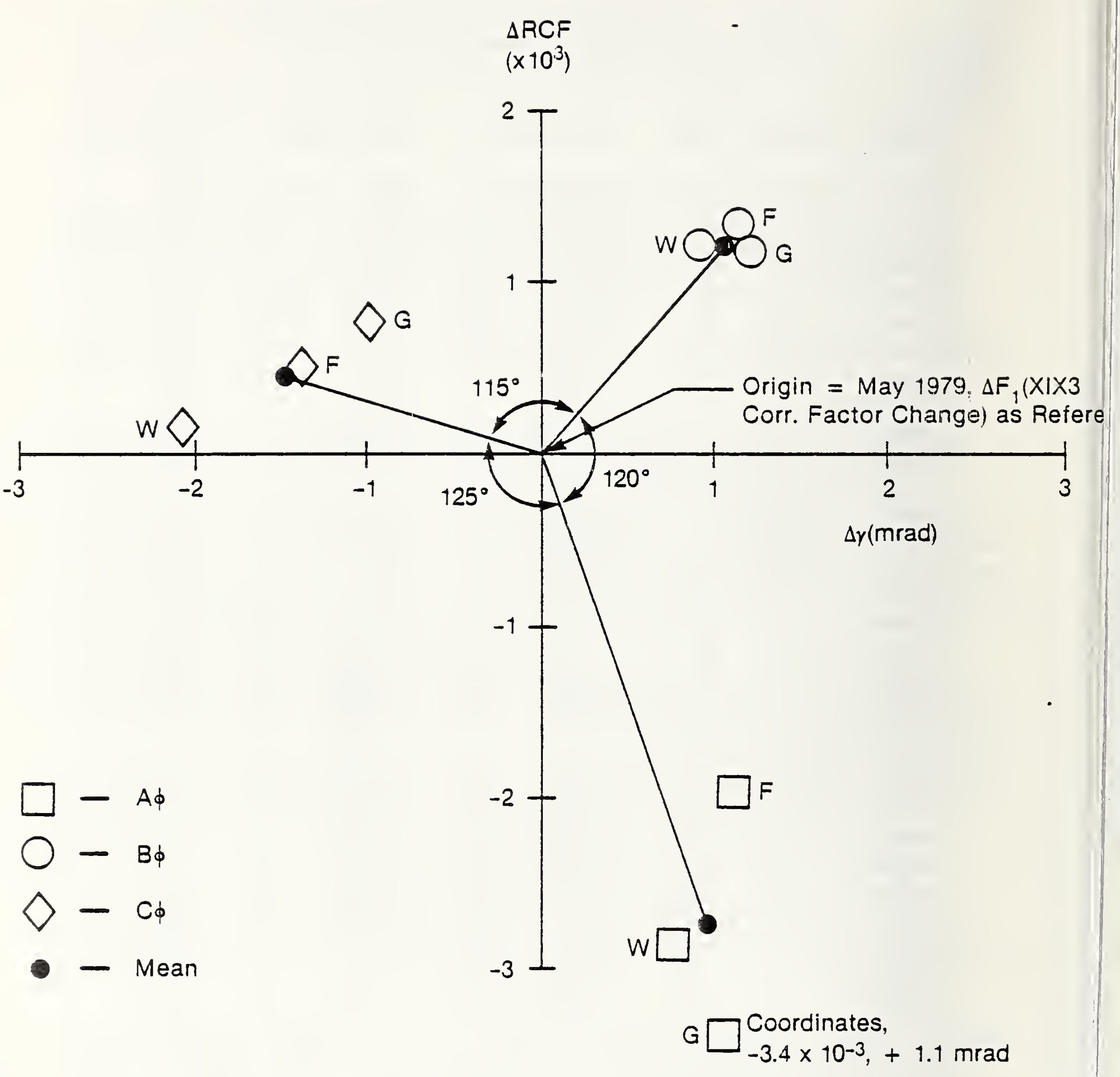


Figure 11. Differences in relaying tap (X2X3) and metering tap (X1X3) changes $(\Delta F_2 - \Delta F_1) = \Delta F_{12}$, May 1979 to March 1980

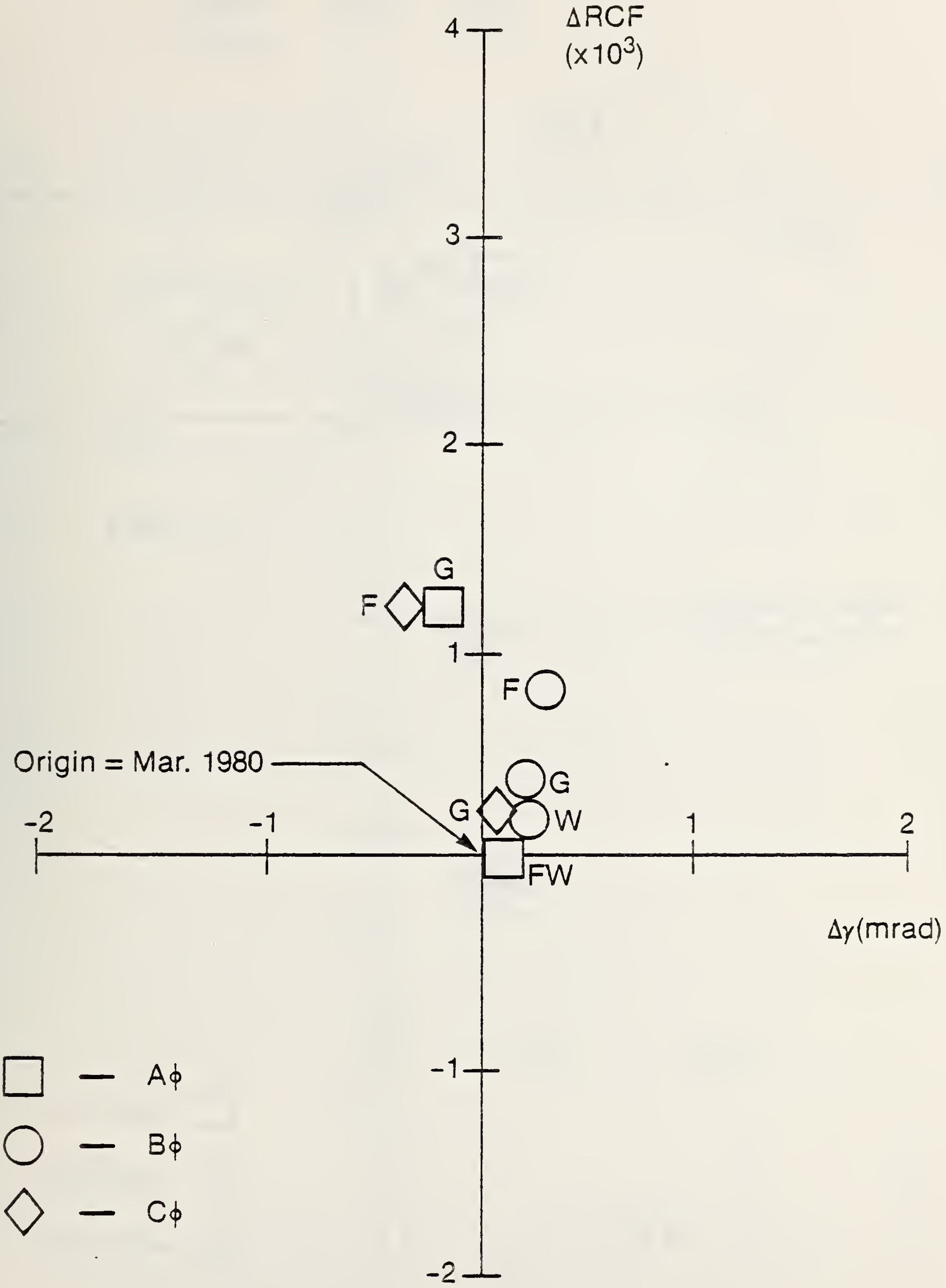


Figure 12. Differences in relaying tap (X2X3) and metering tap (X1X3) changes ($\Delta F_2 - \Delta F_1) = \Delta F_{12}$, March 1980 to Dec. 1980

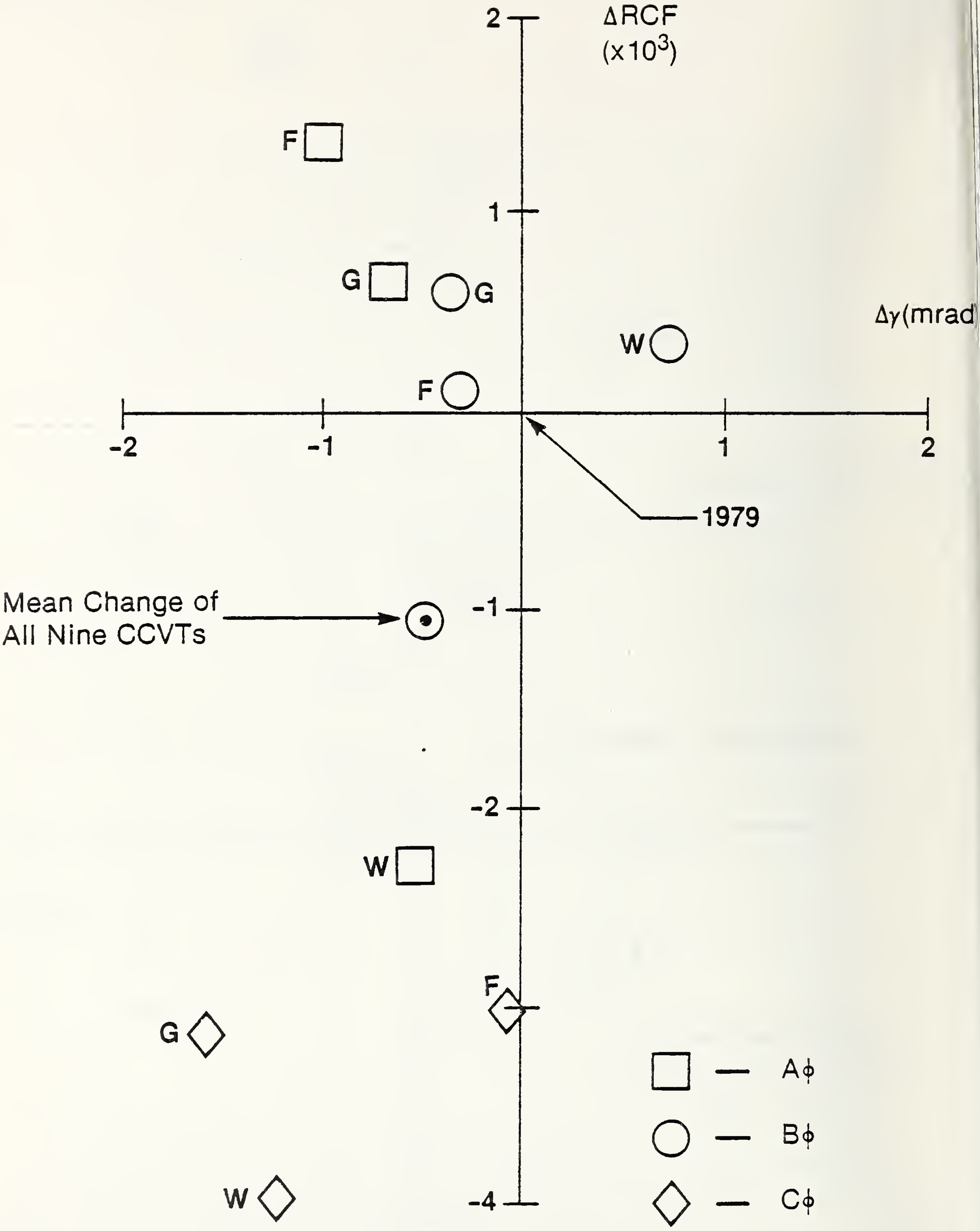


Figure 13. Changes of control house metering RCF and γ, May 1979 to March 1980, after removing estimated adjustment voltages

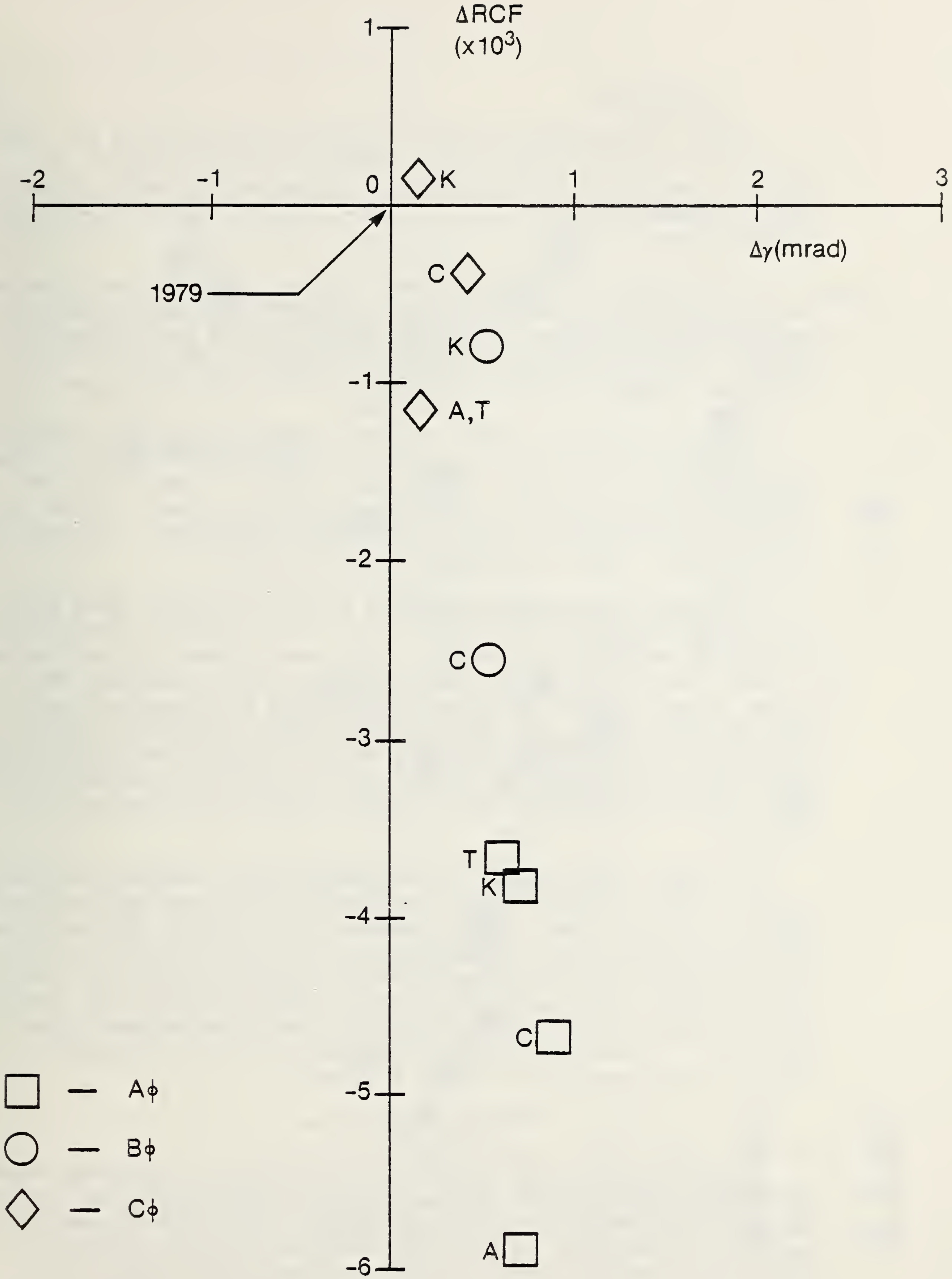


Figure 14. Changes of control house RCF and γ, another utility, Nov. 1979 to May 1980

Finally, figure 15 shows the "revised" history of the GSU X1X3 ratios after the adjustments deduced above have been applied to figure 2. Note that the adjustment produces results which are more closely grouped, especially as to phase, and are nearer the metering parallelogram.

The evidence for this "revised" history is not entirely conclusive, and it is no longer possible to test the hypothesis any further. If the hypothesis is correct, however, it is possible that figure 15 produces a better picture of changes occurring in the CCVTs themselves between May 1979 and December 1980 than does figure 2.

Note from figure 15 that although a number of the CCVTs are well out of metering tolerance, seven out of nine appear at least to have had the same values (±0.1%) in December 1980 as in May 1979. Two devices (A-phase, Franklin, and B-phase, Gypsy), appear to have increased by 0.3 percent and 0.2 percent, respectively. This would not be unexpected, based on our experience with CCVTs.

The March 1980 results from five of the nine CCVTs agree with the December 1980 and the adjusted May 1979 results to within our stated measurement uncertainties. This tends further to confirm that at least five of the devices may have been stable throughout the entire 19-month period (although three of the five were outside of metering tolerance). One device (A-phase Webre) appeared to be 0.2 percent less in March 1980 than both its earlier and later values. This is perhaps unusual behavior, but not a cause for concern in view of the fact that the other A-phase CCVTs did not exhibit this "V effect."

The other three March 1980 results present a somewhat different picture. All three devices are on C-phase; all appear to have been about 0.3 percent lower than in December 1980 and May 1979 (adjusted values), as were both corresponding relaying values for each device. This apparent "V effect" arouses enough suspicion to justify some further tests on the stability of our standard divider, even though previous tests and extensive experience have given us good reason to rely on it. These tests will be carried out as soon as possible. This will be discussed further in section 4.

3.3 Conclusion

Detailed analysis of the data from all three sets of measurements has yielded some evidence for the presence of an unexplained bias in the 1979 measurements. Furthermore, this bias voltage appears to have been of the order of 0.3 volts (mean value of 10 estimates), relatively constant (σ = 0.11 volt), and very roughly 180° out of phase with the A-phase voltage in the substation. Therefore, it may be prudent not to ascribe all the apparent changes in CCVTs between May 1979 and the later measurements to the CCVTs themselves.

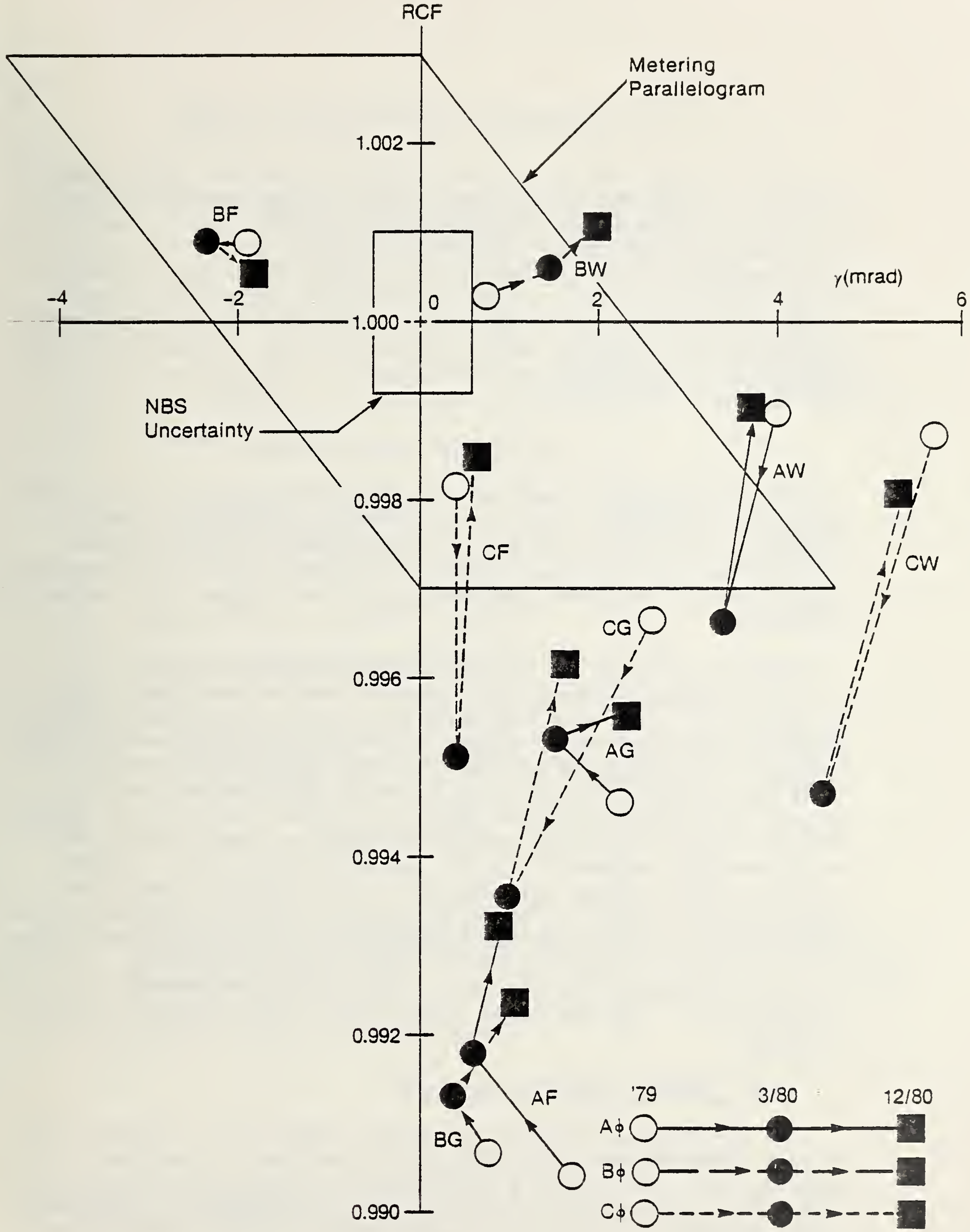


Figure 15. "Revised" history of X1X3 RCF and γ, May 1979 to Dec. 1980

4. EVALUATION OF KNOWN SOURCES OF ERROR

Errors in the calibration of CCVTs can come from three general sources: (1) the NBS calibration system; (2) the substation; and (3) the CCVTs themselves. Insofar as is possible, the following discussion will be divided according to these sources. Since in this investigation we are looking for effects which could account for perturbations of the size of the apparent correlated changes between May 1979 and March 1980, i.e., 0.2 to 0.5 percent for ratio and 1 to 3 mrad for phase angle, the bulk of the discussion will be devoted to sources which could most logically cause errors of that magnitude.

4.1 The NBS Calibration System

The comprehended fixed corrections and error sources in the NBS prototype calibration system are summarized in table 2. Items 1 through 5 and item 7-a are more or less subject to investigation and assignment of estimated limits of systematic and random components. Items 6 and 7-b are either indeterminate or not subject to a priori evaluation.

All the items in the first group above except 1-d, 4-b, 4-c, and 7-a were evaluated and reported upon in great detail in reference [2]. That work was reviewed in the course of this investigation. The results still appear to be valid. The estimates of the standard divider temperature and proximity effects continue to be borne out by field results - the former by many observations of divider ratio before and after periods on-line, the latter by regular shorted divider tests near the 500 kV bus (see especially, p. C-5 and figure C-2, reference [2], for the theory involved). Typical shorted divider voltage measurements yield 10-20 mV or 0.008 to 0.016 percent of 120 V. The largest value of residual ground voltage yet measured was 25 mV, at GSU in December 1980. Some further tests of the divider's stability, and of its voltage, temperature, and proximity dependence are planned, in view of the "V effects" discussed in section 3.2. The remaining items in the first group will now be discussed.

1-d. Magnetic Coupling to Stack

An error can be produced by voltage magnetically induced in the divider capacitor string by currents in the buses or the ground mat. These currents are at most a kilo-ampere or so at a distance of 5-10 m, generating a volt or less out of hundreds of kilovolts. Uncertainty due to magnetic coupling is probably quite a bit less than the value assigned to it.

Table 2. Correction and Error Summary -
NBS Calibration System

Source	Percent Correction	Estimated Percent Uncertainty[a]
1. Standard Divider:		
a. Voltage Dependence	-0.02	± 0.010
b. Temperature Effects	-0.02/hr	± 0.015
c. Proximity Effects	-0.01	± 0.010
d. Magnetic Coupling to Stack	0	± 0.001
2. Compressed Gas Standard Capacitor	0	± 0.007
3. Reference Standard Capacitor	0	± 0.001
4. Bridge:		
a. Ultimate Accuracy	0	± 0.002
b. Zero Offset (Residual P.U.)	0	± 0.010
c. Detector Noise	0	± 0.003
5. Miscellaneous (Undiscovered)	0	± 0.015
6. Operator Error	—	—
7-a. Ground Voltages (Choke-Compensated)	0	± 0.010
Arithmetic Sum of Errors ("Worst-case")		± 0.084
Quadrature Sum of Errors		± 0.030
7-b. Ground Voltages (Uncompensated)	0	± (0.1 to 0.5)

---

[a] At the 3σ confidence level

4-b. Bridge Zero Offset

Error can be produced by magnetic pickup in the current comparator bridge. It is apprehended by balancing the bridge, then reducing bridge voltage to zero and observing detector deflection. This effect may vary from 0.005 percent to 0.04 percent of the ratio being measured, with typical values being 0.01 to 0.02 percent. Most of this error is believed to have been compensated for, either by offsetting the bridge to the residual pickup value, or by determining the offset and applying a correction.

4-c. Detector Noise

Detector noise is a "nuisance" perturbation. It is brought about by low voltage in the battery-powered bridge detector. It manifests itself in a noisy (unstable) detector null, making balance difficult in the fifth (10^{-5}) place. It is normally noticed and corrected well before the stated uncertainty level is reached.

6. Operator Error

Operator error has been listed in table 2 because it has been broached as a possible problem. However, it cannot be given a quantitative value. Our system of double-checking and read-back of data, plus on-the-spot preliminary calculations, and the use of operators accustomed to dealing with very exacting measurements, greatly minimizes operator error. In any event, such an error would be likely to manifest itself as an individual outlying value, not as the series of apparently systematic perturbations being investigated.

7. Ground Voltage

An uncompensated ground voltage appears to be the only source of error in the NBS system which could possibly account for the unexplained voltage postulated to be present in the 1979 measurements. Its typical range in the substation is from 0.1 to 0.6 volts. This represents 0.08 to 0.5 percent or 0.8 to 5 mrad, which encompasses the range of discrepancies being investigated. Furthermore, its "signature" is similar to that produced in the 1979 vs. March 1980 data (fig. 11) by failure of the X1X3 and X2X3 taps to track each other.

But consider the effect of injecting a single voltage (V_g) into the NBS system in this manner, as indicated by the circuit of figure 16. Figure 17 shows the vector diagram resulting from figure 16 (with the size of V_g greatly exaggerated). Note that the vector change in voltage is identical in all three phases, but that the in-phase and quadrature changes, which ultimately determine the changes in ratio correction factor (ΔF) and phase angle ($\Delta\gamma$), are different for each phase. It can be shown that ΔF for each phase is proportional to the magnitude of V_g/V_{phase} multiplied by the

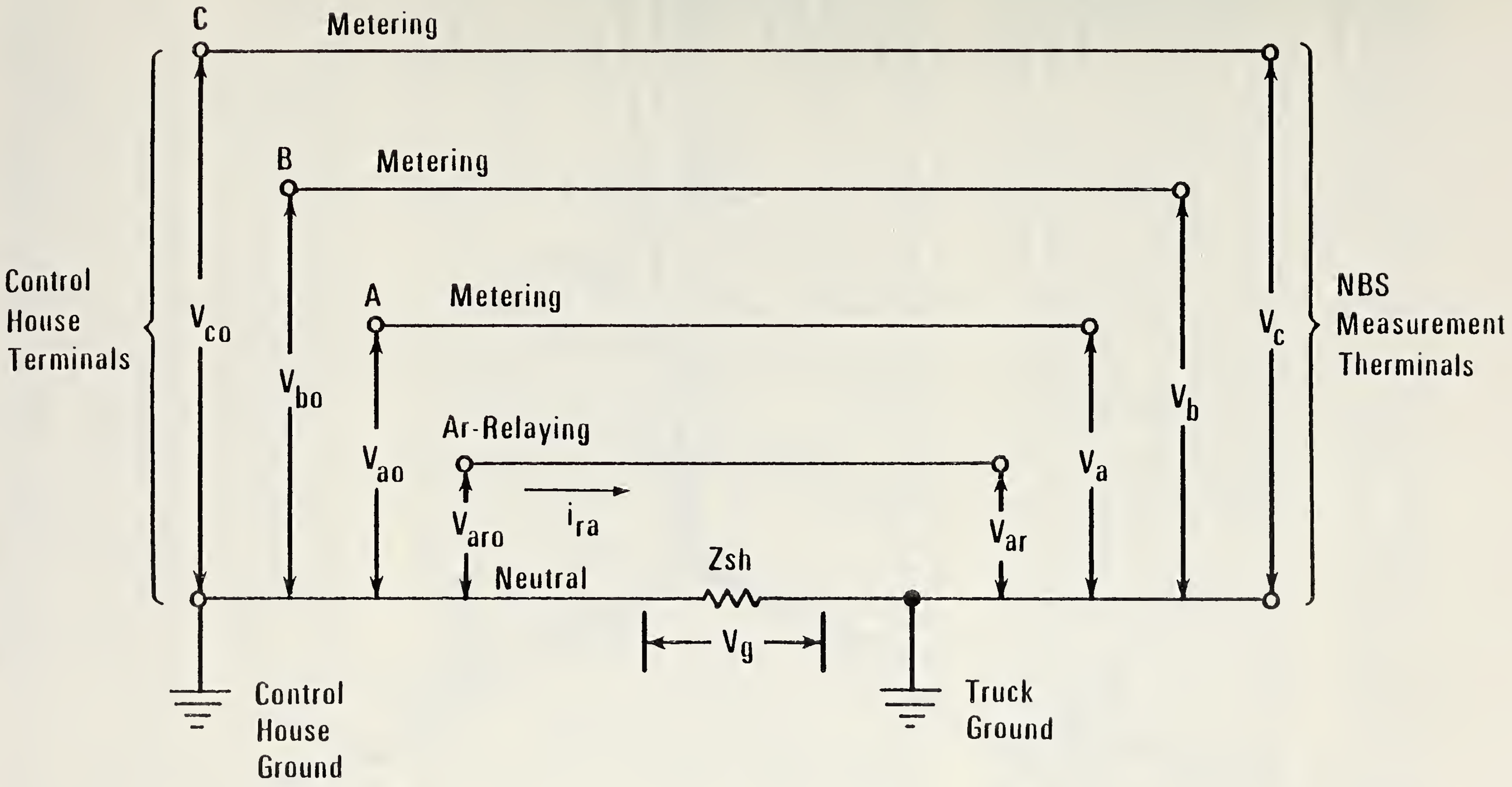


Figure 16. Circuit diagram, single uncompensated voltage, V_g, added in the ground lead between the control house and the NBS bridge

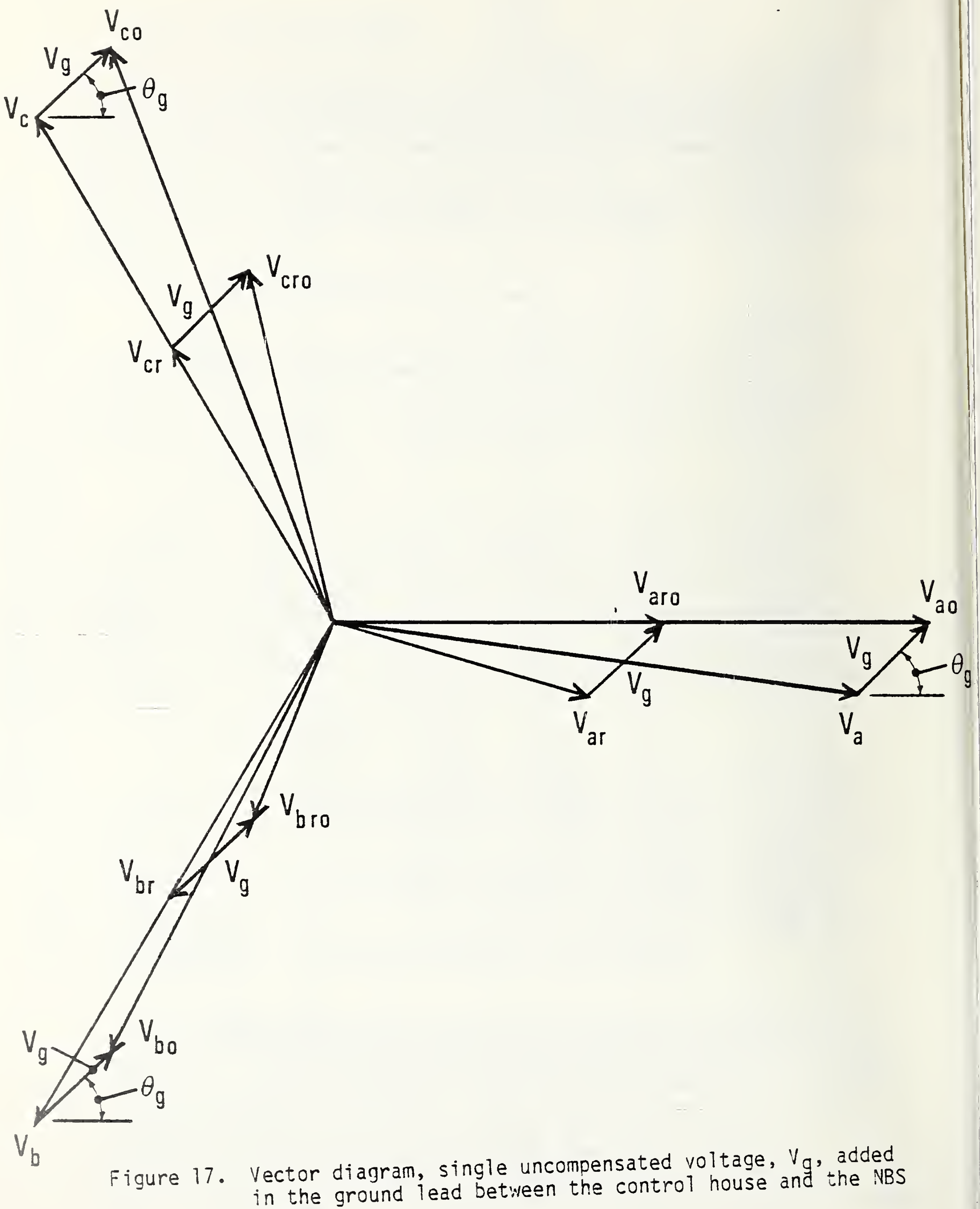


Figure 17. Vector diagram, single uncompensated voltage, V_g, added in the ground lead between the control house and the NBS bridge

cosine of the angle between V_g and V_{phase} (θ_g for A-phase, $\theta_g + 120°$ for B-phase, $\theta_g + 240°$ for C-phase). Similarly, $\Delta\gamma$ is proportional to the magnitude of V_g/V_{phase} multiplied by the sine of the angle between V_g and V_{phase}.

A detailed analysis based on these relationships shows the "signature" of a single injected voltage, in terms of the ΔRCF and $\Delta\gamma$ of figure 11, to be three vectors identical in magnitude and separated by 120°. In figure 11, the magnitude of the A-phase vector is approximately 1.8 times greater than the magnitudes of the B- and C-phase vectors. The "signatures" do not match. However, the difference could be attributed to variations in the unknown injected voltage during the measurement. Our experience has shown that ground voltage can vary by the order of 2:1 over a few hours time. Therefore, the ground voltage hypothesis cannot be dismissed entirely.

In any event, because of the importance of ground voltage differences, compensation for it in the form of coaxial chokes was designed into the original system. But first, let us consider the sources of ground voltage errors. Refer to figure 18, which is a semi-pictorial representation of the CCVT calibration circuit in the substation. For safety reasons, there are three instrumentation grounds in this system (G1, G2, and G3 -- G4 is associated with the CCVT). These are connected to the substation ground grid. Currents flowing in the ground grid (due, e.g., to unbalanced phase voltages) generate voltages $i_{g1}Z_{g1}$, $i_{g2}Z_{g2}$, and $i_{g3}Z_{g3}$, respectively, between these ground points. In addition, magnetic coupling from bus current I or from ground currents, represented by B1, B2, and B3, may induce additional voltages in these ground loops. The summations of these voltages can be represented by ground voltages, V_{g1}, V_{g2}, and V_{g3}. Considering the NBS system only and assuming for the moment that there are no coaxial chokes, V_{g1} is impressed across the standard divider cable shield, and generates an error voltage, $V_{e1} \cong i_{sh1}Z_{sh1}$, directly in series with the voltage to be measured (V_2). A similar effect occurs in the control house loop.

The ground voltage effect, and its compensation by a coaxial choke, can be seen more clearly in figure 19. Figure 19-a shows the ground loop circuit in the absence of the choke. Error voltage $V_e \cong V_g$ as stated, since the cable center conductor is connected to V_g through an impedance approaching infinity ($i_\ell \cong 0$).

Figure 19-b shows the same circuit with the coaxial choke in place. The choke is a 1:1 transformer, formed by winding a number of turns of the signal cable through a high permeability toroidal core. Assume that its magnetizing impedance is Z_L; the resistance and leakage reactance add to Z_{sh}. Thus any voltage, V_{ch}, appearing across the shield conductor of the choke, also appears in the center conductor (diminished only slightly by the combined effect of the

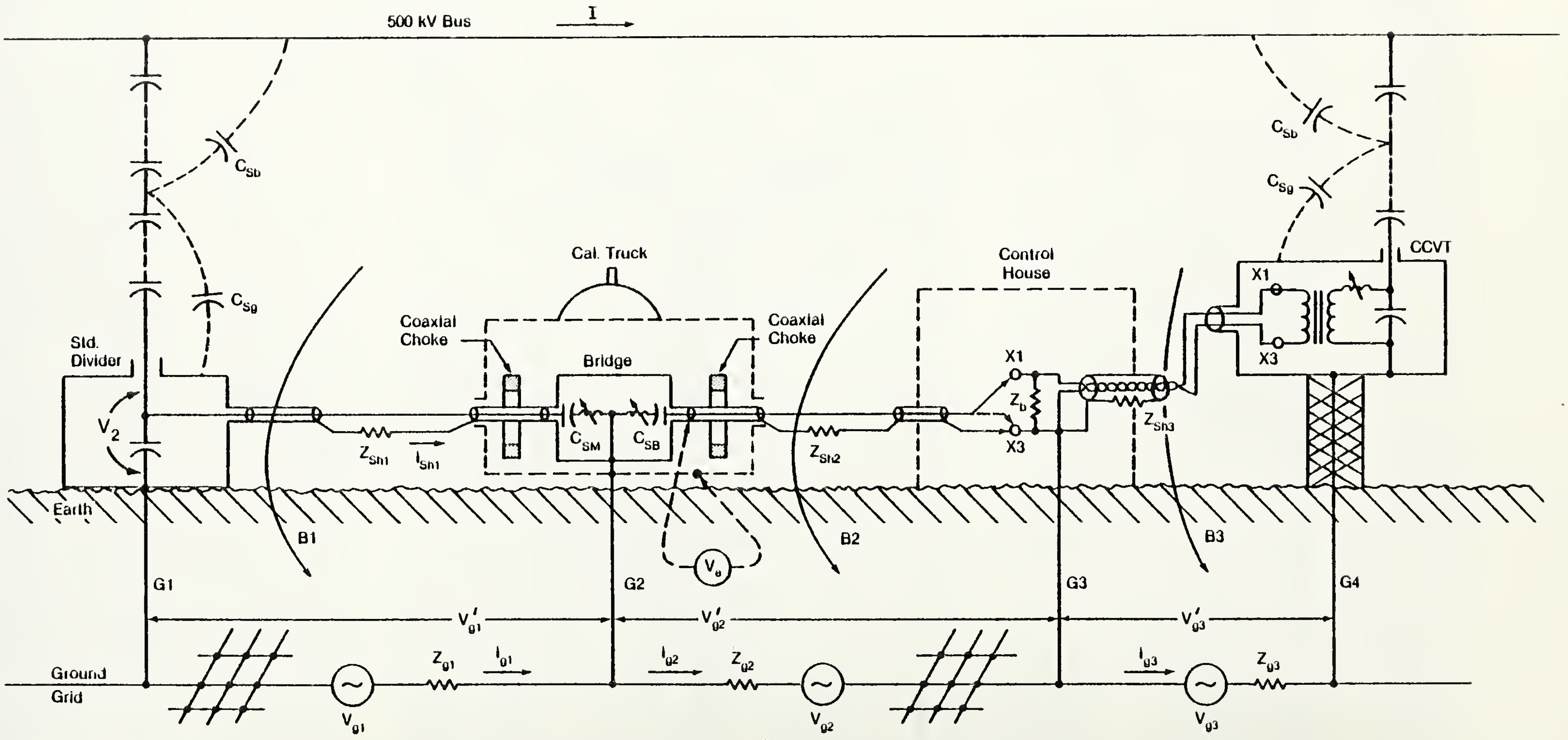
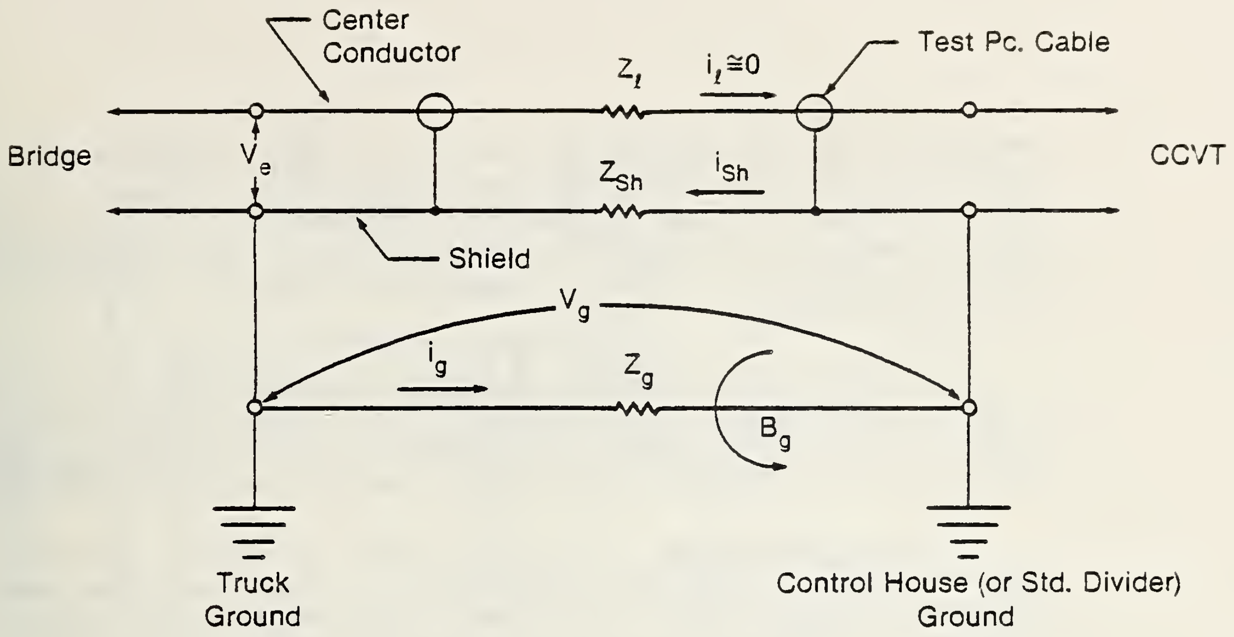
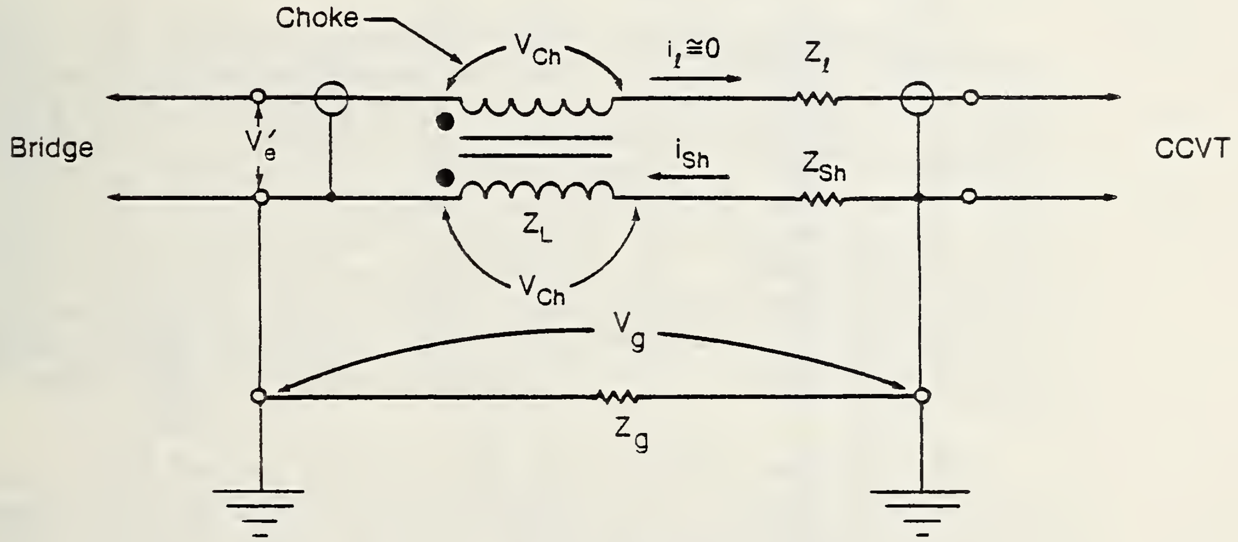


Figure 18. Origin of ground voltages in the field calibration of CCVTs



$$V_e = i_{Sh}Z_{Sh} + i_\ell Z_\ell \cong V_g$$

a. Without Coaxial Choke:



$$V'_e = V_g\left(\frac{Z_{Sh}}{Z_{Sh} + Z_L}\right)$$

$$\cong V_g(Z_{Sh}/Z_L),\ \text{Since } Z_L >> Z_{Sh}$$

b. With Coaxial Choke:

Figure 19. Function of coaxial chokes in eliminating ground voltages

presence of Z_{sh} and the finite value of Z_L) and in opposition. This effectively cancels the ground voltage error. There is a net error voltage, but since the choke is designed so that $Z_L > 50\ Z_{sh}$, V_e is reduced to 1 or 2 percent of V_g. Thus, if V_g, uncompensated (item 7b, table 1) is 0.5%, V_g, compensated (item 7a, table 2) is $\leq 0.5/50 = 0.01\%$.

Since the coaxial chokes are designed specifically to eliminate V_g as an error source, V_g can appear only if these chokes fail to function. Only three such failure modes are admissible: (1) core saturation; (2) grounded cable shield; and (3) open cable shield.

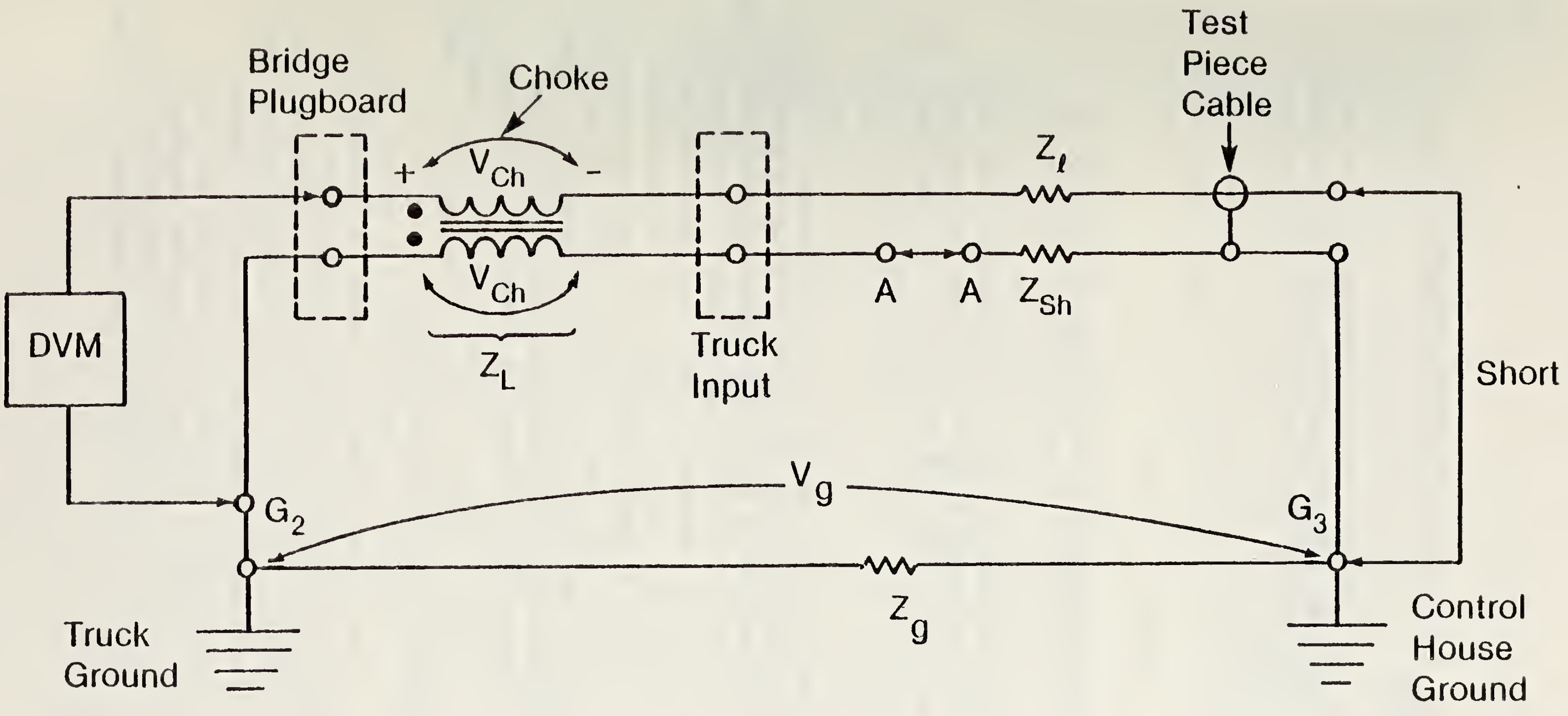
(1) Core Saturation - This occurs when V_g exceeds the choke design voltage. It can be dismissed here, since the chokes were designed and tested for V_g up to two volts, whereas the largest V_g yet seen in practice has been less than one volt.

(2) Grounded Cable Shield - Referring to figure 19-b, a signal cable shield shorted to ground (ahead of the choke in terms of the direction of i'_{sh}) effectively bypasses the choke, returning the circuit to figure 19-a. This can occur, for example, if an uninsulated cable joint touches wet earth, or if the shield insulation at the truck entrance breaks down.

(3) Open Cable Shield - Referring again to figure 19-b, an open cable shield means $Z_{sh} \to \infty$. From the associated equation, note that in this case $V'_e \to V_g$. An open shield is the limit of a subcategory -- bad shield connections. In such cases, Z_{sh} need only approach or exceed Z_L (typically 50-100 Ω) for most of the compensation to be lost. This condition can occur if a cable shield is broken or intermittent, or if there is a poor connection to neutral in the control house. The latter seems more likely, since this connection is made with clip leads (since control house connections are made by utility personnel, this error source is properly associated with the substation, not the NBS system, and will be discussed in section 4.2).

Before further discussion of any of these ground voltage compensation failure modes, it is appropriate to look at the field procedure for detecting and correcting such a failure. This procedure involves two simple voltage measurements, as outlined below, using the circuit shown in figure 20. The procedure, as applied to the truck-to-control house loop (V_{g2}) is:

1. Make the voltage measurement shown in the figure (points A-A connected). Since in a properly designed choke, $Z_L \gg Z_{sh}$, most of V_g appears across Z_L and is transformed 1:1 into the center conductor, so that



Z_ℓ = Center Conductor Impedence

Z_{Sh} = Shield Impedence

Z_L = Coaxial Choke Magnetizing Impedence

Figure 20. Coaxial choke test

$$V_{DVM} = V_{g2} \; (Z_{sh}/Z_L) = V_e \cong 0 \qquad (2)$$

where V_e is the residual error voltage, and is normally <10 mV if the choke is functioning.

2. In the same circuit, repeat step 1 with the shield broken, e.g., at A-A. Now, no current flows through the choke, the center conductor becomes a drop lead, and the DVM is effectively directly across G_2 - G_3. Therefore,

$$V_{DVM} \approx V_{g2} \; . \qquad (3)$$

Note 1: The effect of opening the link A-A can be obtained by disconnecting the shield from G_3 at B in the control house.

Note 2: A less convenient alternative is to disconnect the test piece cable at the truck and measure V_{g2} via either the center conductor or shield (equivalent to step 2 above), then reconnect the test piece cable and repeat step 1 above. This method was in use in 1979 and in March 1980.

This procedure detects any of the three failure modes, so that they can be corrected. Thus the only possibility for ground voltage to introduce error would seem to be for compensation to be intermittent, i.e., present during the above tests and absent during the affected measurements. It seems highly improbable that this condition would persist throughout an entire calibration (May 1979) and be absent throughout two others. It is arguable that such an occurrence was more likely in 1979 and March 1980 than in December 1980, since (1) a less convenient procedure for choke testing was used earlier (see Note 2, above), and (2) the test was performed fewer times (spot checks), whereas, in December 1980, it was performed at least once after each significant circuit change, and more thoroughly documented. In any event, the large changes occurred between 1979 and March 1980, unaccompanied by a change in this test procedure.

In summary, none of the known sources of error in the NBS calibration system seemslikely to account for the changes under investigation here. The quantifiable error sources in table 2 have been summed, both for "worst-case" and for normal random uncertainty. Since even the "worst-case" total uncertainty (± 0.08%) is much less than the changes being sought, these error sources can safely be dismissed. Even ground voltage, the best candidate because of its size and the similarity of its "signature," to the actual "signature" of figure 11, would seem to be an improbable source because of system design and test procedures.

4.2 The Substation

Error sources which might be associated with the substation (exclusive of the CCVTs themselves) include: (a) multiple grounds on neutrals; (b) electrostatic or magnetic coupling to leads; (c) burden changes; (d) temperature coefficients of leads; (e) zero-sequence currents in the neutral; and (f) bad temporary connections to test piece terminals in the control house during calibrations. Since the substation is a complex system not within the general area of NBS expertise, no claims are made for the completeness of this list. The items listed will be discussed in order.

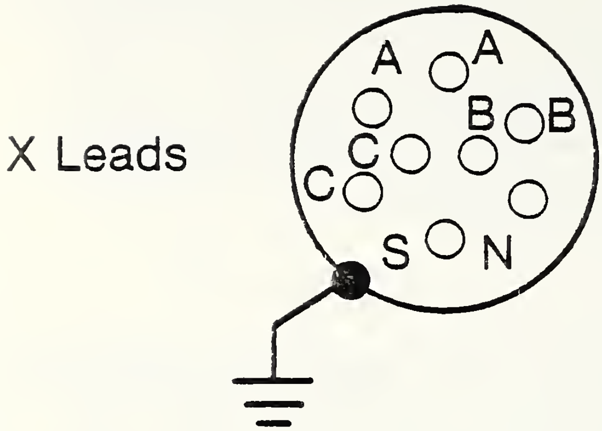
4.2.1 Multiple Grounds on Neutrals

Multiple grounds on the neutrals produce errors for exactly the same reasons as discussed earlier for the NBS system. This is avoided in the CCVT-to-control house circuit (fig. 18, G3-G4 ground loop) by running the signal leads as twisted pairs inside a grounded sheath, and leaving the CCVT end of the neutral ungrounded (X3 in fig. 18). The first step minimizes the effect of B3, the second eliminates the ohmic voltage, $i_{g3}\ Z_{g3}$. If the neutral should be grounded more than once (e.g., wiring error, or short to the sheath), an active loop, exactly analogous to the G1G2 loop discussed earlier, is created and an error voltage equal to V_{g3} or some fraction thereof is introduced. Ohmmeter measurements from neutral to ground with both X3 points ungrounded demonstrated that no such multiple grounds existed in December 1980. These measurements were not made during earlier tests.

4.2.2 Electrostatic or Magnetic Coupling to Leads

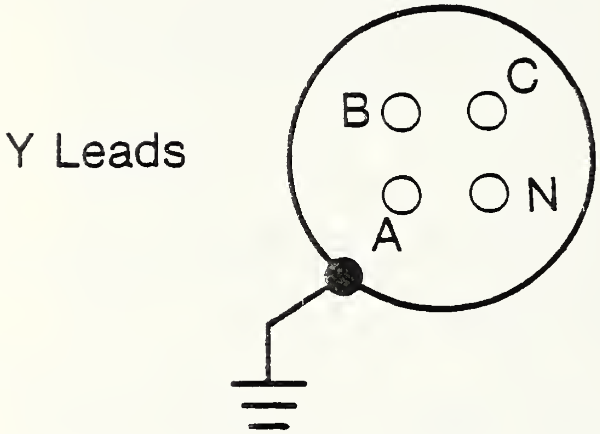
Electrostatic coupling is most unlikely if standard practices are followed. In any event, there seems to be no reasonable way in which it could have changed between calibrations.

Magnetic coupling or, more precisely, changes in magnetic coupling can occur, since the magnitude and direction of bus currents and/or ground grid currents are, in general, different at different times. However, since it is standard practice to run leads twisted inside a multiply grounded shield or, more precisely, as multiconductor cables (fig. 21), with the conductor bundle twisted inside a multiply grounded conduit, it is difficult to imagine an effective loop large enough to produce significant coupling. If for some reason (fig. 21) the X and Y neutrals were interchanged, a much larger loop would be created, but even this would probably be too small to be significant. As an extreme hypothetical case, assume that twisted leads, or even misplaced neutrals in figure 21, are separated so as to form a loop 0.3 m x 100 m (1' x 300'). From simple considerations, it can be calculated that 1 kA in a bus 10 m (30') above, or 10 A ground current 0.6 m (2') away would produce only $V_e \cong 0.25$ volts. Coupling in the actual configuration should be many times smaller.



8-Conductor Cable (#8 Wires)

Ph	Leads
A	X1, X2
B	X1, X2
C	X1, X2
N	X3
S	Spare



4-Conductor Cable (#8 Wires)

Ph	Leads
A	Y2
B	Y2
C	Y2
N	Y3

Figure 21. Disposition of CCVT leads, makeup box to control house

It has also been proposed that cross coupling between the neutral and phase wires, or among phases in intimate proximity inside the same cable, might produce a significant effect. A calculation based on two #8 wires 0.5 mm on centers, a length of 200 m (600 ft), and a Z-burden current (in one wire only) of 1.6 A, yields V_e = 0.12 volts for untwisted wire. Therefore, this coupling source should be totally negligible for a twisted wire.

4.2.3 Burden Changes

A burden change between calibrations could easily produce discrepancies of the order being investigated here. Burden data furnished by GSU after the May 1979 tests disagree significantly for all nine CCVTs with burden data actually measured during the December 1980 tests (table 3). Therefore, the possibility of an undocumented burden change has to be considered. It can be shown that a burden change as small as 20 VA resistive in the relaying circuit on A-phase produces a "signature" on the differences between the changes in the X1X3 and the X2X3 tap ratios which is formally similar to that extracted for the actual system (fig. 11). The unbalanced effect is brought about by unbalanced burden currents from the three phases, returning on a common neutral, and by extra drop in the A-phase relaying leads (assuming that the burden change is in the A-phase relaying circuit). The same change could of course also be produced by an equivalent combination of burden changes in all three phases.

An analysis, formally identical to that performed in section 4.7 for a single ground voltage injected into the neutral, can be carried out to determine what the "signature" of a burden change in one phase would be. The circuit and the vector diagram for a burden, Z_B, added in the A-phase relaying winding only, are shown in figures 22 and 23, respectively. For simplicity all other taps are assumed to be unburdened, and all lead impedances to be equal (Z_l). $V_0(= i_{ra}Z_l)$ in figure 23 is formally identical to V_g in figure 16. Note that the only difference in the vector diagrams of figures 16 and 23 is that V_0 adds twice (2 V_0) to the relaying voltage in A-phase.

Carrying out the same analysis as before, the "signature" of the burden change postulated in terms of the ΔRCF and Δγ of figure 11 again yields three vectors at 120° to each other as expected. But the magnitude of the A-phase vector is approximately 3.25 times greater than the magnitude of the B- and C-phase vectors, whereas the magnitude of the figure 11, A-phase vector is only 1.8 times greater, nearly a 2:1 discrepancy.[9] Once again, the "signatures" do not match.

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[9] The detailed analysis proves trigonometrically what could be inferred intuitively--V_a = 1.8 V_{ar}; therefore, any common influence on ratio (hence RCF, γ) is 1.8 times greater on the relaying tap than on the metering tap. V_0 appears twice in the relaying circuit so that its total effect is 3.6 times greater. The difference is (3.6-1) = 2.6. By identical reasoning for the other phases, the difference is (1.8-1) = 0.8, so that 2.6/0.8 = 3.25.

Table 3. Total Burdens on Calibrated CCVTs at Willow Glen

Line	Phase	VA (Furnished by GSU) 1979	VA (Measured by GSU) Dec. 1980
Franklin	A	87 /-57	50 /-27
Franklin	B	108 /-37	57 /-32
Franklin	C	86 /-45	57 /-52
Gypsy	A	83 /-56	49 /-29
Gypsy	B	104 /-37	58 /-34
Gypsy	C	86 /-45	46 /-52
Webre	A	83 /-56	133 /-41
Webre	B	104 /-37	125 /-54
Webre	C	86 /-45	93 /-56

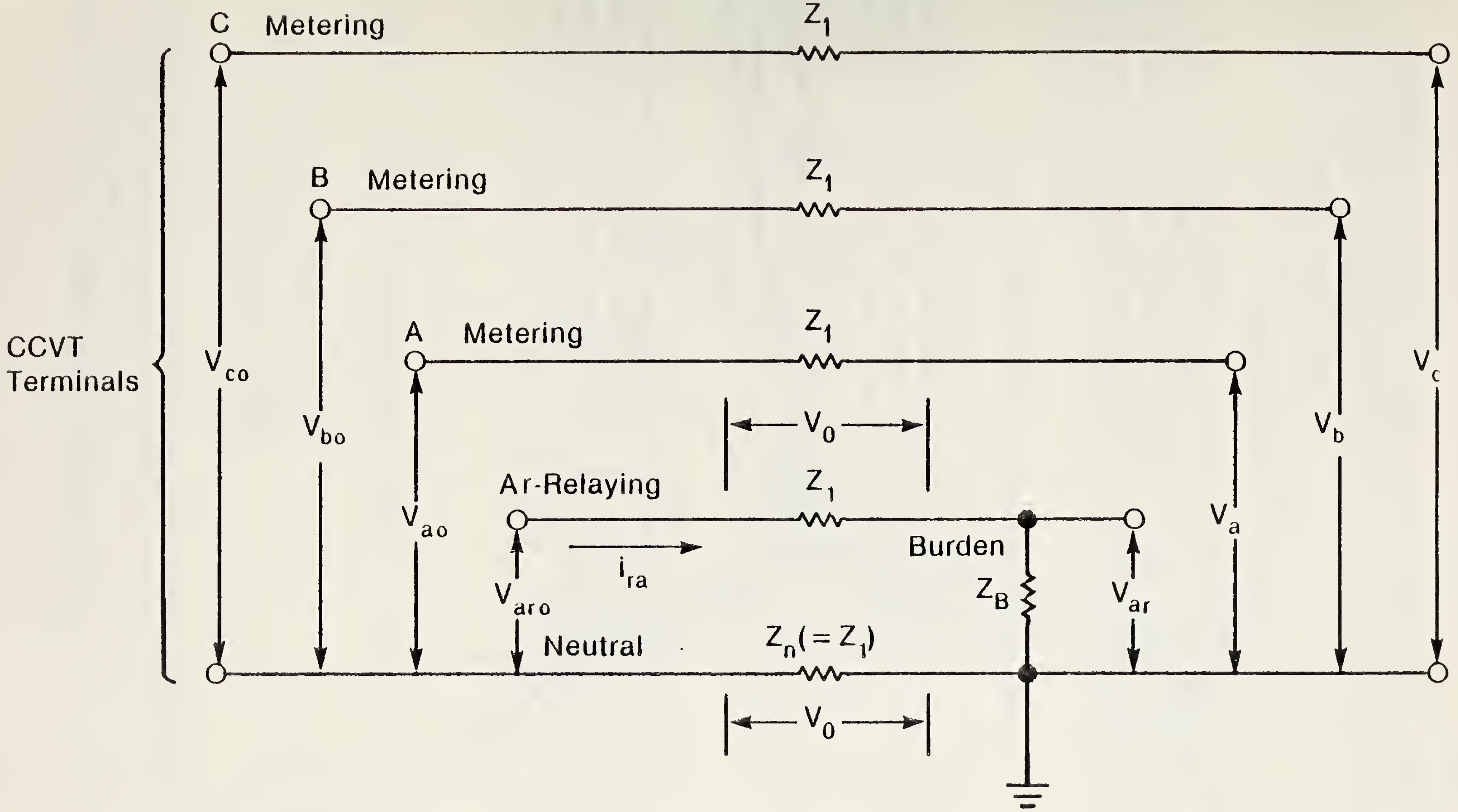

Figure 22. Circuit diagram, burden added to A-phase relaying winding only. Note--B- and C-phase relaying windings not shown

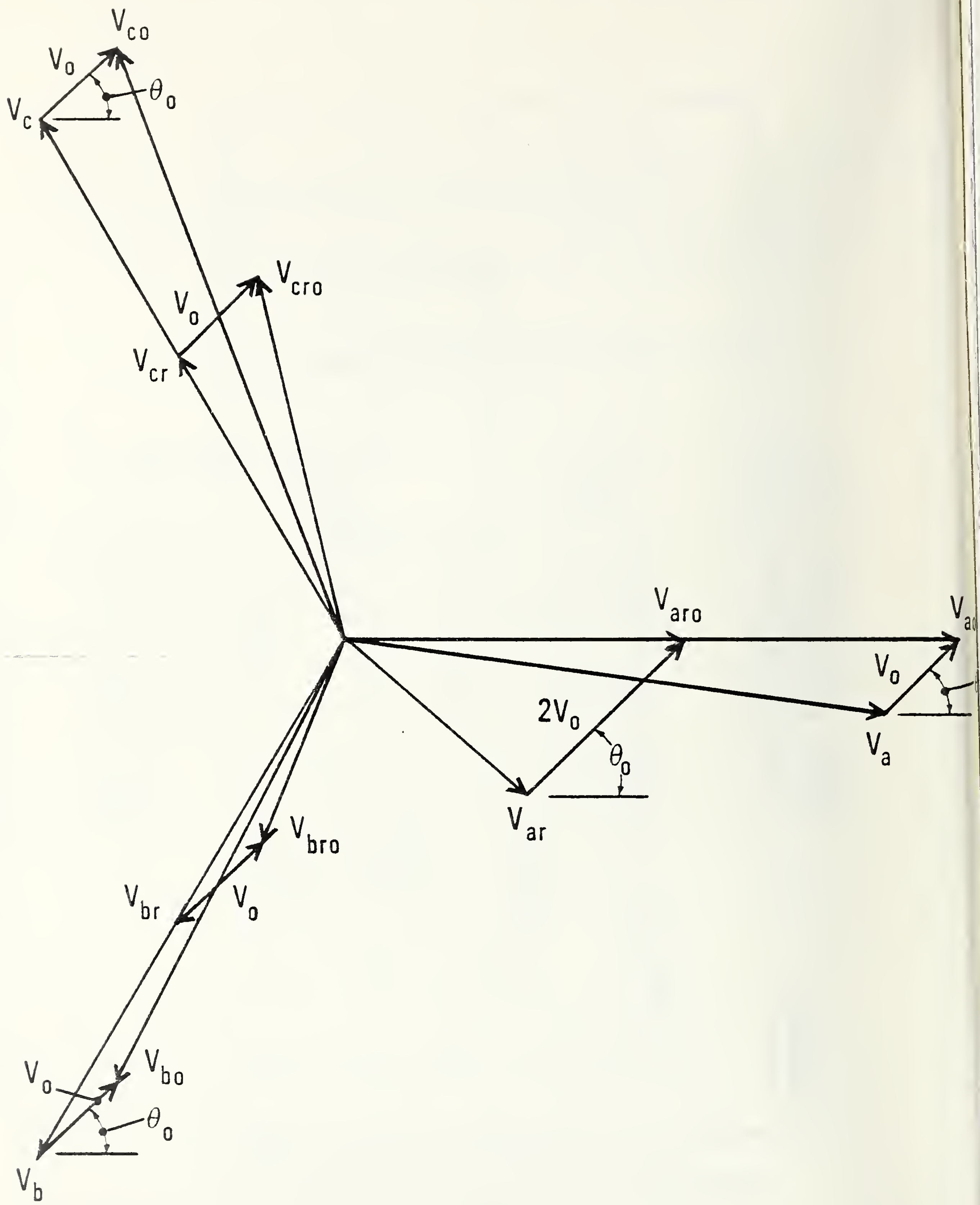

Figure 23. Vector diagram, burden added to A-phase relaying winding only

In addition, in order to obtain the figure 1 grouping by phase, a similar A-phase burden change would have to occur on all three lines. Thus, like other plausible explanations for the subject discrepancies, this one also seems improbable.

4.2.4 Temperature Coefficients of Leads

The long runs (200-300 m) of #8 copper wire involved contribute significant voltage drops (order of 0.8% for 100 VA burden). However, since the total lead drop is less than three times the unknown voltage under investigation, temperature effects are negligible. Simple calculations show that no imaginable temperature change could explain the changes sought.

4.2.5 Zero-Sequence Currents in the Neutral

In a perfectly balanced four-wire three-phase circuit (e.g., three CCVTs with the same burdens and line voltages) no net neutral current flows. If the impedances or the voltages become unbalanced, neutral current will flow. The unbalanced impedance case has already been dealt with (burden change, one phase), and it was shown that net neutral current perturbs the CCVT ratios in all three phases. In practice, line voltages can also become unbalanced. The effect can be determined by perturbing one of the source voltages, e.g., V_a, in the circuit of figure 24.

In figure 24, which shows the metering windings only, for simplicity, assume that all three phase voltages have the same magnitude, that all three phases have the same burden, Z_B, and that all lead impedances are equal (= Z_l) and much smaller than Z_B. Writing and solving the mesh equations for V_a, V_b, and V_c, and taking the appropriate partial derivatives with respect to V_a, it can be shown that

$$\partial F_a/\partial V_a = Z_l/(V_a Z_B) \qquad (4)$$

where F_a = ratio correction factor, phase A. Similarly

$$\partial F_b/\partial V_a = Z_l/(V_b Z_B) \quad \underline{120^\circ} \qquad (5)$$

$$\partial F_c/\partial V_a = Z_l/(V_c Z_B) \quad \underline{-120^\circ} \qquad (6)$$

Assuming some rather extreme values for voltage unbalance, burden, and lead impedance, let $\Delta V_a/V_a = +5\%$, $Z_B = 70\ \Omega$ (Z-burden), and $Z_l = 1\ \Omega$ and find that

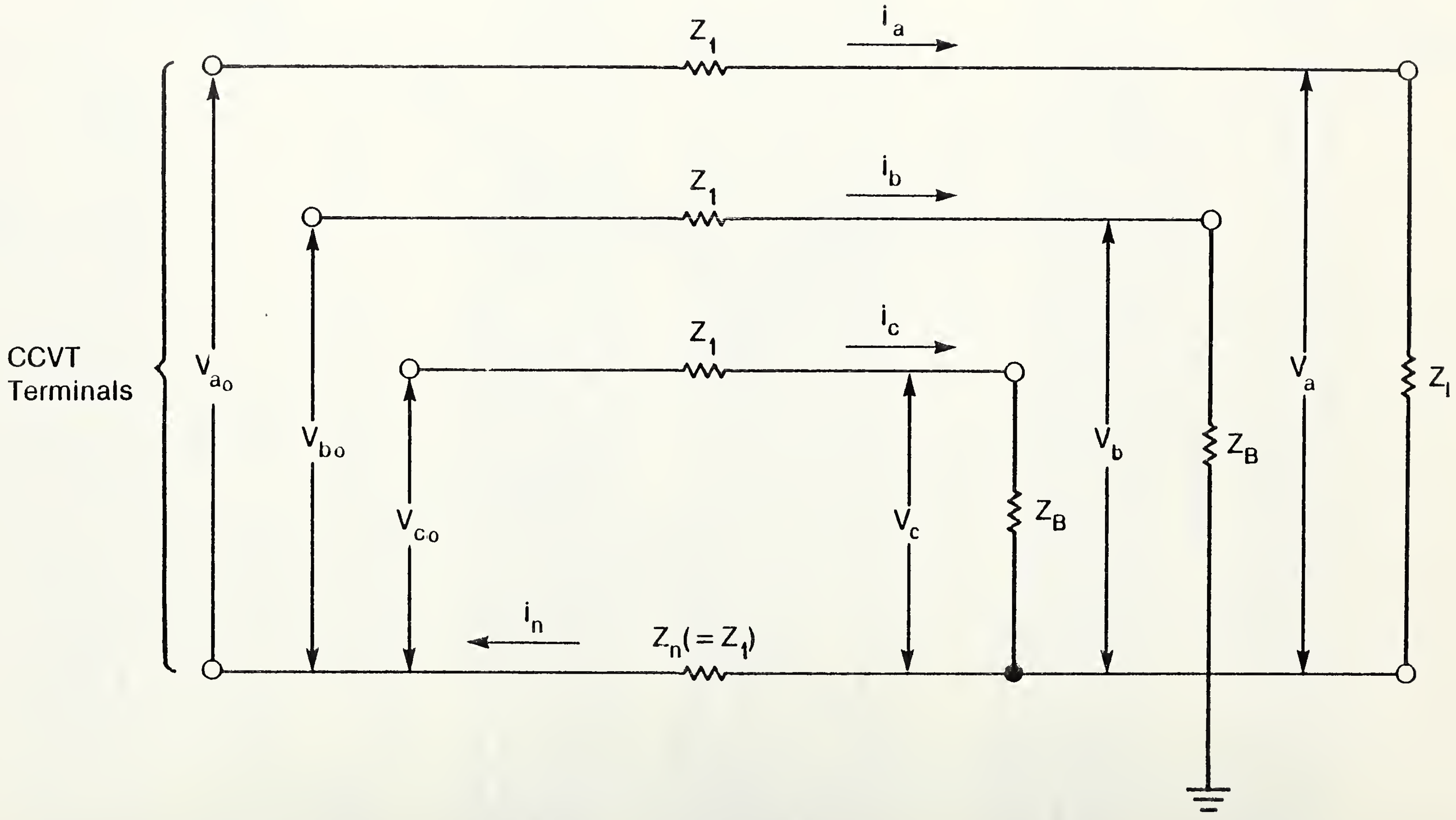

Figure 24. Circuit diagram, balanced voltages and impedances, for study of the effect of unbalancing one phase voltage

$$\Delta F_a \cong +\,0.05\left(\frac{1}{70}\right) \cong 0.07\% \qquad (7)$$

$$\Delta F_b \cong 0.07\%\,(\cos 120^\circ + j \sin 120^\circ) \qquad (8)$$

$$\Delta F_c \cong 0.07\%\,(\cos 120^\circ - j \sin 120^\circ) \qquad (8A)$$

so that $\Delta F_b = 0.035\%$, $\Delta\gamma_b = 0.35\sqrt{3}$ mrad, etc. Thus even very large voltage unbalances operating on large burdens and large lead impedances produce very small effects. More reasonable values might be $\Delta V_a = 2\%$, $Z_1 = 0.6$ ohm, $Z_B = 100$ ohms, for which $\Delta F_a \cong 0.024\%$. Therefore, reasonable zero-sequence currents could not produce the effects seen here.

4.2.6 Bad Temporary Connection of Cable Shield in Control House

This error source was mentioned briefly in conjunction with the discussion of ground voltage errors due to open signal cable shields in the NBS system. Although a bad shield connection could occur elsewhere, it is less likely. All the other shield connections are "permanent," i.e., are made with UHF screw-connection fittings, and made once during the calibration of a phase, whereas the control house shield connection is moved at least once for every test piece. Also, whereas a bad connection to the center conductor will be apparent immediately at the bridge, a bad or open shield connection will not. Because this connection is moved, a proper shield connection as shown by a coaxial choke test (fig. 18), can be lost when the connection is moved during calibration.

Bad shield connection can take the following forms: (1) failure to make the shield connection; (2) clamping the clip lead on wire insulation or terminal board insulation; or, most likely, (3) high contact resistance - due to corrosion or to the panel hardware having been sprayed with an electrically insulating corrosion inhibitor. As pointed out earlier, such bad contacts do not have to be very "bad" (50-100 Ω is sufficient). Contact resistances in the kilohm range are common for corroded contacts. Furthermore, since the contact voltage is less than one volt, even a very thin oxide or sprayed plastic film can produce an insulating contact. Contributing to the possibility of making bad shield connections are the conditions under which these connections are made - cramped, poorly lighted locations, and closely adjacent terminals.

Bad shield connection has been offered as a possible explanation because it can produce spurious voltages of the proper magnitude and signature. However, it does not seem likely that bad shield connections could have been made consistently throughout a whole series of measurements.

In summary, as for the NBS calibration system, it seems improbable that any of the individual substation error sources considered caused the apparent discrepancies in question. Even burden change or bad shield connections would have required a very unusual concentration of errors and/or bad luck in order to have been the culprits.

4.3 The CCVTs

The remaining possible source of the apparent discrepancies is the CCVTs themselves. NBS experience has shown a significant proportion of these devices to be out of metering tolerance. There is also evidence from other sources [4-6] that CCVTs are subject to seasonal and even diurnal cycling of 0.2 percent or more, probably temperature-induced. Regression analysis by one utility [7] of a sizeable amount of data on a dozen CCVTs showed a mean temperature dependence of about -90 ppm/°C, but with a spread of 5:1 in this dependence.

A common failure mode is the shorting of an individual capacitor in the modular stack. This produces an RCF decrease of about 0.4 percent for a 500 kV CCVT if it occurs on the high side of the capacitive divider. The data indicate that ratio decreases of this general magnitude did occur in some of the GSU devices between the first and second measurements. However, if such shorts occurred in the GSU devices, they seem to have "healed" later (see the discussion of fig. 15, section 3.2). Such "healing" seems improbable. Some of the GSU CCVTs are more than 10 years old. Perhaps old CCVTs are subject to minor failures of unspecified or unexpected origins. For example, in the December 1980 intercomparisons at GSU, there was at least one instance in which a relative shift of >0.1 percent occurred between two CCVTs in a period of 10-15 minutes. The only known relevant event during that time was line switching to place the NBS divider on the 500 kV bus. Although it seems improbable, it has been suggested that some phenomenon related to a system fault which affected one phase more than the other two may have caused values in that phase's CCVTs to shift together, or that line switching affects the value of the NBS divider or the CCVT (see the note on the title page).

5. SUMMARY OF RESULTS

From the evidence available, it appears likely that a voltage of the order of 0.3 volts, approximately 180° out of phase with A-phase, may have been present during the May 1979 measurements. Since the March and December 1980 results are in much better agreement, it is postulated that this voltage was not present during the last two sets of measurements. This postulate is reinforced by the fact that adjusting the 1979 data for the effect of this voltage makes those data agree much more closely with the later measurements, and to fall with them into a general pattern observed at another substation (significant shifts between calibrations, almost solely in RCF).

An exhaustive search for the apparent discrepancies, including extremely careful and much more extensive measurements in December 1980, has not yielded a specific cause for them. Two suspects, uncompensated ground voltage and a moderate burden change (20 VA) on the A-phase devices, were singled out for special attention because they have about the right "signature" and magnitude. However, the combination of circumstances required to indict either of these two seems improbable. It is believed that no reasonable combination of other known possible error sources could produce differences of the magnitude seen here. Because of the seeming improbability of all the other causes explored, even the possibility that the CCVTs themselves changed randomly in a seemingly non-random manner cannot be dismissed.

Some conclusions can be drawn. First, in all three of these measurement sets, many of the CCVTs were out of metering tolerance, some by large amounts. Second, further investigation is called for, including the effects of high voltage switching on the NBS divider, and possibly some form of continuous monitoring of a statistically significant number of operating CCVTs.

6. REFERENCES

[1] A Prototype System for On-Site Calibration of Coupling Capacitor Voltage Transformers (CCVTs), D. L. Hillhouse, O. Petersons, and W. C. Sze, PAS Transactions, Vol. PAS-98, No. 3, May/June 1979, p. 1026.

[2] A Prototype Field Calibration System for Coupling Capacitor Voltage Transformers (CCVTs) EPRI EL-690, April 1978.

[3] Requirements for Instrument Transformers, ANSI/IEEE C56.13-1978.

[4] Stability of Capacitor Voltage Transformers for Revenue Metering, K. M. Mitchell, Ontario Hydro Research Quarterly, Vol. 24, No. 2, 1972, pp. 15-19.

[5] Tests Monitor Accuracy of EHV Metering Devices, Electrical World, Jan. 29, 1970, pp. 40-41.

[6] Field Testing of 500 kV Metering Accuracy Coupling Capacitor Voltage Transformers, C. E. Phillips, Pacific Coast Electric Association Engineering and Operating Conference, San Francisco, 1974.

[7] In-Service Performance of Capacitive Potential Devices Used for Revenue Metering, T. A. Dahlke, *Minutes of the Meter and Service Committee*, *AEIC-EEI*, Appendix O, Sept. 1970.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

This report presents the results of an investigation of unexpected variations in nine 500 kV metering CCVTs, tested for Gulf States Utilities at Baton Rouge, LA. These measurements were performed on three occasions - May 1979, March 1980, and December 1980.

On the first two occasions, six out of nine CCVTs were out of tolerance; on the third, four out of nine. More important, the changes between the first two occasions seemed to be correlated by phase, i.e., most of the devices on a given phase shifted in the same general direction and by similar amounts. When analysis failed to provide an explanation for this, the third set of measurements was undertaken.

Analysis of the three sets of data produced some evidence of a bias voltage in the 1979 data. Investigation of all plausible known sources of error in the NBS system, the substation, and the CCVTs themselves failed to produce a probable source for such a bias voltage.

No evidence of consistent malfunction of the NBS system was found. Even allowing for a possible bias in one set of data, a majority of the CCVTs were still outside of metering tolerance. Continuous monitoring of a statistically significant number of operating CCVTs should be considered.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

calibration; CCVT; EHV substations; error sources; high voltage measurements; revenue metering.

13. AVAILABILITY

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