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Tinker AFB, OK 73145**

**COMPARISON OF THE TANDEM CONDUCTIVITY TESTER (TCT)
AND THE COMPLETE OIL BREAKDOWN RATE ANALYZER
MODEL 2 (COBRA 2) FOR DETECTING SYNTHETIC
AIRCRAFT OIL DEGRADATION**

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14. ABSTRACT

At the request of the U.S. Air Force Oil Analysis Program Office (AF OAP) at Tinker AFB, two commercial instruments were evaluated for comparability in the analysis of jet engine oil [synthetic ester (polyol)]: the Complete Oil Breakdown Rate Analyzer (COBRA 2) from NAECO, LLC and the Tandem Conductivity Tester (TCT) from Spectro, Inc. The two instruments were compared by using each to test a single source of thermally degraded aircraft lubricant (Mil-7808 grade 3). The calibration of each instrument was set using a COBRA standard [tricresyl phosphate (TCP) in 1,1,1-(trimethylol) propane triheptanoate (TMPH)] that was obtained from the Joint Oil Analysis Program Technical Support Center (JOAP TSC). Approximately 2 gallons of thermally degraded lubricant obtained from a Tinker engine shop hot oil tank was used as a source of samples throughout the testing process. Since the COBRA 2 unit is currently used by the Air Force to monitor oil degradation it was to be used as a baseline for measuring TCT performance. Precision was similar for both instruments. In our opinion, the TCT instrument provided acceptably similar results to COBRA when measuring the same bulk sample using the Field boat cleaning method and the Laboratory boat cleaning method. The Field and Laboratory TCT boat cleaning methods appeared to produce nearly identical TCT measurement results as indicated by the 1200 sample results obtained with the use of ten different boats. TCT provided stable results when exposed to changing environmental conditions whereas; the COBRA 2 produced relatively unstable readings when exposed to those same short-term temperature changes. The TCT sample boats appeared to be very rugged with no significant damage observed resulting from the prolonged TCT only testing and cleaning cycles. Some slight surface scuffing on the connector pads was observed. The equivalence of ten TCT sample boats was confirmed. The TCT instrument appeared to meet the minimum performance requirements for use by the joint military services within the scope of the AF OAP needs. The TCT is recommended for field and laboratory use provided proper standardization and cleaning procedures are followed. COBRA battery life and state of charge as well as variations in COBRA and TCT operating conditions (temperature) may influence the results during periods of extended use.

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**COMPARISON OF THE TANDEM CONDUCTIVITY TESTER (TCT)
AND THE COMPLETE OIL BREAKDOWN RATE ANALYZER
MODEL 2 (COBRA 2) FOR DETECTING SYNTHETIC
AIRCRAFT OIL DEGRADATION**

SUMMARY

At the request of the U.S. Air Force Oil Analysis Program Office (AF OAP) at Tinker AFB, two commercial instruments were evaluated for comparability in the analysis of jet engine oil [synthetic ester (polyol)]: the Complete Oil Breakdown Rate Analyzer (COBRA 2) from NAECO, LLC and the Tandem Conductivity Tester (TCT) from Spectro, Inc. The two instruments were compared by using each to test a single source of thermally degraded aircraft lubricant (Mil-7808 grade 3). The calibration of each instrument was set using a COBRA standard [tricresyl phosphate (TCP) in 1,1,1-(trimethylol) propane triheptanoate (TMPH)] that was obtained from the Joint Oil Analysis Program Technical Support Center (JOAP TSC). Approximately 2 gallons of thermally degraded lubricant obtained from a Tinker engine shop “hot oil” tank was used as a source of samples throughout the testing process. Since the COBRA 2 unit is currently used by the Air Force to monitor oil degradation it was to be used as a baseline for measuring TCT performance. Precision was similar for both instruments. In our opinion, the TCT instrument provided acceptably similar results to COBRA when measuring the same bulk sample using the “Field” boat cleaning method and the “Laboratory” boat cleaning method. The “Field” and “Laboratory” TCT boat cleaning methods appeared to produce nearly identical TCT measurement results as indicated by the 1200 sample results obtained with the use of ten different boats. TCT provided stable results when exposed to changing environmental conditions whereas; the COBRA 2 produced relatively unstable readings when exposed to those same short-term temperature changes. The TCT sample boats appeared to be very rugged with no significant damage observed resulting from the prolonged “TCT only” testing and cleaning cycles. Some slight surface scuffing on the connector pads was observed. The equivalence of ten TCT sample boats was confirmed. The TCT instrument appeared to meet the minimum performance requirements for use by the joint military services within the scope of the AF OAP needs. The TCT is recommended for field and laboratory use provided applicable standardization and cleaning procedures are followed. COBRA battery life and state of charge as well as variations in COBRA and TCT operating conditions (temperature) may influence the results during periods of extended use.

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PURPOSE:

It is known (2) that synthetic aircraft oil undergoes breakdown during normal use and abnormal stress. The Air Force currently uses conductivity based instrumentation (COBRA) to monitor oil for thermal degradation. Recently, there has been a limited capability to replace and maintain the COBRA instruments. Therefore, the TCT has been selected by the Air Force Oil Analysis Program (AF OAP) Office at Tinker AFB in Oklahoma City as an alternative method to meet the requirement of Technical Order 33-1-37. The AF OAP Office requested the Industrial Chemistry Section JOAP laboratory to compare the performance of two commercial instruments in the breakdown analysis (conductivity) of synthetic ester (polyol) aircraft lubricant: the Complete Oil Breakdown Rate Analyzer (COBRA 2) from NAECO, LLC and the Tandem Conductivity Tester (TCT) from Spectro, Inc. Since the COBRA 2 unit is currently used by the Air Force to monitor oil degradation it would be used as a baseline for measuring TCT performance.

EXPERIMENTAL

Instrument Standardization

The COBRA 2 was standardized with a JOAP tricresyl phosphate (TCP) COBRA standard to read 8. The Tandem Conductivity Tester (TCT), as installed by Spectro, Inc., into the Spectroil M with DOS version software, was standardized with the same standard as the COBRA 2. The TCT and COBRA 2 were set up to accept a two point external calibration: a blank (no sample) with a signal of zero and a COBRA standard with a signal of 8. A set of 11 TCT boats was provided for this study. For initial instrument set-up, a clean dry TCT sample boat and a clean dry COBRA sensor were used to set the zero (blank) value for subsequent measurements. A selected TCT boat was dedicated to standardization only. This boat was filled with fresh COBRA standard to set the instrument "8" value. The other 10 TCT boats were used for routine sample testing only and for the purpose of this testing were considered equivalent. The TCT was configured to run in the "TCT Only" mode and did not perform routine atomic emission spectrometry. Both instruments were restandardized at least every 3 hours of continuous use with occasional check standards run to confirm stability.

Standards and Samples

JOAP TCP COBRA standards with stated values of 8 were used throughout the testing for standardization. A thermally degraded aircraft lubricant (Mil-7808 grade 3) with a COBRA value of approximately 6-8 was used for all sample measurements. Approximately 2 gallons of the degraded lubricant obtained from a Tinker engine assembly shop "hot oil" tank was of sufficient quantity to be used throughout the testing process as the source of replicate samples.

Performance Evaluation

The testing process was set up to evaluate precision (variability) of the COBRA and TCT over both a short (1 day) and long (1 month) time periods. This evaluation involved the analysis of the mean and standard deviation of measurements obtained using two TCT boat cleaning methods and from concurrent use of COBRA. Three analysts conducted separate tests to provide three sets of data for each experiment. COBRA sample handling and cleaning were as per the instruction manual. The two TCT boat cleaning methods were used by all analysts and were

evaluated separately. The “Field” cleaning method (short-term evaluation) involved running the TCT sample, draining the sample, rinsing the boat with new Mil-7808 oil, flushing the residual Mil-7808 from the boat with the next sample, filling the boat with sample, and running the next TCT sample. This procedure allowed the analyst to process 20 TCT sample replicates in a short period of time using the same boat (a separate dedicated boat was used for standardization). This process was then repeated for the other nine TCT boats. The same number of sample replicates were also measured using the “Laboratory” cleaning method (longer-term evaluation) except this technique involved running the TCT sample, draining the sample, immersing the boat in Electron solvent, rinsing with isopropyl alcohol, and air drying for at least 30 minutes before running the next TCT sample. All 10 clean and dry TCT boats were used in sequence enabling the analysts to process 10 samples (one replicate each boat) before repeating the “Laboratory” cleaning.

All sample measurements were single measurements. A series of 20 replicate measurements was made for each TCT boat, analyst, and cleaning method for a total of 1200 TCT measurements. 1200 concurrent COBRA measurements were also performed for a total of 2400 measurements.

TCT Boat Cleaning Method	Number of Boats	Sample Replicates per Boat	Analysts (separate studies)	Total (per method)	COBRA (concurrent tests)
Field	10	20	3	600	600
Laboratory	10	20	3	600	600
Number of samples per technique:				1200	1200
Total number of samples:				2400	

Short-term variability was evaluated first. 20 separate sample replicates were run sequentially in the same boat, by the same analyst, on the same day with cleaning by the TCT “Field” method. Longer term variability was then evaluated by running a single sample in each of the 10 clean, dry TCT boats by one analyst, on the same day then cleaning all boats with the TCT “Laboratory” method. Since the “Laboratory” cleaning method required significant cleaning and drying time (about 30 minutes), 20 replicates in each TCT boat required about 1 month to complete for all 3 analysts. We evaluated the comparability of COBRA and TCT in terms of the differences between the mean and standard deviation of measurements obtained over short and longer time periods.

The COBRA values were manually added to each TCT data line on the Spectroil M before initiating each TCT test. This process was used to capture the concurrent TCT and COBRA measurements as “paired” data points. We evaluated the performance of COBRA vs. TCT using multiple TCT boats with 3 analysts and 2 cleaning methods. Additionally, a “boat integrity test” was performed for all TCT boats at the beginning of each test period by analyzing all clean, dry TCT sample boats for a zero reading.

RESULTS

Short-Term Variability/Comparability

The short-term variability for both COBRA and TCT (“Field” method) as indicated by the measurement standard deviations for each analyst was similar (Table 1). It should be noted that analyst MM encountered significant temperature variations (74° F ± 10° F) as well as a COBRA

battery problem during testing with the mean differences and difference standard deviations reflecting the increased instability of the COBRA instrument to battery state of charge and variations in short-term environmental conditions (Chart 1, middle graph).

As shown by the combined analyst means and mean differences for the TCT “Field” cleaning method (Table 1), the overall short-term comparability indicated that the TCT instrument provided acceptably similar results to COBRA over short time periods. Overall COBRA results showed a greater variability as measured by the combined analyst summary standard deviation compared to the TCT results using the “Field” method. Chart 2 (top graph) shows an overview of the combined measurement data illustrating consistently higher TCT values. TCT and COBRA values varied by about ± 1 unit from the calculated mean difference as illustrated by the Chart 2 (bottom graph). Chart 2 (bottom graph) shows an increasing measurement difference trend (comparability) as the testing progressed in time indicating possible short-term temperature influences and battery related instabilities from the COBRA.

Longer-Term Variability/Comparability

Individual analyst longer-term variability of both COBRA and TCT (“Laboratory” method) was also similar (Table 2), as indicated by the low standard deviations for the analysts’ results.

The combined analyst means and mean differences for the TCT using the “Laboratory” cleaning method (Table 2 & Chart 4) indicated that the TCT instrument provided acceptably similar results to COBRA when measuring the same bulk sample source over longer time periods. Chart 3 (top graph) shows an overview of the combined longer-term measurement data. TCT and COBRA values varied by about ± 1 unit from the calculated mean difference as illustrated by Chart 3 (bottom graph). Chart 3 (bottom graph) shows a nearly constant measurement difference trend as the testing progressed in time indicating possible mitigation of any short-term temperature instabilities from the COBRA.

Pooled Variability/Comparability Data

All short-term and longer-term data were pooled for an overall evaluation of TCT performance. Table 3 indicates that the TCT instrument provided acceptably similar results to COBRA when measuring the same bulk sample source over longer-term and short-term time periods with two different cleaning methods. The two TCT cleaning methods provided nearly identical results as indicated by the summary standard deviations (Table 1 and Table 2). Overall, the TCT appears to provide more precise (less variability) results than the COBRA.

Boat Integrity

All clean dry TCT sample boats were measured at the beginning of each test period for a zero reading. As Chart 5 indicates, the empty boat readings were consistent and provided a steady zero reading at the display (< 0.5 units). At the end of the project, all TCT boats were examined visually with a low magnification hand lens to identify any physical damage. No significant damage such as delamination or cracking was observed (Figure 1.1, Figure 1.2).

DATA

Table 1. Short-Term Variability/Comparability Summary (* 600 Measurements / Field)

Analyst	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
PK	7.1	0.3	7.7	0.4	0.7	0.4
MM	6.3	1.0	7.7	0.5	1.5	1.0
HM	5.4	0.5	7.5	0.3	2.2	0.5
Summary*	6.2	0.9	7.6	0.4	1.4	0.9

Table 2. Longer-Term Variability/Comparability Summary (* 600 Measurements / Lab)

Analyst	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
PK	6.6	0.7	7.4	0.4	0.8	0.7
MM	6.7	0.6	7.4	0.4	0.7	0.7
HM	6.2	0.7	7.0	0.3	0.8	0.7
Summary*	6.5	0.7	7.2	0.4	0.7	0.7

Table 3. Pooled Data Variability/Comparability Summary (* 1200 Measurements)

	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
All Data*	6.4	0.9	7.4	0.5	1.1	0.9

Table 4. Short-Term Variability/Comparability (PK/Field Method/20 Replicates ea Boat)

Boat	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
1	6.9	0.2	7.3	0.4	0.4	0.5
2	7.0	0.0	7.8	0.3	0.8	0.3
3	7.0	0.0	7.4	0.1	0.4	0.5
4	7.0	0.0	7.4	0.3	0.4	0.3
5	7.0	0.0	7.5	0.2	0.5	0.2
6	7.4	0.5	8.0	0.3	0.6	0.6
7	7.1	0.3	8.1	0.2	1.0	0.4
8	7.0	0.0	8.0	0.2	1.0	0.2
9	7.0	0.0	7.9	0.2	0.9	0.2
10	7.1	0.2	8.0	0.2	1.0	0.3
Summary*	7.1	0.3	7.7	0.4	0.7	0.4

*Summary for 200 samples each (COBRA & TCT) for a total of 400 samples

Table 5. Short-Term Variability/Comparability (MM/Field Method/20 Replicates ea Boat)

Boat	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
1	6.9	0.6	7.0	0.2	0.1	0.6
2	6.4	0.5	7.5	0.2	1.1	0.6
3	7.9	0.5	7.9	0.4	0.0	0.6
4 ^t	6.1	0.6	8.1	0.3	2.0	0.6
5 ^t	6.0	0.6	7.5	0.3	1.5	0.7
6 ^t	6.6	0.6	8.4	0.3	1.8	0.6
7 ^t	4.9	1.3	7.5	0.4	3.1	1.1
8 ^{t,b}	6.0	0.0	7.7	0.3	1.7	0.3
9 ^t	6.0	0.2	7.5	1.7	1.4	1.7
10 ^t	6.1	0.3	7.9	0.2	1.8	0.3
Summary*	6.3	1.0	7.7	0.5	1.5	1.0

*Summary for 200 samples each (COBRA & TCT) for a total of 400 samples

^t = room temperature fluctuations

^b = changed COBRA battery

Table 6. Short-Term Variability/Comparability (HM/Field Method/20 Replicates ea Boat)

Boat	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
1	5.1	0.3	7.6	0.2	2.5	0.5
2	6.0	0.2	7.7	0.3	1.7	0.3
3	6.0	0.2	7.8	0.3	1.9	0.5
4	5.6	0.5	7.9	0.2	2.3	0.5
5	5.0	0.0	7.6	0.1	2.6	0.1
6	5.6	0.5	7.4	0.2	1.8	0.6
7	5.2	0.4	7.5	0.1	2.3	0.4
8	5.1	0.3	7.3	0.2	2.2	0.4
9	5.1	0.2	7.2	0.2	2.1	0.3
10	5.1	0.2	7.3	0.2	2.3	0.4
Summary*	5.4	0.5	7.5	0.3	2.2	0.5

*Summary for 200 samples each (COBRA & TCT) for a total of 400 samples

Table 7. Longer-Term Variability/Comparability (PK/Lab Method/20 Replicates ea Boat)

Boat	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
1	6.6	0.8	7.3	0.4	0.7	0.7
2	6.5	0.8	7.5	0.4	0.9	0.8
3	6.6	0.8	7.4	0.4	0.8	0.6
4	6.6	0.8	7.4	0.4	0.8	0.7
5	6.7	0.8	7.4	0.4	0.8	0.8
6	6.7	0.7	7.5	0.4	0.8	0.7
7	6.6	0.8	7.5	0.5	0.9	0.7
8	6.6	0.8	7.3	0.4	0.7	0.7
9	6.6	0.8	7.3	0.4	0.7	0.7
10	6.6	0.8	7.4	0.4	0.8	0.7
Summary*	6.6	0.7	7.4	0.4	0.8	0.7

*Summary for 200 samples each (COBRA & TCT) for a total of 400 samples

Table 8. Longer-Term Variability/Comparability (MM/Lab Method/20 Replicates ea Boat)

Boat	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
1	6.8	0.7	7.4	0.5	0.6	0.7
2	6.5	0.7	7.5	0.4	1.0	0.9
3	6.7	0.8	7.4	0.3	0.7	0.9
4	6.8	0.5	7.5	0.3	0.7	0.6
5	6.8	0.6	7.4	0.3	0.6	0.7
6	6.8	0.6	7.6	0.4	0.8	0.7
7	6.8	0.7	7.6	0.4	0.8	0.8
8	6.8	0.6	7.3	0.3	0.5	0.6
9	6.7	0.6	7.3	0.3	0.6	0.7
10	6.9	0.5	7.4	0.3	0.6	0.5
Summary*	6.7	0.6	7.4	0.4	0.7	0.7

*Summary for 200 samples each (COBRA & TCT) for a total of 400 samples

Table 9. Longer-Term Variability/Comparability (HM/Lab Method/20 Replicates ea Boat)

Boat	COBRA		TCT		DIFF (TCT-COBRA)	
	mean	STDEV	mean	STDEV	mean	STDEV
1	6.1	0.7	6.8	0.2	0.7	0.7
2	6.2	0.7	7.0	0.2	0.9	0.7
3	6.1	0.8	6.9	0.2	0.8	0.7
4	6.3	0.8	7.0	0.2	0.8	0.7
5	6.3	0.7	7.0	0.2	0.7	0.7
6	6.2	0.8	7.1	0.3	0.9	0.7
7	6.2	0.8	7.1	0.3	0.9	0.8
8	6.3	0.6	6.9	0.3	0.7	0.5
9	6.3	0.6	6.8	0.2	0.6	0.6
10	6.3	0.6	7.0	0.3	0.7	0.5
Summary*	6.5	0.7	7.3	0.4	0.7	0.7

*Summary for 200 samples each (COBRA & TCT) for a total of 400 samples

Chart 1. TCT vs. COBRA Short-Term Differences (Analyst Summary)

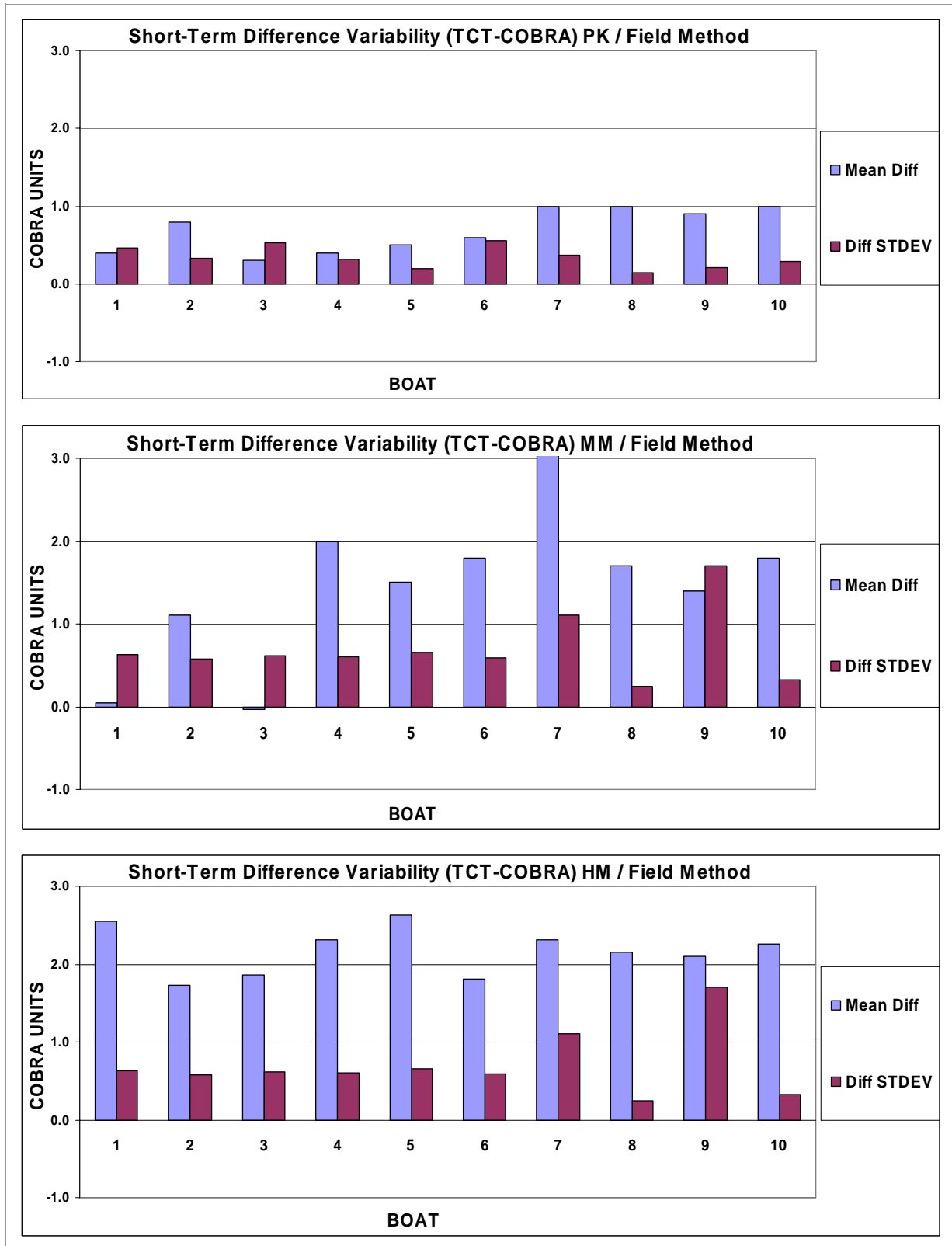
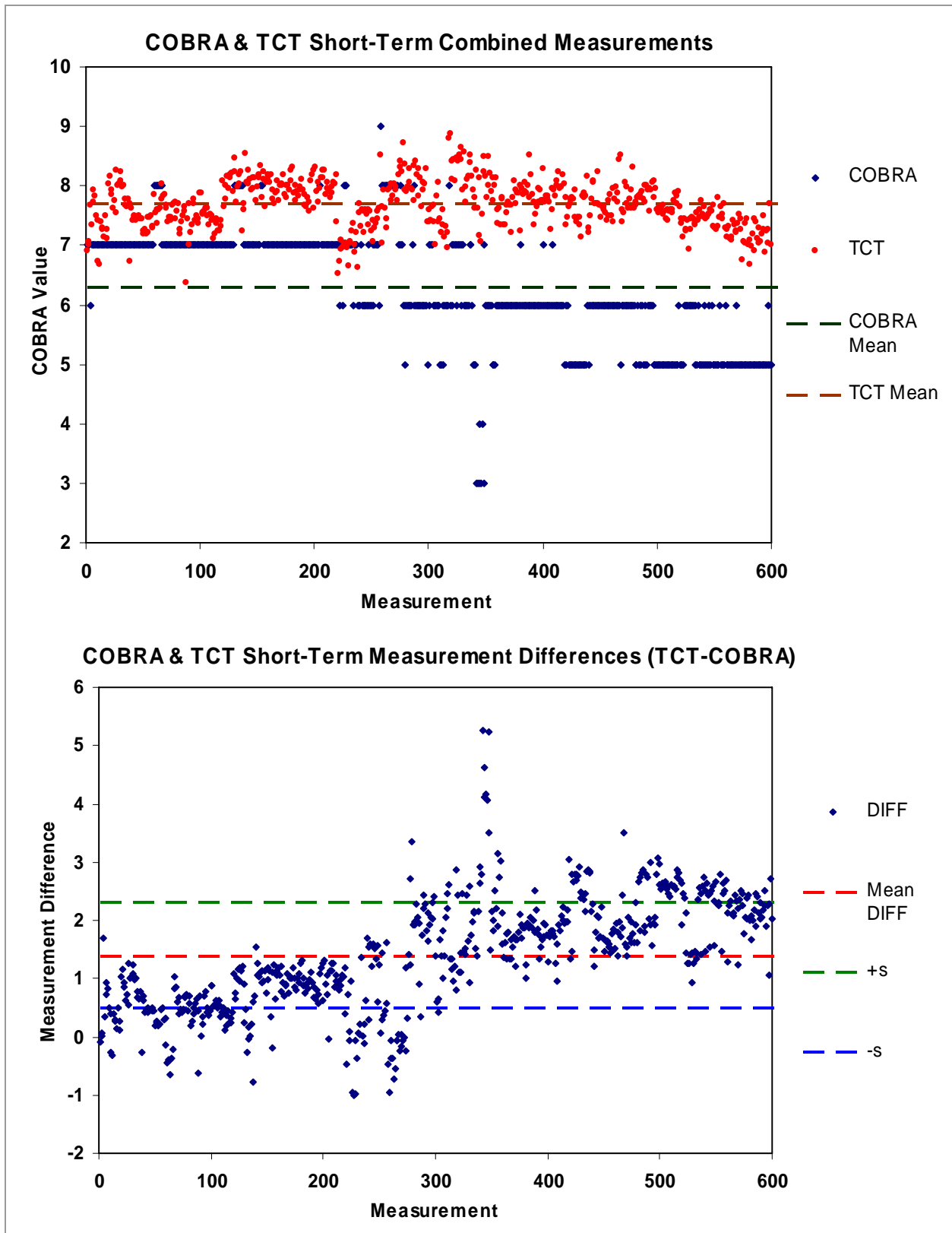
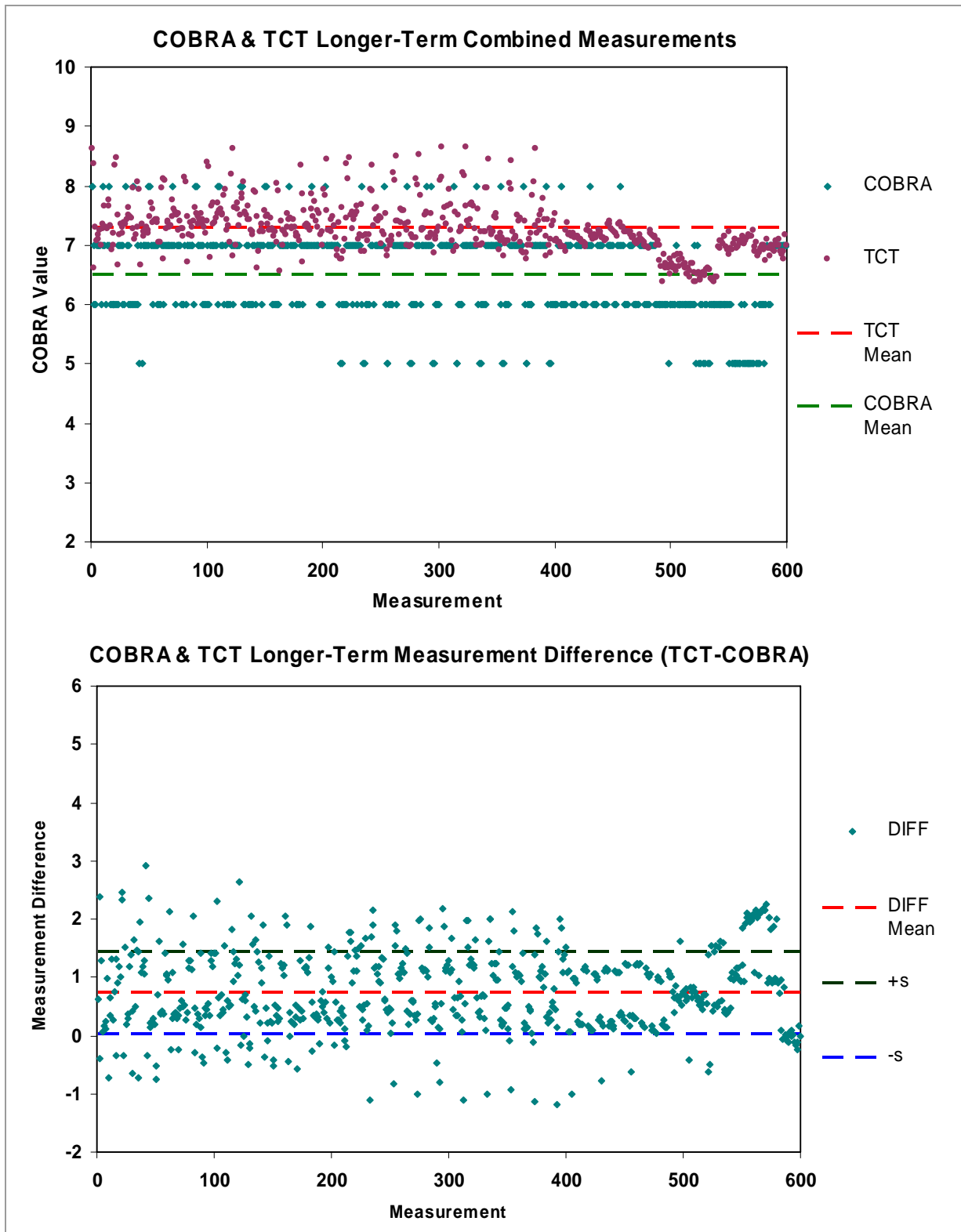


Chart 2. Short-Term Measurement Summary (Sequential)



Note: TCT raw data and difference data plotted at 0.1 unit resolution with COBRA at unit resolution

Chart 3. Longer-Term Measurement Summary (Sequential)



Note: TCT raw data and difference data plotted at 0.1 unit resolution with COBRA at unit resolution

Chart 4. TCT vs. COBRA Longer-Term Differences (Analyst Summary)

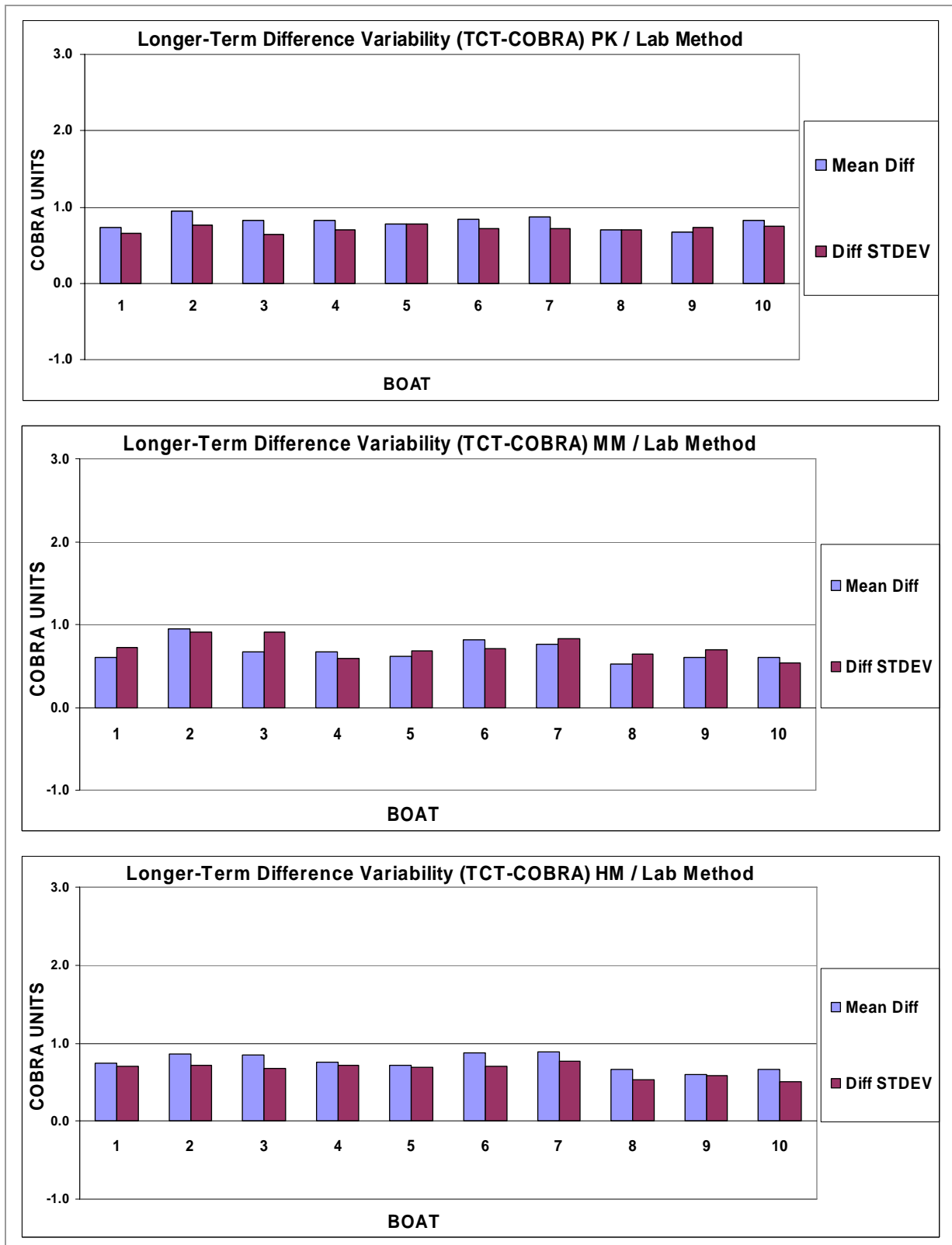


Chart 5. TCT Boat Integrity Test (blank signal @ 0.01 unit resolution)

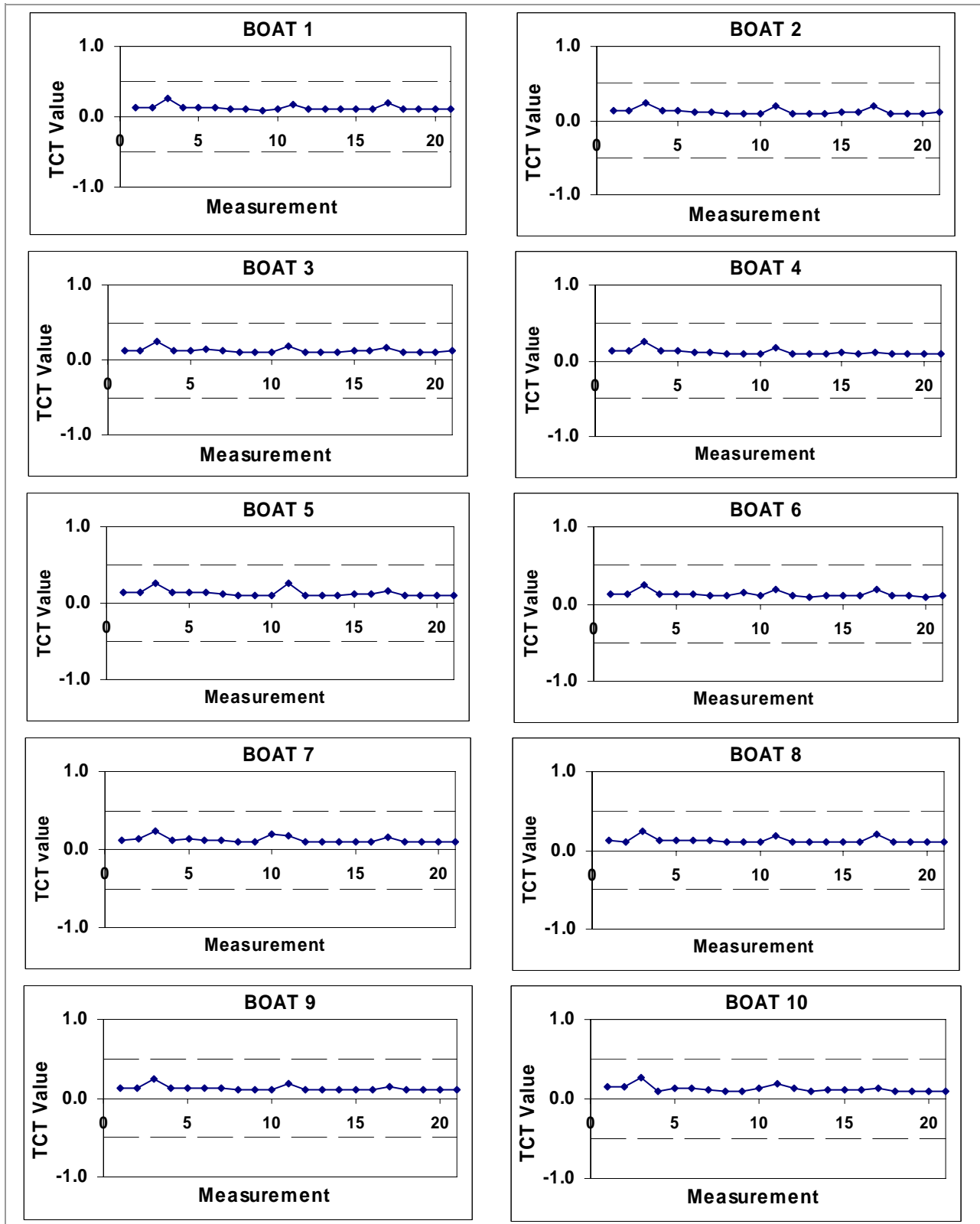


Figure 1.1 TCT boat conductor pad after 120 sample/cleaning cycles (X10)

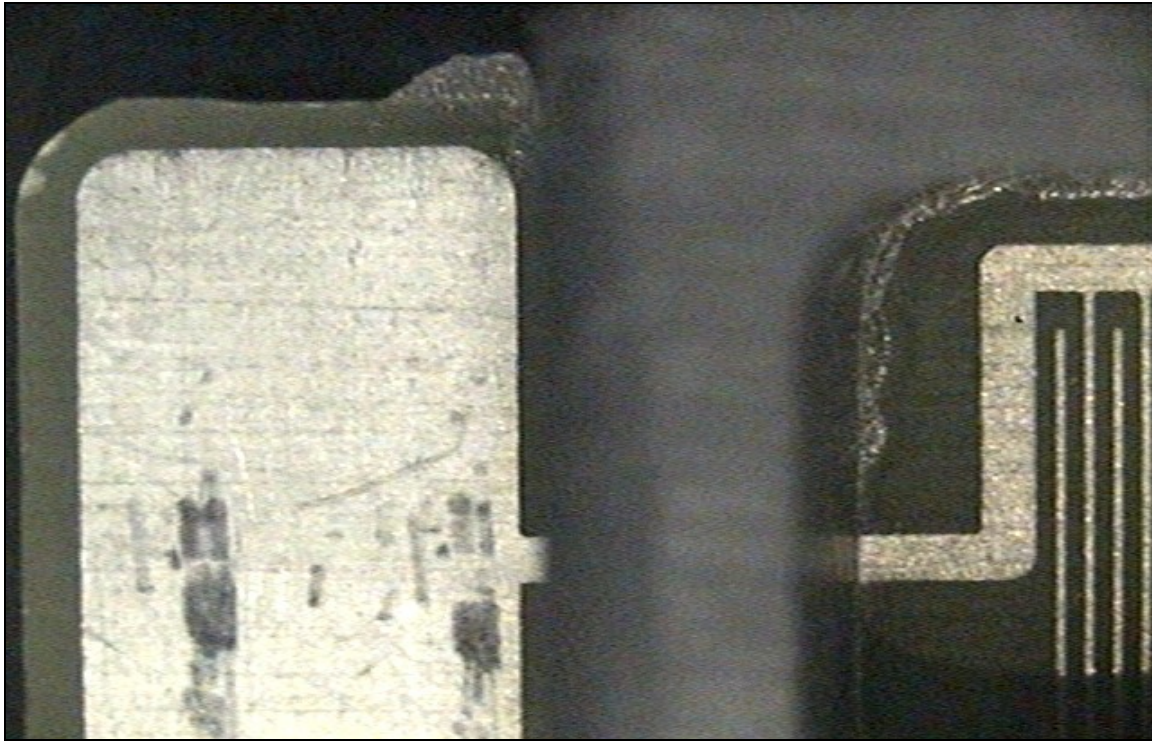
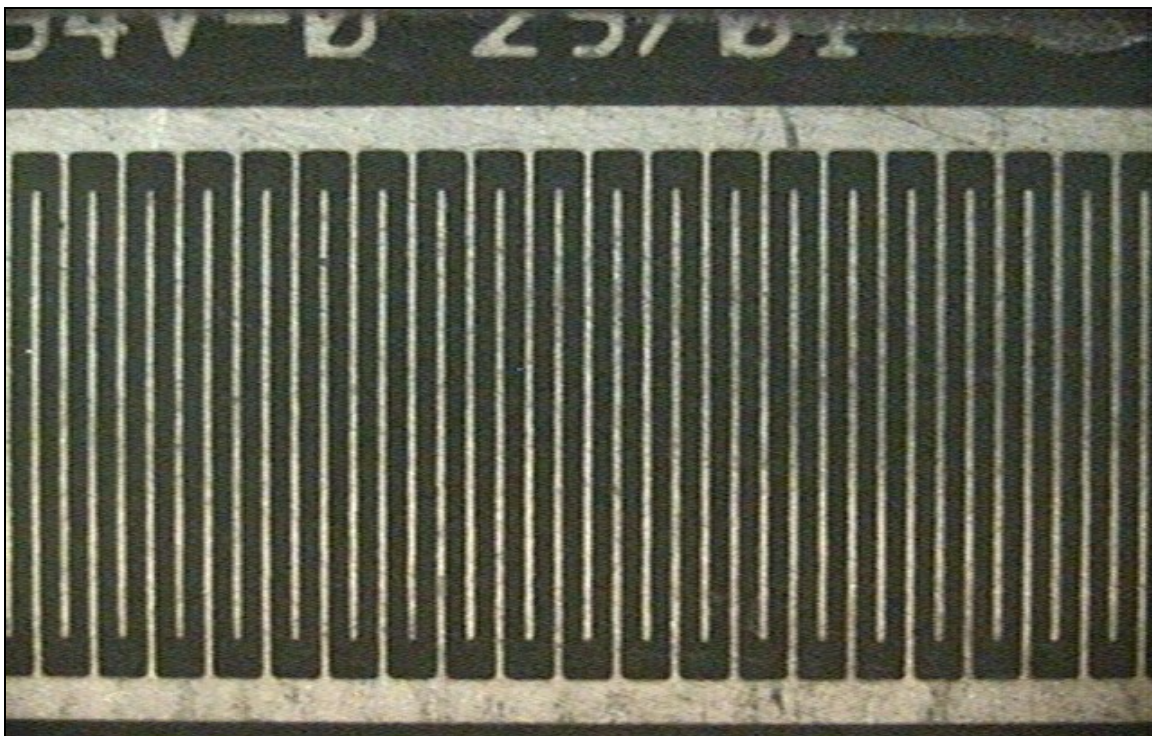


Figure 1.2 TCT boat sensor after 120 sample/cleaning cycles (X10)



Definitions

The computed **standard deviation (s)** represents the predictable dispersion of values about the mean. Where “n” is the number of data points and the “n-1” term in the expression below represents the degrees of freedom (df).

$$s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{(n - 1)}}$$

The **mean** is the computed arithmetic average for a set of values.

$$\bar{x}$$

CONCLUSIONS

Although precision was similar for both TCT and COBRA instruments, TCT measurements appeared to be somewhat less variable than those obtained using COBRA. All 3 analysts’ results were comparable with variability differences attributed to COBRA instrument instability rather than analyst technique or cleaning method differences. The TCT instrument provided acceptably similar results to COBRA when measuring the same bulk sample source using the “Field” boat cleaning method (short-term) and the “Laboratory” boat cleaning method (longer-term). The “Field” and “Laboratory” boat cleaning methods appeared to produce nearly identical TCT measurement results as indicated by the 1200 sample results with the use of ten different boats. TCT provided stable results when exposed to changing environmental conditions whereas; the COBRA 2 produced relatively unstable readings when exposed to those same short-term temperature changes. The TCT instrument appeared to meet the minimum performance requirements for use by the joint military services within the scope of the AF OAP needs. The TCT is recommended for field and laboratory use provided applicable standardization and cleaning procedures are followed (i.e., Technical Orders, Operating Instructions, User Manuals, etc.). Variations in equipment environmental operating conditions as well as COBRA battery life and state of charge should be considered as sources of increased measurement uncertainty during periods of extended use.

The TCT sample boats appeared to be very rugged with no significant damage observed resulting from the prolonged “TCT only” testing and cleaning cycles. Some slight surface scuffing on the connector pads was observed. The equivalence of ten TCT sample boats was confirmed. When using the “Field” cleaning method, the TCT boats should probably be cleaned periodically (at least daily) with the “Laboratory” method to reduce the build-up of sludge, carbon, or other debris on the sensor elements.

Since the error for both COBRA and TCT is about +/- 1 unit it would be acceptable for COBRA vs. TCT measurements to differ by up to 2 units. It is conceivable that a total electronic error (assuming an electronic resolution of 0.1 units) of 2.9 units would provide an acceptable displayed measurement difference. See example below:

For an hypothetical “true” value of 8

	Electronic Resolution Value (hypothetical)	Display Value
TCT	9.4	9
COBRA	6.5	7
Difference	2.9	2

RECOMMENDATIONS

The COBRA manufacturer’s instruction manual recommends recalibration every 3-4 hours of continuous use. Shorter term temperature changes seem to significantly impact the COBRA readings (Chart 1). A modified recalibration interval and/or check standard interval may be required if the COBRA is used continuously under changing environmental conditions. The TCT appears to be more stable to fluctuations in room temperature but still suffers some slight increased variability. Perhaps the larger thermal mass of the TCT incorporated into the Spectroil M spectrometer contributes to the observed stability difference. Further study may be required to determine instrument drift characteristics related to time and temperature.

Another concern arose during testing: COBRA battery life. The COBRA instruction manual states that the battery should be replaced “periodically”. The instrument has no battery state indicator. As was noted above, temperature fluctuations seem to impact both the TCT and COBRA stability and measurement uncertainty. During the “Field” method short-term variability testing (Chart 1, middle graph), analyst MM observed laboratory temperature fluctuations of up to $\pm 10^{\circ}\text{F}$ starting at Boat 4. The COBRA instability became severe during Boat 7 testing as measured with COBRA 8 standards run as a samples (the measured values tended at least 2 units low). It was postulated that there was more wrong than just temperature instability. It was determined that the COBRA alkaline batteries had not been changed in over two years so new rechargeable nickel-cadmium batteries were installed with a marked improvement in signal stability albeit still influenced by some temperature variability. One week later analyst HM observed significant COBRA vs. TCT differences (Chart 1, bottom graph). Since the environmental conditions were stable it was determined that the previously replaced batteries might not have been fully charged and once again needed charging. Perhaps a more defined battery replacement regime might be required.

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