SOP 22

Standard Operating Procedure

for

Calibration of Traffic Speed Gun Tuning Forks and other Acoustic Frequency Emitting Devices

1 Introduction

1.1 Purpose

This Standard Operating Procedure (SOP) describes the procedure to be followed for the calibration of tuning forks which are used to certify traffic control speed guns, and for calibration of other acoustic frequency emitting devices. The procedure may also be used to calibrate tuning forks for applications such as musical tuning. This procedure utilizes either 1) a Global Positioning System Disciplined Oscillator (GPSDO) or 2) an electronic frequency counter that is directly compared to the NIST transmitted frequency standards to reference the Coordinated Universal Time (UTC) standard maintained by the NIST and the United States Naval Observatory (USNO). The accuracy of the calibration is limited by the mechanical instability of the device being tested. Detailed measurement ranges, standards, equipment, and uncertainties for this SOP are generally compiled in a separate document in the laboratory.

1.2 Applicable References

1.2.1 Speed-Measuring Device Performance Specifications: Across-the-Road Radar Module, DOT HS 812 266, Department of Transportation, National Highway Traffic Safety Administration (NHTSA).

1.2.2 NIST SP 432: NIST Time and Frequency Services.

1.2.3 The Use of GPS Disciplined Oscillators as Primary Frequency Standards for Calibration and Metrology Laboratories, M. Lombardi, NCSLI Measure J. Meas. Sci., vol. 3, no. 3, pp. 56-65, September 2008.

1.2.4 Evaluating the Frequency and Time Uncertainty of GPS Disciplined Oscillators and Clocks, M. Lombardi, NCSLI Measure J. Meas. Sci., vol. 11, no. 3-4, pp. 30-44, December 2016.

1.2.5 Time and Frequency Measurements Using the Global Positioning System, Michael A. Lombardi, Lisa M. Nelson, Andrew N. Novick, Victor S. Zhang, Cal Lab Magazine, July, August, September 2001.

1.2.6 NIST Time and Frequency Broadcasts from Radio Stations WWVB, WWV, and WWVH, Matthew Deutch, Ernie Farrow, John Lowe, Glenn Nelson, Dean Okayama, Don Patterson, Douglas Sutton, and William Yates, 2001 NCSLI Workshop and Symposium.

1.2.7 Calibration of Police Radar Instruments, D. W. Allan (NBS), F. H. Brzoticky (CO Dept. of Agriculture), NBS Special Publication 442, Report of the National Conference on Weights and Measures, 1976.

1.3 Prerequisites

1.3.1 Verify that the metrologist is experienced in making frequency measurements.

1.3.2 Verify that suitable check standards are present and used in an active measurement assurance program.

1.3.3 Verify the laboratory environment is within an acceptable temperature and humidity range.

Table 1. Environmental limits for calibrations.

Temperature	**Relative Humidity**
18 ℃ to 25 ℃	40 % to 60 %

2 Methodology

2.1 Summary

A tuning fork, or other acoustic frequency emitting device, is calibrated by measuring its acoustic frequency with an electronic frequency counter that is calibrated, and has metrological traceability through the L1 1 575.42 MHz GPS signal broadcast by the United States Air Force from Colorado Springs, Colorado, referencing the U.S. Naval Observatory (USNO) Coordinated Universal Time (UTC) standard or through comparison with the NIST transmitted radio frequency signal (WWV, WWVH), or telephone frequency signal. No adjustments are made to tuning forks; they are either approved or rejected. Because U.S. law enforcement personnel traditionally use U.S. Customary units, units of miles per hour (mph) are referenced throughout this SOP.

2.2 Equipment / Apparatus

2.2.1 An electronic frequency counter capable of 0.1 hertz (Hz) resolution throughout the range from direct current (DC) to 10 000 Hz.

2.2.2 A transducer to convert sound energy to electrical (DC) energy. The output must be strong enough for counter input sensitivity requirements.

2.2.2.1 A clamping type contact microphone, e.g., Signal Flex SF-30 Universal Tuner Pickup, or similar, is preferable for tuning forks.

2.2.2.2 A microphone, e.g., Shure SM57, Cardioid, Dynamic, or similar, is preferred for other acoustic frequency emitting devices.

2.2.3 A GPS time and frequency reference receiver with antenna.

2.2.4 A short-wave receiver and antenna.

2.2.5 A calculator if converting frequency (Hz) to miles per hour (mph).

2.2.6 A thermometer to measure ambient temperature.

2.3 Reference, Option A, Use of GPSDO

2.3.1 The tuning fork, or other acoustic frequency emitting device, must be in temperature equilibrium with the laboratory environment, typical equilibration time is not less than 2 hours. Read and record the ambient temperature.

2.3.2 Verify that the GPS frequency counter displays “ExtRef” on the display prior to use. This indicates the unit is utilizing the GPS reference receiver output as its reference.

2.3.3 Confirm that the GPS reference receiver signal light is illuminated indicating a locked signal.

2.3.4 Adjust the frequency counter to a gate setting interval of 0.2 s to 0.5 s.

2.4 Reference, Option B, Use of Short-wave Receiver and NIST-transmitted Radio Signal.

2.4.1 The tuning fork, or other acoustic frequency emitting device, must be in temperature equilibrium with the laboratory environment, typical equilibration time is not less than 2 hours. Read and record the ambient temperature.

2.4.2 Assemble the system as shown in Figure 1.

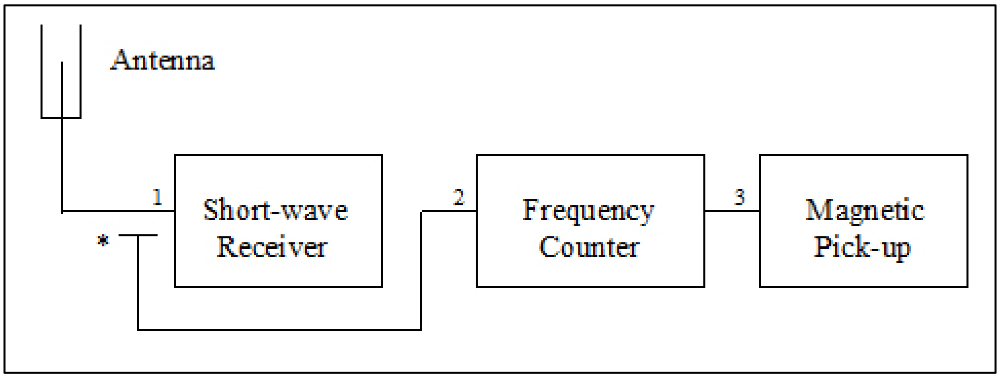

Figure 1. System Configuration.

2.4.3 Tune the short-wave receiver to the best usable standard frequency of 2.5 MHz, 5 MHz, 10 MHz, 15 MHz, or 20 MHz.

2.4.3.1 If the 10 MHz signal is not usable, a frequency divider / multiplier must be inserted at the frequency counter standard frequency output. Set the divider / multiplier to convert the 10 MHz standard frequency output to the best usable WWV(H) frequency.

2.4.3.2 Because of heterodyning, the received WWV signal and the counter standard frequency output will cause the short-wave receiver field strength meter to oscillate. The oscillation rate is directly proportional to the frequency difference between the two signals.

If the meter oscillates three complete cycles or less in 1 second, the frequency counter is accurate enough for tuning fork certification.

If the meter oscillates more than three cycles in 1 second or does not oscillate at all, consult the maintenance manual for "time base oscillator adjustment procedures" or refer the counter to a manufacturer's authorized repair facility.

2.5 Reference, Option C, Use of Tuning Fork Gauge and NIST-transmitted Radio Signal.

2.5.1 The tuning fork, or other acoustic frequency emitting device, must be in temperature equilibrium with the laboratory environment, typical equilibration time is not less than 2 hours. Read and record the ambient temperature.

2.5.2 Verify accuracy of the Tuning Fork Gauge via the NIST telephone signal broadcast via a telephone connection pick-up coil.

Table 2. Reference calibration sources.

Service	Location	Telephone Number	Radio Call Letters	Broadcast Frequencies
NIST	Ft. Collins, CO	(303) 499-7111	WWV	2.5 MHz 5 MHz 10 MHz 15 MHz 20 MHz
NIST	Kauai, HI	(808) 335-4363	WWVH	2.5 MHz 5 MHz 10 MHz 15 MHz
U.S. Naval Observatory (USNO)	District of Columbia	(202) 662-1401 (202) 762-1069	-----	-----
USNO	Colorado Springs, CO	(719) 567-6742	-----	-----
National Research Council (NRC)	Ottawa, Ontario, Canada	(613) 745-1576 (English) (613) 745-9426 (French)	CHU	3.33 MHz 7.850 MHz 14.67 MHz

2.5.3 If the gauge meets accuracy requirements, continue with measurements of the tuning forks. If the gauge does not meet accuracy requirements, it is removed from service and submitted for calibration and adjustment to the manufacturer.

2.6 Procedure, Measure the Tuning Fork Frequency.

2.6.1 Grasp the tuning fork with the clamping type contact microphone near the serial numbered end of the fork. Avoid touching the tuning fork as much as possible to minimize warming the tuning fork thus changing its frequency. Strike the tuning fork with a semi-hard object, e.g., a wood block or a plastic mallet, etc. and immediately place the tuning fork 2.5 cm to 10 cm away from the receiver (alternatively, strike the tuning fork with the material while it is placed near the receiver). Never use a metallic or stone object to strike the tuning fork. Observe the frequency immediately and record the frequency and temperature at the time of the measurement.

2.6.2 Repeat previous step with the tuning fork grasped 180 degrees from the first reading (flip the tuning fork over) and striking the alternate tine.

2.6.3 Repeat previous step again with the tuning fork grasped 180 degrees from the second reading (flip the tuning fork over again) and strike the original tine.

2.6.4 Record the average of the three recorded readings as the oscillation frequency of the tuning fork.

2.7 Take readings of an acoustic frequency emitting device.

2.7.1 Utilize a microphone for this process.

2.7.2 Strike the acoustic frequency emitting device with a semi-hard instrument, e.g., a wood block or a plastic mallet, etc. while the system is placed 2.5 cm to 10 cm away from the receiver. Never use a metallic or stone object. Observe the frequency immediately and record the frequency and temperature.

2.7.3 Repeat the process until a minimum of three stable observations are achieved. This may involve adjusting the proximity of the microphone to the device being tested.

2.7.4 Average the stable frequency observations and record this as the frequency for the item being calibrated.

3 Calculations for Tuning Forks.

3.1 Multiply the average recorded measurement result (tuning fork oscillation frequency) by the appropriate conversion factor shown in Table 4 or use Equation 2 as shown in section 3.2. The calculation of the tuning fork speed, in miles per hour, is determined from Eqn. 1. The speed of light is slower in air than the defined vacuum speed.

$$v = f_d \frac{c}{2 f_0} \qquad \text{Eqn. (1)}$$

3.1.1 Symbols Used in this Procedure

Table 3. Symbols used in the procedure.

Symbol	Description
v	calculated speed for the tuning fork in miles per hour (mph)
f_d	measured tuning fork frequency
c	speed of light in miles per hour; The speed of light is an internationally accepted constant defined to be exactly 299 792 458 m/s (approximately 670 616 629.384 395 1 mph). The offset amount, considered insignificant here, is determined by air pressure, humidity, temperature, pollution amount and type, etc.
f_0	designated radar band frequency

3.2 Table 4 has calculated values for conversion factors from Hz to mph for simplicity and is determined by the band and frequency but may be calculated using Eqn. 2. Unique factors for Kustom Signals, Inc. forks may be required.

$$\text{conversion factor} = \frac{c}{2 f_0} \qquad \text{Eqn. (2)}$$

Table 4. Tuning fork conversion factors.

Band	Frequency (GHz)	Conversion Factor	Conversion Factor (Kustom Signals[1])
X-band	10.525	0.031 858 3	0.031 867 4
K-band	24.150	0.013 884 4	0.013 884 4
Ka1-band	33.800	0.009 920 4	NA
Ka-band	34.700	0.009 663 1	0.009 445 28
Ka-band	35.500	0.009 445 3	

Example: A typical 50 mph K-band fork may have an oscillation frequency of 3 652.4 Hz. Its speed is calculated as follows:

$$3\,652.4 \text{ Hz} \times (0.013\,884\,4 \text{ mph/Hz}) = 50.7 \text{ mph}$$

[1] Kustom Signals, Inc. information is provided as an example with appropriate conversion factors and is not intended as an endorsement or preference.

3.3 Record and report this product as the "speed" of the tuning fork to the nearest 0.01 mph or 0.1 mph as requested.

3.4 The tolerance of a tuning fork is determined by the manufacturer.

3.4.1 A few manufacturers (i.e., Kustom Signals, Inc.) have designed their speed guns to truncate (round-down) to the first whole mile per hour. This is done to give the benefit of fractional speeds to the motorist. Therefore, the tolerance of these tuning forks is:

- 0.00 mph to + 0.99 mph

CAUTION: These speed guns must be mated to their associated tuning forks. These tuning forks cannot be used interchangeably with other speed gun manufacturers. It is recommended that all tuning forks be mated to their respective manufacturer speed guns.

3.4.2 Other manufacturers have designed their speed guns to round to nearest whole mph. These tuning forks have a tolerance of:

- 0.50 mph to + 0.49 mph

4 Measurement Assurance

4.1 Duplicate the process with suitable check standards using the same transducer used to take the observations of the device under test, either the clamping type contact pickup, or the microphone and create a control chart.

4.2 Evaluate the values against the expected limits of the control charts. Plot the values to monitor changes over time. A t-test may be used to check the observed value against the accepted value.

4.3 Check standard observations are used to calculate the standard deviation of the measurement process, s_p.

5 Assignment of Uncertainty

The limits of expanded uncertainty (U) include estimates of the standard uncertainty of the standard (u_s), estimates of the standard deviation of the measurement process (s_p), an estimate for the uncertainty for the resolution of the frequency counter ($u_{counter}$), and an estimate for the uncertainty of the device used to record the ambient air temperature (u_{temp}). These estimates are combined using the root-sum-squared method and the expanded uncertainty reported with a coverage factor (k), based on degrees of freedom, to give an approximate 95 % level of confidence.

5.1 Mechanical instability of a tuning fork, which varies with manufacturer, age, physical condition, etc., is the greatest cause of error in a tuning fork measurement. This has been experimentally shown to be less than ± 0.01 %. This portion of the uncertainty is included in the standard deviation of the process (s_p).

5.2 Temperature changes of a tuning fork will cause its frequency (and thus speed) to change in a sufficiently linear fashion with inverse correlation due to the changing modulus of elasticity with temperature. The change is approximately -0.000132 mph per each rated mph per 1 °F.

Example: At 70 °F, a 50 mph fork is measured to be 50.71 mph. At 10 °F, the measurement will be approximately 51.11 mph:

$$50.71 \text{ mph} + ((-0.000\,132) \times 50 \times (10 - 70)) = 51.106 \text{ mph}$$

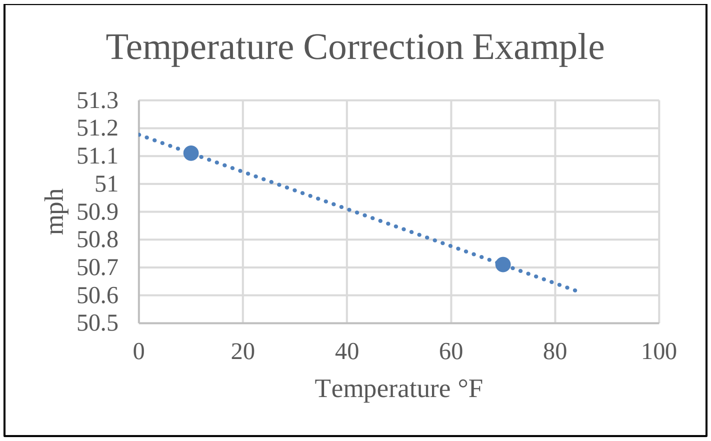

Figure 2. Temperature Correction Example.

5.3 Errors related to the broadcast signals (reference standards) are generally negligible, however may be included in the uncertainty budget (u_s).

Table 5. Example Uncertainty Budget Table.

Uncertainty Component Description	Symbol	Source	Typical Distribution
Uncertainty for the reference standard	u_s	NIST traceable frequency standard (telephone, receiver, GPS clock) NIST website (SP 960-12)	Rectangular
Standard deviation of the process	s_p	Laboratory assessments, pooled standard deviation	Normal
Uncertainty for the mechanical instability of the tuning fork	u_i	Normally included in the standard deviation of the process	Rectangular
Uncertainty of the for temperature effects	u_t	Estimates may be calculated with equations in section 5.2	Rectangular

5.4 Typically, the expanded uncertainty of the measurement process does not exceed ± 0.02 % plus small variations caused by laboratory temperature changes. Normally this impact is less than 0.05 mph.

6 Certificate

Report results as described in SOP No. 1, Preparation of Calibration Certificates. Report the tuning fork serial numbers, tuning fork speed and/or acoustic instrument oscillation frequency (if appropriate), environmental conditions during the calibrations, specifically temperature, and the calculated uncertainties.

7 Acknowledgements and Validation

This SOP and various iterations were developed by the States of Colorado, New Jersey, Alaska, and Virginia with collaboration and input from NIST (and NBS) staff David Allan and Michael Lombardi. This version is a consolidation of the various approaches to reference standards that are successfully being used for the calibration of tuning forks for legal applications.

Tuning fork PTs have been coordinated by Garret Brown from Alaska for laboratory Recognition and Accreditation and for validation of this procedure.