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Determination of Aerial Shell Burst Altitudes

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One type of fireworks data generally only guessed at is the altitudes of aerial shells at the time of their burst. In addition to addressing general curiosity, this data is often necessary when designing major aerial displays. Frequently it is important to know fairly accurately at what altitudes the various shells will appear. The rule-of-thumb, that shells break at about 100 feet per shell inch, may be a handy guide but is only very approximate and does not address differences between shell types and manufacturers. J. G. Taylor (*Pyrotechnica X*) published a theoretical paper which discussed a triangulation method for measuring the height of an explosion in the air. The paper was elegant in its mathematical approach, but may have been somewhat lacking in terms of practicality. The method suggested in this article is less elegant but is also quite practical.

The suggested method is basically the same

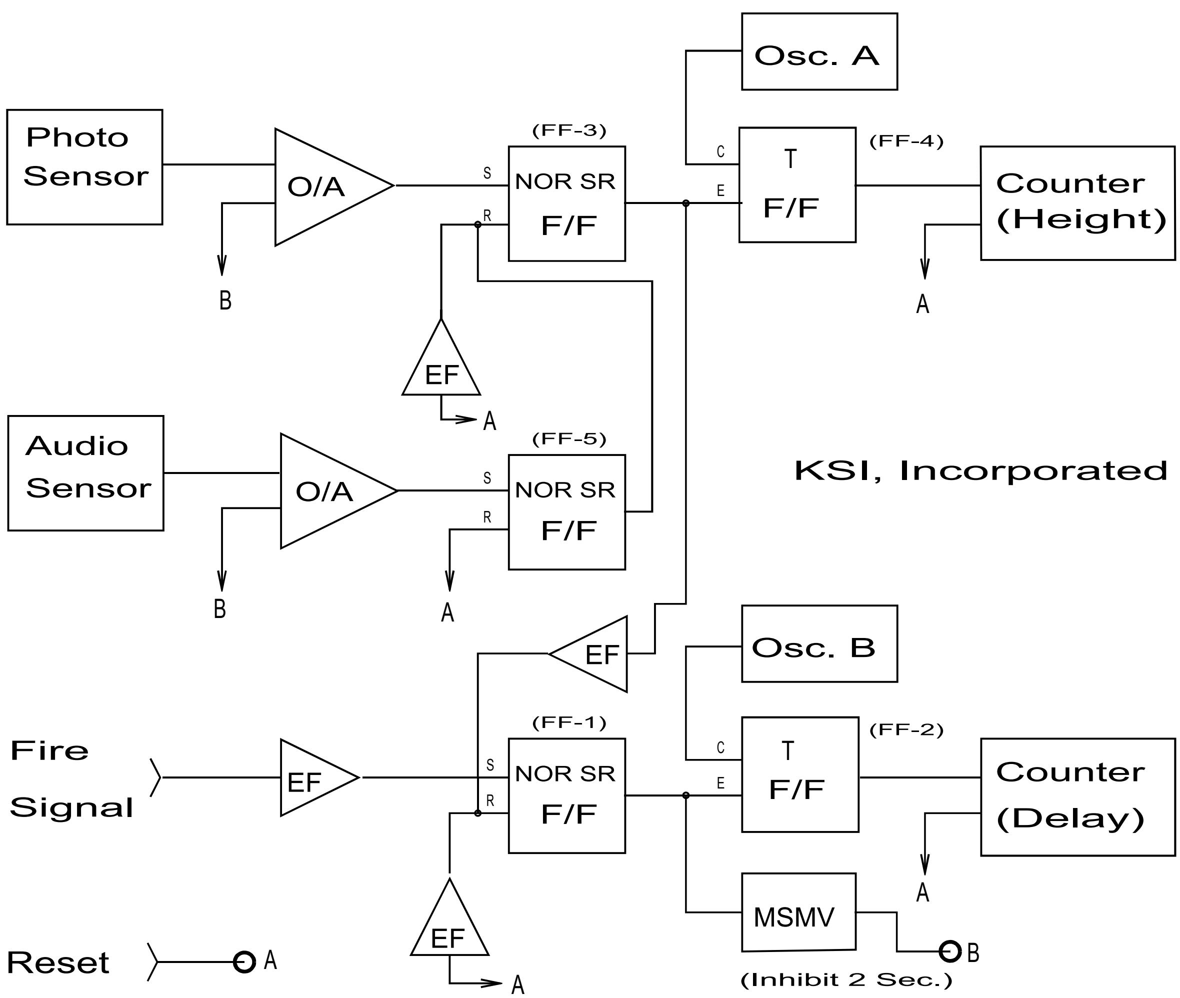

Figure 1. Aerial burst height and delay timer.

one used when people determine the approximate distance to a stroke of lightning by counting the seconds between seeing the flash and hearing the thunder. (The approximate distance in miles equals the time difference in seconds divided by five.) The basis for the method arises from the fact that speed of propagation of light is very high (984,000,000 feet/sec) while that for sound is slow by comparison (1090 feet/sec). In essence, it can be assumed that the flash of light arrives instantaneously, while it takes about 1 second/1000 feet (about 5 seconds/mile) for the sound of the thunder to arrive. The situation is identical for a bursting aerial shell, except that the distances are usually significantly less. If a pair of upward directed sensors (one photo and one audio) is stationed near a vertically firing mortar, and they are used to control the start and stop of a clock timer reading in milliseconds, then the time recorded will approximately equal the altitude of the burst in feet. There are a number of improvements that can be made, but this illustrates the concept.

The block circuit diagram in Figure 1 is one possibility for assembling the electronics to accomplish this measurement. It is certainly not the only way to accomplish the task, and may not even be the best way, but it will serve to illustrate the approach. It also includes circuitry for determining the time between mortar firing and shell burst, another important number needed when designing complex displays. Below is a discussion of how the circuit operates.

The electrical firing signal that is applied to the electric match of the shell in the mortar, is also fed to the measuring unit, shown as “fire signal” in the diagram. This signal is passed through an emitter follower as a safety measure, thus making certain the measuring unit cannot accidentally cause the discharge of the shell. The fire signal is then passed along to a NOR SR (Set/Reset) Flip–Flop (FF–1) which results in its switching to the ON state. The output of this flip–flop is in turn passed to a T (Toggle) Flip–Flop (FF–2), which then responds by allowing clock timing pulses from oscillator B to pass along to a pulse counter. Thus this (delay) counter starts recording clock pulses as soon as the electric match on the shell is energized. The clock pulse counting continues until the shell bursts at altitude. The mechanism by which the shell burst halts the counting of clock pulses is as follows. When the shell bursts, it is witnessed by an increase in the light level from the burst and/or the appearance of stars. This increase in light level is detected by a photo sensor, whose electrical output is amplified using an operational amplifier. The amplified photo signal is fed to a NOR SR Flip–Flop (FF–3), which responds by switching to the ON state. The output of this flip–flop is passed via an emitter follower (for isolation) down to the other input to the fire signal flip–flop (FF–1), which now responds by switching OFF. This in turn results in the interruption of oscillator B clock pulses passing through the T Flip–Flop (FF–2) to the delay counter. The total number of pulses recorded on the delay counter is proportional to the time elapsing between firing the shell and its burst at altitude. Because T Flip–Flops have the characteristic of dividing clock pulses by a factor of two, if oscillator B has an accurate frequency of 2.00 kHz, the counter will record delay time in milliseconds.

The process of determining the altitude of the burst begins as described above by the detection of the light from the shell burst. In addition to the output from the NOR SR Flip–Flop (FF–3) being passed down to turn off the delay counter, it is also fed to a T Flip–Flop (FF–4) which then allows clock pulses from oscillator A to pass on to another counter. Thus this (height) counter starts recording clock pulses as soon as the light from the shell burst is detected. The pulse counting continues until the sound of the shell burst is also detected. The mechanism by which the sound of the shell burst halts the pulse counting is as follows. The sound from the burst is detected by the audio sensor, whose output is amplified using an operational amplifier. The amplified audio signal is fed to a NOR SR Flip–Flop (FF–5), which responds by toggling to the ON state. This output is fed up to the other input of the Photo NOR SR Flip–Flop (FF–3), which now responds by toggling OFF. This in turn results in the interruption of oscillator A pulses passing through the T Flip–Flop (FF–4) to the height counter. The total number of pulses recorded on the height counter is proportional to the time between arrival of the light and sound of the shell burst, which is proportional to the altitude of the bursting shell. Because T Flip–Flops have the characteristic of dividing oscillator pulses by two, and because sound travels at 1090 feet per second (dry air at STP), if oscillator A has an accurate frequency of 2.18 kHz, the counter will record the altitude of the shell burst in feet. Because aerial shells are never fired in dry air, at 760 mm Hg pressure and 0 °C, it is appropriate that oscillator A be capable of being trimmed, so as to be able to calibrate the unit to properly record in feet under the conditions of use.

There remain two aspects of the circuit that have not been discussed. The first is an "inhibit" function provided by a MonoStable MultiVibrator (MSMV) which is triggered by the output of the fire signal NOR SR Flip–Flop (FF–1). This MSMV provides a blocking signal (lasting about 2 seconds) to the operational amplifiers of both the Photo and audio sensors. The purpose of this is to avoid having the Photo and audio sensors mistakenly respond to the firing of the shell from the mortar rather than its burst at altitude. The second aspect is a reset signal (A) and a couple of emitter followers (for isolation) that allow the counters and flip–flops to be reset in preparation for another shell firing.

There are a number of alternatives that might be considered in the circuit design. For example, in place of the visible light Photo sensor, an infrared (IR) Photo sensor could be used. This would offer the potential for use of the instrument during daylight. Also, in place of emitter followers for isolation, opto-isolators (or even in some cases, just diodes) could be used.

The accuracy of the unit will be affected by a number of factors, but none will result in major errors. For example, the spin of a shell will cause its trajectory to curve, resulting in the shell not bursting directly overhead. For typically curving shells this will result in an error of about 1% in measured altitude. Similarly, small lateral displacement errors can result from wind effects. Finally, small errors will result from changes in the speed of sound due to differing atmospheric conditions. However, all these errors are likely to be much smaller than the differences in performance of supposedly identical shells and thus can probably be ignored. An occasional problem is the likelihood that some shells will confuse the unit, resulting in significant errors. For example, a shell-of-shells may not burst with sufficient initial light output for the Photo sensor to detect the burst. Similarly a poka shell may not break with sufficient sound output for the audio sensor to detect the burst. Most problems of this type could be eliminated by adjusting the sensitivity of the sensors, if in fact it is necessary to make measurements for these types of shells.

Calibration of the altitude measuring unit can be accomplished using small salutes at known distances on the ground. The trimming circuit of oscillator A can be adjusted to achieve correct distance measurements. As an alternative, a calibration curve, relating height counter readings and known distances to ground salutes, can be established for the unit. If there is concern regarding the accuracy of the delay timer, that can be checked by simply using a stopwatch.

Although lab work has demonstrated that this approach is practical, there has not been time to assemble or test a prototype instrument. (Also, the author has only limited knowledge of electrical engineering.) It is estimated that the material cost for this unit will be about $200. (Thanks in large measure to Tom Dewille's suggestion of a marvelous pulse counter with LCD readout costing only $35.) This article is presented in the hope that a reader will have the time knowledge and inclination to successfully turn this concept into a piece of practical hardware.

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