ILRS Timing Devices:
Specifications, Error Analysis, and BEST Practices

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Abstract: The Time-Of-Flight (TOF) measurement device is a key component in satellite laser ranging and is a limiting factor in absolute data accuracy, especially at the one millimeter level. Therefore; optimizing the performance of these TOF devices is critical in achieving new scientific accuracy requirements.

In the rest of this paper, we will discuss the key specifications of the ILRS network TOF devices, TOF device error sources and generic BEST TOF device practices.

Introduction:

In Satellite Laser Ranging (SLR), there are two timing measurements, the time (epoch) of laser fire and the roundtrip TOF of the optical pulse. In this paper, we will restrict the discussion to the key system components involved in the TOF measurement (i.e. the TOF device and the master clock).

There are two approaches in measuring the TOF, time interval counting and epoch event timing. In time interval counting, the elapsed time between laser fire and its satellite echo is measured/counted. In epoch event timing, the time of these 2 events (laser fire and satellite echo) are stored, from which a TOF is derived.

Raw satellite TOFs must be corrected (i.e. calibrated) for optical and electronic delays, inherent in a SLR system. This calibration value is commonly referred to as system delay. For a given satellite segment or pass, these calibrated satellite TOFs are compressed into normal points, using the Herstmonceux algorithm, and transmitted expeditiously to the ILRS global data centers.

As the ILRS pushes toward 1 MilliMeter (mm) absolute accuracy, ALL potential error sources must be reduced to much less than (<<) 1 mm to ensure the Root Sum of the Squares (RSS) of all sources is less than 1 mm. TOF devices, in particular, can be a major source of random (i.e. jitter) and systematic error.

Below are the definitions of some terms that will be used throughout the document.

ACCURACY – the deviation of a measurement from a standard. *[Example: range bias]*

PRECISION – the deviation of a set of measurements about their mean. [Example: single shot RMS]

RESOLUTION – the minimum differential measurement, which can be made. [Example: granularity of a TOF device]

STABILITY – a measure of the constancy of some quantity over time. [Example: range bias stability]

JITTER – the random displacement of a signal from its absolute location. [Example: counter jitter]

LINEARITY – the relative accuracy between measurements. [Example: counter linearity]

ALLAN DEVIATION – non-classical statistic used to estimate stability. [Example: frequency stability]

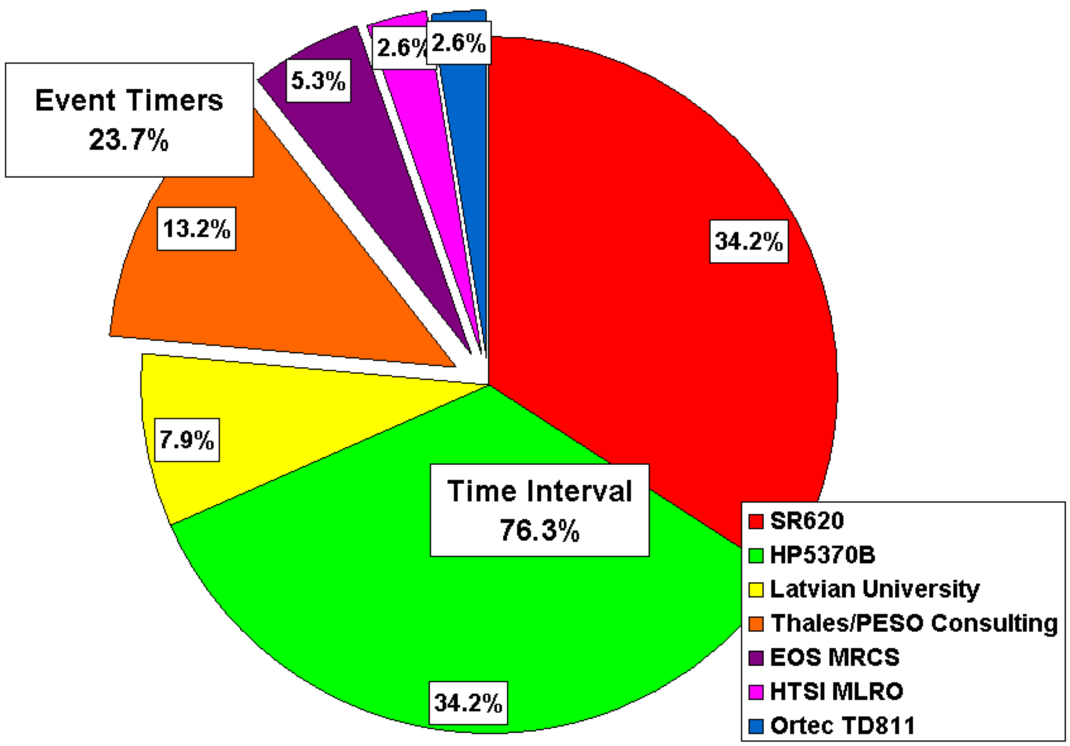
Currently, there are 6 manufacturers of TOF devices used in the ILRS network, each with its own specifications (see Table 1). These specifications were either taken from operational manuals or published papers.

Table 1. ILRS Network TOF Device Specifications

Manufacturer	Curent Model	Year	Approach	Resolution (ps)	Jitter (ps)	Linearity (ps)	Stability [ps/K]	Stability [ps/hour]	Max. repitition rate	Max. TOF (Secs)
SR	620	1988	Interval	4	22	50	5		100	1000
HP	5370B	1982	Interval	20	35	20			10	10
Latvian Univ.	A013a	2002	Interval	10	20	2		2	80	0.209
Ortec	TD811	<1980	Event	100			40			N.A.
PESO Cons.	PET4/TIGO	1999	Event	1.2	3.5	3	<0.3	<0.5	>100	N.A.
EOS	MRCS V.4	1998	Event	2	10	1		1	1000	N.A.
HTSI	MLRO	1998	Event	0.5	<2			0.5	2000	N.A.

Currently, more than ¾ of the approximate 35 ILRS sites have time interval counters, which were manufactured by either Stanford Research Systems, Hewlett-Packard, or the Latvian University. Less than ¼ of the ILRS sites have event timers, which were manufactured by either PESO Consulting & Thales (formerly Dassault), Electro-Optics Systems, Honeywell Technology Solutions Incorporated, or ORTEC EG&G (see Figure 1).

Figure 1. ILRS Network TOF Devices (October 2002)



Below are general PROS and CONS of each type of device:

Time Interval Units

PROS – inexpensive (<10K), can provide sub-centimeter accuracy with proper care and calibration versus a standard

CONS – maximum time-of-flight, laser repetition rate limited to <100Hz, requires special test equipment or multiple counters to measure non-linearity's, may be a limiting factor in 1 mm absolute accuracy

Event Timers

PROS – supports lunar, interplanetary, and KHz ranging, picosecond event timers are NOT a limiting factor in 1mm absolute accuracy

CONS – picosecond event timers are expensive

Error Sources:

The errors and specifications of these different timing devices are different, but the error sources are the same. Below are the equations:

$$TOFErr = \mathrm{Res} \pm (\Delta f_0 / f_0 \times TOF) \pm StartTrErr \pm StopTrErr \pm SysErr$$

$$\mathrm{Res} = \sqrt{[Dev\mathrm{Res}^2 + (STS \times TOF)^2 + StartTrJt^2 + StopTrJt^2] / N}$$

$$TrErr = \sqrt{\frac{(E_{input}^2 + E_{internal}^2)}{input\_slew\_rate}}$$

Abbreviations:

TOFErr – time of flight error
TOF – time of flight
Res - resolution
$\Delta f_0 / f_0$ - timebase (frequency) error
SysErr – systematic error
DevRes – device resolution
STS – short term stability
TrErr – trigger error
TrJt – trigger jitter
E_{input} - input signal noise
$E_{internal}$ - internal signal noise

We will now examine each term in the top equation in detail. The1st term, the resolution, is represented by the 2nd equation. The resolution is a *random* error. It is dependent upon the TOF device resolution, the short term stability of the external timebase (frequency), the TOF device start and stop trigger jitters, and the number of observations in the normal point formation. The TOF device resolutions and jitters are presented in Table 1.

The 2nd term is the timebase error of the external oscillator (i.e. master clock) multiplied by the TOF. The timebase error is commonly represented as $\Delta f_0 / f_0$. In Table 2 below is a representation of the impact of an oscillator error on the range measurement for different satellite time intervals.

Table 2. Influence of $\Delta f_0 / f_0$ on Range Measurement (all units in mm)
(Note: Maximum TOFs in milliseconds (ms) appear in the header row.)

$\Delta f_0 / f_0$	LEO (25ms)	LAGEOS (60ms)	High (200ms)	Lunar (2500ms)	Mars (1,000,700ms)
1.E-07	374.741	899.377	3297.717	37474.057	15000000.000
1.E-08	37.474	89.938	329.772	3747.406	1500000.000
1.E-09	3.747	8.994	32.977	374.741	150000.000
1.E-10	0.375	0.899	3.298	37.474	15000.000
1.E-11	0.037	0.090	0.330	3.747	1500.000
1.E-12	0.004	0.009	0.033	0.375	150.000
1.E-13	0.000	0.001	0.003	0.037	15.000
1.E-14	0.000	0.000	0.000	0.004	1.500
1.E-15	0.000	0.000	0.000	0.000	0.150
1.E-16	0.000	0.000	0.000	0.000	0.015

Legend
>10mm
>1mm but <10mm
<1mm
<0.1mm

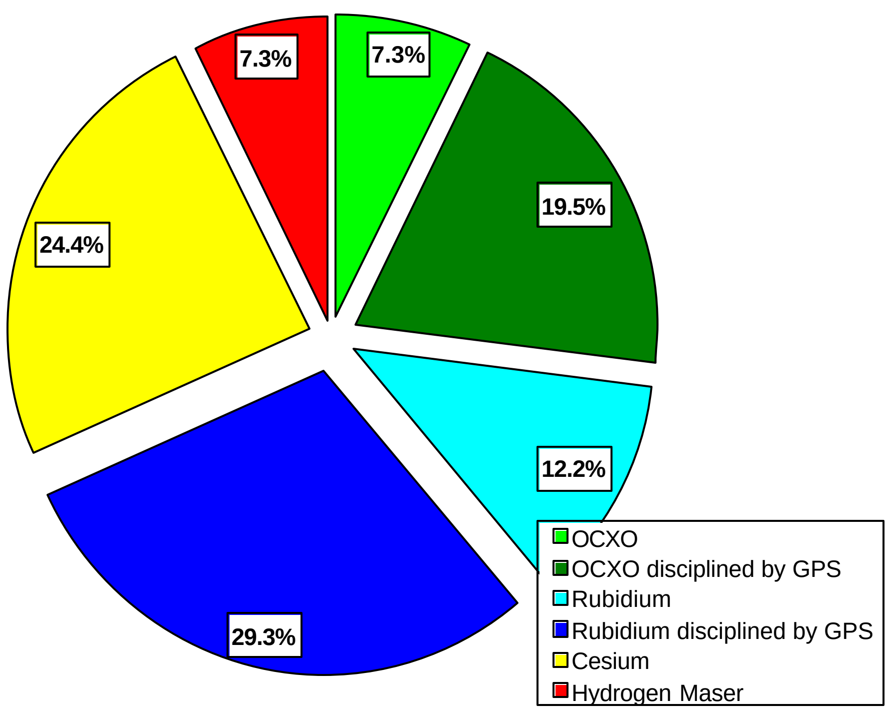
In SLR, for a given $\Delta f_0 / f_0$, the range error is dependent upon the duration of the entire pass (e.g. for LAGEOS less than 50 minutes or 3000 seconds) and the TOF. The timebase error is *systematic* and therefore critical. There are 4 major classes of oscillators, crystal, rubidium, cesium, and hydrogen masers, each having their own range of aging performance represented in Table 3 below. Phase-locking an oscillator to the 1 Pulse Per Second (PPS) from a GPS receiver can enhance the long-term aging effects of crystal and rubidium clocks. Figure 2 below is a usage chart of ILRS network oscillators based on ILRS site log contents.

The 3rd and 4th terms in the top equation are the start and stop trigger errors, which are explained in more detail in the last equation. The trigger error is based upon the input and internal signal noise and input slew rate. The 5th term is the systematic error, which can come from non-linearities and other in-stabilities in timers (i.e. temporal drifts, drift with temperature). These systematic errors can virtually eliminated via proper calibration.

Table 3. Long Term Oscillator Performances

$\Delta f_0 / f_0$	Crystal Performance Range	Rubidium Performance Range	Cesium Performance Range	Hydrogen Maser Performance Range
1.E-07	XXXXX			
1.E-08	XXXXX			
1.E-09	XXXXX			
1.E-10	XXXXX			
1.E-11	XXXXX			
1.E-12		XXXXX		
1.E-13		XXXXX	XXXXX	
1.E-14			XXXXX	XXXXX
1.E-15				XXXXX
1.E-16				XXXXX

Figure 2. ILRS Network Oscillators (October 2002)



Generic BEST Practices:

Below are the BEST practices that are general and applicable to any time of flight device (time interval count or event timer) used for SLR/LLR applications:

1. **Signal integrity:**
   a) Use only high-quality cables and connectors.
   b) Take great care with shielding and grounding in order to make sure that all noise sources are minimized.

2. **External frequency ("Clock source"):**
   a) Supply each timer with a separate, high quality 5 or 10 MHz sine wave;
   b) Make sure that the timer is set up to take an external "clock source":

3. **Power supply:**
   a) Never switch off. If the timer has been switched off for any reason, allow adequate warm up before any operational use. Please refer to the manufacturer's operations manual for more information.
   b) Use a stable mains voltage supply (for this and many other instruments it is useful to monitor the mains voltage regularly and warn when it falls).
   c) Use a transient suppressor to prevent voltage "spikes" reaching the timer.

4. **Environmental Control:**
   a) Maintain a stable working environment around the timer.
   b) Keeping the temperature constant is particularly important.
   c) Monitoring the temperatures of air at the timer air inlet and air outlet will give quick feedback of potential problems;
   d) Maintain a good airflow around and through the instrument.
   e) Be aware that near-by air-conditioning units, cycling on and off, can substantially alter the temperature of the air in the vicinity of the timer, even in a supposedly temperature stabilized room.

5. **Non-linearity/timer calibration:**
   a) For picosecond event timers, perform optical calibration as recommended by the manufacturer.
   b) For time interval counters, either cluster the time interval units to help "average" non-linearities or calibrate each device versus a picosecond event timer and model any non-linearities in data processing.

6. **Jitter:**
   a) Monitor the jitter of the timer at least monthly.

Conclusion:

The error sources of timing devices are very similar; however, the magnitudes of the absolute errors can vary significantly depending upon manufacturer specifications, calibration procedures, maintenance practices and the external timebase (i.e. the oscillator). Pico-second event timers are NOT a limiting factor in achieving 1mm absolute ranging accuracies.

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References:

Below are the references (i.e. papers and/or manuals) sorted by prime author and year.

Appleby, G.M., Gibbs, P., Sherwood, R.A., & Wood, R., 1999, "Achieving and maintaining sub-centimetre accuracy for the Herstmonceux single-photon SLR Facility", Colloquium on SLR-System Calibration Issues, Florence, Italy.

Artyukh Y., 2002, "Time Interval Counter A013 Brochure".

Artyukh Y., Bespal'ko V., Boole E., Lapushka K., 2002, "A010 Family of Time Interval Counters Adapted to SLR Applications", Proc. of the 13th International Workshop on Laser Ranging, Washington DC.

Artyukh Y., Bespal'ko V., Boole E., 2000, "High Resolution Modular Time Interval Counter", Proc. of the 12th International Workshop on Laser Ranging, Matera, Italy.

Degnan J., 1985, "Satellite Laser Ranging: Current Status and Future Prospects", IEEE Transactions on Geoscience and Remote Sensing, Volume GE-23 Number 4, p 398-413.

Gibbs P., 2002, "Results of the SR620 timer comparisons made at the Herstmonceux Workshop", EUROLAS workshop, Herstmonceux, UK.

Gibbs P., 2002, "Inter-comparison of various timing devices against a single SR timer", Proc. of the 13th International Laser Ranging Workshop, Washington DC, USA.

Greene B., Dahl L., Kolbl J., 1996, "Femtosecond Timing of Electronic Pulses for SLR", Proc. of the 10th International Workshop on Laser Ranging Instrumentation, Shangai, China, p. 419-425.

Gurtner W., Utzinger J., 2002, "Counter Calibrations at Zimmerwald", Proc. of the 13th International Workshop on Laser Ranging, Washington DC, USA.

Hamal K., Prochazka I., Blazej J., 1999, "Contribution of the Pico Event Timer to satellite laser station performance improvement", Proc. SPIE Vol. 3865, p. 38-42.

Hamal K., Prochazka I., Blazej J., 1999, "Pico event timer based portable calibration standard for satellite laser ranging", EnviroSense, EurOpto, Munich, Germany.

Hamal K., Prochazka I., 1998, "Pico Event Timer Based SLR Station Upgrade ", Proc. of the 11th International Workshop on Laser Ranging, Deggendorf, Germany, p 137-138.

Hamal K., Prochazka I., 1998, "Picosecond Event Timer for Millimeter Laser Ranging", Proceedings of the 23rd General Assembly Meeting of the European Geophysical Society, Nice, France, published in Annales Geophysicae Supplement, Vol. 16, 1998.

Hewlett-Packard, "5370B Universal Time Interval Counter: Operations and Service Manual".

Ingold J., Eichinger R., Donovan H., Varghese T., Dewey W., Degnan J., 1996, "GPS Steered Rubidium Frequency Standard for the NASA SLR Network", Proc. of the 9th International Workshop on Laser Ranging Instrumentation, Canberra, Australia, p. 277.

Kirchner G., Koidl F., 2000, "Graz Event Timing System: ET", Proc. of the 12th International Workshop on Laser Ranging, Matera, Italy.

Kirchner G., Koidl F., 1996, "MultiCounter Operation at SLR Graz", Proc. of the 10th International Workshop on Laser Ranging Instrumentation, Shangai, China, p. 414.

ORTEC, "ORTEC/EG&G TD811 Time Digitizer Manual".

Prochazka I., Hamal K., 2001, "Portable Calibration Standard for Satellite Laser Ranging - Capabilities and Limitations", 8th International Symposium on Remote Sensing, Toulouse, France.

Standard Research Systems, "MODEL SR620 Universal Time Interval Counter".

Steggarda C., Clarke C.B., Heinick J.M., McClure D., Selden M., Stringfellow R., Bianco G., 1996, "Instrumentation Development and Calibration for the Matera Laser Ranging Observatory", Proc. of the 10th International Workshop on Laser Ranging Instrumentation, Shangai, China, p. 404-413.

Wood R., Appleby G., 2002, "Detecting and Eliminating Errors in the EUROLAS Network", EUROLAS Workshop, Herstmonceux, UK.