It's About Time

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HOW DO WE GET ACCURATE TIME?

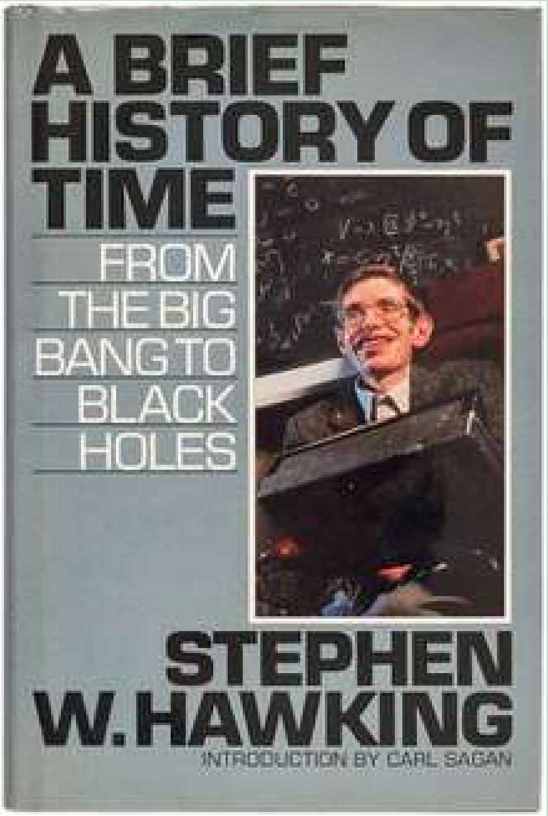
HOW ACCURATE IS OUR TIMING?

HOW RELIABLE IS OUR TIMING?

HOW CAN WE IMPROVE?

What is Time?

HOW CAN WE DETERMINE WHAT THE TIME IS?



How is Time Determined?

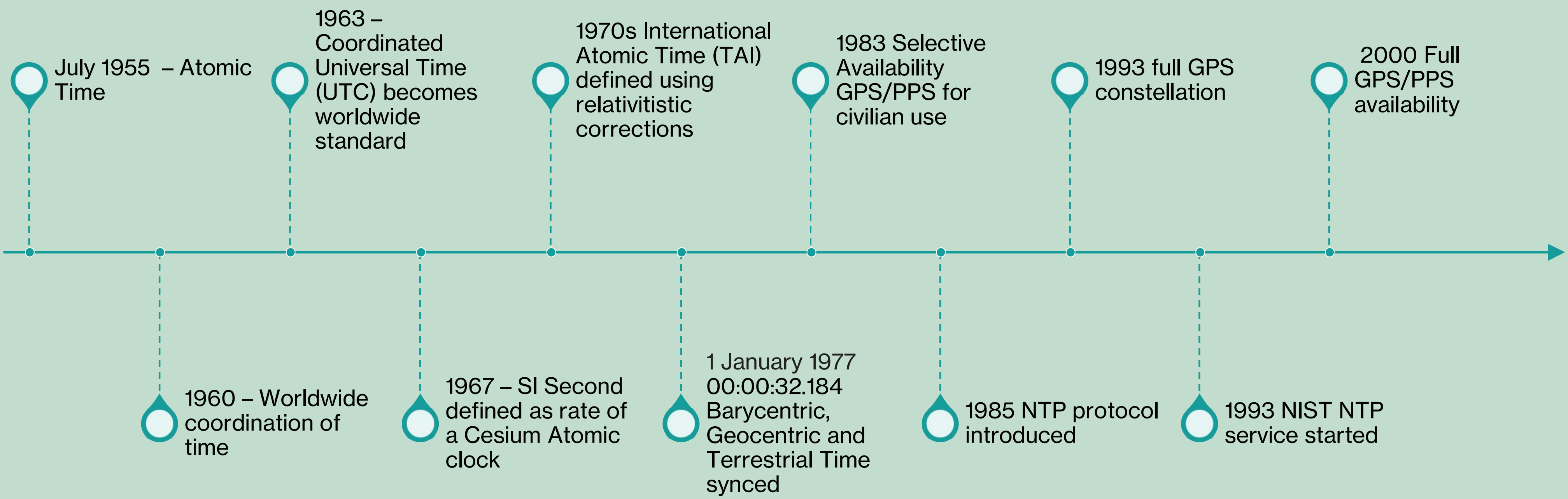
One second is the SI (International System of Units) unit of time. It is defined as the time it takes for 9,192,631,770 cycles of the radiation produced by the transition between two levels of the ground state of a cesium-133 atom. This definition is based on the oscillations of cesium atoms in atomic clocks, providing a precise and consistent standard for time measurement

So an Atomic Clock can measure the INTERVAL of one second

But what is the actual Time?

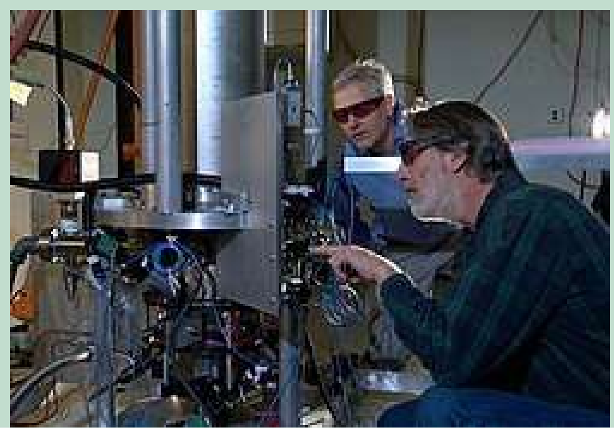
What is the ACTUAL Time?

- Date and Time are ARBITRARY scales – defined by international agreement
- UTC the official international time standard used for civilian time, phones, computers, financial systems etc.
- Coordinated Universal Time (UTC) is based on TAI, with Leap Seconds added to keep Noon within ~1 second of solar time. Maintained by BIPM



How is the Time Measured?

- Consensus of hundreds of Atomic Clocks operated by National Laboratories worldwide
- BIPM takes these times and issues UTC and offsets to UTC for the labs at 5 day intervals in a Monthly Bulletin
- So UTC is only known *RETROSPECTIVELY*, after consensus UTC time determined
- Retrospective offsets for a Lab are usually very small – a few or tens of ns



BIPM Bulletin. https://webtai.bipm.org/ftp/pub/tai/Circular-T/cirt/cirt.447

- CIRCULAR T 447 ISSN 1143-1393
- 2025 APRIL 11, 10h UTC
- BUREAU INTERNATIONAL DES POIDS ET MESURES
- THE INTERGOVERNMENTAL ORGANIZATION ESTABLISHED BY THE METRE CONVENTION
- PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 tai@bipm.org
- The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BIPM Circular T"
- available at https://webtai.bipm.org/ftp/pub/tai/other-products/notes/explanatory_supplement_v0.8.pdf
- 1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
- From 2017 January 1, 0h UTC, TAI-UTC = 37 s.
-

Date 2025 0h UTC	FEB 28	MAR 5	MAR 10	MAR 15	MAR 20	MAR 25	MAR 30	Uncertainty/ns Notes		
MJD	60734	60739	60744	60749	60754	60759	60764	uA	uB	u
Laboratory k				[UTC-UTC(k)]/ns						
AUS (Sydney)	17.5	-2.3	3.3	0.6	-0.9	-9.8	8.8	0.2	3.0	3.0
MSL (Lower Hutt)	4.5	-6.7	3.8	11.0	14.7	13.6	26.1	0.7	2.9	3.0
NIST (Boulder)	-0.1	-0.3	-0.2	-0.0	0.3	-0.1	-0.6	0.2	2.0	2.0

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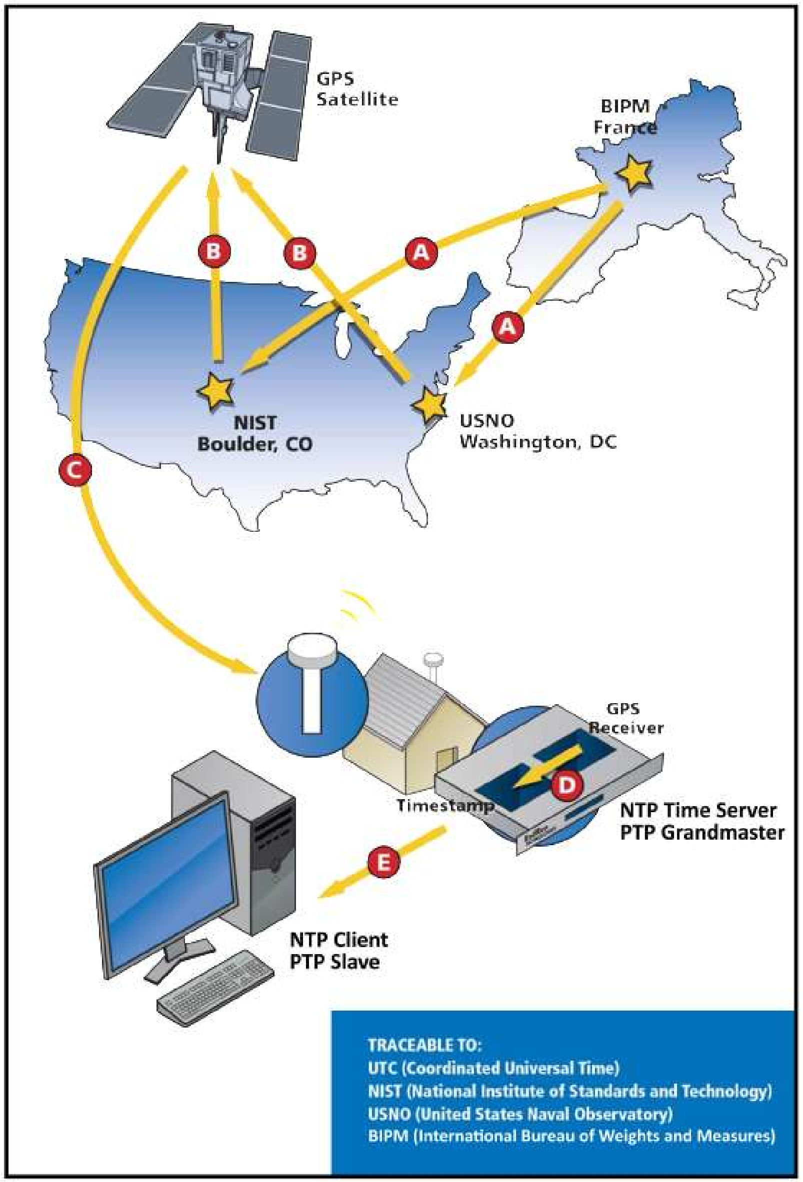
How is Time Distributed?

- National Laboratories keep Atomic Clocks synchonised to UTC as best they can
- Distribute time via various services:
  - Network Time Protocol (NTP) Servers (most National Laboratories)
  - Radio Time Servers (limited services from UK, Germany, USA)
  - Via GNSS satellite networks
- Satellite time distributed by the network operator, e.g. USNO for the US GPS system.

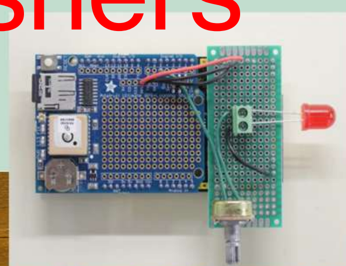


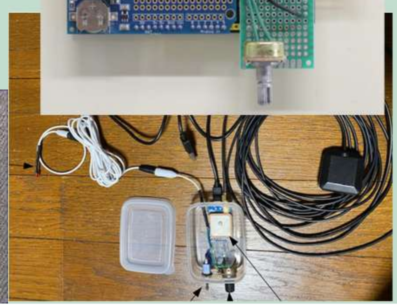
How do Occultationists Receive Time?

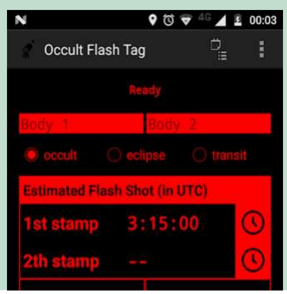
VTIs

GPS Cameras

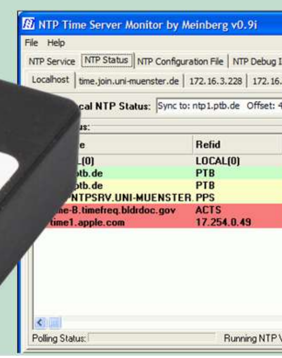
GPS Flashers







PC Discipline



How accurate and reliable are these devices and systems?

How can we know or show how accurate they are?

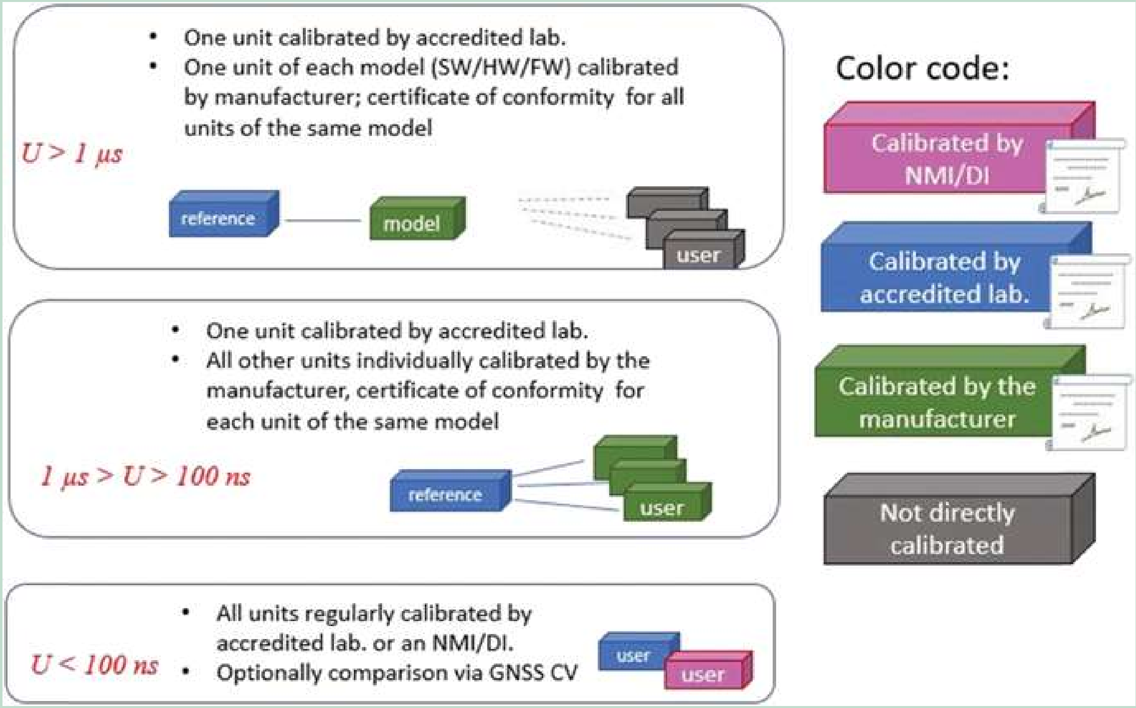
Time Calibration - Traceable Time

- Timing devices must be calibrated to know their accuracy
- Must be traceable to UTC meaning that measurements can be linked back to National or International measurement standards
- Every step in the chain of time transmission must be measured and documented
- Must be repeated regularly

Regular Testing and Calibration of Timing Devices

- For ongoing traceability device(s) need to be tested regularly to ensure performance has not changed
- Any changes to hardware or software may require the testing be repeated
- For low accuracy (> 1 μs), Unit testing of a single, typical device is acceptable
- Such testing should ideally be done by an accredited laboratory

https://iopscience.iop.org/article/10.1088/1681-7575/ac98cb



Example of Traceability Path for GPS Signals

Link	Reference
A	SI Units
B	UTC (NIST)
C	UTC (USNO) US Naval Observatory GPS Time
D	GPS Broadcast Signals
E	GPS Received Signals
F	Users Timing Device
G	Recording Timestamps
H	Users Analysis and Reporting

Link	Reference	Details	Typical Error
A	SI Units	Defined by SI system	1s per 300 MY of Cesium Clocks
B	UTC (NIST)	NIST does their own calibration, BIPM Bulletin	A few ns
C	UTC (USNO) US Naval Observatory GPS Time	USNO compares to UTC (NIST)	A few ns
D	GPS Broadcast Signals	Each GPS satellite synchronised/monitored	A few ns
E	GPS Received Signals	Properties of the GPS receiver. Effects of reflections, ionosphere etc	10-100 ns. Varies by device and conditions
F	Users Timing Device	Varies by device	Varies by device
G	Recording Timestamps	Varies by device	Varies by device
H	Users Analysis and Reporting	Processing, adjustments, corrections, manual handling	Varies by region, software, user

What we don't need to worry about...

Link	Reference	Details
A	SI Units	Defined by SI system
B	UTC (NIST)	NIST does their own calibration, BIPM Bulletin
C	UTC (USNO)	USNO compares to UTC (NIST)
D	GPS Broadcast Signals	Each GPS satellite synchronised and monitored

- Links A to D are managed by NIST
- Not under User control (except to choose a different GNSS satellite constellation)
- Errors are small – a few to tens of ns
- Small compared to other sources of error further down the chain

This is where we need to start to worry…

Link	Reference	Details	Typical Error
E	**GPS Received Signals**	**Properties of the GPS receiver. Affected by transmission, ionosphere, reflections etc**	**10-100 ns. Varies by device and conditions**

- GPS signals affected by ionosphere, local reflections, interference
- GPS receivers each have their own errors, often not fully documented, usually no statement of accuracy or Certificate of Conformity

There is no practical way for us to measure and monitor GPS timing errors

1 PPS to the Rescue…

"The "worst case" uncertainty for a GPSDC where all hardware delays are ignored and uncalibrated could reach 1 μs (1,000 ns), but uncertainties this large are unusual. A 1 μs specification meets the needs of critical infrastructure timing systems, and the GPSDCs deployed in these systems do not need to be calibrated to meet the specifications. They can be trusted to keep time within 1 μs of UTC as long as they are receiving satellite signals and working properly"

- Lombardi, Michael. (2016). **Evaluating the Frequency and Time Uncertainty of GPS Disciplined Oscillators and Clocks.** NCSLI Measure: The Journal of Measurement Science. 11. 30-44. 10.1080/19315775.2017.1316696. https://www.researchgate.net/publication/320798359_Evaluating_the_Frequency_and_Time_Uncertainty_of_GPS_Disciplined_Oscillators_and_Clocks

- **If our required timing accuracy is no better than 1 μs then the 1 PPS of a GPS receiver can be assumed to be accurate enough**
- No need to measure the uncertainties in the GPS signal transmission or GPS receiver processing
- GPS datasheet PPS spec is enough (e.g. 99% < 60 ns)
- Need only measure the uncertainties in the hardware and software handling of the 1 PPS output signal and the downstream timestamp processing

Unbroken chain of calibrations to UTC

- Timing devices that use 1 PPS signal from a GPS receiver can assume that signal to have an accuracy no worse than 1 μs
- Measure and account for the delays and uncertainty in the hardware and software processing of those 1 PPS time signals
- Non-deterministic errors (e.g. random delays or variation caused by software) need to be monitored over a period of time and accounted for statistically (Type A errors)
- Deterministic errors (e.g. hardware time delay, micro-processing clock signals) need to be measured and documented (Type B errors)
- Needs to be repeated regularly

This establishes an unbroken chain of calibrations back to the 1 PPS output of a GPS receiver, which in turn is traceable to UTC with an error of <1 μs

What is under our control at least in principle...

Link	Reference	Details	Typical Error
F	Users Timing Device	Varies by device	Varies by device
G	Recording Timestamps	Varies by device	Varies by device
H	Users Analysis and Reporting	Processing, adjustments, corrections, manual handling	Varies by region, software, user

We are responsible for managing the last links in the chain

How Have our Timing Devices Been Tested?

- A wide variety of timing devices and recording systems in common use
- Only limited testing of these systems has been published or is available publicly
- Much of that testing is old and has not been repeated
- Various test devices (e.g. EXTA, SEXTA, NEXTA, StampOfApproval) developed as one off, DIY, or limited production
- Most device developers assert time back to the GPS 1 PPS, but often with insufficient technical detail to evaluate these assertions

Few, if any, of our timing devices are calibrated traceable to UTC

Example: Watec 910HX using IOTA-VTI

- **Watec 910HX** Internal camera acquisition delays measured by Dangl in 2013 using EXTA
- **EXTA** device designed by Dangle, only published on website
  http://www.dangl.at/exta/exta_e.htm.
    - Statement of 1 us to the 1 PPS and a <70 us LED offset error but sparse details of that measurement
- **SEXTA** device used by Barry et al in 2015 to measure timing of **IOTA-VTI** with a ***Watec 120N***
- **SEXTA** 1 PPS processing delays measured at 0.165 ms delays
  – good evidence that **SEXTA** was accurate to < 2 ms as claimed
- Chain back to UTC is broken – no actual link through the devices
- Broken physically – tests on different physical devices in different places
- Broken in time – 2013, 2015 and the intervening 10 years

Estimated Accuracy of Timing Devices

Based **solely** on published journals or publicly available information

Assumes working and operated properly. **NOT** proof of traceability to UTC

System	**Estimated Accuracy**	**Testing Status**
Astrid	1 micro-second range	Self tested by designer
DVTI+CAM	1 ms tested. Possibly sub-ms	Tested used EXTA. EXTA self-tested by designer
QHY174M-GPS	1 micro-second (asserted) 1-2 ms, possibly 0.1ms (tested)	Asserted by QHY. Testing using SEXTA or NEXTA
Analog Camera and VTI	0.1 ms - IOTA-VTI 1-2 ms for others	By assertion of the VTI designer back to GPS receiver PPS specifications. Testing of camera corrections 10+ years ago using EXTA. Assumes all devices are working to original specs.
GPS flash timing (Camilleri method)	~5 ms at worst	Published testing by Camilleri. Better accuracy possible for shorter exposures
GPS flash timing (generic with weak protocols)	5-20 ms	Ad hoc testing or self-assertion, unpublished. If rolling shutter and other effects not accounted for errors of up to ~20 ms would be expected for small sensor cameras, larger errors for large sensors
NTP	~15 ms	Published testing by Gault. Rolling shutter delays need to be accounted for. Some PCs may not be stable enough to achieve this accuracy
PC clock discipline using GPS NMEA or PPS	5-10 ms for NMEA Low ms for PPS Up to 20 ms errors if rolling shutter not corrected for	Likely range based on ad-hoc testing. Limited standardisation so depends on the user's. Rolling shutter delays need to be accounted for. Vulnerable to GPS errors and Windows processing delays

Reliability of Timing Devices

- What could go wrong?
- How often does it go wrong?
- How can the user know something has gone wrong?
- How can they recover?
- Examples:
  - Leap second errors
  - Loss of GPS
  - User error
  - Uncorrected Rolling shutter delays

Ideas for Reliability Classification?

Class One – Timestamps in output. No user input or adjustment require. e.g. Astrid, DVTI+CAM

Class Two – Timestamps in output. User setup required. e.g QHY174GPS

Class Three – Timestamps in output but requires user to process timestamps and/or apply corrections. e.g. all VTIs

Class Four – Requires adjustments from other systems. e.g. GPS flash timing, PC disciplined

From a Scientific or Technical, most of our timing systems would be considered uncalibrated and untested with an unknown timing accuracy

If we want to be treated like “professionals” and not “amateurs” our time basis should be up to “professional” standards

… I really hope the “professionals” test and calibrate

HOW CAN WE SHOW OUR TIMING DEVICES ARE ACCURATE?

How can we do this as a bunch of amateurs?

Standard Testing Requirements and Processes	Reference Timing Devices, Calibrated to UTC
Unit Testing of Common Devices	Distribute Reference Devices/Designs
User Calibration or Checks	Monitoring

We are SO CLOSE to being able to do this!

- Improved GPS flasher designs
- Better understanding of GPS flash timing methods
- Better understanding of CMOS cameras, rolling shutter etc
- Better understanding of how Windows PC perform

Plus

- Some very smart and capable people worldwide

We have the pieces of the puzzle

– just need to put them together

What about YOUR Timing System?

- How do you know that your timing system is producing accurate timestamps?
- How do you know if it is still working properly 5, 10 or even 15 years after it was first built?
- How do you know if it gives reliable and consistent timestamps?

What can you do now to check your timing?

- Get and Independent time source (e.g. PC disciplined NTP)
  - Basic tests for gross errors (e.g. > ~1 s)
- Compare to other timing devices/cameras
- Much more accurate tests possible using GPS Flash Timing
- Test your setup regularly
- Support the development of improved testing and calibration

It's About Time

To Show we Know the Time