

ON THE QUALITY OF WET TIME

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Abstract. The goal of the WET collaboration is to produce a photometric light curve as continuous and accurate as possible, given the weather and technical constraints. In order to join light curves from different observers, it is important that all observer's clocks are accurately synchronised with Universal Time, and with a precision substantially better than one second. This requires vigilance and careful checking by the observer, who needs to be familiar with the instrument and how the integration intervals are determined. This is in particular important with the introduction of the more complex CCD photometers. Ideally each observer should have access to their own time source, and a GPS solution is recommended. It is also important that the information about timing peculiarities are carefully checked and recorded and passed on to the data analysts.

Key words: instrumentation, continuous photometry, timing accuracy, synchronisation

1. INTRODUCTION

The Whole Earth Telescope (WET) is a collaboration of observers who conduct coordinated time series photometry using different telescopes distributed around the Earth. The essential goal of the “instrument” is to obtain continuous time series photometry on a selected pulsating target star (or stars) over an extended period. A typical WET run involves a dozen telescope sites, an approximately two week observing window, and a continuously manned “control” centre (HQ). This last part of the instrument is important for coordinating the campaign and providing a continuing “first look” analysis of the data stream in, as near as possible, real time.

Precision time series photometry with integration times of seconds is required to study the many (mainly compact) stars that pulsate with periods in the range of about 100s to 1000s. If the pulsator is complex and multiperiodic, then an extended light curve with (ideally) no gaps is an essential observational beginning. Due to the effective switching on and off of the signal, data gaps produce artificial power in Fourier space at frequencies where there is no real signal: this makes it difficult, if not impossible, to disentangle the real from the unreal. The WET as an instrument was originally conceived by Ed Nather (Nather et al. 1990) to achieve the objective of eliminating data gaps and consequently minimising this frequency “aliasing”. Uniformity of instrumentation to facilitate combining the data segments, and an active control centre were important parts of the WET’s design specification as an instrument. As necessary, experienced and trained observers were sent to non-WET telescope sites in order to achieve this uniformity. These factors — the active control centre, in particular — make a WET run more than a multi-site campaign and closer to a single instrument.

It is obvious that the WET is an expensive instrument to operate, even though much of the cost is now distributed among the various collaborators. If one adds up the costs associated with a particular run, such as instrumentation development, telescope time, observer’s time, logistics and travel costs, control centre costs (which normally involves flying in people experienced in the art of the data reduction) and post campaign analysis costs etc, one ends up with a tidy sum indeed. It should go without saying that the combined significant expenditure should lead to an effective end result: good science.

We would like to discuss one relatively simple problem, with an apparently simple solution, that can (and perhaps has) led to unnecessary degradation of the overall WET data set. This is the requirement for accurate timing and time synchronisation of the various contributing data sets.

2. THE IMPORTANCE OF TIME IN WET

A WET data set consists of an aggregation of many light curves, each modulated by the contributing frequencies, from different observers at varying times, and the same observer at different times. The key goal of the data reduction procedure is to stitch all these light curves (each expressed in light level modulation amplitude) together. In order to obtain a coherent combined time series without

artifacts due to timing differences, it is imperative that each observer’s integration intervals are accurately known and synchronised to a common time standard – UTC. This requirement is fairly obvious and certainly fundamental to the work, and was an important design component of the WET instrument. But, all vigilant observers and experimentalists should always be asking whether their fundamentals are correct. So, it is important to ask how the WET instrument might achieve this common time standard, and examine what the practice has been.

Many of the pulsating white dwarf stars observed by the WET are extremely good clocks. In some cases they are superior to the atomic clocks and are competitive with the pulsar clock standards (Kepler et al. 2000). So, instrument clocks contributing to WET should be both internally consistent and synchronised overall to a uniform time standard. This will then permit season to season comparison of the detected frequencies and phases without clock errors from instrumental artifacts. Lack of internal uniformity of the WET clocks will introduce unnecessary problems in the identification of low amplitude signal peaks rising above the “grass” noise of the Fourier transforms.

One can ask three relevant questions about WET timing: (1) what accuracy in timing do we need?, (2) how do we achieve this?, and (3) how successful have we been?

In response to question 1, we can say that the behaviour of most objects being observed demands that the timing accuracy should be (substantially?) better than seconds from data segment to data segment within a run, and from season to season. The highest target frequencies observed have periods of ~ 100 s, and the integration times used are typically 5 s or 10 s. (the shortest integration time so far in a WET run has been 2 s for the pulsating eclipsing sdB binary object PG 1336-018 observed during XCov18. If there are timing errors in the integration interval, and between intervals in different light curves, this will effectively introduce extra noise and errors in the modulated signal. However, given that there is already photon counting noise and other (atmospheric) noise contributions in the signal, a small contribution from timing errors is, if not desirable, at least acceptable. One could argue, therefore, that time accuracy of “better than seconds” is adequate for integration times of 5 or 10 seconds.

Achieving this accuracy for each observer requires meeting two basic rather obvious instrumentation goals: an easily achievable one, and a more elusive one, in no small part due to the much greater

likelihood of human error in a large group. First, the individual photometers should have a known and stable integration time. Modern electronics readily makes available stable oscillators, so this goal should be easy. Second, the photometer's integration interval should be properly and accurately synchronised to a common WET clock, and this clock should be synchronized to world atomic time via UTC. There are pitfalls in ensuring this is so for all observers. However, if each observer does this properly, then the WET clock can be used to check the reliability of the photometer clock. One might say that each observing run requires a satisfactory WET clock, and all observer's clocks should agree with this WET clock. If this is starting to sound like a treatise on relativistic clock synchronisation, then it is probably no accident, but fortunately we don't have to concern ourselves with intrinsically different clock rates!

In the following sections, in answering the third question above, we will discuss some mainly anecdotal evidence of how successful the WET collaboration has been in achieving the required timing goals.

3. TIME SYNCHRONISATION WITH P/M PHOTOMETERS

As mentioned above, the basis of a good photometer clock is a stable oscillator. An electronic oscillator with satisfactory stability for a night's run requires crystal control, preferably using a compensated crystal. Better still is an oven heated crystal whereby improved stability is obtained by using a temperature-controlled oven to minimise thermal effects on the crystal. Appropriate signals from the clock are then used to control the counting circuitry in the photometer. For many years digital circuit controls have been able to work at microseconds or better, so accurate photon counting can be achieved with negligible dead time.

In the early days of the WET, a small portable counting unit designed by Chris Clemens was promoted by the Texas group as part of the standard WET photometer. This unit communicates via a standard serial line with a PC that runs the "Quilt" acquisition program developed by Ed Nather. Combining the small microprocessor-controlled counting unit with a PC in the form of a laptop makes a very convenient and portable data acquisition unit indeed.

The clock in the Clemens unit is controlled by a quality compensated crystal. However, it needs to be synchronised with an external clock. Electronic synchronisation is possible to either an external rising or falling edge electronic signal. If the clock has been so synchronised, this is communicated to the Quilt program, and a special

mark is placed in the time stamp Quilt file header. The absence of such external synchronisation is signalled by the mark ‘~’ adjacent to the start time in the header. But, there was no provision for selecting which edge (rising or falling) of the comparison signal to use (except to move a “jumper” on the timing card itself).

This all worked properly in earlier versions of the software (Quilt 7 and 8), and the first versions of Quilt 9. However, the current version of the software in widespread use (Quilt 9.13) does not work as indicated in the documentation, but it does work in an undocumented way. Another problem with the synchronisation from an external source was to find a proper clock with a 1 Hz pulse when being a guest observer at an observatory.

This led to two schools of thought:

One view was that this electronic process should be used, and one should rely on the observer to be knowledgeable about the input clock signal. The opposing view was that it was in fact better to accept a lower precision and rely on the observer to align the clocks visually rather than risk the possibility of introducing unknown systematic errors of up to 0.5 seconds (for a symmetrical square wave synchronising pulse).

The view opposing electronic synchronism for these units appears to have prevailed, and maintaining the required clock alignment visually (or using a suitable audio signal) has become the common practice. Another significant reason for this approach is the lack of a reliable electronic time signal in a suitable form at many telescope domes. This is rather ironic as astronomers were the original timekeepers. The simple fact is that the majority of astronomers do not need time to a precision of seconds for their observations.

So, the common practice during WET runs with these photometers has become synchronisation of the Quilt software clock with the local observatory clock by the eye/ear method, and synchronisation with the WET HQ clock using international telephone calls by the voice/ear method! Careful eye/ear clock synchronisation can be as precise as a few tenths of a second, but it is subjective and prone to error. Still, an experienced observer can ensure that the Quilt (or equivalent) software clock is synchronised to the observatory clock to significantly better than a second (perhaps approaching 0.2 s), by making regular comparisons with the Quilt clock display.

Whether the observatory clock is correct is another matter and requires an independent check. With the rise of the internet, a convenient visual source of time is available from this source. This is the

Java clock provided by the US Naval Observatory, however varying network delays are a major problem. Another method using the internet, that is definitely superior, is to use a program to communicate with one of the time servers. These programs estimate the network delays by measuring return communication times (see conclusions below).

Synchronisation between WET observing sites and WET HQ is surely no better than about 1 second using the above telephone line method. The availability of the GPS network of satellites should, if used properly by the WET, ensure that we routinely have local and communal correct timing synchronisation. Prior to converting to the more convenient and portable WET instrumentation and software, one of us (DJS) had developed and used a fast photometric system that derived its timing signals from a very flexible specially designed external clock. This clock used a commercial oven heated crystal and was easily synchronised with external time such as WWV or GPS to accuracies of milliseconds or better than microseconds, respectively. The integration timing of the photometer counting circuitry was directly controlled by clock signals. This instrument is described in Sullivan (1995).

The use of portable GPS clocks by WET observers has been suggested previously (Sullivan 1995). The difficulty is that, in spite of the widespread use and availability of low cost GPS receivers most of them do not present accurate time electronically, and some units have even been observed to present time visually that is a significant fraction of a second out. Also some GPS receivers require continuous access to GPS signals to maintain the required oscillator stability: take them indoors and they can lose more than a second reasonably rapidly. This is ironic as the very basis of GPS ranging measurements is very precise measurement of signal propagation times between extremely accurate synchronised clocks. In short, for your GPS receiver (large or small, expensive or inexpensive) to work correctly at all, it must have an internal clock mechanism that maintains synchronism (with the assistance of the GPS signals) with GPS time (and thereby UTC with some known offset) to an accuracy in the nanosecond range (never mind seconds).

Most of the existing WET standard (Texas) photometers are quite old, (the one in Tromsø was built in Texas in 1976), with a last major improvement with the introduction of the third channel in 1995 (Kleinman et al 1995). In the new series of the Vilnius design classical WET photometer (Ališauskas et al. 2000), the frequency of an internal oscillator is continuously adjusted with a microprocessor

using a 1Hz pulse from GPS. The start time of every measurement is in this case claimed to be better than $2\mu\text{s}$. Four units of this instrument has been build (Italy, Poland, Turkey and Lithuania), and a fifth unit may be assembled in Vilnius when needed.

4. TIME SYNCHRONISATION WITH CCD's

The increasing use of CCD photometers in WET campaigns has introduced new time accuracy and synchronisation problems. Provided the timing details are known, there should be no problems with the frame transfer CCDs. If the frame transfer process is initiated by a known external signal then "all" that is required is for this external signal to be correctly synchronised. The Roper Scientific frame transfer CCD camera system under development by the University of Texas at Austin group (spearheaded by Ed Nather) is in this category, and accurate time synchronisation is now reliably and routinely achieved (see conclusions below).

If the CCD system does not utilise frame transfer, or it doesn't have an extremely fast readout system, we have to introduce a shutter. Then we need to know exactly when this shutter opens and closes. This may need to be found by experiment, or possibly by an open/close pulse generated by the shutter itself, if available.

Furthermore, if we use some program sequence to accomplish the readouts as well as some preprocessing of data, this may result in overheads which take variable lengths of time depending on the state of the control computer. So, to be safe a clock should be read at the same time as the data is read off the chip, and the rest can be done asynchronously.

For the Nordic Optical Telescope, we (J.-E. Solheim and collaborators) have made use of an existing CCD controller, built by the Copenhagen Astronomical Observatory. This takes time from an instrument computer, and even if we set it precisely before we start observations, and the readout is done by our own program at the lowest level, we face some limitations: the timestamps given are truncated to the nearest second, which means that the moment of time can be up to one second later than the time given. The length of integration, even if it is fixed, say like 20 s, may be 1-2 ms longer, due to some "unknown" overheads, which we cannot control. This gives a drift of 2-3 s for a long run. This may be turned to a blessing, since this drift will tell us exactly when the truncated readout changes from a 0 to 1 and from a 1 to 2 in the last digit, and then we can more precisely i.e. to the nearest 1/100 s, determine the

start and the end of the run – if the instrument computer keeps the time to that precision during the run. The whole sequence has to be started manually but with some experience it is possible to start on the correct truncated second - but one can be 999 ms too late.

For the Tromsø, made CCD photometer (Østensen & Solheim 2000), we still have a shutter, but in addition to the Copenhagen Observatory controller, we have introduced our own timing card, made by the Vilnius group, which takes time from a GPS receiver, and this time is written as timestamp for the each data that is read from the chip. The limitation is again the number of bits which do not allow higher precision than 1 second. However, in this case we have a software starting routine, which starts at an equal second, modulus the integration time length after the minute. Still there may be some delay after the starting second and the actual start of integration.

5. CONCLUSION AND POSSIBLE SOLUTIONS

Ensuring that each WET run has a uniform time standard correctly synchronised with UTC, and that in turn all observer's clocks are accurately synchronised with this time, will continue to be a goal that we must actively ensure is met. There is no substitute for vigilance and regular careful checking. Each observer should be familiar enough with the instrument they use, such that they know with confidence how the integration intervals are determined. This especially applies to the more complex CCD systems. Measurements should be made to determine the facts if necessary and regular checks carried out.

Ideally, each observer should have access to their own source of time provided by a reliable clock. If this clock agrees with the proverbial "observatory clock", or another source of (reliable) time, then the observer can start to have confidence that their time standard is correct.

In the modern GPS era there should be no difficulty in achieving the goal that all observers have their own reliable portable source of time that is effectively part of the photometer. The main difficulty is in finding a GPS clock that accurately passes on UT time. Observers should not assume their GPS clock does this, and it should be checked against a known source of time.

On the market now is a small portable unit that is ideal for this purpose. It sells for less than US\$1500 and is manufactured by Trimble in the US — they call their receiver a "Thunderbolt

GPS Disciplined Clock". This device uses up to 8 GPS satellites and passes on accurate electronic time in the form of a one second pulse. Other details, such as actual time and system configuration information are provided via a string of bytes from a standard serial port. This is very similar to the Magellan unit mentioned above. However, the difference here is that the Trimble unit is very likely to be available for an extended period as it was obviously designed to meet the demand accurate time coming from the world marine market. Given that this market includes leisure boating it is many orders of magnitude larger than astronomers in need of time.

It is instructive to relate the experiences of two observing groups seeking sources of accurate time. First, one of us (D. J. Sullivan) has been confident about the accuracy of their photometer time source for many years. This confidence is based on the following procedure. The primary source of time at all observing sites used during WET runs (Mt. John, Siding Spring, Mt. Stromlo and Mauna Kea Observatories) has been the portable Magellan GPS unit mentioned above. This unit will function with only one GPS satellite detected (provided it knows where it is), but there is usually no difficulty in detecting the four satellites it needs for normal operation. When this source of time agrees with another source (such as WWV, or VNG in Australia and NZ until recently), then observer confidence in accurate local time is both high and justified.

The second example comes from the Texas group. Ed Nather, Don Winget and collaborators at McDonald Observatory now use a Trimble GPS unit attached to their frame transfer CCD system as the primary source of time for the instrument. In addition, as a check, the GPS time is regularly compared with time derived over the internet from one of the time servers that are now available. Programs that monitor these time servers estimate the time delay between the server and the local user, and hence provide "accurate" local time. Given the possible variability of network delays, it would not be wise for an observer to rely on this source as the primary local standard, but it is a perfectly adequate secondary source. McDonald experience has shown that the GPS - network time difference is in the millisecond range.

As experience from a third group could be added that J.-E. Solheim uses a hand held Garmin 12XL Personal Navigator to check the various other time sources available at the visiting observatories, and to compare with the WET times given from the HQ. In many cases this has proven as a good device to find out which of the clocks are the correct ones. However, this device needs to "see" its satellites,

and has a tendency to loose up to one second when going inside the dome and the view of satellites are lost.

Finally, we stress the importance of writing down the time checks done, and measure possible drift in the timing, and report this to the HQ as part of the log that follows the data. About the data format, see the paper by Riddle & Kawaler (this proceedings).

There is a very good reason for an observer taking a lot of care about their time source. Quite simply, if the observer's data are not properly synchronised to the correct time standard, and this is detected or suspected in the data analysis, they are more than likely to be removed from the final analysis. No observer wants their hard earned data to suffer this fate.

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