

ULTRA-FAST ROTATORS:
RESULTS AND RECOMMENDATIONS
FOR OBSERVING STRATEGIES

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Lightcurves and amplitudes for two ultra-fast rotating near-Earth asteroids with rotation periods < 20 s observed from Great Shefford Observatory during close approaches in April 2021 are reported: 2021 GQ10 and 2021 HN. The interpretation of lightcurves where exposure length is likely to be a sizable fraction of the rotation period is discussed. Observing strategy recommendations are made to optimize exposure length in near-real time, maximizing the chance of detecting ultra-fast rotation in small objects.

Photometric observations of near-Earth asteroids during close approaches to Earth during April 2021 were made at Great Shefford Observatory using a 0.40-m Schmidt-Cassegrain and Apogee Alta U47+ CCD camera. All observations were made unfiltered and with the telescope operating with a focal reducer at $f/6$. The $1K \times 1K$, 13-micron CCD was binned 2×2 resulting in an image scale of 2.16 arc seconds/pixel. All the images were calibrated with dark and flat frames and *Astrometrica* (Raab, 2018) was used to measure photometry using APASS Johnson V band data from the UCAC4 catalogue. *MPO Canopus* (Warner, 2021), incorporating the Fourier algorithm developed by Harris (Harris et al., 1989) was used for lightcurve analysis.

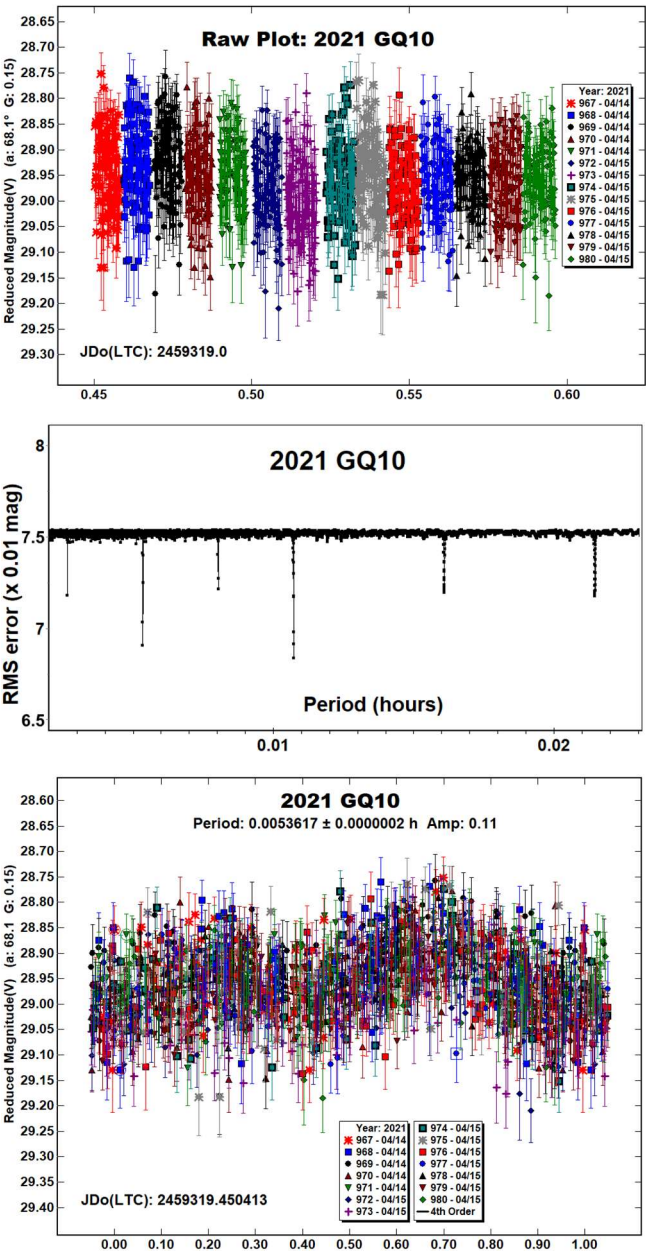
No previous results for 2021 GQ10 or 2021 HN are contained in the LCDB (Warner et al., 2009) and no previously reported results have been found in searches of the Astrophysics Data System (ADS, 2021) or from wider searches.

Number	Name	Integration times		Max intg./ Min Period		a/b	Points	Fields
2021	GQ10	4.6-6.3	0.326	1.03	1384	14		
2021	HN	2.7-3.7	0.236	1.3	1062	13		

Table 1. Ancillary information, listing the integration times used (seconds), the fraction of the period represented by the longest integration time (Pravec et al., 2000), the calculated minimum elongation of the asteroid (Kwiatkowski et al., 2010), the number of data points used in the analysis and the number of times the telescope was repositioned to different fields.

2021 GQ10. Discovered on 2021 Apr 14 with the 1.05-m Schmidt at the Tokyo-Kiso station, 9 hours after a very close approach to within 0.5 Lunar distances (LD) of Earth (Melnikov et al., 2021). It was observed from Great Shefford for a continuous period of 3.5 h starting at 2021 Apr 14.95 UTC, sky motion was high but decelerating, from 83 to 59 arcsec/min by the end. Due to the apparent speed, the telescope was repositioned 14 times and for each new field, the exposure length was adjusted if necessary to ensure the object trailed 3 pixels, for consistency when measuring in *Astrometrica*. This resulted in exposures being increased from an initial 4.6 s to 6.3 s at the end. The average gap between consecutive images was 1.7 s. Analysis of the 1384 measurable images initially

indicated little or no periodic variation over a range of 0.01 – 6 h. A raw plot has indications of small variations between individual Canopus sessions but attempting a solution results in an unsatisfactory period (3.7 h), similar to the span of observations and an amplitude smaller than the underlying noise in the measurements. However, checking for very short periods revealed a set of solutions with $P < 75$ s. As discussed in Birtwhistle (2021b), RMS minima at very small P are very narrow and need investigating with the step size in Canopus set to the highest resolution to determine the best fit. The period spectrum here has a linear x-axis and shows 6 RMS minima between 10 and 77 s, with a monomodal solution at 0.0027 h, bimodal solution at 0.0054 h and quadrimodal at 0.011 h. When investigated individually the bimodal and quadrimodal minima have the strongest signals and match each other to 0.00001 magnitudes. Examining the quadrimodal solution with the Canopus Split Halves function shows the two halves matching to within 0.02 magnitudes and with the overall RMS fit of the solution being 0.07 the two halves are essentially the same and the bimodal solution is taken in preference here.

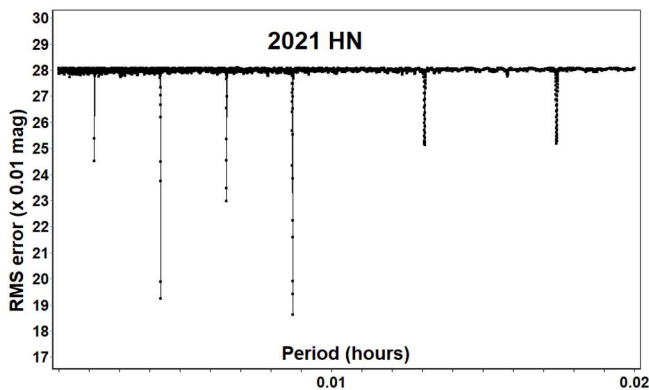


Number	Name	yyyy mm/ dd	Phase	LPAB	BPAB	Period(h)	P.E.	Amp	A.E	H
2021	GQ10	2021 04/14–04/15	69.5, 70.7	213	34	0.0053617	0.0000002	0.11	0.05	26.7
2021	HN	2021 04/18–04/18	52.2, 56.1	203	27	0.0043581	0.0000001	0.74	0.15	26.9

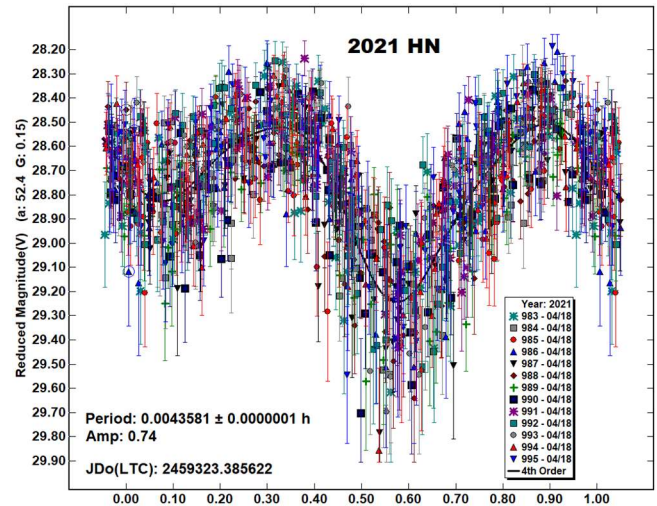
Table II. Observing circumstances and results. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extrema during the period. LPAB and BPAB are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). H is the absolute magnitude at 1 au from Sun and Earth taken from the Small-Body Database Browser (JPL, 2021).

It is possible that exposure length or exposure cadence can cause artificial periodic effects in a short period lightcurve, but due to the exposure length being changed throughout, these effects are likely to be minimised in this analysis. During the observing period, exposure length was increased by 37% and overall cadence (exposure length + gap between consecutive exposures) changed by 21%, with the largest number of exposures using the same settings being 15% of the total. The lightcurve is noisy, with a small amplitude of 0.11 and an ultra-fast rotation period of 19.3 s. This is discussed later due to the likelihood of significant lightcurve smoothing being present. During the 3.5 h of observation the 19.3 s period indicates that 2021 GQ10 completed 657 revolutions. The estimated diameter is ~14 m based on the value of $H = 26.65$ (JPL, 2021) assuming the NEO default albedo value of 0.20 (Warner et al., 2009).

2021 HN. JPL lists this Apollo with $H = 26.9$ (JPL, 2021), suggesting an approximate diameter of 12 m. It was discovered at the Mt. Lemmon station of the Catalina Sky Survey 2 days before passing Earth at 0.66 LD (Bacci et al., 2021) and followed from 2021 Apr 18.89 UTC for 109 min during the last part of its approach, at a range of 1.6 LD. Its sky motion increased from 107 to 147 arcsec/min during that period. As with 2021 GQ10, exposures were automatically adjusted to keep the trailing of the object 3 pixels long, decreasing from 3.7 to 2.7 s during the period of observation. The telescope was repositioned 13 times and exposure lengths were changed 11 times, in 0.1 s decrements. The average gap between images was again 1.7 s. During image capture large variations in magnitude were obvious between consecutive exposures, with the object being visible in all images, though faint at some minima. A period search revealed 6 potential solutions, all at values of $P < 63$ s. Similar to 2021 GQ10, in this linear scaled Period Spectrum, the monomodal solution is on the left at 0.0022 h, with bimodal at 0.0044 h and the apparently strongest signal from the quadrimodal solution at 0.008 h. However, investigating each minima individually with the highest resolution, smallest step size in Canopus shows the bimodal solution actually gives the best fit.



2021 HN has an ultra-fast rotation period of 15.7 s with amplitude of 0.74 and completed 417 rotations while under observation.



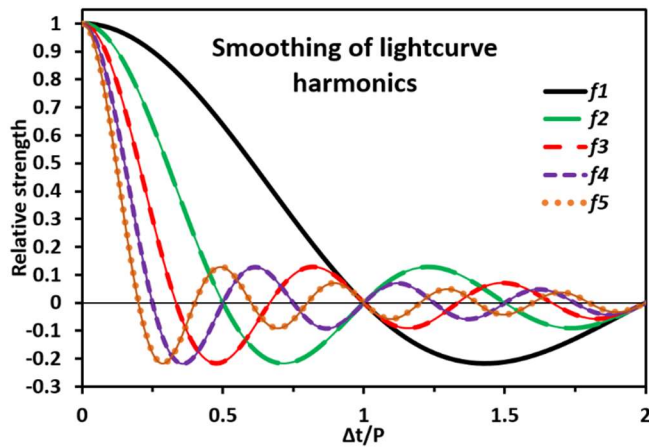
Interpreting lightcurves of ultra-fast rotators.

The optimum exposure time Δt required to detect the second (and normally strongest) harmonic in a lightcurve of period P is developed in Pravec et al. (2000), examining the trade-off between a longer exposure giving better signal to noise ratio but also causing increasing smoothing of the lightcurve as Δt approaches or exceeds $0.5 P$. The optimum integration time for a detection of the second harmonic is determined there to be $0.185 P$. Further, the apparent lightcurve, observed with exposure length Δt is shown to not have the same shape as the real lightcurve, instead, its Fourier coefficients are the Fourier coefficients of the true lightcurve multiplied by factors:

$$f_n = \frac{P}{\pi n \Delta t} \sin\left(\frac{\pi n \Delta t}{P}\right) \quad \text{for } n = 1 \text{ to } m \quad (1)$$

where m is the highest significant order in the Fourier series.

It can be seen that when $f_n = 0$ then the contribution of the n^{th} harmonic to the overall lightcurve will be zero, i.e., that harmonic is completely smoothed out. This occurs when $n \Delta t / P$ is integer, therefore in the intuitively obvious case where $\Delta t = P$ all harmonics are smoothed out and the lightcurve becomes a straight line. The second harmonic is smoothed out when $\Delta t = P/2$, the third when $\Delta t = P/3$ and $2P/3$ and so on. Depending on the (unknown) amplitude of the individual harmonics in the real lightcurve, the observed lightcurve can radically change shape with an unfortunate choice of Δt . To examine this further, Eq. 1 is used to plot values of f_n for the first 5 harmonics, for $\Delta t / P$ in the range of 0 to 2:



As $\Delta t \rightarrow 0$, all the factors, $f_n \rightarrow 1$, the result being an observed lightcurve with no smoothing, matching the real lightcurve of the object, but of course at $\Delta t = 0$, no signal would be recorded. As Δt increases, each factor in turn reduces to 0 when $n\Delta t/P$ is integer and soon afterwards reaches a small negative extreme, before oscillating between positive and negative peaks of decreasing amplitude. In most lightcurves, where the second harmonic is the strongest, selecting exposure time $\Delta t = 0.5 P$ will completely remove the contribution of the 2nd (and also the 4th) harmonic. Doing so will also cause the amplitude due to the 1st harmonic to reduce to 0.64 of its real value and likewise, the 3rd and 5th harmonics reduce to -0.21 and 0.13 of their real values respectively. At any value of non-integer $\Delta t / P$, the individual harmonics will be unequally affected. Depending on the values of the real Fourier coefficients and of Δt , these changing strengths of individual harmonics can result in the observed lightcurve having drastically reduced amplitude, reversal of phase and apparent corruption of shape, for instance, a real bimodal lightcurve may appear monomodal, trimodal or with a higher order shape. The observed lightcurve of any object with a strong 2nd harmonic in its real lightcurve, if observed with a value of Δt approaching or exceeding 0.5 P is likely to be so severely distorted as to make interpretation of the real curve difficult or impossible.

To assess the effect of smoothing on real lightcurves, a set of bimodal lightcurves previously reported (Birtwhistle, 2018, 2021a, 2021c) and listed in Table III were selected to represent a range of harmonic strengths. In all cases, during data collection, $\Delta t \leq 0.10 P$ and therefore smoothing effects can be expected to be minimal in the dominant lower order harmonics (at $\Delta t = 0.10$, $f_1 = 0.98$, $f_2 = 0.94$) and so are referred to here as their “real” lightcurves.

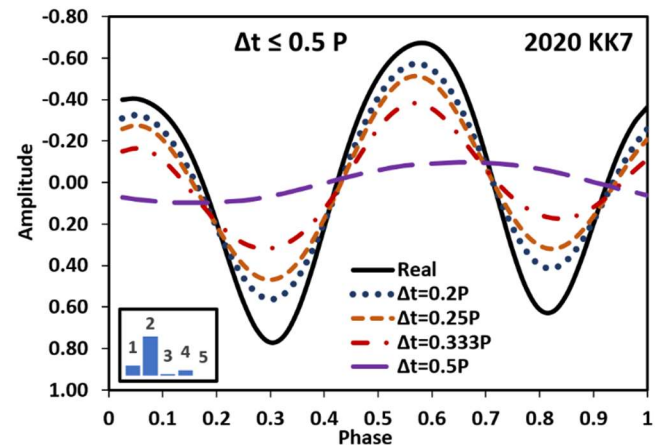
Number	Name	$\Delta t/P$	Obs	P(s)	Ampl.	H	Ref.
2012	XE54	0.039	101.8	0.29	25.4	2018	
2018	CB	0.003	326.6	0.24	25.9	2021a	
2018	GE3	0.004	1113	0.92	23.8	2021a	
2020	KK7	0.082	46.4	1.44	26.2	2021a	
2021	FH	0.101	64.5	0.21	26.7	2021c	

Table III. NEOs used in lightcurve modelling, listing the fraction of the period represented by the longest integration time (Pravec et al., 2000), rotation period in seconds, amplitude in magnitudes, the absolute magnitude at 1 au from Sun and Earth taken from the Small-Body Database Browser (JPL, 2021) and the (Birtwhistle) reference to the original lightcurve.

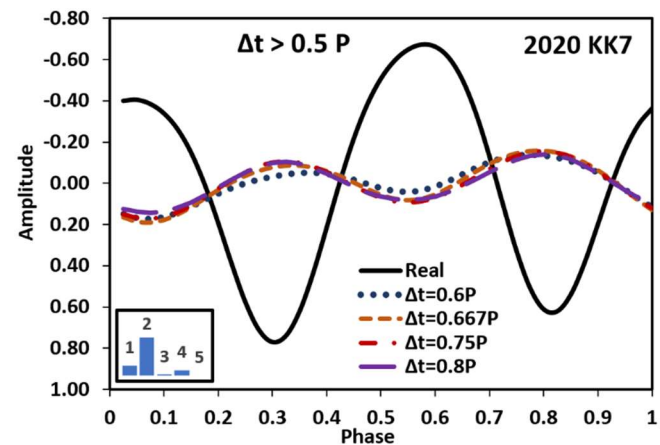
Two figures are given for each object, labelled “ $\Delta t \leq 0.5 P$ ” and “ $\Delta t > 0.5 P$ ”, both include a solid line representing the real lightcurve. Broken lines are given in the first figure for the calculated smoothing effects of $\Delta t = 0.2, 0.25, 0.333$ and $0.5 P$, i.e., matching the 5th, 4th, 3rd and 2nd harmonics respectively and the second figure for the effects of $\Delta t = 0.6, 0.667, 0.75$ and $0.8 P$ matching the 5th, 3rd, 4th and 2nd harmonics respectively. Inset into each plot is a small figure showing the relative strengths of harmonics 1 to 5 in the real lightcurve.

For all objects, the first figure shows that the real curves are only recognisable for $\Delta t \leq 0.333 P$. With increasing Δt the amplitude decreases and in addition, small, higher order detail is smoothed out occasionally (e.g., 2021 FH between $0.75 < P < 1$). Again, for all objects, at $\Delta t = 0.5 P$, where the amplitudes due to the 2nd and 4th harmonics are reduced to zero, significant distortion occurs and the strongest remaining harmonics dominate the lightcurve. In most cases this is the 1st harmonic and result in apparent monomodal lightcurves but occasionally the 3rd harmonic is strong enough to cause visible effects. The diagrams are summarised below:

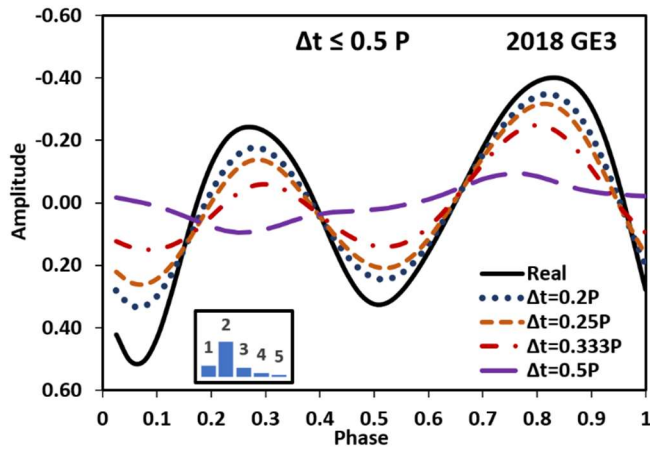
2nd harmonic dominant, 1st harmonic weak. (2020 KK7). A shallow monomodal lightcurve results after removal of the dominant 2nd (and the weaker 4th) harmonic contribution at $\Delta t = 0.5 P$.



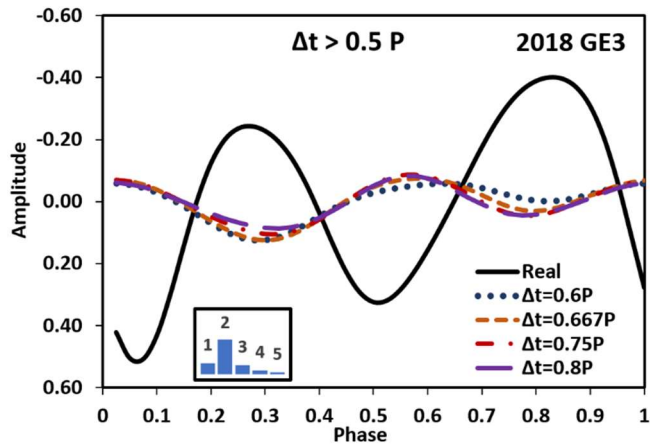
Values of $\Delta t > 0.5 P$ all show low amplitude bimodal variation but with the opposite phase to the real curve:



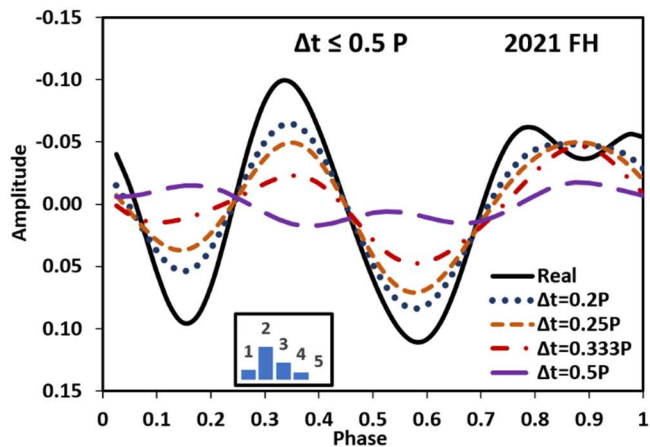
2nd harmonic dominant, 1st harmonic weak, 3rd harmonic rivals 1st. (2018 GE3). At $\Delta t = 0.5 P$, again, a very shallow lightcurve and with the 1st and 3rd harmonics being of almost equal strengths, this shows up as slight irregularities in the otherwise monomodal curve.



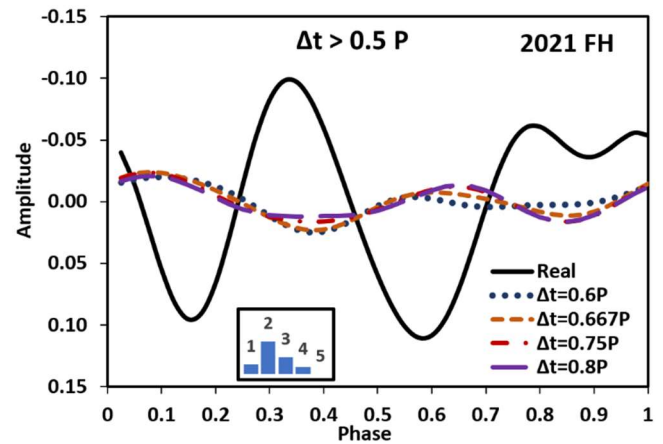
Again, for values of $\Delta t > 0.5 P$, all show low amplitude bimodal variation with the opposite phase to the real curve:



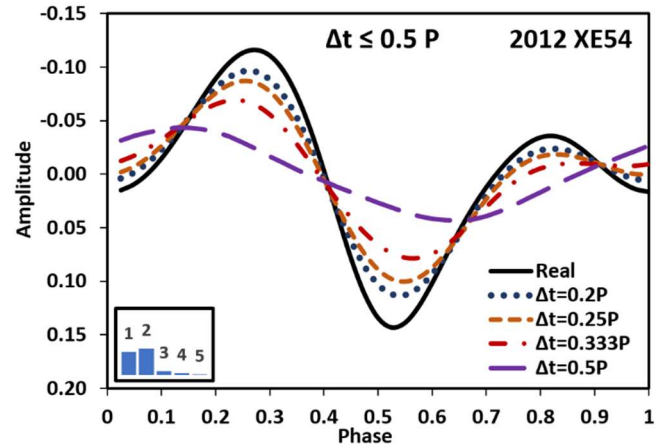
2nd harmonic dominant, 3rd harmonic weak but stronger than 1st. (2021 FH). The 3rd harmonic is revealed as a very low amplitude trimodal lightcurve at $\Delta t = 0.5 P$.



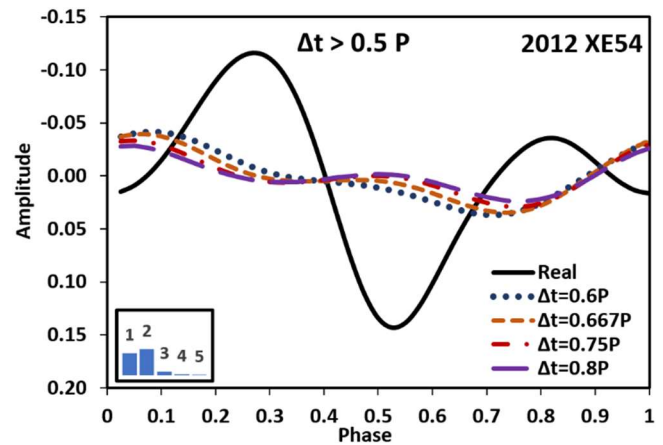
All the curves of $\Delta t > 0.5 P$ are similar, bimodal, with very low amplitudes and again, with the opposite phase to the real lightcurve:



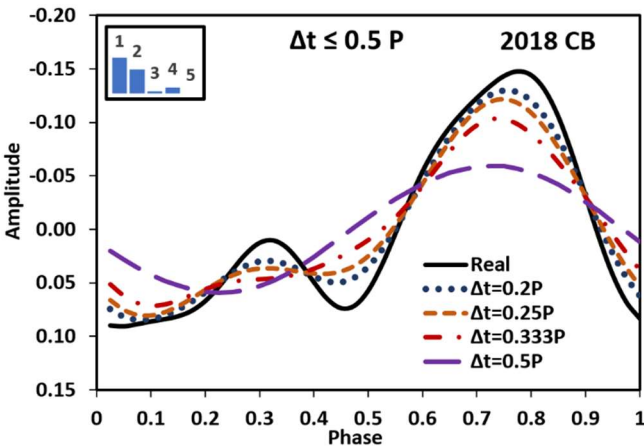
2nd harmonic dominant, 1st harmonic strong. (2012 XE54). A relatively strong 1st harmonic produces a well-defined, and regular monomodal curve at $\Delta t = 0.5 P$ and with moderate amplitude compared to the real lightcurve:



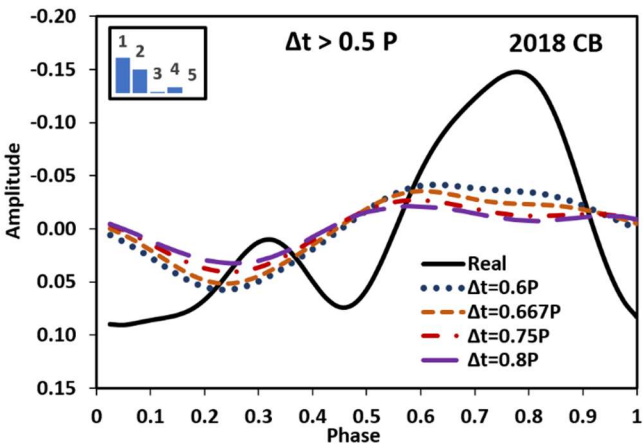
For values of $\Delta t > 0.5 P$, the low amplitude bimodal curves bear little resemblance to the real curve, but again have the opposite phase:



1st harmonic dominant, 2nd harmonic strong. (2018 CB). In this uncommon situation, the result of the 2nd harmonic being suppressed when $\Delta t = 0.5 P$ leaves the dominant 1st harmonic to produce a relatively strong monomodal curve, with the amplitude being ~ 0.5 of the real amplitude. The curve at $\Delta t = 0.333 P$ is smoothed enough to also be interpreted as monomodal:



For all values of $\Delta t > 0.5 P$, all curves appear monomodal with still moderate but successively decreasing amplitudes:



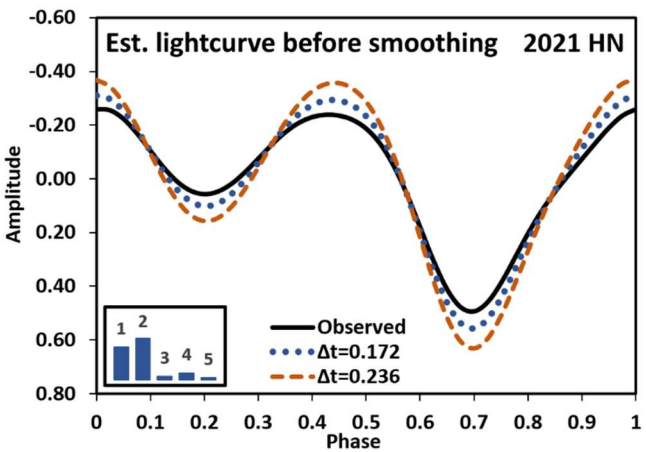
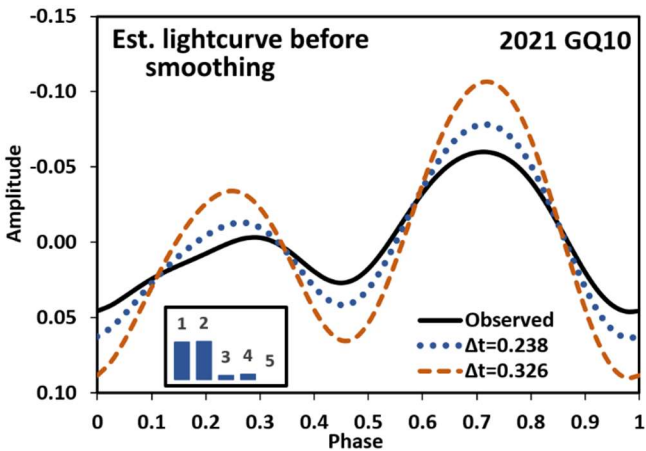
Of course, when imaging a minor planet with unknown period, the observer is initially not able to make the choice of $\Delta t = 0.185 P$, however for all but the fastest rotators, exposures will probably be shorter than this optimum level and smoothing will not be an issue. By chance, 2021 HN was observed with exposure lengths spanning the optimal value for recording the 2nd harmonic, with Δt spanning $0.172 - 0.236 P$ but still, this range will have reduced the strength of the 2nd harmonic by up to $1/3$ and significantly distorted the values of the potentially weaker 3rd, 4th and 5th harmonics, see Table IV.

$\Delta t / P$	f_1	f_2	f_3	f_4	f_5	Relates to
0.172	0.95	0.82	0.62	0.38	0.16	2021 HN
0.236	0.91	0.67	0.36	0.06	-0.14	2021 HN
0.238	0.91	0.67	0.35	0.05	-0.15	2021 GQ10
0.326	0.83	0.43	0.02	-0.20	-0.18	2021 GQ10

Table IV. Factors from Eq. 1 reducing the real amplitude of harmonics 1 - 5 for the exposure lengths used for 2021 GQ10 and 2021 HN.

However, the exposure lengths for 2021 GQ10, with Δt ranging between 0.238 and $0.326 P$, will have had a more dramatic consequence, effectively suppressing most and negating some of the amplitude due to the 3rd, 4th and 5th harmonics and reducing the 2nd harmonic to 0.43 of its real value, significantly more than the reduction to the 1st harmonic, to 0.83 of its real value.

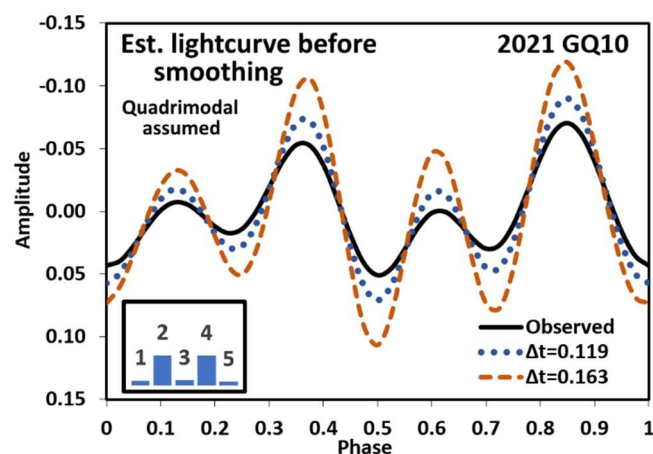
If a factor f_n is close to unity and therefore the contribution from the related harmonic only moderately affected by smoothing, to get a first order approximation of the real lightcurve, the factor can be used to remove its effect from the Fourier coefficients obtained from the observed lightcurve. But as the factor approaches 0 at $\Delta t = P / n$ and beyond, the contribution of that harmonic to the real lightcurve cannot be reconstructed safely, lack of precision in the observed Fourier coefficients being compounded by numerically small values of f_n with a dependency on f_n^{-1} . With the assumption that the contribution from the 3rd and higher harmonics in the real lightcurves of 2021 GQ10 and 2021 HN are relatively minor, only the 1st and 2nd harmonics from the observed lightcurves have been adjusted by f_n^{-1} to reconstruct a first order estimate of what the “real” lightcurves may have been. Figures labelled “Est. lightcurve before smoothing” include a solid line for the lightcurve as derived from observations and broken curves estimating the real lightcurve for the range of Δt used in the observations of that object. As with the other figures, the inset plots of relative harmonic strengths are for the observed lightcurves.



These estimates imply the amplitude for 2021 GQ10 may have ranged between 0.14 and 0.20 in the absence of lightcurve smoothing, rather than the observed 0.11 amplitude. Similarly, for 2021 HN the real amplitude is estimated to be between 0.87 and 1.00, compared to the observed amplitude of 0.74. For both objects, the range of amplitudes due to changing exposure lengths will have contributed to the amount of scatter in the phased lightcurve plots.

The observed lightcurve shape and period determined for 2021 HN is expected to be close to reality, the large observed amplitude and the dominance of the 2nd harmonic both imply only moderate smoothing, as would also be expected from the values of Δt utilised. However, the same is not true for 2021 GQ10, where the observed amplitude is small and the 1st and 2nd harmonics are of approximately equal strength. It is of course possible for the object to be relatively spherical and for it to have been presenting an approximately pole-on aspect to produce the observed lightcurve.

But can the question be answered whether smoothing has modified the real lightcurve to the point where the period and shape are being misinterpreted? Firstly, it is noted that in the set of real lightcurves presented earlier, even in the range $0.5 \leq \Delta t < P$, with significant smoothing and drastically reduced amplitudes, they still reveal periodicity related to the strongest remaining harmonics, so in practice, a real bimodal lightcurve could be interpreted as having a period 2, 1, 2/3 or 1/2 of the real period, assuming the effects of harmonics higher than the 4th will be insignificant. The observed bimodal lightcurve for 2021 GQ10 is distinctly asymmetric, most clearly seen in the “Est. lightcurve before smoothing” figure, suggesting that monomodal and trimodal solutions are unlikely. The period spectrum also indicates a bimodal or quadrimodal solution is preferred. If quadrimodal, then the period would be 38.6 s and the largest $\Delta t / P$ value of $6.3 / 38.6 = 0.163$ would imply there would not be enough lightcurve smoothing in the principal harmonics to radically change the overall lightcurve shape (where $f_1 = 0.96, f_2 = 0.84, f_3 = 0.66, f_4 = 0.45$). However, in forcing the observed data points to a quadrimodal solution, the values of f_2 and f_4 applied to the amplitude of the 2nd and 4th harmonics imply that the 4th harmonic in the real lightcurve would have to be an implausible 1.9 times larger than the 2nd harmonic. The figure labelled “Quadrimodal assumed” shows this solution, together with dashed lines for the estimated lightcurves before smoothing and as with the other figures, the inset plot of relative harmonic strengths is for the observed lightcurve.



With other interpretations improbable, it is concluded that most likely, 2021 GQ10 does have an ultra-fast rotation period of 19.3 s and a bimodal lightcurve of observed amplitude 0.11 that, if observed with shorter exposure times would have been ~ 0.2 magnitudes.

Conclusions and Recommendations.

Both 2021 GQ10 and 2021 HN are very small objects of estimated diameter < 15 m and were making very close approaches to Earth, causing them to be bright enough (16th magnitude) to record with short exposures and also moving fast enough that exposures had to be kept short to stop the objects trailing excessively. This combination was conducive to revealing their very short periods. However, in different circumstances, for slower moving small objects (say $H > \sim 24$, where rotation period could be expected to be anywhere from a few hours to sub-minute) and where longer exposures *could* be used, a visual check of the images in near real-time to look for variation is worthwhile.

- If regular variation is apparent, then making an estimate of the period, to allow for an initial determination of $0.185 P$ will allow exposure length to be optimised accordingly if needed.
- If there is no obvious variation up to some tens of minutes it may be worth sacrificing some S/Nr and shortening exposures to a few seconds to see whether any very short-term magnitude variation can be detected, before reverting to longer exposures if nothing is apparent.
- If significant amplitude variations are seen between consecutive exposures, it is unlikely the true period will be obvious during data collection, especially if exposure cadence is a significant fraction, or longer than the true period. Therefore, acquiring several sets of images with differing but short exposure lengths may allow the true period to be resolved more clearly in later analysis than keeping to a single exposure length for the entire duration of observation.

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SERENDIPITOUS ASTEROIDS

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We present here a byproduct of a large photometric survey of slow rotators led since the year 2013. The observations within the campaign sometimes serendipitously registered additional asteroids moving in the same field with the main target. Here we gather all 24 such asteroids, which had strong enough S/N, and also presented any traceable brightness variations, and we estimate their rotation periods and amplitudes. For best covered lightcurves we also present their plots. For ten asteroids there were apparently no previous period determinations. All the lightcurve data for these serendipitous asteroids are now uploaded to ALCDEF for the use in future spin/shape studies.

Since the year 2013 a worldwide photometric campaign of slowly rotating asteroids has been conducted at AOI AMU, led by coauthor A. Marciniak. The campaign is aimed at reducing the selection effects against slow rotators and low amplitude targets, to complement the set of asteroid spin and shape models for more realistic picture of the main-belt asteroids, and also for determinations of their sizes and thermal properties (see Marciniak et al. 2015 for the campaign description, and, e.g., Marciniak et al. 2019 for the results).

As a byproduct, sometimes additional asteroids are unexpectedly captured in the same field of view with the main target. When their signal-to-noise ratio is high enough for photometry of acceptable quality we measure them as well in an additional circular aperture. Moreover, there are cases when the on-sky movement of the main target is similar to that of the additional asteroid. Then the other can also be captured in more than one night, enabling to complement its lightcurve and to determine rotation period with greater precision.

Such serendipitous asteroids with strong enough signal were not found often in our programme, due to small fields of view and small sizes of most of the telescopes used. Still, over the years we gathered a substantial collection containing 24 targets, that is summarised in Table 1.