Using Low-cost Receivers for Multi-GNSS Time Transfer

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***Abstract*— New global navigation satellite systems (GNSS) such as BeiDou and Galileo are now available and potentially useable for time transfer. Low-cost receivers suitable for time transfer are also now being offered with multi-GNSS capabilities. Preliminary data on the time transfer performance of three low-cost receivers are presented and discussed.**

Keywords*— *GNSS time transfer; GPS; BeiDou; Galileo; GLONASS

I. Introduction

The availability of new global navigation satellite systems (GNSSs) such as BeiDou and Galileo offers the possibility of enhancements to solely GPS-based time transfer [1]. The additional satellite observations available from a multi-GNSS receiver can be used to improve time transfer stability. Validation of the integrity of timing signals in real time, and in post-processing, by inter-comparing the various GNSSs is also a useful new capability. The use of GLONASS in time transfer has been studied for some time [2], and as BeiDou and Galileo have become operational, these too are now being actively investigated [3],[4].

The GNSS receivers typically used in timing laboratories are multi-frequency, multi-GNSS and can use an external clock's 10 MHz and 1 pps signals as a reference for their measurements. These receivers cost upwards of US$10000.

Low-cost (<US$100) timing receivers are in common use in applications such as computer network synchronization. These receivers are distinguished from positioning receivers by their provision of a 1 pps output aligned to a time scale such as UTC and having 'timing modes' where they fix their position and can subsequently operate with only one visible satellite. Some of these receivers can report the raw measurements needed for time transfer based on the CGGTTS and RINEX data formats, and it is this subset of receivers that we focus on here.

Using low-cost receivers for time transfer involves some compromises. Such receivers are typically single frequency only, so ionospheric delay measurements are unavailable; this can be addressed in post-processing, however. Low-cost receivers also have fewer processing resources, so there can be limitations on the numbers and combinations of GNSS that can be simultaneously tracked, limiting the improvements to be had from multi-GNSS operation.

Most critically, the link between the time scale used for measurements reported by the receiver and the laboratory clock must be made via the receiver's output 1 pps and an external time interval counter. The receiver's 1 pps typically has a sawtooth error of tens of nanoseconds in amplitude. This can usually be corrected in post-processing via information reported by the receiver but there is still residual noise at the nanosecond level. This means that it is not possible to make use of the much higher precision carrier phase measurements that are available from some of these receivers, and time transfer is limited to the coarser code measurements. The carrier-phase measurements may still be useable for precise positioning, however, for example in a base-rover configuration.

Although state of the art time transfer performance is not available from the receivers we have tested, there are applications where the compromise is acceptable. For example, we use low-cost systems to provide continuous traceability of time of day for remote domestic users [5]. In these applications, time of day is only accurate to 10 μs at the point of generation, so time transfer accurate to 1 μs is sufficient. However, future applications, such as measurement of a Precise Time Protocol signal, might push this down to 10 ns.

Here, we characterize the multi-GNSS performance of two low-cost receivers that we have been using primarily for GPS time transfer for the past four years, and of a third receiver that has only become available recently. We also present some practical time transfer results.

II. Methods

A. Measurement setup

For the time transfer tests, the receiver under test is connected to a choke-ring antenna shared with the reference receiver, a Septentrio PolaRx4TR PRO multi-GNSS receiver, via a splitter. This arrangement allows the comparison of raw receiver measurements without further corrections, establishing the noise floor for time transfer. The Septentrio receiver clock is synchronized to a Microsemi 5071A cesium clock.

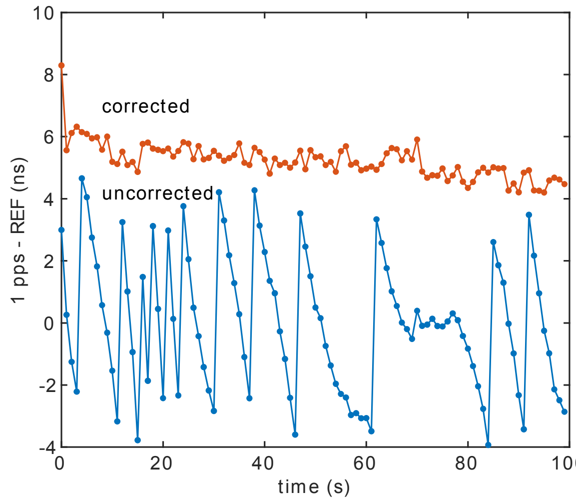

Fig. 1. Uncorrected and sawtooth-corrected 1 pps output of the ZED-F9P, measured against a cesium standard. The corrected data have been offset for clarity.

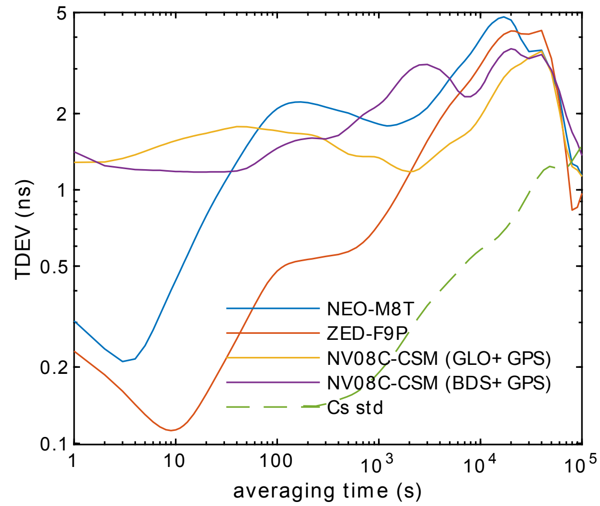

Fig. 2. Time deviation (TDEV) of the sawtooth-corrected 1 pps of the tested receivers, measured against a cesium standard. TDEV of the cesium standard is shown for comparison.

B. Receivers

Three receivers were tested: the NVS Technologies NV08C-CSM, the ublox NEO-M8T and the ublox ZED-F9P, which has only become available very recently. The NV08C-CSM is a 32 channel receiver which tracks GPS, GLONASS and BeiDou. The NV08C-CSM has been used by us for practical GPS time transfer for four years. The NEO-M8T is a 72 channel receiver which can track all four current GNSS, in various combinations, up to a total of three GNSS. The ZED-F9P is a 178 channel receiver which can simultaneously track all GNSS and report dual frequency measurements. For GPS, the L2C signal is tracked, so that dual frequency observations are not possible for all satellites in the current (April 2019) GPS constellation.

C. Configuration of receivers

The internal time-scale in the receivers we report on here is not configurable. GPS is used as the internal time scale by the ublox receivers, at least when GPS is tracked and the output 1 pps is GPS-aligned. The NV08C-CSM appears to use each GNSS's time scale as the reference for the respective pseudorange measurements. This is quite clear with the GLONASS data, which exhibits steps unless the appropriate timescale corrections are made.

Typically, we configure receivers to output a 1 pps that is aligned with the receiver's reference timescale for pseudorange measurements, so that there are no intermediate time scale corrections that might introduce further noise. The NV08C-CSM, however, did not operate well with a GPS-aligned pps. Satisfactory operation was obtained with a UTC-aligned pps, however. The receiver's reported UTC-GPS and GPS-GLONASS offsets were used to make the necessary timescale corrections.

The NV08C-CSM supports tracking of only two GNSS concurrently. We therefore configured it for GPS+GLONASS and GPS+BeiDou for the tests. The NEO-M8T can track up to three GNSS concurrently; we configured it with GPS plus one other GNSS for the tests. Occasional tracking problems were observed if GPS was not also used.

D. Data processing

Pseudorange measurements from the receivers under test were combined with sawtooth-corrected measurements from the time-interval counter to produce RINEX observation files. Receiver-provided corrections were also applied, as well as necessary timescale translations, in the case of the NV08C-CSM. All processing was performed with *mktimetx*, an application available as part of OpenTTP [6,7].

The RINEX observations from each receiver are matched in common-view. An unweighted average of receiver measurements is calculated at each observation time with no filtering. Typically, 5 to 10 satellites are in view, depending on the GNSS. GLONASS data are averaged assuming that any inter-channel biases are negligible. The documentation for the receivers states that GLONASS inter-channel biases have been calibrated.

One complication with the ublox receivers is that the reported pseudoranges exhibit N ms ambiguities. Our processing software currently supports resolving these for GPS via a calculation using the broadcast ephemeris, but not for any other GNSS. For the noise floor measurements, we simply removed the steps, using the initial measurement as a reference point. For practical time transfer, we used the pseudoranges reported by the Septentrio to resolve the ambiguities and produce a corrected RINEX observation file.

III. DISCUSSION

A. Sawtooth correction

The receiver 1 pps exhibits a periodic offset when compared with a more stable reference because the receiver can only set its output with a resolution determined by the period of its clock T. The 1 pps offset then drifts, until the error approaches T, when the 1 pps is stepped, creating a

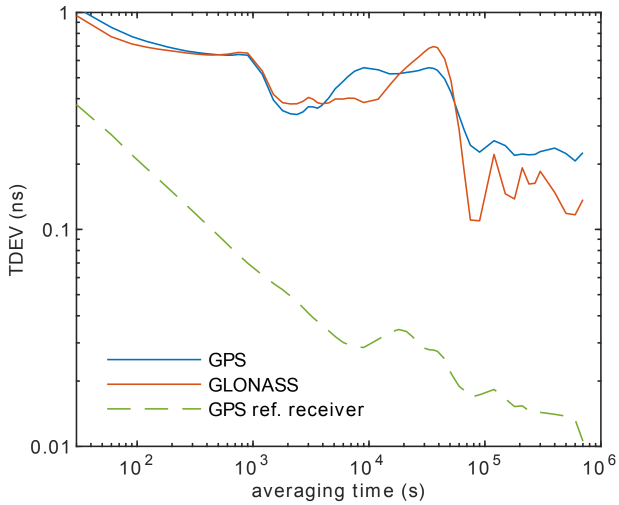

Fig. 3. Time deviation (TDEV) of NV08C-CSM GPS and GLONASS pseudorange differences with respect to the PolaRx4TR PRO. TDEV of the GPS pseudorange differences for a PolaRx4TR PRO and PolaRx2eTR is shown for comparison.

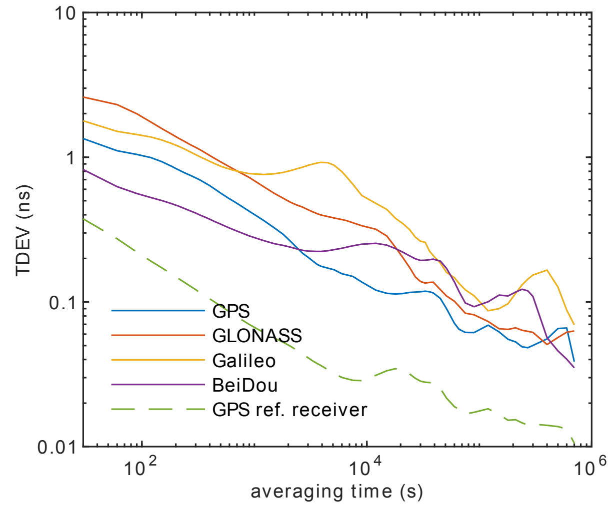

Fig. 4. Time deviation (TDEV) of NEO-M8T pseudorange differences with respect to the PolaRx4TR PRO. TDEV of the GPS pseudorange differences for a PolaRx4TR PRO and PolaRx2eTR is shown for comparison.

characteristic sawtooth (Fig. 1). The period of the sawtooth is typically short by design so that it can be rapidly averaged and ranges from 5 to 10 s. For the NV08C-CSM the sawtooth peak-to-peak amplitude is 38.5 ns. For the NEO-M8T it is about 20 ns while for the ZED-F9P it is about 10 ns.

The receiver has an internal estimate of the error in the output 1 pps which can be accessed, allowing the sawtooth to be corrected in post-processing (Fig. 1). The correction is an imperfect estimate so there is residual noise after it is applied. Fig. 2 shows the time deviation (TDEV) of the tested receivers' sawtooth-corrected pps, compared with a cesium beam standard. The TDEV of the cesium standard, measured with respect to another cesium standard, is shown for reference. The NV08C-CSM has a relatively flat, but higher TDEV out to about 1000 s whereas the NEO-M8T and ZED-F9P have significantly lower TDEV at averaging times τ less than 1000 s. The ZED-F9P is best at short τ. At τ greater than about 20 000 s, the receivers have a similar TDEV.

The higher TDEV of the NV08C-CSM has its origin in periods of operation where the output 1 pps becomes noisier and the sawtooth correction is less effective. These periods of noisy operation last for up to a day. During the periods of less noisy operation, the short term TDEV is similar to that of the ublox receivers. Long (at least 30 days) periods were observed when this behavior was not evident; its cause is not known.

The 1 pps of the NV08C-CSM is aligned with UTC, and some differences are evident in the TDEV observed with the two GNSS combinations tested (Fig. 2). In particular, the BDS+GPS combination shows a distinct bump at around 2000 s that is not evident in the GLONASS+GPS combination.

B. Time transfer noise floor

We characterized receiver time transfer performance by comparing satellite pseudorange measurements with those obtained using the reference receiver (Figs. 3–5). This represents the noise floor for time transfer with the particular reference receiver we used and for our measurement conditions. The results are not expected to be substantially different if another reference receiver was used; similar results were obtained with a Septentrio PolaRx2eTR as the reference receiver, for example.

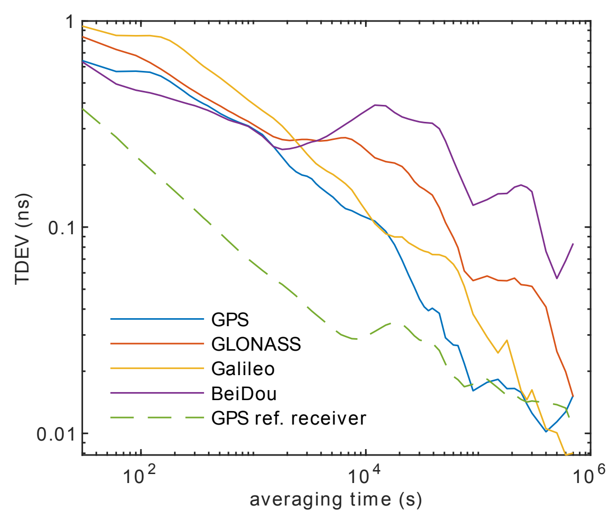

Fig. 5. Time deviation (TDEV) of ZED-F9P pseudorange differences with respect to the PolaRx4TR PRO. TDEV of the GPS pseudorange differences for a PolaRx4TR PRO and PolaRx2eTR is shown for comparison.

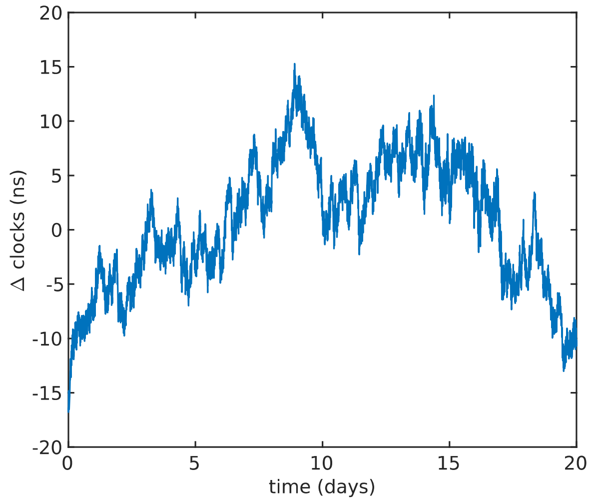

Fig. 6. GPS time transfer between a cesium standard and H-maser on a 1600 km baseline, using the reference receiver. A constant frequency offset has been removed.

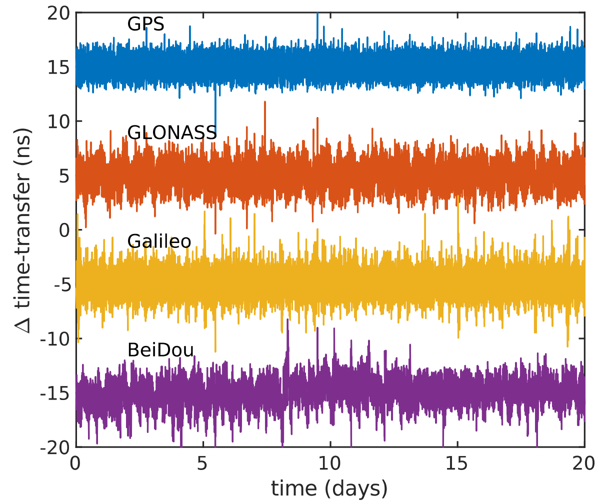

Fig. 7. Time transfer differences between a PolaRx5TR-PolaRx4TR PRO and a PolaRx5TR-ZED-F9P for different GNSS with baseline as in Fig. 6. Data are offset for clarity.

Results obtained for the NV08C-CSM are shown in Fig. 3. GLONASS data were similar to GPS. BeiDou was tested but unsatisfactory results were obtained. Without a timescale correction as described above, the data show a sustained drift of 1 ns/day for the 30 day period examined. Attempts to translate the timescale to BeiDou time did not correct this behavior satisfactorily. The receiver itself does not provide an estimate of BeiDou time with respect to any other GNSS. We therefore attempted to correct the BeiDou data using data published in the BeiDou ephemeris but this was unsuccessful.

The ublox NEO-M8T showed similar performance for all four GNSS (Fig. 4). BeiDou performed best at τ less than 1000 s, but GPS and GLONASS were best at longer averaging times. At one day averaging time, all four GNSS performed similarly.

Overall, the ZED-F9P performed best, with lower TDEV for all GNSS, except for slightly noisier behavior for BeiDou at long averaging times (Fig. 5). GPS time transfer is only two times noisier than for the reference system at short averaging times, and is the same beyond one day.

C. *Practical time transfer*

For a test of practical time transfer, we used data from the IGS station CEDU, which is about 1600 km from our location in Sydney, Australia. CEDU is equipped with a Septentrio PolaRx5TR referenced to an H-maser. We only considered single-frequency, code based (C1C for Galileo, GLONASS and GPS; C2I for BeiDou) time transfer.

RINEX data were processed using r2cggtts [1], and the 30 s sampled output was used. This processing uses the broadcast ephemeris for satellite clocks and orbits and the Klobuchar ionosphere model for the ionosphere correction. Precise surveyed co-ordinates were used for the antennas. Fig. 6 shows the difference of the two clocks with a constant frequency offset removed, obtained via GPS time transfer and with the reference receiver.

As a demonstration of practical time transfer, time transfer data were computed on the links formed to CEDU using the ZED-F9P and reference receivers at the Sydney site. The data for the ZED-F9P were then differenced with respect to the data for the link formed with the Sydney reference receiver (Fig. 7). The TDEV of these differences is shown in Fig. 8. The TDEV of the two clocks using a GPS link and the reference receiver is also shown for comparison. All four GNSS perform similarly at averaging times less than 1000 s, consistent with the behavior observed in Fig. 5. At longer averaging times, GPS and Galileo perform best. BeiDou time transfer noise increases at averaging times longer than 1 day, whereas the other GNSS are still averaging down. At all averaging times considered, TDEV is less than 1 ns i.e. the

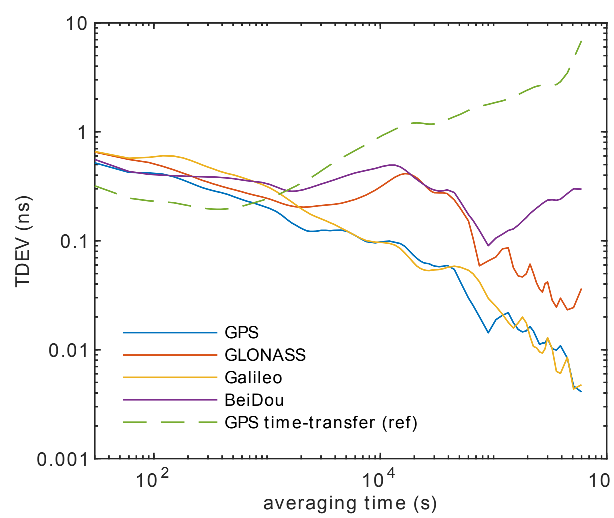

Fig. 8. Time deviation (TDEV) of the time transfer differences shown in Fig. 7. TDEV of the time transfer data shown in Fig. 6 (the dashed line) is also shown for comparison.

excess noise is less than 1 ns. Where code-based time transfer is being used, rather than the more precise carrier-phase time transfer, the performance compromise is acceptable.

IV. CONCLUSIONS

We have characterized three receivers for multi-GNSS time transfer, highlighting some of the challenges that are presented and considerations that are necessary when using them for time transfer.

Of the three receivers the ZED-F9P performed best. Considering its dual frequency capabilities, which facilitate self-survey of an accurate antenna position and the use of measured ionosphere, it is an attractive choice for time transfer. Nonetheless, for applications with moderate accuracy demands, the other two receivers are also suitable. In particular, at the averaging time implicit in CGGTTS-based time transfer (780 s), the excess time transfer noise is below 1 ns for all receivers and GNSS.

Future work will examine the ZED-F9P in more detail, in particular to characterize its capability for P3 code time transfer.

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