5G-NR GNSS independent time and frequency synchronization in NTN scenarios

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In recent years, we observed a growing interest to re-use the terrestrial 5GNR waveform over satellite links. The 5G-NR radio waveform is based on multi-carrier Orthogonal Frequency Division Multiplex (OFDM) modulation while legacy satellite waveforms like DVB-S2X and DVB-RCS are based on Square Root Raised Cosine (SRRC) pulse shaped single carrier transmissions. Next to some clear advantages of OFDM for multi-channel transmissions, there are some drawbacks. A critical disadvantage is the higher sensitive to time and frequency misalignment of the terminal. Terminal misalignment in time or frequency will result in non-orthogonality of the different subcarriers in the OFDM waveform and cause Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI). 5G-NR thus needs tight synchronization.
The 5GNR standardisation body (3GPP) has put forward the use of Global Navigation Satellite Systems(GNSS) and satellite orbit information to pre-compensate the mobility effects. The aim of the present solution is to avoid the GNSS information dependency for reliable communication. This paper will first review the critical synchronization accuracy needs and the Doppler requirements for 5G-NR Non-Terrestrial Networks(NTN). Next, we explore different tracking options highlighting their shortcomings and finally we propose a novel solution based on higher order closed loop tracking.

1. Requirements

1.1. 5G-NR Synchronization needs

Compared to Terrestrial Networks (TN), the tight synchronization requirement of 5GNR OFDM waveforms becomes increasingly difficult to achieve in Non-Terrestrial Network (NTN) scenarios because of two main reasons. First, because the radio frequencies are typically roughly 10 times higher (Ku or Ka-band instead of L or S- band), making it more difficult to guarantee absolute carrier frequency accuracy and stability. Secondly, because the longer link delays do not allow fast corrections of timing alignment errors with the same mechanism as in terrestrial networks.

The 3GPP release 17 baseline for NTN links assumes the time and frequency offsets can be compensated based on the availability of terminal GNSS data and satellite orbit information. The GNSS dependency is new compared to legacy satellite networks. GNSS dependency has some important drawbacks : Availability is not always guaranteed (e.g. in hostile environments), the power consumption is not negligible and the logon time increases. So, in some use cases, there is a need for GNSS independent operation.

Numerology μ	SCS [kHz]	CP [us]
0	15	4.69
1	30	2.34
2	60	1.17
3	120	0.59
4	240	0.29

(a) 5G-NR CP length and SCS in function of μ.

Relative SCS offset [%]	ICI level [dB]
0.5	-41.5
1	-35.5
2	-29.5
5	-21.5
10	-15.5

(b) ICI in function of frequency offset.

Table 1: 5G-NR SCS and CP.

The CP-OFDM waveform used in 5GNR is resilient to time mismatches as long as uncertainties are limited and do not exceed the Cyclic Prefix (CP). Misalignment above the CP will cause ISI. In 5GNR, the CP length depends on the numerology and ranges from 4.7us for numerology 0 to 0.29us for numerology 4 (see table 1a). So lower numerologies are more resilient to time misalignment.

The frequency misalignment is also critical, all sub-carrier misalignment will cause Inter Carrier interference(ICI). Table 1b shows simulation results where the ICI level is measured in function of the frequency offset. A frequency misalignment of 1% of the subcarrier spacing (SCS) will cause an acceptable ICI level of -35dB and should allow operation up to SNR levels of 20dB. Note how on contrary to time offsets for frequency resilience the higher numerologies (corresponding to higher SCS) are more robust.

Assuming a frequency accuracy need of 1% of SCS, a time accuracy of 0.5 CP and taking the worst numerology, the required frequency and time accuracies for limited ICI and ISI are respectively 150Hz and 0.15usec. It is worth noting that the 5G-NR OFDM waveform is more sensitive to misalignment than legacy satellite return channel waveforms like DVB-RCS or MRC[3]. For those legacy satellite waveforms, typical uncertainties of 3kHz and 10us can be accepted.

1.2. Doppler requirements

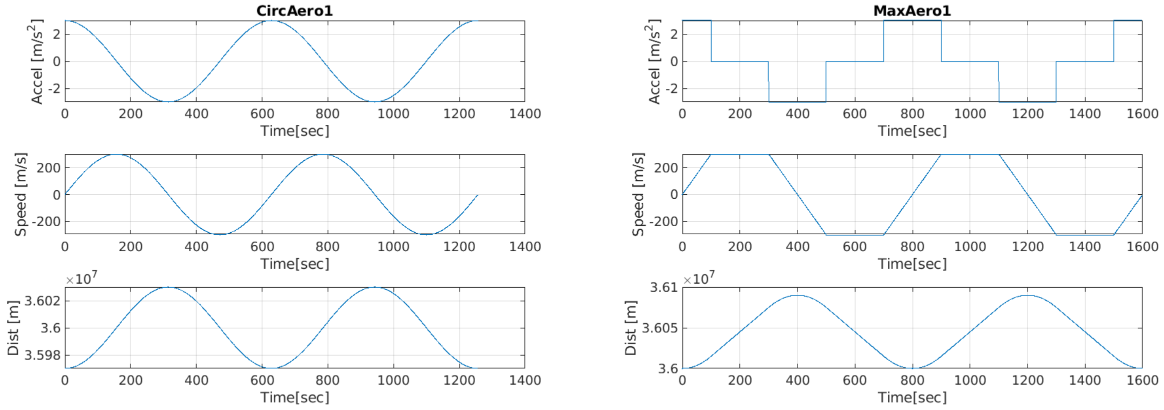
In this section, typical terminal and satellite mobility use cases for GEO (Geostationary orbit) and LEO (Low Earth Orbit) satellites are defined. The use cases cover the scenarios defined in the 3GPP NTN report [1].

The user equipment (UE) mobility profiles are defined and can be combined with LEO or GEO satellite link delays. For satellite movement low and high LEO passes are emulated. The different profiles are shown in figure 1. In those figures, the lower curve shows the link distance in function of time. The middle curve shows the terminal speed (in direction of satellite) and the top curve shows the acceleration (in direction of satellite) in function of time. The terminal mobility is modelled via circular UE movement profiles (Fig. 1a) or constant acceleration UE movement profiles (Fig. 1b). The maximum speeds and accelerations for the different profiles are summarised in table 2. Note how CircAero4 and MaxAero4 are very severe profiles that go beyond the scope of commercial connectivity. The LEO profiles are modelled based on circular orbits around earth with a zenital pass. Two reference cases are simulated a low orbit at 400km altitude and a high orbit LEO profile at 1500km altitude(Fig. 1c and 1d).

Label	a $[m/sec^2]$	v $[m/sec]$	Remark
CircAero1	3	300	Circular movement 0.7 to 1.3 G commercial flight
CircAero2	10	100	Circular movement 0 to 2 G with maritime speed
CircAero3	10	300	Circular movement 0 to 2 G with aero speed
CircAero4	100	2400	Circular movement Extreme 10G and Mach7
MaxAero1	3	300	Abrupt a changes 0.7 to 1.3 G commercial flight
MaxAero2	10	100	Abrupt a changes 0 to 2 G with maritime speed
MaxAero3	10	300	Abrupt a changes 0 to 2 G with Aero speed
MaxAero4	100	2400	Abrupt a changes Extreme 10G and Mach7
LeoLow	130	8000	Low altitude (400km) zenital LEO pass
LeoHigh	27	5500	High altitude(1500km) zenital LEO Pass
ClockDrift1			0.01ppm/sec clock drift
ClockDrift2			0.001ppm/sec clock drift
ClockDrift3			Random walk 0.001ppm/sec, Allan Var 1e-9 at 1sec)
ClockDrift4			Random walk 0.0001ppm/sec, Allan Var 1e-10 at 1sec)
Stable			No drift, nor offsets

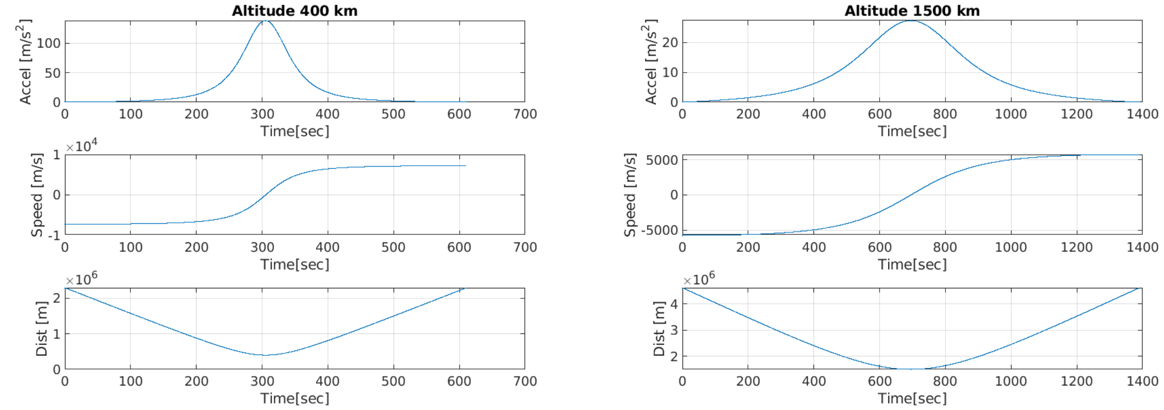
Table 2: Terminal and satellite mobility accelerations and speeds.

Next to Doppler offsets originating from terminal or satellite movements, the UE clock reference can be subject to drift. The clock drift can also be tracked by the frequency tracking loop. To assess the clock tracking performance, clock drift profiles are also included in table 2. The clock drift profile includes fixed



(a) Circular aero mobility profile

(b) Maximum acceleration mobility profile



(c) Low Leo profile

(d) High Leo profile

Figure 1: Doppler profiles

drift profiles (ClockDrift 1 and 2) and random walk profiles (ClockDrift 3 and 4). Finally a Stable system with no drift and only noise on the channel is added to evaluate the loop performance with only AWGN noise and no time or frequency drifts impairments.

The link delay is proportional to the link distance d. The instantaneous link delay can be computed as follows:

$$Delay = d/c * 2$$

where c is the speed of light.

The frequency offsets are proportional to the speed and the RF frequency. For all the simulations below an RF frequency of 30GHz is assumed. Excluding relativistic effects, the offsets can be computed as:

$$F_{Off} = v/c * F_{RF} * 2$$

where c is the speed of light and F_{RF} is the RF carrier center frequency. In this paper an RF frequency of 30GHz is assumed.

The factor two in both equations above accounts for the doubling of the perceived speed and distance changes due to forward and return paths assuming bent pipe satellites. This means two hops delay (UE to Hub and Hub to UE) is assumed between the transmission and the estimator feedback in the loops. The solution also applies for regenerative satellites, the loop delay can then be halved.

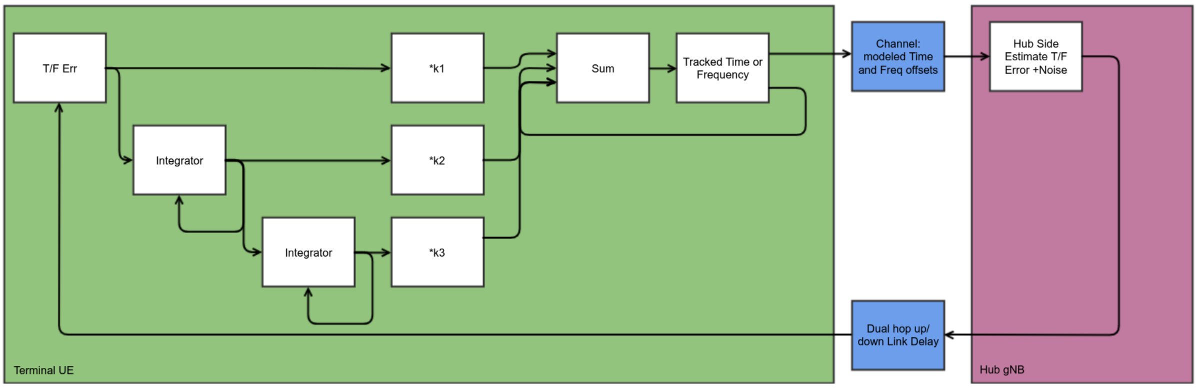


Figure 2: Time or frequency UE tracking loop

2. Tracking Loops

2.1. Hub Loop

As opposed to the navigation data (GNSS) based time and frequency compensation method proposed by 3GPP, the solution proposed in this paper is based on closed loop tracking of the terminal carrier frequency offsets and symbol time offsets. Hub (gNodeB) side estimates are used to compensate the terminal transmission time and transmission carrier center frequency. A closed loop timing correction is not new, i.e., closed loop timing correction is already applied in 5G-NR TN with the Timing Advance (TA) mechanism. However, when moving to NTN, the higher link propagation delay is limiting the speed of the TA corrections and the faster movements require faster corrections. The closed loop frequency correction does not yet exist in current 5G-NR standard. Similarly, the closed loop time and frequency tracking solutions are also applied in legacy DVB-S2X/RCS systems using first order closed loops, but, as see in section 1.1 when using OFDM, the required tracking accuracy is higher making the first order loop correction used in DVB-RCS inadequate.

NTN satellite links require faster corrections because of faster variations of time and frequency errors. Unfortunately, the high link delay will not allow fast loop corrections resulting in large residual errors. To overcome those limitations of first order correction loops, we propose higher order closed loops. More specifically, higher order control loops for time and frequency will correct Doppler carrier frequency errors, Doppler carrier frequency rate errors, symbol time errors and symbol rate errors.

Note that for regenerative satellites, the hub (gNodeB) can be in the satellite and that the proposed approach scales to regenerative satellites as well.

The proposed loop is shown in figure 2. The same loop structure is used for time and frequency error corrections. The left side is the UE implementing the loop logic and keeping the loop states. The right side is the hub, mainly estimating the transmission time errors and frequency errors that will be used to update the loop states. Note that the loop logic is located at the UE side. This allows a per sample update of the frequency and time corrections while keeping the feedback error message rate lower. The only parameter fed back from hub to terminal is the estimated error, all integration operations are computed at UE side. Having the loop logic at hub side and sending back the corrections is possible, but would results in larger absolute correction steps depending on the update period. Or it would require more parameters like the correction, the correction drift and the drift variation.

The loop is characterised by three parameters k_1, k_2 and k_3. The relation between k_n parameters and loop parameters like time constant Tc and damping factor ζ are given in table 3. The loop performance for step and ramp responses is also given table. The carrier frequency offset is proportional to speed, so a constant speed will result is a fixed frequency offset, while the delay is proportional to distance, so a constant speed will result in a ramp response. For a constant speed, a zero delay steady state error cannot be achieved via a first order loop, it can be achieved via a second order loop or higher.

Loop order	Parameters	Expected performance	Derived k_1, k_2, k_3
First order	Tc	Will zero step response	$k_1 = 1/Tc$ $k_2 = k3 = 0$
Second order	Tc , ζ	Will zero ramp response	$\omega_n = 1/(\zeta * tc)$ $k_1 = \zeta * \omega_n$ $k_2 = \omega_n^2$ $k_3 = 0$
Third order	Tc , ζ , $k3factor$	Will zero second order variation	$\omega_n = 1/(\zeta * tc)$ $k_1 = \zeta * \omega_n$ $k_2 = \omega_n^2$ $k_3 = 1/tc^3/k3factor$

Table 3: Tracking loop parameters and performances.

The implementation of higher loop order will only change the UE side algorithms and require no changes in waveform. Only limited signalling improvements are required allowing a MAC CE message to send both the time and frequency errors back to the terminal. The MAC CE message for TA correction already exists and can be reused.

2.2. Local Loop

Another solution for GNSS independent time and carrier frequency offset tracking is terminal slaving to the forward link carrier. In this solution, all terminals will slave their clock to the terminal downlink and adapt their uplink frequency accordingly. At first sight, this is a very appealing solution as no feedback message from hub to UE are required, limiting the signalling overhead.

Unfortunately, the downlink frequency offset measurements do not allow to differentiate frequency offsets originating from Doppler effects and offsets originating from local reference clock offsets. Both effects require an opposite correction as explained in [4]. Wrong allocation of the frequency error source will result in doubling the error instead of compensating the error. The same paper proposes some solutions for independent estimations of the local reference clock offsets and the Doppler offsets. However, the solution requires very wideband downlinks, while achieving poor estimation accuracy. As a result, the forward synchronization solution only works for fixed terminals (no mobility offsets) or terminals with a very accurate reference clock requiring no clock offset tracking. For local loop tracking of the Doppler frequency offset and an RF frequency of 30GHz, the local clock accuracy should be 150Hz/30GHz = 5ppb which seems very unreasonable.

The local loop has another notable advantage, namely it does not require periodic time or frequency error control messages from the hub to the UE, limiting the control messages overhead cost. This also means it can be implemented without the need for new MAC layer messages in 3GPP standard.

The local loop can be extended to delay tracking, but will only cope with differential delay errors. The UE has no absolute time reference to measure the absolute time misalignment. The absolute correction has to come from the Hub via the existing timing advance mechanism.

3. Time and Frequency Error estimators

For both time and frequency errors, the error estimator quality is important for the tracking loop performance. Realistic estimators inaccuracies are taken into account in the loop simulations. The time error estimation is based in the DMRS symbols of the received waveform in HUB. As the DMRS overhead is more or less constant with the allocation bandwidth (number of resource blocks (RB)), the quality of the estimator is improving with higher bandwidth allocations. To avoid poor time error estimators in low bandwidth allocations, the DMRS density will be increased for lower bandwidth. Nevertheless, for low allocation bandwidth in combination with low SNR the timing loop performance can be limited by the estimator quality.

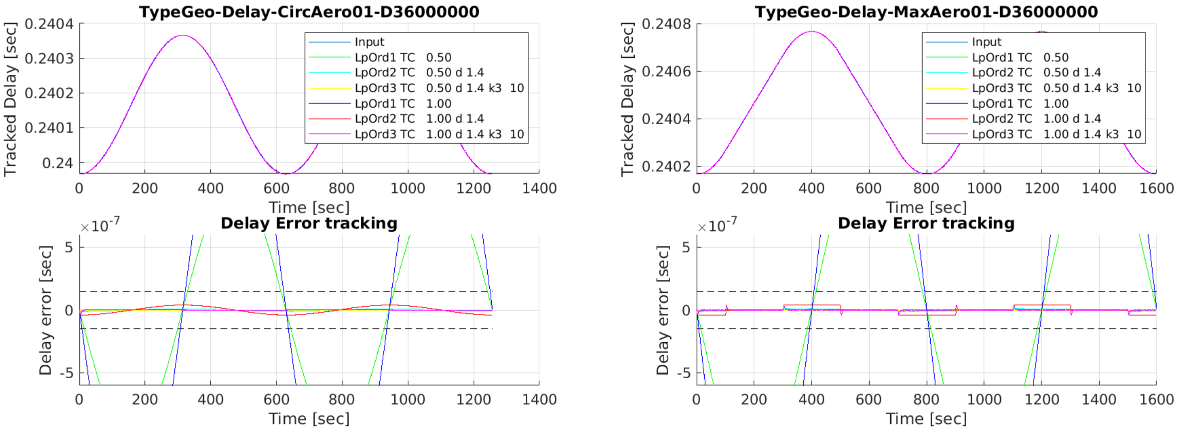
The loop update period was assumed to be one update per 5G-NR frame of 10ms. This requires and overhead message for each UE every 10ms.

The frequency error estimator is based on two consecutive DMRS phase measurements spaced by one frame of 10ms. The quality of the frequency estimate changes with SNR.

4. Simulation Results

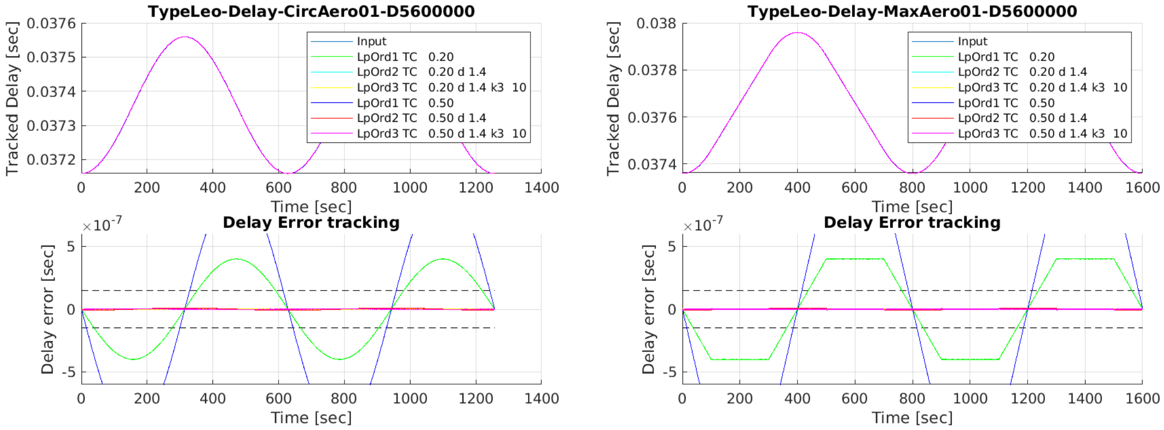
4.1. Delay tracking results

Figure 3 shows some delay tracking results for GEO and LEO terminal mobility. The figures show transient delay changes due to mobility profile for circular and constant acceleration profiles for different loop orders. The top figure shows the changing delay and the tracked delay, the bottom figures show the differences between both corresponding to the tracking error. The dotted black line is the maximum allowed time misalignment for optimal performance, here 0.15us. Figures 4a and 4b show the Geo profiles with loop time constants of 0.5 and 1 second. Faster loops are not possible due to link delay. Figures 3c and 3d show similar results for LEO profiles. The time constants are 0.2 and 0.5 seconds. These can be smaller because of the smaller loop delay, resulting in better tracking performance. One can see that LEO allows faster loops and as a consequence better tracking of the mobility profiles delay changes.



(a) GEO Circular UE movements

(b) GEO maximum acceleration UE movements



(c) LEO Circular UE movements

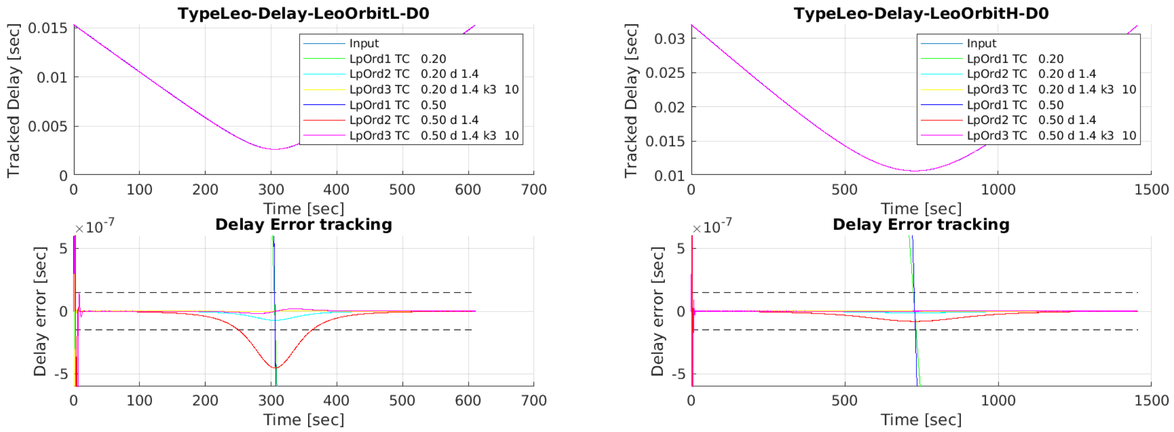
(d) LEO maximum acceleration UE movements

Figure 3: Delay transients

Next the LEO satellite mobility case is shown in figure 4. The low orbit is much more critical than the high orbit because of the higher associated accelerations. Still thanks to the lower loop delay (compared to GEO), the third order tracking can give good performances in both cases.

For none of the use cases, a first order loop meets the target requirements. The second and third order loops are better. The third order loop will zero the steady state error for constant acceleration segment, while the second order loop will have a steady state error, so the third order loop is preferred.

Also note how UE mobility tracking in GEO conditions is more critical than LEO satellite mobility with a third order loop.



(a) GEO Circular UE movemements

(b) GEO maximum acceleration UE movements

Figure 4: Delay transients

Table 4 shows the RMS and peak errors for all the tested profiles with optimal delay tracking loop parameters. For GEO profiles, the loop filter parameters are : $Tc = 1sec$, $\zeta = 1.4$ and $k3factor = 10$. For LEO profiles, the same filter is used with $Tc = 0.2sec$. In LEO conditions the performance is limited by the error detector performance explaining the same figures for all mobility profiles in the table, while for GEO, the performance is limited by the loop speed.

One can see that the 0.15us peak error target is achieved for all profiles except the CircAero4 and the MaxAero4. But even here a 1.2us peak error could be acceptable for numerology 0 or if only occurring in rare events.

4.2. Frequency tracking results

Similarly to the time results, figure 5 shows frequency tracking results. In this case the black dotted lines show the frequency tracking success criteria of 150Hz. Again LEO tracking (5c and 5d) is less critical than GEO (5a and 5b) because faster loops are allowed. Similarly a first order loop will not meet the requirement and the lower time constants give the best results. The frequency transients for the abrupt changes in acceleration create high error peaks transients that cannot be tracked.

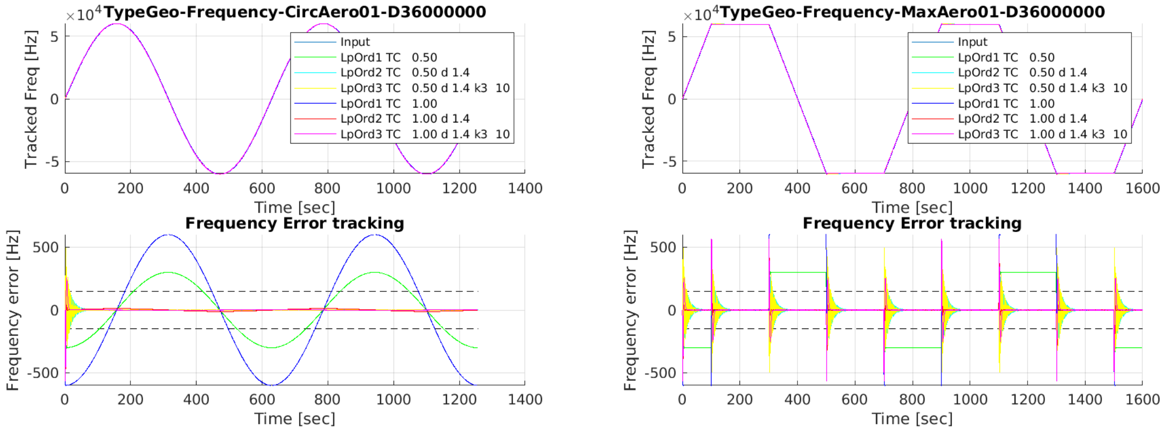
Note how the delay is proportional to the distance while the frequency is proportional to the speed. The constant acceleration causes a ramp response for frequency offset that can be zeroed with second order loop. While for the delay (4b) a third order loop was required to zero the constant acceleration step.

Leo tracking performance is shown in figure 6 for low and high pass profiles.

Table 5 shows frequency tracking results for several Doppler profiles. All profiles are configured with third order loop with $\zeta = 1.4$ and $K3factor = 10$. For the GEO profiles the optimal Tc is 1 sec, for the LEO profiles the loop Tc is set to 0.2sec and for the local tracking there is no delay in the loop and the

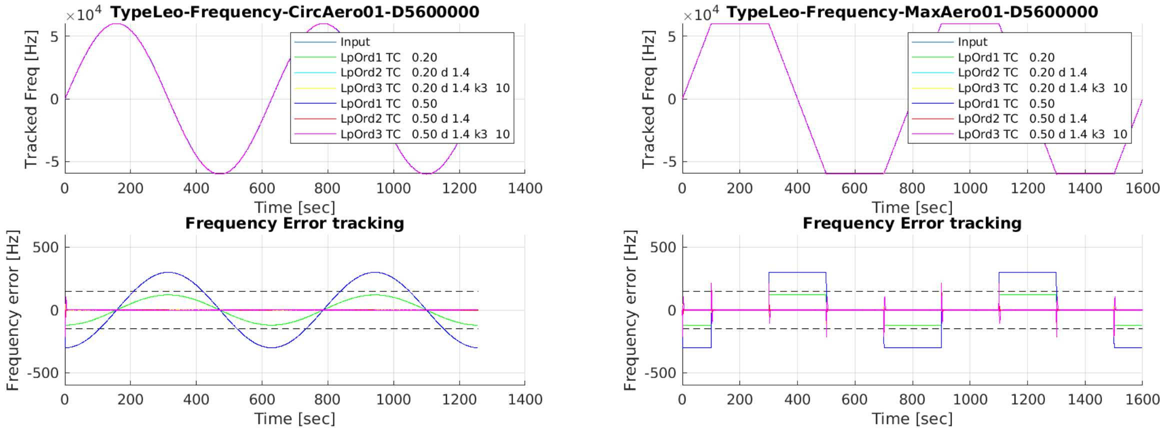
Profile		RMS Error [usec]			Peak Error [usec]		
		-10dB	0dB	10dB	-10dB	0dB	10dB
Geo	CircAero01	0.003	0.002	0.001	0.009	0.006	0.003
	CircAero02	0.046	0.046	0.046	0.068	0.066	0.065
	CircAero03	0.016	0.016	0.016	0.029	0.026	0.023
	CircAero04	0.195	0.196	0.196	0.279	0.279	0.277
	MaxAero01	0.006	0.005	0.005	0.042	0.039	0.039
	MaxAero02	0.054	0.054	0.054	0.128	0.130	0.128
	MaxAero03	0.031	0.031	0.031	0.131	0.129	0.128
	MaxAero04	0.351	0.351	0.350	1.276	1.276	1.275
Leo	CircAero01	0.004	0.003	0.001	0.019	0.010	0.004
	CircAero02	0.004	0.003	0.001	0.014	0.008	0.003
	CircAero03	0.004	0.003	0.001	0.017	0.010	0.004
	CircAero04	0.004	0.003	0.002	0.015	0.010	0.005
	MaxAero01	0.004	0.003	0.001	0.018	0.012	0.004
	MaxAero02	0.004	0.003	0.001	0.016	0.011	0.006
	MaxAero03	0.004	0.003	0.001	0.017	0.012	0.006
	MaxAero04	0.007	0.007	0.006	0.058	0.054	0.051
	LeoOrbitL	0.004	0.002	0.001	0.014	0.009	0.004
	LeoOrbitH	0.004	0.002	0.001	0.018	0.010	0.004

Table 4: Delay tracking errors with optimal loop and NRB 20 for SNR level -10,0 and 10dB.



(a) GEO Circular UE movements

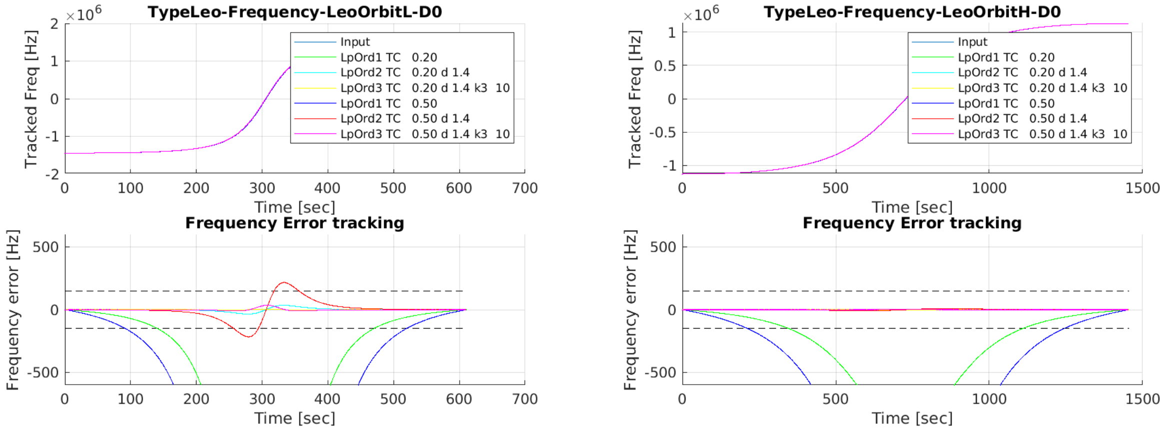
(b) GEO maximum acceleration UE movements



(c) LEO Circular UE movements

(d) LEO maximum acceleration UE movements

Figure 5: Frequency tracking



(a) Frequency tracking for low Leo profile

(b) Frequency tracking for high Leo profile

Figure 6: Frequency tracking transients

loop time constant can be 0.05sec. Note that those optimal setting were simulated but are logical. The faster the loop the better the tracking. However, the Tc cannot be shorter than the loop delay as this will result in an unstable oscillating loop.

One can observe that the performance is independent of the SNR for both the GEO and LEO cases. This is an indication that the performance is limited by the loop delay and not by the estimator quality. Only for the local loop the estimator accuracy can be limiting.

Assuming a maximum allowed peak error of 150Hz one can see that in GEO case only the CircAero1 and 3 profiles comply and that only the more stringent clock drift profile comply. For LEO profiles, the situation is better where most tested profiles comply.

5. 3GPP Standard changes

The proposed approach of higher order time and frequency tracking requires only minor changes to the 3GPP standard. The standard already foresees MAC CE timing advance correction messages, while a frequency correction is missing. The signalling should be extended to allow time and frequency errors signalling to the UE.

The solution in this paper allows GNSS free tracking once a terminal is logged in and is more or less aligned to the network. The 5GNR logon wavefrom(PRACH) only allows limited time and frequency uncertainties. NTN logon without GNSS information and resulting high time and frequency uncertainties will also require some changes to the RACH waveform. That problem requires a dedicated study but note that problem was solved for legacy satellite waveforms via for example [2].

6. Conclusion

GNSS independent time and frequency tracking is critical, but possible for typical UE mobility scenarios with the proposed higher order tracking loops. Closed loop time tracking is possible for all mobility cases in GEO and LEO delay conditions. Carrier center frequency tracking is more critical. The terminal mobility scenario with abrupt acceleration changes combined with GEO delay is more challenging than the LEO satellite movements tracking, despite the higher speeds and accelerations of the satellite.

Frequency tracking performance can be improved via local loop tracking. Unfortunately, the local loop will not correct the clock offsets or clock drifts and will require an accurate local reference clock.

Profile		RMS error [Hz]			Peak Error [Hz]		
		-10dB	0dB	10dB	-10dB	0dB	10dB
Geo	CircAero01	0.528	0.464	0.427	1.458	1.124	0.792
	CircAero02	137.340	137.350	137.360	194.700	194.510	194.250
	CircAero03	15.701	15.676	15.677	22.707	22.611	22.261
	CircAero04	244.420	244.410	244.400	345.980	345.840	345.680
	MaxAero01	59.037	59.033	59.024	562.580	562.870	562.540
	MaxAero02	622.120	622.120	622.130	1875.600	1875.900	1875.700
	MaxAero03	359.220	359.200	359.200	1875.400	1875.100	1874.900
	MaxAero04	4016.000	4015.900	4015.900	18750.000	18749.000	18749.000
	ClkDrift01	166.790	166.830	166.810	1124.400	1124.600	1124.200
	ClkDrift02	16.640	16.713	16.688	112.130	112.760	112.460
	ClkDrift03	69.853	71.446	71.436	312.850	252.250	251.920
	ClkDrift04	7.227	7.042	7.052	26.510	28.495	28.362
	Stable	0.294	0.193	0.062	1.046	0.720	0.236
Leo	CircAero01	0.620	0.395	0.124	2.450	1.581	0.516
	CircAero02	1.346	1.200	1.141	3.215	2.473	1.937
	CircAero03	0.622	0.426	0.175	2.453	1.534	0.563
	CircAero04	2.070	1.998	1.967	5.050	3.928	3.083
	MaxAero01	5.015	4.989	4.982	104.600	104.710	104.580
	MaxAero02	52.466	52.543	52.495	348.850	348.850	348.340
	MaxAero03	30.307	30.314	30.303	348.880	348.930	348.390
	MaxAero04	338.820	338.810	338.810	3483.500	3483.400	3482.700
	LeoOrbitL	0.745	0.617	0.522	4.221	3.109	2.501
	LeoOrbitH	0.601	0.380	0.121	2.326	1.520	0.445
	ClkDrift01	14.085	14.078	14.077	208.390	208.870	208.960
	ClkDrift02	1.541	1.456	1.416	21.106	21.367	20.947
	ClkDrift03	30.075	29.321	29.323	130.500	125.790	125.740
	ClkDrift04	3.079	2.968	2.929	11.134	12.128	12.452
	Stable	0.634	0.389	0.128	2.743	1.912	0.540
Loc	CircAero01	1.163	0.723	0.229	4.949	3.170	0.926
	CircAero02	1.145	0.714	0.231	4.678	3.007	0.885
	CircAero03	1.149	0.732	0.229	5.345	2.757	0.873
	CircAero04	1.133	0.704	0.228	4.516	2.873	0.892
	MaxAero01	1.284	0.920	0.600	22.768	23.517	22.827
	MaxAero02	5.962	5.937	5.880	76.782	76.843	75.710
	MaxAero03	3.584	3.455	3.395	75.702	76.097	75.432
	MaxAero04	37.957	37.930	37.913	755.760	755.720	754.380
	LeoOrbitL	0.670	0.601	0.521	3.360	2.915	2.475
	LeoOrbitH	0.474	0.301	0.096	1.861	1.206	0.346
	Stable	0.993	0.634	0.199	4.280	2.865	0.849

Table 5: Frequency tracking errors with optimal loop and NRB 20 for SNR level -10,0 and 10dB.

References

[1] ’3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks(NTN) (Release16)’.

[2] Daniel Delaruelle. ’Robust Logon Waveform Deployed in Large Mobile Satellite Access Networks’. *Ka Conference*, (2019).

[3] Philippe Delbeke et al. ’Multi Resoltion Coding(MRC) Satellite waveform’. *Ka Conference*, (2021).

[4] Zhipeng Lin Xingqin Lin. ’Doppler Shift Estimation in 5G New Radio Non-Terrestrial Networks’. (2021).