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USING LOCATA TO AUGMENT GNSS IN A KINEMATIC URBAN ENVIRONMENT

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ABSTRACT: GNSS has become one of the most widespread measurement technologies, widely used in GIS, mobile mapping applications and civil engineering. Utilisation of differential techniques offers cm-level positioning accuracy. Identified drawbacks are the requirement for line of sight to the satellites and accuracy dependent on the geometric distribution of the satellites. Especially the latter is paramount for any surveying or mobile mapping application in the urban environment. The utilisation of additional constellations (GLONASS, GALILEO or COMPASS) only partly mitigates the problem.
Locata is an Australian terrestrial positioning technology, based on the pseudolite concept. It's unique in its utilisation of the 2.4GHz ISM band and proprietary TimeLoc procedure, allowing for network synchronisation at the nanosecond level.

This paper focuses on the tight integration of GNSS with Locata, in order to address the described drawbacks and to provide cm level positioning in areas currently "difficult" for GNSS – such as urban canyons. This paper describes the intended deployment and utilisation of the integrated system in the typical urban environment where availability of GPS can be limited or even non-existent, depending on the time and location.
The verification of the integration methods has been carried out using simulated GPS and Locata data. Also presented is an application simulation in a typical urban canyon environment (Canary Wharf, London, UK) using proprietary software developed at the University of Nottingham. Simulation of the proposed integration algorithms, using a real life scenario, has shown promising results with centimetre-level positioning accuracy on the moving platform. The algorithm provides code ambiguity estimation for both Locata and GPS on-the-fly, without prior knowledge of the position, providing predominantly 3D position on the cm level.

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) such as GPS are widely used for high accuracy (< 10 cm) surveying and mapping applications. This is mostly due to the systems high accuracy and ease of use. However the GNSS position solution is highly dependent on the availability and geometric distribution of the satellites. GNSS requires the line of site to at least 5 satellites to calculate a position in real time and using On The Fly (OTF) RTK or Network RTK techniques. With large percentage of mapping applications conducted in urban environments, obstructions such as manmade structures, overpasses, tall buildings and vegetation, limit the utilisation of the system. Research at the University of Nottingham (Roberts et al. 2006) has shown the effects caused by the 'hole' in the coverage of the GPS constellation roughly between 315° and 45° in the UK. Although the utilisation of additional constellations (GLONASS, GALILEO and COMPASS) in the future will go some way to improving the situation it will not overcome all of these problems and the lack of open sky will still lead to poor geometry (Hancock, Roberts & Taha 2006).

The proposed solution to this problem is the utilisation of a complimentary ground positioning system, as an augmentation to the GNSS satellite constellation. Locata is a terrestrial positioning technology, with position obtained using both code and carrier phase calculations, similar to GNSS. The system offers coverage of up to 10km - ideally suited for large engineering works, such as current use in open cast mining (Barnes et al. 2007). Previous work at the University of Nottingham has shown Locata's potential for the centimetre level mapping accuracies in urban environments (Montillet 2008).

This paper focuses on the utilisation of this ground based navigation system to augment and support GNSS and describes the intended deployment and utilisation of tight integration of GNSS and Locata systems, in the typical urban environment where availability of the GPS signal can be limited or even non-existent. This augmentation approach is intended to reduce the need for a clear view of the sky, improve geometry, offer additional integrity control combined with rapid deployment of the system on the dynamic platform including ambiguity resolution of both systems, on the fly. The research goal is to maintain cm level accuracy in "problematic" areas.

The verification of integration methods has been carried out using simulated GPS and Locata data. Also presented is an application simulation in typical urban canyon environment (Canary Wharf, London, UK) using proprietary software developed at the University of Nottingham.

2. LOCATA

The concept and utilisation of pseudolite terrestrial positioning technology has been in development since the early days of GPS. Utilisation includes GNSS augmentation during approach and landing (Lee et al. 2008), sea port approach (Dietz et al. 2007) and implemented in the GALILEO project (Schlotzer, Martin & Voithenberg 2007; Gottifredi et al. 2008). Due to licensing issues surrounding the use of the GNSS signal on L1 GPS frequency, the University of Nottingham decided to focus on non-L1 system. Locata system was chosen, transmitting GNSS-like signals on the license free 2.4GHz ISM band.

Locata is a terrestrial positioning technology, developed by the Australian Locata Corporation, significantly differing from the standard pseudolite concept by introducing:

- Dual frequency signal (S1&S6) within the 2.4 GHz license free ISM Band, preventing GNSS receivers front-end saturation (Parkinson et al. 1996).
- Digital signal and Direct Sequence Code Division Multiple Access (DS-CDMA) (Parkinson et al. 1996) to combat near-far effect, noise and interference.
- Two spatially separated transmitting antennas (Fig. **7**).
- Clustering of signals (2x2) to detect and mitigate noise and multipath (Fig. **7**).

- TimeLoc procedure to precisely synchronise the network (LocataNet) (Montillet et al. 2009).

A network of Locata transceivers ('LocataNet') has one master device with others acting as a slaves. To maintain a constant timeframe slave units synchronise with the master, transmitting network time, in TimeLoc procedure. A slave can also synchronise with another slave (cascade synchronization) if master is not visible.

Each Locatalite setup consists of two transmitting (Tx1 and Tx2) and one receiving (Rx) antennas (Fig. **7**). Spatial separation of transmitters is intended as multipath mitigation.

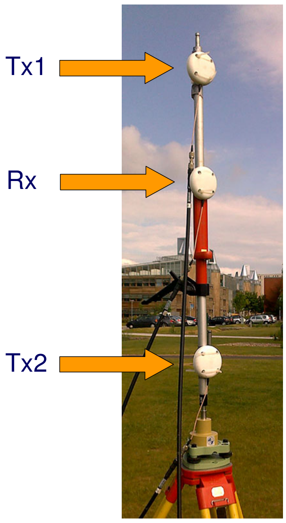

Fig. 7 Locatalite (transmitters Tx1 and Tx2 and receiver Rx)

To utilise TimeLoc, Tx1 and Rx coupling is required to transmit and receive signal, therefore a spatial separation between unit's antennas and clear view to the master is paramount.

The system positions in a GNSS-like fashion, by providing position and receiver clock estimates. Successful 3D trilateration requires visibility to at least four Locatalites. As its transceivers are often nearly coplanar, due to environmental restrictions, accuracy of vertical coordinates can be limited. As with any terrestrial positioning system, Locata is highly susceptible to fading multipath effects.

2.1 Application of the system

Prior research (Montillet et al. 2009) has shown the capacity of Locata to position to centimetre accuracy using carrier phase solutions, providing positional solution in the areas "difficult" for GNSS.

This is currently utilised in the open cast mining environment of the Venetia diamond mine in South Africa (1.2 x 0.8 km and 0.25 km deep) with Locata and GPS systems utilized for

machine control (Barnes et al. 2007). Locata ambiguity is solved using a known point (GPS position+QC feed), as presented on Fig. **7**. System predominantly uses
If at any point, the accuracy of the GPS system falls below a set threshold (usually due to poor visibility of the sky, away from central area of the pit) Locata will provide a position, predominantly as a 2D solution, due to coplanarity restriction of the transmitters.

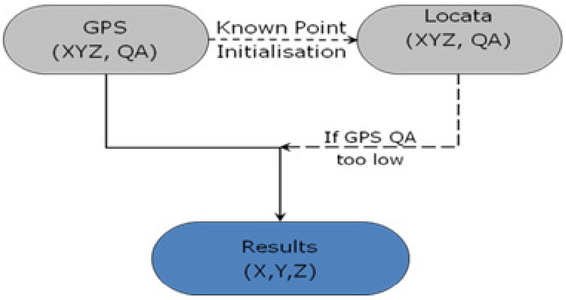

Fig. 8 Current integration as utilised by Locata Corp

This approach can be utilised in any environment with limited sky visibility, such as urban canyon. Weaknesses of this approach are:

- Provision of predominantly 2D position by the Locata system.
- Lack of position determination when the number of signals for **both** systems falls under the required limit (4 signals).
- Inability for the Locata system to initialise (solve ambiguity) without the presence of the working GPS system.

2.2 Proposed Tightly Coupled Integration

Current research is addressing limitations, presented in 2.1 by tightly coupled integration (Grewal, Weill & Andrews 2006) and provision of combined GNSS and Locata solution (Fig. **9**). This work develops previous research (Rizos et al. 2010) in this area and does not only offers the benefit of integrated geometry (Meng X. 2003; Yang, He & Chen 2010) but also extends the capacity of the system for both Locata and GPS. With this approach, two or more Locatalite/GPS-satellites are required for a working system, providing that total number of visible signals exceeds five (due to additional unknown), offering additional flexibility, limiting deployment cost and providing direct applications in urban canyon or other difficult environments.

Currently, the main limit for the Locata use in general civil engineering real time applications is the lack of on the fly (OTF) ambiguity resolution (AR). The Locata system cannot utilise the LAMBDA method (Bertsch 2009; Shockley & Rackquet 2006), due to unresolved phase tracking biases. The novelty of the current research lies in combining GPS and Locata observations to solve AR on the fly and provide accurate 3D position, while keeping Locata ambiguities as float and fixing GPS ones only.

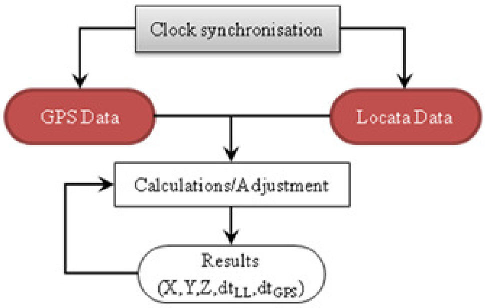

Fig. 9: Tightly coupled integration

Terrestrial system augmentation (Meng, Dodson & Roberts 2007; Yang, He & Chen 2010), has shown an improvement in vertical accuracy, network geometry and consequently 3D position quality, a large contrast to current Locata's weak vertical component determination. Synchronisation of the clocks is a main limit for the system's performances. Locata's TCXO oscillator, same as in the geodetic grade GPS receivers, has been theoretically proven sufficient for the integration if high update rates are implemented and TimeLoc is maintained (Bonenberg et al. 2009). This has been proven practically – v4.x firmware update provide synchronisation to the GPS timeframe within the required accuracy.

Fig. **10** compares Locata and GPS rover PPM output, with correlation on the ns level.

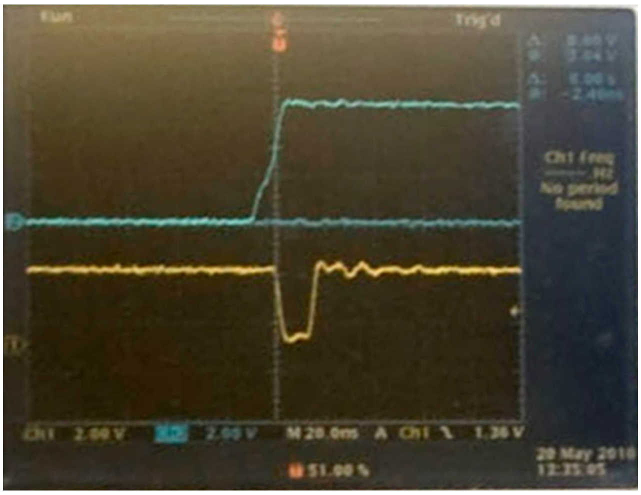

Fig. 10 Comparison of Locata (yellow) and GPS (blue) PPM signal

3. METHODS

A Data simulation was selected to verify show integration capacity. Experiment is based on the real life data collected at the Numarela Test Facility (NTF). Additionally a hypothetical scenario simulations (in section 5) was used to present system utilisation in the urban environment.

3.1 Numarela Test Facility (NTF)

NTF is a dedicated, 30 acre large, outdoor test facility located in Australia, in proximity to the Snowy Mountains and with ten permanent Locata stations. Its main utilisation is verification of the Locata performance.

For the purpose of this exercise, only six locations have been used. The average distances between stations exceed 600m (maximum over 1.3km) with average height difference of 13m, (maximum of 32m), offering good vertical and horizontal geometry.

The simulation consists of series of circular vehicle movements around a 15m high station. GPS L1 phase and code data was generated using a GPS hardware simulator. Errors due to the Troposphere, Ionosphere and Multipath were purposely not included to simplify the integration process. For Locata, only S1 phase and code data from one antenna (transmitter) has been simulated using a software simulator. Simulation for both systems included receiver clock errors and signal noise (on centimetre level for carrier and 2-4 meters for code observations).

3.2 Ambiguity resolution algorithm

Proposed ambiguity resolution (AR) algorithm is based on (Bertsch 2009), utilising several epochs to calculate ambiguity using Least Square Adjustment (LSA). The novelty here is the integration with GPS and revised calculation procedure. This approach offer 3D positions without height fixing (Bertsch 2009; Shockley & Rackquet 2006), therefore no prior knowledge is required.

The rover position and ambiguities for each epoch are being solved by minimising bias (*v*) in equation (1). Due to non-linearity of the solution (3), it is iterated until corrections (2) are lower than the defined threshold.

$$L = Ax + v \tag{1}$$

$$\hat{dx} = (A^T A)^{-1} A^{-1} L \tag{2}$$

$$\bar{x} = \hat{x} + \hat{dx} \tag{3}$$

were *A* is the observation matrix, *x* is the vector of unknowns and *L* is the difference between predicted and observed values.

In order to reduce the system bias, single difference (SD) is used. In case of Locata, we are referring to the linear combination of two signals from single receiver, different from GPS definition.

Observation matrix for single epoch (A_e) can be defined as

$$A_e = \begin{bmatrix} \frac{\partial \triangle \phi_e^{12}}{\partial x_e} & \frac{\partial \triangle \phi_e^{12}}{\partial y_e} & \frac{\partial \triangle \phi_e^{12}}{\partial z_e} \\ \dots & \dots & \dots \\ \frac{\partial \triangle \phi_e^{1j}}{\partial x_e} & \frac{\partial \triangle \phi_e^{1j}}{\partial y_e} & \frac{\partial \triangle \phi_e^{1j}}{\partial z_e} \end{bmatrix} \tag{4}$$

where $\Delta\Phi^{1j}$ is a difference between master Locata transmitter and all other transmitters.

The final matrix A_x (were x indicates either LL or GPS) is formulated by combining observation matrixes (4) for each epoch e_n

$$A_x = \begin{bmatrix} A_{e_1} & \dots & 0 \\ \dots & \dots & \dots \\ 0 & \dots & A_{e_n} \end{bmatrix} \tag{5}$$

with diagonal matrixes of ambiguity differences ΔN_x producing final observation matrix A

$$A = \begin{bmatrix} A_{LL} & \triangle N_{LL} \\ A_{GPS} & \triangle N_{GPS} \end{bmatrix} \tag{6}$$

Unknowns (x) are rover coordinates for each epoch and ambiguity differences ΔNx (assuming that no cycle slips occurred). Note that, for simplicity reasons, the GPS part of the matrix is also calculated using single differencing, due to removal of troposphere and ionosphere errors (signal delay) from modelling. The solution for each epoch is calculated by solving equation (1) with respect to x. Note that submatrix A_{LL}, on its own is prone to singularity, due to Locata coplanarity.

3.3 Factors not included in simulation

Two main factors affecting the position accuracy and not present in the simulation are the multipath and troposphere delay.

Multipath occurs when apart from direct signal rover receives an non-direct signal, reduced in power and with shifted phase (Kaplan 2006). Phase shift tend to be smaller than ¼ of a length (Yang, He & Chen 2010), but can be especially dangerous during the TimeLoc procedure, affecting synchronisation. The problem is partly mitigated by Locata's spatially separated antennas, pulse signal and dual frequency (Barnes et al. 2006; Khan, Rizos & Dempster 2010; Montillet et al. 2009).

Due to nature of ground based positioning systems, **troposphere delay** is another major contributor to the error budget, much more prominent than in the space systems. Due to large distance variation, differential of observations won't remove this effect and modelling has to be utilised instead. Prior research (Jianguo Jack et al. 2008; Jianguo Jack et al. 2005) identified RTCA's LAAS model as most appropriate for this use.

4. SYMULATION RESULTS

Calculations are based on data simulated by the Spirent GSS8000 hardware simulator (for GPS) and dedicated Matlab software simulator (for Locata). The trajectory consisted of 16 growing circles with the same centre (5m away from nearest transmitter) and provided 614 epochs of data. Rover was moving with a constant speed throughout the test.

Both Locata and GPS ambiguities are estimated starting from a initial guess roughly in the centre of the Locata network (100-300m away from true positions) using the method described in paragraph 3.2. Locata ambiguities were calculated as floats, without utilising any integer fixing procedure such as LAMBDA (Bertsch 2009). The initial 600 epochs (without any filtering applied) were used to calculate best fit Ambiguity Resolution (AR). The results presented in **Błąd! Nie można odnaleźć źródła odwołania.** are from the remaining epochs, processed one epoch at the time while holding calculated float ambiguities fixed. **Błąd! Nie można odnaleźć źródła odwołania.** presents all combinations of 6 signals (LL/GPS #) and the number of epochs used for each solution (Epoch #). Solutions that failed to reach dm level (average) are not presented.

Degeneration in the solution is visible if more than 50 epochs are used for a single LSA solution, with an exception for over defined 6+6 scenarios. This is likely the effect of the Locata's float ambiguity resolution and its limiting performance of the system. Therefore it is important to use a reasonable number of epochs for a solution, utilising advanced data filtering, or other mathematical methods (such as a Kalman filter) to estimate the best float result. This is especially visible if only a minimal number of observations are present (as in urban canyons).

Tab. 1. Simulation Results

LL #	**GPS #**	**Epoch #**	**Hz**		**V**	
			Max	**Av**	**Max**	**Av**
3	3	10	0.424	0.395	0.111	0.100
4	2	10	0.240	0.219	0.141	0.121
6	6	10	0.013	0.009	0.052	0.035
3	*3*	*50*	*0.019*	*0.013*	*0.021*	*0.016*
4	2	50	0.016	0.011	0.025	0.014
6	6	50	0.027	0.023	0.049	0.032
3	*3*	*100*	*0.030*	*0.018*	*0.033*	*0.023*
4	2	100	0.018	0.010	0.032	0.021
6	6	100	0.025	0.021	0.052	0.035
3	*3*	*300*	*0.278*	*0.262*	*0.202*	*0.149*
4	2	300	0.023	0.012	0.024	0.014
6	6	300	0.017	0.014	0.044	0.027

Due to the calculation method, simulation is biased towards the Locata system, as conventional GPS data processing method (utilising double differencing (DD)) should yield better results than simulated. Results presented also don't include theoretically possible value of five combined signals from Locata and GPS (2+3 or 3+2). This is not possible in this simulation as not all signals are simulated (only one signal per each LL and GPS "satellite") and simplified LSA method is unable to resolve ambiguities.

5. APPLICATION

In order to verify the feasibility of utilising a combined system in an urban environment, a simple simulation environment has been created. With the prior knowledge of GPS satellite orbits, Locata positions and rover trajectory, a software simulation predicts the visibility of the signal at every given location. Simulation is carried out in the Canary Wharf area in London, famous for massive skyscrapers. 0.9km long trajectory is marked in red, with positions of 5 Locata are indicated in green (Fig. **11**).

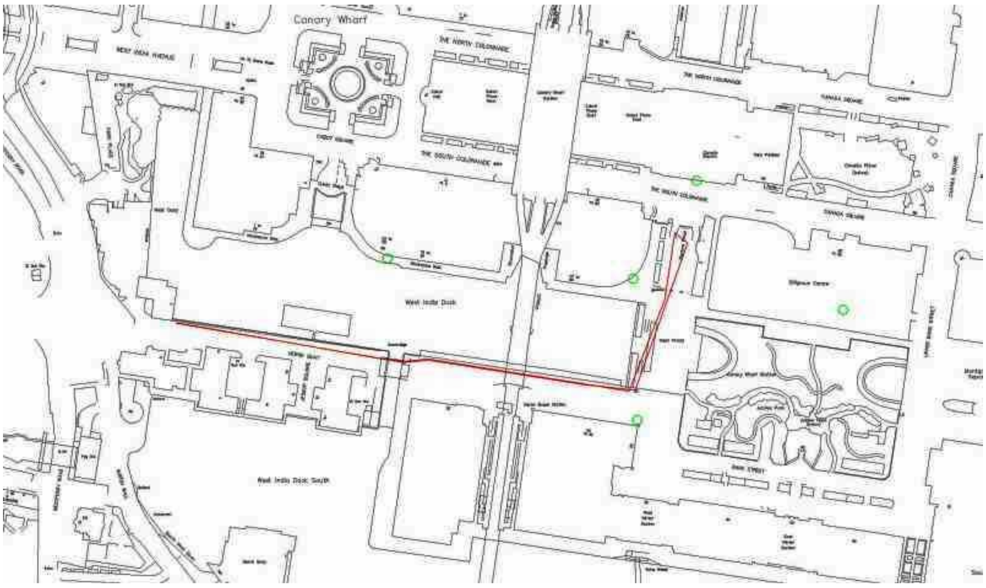

Fig. 11. Simulation layout (Locata – green, trajectory – red)

Simplified outline of nearest building has been provided and 10 degree cut-off angle selected for GPS. Locata has been positioned on the building roofs, highlighting the "shadowing" effect of the skyscrapers. At the current stage, the software does not include degenerating effects of multipath (building reflection), noise, tropospheric delay and interference. A 100 epoch sample has been used to calculate visibility of both GPS and a combined system (Fig. **12**).

The integrated system offers better availability for both theoretically achievable solution (dashed line, 5 signals, 64% positional availability) and currently achievable solution of 6 signals (continuous line, 6 signals, 54%), comparing with GPS only solution (22%). Presented results could be further improved by positioning dedicated Locata units closer to the ground level (on the lamp post for example) within dedicated movement "corridors".

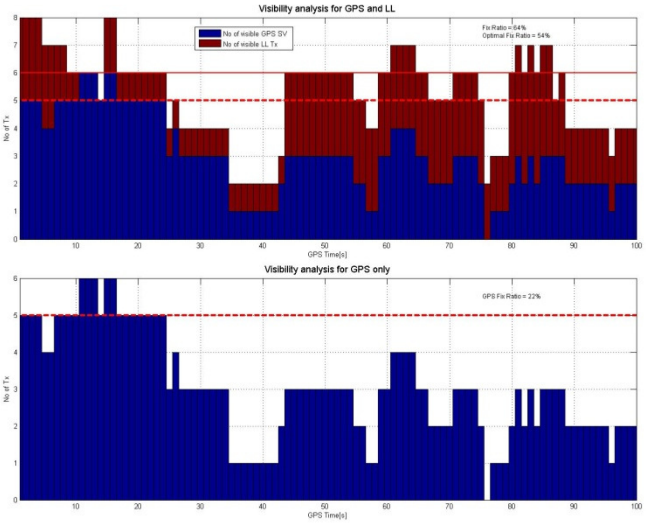

Fig. 12 Comparison of GPS only (blue) and LL aided solution (red)

Results demonstrate the application of the Locata augmentation of GNSS. The static nature of Locatalites can also provide the integrity control mechanism, guarding against GNSS outage, as described in (Bonenberg, Hancock & Roberts 2010).

6. CONCLUSION

Locata is a terrestrial positioning technology, based on the pseudolite concept. It is unique in utilising the dual signal frequency on the 2.4 GHz license free frequency band with two spatially separated transmitting antennas, and the TimeLoc procedure, allowing for the networks synchronisation at the nanosecond level. Currently the Locata system is used commercially as an augmentation for GPS in the open cast mining environment. One of the shortcomings of this integration is predominantly weak vertical component which results in a 2D only position fix.

This work focuses on the integration of GPS and Locata, giving an integrated solution providing not only better geometry (3D) but also improved availability of positional solution. Simulation of the proposed integration algorithms, using a real life scenario, has shown promising results with centimetre-level positional accuracy on the moving platform. The capacity of the integrated system to solve code ambiguites for both Locata and GPS on-the-fly without prior knowledge of the position offers exciting possibilities in the area of civil engineering, GIS, mobile mapping applications, machine navigation and control. The flexibility of the system deployment and 3D kinematic positioning and ambiguity resolution makes Locata constellation an ideal GNSS augmentation tool for large scale construction or monitoring works, when current equipment cost cease to be a limiting factor. Monitoring of essential structures (airports, seaports, factory sites, bridges in dense urban, or other obstructed areas) is of special interest to authors.

Simulation of simplistic urban scenario demonstrated proof of concept deployment and utilisation of integrated system in the limited sky visibility environment.

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