Improving real-time deformation monitoring quality by network RTK

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- when it has to be right

We are living in a dynamic world, to protect our life, property and infrastructures, we need continuously monitoring


Landslide (Hong Kong)


Earthquake


High rise building


Water dam stability


Rail settlement

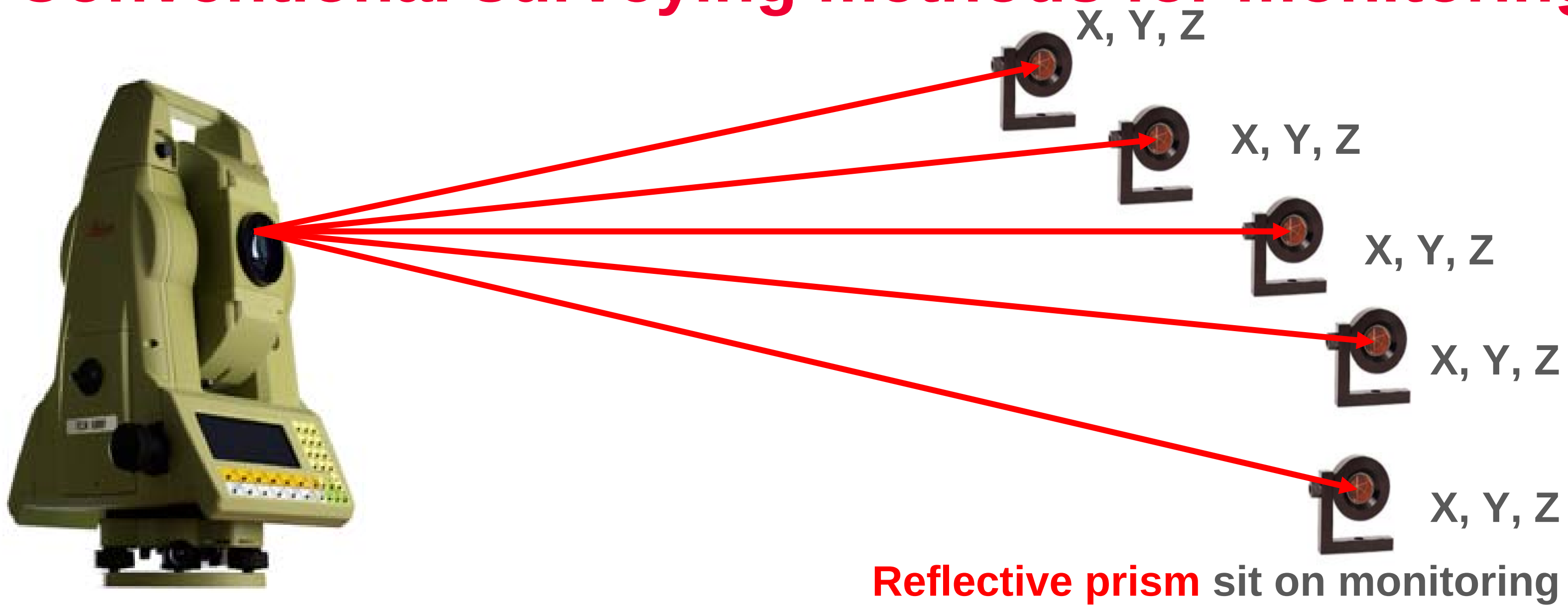

Bridge vibration &

health monitoring


Open pit mine

Conventional surveying methods for monitoring

(A)



Reflective prism sit on monitoring object

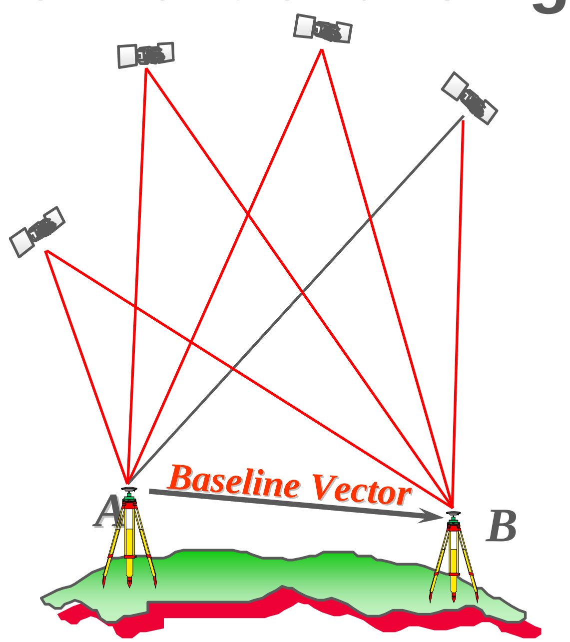
High precision Total Station

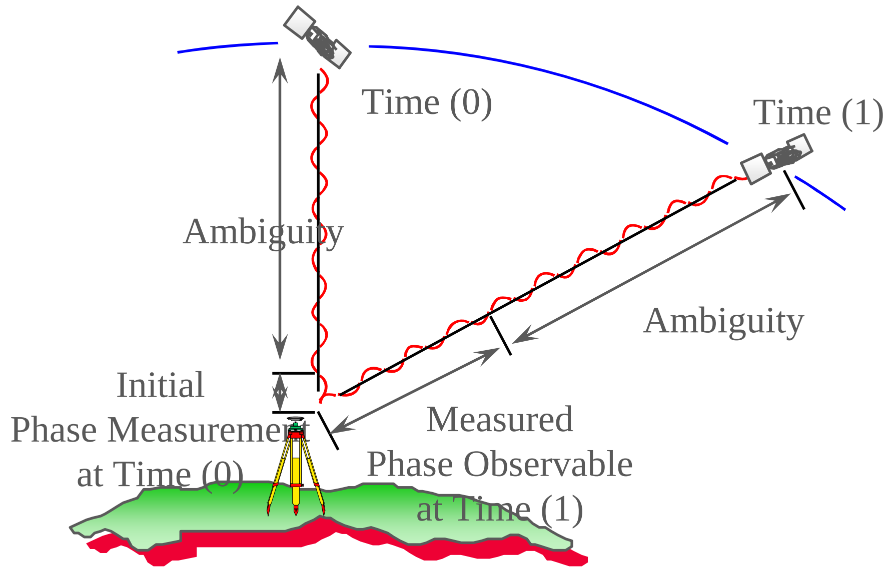
(B)

Precise Leveling using optical or digital level with invar staff to measure height value of settlement ground point

- Line of sight problem
- Labor intensive
- High long term cost
- Time consuming
- Only Small area coverage
- Non-automatic, low efficiency

Solution: Applying GNSS RTK in monitoring
(Conventional single baseline RTK approach)



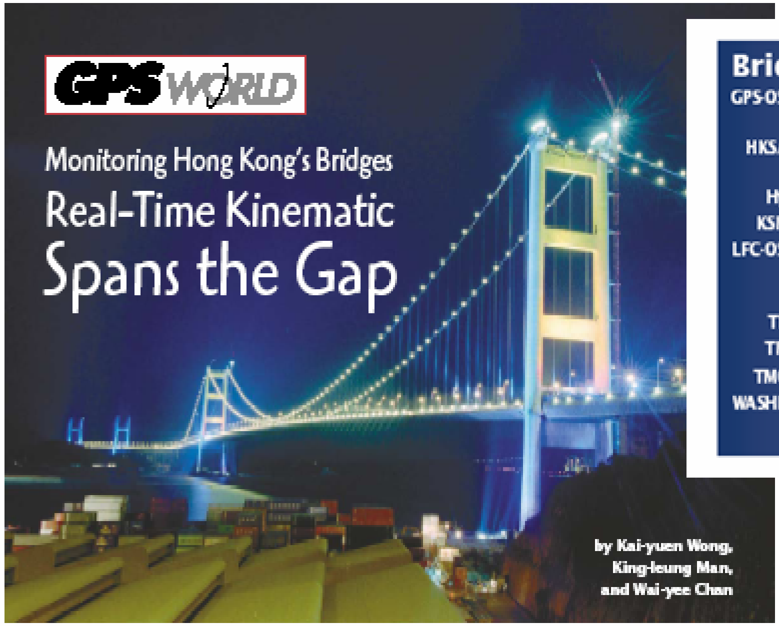


- Setup at least one **GNSS base station on a stable area** with **accurate coordinates** (control point)
- The GNSS base station **track the same group of satellites** as the monitoring GNSS station, so the base station calculate the **GNSS correction data** and **transmit to monitoring station**
- Monitoring station GNSS receiver **resolve integer ambiguity** to get **3D coordinates**. RTK **accuracy to around 10mm + 1ppm** (horizontal), **20mm + 1ppm** (vertical)

Advantages of applying GNSS RTK in monitoring

- **Fully Automatic, less human interference**
- **All weather operation, 7 x 24 round the clock**
- **Achieve Real-Time, 3D absolute coordinates of monitoring points**
- **No need line of sight to monitoring point targets**
- **high measurement rate (upto 20Hz)**
- **Can detect sudden movement / changes, enable quick alert mechanism to engineers (e.g. SMS, email message, etc)**
- **Can measure over long baselines, large monitoring area coverage**
- **No concurrent payment for receiving GPS data from satellites**
- **low maintenance and a long service life**

Example – HK Tsing Ma Bridge adopted conventional GPS RTK for bridge health monitoring



Modern cable-supported bridges carry enormous loads across great distances, in part due to their designed capability to move, ever so slightly, under varied conditions. In Hong Kong, a real-time kinematic (RTK) GPS monitoring system provides the centimeter-level accuracy, in all weather conditions, to detect bridge movements beyond normal ranges. Engineers can then conduct inspections or maintenance needed to maintain longterm structural health.

Kai-yuen Wong (Ir, chartered engineer) is senior engineer in the Bridge Health Section of Tsing Ma Control Area Division, Highways Department, Hong Kong Special Administrative Region. King-leung Man and Wai-yee Chan (Ir, chartered engineers) are engineers in the same Bridge Health Section.

Hong Kong's Tsing Ma Bridge is the world's longest span suspension bridge carrying both road and rail traffic. As with other longspan cable-supported bridges, it can move from several centimeters to several meters under different types of loading conditions.

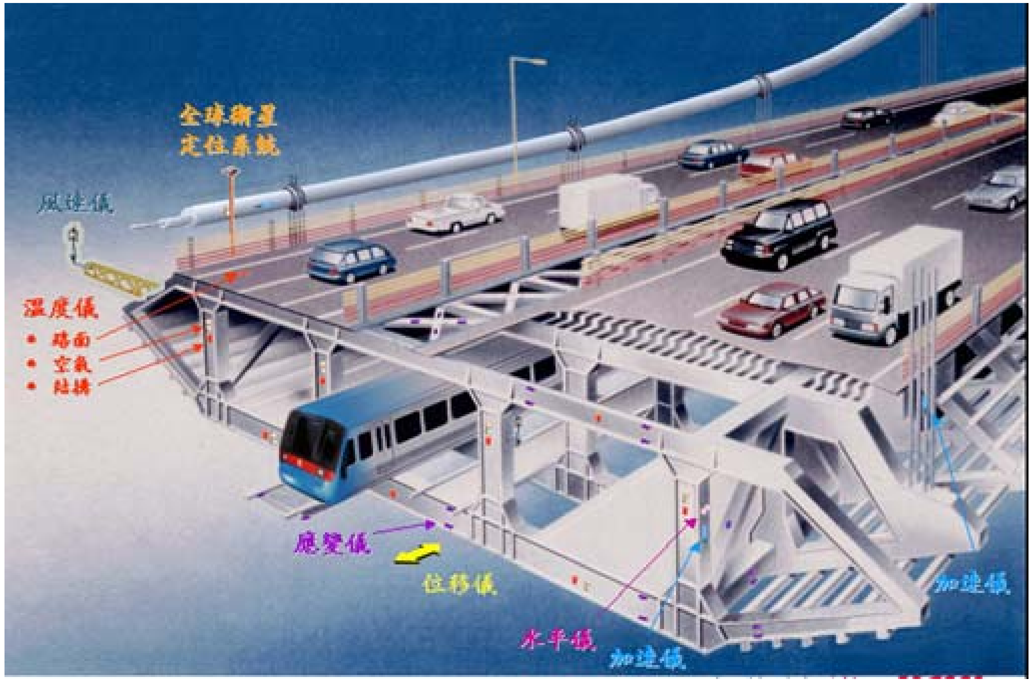
Although these displacements or deformations may not create hazardous conditions for traffic actually on the bridge, as they increase in size, they significantly affect the bridge's structural integrity and maintenance needs. Real-time measurement accuracy of GPS has improved to centimeter-level precision recently, making it well-suited to monitor variations in three-dimensional bridge motion in response to wind, temperature, and traffic loads. This article describes the layout and technical performance requirements of such a system and discusses the results in bridge structural health monitoring.

The Highways Department of Hong Kong Special Administrative Region designed the Wind and Structural Health Monitoring System (WASHMS) for three large cable-supported bridges, Tsing Ma Bridge, Kap Shui Mun Bridge, and Ting Kau Bridge, in the Tsing Ma Control Area (TMCA) of western Hong Kong. Tsing Ma Bridge measures 1,377 meters across the Ma Wan shipping channel. Built at a cost of approximately

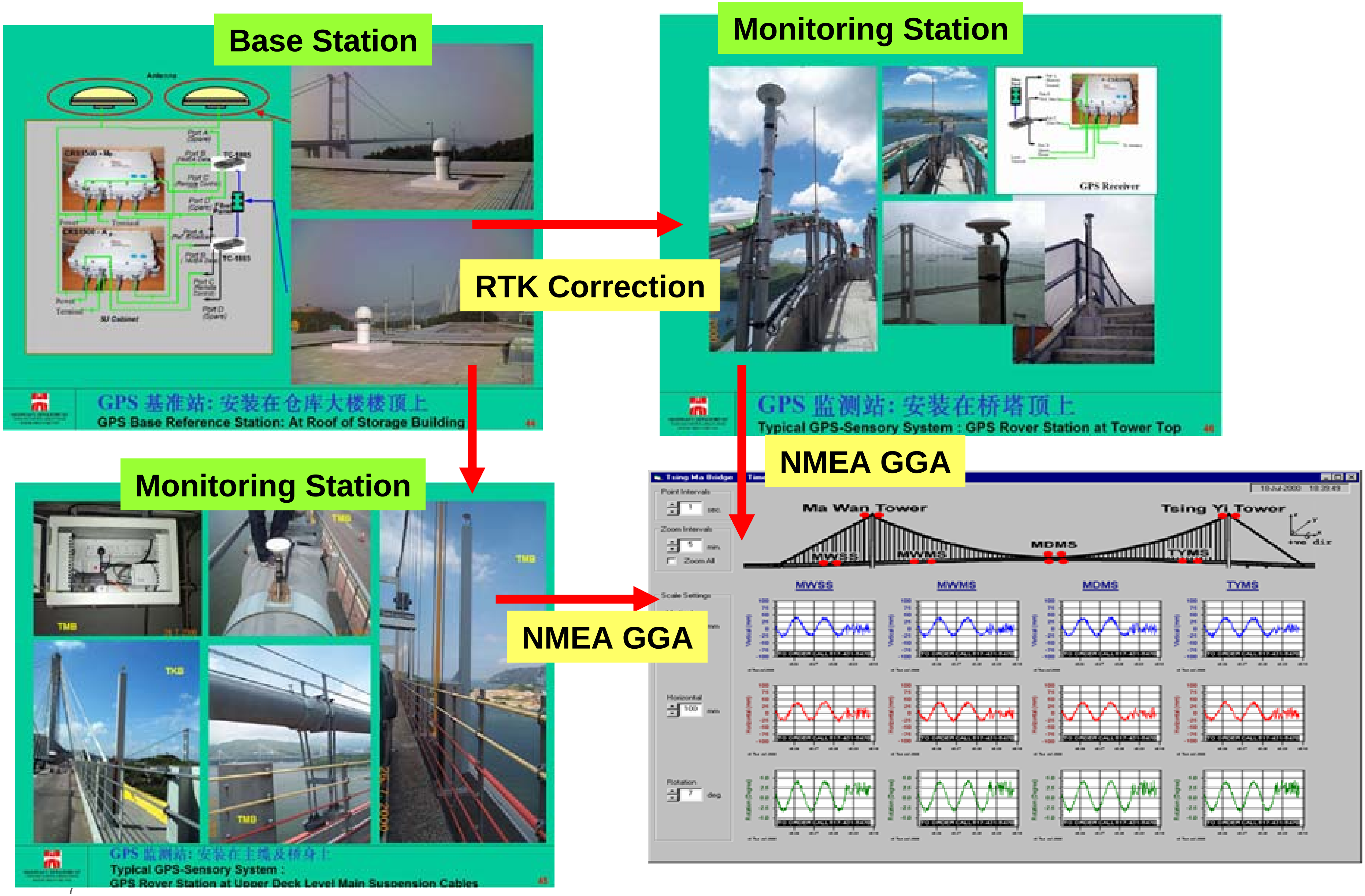
Bridge Acronyms

GPS-OSIS	GPS On-Structure Instrumentation System
HKSAR	Hong Kong Special Administrative Region
HyD	Highways Department
KSMB	Kap Shui Mun Bridge
LFC-OSIS	Lantau Fixed Crossing — On-Structure Instrumentation System
TKB	Ting Kau Bridge
TMB	Tsing Ma Bridge
TMCA	Tsing Ma Control Area
WASHMS	Wind and Structural Health Monitoring System

Receiver atop Tsing Ma Bridge tower, with Kap Shui Mun Bridge in the distance



GPS Base & Monitoring Stations with result display



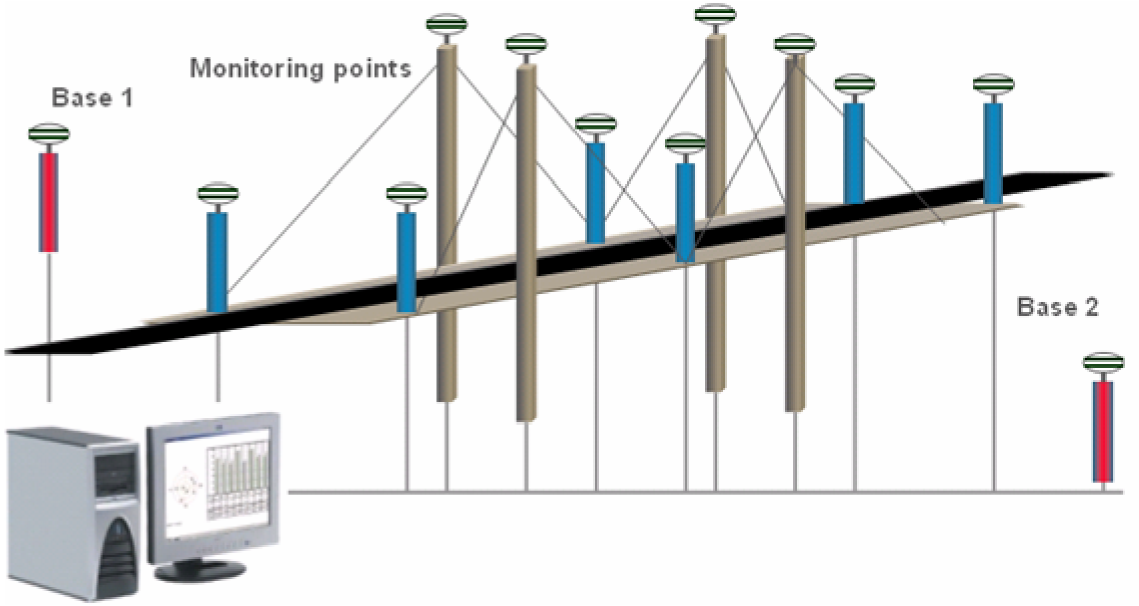
Centralized GNSS RTK Monitoring Approach

Principles :

- Only **one way data streaming** from all GNSS receivers (no matter base stations or monitoring stations) to a **central data processing facility.** (no need to send GNSS correction data from base to monitoring receivers)

- **Defining baselines** and **RTK integer ambiguity resolution** are performed by **software with RTK algorithm** at the data processing facility **BUT NOT** at the GNSS receivers. (GNSS receivers don't need RTK computation capability, it's only a data streaming machine)

- Each monitoring point is now possible to be **computed by multiple base stations simultaneously**. >> cross-checking, redundant measurements to increase monitoring reliability



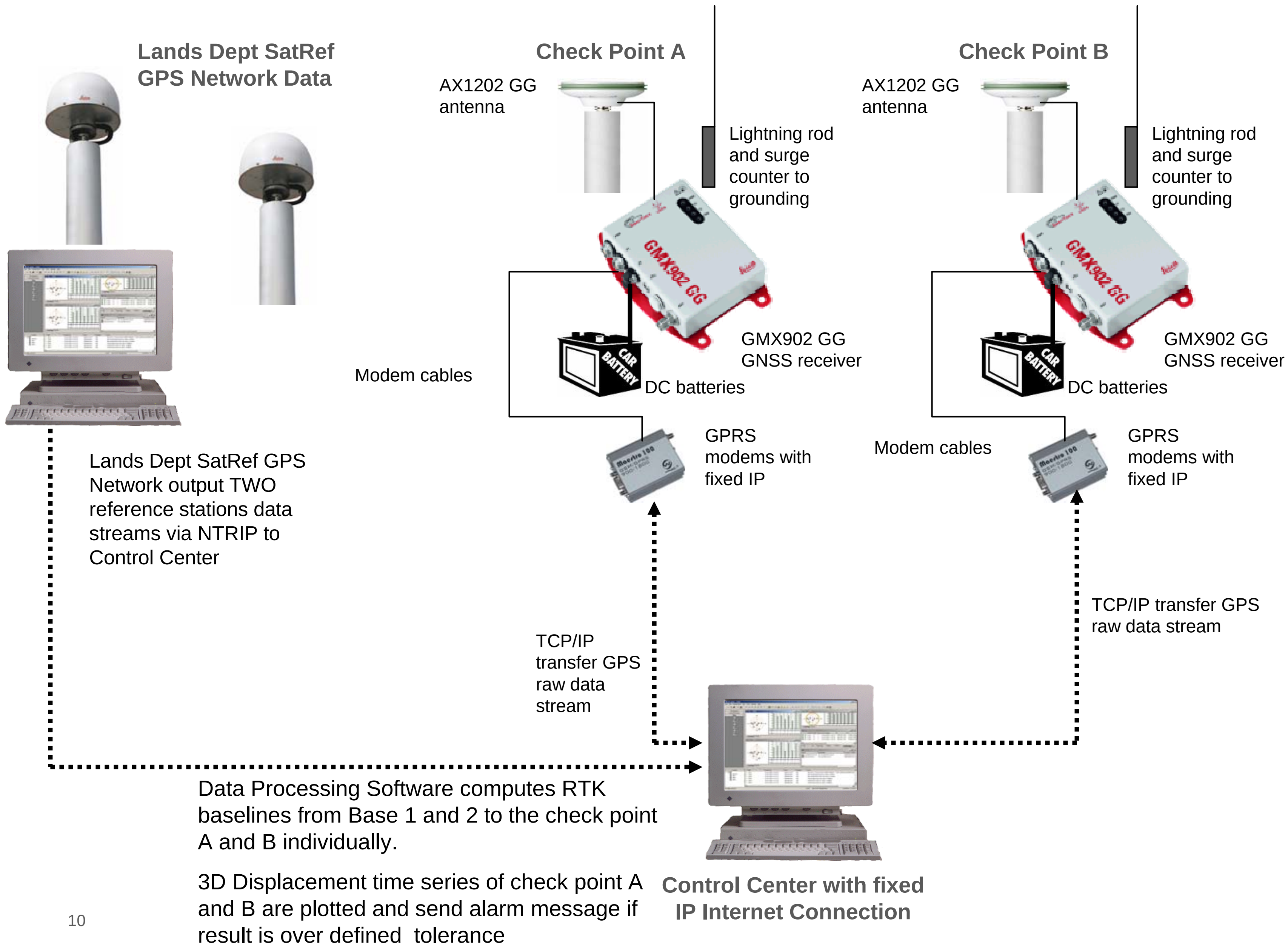
A typical case using centralized GNSS RTK in HK
Seawall Monitoring, CEDD Ports Work

Project Objectives :

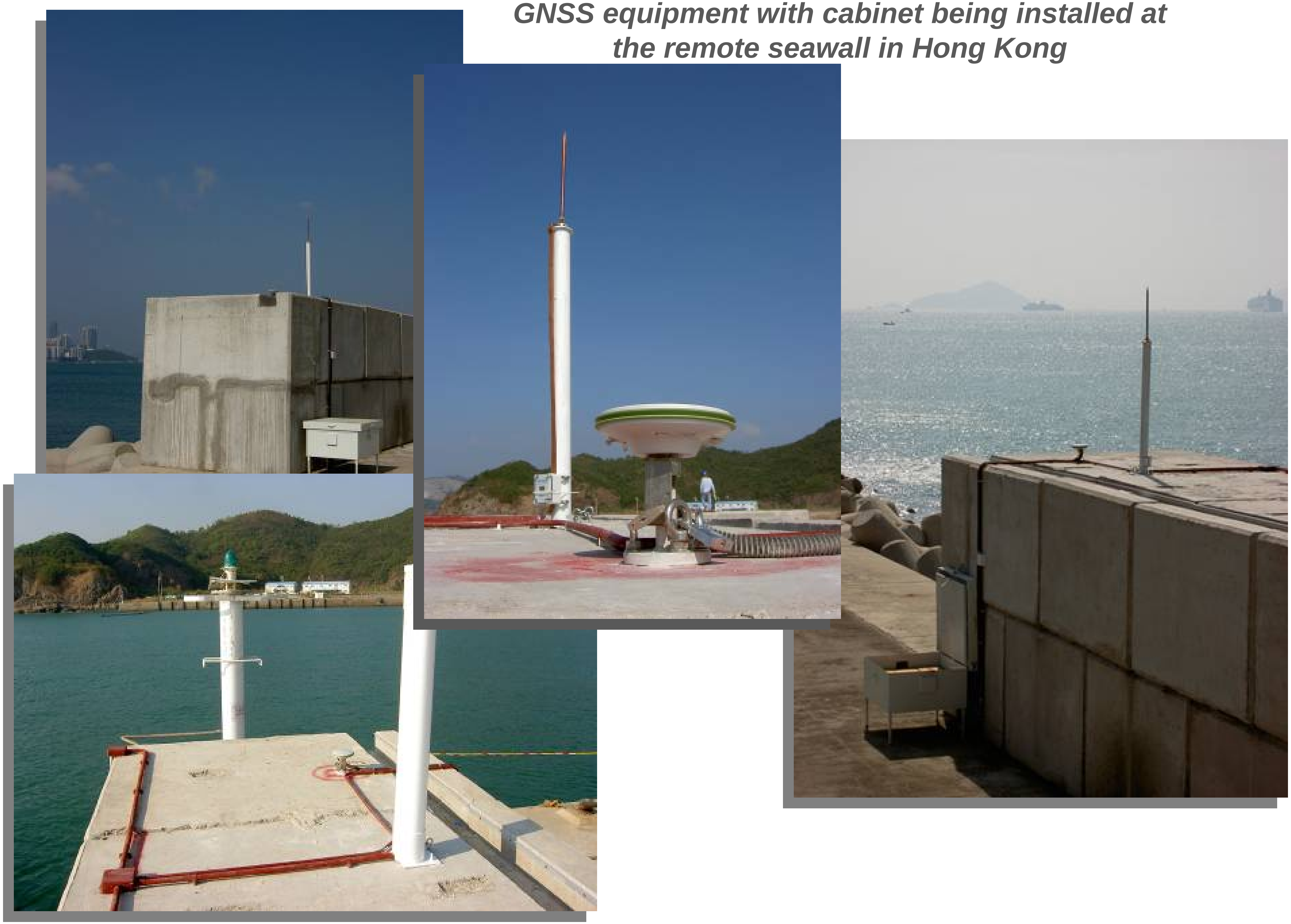
- Ensure safety of seawalls in HK
- Replace monitoring by traditional manual methods because they are time consuming and manpower involved with human life risk in typhoon periods.
- Real-time displacement presentation
- Multiple levels auto alert to engineers
- Fully automatic, day and night, 24/7

Seawall infrastructure in Hong Kong

GNSS Seawall Monitoring System Diagram

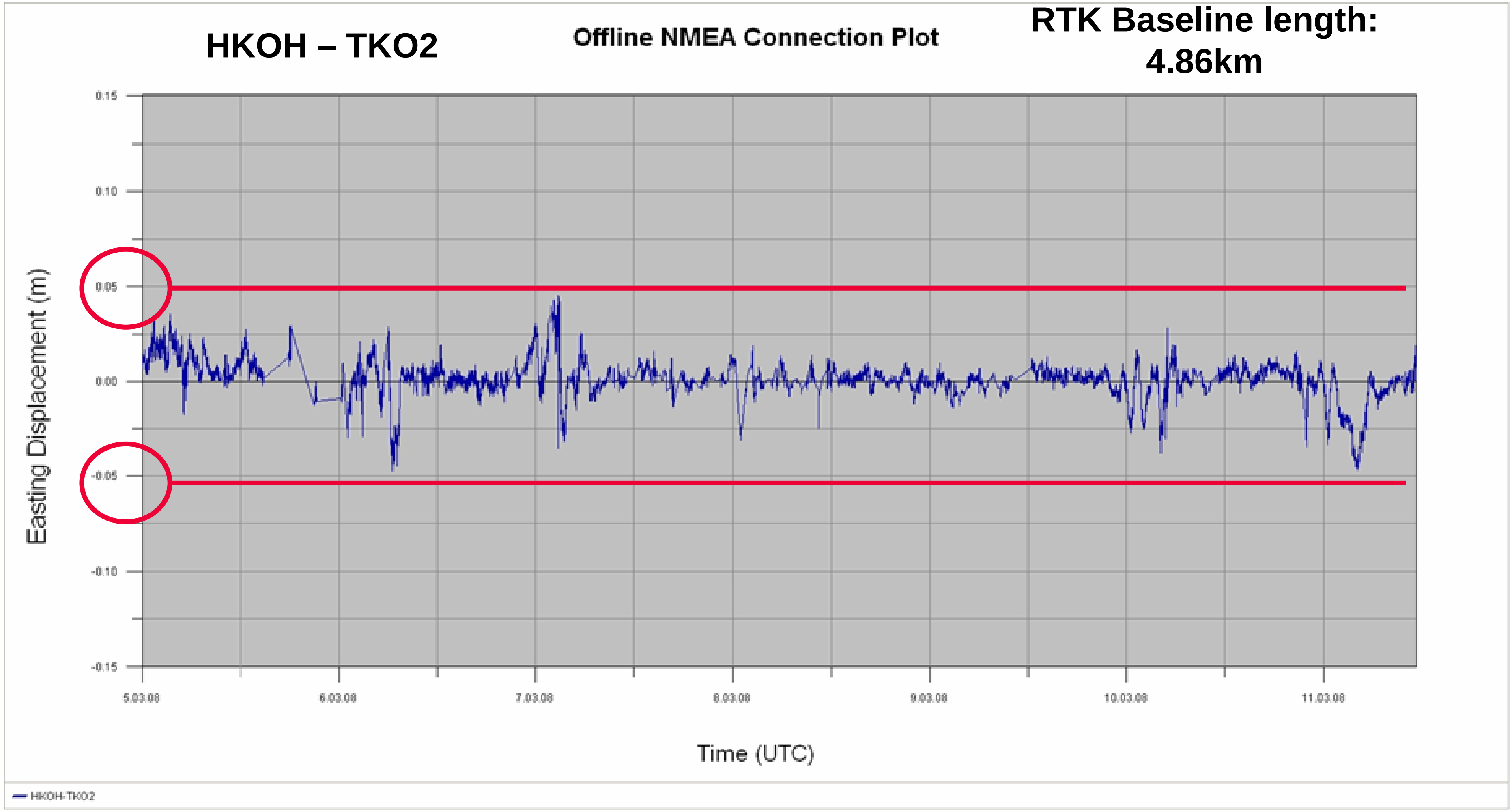


GNSS equipment with cabinet being installed at the remote seawall in Hong Kong



GNSS equipment, GPRS modem, power supply being installed inside a cabinet

7 days RTK displacement time series.
We have a problem !!



7 days RTK displacement time series.
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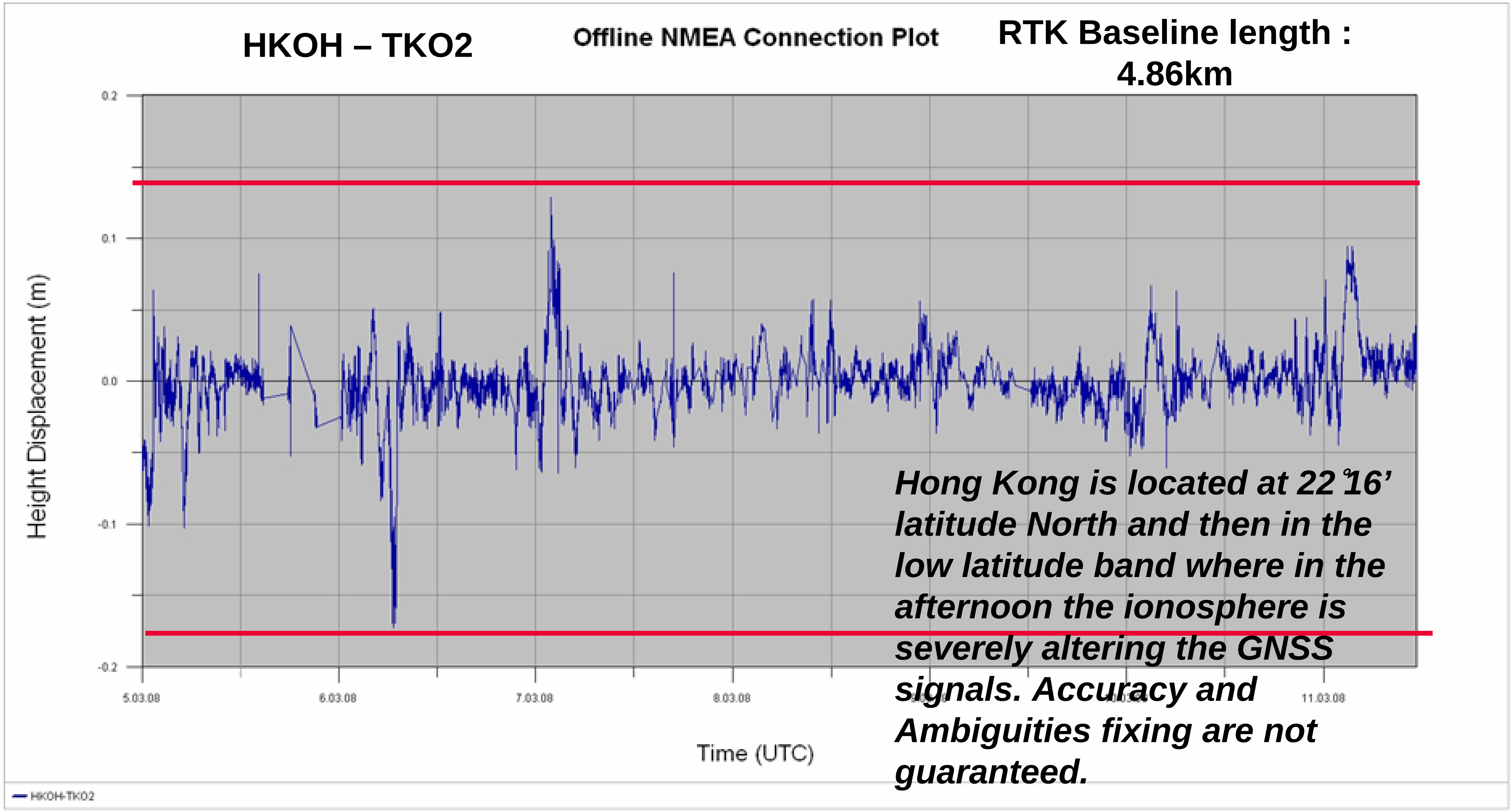
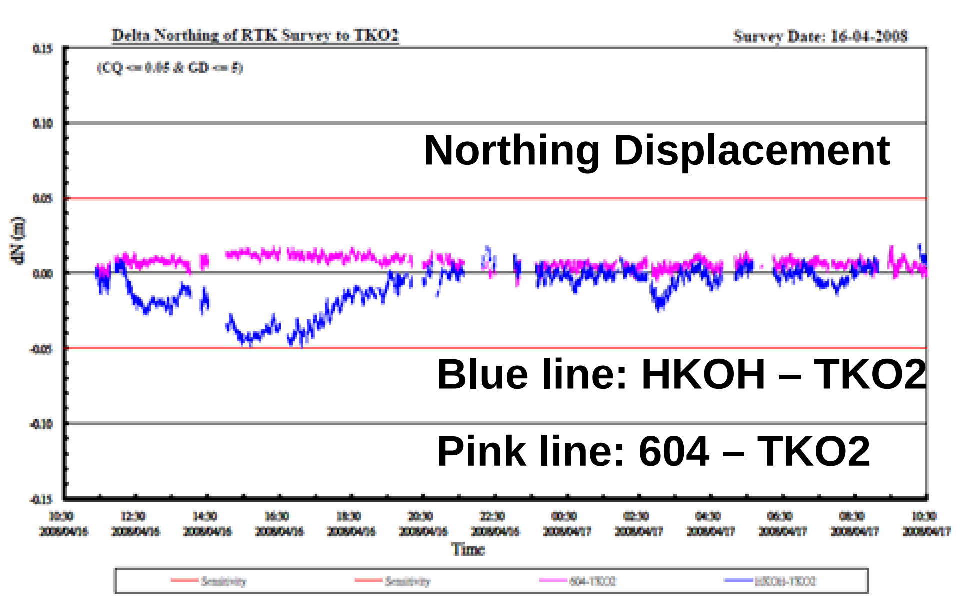
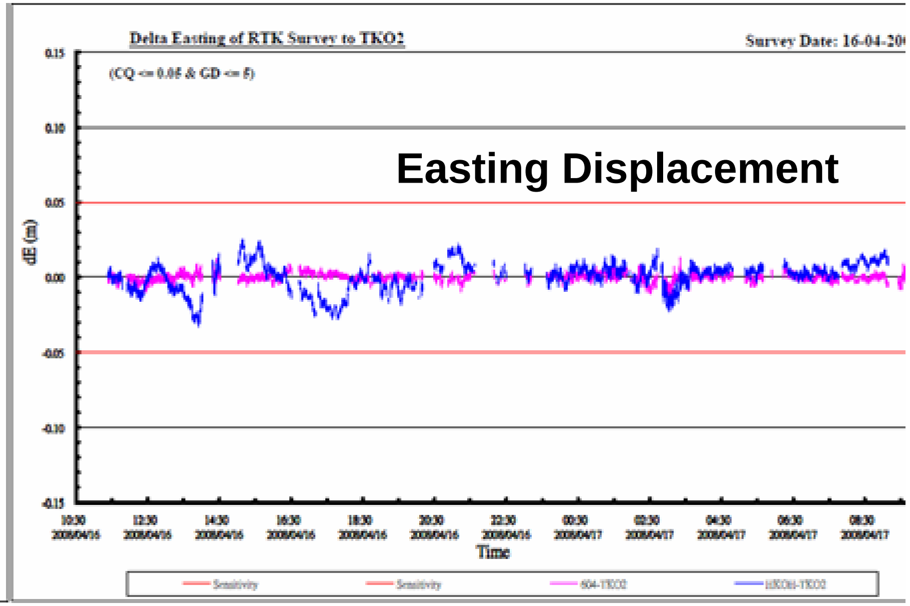
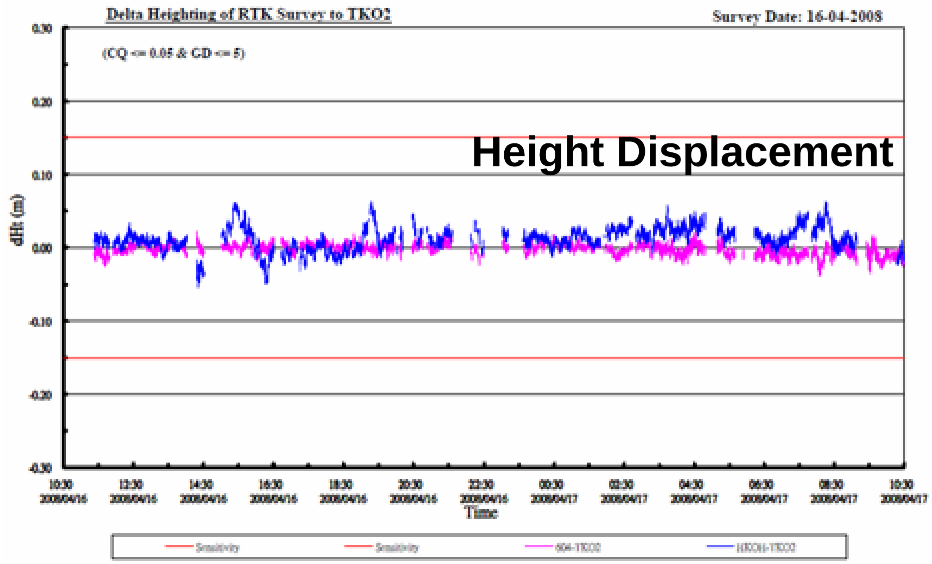


Hong Kong is located at 22°16' latitude North and then in the low latitude band where in the afternoon the ionosphere is severely altering the GNSS signals. Accuracy and Ambiguities fixing are not guaranteed.

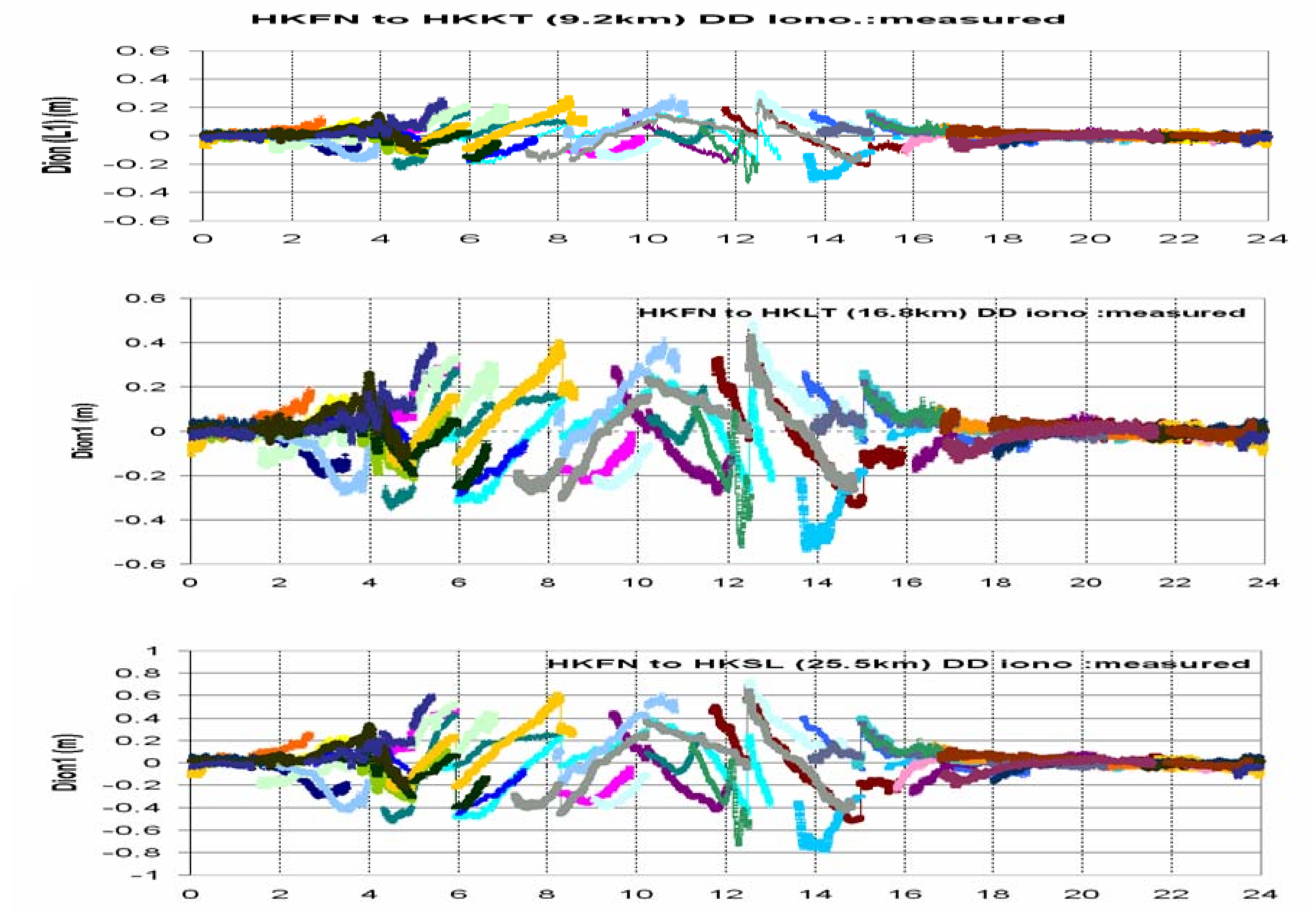
Trial of setting up a RTK base station (Trig 604) close to monitoring points (less than 1km) – 24 hours measurement







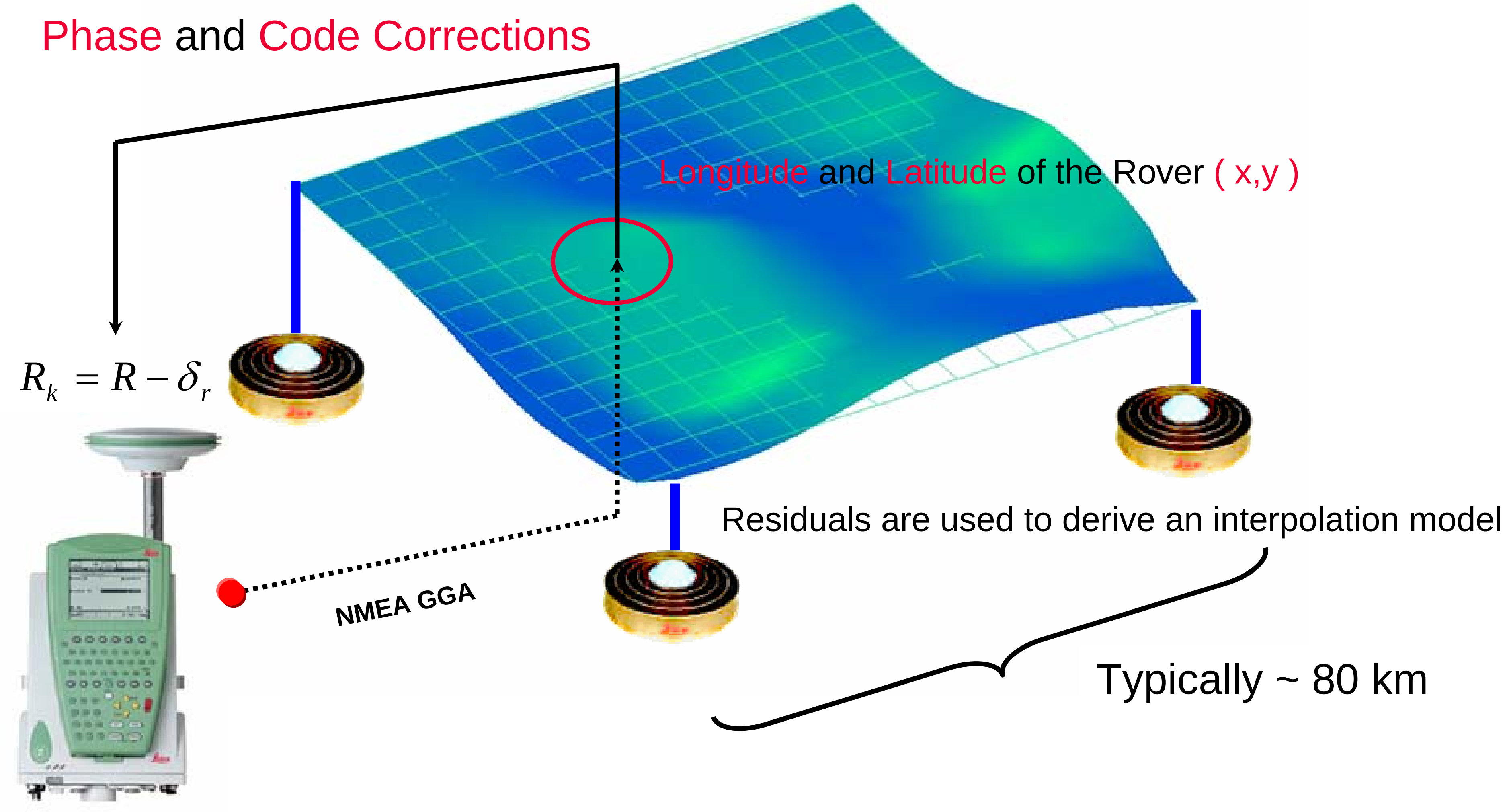
Effect of Ionosphere turbulences in Hong Kong



Solution: GNSS Network RTK Approach in Monitoring

$$\delta_{r0} = \alpha\left(N_0(\varphi - \varphi_R) + E_0(\lambda - \lambda_R)\cos(\varphi_R)\right)$$

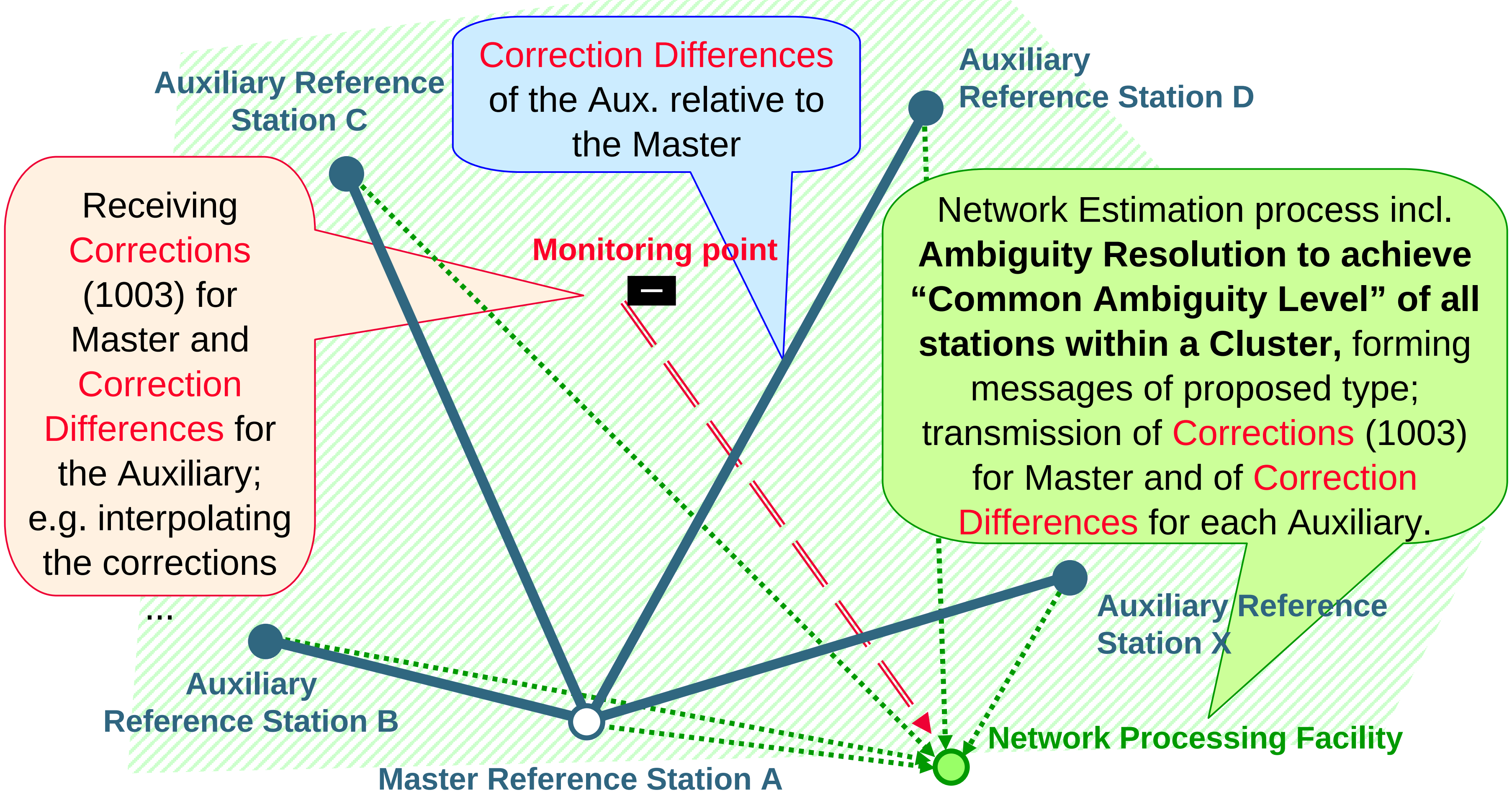
$$\delta_{r1} = \beta \cdot H\left(N_1(\varphi - \varphi_R) + E_1(\lambda - \lambda_R)\cos(\varphi_R)\right)$$



Principle of The Master Auxiliary Concept

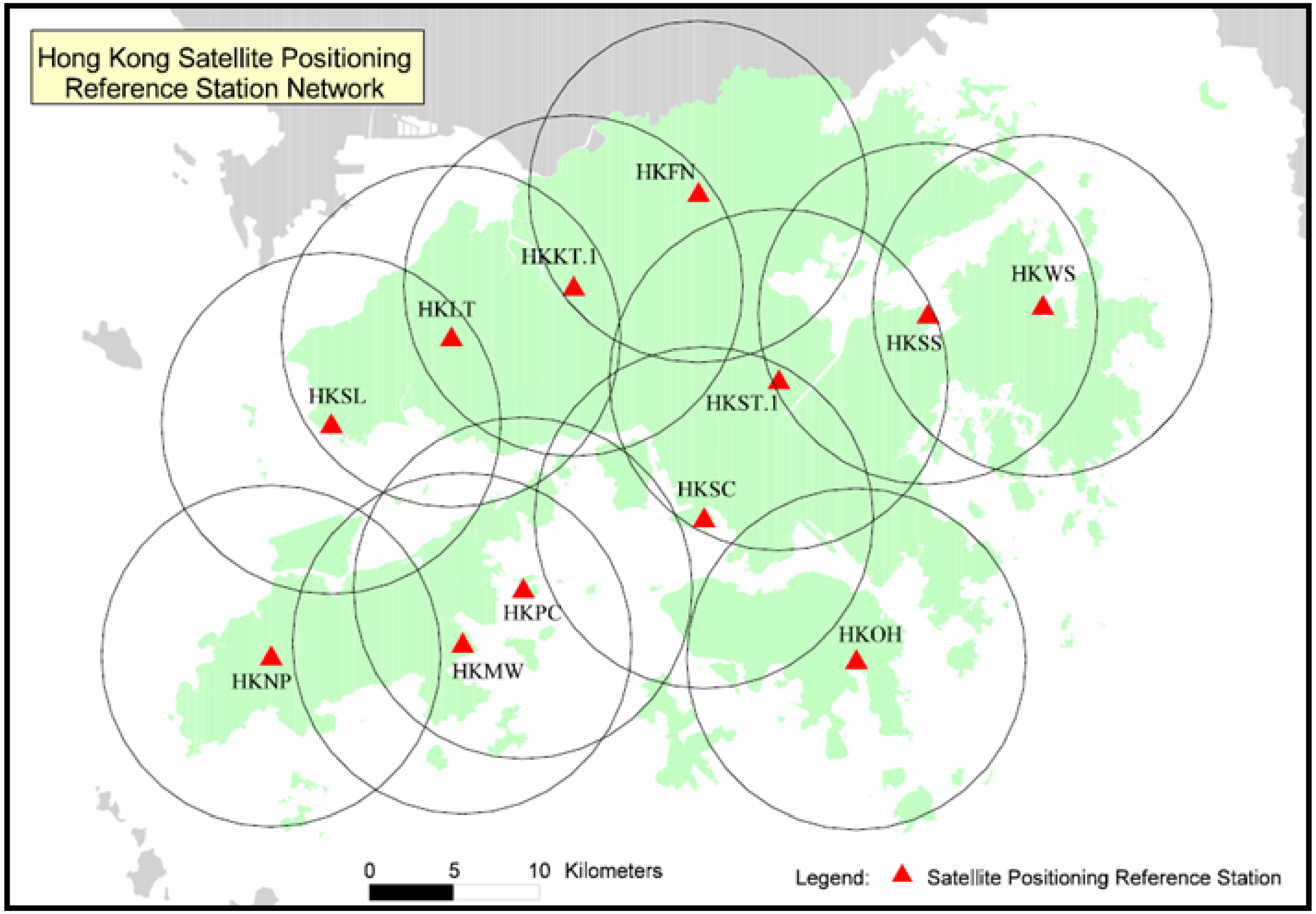
One Master Reference Station

Some Auxiliary Reference Stations ➔ One Network Cell



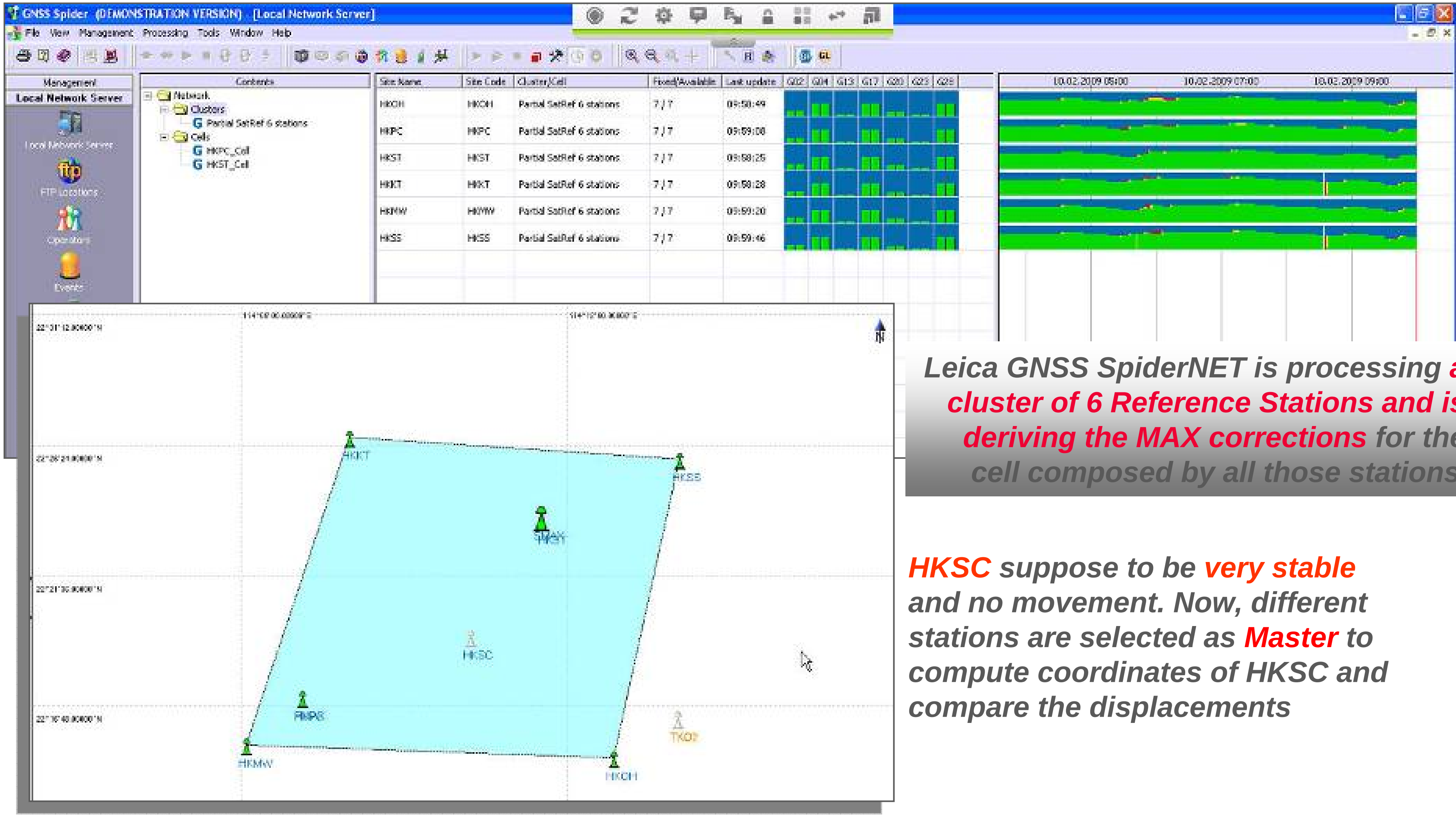
Proof Of Concept :

Simulation Test using Reference Station Data from HK SatRef Network



Simulation Test of generating MAX network RTK correction form a cluster of 6 CORS of SatRef and apply it to fix simulated monitoring point - HKSC

Processing in Real Time “L1 & L2” and “L1 only” GPS data



*Leica GNSS SpiderNET is processing **a cluster of 6 Reference Stations and is deriving the MAX corrections** for the cell composed by all those stations.*

***HKSC** suppose to be **very stable** and no movement. Now, different stations are selected as **Master** to compute coordinates of HKSC and compare the displacements*

Real-time computation result screen of simulation test – by Spider software

Processing in Real Time L1 & L2 , L1 only GPS data

L1 + L2

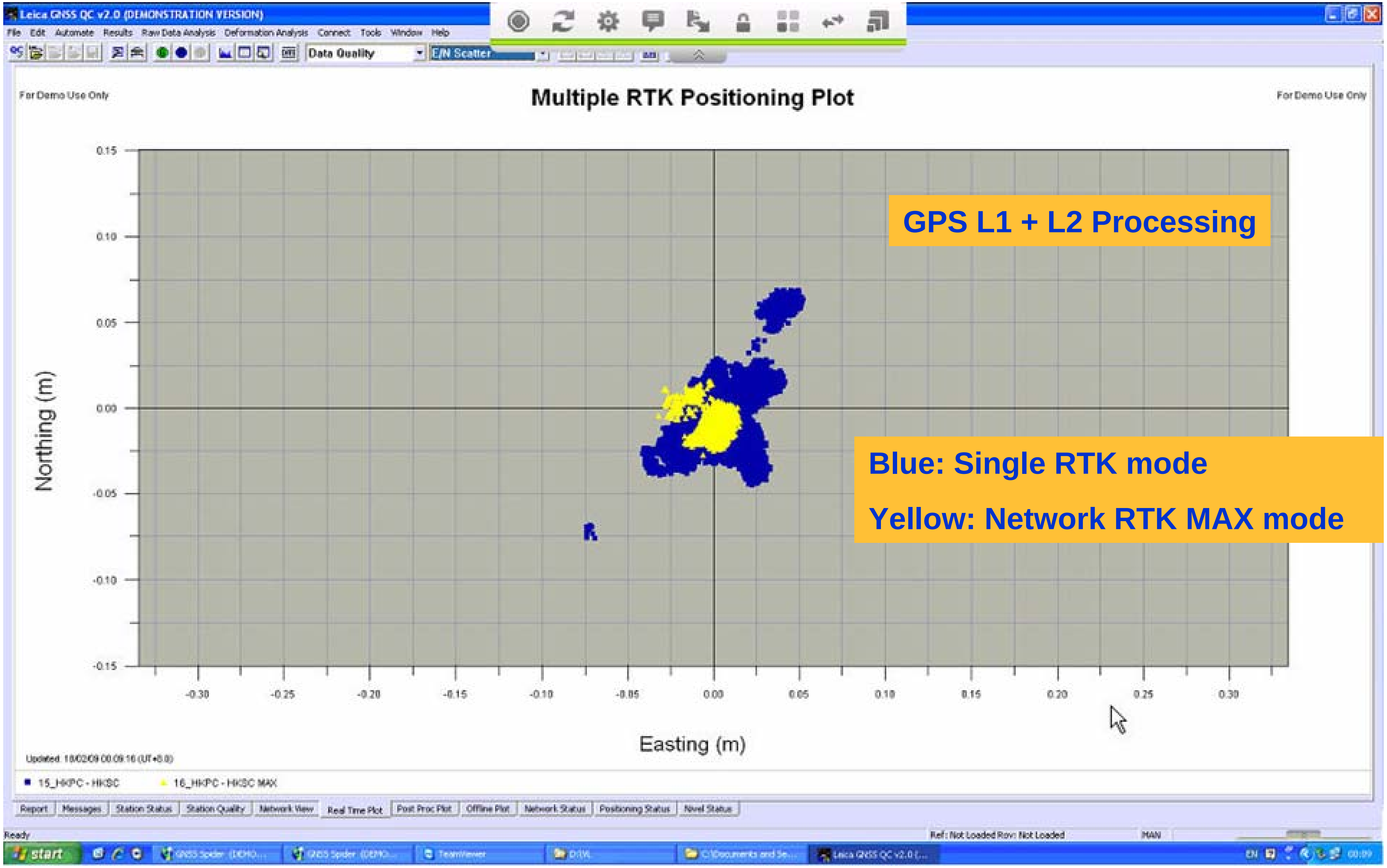
	CQ [m]	GDOP	Sats	Last Change	Latitude	Longitude	Height	Distance	Product Name	Site code
yes	0.017	2.7	8	18.02.2009 00:26:33	22° 19' 19.81894" N	114° 08' 28.27695" E	20.2268	11.419 km	HKPC - HKSC	HKSC
yes	0.013	2.7	8	18.02.2009 00:25:47	22° 19' 19.81907" N	114° 08' 28.27663" E	20.2210	11.419 km	HKPC - HKSC MAX	HKSC
yes	0.019	2.7	8	18.02.2009 00:26:28	22° 19' 19.81923" N	114° 08' 28.27652" E	20.2247	9.233 km	HKST - HKSC	HKSC
yes	0.013	2.7	8	18.02.2009 00:25:58	22° 19' 19.81912" N	114° 08' 28.27657" E	20.2220	9.233 km	HKST - HKSC MAX	HKSC
yes	0.014	2.7	8	18.02.2009 00:26:26	22° 19' 19.81953" N	114° 08' 28.27658" E	20.2233	12.211 km	HKOH - HKSC	HKSC
yes	0.013	2.7	8	18.02.2009 00:26:32	22° 19' 19.81906" N	114° 08' 28.27667" E	20.2282	12.211 km	HKOH - HKSC MAX	HKSC
yes	0.030	2.7	8	18.02.2009 00:26:21	22° 19' 19.81934" N	114° 08' 28.27652" E	20.2130	9.233 km	HKST - HKSC L1 Only	HKSC
yes	0.018	2.7	8	18.02.2009 00:25:58	22° 19' 19.81917" N	114° 08' 28.27654" E	20.2231	9.233 km	HKST - HKSC MAX L1 Only	HKSC
yes	0.020	2.7	8	18.02.2009 00:26:02	22° 19' 19.81893" N	114° 08' 28.27689" E	20.2178	11.419 km	HKPC - HKSC L1 Only	HKSC
yes	0.016	2.7	8	18.02.2009 00:25:47	22° 19' 19.81908" N	114° 08' 28.27662" E	20.2231	11.419 km	HKPC - HKSC MAX L1 Only	HKSC
yes	0.020	2.7	8	18.02.2009 00:26:26	22° 19' 19.81946" N	114° 08' 28.27660" E	20.2222	12.211 km	HKOH - HKSC L1 Only	HKSC
yes	0.018	2.7	8	18.02.2009 00:26:32	22° 19' 19.81912" N	114° 08' 28.27668" E	20.2276	12.211 km	HKOH - HKSC MAX L1 Only	HKSC

L1 Only

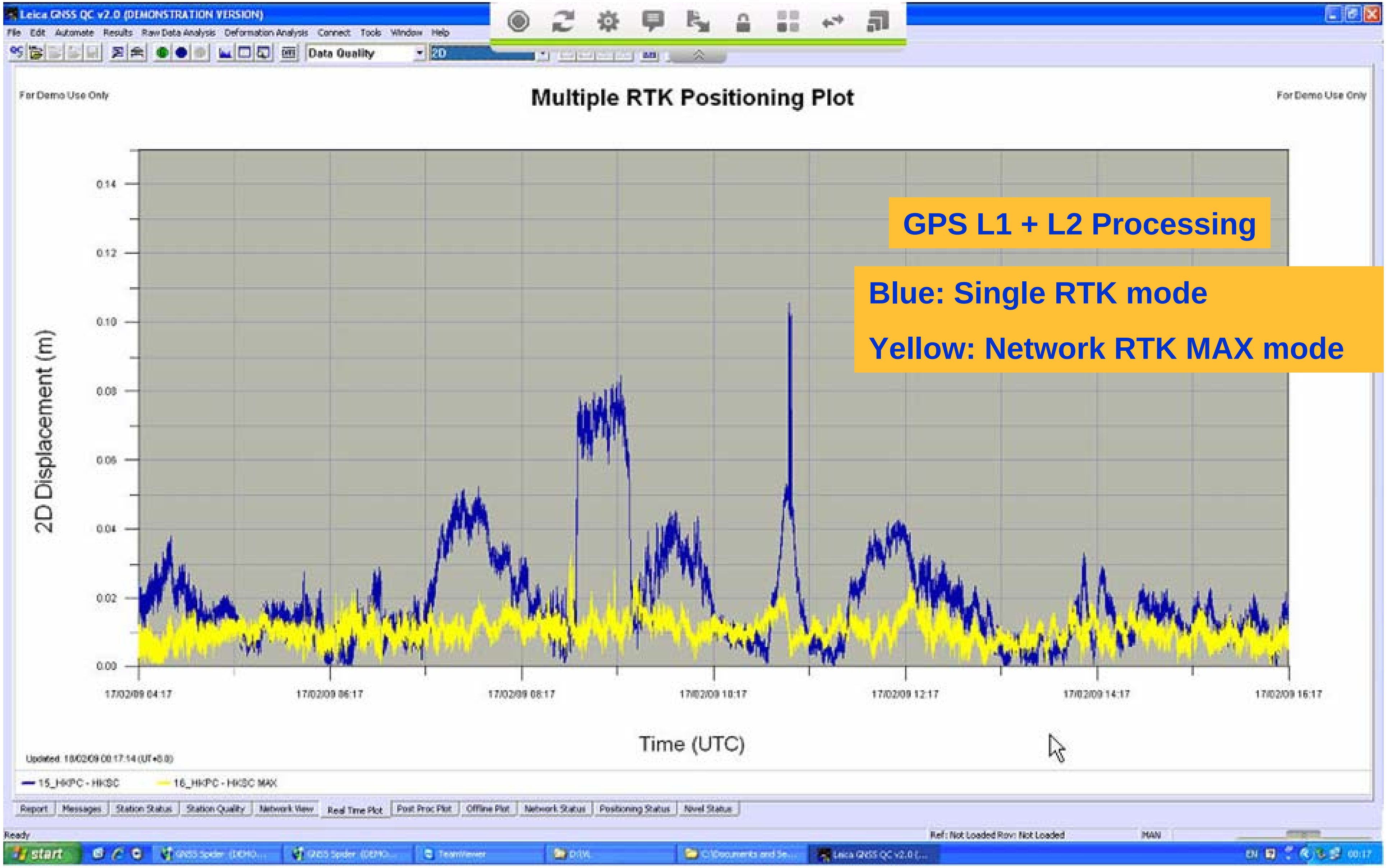
Compare different baselines result using Single RTK mode and the MAX mode !

Leica GNSS Spider Site Server with the Positioning option allows the operator to process any combination of baselines between the reference stations and the monitoring stations by using L1 & L2 or L1 only and by using different real-time ambiguities fixing strategies.

2D Scatter Plot – HKPC to HKSC (11.4km baseline) 12:00pm – 12:00am HK Time (12 hours measurement)



2D Displacement – HKPC to HKSC (11.4km baseline) 12:00pm – 12:00am HK Time (12 hours measurement)

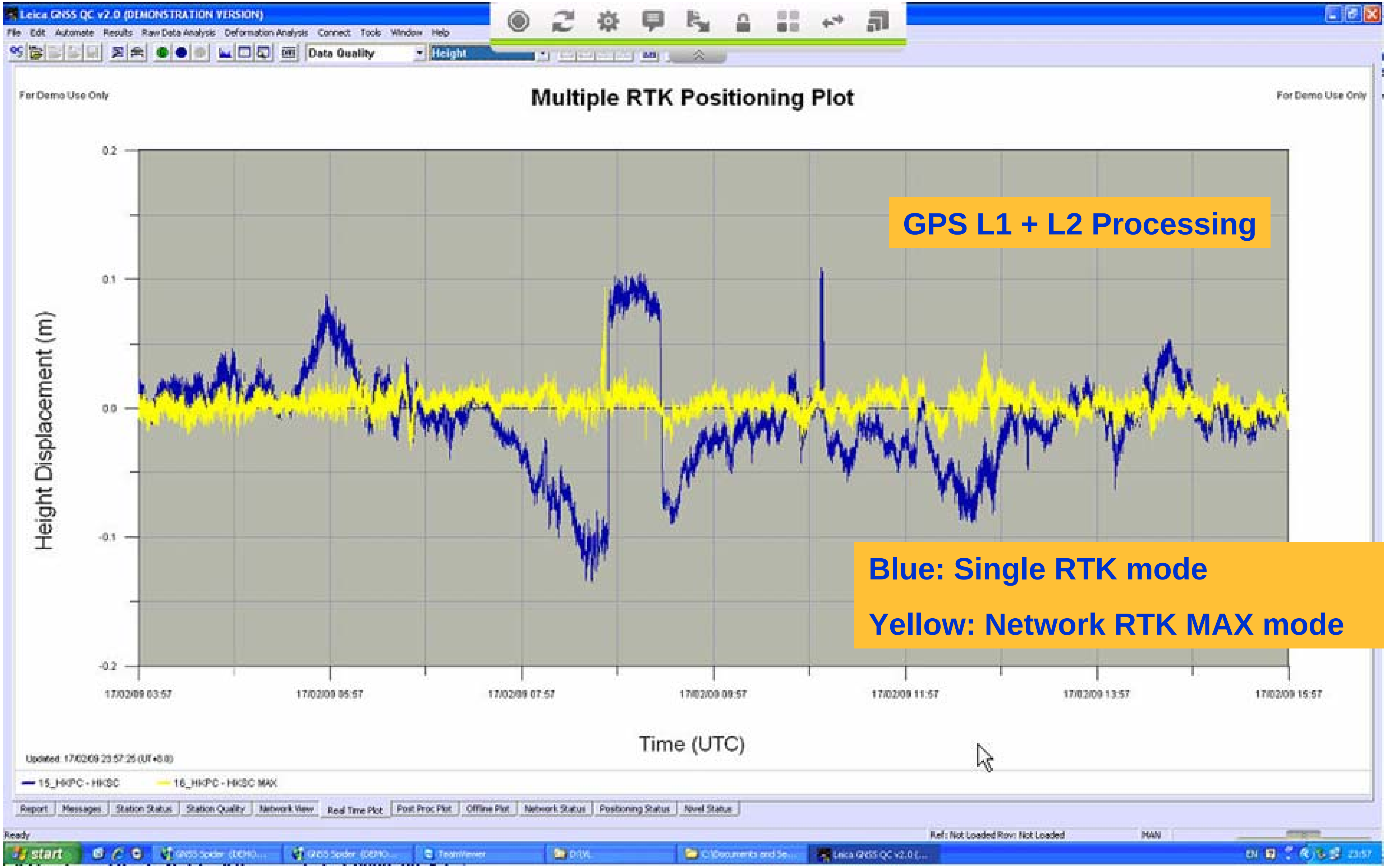


GPS L1 + L2 Processing

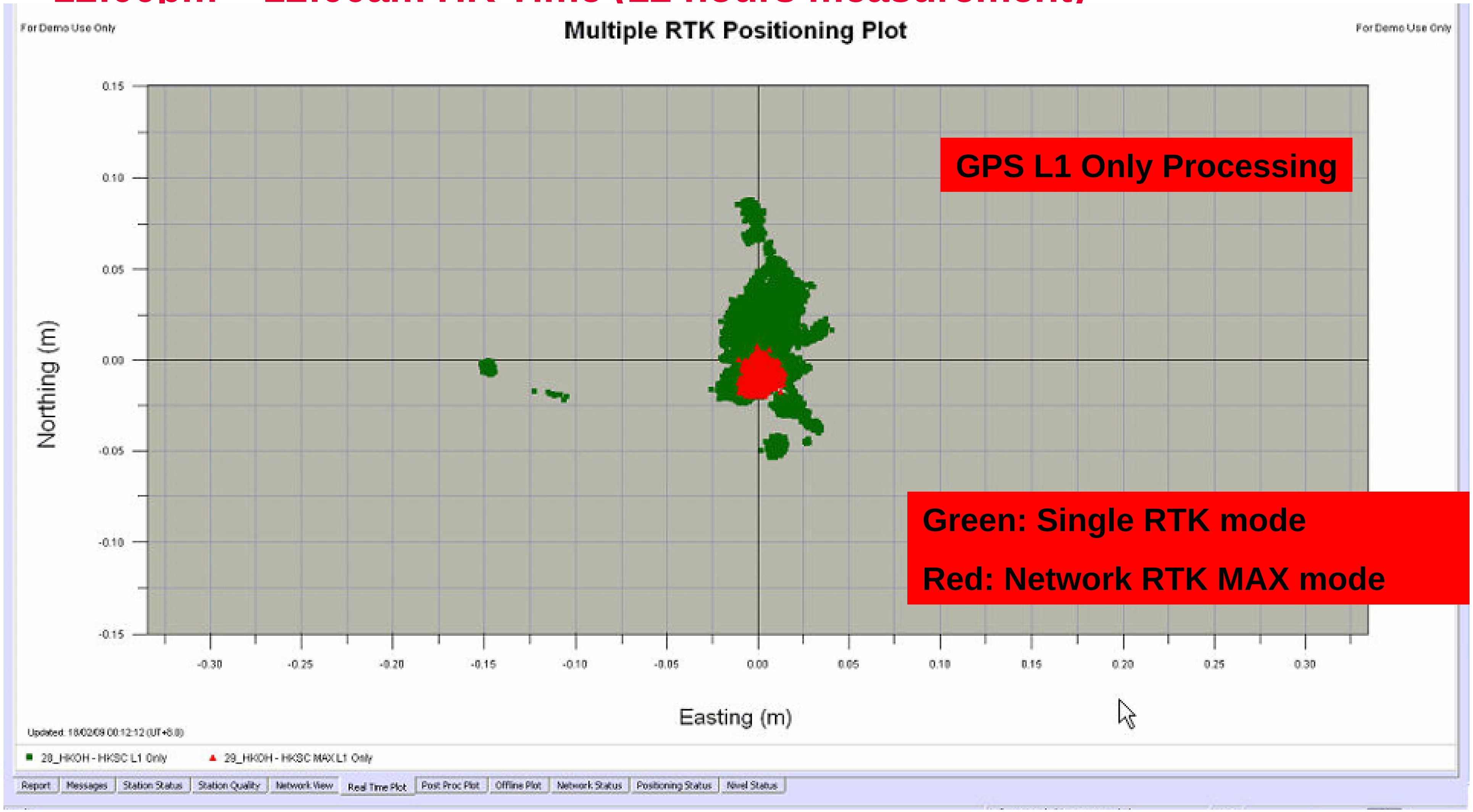
Blue: Single RTK mode

Yellow: Network RTK MAX mode

Height Displacement – HKPC to HKSC (11.4km baseline)
12:00pm – 12:00am HK Time (12 hours measurement)



Single GPS RTK vs GPS Network RTK MAX
Processing in Real Time L1 only GPS data
2D Scatter Plot – HKOH to HKSC (12.2km baseline)
12:00pm – 12:00am HK Time (12 hours measurement)



Single GPS RTK vs GPS Network RTK MAX

Processing in Real Time L1 only GPS data

2D Displacement Plot – HKOH to HKSC (12.2km baseline)

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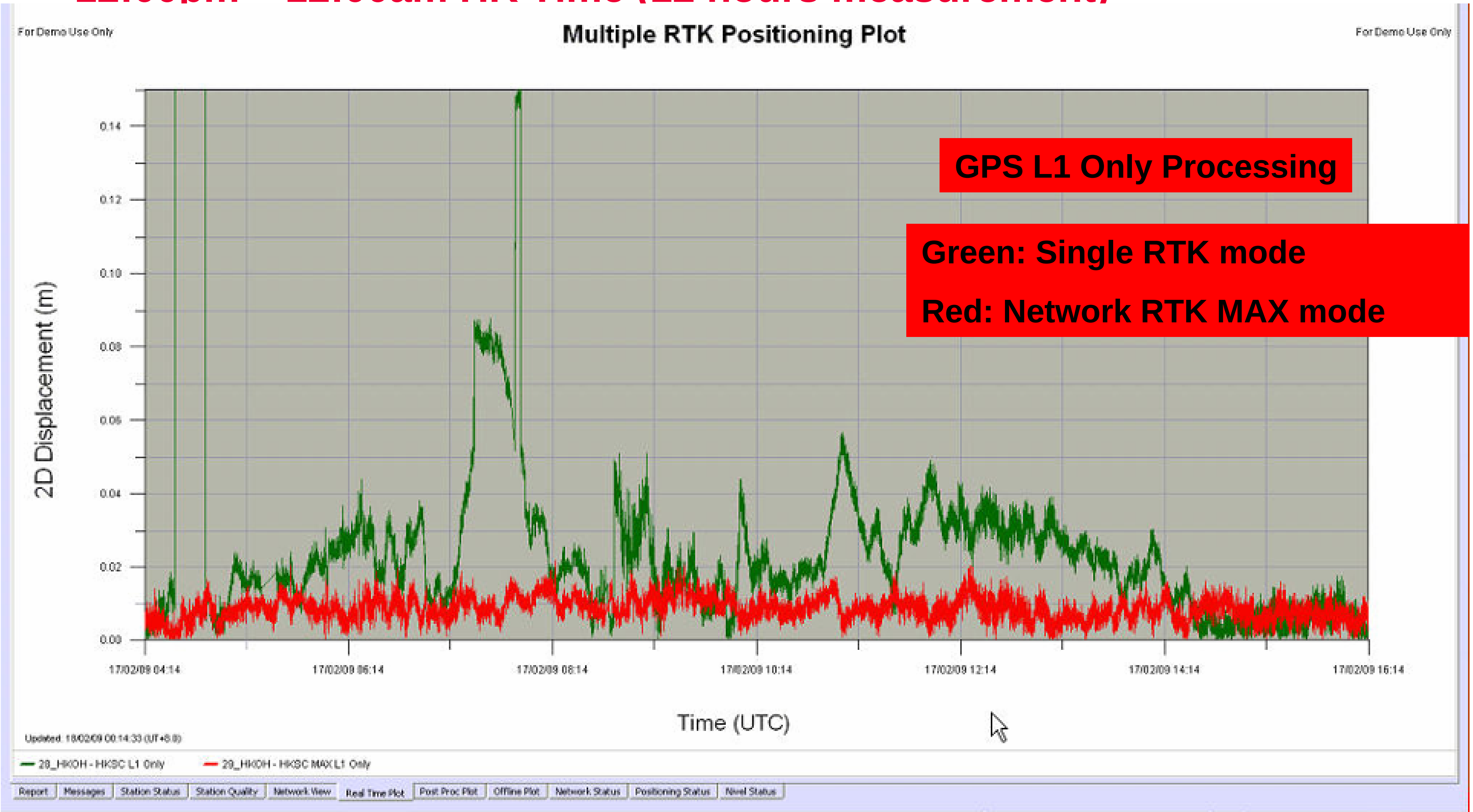

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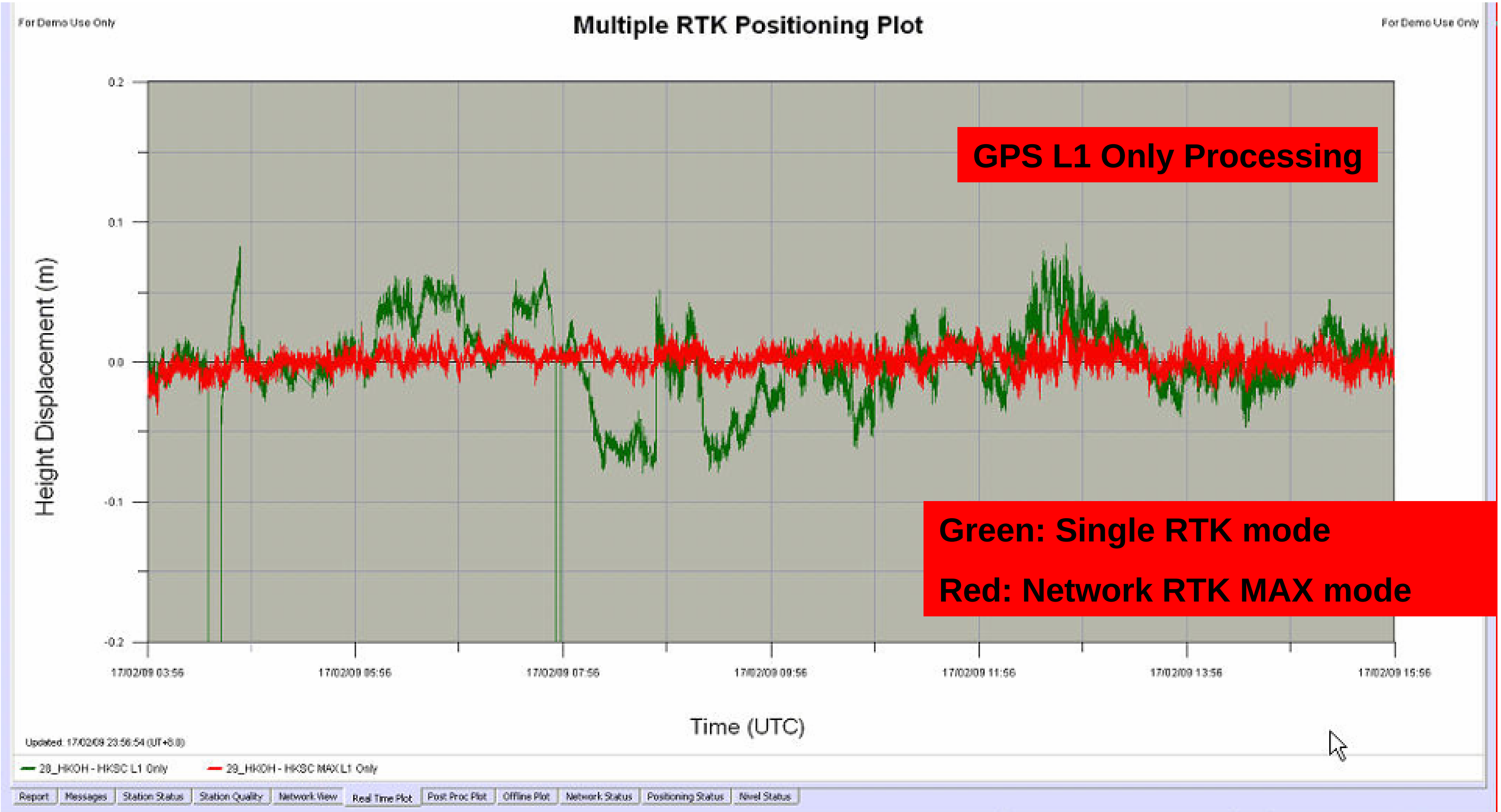
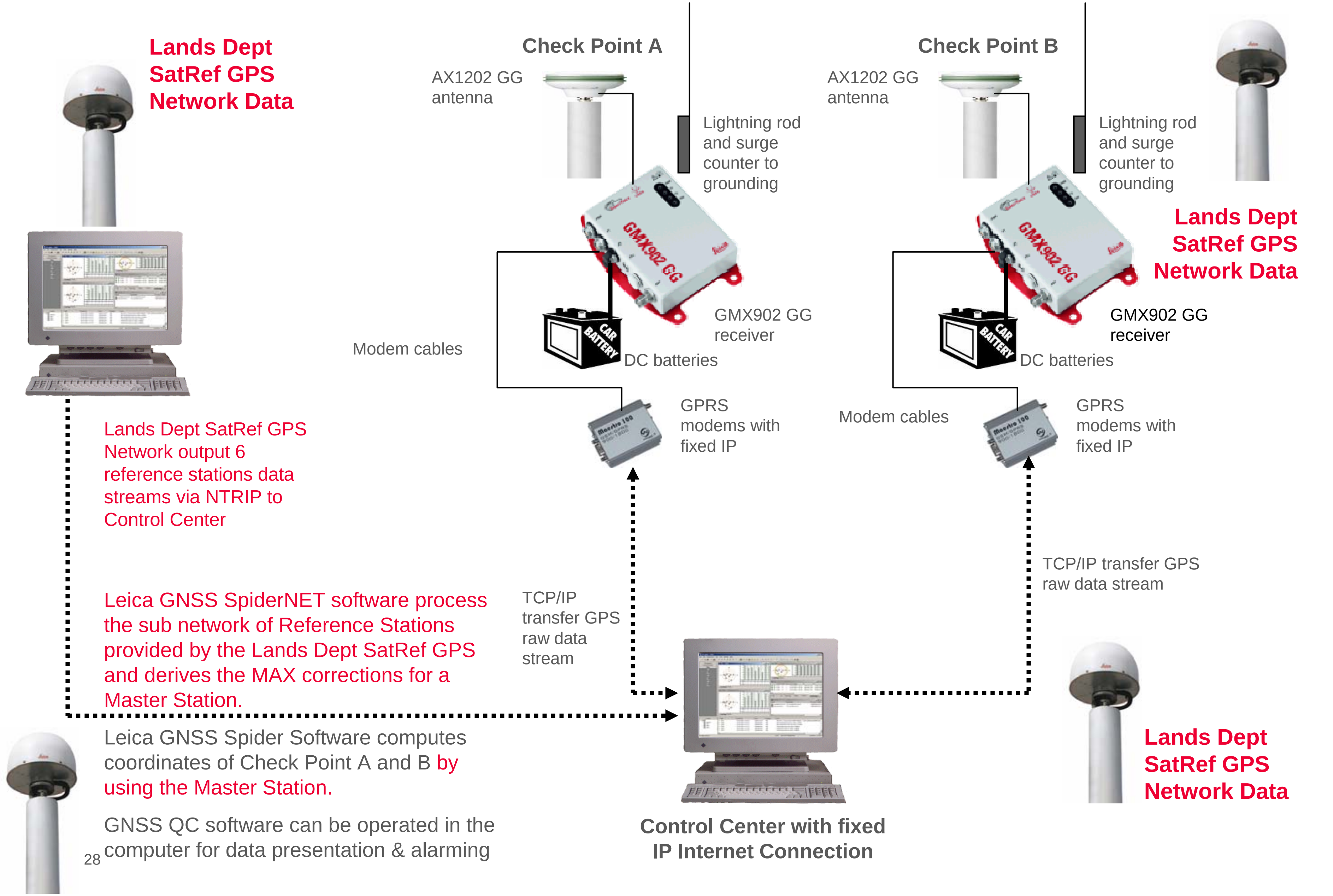
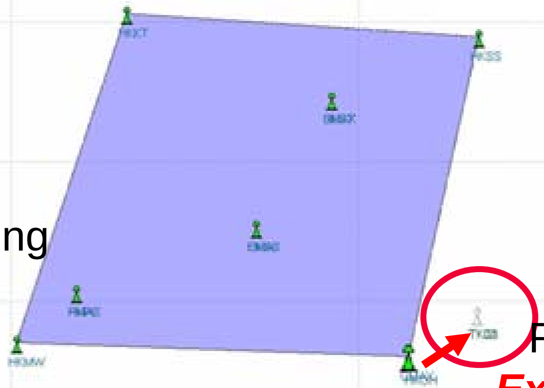


GNSS Network RTK aided Seawall Monitoring System Diagram

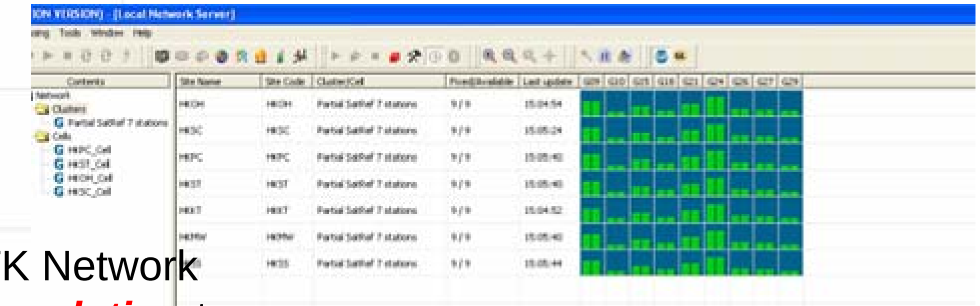


Trial test of modifying the seawall monitoring system using Centralized Network RTK – MAX correction approach

2 GNSS receivers share one antenna in the test. One receiver stream raw data to SpiderNet software via GPRS for centralized Network RTK monitoring. Another receiver receive act as a normal rover to get SatRef RTK correction for fixing the point on site



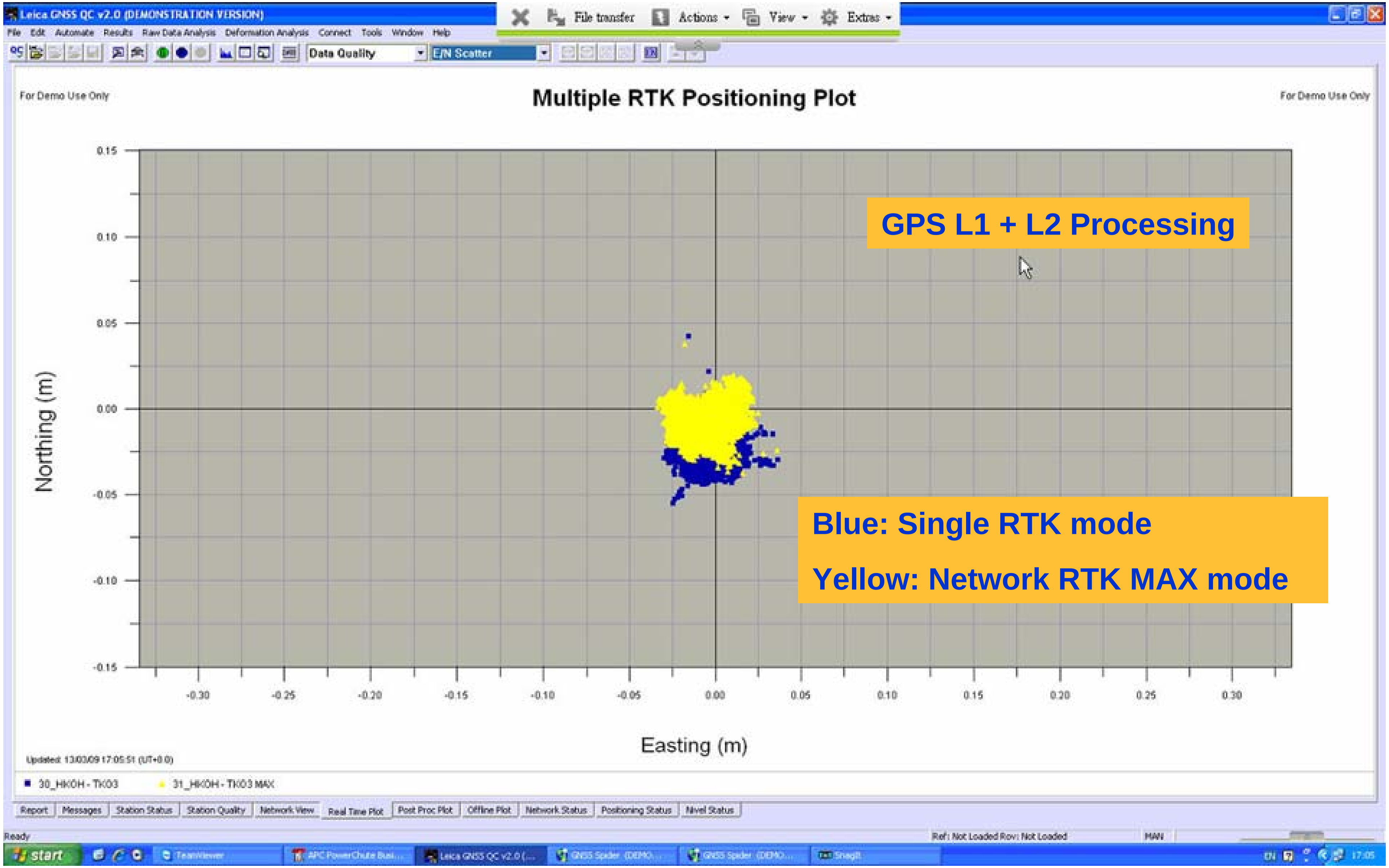
SpiderNet software operational interface during this testing



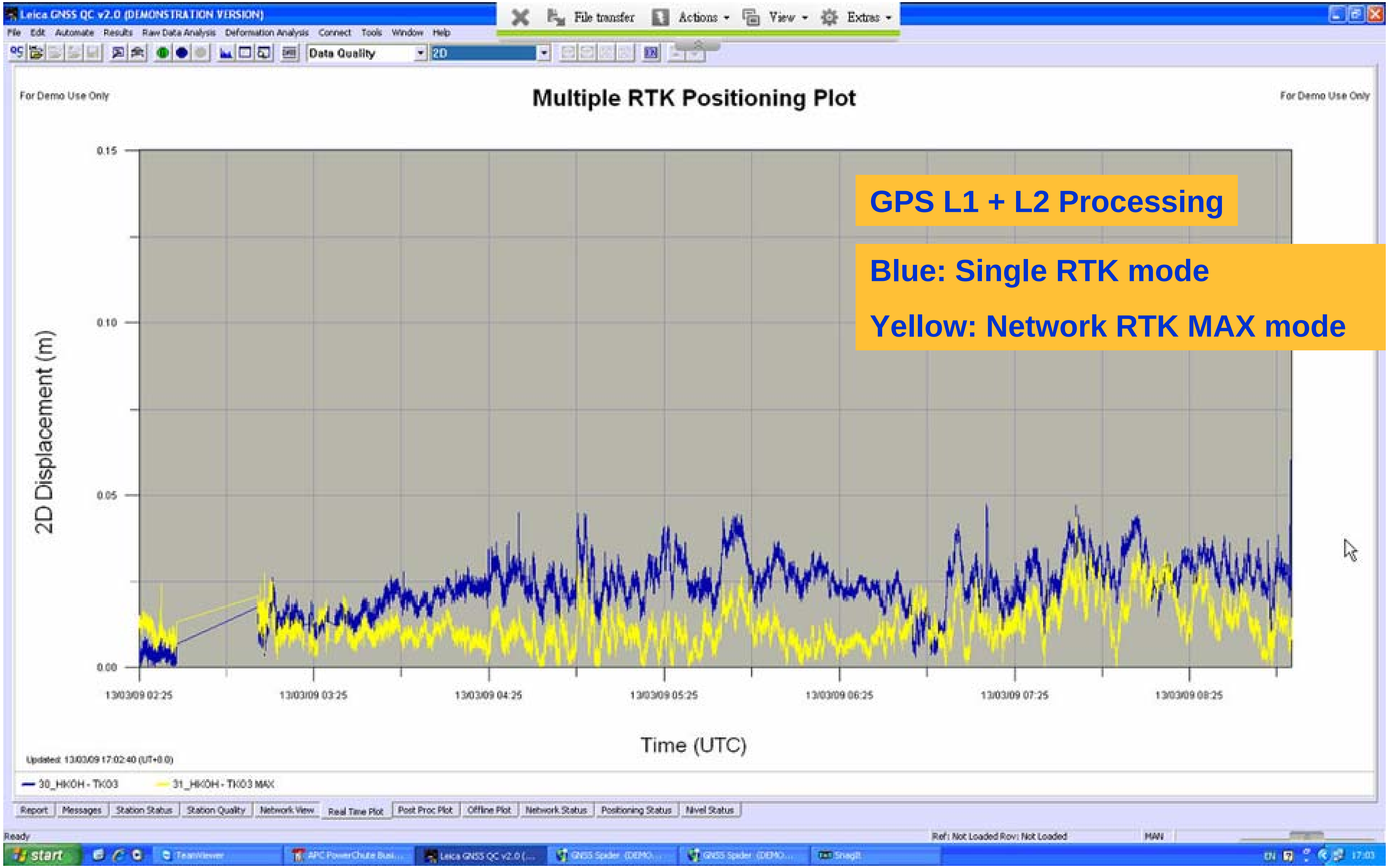
RTK Network ***Extrapolation*** to measure monitoring point

A cluster of 7 stations of SatRef network is formed to create MAX correction for computing the seawall monitoring point

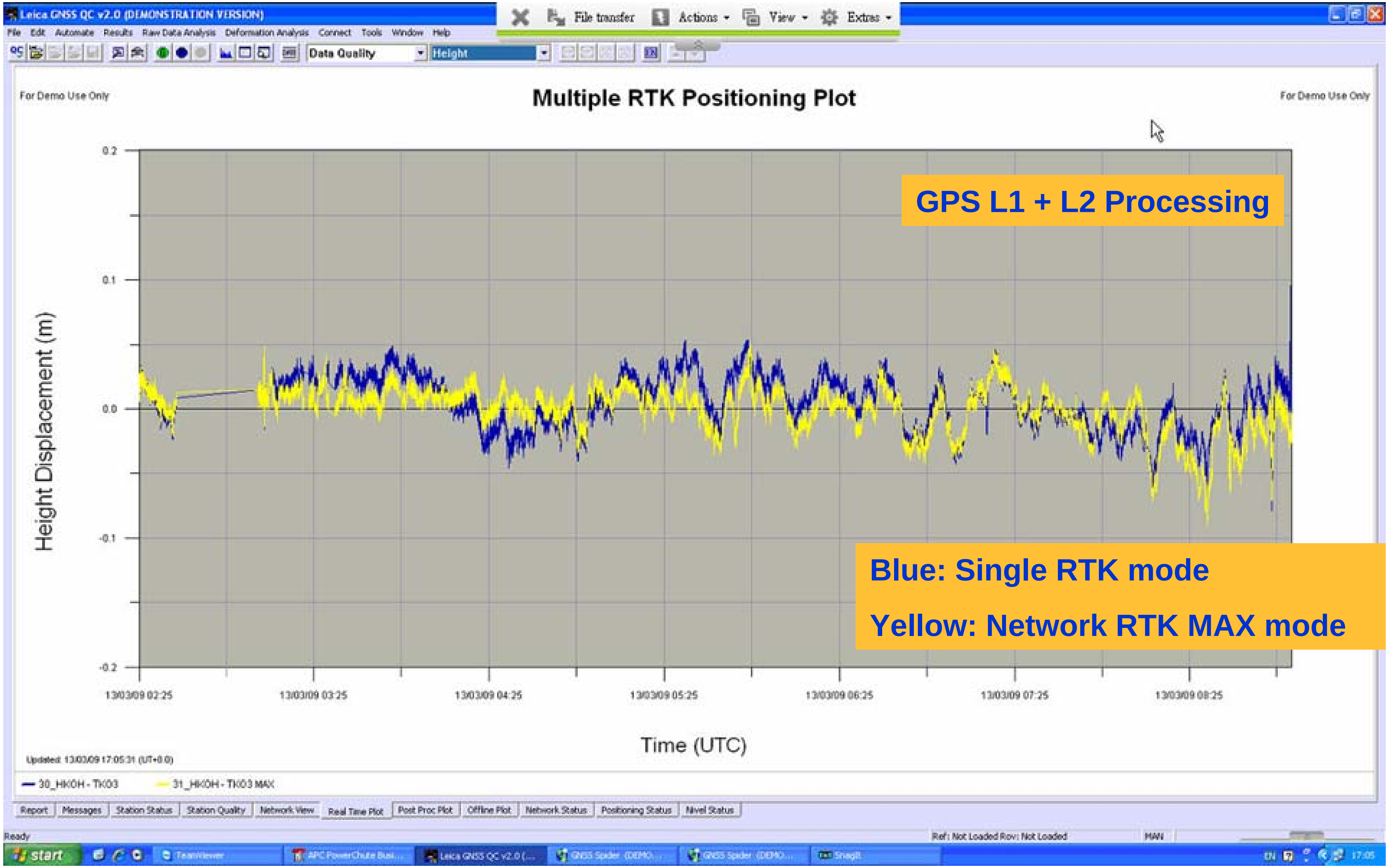
2D Scatter Plot – HKOH to TKO3 (4.86km baseline)
10:30am – 05:00pm HK Time (6.5 hours measurement)



2D Displacement Plot – HKOH to TKO3 (4.86km baseline) 10:30am – 05:00pm HK Time (6.5 hours measurement)



Height Displacement Plot – HKOH to TKO3 (4.86km baseline)
10:30am – 05:00pm HK Time (6.5 hours measurement)



Summary of Key Findings

The practical results are demonstrating that the combination of GNSS Network RTK resources within a GNSS Monitoring projects have outstanding advantages :

- **Users can achieve very consistent and homogeneous accurate monitoring data result over the whole GNSS network area (even outside the network region by extrapolation)**

- **Higher chance and quicker RTK initialization for monitoring points**

- **The distance dependent error is mitigated and is especially beneficial for monitoring projects located in the low latitude band where the ionosphere turbulences are affecting seriously on the GNSS signals processing**

- **Possibility to mix dual frequency receivers (GNSS Network) with affordable single frequency receivers for slow motion monitoring**

- **No need to establish single base station for monitoring task if there is a GNSS network service available, save cost**

- **Multiple reference stations in a network provide good redundancy and high availability for continuously monitoring tasks**

Thank You Very Much for Your Attention

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