



大地測量課程

衛星定位測量 (Satellite Positioning)

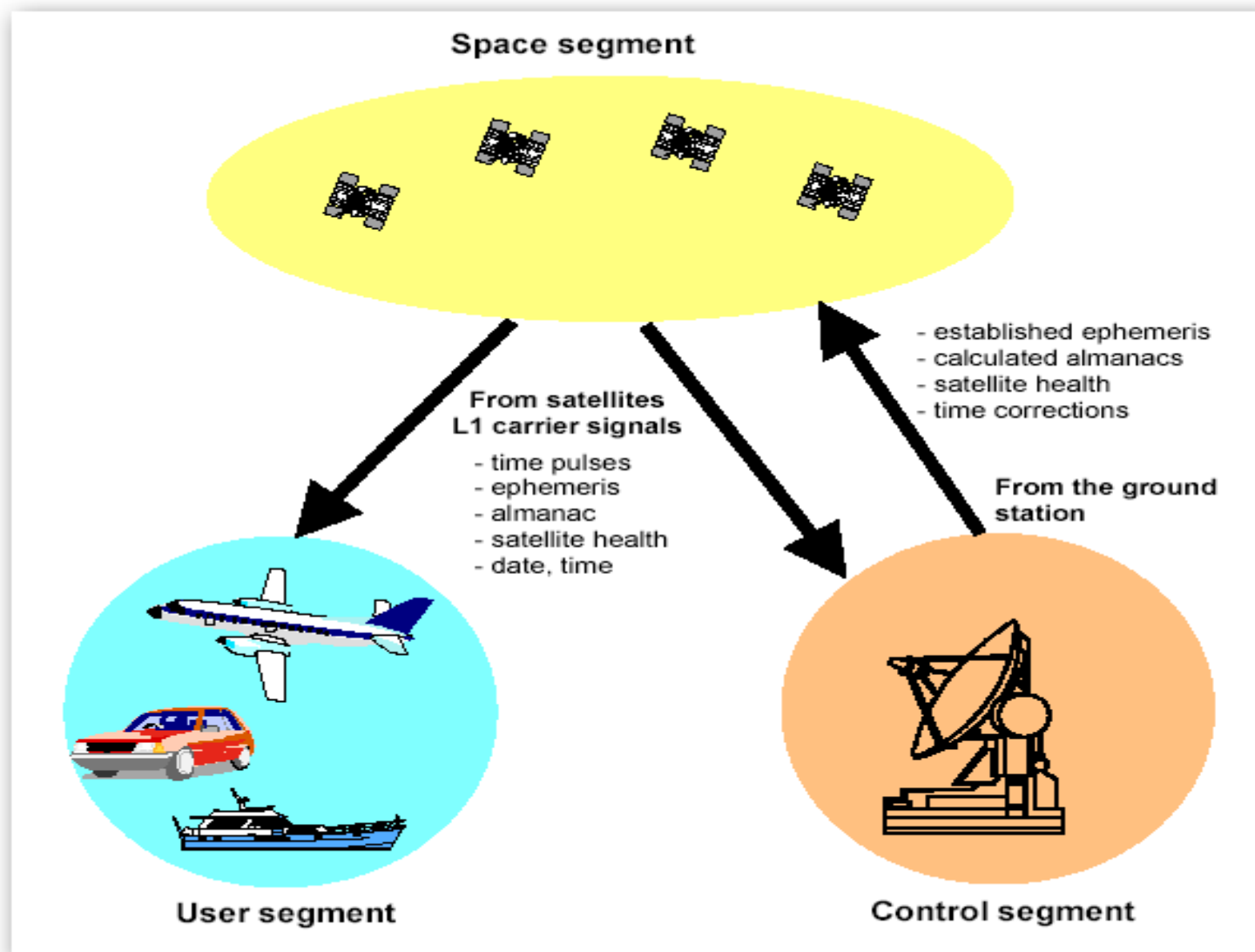
張嘉強

健行科技大學
應用空間資訊系



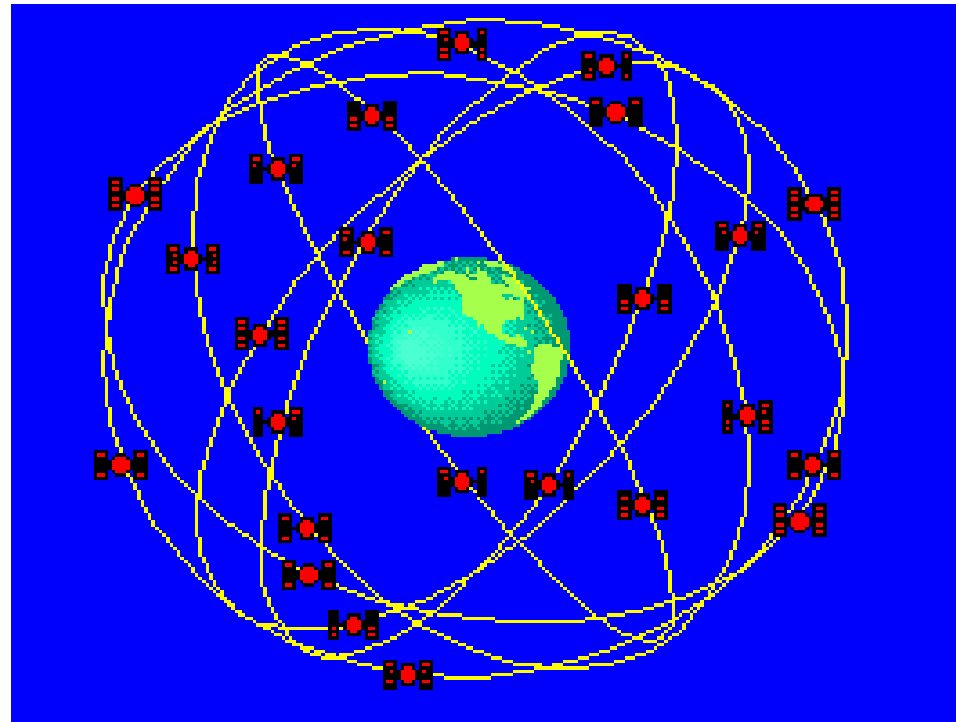


GPS運作單元





GPS衛星分布



21+3(24+3)顆衛星

20200公里高度

全球3-D分佈

6個軌道面

12小時週期

每一時刻至少4顆衛星

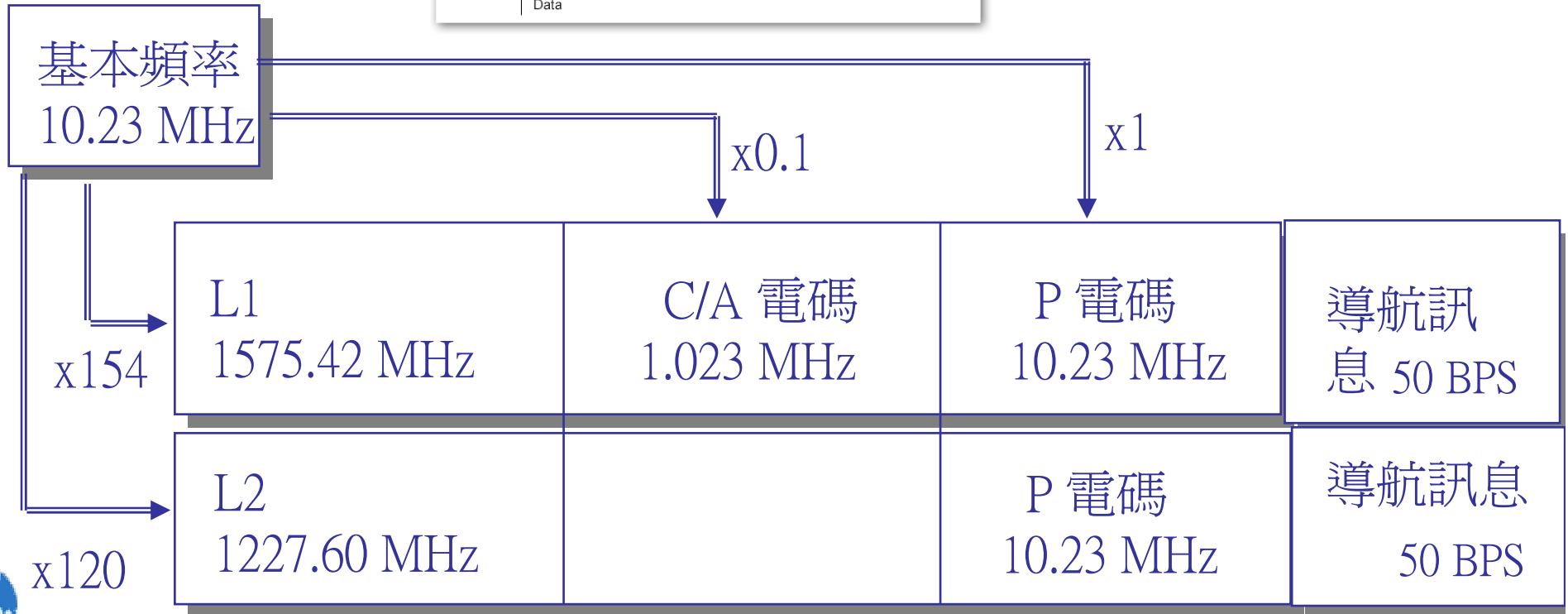
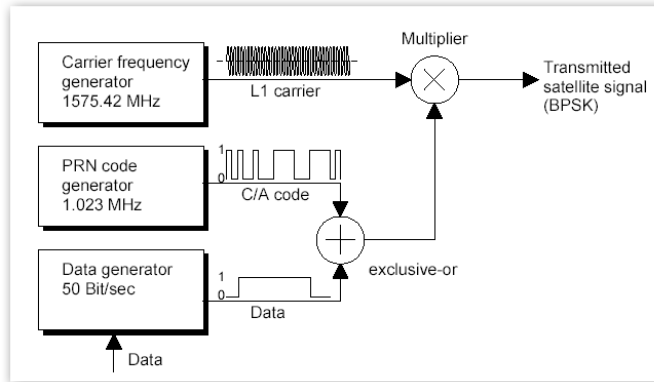
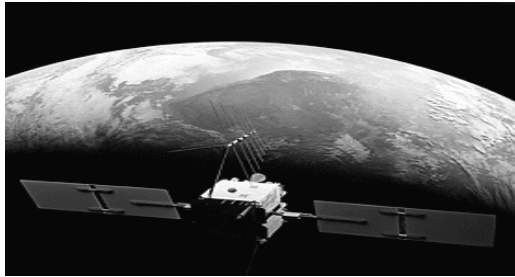
55度軌道傾角

地平面以上5小時



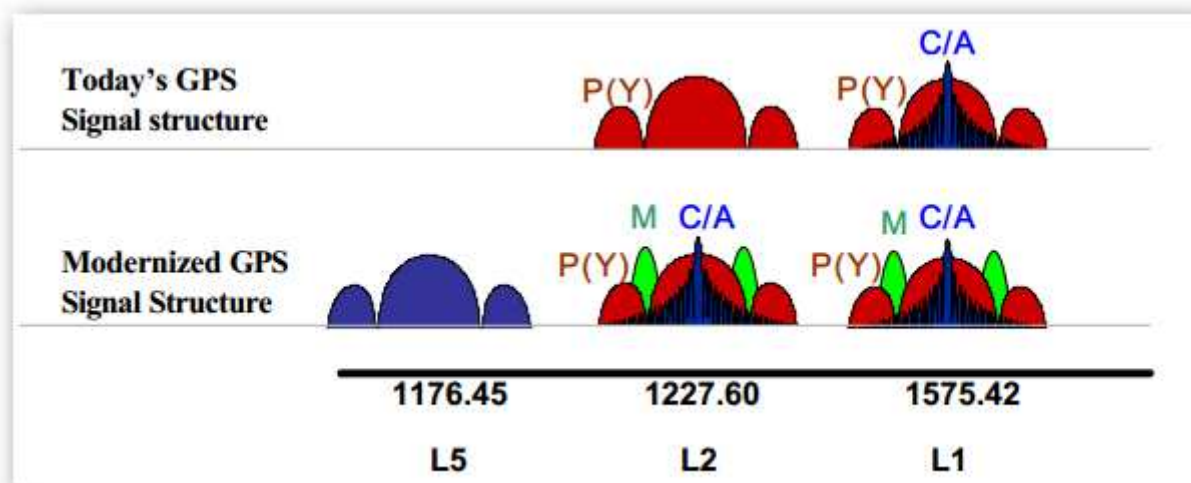
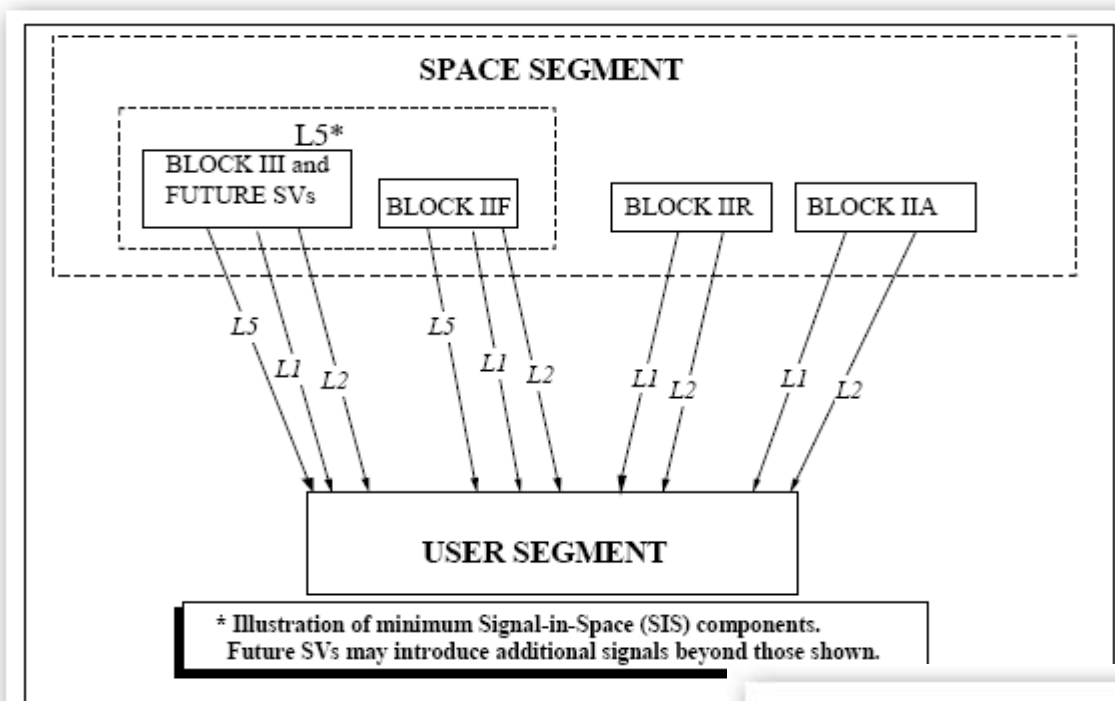


GPS信號結構(原設計)



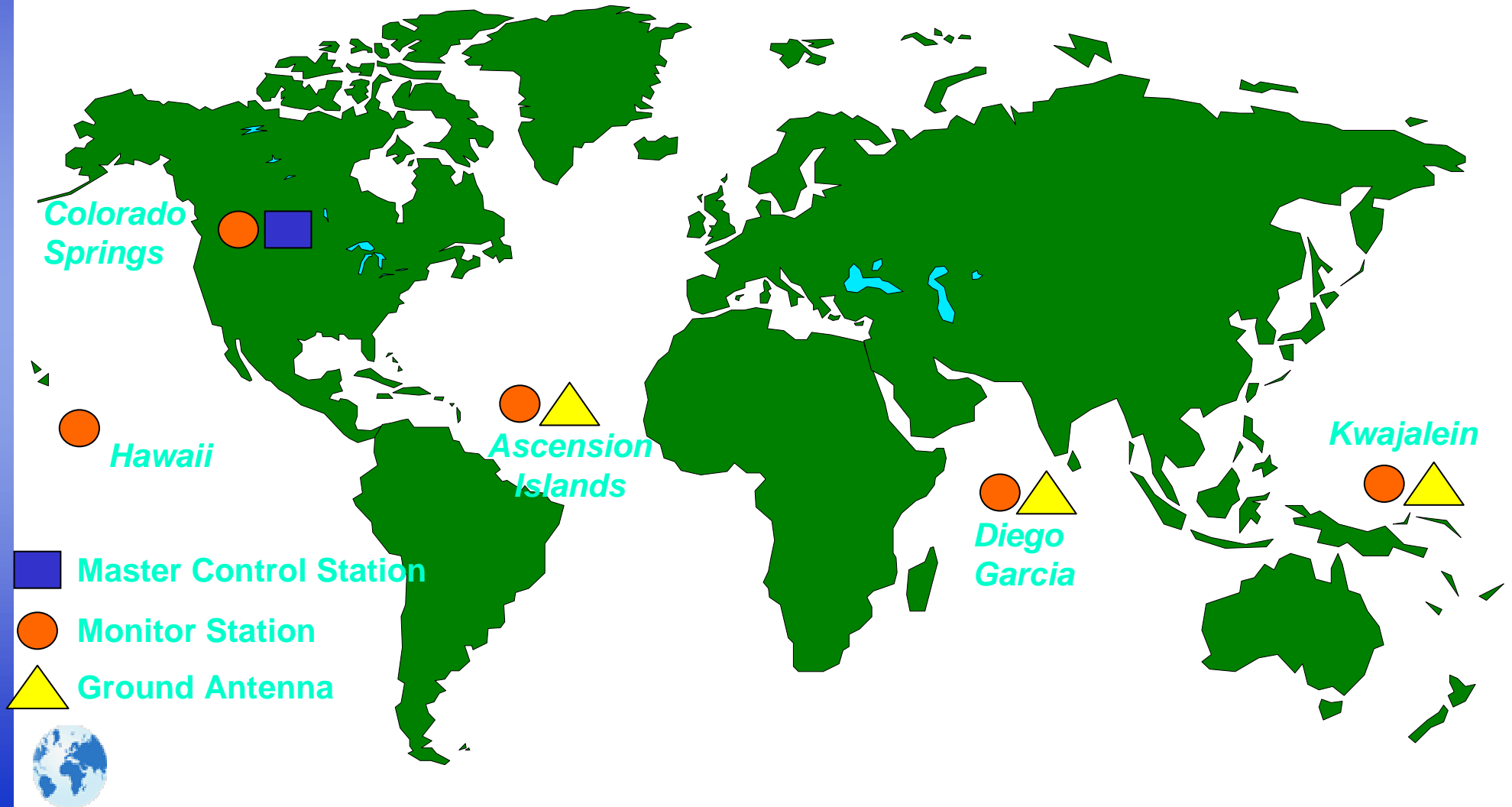


GPS三頻信號(現代化)



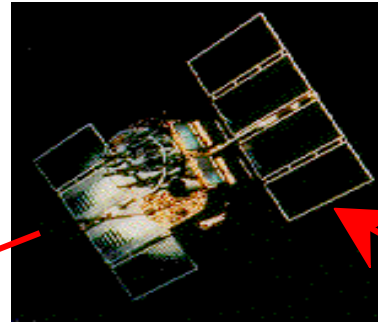


GPS地面監控站(原設計5站)

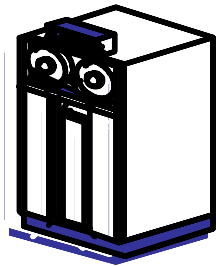




監控站運作程序

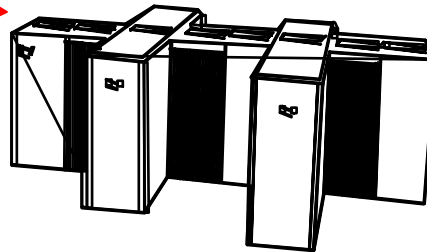


- *Observe ephemeris and clock*

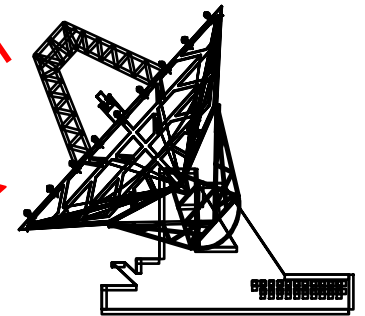


Monitor Stations

- *Correct Orbit and clock errors*
- *Create new navigation message*



Falcon AFB



Upload Station





GPS接收機類型

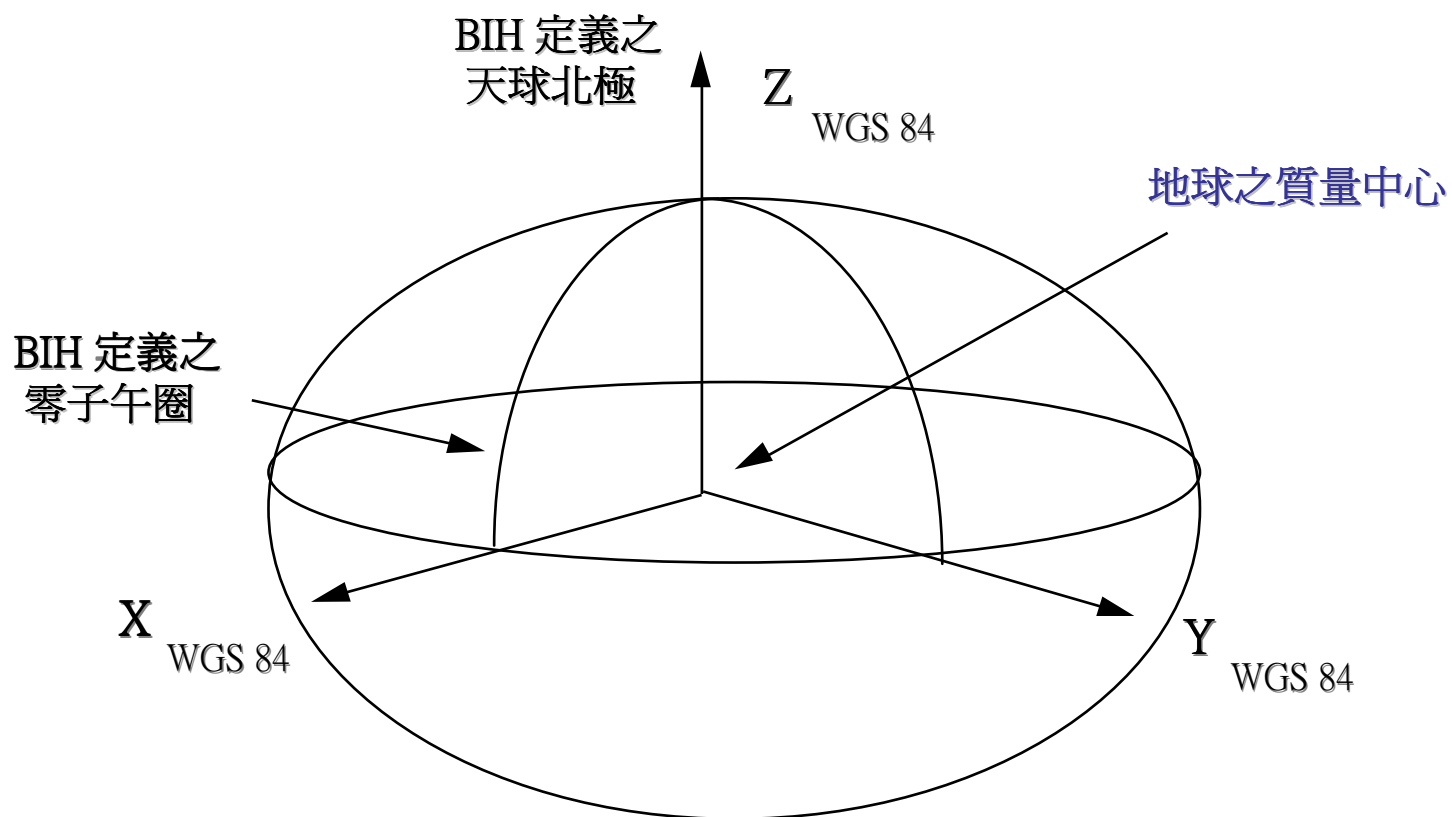
- 導航型 (L1 C/A code range)
 - 導航器
 - 軌跡紀錄器
- 大地型 (L1/L2 phase + C/A + P)
 - 野外型
 - 追蹤站型





GPS坐標基準 (WGS84)

World Geodetic System 1984



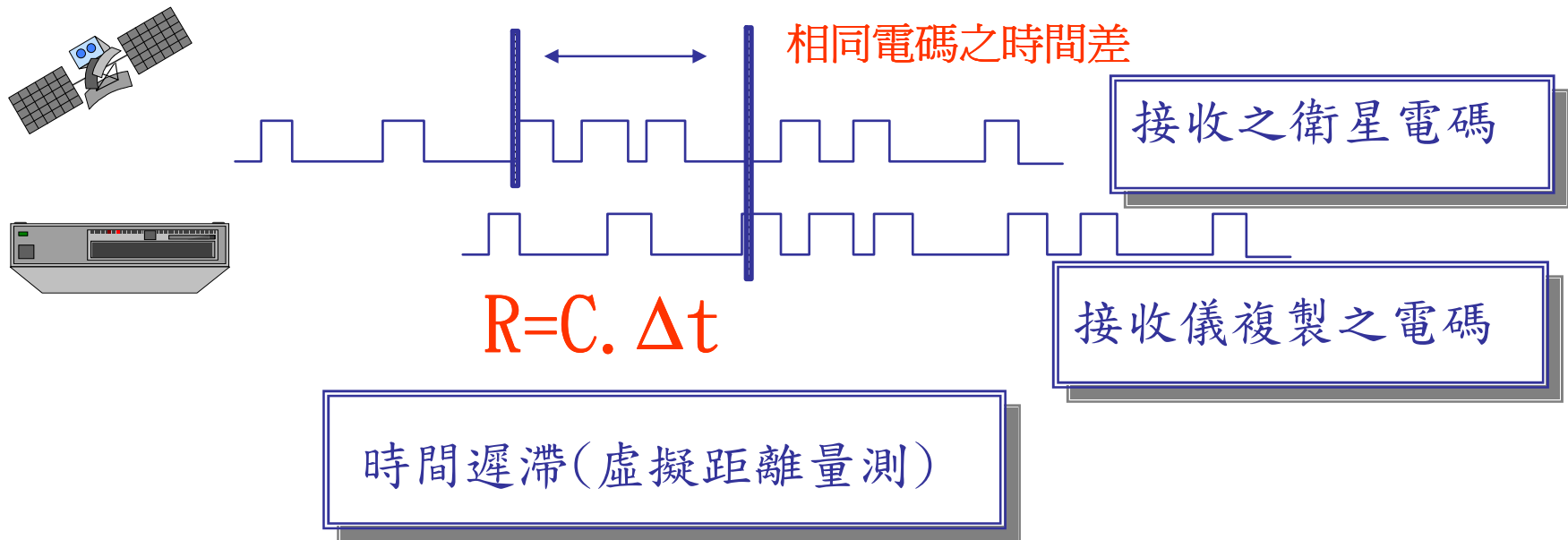
Identical to ITRF and TWD97!





GPS基本觀測量

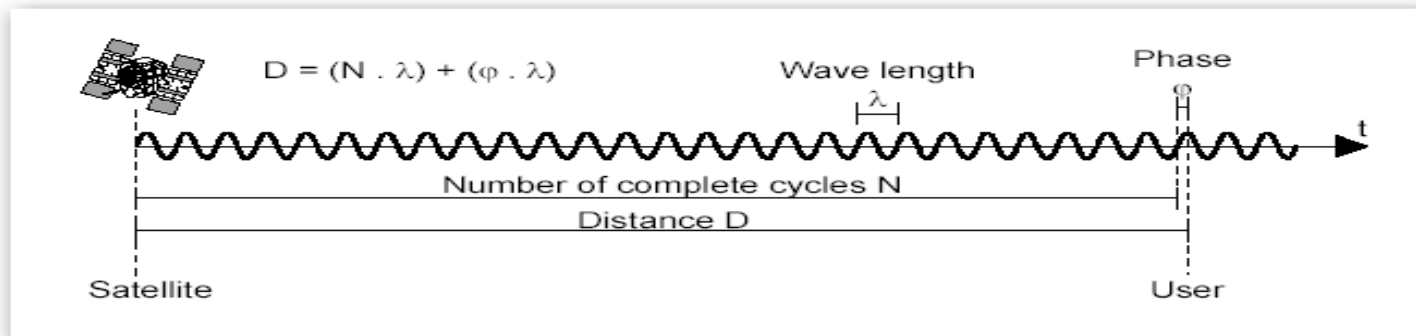
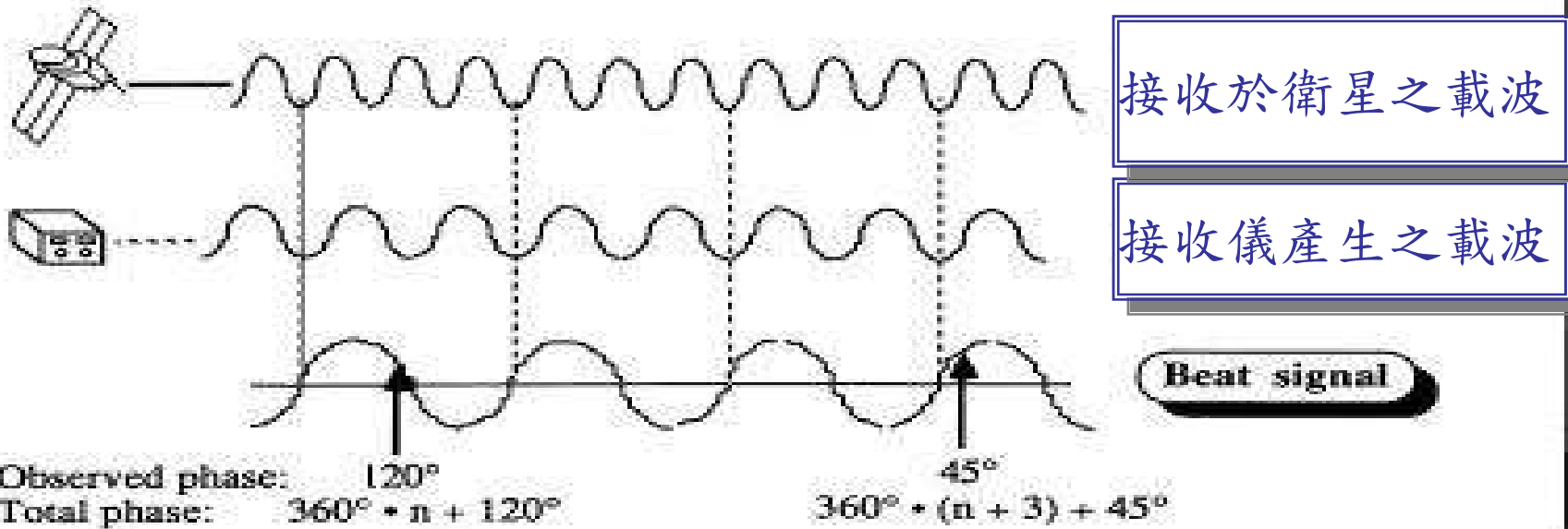
- 虛擬距離 (pseudo-range)





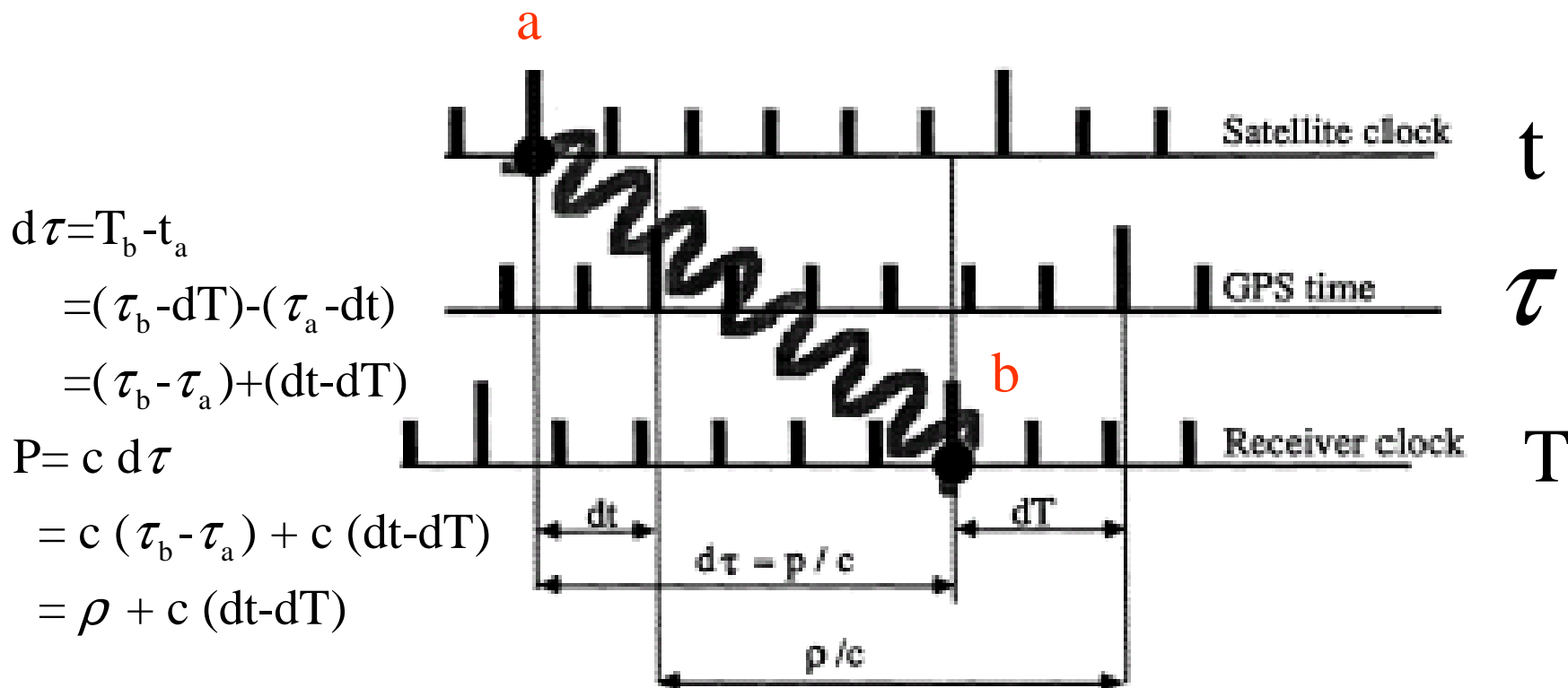
GPS基本觀測量

- 載波相位 (carrier phase)





虛擬距離觀測方程式



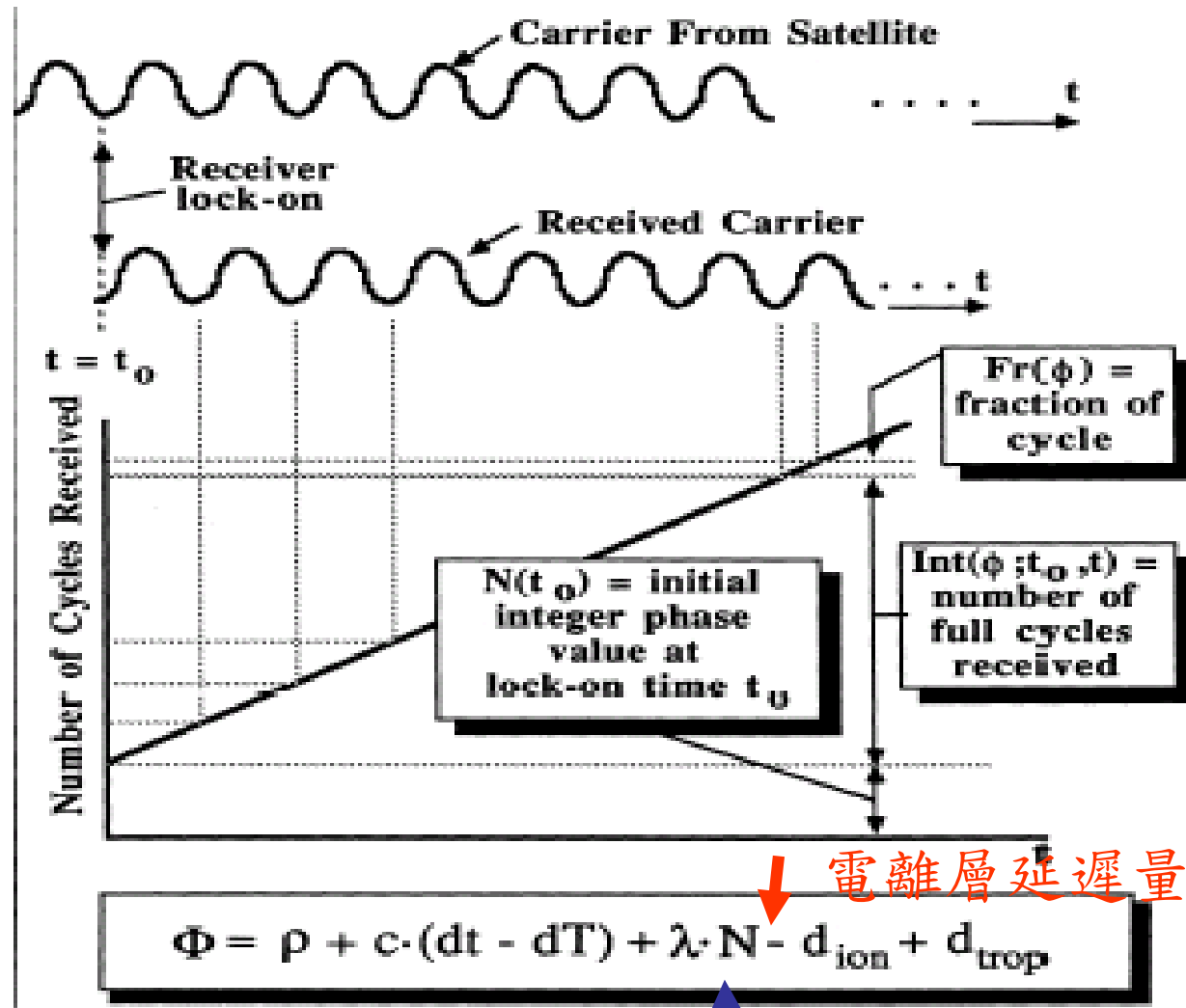
虛擬距離 真實距離 衛星及接收器時錶差
電離層及對流層延遲

$$p = \rho + c \cdot (dt - dT) + d_{ion} + d_{trop}$$





載波相位觀測方程式



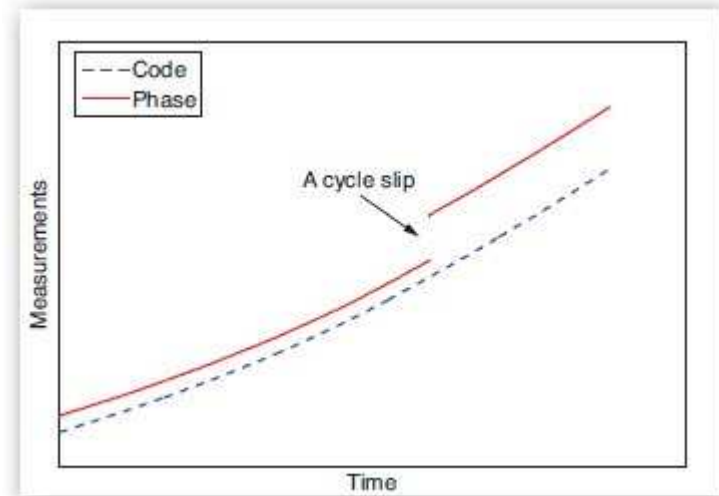
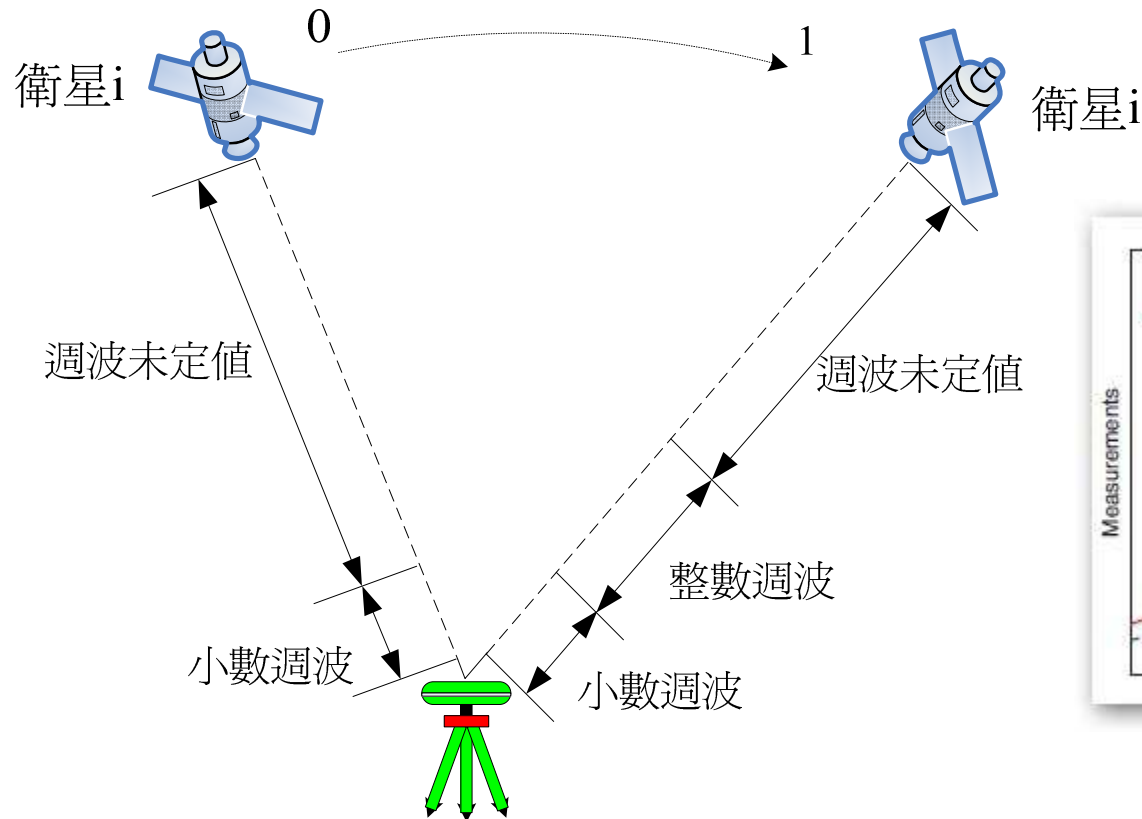
電離層延遲量變號

相位起始未定值(ambiguity)



相位起始整數週波未定值

Integer ambiguity (N)

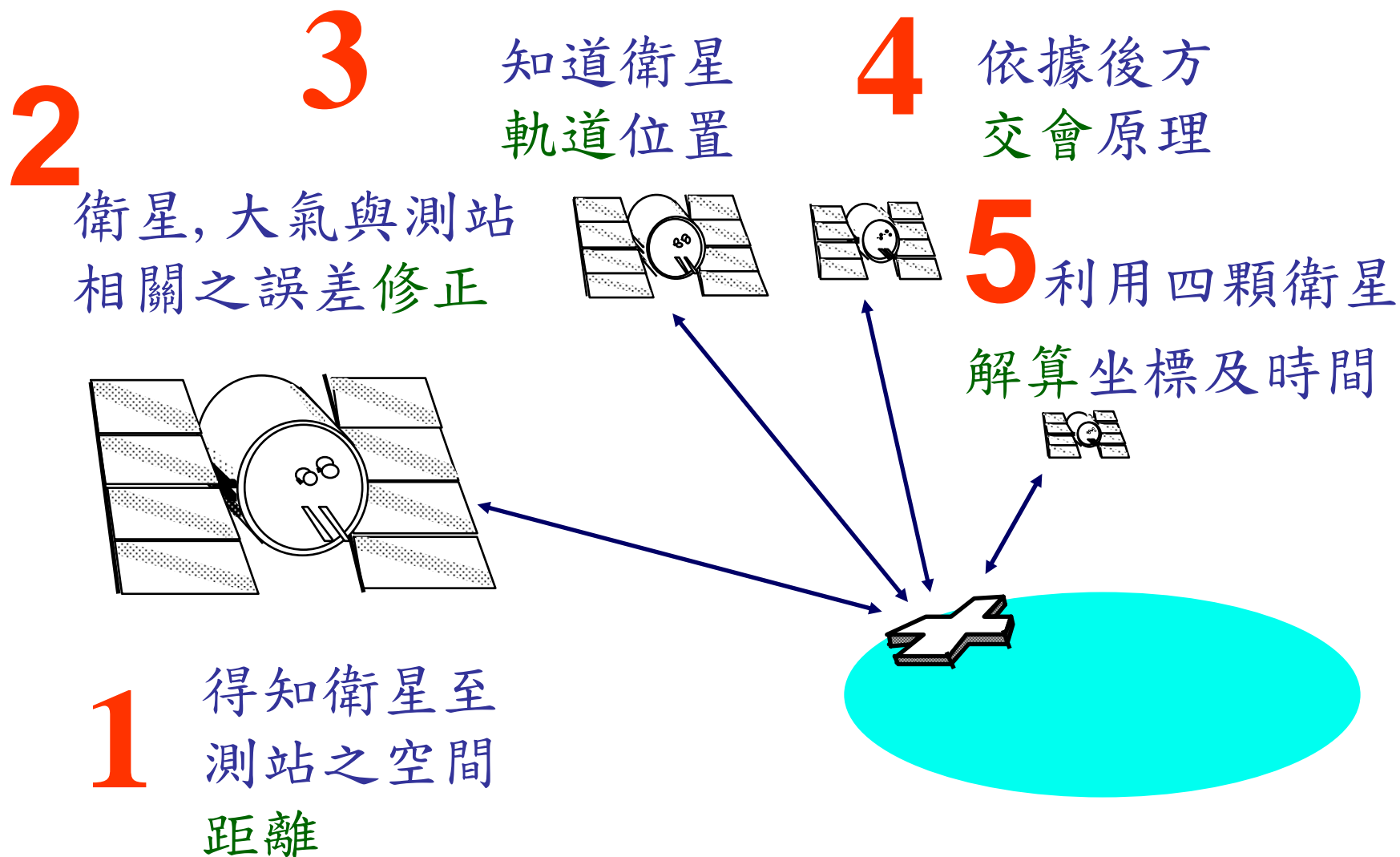


Remain constant if no **cycle slip** (周波脫落) occurred / Solved for RTK



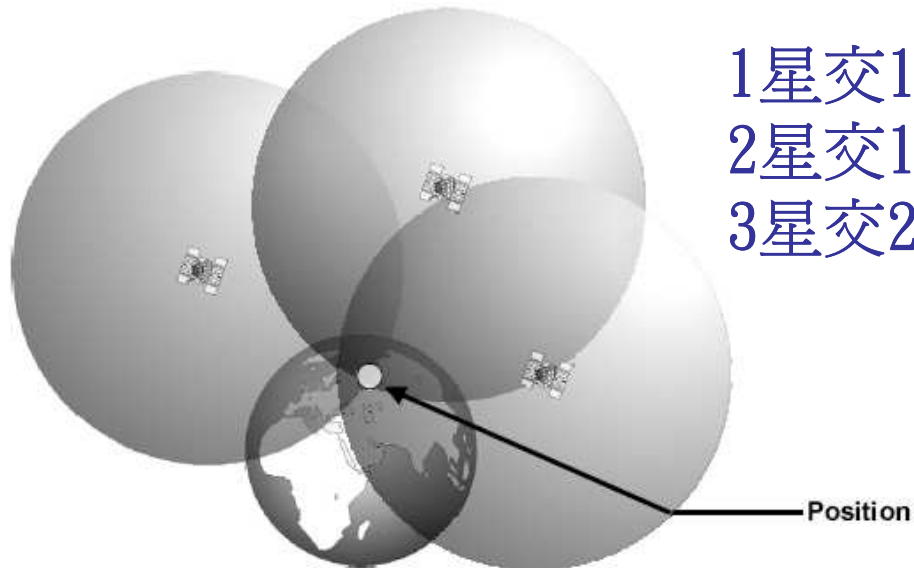
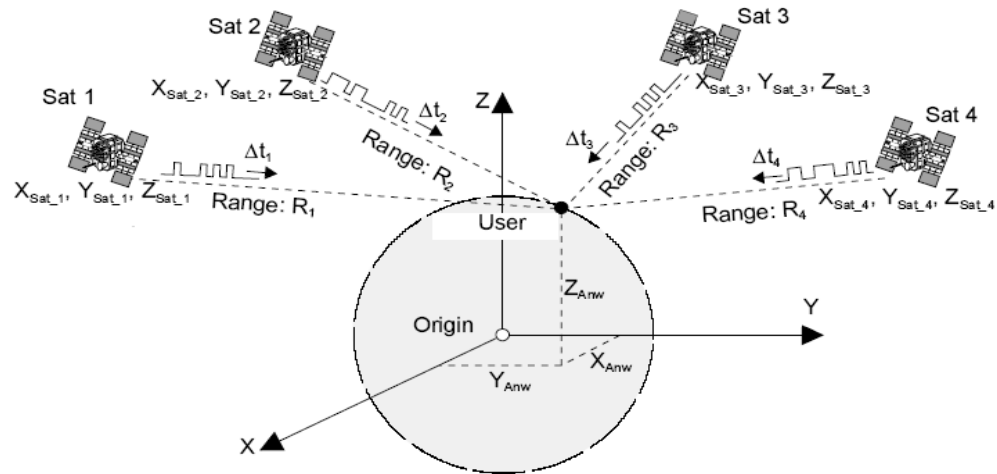
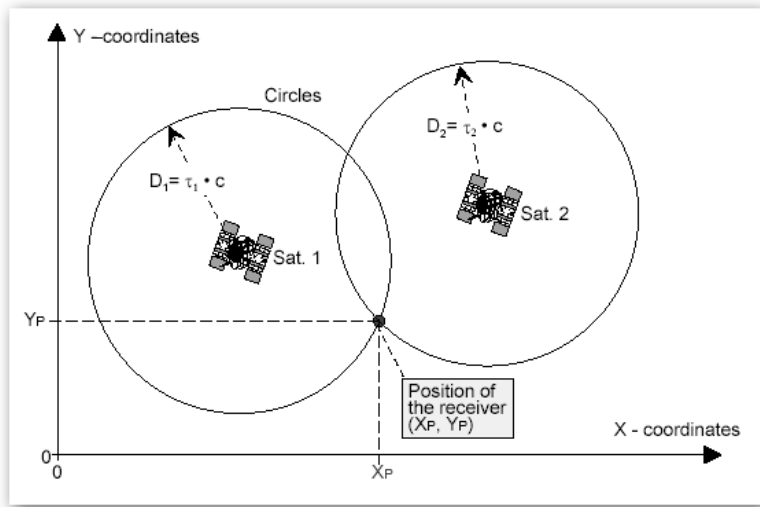


GPS定位基本要素

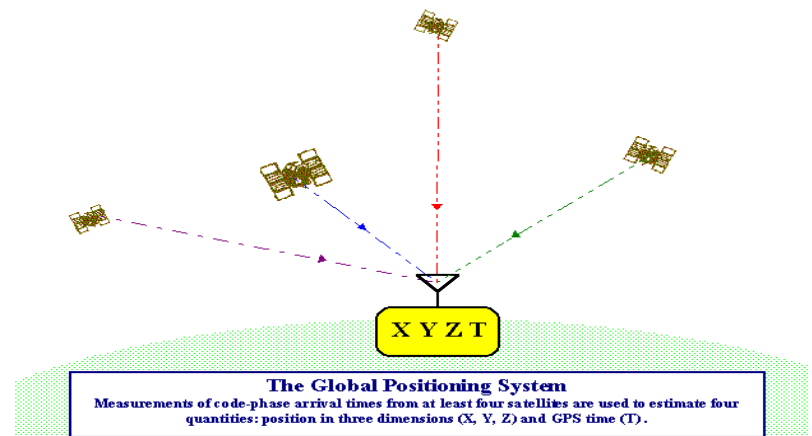




交會定位原理



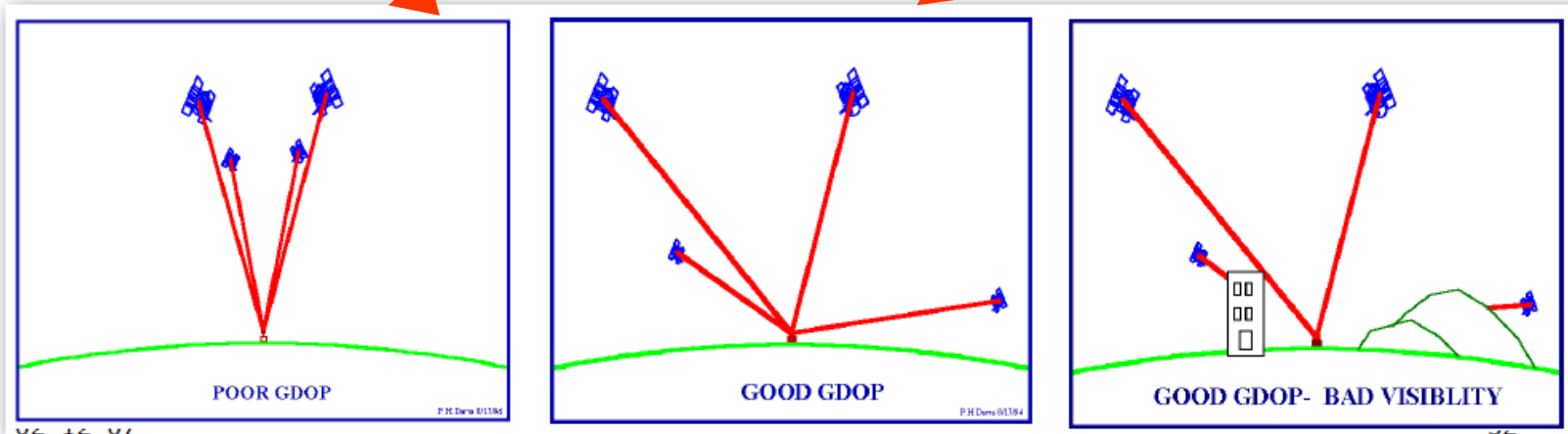
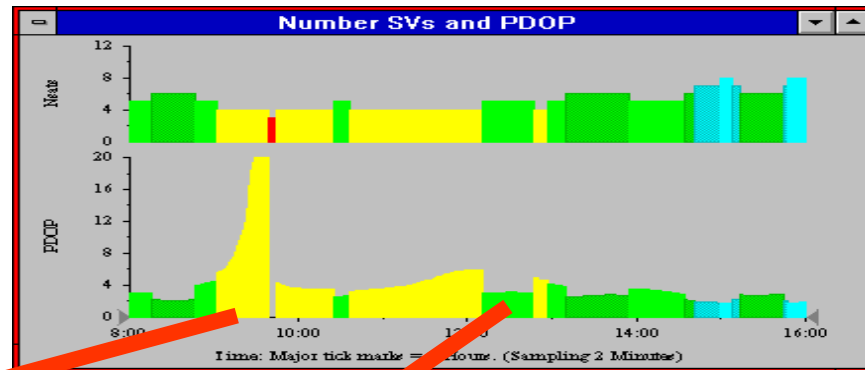
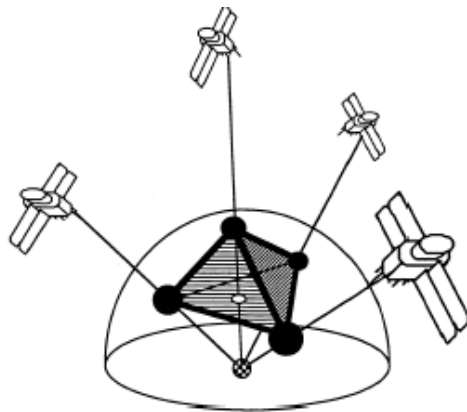
1星交1球
2星交1圓
3星交2點





精度稀釋因子(DOP)

Dilution of Precision



幾何條件差 = DOP值大 = 定位精度差

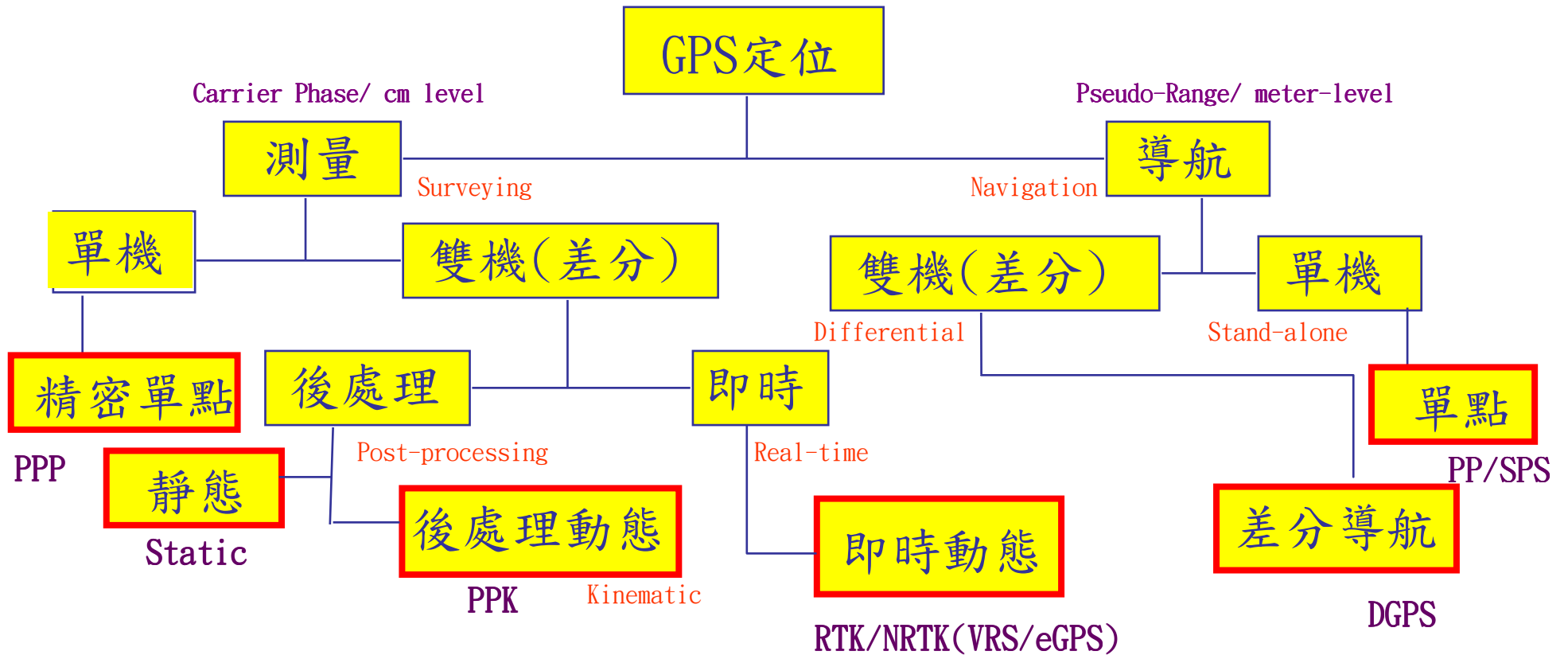
$$\sigma = \text{DOP} \cdot \sigma_0$$

Positioning accuracy = Geometry (Dilution of Precision) * Measurement accuracy



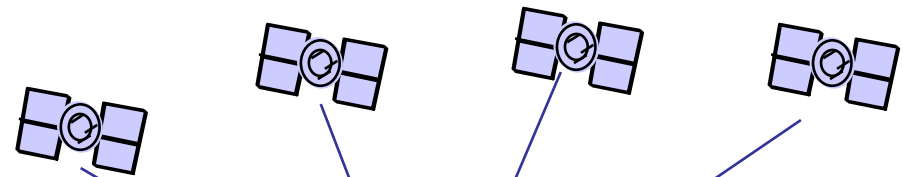


GPS定位方法分類



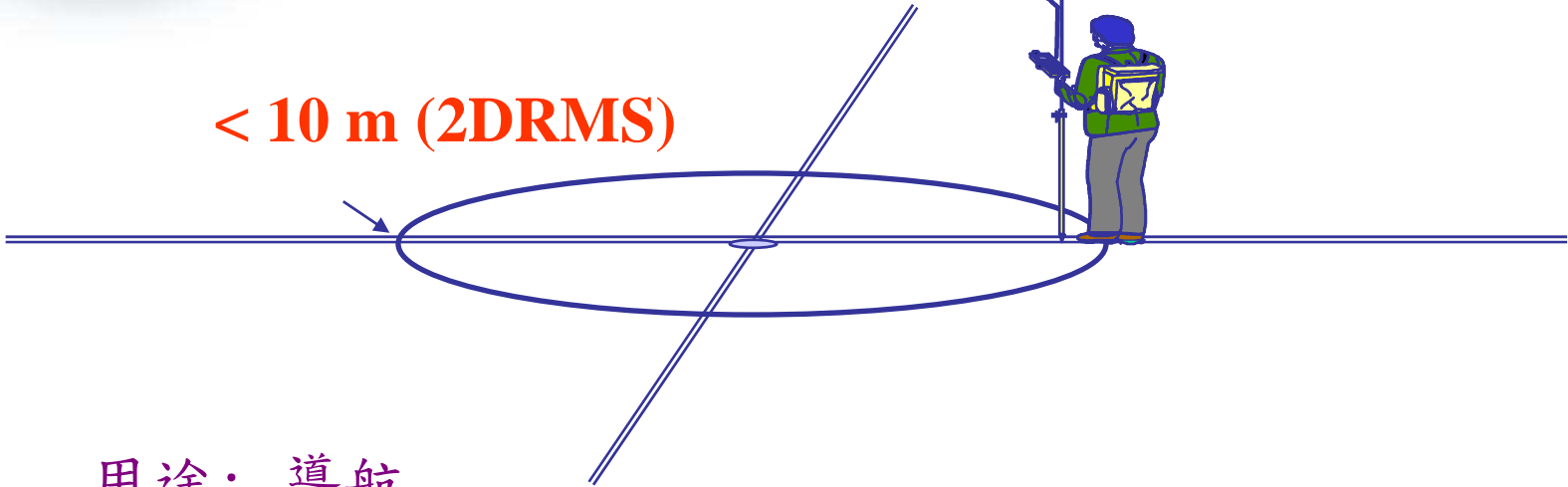


單點定位



C/A 虛擬距離量

< 10 m (2DRMS)



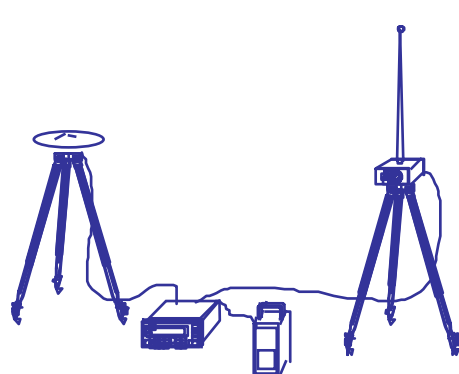
用途：導航





DGPS定位

配置無線電發送裝備



DGPS基站

差分改正量

L1 C/A 虛擬距離量

配置無線電接收裝備



< 2 m

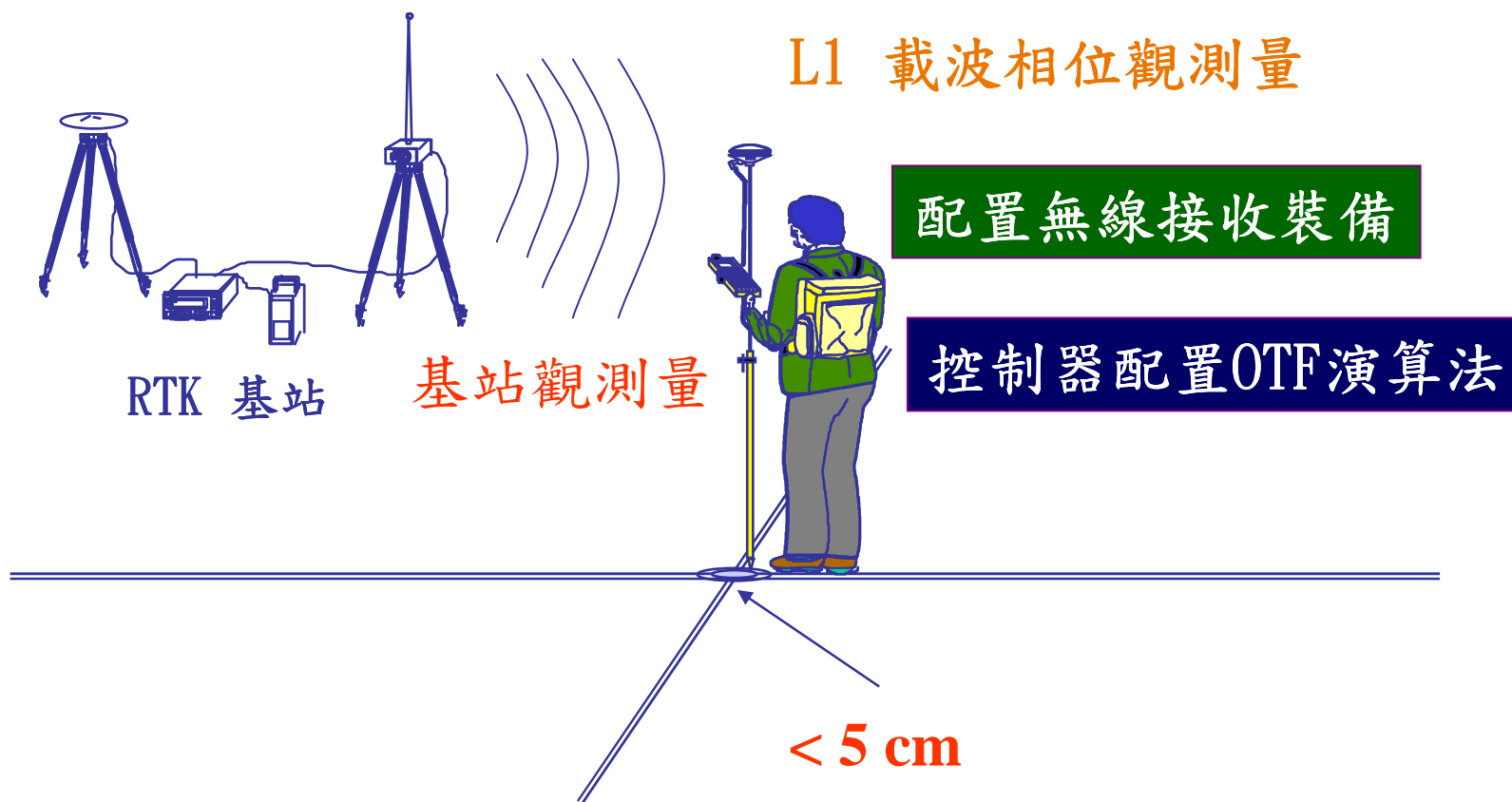
用途：調查





RTK 定位

配置無線發送裝備(或自設手機基地台)



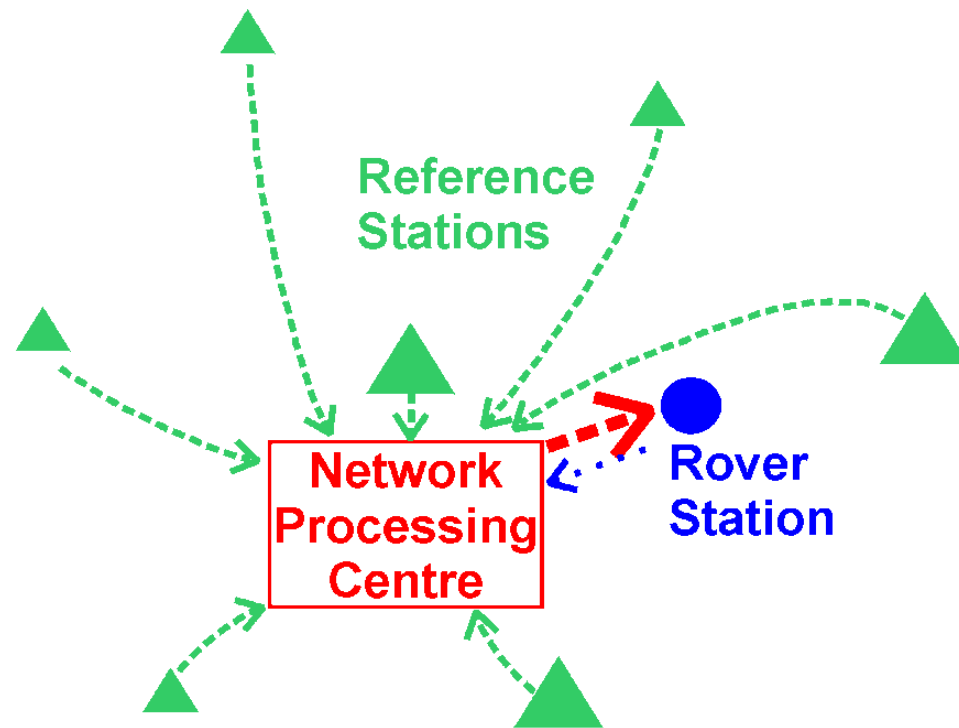
用途：放樣/導線/戶地/複丈





NRTK 定位

Network RTK (網形RTK)





VRS運作程序

Virtual Reference Station

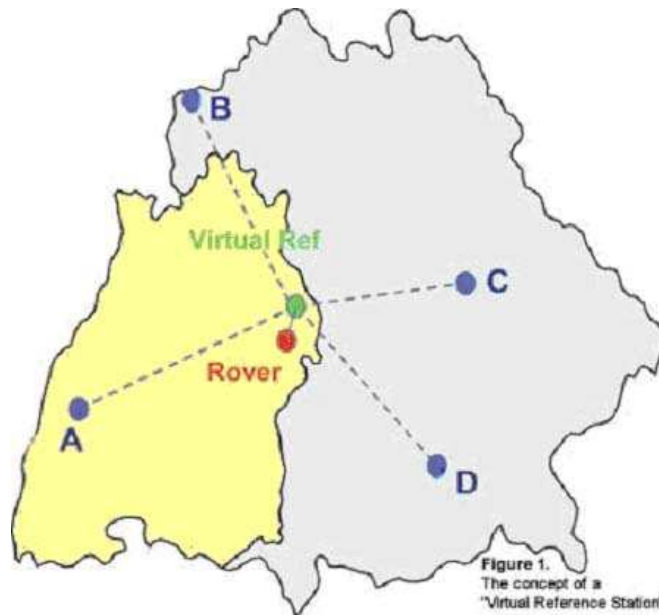
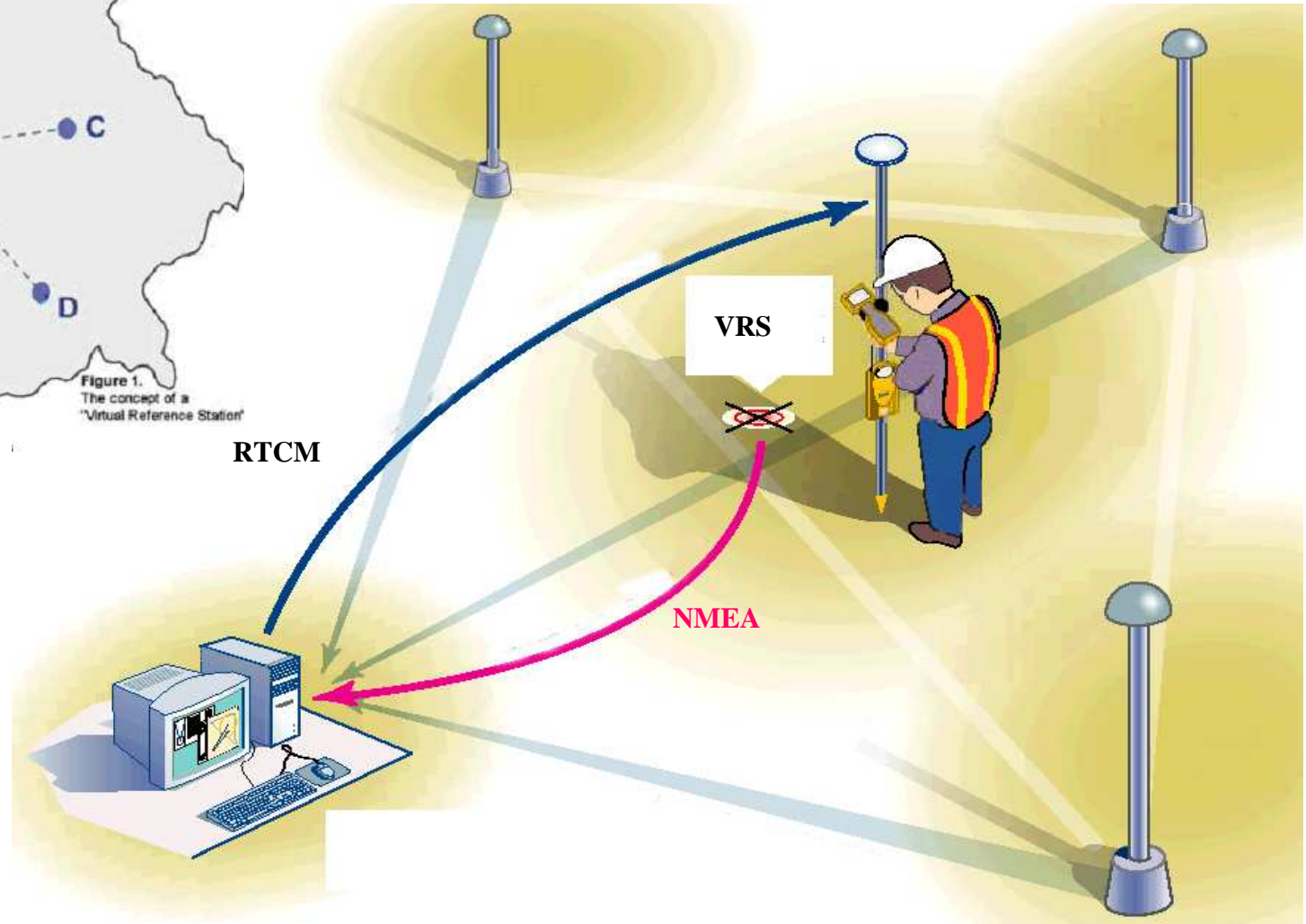


Figure 1.
The concept of a
"Virtual Reference Station"





VRS作業步驟

- 基準站區域網建立觀測資料庫並進行網形平差
- 基準站網解算建立區域性誤差修正資料庫
- 移動站利用無線數據通訊傳輸技術將單點定位之NMEA格式位置資訊登錄於控制中心
- 控制中心依移動站位置坐標進行系統誤差內插計算
- 組成VRS 虛擬觀測資料以RTCM格式回傳移動站
- 移動站接收GPS觀測量並結合VRS 虛擬觀測資料（視為基站），以進行超短基線形式之 RTK定位解算

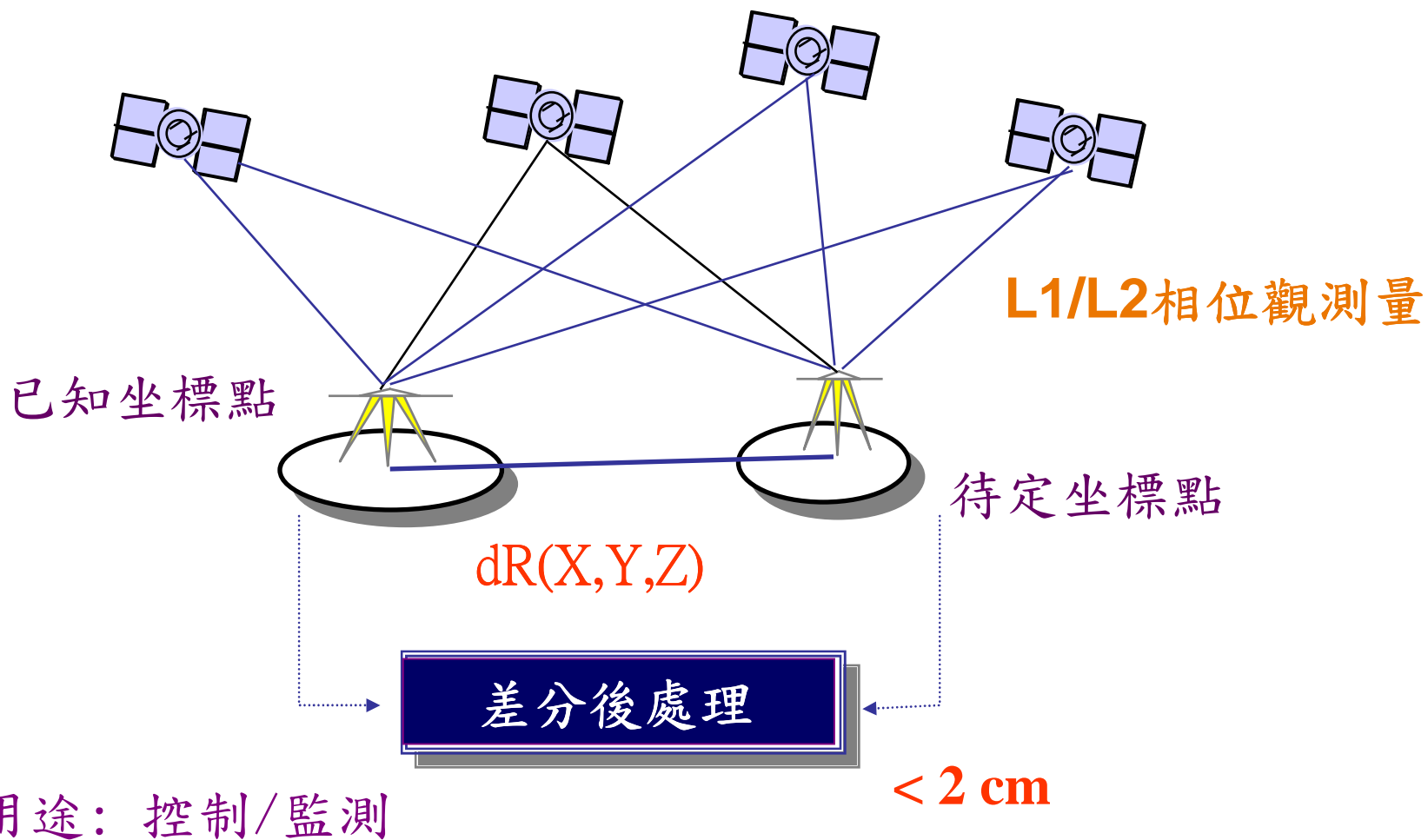


NRTK作業優點

- 可擴大有效作業範圍
- 使用者無需架設主站
- 資料傳輸品質較為穩定
- 可提供區域性較高精度的定位誤差改正資訊
- 初始化時間及相位未定值解算較不因距離增長而出現困難
- 可降低定位精度與選用基站之相關性
- 基站坐標較為一致且易維護
- 系統精度及品質較為穩定可靠

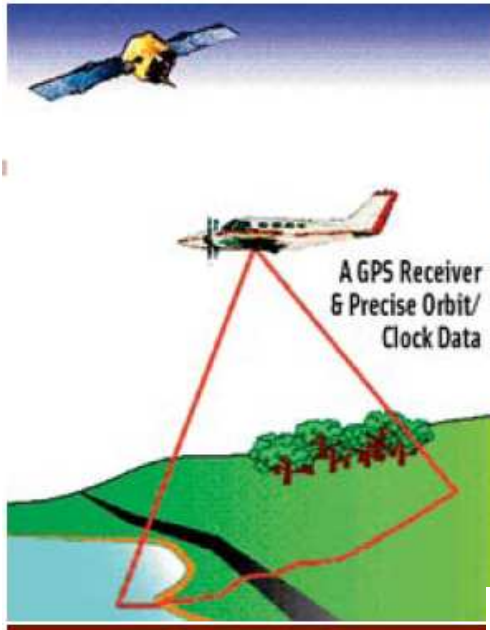


靜態相對定位

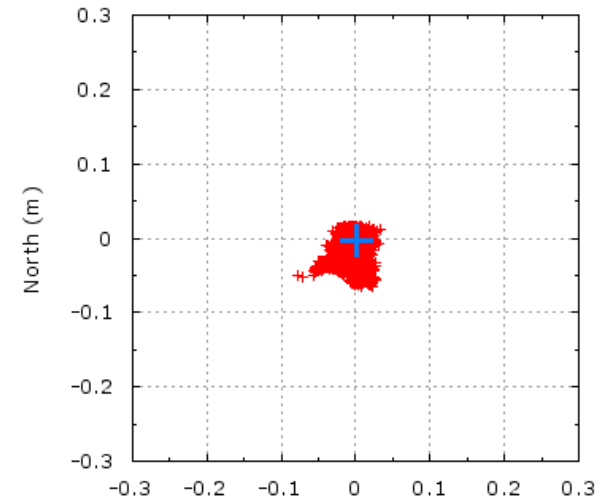




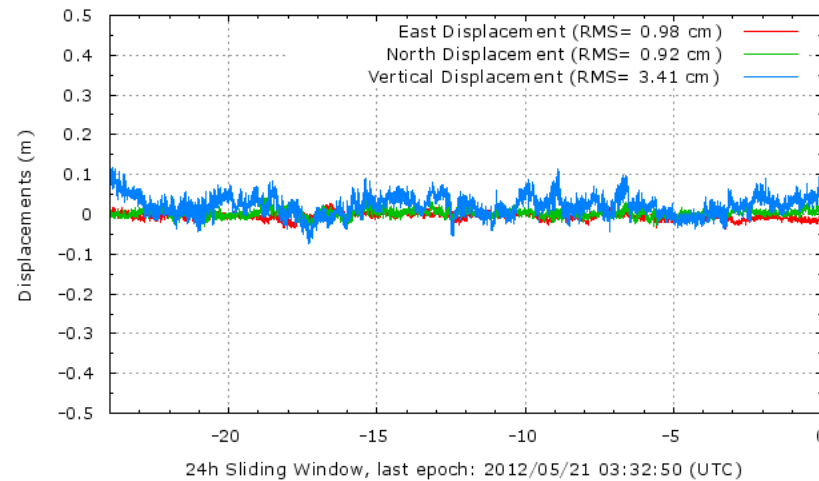
PPP 定位



Last displacements for TLSE(f), real time PPP
2012/05/21 03:32:55 (UTC) - (c) CNES



Displacements for KIRO, real time PPP - (c) CNES

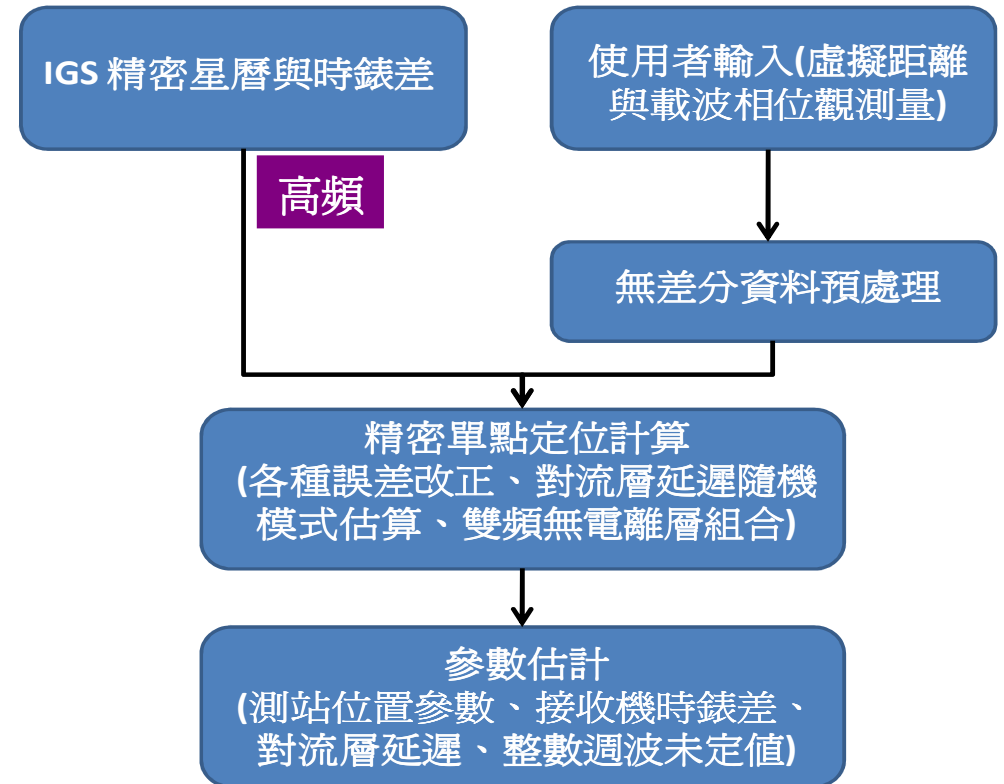




PPP資料處理

• 嚴密處理三大類誤差來源：

- **衛星有關**：衛星時錶差、軌道誤差、衛星天線相位中心偏差
- **訊號傳播有關**：對流層延遲、電離層延遲、相對效應
- **接收儀/測站有關**：接收儀時錶差、天線相位中心偏差、地球固體潮改正、海洋負載改正、地球自轉改正、多路徑效應





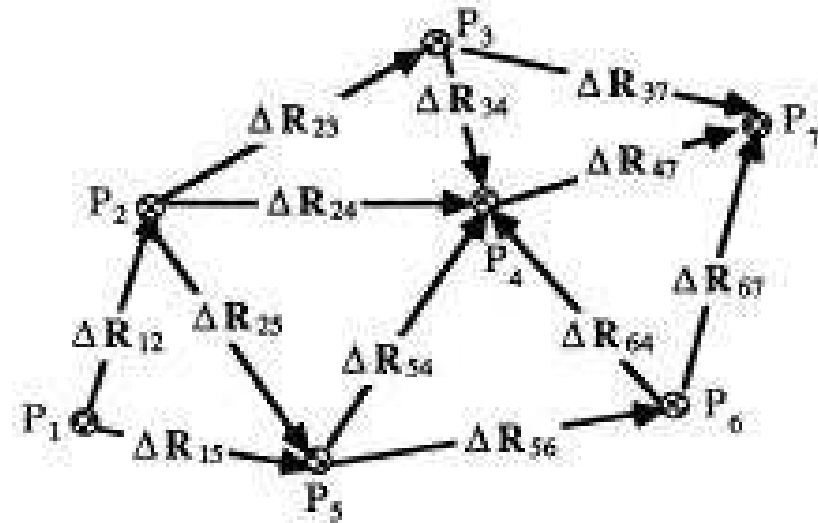
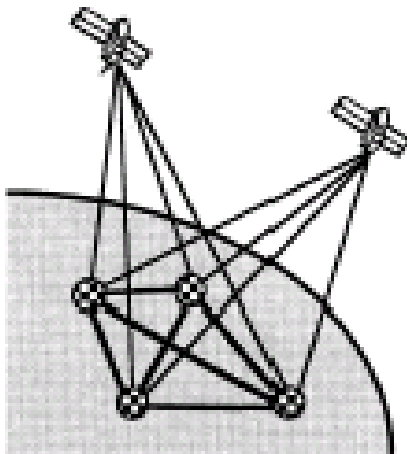
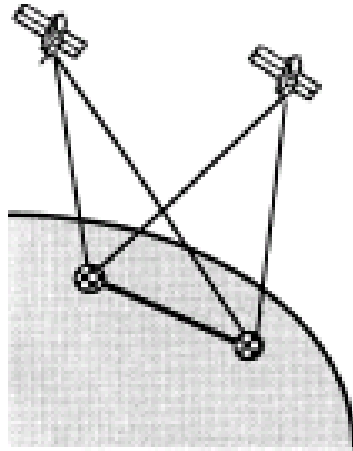
GPS定位特性分析

項目	觀測量		觀測型態		機款		資料		時間		星曆		精度等級	用途
	虛擬距離	載波相位	單機	雙(多)機	單頻	雙頻	單(少)筆	多筆	即時	後處理	廣播	精密		
PP	✓		✓		✓		✓		✓		✓		3~5m	導航
DGPS	✓			✓	✓		✓		✓		✓		1m	調查
PPP		✓	✓			✓	✓			✓		✓	10~20cm	航測
RTK/ NRTK		✓		✓		✓	✓		✓		✓	✓(UR)	3~6cm	地籍
PPK		✓		✓		✓	✓			✓		✓	2~5cm	船測
Static		✓		✓		✓		✓		✓		✓	1~3cm	控制





基線與網形



Provided all ΔR_{ij} are in the same coordinate

system as R_1 we have (for example):

$$R_7 = R_1 + \Delta R_{12} + \Delta R_{24} + \Delta R_{47}$$





相位觀測量的線性組合

- 線性組合(linear combination)

$$\Phi = n_1 \Phi_1 + n_2 \Phi_2$$

- 窄巷(narrow lane)

$$\text{when } n_1 = n_2 = 1 \text{ then } \Phi_n = \Phi_1 + \Phi_2$$

- 寬巷(wide lane)

$$\text{when } n_1 = 1, n_2 = -1 \text{ then } \Phi_w = \Phi_1 - \Phi_2$$

- 無電離層(ionosphere-free)

$$\text{when } n_1 = 1, n_2 = -\frac{f_{L2}}{f_{L1}} \text{ then } \Phi_{Lc} = \Phi_1 - \frac{f_{L2}}{f_{L1}} \Phi_2$$

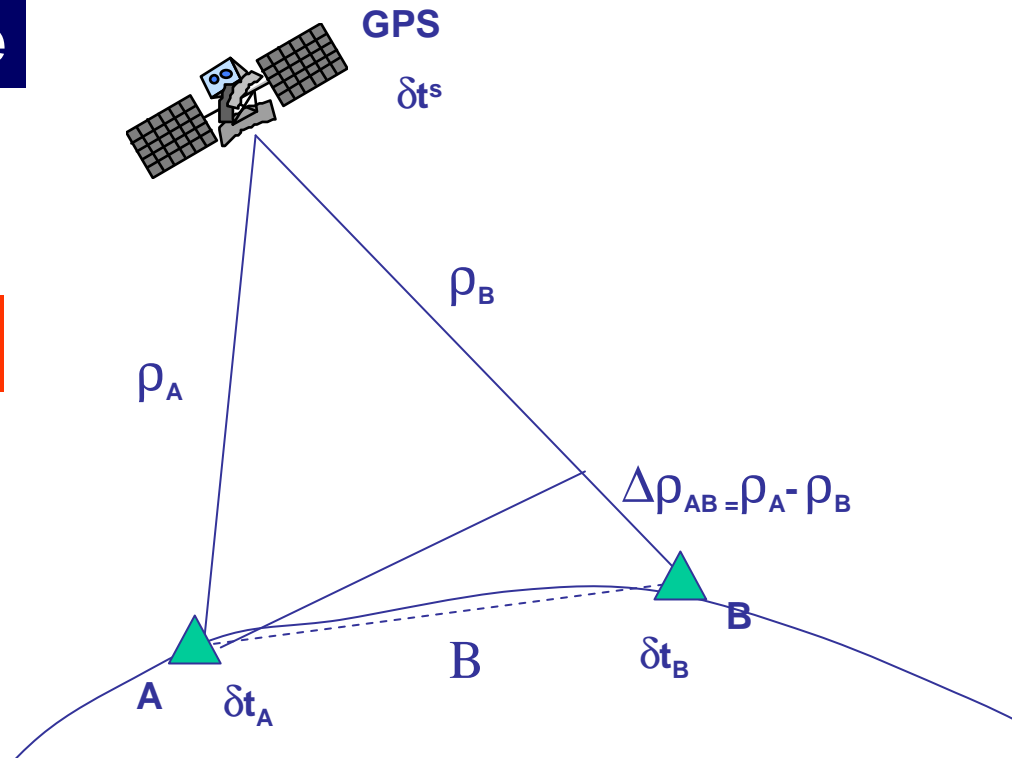




一次差觀測

Single Difference

衛星錶差 可消除



$$\Delta(\cdot) = (\cdot)_{\text{receiver 2}} - (\cdot)_{\text{receiver 1}}$$

$$\Delta p = \Delta \rho - c \cdot \Delta dT + \Delta d_{\text{ion}} + \Delta d_{\text{trop}}$$

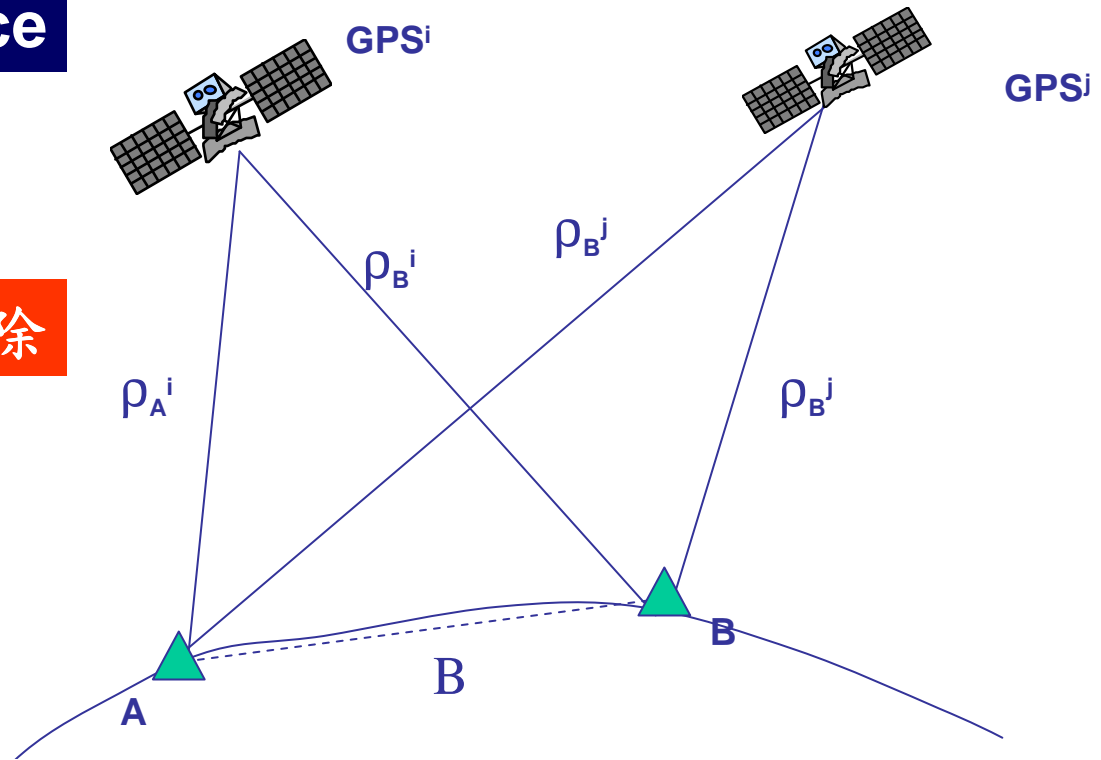
$$\Delta \Phi = \Delta \rho - c \cdot \Delta dT + \lambda \cdot \Delta N - \Delta d_{\text{ion}} + \Delta d_{\text{trop}}$$



二次差觀測

Double Difference

接收器錶差 可消除



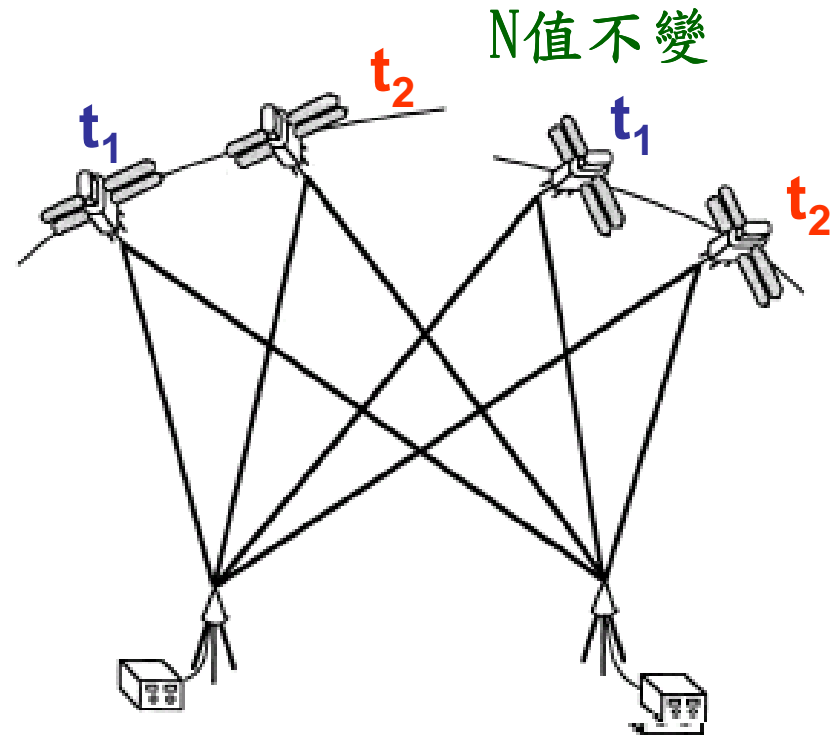
$$\nabla\Delta p = \nabla\Delta \rho + \nabla\Delta d_{ion} + \nabla\Delta d_{trop}$$
$$\nabla\Delta\Phi = \nabla\Delta \rho + \lambda \cdot \nabla\Delta N - \nabla\Delta d_{ion} + \nabla\Delta d_{trop}$$



三次差觀測

Triple Difference

相位未定值 可消除



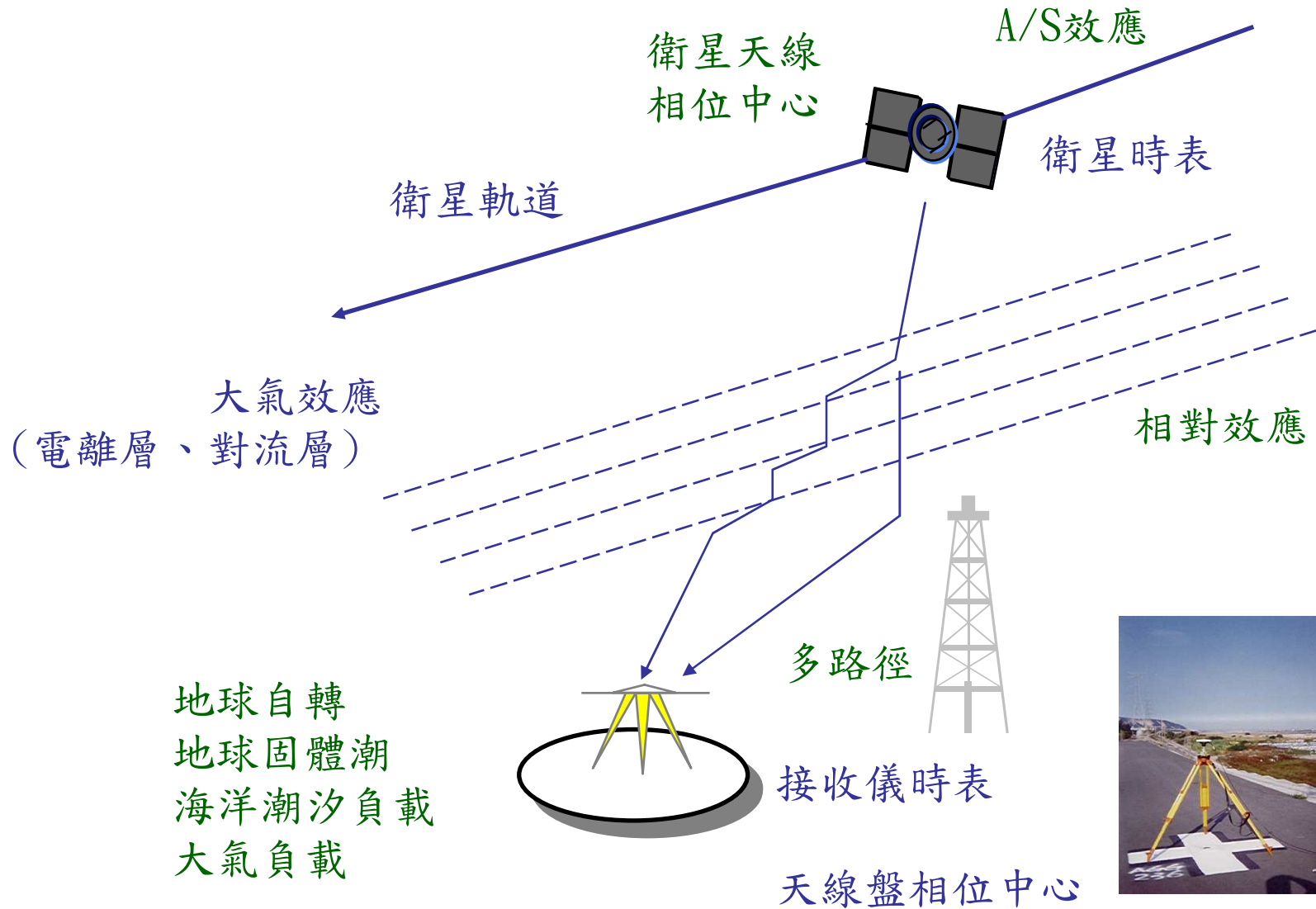
$$\delta \nabla \Delta p = \delta \nabla \Delta \rho + \delta \nabla \Delta d_{\text{ion}} + \delta \nabla \Delta d_{\text{trop}}$$

$$\delta \nabla \Delta \Phi = \delta \nabla \Delta \rho - \delta \nabla \Delta d_{\text{ion}} + \delta \nabla \Delta d_{\text{trop}}$$



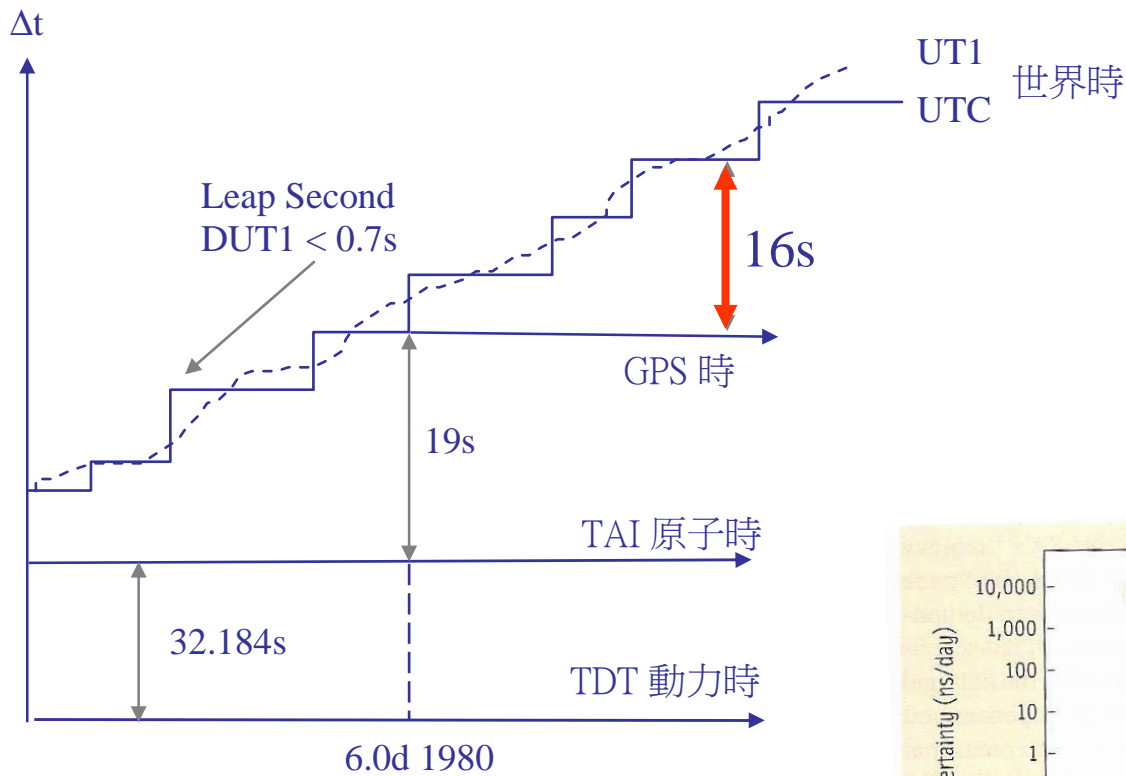


GPS誤差來源





GPS衛星時表



UTC=GPS-16s (July 2012)

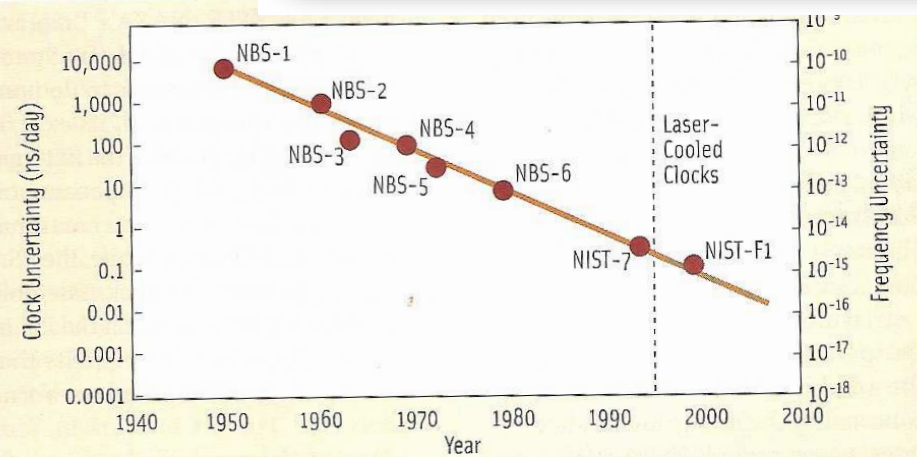
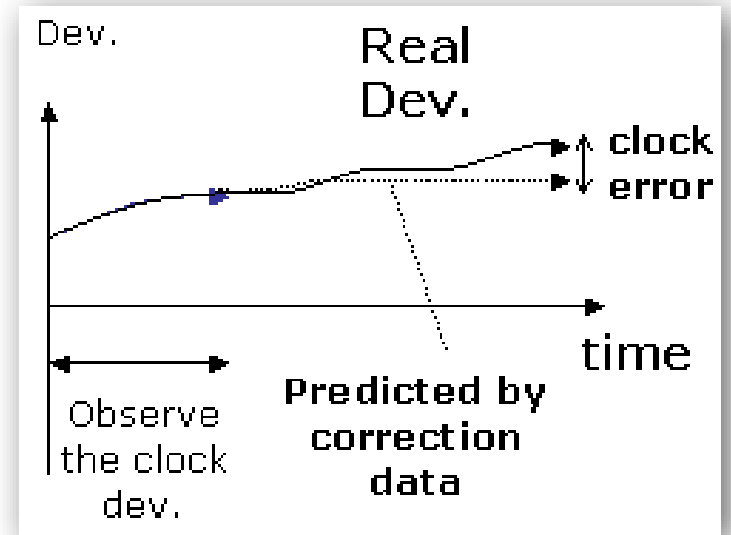


FIGURE 1 Accuracy of terrestrial caesium atomic clocks at the National Institute of Standards and Technology. The NIST-7 is an optically pumped, thermal atomic-beam, microwave caesium spectrometer and the NIST-F1 is a caesium fountain atomic clock





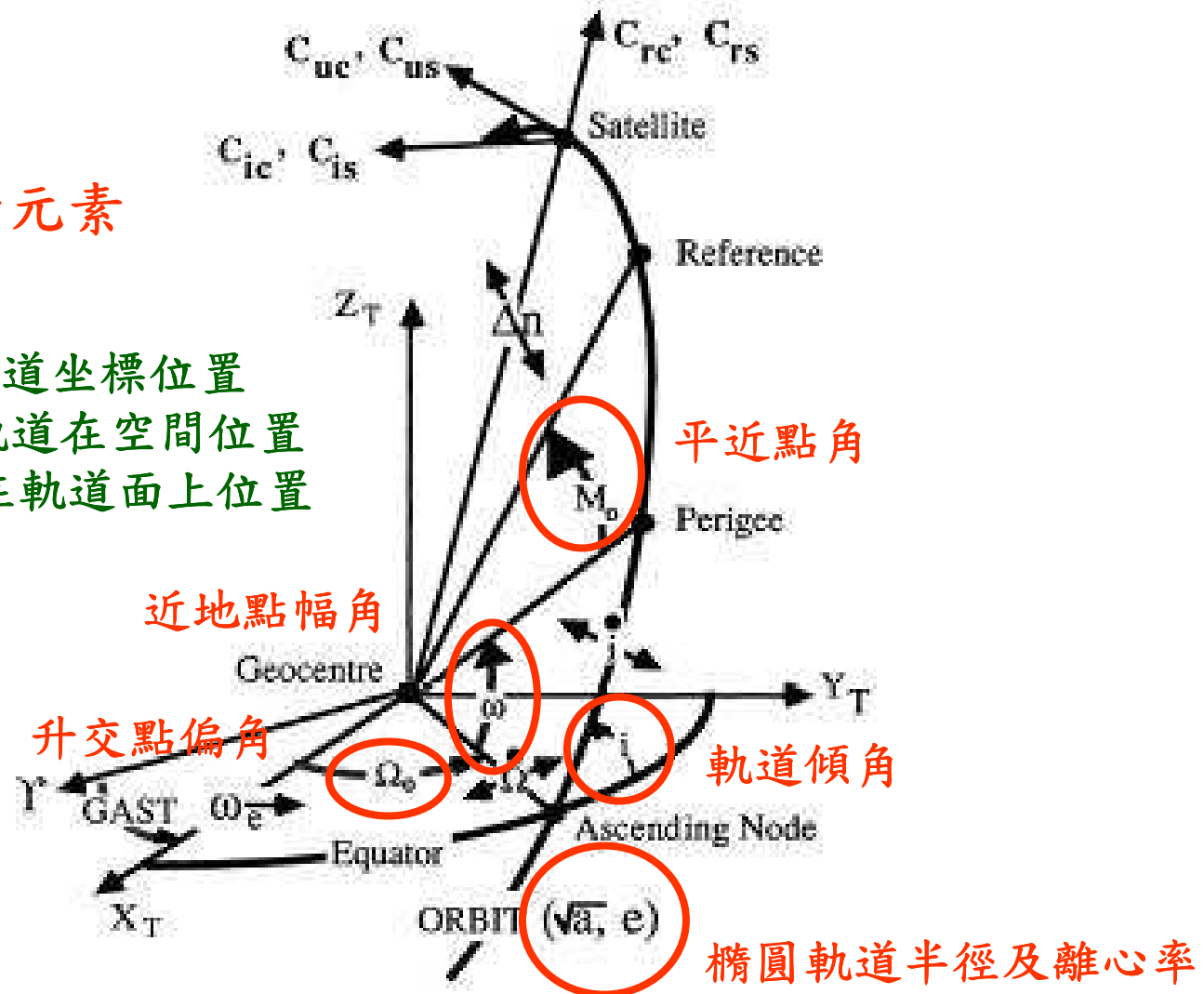
衛星軌道參數

克卜勒軌道六元素

(Ω, i) 描述軌道在赤道坐標位置

(Ω, ω, i) 描述橢圓軌道在空間位置

(a, e, M) 描述衛星在軌道面上位置





廣播星曆資料格式

2.10	N: GPS NAV DATA	RINEX VERSION / TYPE
XXRINEXN V2.10	AIUB	3-SEP-99 15:22
		PGM / RUN BY / DATE
EXAMPLE OF VERSION 2.10 FORMAT		COMMENT
.1676D-07 .2235D-07 -.1192D-06 -.1192D-06		ION ALPHA
.1208D+06 .1310D+06 -.1310D+06 -.1966D+06		ION BETA
.133179128170D-06 .107469588780D-12 552960 1025		DELTA-UTC: A0,A1,T,W
13		LEAP SECONDS
		END OF HEADER
6 99 9 2 17 51 44.0 -.839701388031D-03 -.165982783074D-10 .000000000000D+00		
.910000000000D+02 .934062500000D+02 .116040547840D-08 .162092304801D+00		
.484101474285D-05 .626740418375D-02 .652112066746D-05 .515365489006D+04		
.409904000000D+06 -.242143869400D-07 .329237003460D+00 -.596046447754D-07		
.111541663136D+01 .326593750000D+03 .206958726335D+01 -.638312302555D-08		
.307155651409D-09 .000000000000D+00 .102500000000D+04 .000000000000D+00		
.000000000000D+00 .000000000000D+00 .000000000000D+00 .910000000000D+02		
.406800000000D+06 .000000000000D+00		

Klobuchar



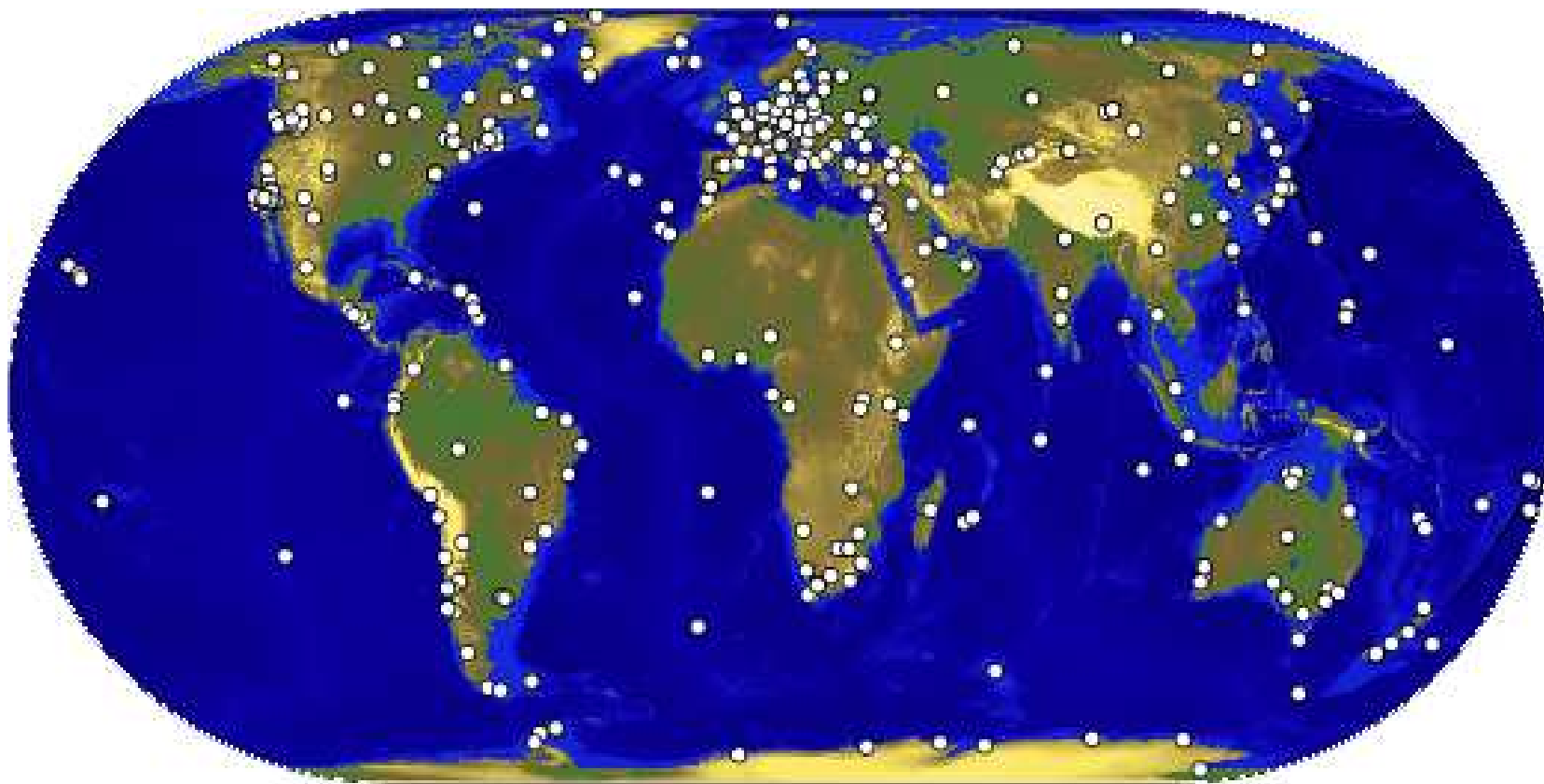
廣播星曆軌道參數

t_{oe}	軌道參數的參考時刻	時間參數 1 項
\sqrt{a}	a:軌道半長軸	Kepler軌道元素 6 項
M_0	參考時刻的平近點角	
e	軌道的離心率	
ω	參考時刻的近地點角距	
i_0	參考時刻的軌道傾角	
Ω_0	參考時刻的升交點經度	
Δn	平均角速度修正量	軌道攝動改正參數 9 項
\dot{i}	軌道傾角的變化率	
$\dot{\Omega}$	升交點經度的變化率	
C_{uc} 、 C_{us}	升交點角距的攝動改正量	
C_{rc} 、 C_{rs}	衛星向量的攝動改正量	
C_{ic} 、 C_{is}	軌道傾角的攝動改正量	



全球GNSS服務(IGS)

International GNSS Service (2005.03)





精密星曆格式 (SP3)

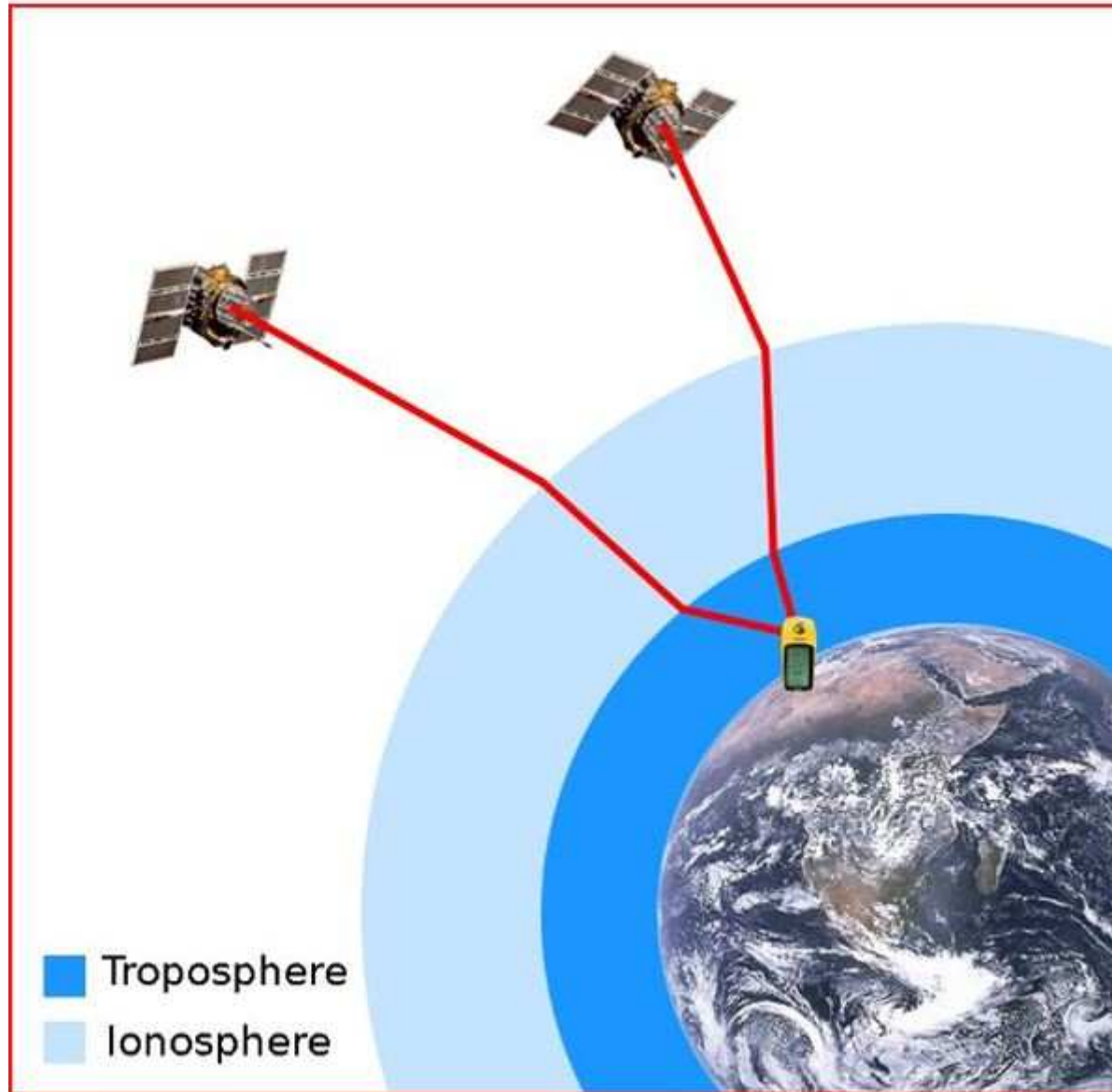
```
#aV1993 1 29 0 0 0.00000000 96 d ITR91 FIT JPL
## 681 432000.00000000 900.00000000 49016 0.00000000000000
+ 19 1 2 3 12 13 14 15 16 17 18 19 20 21 23 24 25 26
+ 27 28 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
+ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
+ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
+ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++ 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
++ 10 11 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
++ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
%e cc cc cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc
%e cc cc cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc
%f 0.0000000 0.000000000 0.000000000000 0.0000000000000000
%f 0.0000000 0.000000000 0.00000000000 0.000000000000000
%i 0 0 0 0 0 0 0 0 0
%i 0 0 0 0 0 0 0 0 0
/* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
/* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
/* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
/* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
* 1993 1 29 0 0 0.00000000
P 1 14722.638510 6464.319150 -21020.844810 -8.059218
V 1 -1196.628800 26950.022500 7502.277100 0.000000
P 2 -24023.155300 -11843.563990 -1675.647210 -10.813964
V 2 -769.152700 -3247.508000 31255.023300 0.000000
P 3 2074.555420 19025.998840 17928.366120 -430.859048
V 3 -6873.932300 22421.664200 -23147.529600 0.000000
```

Version c with GPS & GLONASS solutions

15 minutes interval



大氣延遲誤差

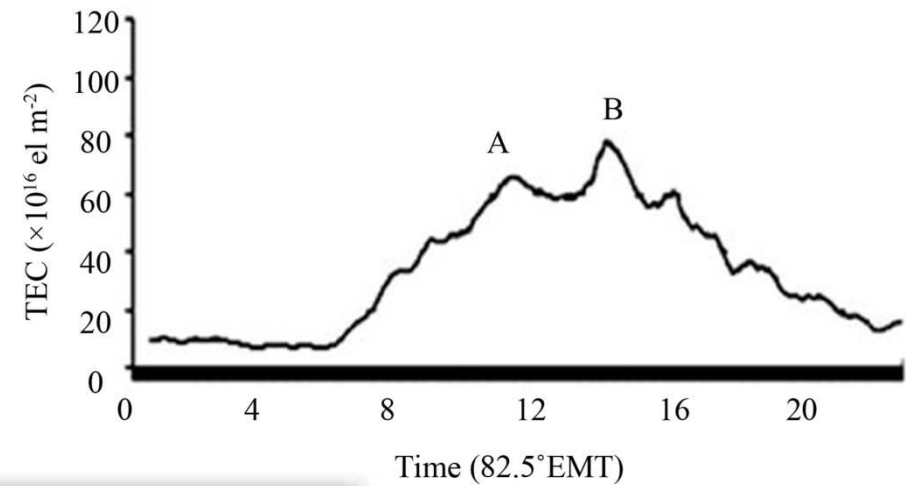
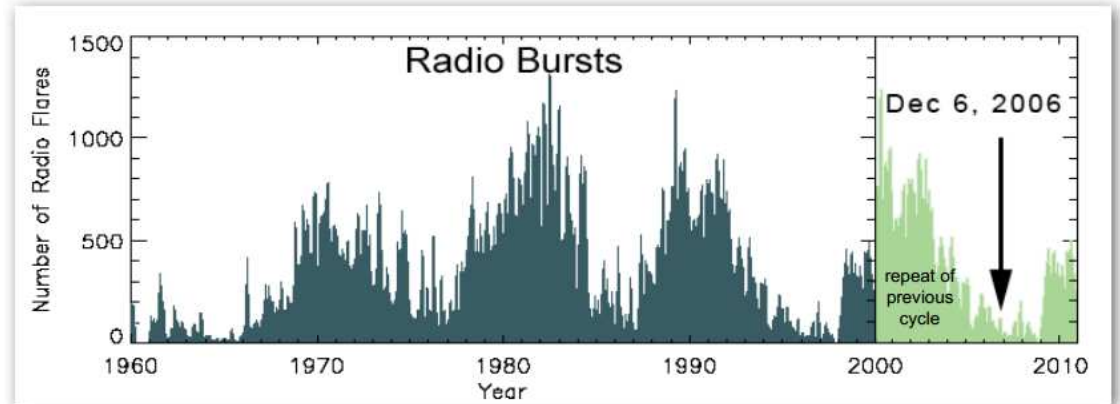
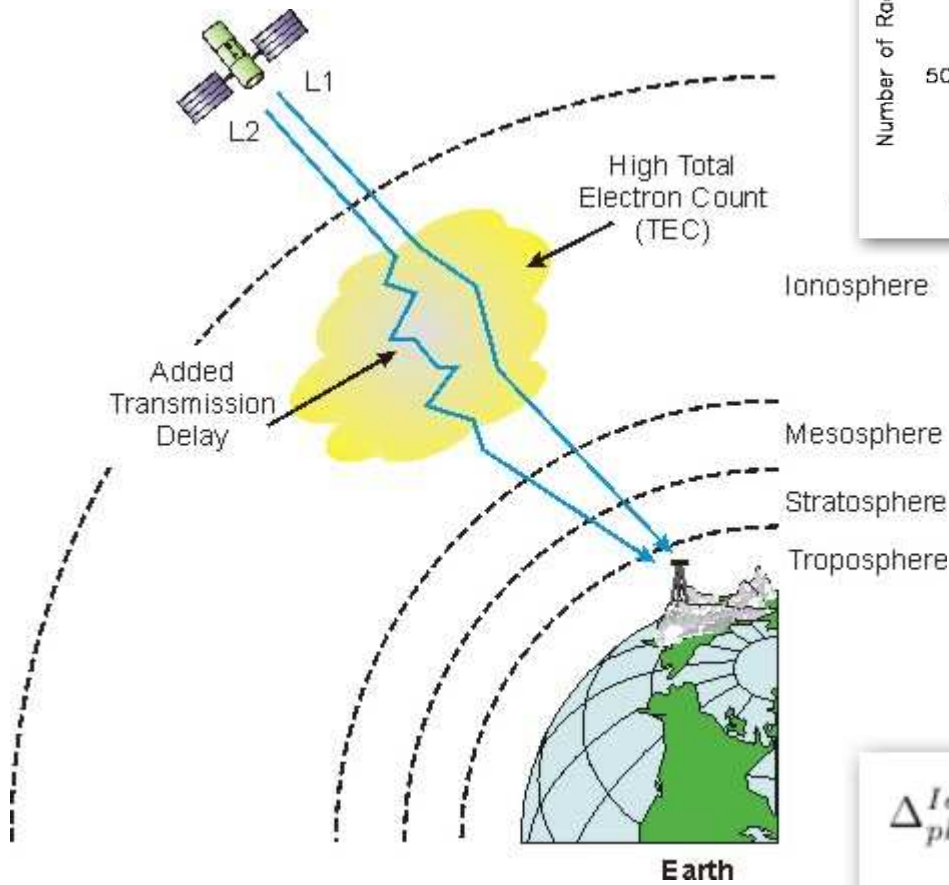


60-1000 km





電離層延遲



$$\Delta_{ph}^{Iono} = -\frac{40.3}{f^2} TEC$$

$$\Delta_{gr}^{Iono} = \frac{40.3}{f^2} TEC$$





電離層改正

- 導航-Klobuchar

$$\Delta T_v^{\text{iono}} = A_1 + A_2 \cos\left(\frac{2\pi(t - A_3)}{A_4}\right)$$

where

$$A_1 = 5 \cdot 10^{-9} \text{ s} = 5 \text{ ns}$$

$$A_2 = \alpha_1 + \alpha_2 \varphi_{IP}^m + \alpha_3 \varphi_{IP}^{m^2} + \alpha_4 \varphi_{IP}^{m^3}$$

$$A_3 = 14^{\text{h}} \text{ local time}$$

$$A_4 = \beta_1 + \beta_2 \varphi_{IP}^m + \beta_3 \varphi_{IP}^{m^2} + \beta_4 \varphi_{IP}^{m^3}$$

$$\cos \varphi_{IP}^m = \sin \varphi_{IP} \sin \varphi_P + \cos \varphi_{IP} \cos \varphi_P \cos(\lambda_{IP} - \lambda_P)$$

- 測量-L1/L2雙頻組合

$$\Phi_{L1/L2} = \Phi_{L1} - \frac{f_{L2}}{f_{L1}} \Phi_{L2}$$

或

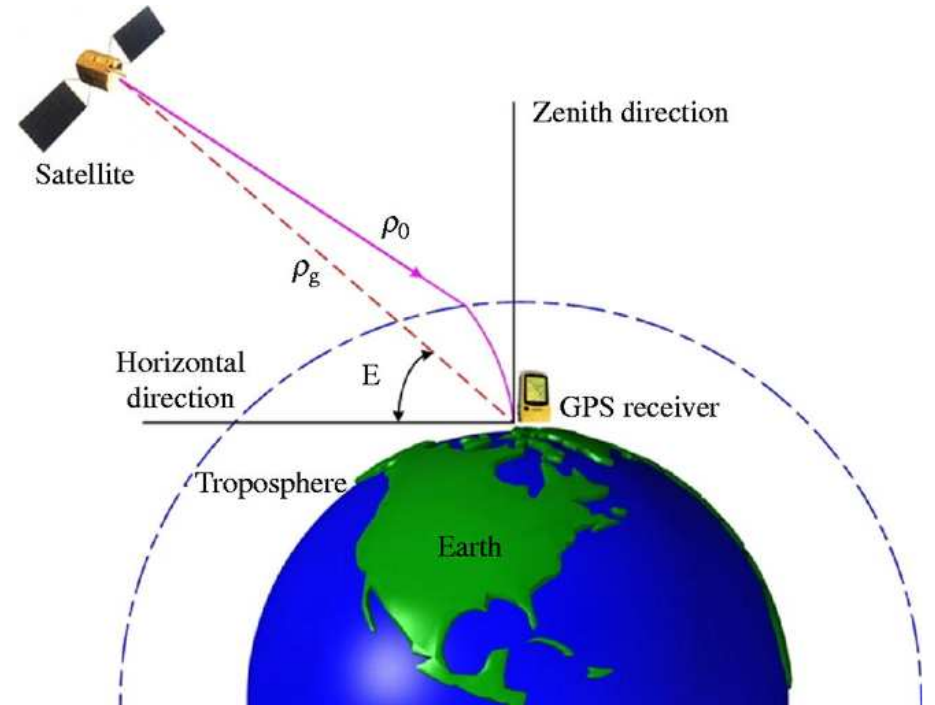
$$\Phi_{IF} = -\frac{f_1^2}{f_1^2 - f_2^2} \times \Phi_a^1 + \frac{f_2^2}{f_1^2 - f_2^2} \times \Phi_a^2$$





對流層延遲

- 中性大氣層與信號頻率無關
- 天頂總延遲量約為2.5公尺
- 可分為乾延遲與溼延遲
- 乾延遲約佔95%
- 乾延遲可由溫度與壓力模式化
- 溼延遲與水汽壓力有關



refractivity

$$N = (n - 1) 10^6$$

$$N = \underbrace{\left[\frac{77.6 P}{T} \right]}_{N_{\text{dry}}} + \underbrace{\left[3.73 \times 10^5 \frac{e}{T^2} \right]}_{N_{\text{wet}}}$$





對流層改正

- Saastamoinen 全球標準模式 (1973)

$$\Delta L = \frac{2.277 \cdot 10^{-3}}{\cos(90^\circ - \nu)} \left(P_0 + \left(\frac{1255}{T_0} + 0.05 \right) \cdot e_0 - 1.16 \cdot \tan^2(90^\circ - \nu) \right)$$

ν : 垂直角 (天頂距 $z = 90^\circ - \nu$)

- 輸入參數: 地表絕對溫度(T)、水氣偏壓(e)
及
大氣壓(P)





對流層改正

- Modified Hopfield 全球標準模式 (1974)

$$D_i^{trop} = 10^{-12} N_i \left[\sum_{k=1}^9 \frac{\alpha_{k,i}}{k} r_i^k \right]$$

其中

i : 分別表示乾 ($i=d$) 或濕 ($i=ww$) 部分的分量

ε : 衛星仰角 ($=90^\circ - \text{天頂距}$)

$$r_i = \sqrt{(R_E + h_i)^2 - (R_E \cos \varepsilon)^2} - R_E \sin \varepsilon$$

其他參數的定義為：

$$\alpha_{1,i} = 1$$

$$\alpha_{3,i} = 6a_i^2 + 4b_i$$

$$\alpha_{5,i} = a_i^4 + 12a_i^2b_i + 6b_i^2$$

$$\alpha_{7,i} = b_i^2(6a_i^2 + 4b_i)$$

$$\alpha_{9,i} = b_i^4$$

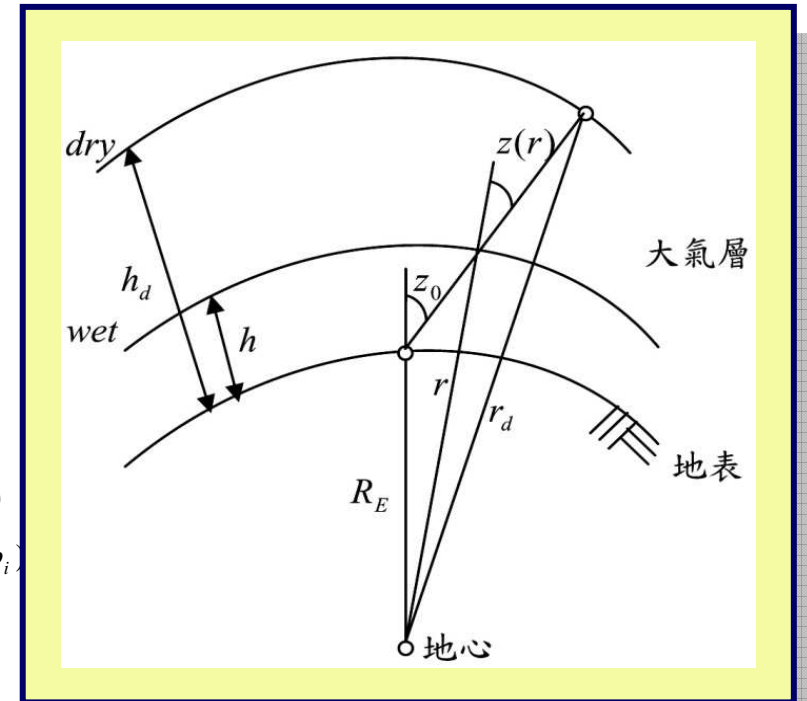
$$\alpha_{2,i} = 4a_i$$

$$\alpha_{4,i} = 4a_i(a_i^2 + 3b_i)$$

$$\alpha_{6,i} = 4a_ib_i(a_i^2 + 3b_i)$$

$$\alpha_{8,i} = 4a_ib_i^3$$

其中 $a_i = -\frac{\sin \varepsilon}{h_i}$, $b_i = -\frac{\cos^2 \varepsilon}{2h_i R_E}$



- 輸入參數：測站高度及衛星仰角



對流層改正

• Niell 模式 (1996)

$$D_{dry}^{trop}(\epsilon) = \frac{\frac{1}{1 + \frac{a_{dry}}{1 + \frac{b_{dry}}{1 + c_{dry}}}}}{\sin \epsilon + \frac{a_{dry}}{\sin \epsilon + \frac{b_{dry}}{\sin \epsilon + c_{dry}}}} + \left[\frac{1}{\sin \epsilon} - \frac{\frac{1}{1 + \frac{a_{ht}}{1 + \frac{b_{ht}}{1 + c_{ht}}}}}{1}}{\sin \epsilon + \frac{a_{ht}}{\sin \epsilon + \frac{b_{ht}}{\sin \epsilon + c_{ht}}}} \right] \times \frac{H}{100}$$
$$D_{wet}^{trop}(\epsilon) = \frac{\frac{1}{1 + \frac{a_{wet}}{1 + \frac{b_{wet}}{1 + c_{wet}}}}}{\sin \epsilon + \frac{a_{wet}}{\sin \epsilon + \frac{b_{wet}}{\sin \epsilon + c_{wet}}}}$$

ϵ = 衛星仰角

H = 高程

$$a_{ht} = 2.53 \times 10^{-5} km$$

$$b_{ht} = 5.49 \times 10^{-3} km$$

$$c_{ht} = 1.14 \times 10^{-3} km$$

而 a_{dry} 、 b_{dry} 、 c_{dry} 、 a_{wet} 、 b_{wet} 、 c_{wet} 在各緯度的平均(average)係數數值

可查表得。





投影(映射)函數

• Mapping Function

- 標準模型估值多是處於天頂方向
- 但觀測到的GPS衛星分別處於不同高度，對流層延遲即會隨著衛星仰角而變化
- 須利用映射函數把天頂方向的對流層延遲量(ZTD) 映射到不同仰角衛星處的傾斜路徑上 (slant path) 的對流層延遲

(摘自Misra and Enge, 2001)

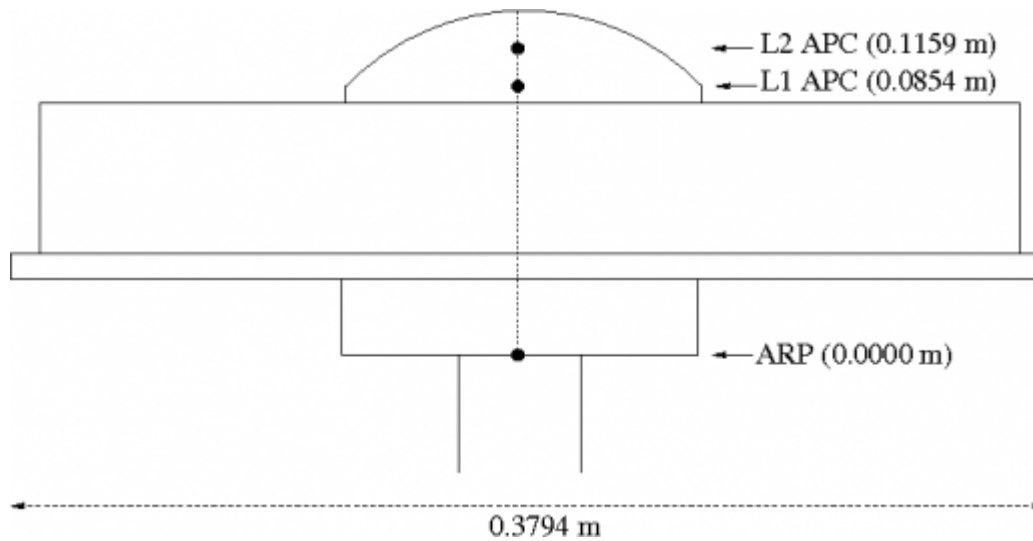
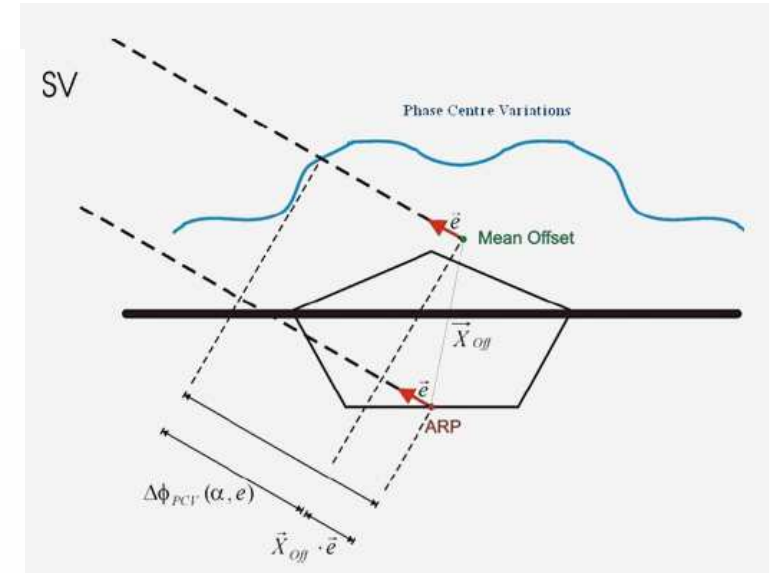
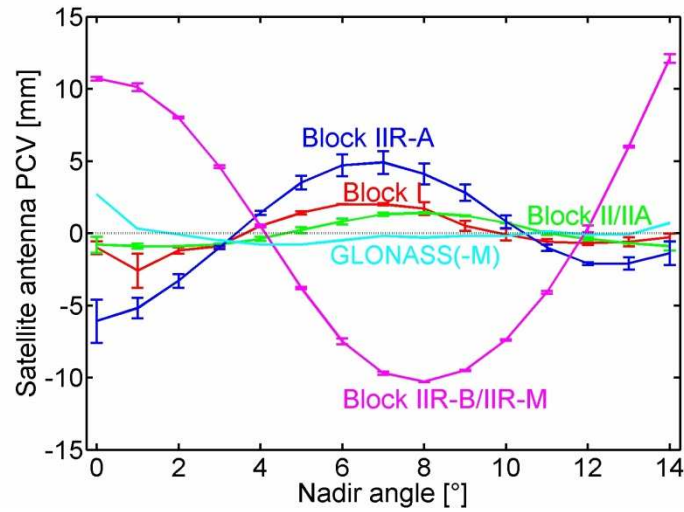
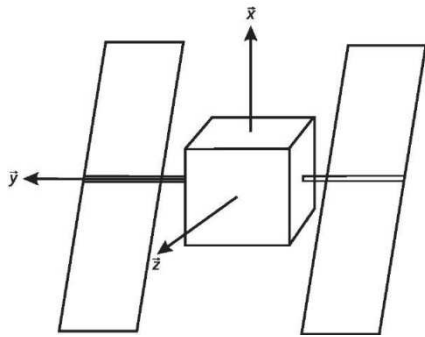
$$MF(\varepsilon) = 1.001 / \sqrt{(0.001)^2 + 0.002 + \sin^2 \varepsilon}$$

(Black and Eisner, 1984)

基本函數: $1/\sin(\nu)$



天線相位中心

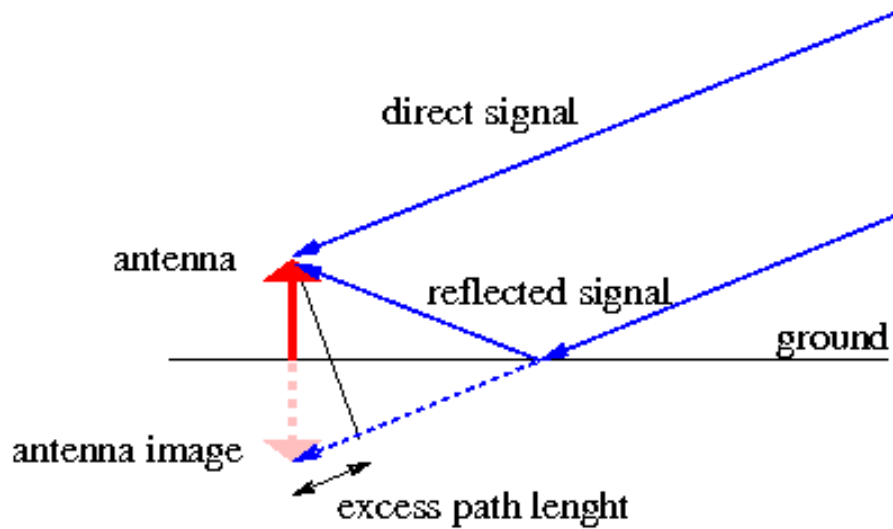


igs08.atx 改正模式





多路徑效應



teqc

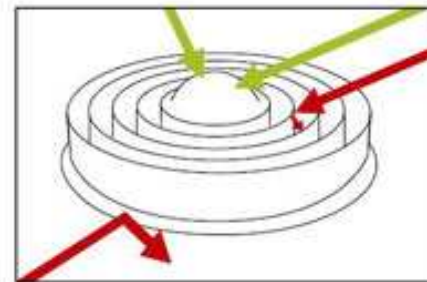
$$MP1 \equiv p_1 - \left(1 + \frac{2}{\alpha - 1}\right)\Phi_1 + \left(\frac{2}{\alpha - 1}\right)\Phi_2$$

$$MP2 \equiv p_2 - \left(\frac{2\alpha}{\alpha - 1}\right)\Phi_1 + \left(\frac{2\alpha}{\alpha - 1} - 1\right)\Phi_2$$

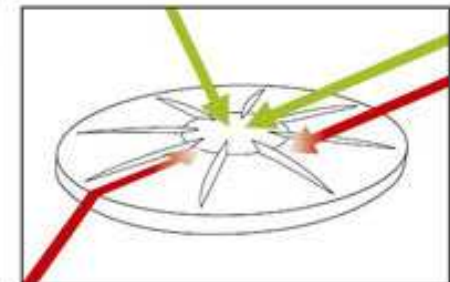


GROUND PLANES AND MULTIPATH SIGNALS

- Signals striking at shallow angles attempt to create surface waves
- Signals from below the horizon must be eliminated



1) Choke Ring weakens multipath signals



2) Zephyr Geodetic 2 consumes multipath signals

Desirable signals are shown in green; undesirable signals are shown in red.



chock ring 天線盤



全球導航衛星系統(GNSS)

- Global Navigation Satellite Systems
 - Global Positioning System (GPS, USA)
 - GLObal Navigation Satellite System (GLONASS, Russia)
 - Galileo (EU)
 - Beidou/Compass (China)
- Regional Augmentation Systems
 - Quasi Zenith Satellite System (QZSS, Japan)
 - Indian Regional Navigation Satellite System (IRNSS, India)
 - Multi-Constellation Augmentation Service System (MASS, China)





GNSS系統比較

項目	GPS	GLONASS	Galileo	BeiDou
衛星數	24+3	24	27+3	30+5
軌道面個數	6	3	3	6
軌道高度	20, 200公里	19, 100公里	23, 222公里	21, 150公里
運行週期	11小時58分	11小時18分	14小時06分	12小時36分
軌道傾角	55度	64.8度	56度	55度
載波頻率	L1:1575.42 MHz	L1: 1598.0625-1619.3125 MHz	E2-L1-E1: 1559-1592 MHz	B1I:1561.098 MHz
	L2:1227.60 MHz	L2: 1242.9375-1251.6875 MHz	E5a-E5b: 1164-1215 MHz	B2I:1207.140 MHz
	L5:1176.45 MHz	L3:1202.025 MHz	E6: 1260-1300 MHz	B3:1268.52 MHz
時間系統	UTC (USNO)	UTC (SU)	UTC (GST)	UTC (NTSC)
坐標系統	WGS-84	SGS-E90 (PZ-90)	GTRF(ITRF)	CGCS2000(ITRF)





GNSS 多頻電碼

Item	Frequency MHz	Constellations supported
1	1176.45	GPS L5 Galileo E5a QZSS
2	1227.6	GPS L2, P and M codes QZSS
3	1246	Glionass L2
4	1561.098	Beidou B1
5	1575.42	GPS L1 C/A, P and M codes Galileo E1 QZSS
6	1602	Glionass L1
7	1207.14	Beidou B2, Galileo E5b, Glionass G3
8	1542	SBAS based on Inmarsat (Omnistar, Starfire)

System	Blocks	Signals	Sats
GPS	IIA	L1 C/A, L1/L2 P(Y)	8
	IIR-A/B	L1 C/A, L1/L2 P(Y)	12
	IIR-M	+L2C	7
	IIF	+L5	4
GLONASS	M	L1/L2 C/A + P	24
	K	+L3	(1)
BeiDou	GEO	B1, B2, B3	5
	IGSO	B1, B2, B3	5
	ME0	B1, B2, B3	4
Galileo	IOV	E1, (E6), E5a/b/ab	(4)
QZSS	n/a	L1 C/A, L1C, SAIF L2C, E6 LEX, L5	1
IRNSS	n/a	L5,S	(1)



GNSS衛星數的效益

