

國立中央大學全球定位科學與應用研究中心 (GPS Science and Application Research Center, NCU)，太空遙測研究中心 電離層探測實驗室(Ionosphere Sounding Lab, CSRSR, NCU)

內太空環境對現代民生與國防的影響

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內容：

- 一、背景說明：內太空環境無線電波傳播 –
從電報到全球定位系統
- 二、電離層觀測、模式建立、與遠距高頻無線
電波通訊應用
- 三、電離層環境對全球定位系統影響：定位誤差、
無線電波閃爍效應、與軟體接收機開發
- 四、無線電波傳播與超水平雷達
- 五、結論



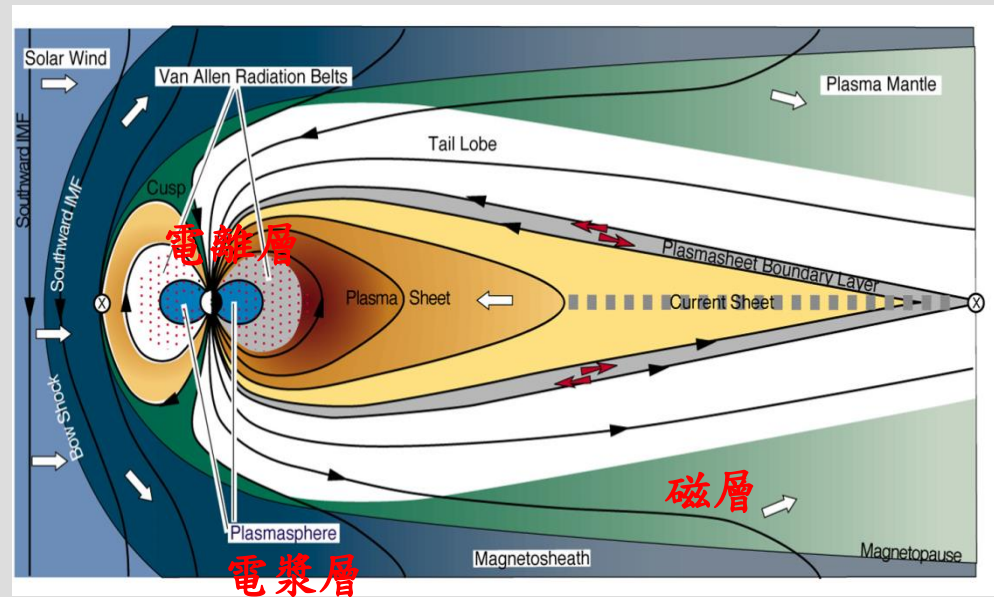
一、背景說明：

內太空(近地太空)環境無線電波
傳播－從電報到全球定位系統

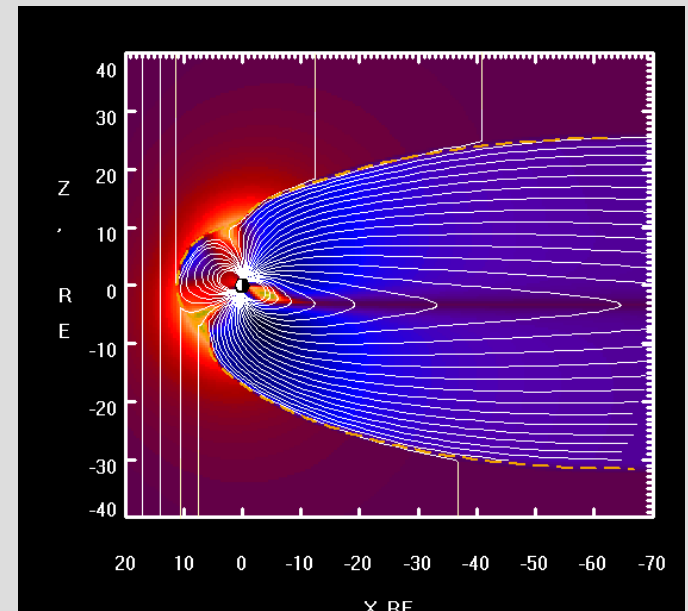
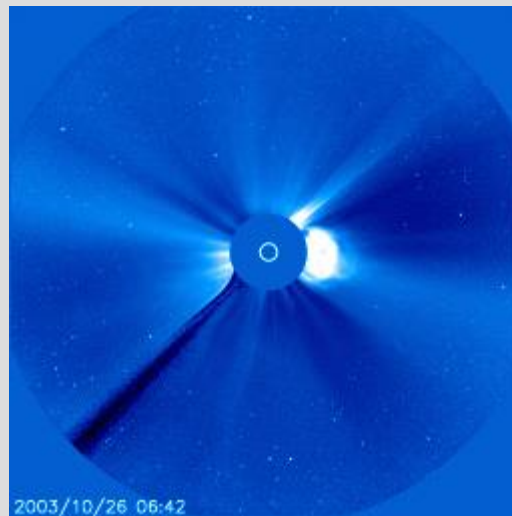


內太空環境:

電離層 (60 .. 2000 km)、
電漿層(2000 .. 40000km)、
磁層(>40000km)



太陽風對地球
內太空環境的影響



內太空無線電波傳播媒介：電離層形成與結構

電離層形成主要因素：太陽輻射與大氣層；

主要結構：D, E, F1 & F2層次

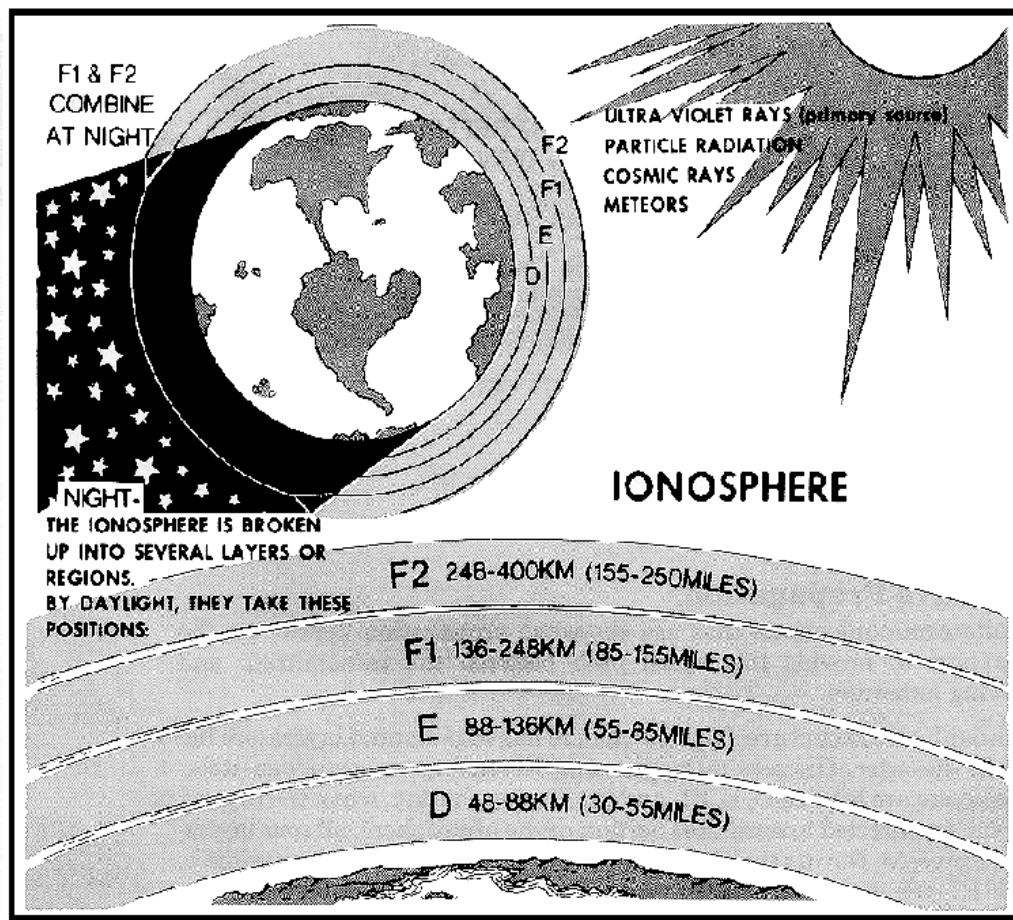
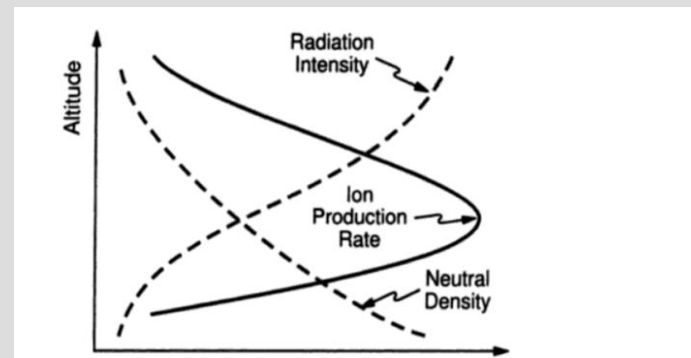
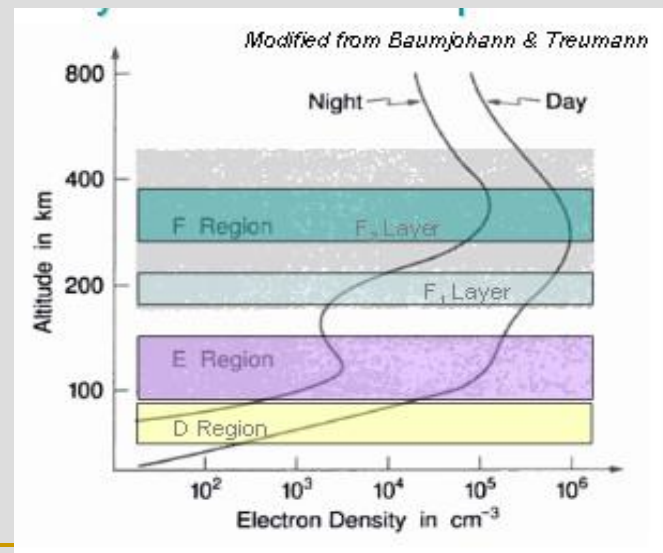


Figure 2-13. Average layer distribution of the ionosphere.

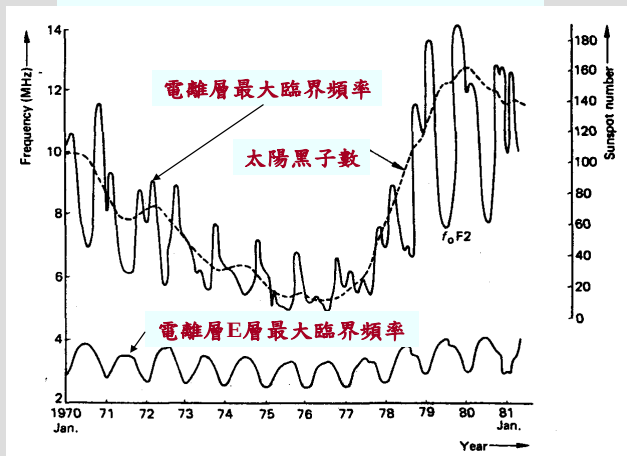


電離層形成：the Appleton layer

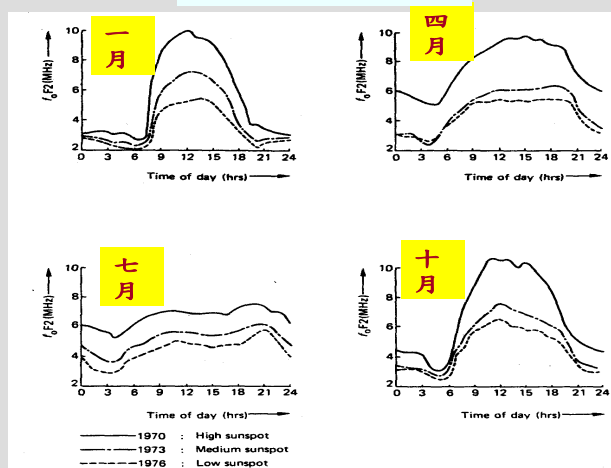


電離層臨界頻率變化之基本特性

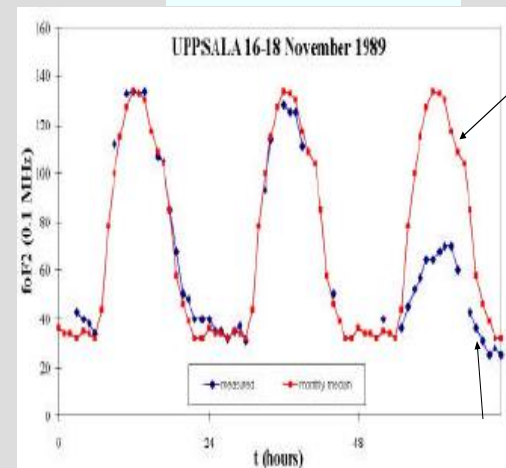
太陽活動性變化



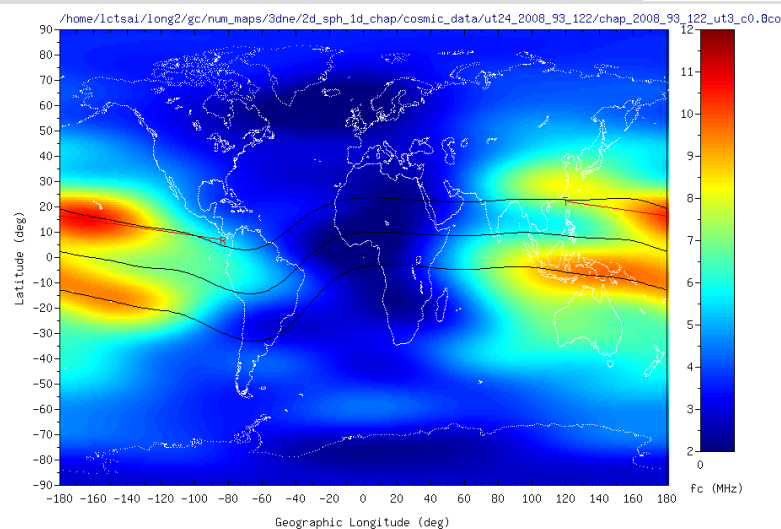
季節變化



日夜變化



全球經緯度變化



內太空環境無線電波傳播重要歷史

- 1909: The Nobel Prize in Physics of 1909 was awarded jointly to Guglielmo Marconi and Karl Ferdinand Braun "*in recognition of their contributions to the development of wireless telegraphy*"



Guglielmo Marconi

Karl Ferdinand Braun

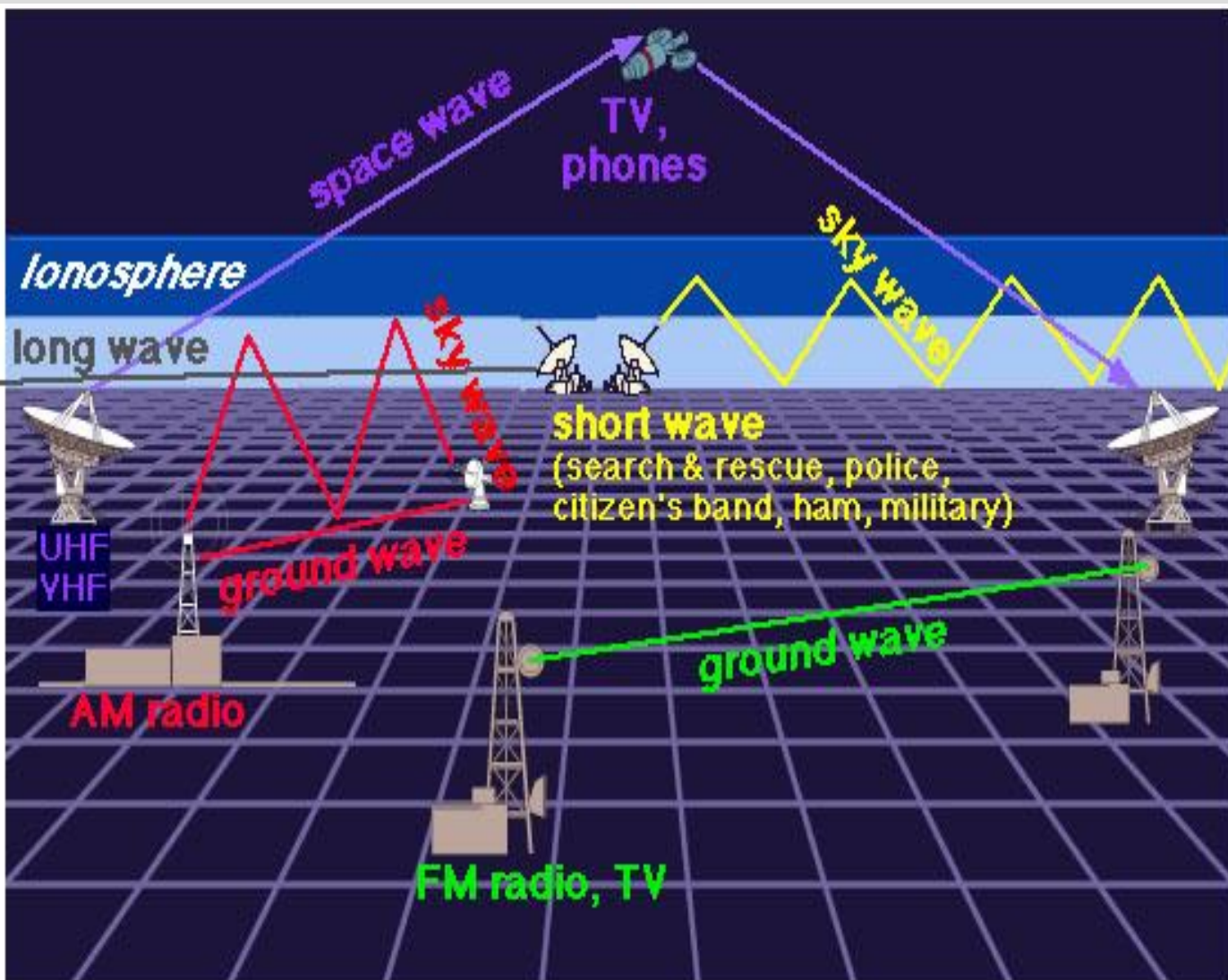


- 1947: Edward V. Appleton awarded Nobel Prize in Physics "*for his investigations of the physics of the upper atmosphere especially for the discovery of the so-called Appleton layer*".



Edward V. Appleton

中長距離無線電波傳播方式與種類



1. **Space wave:** 空間波，頻率範圍: VHF/UHF

2. **Sky wave:** 天波，頻率範圍: MF/HF

3. **Ground wave:** 地波，頻率範圍: LF/MF/HF/VHF

LF(低頻): 30~300 KHz

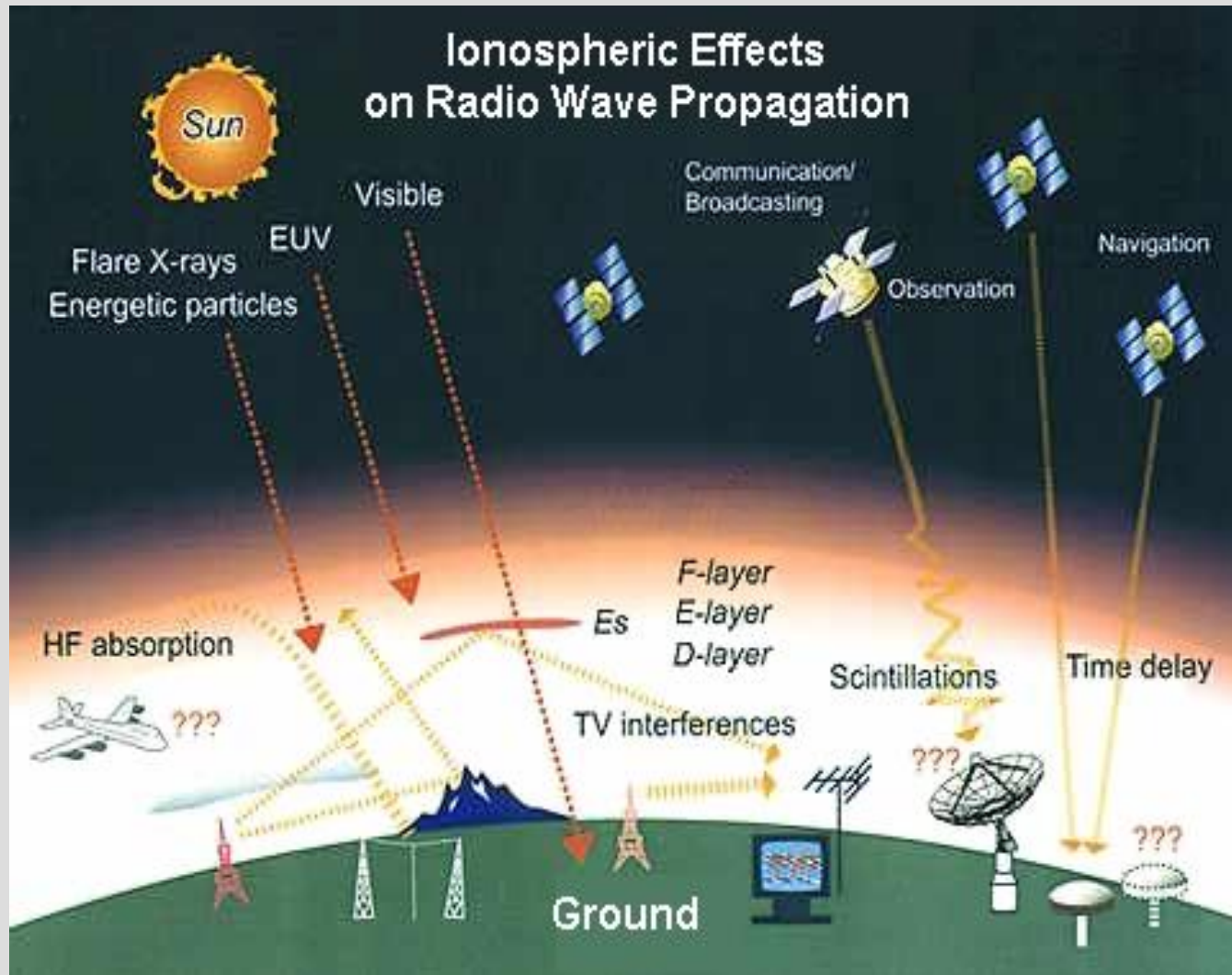
MF(中頻): 0.3~3 MHz

HF(高頻): 3~30 MHz

VHF(特高頻): 30~300 MHz

UHF(超高頻): 0.3~3 GHz

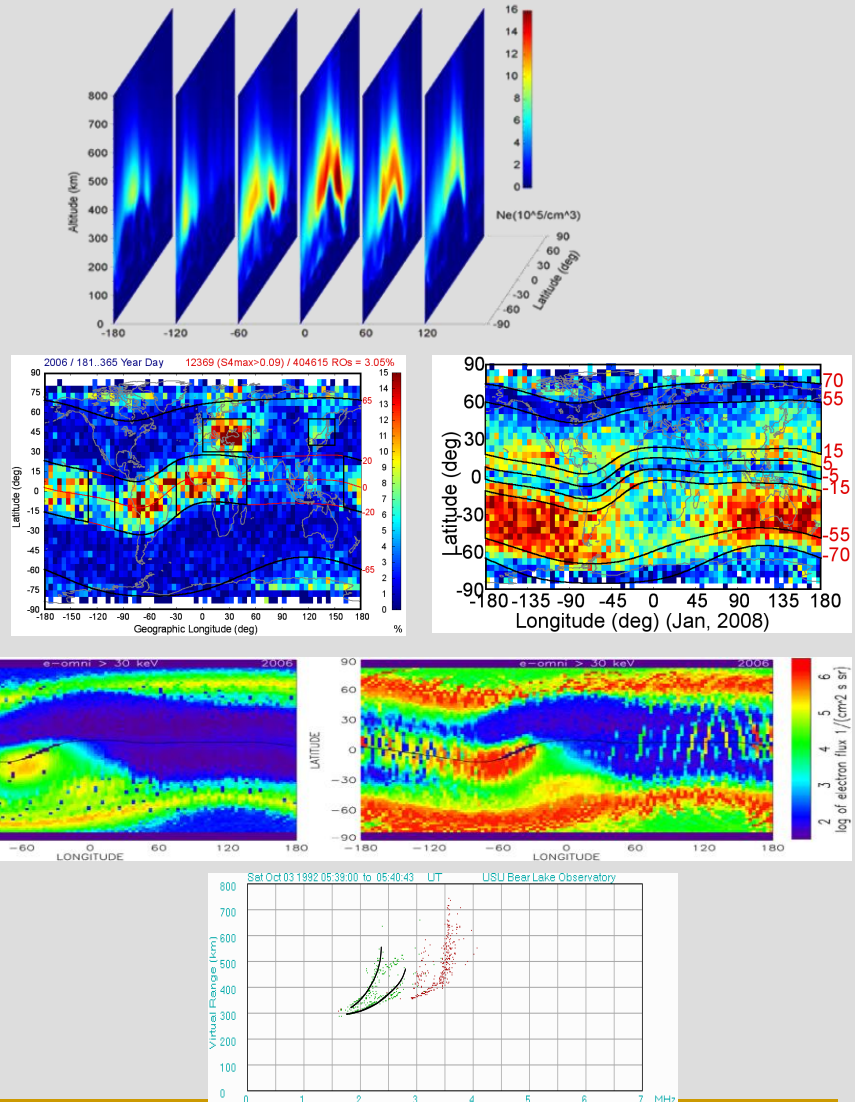
電離層對無線電波傳播影響



- MF/HF 天波傳播
波導管效應：為衛星通訊外，唯一有效的長距離無線通訊方式
- MF/HF 天波傳播
波衰減效應
- 無線電波傳播時間延遲及相位領先效應
- 無線電波傳播多途徑干擾效應
- 無線電波強度、相位及頻率閃爍效應及信號失鎖

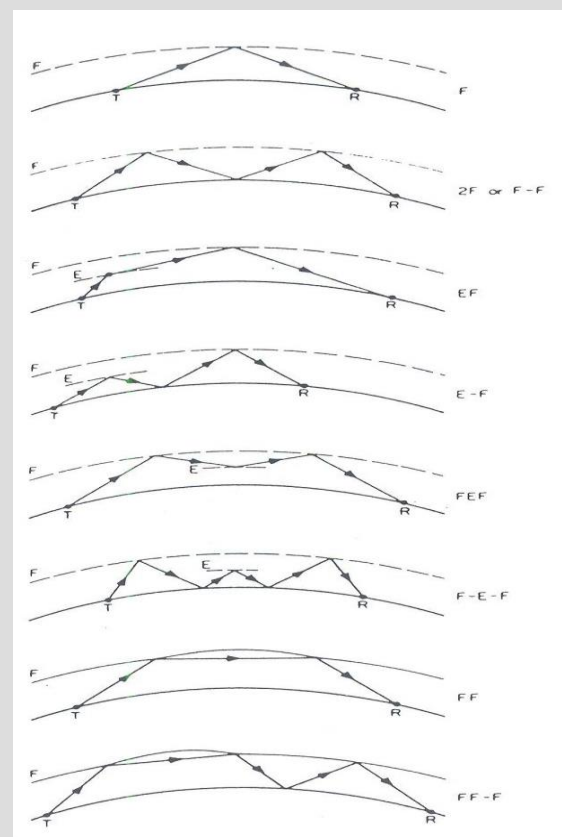
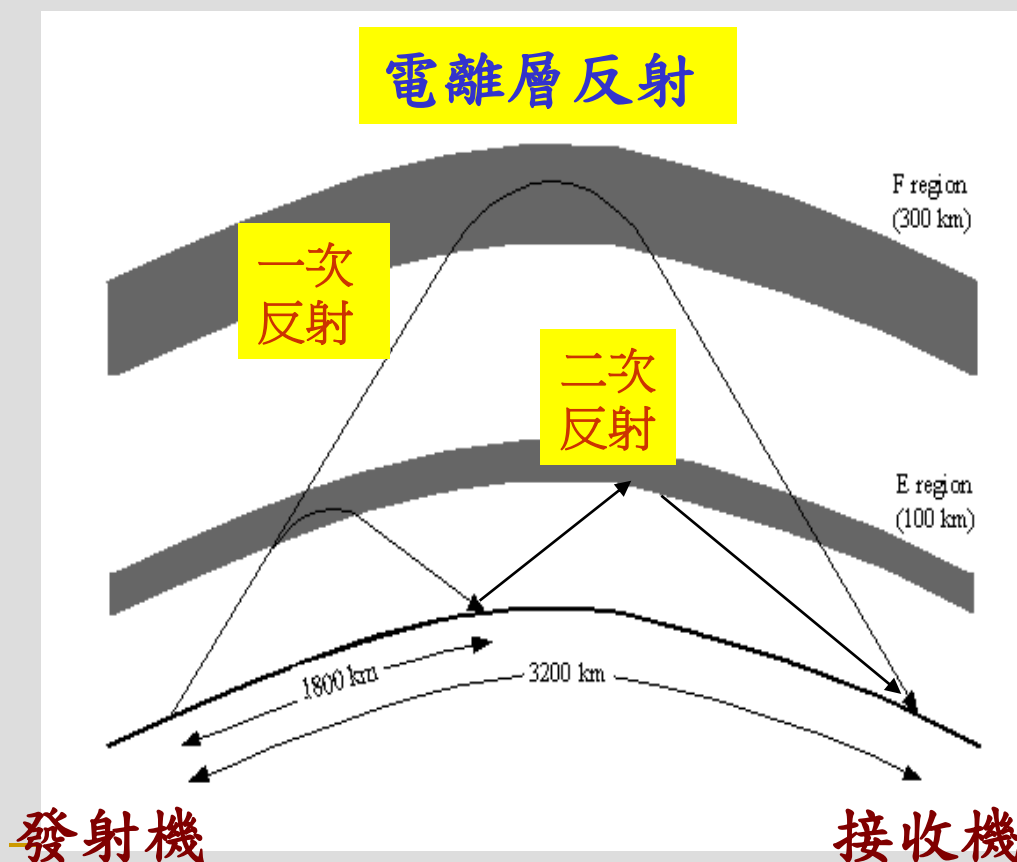
小結：電離層對無線電波傳播影響主要議題

- 區域或全球電離層電子密度分佈與動態變化
- 區域或全球電離層電子密度不規則體分佈與動態變化
- 太陽風暴
- 電離層熱洞化研究 (減少電離層電子密度)



二、電離層觀測、模式建立、與遠距高頻無線電波通訊應用

電離層與高頻無線電波天波傳播模式

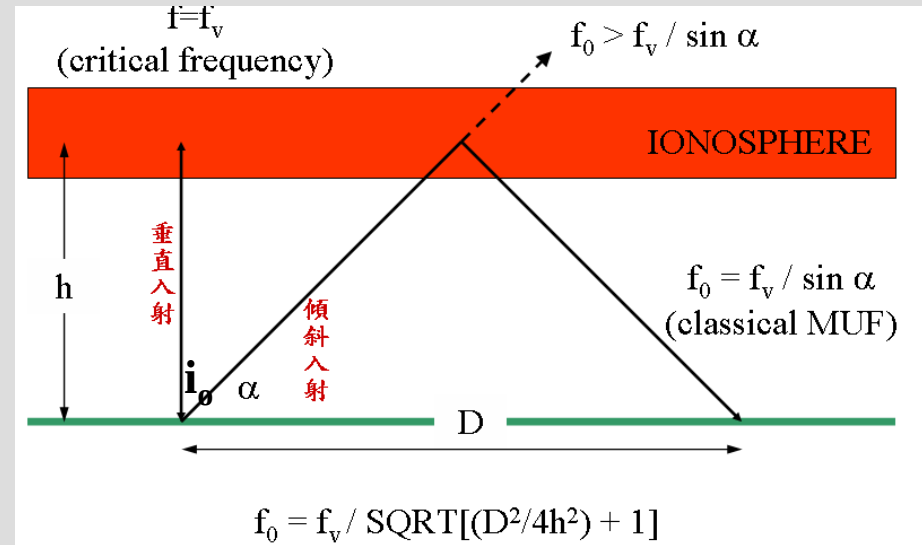


無線電波天波傳播最大可用頻率之定義

The SEC Law :

$$MUF = f_v \sec i_o$$

$$f_v(\text{Hz}) = \sqrt{80.6 n_e (\# / m^3)}$$

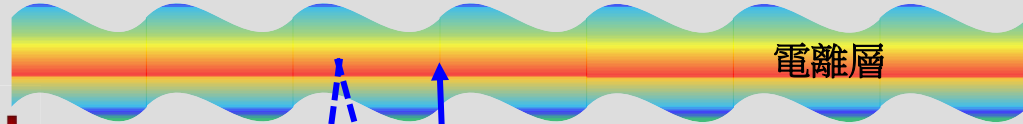
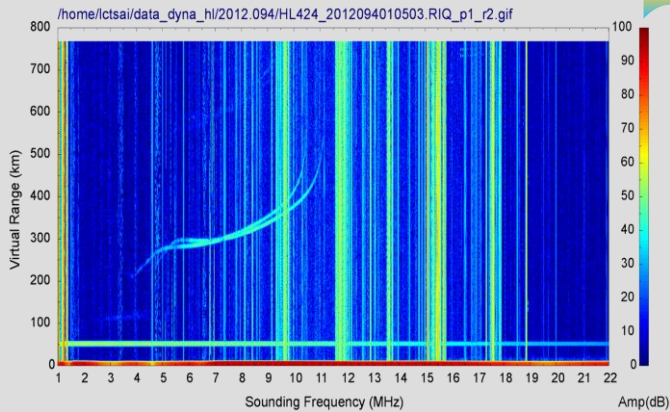


若發射短波電波頻率超過 $f_v \sec i_o$ ，則電波將會穿透電離層，而不會被反射回地面，其中 f_v 為垂直傳播反射點處的最大臨界頻率 (Vertical critical frequency)， n_e 為電離層最大電子密度。因此欲進行電離層短波傳播，操作頻率必須小於或等於最大可用頻率，亦即 MUF。在實際的電波傳播應用上，則通常使用最佳操作頻率 FOT，來作為短波通訊之用，亦即 $FOT = 0.834 * MUF$

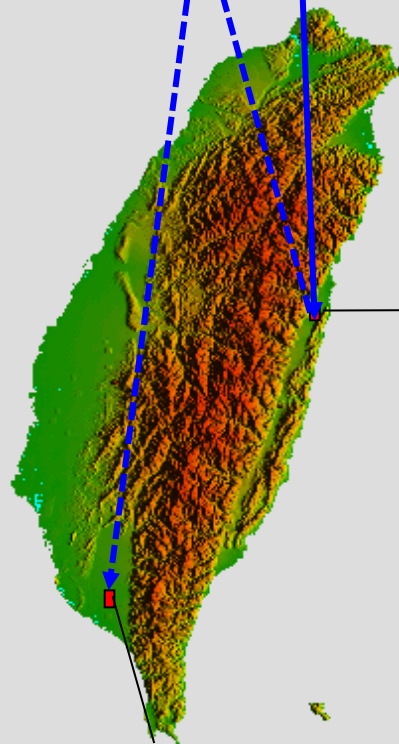
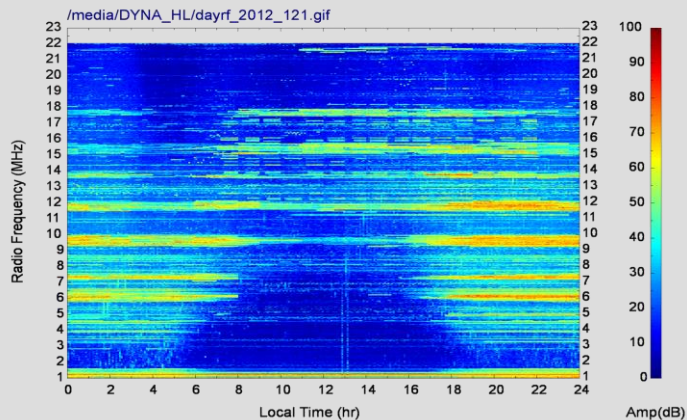
系統一：臺灣動態式電離層觀測網系統

花蓮站(國立東華大學)與屏東龍泉站

電離層觀測

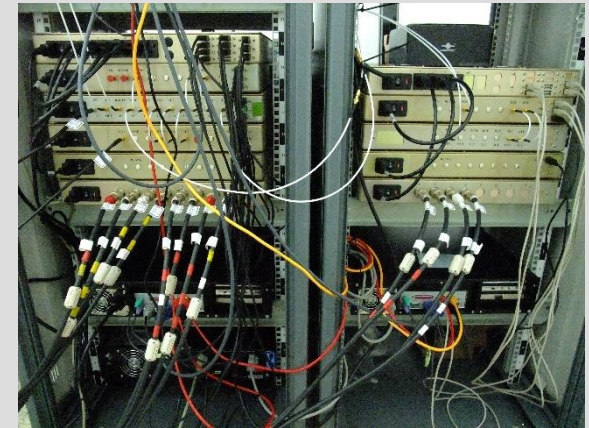


中高頻頻帶環境噪音觀測



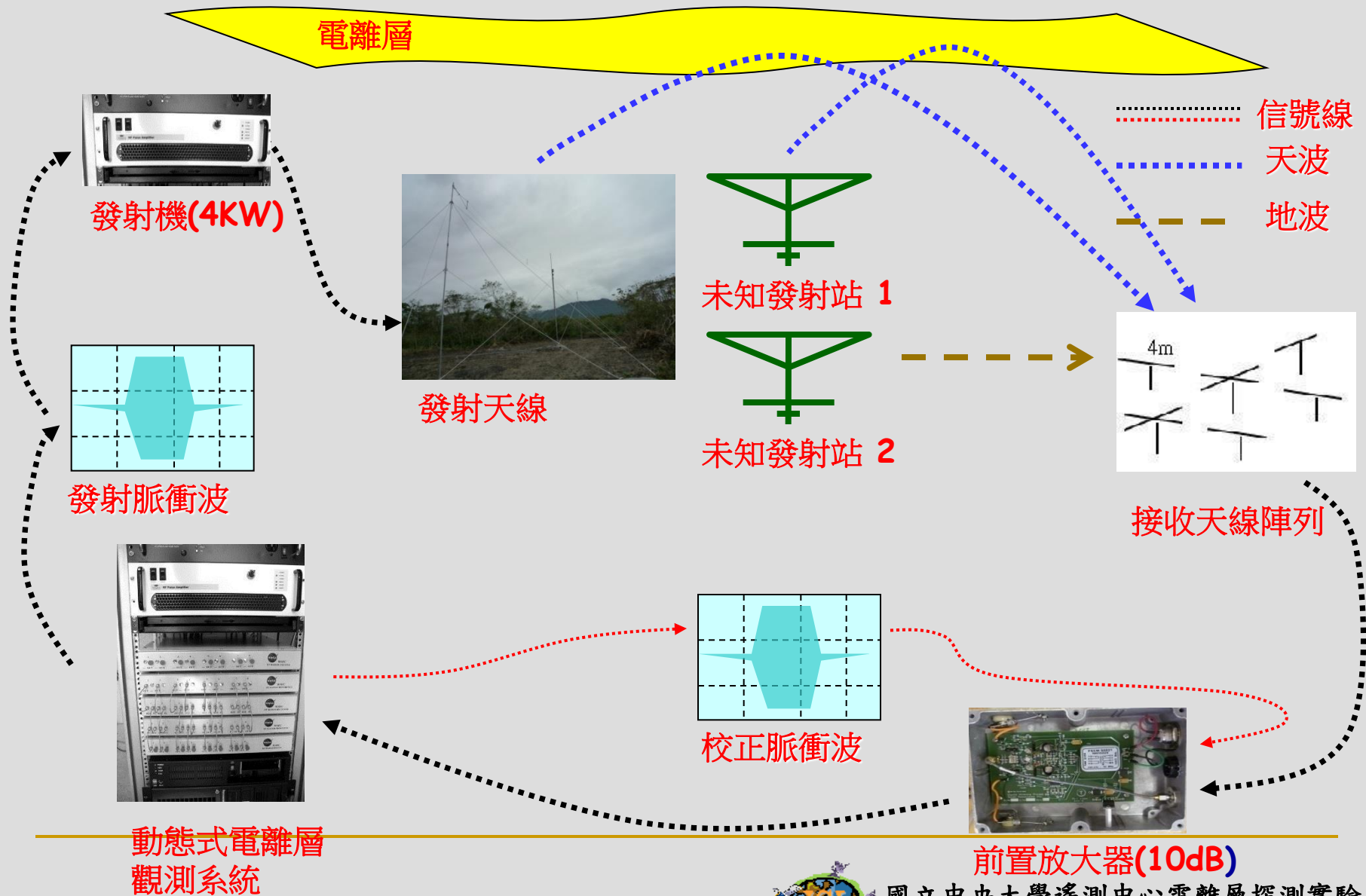
花蓮(國立東華大學)
(23.89° N, 121.55° E)

屏東龍泉
(22.67° N, 120.60° E)

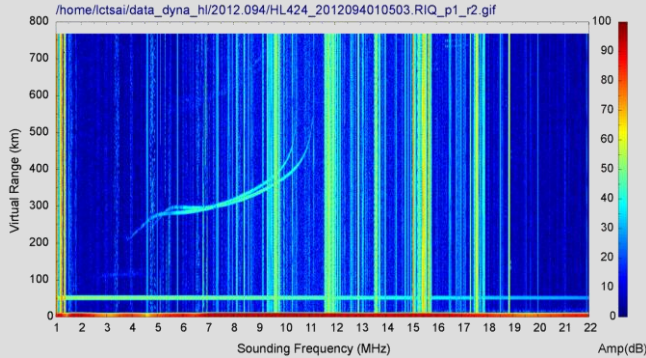


花蓮(或中壢)站動態式電離層觀測系統操作釋意圖

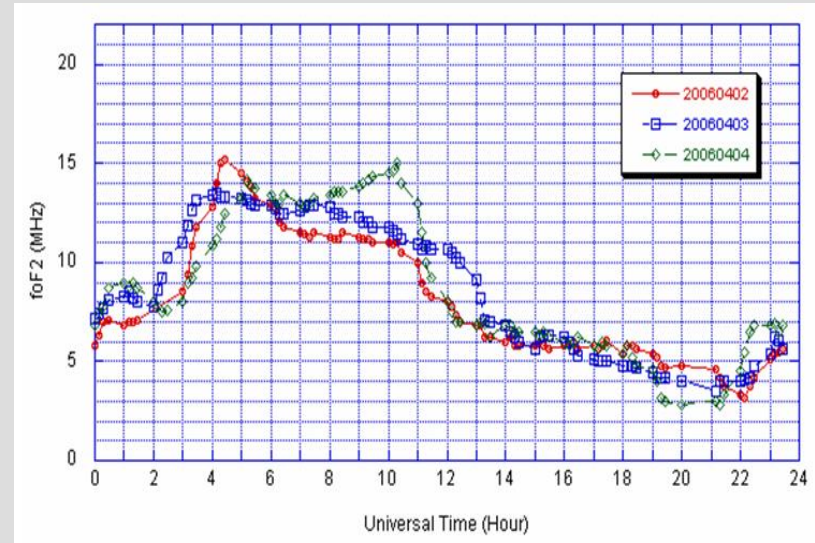
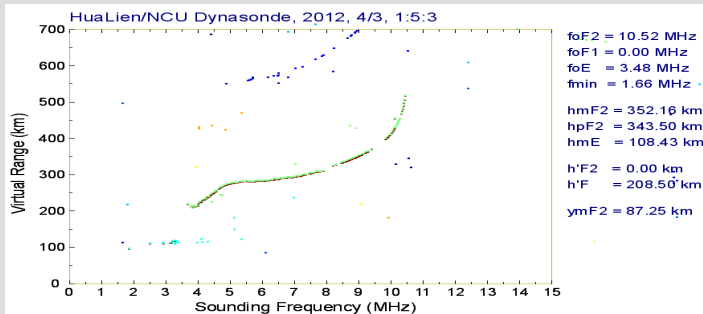
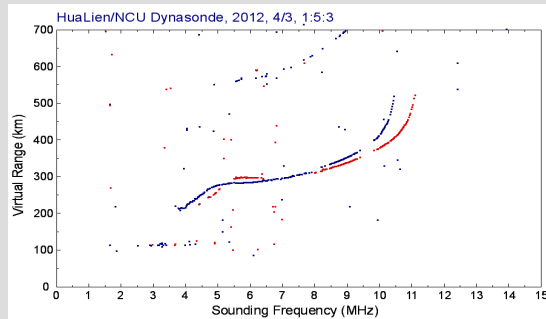
電離層



電離層觀測實例：電離圖自動判讀電離層參數與垂直通訊最高可用頻率(vertical MUF)觀測實例



電離圖：
空間干涉式
相位測量判
別正常型與
異常型電離
層回波



電離層F層臨界頻率參數即為垂直通訊
最高可用頻率(vertical MUF)參考值

自動判讀電離層參數：
應用模糊理論於電離層E層、F層等
回波分類、軌跡判讀、與電離層參
數自動判讀。

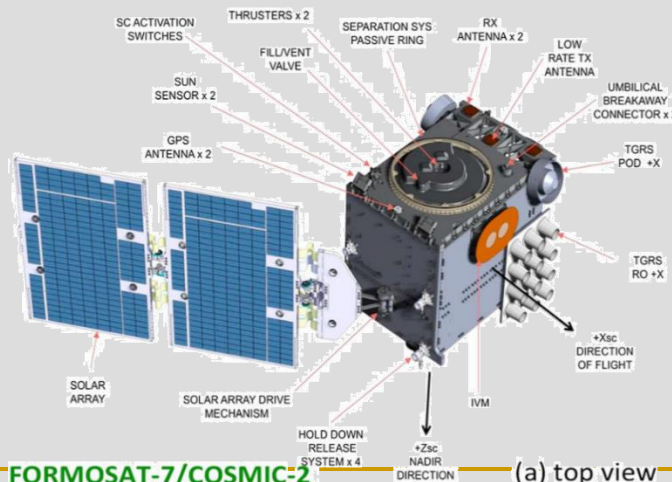
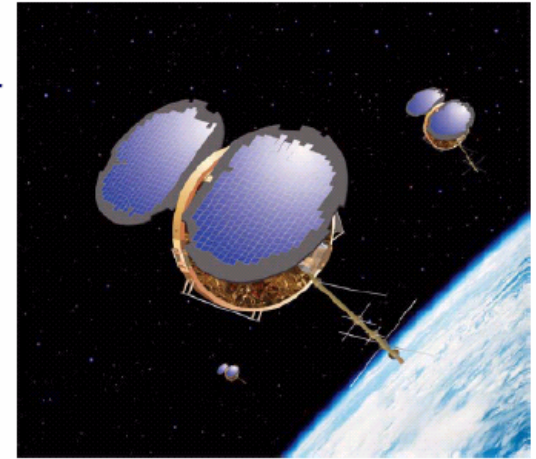


系統二：福衛三號與福衛七號 GPS/GNSS信號 電離層掩星觀測

福衛三號:FormoSat3/
Constellation Observing
System for Meteorology,
Ionosphere and Climate
(COSMIC)

福衛七號:
FormoSat3/COSMIC2

- Number : Six Small Satellites
- Weight : ~ 61 kg (with payload and fuel for each satellite)
- Shape : Disc-shape of 116cm diameter and 18cm in height
- Orbit : 800km altitude, circular,
- Inclination Angle: 72 degree
- Power: ~ 81 W orbit average
- Communication: S-band uplink and downlink
- Design life : > 5 years
- Launch date : April 15, 2006



First Phase Launch (no 2nd phase mission)

Mission Constellation

6 satellites
(low inclination 24 deg, mission altitude ~720 km, & separation 60 deg)

Mission Payload

GPS & Glonass Rx

Science Payload

•2-band beacon
•plasma drift/fluctuation sensor (~10kg, 22W)

Launch Schedule

June 25, 2019

Mission Duration

10 years



福衛三號與福衛七號 GPS/GNSS信號掩星觀測 與電離層垂直電子密度反演

假設區域性電離層電子密度球型對稱以及 GPS
信號直線傳播：

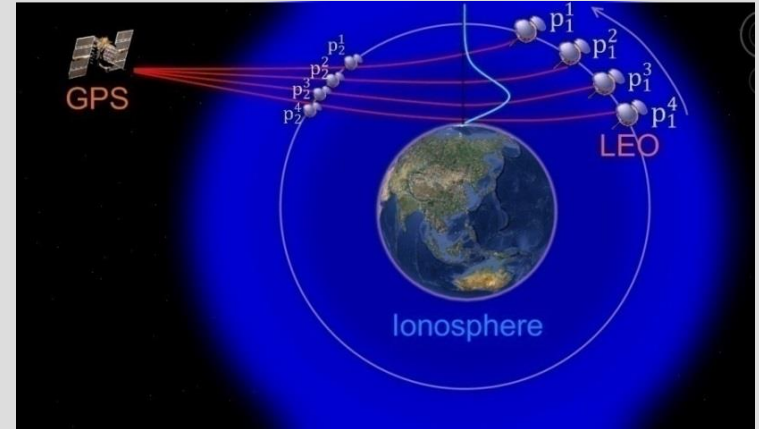
1. 電離層掩星觀測水平全電子含量 (TEC')量測

$$TEC'(r_t) = pTEC(P_1(r_t)) - pTEC(P_2(r_t)) \cong 2 \int_{r_t}^{r_{LEO}} \frac{r N_e(r)}{\sqrt{r^2 - r_t^2}} dr$$

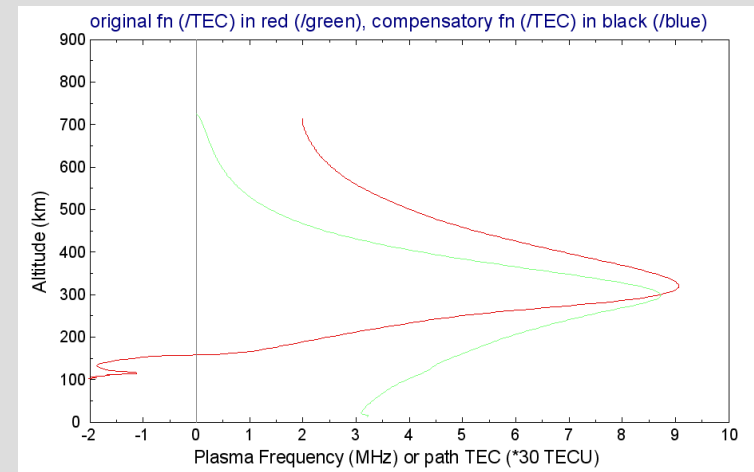
where $pTECs$ are the path TECs from GPS to LEO,
and P1 and P2 are the occulting and auxiliary
positions during a GPS RO observation.

2. 應用 the Abel inversion 於電離層垂直電子密度 反演

$$N_e(r_t) = -\frac{1}{\pi} \int_{r_t}^{r_{LEO}} \frac{dTEC'(r)/dr}{\sqrt{r^2 - r_t^2}} dr.$$

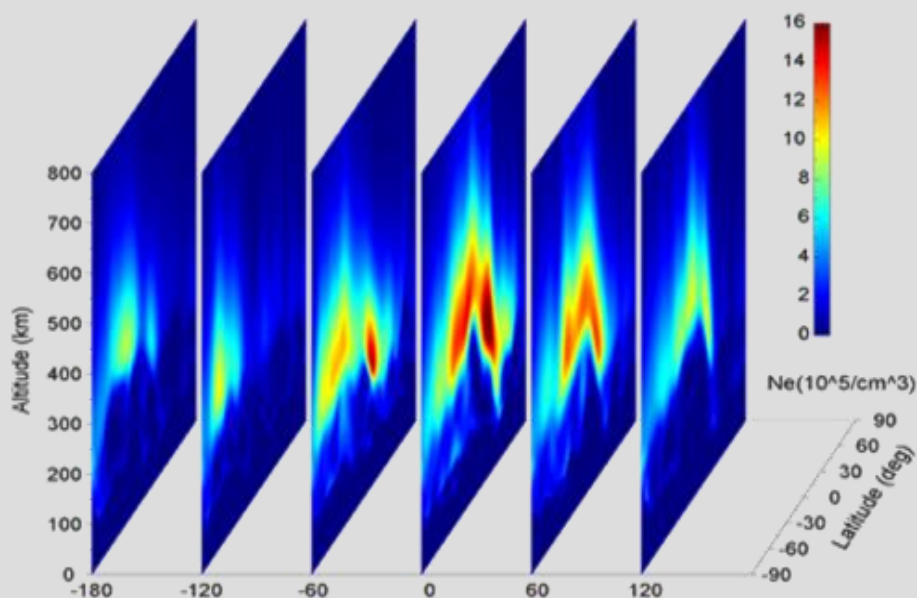
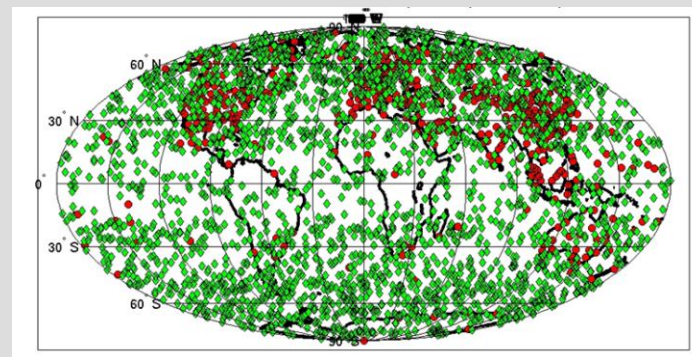


電離層水平全電子含量 (綠色線)量測
與垂直電子密度反演(紅色線)實例

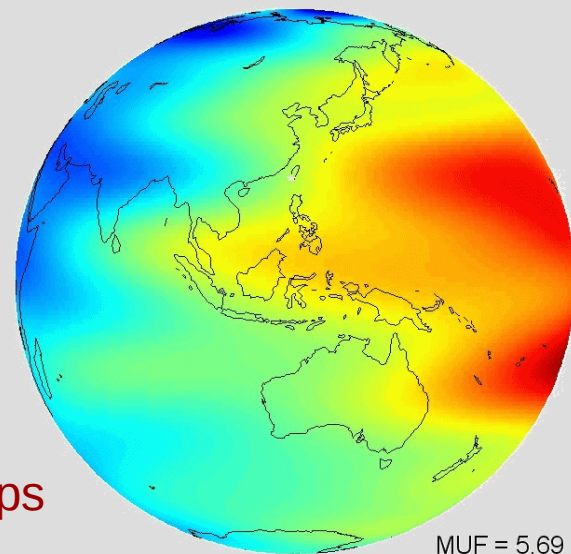


全球即時電離層數值模式系統：臺灣自主 電離層模式(the TaiWan Ionospheric Model, TWIM)

- 利用查普曼層(Chapman Layer)方程式擬合福衛三號觀測之電離層電子密度剖面，求出最大電子密度值，再利用球面諧波多項式，擬合最大電子密度觀測值，得到全球分布。



foF2 maps
in UT

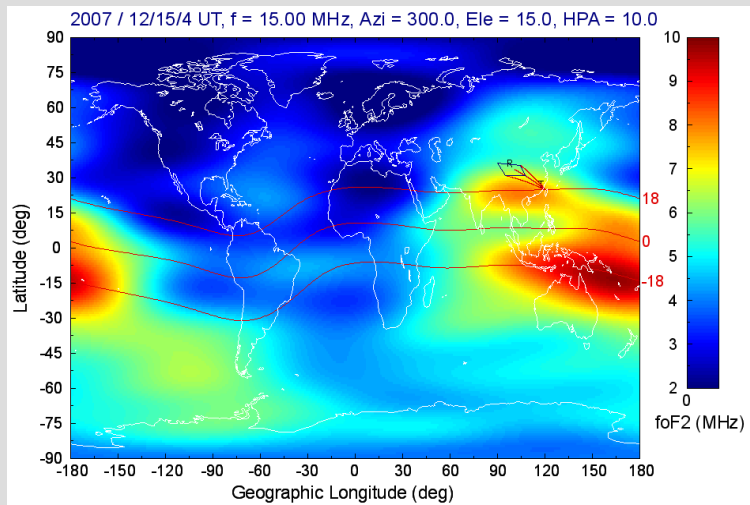


MUF = 5.69 MHz

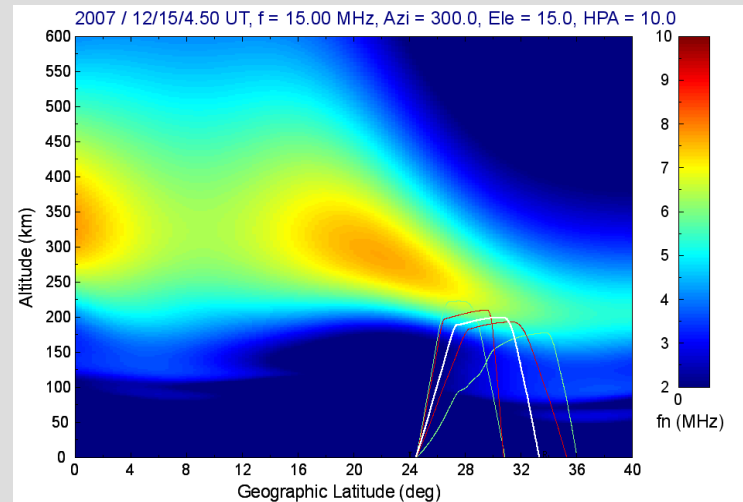


無線電波天波傳播路徑預測線上系統服務

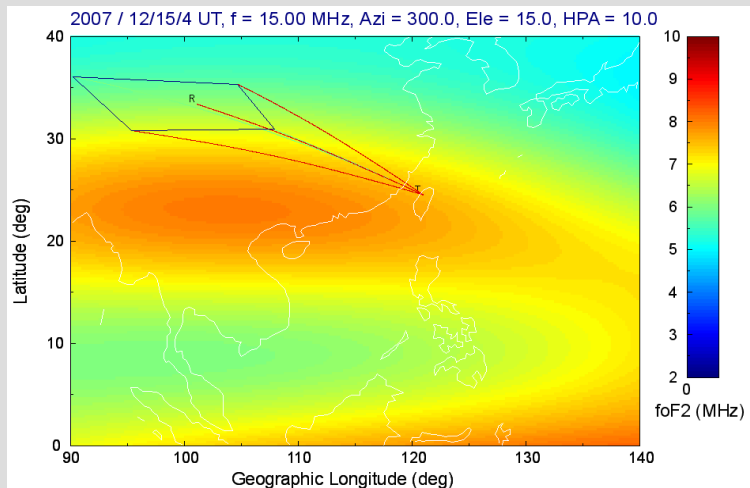
電波傳播路徑全球俯視圖



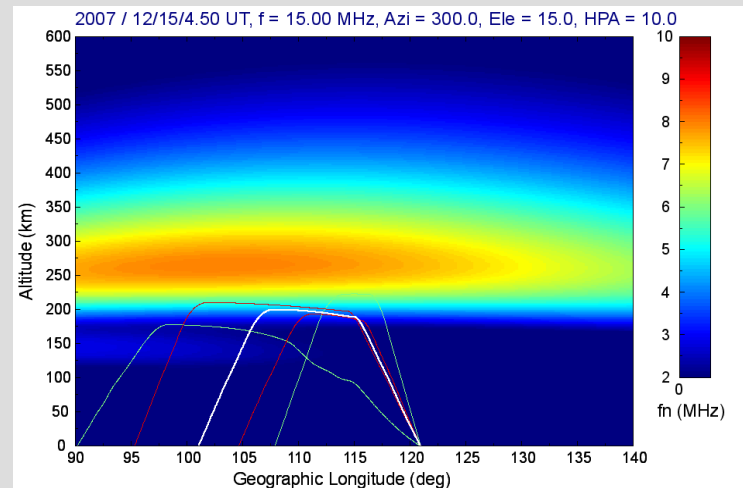
電波傳播路徑區域緯度側視圖



電波傳播路徑區域俯視圖



電波傳播路徑區域經度側視圖

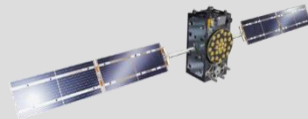


三、電離層環境對全球定位系統影響：定位誤差、無線電波閃爍效應(原因包含電離層F層與散塊E層不規則體)、與軟體接收機開發

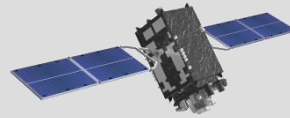
現代民生交通與國防的感官器：全球定位系統



美國 GPS



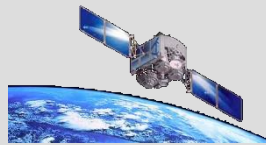
歐洲 Galileo



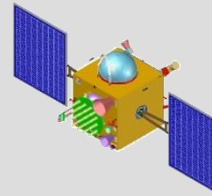
日本 QZSS



俄羅斯 GLONASS



中國 BeiDou

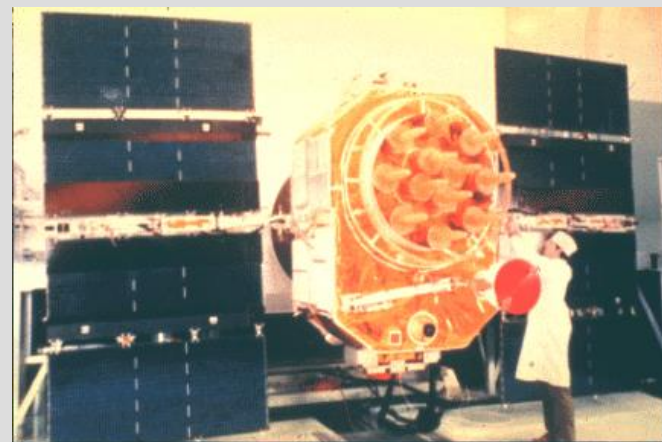


印度 IRNSS

Global Positioning System (GPS)

衛星特性與基本參數

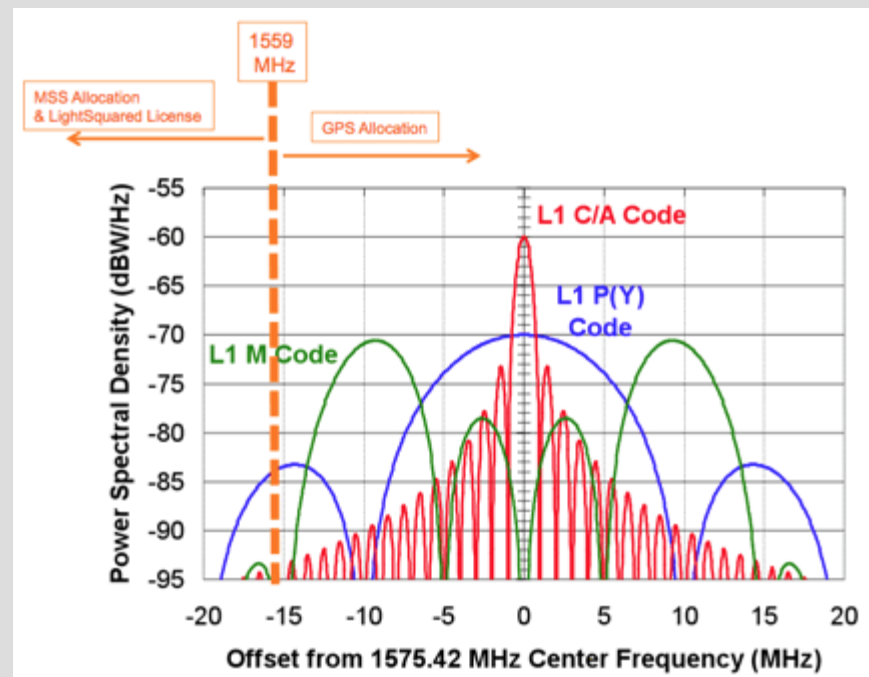
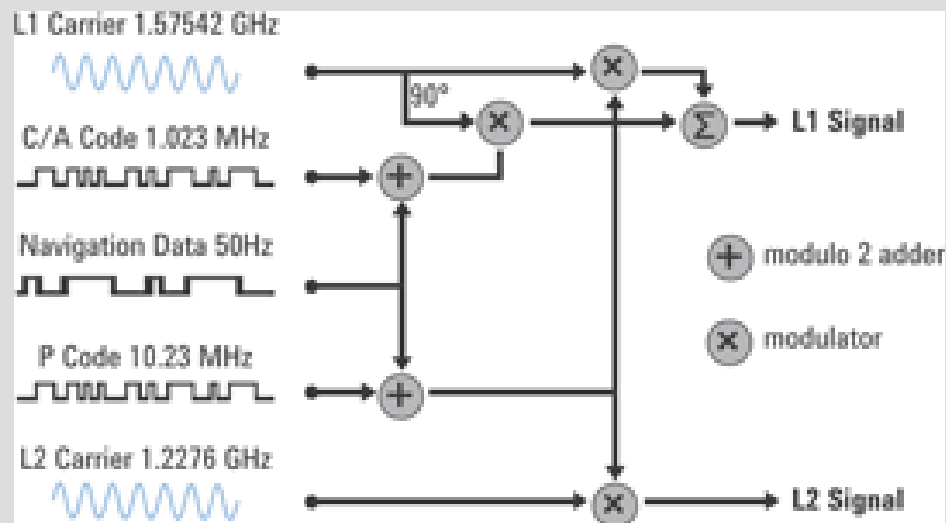
- 衛星軌道高度: 20200 km
- 衛星數目: 24~32顆 ; 衛星軌道面 : 6
- 衛星繞地週期: 11 hr 58 min
- 衛星軌道傾角: 55 degrees
- 無線電波信號載波頻率 : 1575.43 MHz (L1 band, $10.23 \text{ MHz} * 154$), 1227.60 MHz (L2 band, $10.23 * 120$), **1176.45 MHz (L5 band)**
- 無線電波 : 右旋圓形極化波
- 信號碼: C/A-code (1.023 MHz), P-code (10.23 MHz)
- 導航訊號碼 : 50 bit/sec



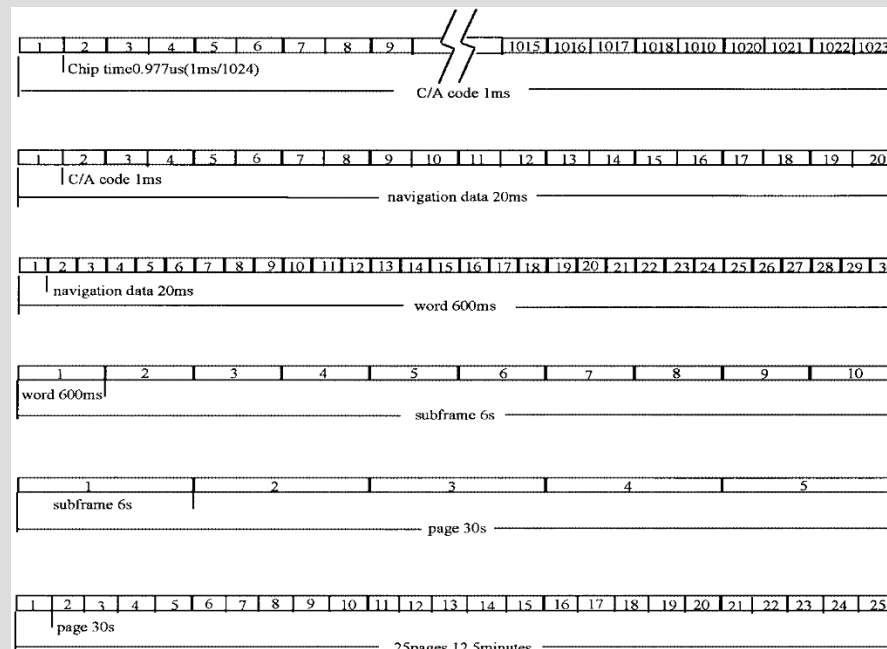
A GPS Block II satellite

Global Positioning System (GPS) 主要應用

- Navigation (導航)
- Surveying (測量)
- Geodynamics and geophysics
- Remote Sensing (troposphere, ionosphere, and ocean)
- Time and frequency transfer



GPS 導航信息結構



Navigation message

Navigation message = 25 frames = 125 subframes = 1250 words = 37,5kb = 12,5min

subframe = 10 words = 300bit = 6s

word = 30bit = 0,6s

frame
= 5 subframes
= 1,5kb = 30s

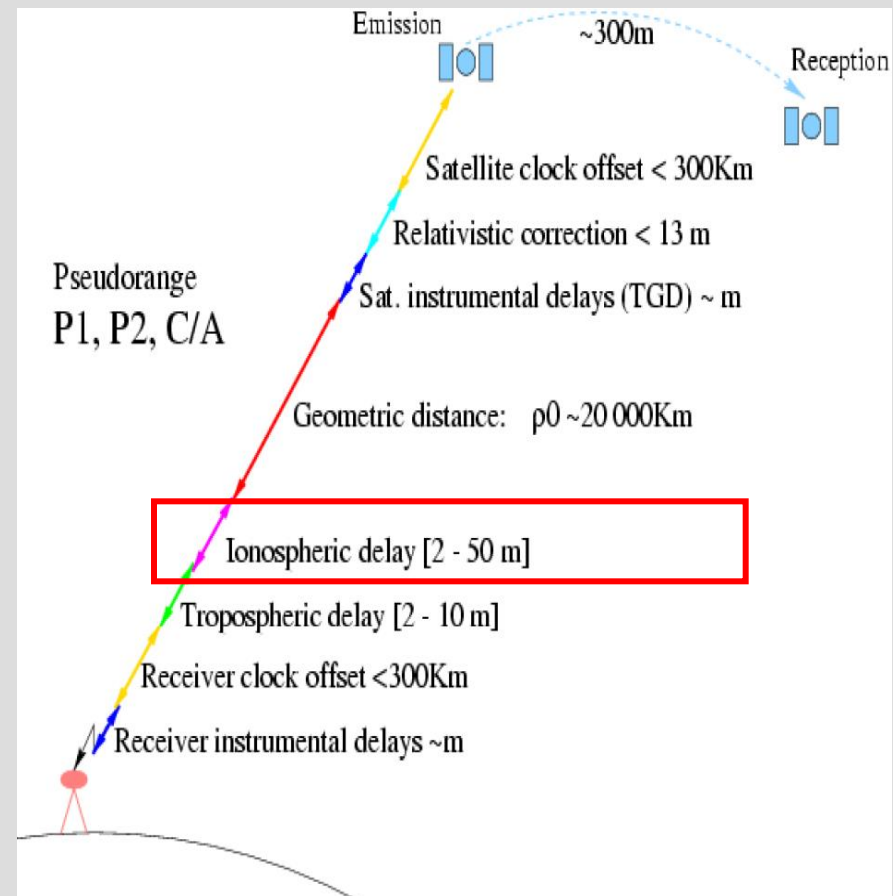
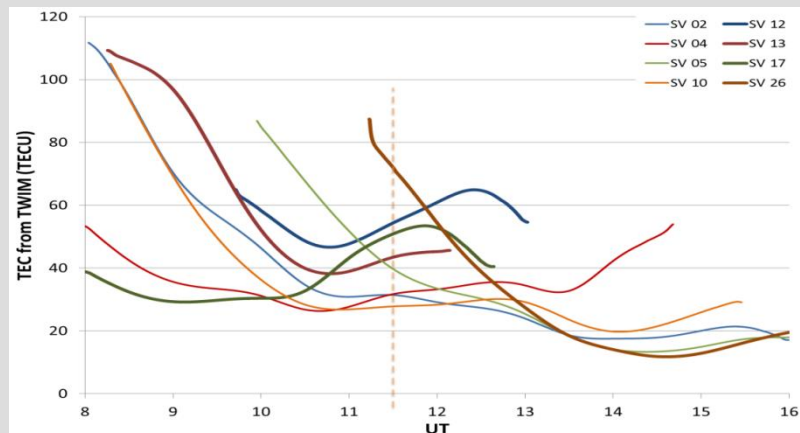
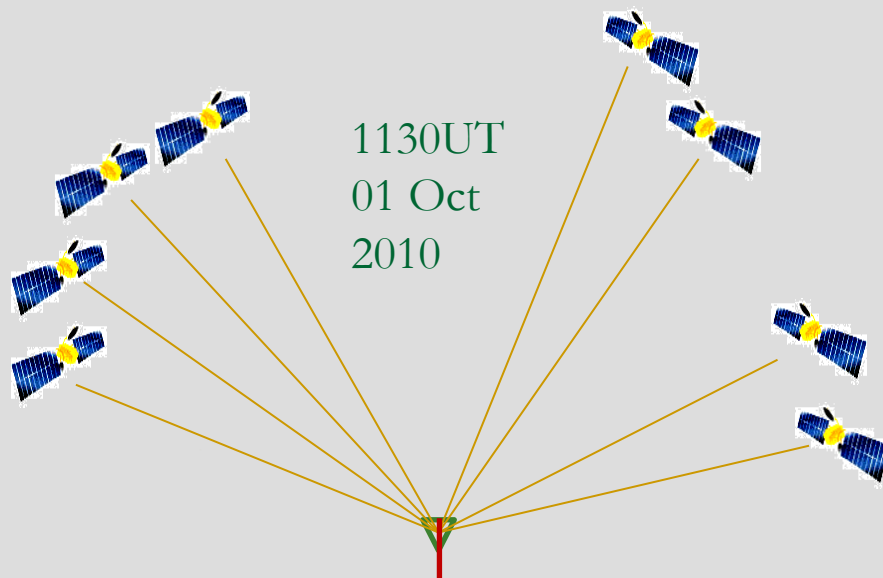
	1	2	3	4	5	7	6	7	8	9	10
1. subframe	TLM	HOW	GPS week, satellite status and health, correction for atomic clock								
2. subframe	TLM	HOW	1/2 satellite ephemeris data								
3. subframe	TLM	HOW	2/2 satellite ephemeris data								
4. subframe	TLM	HOW	satelites SV 25-32 almanac; SV 1-32 health and status of AntiSpoofing; data for ionosferic model								
5. subframe	TLM	HOW	satelites SV 01-24 almanac								

subframe contains in every frame always the same data

subframe contains in every frame one page from 1 to 25



電離層環境對全球定位系統的定位誤差影響



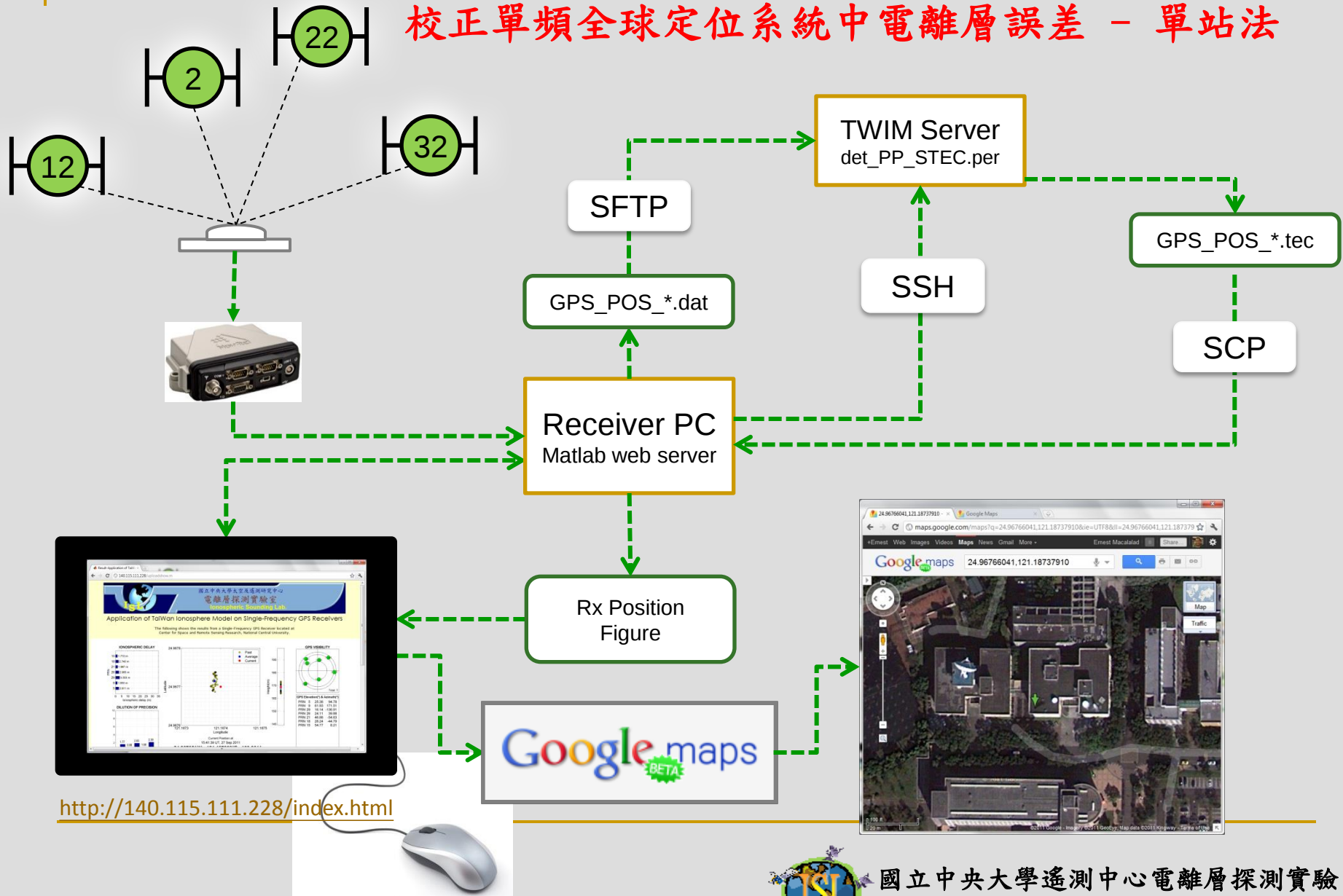
解決方法: 雙頻(L1 & L2) 或 三頻(L1, L2, & L5)系統

L1 band: 1.57542 GHz, L2 band: 1.22760 GHz, L5 band: 1.17645 GHz

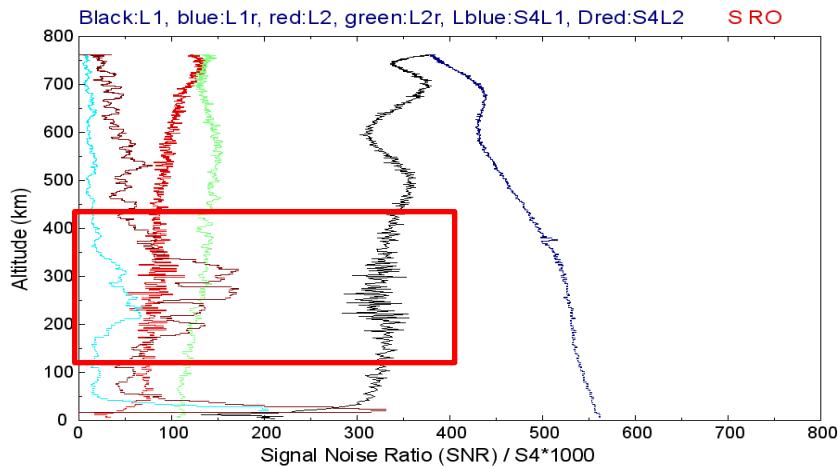


臺灣自主電離層模式(TWIM)應用：

校正單頻全球定位系統中電離層誤差 - 單站法

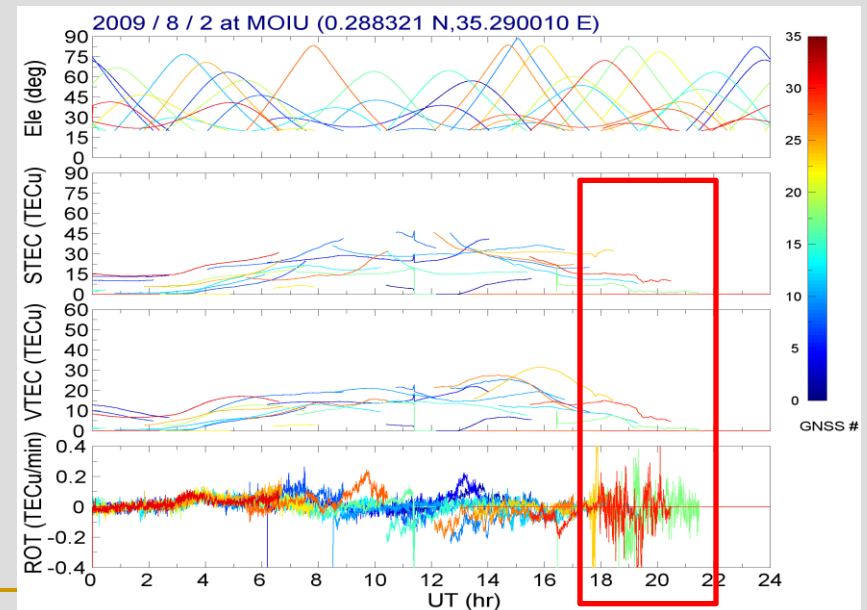
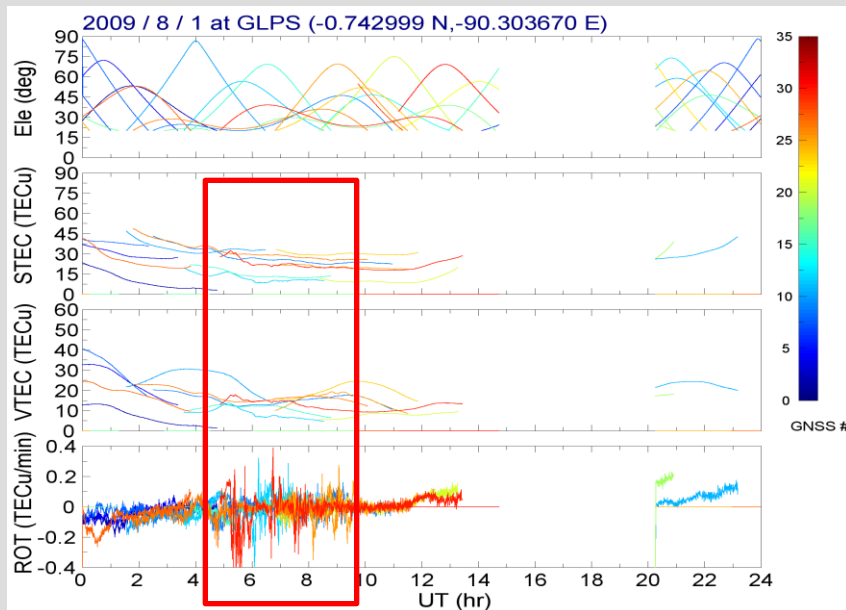


電離層環境對全球定位系統的無線電波閃爍效應影響

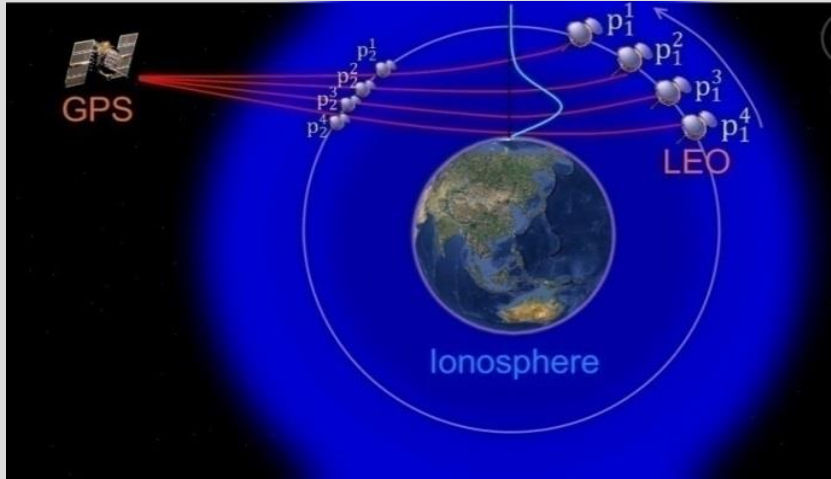


GPS/GNSS 信號 地面與衛星接收觀測影響：

1. 虛擬距離錯誤，造成定位誤差
2. 相位失鎖，造成定位誤差
3. **GPS/GNSS信號太弱，造成無法追蹤定位**



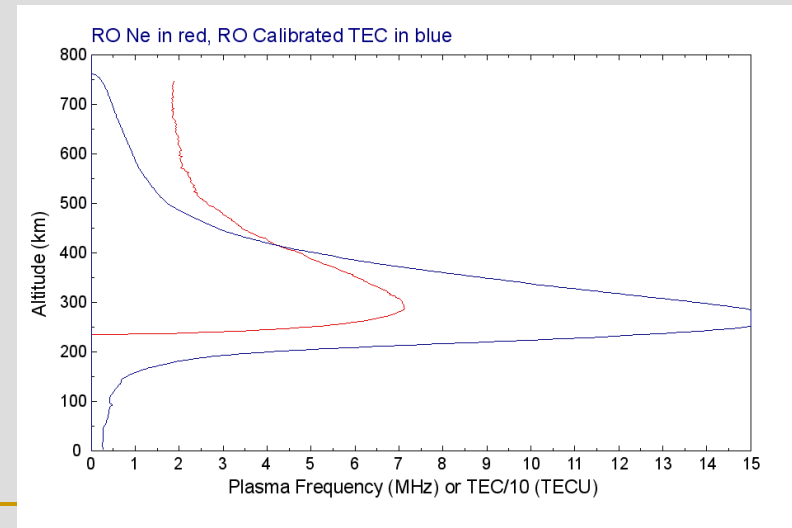
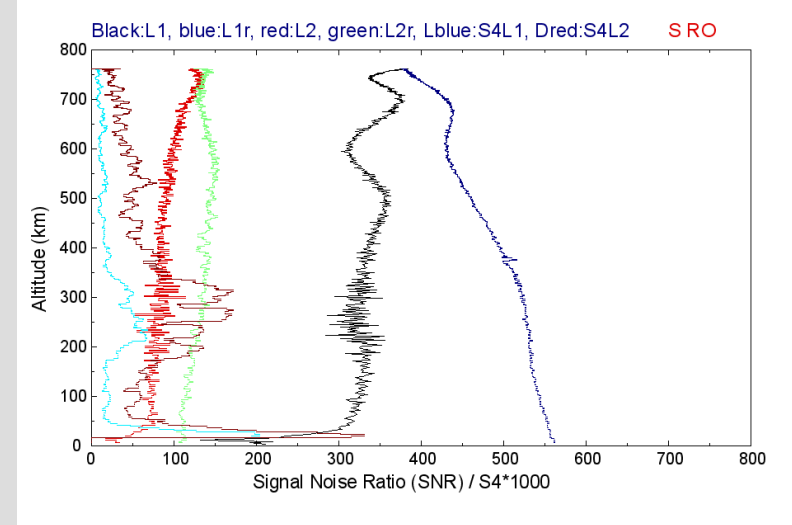
應用福衛三號掩星資料於全球電離層F層不規則體閃爍現象觀測



$$S_4 = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle}$$

$$N_e(r_t) = -\frac{1}{\pi} \int_{r_t}^{r_{LEO}} \frac{dTEC'(r)/dr}{\sqrt{r^2 - r_t^2}} dr$$

- We study the ionospheric irregularity based on GPS RO L1 observations only because L2 signals are much weaker.



應用福衛三號掩星觀測資料於全球電離層閃爍現象全球分佈分析 (閃爍現象定義: undersampling $S4_{max} > 0.09$)

重要影響區域：

A. Central Pacific Area:

$-20^{\circ} \sim 20^{\circ}$ dip latitude,
 $160^{\circ} \text{ E} \sim 130^{\circ} \text{ W}$

B. South American Area:

$-20^{\circ} \sim 20^{\circ}$ dip latitude,
 $100^{\circ} \text{ W} \sim 30^{\circ} \text{ W}$

C. African Area:

$-20^{\circ} \sim 20^{\circ}$ dip latitude,
 $30^{\circ} \text{ W} \sim 50^{\circ} \text{ E}$

D. European Area:

$30^{\circ} \sim 55^{\circ} \text{ N}, 0^{\circ} \sim 55^{\circ} \text{ E}$

E. Japan Sea Area:

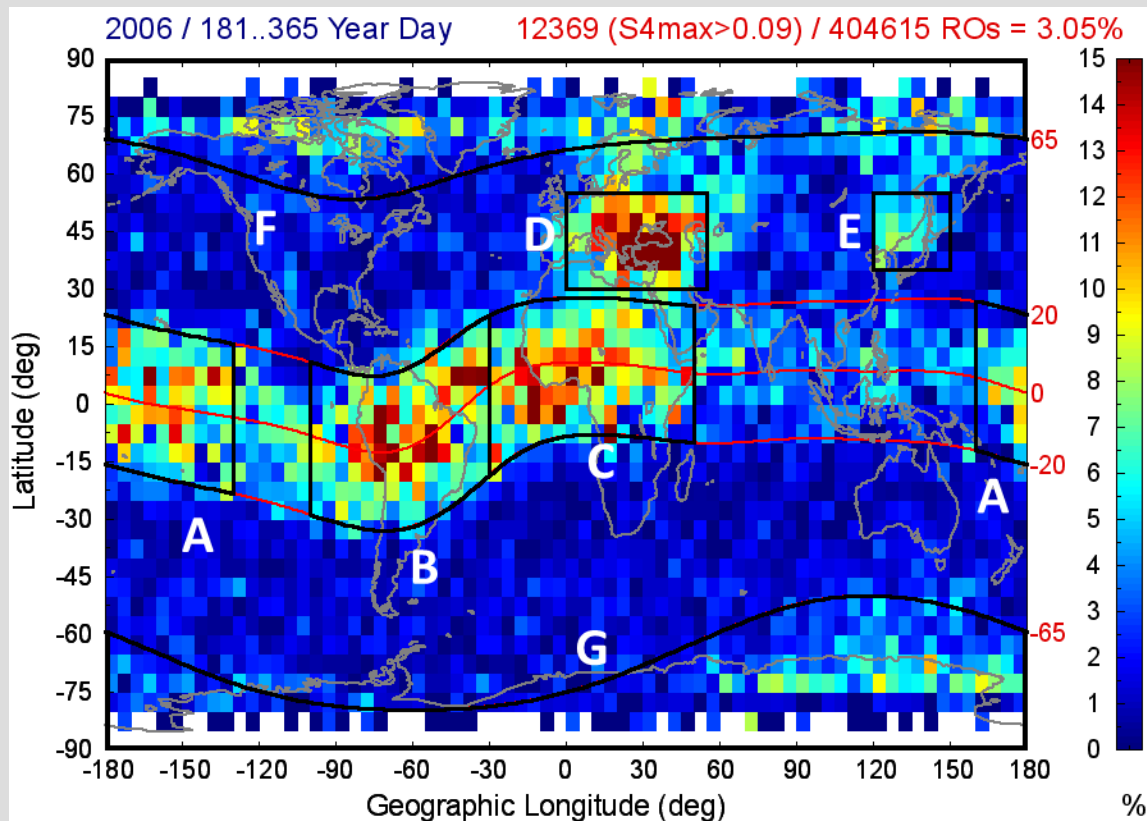
$35^{\circ} \sim 55^{\circ} \text{ N}, 120^{\circ} \sim 150^{\circ} \text{ E}$

F. Arctic Area:

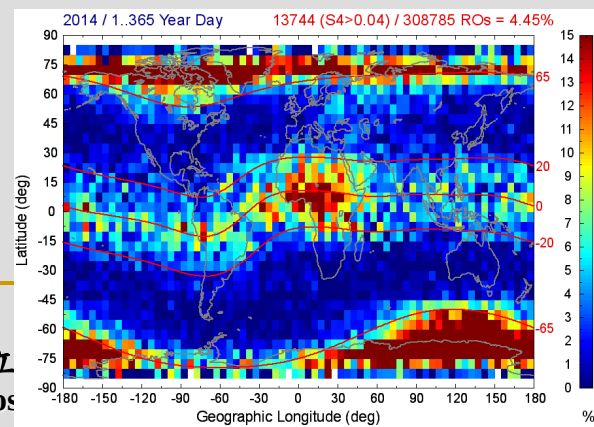
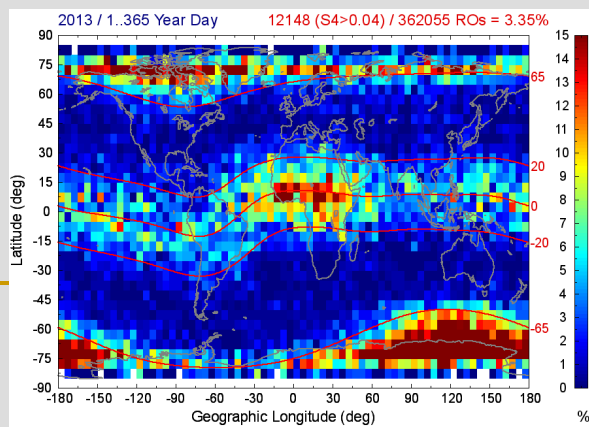
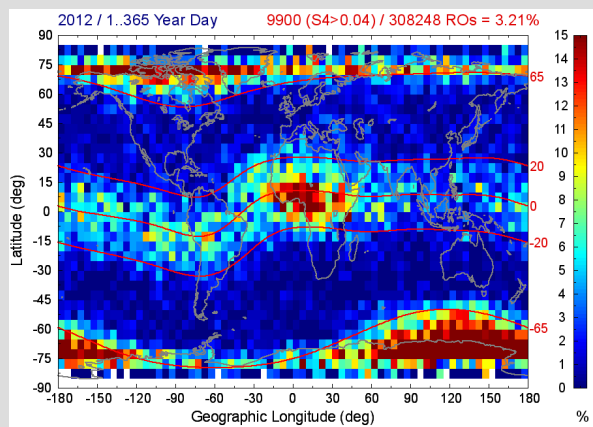
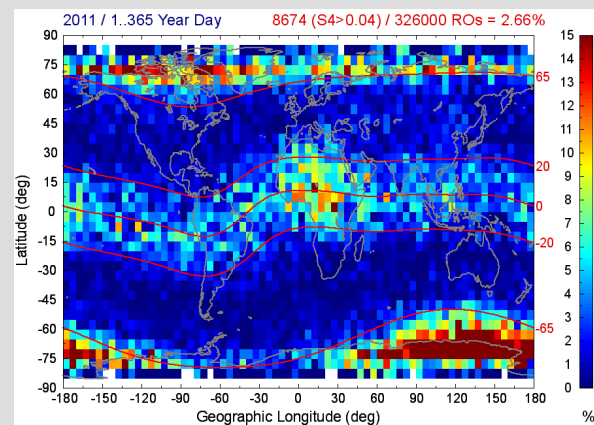
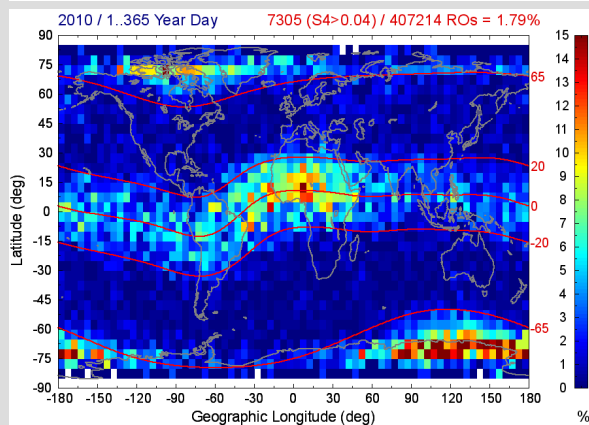
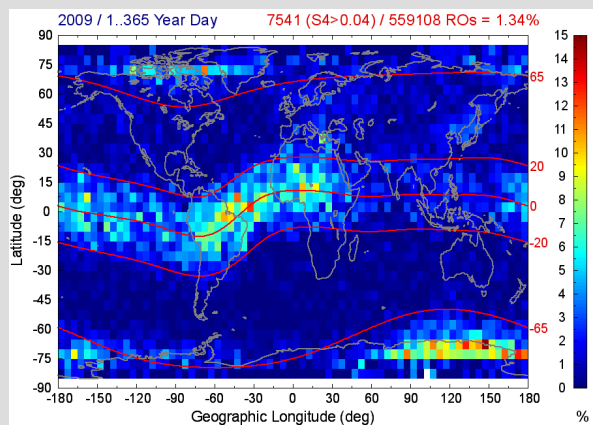
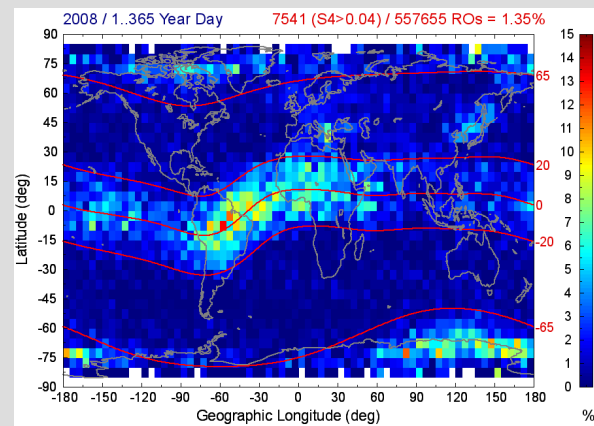
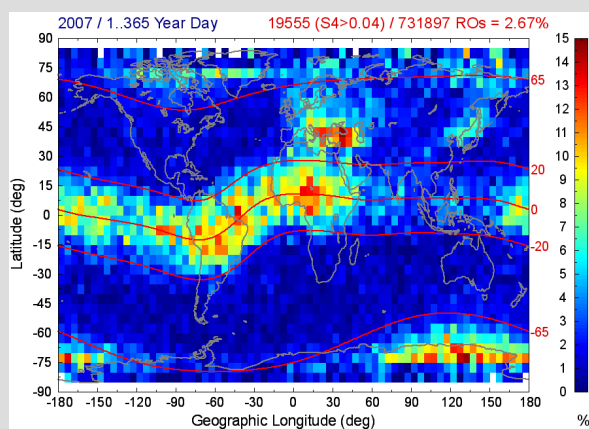
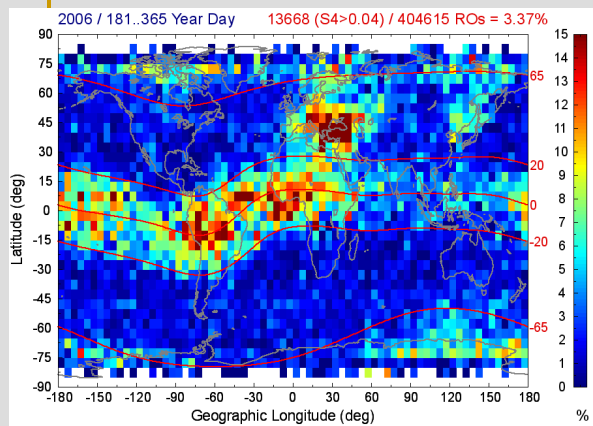
$> 65^{\circ}$ dip latitude

G. Antarctic Area:

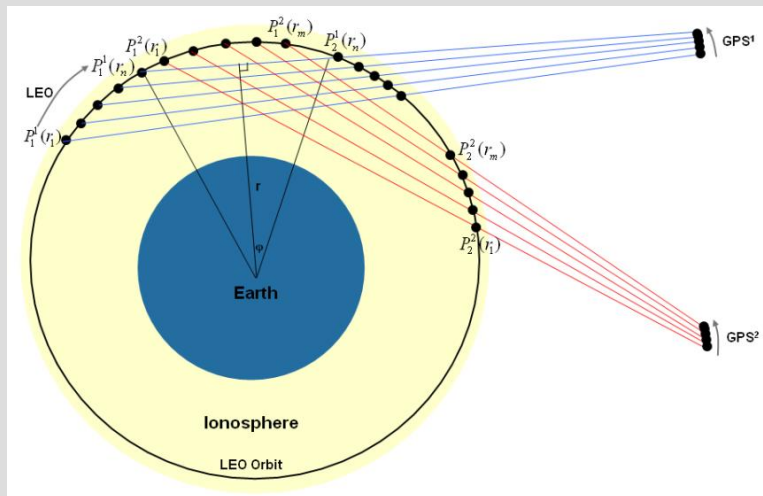
$< -65^{\circ}$ dip latitude



全球電離層閃爍現象發生率年度分佈(2006~2014)



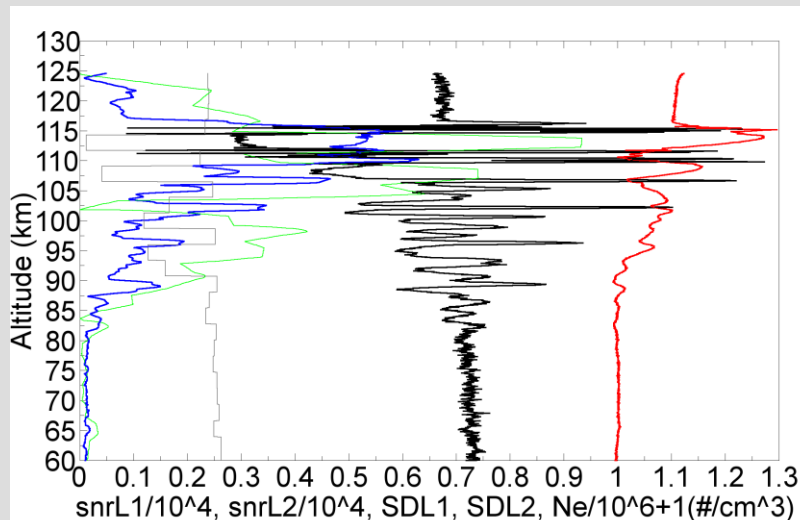
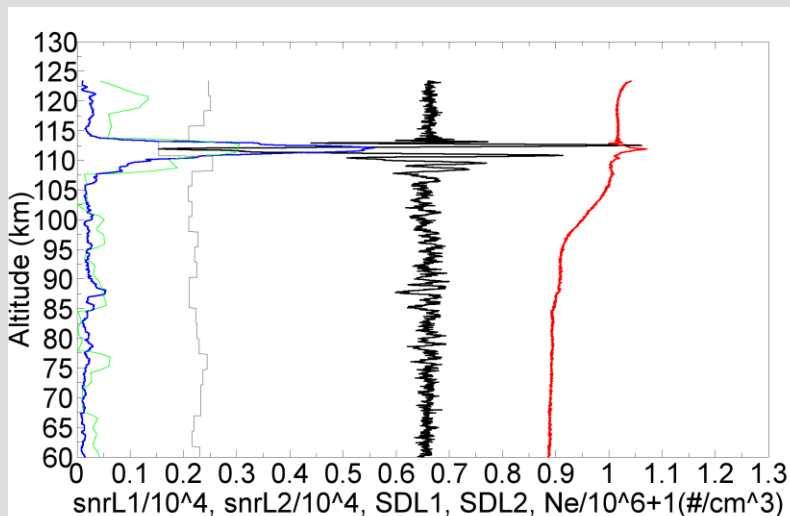
應用福衛三號掩星資料於全球電離層散塊E層 (sporadic E layer) 現象觀測



$$N_e(r_t) = N_e(r_{top}) - \frac{1}{\pi} \int_{r_t}^{r_{top}} \frac{d TEC'(r)}{\sqrt{r^2 - r_t^2}} dr$$

$$SDL1 \text{ (or } SDL2) = \sqrt{\left(\frac{A - \langle A \rangle}{\langle A \rangle} \right)^2}$$

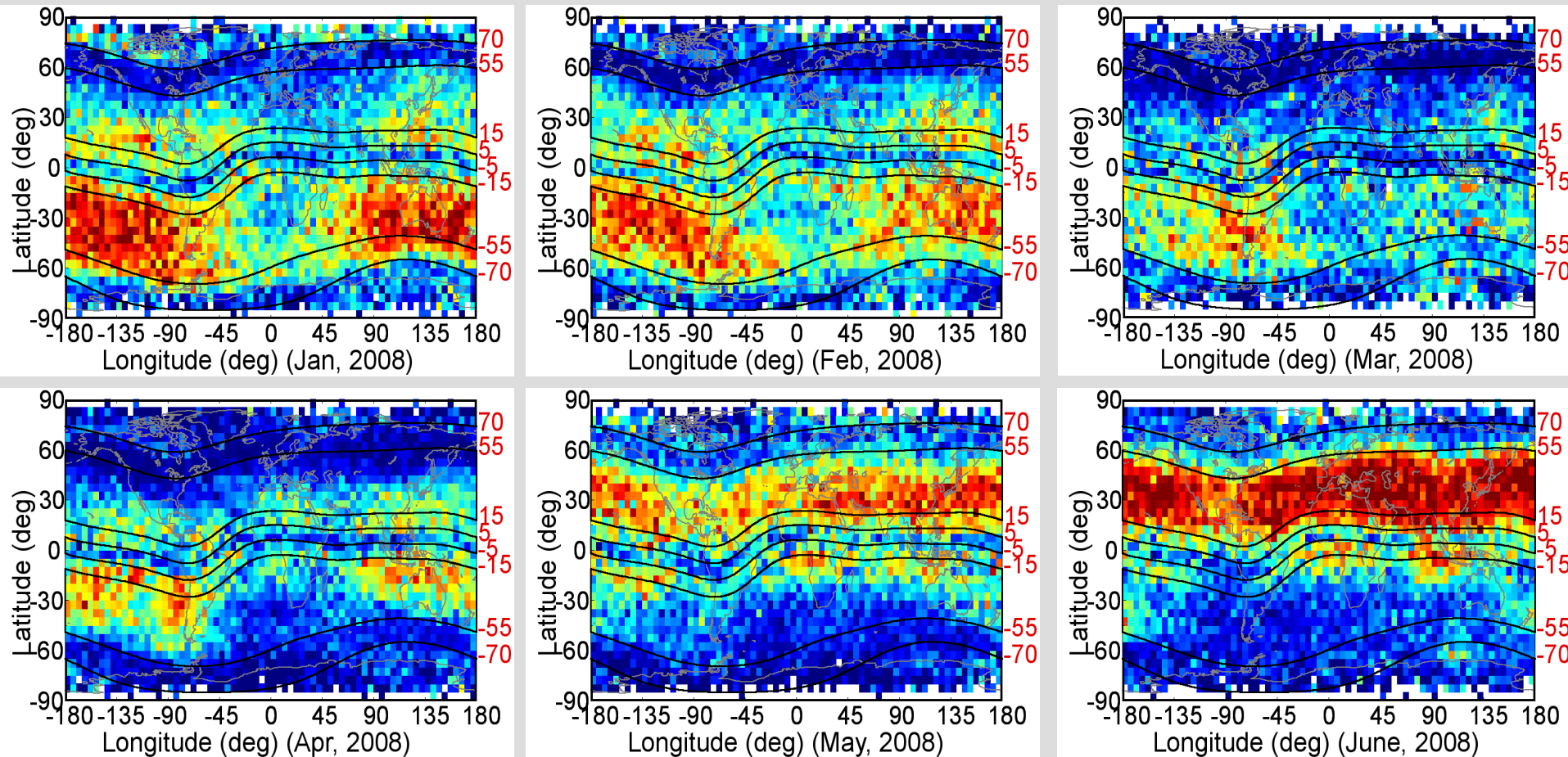
- We study the ionospheric sporadic E layer based on GPS RO L1 observations only because L2 signals are weaker and have no



Limb-viewing L1- and L2-band SNR amplitude profiles (in black and gray), the normalized amplitude standard deviation SDL1 and SDL2 profiles (in blue and green), and the biased N_e profile (in red).



全球電離層散塊E層發生率分佈1至6月月變化(in 2008)

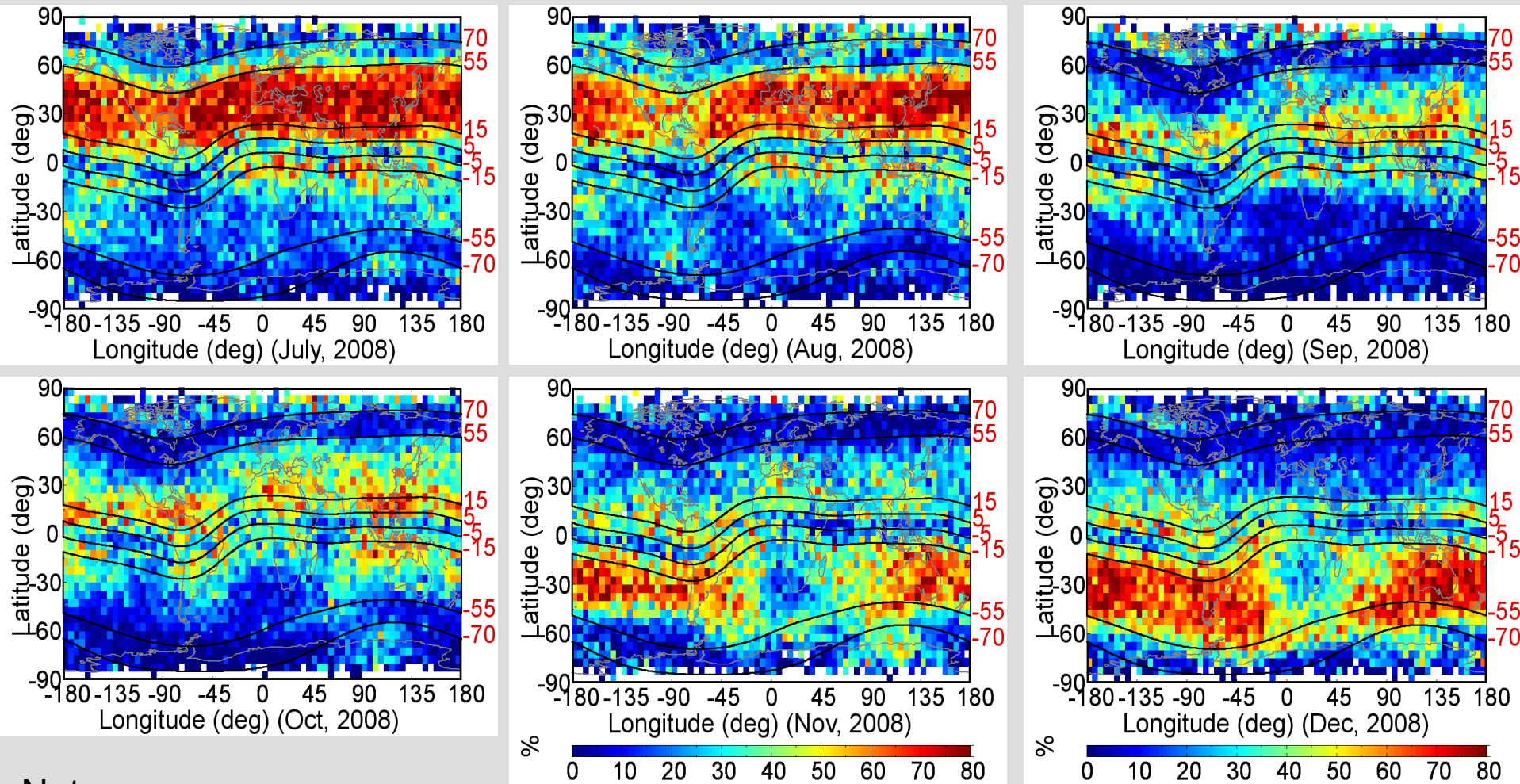


Notes:

- These are dense Es occurrences at geomagnetic mid-latitudes but weak over the geomagnetic equator and two auroral zones.
- Strong seasonal Es occurrence variations at mid-latitudes with highest rates during hemispheric summers.



全球電離層散塊E層發生率分佈7至12月月變化(in 2008)

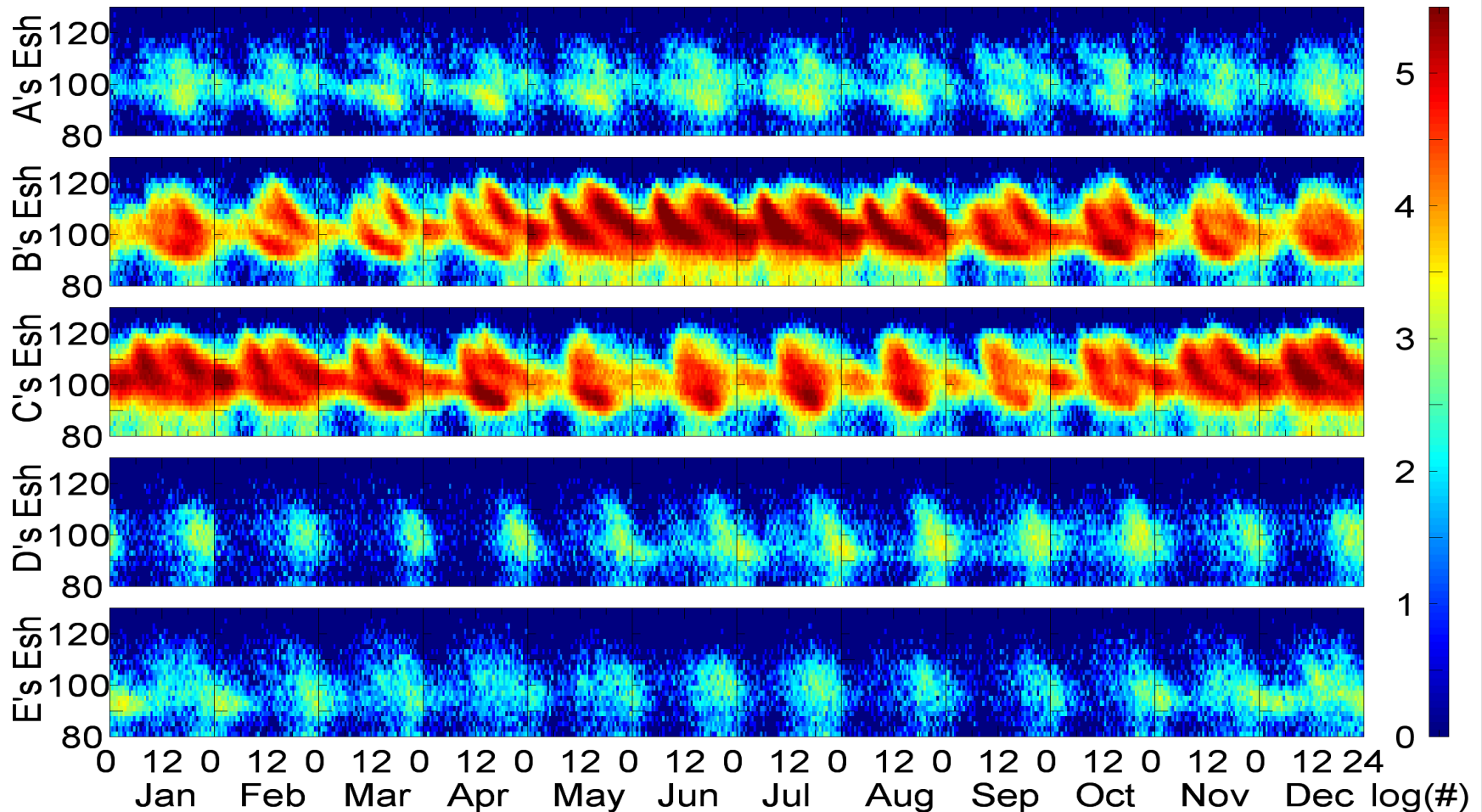


Notes:

Es occurrence depletion at mid-latitudes around the American area and around the South Atlantic and African area during northern and southern hemispheric summers separately.



每月區域電離層散塊E層移動變化

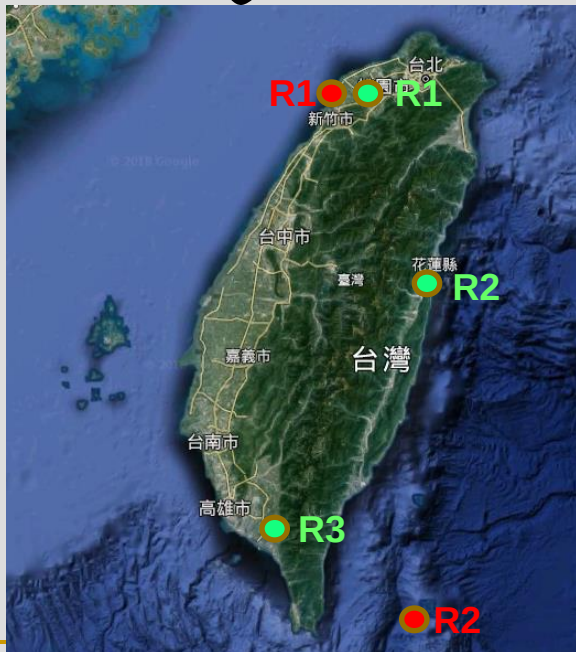
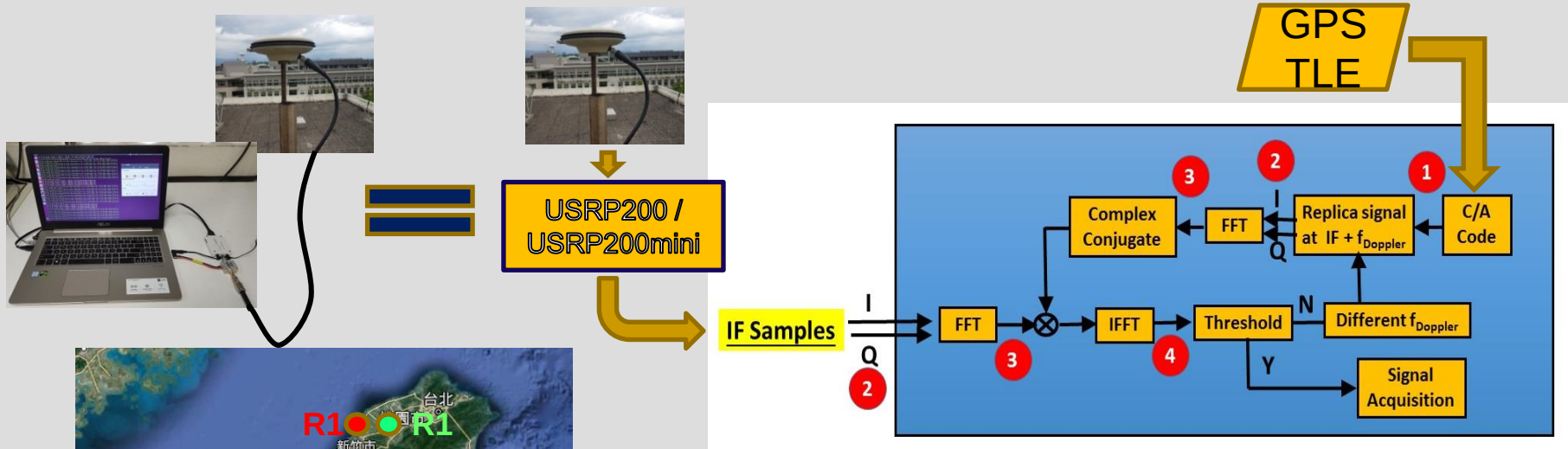


- Semidiurnal behaviour in mid-latitude hemispheric summers with a descending movement.
- The Es semidiurnal behaviour generally tides in around 6 and 14 LT separately with layer altitudes descending from 120 to 90 km at an average rate of about 2.1 km/hr.



GPS軟體接收機開發

應用：電離層不規則體觀測、海面波浪觀測、信號干擾監測與干擾源研究



Ionosphere observation stations (in green):

R1: Chungli * 2 (24.968N, 121.187E)

R2: Hualien (23.897N, 121.551E)

R3: Longquan (22.670N, 120.597E)

Sea-surface wave observation stations (in red):

R1: Xinwu (24.966N, 121.008E)

R2: Lanyu * 2 (22.037N, 121.559E)

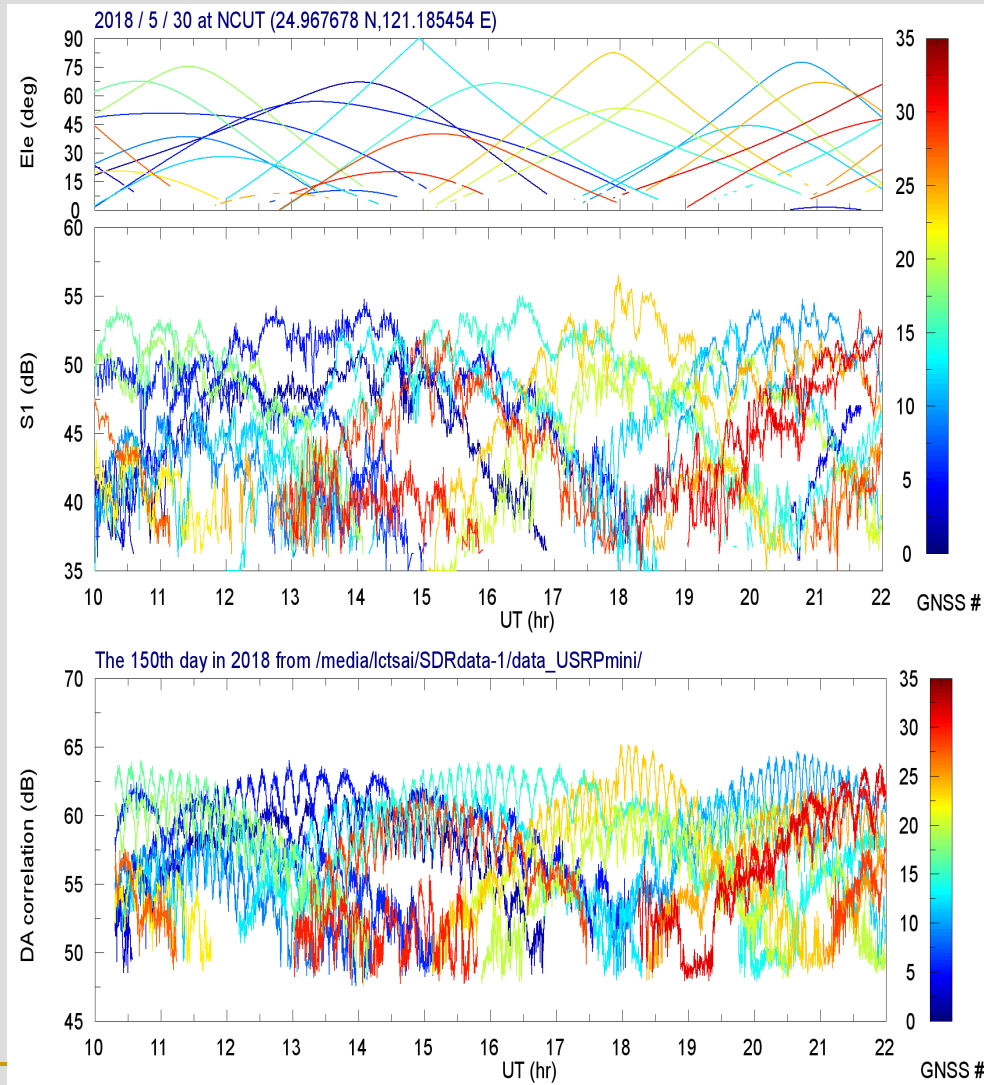


中央大學 GPS 軟體接收機與 JPL/SEGAL GPS/GNSS 接收機 L1 頻段信號觀測比較

Space & Earth Geodetic Analysis Lab (SEGAL), Portugal, GNSS receiver



NovAtel_ GPS702 + USRP_B2000



軟體接收機優點：

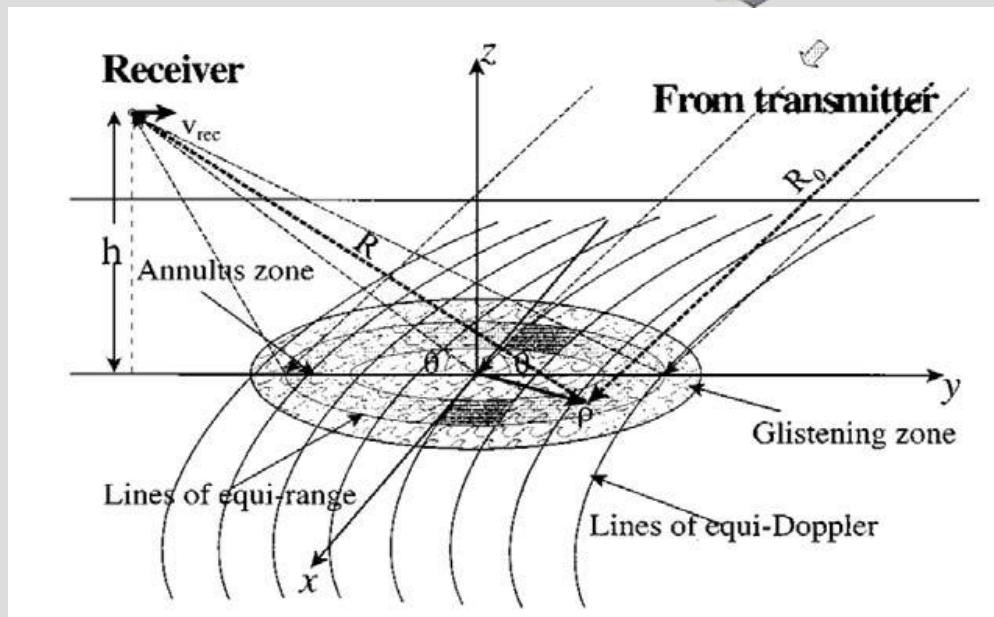
1. 取樣頻率高 (最高 1KHz)
2. Doppler 頻率(或相對速度)解析度高
3. C/A 碼延遲量解析度高

應用：電離層不規則體觀測、海面波浪觀測、信號干擾監測與干擾源研究

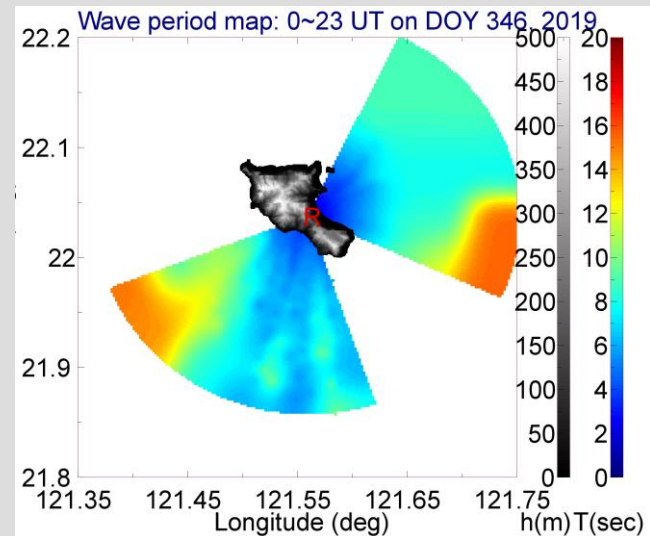
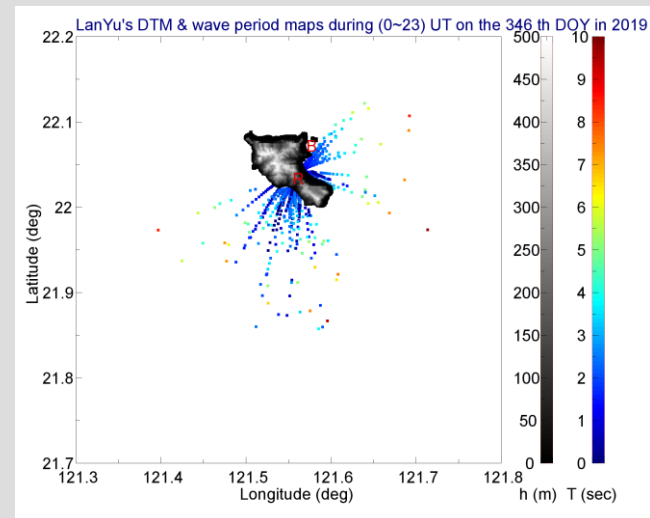
軟體接收機缺點：
電腦資源(儲存與計算)需求大



GPS 反射信號處理分析於海象觀測與研究



Picture copied from
Zavorotny & Voronovich
(2000)

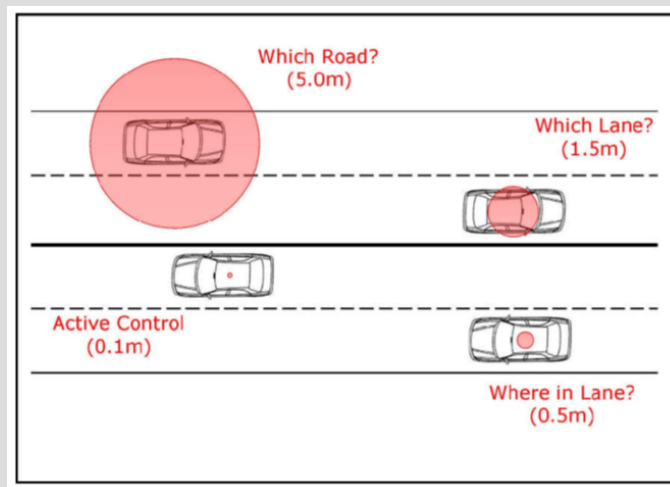


小結：問題與討論

- GPS 信號可否干擾？
如何干擾？
如何分辨干擾為電離層閃爍效應或人為干擾？
如何找干擾源？



- 臺灣是否需要自主定位系統？
- 臺灣自主定位系統如何建置？



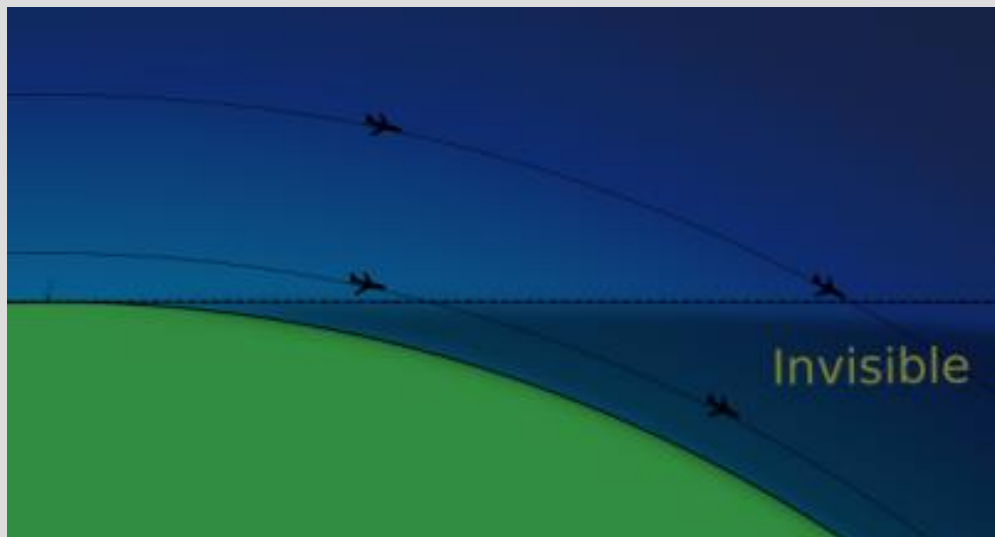
Source:
Stephenson, et al. (2011) in
Proceedings of
the 8th ISLBS



四、無線電波傳播與超水平雷達

(超視訊雷達)

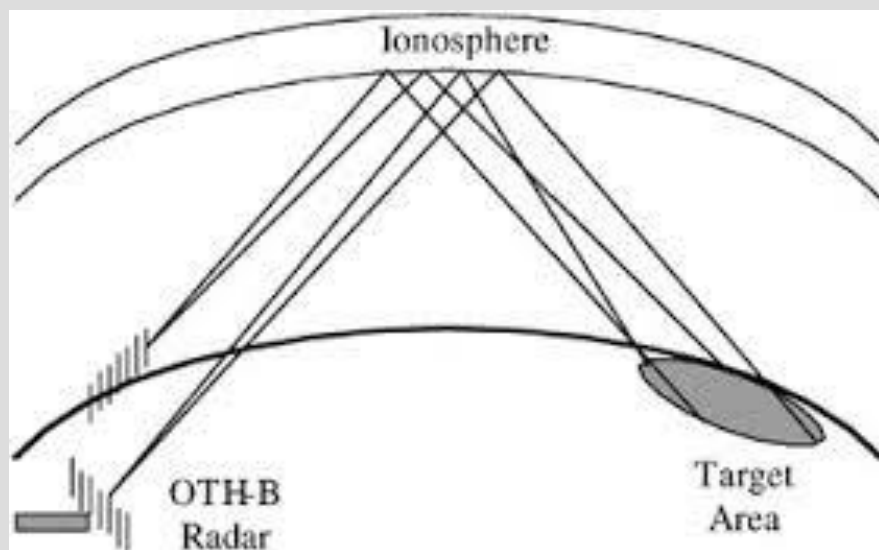
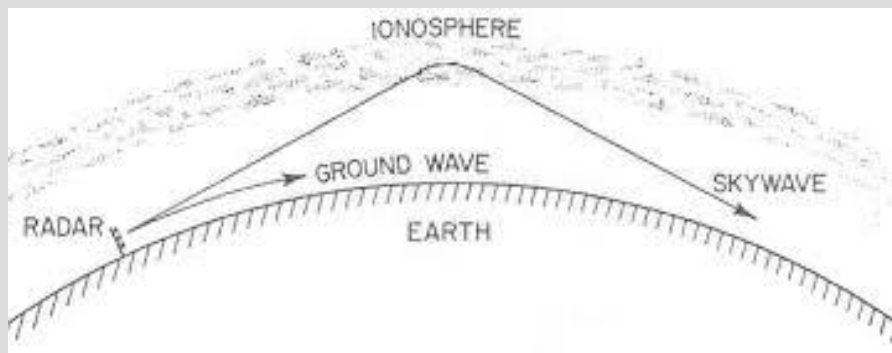
一般視訊雷達



網路圖資

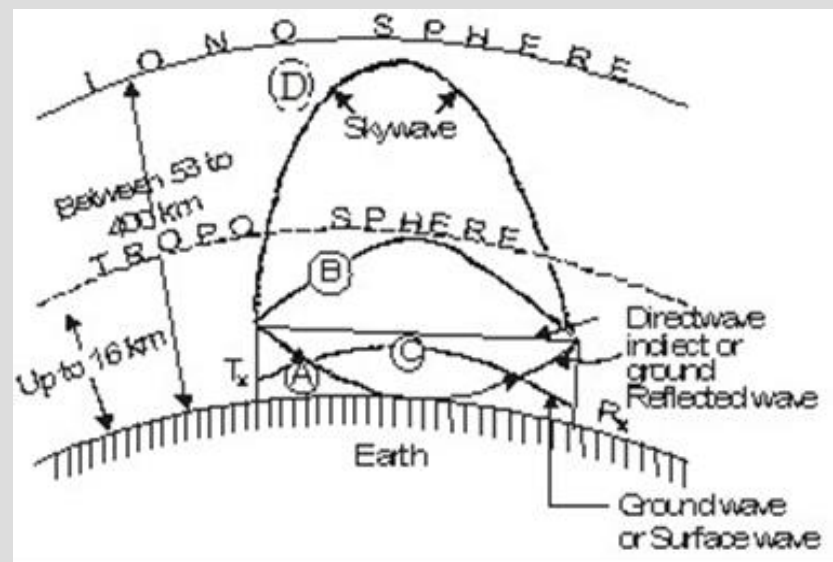


無線電波天波與地波傳播應用超水平雷達



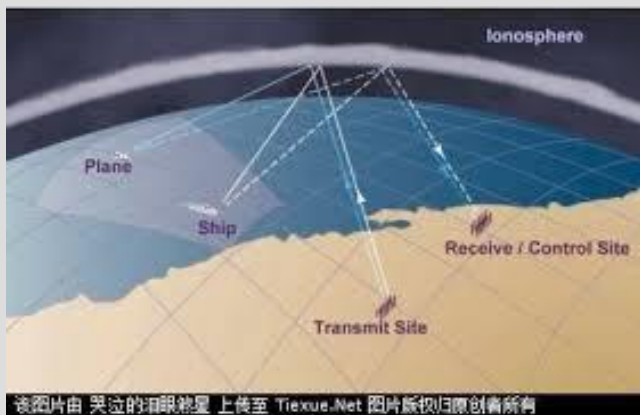
天波型超水平雷達

地波型超水平雷達



- A. 空間波：發射機與接收機直接傳播與經地面反射傳播
- B. 大氣對流波：因為低層大氣溫度、壓力、溼度等因素改變了折射係數的梯度而造成的傳播
- C. 表面波：地表面電波傳播

天波型超水平雷達(超視訊雷達)

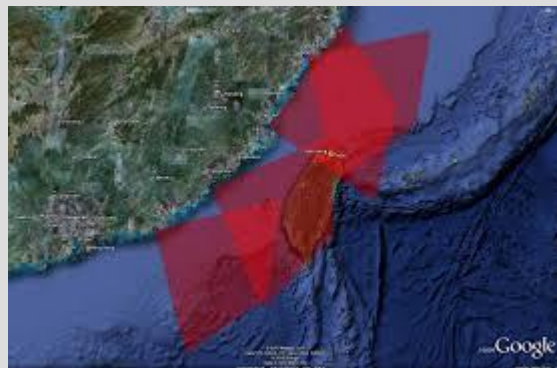


1. 威力範圍(相當於12架E-3A預警機偵測範圍)
距離：800 - 3500km
方位：90°扇區
高度：電離層至地(海)表面任何高度
2. 定位精度：
相對測距精度：2 - 4km
絕對測距精度：10 - 20km
方位精度：可選波束寬度的1/10 (~ 0.5°)
3. 探測目標類型：移動中飛機(含軍用機及隱形飛機)、船隻，和導彈
4. 目標分辨率
距離分辨率：20 - 40km
方位分辨率：取決于波束寬度 (~ 0.5°)
都卜勒分辨率：0.1 Hz
5. 信號目標能見度：SCV $\geq$ 70Db
6. 系統時間可用度 $\geq$ 90%
7. 工作頻率：6 ~ 28MHz，視偵測距離，電離層狀況而定

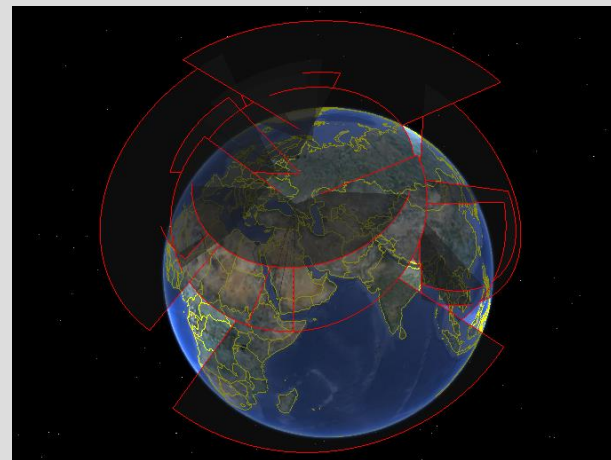
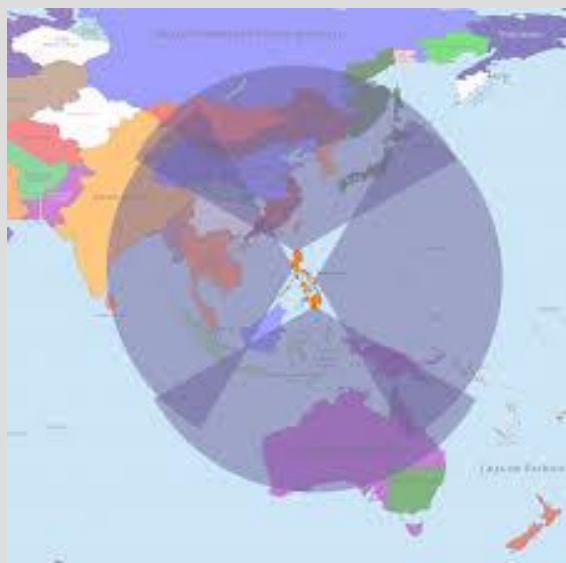
網路圖資



已知主要超水平雷達布置位置與目標範圍(網路資料)



地波型超水平雷達



網路圖資



國立中央大學遙測中心電離層探測實驗室
Ionospheric Sounding Lab. CSRSR. NCU. R.O.C

五、結論：

- 短波(高頻)天波通訊為一有效遠距通訊方法，相對於衛星通訊更為經濟、安全、保密、與戰場必要性。
- 全球定位系統為現代民生交通與國防重要戰略與戰術系統，相關系統無線電波傳播主要媒介電離層相關監測與研究有其必要，如何監測全球定位系統信號干擾亦有其必要。
- 福衛三號與未來福衛七號掩星觀測實為全球電離層相關監測與研究的重要資料。
- 超水平雷達(超視訊雷達)對台灣國防的助益與威脅為何？應對與反制方法為何？



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謝謝指教！

