# HONG KONG OBSERVATORY

Technical Note No. 98

COMPARISON OF LORAN-C AND GPS
RADIOSONDE MEASUREMENTS IN HONG KONG

by

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# I. Introduction

The Hong Kong Observatory (HKO) has been operating an Upper-Air Meteorological Station at King's Park (station code: 45004, location: 22.31 N, 114.17 E) since 1951. In 1993, a Vaisala DigiCORA system was installed. GPS windfinding technology was employed in 1997 with the DigiCORA upgraded to include a GPS windfinding module. The performance of the GPS radiosondes was reported in Wong *et al* (1998) who concluded that there was very good agreement between the GPS and OMEGA wind measurements. However, it is understood that some users of GPS-based radiosondes have expressed concern regarding the rate of failures of these systems and the World Meteorological Organization is conducting a review on the use and reliability of GPS radiosondes (WMO, 1999).

The experience of Hong Kong in GPS radiosondes was that the failure rate is about 23% in 1998. After the introduction of more stringent launch procedures in 1999 the failure rate was reduced to 6%. In view of the high cost of the GPS radiosondes and the tedious pre-launch checking procedures, the Hong Kong Observatory has explored the use of LORAN-C windfinding technology. This option was previously not pursued due to the vulnerability of the LORAN-C signals to interference from atmospheric electricity and the uncertainty in the availability of NAVAID signals in the future. However, recently it has been reported that LORAN-C is guaranteed to be operational until 2003 (Hovius *et al*, 1998). The capital cost for upgrading the DigiCORA to LORAN-C capable is more than offset by the savings achieved in one year of using the more cost-effective radiosondes on fair weather days. The DigiCORA system was upgraded to include a LORAN-C windfinding module in early 1999.

This paper aims to compare the performance of the LORAN-C and GPS radiosondes and study the LORAN-C and GPS coverage in the region of Hong Kong so as to establish criteria for selecting the most suitable method for operation under the prevailing conditions.

## II. Comparison of Simultaneous LORAN-C and GPS Measurements

Since the LORAN-C and GPS radiosondes use the same sensors for pressure, temperature and humidity, only the winds measured by the two systems are compared. Following the work of Wong *et al* (1998), a total of ten twin flights in the "40-metre vertical" configuration were conducted in March to April 1999. The LORAN-C radiosonde (Vaisala RS80-15L) was mounted to a 20-m string underneath a TOTEX 500-g balloon with the GPS radiosonde (Vaisala RS80-15G) hanging further downward by a 40-m long string. The launch times of these ten flights are listed in Table 1.

Winds were calculated at 12 standard pressure levels, namely, 925, 850, 700, 500, 400, 300, 200, 150, 100, 70, 50 and 30 hPa. Table 2 shows the direct differences (see for example, Kurnosenko 1996) of the LORAN-C data minus the GPS data (LORAN-C - GPS) in the wind direction and speed as well as the respective standard deviations at each standard pressure level. The direct differences in direction and speed are in the range of -12.6 to 1.6 degrees and -0.3 to 1.7 m/s respectively. The standard deviations of the direct differences are within 3 to 24 degrees for wind direction, and within 0.8 to 2.4 m/s for wind speed. The wind direction exhibits a slight counter-clockwise bias in the troposphere and becomes more prominent in the stratosphere.

Table 3 gives the direct differences (LORAN-C - GPS) of the east-west and north-south wind components, as well as their standard deviations. The winds from the east and north are taken as negative, following usual meteorological convention. The direct differences in the east-west component range from -1.3 to 0.6 m/s and in the north-south component -0.9 to 1.9 m/s. No significant systematic differences in the measurements are observed. The direct differences at all levels in the troposphere apart from the lowest level at 925 hPa are less than 1 m/s. It has been widely reported that NAVAID tracking data are often of poor quality early in a balloon ascent (see for example ,WMO 1996). The 40-metre string on the unwinder takes a few minutes to fully unwind. With an ascent rate of 300 m/min it takes only one minute for the radiosonde to reach the 925-hPa level. At this time the unwinder has not unwound fully causing the radiosondes to pendulate underneath the balloon. The large direct differences in speed and direction at the lower levels might be attributable to the pendulum effect.

The direct differences in the north-south components are slightly larger than those in the east-west components, probably due to the fact that the LORAN-C stations in south China are aligned almost in a straight line at about 150 km to the north of Hong Kong in the east-west direction. The effect of this geometry is such that computation of winds in the east-west direction will be more accurate than the north-south direction. The effect of the geometry of the LORAN-C chains on the wind measurements will be further elaborated in Section 4. The standard deviations of the direct differences range from 0.7 to 2.1 m/s for the east-west components and 1.3 to 3.5 m/s for the north-south components.

The random errors of the LORAN-C and GPS windfinding systems have been established to be 0.6 - 3 m/s and 0.4 - 2 m/s respectively (WMO, 1996). For the (LORAN-C - GPS) comparisons the range of random errors is hence 0.7 - 3.6 m/s. The standard deviations of the direct differences of the east-west and north-south components are well within this range.

Figures 1 and 2 show the scatter diagrams and the least squares best fit of the east-west component and the north-south component measured by the LORAN-C versus that by the GPS radiosondes. Each data point in the scatter diagrams represents a component value measured at a standard pressure level of an individual launch. The correlation coefficients for both components are close to 1. The least squares best fit for both components exhibits a slope close to 1 and an intercept close to 0, indicating no significant systematic difference between the two windfinding systems.

## III. GPS Coverage

The GPS is a very high accuracy radio navigation system based on radio signals transmitted from a constellation of 25 satellites orbiting the Earth in six planes. The constellation of satellites is configured so that in any location worldwide a minimum of four satellites appear above the horizon at all times. Accurate wind computations require signals from a minimum of four satellites.

The Standard Positioning Service Performance Specification (US Coast Guard Navigation Centre, 1995) specifies that the global average coverage standard is 99.9% and the worst-case point coverage standard is 96.9%. The standard refers to the probability of four or more satellites in view over any 24-hour interval, with a mask angle of 5 deg above the horizon and a constellation as defined in the almanac.

The Vaisala DigiCORA GPS windfinding system operates in a differential mode. This requires simultaneous reception of the GPS signals by a receiver at the ground station as well as the receiver on the radiosonde. The view of King's Park GPS aerial is not free of obstructions in all directions towards the horizon, due to the surrounding buildings. Obstruction of view is particularly severe in the southeast direction because of the station office. The GPS aerial mounted on the radiosonde also does not have a clear view of the horizon due to the location of the aerial, as well as the fact that the radiosonde is always tilted during flight. Yeung and Sin (personal communication, results reproduced in the Appendix) compared the number of satellites in view at King's Park, and the radiosonde during flight, with the constellation generated from the almanac. It was found that the DigiCORA could only use satellites at an angle of 30 deg or more above the horizon for wind computation.

The coverage standard in the Hong Kong region at nominal launch time was re-computed using a mask angle of 30 deg. The monthly and annual values for the year 1999 and 2000 are listed in Table 4. It is observed that the probability of achieving satellite lock in May, August and November in 1999 and April in 2000 can be as low as 78 to 83%. The overall coverage standard is only 92% which is 5% lower than the worst-case point coverage standard based on a 5 deg mask angle.

In 1998, the failure rate of the GPS radiosondes is 23%. Problematic ascents were mainly due to the launching of faulty GPS radiosondes and also the failure to maintain satellite lock during flight due to insufficient satellites in the field of view of the GPS aerials. A set of stringent launch procedures were implemented in 1999.

These include a zero wind check to ensure satellite lock on ground to avoid sending up faulty radiosondes, and the use of a constellation forecast software to plan launch windows that has enough GPS satellites in view to ensure satellite lock after launch. With the implementation of these procedures, the failure rate fell to 6%. However, the launch procedures are quite laborious requiring about 20 minutes for the pre-launch checks.

The zero wind check procedure is developed through a number of iterations with the supplier of the GPS radiosondes. Before launch the radiosonde is activated and taken outdoor to a location where the GPS local antenna is within line of sight but at a distance of at least 30 m from the radiosonde. The radiosonde is kept in an upright position with a wide view to the sky without any shadowing by buildings. After one to two minutes the DigiCORA should display zero wind. If the radiosonde is faulty or insufficient satellites are tracked the display will show slashes (////). By consulting the GPS almanac the operator will determine whether the radiosonde has to be replaced or the launch time has to be deferred for a better satellite geometry.

A number of constellation forecast software are available commercially. Some of them can be found from the links of the US Coast Guard Navigation Centre homepage (www.navcen.uscg.mil).

## IV. LORAN-C Coverage

The LORAN-C system is a relatively high accuracy long range navigational aid operating in the low frequency band centred on 100 kHz. As its primary purpose is for marine navigation in coastal areas, LORAN-C coverage is only provided in certain parts of the world, mostly in maritime areas of the Northern Hemisphere.

In the South China Sea, East China Sea and the western North Pacific there are four LORAN-C chains, namely the China South Sea chain GRI 6780, China North Sea chain GRI 7430, China East Sea chain GRI 8390 and North West Pacific chain GRI 8930. The positions of the master (M) and secondary stations (W, X, Y, Z) of these chains and their distance from Hong Kong are shown in Figure 3 and also listed in Table 5. At the frequency of 100 kHz signal propagation for ground waves is limited to some 1500 km so only all stations of chain 6780, stations M and X of chain 7430, stations M, X and Y of chain 8390 can possibly be used in Hong Kong. The Vaisala DigiCORA LORAN-C system has a cross chain tracking capability, so that signals from one to two LORAN-C chains can be used together. The computation of winds uses all the reliable LORAN-C signals available, rather than a bare minimum of three.

A study was conducted in May to July 1999 on the coverage of the LORAN-C chains. LORAN-C signals were monitored on 95 cases, all of which had no thunderstorm activities in the vicinity of Hong Kong. DigiCORA output two parameters: the signal strength of individual LORAN-C stations and the Horizontal Dilution of Precision (HDOP) of the geometry of the LORAN-C stations. Signal strength ranges from 1 to 9. It is observed that the DigiCORA system will only use stations with signal strength greater than or equal to 8. The HDOP is a parameter commonly used to describe the effect of the "geometry of the terrestrial transmitters relative to the radiosonde with sufficient signal strength for use in the computation of winds" on the accuracy of the computed winds (Jaatinen and Pala, 1998). The rule of thumb for interpreting HDOP is as follows (Jaatinen and Pala, 1998):

| HDOP | Influence in windfinding |
|---|---|
| < 5 | GOOD geometry, reliable winds |
| > 10 | POOR geometry, missing winds |
| > 20 | BAD geometry, probably no wind |

Since LORAN-C propagation conditions vary with time of the day and atmospheric electricity conditions, there is a need to study the availability of the four LORAN-C chains. Availability of a particular station is defined as the number of cases with signal strength ≥ 8 over the total number of cases. The findings are listed in Table 6.

It is observed that chain 6780, due to its proximity to Hong Kong, was always available. Stations in chains 7430, 8390 and 8930 were also available for 10 to 40% of the time. During the test period, in addition to chain 6780, there were always one or more stations of the other chains available. This is very fortunate for the operations in Hong Kong since the geometry of chain 6780 is a straight line at about 150 km to its north in an east-west orientation. If the radiosonde moved far enough to the north, which could happen in situations of very deep trough approaching Hong Kong from the west giving rise to southwesterly winds in depth, the stations of chain 6780 would fall on the same line when viewed from the radiosonde receiver. In this case computation of the north-south component of the wind becomes impossible and stations from the other chains are therefore essential to maintain a good geometry for windfinding.

The situation discussed above can be viewed in the context of the HDOP. The DigiCORA LORAN-C cross chain tracking capability was manually inhibited to study the effects of different geometries. Table 7 shows the HDOP for different combinations of the chains. It is observed that the combination of chain 6780 with any one of the other three chains significantly reduced the HDOP from 2.8 to less than 2. Without chain 6780 windfinding becomes impossible with the other three chains.

Figures 4a and 5a show the trajectories of the radiosondes launched in the synoptic situation of a surface trough to the north of Hong Kong and a deep mid-tropospheric westerly trough approaching Hong Kong from the west (Figures 4b and 5b). Under such conditions there was a layer of south to southwesterlies in the lower troposphere and the radiosonde would drift northwards. The DigiCORA system was set to use chain 6780 in solo. In these two cases HDOP could be maintained at a value of 2.8 and the radiosondes only managed to travel about 6 km to the north then engaged by the upper level winds which eventually took them to the southwest of Hong Kong. Therefore good geometry for windfinding could still be maintained even under these unfavourable scenarios.

For LORAN-C radiosondes the launch procedures are relatively simple as the geometry of the transmitters is fixed. The pre-launch checks take about 10 minutes which is only half of that required by the GPS radiosonde.

Up to the end of September 1999 a total of 70 LORAN-C radiosondes were launched on days when no thunderstorm warnings issued by the HKO's Central Forecasting Office (CFO) were in force. Only one ascent failed in wind finding. The failure rate is hence less than 2%.

A major change in the availability of NAVAID signals is underway. International navigational operations have mainly moved to navigation using signals from the GPS satellites. These satellite signals have largely replaced reliance on signals from fixed terrestrial transmitters. However, for various reasons, some places have chosen to persist with terrestrial navigational systems. It has been reported that LORAN-C is guaranteed to be operational until 2003 (Hovius *et al*, 1998).

## V. Conclusions

The comparison of the ten soundings with LORAN-C and GPS radiosondes paired in the "40-metre vertical" configuration shows very good agreement between the LORAN-C and GPS wind measurements. The standard deviations of the direct differences of the wind speed are within the range of the expected random error for LORAN-C - GPS winds. No significant systematic difference could be observed in the wind measurements of the LORAN-C and GPS windfinding systems. There is a strong positive relationship in the east-west and north-south components themselves for the two windfinding systems, with a correlation coefficient of 0.995 for the east-west component at all pressure levels and 0.946 for the north-south component.

A set of stringent pre-launch checking procedures have been implemented for the GPS radiosondes to reduce the failure rate from 23 % to 6%. However, due to the use of a 30 deg mask angle the coverage of GPS may drop to as low as 78% in some months. Furthermore, because of the tedious pre-launch checking procedures and the fact that GPS radiosondes are more costly, the GPS windfinding system shall only be used on days when atmospheric electricity interferes with the LORAN-C signal to the extent that less than three stations can be tracked with sufficient strength. The GPS windfinding system will however also serve as a hot standby to the LORAN-C system.

Since LORAN-C radiosondes are substantively more cost effective than the GPS ones, and it has been established that the LORAN-C chains trackable by the DigiCORA system constitute good geometry for accurate windfinding, the Hong Kong Observatory will switch to LORAN-C radiosondes whenever the prevailing operational conditions permits. Operationally LORAN-C radiosondes are used when no thunderstorm warning issued by the CFO is in force at the launch time.

An analysis of the benefits of using mixed GPS and LORAN-C radiosondes over GPS radiosondes only is shown in Table 8. Apparently the use of mixed GPS and LORAN-C radiosondes can achieve about 22% savings in radiosonde cost and 50% savings in operator time over those of using GPS radiosondes alone.

# References


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Table 1. Launch Time of the Twin Flights

| Flight no. | Launch Time (UTC) | |
|---|---|---|
| | Date | Hour |
| 1 | 8 March 1999 | 06 |
| 2 | 10 March 1999 | 06 |
| 3 | 11 March 1999 | 00 |
| 4 | 11 March 1999 | 06 |
| 5 | 12 March 1999 | 06 |
| 6 | 15 March 1999 | 06 |
| 7 | 17 March 1999 | 06 |
| 8 | 19 March 1999 | 06 |
| 9 | 29 April 1999 | 06 |
| 10 | 30 April 1999 | 00 |

Table 2. Direct Differences (LORAN-C - GPS) in Wind Direction and Speed and Their Standard Deviations

| Pressure (hPa) | Wind Direction (deg) | | Wind Speed (m/s) | | Number of Cases |
|---|---|---|---|---|---|
| | Direct Differences | Standard Deviations | Direct Differences | Standard Deviations | |
| 30 | -12.6 | 20.0 | 0.2 | 2.4 | 10 |
| 50 | -9.3 | 24.0 | -0.3 | 1.3 | 10 |
| 70 | -10.9 | 19.0 | -0.1 | 1.2 | 8 |
| 100 | -9.0 | 10.7 | 0.6 | 1.8 | 10 |
| 150 | -1.8 | 3.2 | -0.2 | 0.9 | 10 |
| 200 | -0.1 | 3.7 | 0.1 | 1.0 | 10 |
| 300 | -0.6 | 4.8 | 0.4 | 0.8 | 10 |
| 400 | -1.4 | 6.4 | 0.4 | 1.1 | 9 |
| 500 | 1.6 | 5.7 | 0.4 | 1.5 | 10 |
| 700 | 0.0 | 6.8 | -0.1 | 1.5 | 10 |
| 850 | -3.5 | 13.4 | 1.7 | 2.2 | 10 |
| 925 | -4.1 | 12.2 | 1.6 | 1.5 | 8 |

Table 3. Direct Differences
(LORAN-C - GPS) in East-West and North-South Components

| Pressure (hPa) | East-West Components (m/s) | | North-South Component (m/s) | | Number of Cases |
|---|---|---|---|---|---|
| | Direct Differences | Standard Deviations | Direct Differences | Standard Deviations | |
| 30 | -1.3 | 2.1 | 0.8 | 2.6 | 10 |
| 50 | 0.5 | 1.6 | 0.9 | 1.8 | 10 |
| 70 | 0.5 | 1.0 | -0.9 | 2.7 | 8 |
| 100 | 0.5 | 1.4 | 1.9 | 2.6 | 10 |
| 150 | -0.4 | 0.8 | 0.5 | 1.3 | 10 |
| 200 | 0.0 | 1.1 | -0.3 | 1.4 | 10 |
| 300 | 0.2 | 0.7 | 0.3 | 2.2 | 10 |
| 400 | 0.6 | 1.1 | 0.8 | 3.0 | 9 |
| 500 | 0.1 | 1.0 | 0.3 | 2.3 | 10 |
| 700 | -0.3 | 1.4 | -0.1 | 1.5 | 10 |
| 850 | -0.6 | 1.6 | 0.8 | 3.5 | 10 |
| 925 | -1.3 | 2.1 | 1.5 | 2.0 | 8 |

Table 4. GPS Coverage Standard at
Hong Kong Based on a Mask Angle of 30 Degree

| Month | Coverage Standard (%) | |
|---|---|---|
| | 1999 | 2000 |
| January | 94 | 100 |
| February | 89 | 89 |
| March | 89 | 89 |
| April | 100 | 83 |
| May | 83 | 100 |
| June | 94 | 100 |
| July | 100 | 89 |
| August | 83 | 89 |
| September | 100 | 89 |
| October | 94 | 89 |
| November | 78 | 89 |
| December | 94 | 94 |
| **Overall** | **92** | **92** |

Table 5. Positions and Distance of LORAN-C Stations from Hong Kong

| Chain GRI | Position | | Distance from H.K. (km) |
|---|---|---|---|
| | Lat.(°) | Lon.(°) | |
| 6780M | 23.97 | 111.72 | 311 |
| 6780X | 23.72 | 116.90 | 320 |
| 6780Y | 22.54 | 107.22 | 714 |
| 7430M | 37.06 | 122.32 | 1816 |
| 7430X | 31.07 | 118.89 | 1080 |
| 7430Y | 42.72 | 129.11 | 2656 |
| 8390M | 31.07 | 118.89 | 1080 |
| 8390X | 23.72 | 116.90 | 320 |
| 8390Y | 37.06 | 122.32 | 1816 |
| 8930M | 34.40 | 139.27 | 2786 |
| 8930W | 26.61 | 128.15 | 1491 |
| 8930X | 24.29 | 153.98 | 4054 |
| 8930Y | 42.74 | 143.72 | 3547 |
| 8930Z | 36.18 | 129.34 | 2124 |

Table 6. Availability of the LORAN-C Stations (%)

| Chain ID | 6780 | 7430 | 8390 | 8930 |
|---|---|---|---|---|
| M | 100 | 39 | 39 | 9 |
| X | 100 | 38 | 39 | 12 |
| Y | 100 | 0 | 34 | 0 |
| W | | | | 20 |
| Z | | | | 0 |

M = master station

X,Y = first & second secondary stations for chains 6780, 7430, & 8390

W,X,Y,Z = first, second, third, & fourth secondary stations for chain 8930

Table 7. HDOP of Different Geometries

| Chain combination | HDOP |
|---|---|
| 6780 | 2.8 |
| 7430 | insufficient number of stations |
| 8390 | |
| 8930 | >20 |
| 6780+7430 | 1.9 |
| 6780+8390 | 1.7 - 2.8 |
| 6780+8930 | 1.7 ~ 2.8 |
| 7430+8390 | >180 |
| 8390+8930 | >180 |

Table 8. A Benefit Analysis of Using
Mixed GPS/LORAN-C Radiosondes Over GPS Radiosondes Only

| | Mixed GPS and LORAN-C | GPS Only |
|---|---|---|
| Cost of routinely launched radiosondes per annum[(1)] | 81% | 100% |
| Cost of additional radiosondes for repeat ascents per annum[(2)] | 2% | 6% |
| Total cost of radiosondes per annum | 83% | 106% |
| **% benefit in terms of radiosonde cost per annum** | **22%** | |
| Operator time in minutes per annum for pre-launch checks[(3)] | 14,600 | 29,200 |
| Operator time in minutes per annum for pre-launch checks for repeat ascents | 476 | 876 |
| Total operator time in minutes per annum | 15,076 | 30,076 |
| **% benefit in terms of operator time per annum** | **50%** | |

(1) Cost expressed in "cost per annum" of routinely launched GPS radiosonde. GPS radiosonde is 28% more expensive than LORAN-C radiosonde. There is thunderstorm activity on an average of 46 days in a year according to the Hong Kong Thirty-year Normal (Hong Kong Observatory, 1999). GPS radiosondes have to be used on these days.

(2) Based on an average failure rate of 6% for GPS radiosonde and 2% for LORAN-C radiosonde.

(3) Based on 20 mins for GPS radiosonde and 10 mins for LORAN-C radiosonde.

# Appendix

Yeung S.W. and K.C. Sin studied the GPS coverage in Hong Kong. An experiment was carried out to compare the number of satellites in view at King's Park and the radiosonde during flight with the constellation generated from the almanac. Their findings are summarized below.

The Vaisala DigiCORA GPS windfinding system operates in a differential mode. This requires simultaneous reception of the GPS signals by the ground station at King's Park as well as the radiosonde in flight. The number of satellites used in windfinding is displayed in real-time on the DigiCORA. These data were compared to the constellation generated from the almanac using mask angles of 5, 20 and 30 deg. The results are shown in the following table:

Table: Percentage Number of Occasions When The Number of Satellites Used By The DigiCORA is Less Than The Constellation Generated From the Almanac

(No. of cases = 56)

| Date | Mask Angle | | |
|---|---|---|---|
| | 5 deg | 20 deg | 30 deg |
| 981202 | 100 | 100 | 0 |
| 981205 | 80 | 67 | 0 |
| 981205 | 76 | 18 | 0 |
| 990301 | 80 | 44 | 11 |
| 990302 | 85 | 44 | 0 |
| 990305 | 80 | 22 | 0 |

In summary, the DigiCORA could only use satellites at an angle of 30 deg or more above the horizon for windfinding.

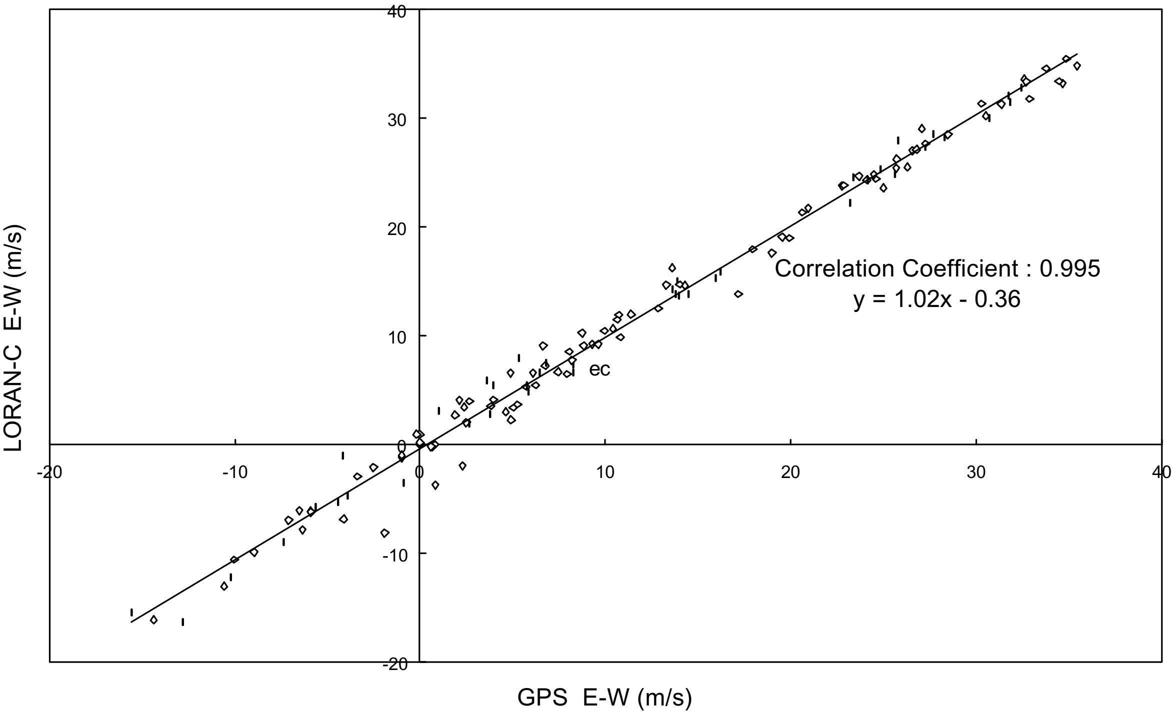



Figure 1. Scatter Diagram of the East-West Components
Measured by the LORAN-C and GPS Wind-finding Systems

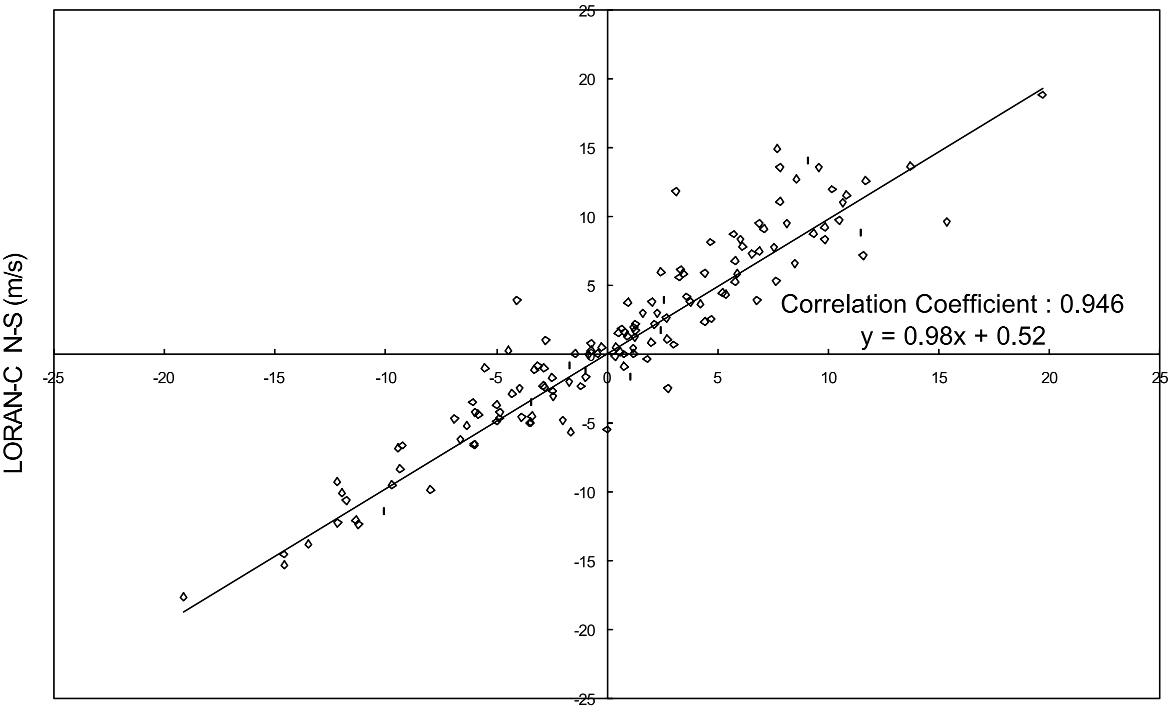



Figure 2. Scatter Diagram of the North-South Components
Measured by the LORAN-C and GPS Wind-finding Systems

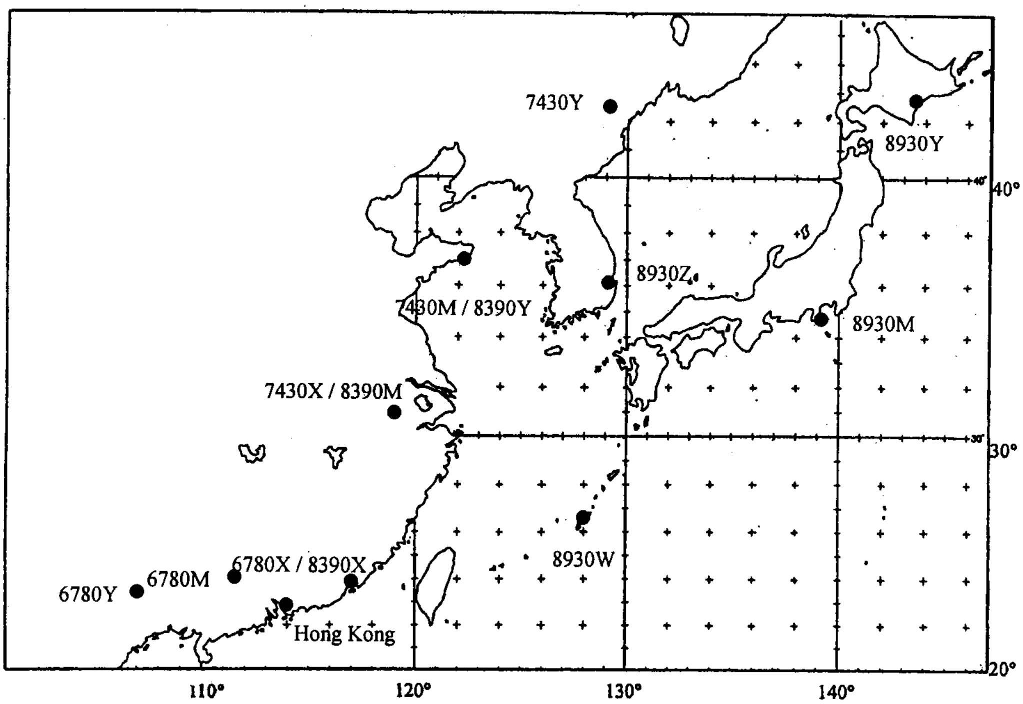



Figure 3. Locations of LORAN-C Chains

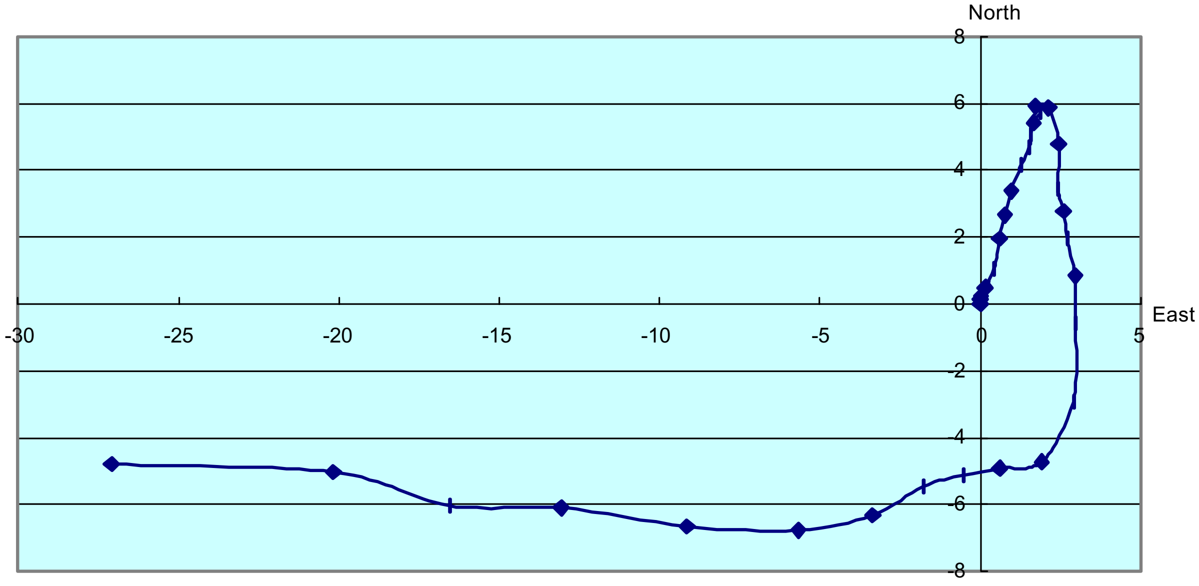
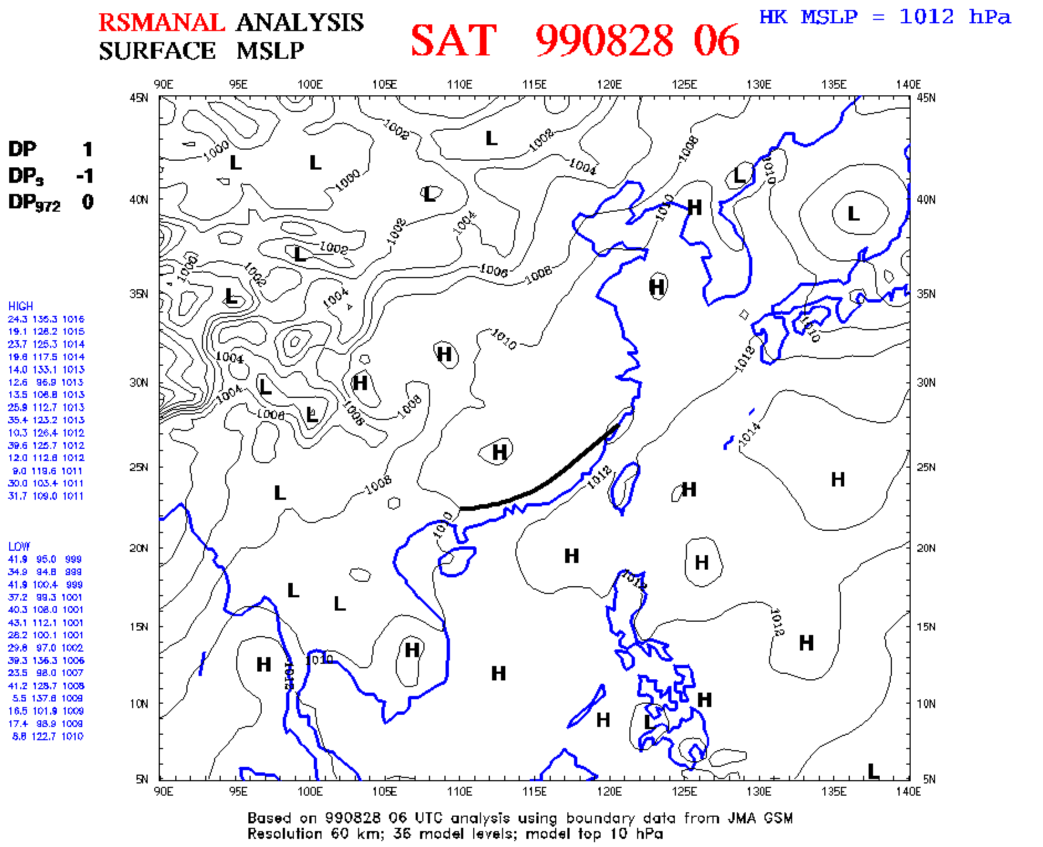



Figure 4a. Position Plot for Ascent at 990828 06 UTC



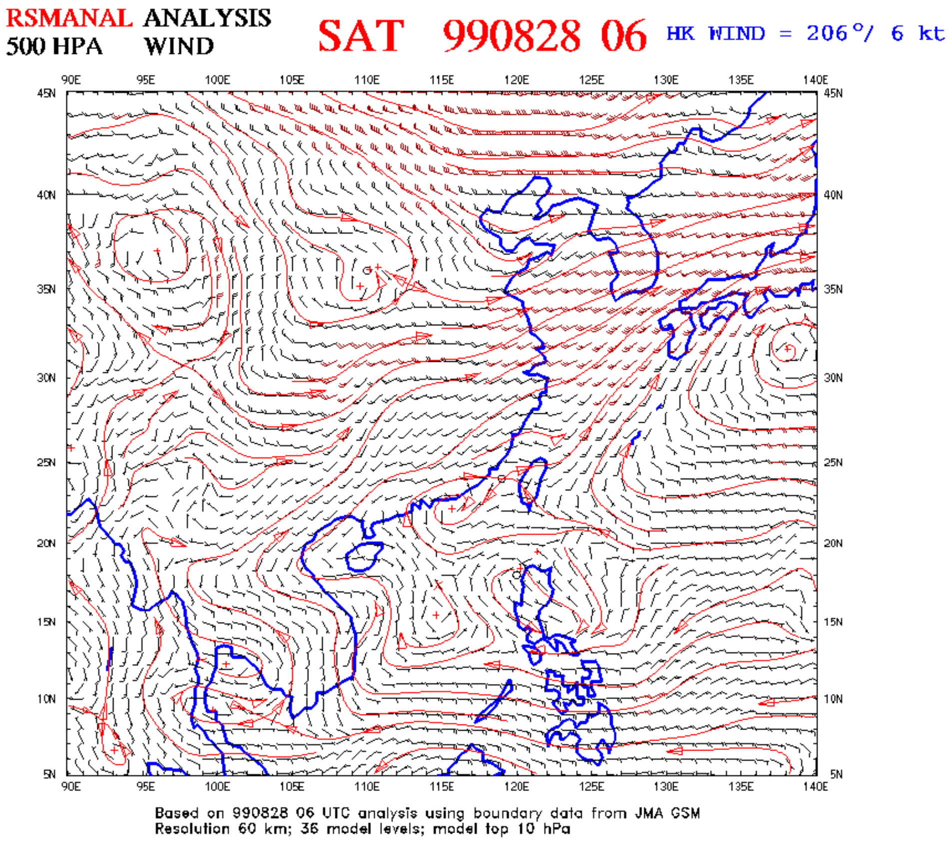




Figure 4b. Synoptic Situation at 990828 06 UTC

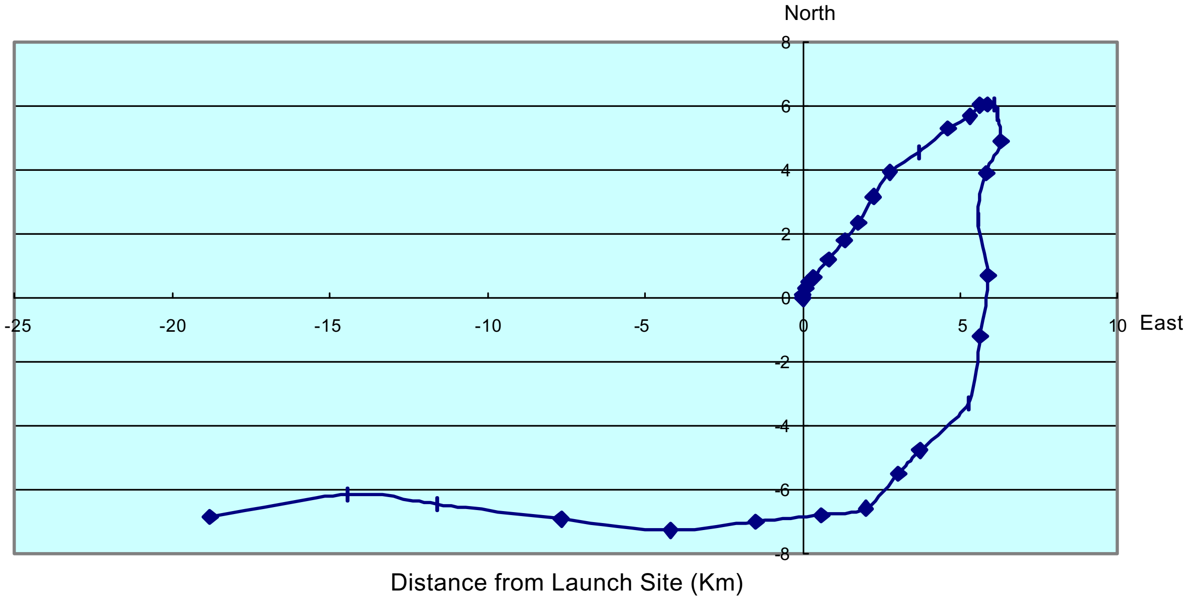



Figure 5a. Position Plot for Ascent at 990830 00 UTC

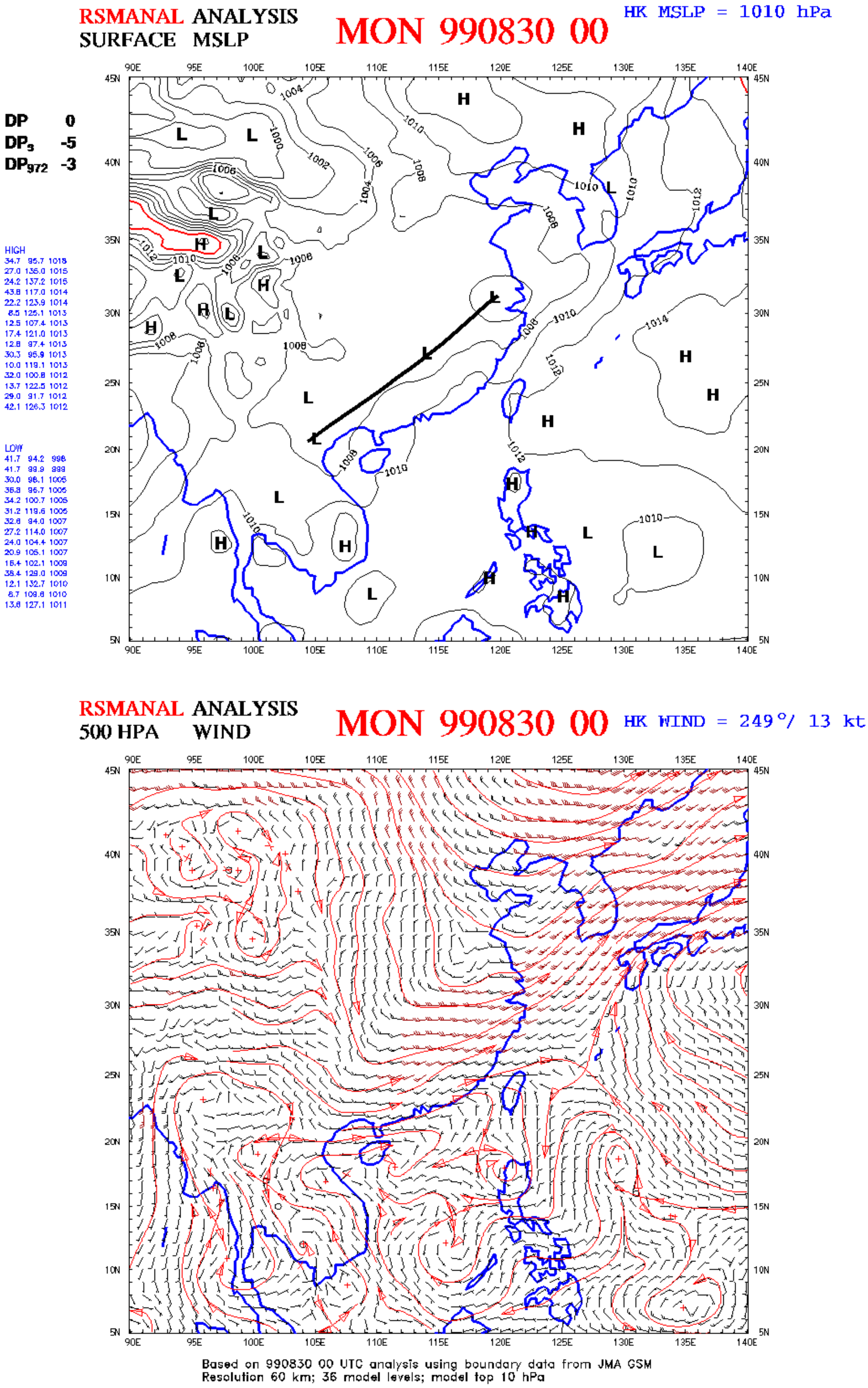



Figure 5b. Synoptic Situation at 990830 00 UTC