LORAN-C AND OMEGA NAVIGATION SYSTEM TESTS
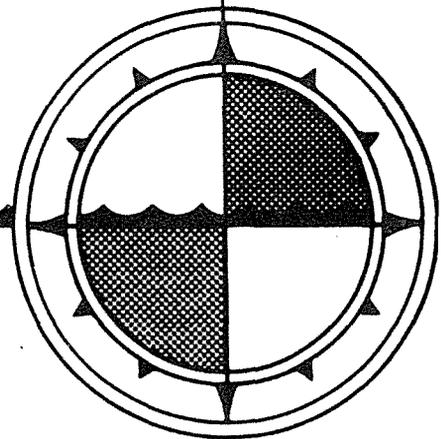# IN THE BEAUFORT SEA

by

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A.

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Abstract

This report describes Loran-C skywave reception in the Beaufort Sea. The accuracy of Loran-C positions using this mode of reception is evaluated. Omega reception was also monitored in the Beaufort Sea and the accuracy of positions obtained with an MX1105 Satnav/Omega receiver are given.
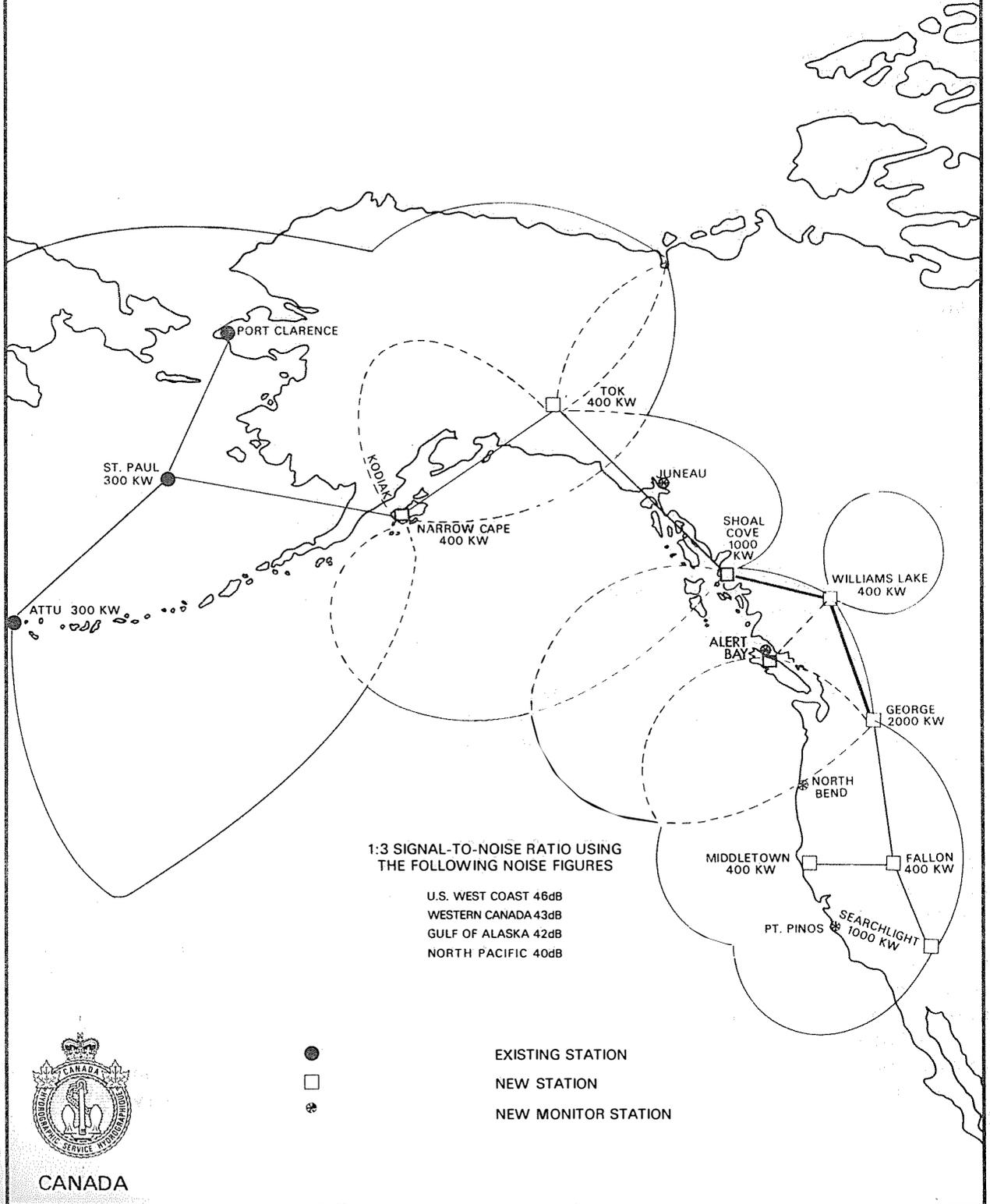
Acknowledgements

Introduction

The Beaufort Sea extends northward from the Canadian and Alaskan coasts into the Arctic Ocean west of Longitude 128°W. It is an area of intensive petroleum resource exploration activity and there is a possibility that oil tanker traffic will develop in the next few years. The continental shelf extends up to 75 nautical miles (nm) out from the low-lying coastline. The shelf is liberally scattered with shoal pingo-like features which rise to within 16 metres (m) of the surface. These shoals, together with the poor radar targets presented by the low-lying coast, present problems for the navigator who already has to cope with the usual hazards of arctic navigation.

Several navigation systems and techniques are available in the Beaufort Sea. This area is, of course, covered by the U.S. Navy Satellite Navigation system (Satnav) and by Omega. There is a potential for limited Loran-C reception using skywaves from the existing chains in Alaska. Seven radar beacons operate from positions along the shore, providing targets with radar ranges of up to 25 nm. Several air radio direction finder beacons exist in the area, and V.L.F. (Very low frequency) transmissions may be available from several stations in the northern hemisphere. The oil exploration companies use a number of precise inshore positioning systems such as Argo and Syledis. The Polar Continental Shelf Project (PCSP) of the Department of Energy, Mines and Resources intermittently operates a Decca 6F chain providing coverage of portions of the Beaufort Sea. So for offshore navigation, there already exist three potentially useful systems covering all of the Beaufort Sea: (1) Satnav, (2) Omega, (3) Loran-C.

Satnav provides accurate fixes on the average every 50 minutes at these latitudes. However gaps between passes may be as long as three hours, either due to the geometry of the current satellite orbital configuration or to interference occurring when two satellites are above the horizon. The Satnav system has been successfully used in this area since 1970 and continues to be used for precise drill ship positioning, survey work and general navigation. However unless Satnav position information is integrated with data from some other system it does not provide continuous positioning information.

Omega is one of the radio navigation systems that provide continuous coverage in the area. Phase comparisons are made using V.L.F. signals (10.2, 11.3 and 13.6 Khz). This system, unless used in conjunction with Satnav or with local monitor, does not provide the accuracy that is usually required for navigation on the continental shelf. Omega reception is also subject to diurnal propagation changes, sudden ionospheric disturbances, polar cap disturbances and from inadequately modelled propagation path conductivity variations. Signals from four of the eight Omega stations can be regularly received in the Beaufort Sea area. The stations are Norway (A), Hawaii (C), North Dakota (D) and Japan (H). It is interesting to note that the V.L.F. propagation path from Norway to the Beaufort Sea does not pass over the Greenland icecap. Therefore this particular signal is not as strongly attenuated as it is in the eastern Canadian Arctic.

LORAN C COVERAGE IN THE NORTH EAST PACIFIC

PORT CLARENCE

TOK
400 KW

KODIAK

ST. PAUL
300 KW

JUNEAU

NARROW CAPE
400 KW

SHOAL
COVE
1000
KW

WILLIAMS LAKE
400 KW

ATTU 300 KW

ALERT
BAY

GEORGE
2000 KW

NORTH
BEND

1:3 SIGNAL-TO-NOISE RATIO USING
THE FOLLOWING NOISE FIGURES

MIDDLETOWN
400 KW

FALLON
400 KW

U.S. WEST COAST 46dB
WESTERN CANADA 43dB
GULF OF ALASKA 42dB
NORTH PACIFIC 40dB

PT. PINOS

SEARCHLIGHT
1000 KW

EXISTING STATION

NEW STATION

NEW MONITOR STATION

CANADA

BEAUFORT SEA

BANKS

ISLAND

CANMAR
EXPLORER I

NERLERK

CAPE
PARRY

MACKENZIE

BAY

TUKTOYAKTUK

N.W.T.

YUKON

SCALE OF MILES

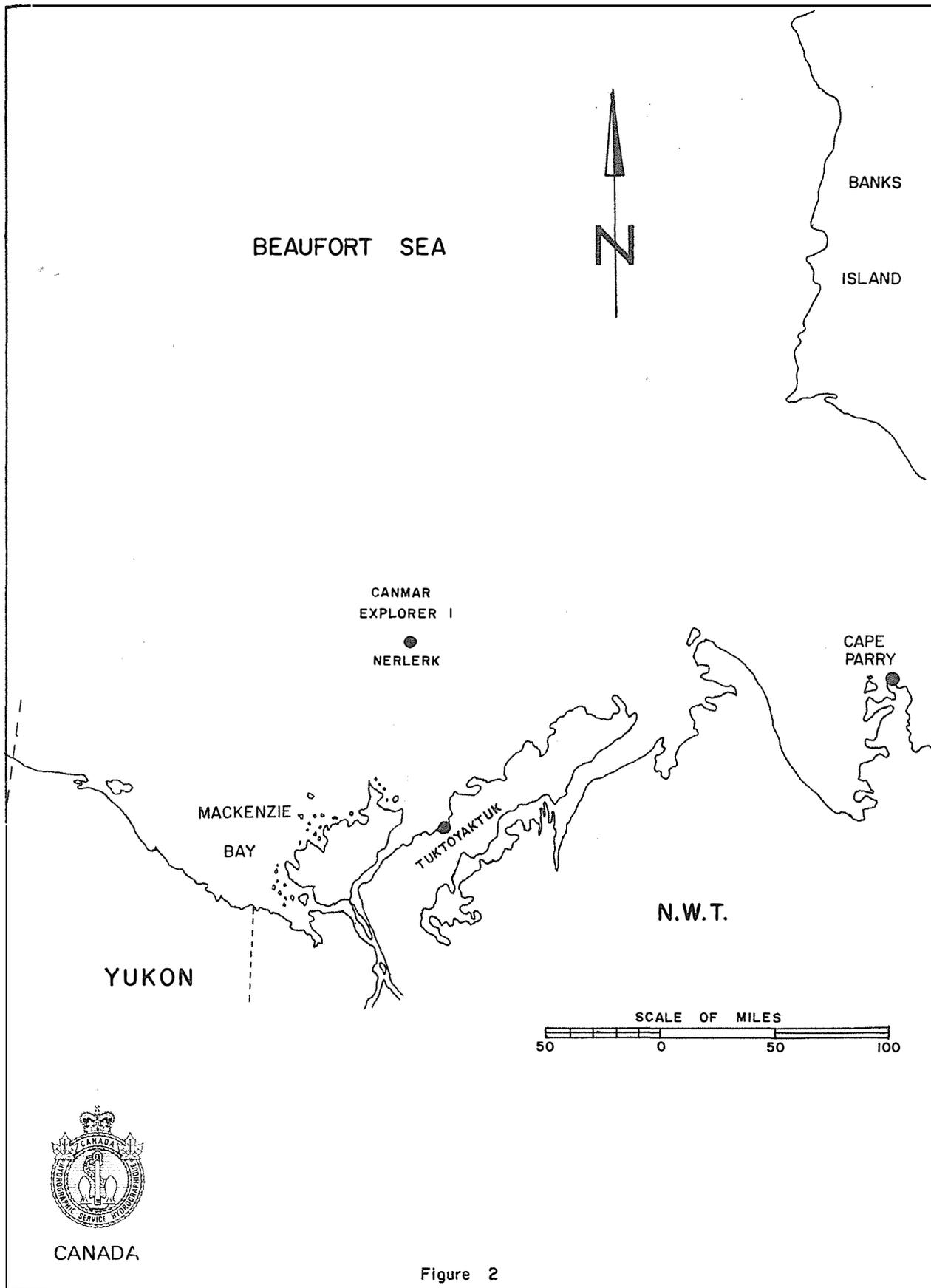50   0   50   100

CANADA

Figure 2

Two Loran-C chains operate in Alaska, and are designed to provide groundwave coverage of the Gulf of Alaska and the Bering Sea. However, Loran-C has a predicted one-hop skywave range of about 1300 nm. Therefore, transmissions from five stations in Alaska can usually be received. One of the signals, from Tok (7690 M) can be reliably received on groundwave, at least during the summer. The other stations providing skywave coverage are Narrow Cape (7960-X, 9990-Z), Shoal Cove (7960-Y), St. Paul Is. (9990-M) and Port Clarence (9990-Y). (See Figure 1.)

Purpose of Tests

Reports of reasonably reliable Loran-C reception were received from ship operators in the Beaufort Sea in 1977 and 1978. In response to these reports a series of tests was made in August, 1979. In addition to the Loran-C measurements the opportunity was taken to investigate Omega reception in the area.

The Loran-C tests were made to show the availability and stability of signals from the Alaska transmitters at three sites in the Beaufort Sea area, (1) at Tuktoyaktuk, (2) at the Nerlerk M-98 drill site in CANMAR *Explorer 1* and (3) at Cape Parry. (See Figure 2.) The tests were designed to establish the extent of Loran-C groundwave reception, the reliability and stability of Loran-C skywave reception, and the accuracy of time difference (T.D.) and time of arrival (T.O.A.) position lines. Data were collected to define the signal to noise ratio (S.N.R.), the envelope to cycle difference, the receiver gain (which can be related to field strength), the T.O.A. and T.D. of Loran-C signals.

Omega data were collected at Tuktoyaktuk and in CANMAR *Explorer 1*. For this navigation system signal to noise and position information were measured at both sites. An attempt was also made to estimate the effect of differential corrections to Omega positions. However, the permanent Omega monitor at Inuvik was not operational when the measurements were being made in the Beaufort Sea. Some data from this monitor were made available by the United States Coast Guard for a short period after our observations were made.

Equipment

To monitor the Loran-C signals in the Beaufort Sea an Austron Loran-C receiver system was used. The system was controlled by a monitor program similar to that used for operatioal chain monitoring. The system was made up of the following equipment:

1 Austron 5000 Monitor Receiver
1 D.E.C. PDP8E Computer
1 T.I. A.S.R. 733 Data Terminal
1 H.P. 5062-C Cesium Frequency Standard.

Loran-C T.D., phase, gain, cycle and noise information was logged on Phillips cassettes and later transcribed to Hewlett Packard cartridges for data processing.

To monitor the Omega signals Magnavox 1105 Satellite/Omega Navigator was used. This instrument was lent to the CHS by the Magnavox Government and Industrial Electronics Company of Torrance, California, through Marinav Ltd. of Ottawa, Ontario. The MX1105 combines information from a single channel (400 mhz) satellite navigation system receiver with data from a three frequency Omega receiver through a Z80 microprocessor. This system produces satellite positions, Omega positions and signal/noise and position line bias information, also integrated position estimates from both navigation sensors. Provision is also made for ship's log and gyro input, although this feature was not used in the tests. The MX1105 designates the integrated positions - Nav. 1 for the Satnav/Log/Gyro combination and Nav.2 for the Satnav Omega combination.

Measurements at Tuktoyaktuk

Loran-C signals were monitored at Tuktoyaktuk, in CANMAR *Explorer 1* and at Cape Parry. At Tuktoyaktuk, the Loran-C equipment was set up at the Polar Continental Shelf Project (PCSP) base. The antenna, a 2.5 m whip, was placed on the roof of the building about 10 m above the ground and about 15 m above sea level, well clear of all obstructions. Monitoring started at 1500 local time (2200Z) on August 4th, 1979. The transmissions for the Gulf of Alaska Chain (7960) from Tok (Master) and from Narrow Cape (X-Secondary) were quickly acquired. The transmissions for Bering Sea Chain (9990) from Port Clarence (Y-Secondary) and again from Narrow Cape (Z-Secondary) were also easily acquired. At about 0100 local time, just after sunset, the signals from Shoal Cove (7960, Y-Secondary) and from St. Paul Is. (9990, Master) were acquired. The signals from these five stations were tracked continuously for 72 hours with only occasional cycle skips on the transmissions from Shoal Cove, Narrow Cape and St. Paul Is. A data set, defining T.O.A., T.D., Gain, Noise and Cycle, was logged every 15 minutes.

Some interference to Loran-C reception was observed at Tuktoyaktuk. This interference was observed on the scope of the Austron 5000 receiver as a transmission somewhere close to 100 Khz formed into a continuous pulse train, the pulse envelope having a wavelength approximately ten times that of the basic frequency. This continuous pulse train swept across the scope with an apparent repetition interval of 85,000 microseconds. The pulses reached their maximum amplitude during the afternoon, then decreased to a minimum at night.

A spectrum analyser showed a reasonably clean spectrum around 100 Khz, with the Loran-C signals easily identifiable above the noise, at about -100 dbm. However, the analyser did show a pulsed transmission sweeping this area of the spectrum. The Tuktoyaktuk DEW line station chief reports interference on some of their equipment at 121.5 Khz.

The Omega and Satnav antennae for the MX1105 system were also placed on the roof of the PCSP base at Tuktoyaktuk about 3 m away from the Loran-C antenna and from each other. It took this system about 6 hrs to acquire and synchronise with the Omega transmissions of Tuktoyaktuk. Data relating to Omega and integrated positions, and Omega signal quality were logged every

30 minutes for 72 hours. For the next 48 hrs the MX1105 system was used as
a stand-alone Omega receiver and Omega position data was again logged every
30 minutes.

Measurements at Nerlerk in *Explorer 1*

Radio navigation signals were monitored in CANMAR *Explorer 1*, a drill
ship working about 60 nm north of Tuktoyaktuk in the Beaufort Sea. The
ship was, for our purposes, stationary on the drill site. The Loran-C
antenna was mounted on the bridge wing about 15 m above sea level. The
Omega and Satnav antenna were placed on the flying bridge about 20 m above
sea level. The drill rig tower was about 30 m northwest of the antenna and
obviously such a massive structure would not enhance low frequency phase
measurements. Also the drill ship provided a ''noisy'' environment for
monitoring radio signals. However, no major distortions in accuracy of
position data collected in CANMAR *Explorer 1* could be attributed to either
the rig or the ''noise''.

In the drill ship, Loran-C signals from Tok (7960-Master), Narrow Cape
(7980 - X-Secondary, 9990 - Z-Secondary) and Port Clarence (9990 - Y-Secondary)
were quickly acquired under daytime conditions. The transmission from Shoal
Cove (7960 - Y-Secondary) was acquired at sunset. It was not possible to
acquire the signal from St. Paul Is. (9990 - Master) until the second night
in the ship. Transmissions from these five stations were monitored for
72 hrs. Considering the noisy environment, receiver tracking ability
appeared acceptable as only about two cycle skips per day were experienced
for each station; except Tok which was completely stable.

Difficulty was experienced in acquiring the Omega signals onboard the
drill ship. The MX1105 was operated for 24 hrs before synchronization
with the Omega transmissions was established. Once synchronization had
occurred, strong signals were received from five Omega transmitters
(A, C, D, G, H) for the following 24 hrs. At this time, the MX1105 was put
into the Omega stand-alone mode. However, the system lost the Omega signals
at about 0200 local time (middle of the night). Upon re-synchronization
only three Omega stations (C, D, G) were tracked and they were erratic.
Good position data was not obtained again until well after sunrise from
either the integrated or stand-alone Omega systems.

Measurements at Cape Parry

Only Loran-C transmissions were monitored at Cape Parry, which is 180 nm
east of Tuktoyaktuk. The Loran-C monitoring equipment was set up at the
DEW line site and the whip antenna was mounted on the roof of the building
about 100 m above sea level and 80 m from the radar dome. Signals from
four Loran-C stations were monitored for 48 hrs. Stations at Tok (7960 -
Master), Narrow Cape (7960 - X-Secondary; 9990 - Z-Secondary) and Port Clarenc
(9990 - Y-Secondary) were acquired within 3 hrs of setting up during the
afternoon. Shoal Cove (7960 - Y-Secondary) could not be acquired until
sunset. It was not possible to acquire the signal from St. Paul Is.
(9990 - Master) during this 48 hr period. Radio interference throughout

the monitoring period at Cape Parry was minimal. An attempt was made to track skywave from Tok (7960 - Master) during the night at about 0100 local time. The skywave on this transmission was distinctly separated from the groundwave for only a short period of time, but enough measurements were made to enable the night time ionospheric height to be estimated.

Loran-C Data

Figures 3 through 8 show the information collected at Tuktoyaktuk for the two chains monitored. Times of arrival, in microseconds, of the various transmissions are plotted for the three days. All but the signals from Tok (7960 - Master) show the effects of skywave propagation. The cycle number shown on the graphs is related to envelope-to-cycle-difference (E.C.D.):

$$E.C.D. = (3.0 - Cycle\ \#) \times 10.$$

Gain numbers from the Austron Loran-C Monitor system are shown on these figures. They can be related to field strengths for the signals through:

$$F = 50 \times 10^{\frac{110 - Gain\ \#\ (db)}{20}}$$

where F = Field Strength (microvolts per metre).

Data collected at Nerlerk (CANMAR *Explorer 1*) is shown in Figures 9 through to 14. Again all the T.O.A.'s plotted, except those from Tok (7960 - Master) show skywave activity. The measurements made at Cape Parry are graphed in Figures 15 through to 19.

Omega Data

The position data generated by the MX1105 Omega/Satnav system are shown in the figures in Appendix I. In this appendix the latitudes and longitudes for Satnav fixes, for the integrated (Nav. 2) positions and for the Omega fixes are plotted as time series, for each day and as three day blocks.

Scatter plots for the positions given by the MX1105 at Tuktoyaktuk, from Satnav, Omega and integrated (Nav. 2) outputs are shown in Figures 20 to 24. Figures 25, 26 and 27 show the scatter plots of positions from the MX1105's three position outputs at Nerlerk (CANMAR *Explorer 1*).

Loran-C Reception - Groundwave from Tok

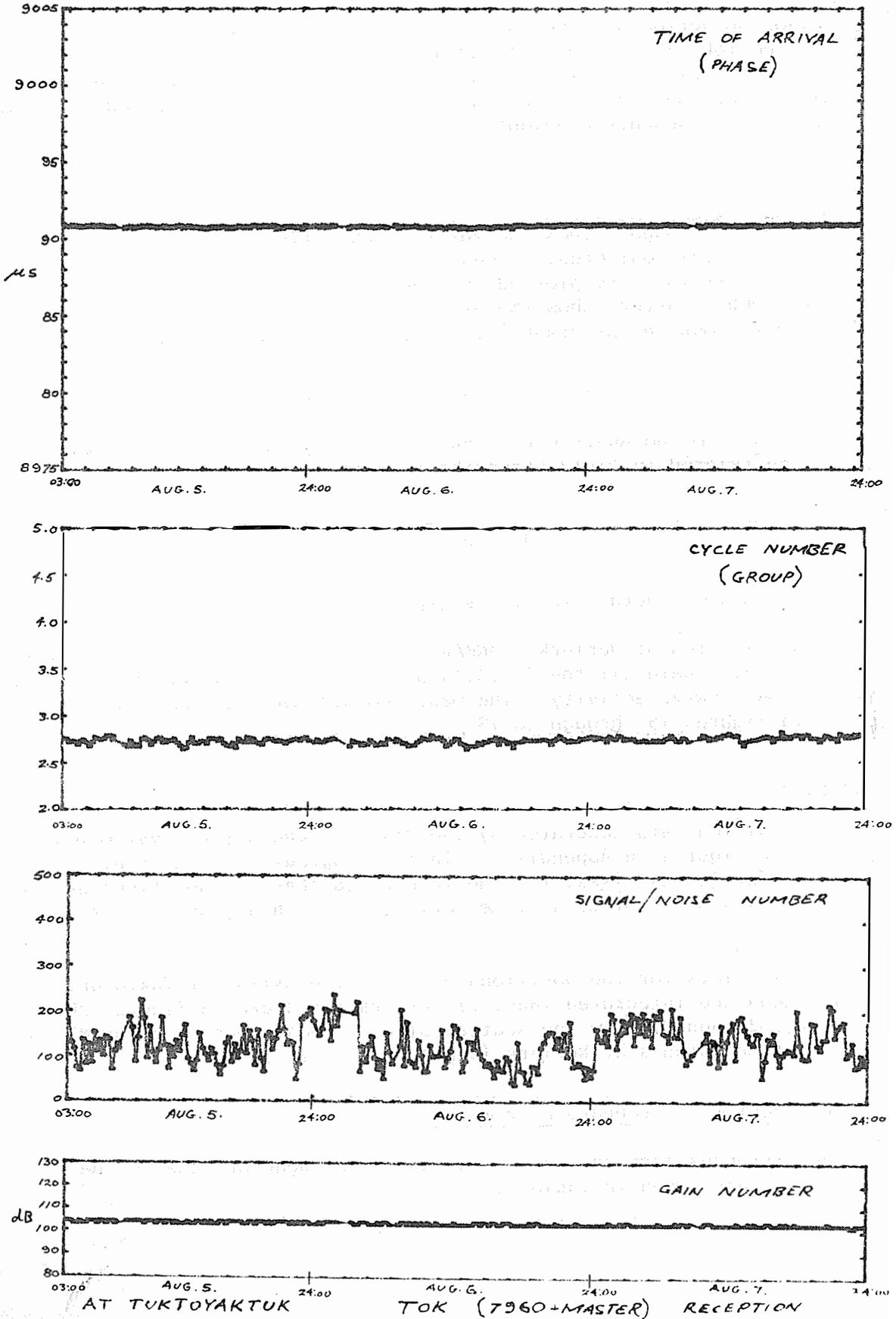The distances from the monitor sites in the Beaufort Sea to the transmitters are given in Table 1.
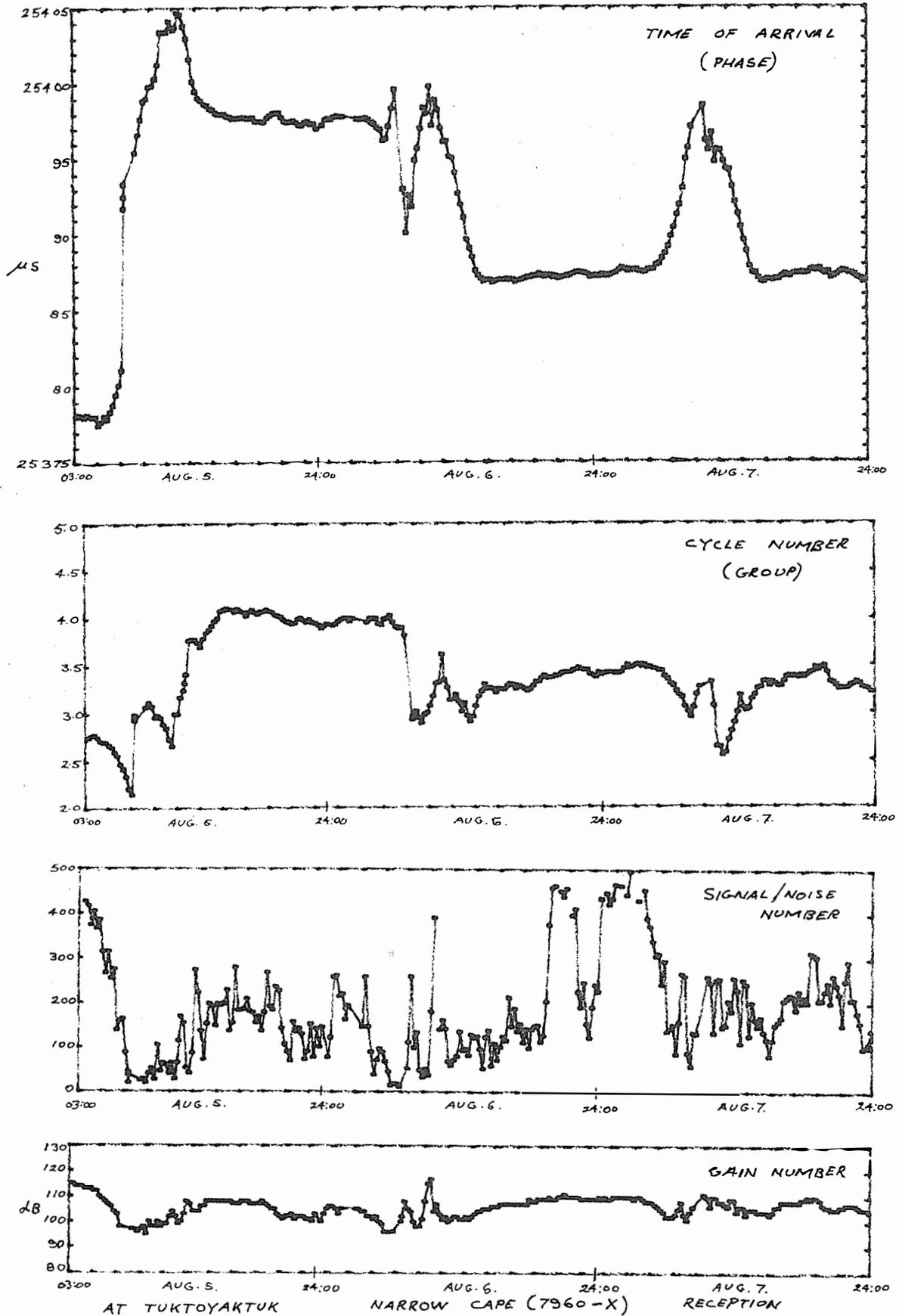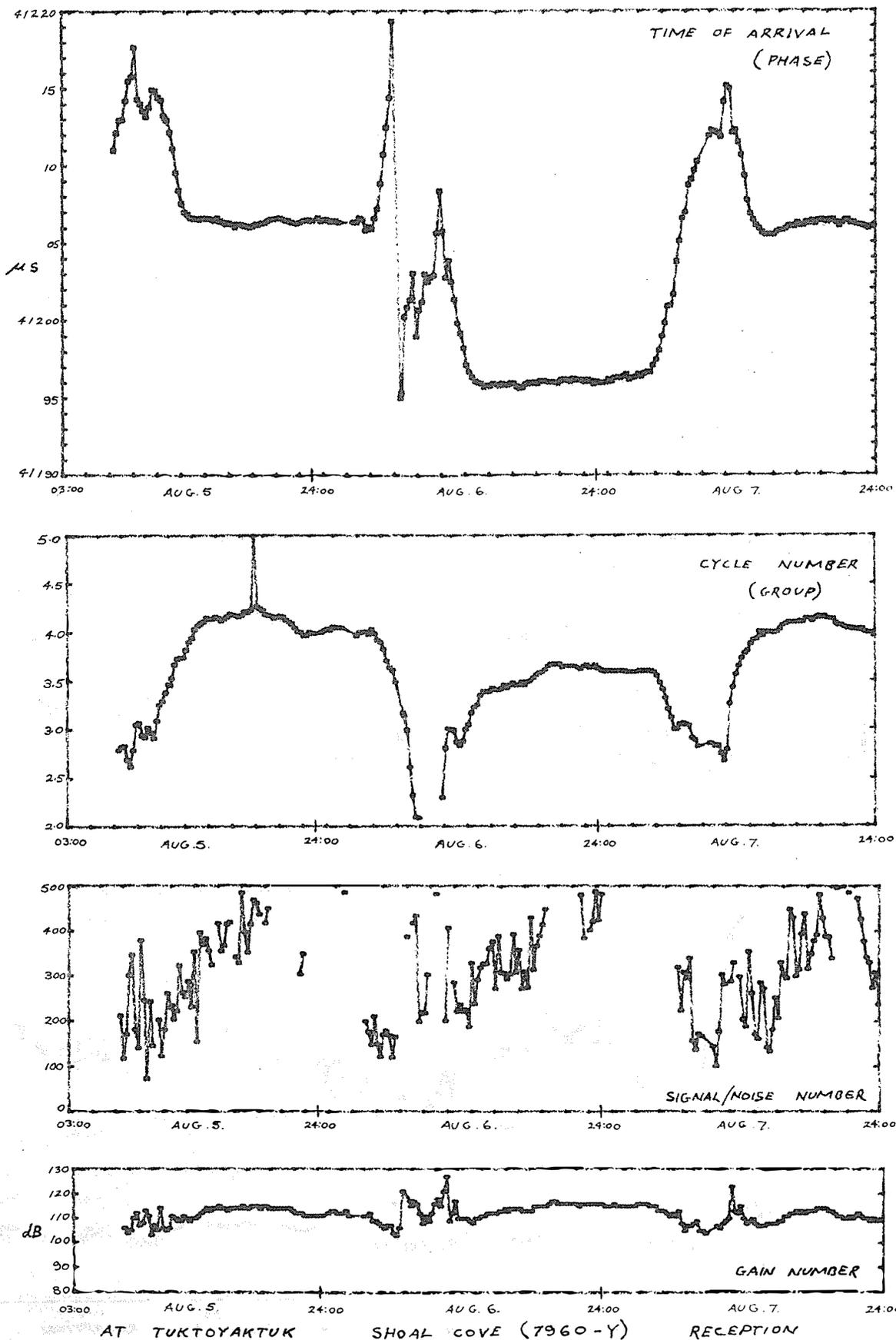
Figure 3

Figure 4

Figure 5

Figure 6

TIME OF ARRIVAL (PHASE)

CYCLE NUMBER (GROUP)

SIGNAL/NOISE NUMBER

GAIN NUMBER

AT TUKTOYAKTUK   PORT CLARENCE (9990-Y) RECEPTION

Figure 7

TIME OF ARRIVAL (PHASE)

CYCLE NUMBER (GROUP)

SIGNAL/NOISE NUMBER

GAIN NUMBER

AT TUKTOYAKTUK   NARROW CAPE (9990-Z)   RECEPTION
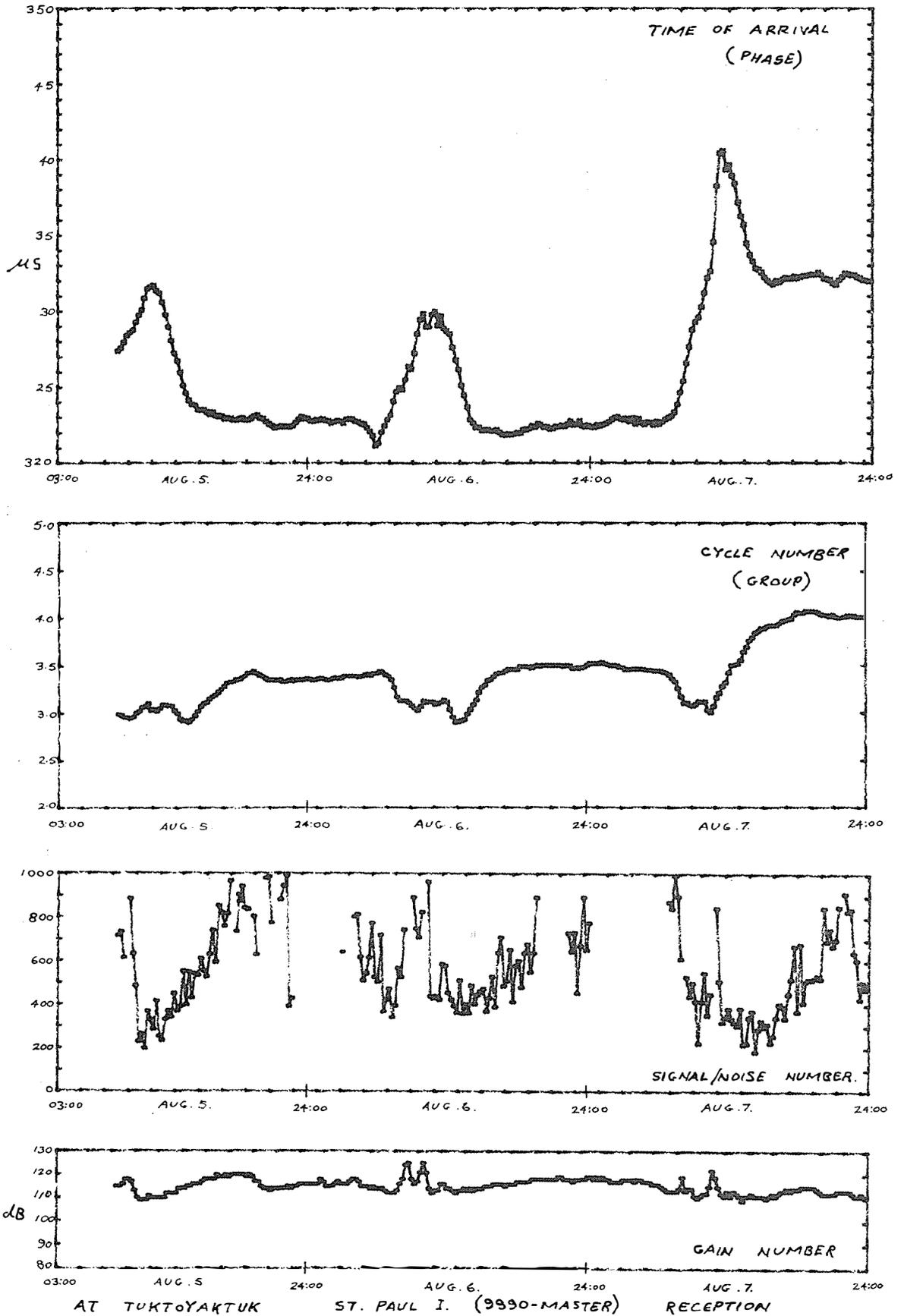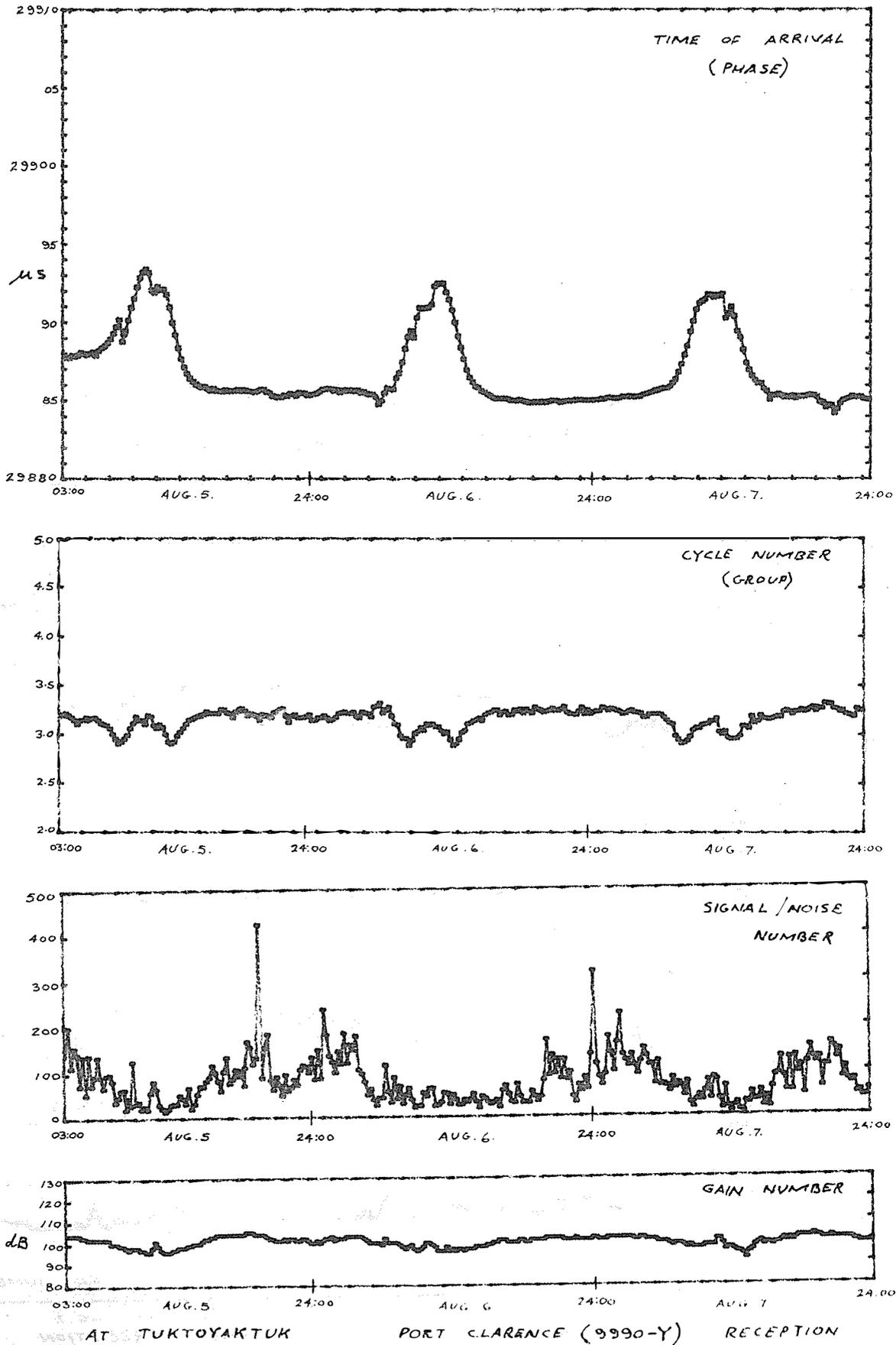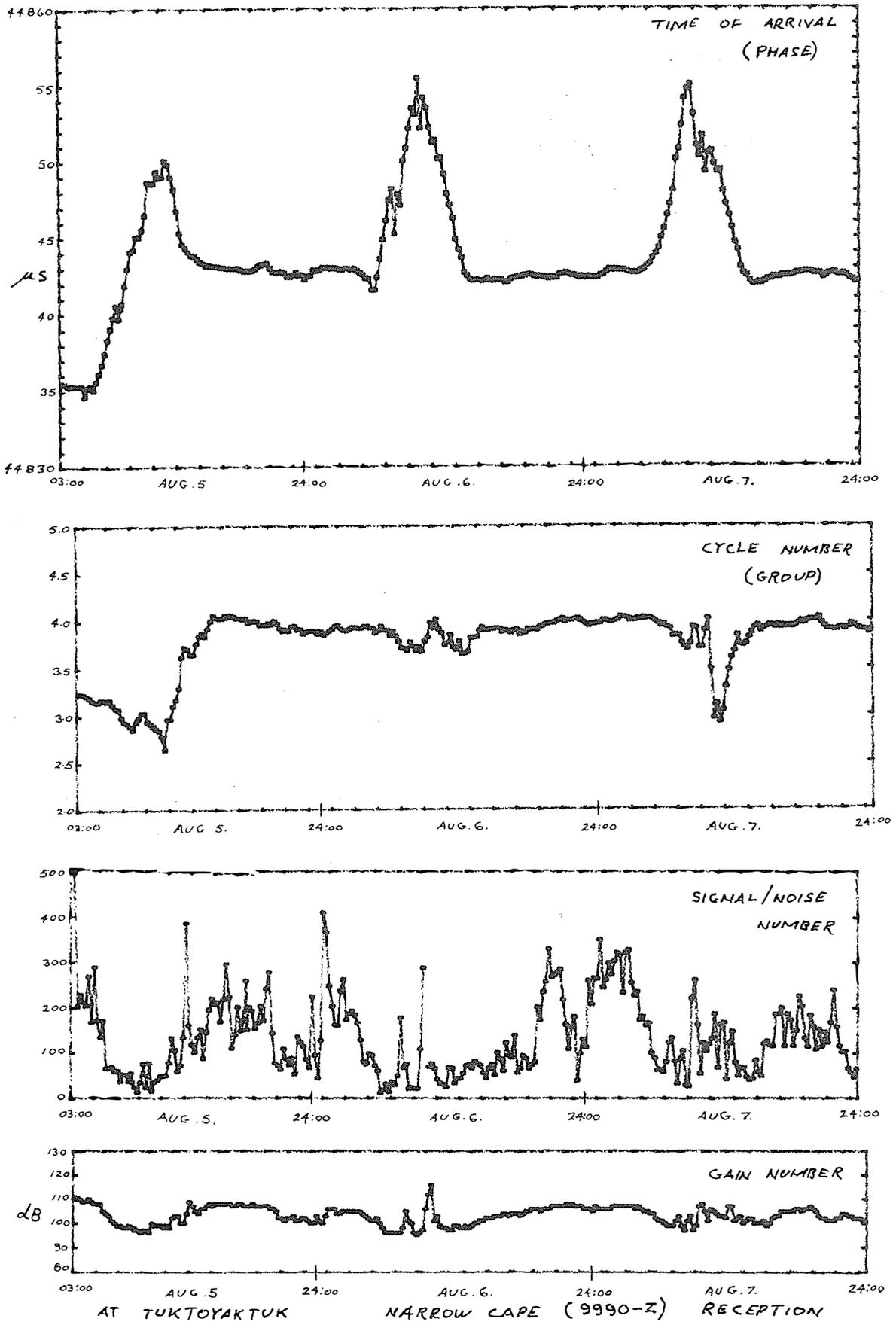
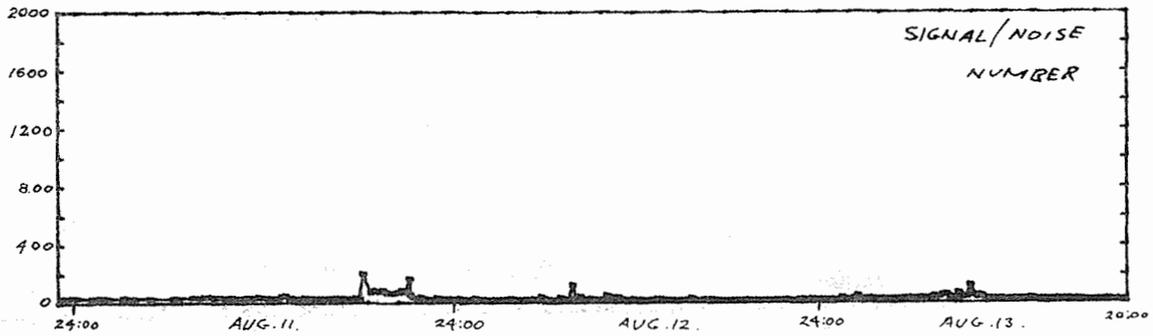Figure 8

Figure 9

Figure 10
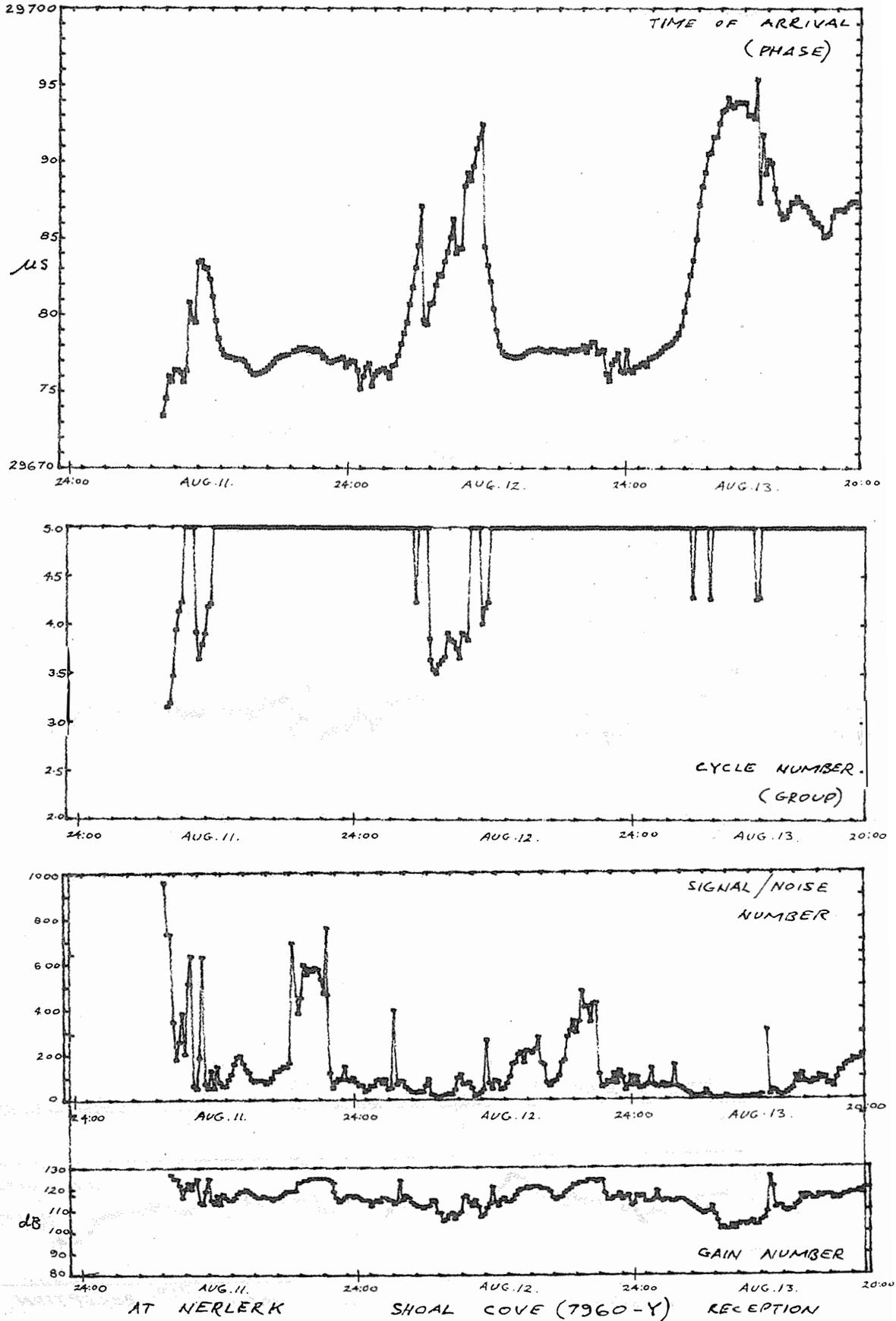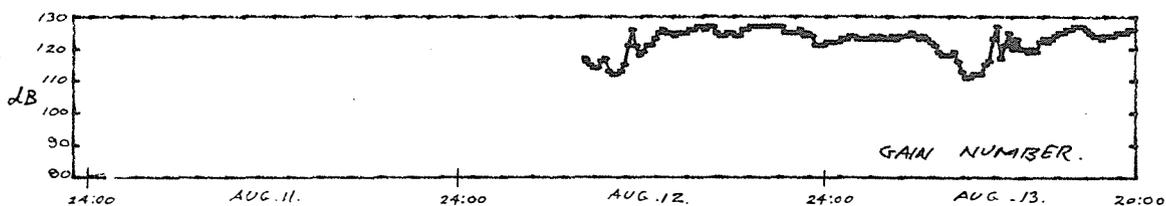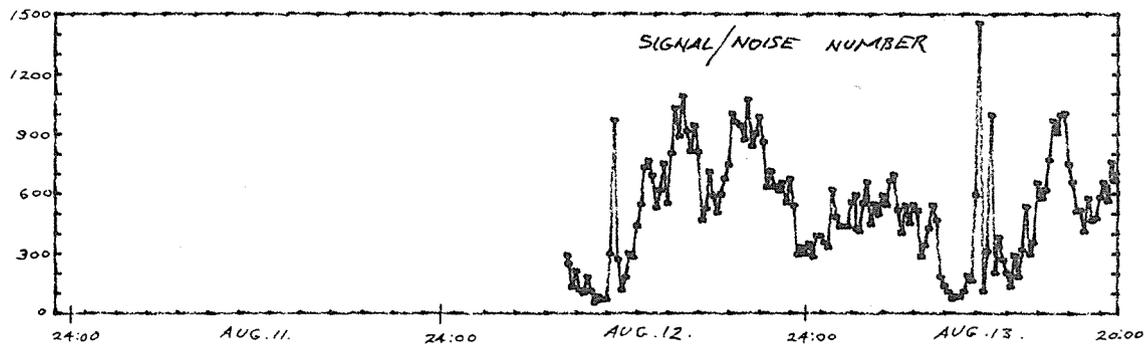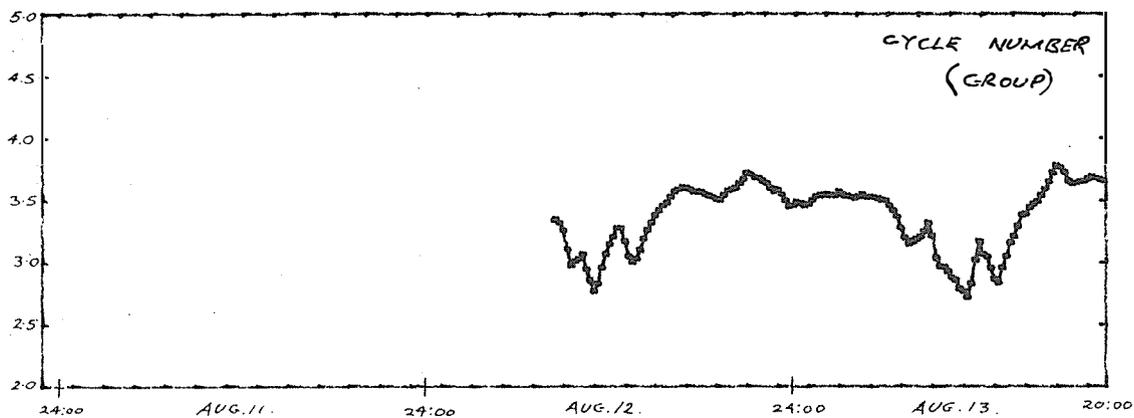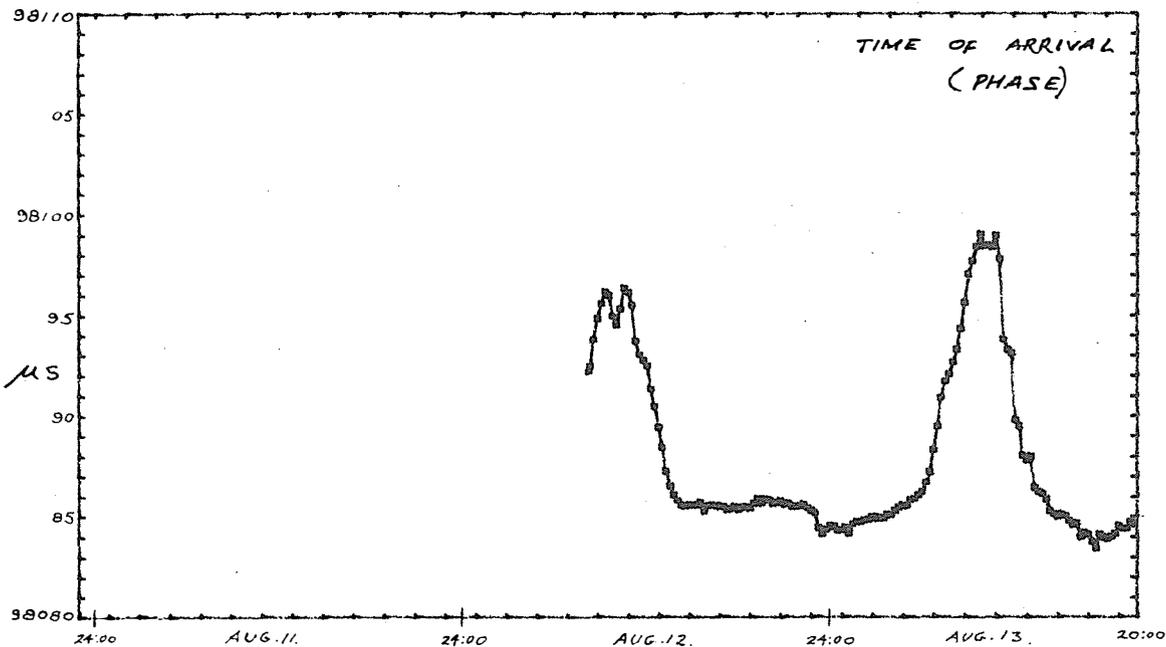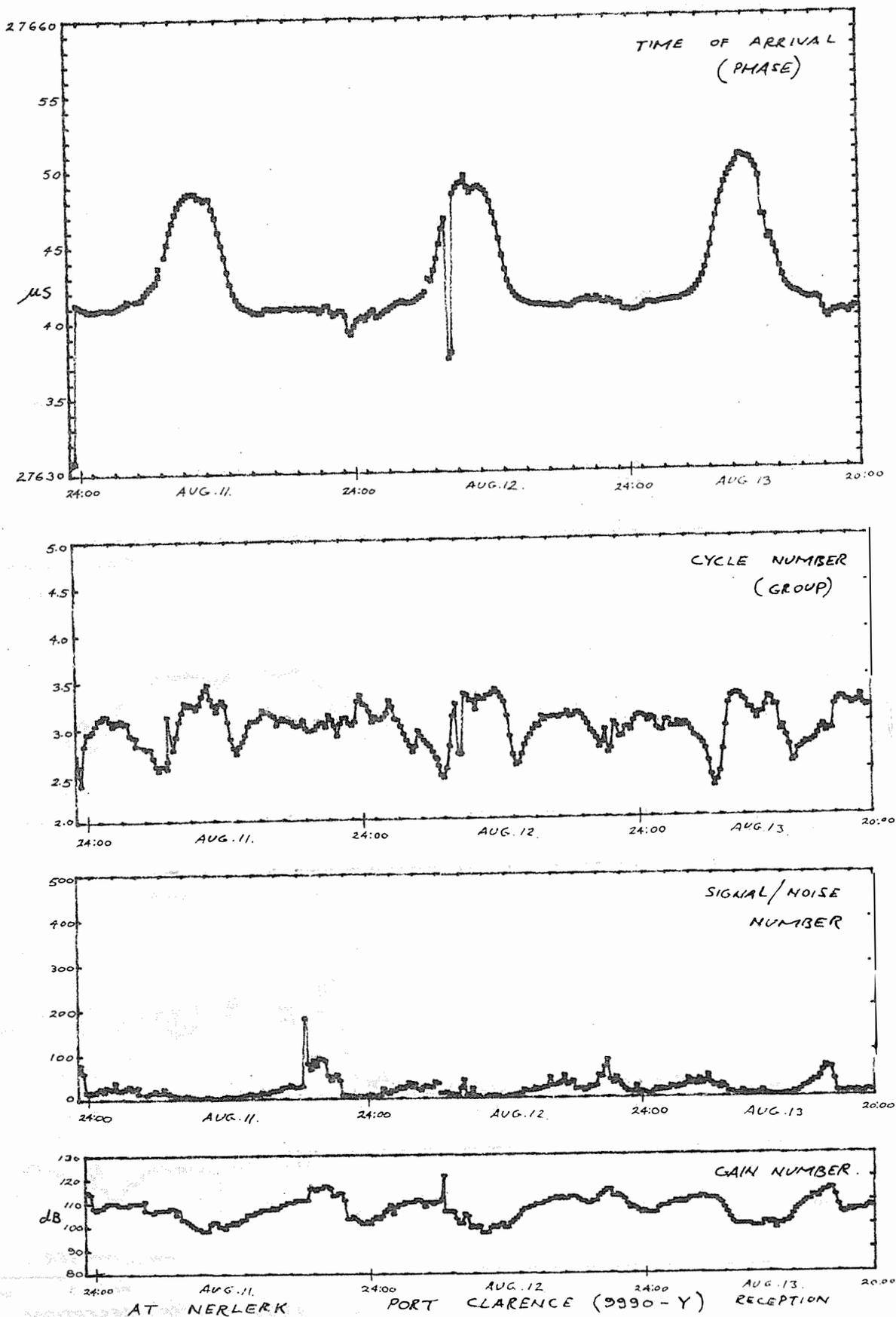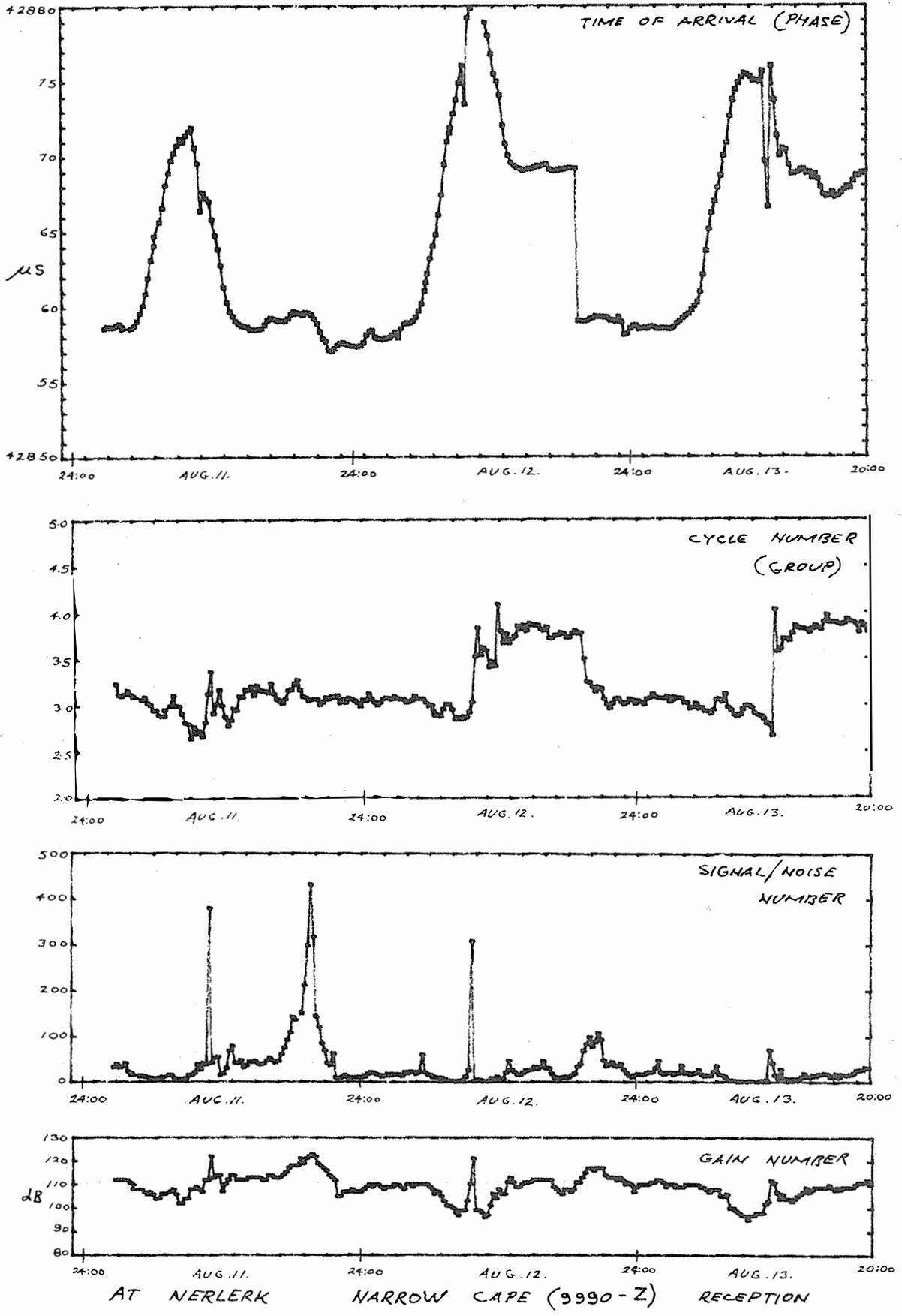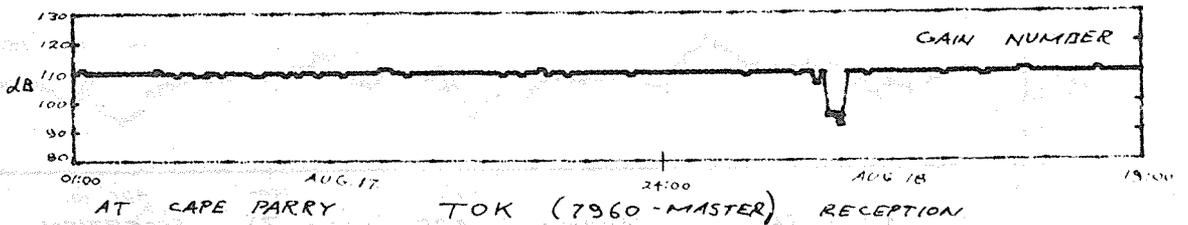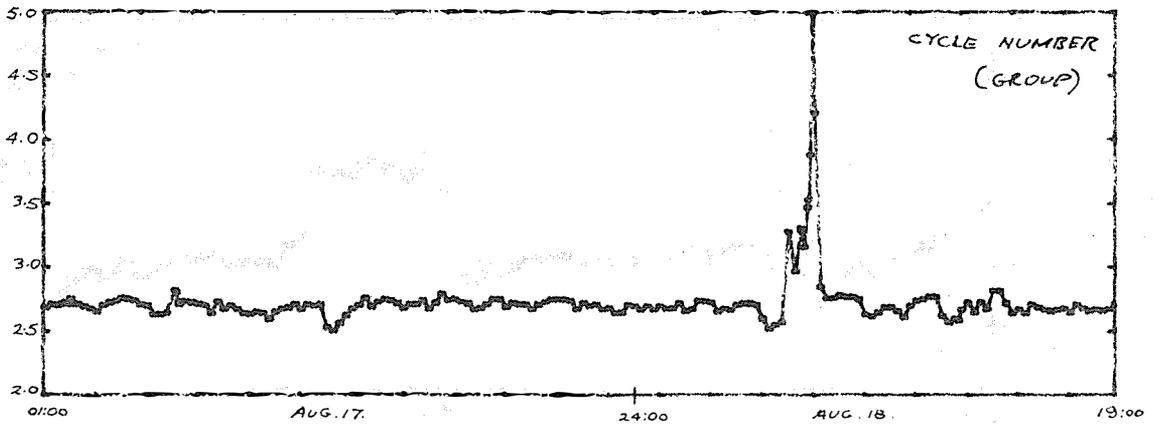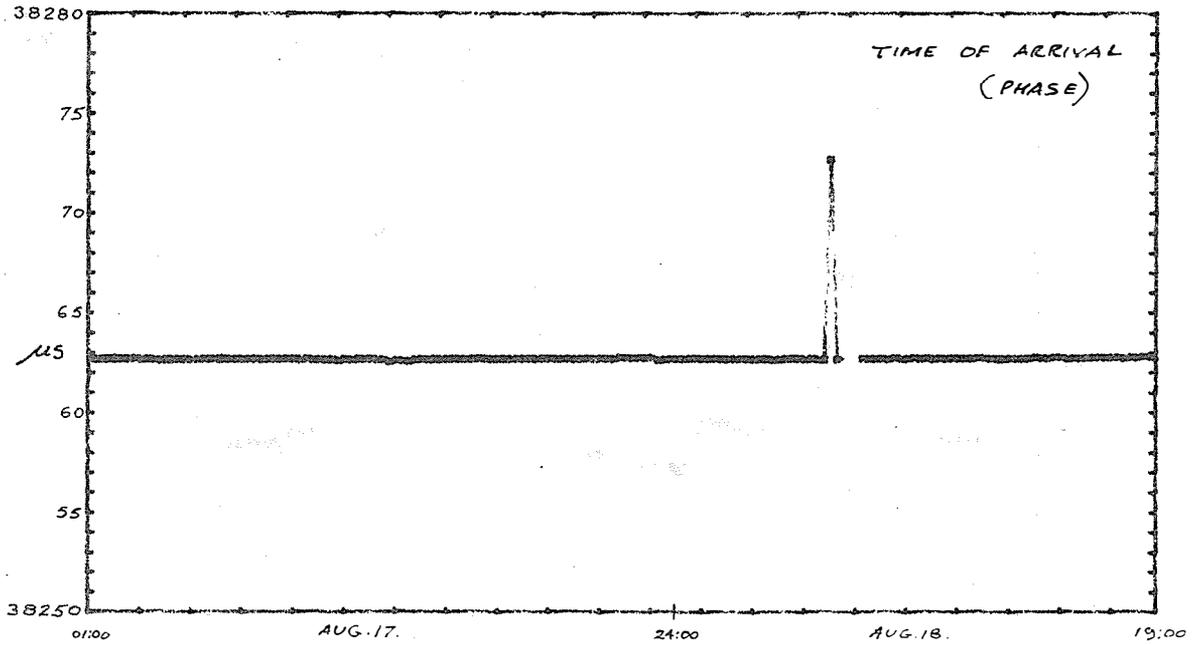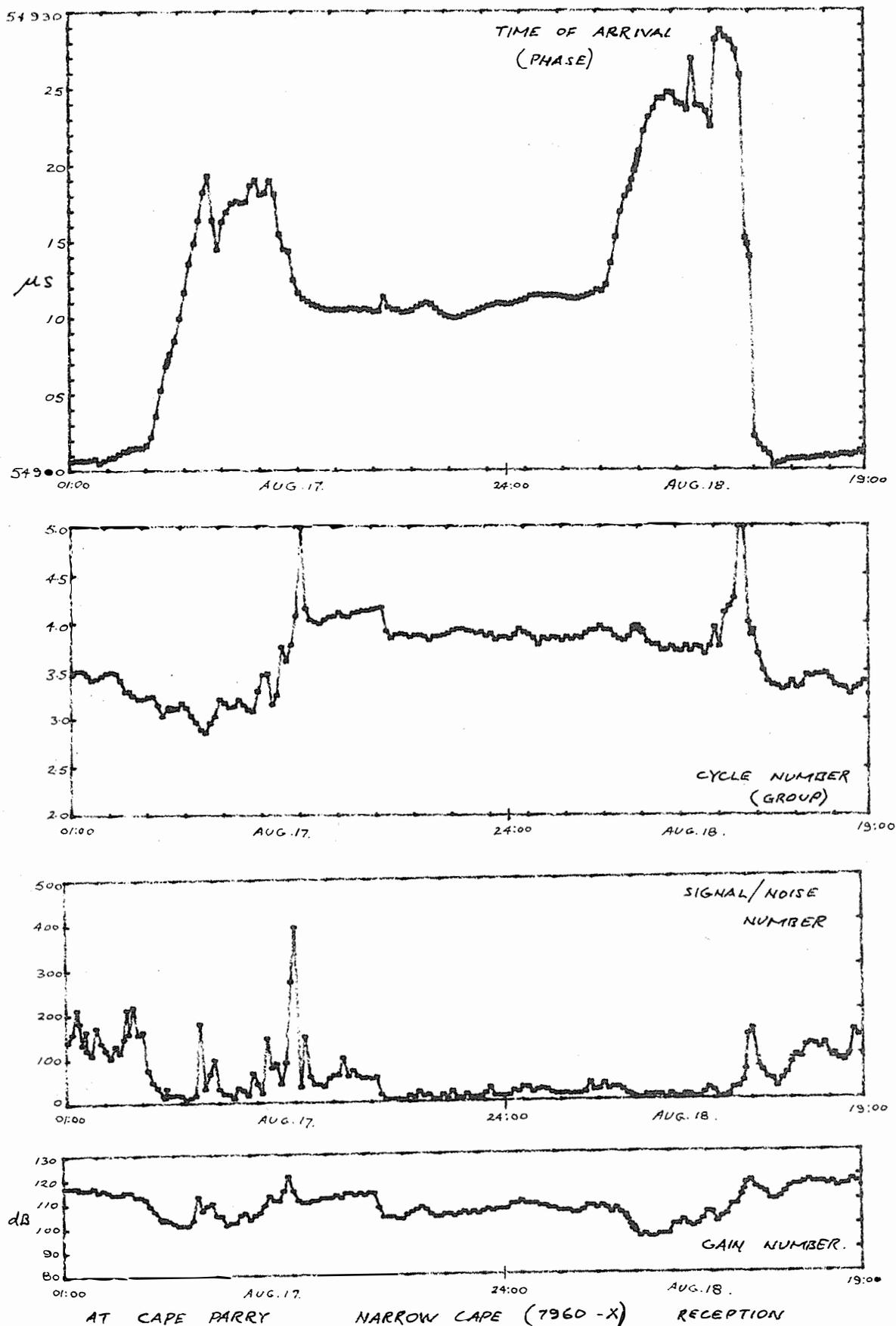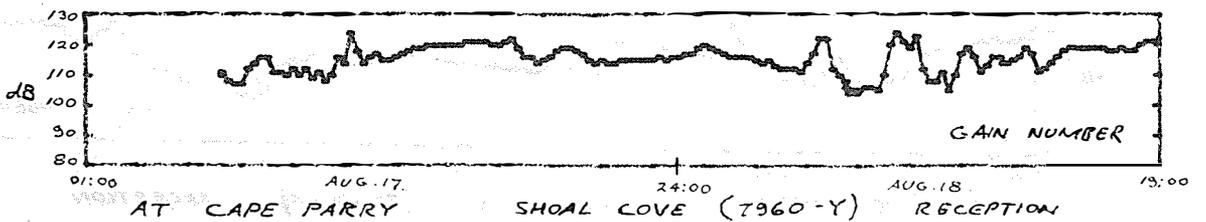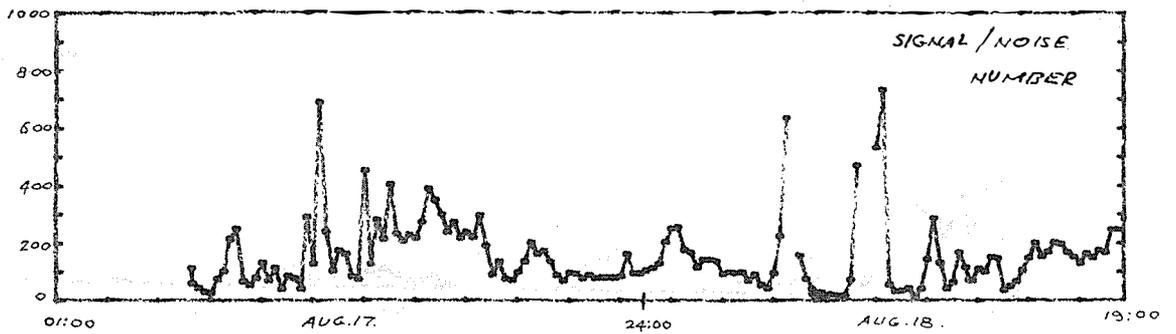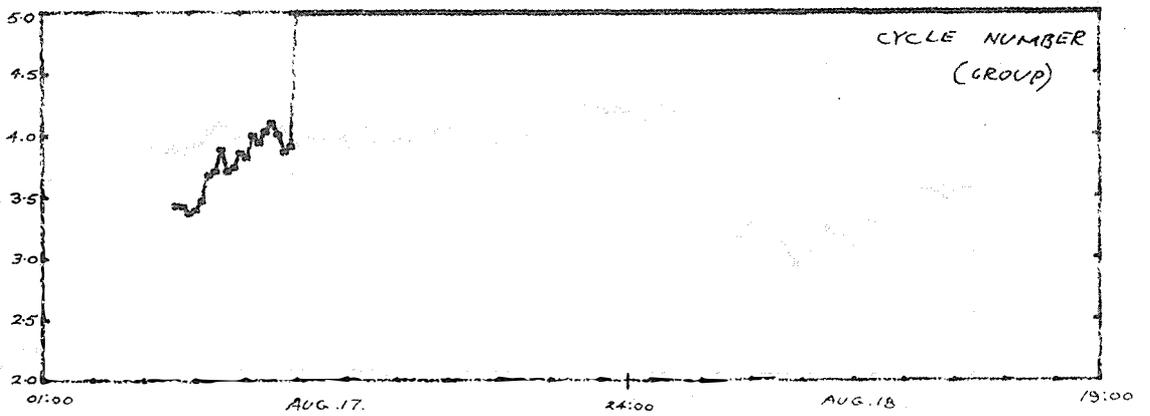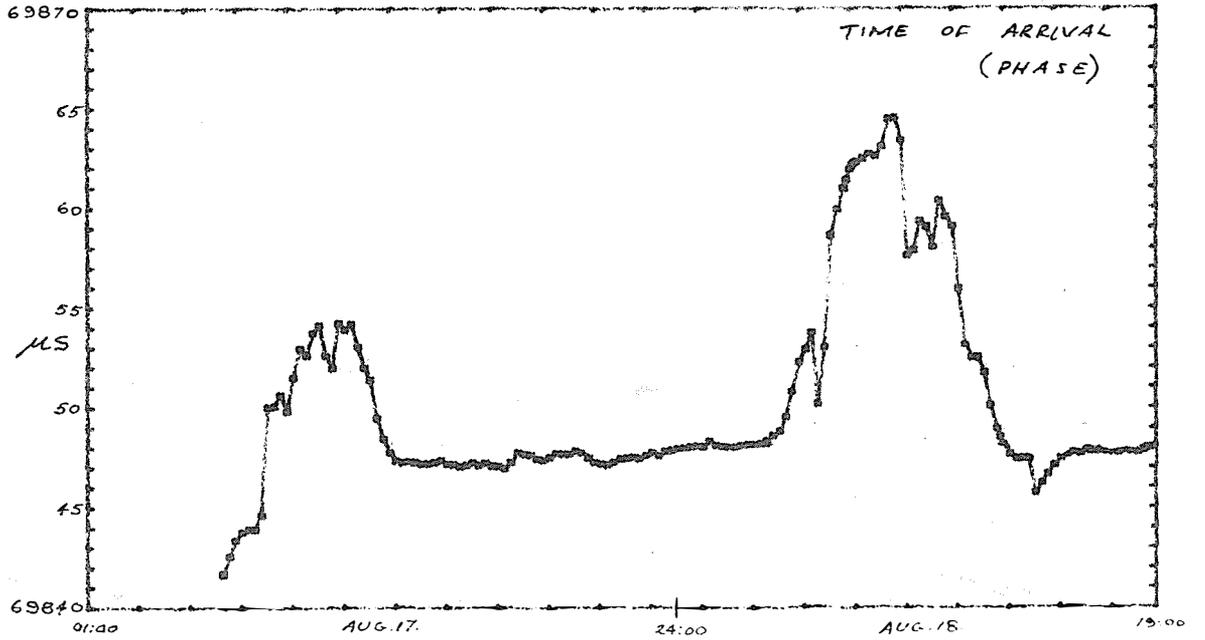
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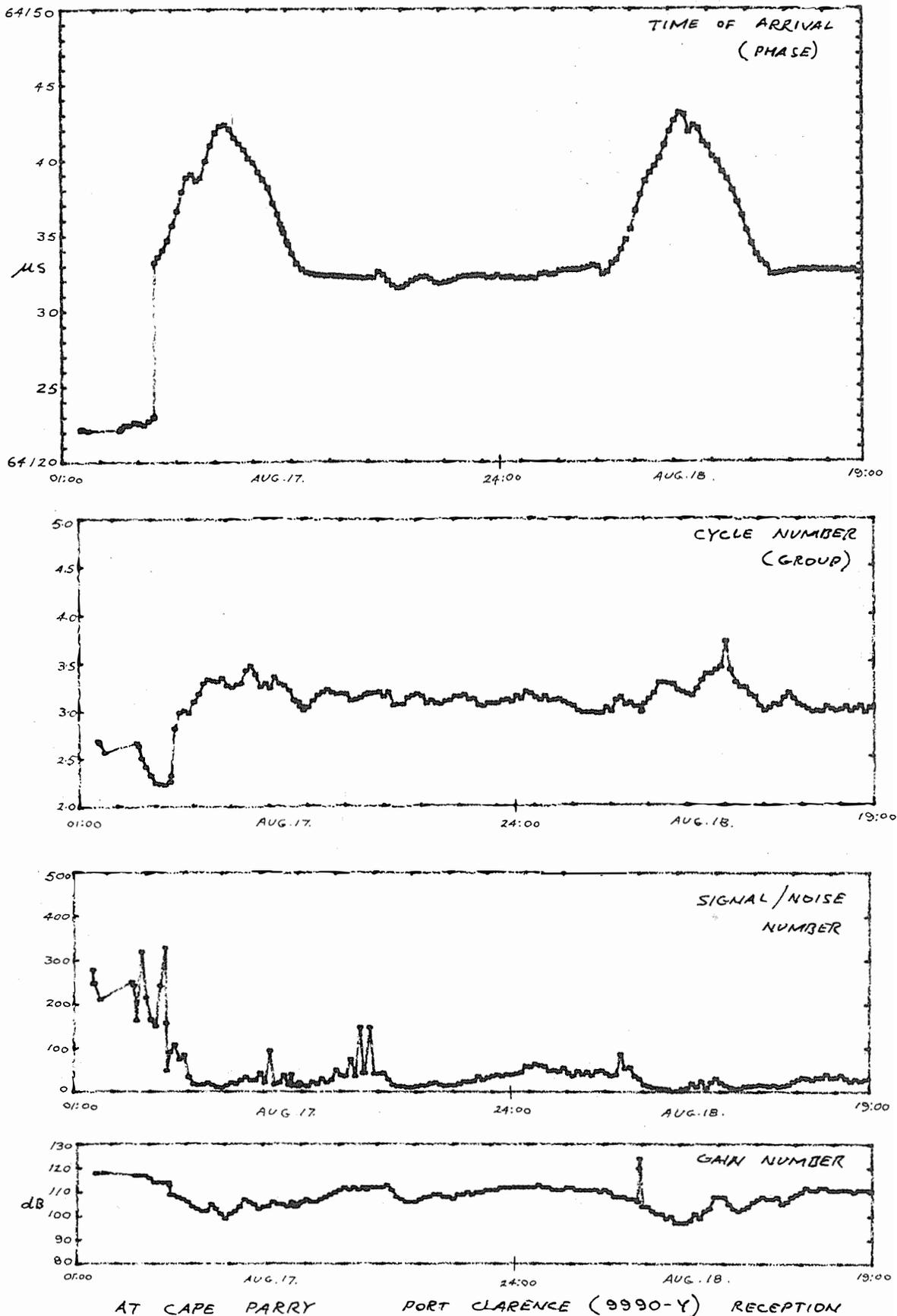
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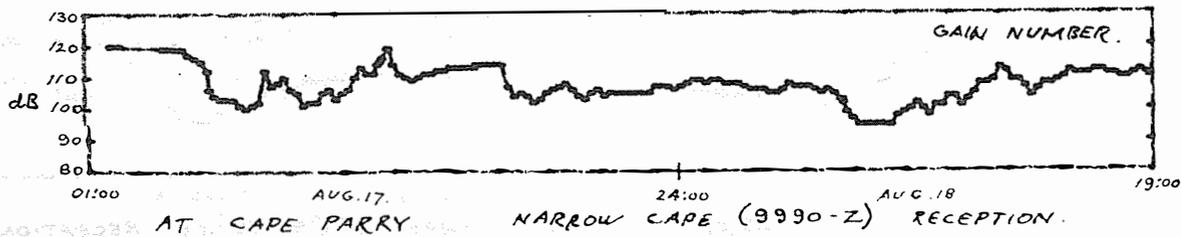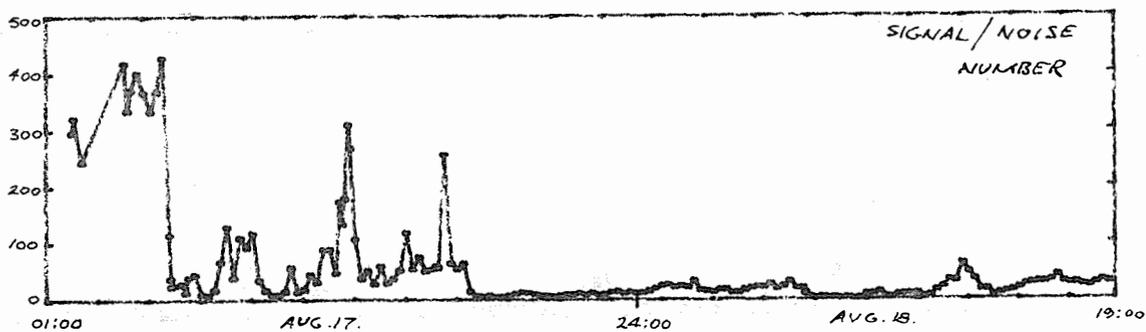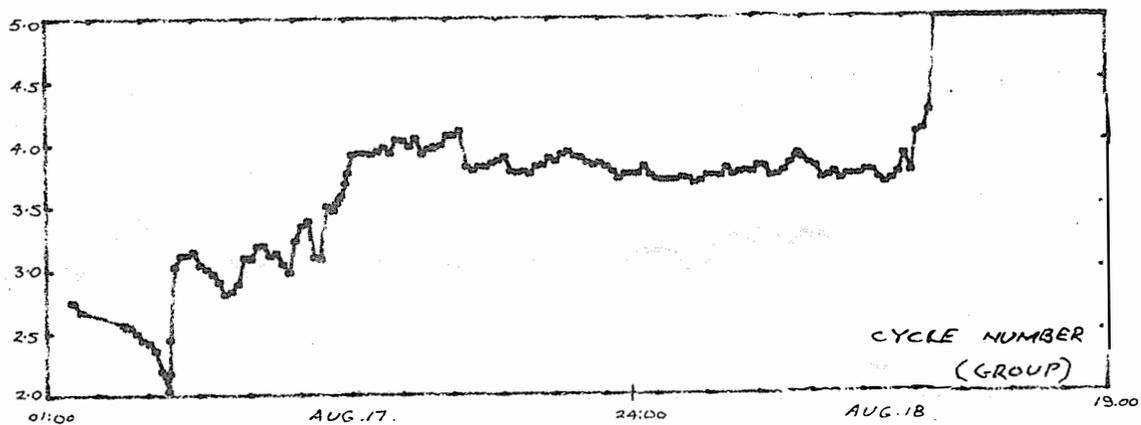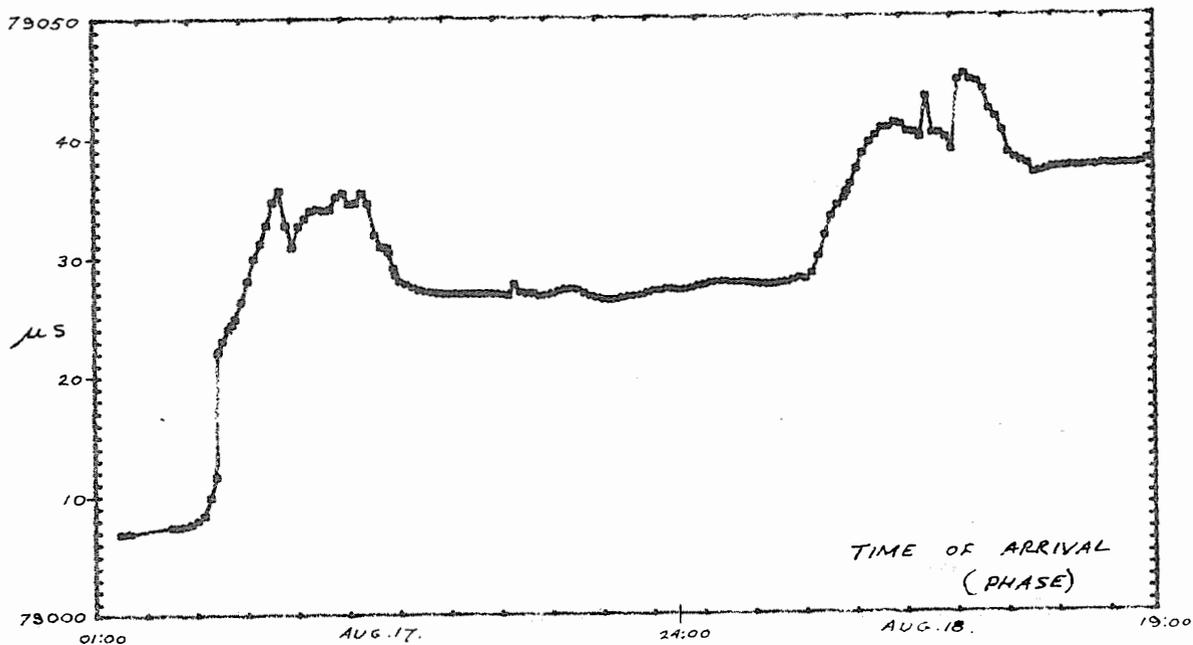
Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 21

TUKTOYAKTUK   69° - 26.29'   133° - 02.18'   W.G.S

MEAN LATITUDE   69° - 26.30'
STANDARD DEVIATION   0.40' (749 m)

MEAN LONGITUDE   133° - 02.16'
STANDARD DEVIATION   2.21' (1446 m)

COVARIANCE   896117.44 m²
CORRELATION COEFFICIENT   0.83

TUK
OMEGA FIX   AUG. 2 - 5.

LAT.

LONG.

Figure 22

Figure 23

TUKTOYAKTUK   69°-26·29'   133°-02·18'   W.G.S.

MEAN LATITUDE   69°-27·84'
STANDARD DEVIATION   0·46' (861 m)

MEAN LONGITUDE 132°-59·93'
STANDARD DEVIATION   2·71' (1773 m)

COVARIANCE   617569·04 m²
CORRELATION COEFFICIENT   0·40

LAT.

TUK.

OMEGA FIX.   AUG. 6,7.
SATELLITE INPUT DISABLED

LONG.

30

TUKTOYAKTUK   69° - 26.29'   133° - 02.18'   W.G.S.

MEAN   LATITUDE   69° - 28.00'
STANDARD   DEVIATION   0.35'   (654 m)

MEAN   LONGITUDE   132° - 59.91'
STANDARD   DEVIATION   1.50'   (977 m)

COVARIANCE   137640.65 m²
CORRELATION   COEFFICIENT   0.22

LAT.

TUK.

NAV. 2. POSITION   AUG. 6, 7.

SATELLITE   INPUT   DISABLED

69° - 31'
30'
29'
28'
27'
26'
69 - 25'

133-11' 10' 09' 08' 07' 06' 05' 04' 03' 02' 01' 133-00' 59' 58' 57' 56' 55' 54' 53' 52' 51' 50' 49' 48' 132°-47'

LONG.

Figure 24

Figure 25

NERLERK   70°-27.78'   133°-29.71' W.G.S.

MEAN LATITUDE 70°-27.75'
STANDARD DEVIATION 0.04' (65 m)

MEAN LONGITUDE 133°-29.86'
STANDARD DEVIATION 0.18' (112 m)

COVARIANCE 561.41 m²
CORRELATION COEFFICIENT 0.08

NERLERK.
SATELLITE FIX. AUG. 12, 13.

LAT.

LONG.

70°-28.00"
50"
40"
30"
20"
10"
70°-27.00"

133°-32'   31'   30'   29'   133°-28'

32

Figure 26

70°-29'

28'

27'

LAT.

NERLERK   70°-27.78'   133°-29.71'   W.G.S.

MEAN LATITUDE 70°-27.79'
STANDARD DEVIATION   0.16' (301 m)

MEAN LONGITUDE 133°-29.85'
STANDARD DEVIATION   0.79' (489 m)

COVARIANCE   -24083.87 m²
CORRELATION COEFFICIENT -0.16

NERLERK

NAV.2. POSITION   AUG. 12, 13.

70°-26'
133°-35'   34'   33'   32'   31'   30'   29'   28'   27'   26'   25'   24'   133°-23'

LONG.

Figure 27

34

Table 1

Distances to Transmitters (in nautical miles)

Transmitter	Tuktoyaktuk	Nerlerk (*Exp.1*)	Cape Parry
Tok	435.87	481.54	591.35
Narrow Cape	882.04	920.68	1043.99
Shoal Cove	843.81	906.12	903.40
St. Paul Is.	1218.54	1230.74	1396.80
Port Clarence	813.29	808.12	985.42

The theoretical extreme usable ranges of the stations, assuming a receiver that will acquire the signal with a signal-to-noise ratio of 1/3, an average conductivity along the groundwave propagation path of 0.001 mhos/metre, and an atmospheric noise level of 55db above 1 microvolt per metre, are listed in Table 2.

Table 2

Theoretical Receivable Ranges (Groundwave)

Transmitter	Peak Power	Range
Tok	540 kw	540 nm
Narrow Cape	400 kw	520 nm
Shoal Cove	540 kw	540 nm
St. Paul Is.	275 kw	490 nm
Port Clarence	1000 kw	570 nm

As predicted, only the transmissions from Tok were received by groundwave propagation. At Cape Parry, 590 nm from Tok the signal was not acquired instantaneously as at the other monitoring sites. Therefore, it appears that approximately 600 nm is the maximum overland range of the Tok transmission to the Beaufort Sea area. This 600 nm range is slightly higher than the predicted 540 nm maximum range and may imply the possibility of slightly higher ground conductivities (0.001 mhos/metre) than were used in the prediction.

Using the gain measurements from the Austron 5000 monitor system, field strengths in the Beaufort Sea ranged from 110 microvolts/metre at Tuktoyaktuk down to 40 microvolts/metre at Cape Parry for the Tok signals. The noise numbers observed on our receiver seldom exceeded 250 at Tuktoyaktuk, 150 at Nerlerk (*Explorer 1*) and 100 at Cape Parry. So actual noise levels in the Beaufort Sea this August appeared to be fairly low, ranging from -20 db above 1 microvolt/metre to -10 db above 1 microvolt/metre. Diurnal variations in noise level were not detectable. Envelope-to-cycle-difference from the Tok transmission ranged from -2 to -3 microseconds at the monitor sites. Signal acquisition was satisfactory at the two western sites and tracking ability was good at all three sites.

Loran-C Skywave Reception

First hop Loran-C skywave transmissions have a theoretical maximum range of about 2300 nm. Therefore the Beaufort Sea should be well within skywave reception range of the Alaska Loran-C stations. However, the signals from St. Paul Is. (9990 - Master) were difficult to acquire at Tuktoyaktuk and Nerlerk, and were not acquired at all at Cape Parry. The St. Paul Is. transmitter has a peak power of 275 kw. It was also impossible to acquire the Shoal Cove signals at any of the monitor sites during day time, even though this station has a peak power of 540 kw.

Loran-C Reception from Narrow Cape

Narrow Cape transmissions were quickly acquired at Tuktoyaktuk and at Nerlerk. They were tracked reasonably steadily at all three sites, although cycle skips occurred on most nights when the signals were monitored. Figures 4, 8, and 10 show a correlation of change in T.O.A. and the variation in measured E.C.D. as the ionospheric height rises and falls at sunset and sunrise. A diurnal variation is also seen in the gain and noise data.

Shoal Cove Reception

This station has a north-south propagation path to the Beaufort Sea and consistent tracking of Shoal Cove signals is difficult. Two or three cycle shifts were noted each night. At Nerlerk and at Cape Parry the monitor system could only erratically indicate a cycle number. Signal to noise measurements and receiver gain numbers indicated a weak signal. At Tuktoyaktuk large diurnal variations in E.C.D. were noted as the ionosphere changed height. It was possible to track third cycle of this signal for only one daylight period at Tuk.

St. Paul Is. Reception

At Tuktoyaktuk and at Nerlerk the St. Paul Is. signals were tracked quite steadily. Cycle skips occurred on one night at Tuktoyaktuk and one of the two nights at Nerlerk. E.C.D. at Tuktoyaktuk showed a marked correlation to shifts in ionospheric height. At Nerlerk, E.C.D. measurements also show this correlation although the logging period was limited. Signal to noise and receiver gain data indicate a weak signal; and as it was not possible to monitor this signal at Cape Parry it is assumed its range limit is somewhere around Longitude 132°W.

Port Clarence Reception

The east-west path from Port Clarence to the Beaufort Sea provides good skywave propagation conditions. A stable signal was received at all three monitoring sites.

Only one cycle skip occurred during the monitoring periods at Nerlerk and one at Cape Parry. The E.C.D. measurements show a distinct dip as the ionosphere rises at sunset. There is a slight recovery in E.C.D. during the night; then there is another distinct dip at sunrise as the ionosphere returns to daytime levels. This effect is seen best in the data collected at Tuktoyaktuk in Figure 7. Signal/noise and gain data indicate the Port Clarence signal was the strongest and most stable of the available skywave signals. The path from Port Clarence to the Beaufort Sea does not experience complete night effect during early August. Therefore, the change in ionospheric height will probably be less that for the other transmission paths monitored.

Skywave E.C.D. and T.O.A. Variation

As noted earlier, when the T.O.A. of a Loran-C transmission is delayed due to a rise in ionospheric height, the E.C.D. changes. Therefore, it may be possible to use E.C.D. measurements to predict change in T.O.A., assuming E.C.D. does not change due to other causes within the limited area of interest to the operator. The relationships of E.C.D. to changes in T.O.A. can be seen in Figure 32. If, an E.C.D. measurement could be used to predict change T.O.A. it would be independent of time and estimates of ionospheric height. Thus the use of skywave Loran-C position lines could be extended to the periods after sunset and before sunrise when the ionosphere is moving rapidly. A simple quadratic model, based change of E.C.D. per hour, gives the absolute value of change of T.O.A. for the next hour.

$$|\Delta T_{i+1}| = -0.15(\Delta C_i) + 0.38(\Delta C_i)^2$$

where ΔC_i = change of E.C.D. during the preceding hour

ΔT_{i+1} = predicted change of T.O.A. during the forthcoming hour.

This model was based on the nice data from the Port Clarence transmissions received at Tuktoyaktuk. When used to predict changes of T.O.A.s for other transmissions, it produces estimates with rms errors of about ±1 microsecond per hour. If E.C.D. measurements are to be used as predictions for T.O.A. changes, obviously a physical explanation will be required for the relationship. It may then be possible to derive a general and more accurate model.

Skywave Propagation Corrections

Several authors have reported on skywave propagation models that predict phase lags and their diurnal and seasonal variations. These works are reviewed in Reference 2. For low frequencies, 70 to 245 Khz, Belrose estimates that the effective heights of ionospheric reflection are about 90 km at night and 72 km by day, at ranges in the order of 1000 km (3). Davies (Ref. 2, p.418) gives the following equation to relate phase change to height change
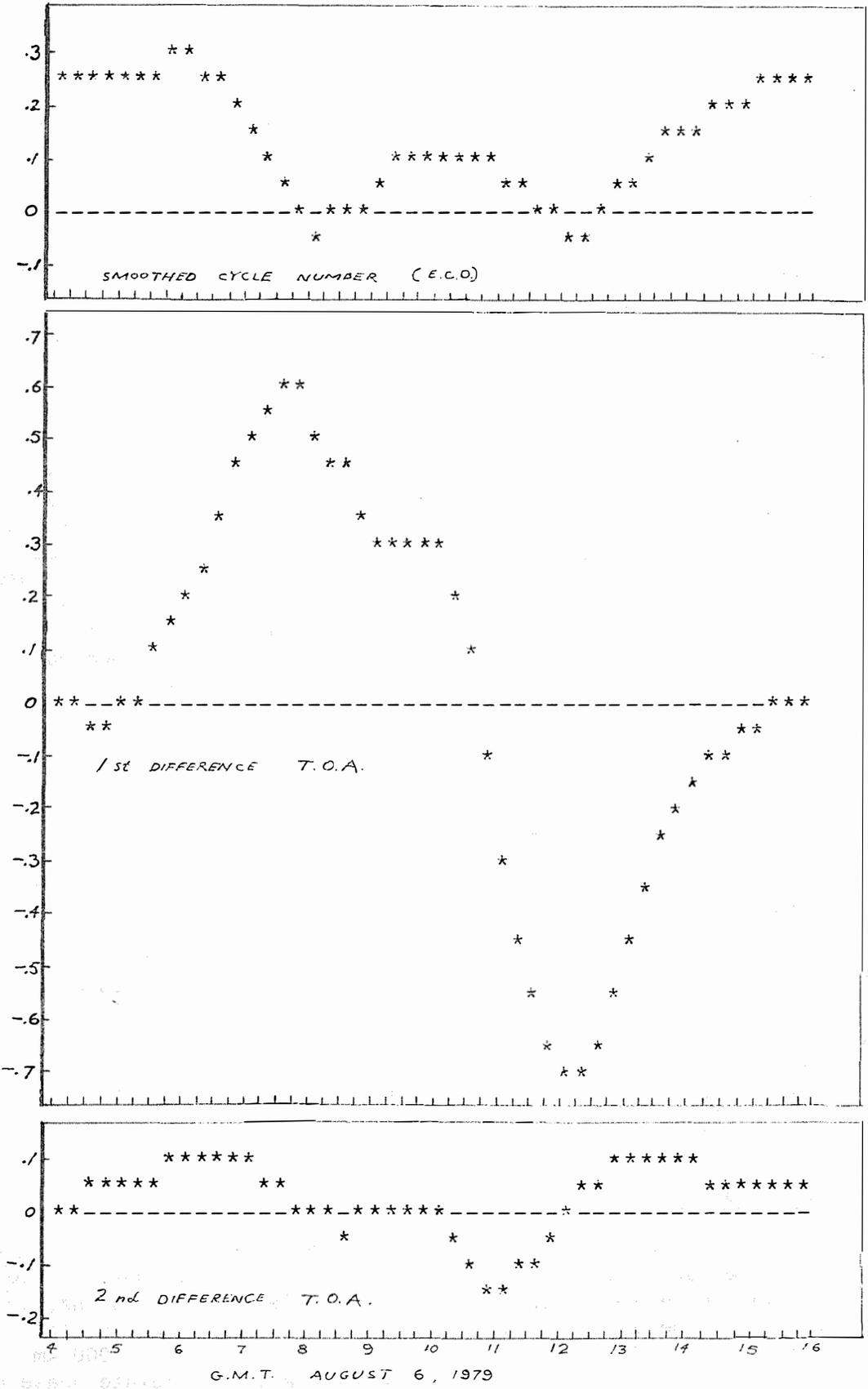
Figure 32

$$\Delta\phi = 2\pi d \left[\frac{h}{2a} + \frac{\lambda^2}{16h^2}\right] \frac{\Delta h}{h} \quad \text{radians}$$

where $\Delta\phi$ = phase change in radians

d = distance, transmitter to receiver (km)

h = mean ionospheric height (km)

Δh = height change (km)

λ = wavelength (km)

a = earth radius (6371 km)

With specific reference to Loran-C, Doherty in Reference 4 found phase changes equivalent to a 22 km apparent height change when working in the Bering Sea. Work in Norway, described in Reference 5 (Larsen and Thrane) reports that effective reflection heights for Loran-C pulses to be between 50 and 60 km during the day and about 83 km at night, for a range of 300 km. It appears that Larsen and Thrane calculate only a slight change in effective height with range.

Automated Offshore Navigation Inc., referred to by D. Livingston (Bedford Institute of Oceanography, Dartmouth, N.S.) in Reference 6, gives a geometric model to predict skywave phase delays.

$$\Delta d = \frac{91-59}{2} \; Sin\left\{2.\arctan\left[\frac{91+6371\cdot(1-Cos\;\theta)}{6371\cdot Sin\;\theta}\right]\right\}$$

where $\theta = 4.5 \cdot 10^{-3} \cdot D$

D = distance (km)

and Δd = delay in km due to ionospheric shift from 59 to 91 km.

The United States Defense Mapping Agency uses another formula to compute Loran-C skywave delays.

(a) $D' = \dfrac{N}{C}\left[2\sqrt{(h^2 + 4a(a+h))\;\sin^2\left(\dfrac{S}{4Na}\right)} - \dfrac{S}{N}\right]$ $0 \leqslant S \leqslant NS\;max$

(b) $D = D' - d$

where D = Total Skywave Delay in microseconds

D' = Principal part of the Nth hop skywave delay in microseconds

$d = -0.3 + 0.00208S$ $0 \leqslant S \leqslant NS\;max$

$d = -0.3 + 0.00208NS\;max$ $NS\;max < S$

N = Number of hops

C = Velocity of light = $299.792458 \times 10^{-3}$ km/microsecond

h = Apparent height of the ionosphere in kilometres
91 kilometres (night) and 73 kilometres (day)

a = Effective earth radius = 8490 kilometres

S = Groundwave path length in kilometres

S max $2\sqrt{2ah}$

NS max $N(2\sqrt{2ah})$

When NS max < S the value of D' becomes a constant formula (a) becomes:

$$D' = \frac{N}{C}\left[2\sqrt{h^2 + 4a(a + h)\sin^2\left(\frac{S\ max}{4Na}\right)} - \frac{S\ max}{N}\right]$$

Loran-C Diurnal T.O.A. Changes

The observed changes in Loran-C T.O.A.s due to change in ionospheric height are listed in Table 3.

Table 3

Loran-C Diurnal Phase Changes   (in microseconds)

At Tuktoyaktuk.

	7960X	7960Y	9990M	9990Y	9990Z
Obs. Night 1	11.7	11.8	8.8	8.0	13.1
" " 2	12.0	12.5	8.2	7.3	13.2
" " 3	11.0	9.3	8.6	6.7	12.9

At Nerlerk, CANMAR *Explorer 1.*

	7960X	7960Y	9990M	9990Y	9990Z
Obs. Night 1	13.2	7.8	-	7.8	13.6
" " 2	16.6	8.7	11.8	8.9	13.0
" " 3	16.2	9.2	13.6	10.4	11.7
Predicted (N.B.S.)	8.1	8.0	10.9	7.1	8.1
" (D.M.A.)	17.4	17.5	-	18.2	17.4

The two predictions for Nerlerk are based on the National Bureau of Standards (N.B.S.) (Reference 4) and the Defense Mapping Agency (D.M.A.) (see page 28) methods. Ionospheric heights are assumed to be 73 km in the day and 91 km at night, thus the change in height is 18 km. The observed shifts fall between the two predictions, but are generally closer to the N.B.S. method. Using average observed phase changes, the height changes can be computed from Reference 4, p.414.

$$\Delta h = \Delta\phi\ \frac{\lambda}{2\pi}\sqrt{\frac{d^2 + h^2}{2h}}$$

where Δh = change in ionospheric height (km)
          $\Delta\phi$ = observed phase shift (radians)
          h = mean height (km)

```
2d = ground distance (km)
 λ = wave length (km)
```

The changes, in the height of the ionosphere between day and night are given in Table 4.

Table 4

Estimated Change of ionsopheric Height (in km)

	7960X	7960Y	9990M	9990Y
At Tuktoyaktuk	17.4	16.1	17.7	10.2
At Nerlerk	24.0	13.2	26.5	12.4

The observations of diurnal phase shift show a wide variation in the changes in ionospheric heights.

An attempt was made at Cape Parry to measure the difference between the T.O.As of the ground and skywaves from Tok. The difference in T.O.A. from short period at the middle of the night was 51.5 ± 1.1 microseconds. The difference, predicted by the D.M.A. method, is 54.1 microseconds.

As can be seen from all the T.O.A. data collected, the ionosphere is only stable during the summer night for a very short period. The ionosphere starts to rise immediately after sunset at the receiver. As all the transmitters used were to the west of the test area, the signals do not stabilize until well after local sunrise at the receiver. There are only 14 hours of stable signal availability, during August, which is the peak of the operational season in the Beaufort Sea. This time, of course, decreases as winter approaches.

Loran-C Position Lines

Two types of position lines can be generated by a Loran-C chain. T.O.A.'s can be used as ranges from the transmitters if a precise frequency standard is available, and if synchronization corrections are applied to the T.O.A.'s to reduce them to ranges. The observed stability (daytime) of the T.O.A.'s from the transmissions available in the Beaufort Sea is listed in Table 5.

Table 5

Daytime T.O.A. Stability

(Standard deviation in microseconds)

	Groundwave	Skywave				
	7960-M	7960-X	7960-Y	9990-M	9990-Y	9990-Z
At Tuktoyaktuk	0.05	0.27	0.32	0.42	0.44	0.37
At Nerlerk (*Expl. 1*)	0.06	0.56	0.35	0.25	0.44	0.92
At Cape Parry	0.03	0.30	0.56	-	0.28	0.29

As the nights in August are so short the ionosphere does not settle at a higher altitude for any length of time. Therefore, it is not possible to estimate accurately the stability of T.O.A.'s at night. The instability for T.O.A.'s during the brief period when the ionosphere is at its highest level appears to be about two to three times greater than that observed during the day.

The correlations between T.O.A. errors appear to be relatively high. Typical observed correlations are tabulated in Table 6 for daylight hours.

Table 6

T.O.A. Correlations

	7960M	X	Y
7960M	1	0.40	0.13
X	0.40	1	0.73
Y	0.13	0.73	1

	9990M	Y	Z
9990M	1	0.93	0.99
Y	0.93	1	0.95
Z	0.99	0.95	1

The effect of skywaves on the T.O.A. errors is clearly seen in the above table.

In daytime, a fix using Loran-C T.O.A.'s (precisely synchronized) should have a radial error of ±500 m (1 sigma confidence level) or less, depending on the number of position lines used.

Four Loran-C time differences are available in the western Beaufort Sea. The estimates of the errors associated with these hyperbolic position lines are listed in Table 7. The data sets used to generate Table 7 are independent of those used for Tables 5 and 6.

Table 7

Daytime T.D. Stability
(Standard deviation in microseconds)

	Tuktoyaktuk	Nerlerk	Cape Parry
7960X	0.27	0.52	0.29
y	0.14	0.35	0.24
9990Y	0.16	0.28	-
Z	0.27	0.33	-

So, if accurate skywave corrections were possible, a Loran-C hyperbolic fix, taken about 60 nm north of Tuktoyaktuk should have an accuracy of ±3 km for the Gulf of Alaska Chain (7960) and ±1.5 km from the Bering Sea Chain (9990). Due to uncertainties in skywave measurements the above accuracy

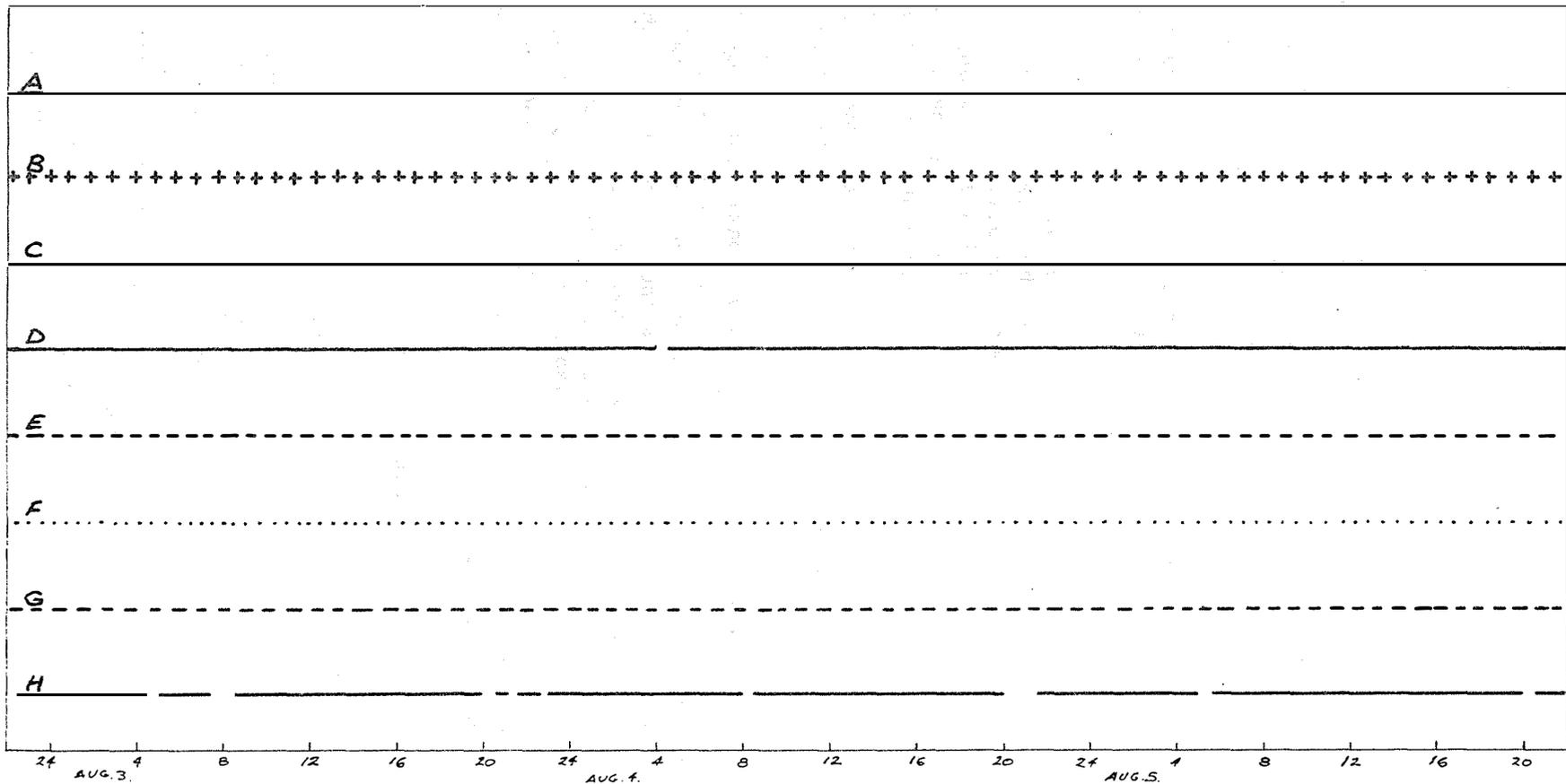estimates should probably be doubled.

Omega Reception

Reference 7 (Vass) predicts that Omega stations A (Norway), C (Hawaii), D (North Dakota) and H (Japan) will be received in the Beaufort Sea, during summer daylight with adequate signal-to-noise ratio and insignificant modal interference. Figures 28 and 29 show the Omega stations used by the MX1105 system, and those with low signal strength, at our two monitor sites at Tuktoyaktuk and Nerlerk (*Explorer 1*). These data confirm the predictions, except that H (Japan) at Tuktoyaktuk was not used continuously as its signal-to-noise ratio intermittently dropped below that acceptable for fixing. The MX1105 uses a pseudo-ranging technique for positioning that requires signals from at least three stations. This number of required signals was available throughout the monitoring period at both sites with the exception of one overnight period at Nerlerk.

On this occasion the Omega section of the MX1105 system did, what can best be described as, "latch-up". After two hours the receiver re-synchronized on Omega stations C (Hawaii), D (North Dakota), and G (Trinidad), but exhibited low signal-to-noise ratios for A (Norway) and H (Japan). During this period poor positions were produced by the system. Five hours later the MX1105 "latched-up" again, but after a further two hours re-synchronized on the usual four stations A, C, D, H. It is difficult to find the causes for this one failure of the MX1105 system. This failure can probably be attributed to external reception conditions rather than an intermittent receiver fault.

United States Coast Guard, through the Canadian Coast Guard made available some data from their Omega monitor station at Inuvik Airport. Regrettably the monitor was not working when our measurements were made in the Beaufort Sea. However, the monitor data from Inuvik, covering a short period from Aug. 21st to Aug. 23rd confirmed to some extent our data from Tuktoyaktuk and *Explorer 1*. During this short period the monitor tracked Omega station A (Norway), C (Hawaii) and H (Japan) reliably. Omega station D (North Dakota) was not tracked during this period as it was down for maintenance. Table 8 gives the range of signal-to-noise ratio and number of cycle skips experienced during this short period.

Table 8

Omega Monitor - Inuvik (34 hrs only)
Signal-to-Noise Range (db)

	High	Low	# of times cycle skips occurred
A	0	-70 approx.	2
C	3	-33	1
D	not operational	-----------------------------	
H	-5	-70 approx.	5

A

B ++

C

D

E -------------------------------

F ....

G -------------------------------

H

24 AUG.3. 4   8   12   16   20   24 AUG.4. 4   8   12   16   20   24 AUG.5. 4   8   12   16   20

─────────────   STATIONS USED.

─ ─ ─ ─ ─ ─ ─   STATIONS WITH LOW SIGNAL.

+++++++++   STATIONS WITH LOW SIGNAL AND MODAL INTERFERENCE.

....   STATION USED FOR CALIBRATION

OMEGA RECEPTION STATUS ─ TUKTOYAKTUK.

Figure 28

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OMEGA RECEPTION STATUS — NERLERK
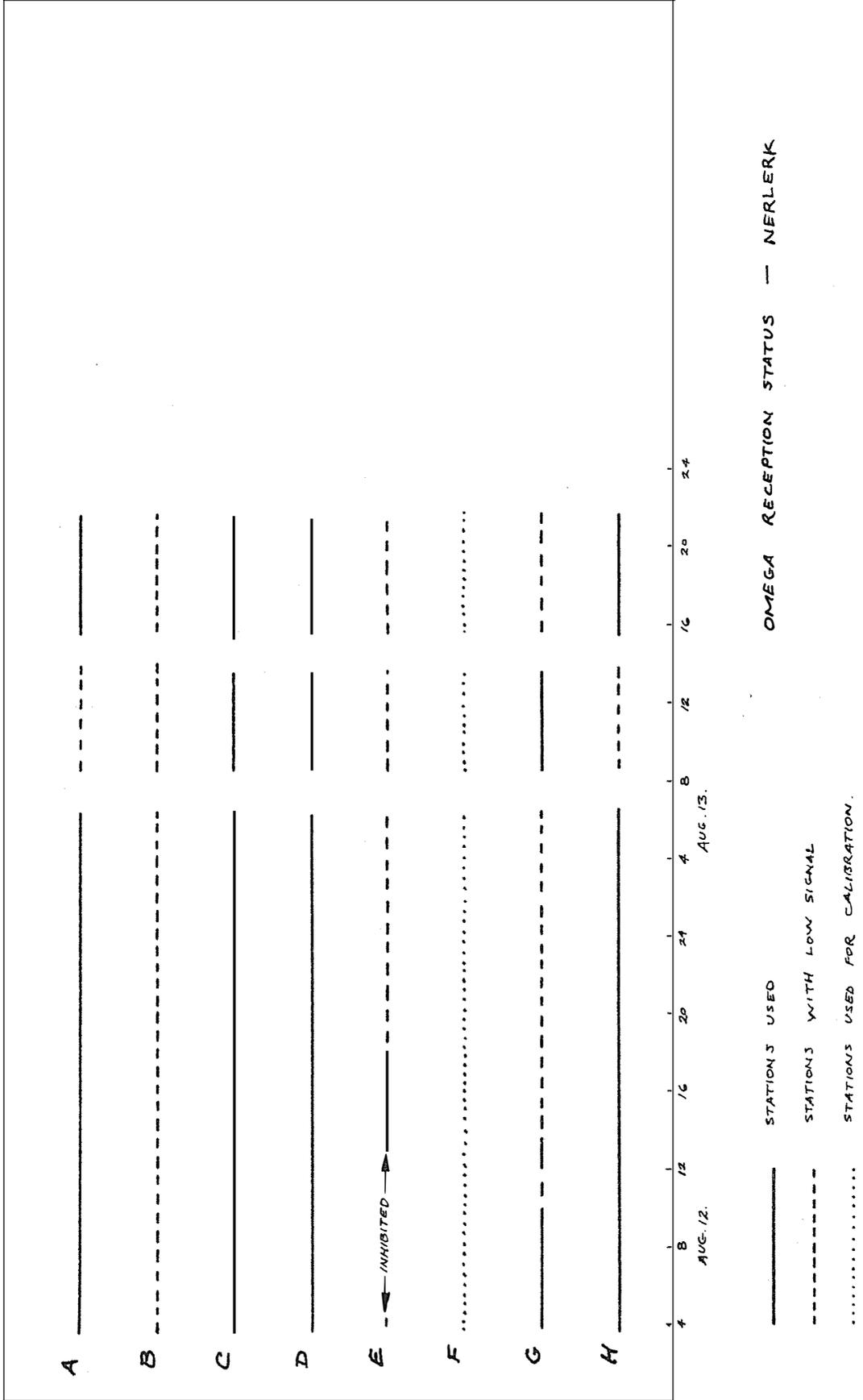
Figure 29

Integrated Satnav/Omega Positions

The MX1105 Satellite/Omega navigator produces four estimates of position (1) Single Channel Satnav fixes, (2) Omega stand-alone fixes (3) Integrated Satnav and ships gyro and speed log positions (Nav. 1) and (4) integrated Satnav and Omega positions (Nav. 2). All position data were collected with the receiver stationary, therefore Nav. 1 positions are not relevant to our measurements. The estimates of the errors associated with the other types of position are given in Tables 9 and 10 for Tuktoyaktuk and *Explorer 1* respectively.

Table 9

Tuktoyaktuk - Overall Omega/Satnav Accuracies from
MX1105 Receiver

Standard Deviations in metres

	Lat.	Long.	Radial	Correlation
Satnav.	196	146	244	-0.13
Omega	749	1446	1628	+0.83
Integrated	556	388	678	+0.26

Table 10

Nerlerk - CANMAR *Explorer 1* - Overall Omega/Satnav Accuracies
from MX1105 Receiver

Standard Deviations in metres

	Lat.	Long.	Radial	Correlation
Satnav.	65	112	130	+0.08
Omega	777	907	1194	-0.44
Integrated	301	489	574	-0.16

Also, as the measurements were made with the MX1105 stationary, additional errors in Satnav positions are to be expected on a moving ship. These errors in the Satnav position will propagate through to increase the errors in both the integrated and Omega positions. However, if both ship's log and gyro, and Omega are available for velocity input to the Satnav fixes then this increase in error should not be excessive.

Figure 30 shows the stability of the Omega and integrated positions at Tuktoyaktuk by their latitude and longitude co-ordinates. The initial variations, seen at the left of the graphs show the settling effect immediately after startup of the equipment. Diurnal variations in the accuracy of the Omega signals are also apparent. These variations, due to changing day and night propagation conditions are not carried through, to any great extent, to the integrated (Nav. 2) positions. These diurnal changes in error, and the lack of them for the integrated position, are tabulated in Table 11. Figure 31 shows the stability of the co-ordinates produced by

the MX1105 when used as a stand-alone Omega receiver. Two features are
discernible from these graphs (1) the effect of the smoothing introduced by
the integration algorithm and (2) the constant offset of about 2 minutes of
latitude and 2 minutes of longitude, when compared to the true position, due
probably to inaccuracies in the Omega propagation models used. The observed
errors and constant offsets for the stand-alone Omega data are given in
Table 12.

Table 11

Diurnal Variations in Accuracies from MX1105 Receiver

Standard Deviation in metres

Day	Lat.	Long.	Radial	
			Omega - Night	
Aug.3	1321	2602	2918	(Start up)
4	663	1388	1538	
5	580	1260	1387	
R.M.S.			1464	(Start up excluded)
			Integrated - Night	
3	1046	318	1093	(Start up)
4	311	213	377	
5	262	482	548	
R.M.S.			470	(Start up excluded)
			Omega - Day	
3	233	371	438	
4	432	566	712	
5	378	464	598	
R.M.S.			593	
			Integrated - Day	
3	125	329	352	
4	344	451	567	
5	364	344	500	
R.M.S.			481	
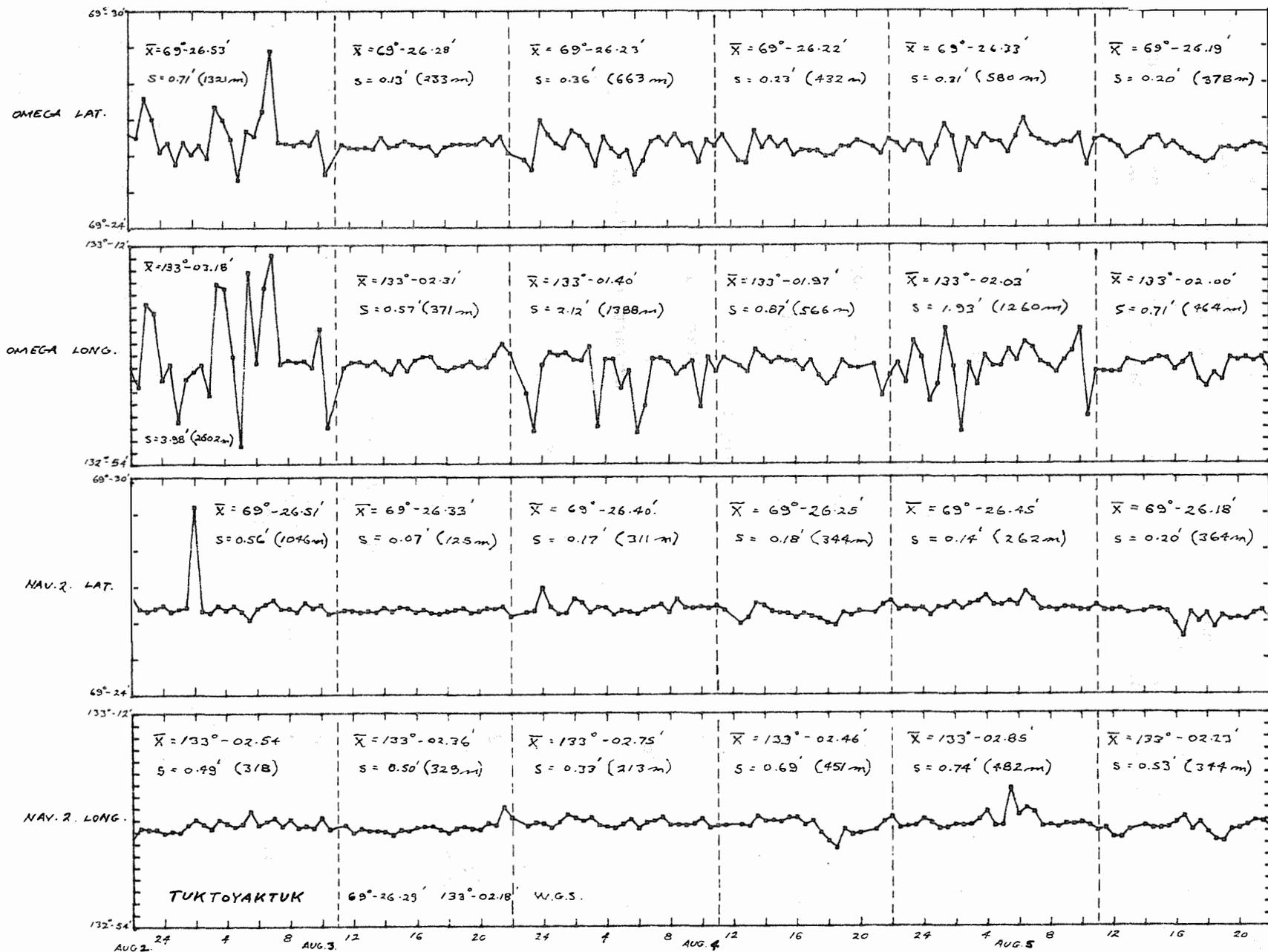
Figure 30
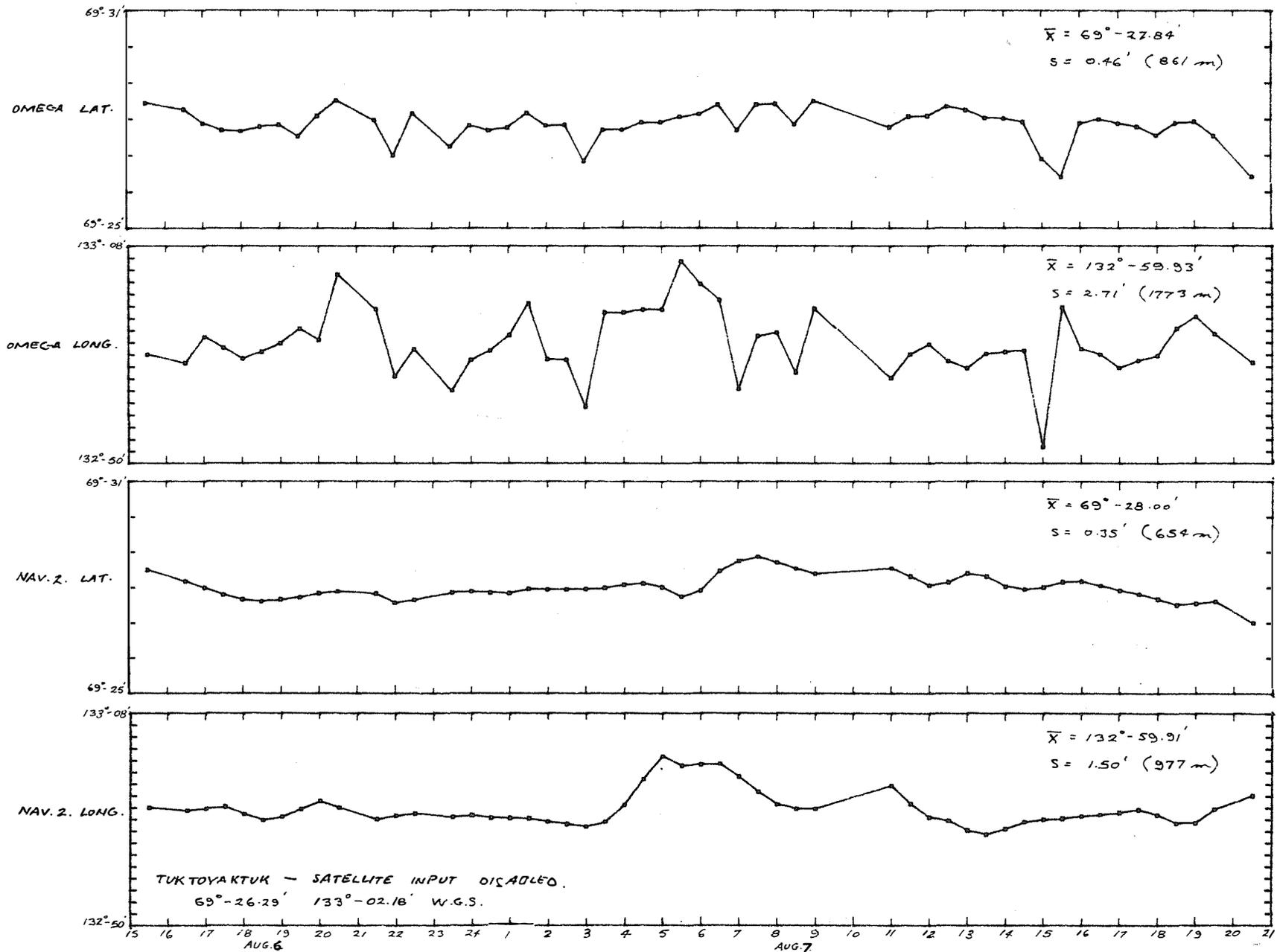
Figure 31

Table 12

Tuktoyaktuk - Stand-Alone Omega Accuracies
MX1105 Receiver

(metres)

	Lat.	Long.	Radial
Omega			
Offset	2870	1459	3220 (1.7 nm)
St. Dev.	861	1773	1971
Smoothed			
Offset	3166	1472	3491 (1.9 nm)
St. Dev.	654	977	1175

Conclusions

1. Loran-C Reception

The Gulf of Alaska (7960) and Bering Sea (9990) Loran-C chains can be received fairly reliably west of Tuktoyaktuk (Longitude 132°W) in the Beaufort Sea. However, only one transmission, that from Tok (7960 - Master) can be received on groundwave. Skywave signals are available from the other Alaska stations. As two chains are available in the western Beaufort Sea, operators in this area would find it advantageous to use receivers that can track both chains simultaneously.

2. Loran-C Chart Lattices

Two lattice overlays have been prepared for Chart 7650 (scale 1:500,000). The overlay for the Gulf of Alaska (7960) lattice shows skywave correction and combined skywave/groundwave corrections. The combined corrections assume an overland conductivity for the Tok transmission of 0.001 mhos/metre. The overlay for the Berin Sea (9990) lattice shows skywave corrections only. In both cases, skywave corrections were made using the U.S. Defense Mapping Agency method, assuming ionospheric heights of 73 km (day) and 91 km (night).

3. Loran-C Accuracies

The hyperbolic fix geometry for both the chains available in the Beaufort Sea is weak. The instability of the ionosphere, even during the day, produces uncertainties in skywave corrections. Correct cycle identification is also a problem when using skywaves. Therefore, fixes produced by time differences from the Alaska chains (7960 and 9990) are likely to have errors, at the one sigma level, of ±6 km, even during the day.

Using Loran-C in the passive ranging mode, assuming frequent satellite fixes, it should be possible to obtain continuous positioning with errors at

the one sigma level of ±500 m during the fourteen hour long summer day. Position errors have not been estimated for Loran-C fixes produced by time differences, or by ranges, obtained during the night.

4. Relationship of Skywave T.O.A. and E.C.D.

The change in Loran-C skywave transmission T.O.A. due to shift in ionospheric height appears to be reflected by a change in E.C.D. If applications for Loran-C skywave transmissions are found in the Canadian Arctic, it may be possible to use the relationship between E.C.D. and change of T.O.A. to predict more accurately skywave corrections for real-time use.

5. Omega Reception

The availability of Omega signals in the Beaufort Sea appears to follow the predictions given in the literature on Omega reception. However, there do appear to be interruptions to continuous reception that decrease the potential usefulness of this system in the Beaufort Sea. In addition, to sudden ionospheric disturbances and polar cap anomalies, Omega reception may also be effected by local weather conditions.

6. Omega Accuracies

The MX1105 Satnav/Omega receiver produces integrated fixes with errors, at the one sigma level, of less than ±500 m when stationary. There is no statistically detectable change in accuracies between day and night. The stand-alone Omega feature on the MX1105 produced fixes with constant offsets of 3.5 km and random errors of ±2 km. As the MX1105 receiver produces positions from several sources, it appears to overcome many of the problems associated with Omega use in high latitudes and the errors associated with these positions are in the same order as those expected from differential Omega.

7. Beaufort Sea Positioning

As the existence of submarine pingoes adds to the usual hazards of Arctic navigation in the Beaufort Sea, and deep draught shipping traffic is expected to increase, there is a need for a reliable general purpose radio navigation aid in the area. This need could be met by differential Omega, or by a system such as the MX1105, if Omega reception can be proved reliable.

In this regard, a detailed analysis of data from existing Omega monitors in the Canadian Arctic, especially at Inuvik, would be extremely useful.

An Accufix-type Loran-C chain may also meet the need for reliable and accurate navigational coverage of the Beaufort Sea. Such a Loran-C type system would also meet some resource exploration company and government survey requirements. However, to use a Loran-C system efficiently, several unknown parameters, such as conductivities over permafrost, conductivities over mixtures of ice and brackish water, transmitted power required for reliable signal tracking and cycle identification, and seasonal variations in these parameters, should be defined by further field work.

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Appendix 1

Detailed Position Data from the MX1105

Satnav/Omega Receiver

Figure 1

TUKTOYAKTUK   69°-26.25'   133°-02.18' W.G.S.

MEAN LONGITUDE   133°-02.18'
STANDARD DEVIATION   0.22' (146 m)

LONG.

TUK.

SATELLITE FIX. (LONGITUDE)
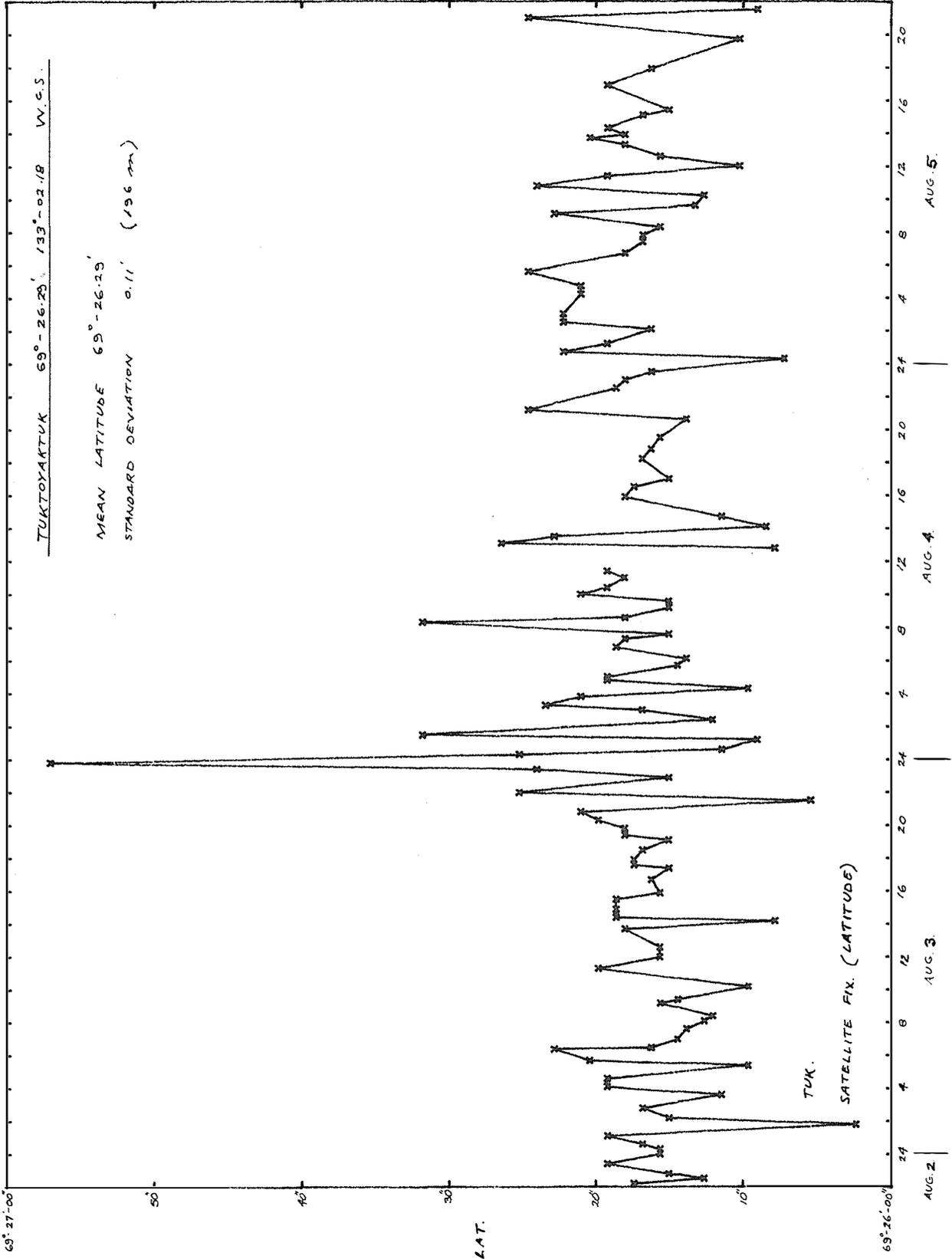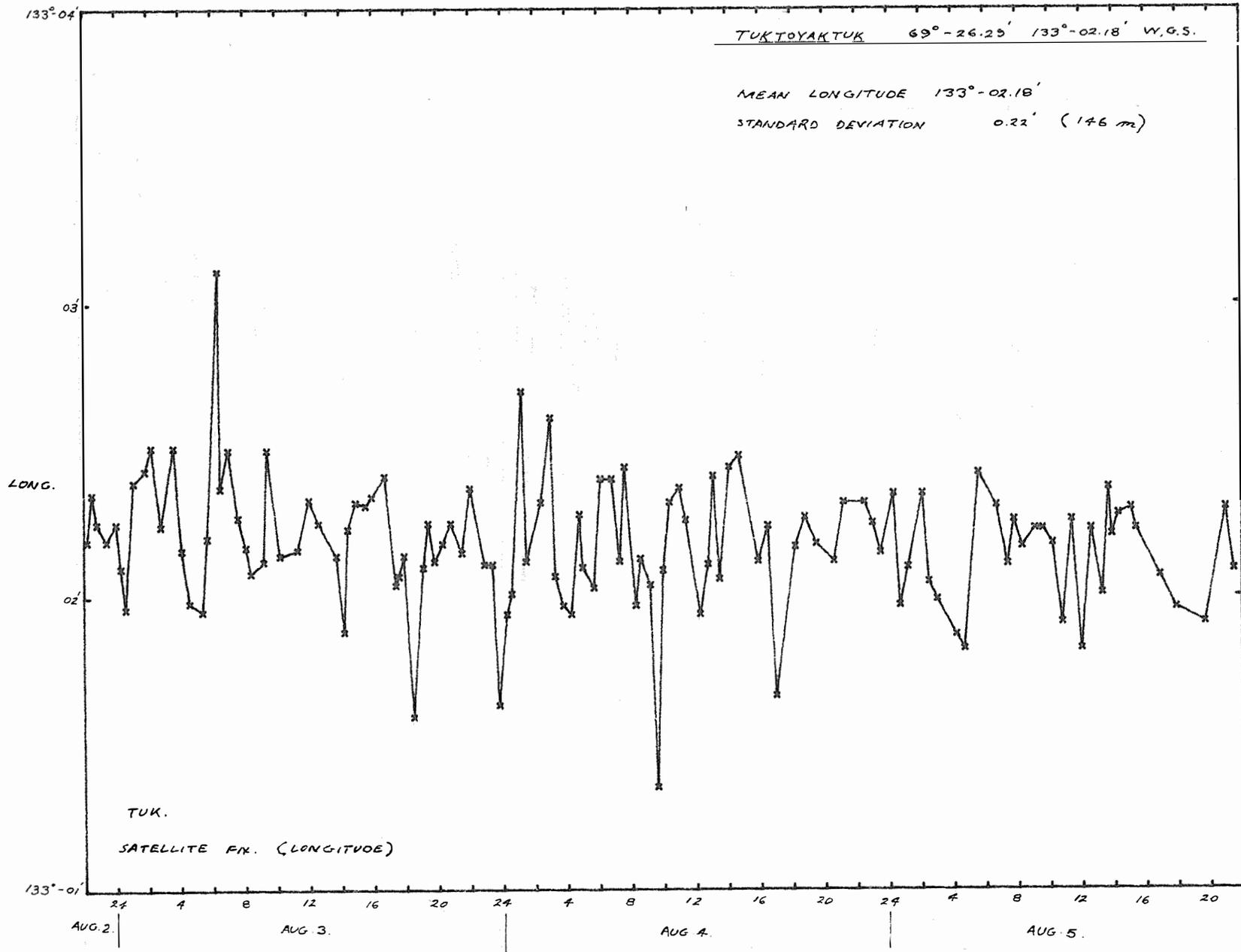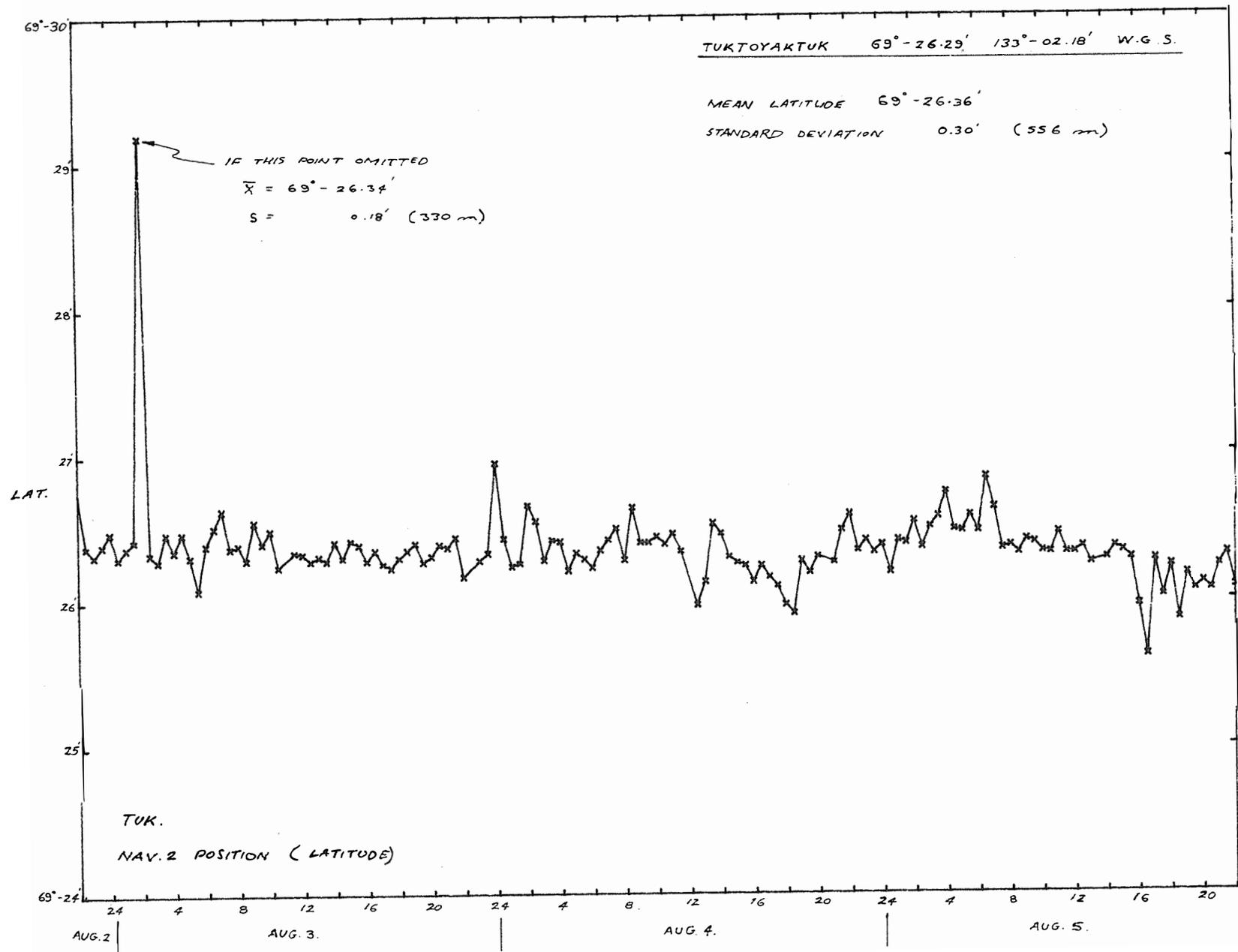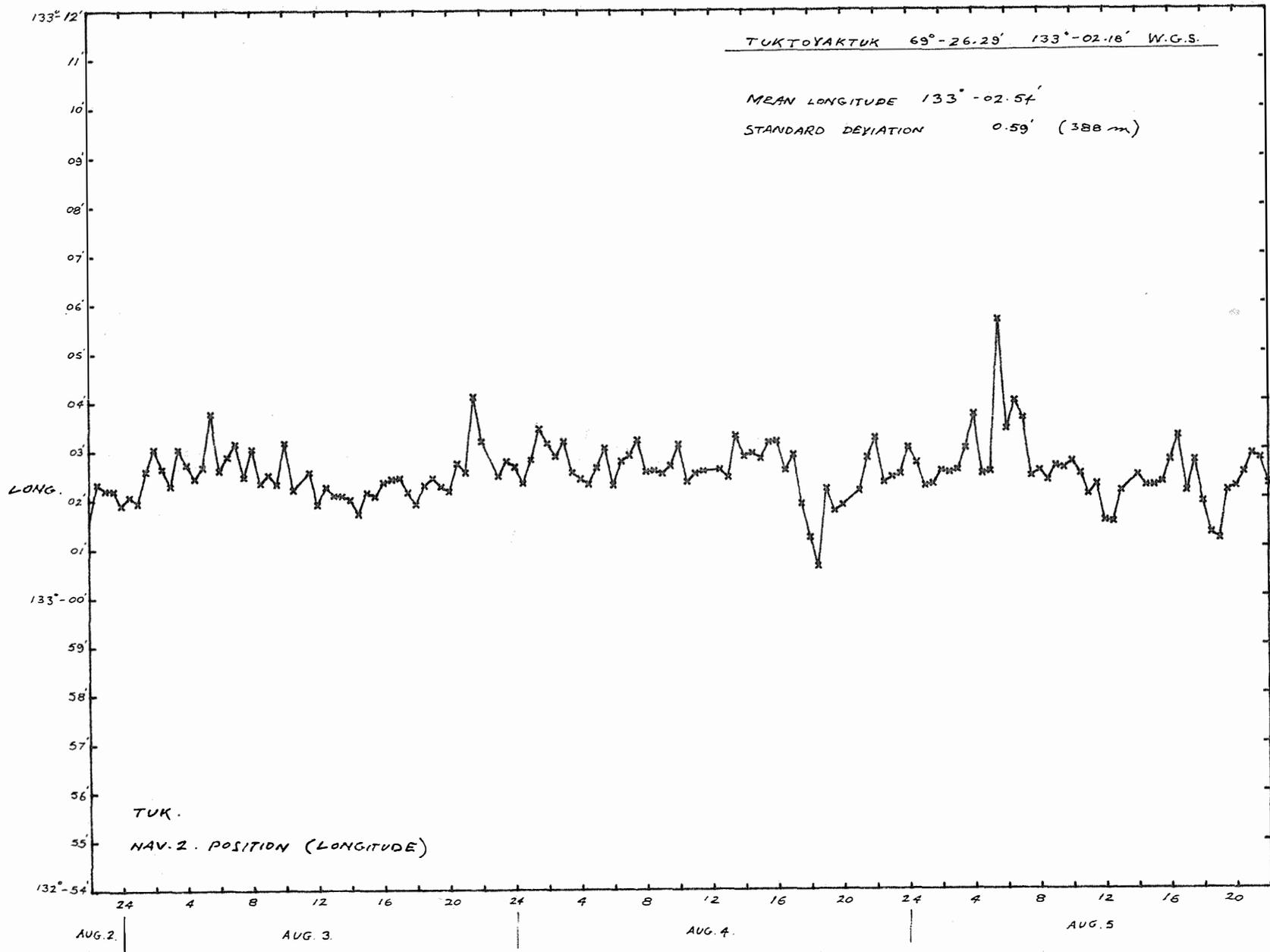
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Figure 3

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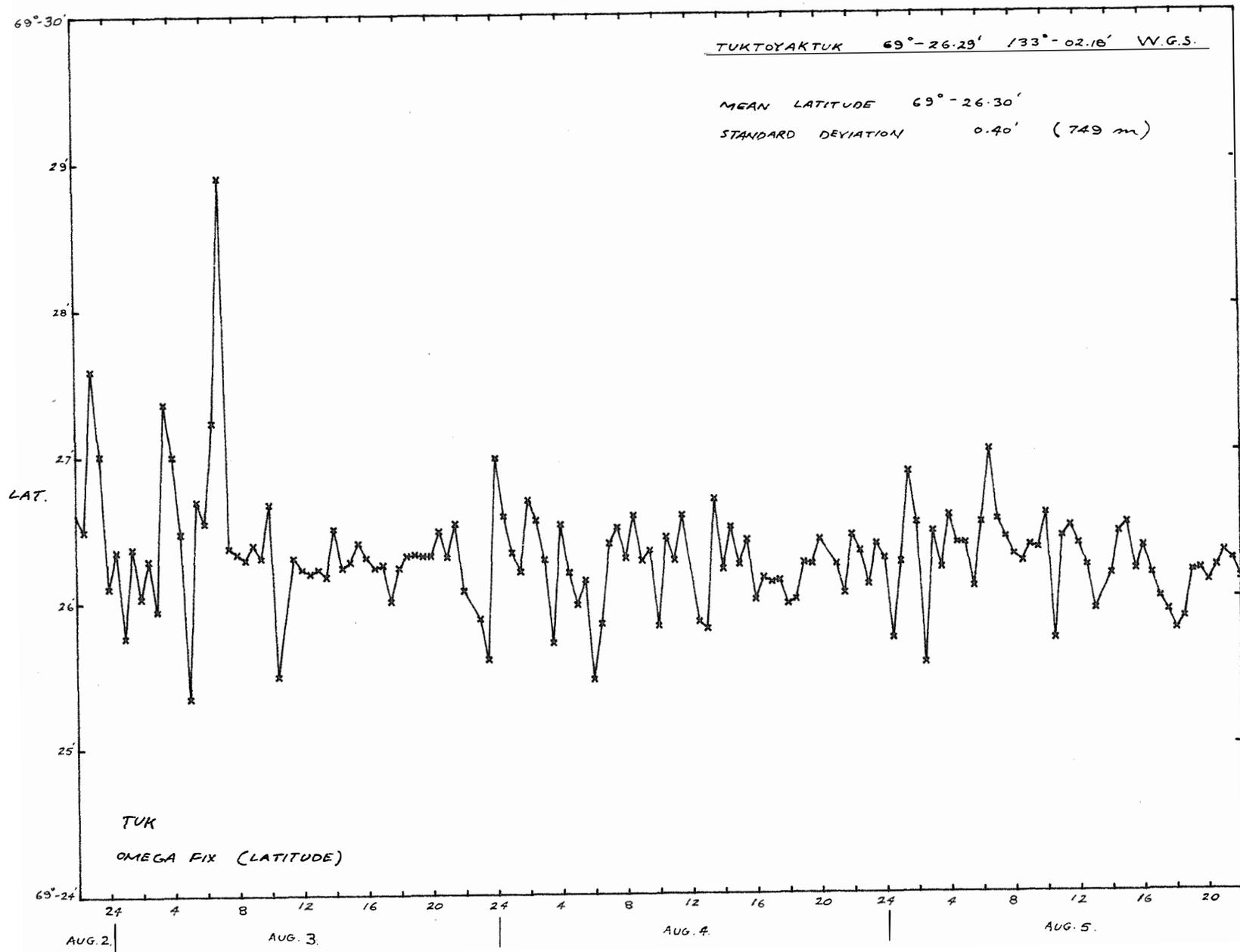
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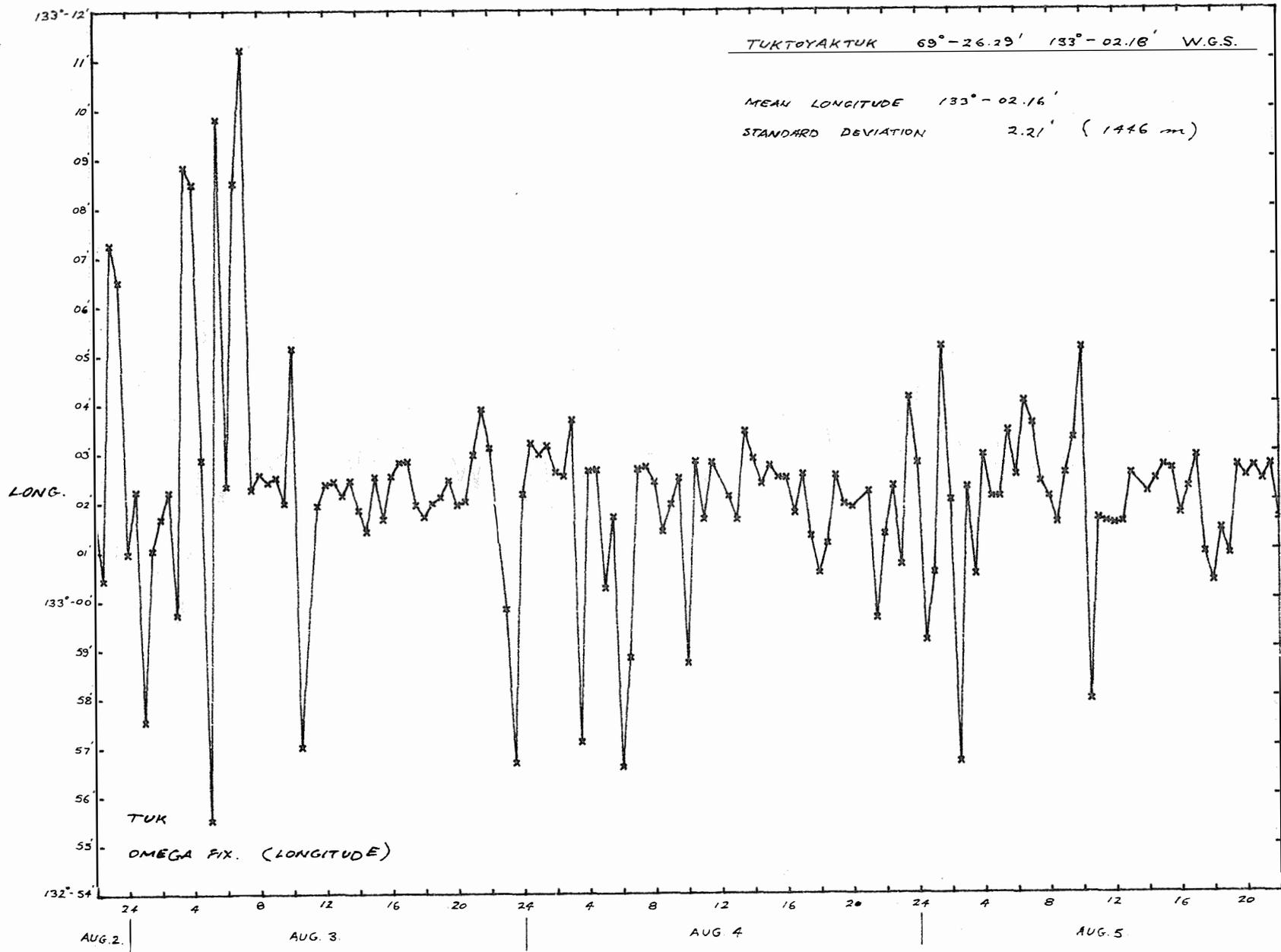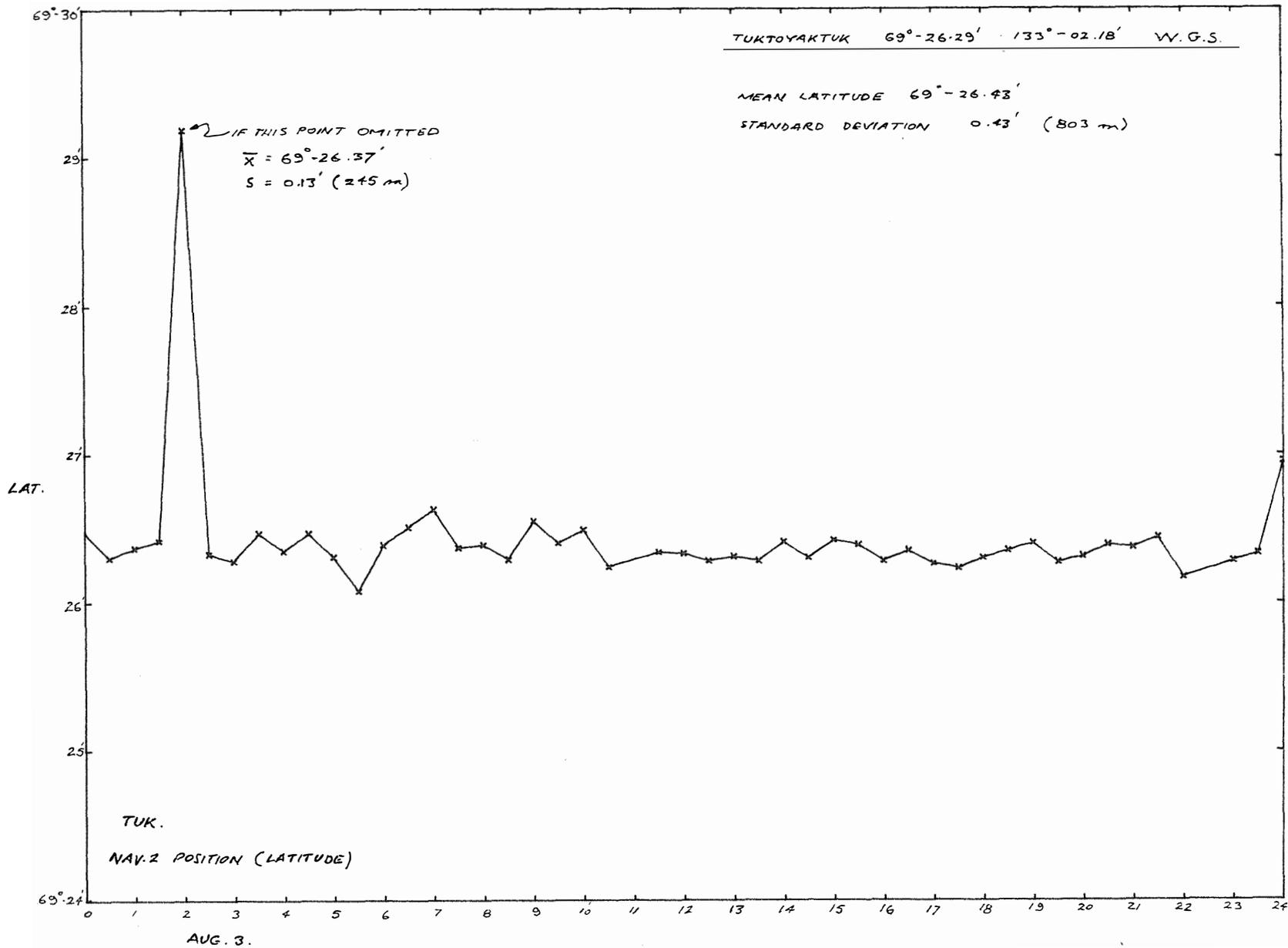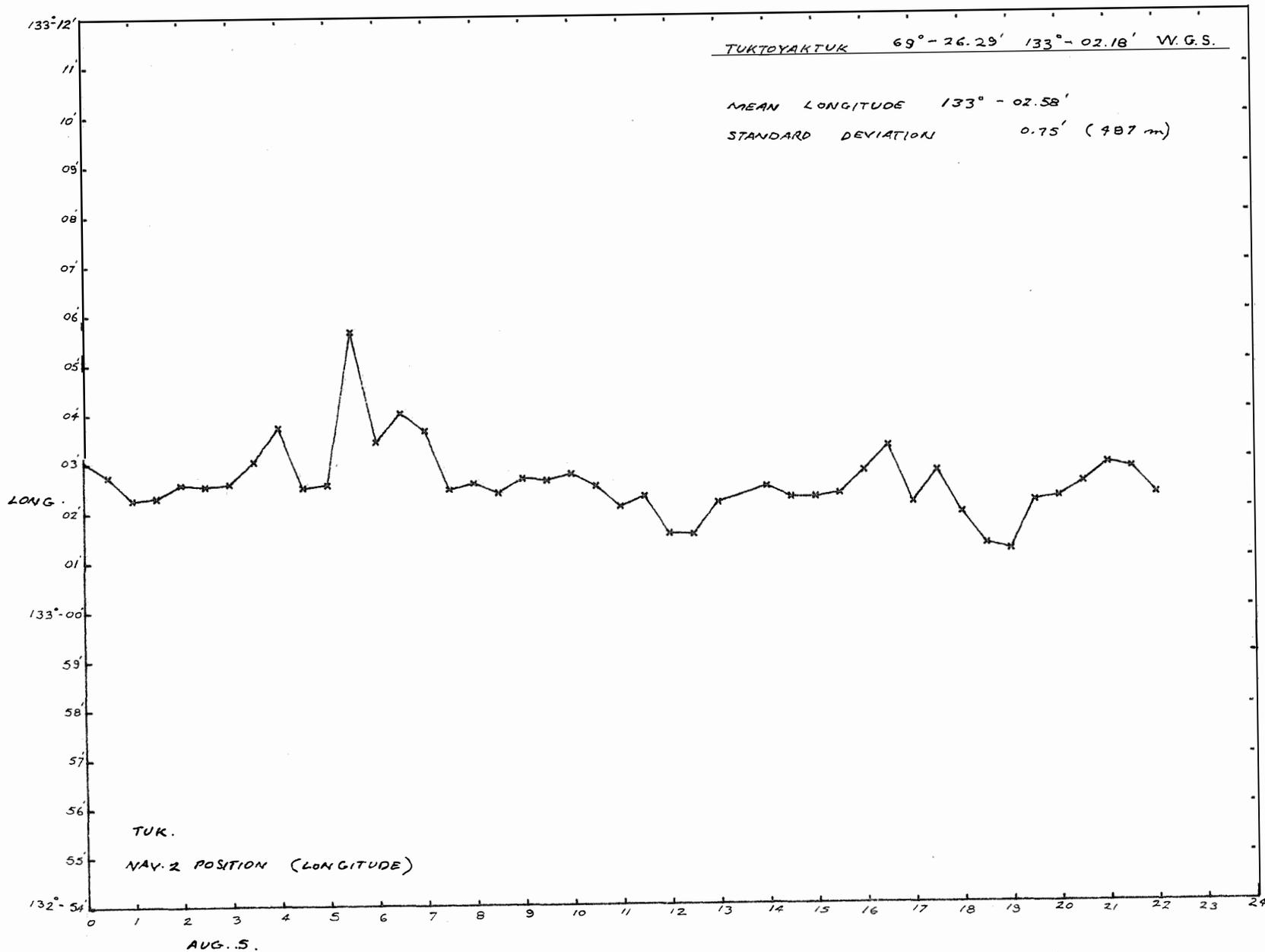
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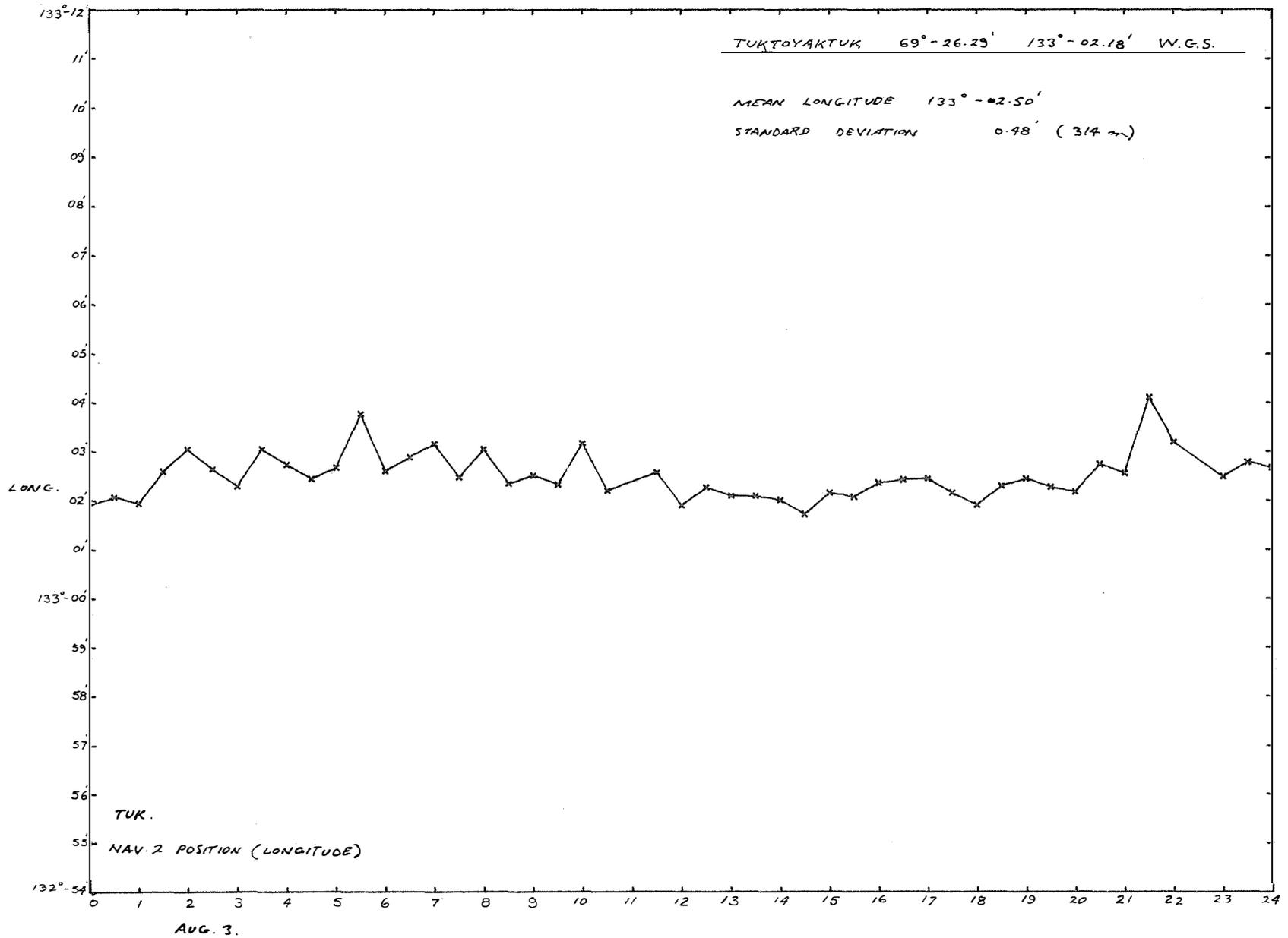
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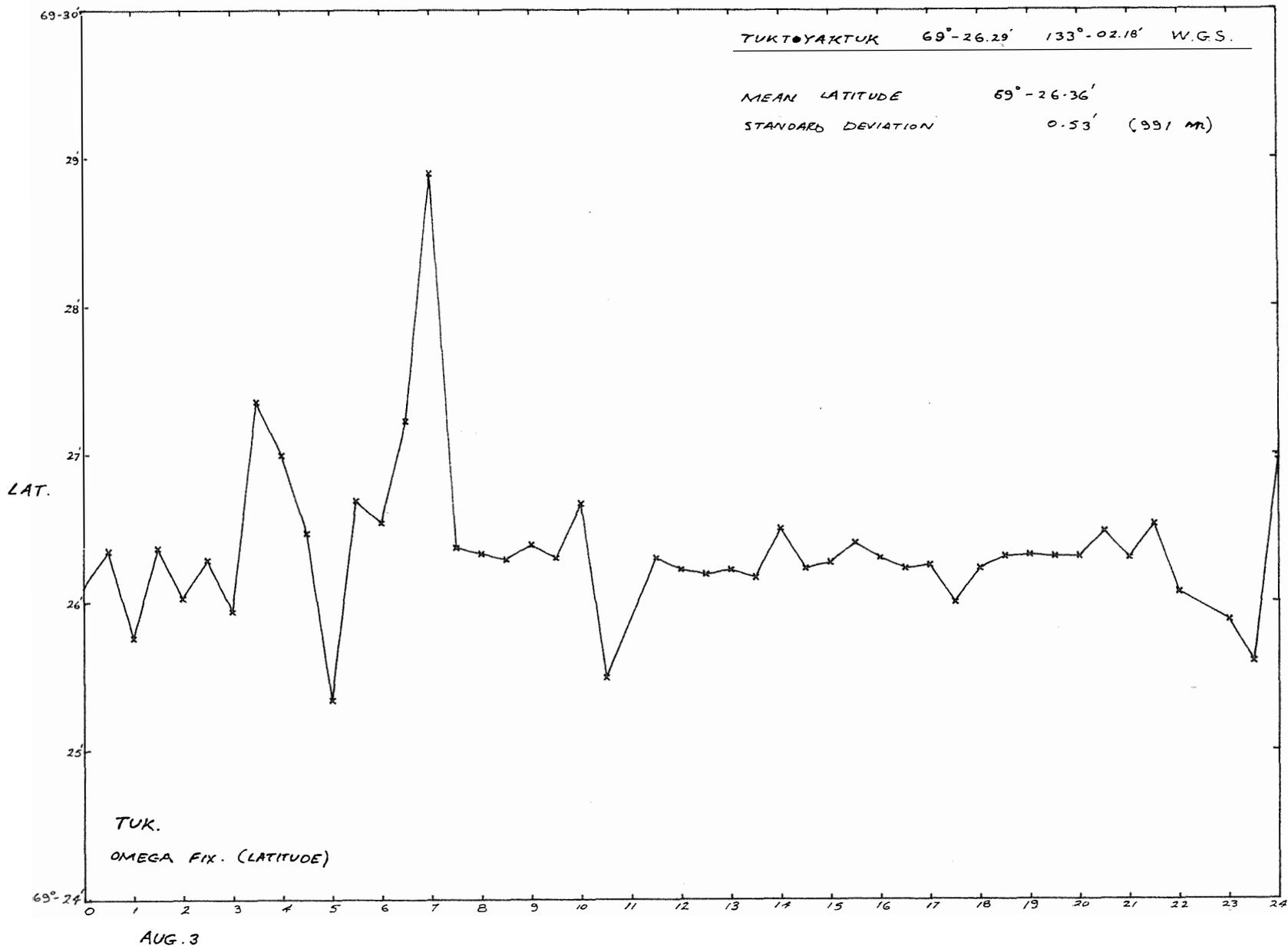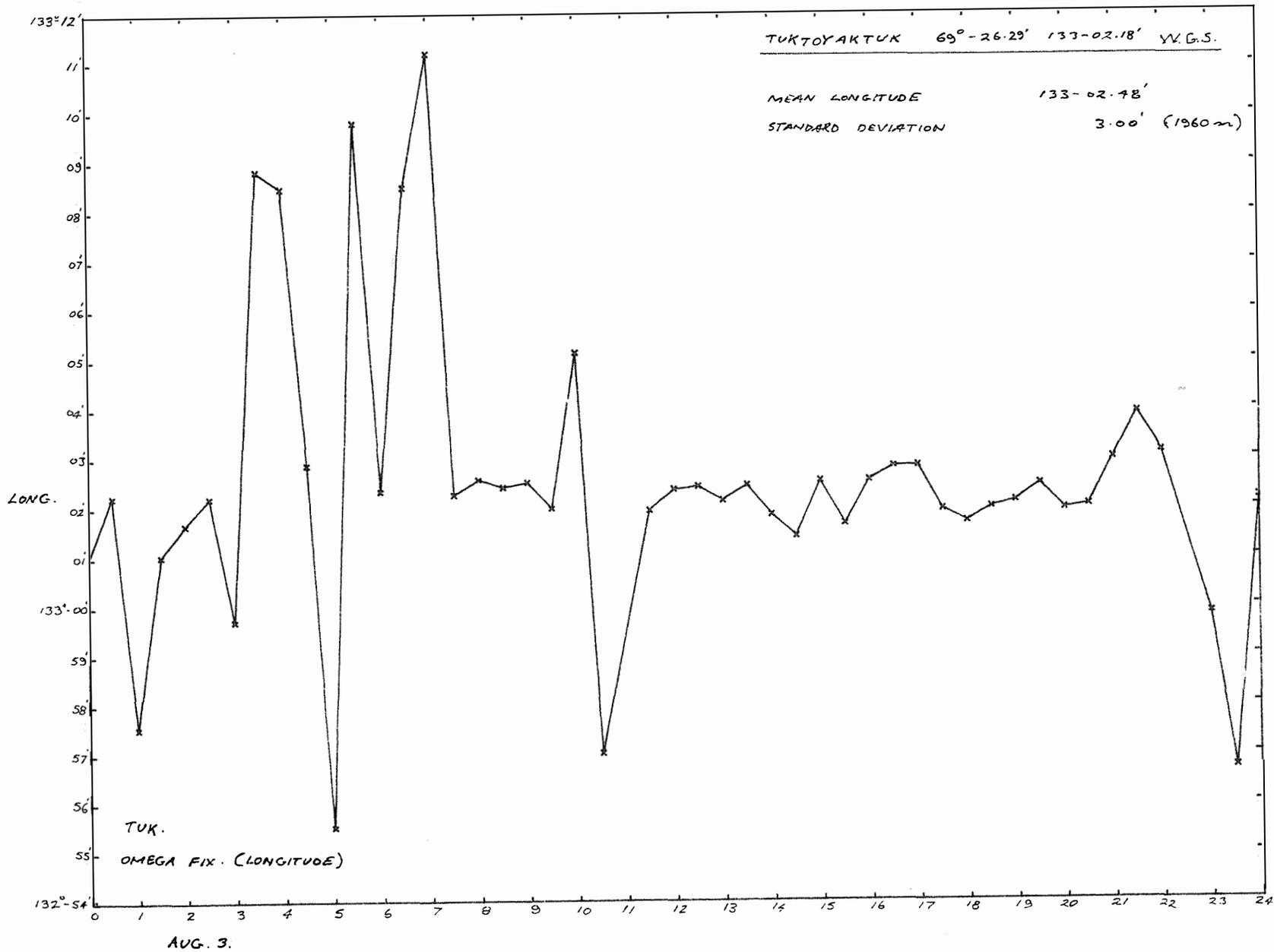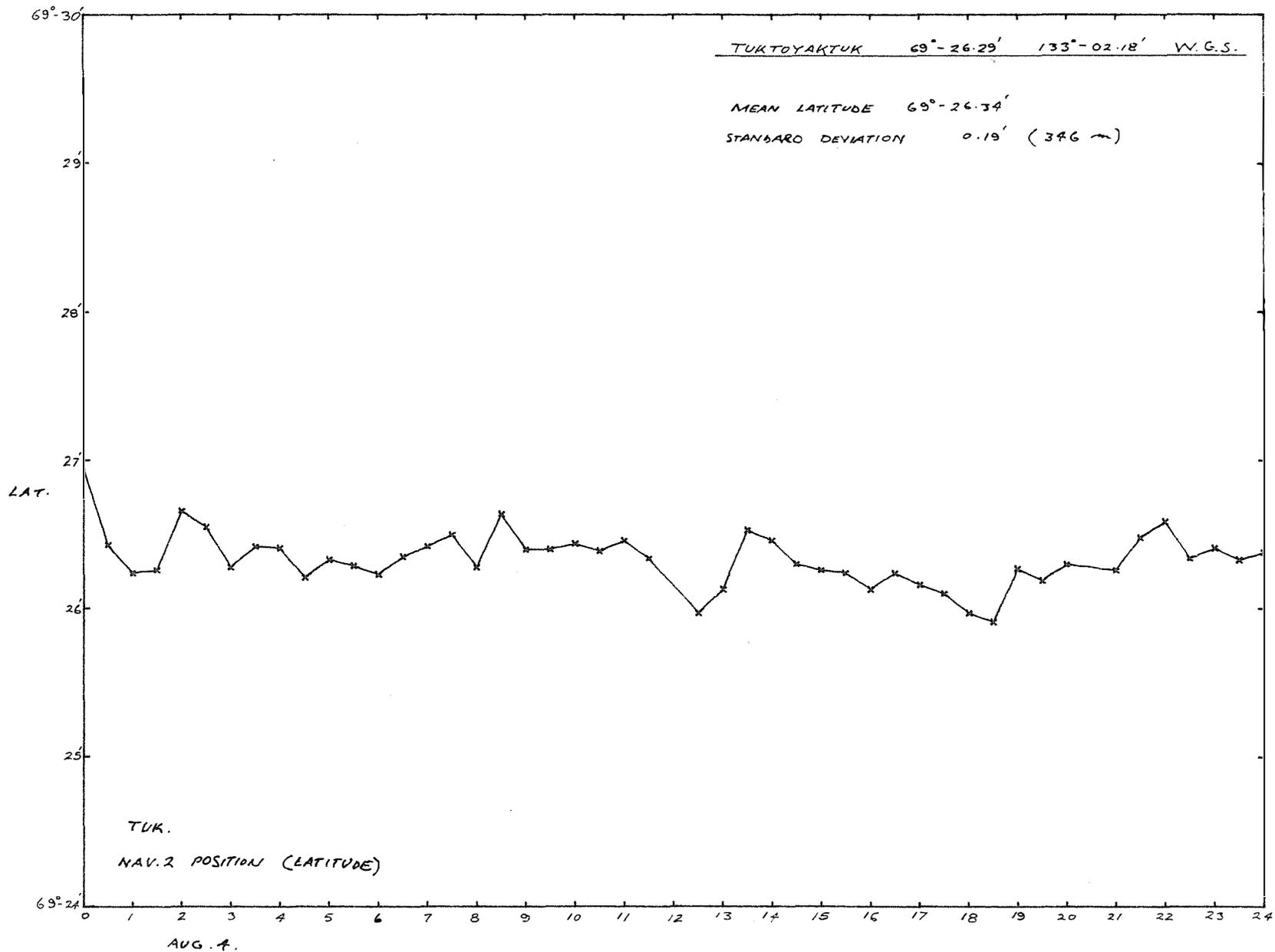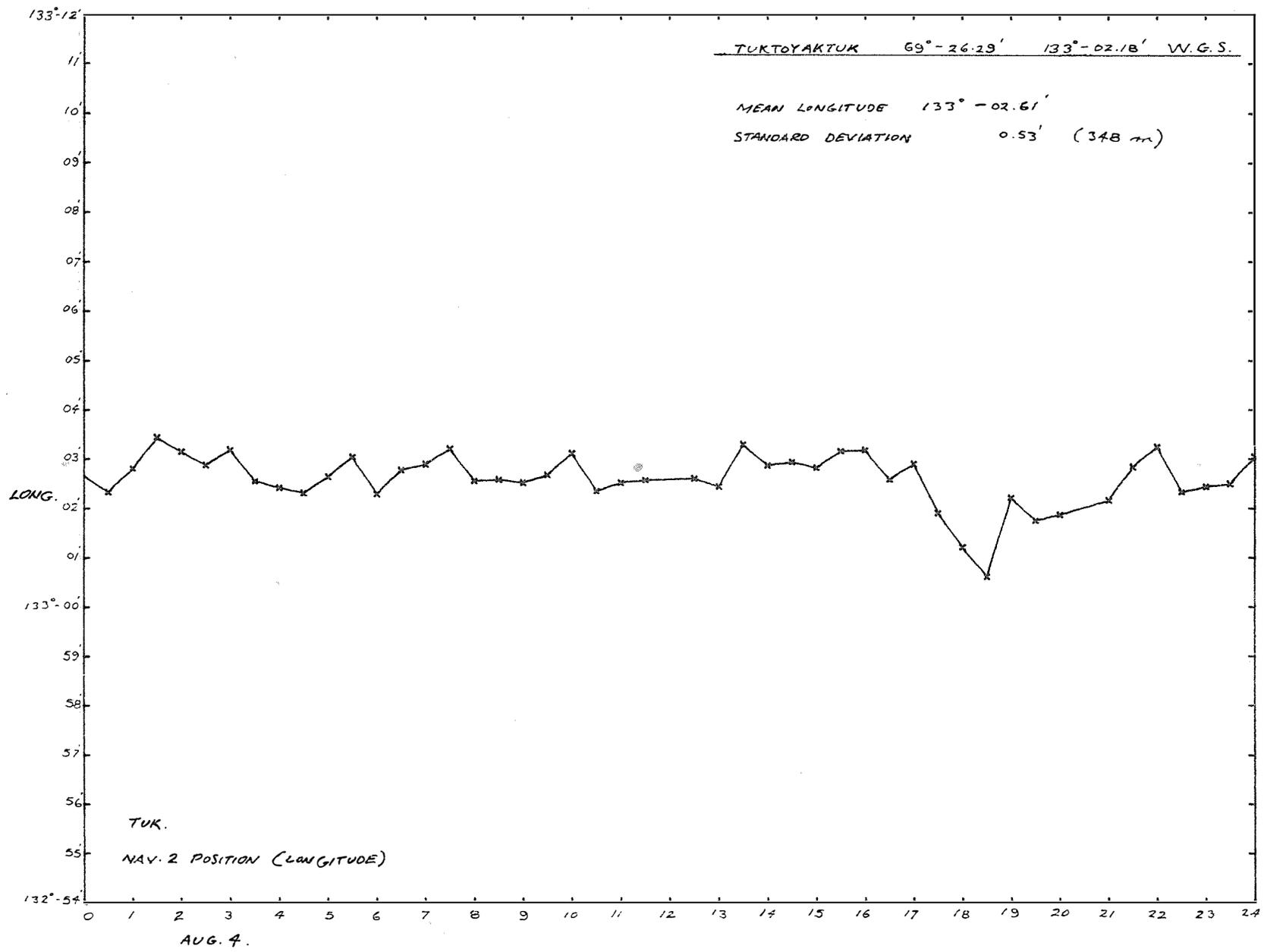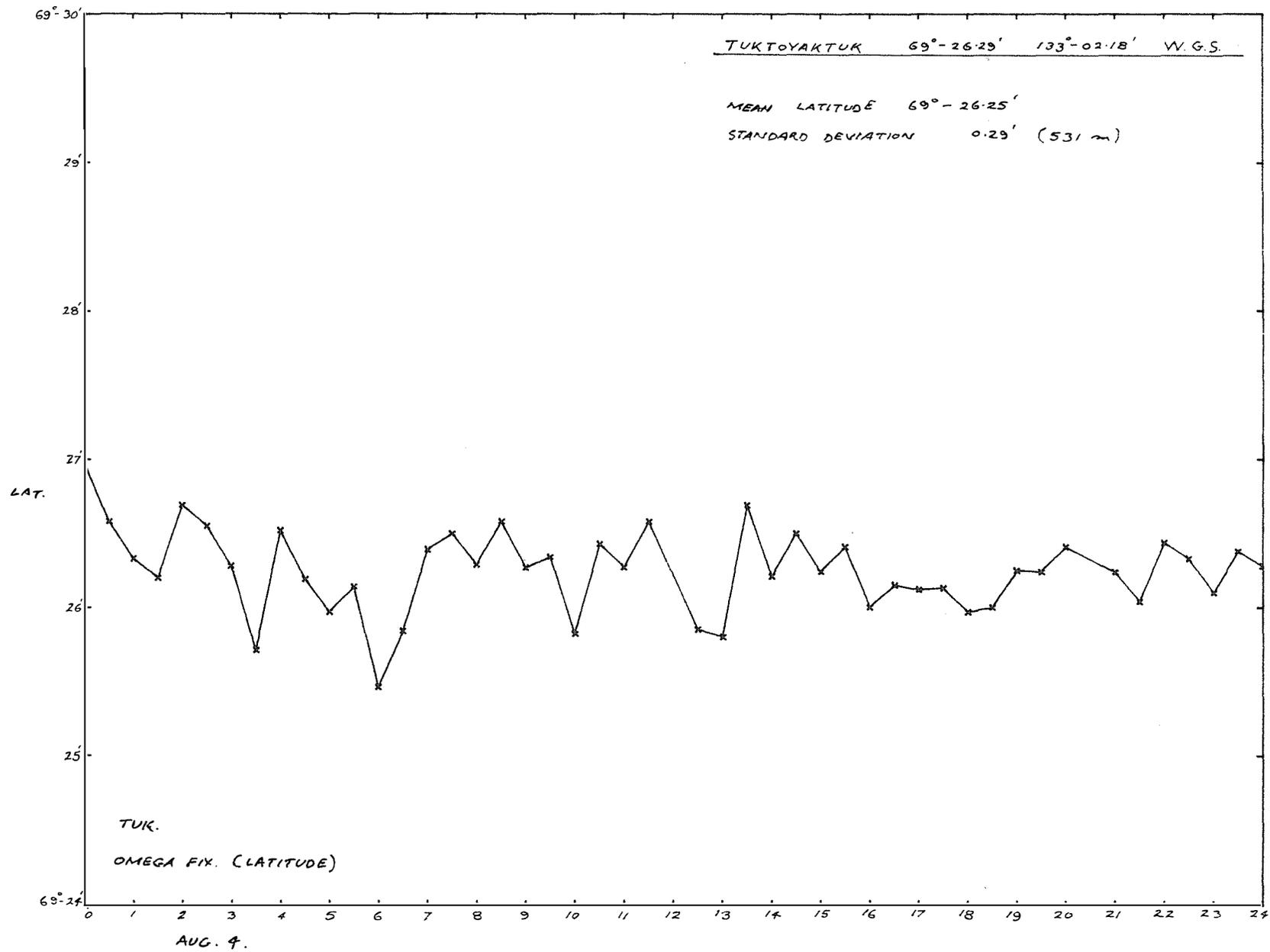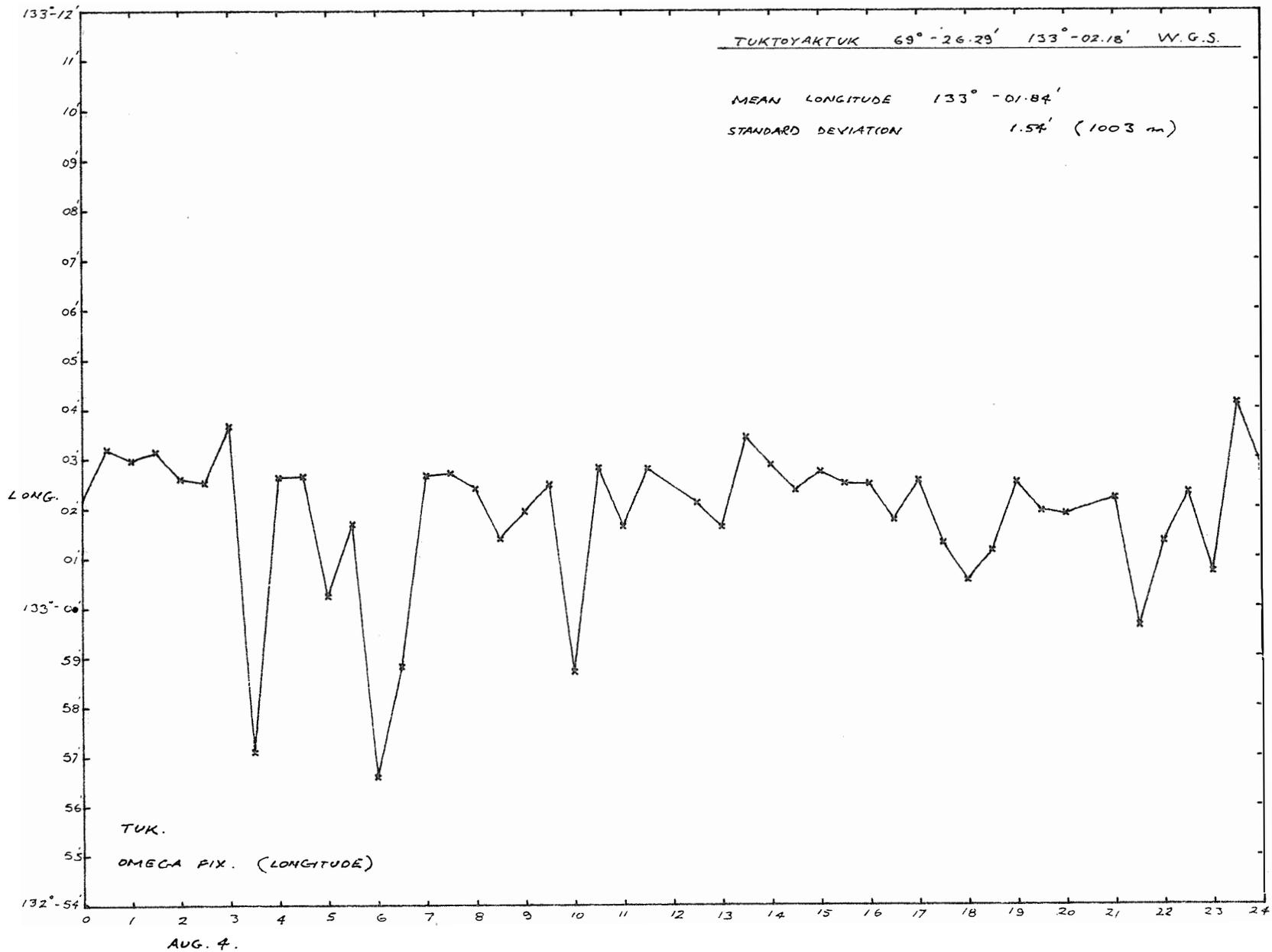
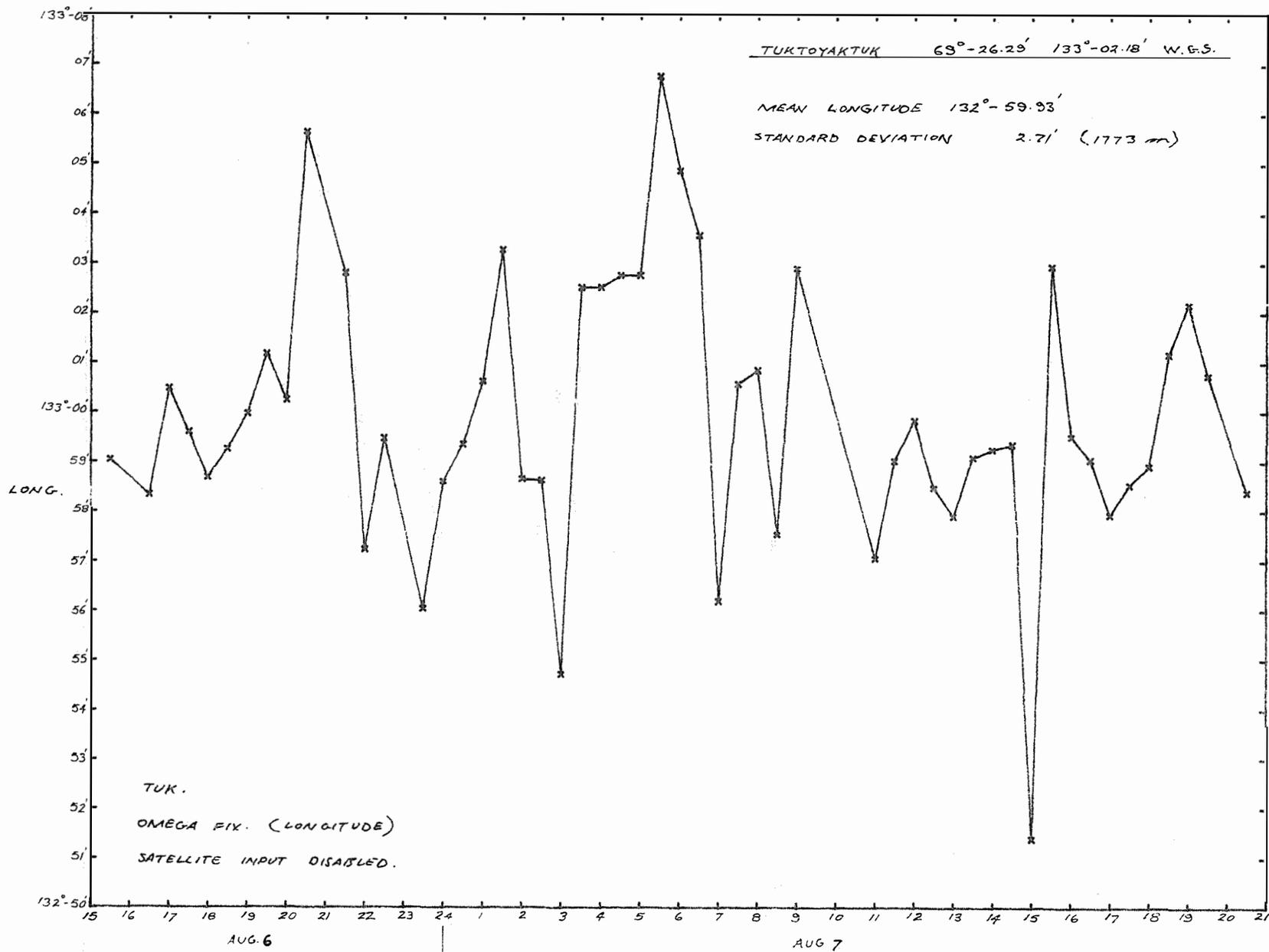TUKTOYAKTUK   69° - 26.29'   133° - 02.18'   W.G.S.

MEAN LONGITUDE   133° - 02.50'

STANDARD DEVIATION   0.48' (314 m)

LONG.

TUK.

NAV. 2 POSITION (LONGITUDE)

AUG. 3.

64

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

TUKTOYAKTUK   69° - 26.29'   133° - 02.18'   W.G.S.

MEAN LATITUDE   69° - 27.84'
STANDARD DEVIATION   0.46'   (861 m)

TUK.
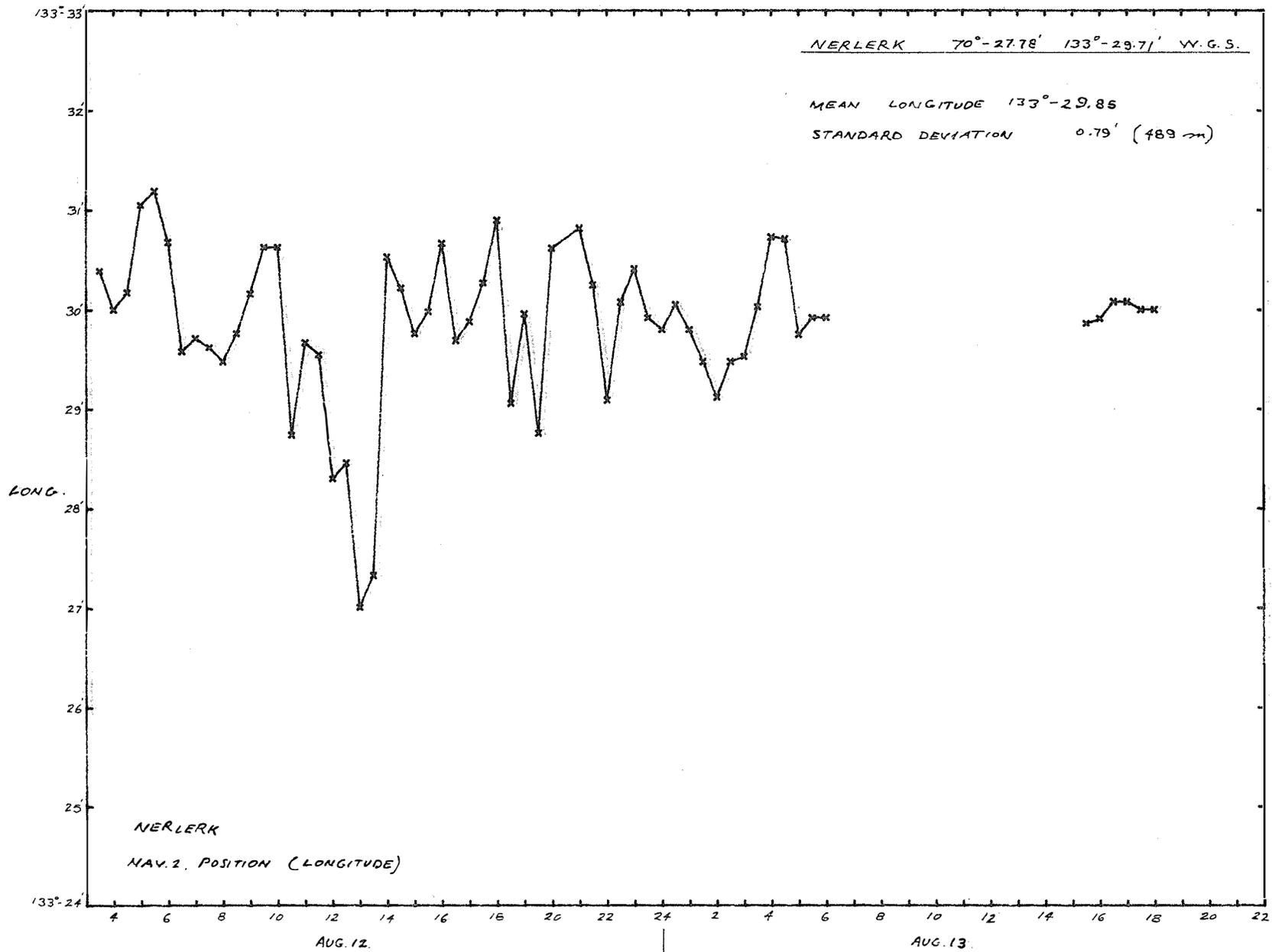
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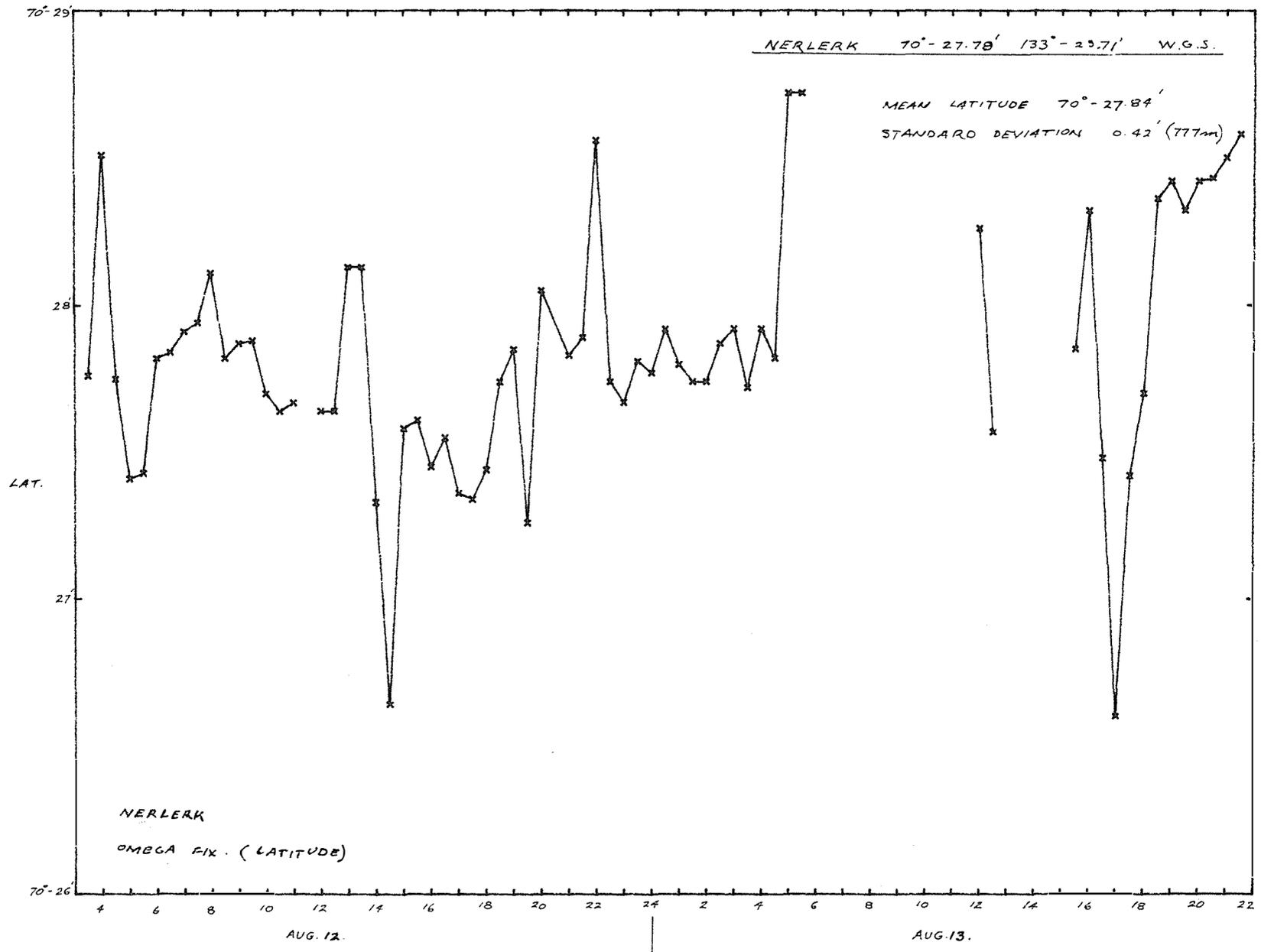
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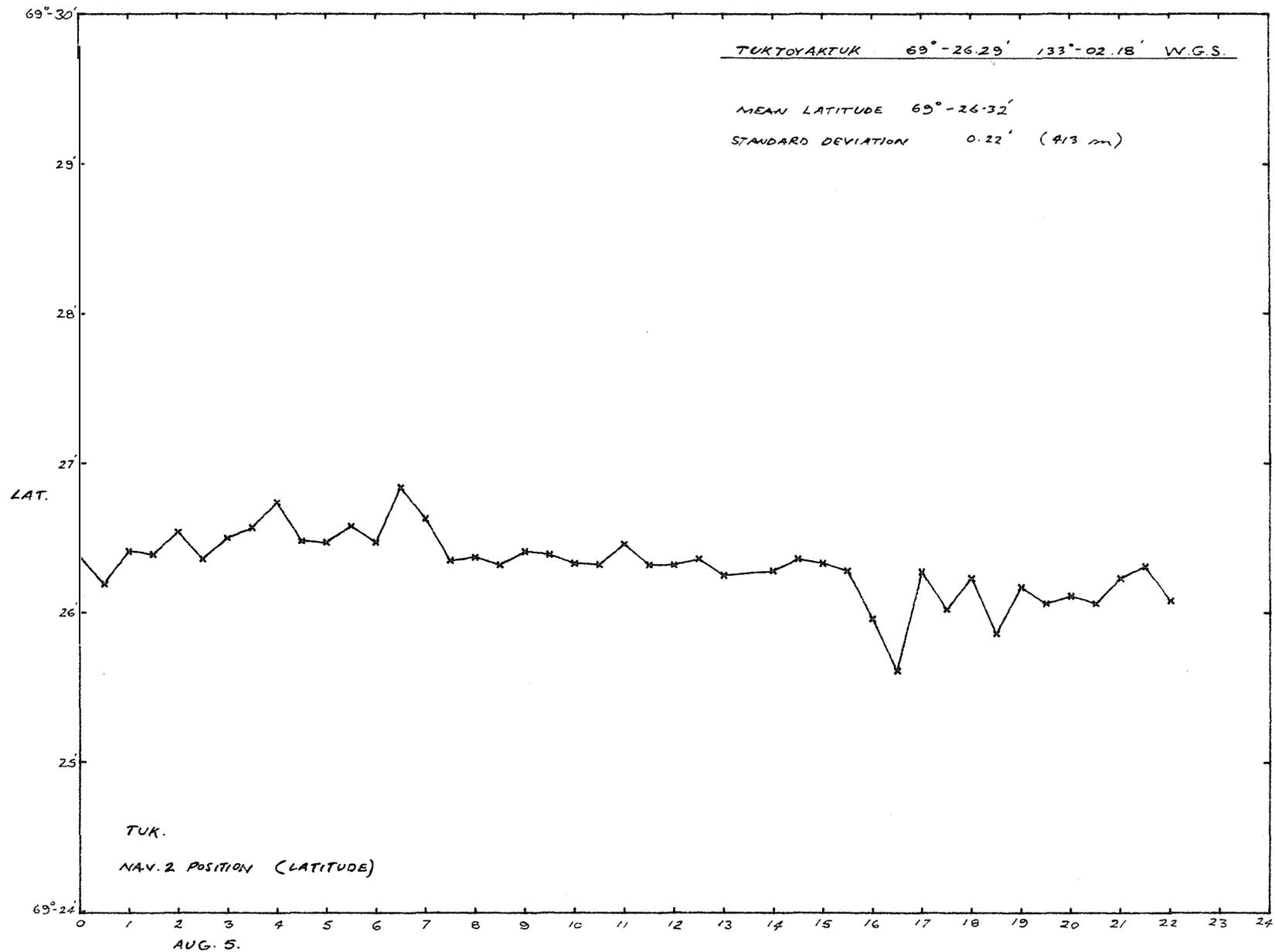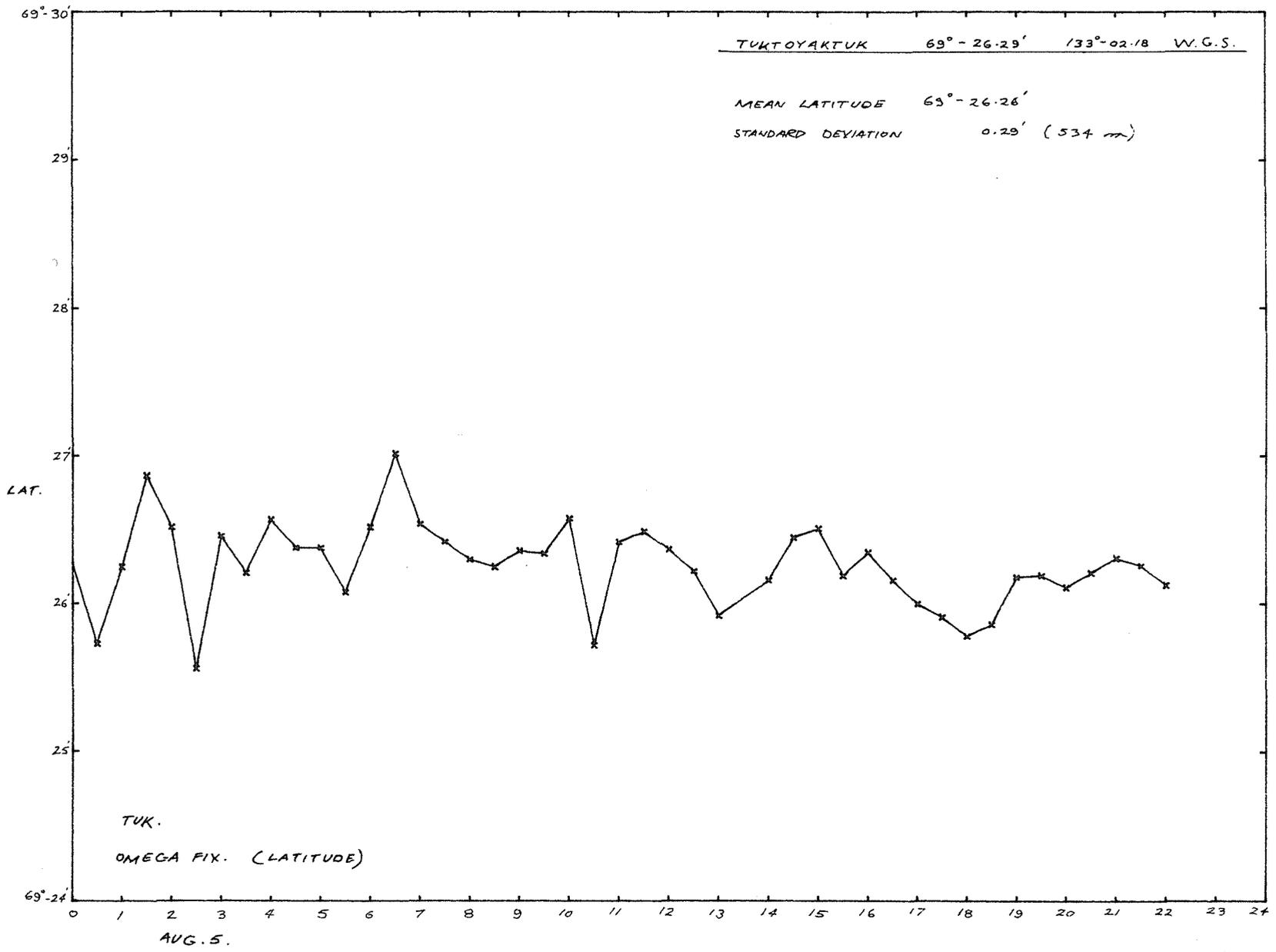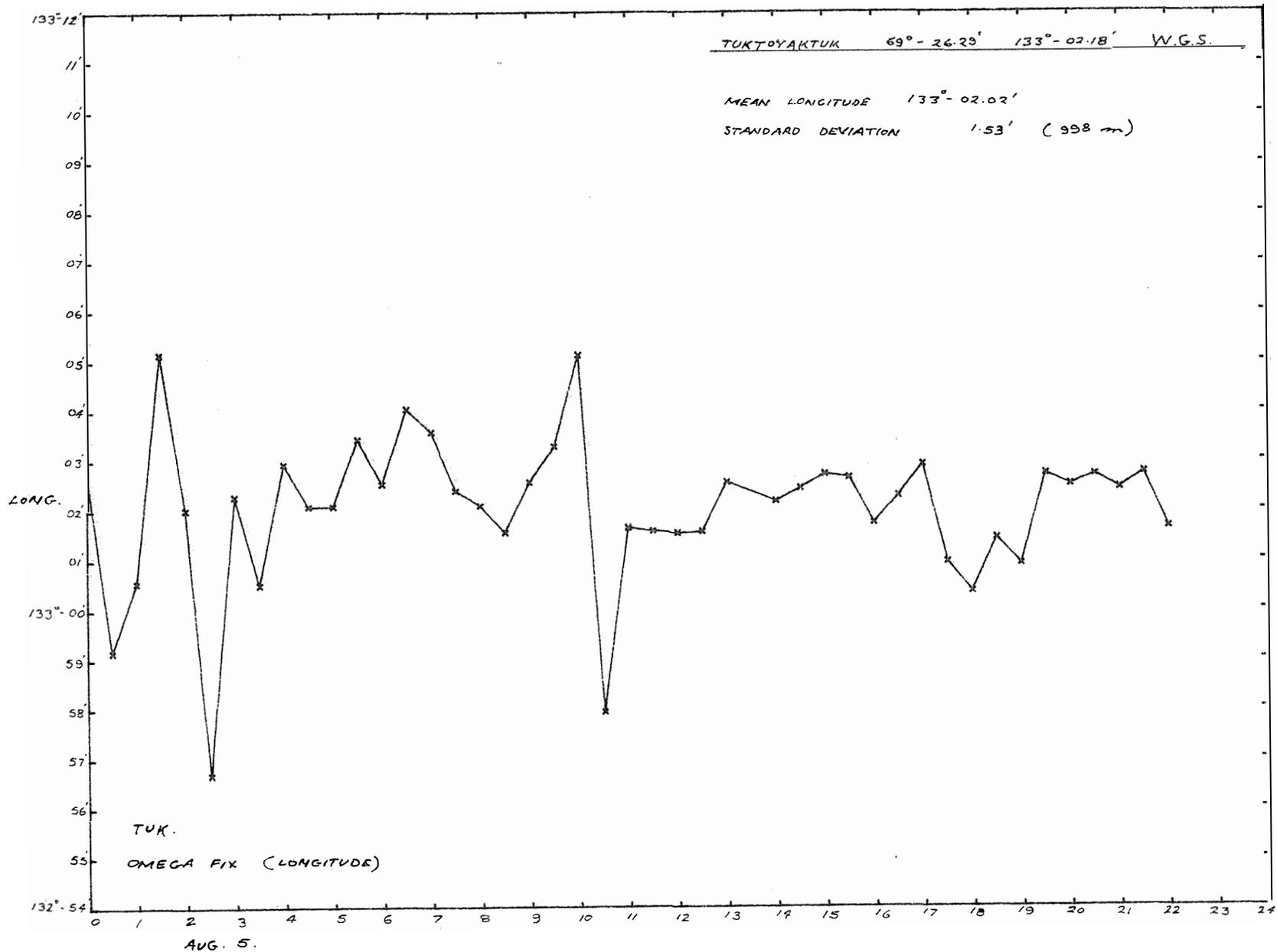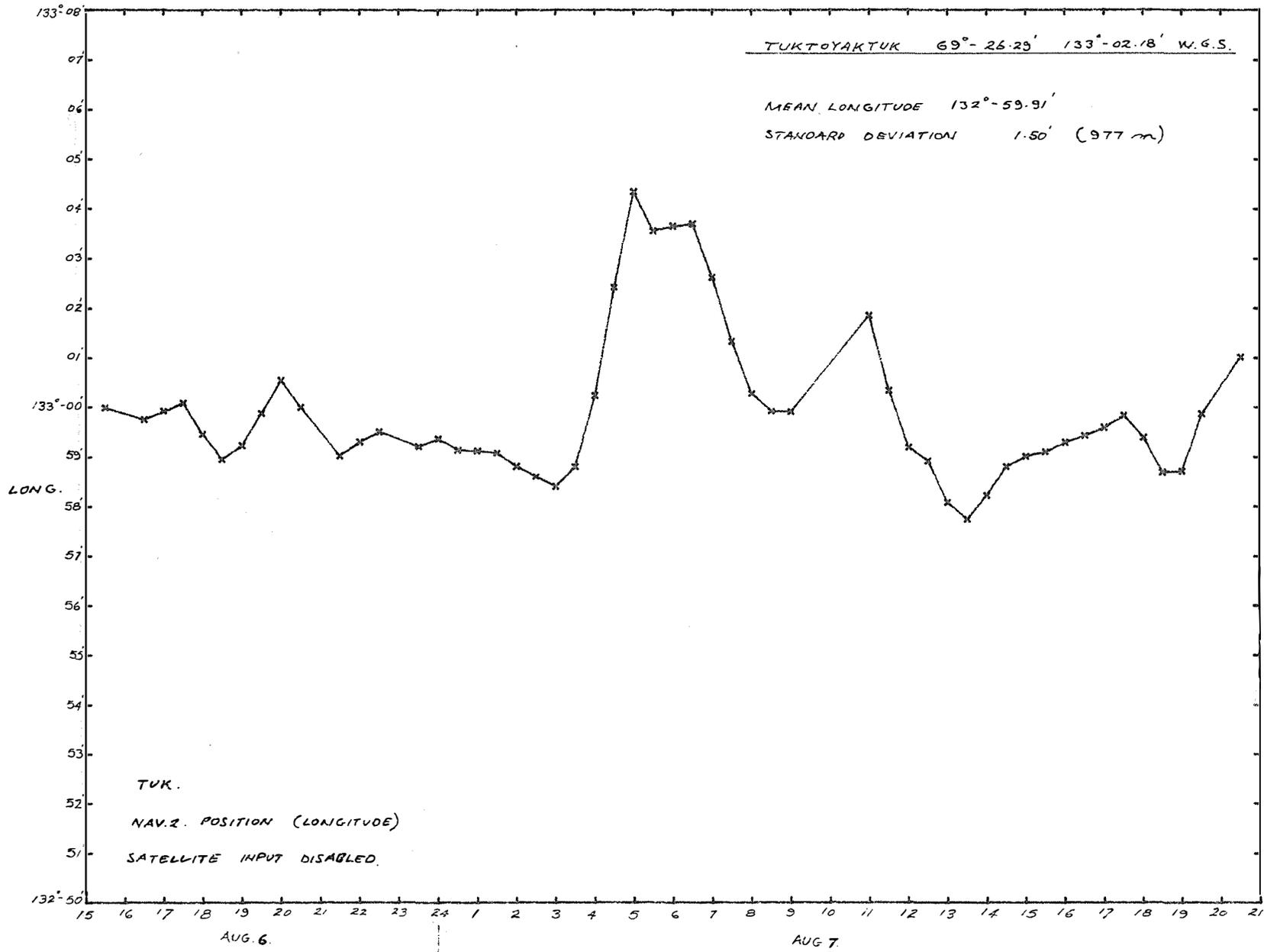
Figure 20

Figure 21

Figure 22

Figure 23

Figure 24

Figure 25

Figure 26

NERLERK 70°- 27.78' 133°- 23.71' W.G.S.

MEAN LATITUDE 70°- 27.84'
STANDARD DEVIATION 0.42' (777m)

NERLERK

OMEGA FIX . (LATITUDE)

AUG. 12.

AUG. 13.

83

Figure 27

Figure 28