



The Impact of an Active Solar Cycle on DGPS Positioning Performance

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FUGRO CHANCE INC.



Overview

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Fugro Chance Services Using GPS

GPS Background

- Autonomous GPS
- GPS Error Sources
- Differential GPS
- GPS Performance Levels
- Impact of the Ionosphere on GPS

Monitor Data

- 1999 African DGPS
- 2000 South America / Africa DGPS
- 2003 South America Scintillations
- 1999 October 22 Event, Gulf of Mexico Performance

Conclusions



Marine Construction Survey



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Pile Installation



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Airborne Survey Operations

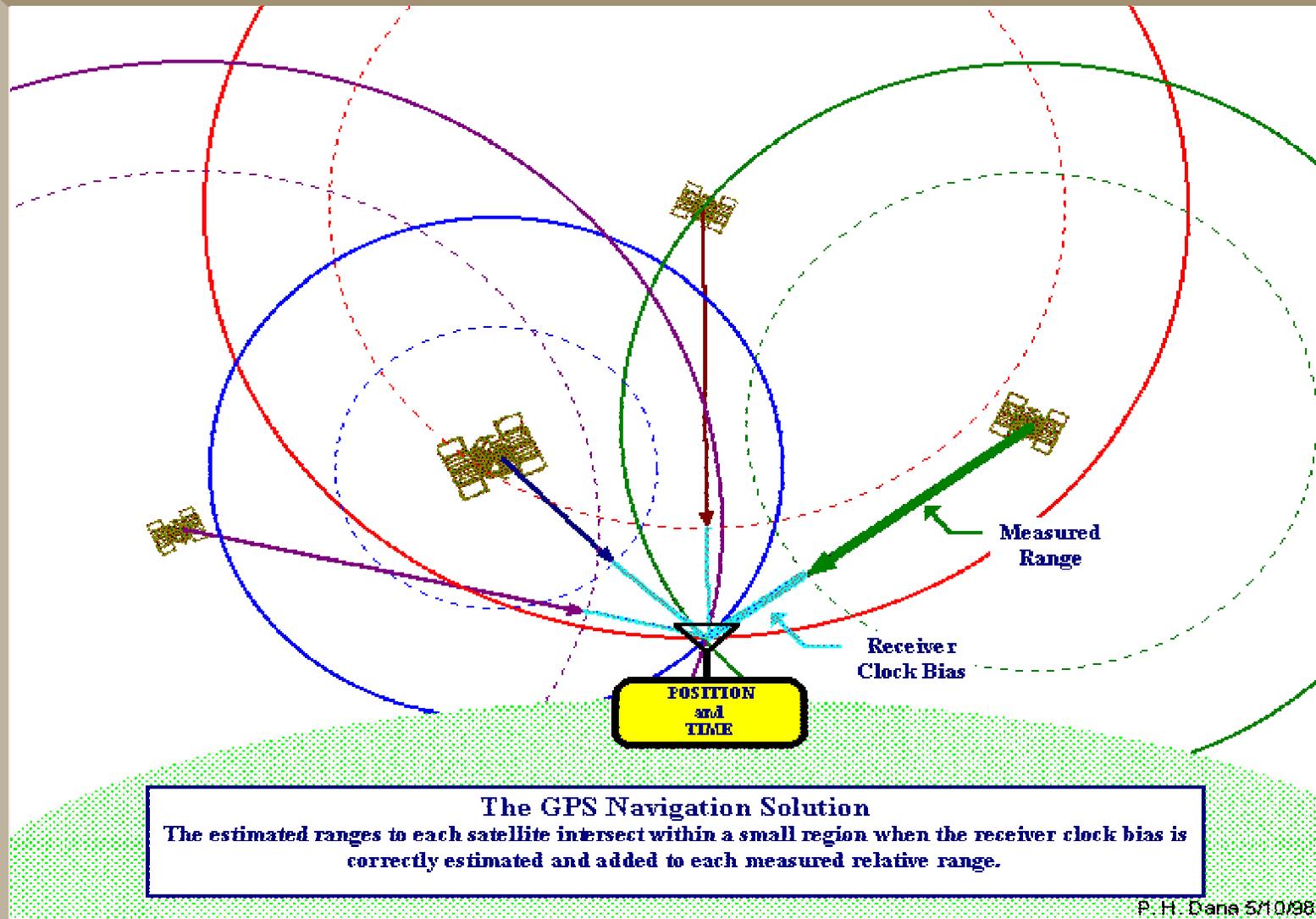
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Stand Alone GPS Positioning

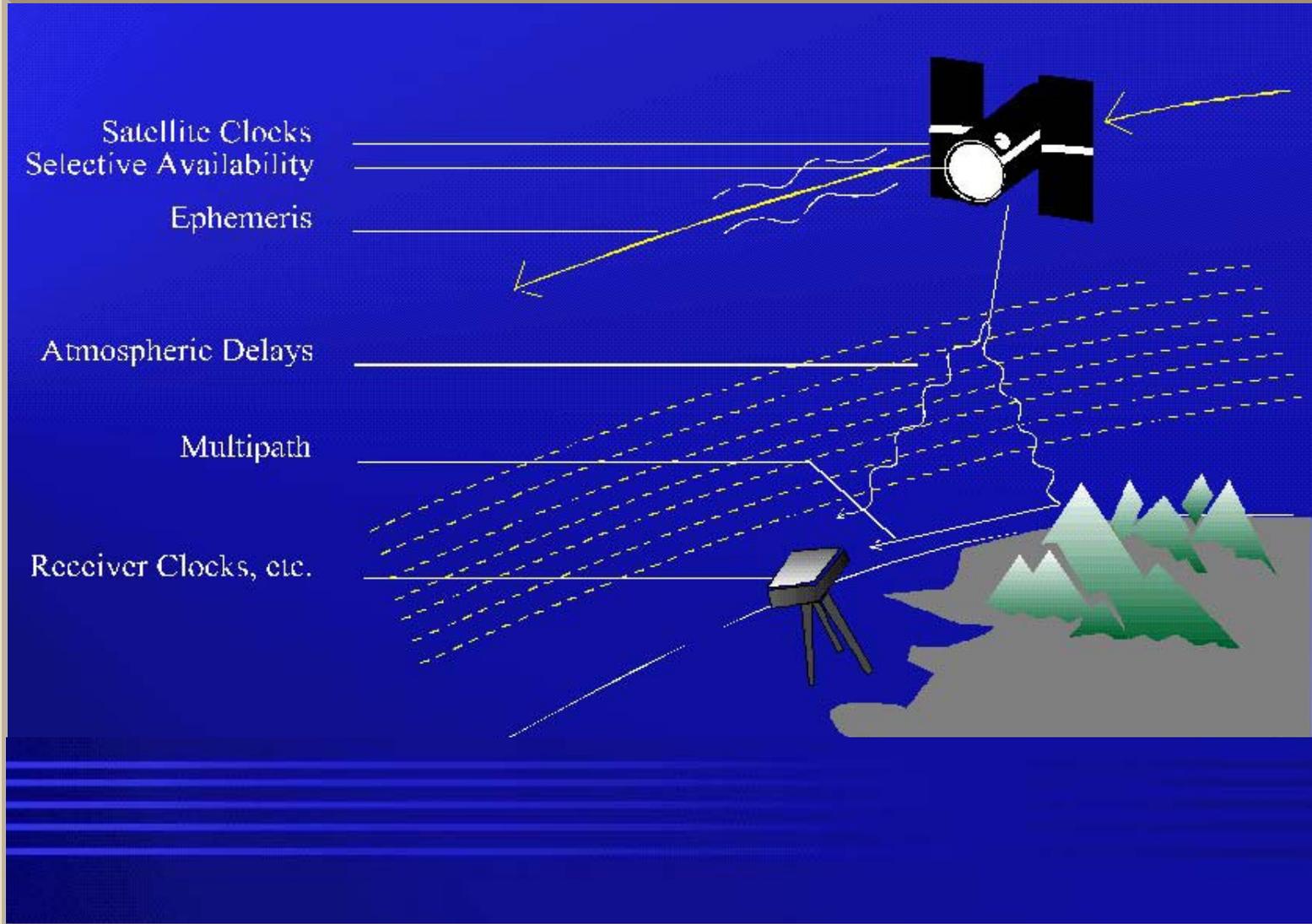


The GPS Navigation Solution
 The estimated ranges to each satellite intersect within a small region when the receiver clock bias is correctly estimated and added to each measured relative range.



Common GPS Error Sources

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Why Differential GPS



Differential GPS – DGPS

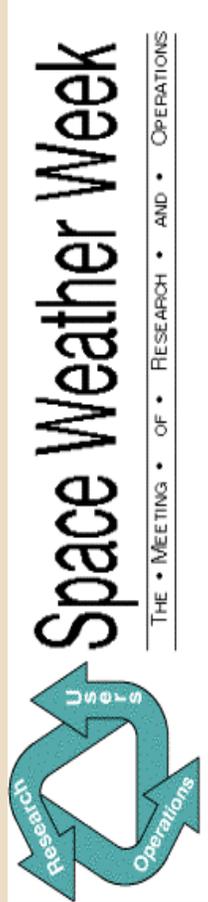
- Increased level of position accuracy over stand alone or autonomous GPS by use of satellite range corrections from a reference receiver at a known location
- Common error sources between reference and remote or user receiver are removed (e.g. iono, tropo, clock)
- Remain subject to spatial (distance) and temporal (time) decorrelation on position (e.g. orbit and S/A)
- .01 to 3 meter positioning possible depending on range and method (Integer RTK, Float RTK or standard DGPS)



Differential GPS Works Because

- Modern GPS receivers have high measurement precision and accuracy providing consistency between reference and rover receivers
- At short ranges (< 50 km) most errors are correlated and canceled (Kinematic GPS cm level positioning)
- At long ranges (> 500 km) many errors still can be removed by DGPS providing meter level positioning
- With a 'GOOD' GPS constellation the DGPS solution is statistically robust and reliable

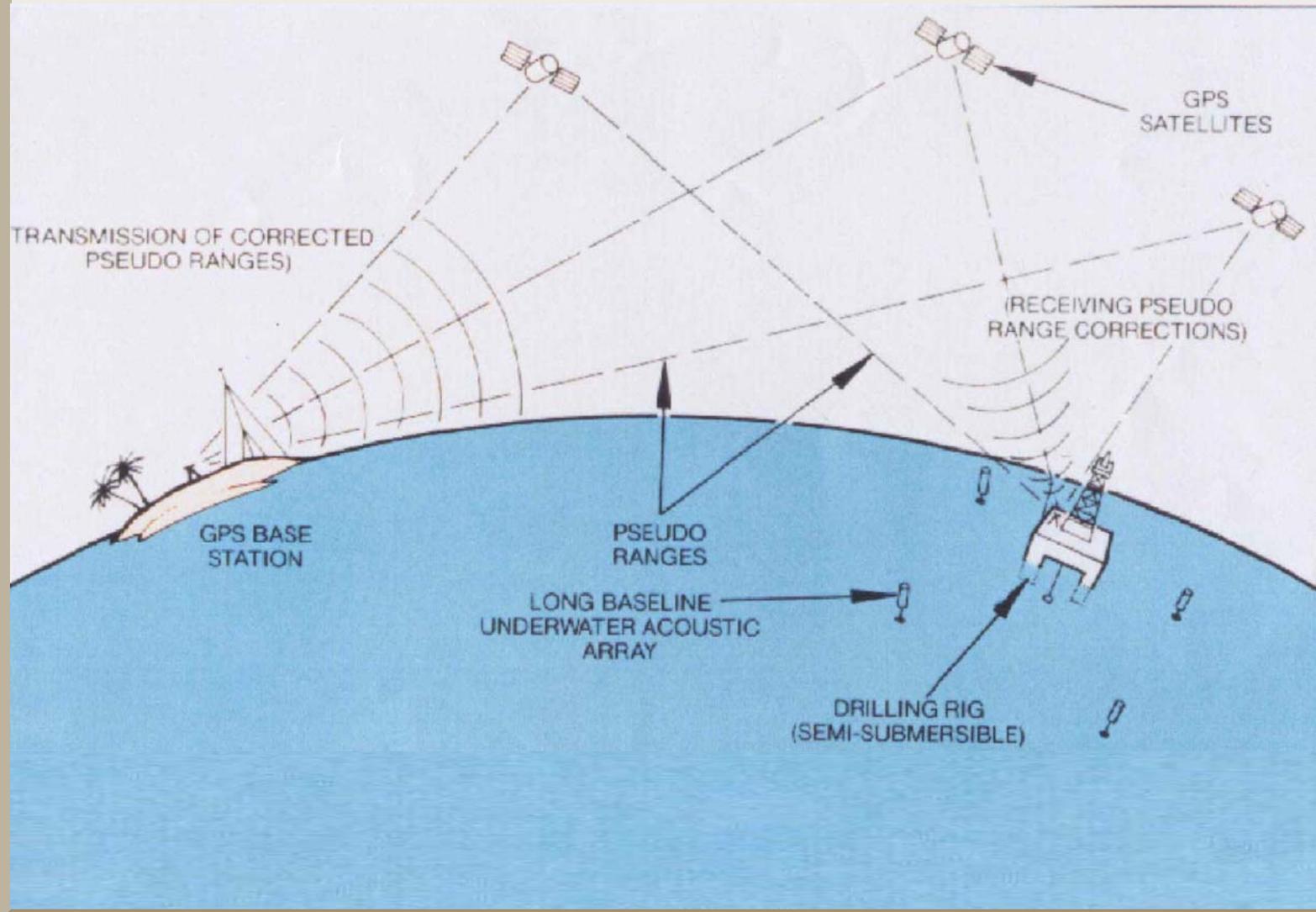
Any changes to the operating environment which adversely impacts the fundamentals will limit operational success.



Single Site Differential

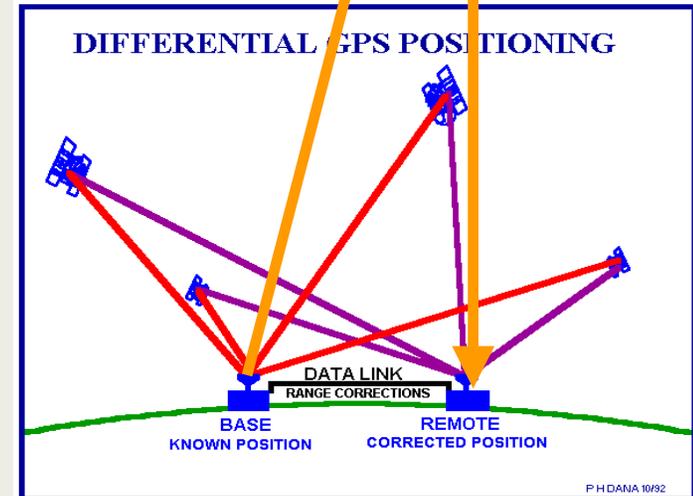
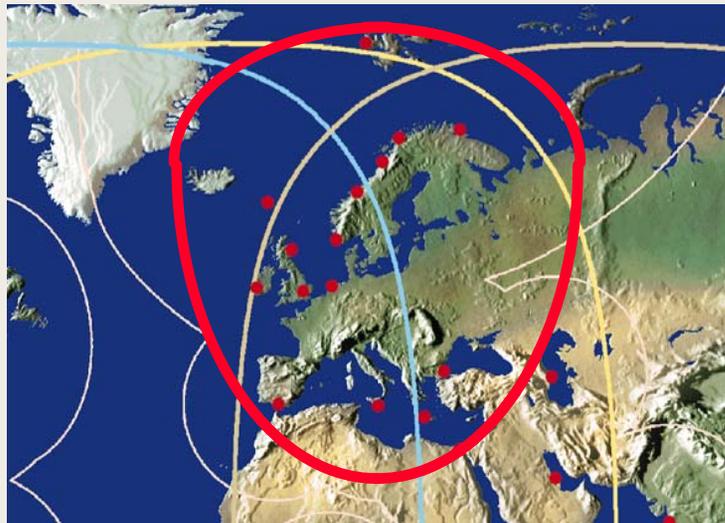
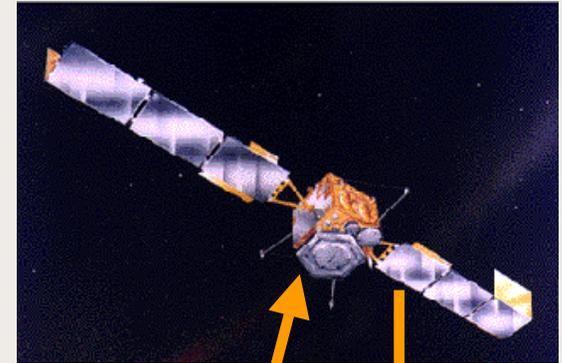
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DGPS Services Via Satellites

Geostationary Satellites for DGPS Corrections Distribution



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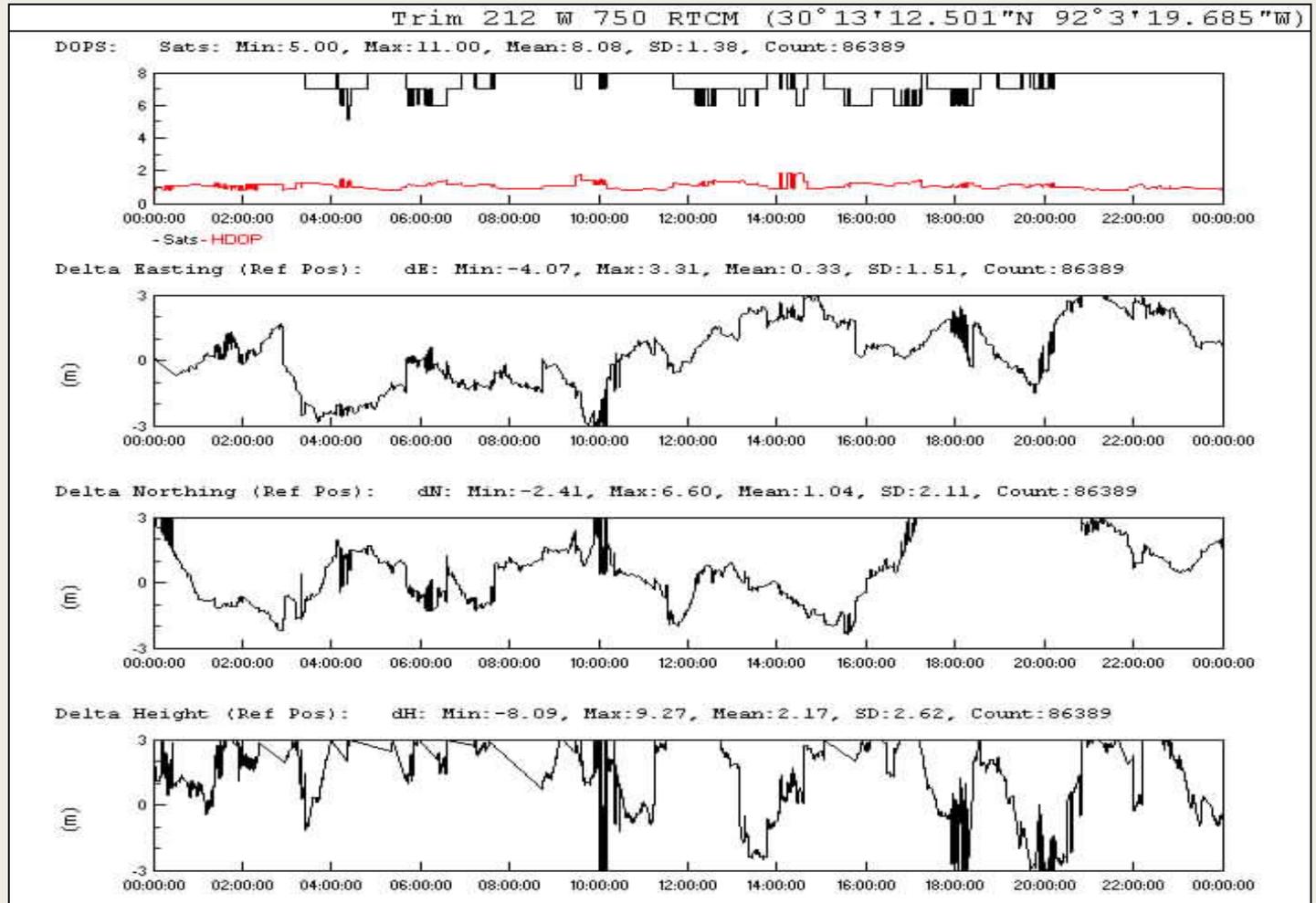




Stand Alone GPS Performance

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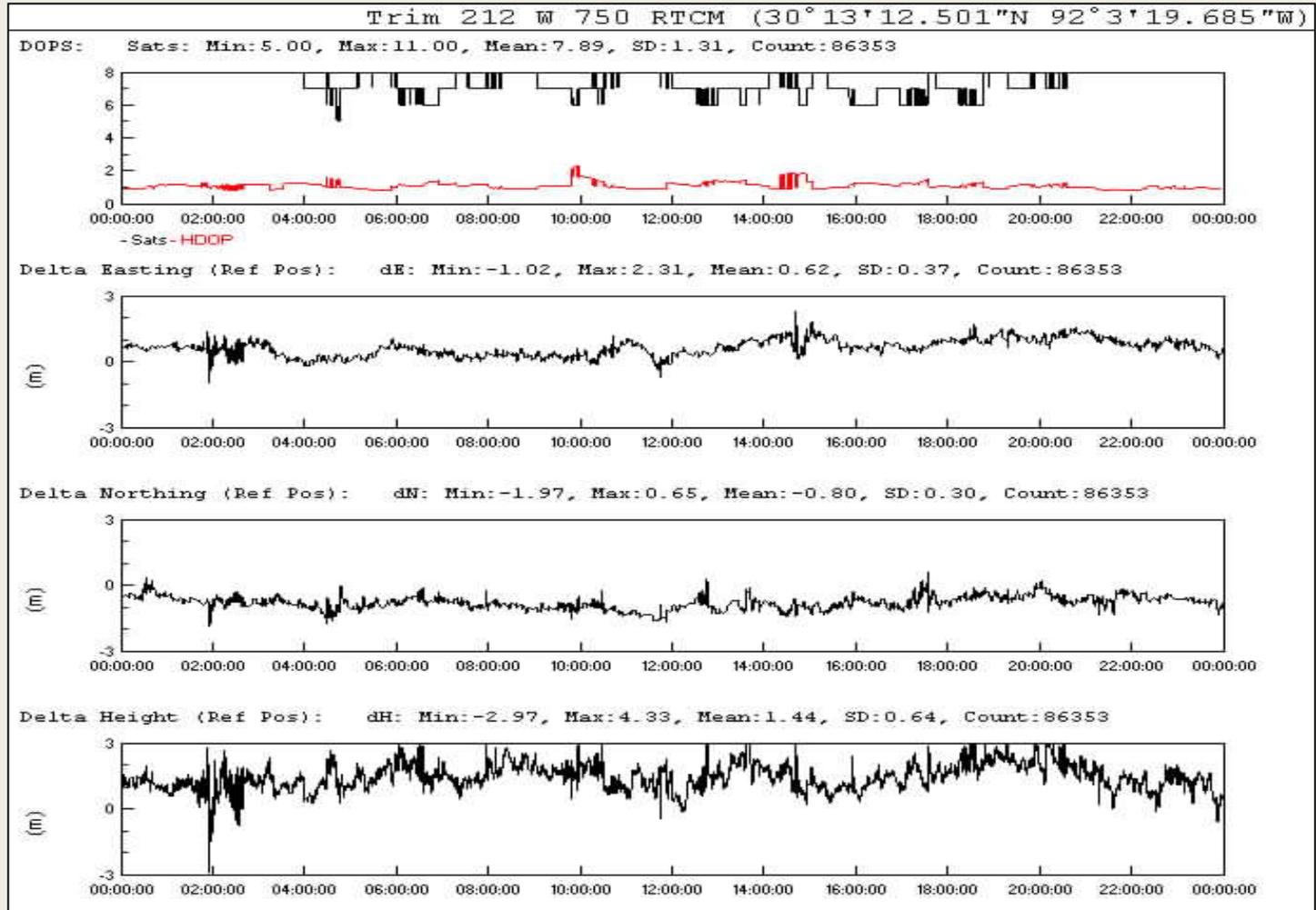
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Single Site Differential

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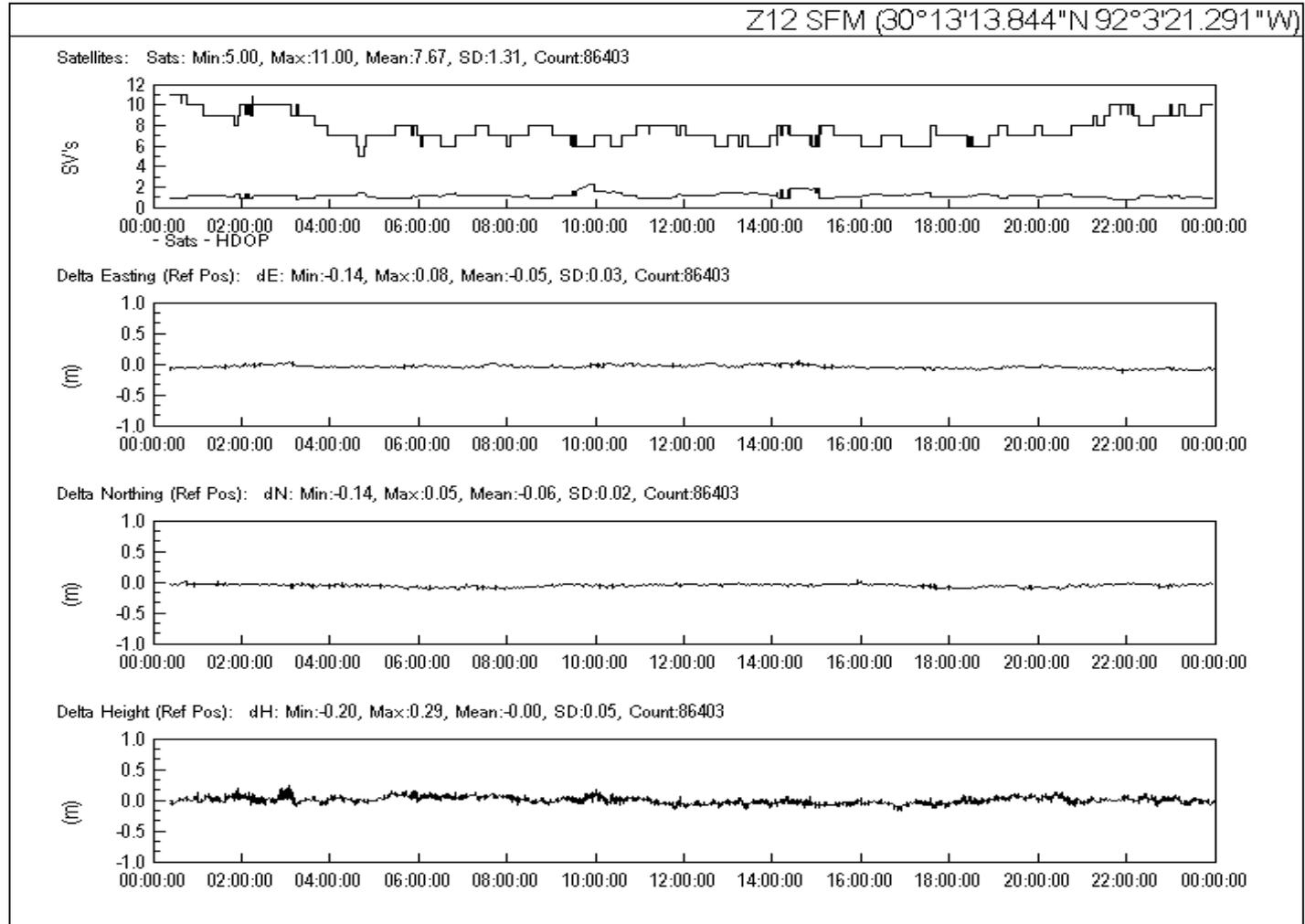




High Performance DGPS

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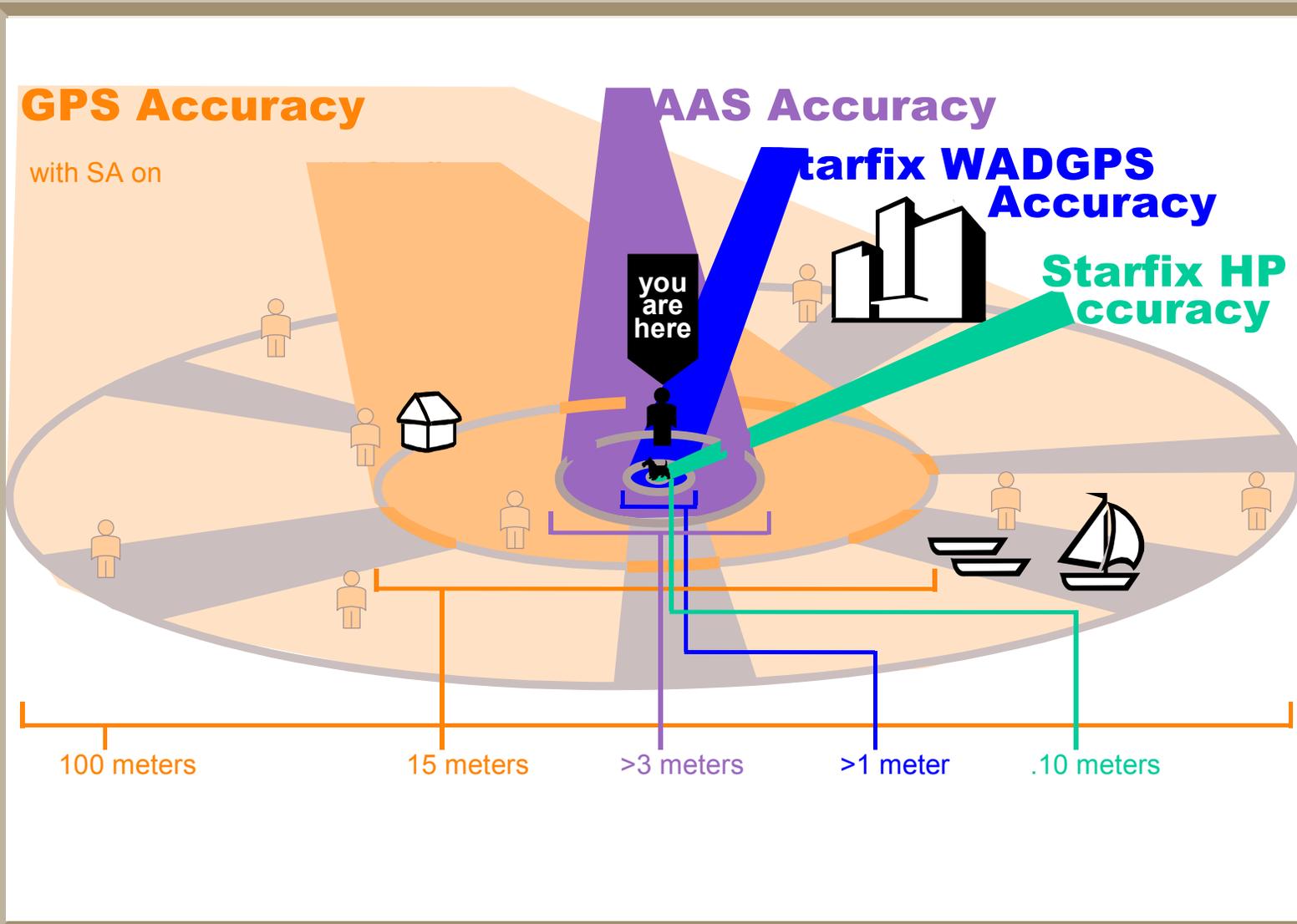
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DGPS Accuracy Comparison

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The Ionosphere Is a Major Error Source for GPS Users

- Extreme along the Geomagnetic Equator
 - Greatest impact typically after sundown local time
 - Most severe, commercially, in South America (Brazilian region)
- Can impact in mid latitude regions if extreme
- Average daytime zenith delay at L1 is 5–15 m
 - Up to 36 m at equator during solar maximum
 - Elevation dependent: 5 deg elevation 3 x Zenith delay
- Seasonal variation: November 4 times July
- Sunspot cycle variation (11 yr): Max 4 times minimum





Ionospheric Problems

Primary Impact of High Geomagnetic Activity on GPS

- De-correlation of errors between reference and user
Impact is greater on Code vs. Carrier measurements
- Most severe in equatorial regions, affecting baselines from a few hundred km, up to 12 or more hours a day, almost daily

- Scintillations

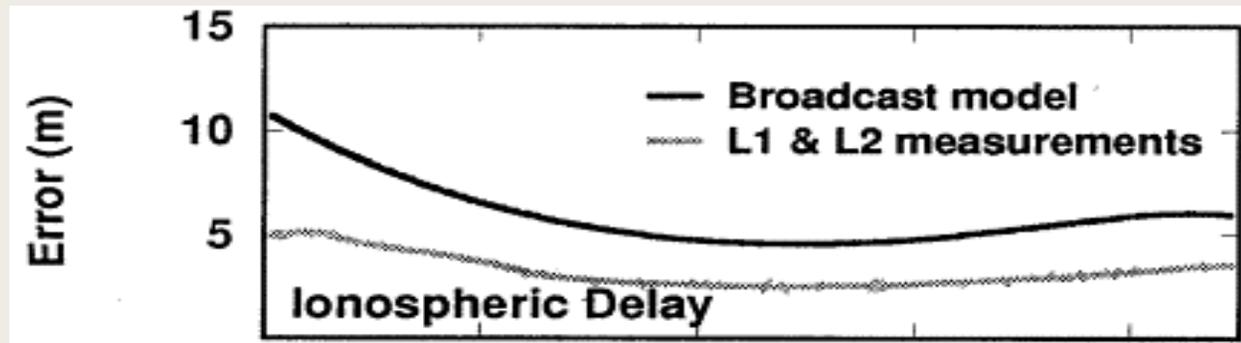
Rapid phase and amplitude variations on the GPS signal, causing GPS satellite loss of lock



Ionospheric Mitigation Techniques

Ionospheric Delay Can Be Modeled or Measured

- GPS Broadcast model (50% error in TEC)
- IRI-90, Bent, PIM (30% error in TEC). Requires near real-time geophysical information
- Ionospheric Models based on dual-frequency GPS measurements (1-2 m error at L1)
- Direct measurement from dual frequency GPS (PPS)





Regions of High Susceptibility

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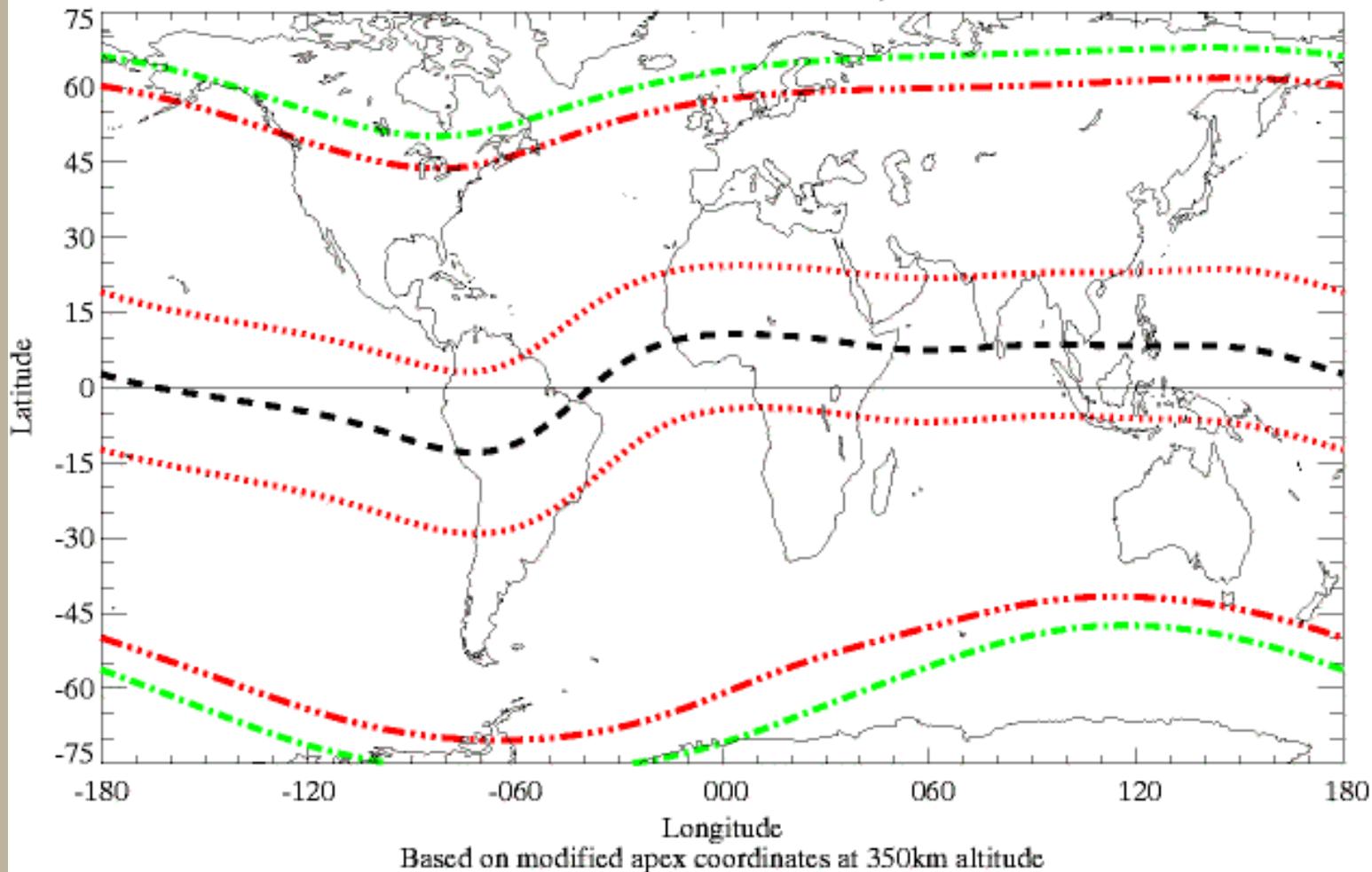
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Geomagnetic (350km Apex) Boundaries of Interest

<http://www.nwra-az.com/ionoscint/maps/maps.html>

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Ionospheric Models



Standard
GPS Iono
Model

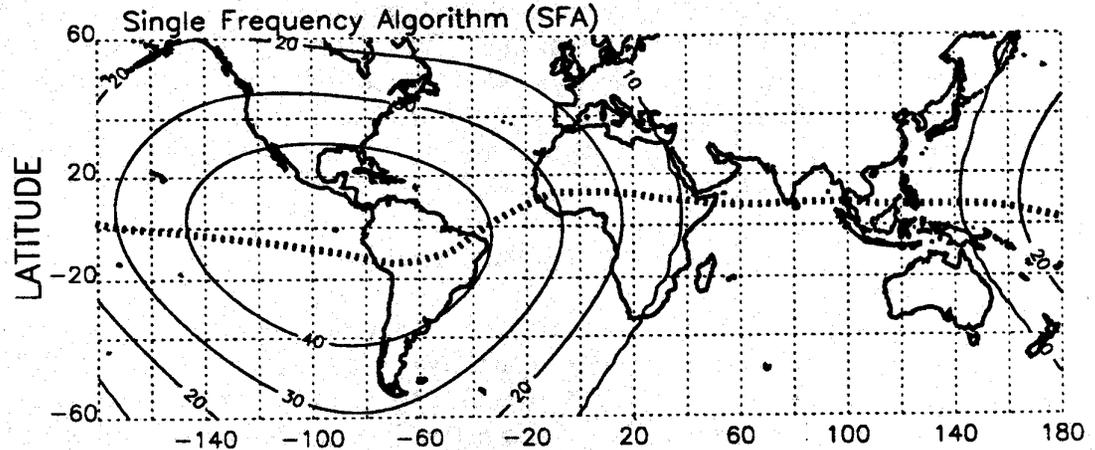


Figure 1) ICA contours of ionospheric TEC for equinoctial solar moderate conditions at 20 hours UT.

Accurate
PIM Iono
Model

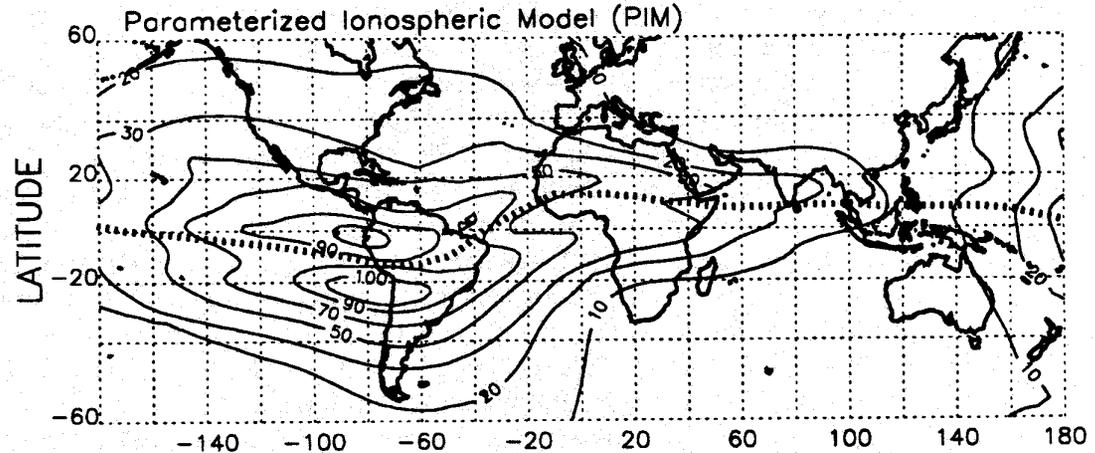


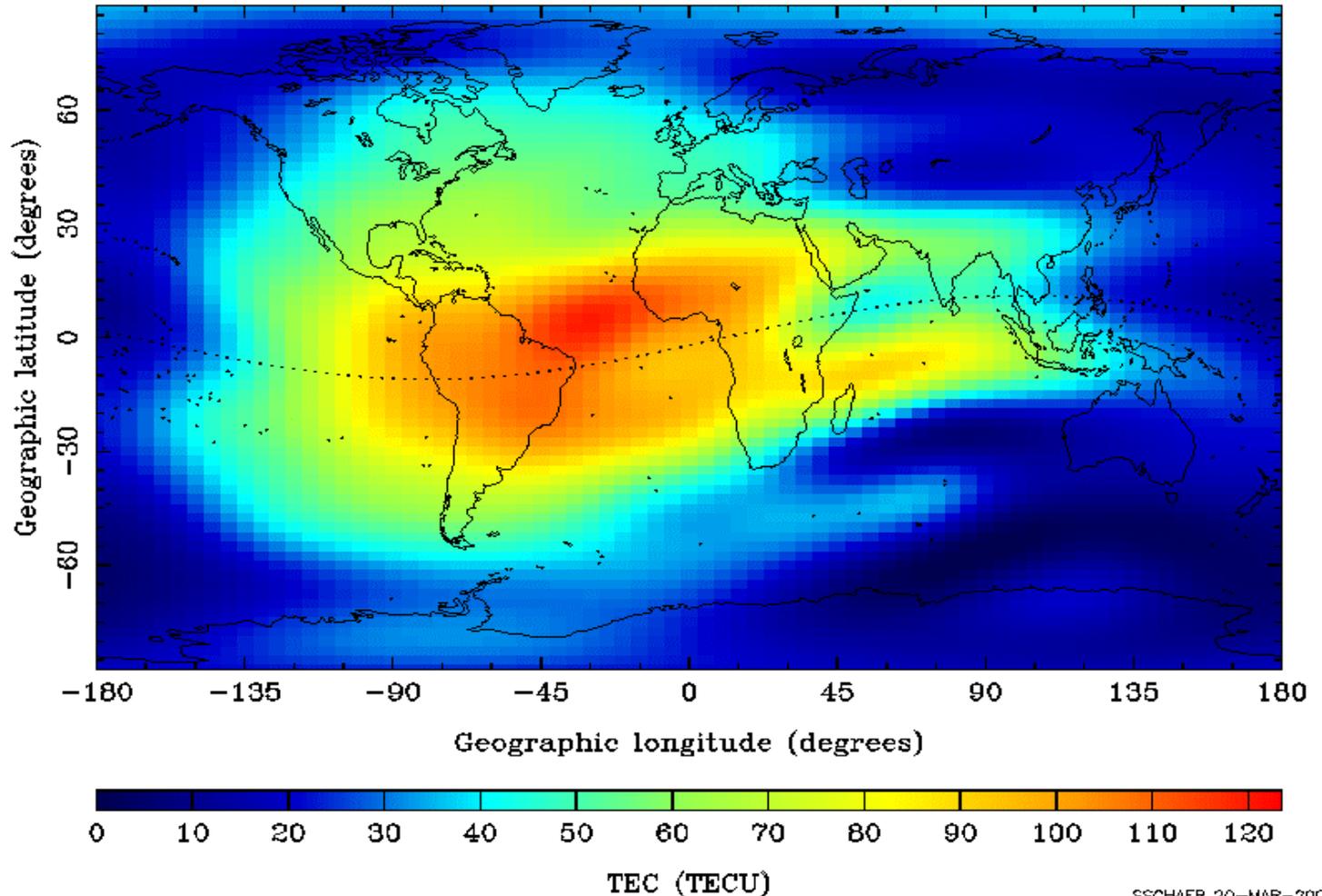
Figure 2) PIM contours of ionospheric TEC for equinoctial solar moderate conditions at 20 hours UT.

1 TECU=0.16 m

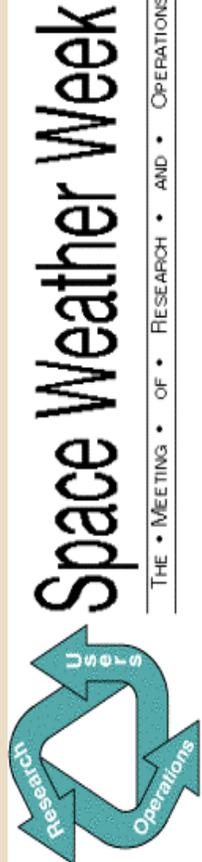


Global Ionosphere MARCH 14, 2000

CODE'S GLOBAL IONOSPHERE INFO FOR DAY 074, 2000 - 17:00 UT



SSCHAER 20-MAR-2000 14:19





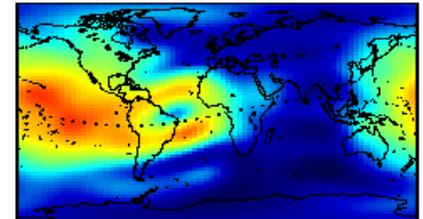
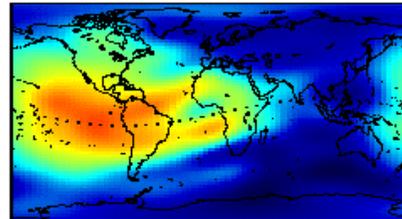
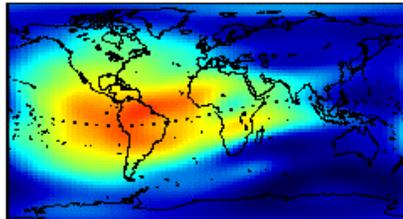
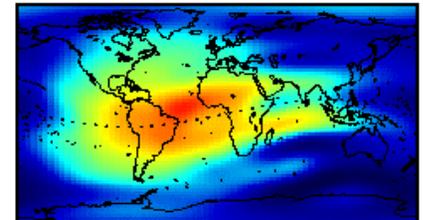
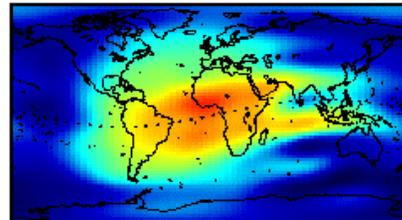
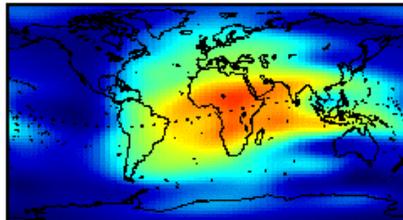
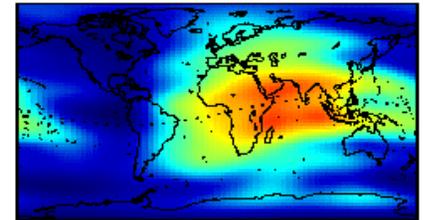
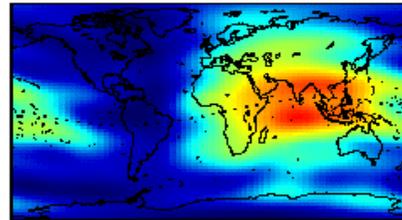
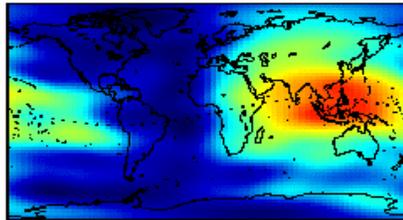
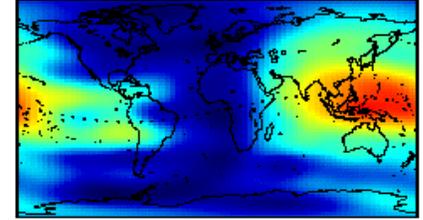
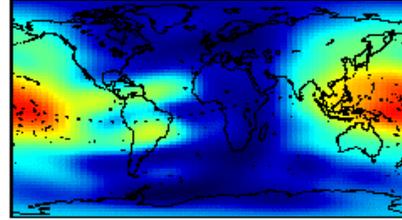
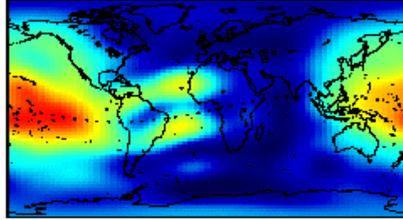
Global Ionosphere

MARCH 14, 2000

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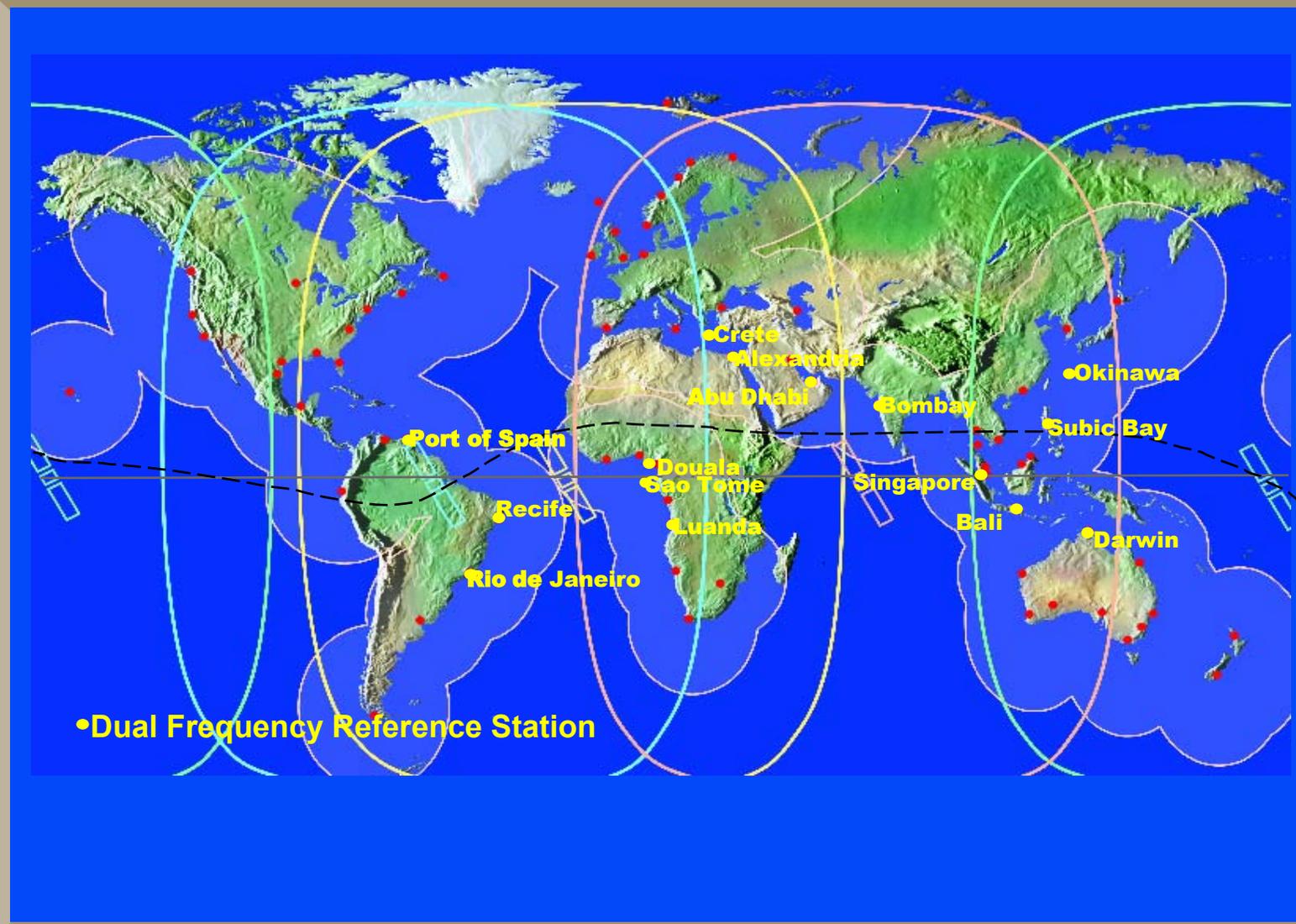
A circular diagram with three arrows forming a clockwise cycle. The top arrow is labeled "Users", the right arrow is labeled "Operations", and the bottom arrow is labeled "Research".



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Reference Network Distribution

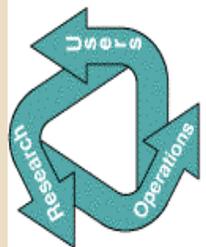


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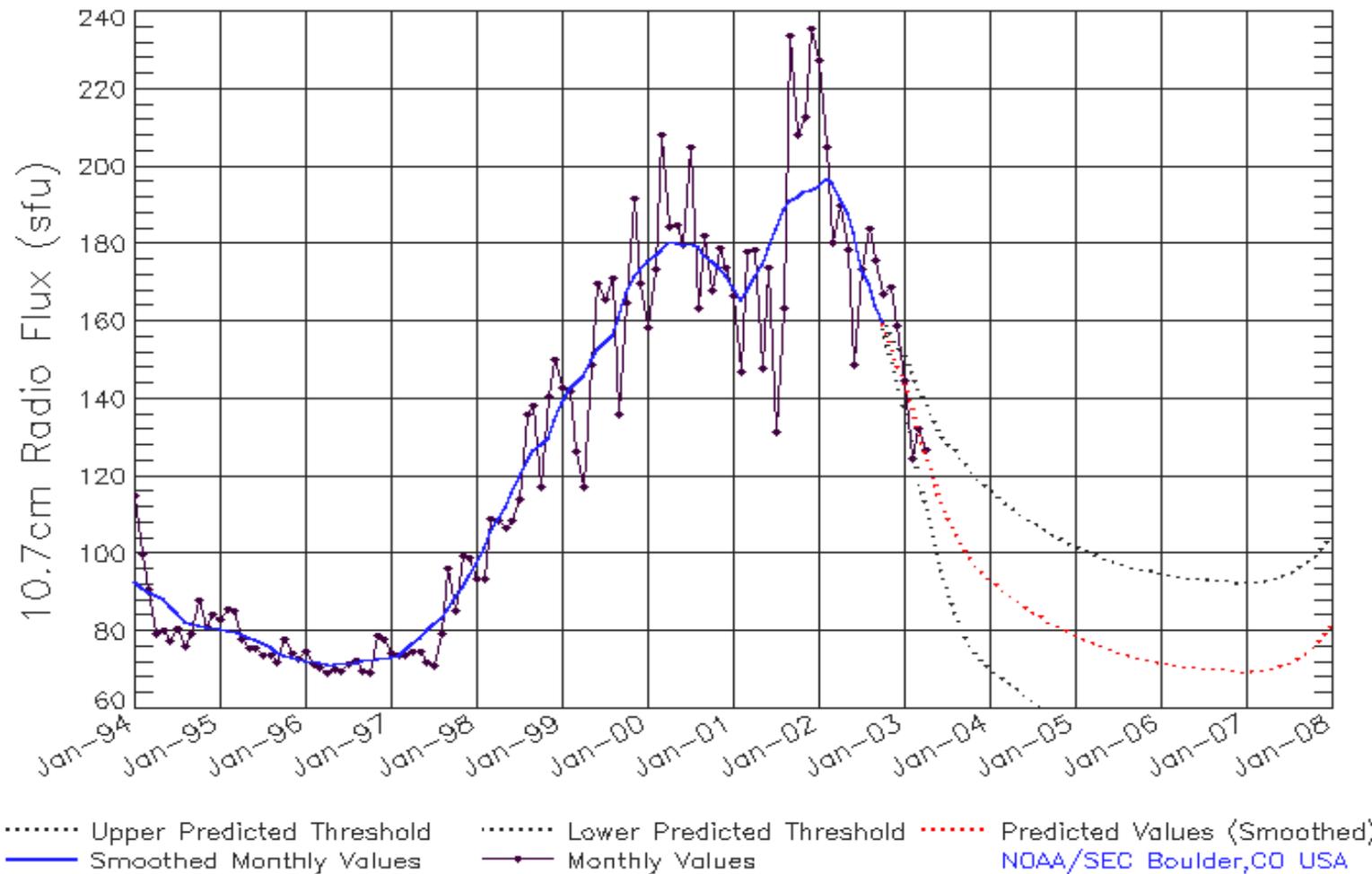


Cycle 23 Solar Activity History

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ISES Solar Cycle F10.7cm Radio Flux Progression
Data Through 30 Apr 03





Impact of Solar Activity On GPS Users

Problems Attributed to Solar Activity Starting in 1998

- Increasing levels of position noise depending on work area
- RTK initialization/re-initialization problems
- Satellite tracking problems caused by scintillations
- In mid latitudes symptoms first appear with $A_p > 40$ and $F_{10.7}$ flux values > 150





1999 DGPS Performance

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African Baselines

- Douala - Luanda 1500 Km
- Pointe-Noire Luanda 469 km

Single Frequency

- Using Klobuchar GPS IONO Model

Dual Frequency

- Computing IONO value from measurements

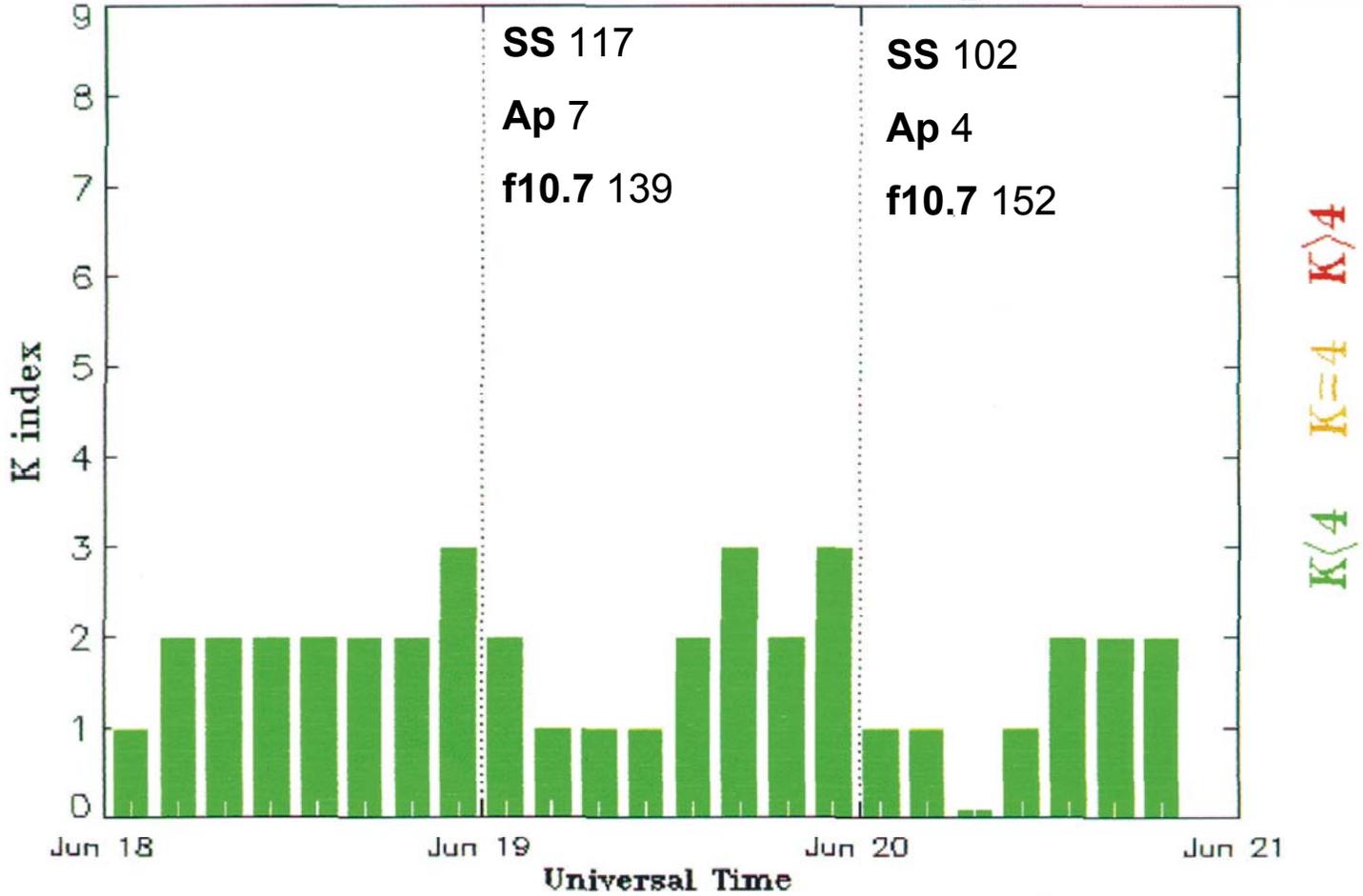


Index Levels June 18-20, 1999

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Estimated Planetary Kp index (3 hour data) Begin: 1999 Jun 18 0000UT



Updated 1999 Jun 20 23:45:09

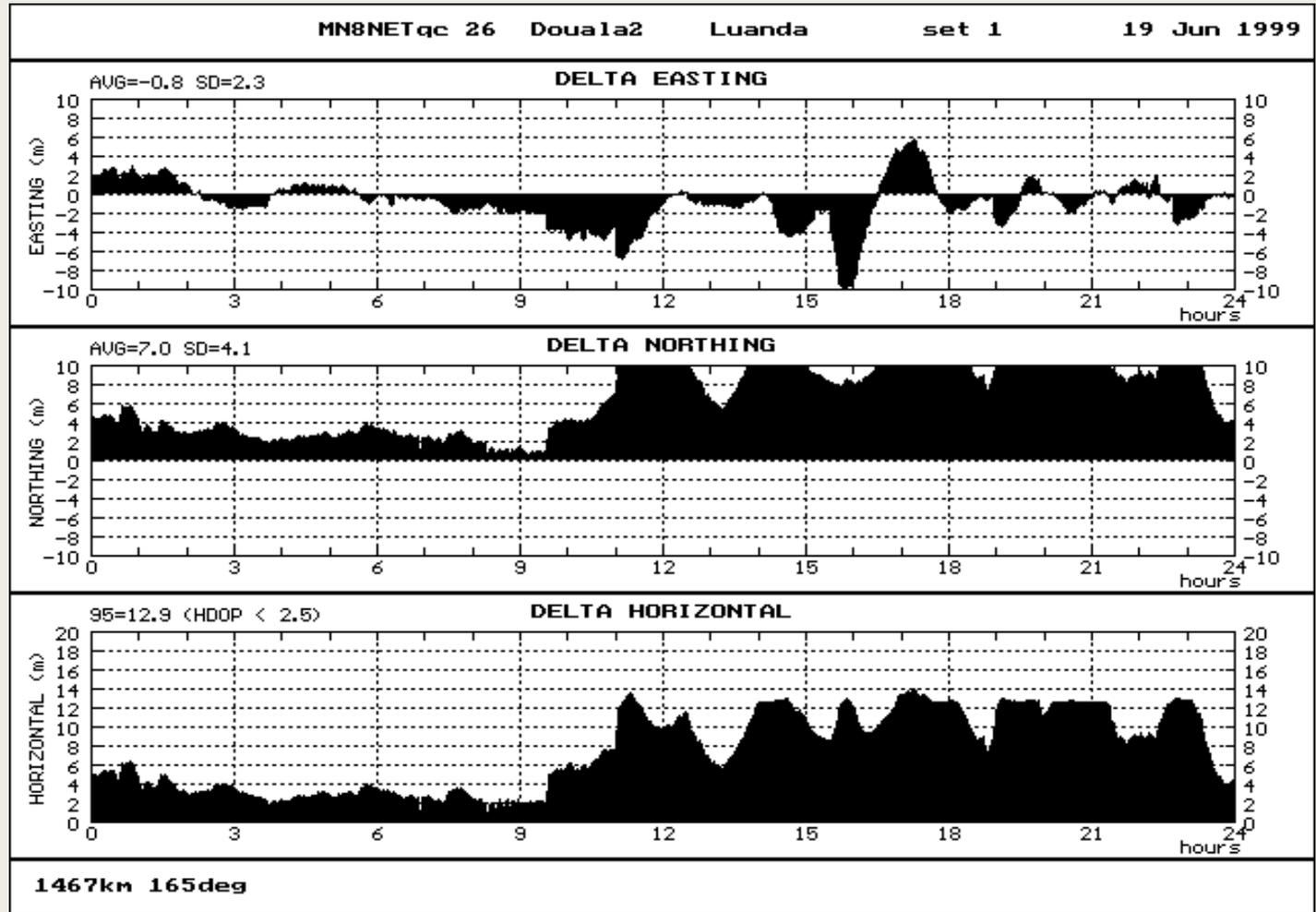
NOAA/SEC Boulder, CO USA



Single Frequency Douala - Luanda (1467 km) June 19, 1999

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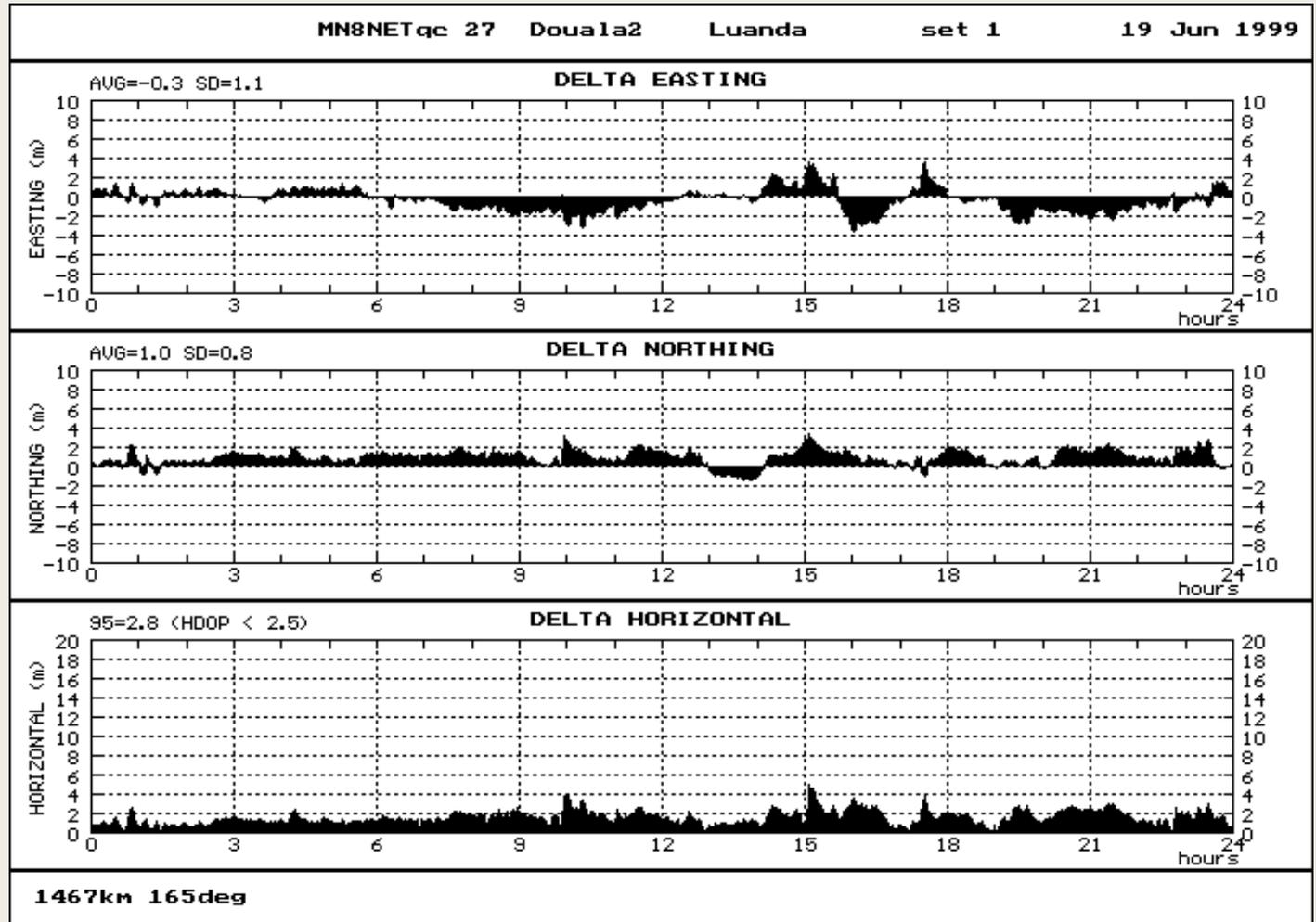
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Dual Frequency Douala - Luanda (1467 km) June 19, 1999

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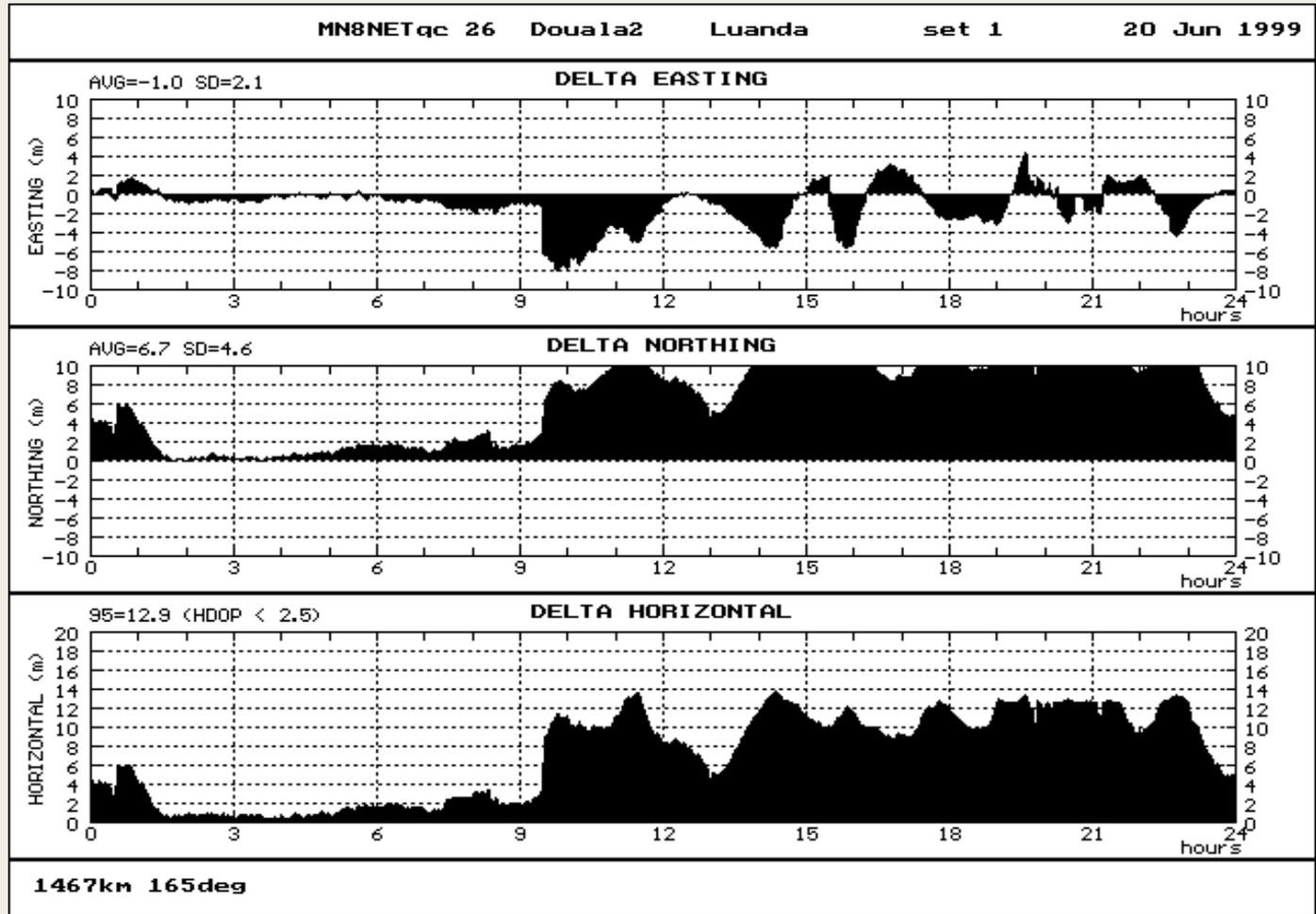
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Single Frequency Douala - Luanda (1467 km) June 20, 1999

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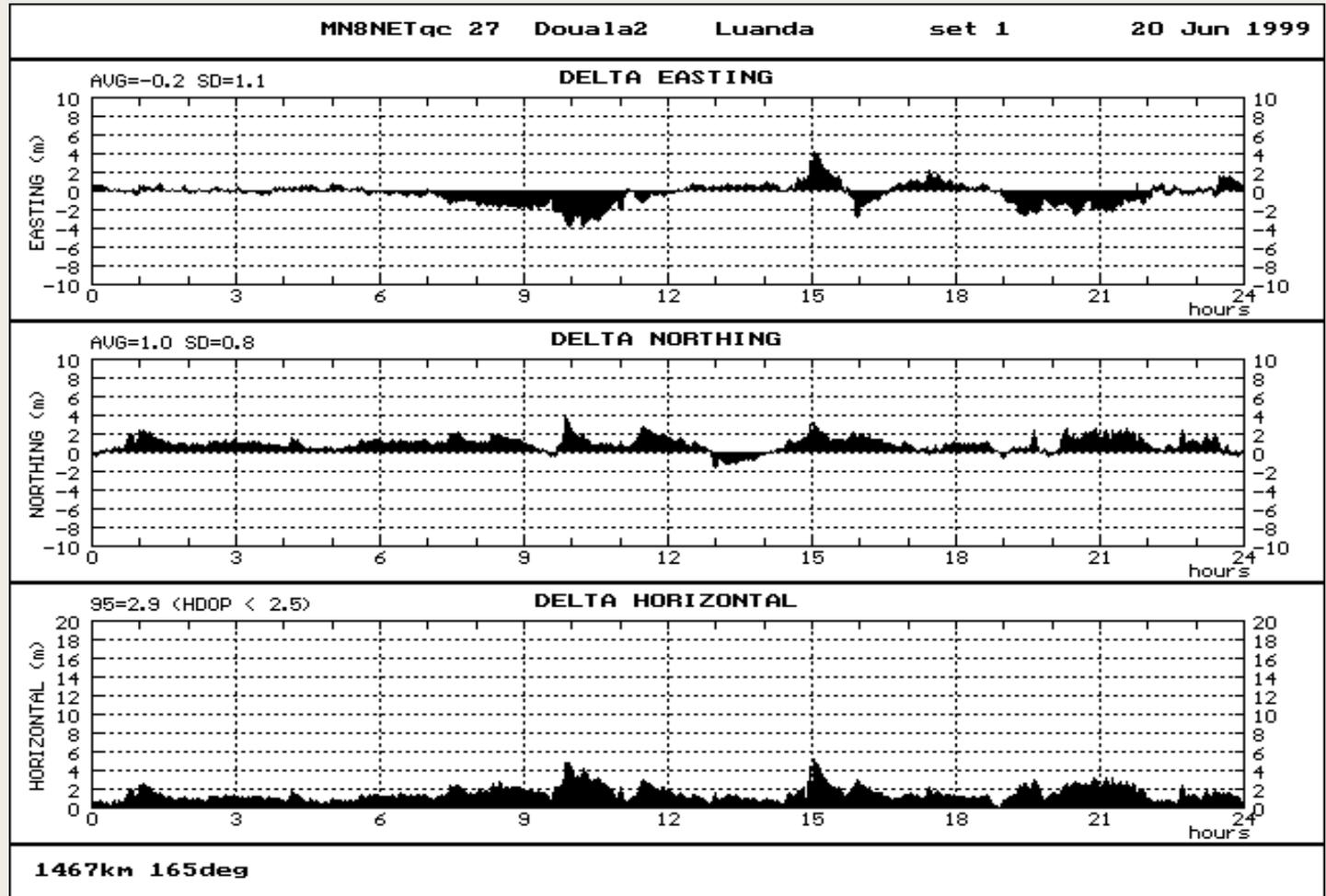
Precision GPS And Communications



Dual Frequency Douala - Luanda (1467 km) June 20, 1999

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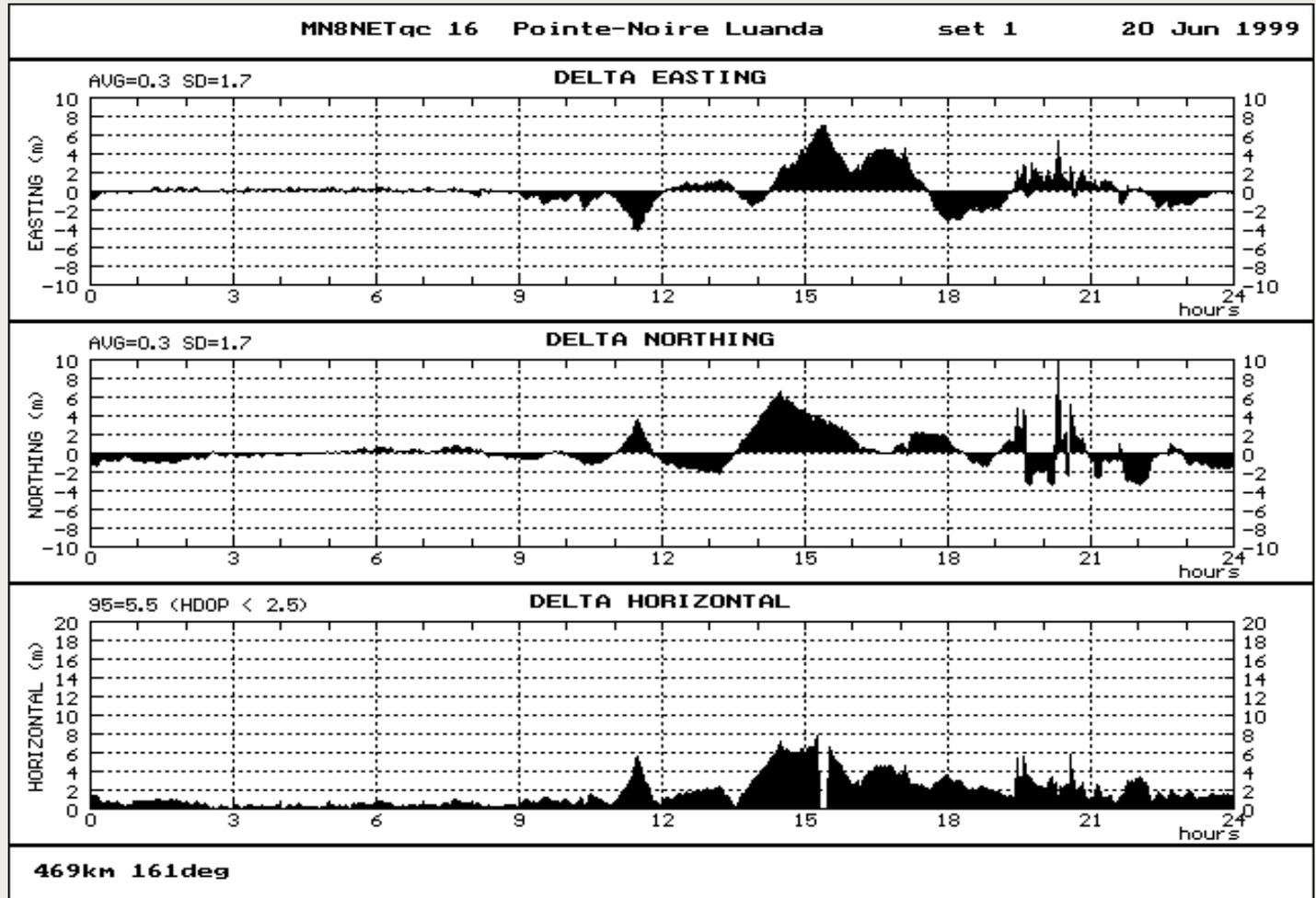
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Single Frequency Pointe-Noire Luanda (469 km) June 20, 1999

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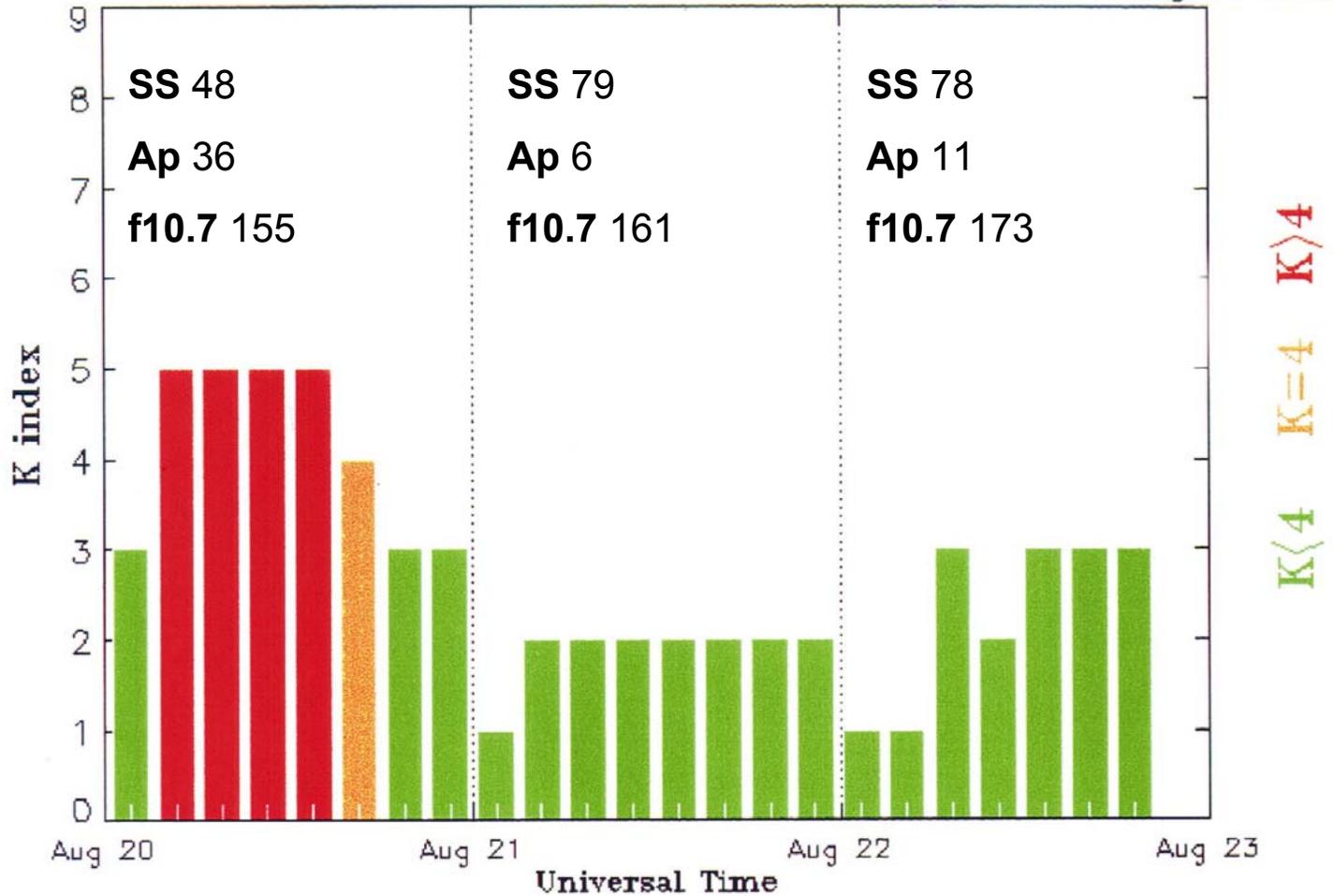


Index Levels August 20-22, 1999

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Estimated Planetary Kp index (3 hour data) Begin: 1999 Aug 20 0000UT



Updated 1999 Aug 22 23:45:07

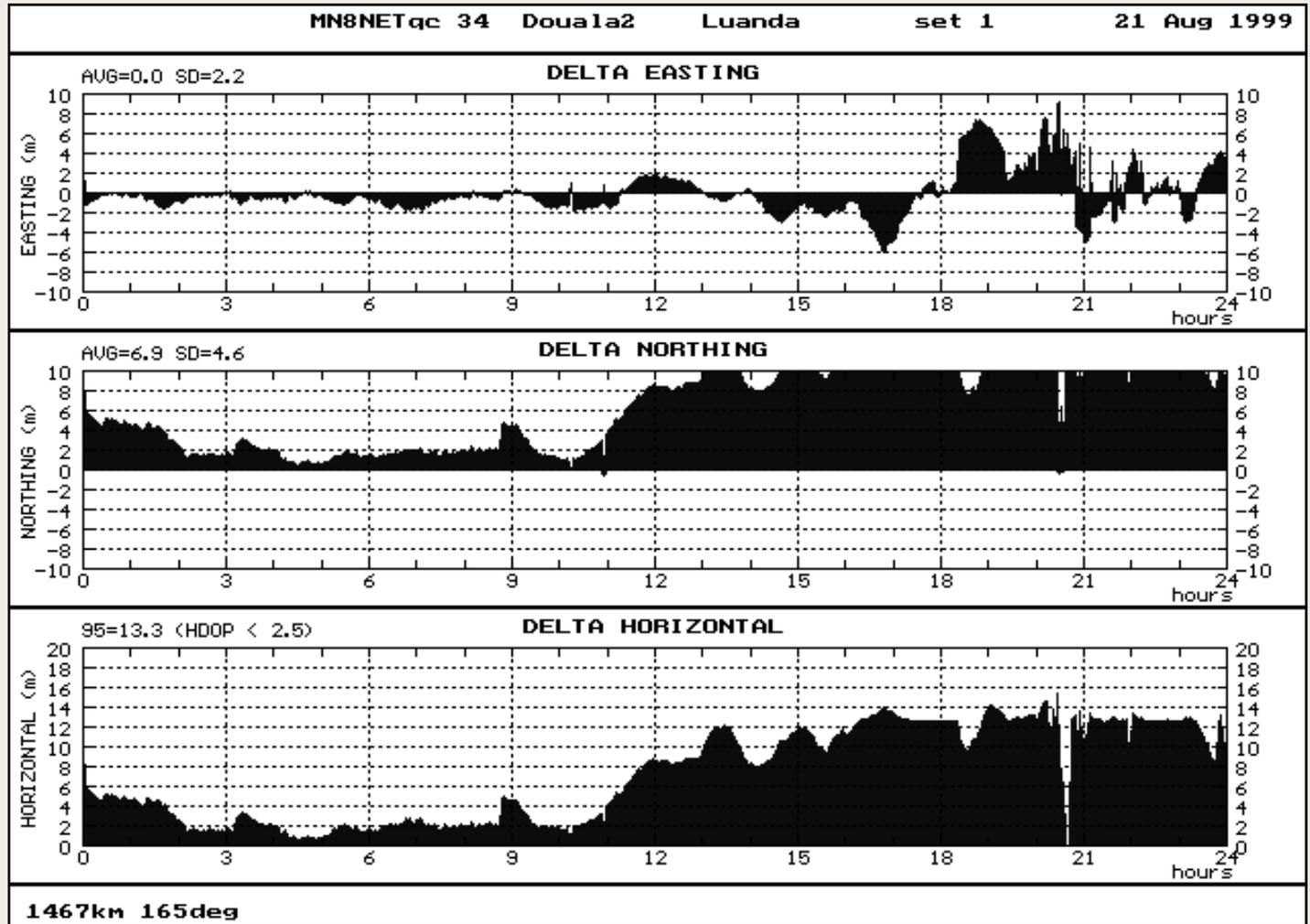
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Single Frequency Douala - Luanda (1467 km) August 21, 1999

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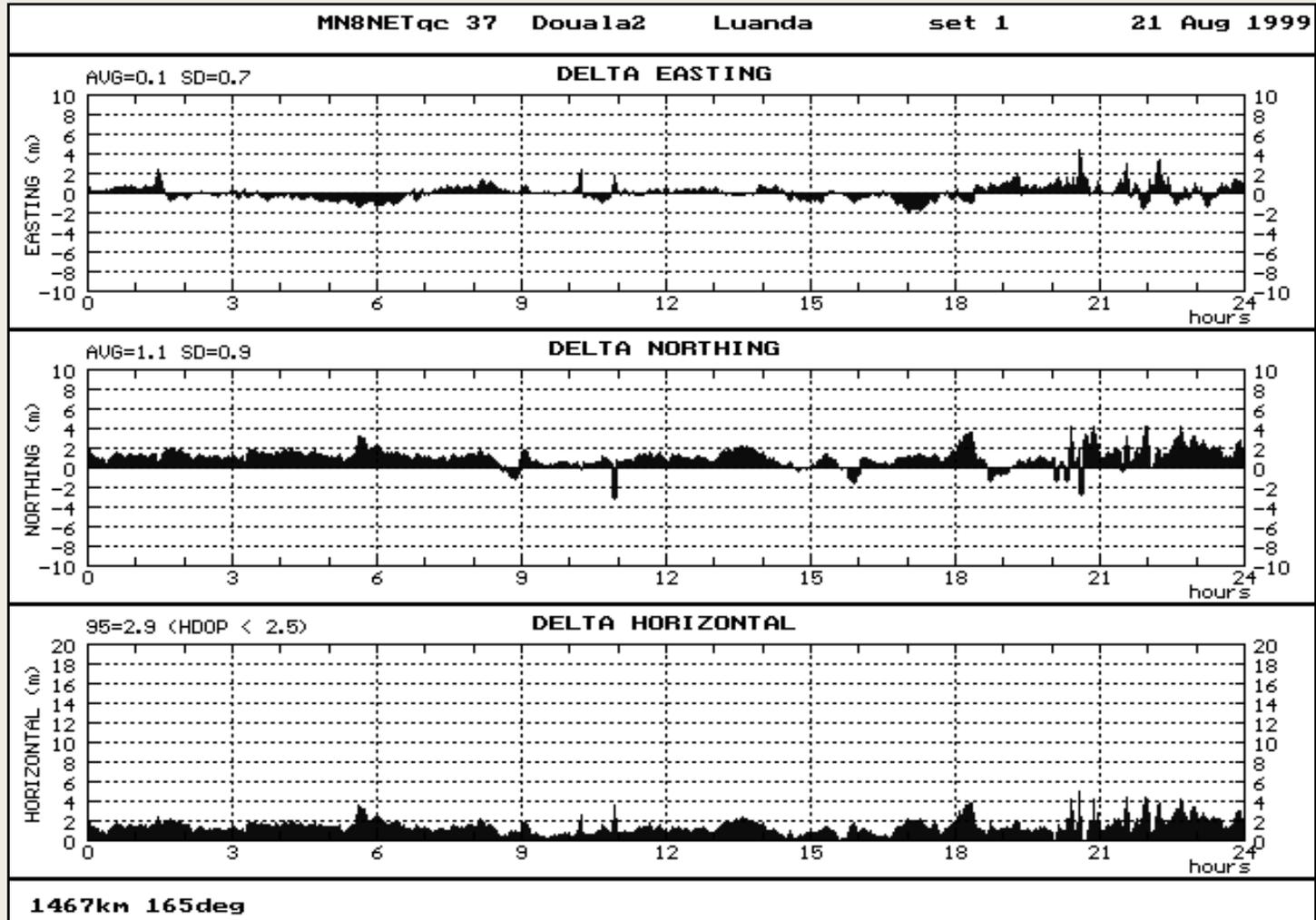
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Dual Frequency Douala - Luanda (1467 km) August 21, 1999

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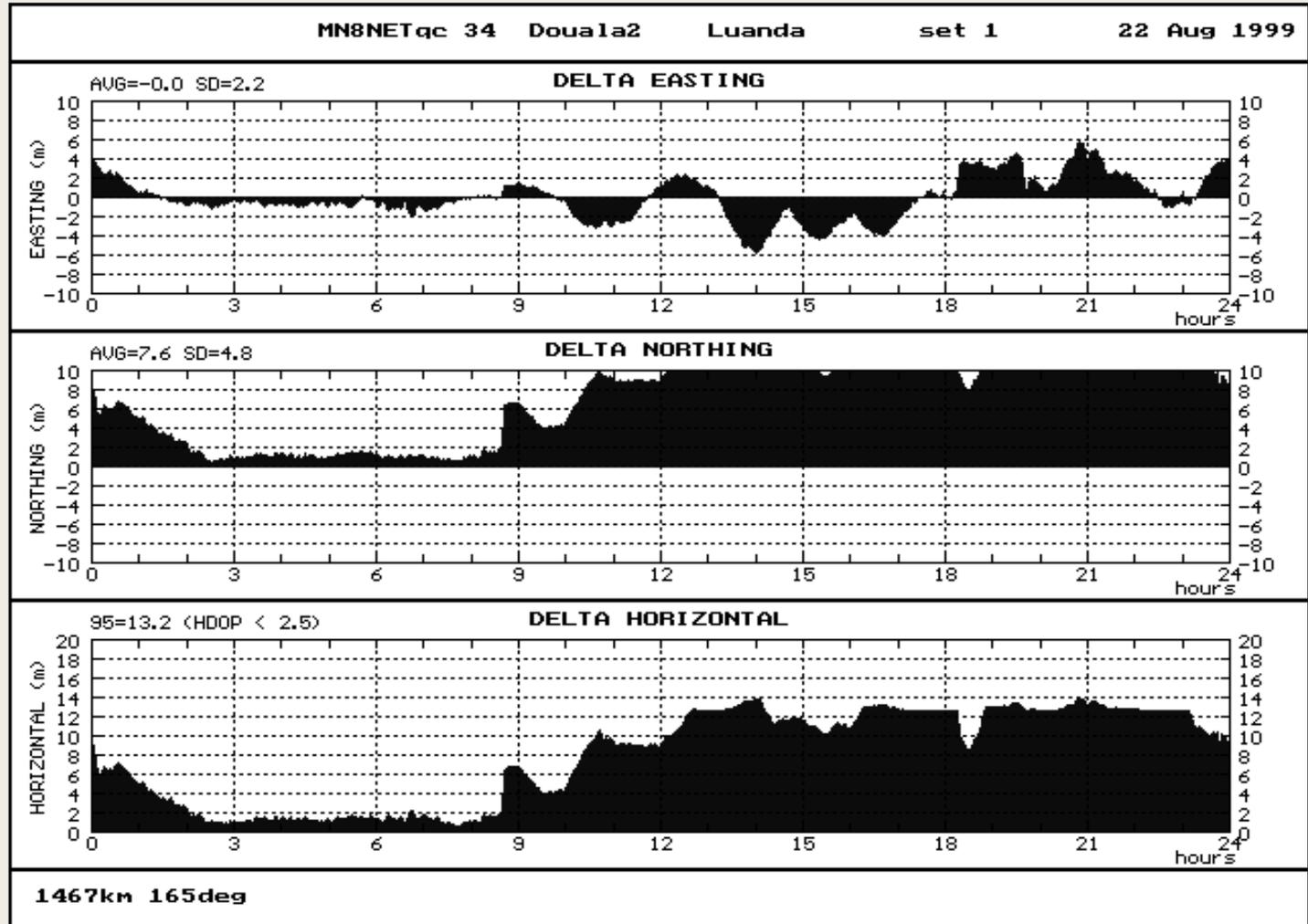




Single Frequency Douala - Luanda (1467 km) August 22, 1999

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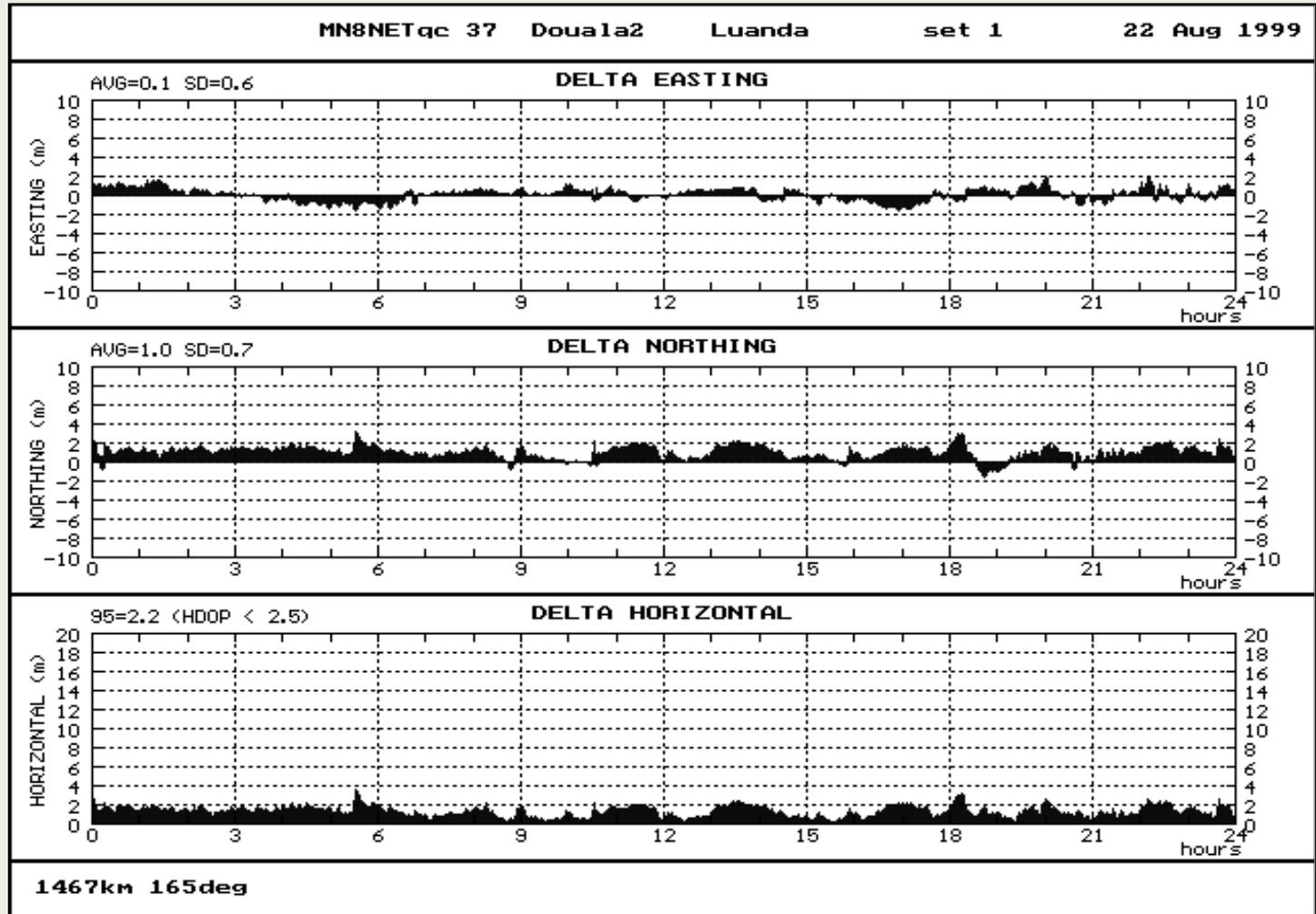




Dual Frequency Douala - Luanda (1467 km) August 22, 1999

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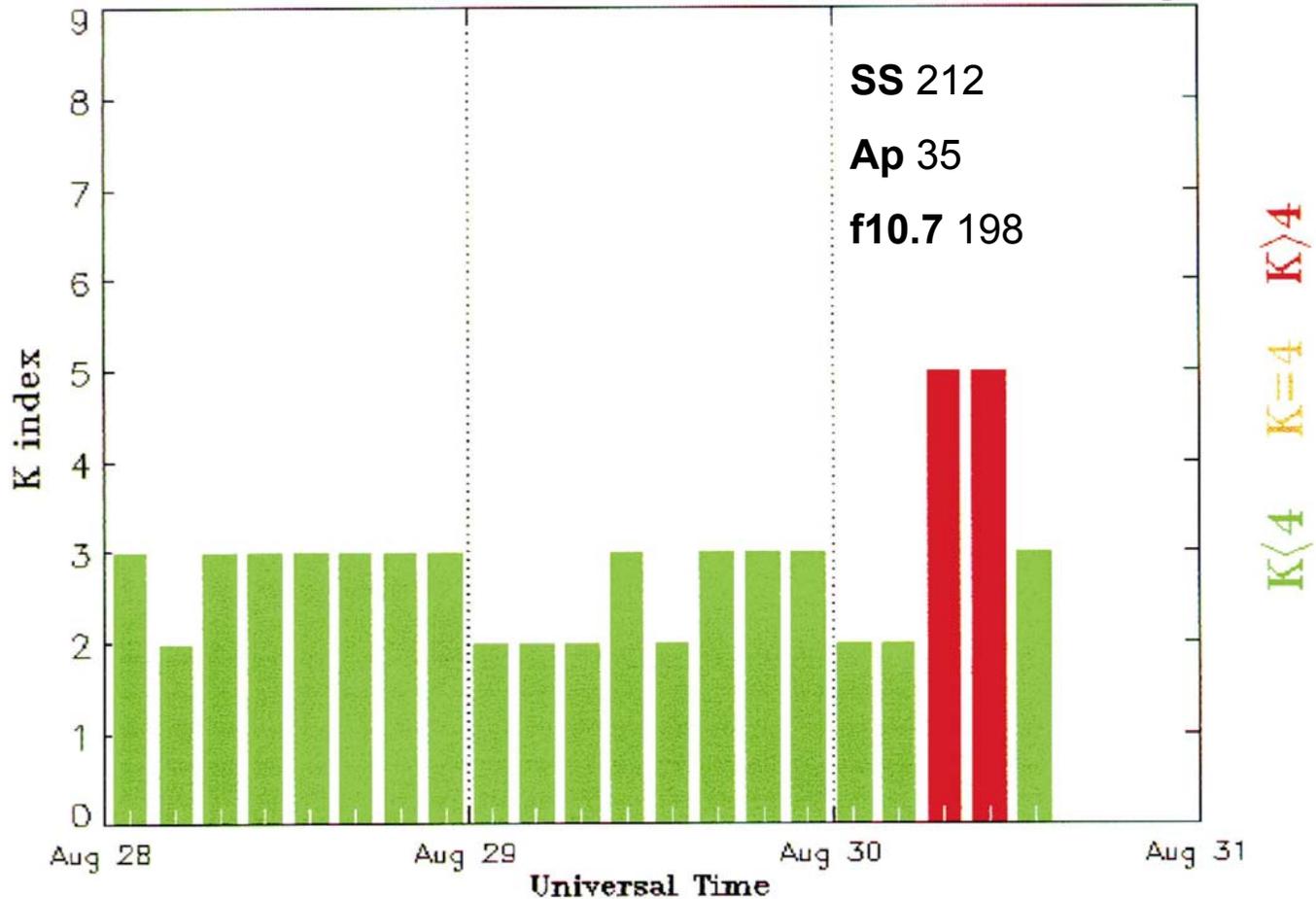


Index Levels August 28-30, 1999

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SS 212

Ap 35

f10.7 198

K < 4 K = 4 K > 4

Updated 1999 Aug 30 17:00:09

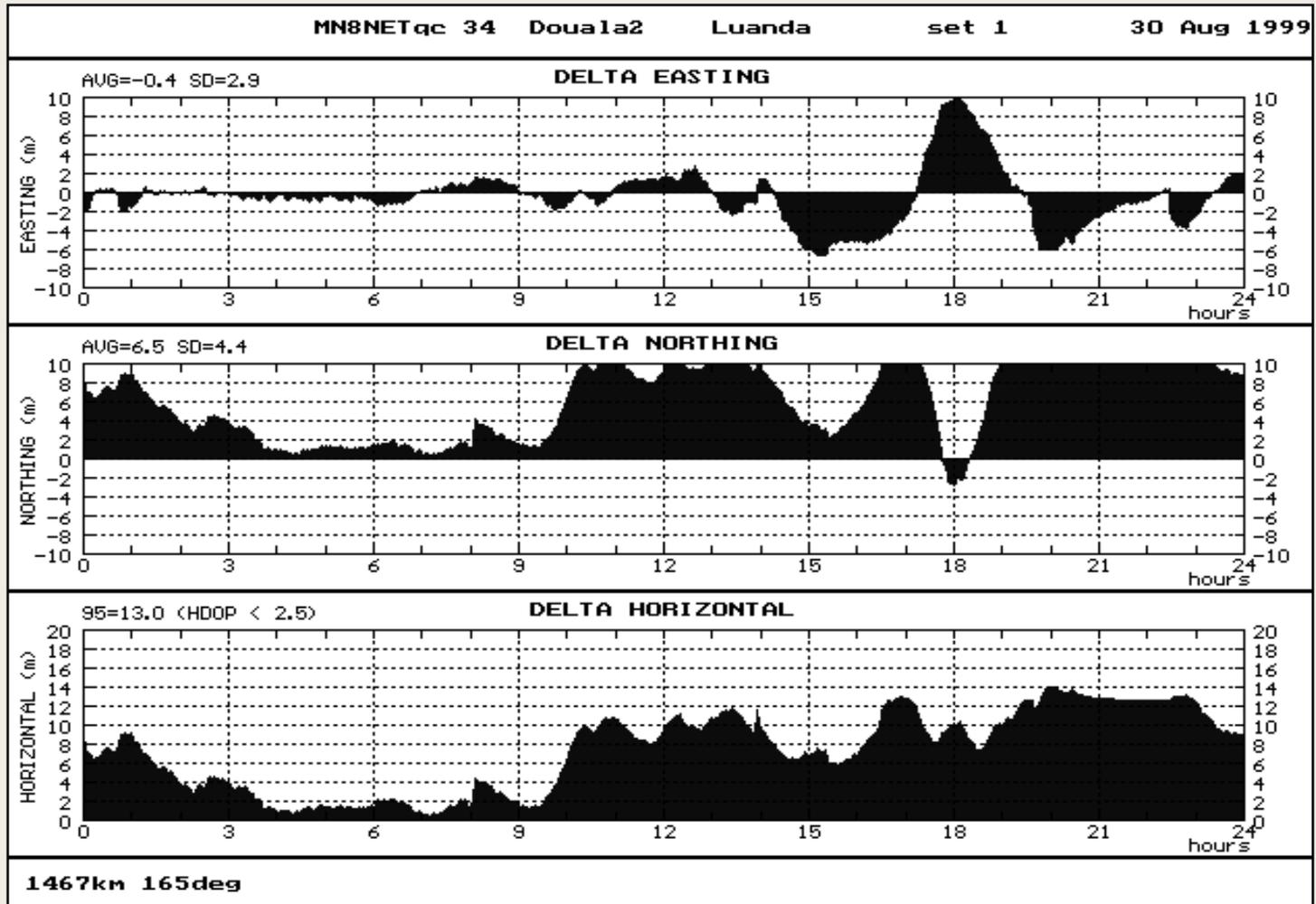
NOAA/SEC Boulder, CO USA



Single Frequency Douala - Luanda (1467 km) August 30, 1999

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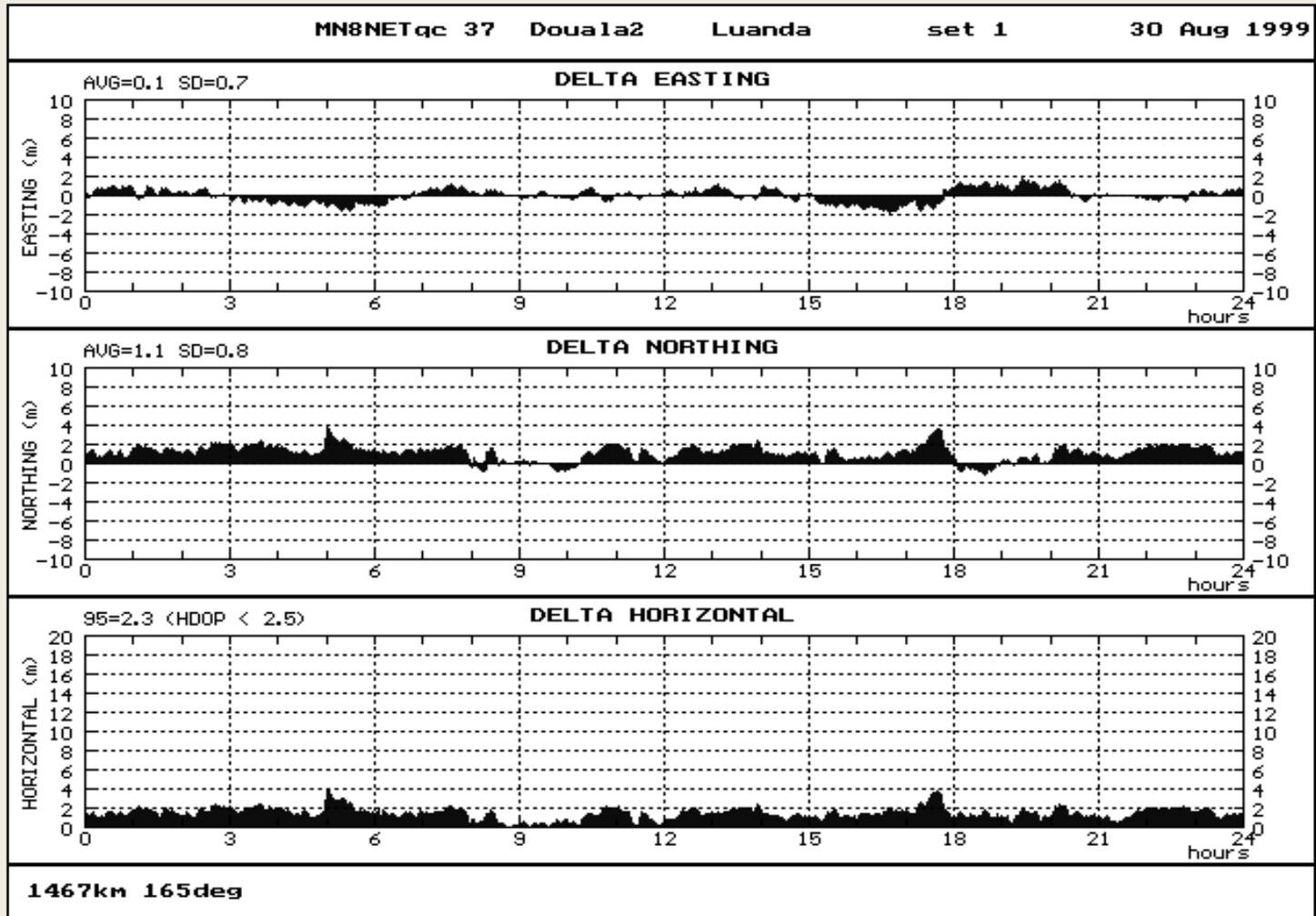




Dual Frequency Douala - Luanda (1467 km) August 30, 1999

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2000 DGPS Performance

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Scintillation Problems

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Index Levels

February 14-16, 2000

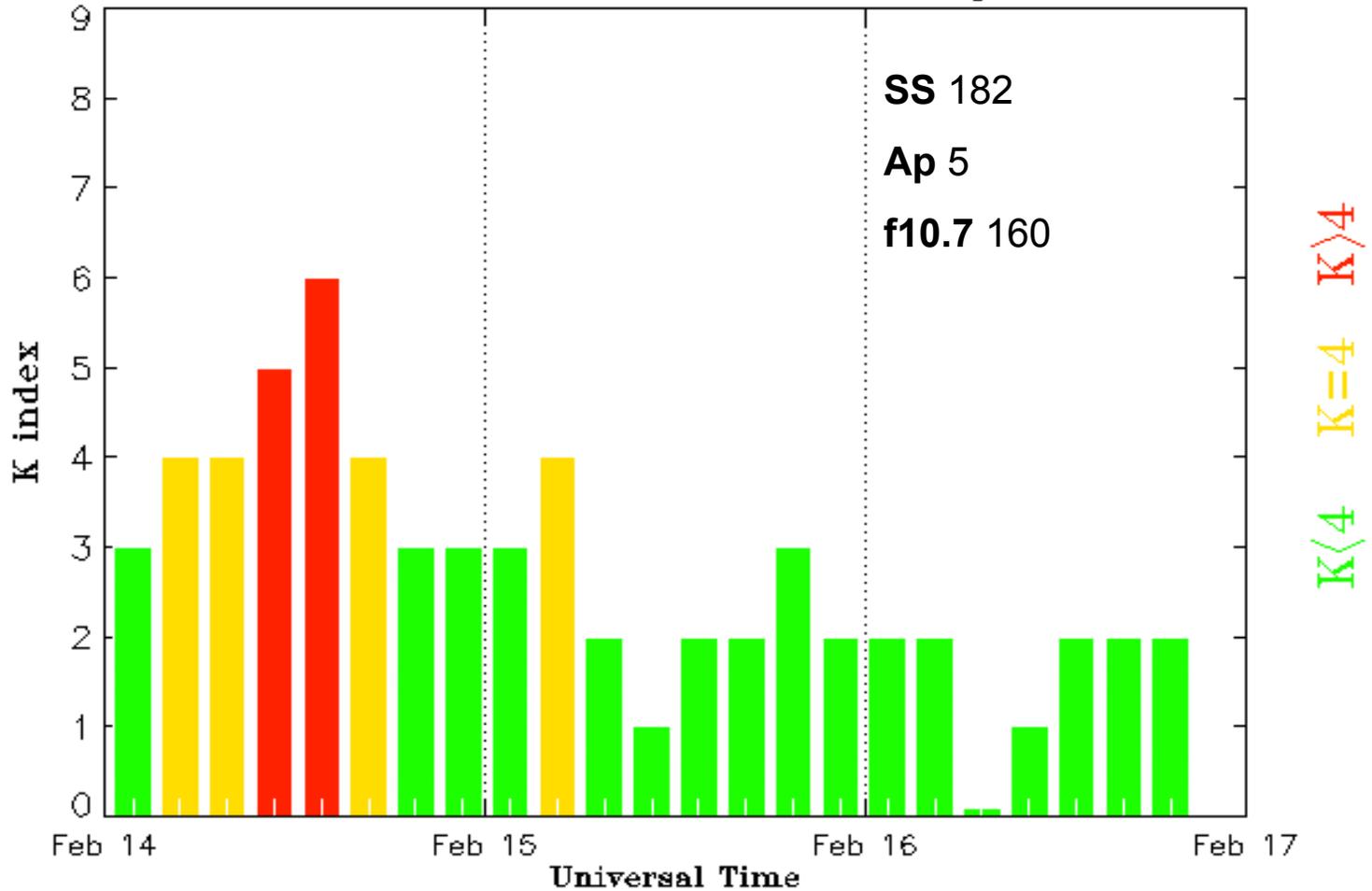
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Estimated Planetary Kp index (3 hour data)

Begin: 2000 Feb 14 0000UT



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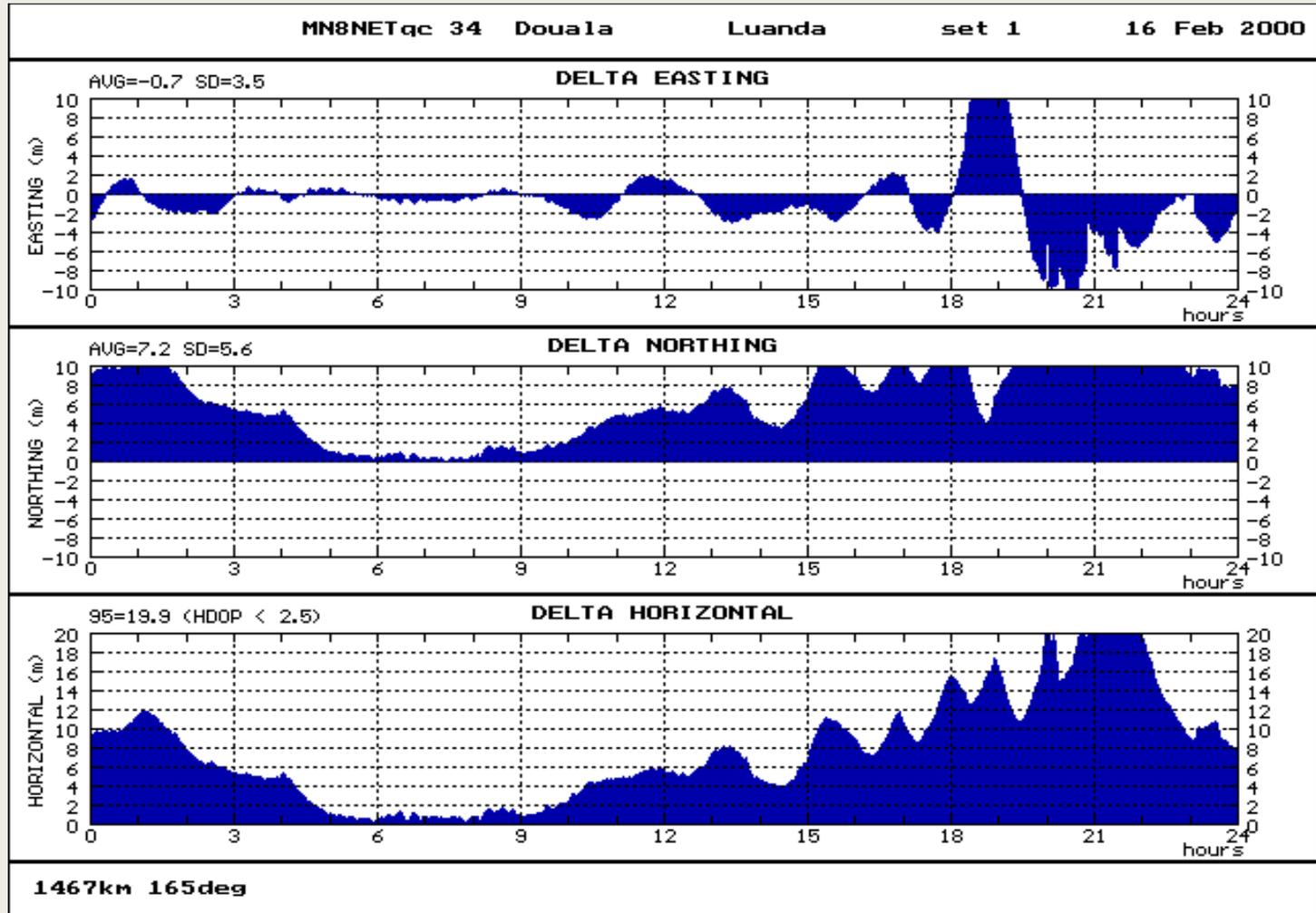
NOAA/SEC Boulder, CO USA



Single Frequency Douala - Luanda (1467km) Feb 16, 2000

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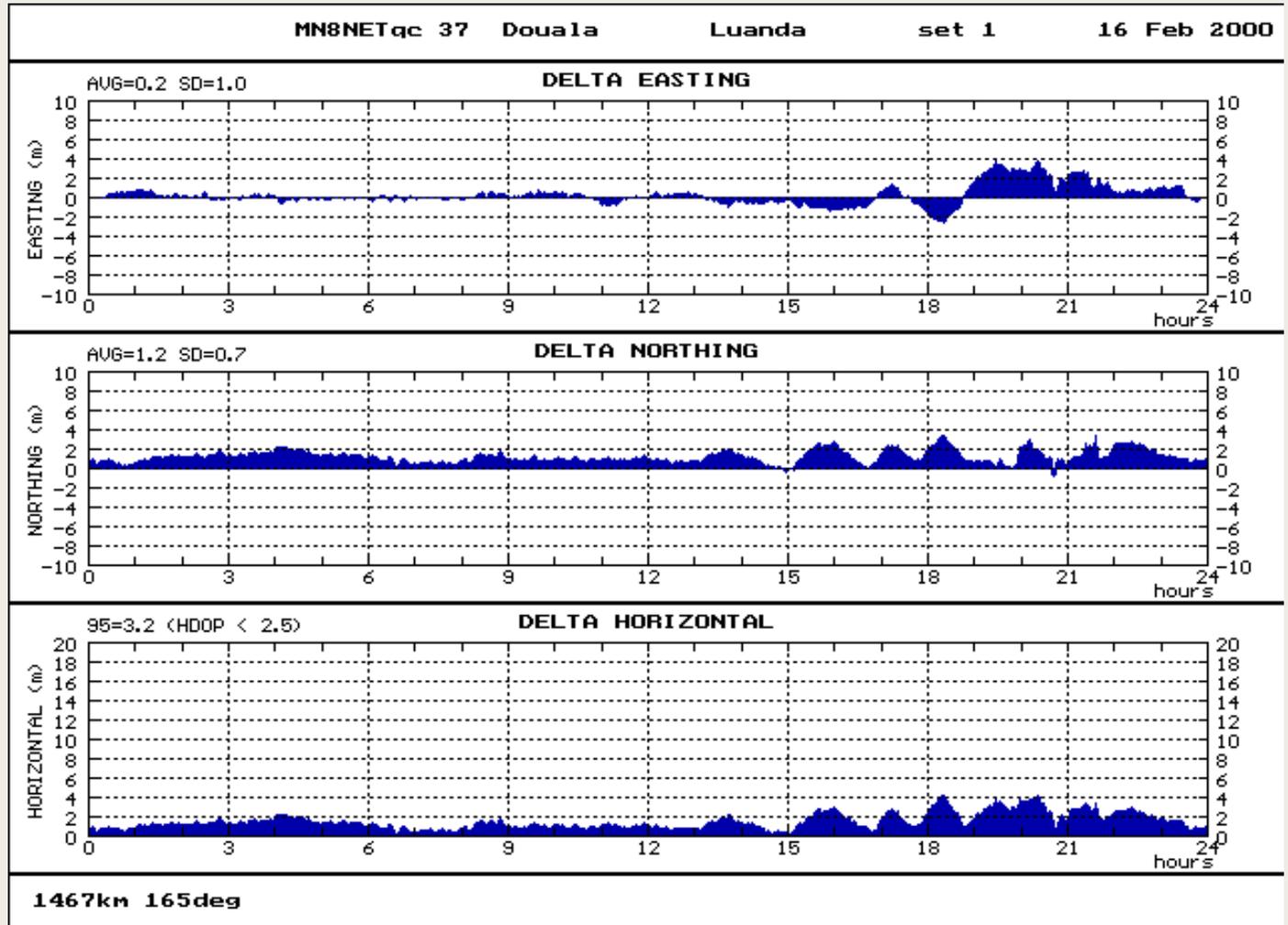
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Dual Frequency Douala - Luanda (1467km) Feb 16, 2000

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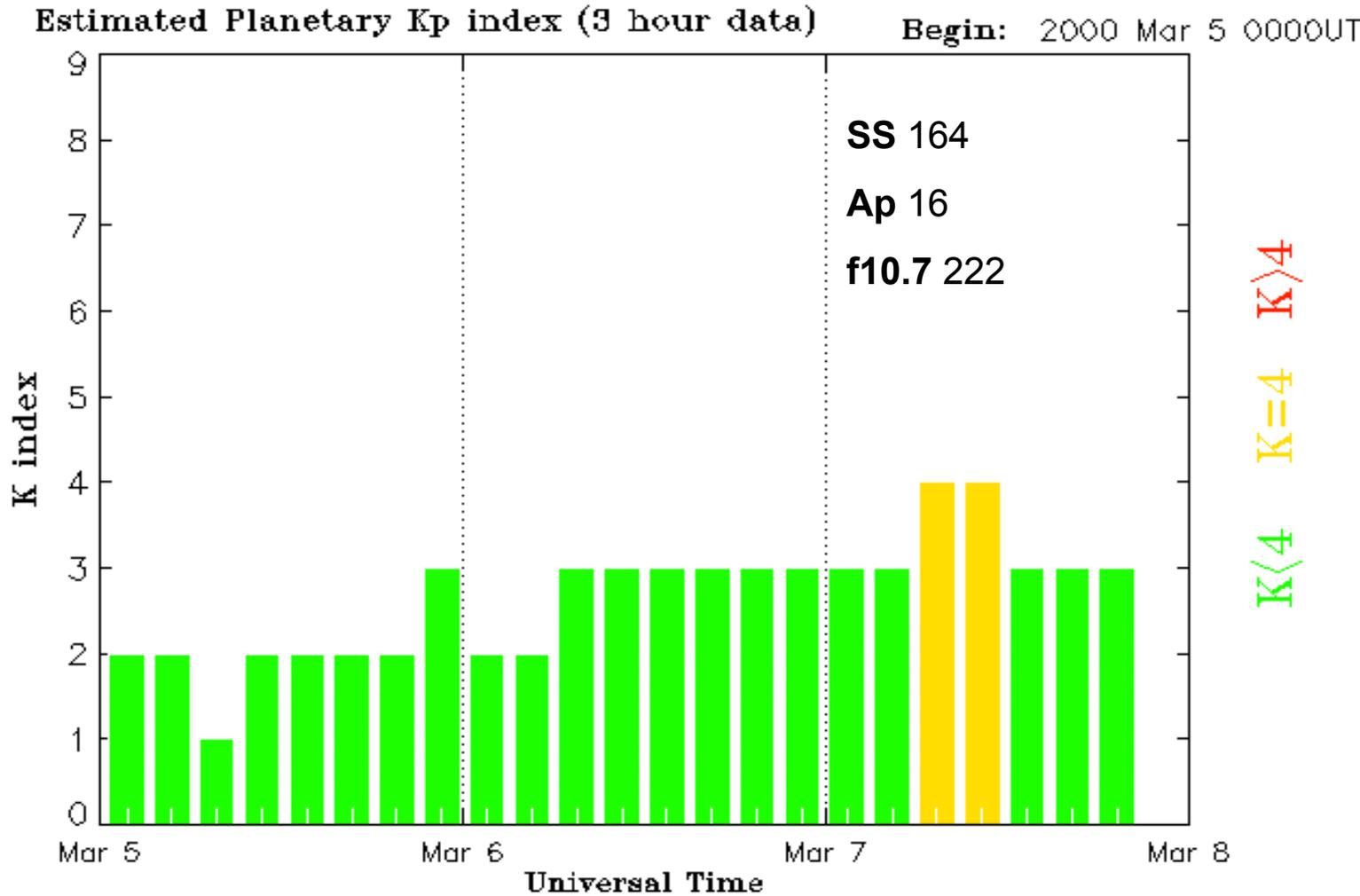
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Index Levels

March 7, 2000

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Updated 2000 Mar 7 23:45:02

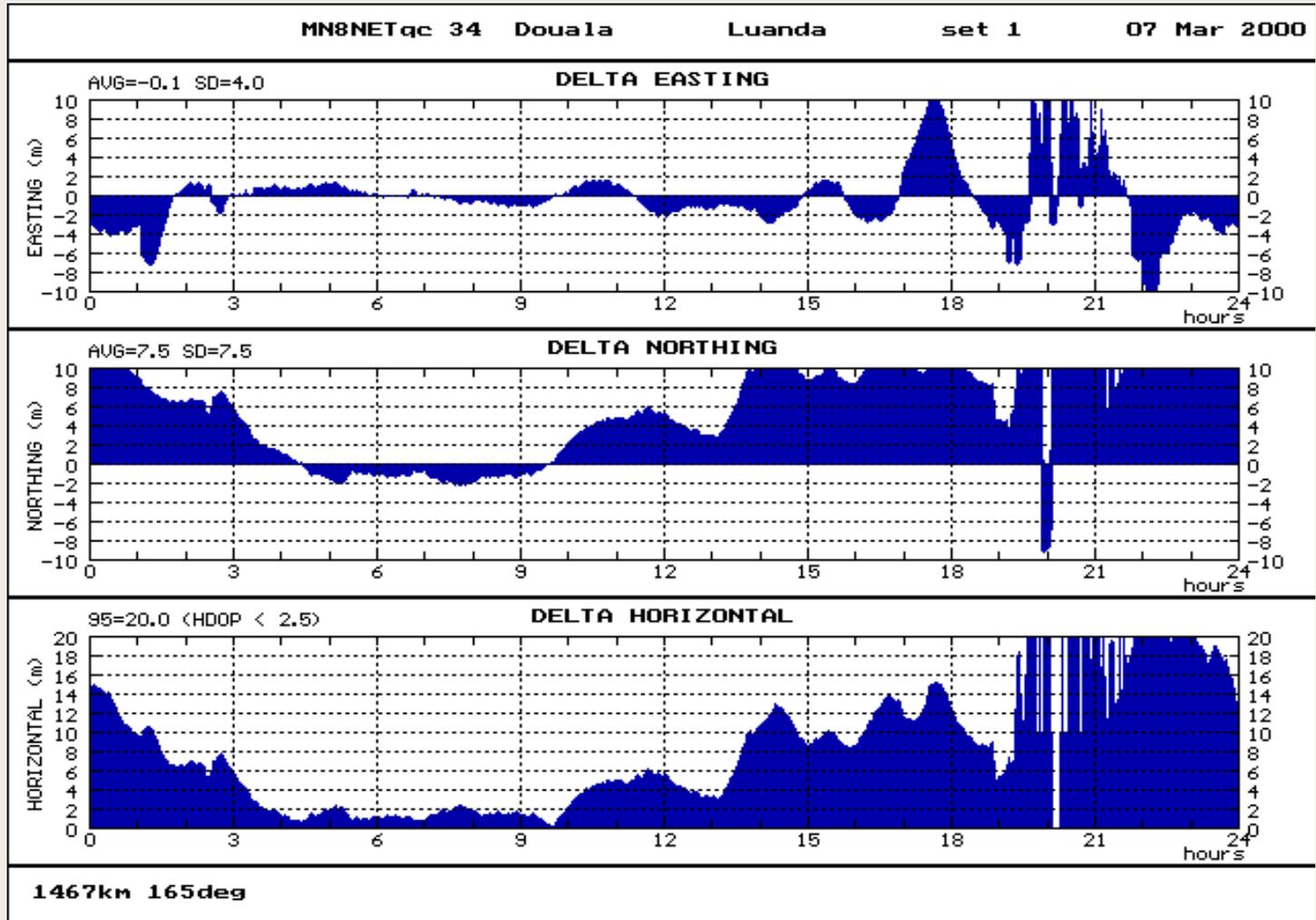
NOAA/SEC Boulder, CO USA

Single Frequency/Scintillations Douala - Luanda (1467km) Mar 7, 2000



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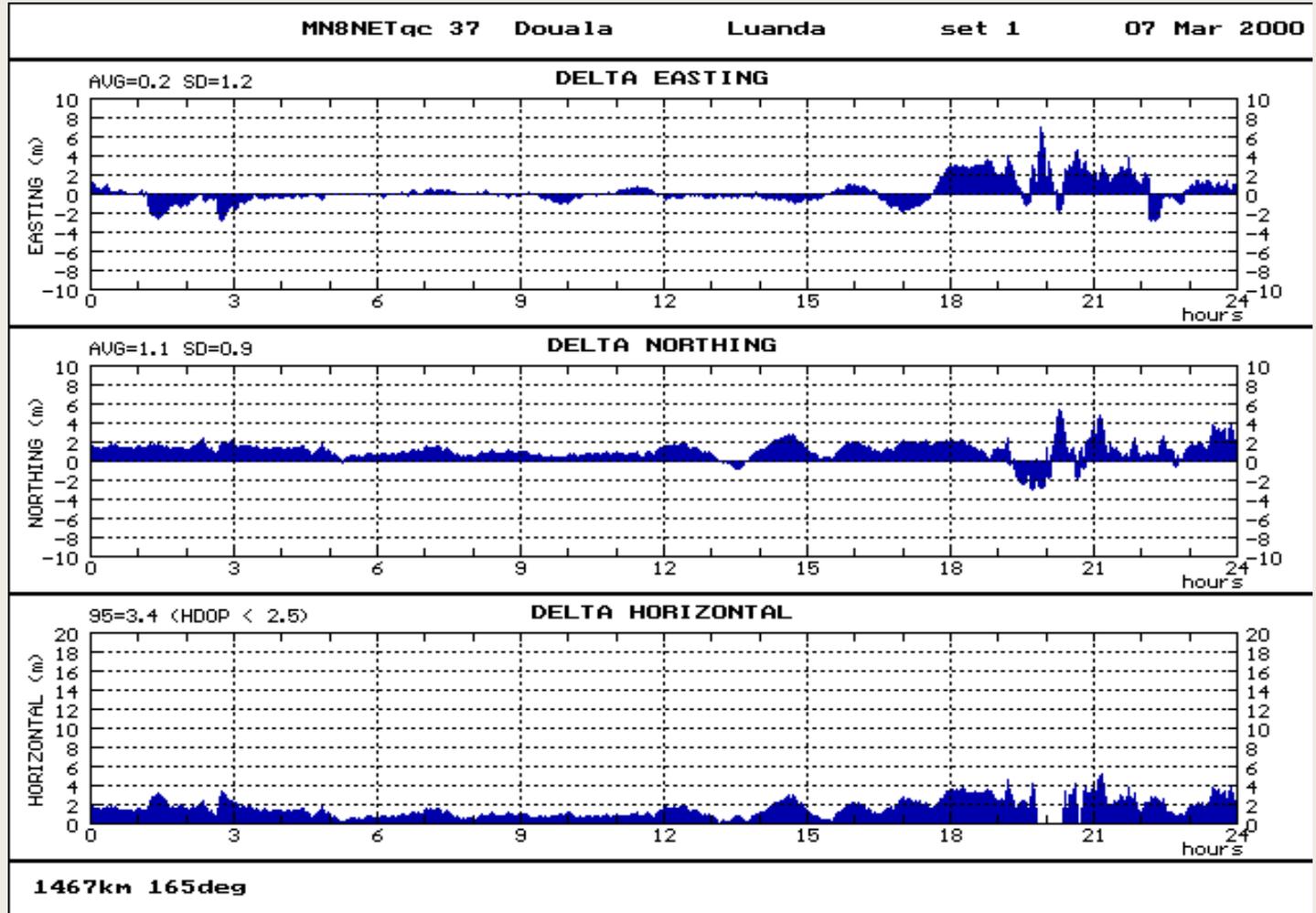




Dual Frequency/Scintillations Douala - Luanda (1467km) Mar 7, 2000

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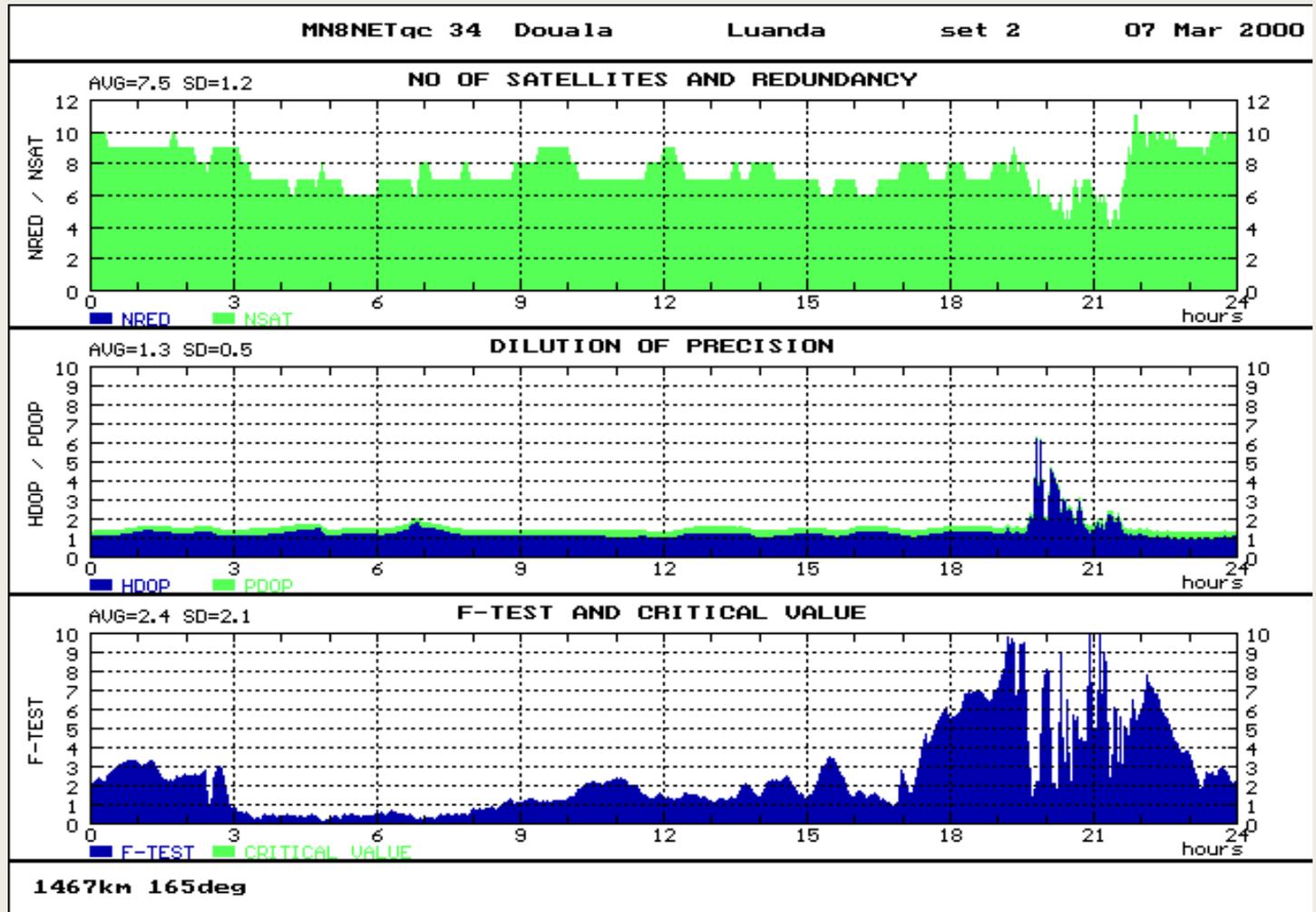




Single Frequency/Scintillations Douala - Luanda (1467km) Mar 7, 2000

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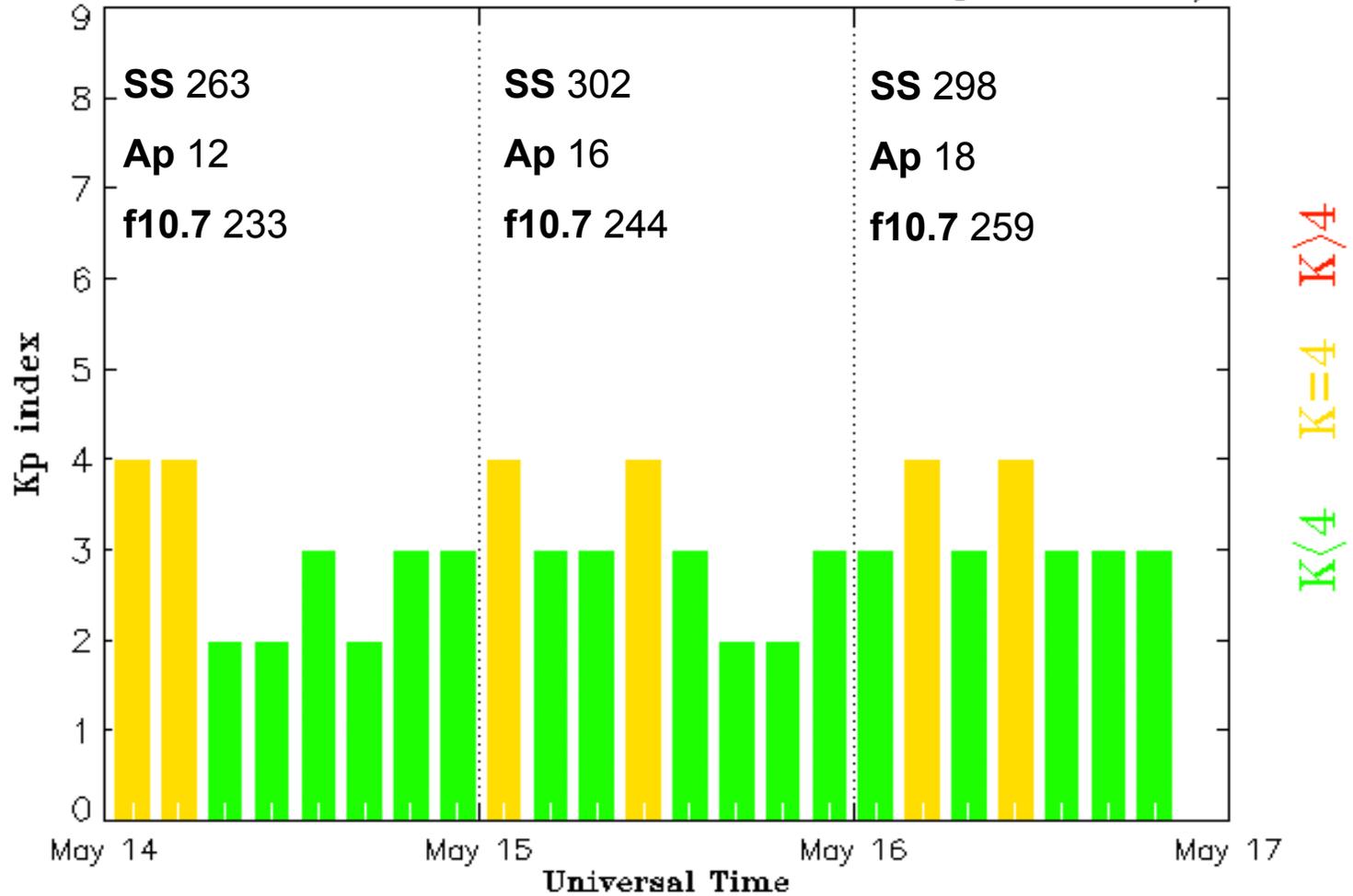
Index Levels May 14-16, 2000

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Estimated Planetary K index (3 hour data)

Begin: 2000 May 14 0000UT



Updated 2000 May 16 23:45:02

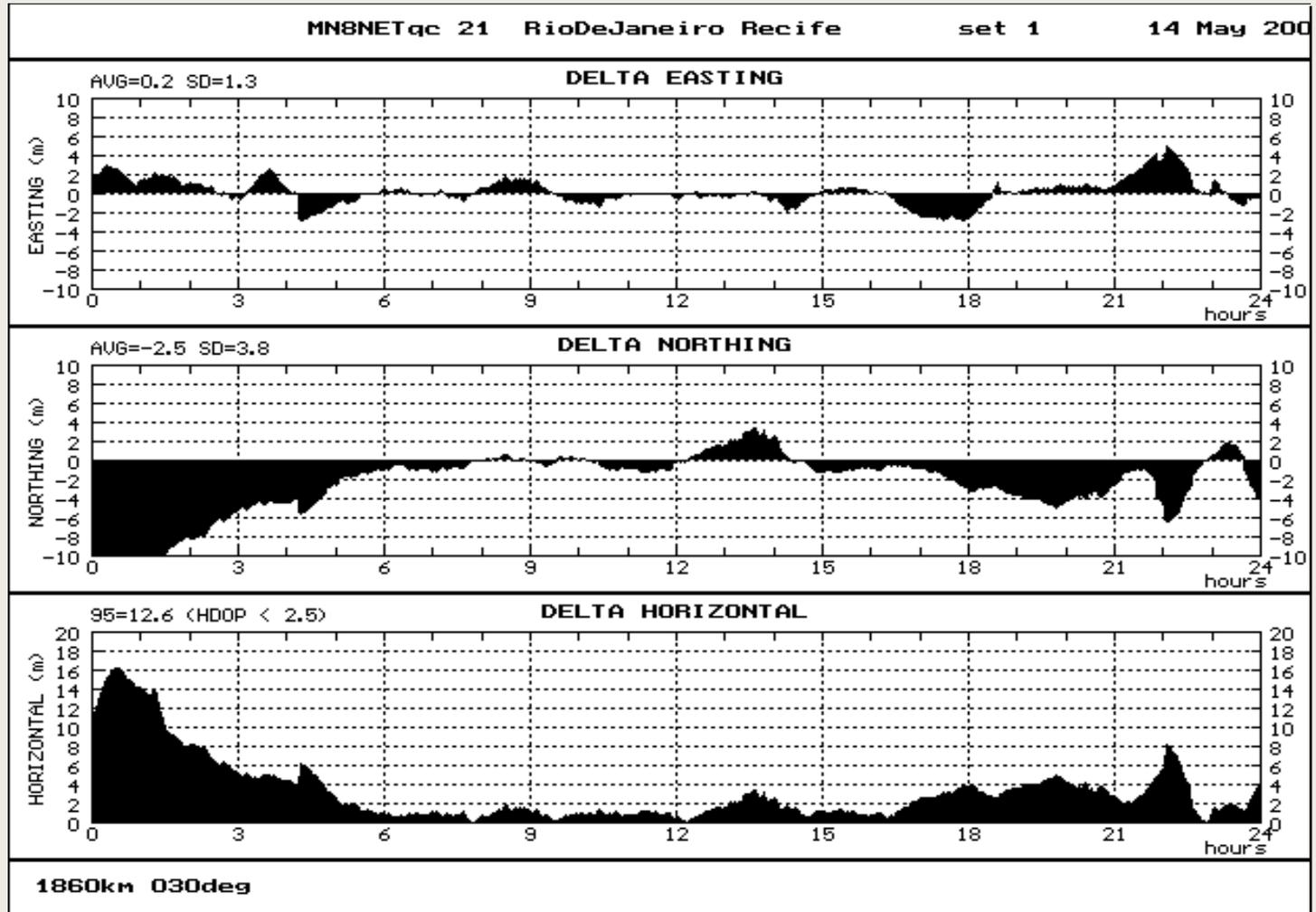
NOAA/SEC Boulder, CO USA



Single Frequency Rio de Janeiro - Recife 1860km May 14, 2000

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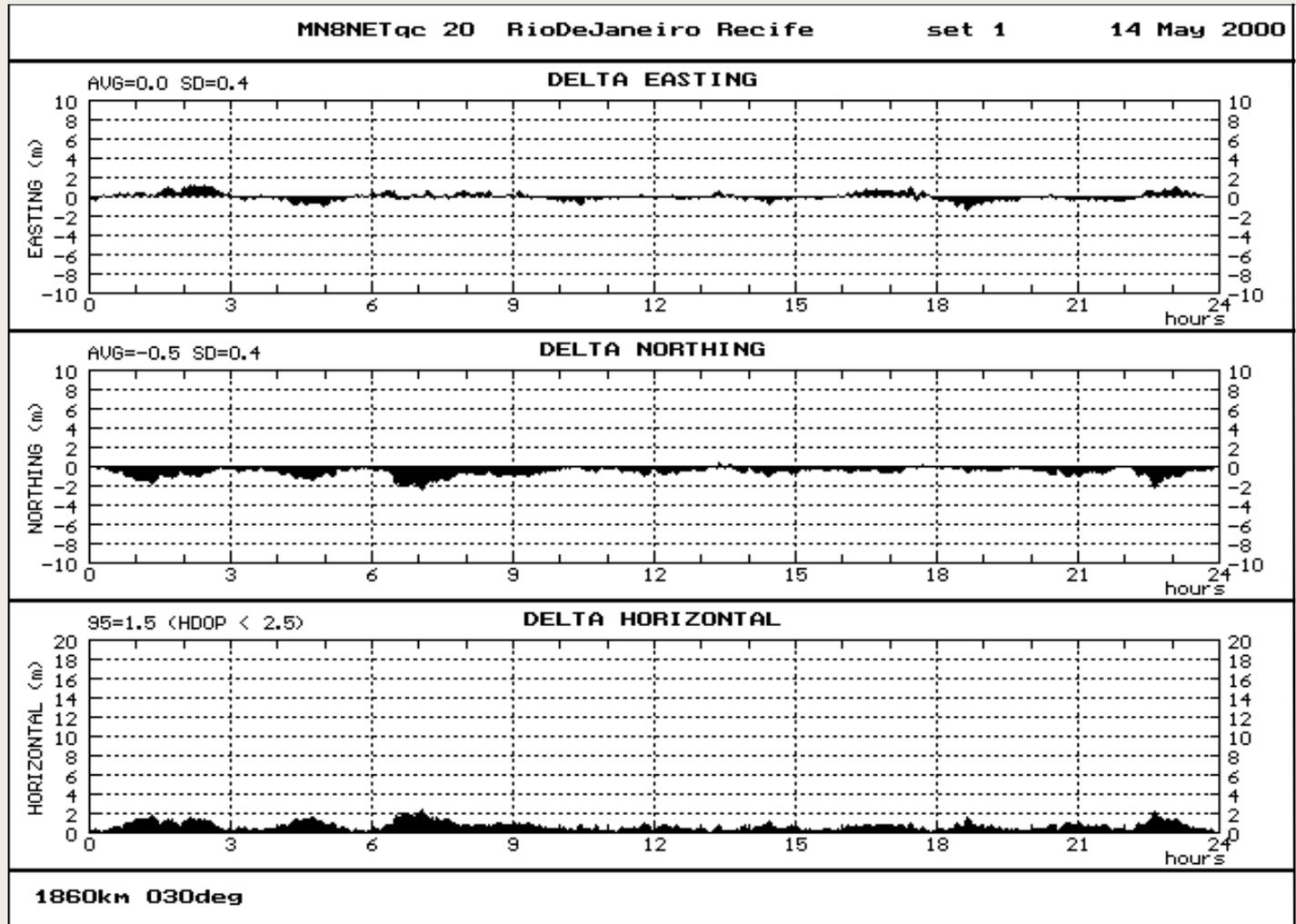
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Dual Frequency Rio de Janeiro - Recife 1860km May 14, 2000

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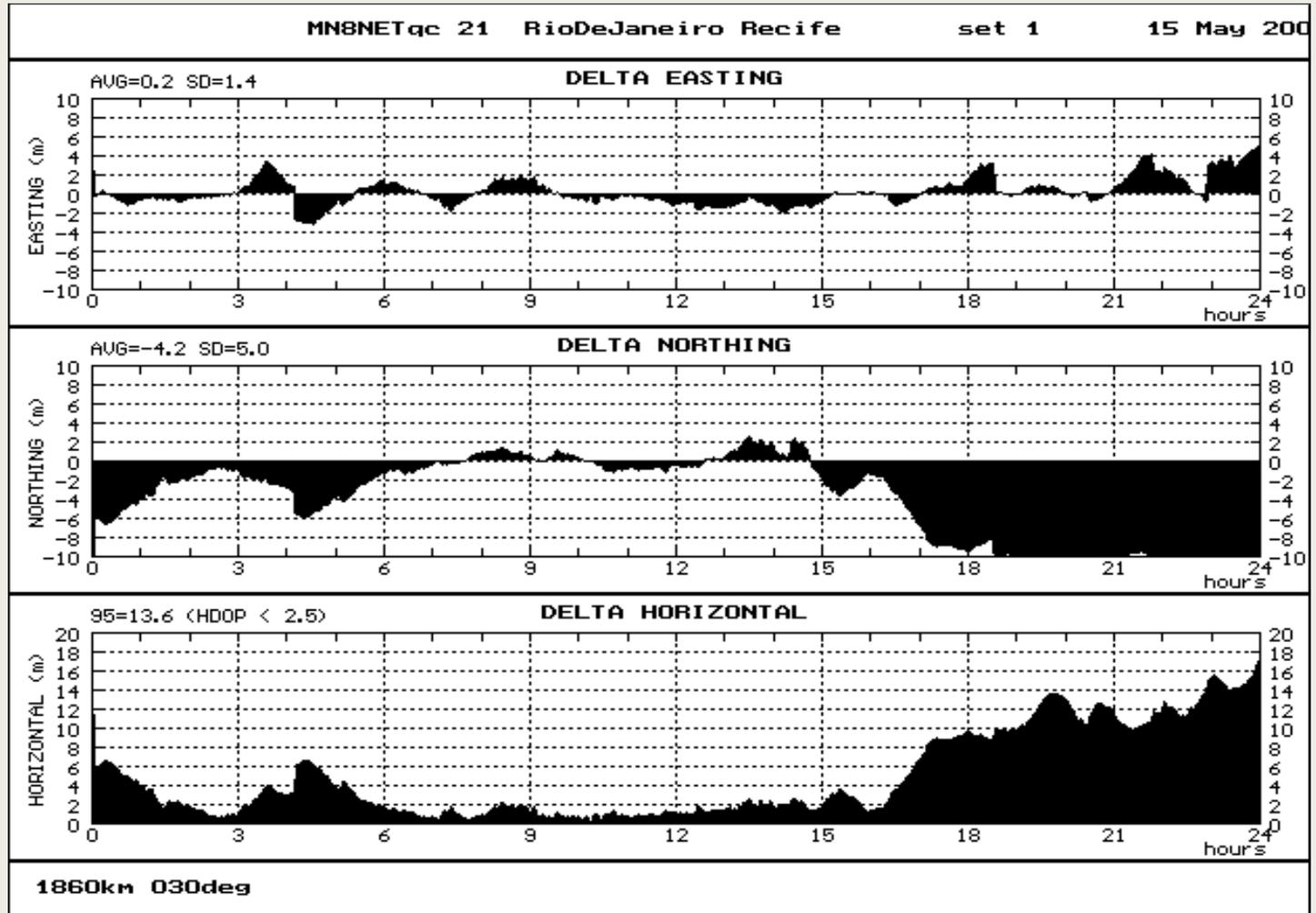




Single Frequency Rio de Janeiro - Recife 1860km May 15, 2000

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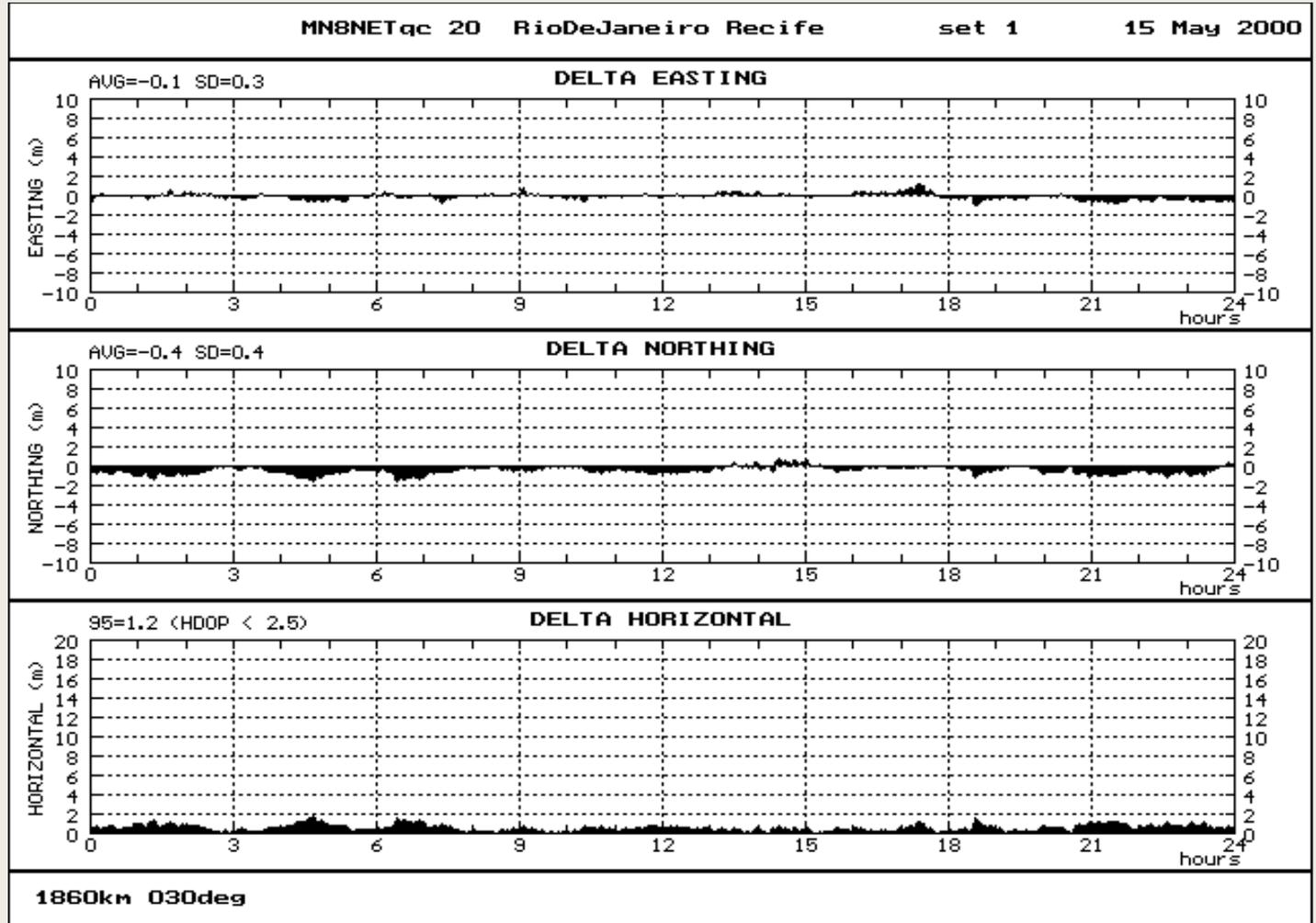




Dual Frequency Rio de Janeiro - Recife 1860km May 15, 2000

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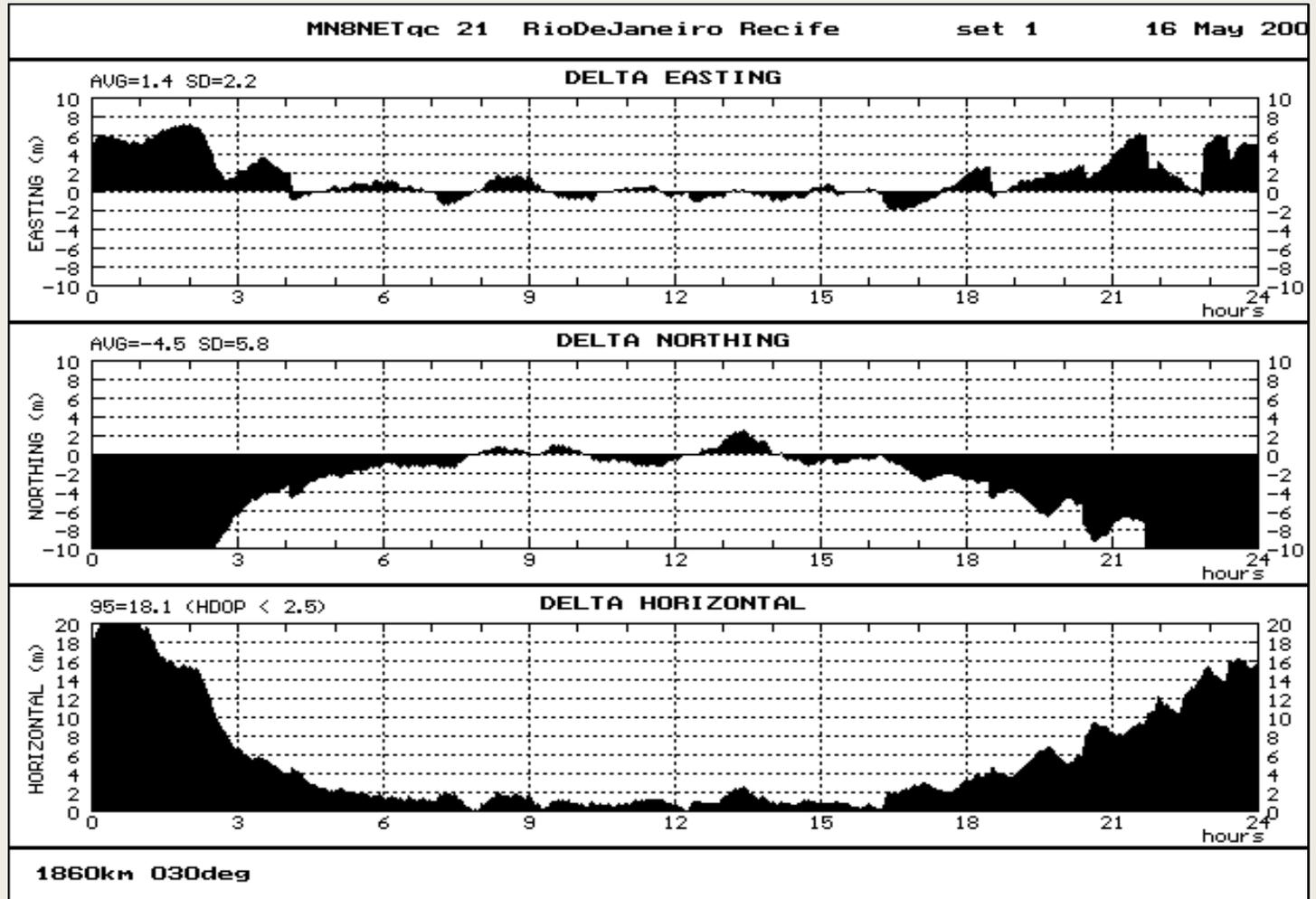
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Single Frequency Baseline Rio de Janeiro - Recife 1860km May 16, 2000

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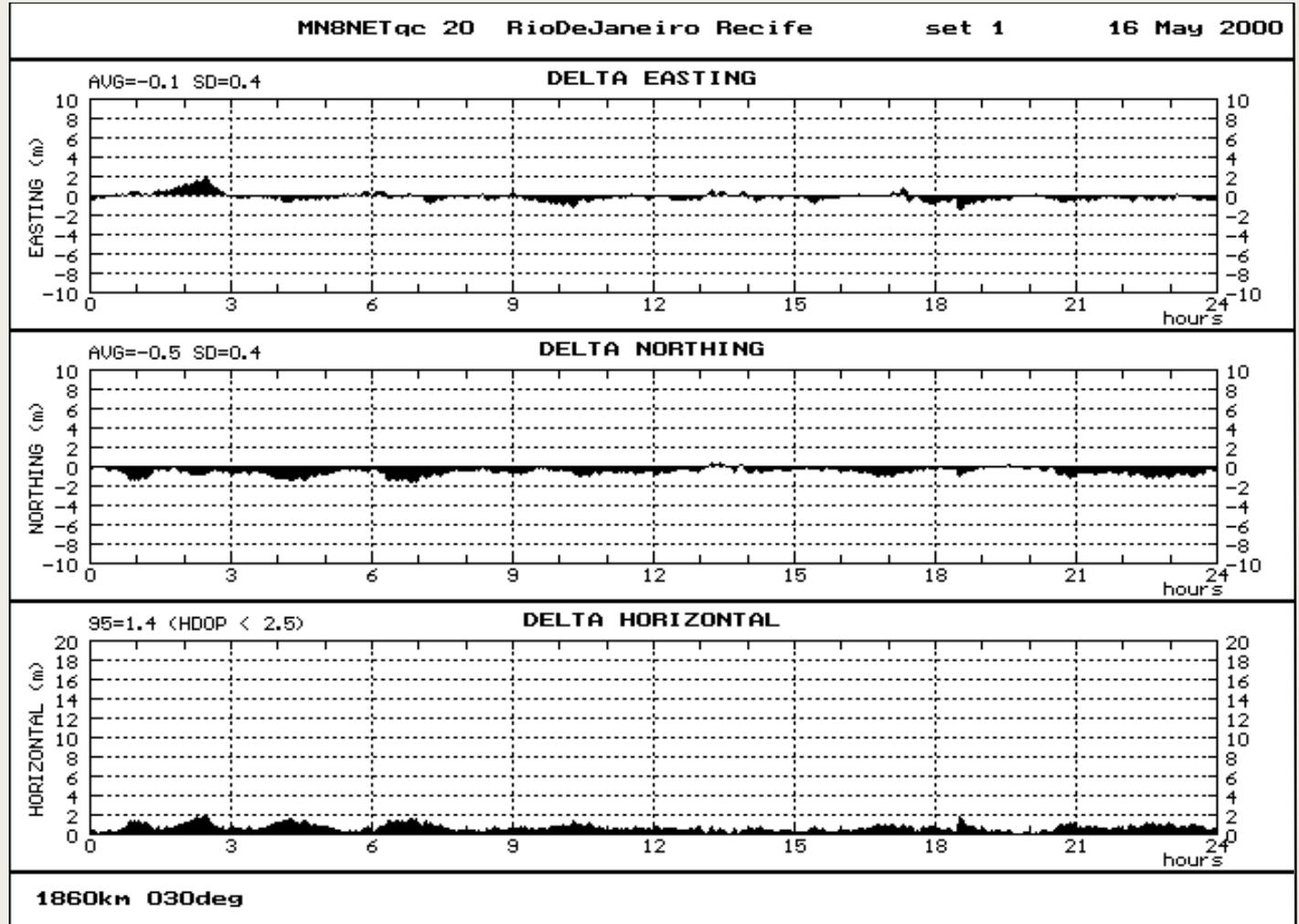




Dual Frequency Baseline Rio de Janeiro - Recife 1860km May 16, 2000

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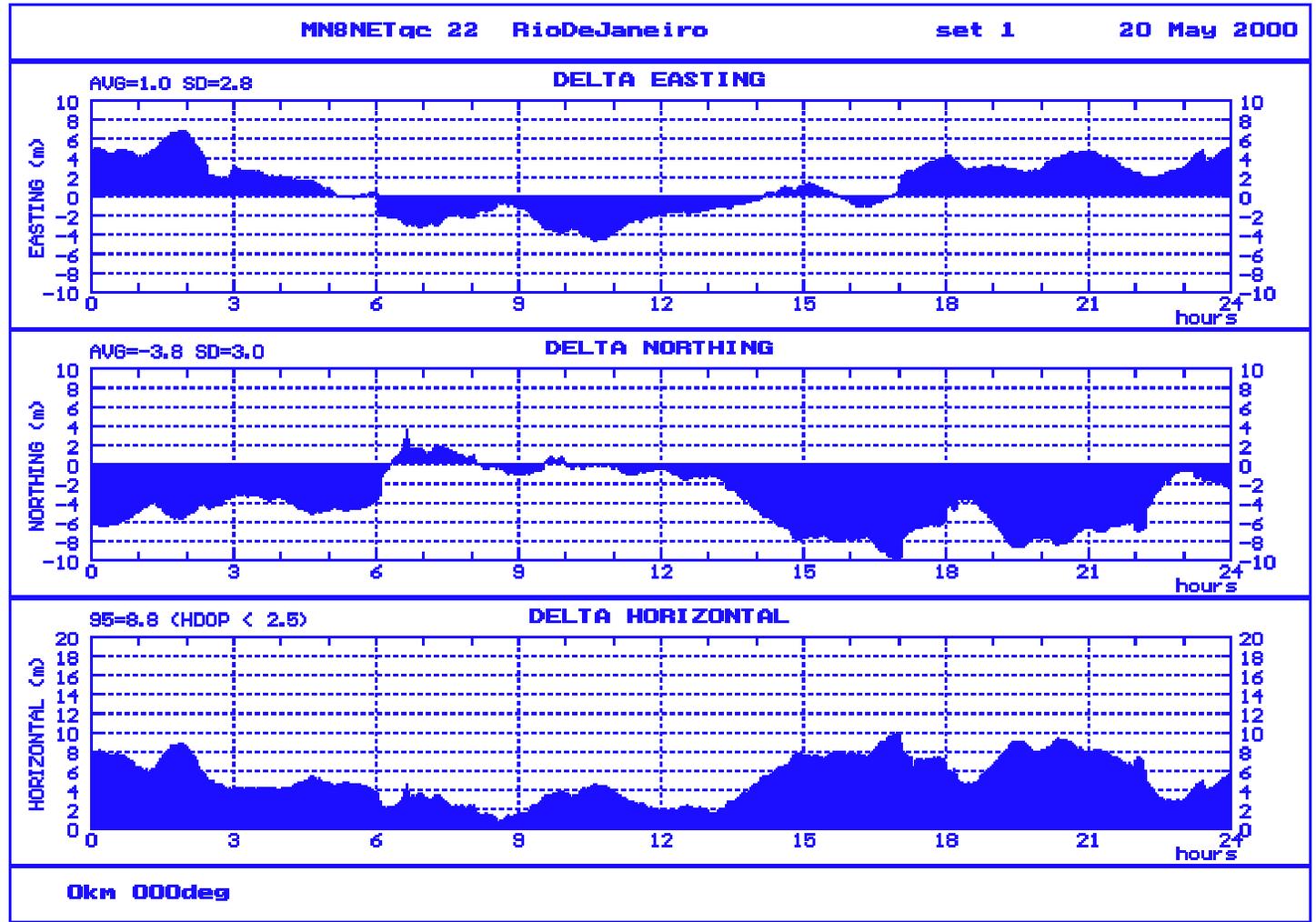
Precision GPS And Communications



Single Frequency Autonomous Rio de Janeiro May 20, 2000

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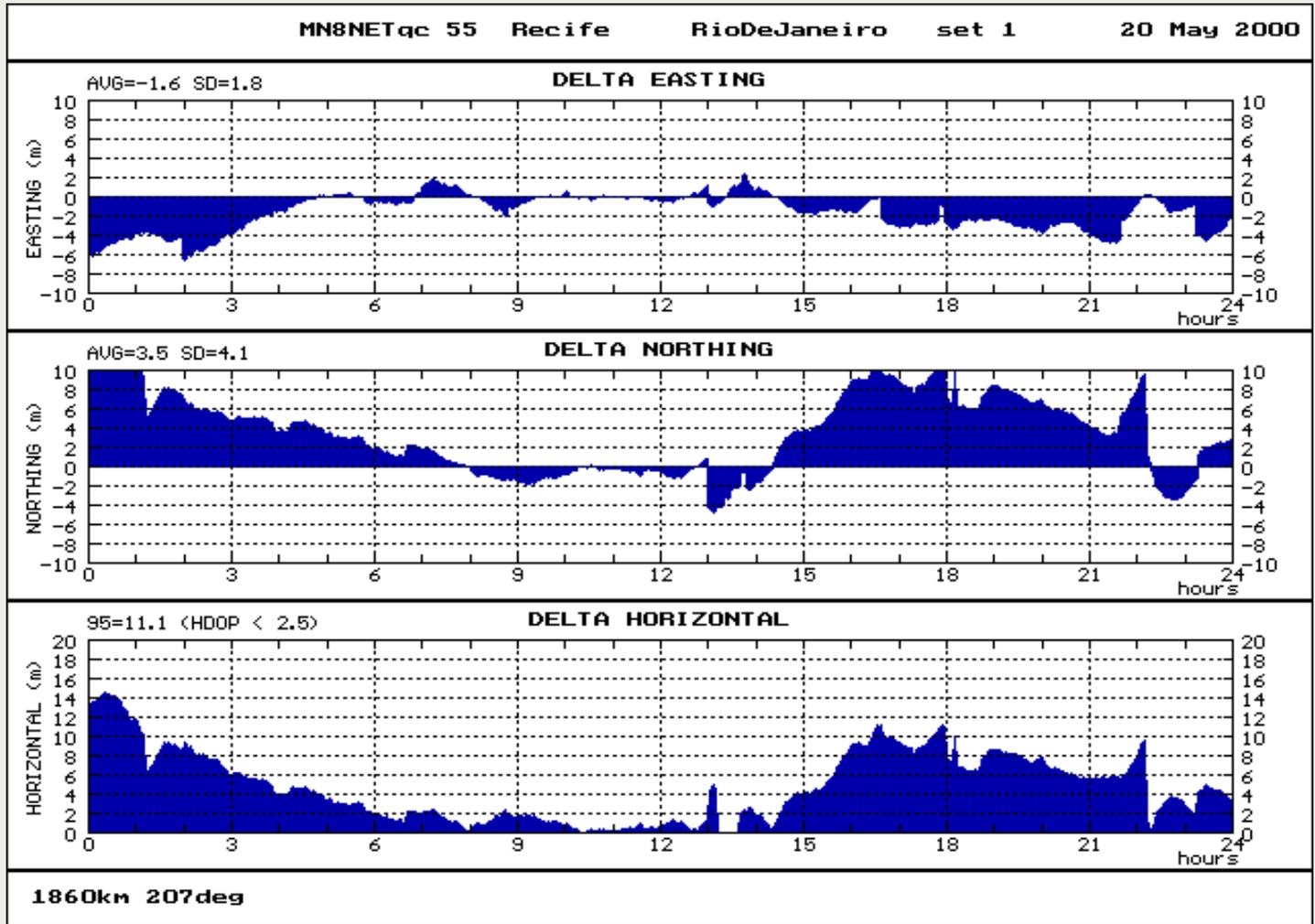




Single Frequency (DGPS) Rio de Janeiro-Recife (1860km) May 20, 2000

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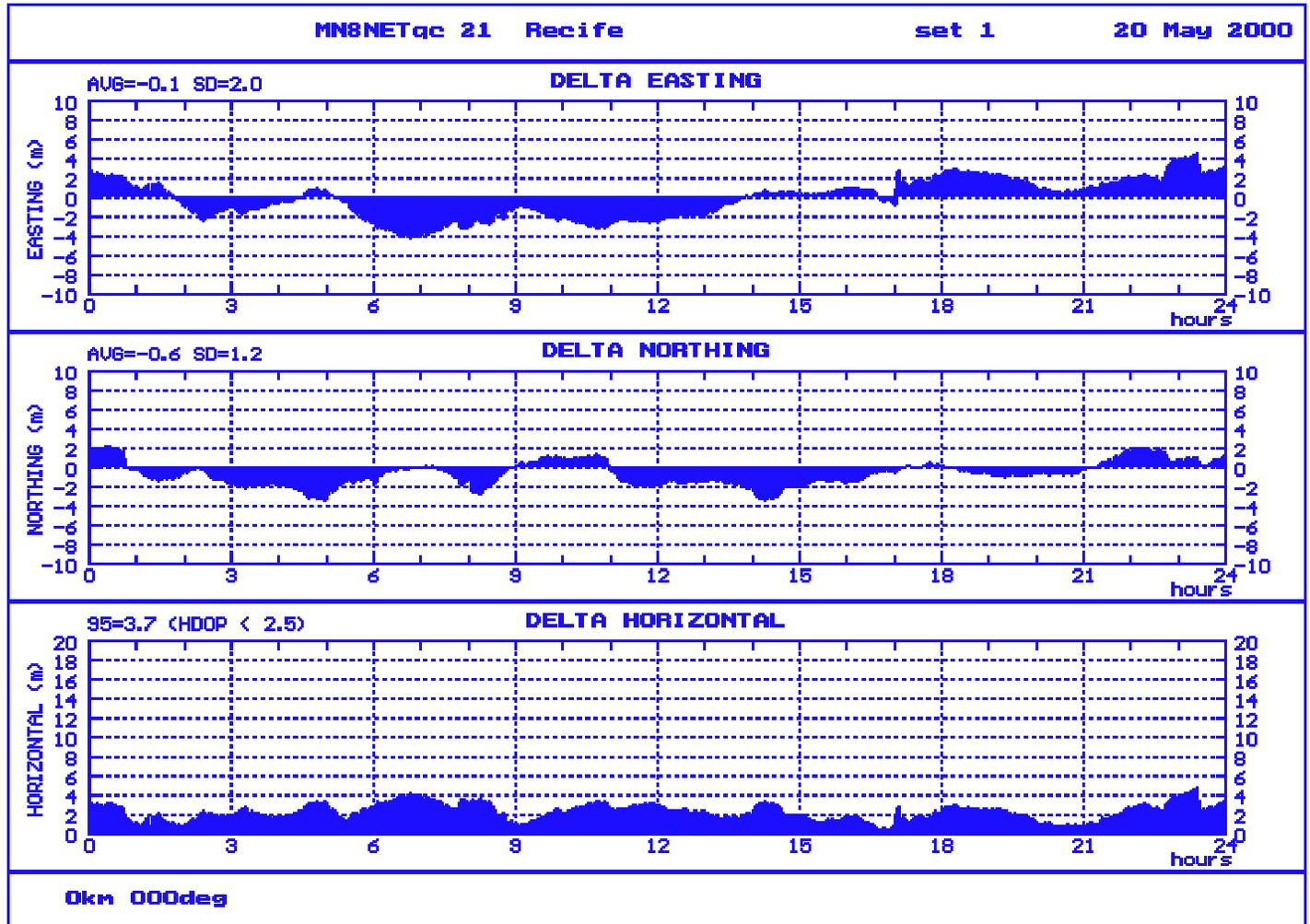


Dual Frequency Autonomous Recife

May 20, 2000

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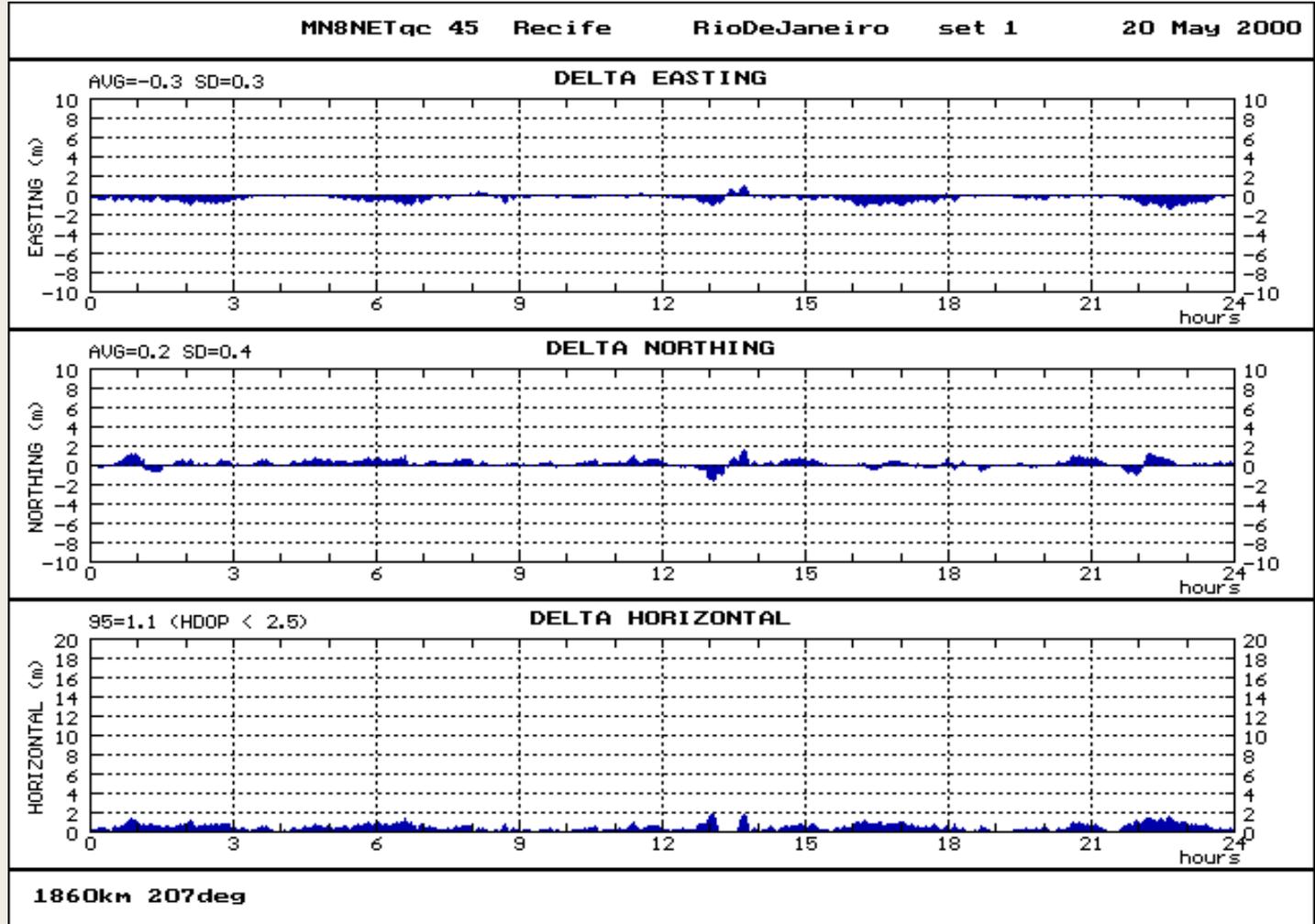




Dual Frequency (DGPS) Rio de Janeiro-Recife (1860km) May 20, 2000

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2003 DGPS Performance

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South American Baselines

- Rio de Janeiro – Vitoria 420 km

Scintillation Problems

Dual Frequency Data

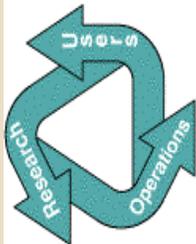
- Computing IONO value from measurements



South American Scintillations February 2, 2003

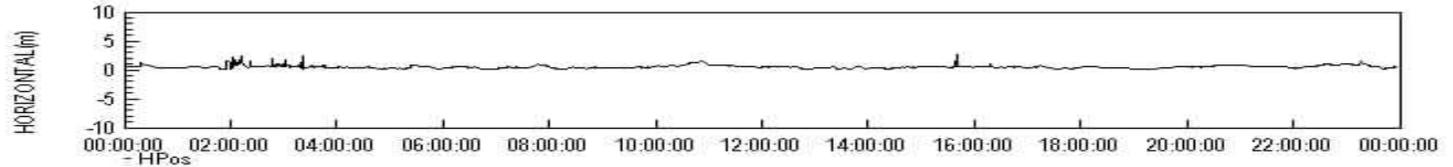
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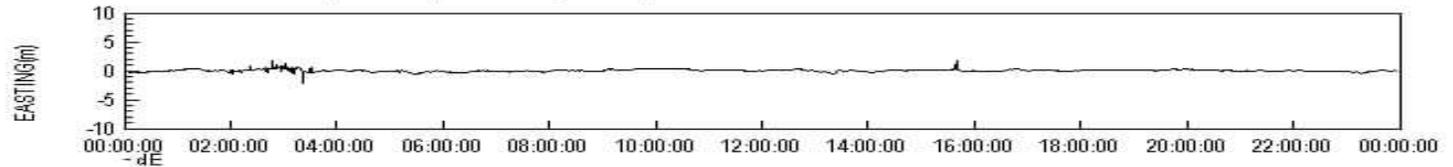


GPS Network Monitor (Rio HP (Mon) : Vitoria HP (Ref) : Iono Free : 95% = 1.02)

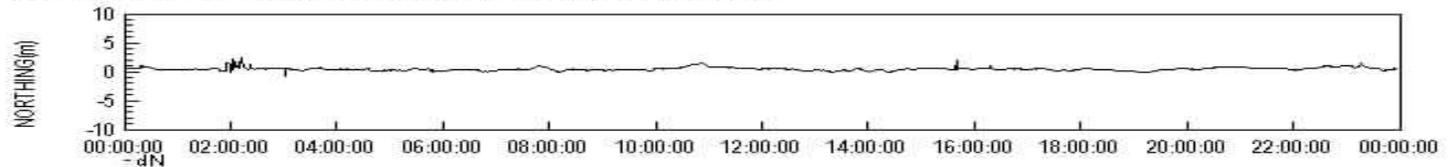
DELTA HORIZONTAL: HPos: Min:0.01, Max:2.61, Mean:0.50, SD:0.25, Count:6417



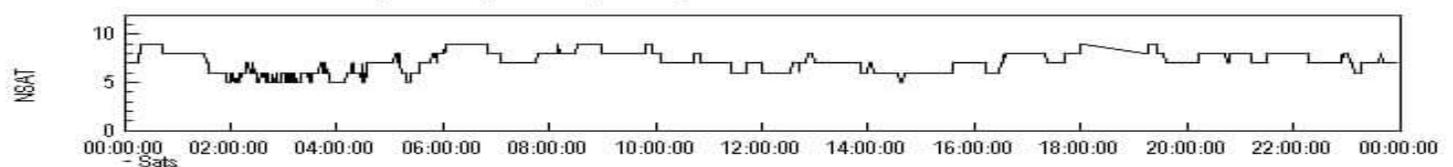
DELTA EASTING: dE: Min:-2.49, Max:2.05, Mean:0.01, SD:0.21, Count:6417



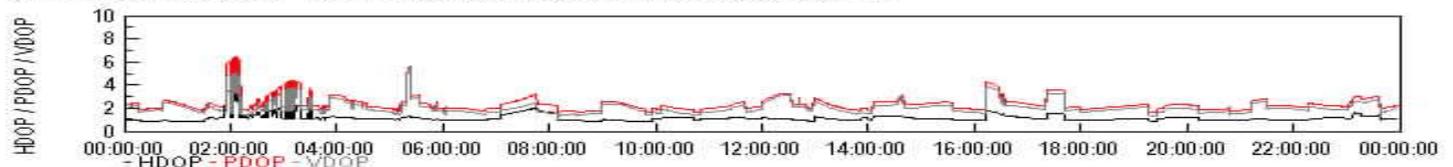
DELTA NORTHING: dN: Min:-1.08, Max:2.58, Mean:0.45, SD:0.26, Count:6417



NO. OF SATELLITES: Sats: Min:5.00, Max:9.00, Mean:7.13, SD:1.04, Count:6417



DILUTION OF PRECISION: HDOP: Min:0.81, Max:3.96, Mean:1.16, SD:0.36, Count:6417



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South American Scintillations

February 11, 2003

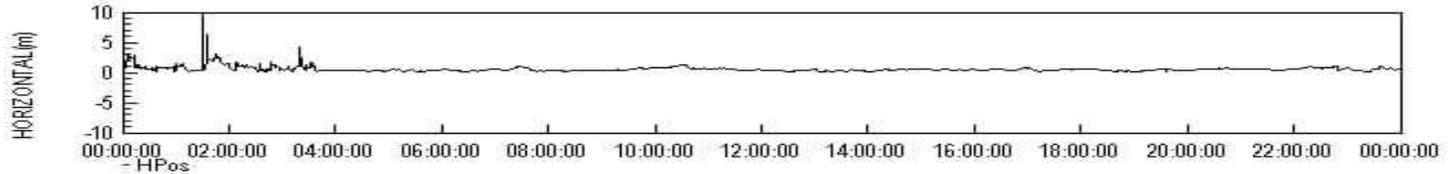
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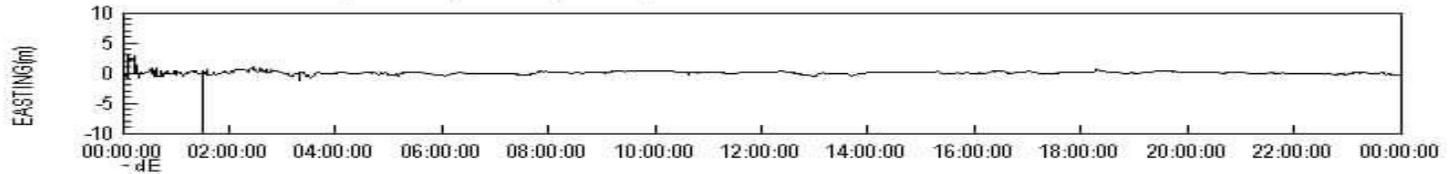


GPS Network Monitor (Rio HP (Mon) : Vitoria HP (Ref) : Iono Free : 95% = 0.94)

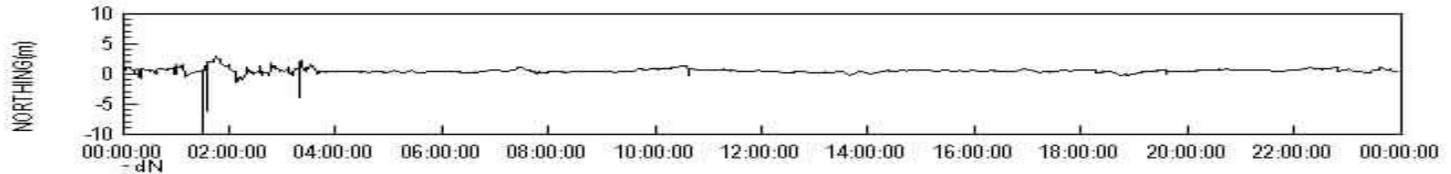
DELTA HORIZONTAL: HPos: Min:0.01, Max:100.76, Mean:0.57, SD:1.77, Count:6685



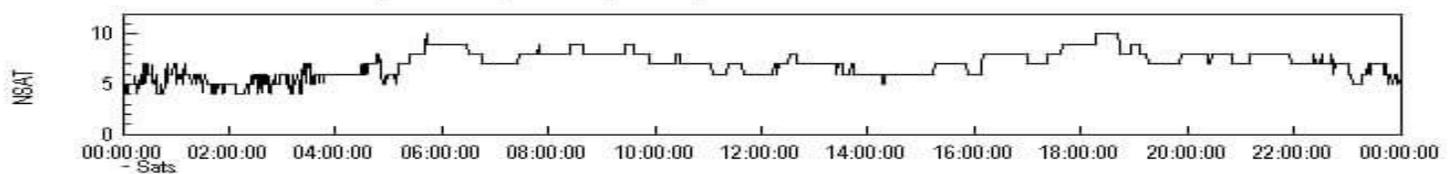
DELTA EASTING: dE: Min:-89.54, Max:3.10, Mean:0.01, SD:1.57, Count:6685



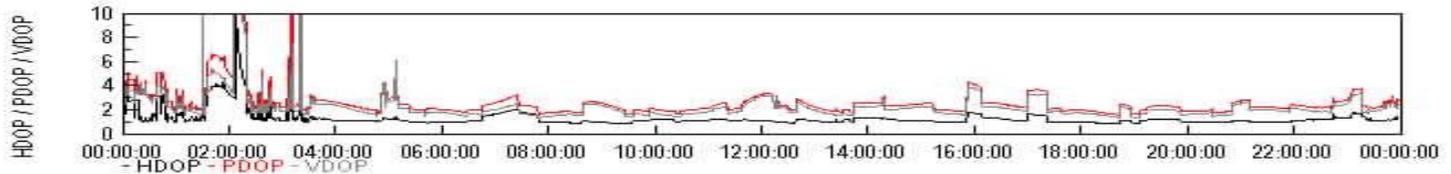
DELTA NORTHING: dN: Min:-46.21, Max:3.06, Mean:0.42, SD:0.89, Count:6685



NO. OF SATELLITES: Sats: Min:4.00, Max:10.00, Mean:6.98, SD:1.26, Count:6685



DILUTION OF PRECISION: HDOP: Min:0.80, Max:180.80, Mean:1.46, SD:3.92, Count:6685



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South American Scintillations

February 12, 2003

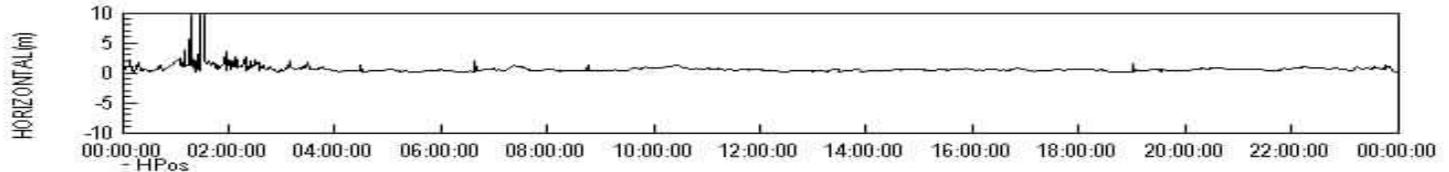
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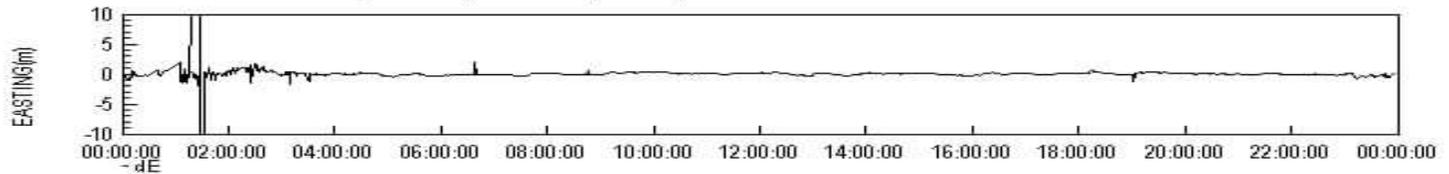


GPS Network Monitor (Rio HP (Mon) : Vitoria HP (Ref) : Iono Free : 95% = 0.98)

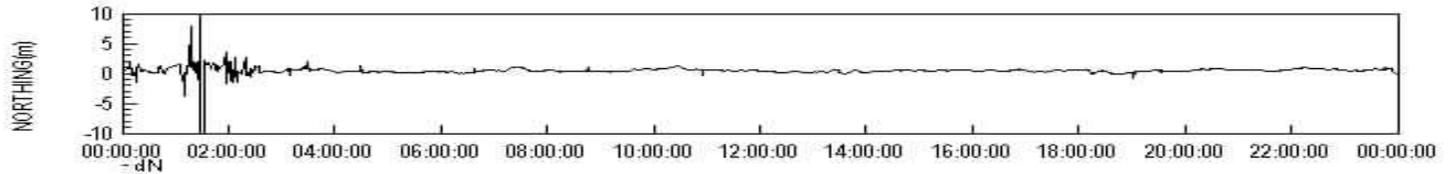
DELTA HORIZONTAL: HPos: Min:0.01, Max:1480.44, Mean:1.07, SD:21.02, Count:6525



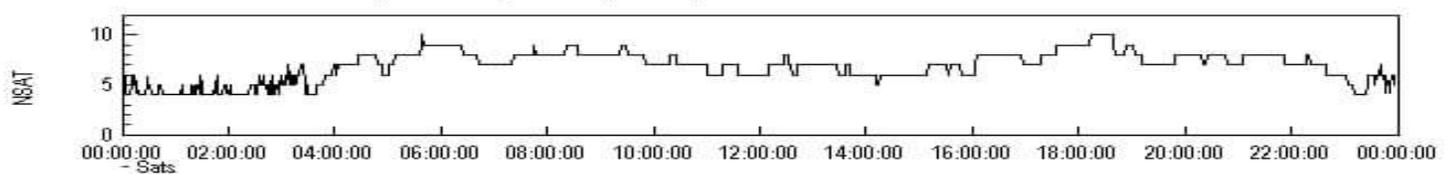
DELTA EASTING: dE: Min:-370.50, Max:63.81, Mean:-0.16, SD:7.04, Count:6525



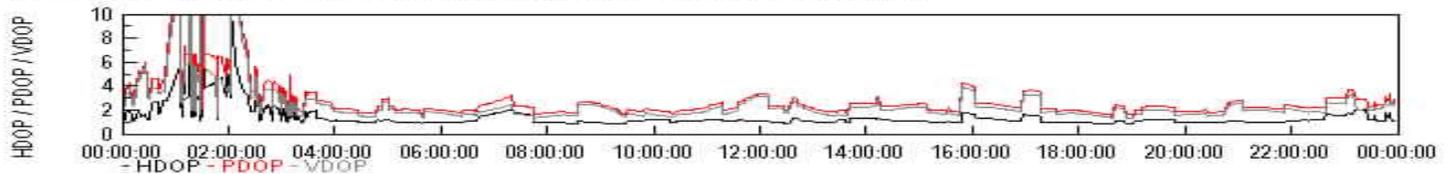
DELTA NORTHING: dN: Min:-457.42, Max:1466.55, Mean:0.62, SD:19.83, Count:6525



NO. OF SATELLITES: Sats: Min:4.00, Max:10.00, Mean:6.98, SD:1.38, Count:6525



DILUTION OF PRECISION: HDOP: Min:0.80, Max:1849.94, Mean:2.01, SD:27.11, Count:6525



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South American Scintillations

March 12, 2003

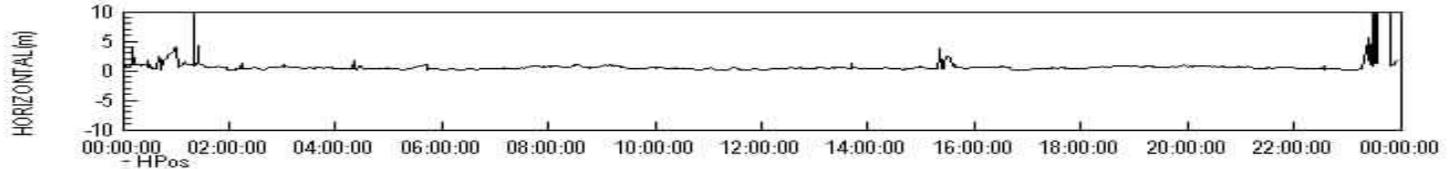
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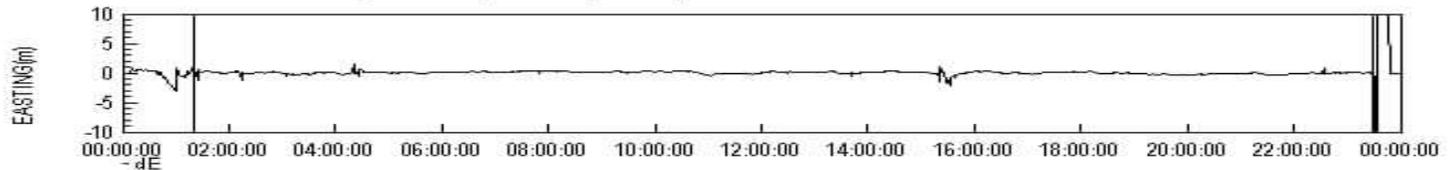


GPS Network Monitor (Rio HP (Mon) : Vitoria HP (Ref) : Iono Free : 95% = 0.90)

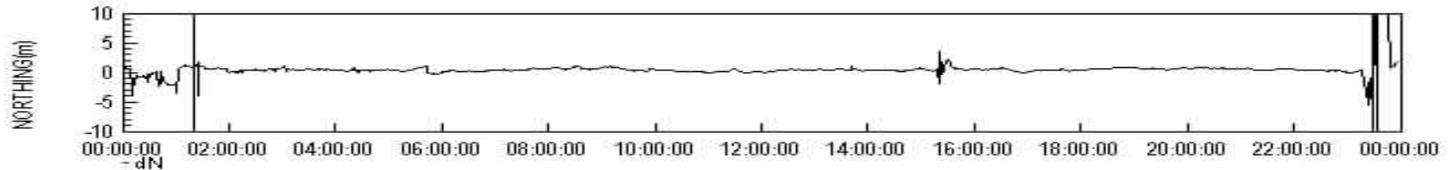
DELTA HORIZONTAL: HPos: Min:0.01, Max:1257.23, Mean:1.23, SD:21.55, Count:6729



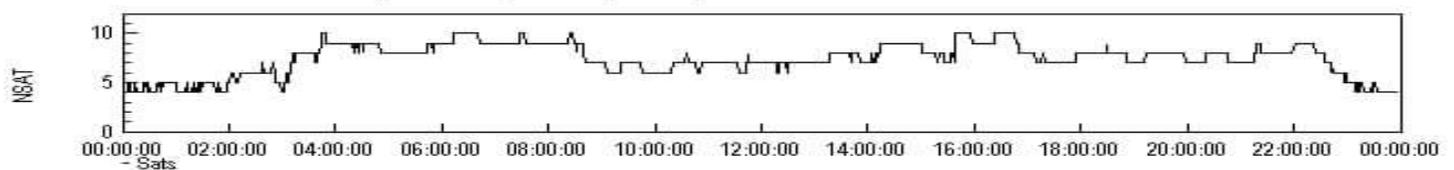
DELTA EASTING: dE: Min:-363.04, Max:220.69, Mean:0.08, SD:7.29, Count:6729



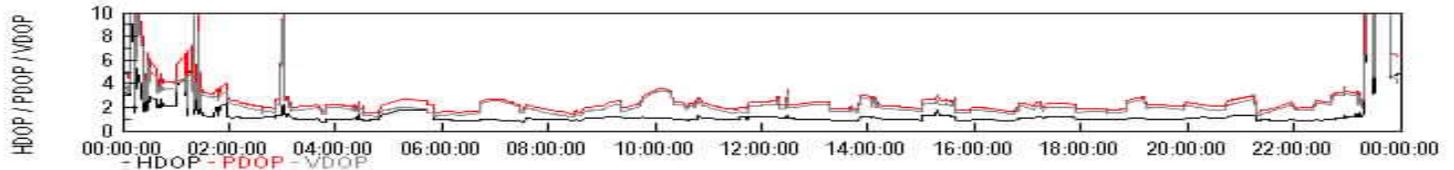
DELTA NORTHING: dN: Min:-185.94, Max:1248.58, Mean:0.70, SD:20.31, Count:6729



NO. OF SATELLITES: Sats: Min:4.00, Max:10.00, Mean:7.36, SD:1.60, Count:6729



DILUTION OF PRECISION: HDOP: Min:0.78, Max:8076.56, Mean:5.31, SD:143.01, Count:6729



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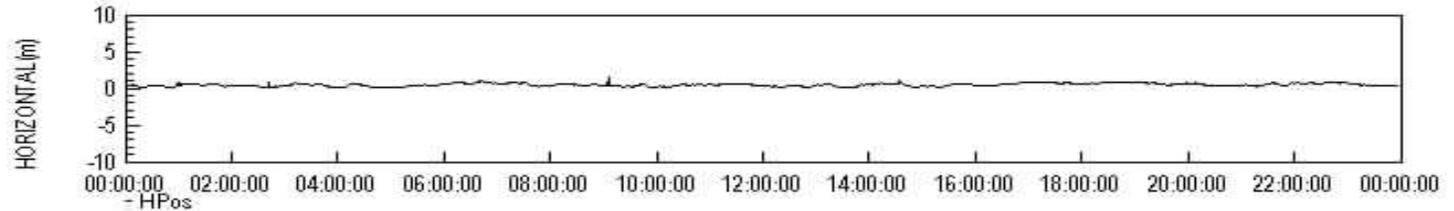
South American Scintillations

April 7, 2003

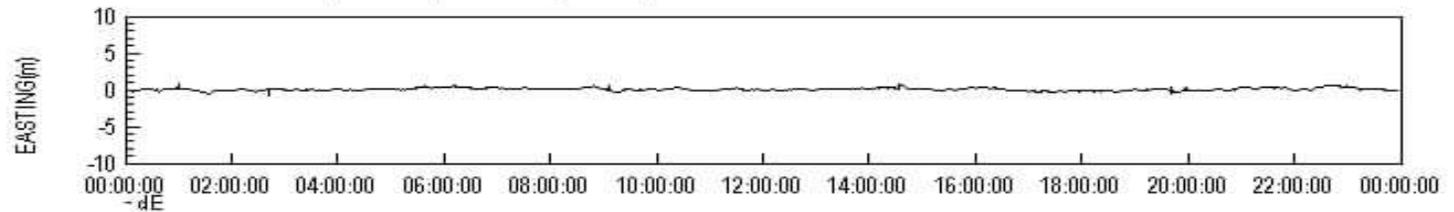


GPS Network Monitor (Rio HP (Mon) : Vitoria HP (Ref) : Iono Free : 95% = 0.80)

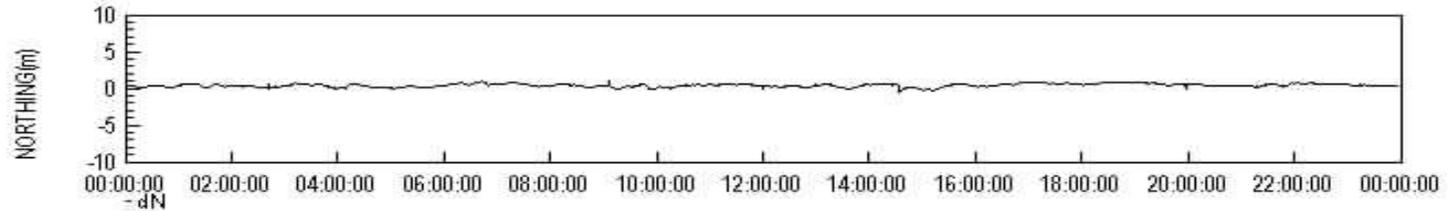
DELTA HORIZONTAL: HPos: Min:0.00, Max:1.49, Mean:0.45, SD:0.21, Count:6580



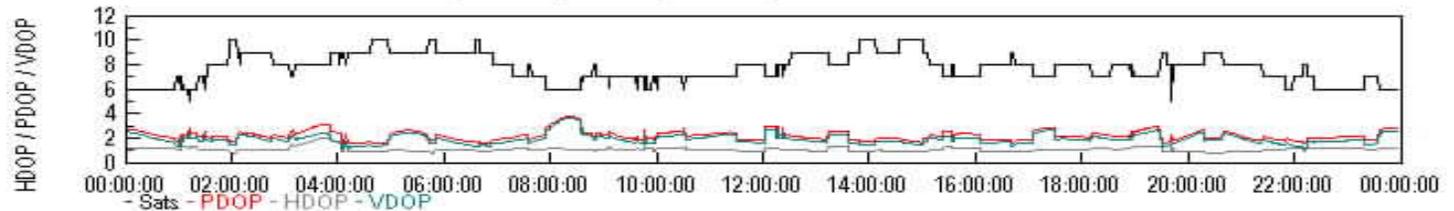
DELTA EASTING: dE: Min:-0.98, Max:0.82, Mean:0.05, SD:0.18, Count:6580



DELTA NORTHING: dN: Min:-0.59, Max:1.35, Mean:0.39, SD:0.23, Count:6580

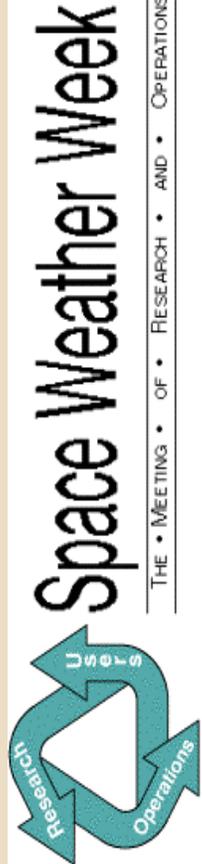


DILUTION OF PRECISION: Sats: Min:5.00, Max:10.00, Mean:7.76, SD:1.14, Count:6580



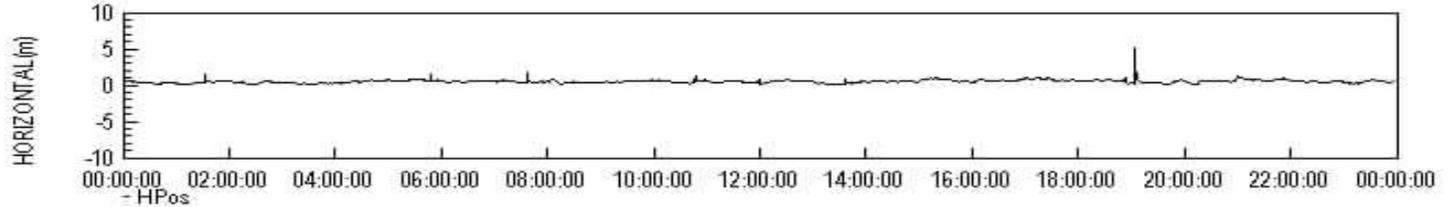


South American Scintillations May 1, 2003

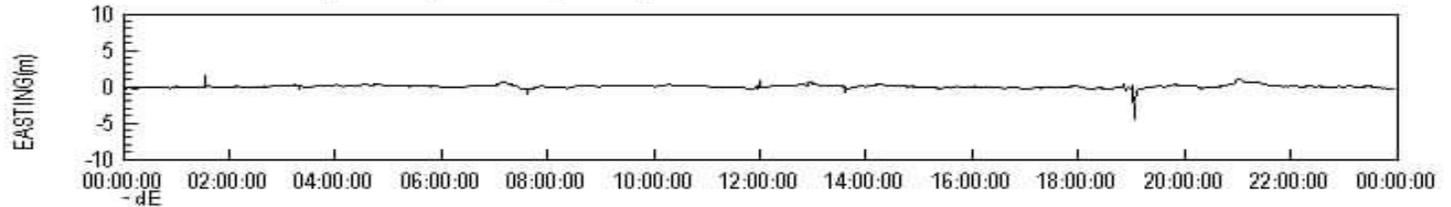


GPS Network Monitor (Rio HP (Mon) : Vitoria HP (Ref) : Iono Free : 95% = 0.85)

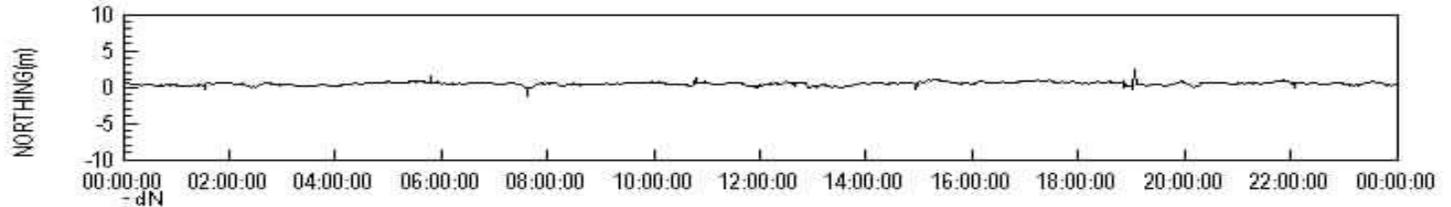
DELTA HORIZONTAL: HPos: Min:0.01, Max:5.29, Mean:0.49, SD:0.22, Count:6573



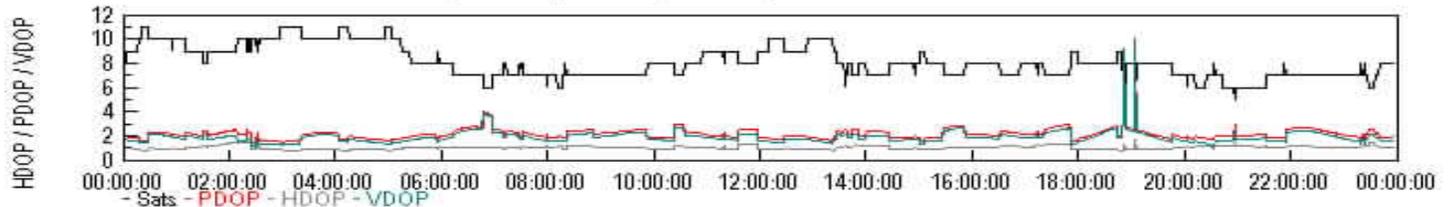
DELTA EASTING: dE: Min:-4.61, Max:1.70, Mean:0.00, SD:0.22, Count:6573



DELTA NORTHING: dN: Min:-1.45, Max:2.61, Mean:0.44, SD:0.22, Count:6573



DILUTION OF PRECISION: Sats: Min:5.00, Max:11.00, Mean:8.10, SD:1.28, Count:6573





Effects of Solar Activity In GOM

The following slides show the effects on GPS performance of a CME originating October 18, 1999, striking the earth's magnetosphere on October 22, 1999.

- Indices
- High Performance (L1) GPS Results
- WASS Results
- DGPS Results



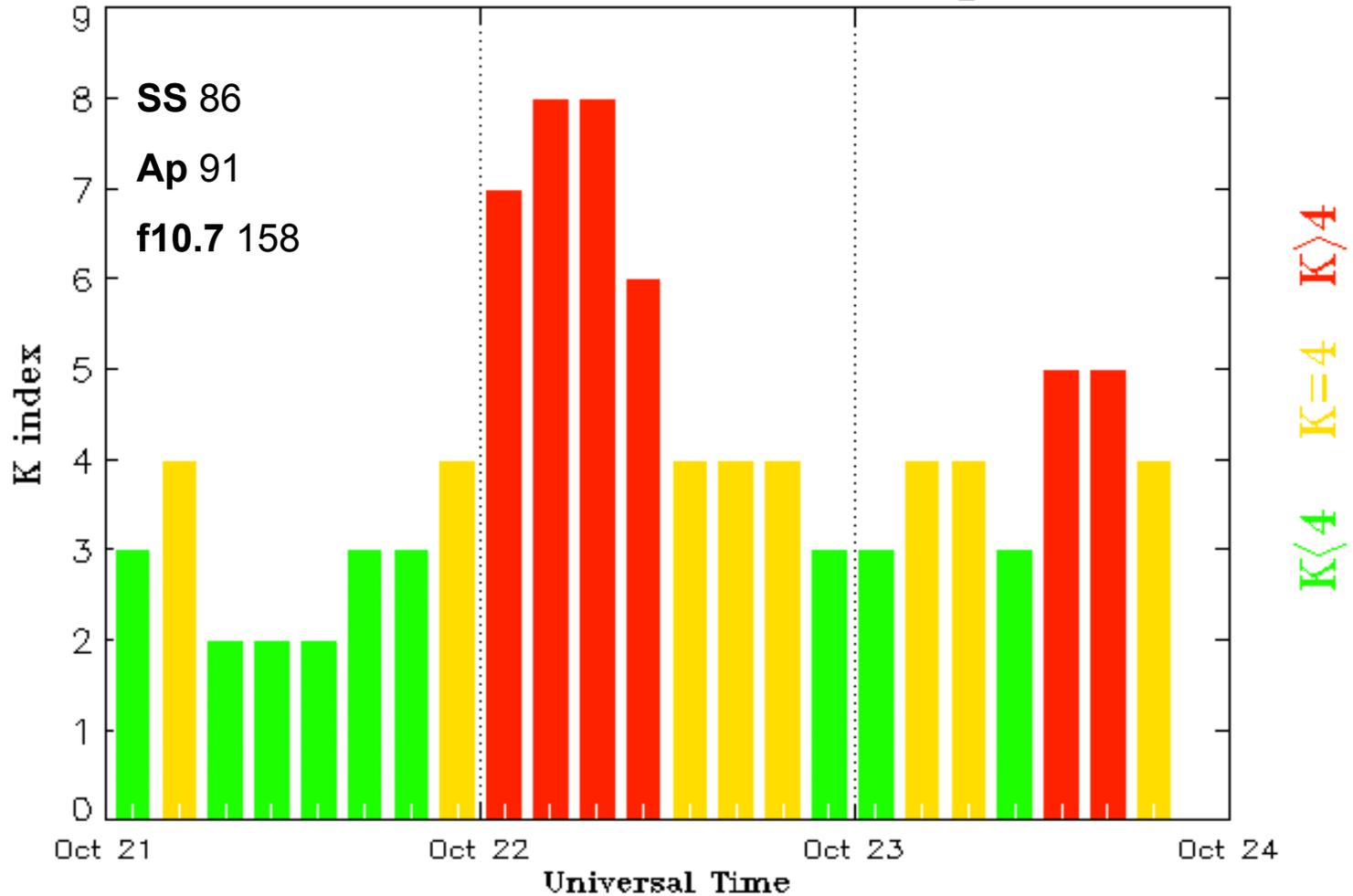


Exceptional Solar Event October 22, 1999

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Estimated Planetary Kp index (3 hour data) Begin: 1999 Oct 21 0000UT



SS 86
Ap 91
f10.7 158

K < 4 K = 4 K > 4

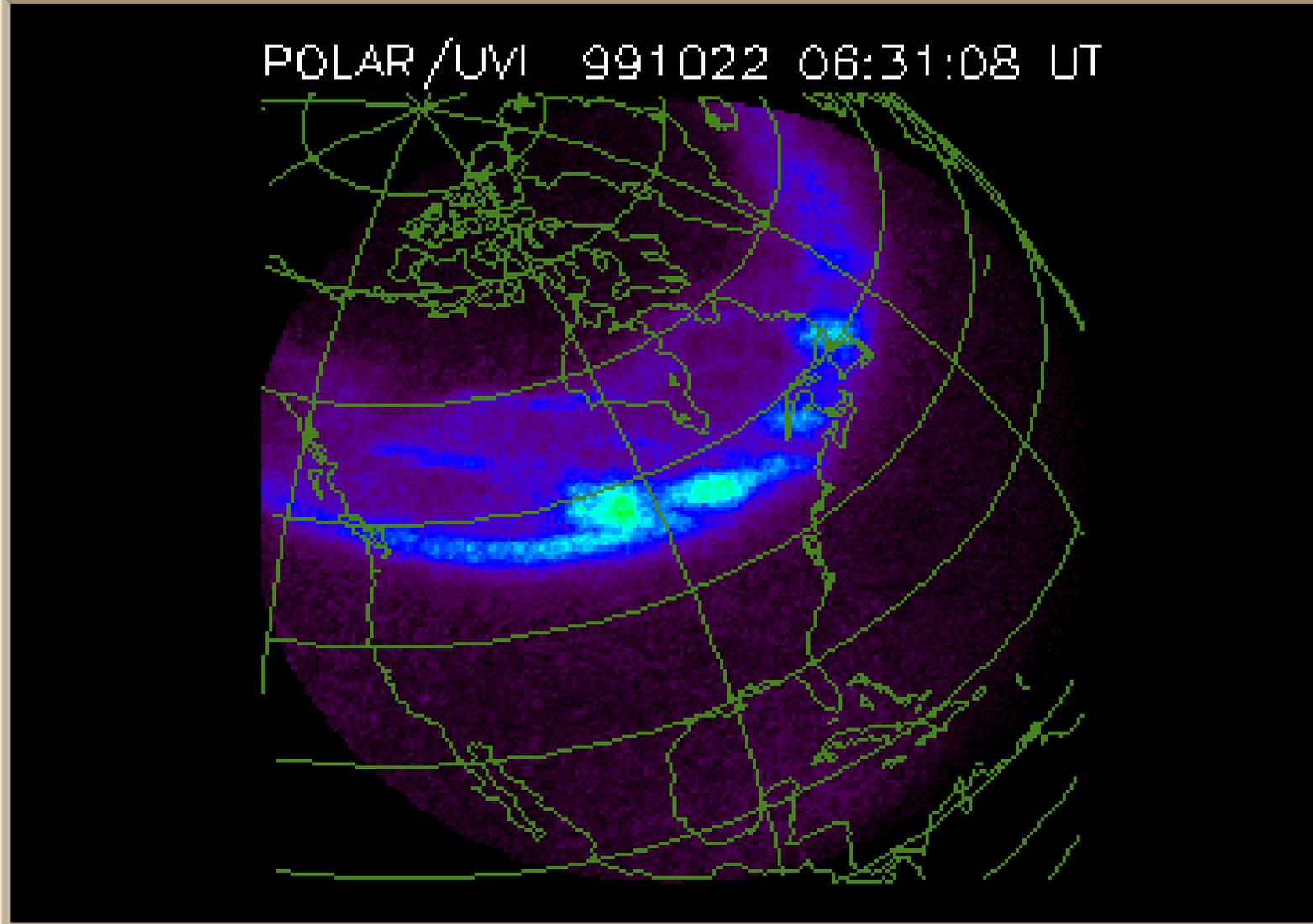
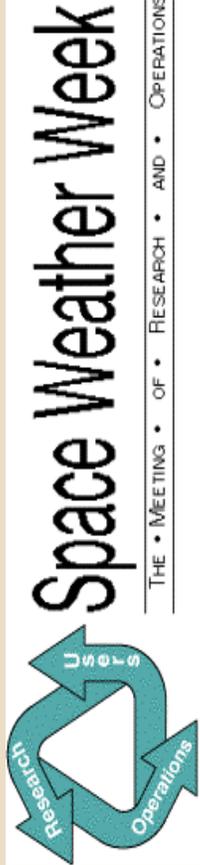
Updated 1999 Oct 23 23:45:14

NOAA/SEC Boulder, CO USA



UV Image of Aurora

October 22, 1999



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Single Frequency High Performance GPS

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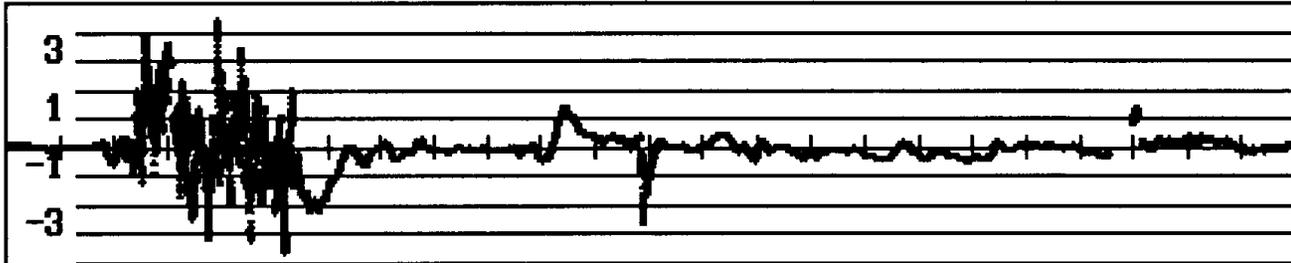
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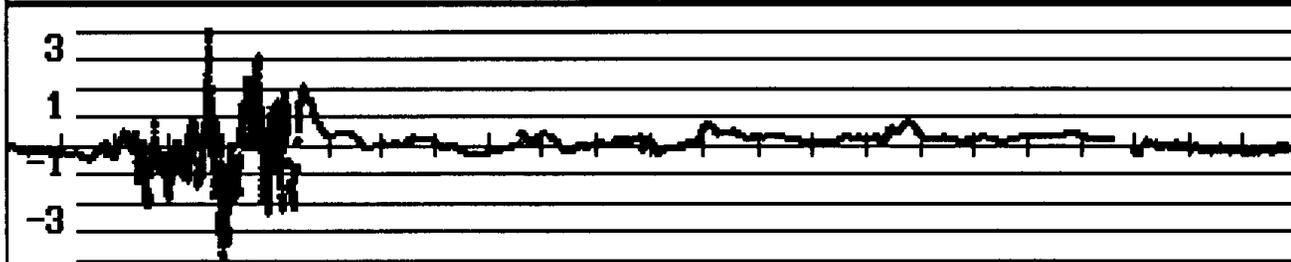
Day 294 0 to 24 Hrs.

PWADS/PCOR GULF

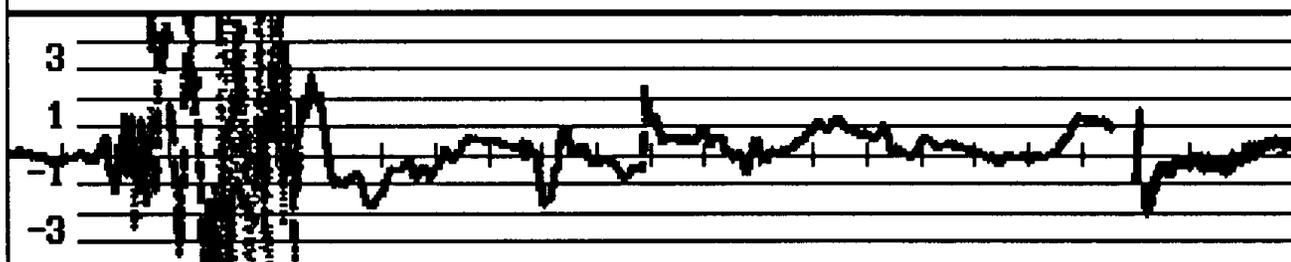
LAT
Meters
Mean -0.023
SD 0.615



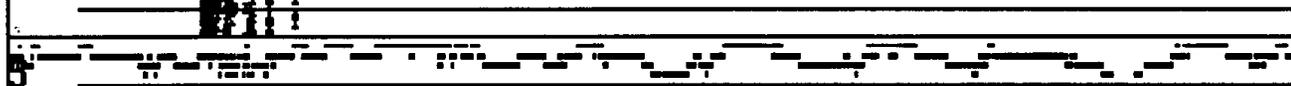
LON
Meters
Mean 0.018
SD 0.476



HGT
Meters
Mean 0.093
SD 1.245



Num SV
08.0





Day Following Solar Event

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Day 295 0 to 24 Hrs.

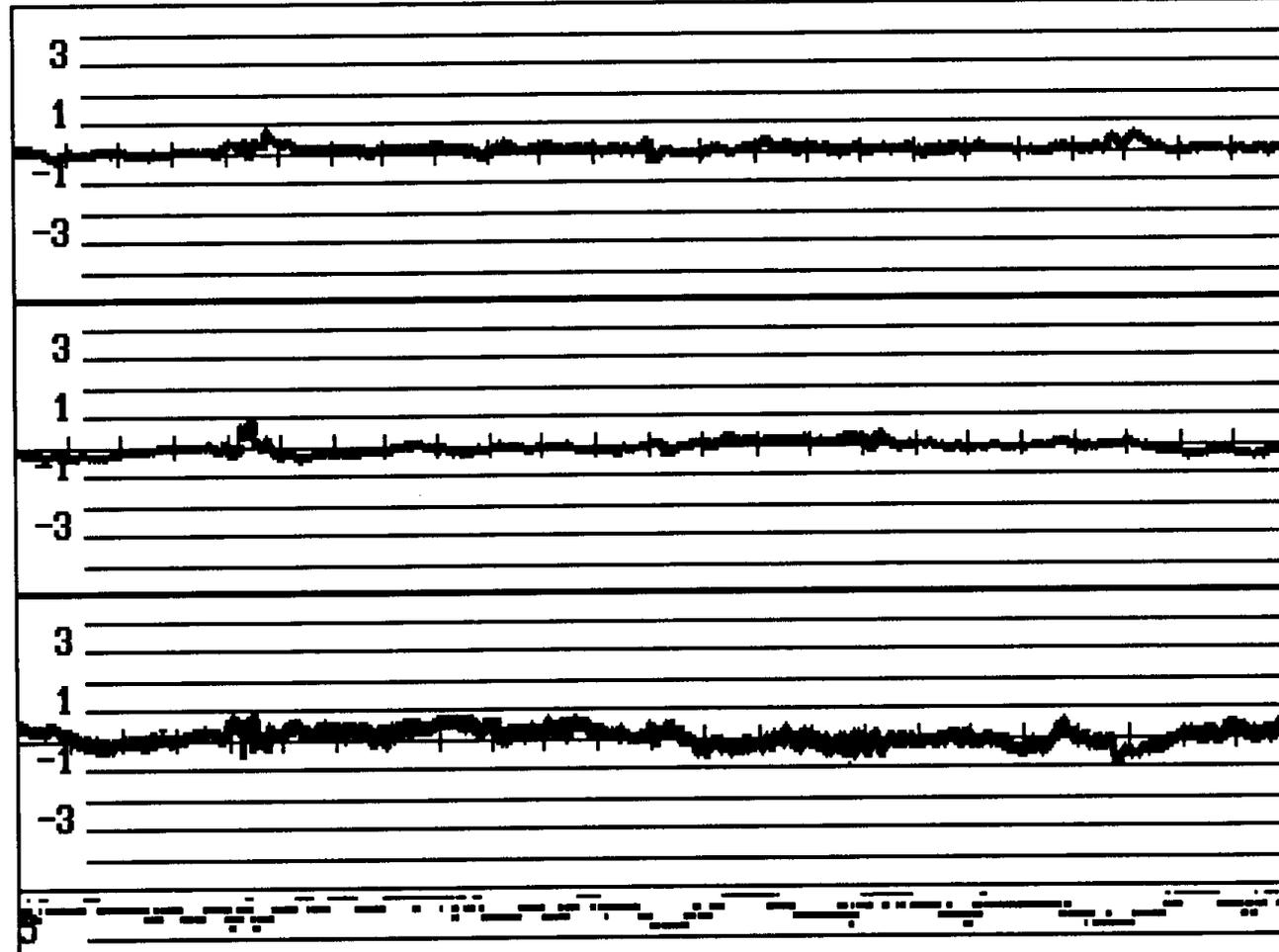
PWADS/PCOR GULF

LAT
Meters
Mean .077
SD 0.120

LON
Meters
Mean -0.101
SD 0.164

HGT
Meters
Mean 0.044
SD 0.282

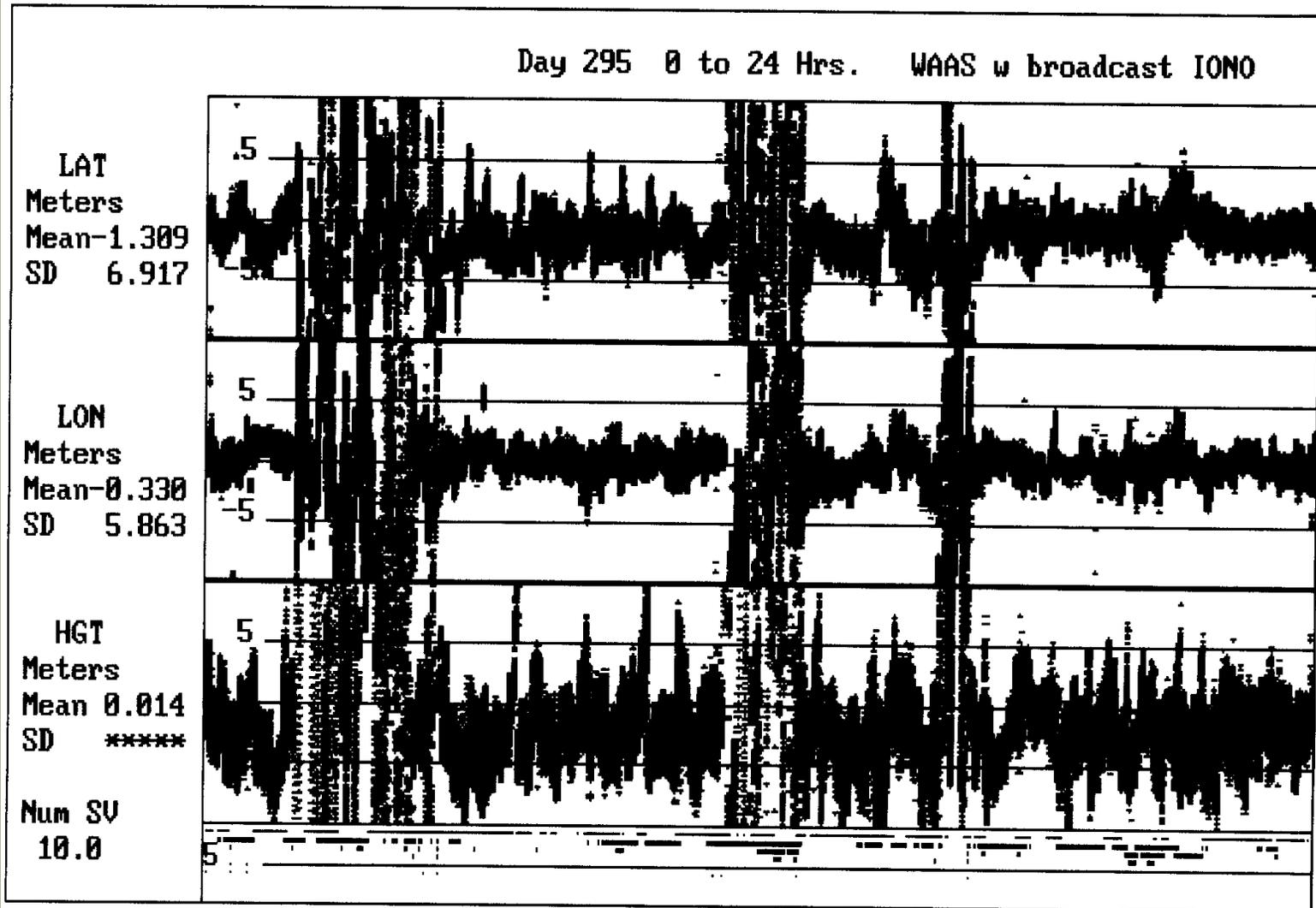
Num SV
00.0



Precision GPS And Communications



Solar Event Effect on WAAS Results





Day Following Solar Event

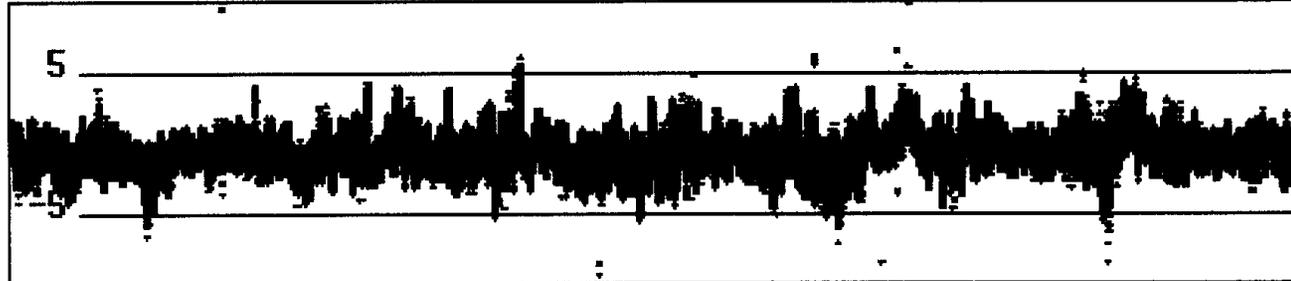
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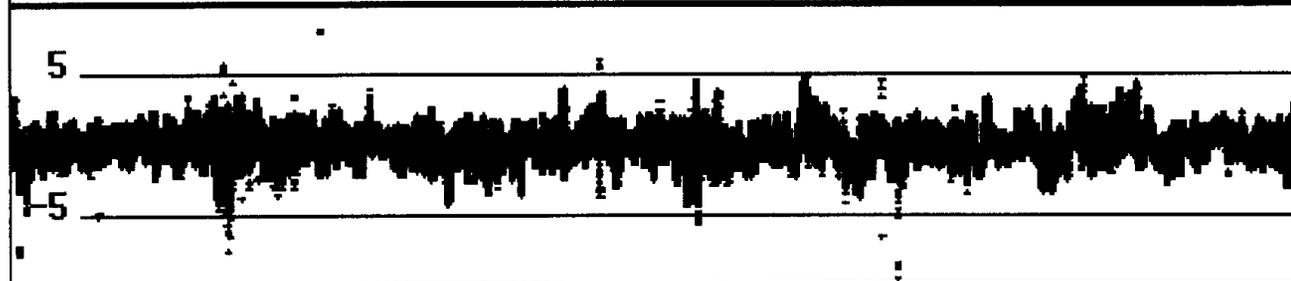


Day 296 0 to 24 Hrs. WAAS w broadcast IONO

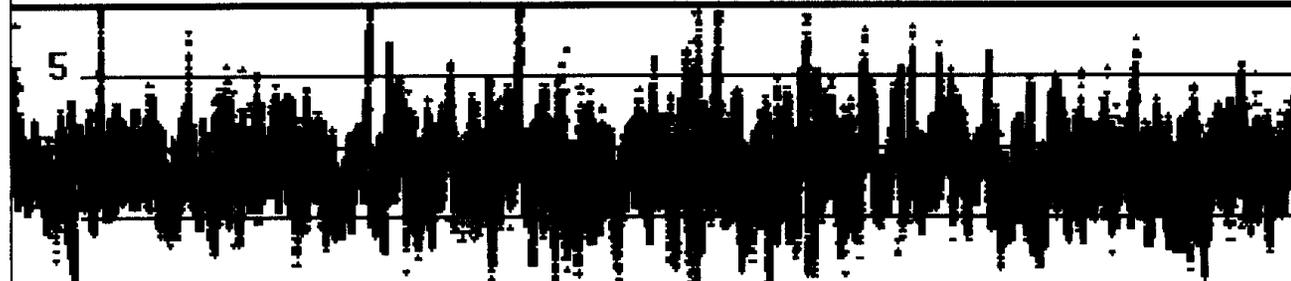
LAT
Meters
Mean- .631
SD 1.278



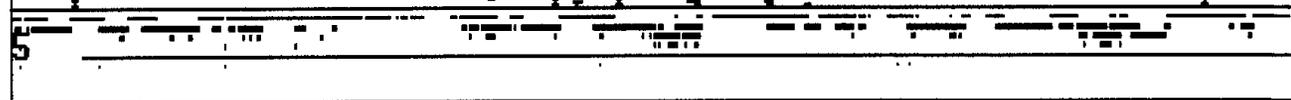
LON
Meters
Mean 0.018
SD 1.028



HGT
Meters
Mean-1.524
SD 2.618



Num SV
09.0



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Solar Event Effect on Multi Ref DGPS

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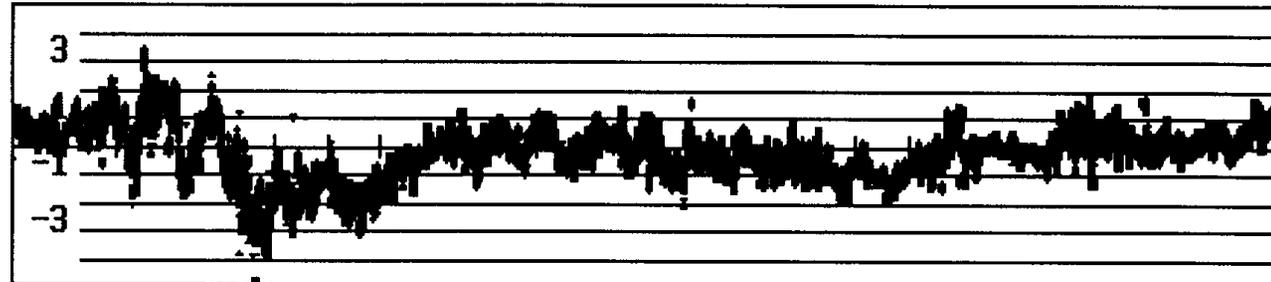
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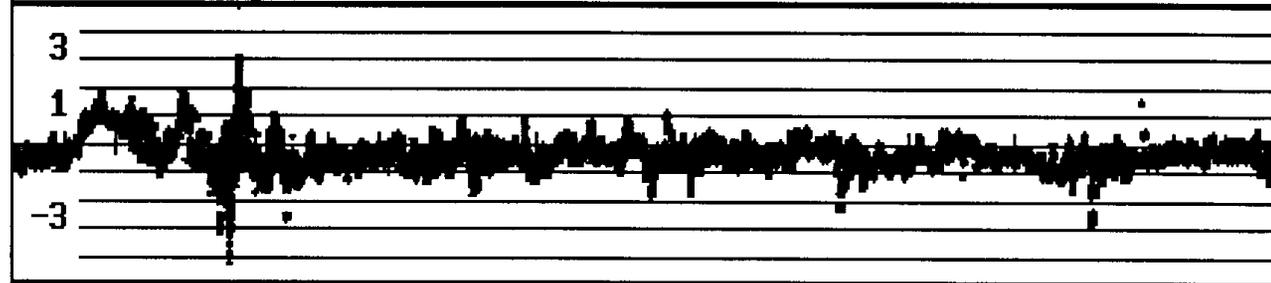
Day 296 0 to 24 Hrs.

Trim 212 JA VBS

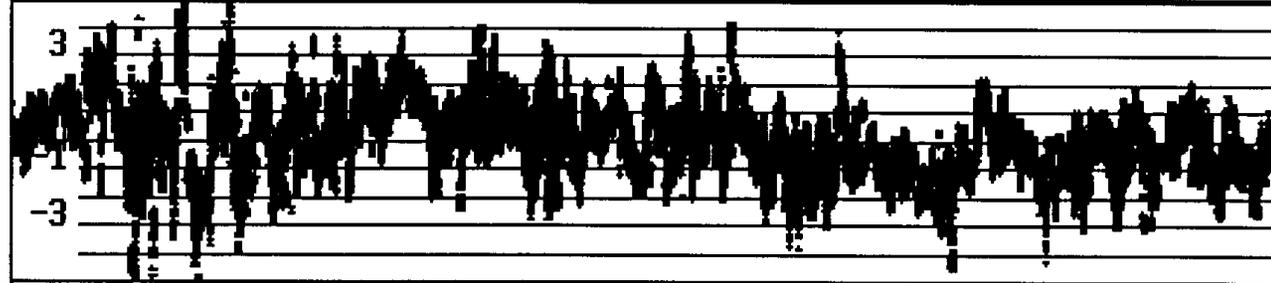
Lat
Meters
Mean -0.2
SD 00.9



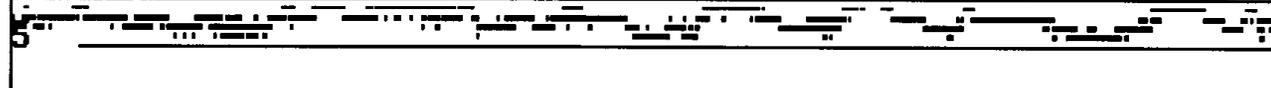
Long
Meters
Mean -0.4
SD 00.5



HGT
Meters
Mean 0.0
SD 01.3



Num SV
07.0





Day Following Solar Event

Space Weather Week

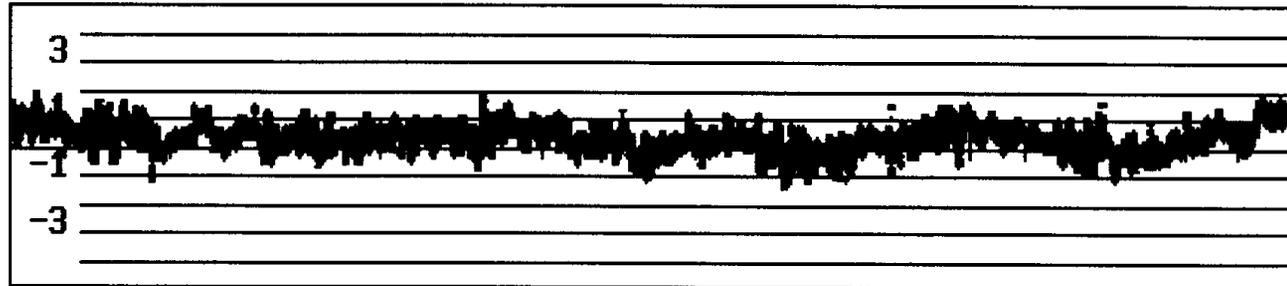
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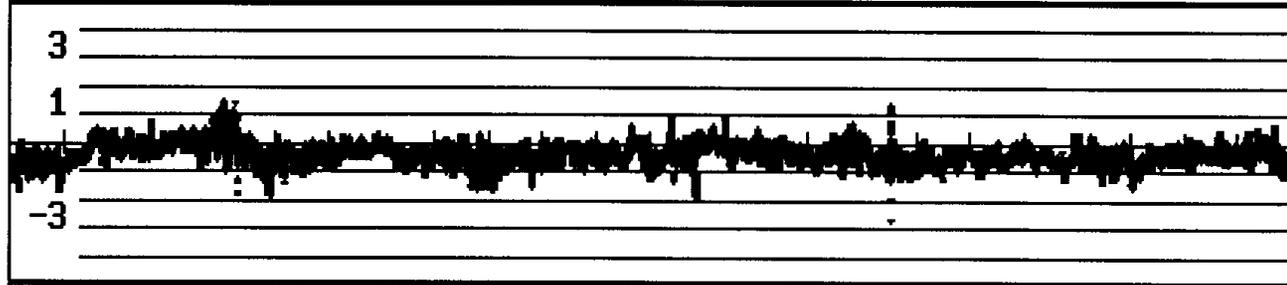
Day 297 0 to 24 Hrs.

Trim 212 JA VBS

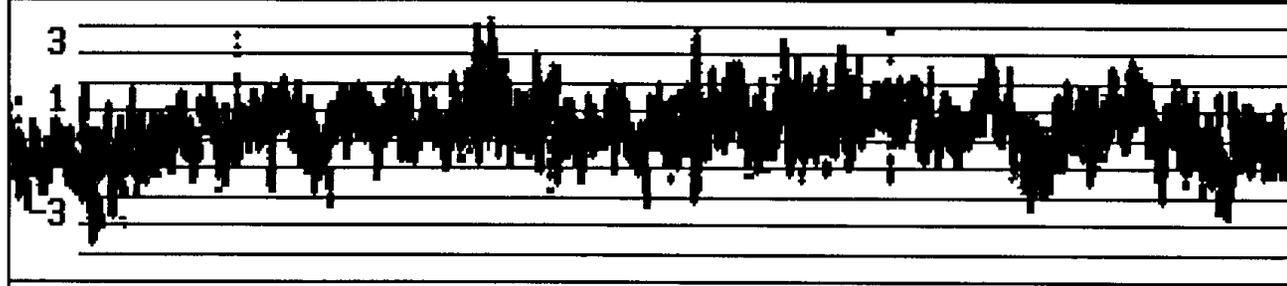
Lat
Meters
Mean 0.4
SD 00.4



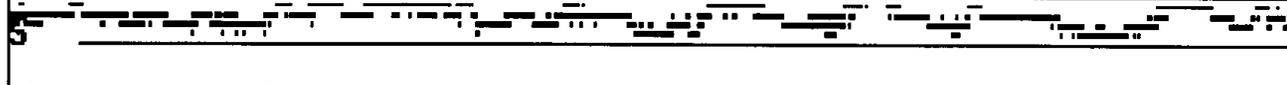
Long
Meters
Mean -0.4
SD 00.4



HGT
Meters
Mean 0.4
SD 00.9



Num SV
07.0





Other Reported Problem Areas

- Offshore Alaska (Bering Sea)
- Guam
- Indian West Coast (Arabian Sea)
- Trinidad
- Southern Florida / Bahamas





Conclusions

At the height of solar cycle 23 there was considerable impact on DGPS performance due to the active Ionosphere.

Along the geomagnetic equator the performance degradation has generally followed the F10.7 flux levels.

Since the peak of the cycle the problem has decreased in most areas but there remain "hot spots".

In the mid latitude regions, DGPS performance degradation is limited to periods of geomagnetic activity at the Major Storm level (Ap >40 and F10.7 flux >150).

When the GPS constellation is degraded the impact of an active ionosphere on GPS performance is increased due to lack of satellite redundancy.

Reporting of possible upcoming solar events (Significant CME impacts and high speed coronal streams) has allowed us to better manage our resources to reduce activities during high geomagnetic storm levels.





Additional Slides

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Sample Satellite/IONO Status Report

How does the GPS Control Segment Select the Broadcast IONO Parameters

How the GPS Constellation Impacts GPS Positioning Performance

Typical GPS Error Magnitudes

Referenced Web Sites and Contact Information



Sample Satellite Space Weather Update

Satellite Status / Space Weather Update May 9, 2003

Satellite Status:

28 healthy GPS Satellites. SVN/PRN 22 remains unhealthy.

GPS Launch Status:

The third and final launch of the year is scheduled for July 24th (originally July 18).

Satellite Maintenance:

No outstanding satellite maintenance: SVN/PRN 26 was set healthy early this morning.

ONO Status:

We have been under active to minor storm conditions for the last three days due to multiple coronal streams and a possible CME impact: the solar wind peaked at over 800 km/sec early this morning. Fortunately the solar flux has been low, limiting the impact on GPS positioning in active areas. I am seeing little scintillation impact in South America or Africa over this period.

Current Solar Conditions:

Solar wind speed, 780 km/sec; Sunspot number, 33; F10.7cm; flux, 101; Kp, 5; Ap, 33 (minor storm); IMF is South.

Geomagnetic Forecast:

Expect the geomagnetic field to be unsettled to minor storm through May 12th due to high speed coronal stream.





How Are the GPS IONO Parameters Selected

The GPS control segment is reported to use the running mean of the previous five-day solar radio flux at the 10.7 cm wavelength, called F10.7, to choose among ten sets of ionospheric coefficients.





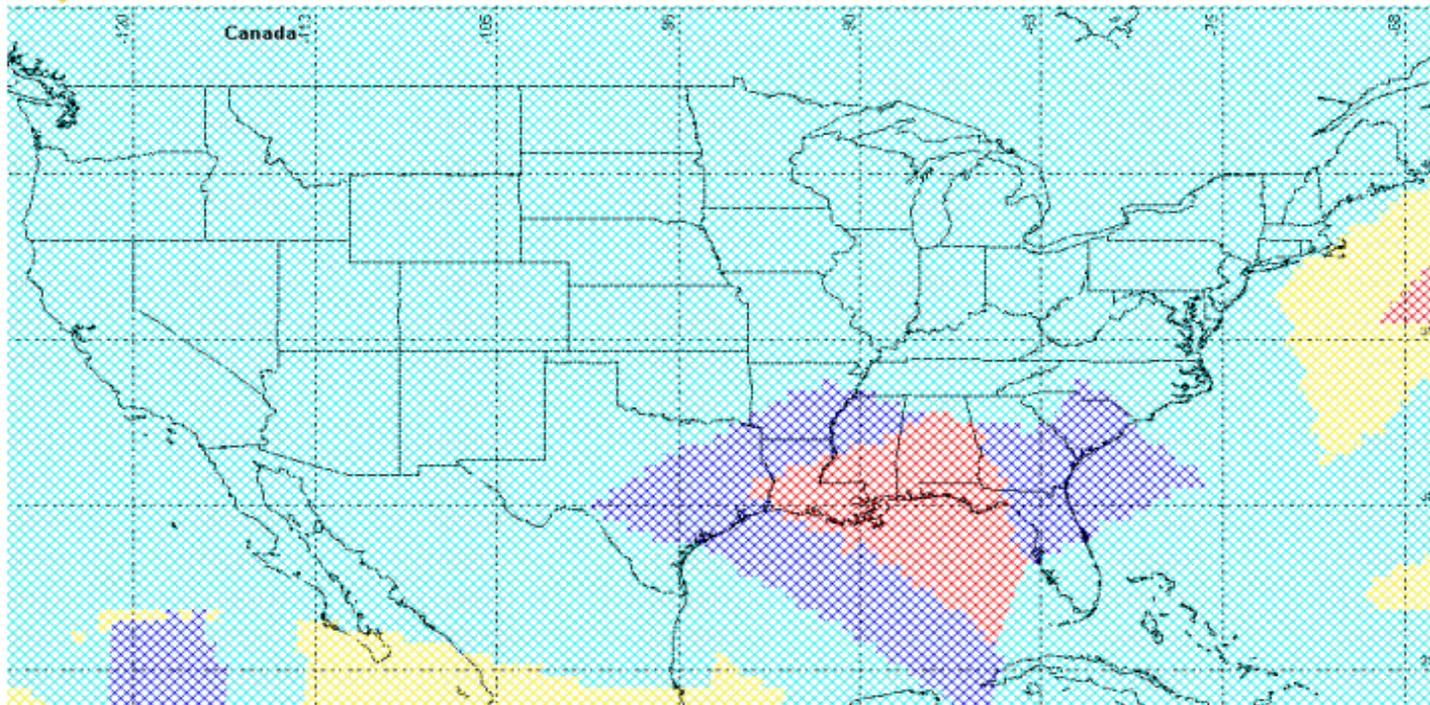
The Satellite Constellation Matters Maximum DOP - 5° Mask in October



https://www.peterson.af.mil/GPS_Support/

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CONUS PDOP Assessments



GPS Support Center	2SOPS Almanac: sem1187_J283	Production Date: 111301z Oct 2002	0-2	6-9	
Analysis Start: 170000z Oct 2002	Satellite Selection: Best4	Metric: Magnitude of PDOPMax	2-4	9-12	
Analysis Stop: 172400z Oct 2002	Time Increment: 60 seconds	Mask Angle: 5 degrees	4-6	12- >12	
Grid Increment: 0.5 degrees	Altitude: 0 meters	< 4 SVs			
PRNs Removed	21	17	22		
Removal Start	170000z Oct 2002	170000z Oct 2002	171800z Oct 2002		
Removal Stop	172359z Oct 2002	172359z Oct 2002	172359z Oct 2002		

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World Constellation DOP Peaks - October

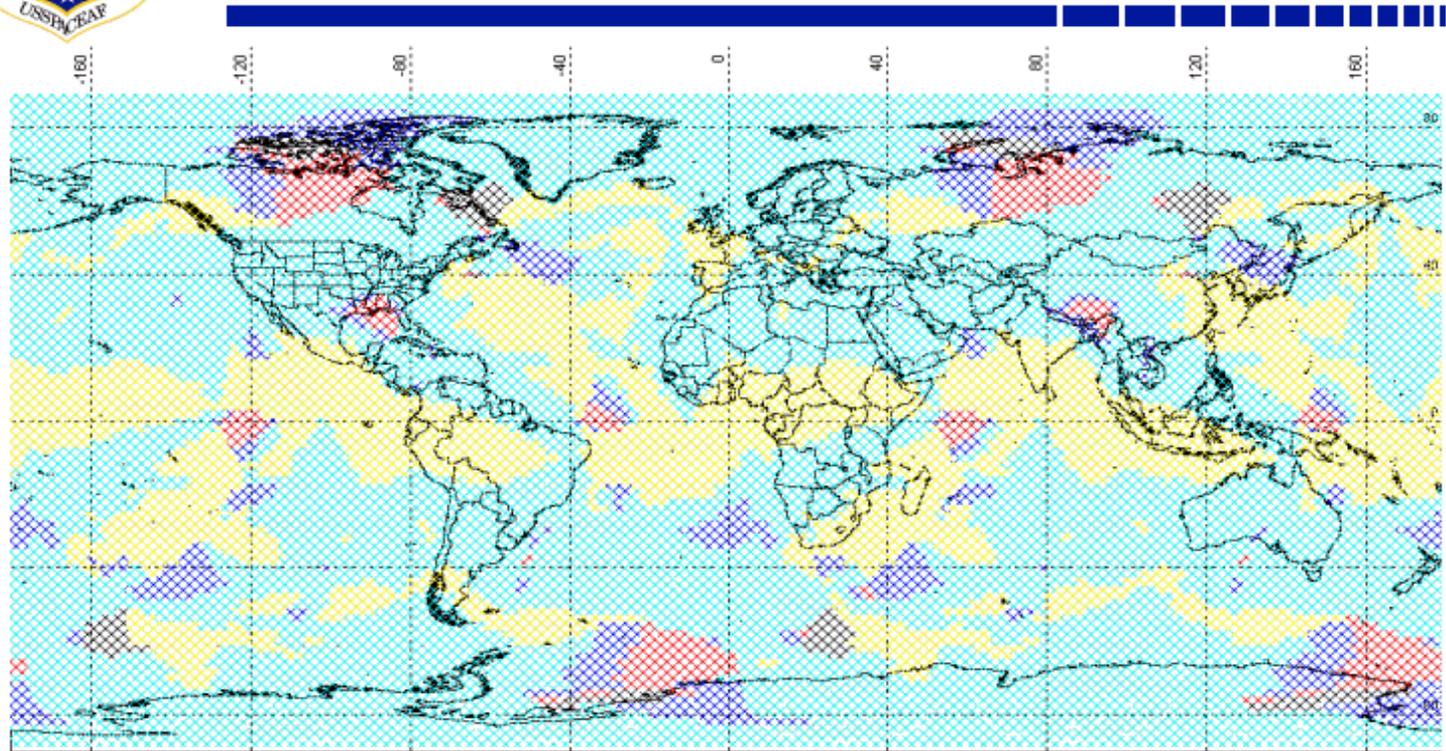
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World PDOP Assessment



GPS Support Center	2SOPS Almanac: sem1187_J282	Production Date: 101455z Oct 2002	0-2	6-9	
Analysis Start: 130000z Oct 2002	Satellite Selection: Best4	Metric: Magnitude of PDOPMax	2-4	9-12	
Analysis Stop: 132400z Oct 2002	Time Increment: 60 seconds	Mask Angle: 5 degrees	4-6	12- > 12	
Grid Increment: 2 degrees		Altitude: 0 meters	< 4 SVs		
PRNs Removed	21				
Removal Start	130000z Oct 2002	130000z Oct 2002			
Removal Stop	132359z Oct 2002	132359z Oct 2002			

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Typical GPS Error Magnitude

- Clock 1 m
- Ephemeris (orbit) 1 m
- Selective Availability (S/A) 10 -100 m
- Troposphere 2-20 m
- Ionosphere 5-45 m
- Pseudo Range Noise .1-1 m
- Receiver Noise .2-1 m
- Multipath (reflections) .5 m





Referenced Web Sites Contact Information



- Current Kp Index http://www.sec.noaa.gov/rt_plots/kp_3d.html
- Geomagnetic Equator Plot <http://www.nwra-az.com/ionoscint/maps/maps.html>
- Solar Cycle Status <http://www.sec.noaa.gov/SolarCycle/>
- GPS Interference <http://www.uscg.mil/hq/gm/moa/docs/11-02.htm>
- GPS Interruptions <http://www.navcen.uscg.gov/gps/gpsnotices/default.htm>
- DOP Plots https://www.peterson.af.mil/GPS_Support/
- Planning http://www.trimble.com/planningsoftware_ts.asp?Nav=Collection-8425
- GPS NANU Subscriptions <http://www.navcen.uscg.gov/gps/subscribe.htm>

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