Summary

Universal Time solution combined by IERS is mainly based on VLBI inertial techniques.

Although space techniques like SLR or GPS have reached a remarkable precision they do not give access to a highly accurate non-rotating reference frame, which restricts the possibility of determining directly UTI from the processing of their observations.

Due principally to uncertainties in the even zonal harmonics and in various models (ocean tides), long-term error drifts are introduced in the node motion and consequently in UTI of which estimation is completely correlated with the node variations.

It is however possible to use the valuable short-term fluctuations given by GPS calibrated with the long-term variations of the solution given by inertial techniques to derive a composite UTI solution of great interest for its precision and time resolution but also for its economic advantage.

Precision of UT based on VLBI and GPS techniques

VLBI UTI Precision:

One -hour intensive (daily)	15 μs
24-hour (7-days)	7 μs

- high-frequency variations of UT(GPS) for densification:

based on

- one solution (CODE or EMR) :	27 μs
- a combined solution of 3 GPS solutions :	25 μs

Near-real time using GPS for prediction

Operational precision in case of VLBI contribution every 10, 20 or 30 days. UTI (GPS) is used from the last VLBI data.

VLBI sampling	UT1 precision
10 days	**200** μs
20 days	**300** μs
30 days	**500** μs

Conclusions

- Long-term GPS "UT1" series not directly usable for Earth Orientation

Possibility to use external reference (VLBI, IERS) for long-term calibration.

- Combined UTI solution routinely computed at IERS/BC

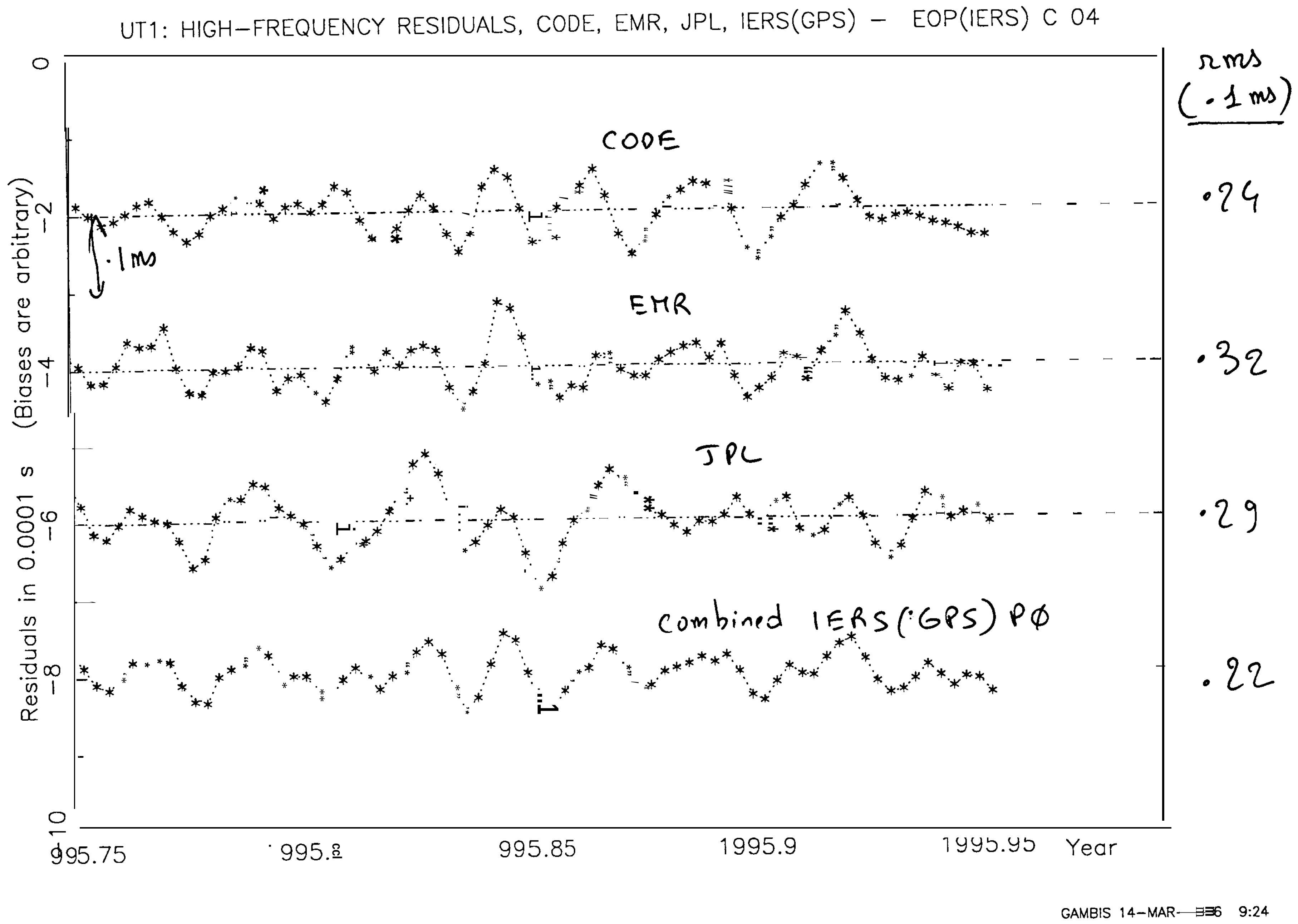
- Precision comparable to other series (NOAA, USNO, CSR).

Combination of independent UTI (GPS) solutions improves the final solution by elimination of white noise.

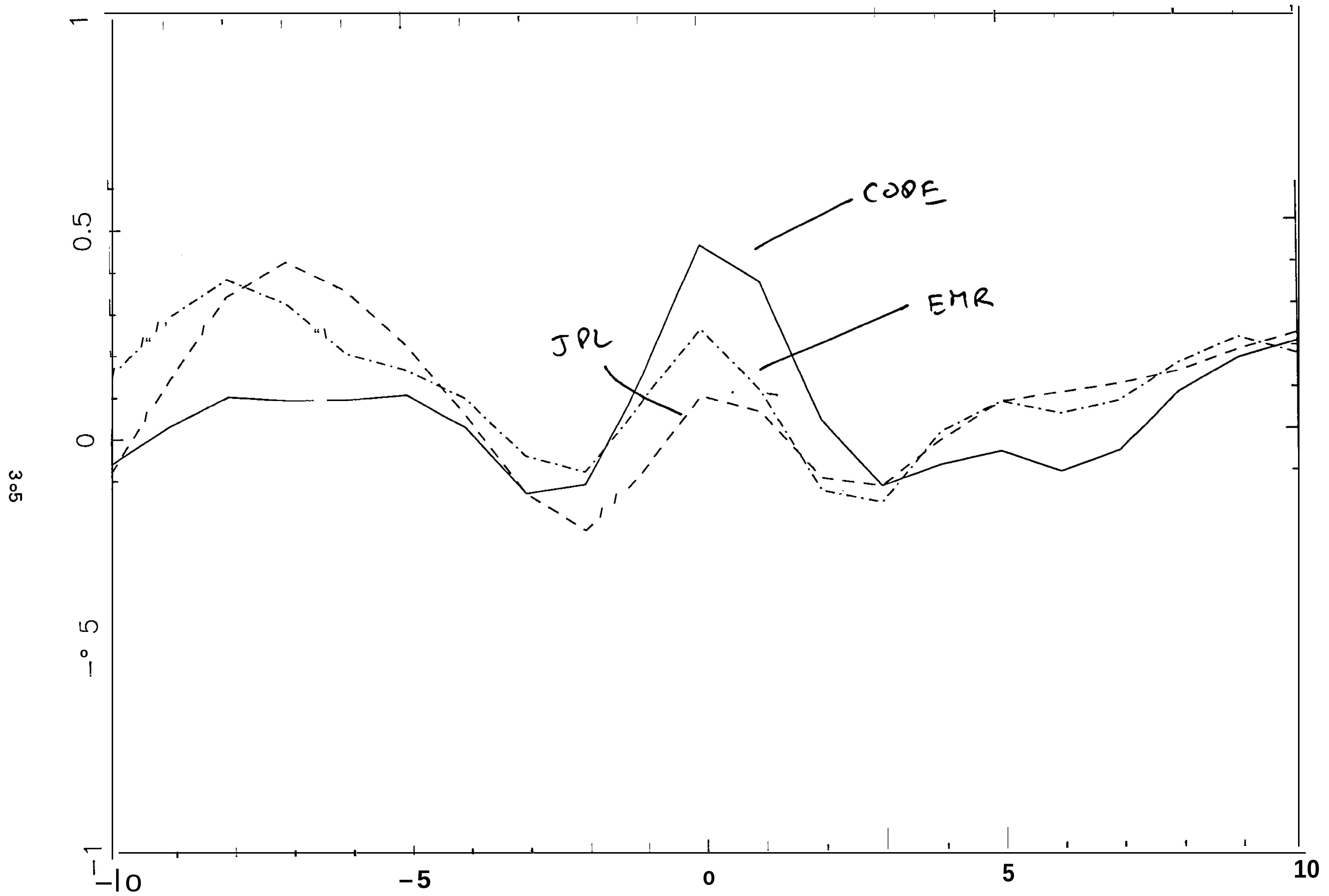
- High sampling contribution (1 day).

Operational precision in case of VLBI contribution every 10, 20 or 30 days. UT1(GPS) is used from the last VLBI data.

VLBI sampling	UTI precision
10 days	0.2 ms
20 days	0.3 ms
30 days	0.5 ms


UT1: HIGH-FREQUENCY RESIDUALS, CODE, EMR, JPL, IERS(GPS) - EOP(IERS) C 04
rms (.1 ms)
CODE
EMR
JPL
combined IERS(GPS) P0
.24
.32
.29
.22
.1 ms
Residuals in 0.0001 s (Biases are arbitrary)
0
-2
-4
-6
-8
10
995.75
995.8
995.85
1995.9
1995.95
Year
GAMBIS 14-MAR-1996 9:24

CORRECTION BETWEEN HIGH–FREQUENCY VARIATIONS OF CODE, EMR AND JPL



Over 1995.75 → 1996.0

GAMBIS 14–MAR–1996 19:50

SPECIAL GPS SOLUTIONS BASED ON ITRF94

Z. Altamimi
institute Geographique National
France

ITRF94_Pl : Extract of GPS stations from ITRF94 solution at **93.0**

ITRF94_P2 : Combination of the 3 GPS solutions used in the ITRF94 Expressed in the ITRF94

ITRF94_P3 : Combination of VLBI, SLR, DORIS and local ties for GPS stations

Comparison ITRF94_P1/P2 at 93.0

	N	SP cm	Su cm	Sx cm	WSP cm	WSU cm	WSX cm
ITRF94_P1	80	.3	.4	.3	.2	.4	.3
ITRF94_P2	80	.2	.7	.5	.1	.3	.2

Comparison ITRF94_P1/P3 at 93.0

	N	SP cm	Su cm	Sx cm	WSP cm	WSU cm	WSX cm
ITRF94_P1	46	.4	.4	.4	.3	.4	.3
ITRF94_P3	46	.7	1.6	1.1	.6	.8	.6

Comparison ITRF94_P2/P3 at 93.0

	N	SP cm	Su cm	Sx cm	WSP cm	WSU cm	WSX cm
ITRF94_P2	46	.5	1.2	.8	.2	.4	.3
ITRF94_P3	46	1.0	2.0	1.4	.9	1.2	1.0

Ashtech Radome Tests
on
Dorne-Margolin Choke Ring Antennas

R. King, A.E. N'ell, McClusky, and T. Herring

GPS Systems

2 Ashtech Z-12s - with or without Ashtech radome

1 AOA TurboRogue - no radome

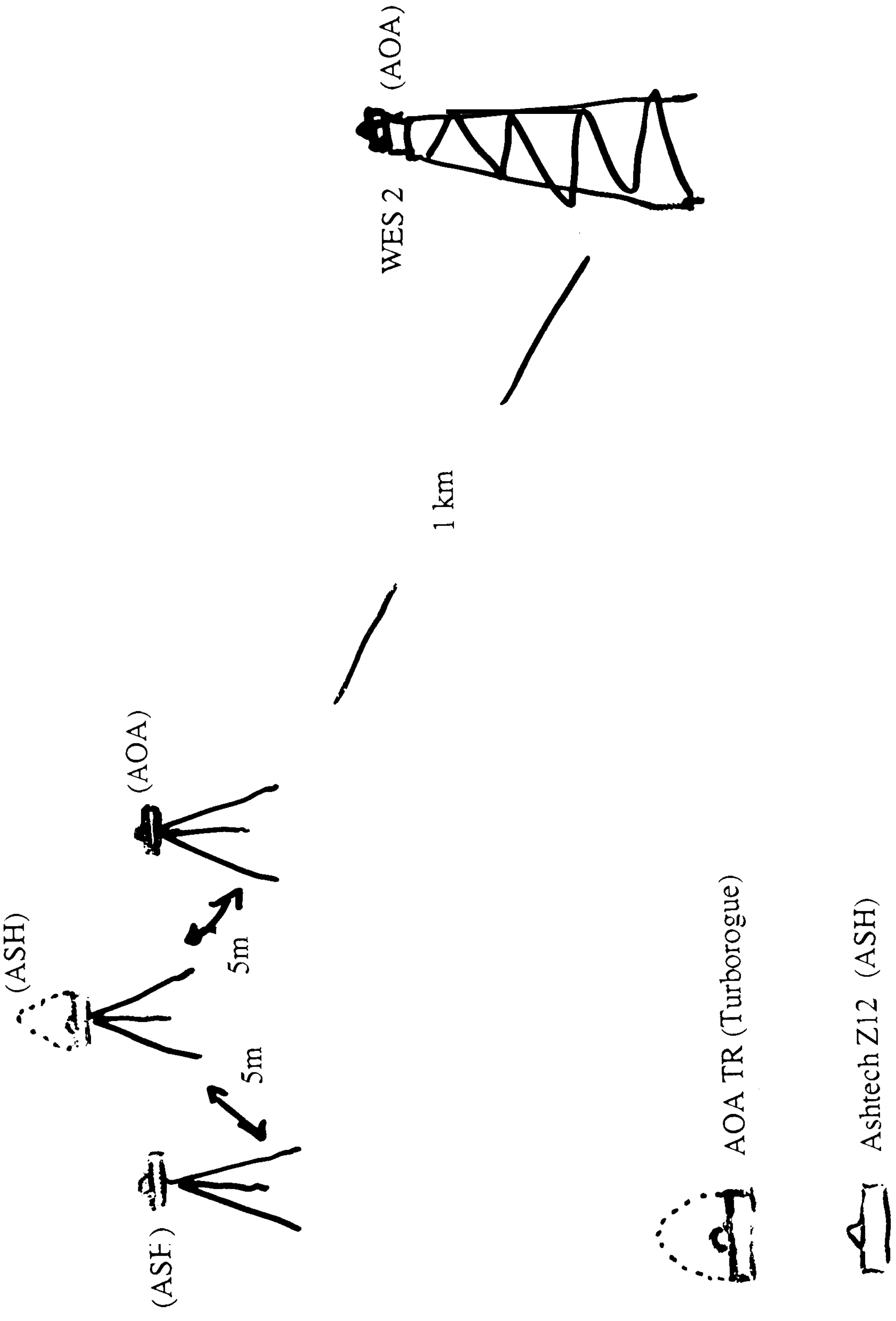
Dorne-Margolin choke ring (DM/CR) antennas

~5 meter separation of antennas

LC observable

Solve for antenna positions and tropospheres relative ⊝WES2

(TurboRogue DM/CR ~: km away)


WES 2
(AOA)
1 km
(AOA)
(ASH)
5m
5m
(ASH)
AOA TR (Turborogue)
Ashtech Z12 (ASH)

Ashtech Radome Tests
on
Dorne-Margolin Choke Ring Antennas

<u>No-Radome Solutions</u>

1) Height difference compared to theodolite leveling
15° and 5° minimum elevation:

AshtechE - AOA 1 mm
AshtechW - AOA 10 mm

Use "standard antenna on tripod & do absolute position differences

2) Interchange AOA and Ashtech DM/CR antennas on AshtechW

< 2 mm difference in any coordinate

<u>Effect of Radome</u>

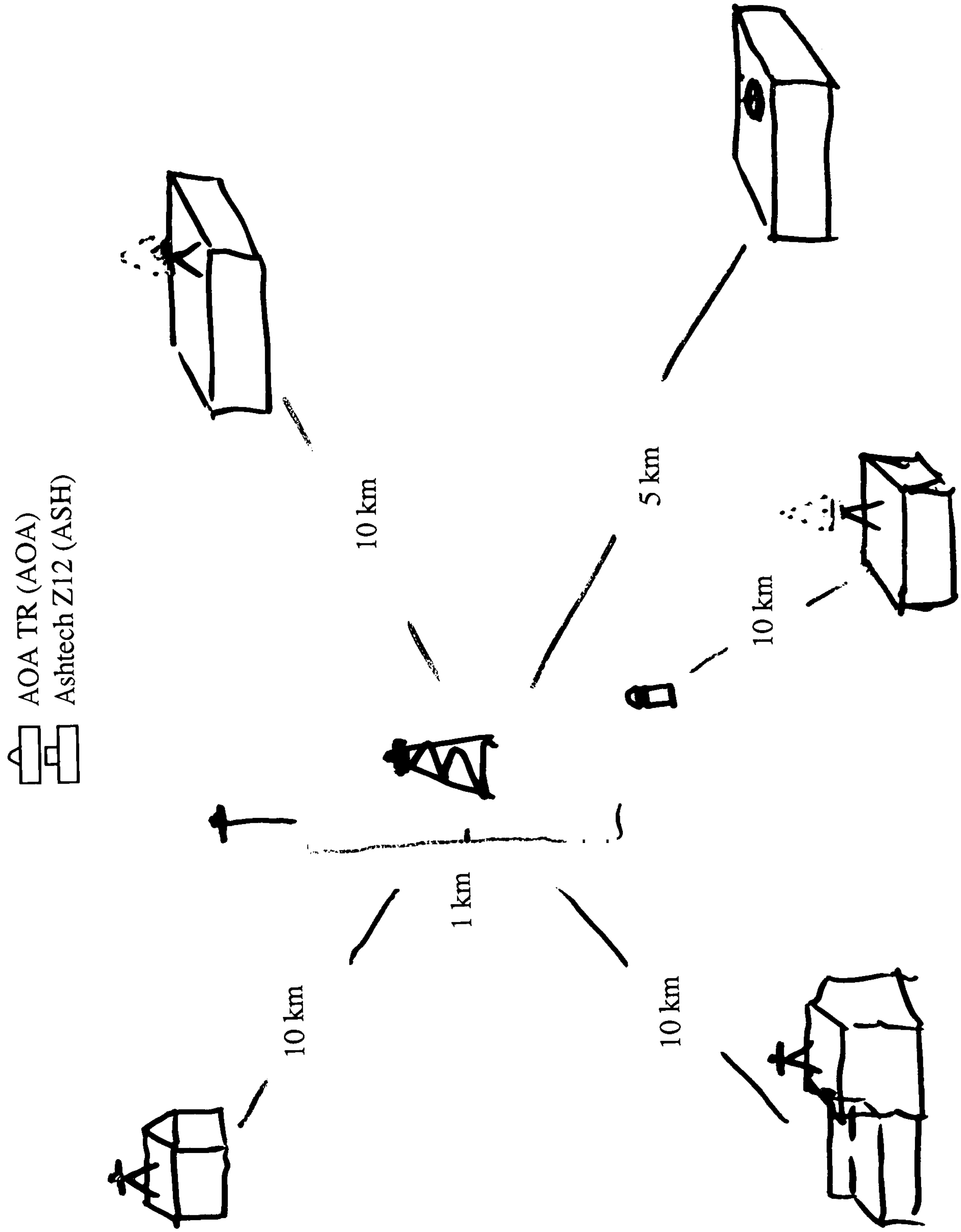
Add radome to AshtechE

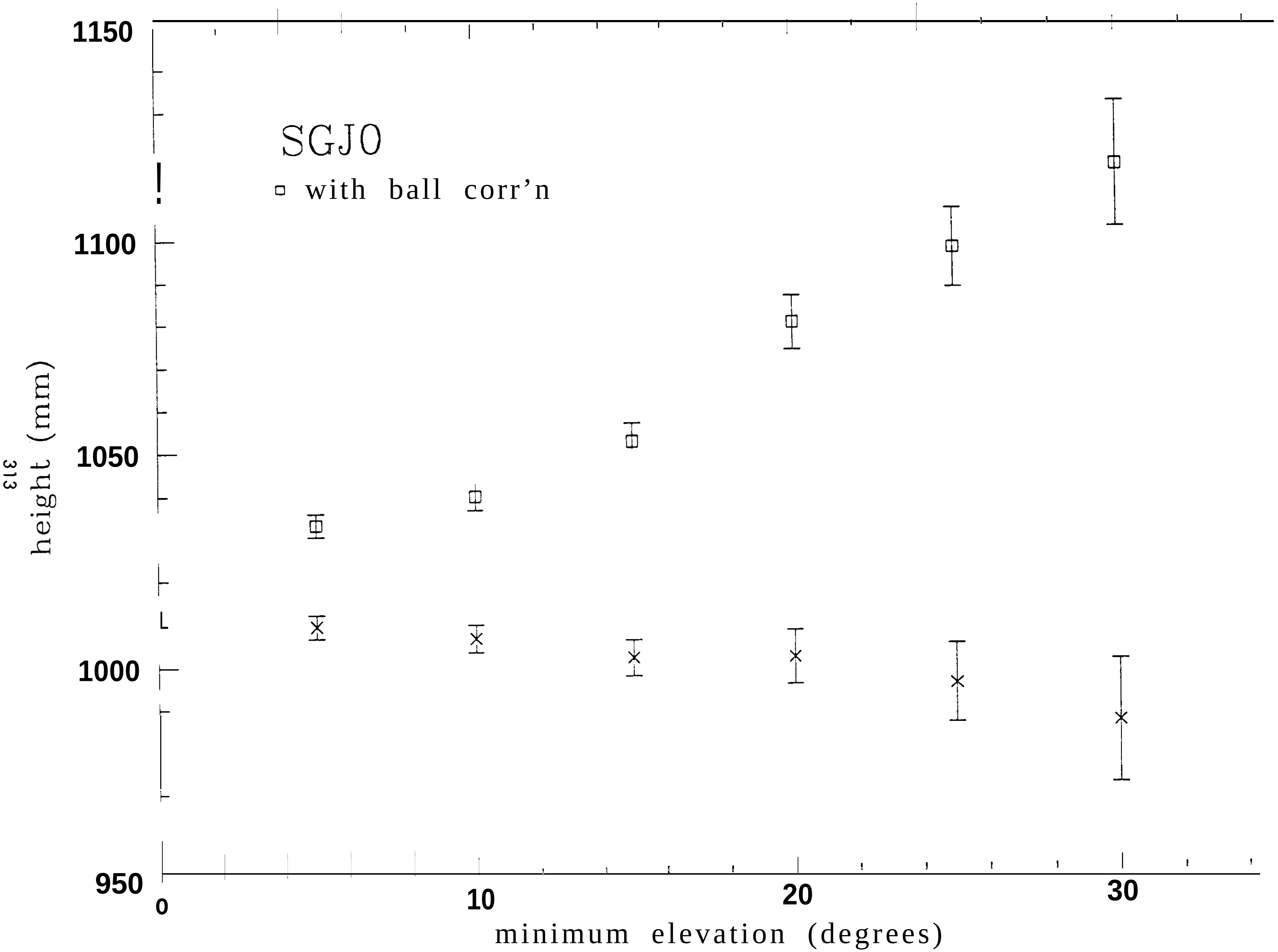
elev_min	Ah
15°	-15 ± 2 mm
5°	-5 ± 2 mm

UNAVCO -10 mm

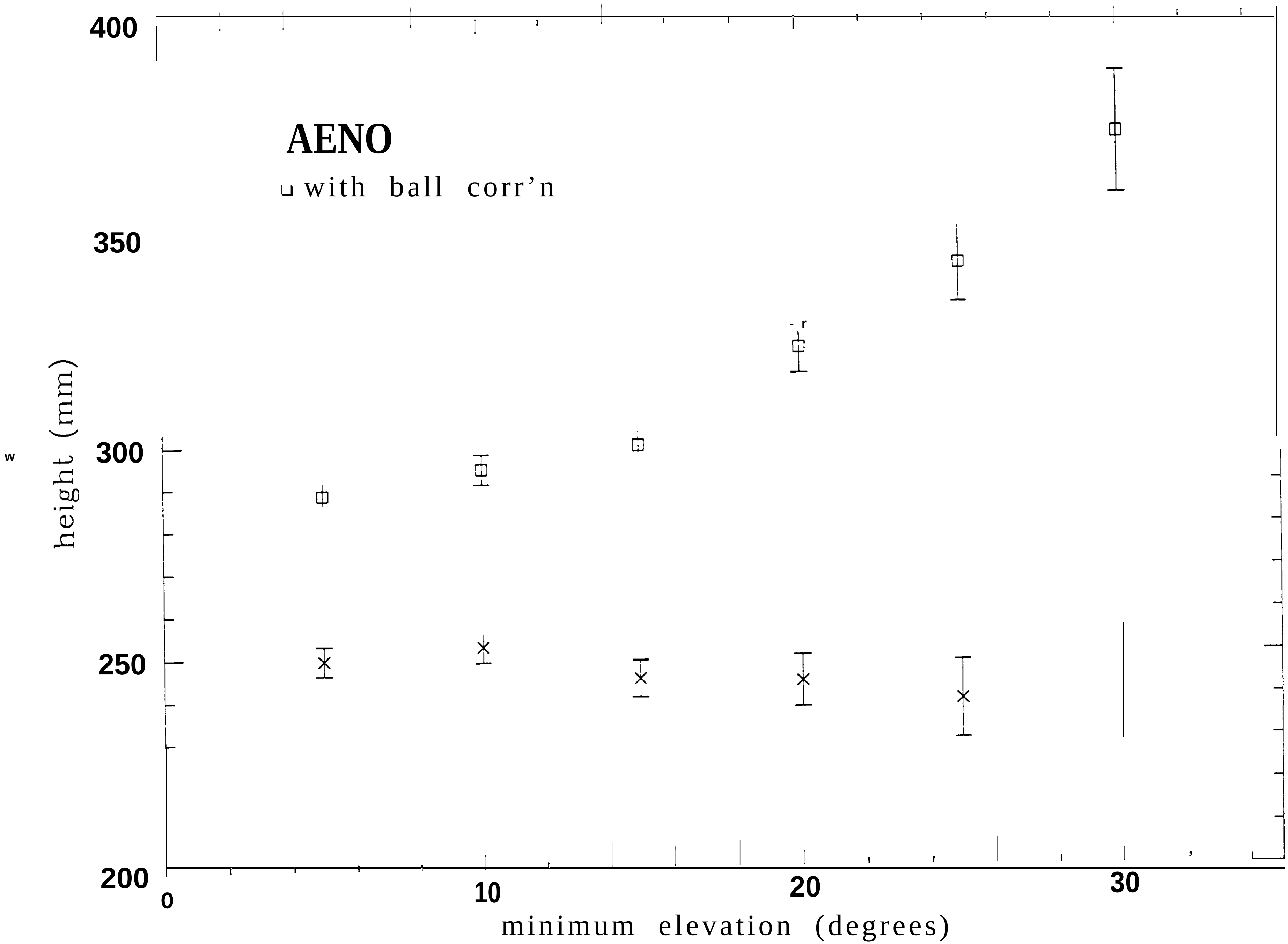
Don't use radomes without testing effect

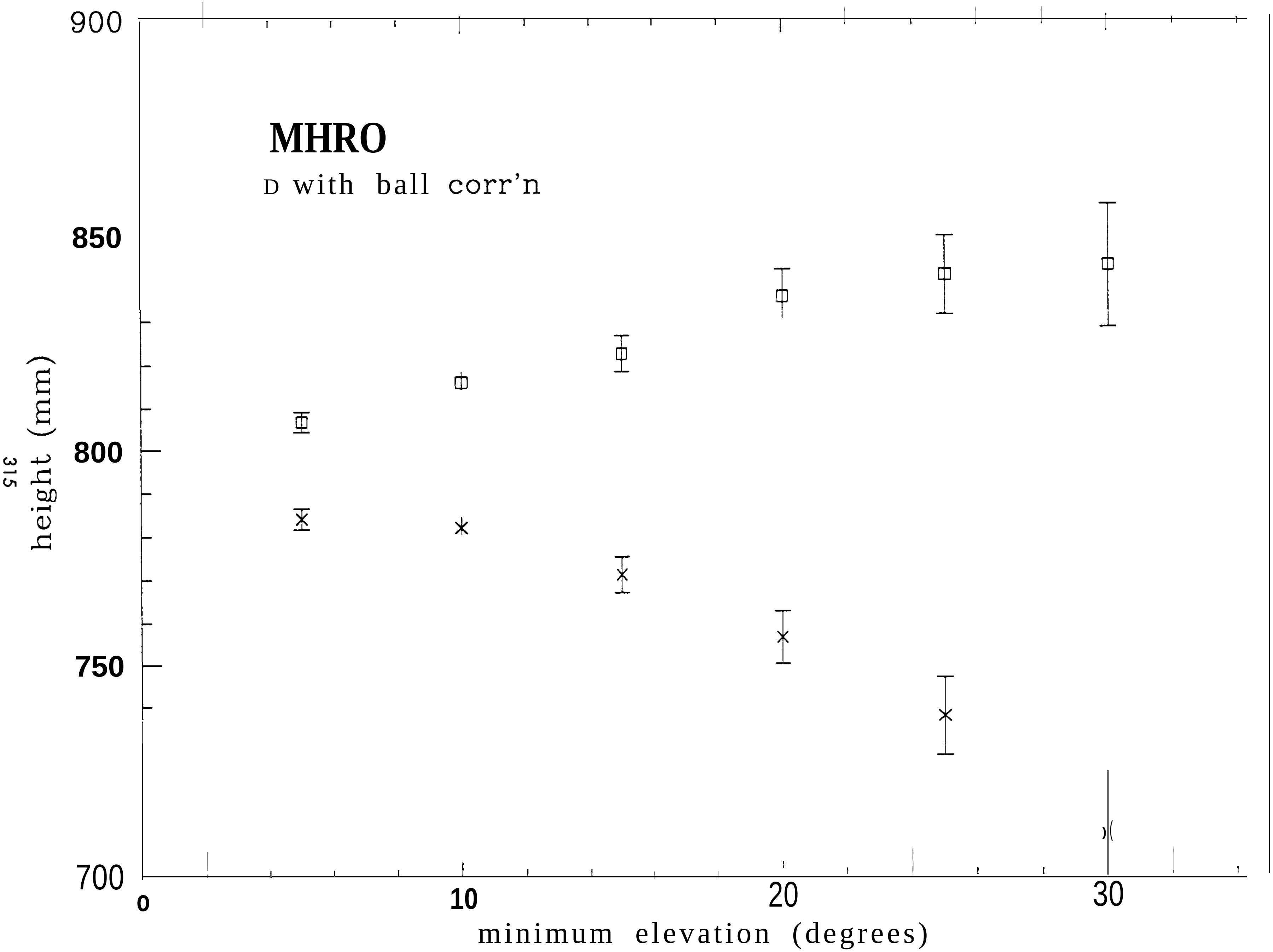
A. E. **Niell**
NRC Workshop
96/03/1 1

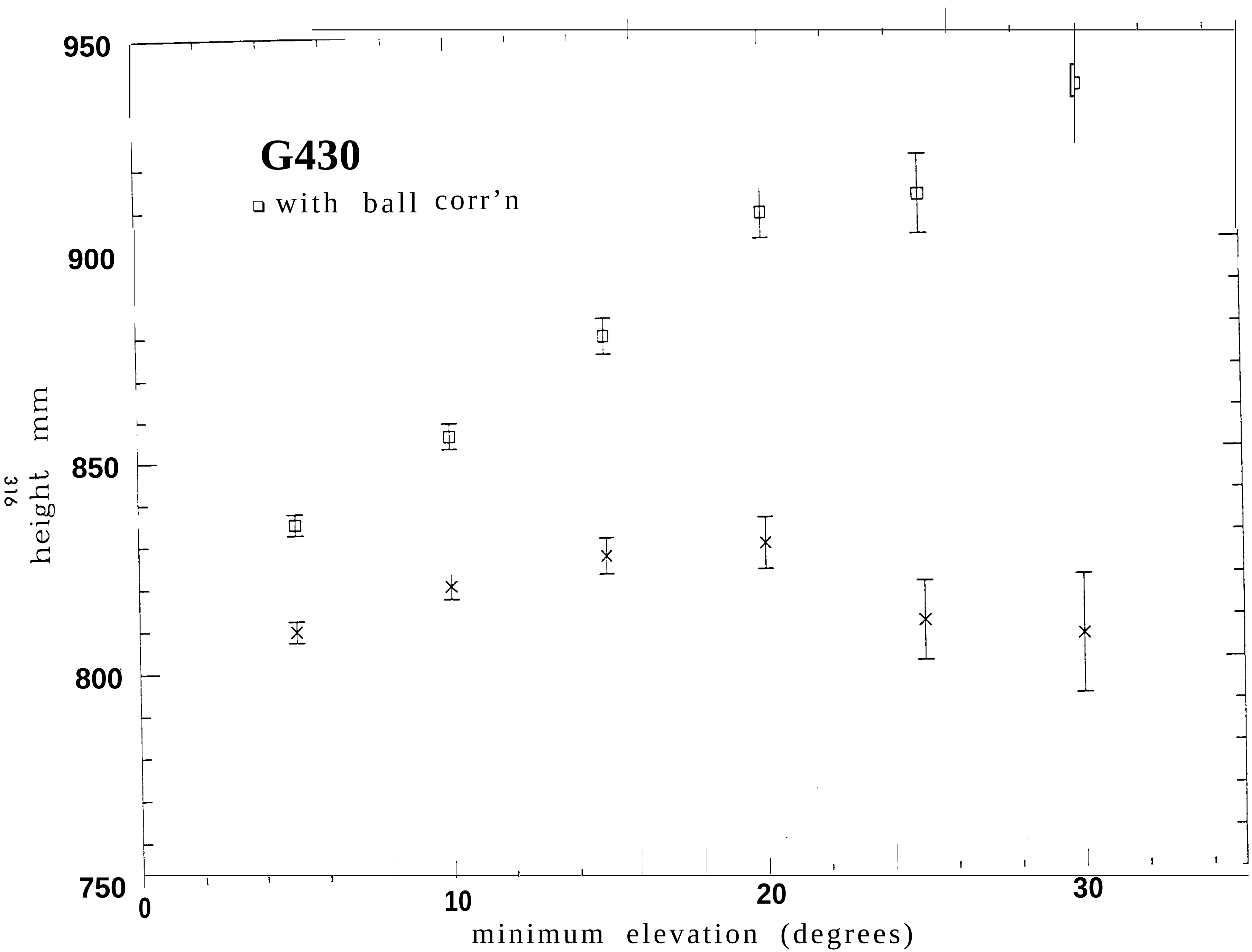

AOA TR (AOA)
Ashtech Z12 (ASH)
10 km
5 km
10 km
1 km
10 km
10 km



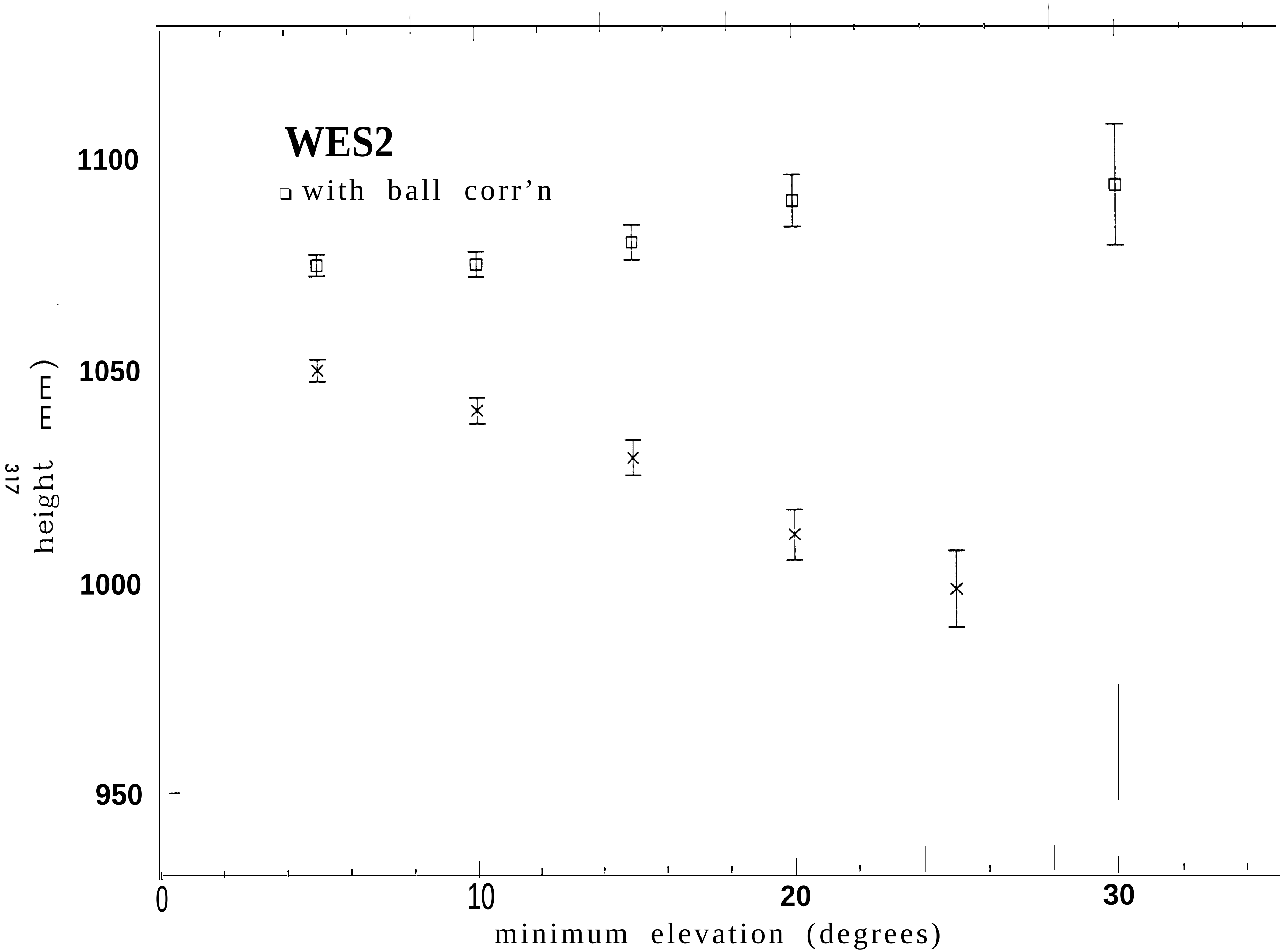
SGJO
with ball corr'n
1150
1100
1050
1000
950
0
10
20
30
minimum elevation (degrees)
height (mm)
313


AENO
with ball corr'n
height (mm)
minimum elevation (degrees)
400
350
300
250
200
0
10
20
30

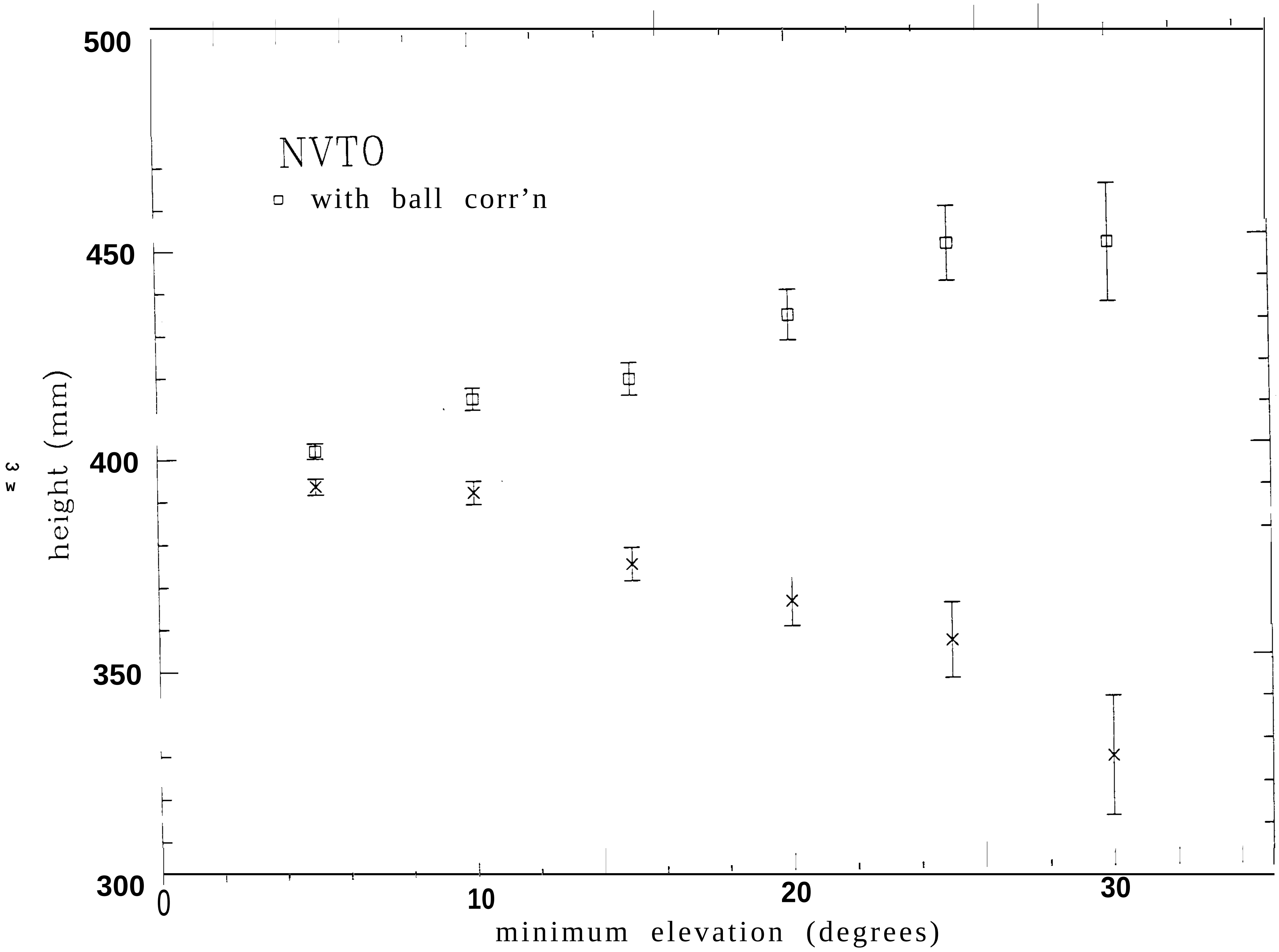

MHRO
D with ball corr'n
900
850
800
750
700
height (mm)
315
0
10
20
30
minimum elevation (degrees)



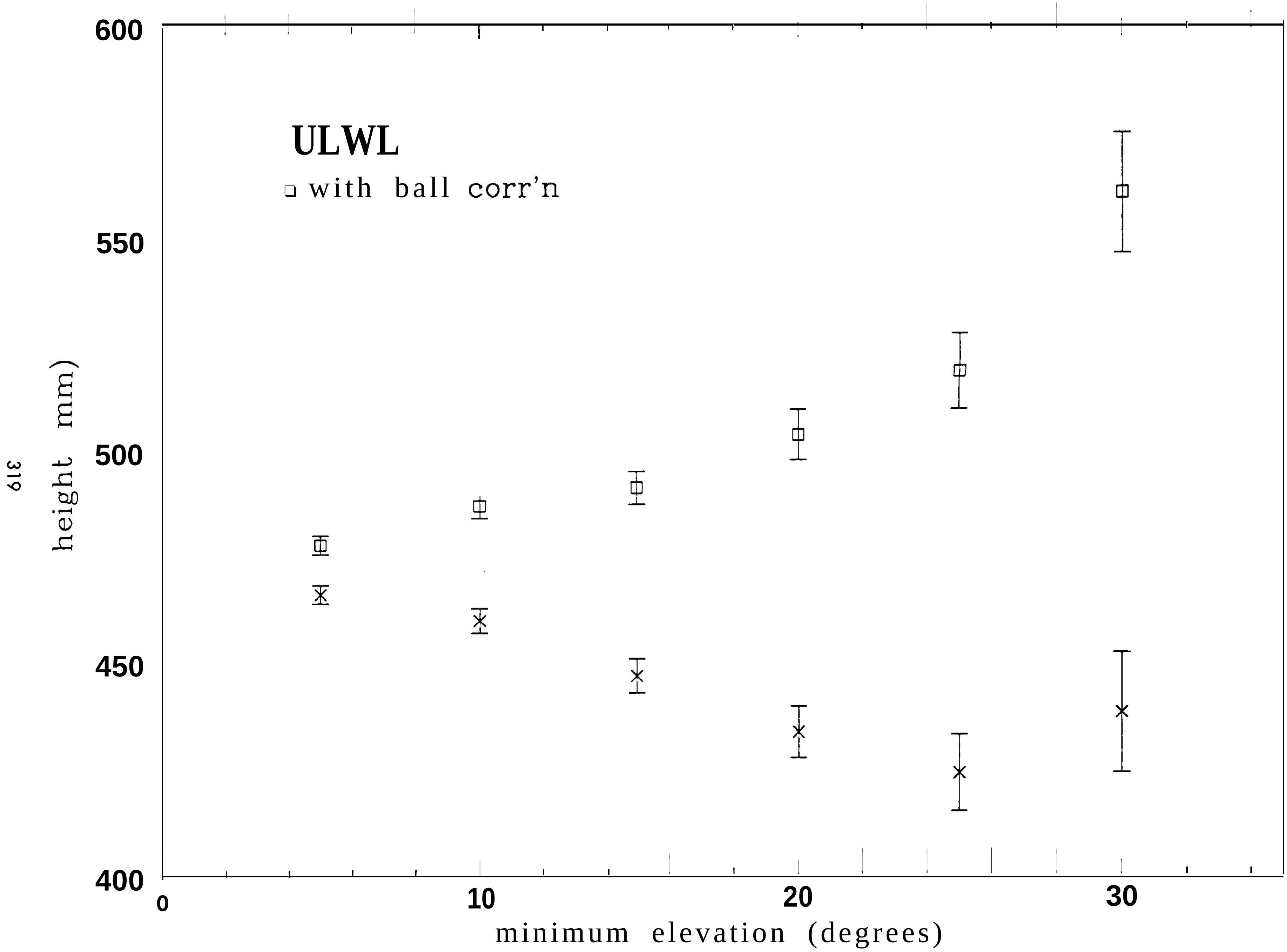
G430
with ball corr'n
height mm
316
950
900
850
800
750
0
10
20
30
minimum elevation (degrees)



WES2
with ball corr'n
1100
1050
1000
950
height (mm)
317
0
10
20
30
minimum elevation (degrees)



NVTO
with ball corr'n
height (mm)
ε w
500
450
400
350
300
0
10
20
30
minimum elevation (degrees)



600
550
500
450
400
0
10
20
30
ULWL
□ with ball corr'n
height mm)
minimum elevation (degrees)

RECOMMENDATIONS

1) **For choke ring antennas do NOT apply any correction**

2) **At all sites compare height difference to levelling to 2 near-by (5m) antennas (as function of elevation)**

ANTENNA PHASE CENTER OFFSETS AND VARIATIONS ESTIMATED FROM GPS DATA

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Astronomical Institute
University of Berne
Switzerland

IGS ANALYSIS CENTER WORKSHOP

in
Silver Springs , USA

March 19-21, 1996

Content:

1. Introduction
2. Calibration Campaigns, Processing Strategy
3. Mean Phase Center Offsets
4. Elevation- and Azimuth-Dependent Variations
5. Conclusions/Recommendations

Introduction

- **Two types of biases:**

  – Combination of *different antenna* types
  → main effect in height (up to 10 cm).
  Relative calibration possible with GPS data from very short, known baselines.

  – On long baselines for the *same antenna* type
  → main effect in baseline length (up to 0.01 ppm).
  Absolute calibration only possible with chamber measurements.

- **Impact on the IGS:**

  – Densification of the IGS network using different receiver/antenna types.

  – Antenna changes at the IGS sites.

  – Systematic biases in results when changing the elevation cut-off angle (e.g. for AS data).

Antenna Calibration Campaigns

Thun'94:

- 2 24-hour sessions
- Antennas switched between sessions
- Organized by the *Federal Office of Topography*, Switzerland

Wettzell'95-1:

- **4** 24-hour sessions
- Antennas switched and rotated by 180 degrees between sessions
- Organized by the *Institute for Applied Geodesy*, Germany

Antenna (Receiver)	**Thun'94**	**Wett'95**	**B**
ROGUE DORNE MARGOLIN T	1	3	x
ROGUE DORNE MARGOLIN B	---	1	
4000ST L1/L2 GEOD (SN 14532)	2	2	x
TR GEOD L1/L2 (SN 22020, w+w/o GP)	2	2	x
SR299E EXTERNAL (w+w/o GP)	2	---	
SR299 INTERNAL	---	2	
ASHTECH GEOD L1/L2 P (SN 700228)	2	2	

Estimation Strategy

The Bernese GPS Software was modified to:

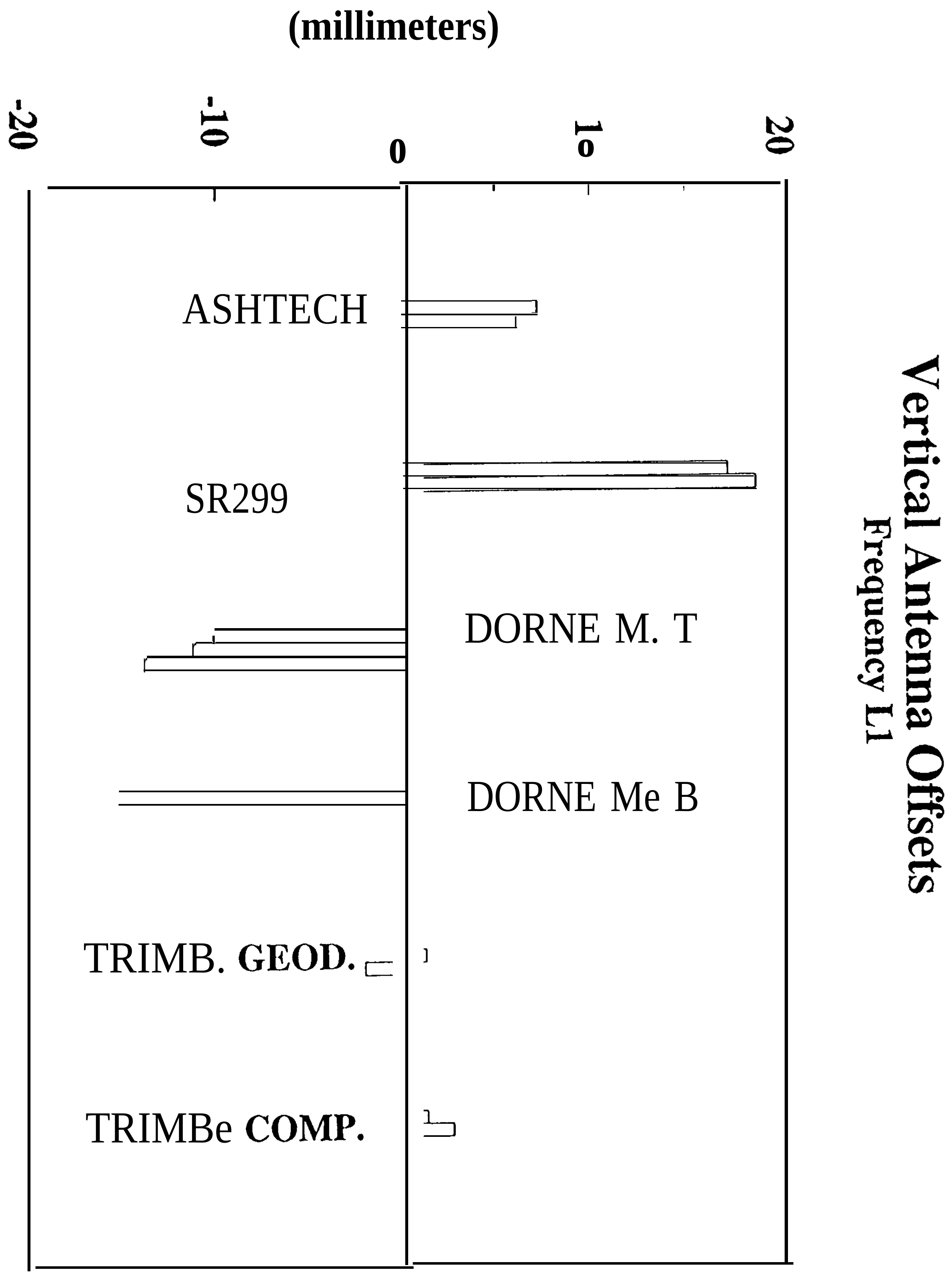
- Estimate antenna phase center *offsets.*
- Estimate *elevation- and azimuth-dependent* phase center variations.
- Allow for different antenna *orientations.*

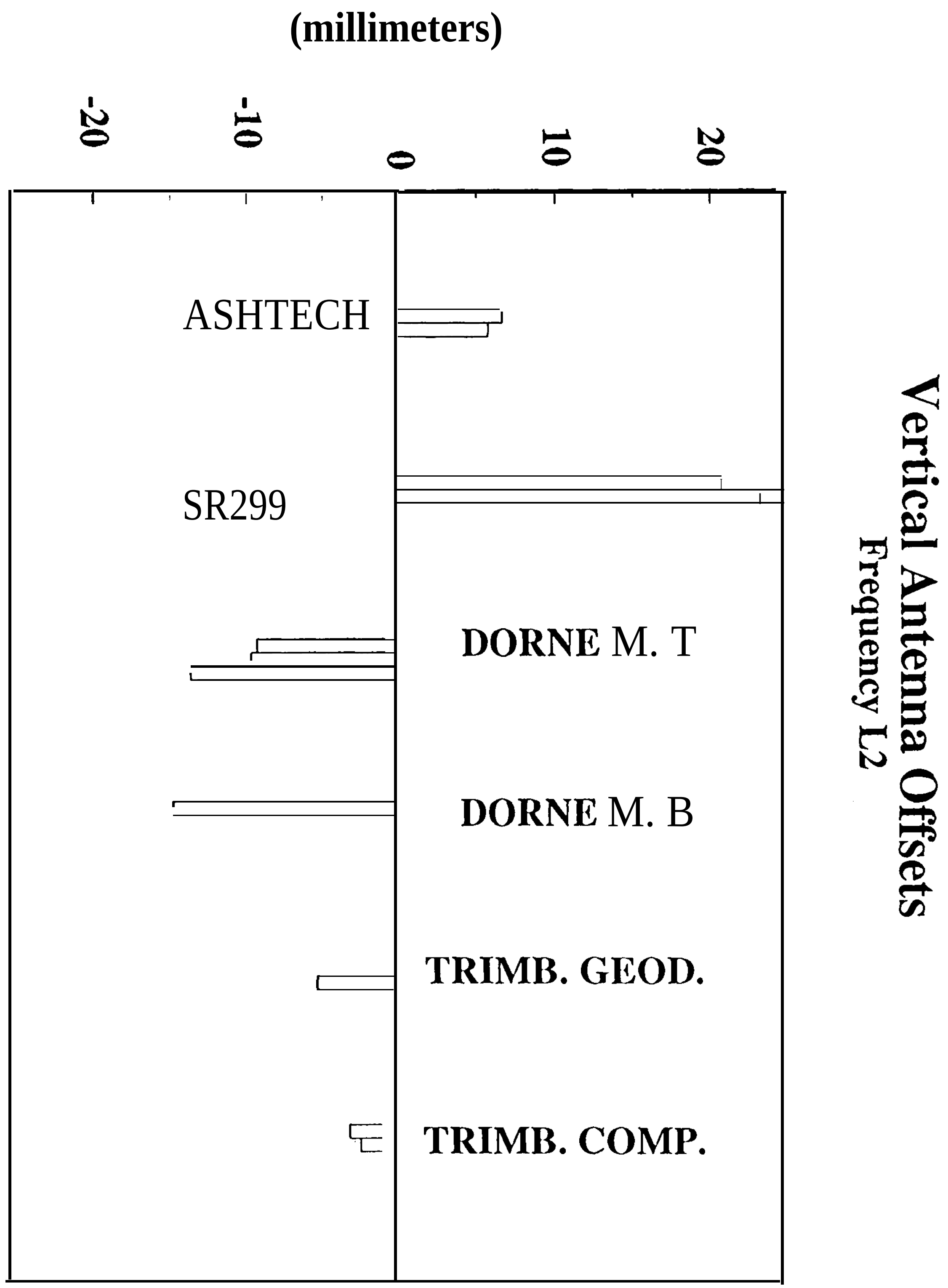
Estimation of Mean Phase Center Offsets:

- Mean phase centers depend on the elevation cut-off angle. We used a cut-off of 20 degrees.
- Wettzell: The horizontal antenna offsets and the horizontal site coordinates could be estimated *simultaneously* (rotation of the antennas).
- Thun: Site coordinates fixed to ground truth.

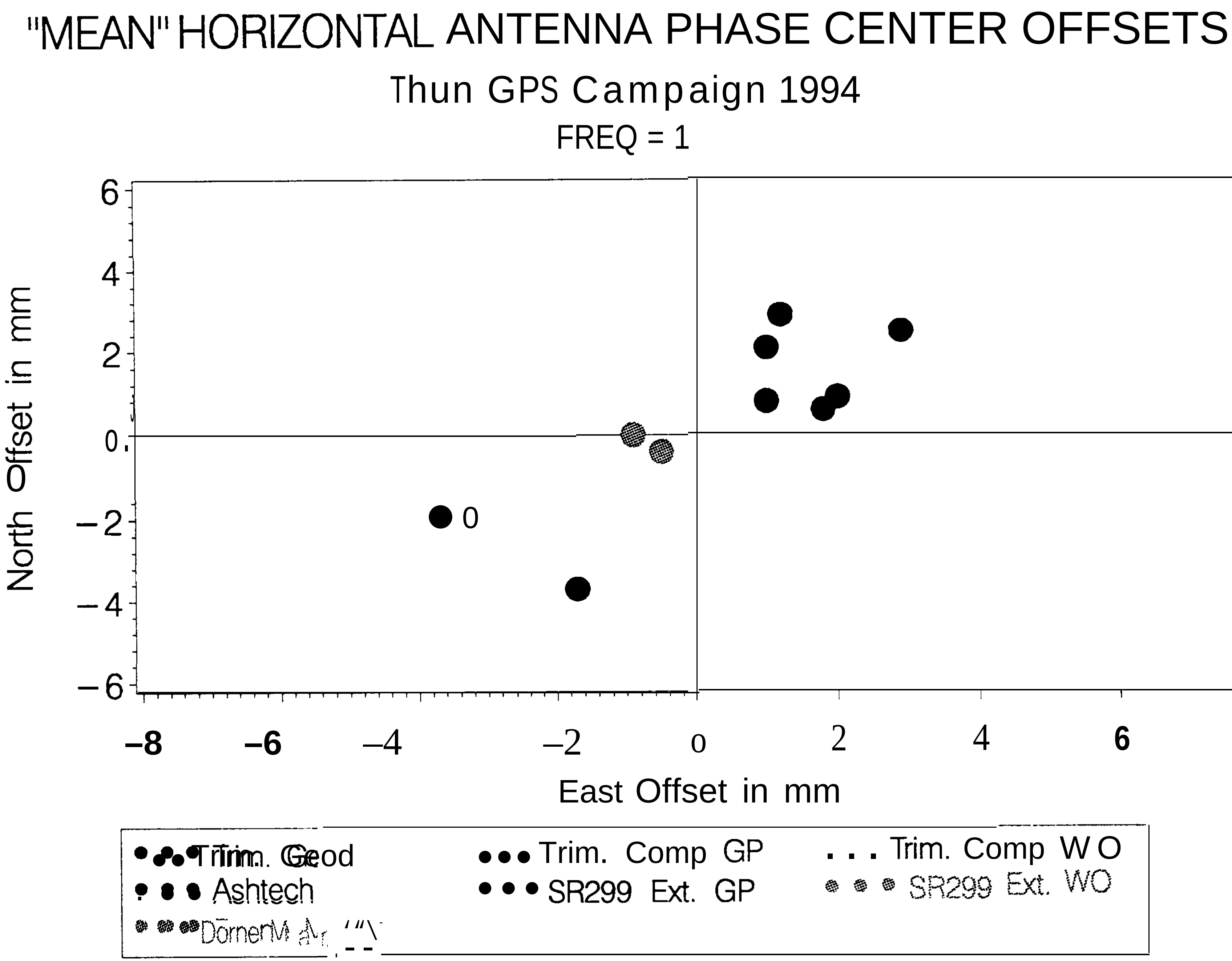
Elevation- and Azimuth-Dependent Variations:

- Model: *Spherical harmonics* or a *grid.*
- Estimation of *elevation-dependent* variations: The station heights have to be known and fixed.
- Estimation of *azimuth-dependent* variations: Due to the rotation of the antennas the azimuth-dependency could be estimated together with the horizontal site coordinates.


Vertical Antenna Offsets
Frequency L1
(millimeters)
-20
-10
0
1o
20
ASHTECH
SR299
DORNE M. T
DORNE Me B
TRIMB. GEOD.
TRIMBe COMP.



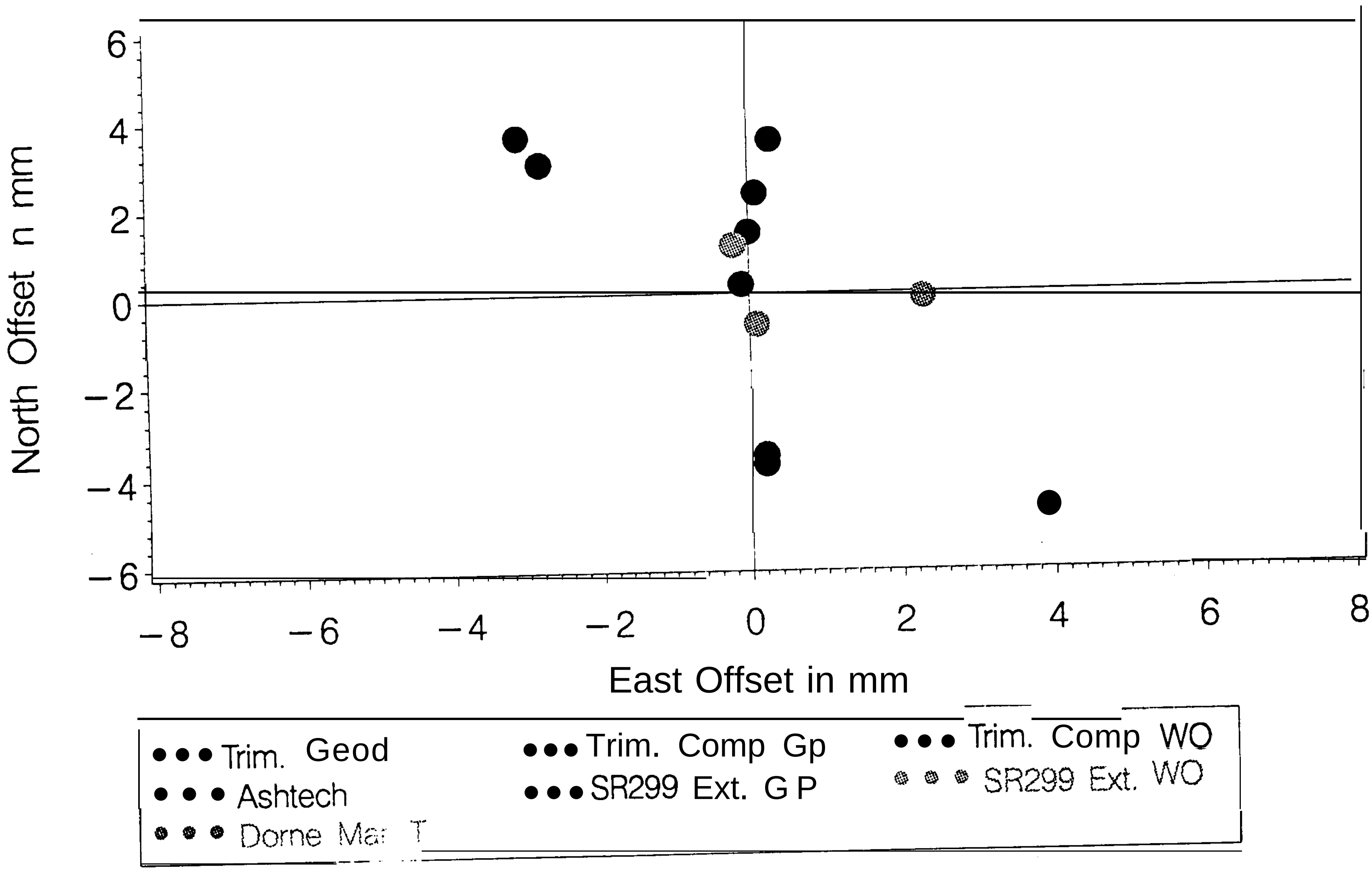
Vertical Antenna Offsets
Frequency L2
(millimeters)
-20
-10
0
10
20
ASHTECH
SR299
DORNE M. T
DORNE M. B
TRIMB. GEOD.
TRIMB. COMP.


"MEAN" HORIZONTAL ANTENNA PHASE CENTER OFFSETS
Thun GPS Campaign 1994
FREQ = 1
North Offset in mm
East Offset in mm
6
4
2
0
-2
-4
-6
-8
-6
-4
-2
0
2
4
6
8
Trim. Geod
Ashtech
Trim. Comp GP
SR299 Ext. GP
Trim. Comp WO
SR299 Ext. WO

“MEAN HORIZONTAL ANTENNA PHASE CENTER OFFSETS

Thun GPS Campaign 1994

FREQ = 2

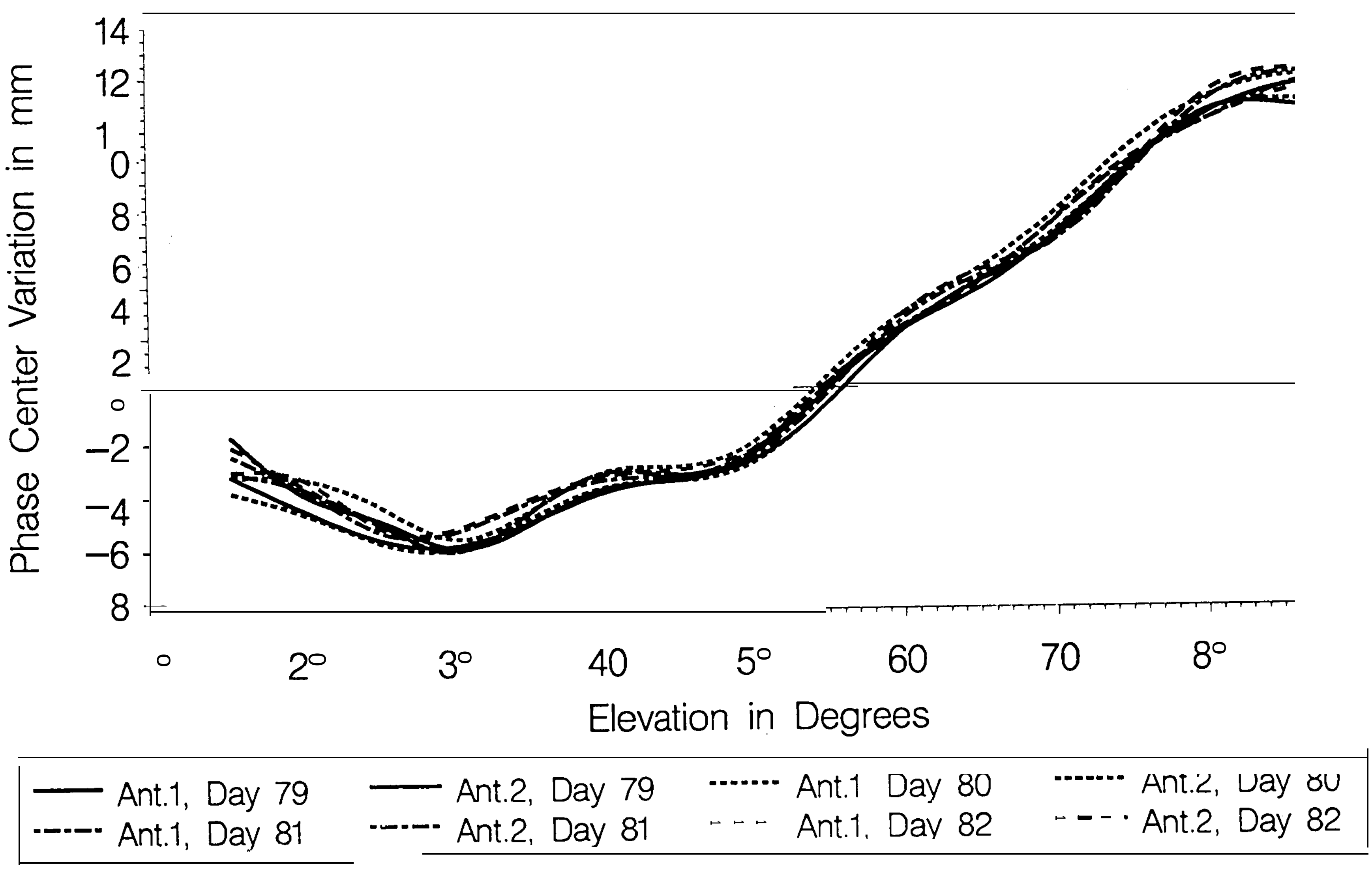


32ω

ELEV.-n≤P. PCV R≷PEATABILITY FOR nORzE MARGOLIN T

Reference: Dorne Margolin T; Wettzel Campaign

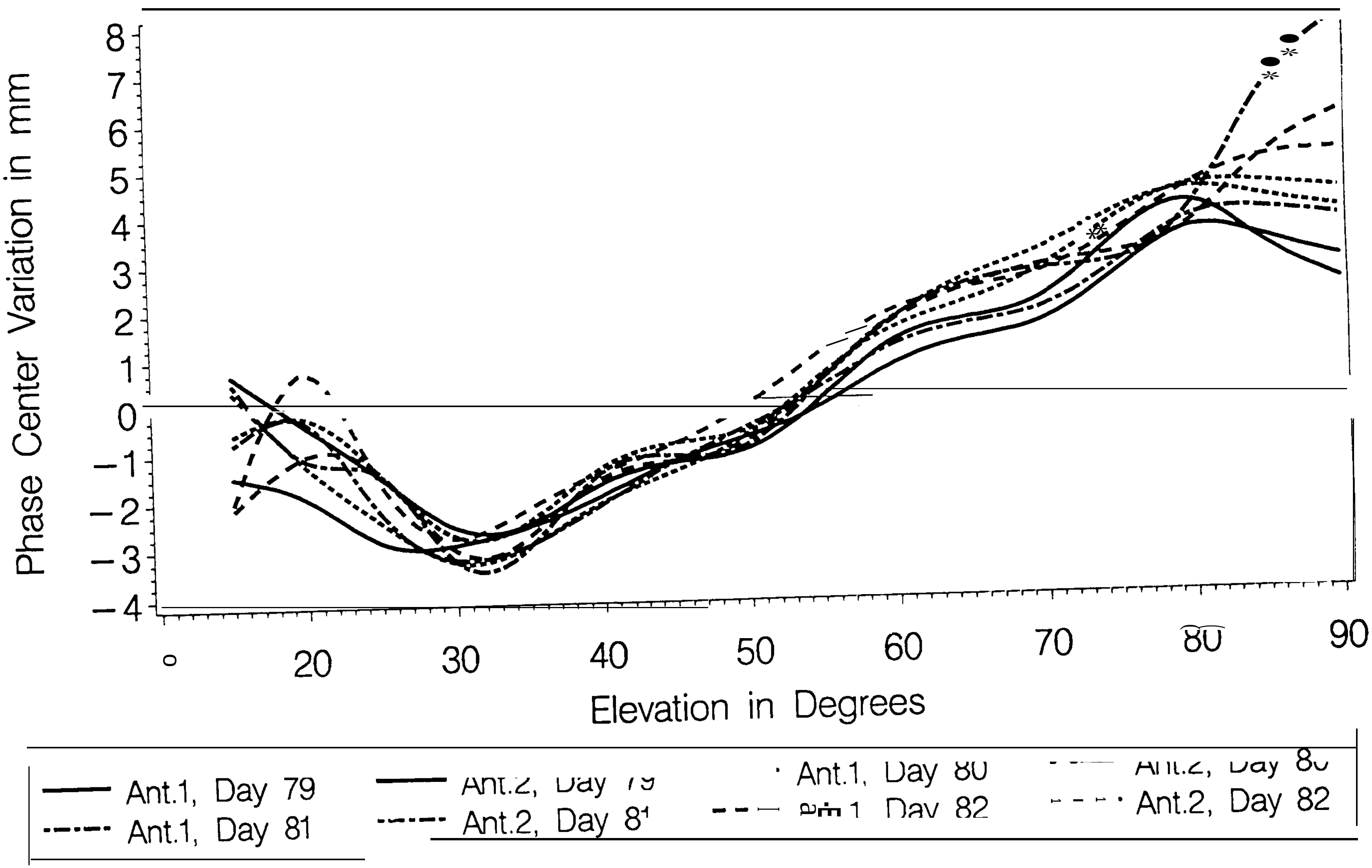
FREQ=1



ELEV. DEP. PCV REPEATABILITY FOR DORNE MARGOLIN T

Reference: Dorne Margolin T; Wettze Campa'gn

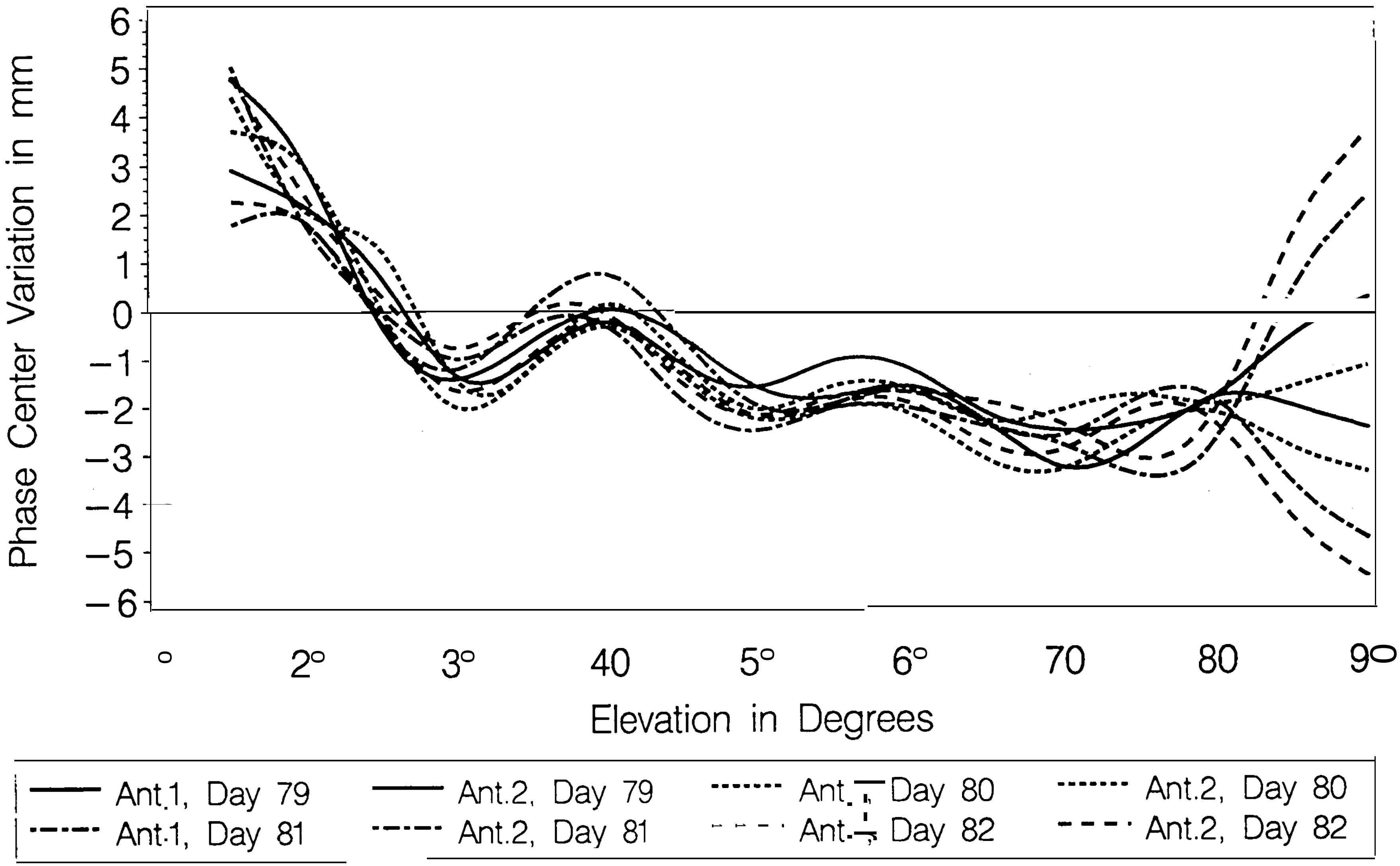
FREQ = 2



ELEV.-DEP. PCV REPEATABILITY FOR SR299 INTERNAL

Reference: Dorne Margolin T; Wettze Campaign

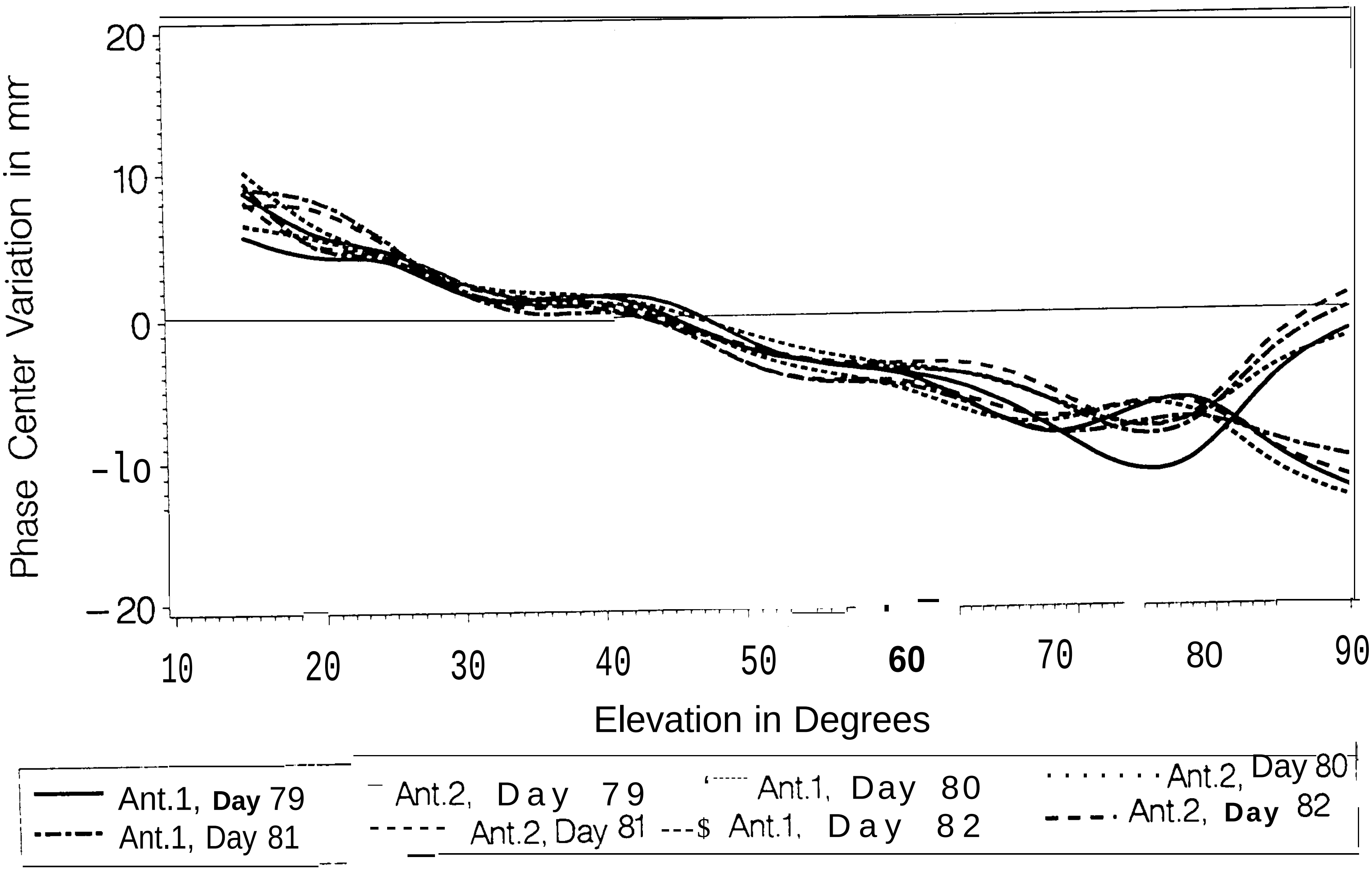
FREQ=1

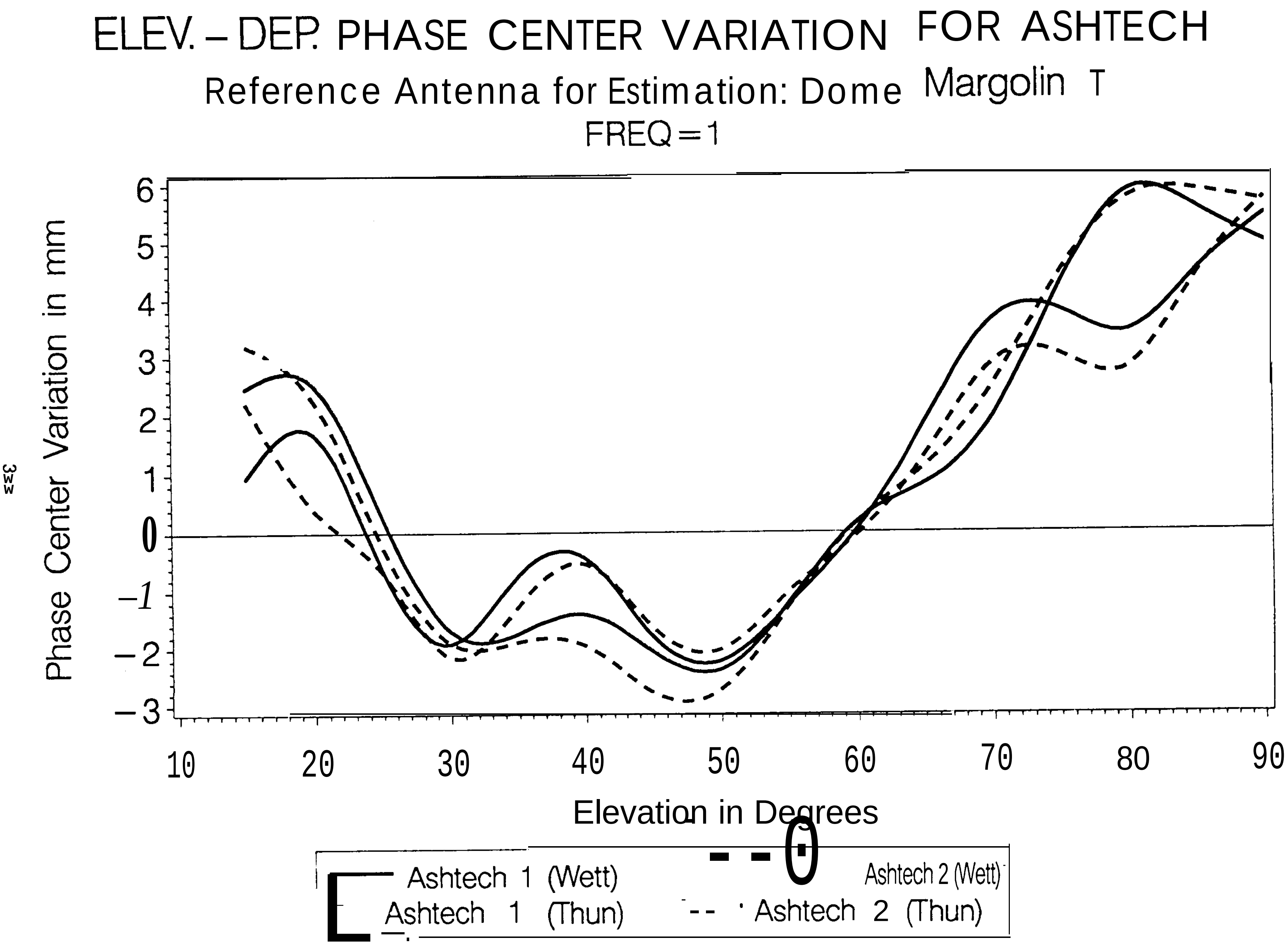


ELEV. – DEI? PCV REPEATABILITY FOR SR299 INTERNAL

Reference: Dome Margolin T; Wettzell Campaign

FREQ=2

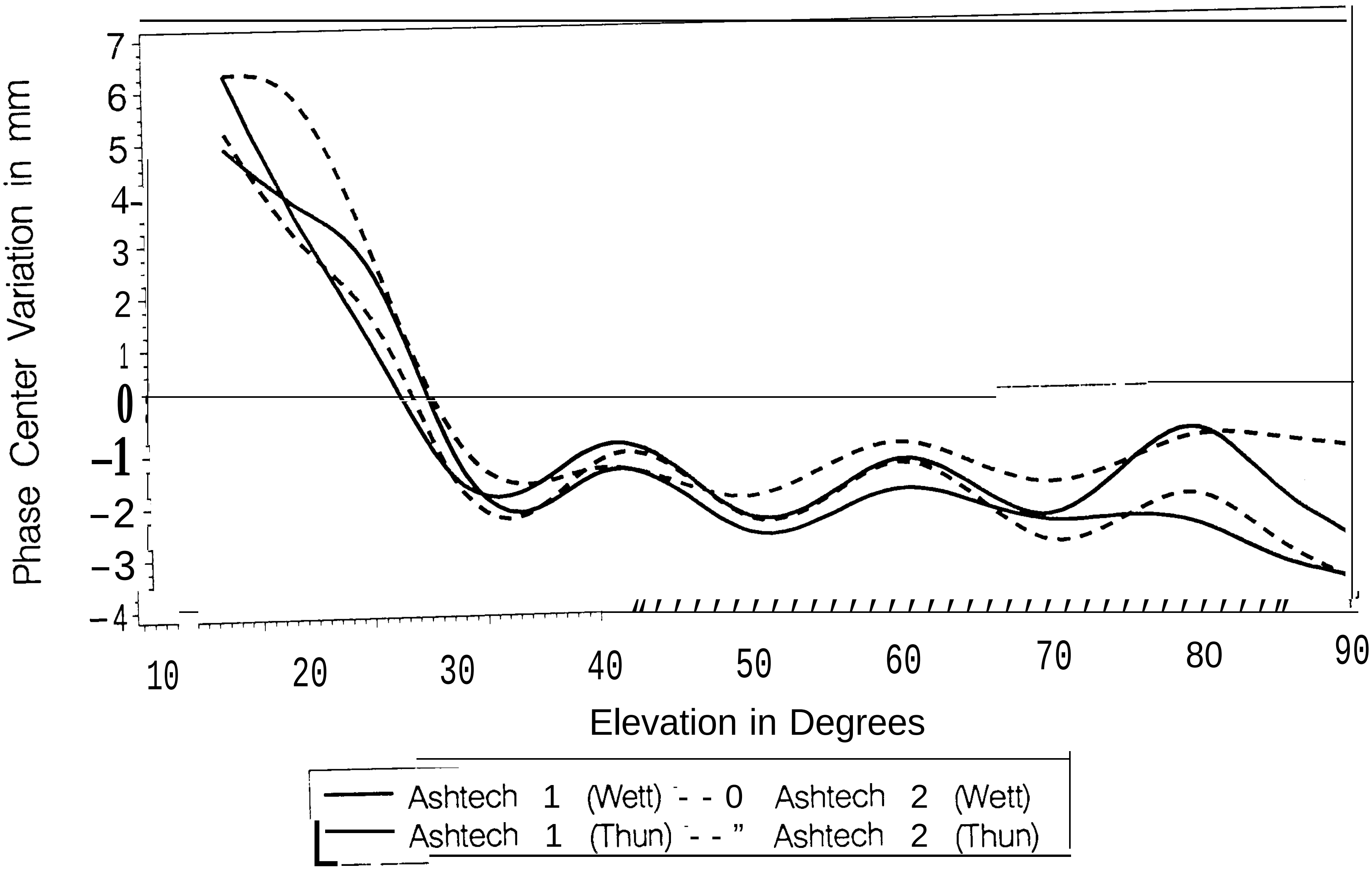



ELEV. – DEP. PHASE CENTER VARIATION FOR ASHTECH
Reference Antenna for Estimation: Dome Margolin T
FREQ = 1
Phase Center Variation in mm
6
5
4
3
2
1
0
–1
–2
–3
10
20
30
40
50
60
70
80
90
Elevation in Degrees
Ashtech 1 (Wett)
Ashtech 1 (Thun)
Ashtech 2 (Wett)
Ashtech 2 (Thun)

ELEV. – DEP. PHASE CENTER VARIATION FOR ASHTECH

Reference Antenna for Estimation: Dome Margolin T

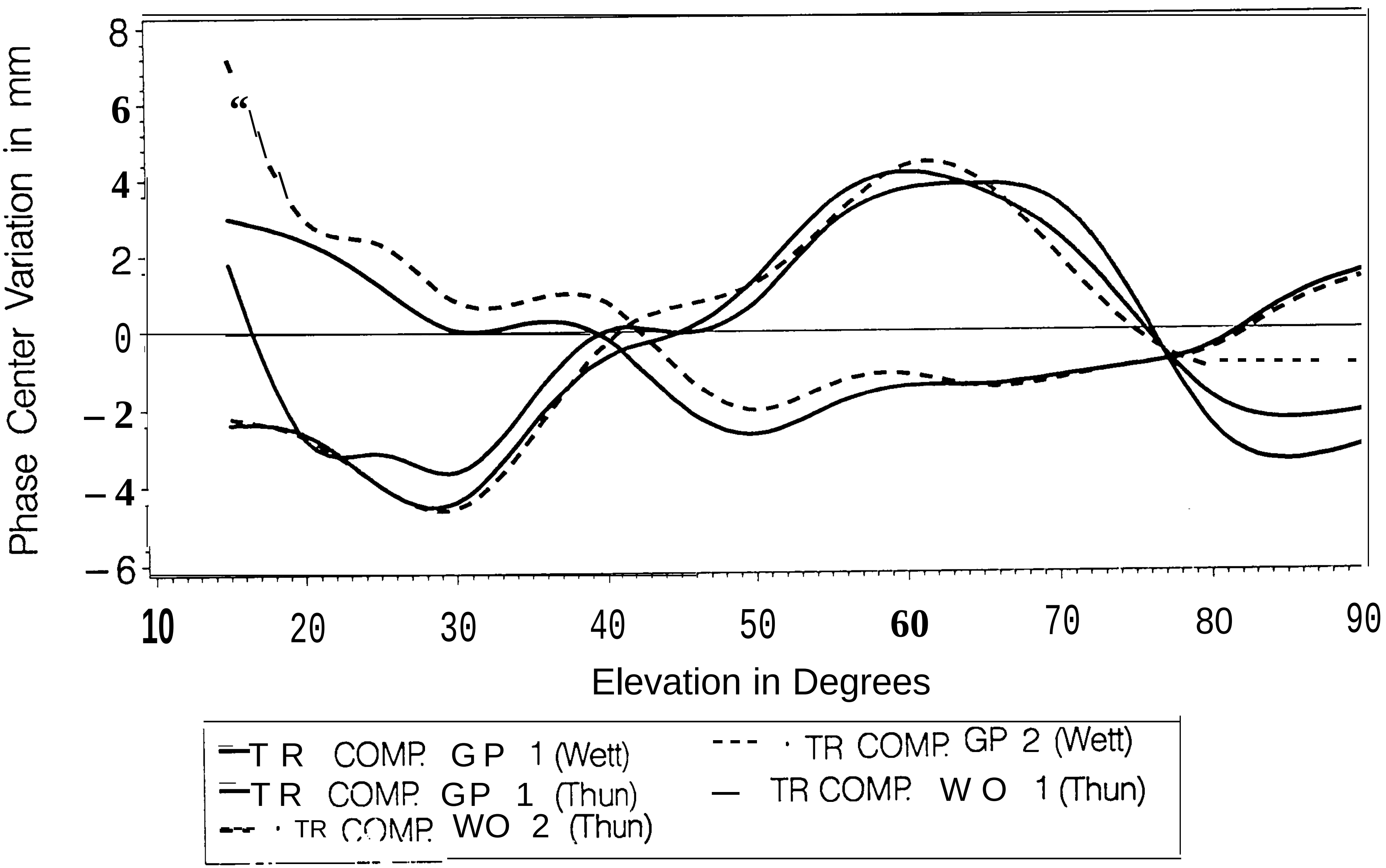
FREQ = 2



ELEV. – DEP. PHASE CENTER VARIATION FOR TRIMBLE COMPACT

Reference Antenna for Estimation: Dome Margolin T

FREQ=I

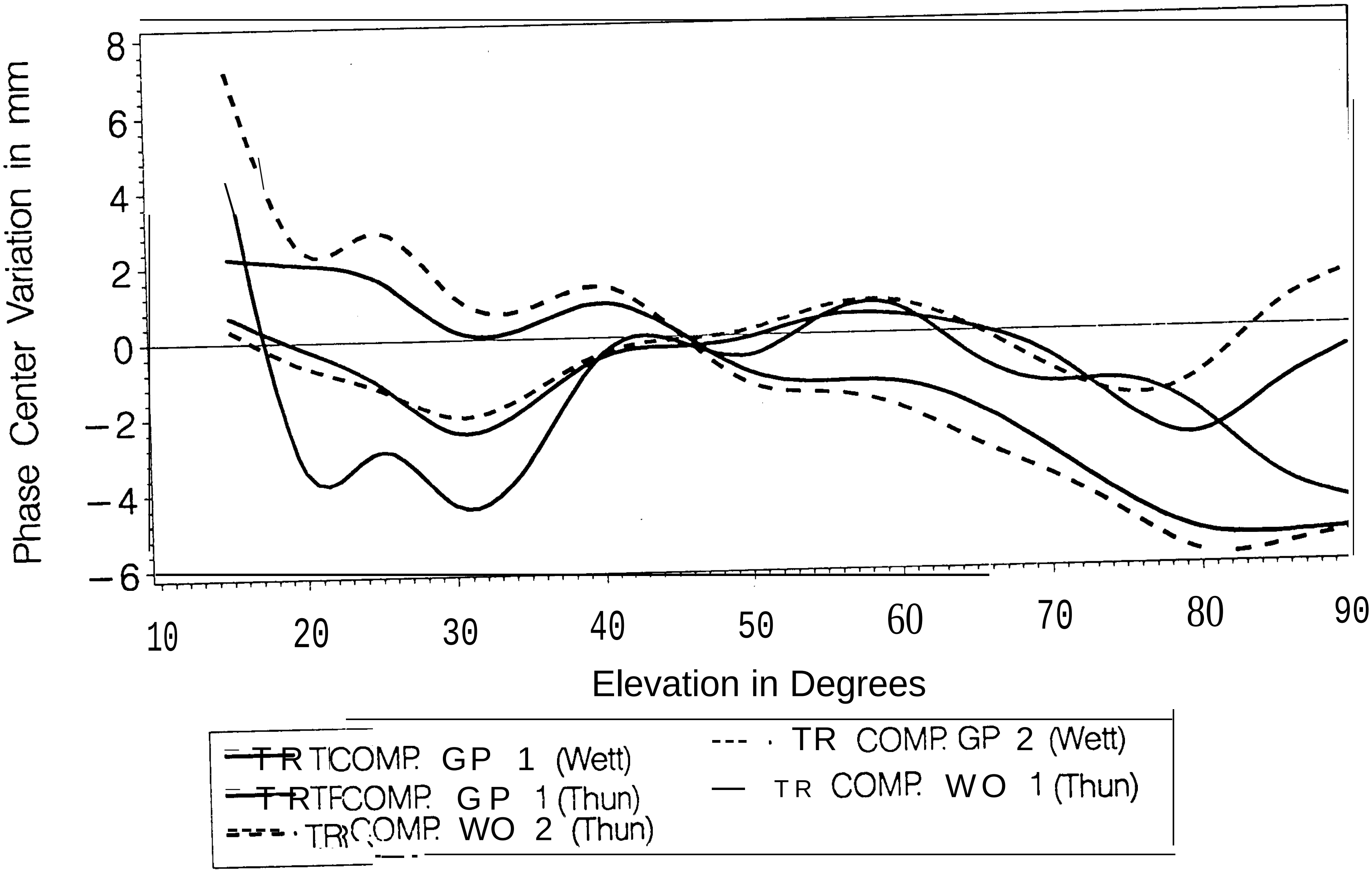


ELEV. – DEP. PHASE CENTER VARIATION FOR TRIMBLE COMPACT

Margolin T

Reference Antenna for Estimation: Dome

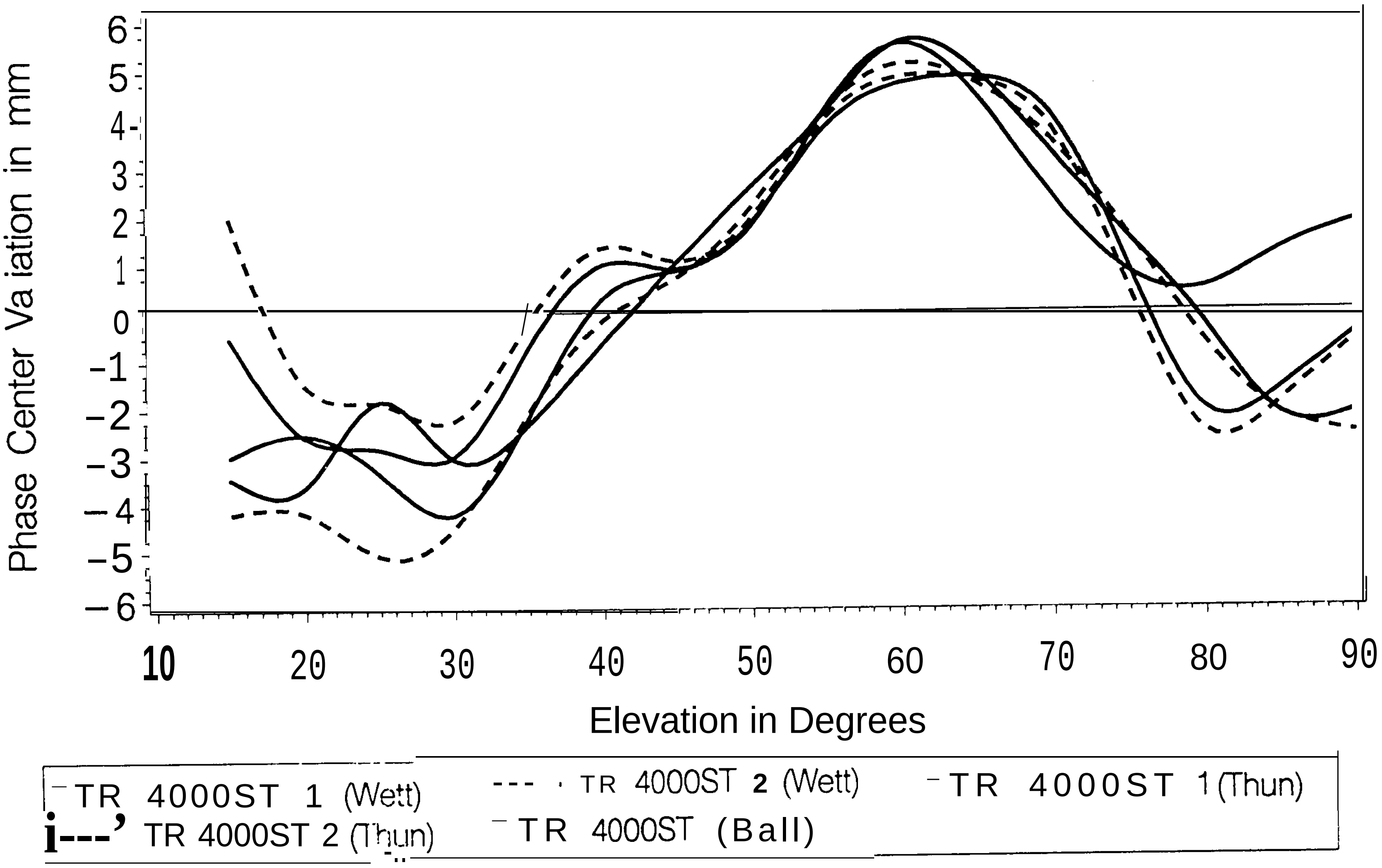
FREQ = 2

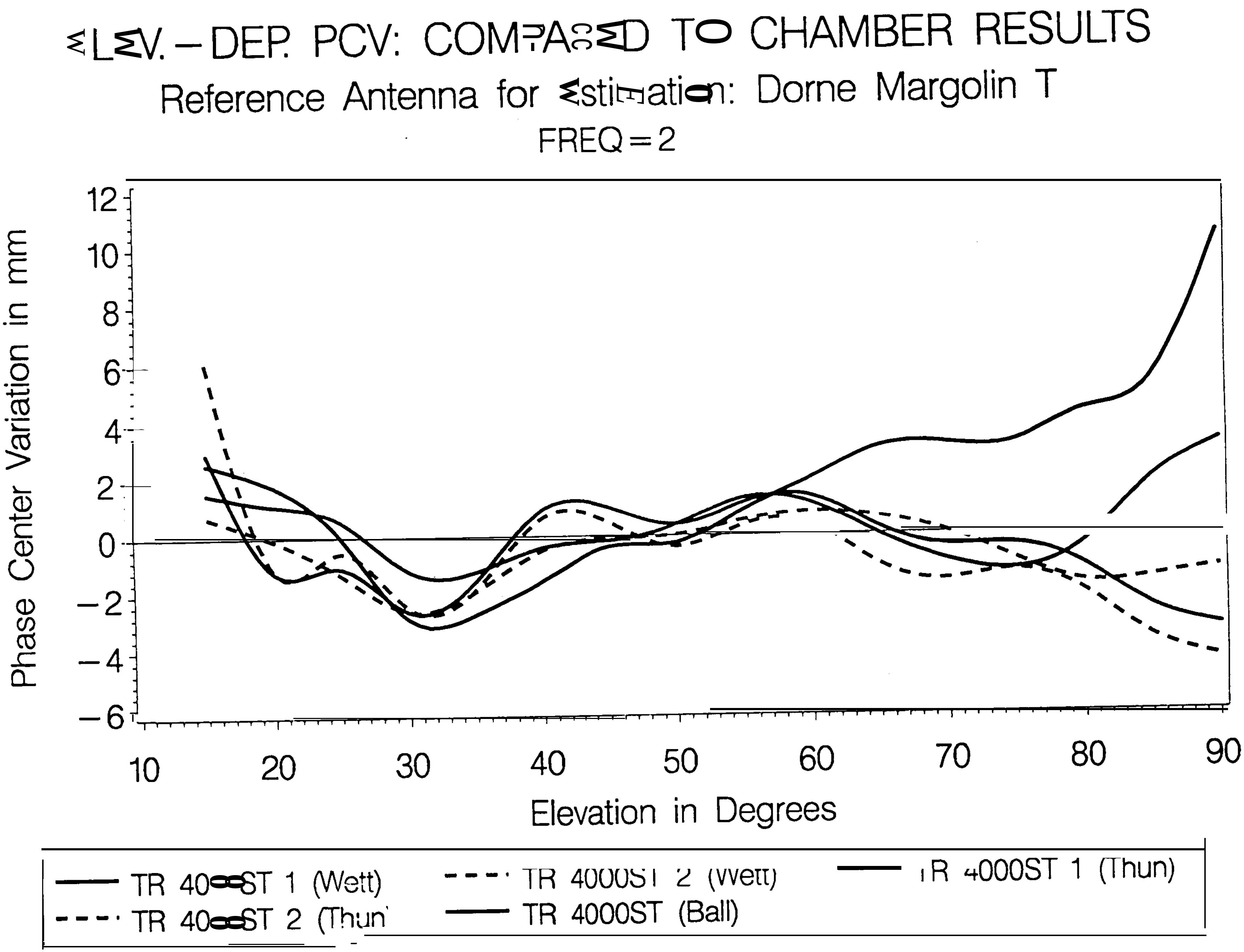


ELEV. – DEP. PCV: COMPARED TO CHAMBER RESULTS

Reference Antenna for Estimation: Dome Margolin T

FREQ = 1

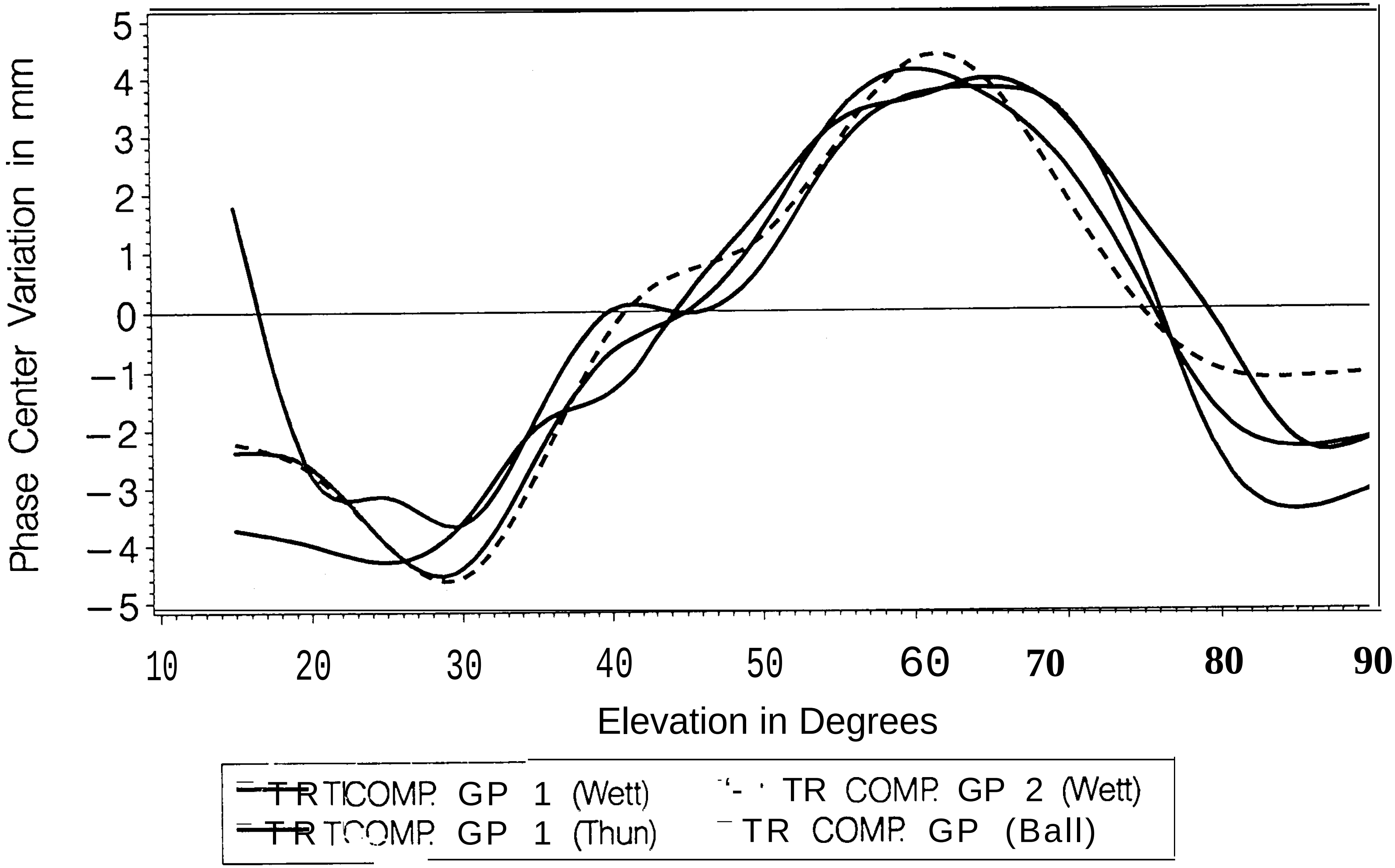



ELEV.-DEP. PCV: COMPARED TO CHAMBER RESULTS
Reference Antenna for Estimation: Dorne Margolin T
FREQ=2
Phase Center Variation in mm
12
10
8
6
4
2
0
-2
-4
-6
10
20
30
40
50
60
70
80
90
Elevation in Degrees
TR 4000ST 1 (Wett)
TR 4000ST 2 (Wett)
TR 4000ST 1 (Thun)
TR 4000ST 2 (Thun)
TR 4000ST (Ball)

ELEV. – DEf? PCV: COMPARISON TO CHAMBER RESULTS

Reference Antenna for Estimation: Dome Margolin T

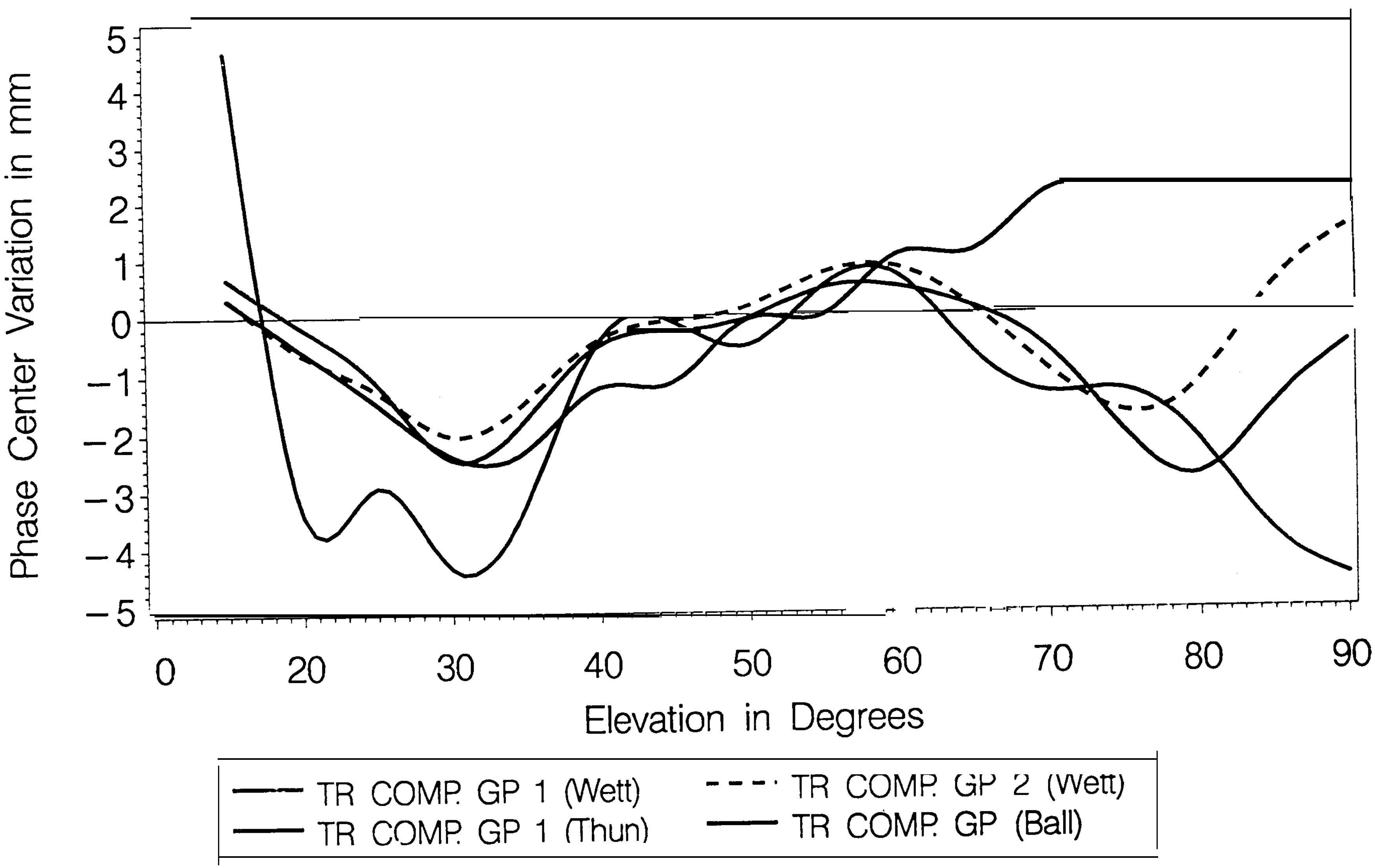
FREQ = 1



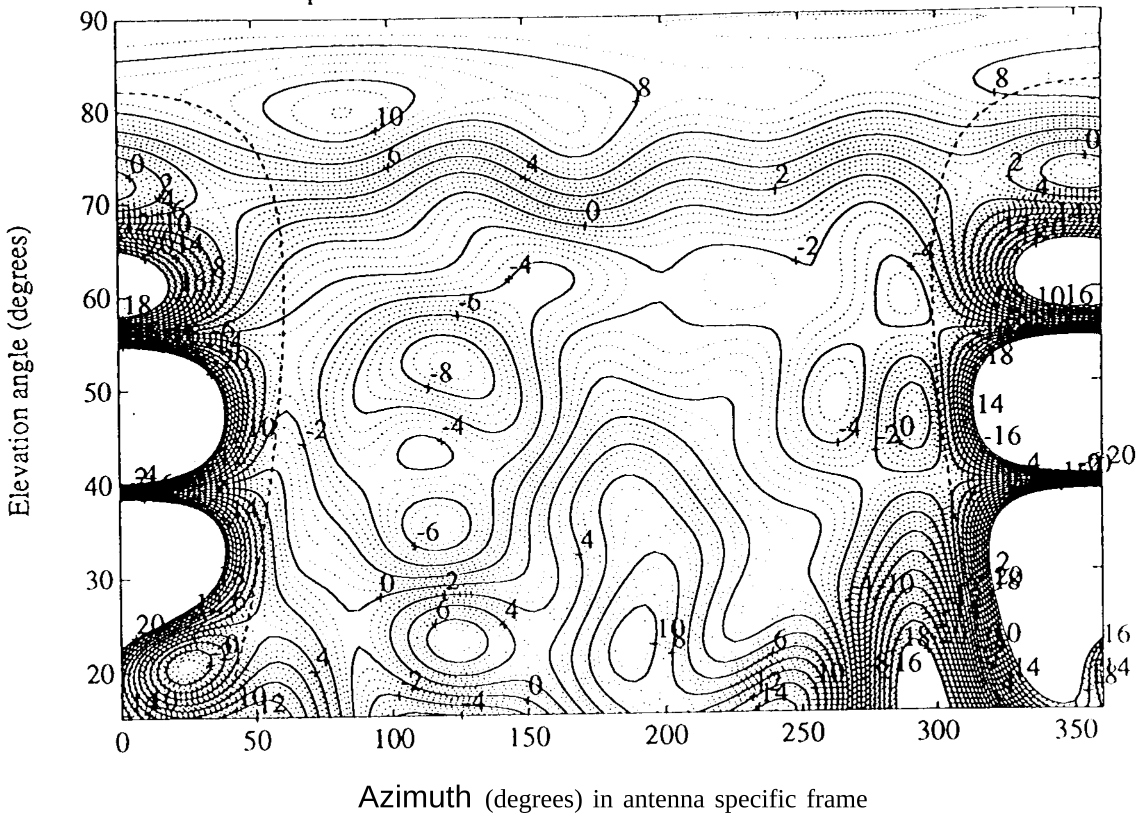
ELEV.-DEP. PCV: COMPARISON TO CHAMBER RESULTS

Reference Antenna for Estimation: Dorne Margolin T

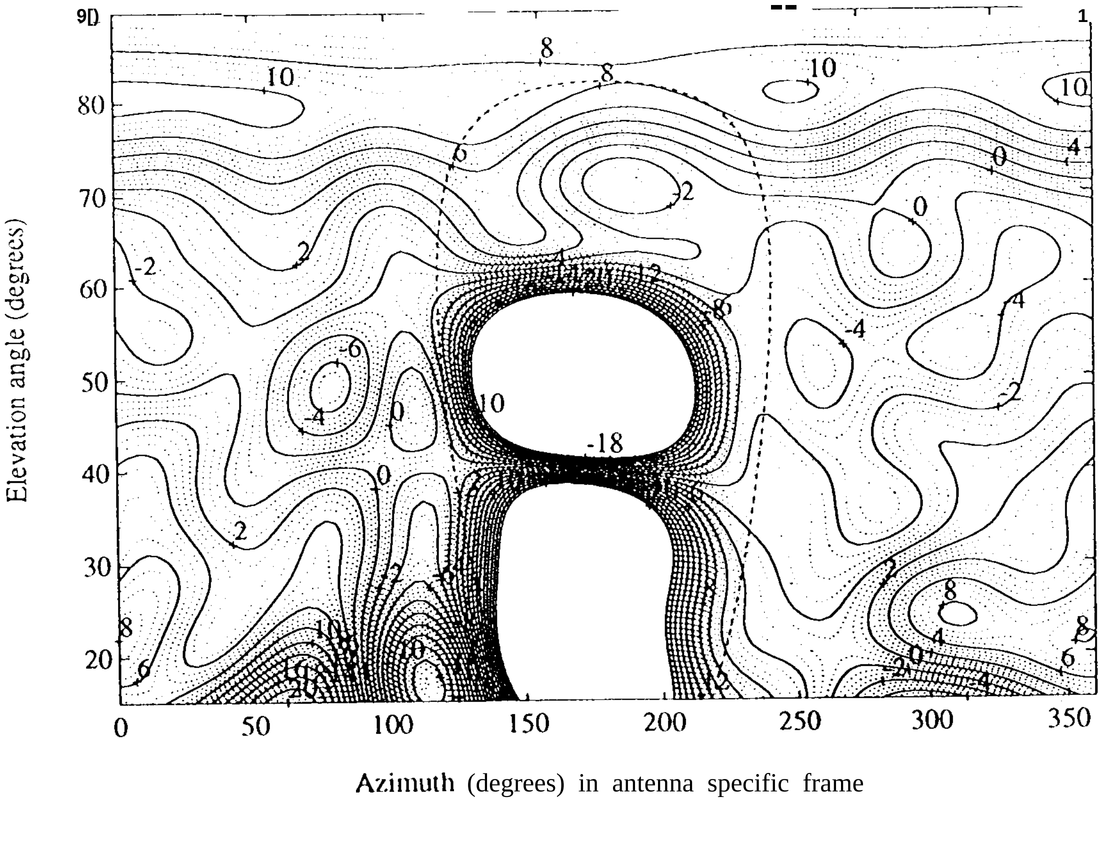
FREQ=2



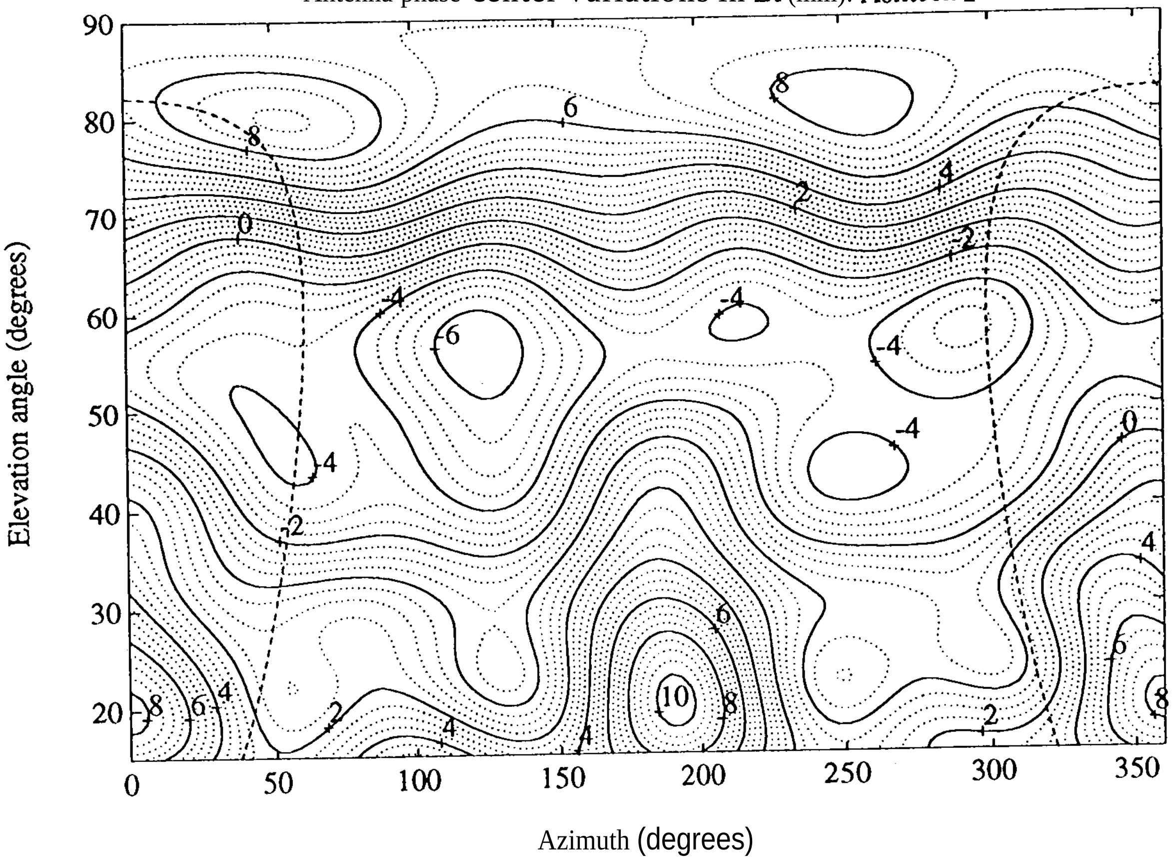
Antenna phase center variations in L1 (mm): Ashtech 1, only day 079



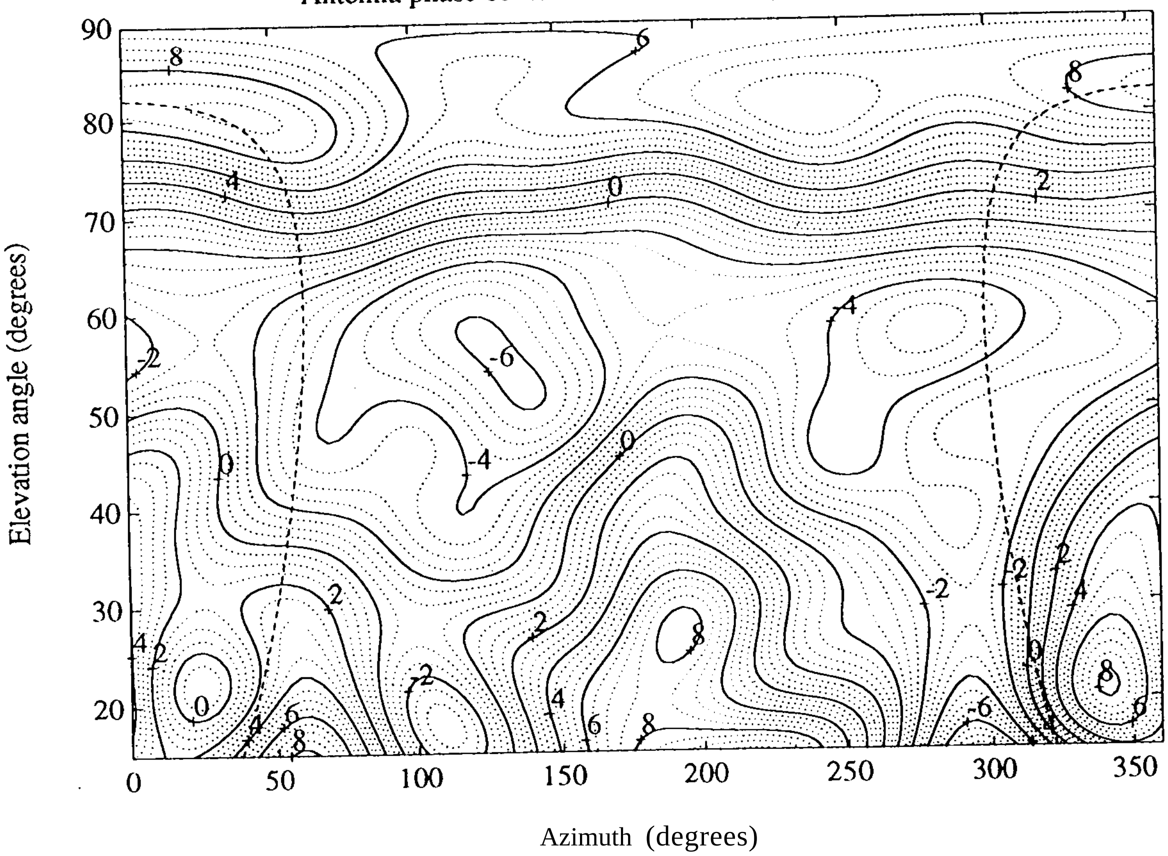
Antenna phase center variations in L 1 (mm): Ashtech 1, only day 080



Antenna phase center variations in L1 (mm): Ashtech 2

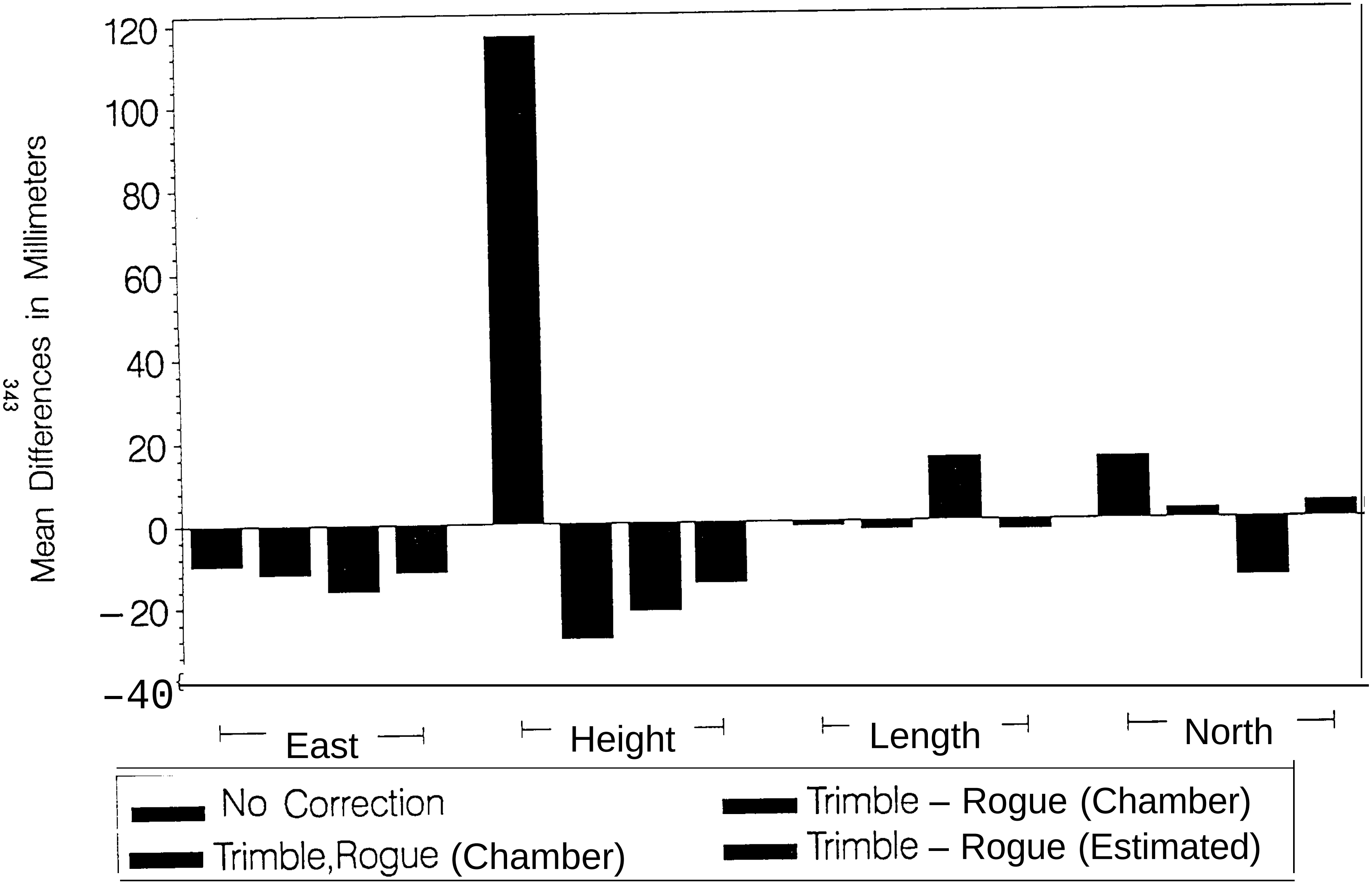


Antenna phase center variations in L1 (mm): Ashtech 1



ANTENNA PHASE CENTER VARIATIONS (L3)

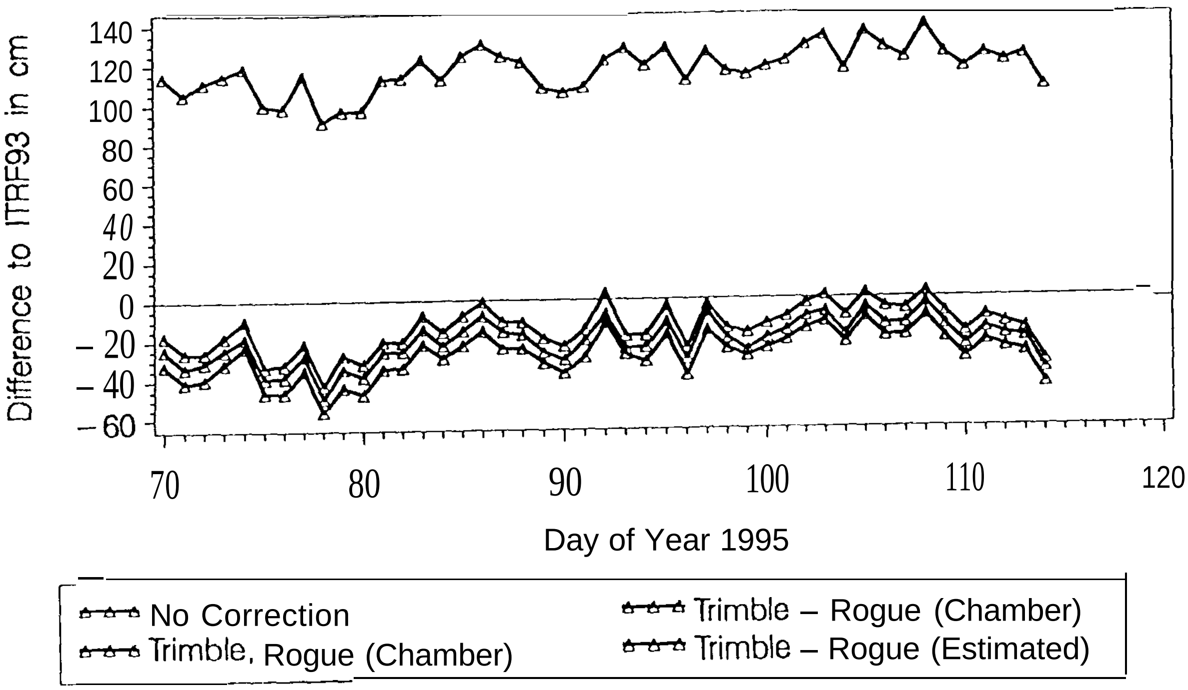
Baseline ONSA – ZIMM (1207 km) compared to ITRF93 (*50* Days)



ANTENNA PHASE CENTER VARIATIONS (L3)

Baseline ONSA – ZIMM (1207 km) compared to ITRF93

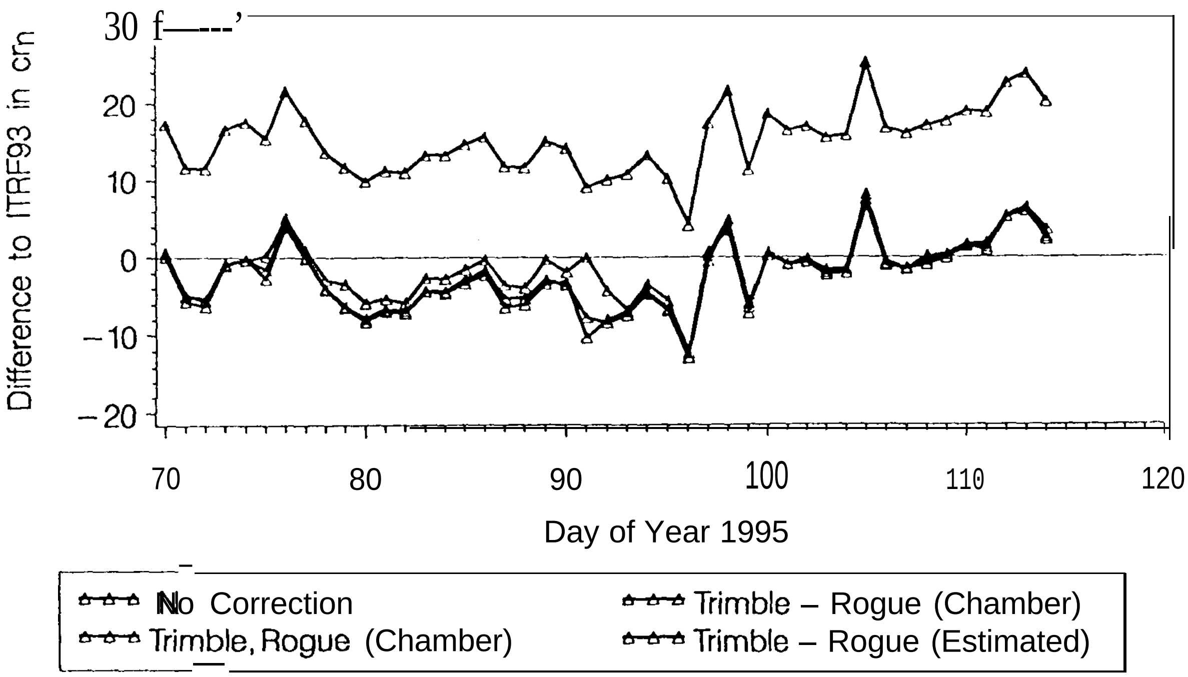
Component = Height

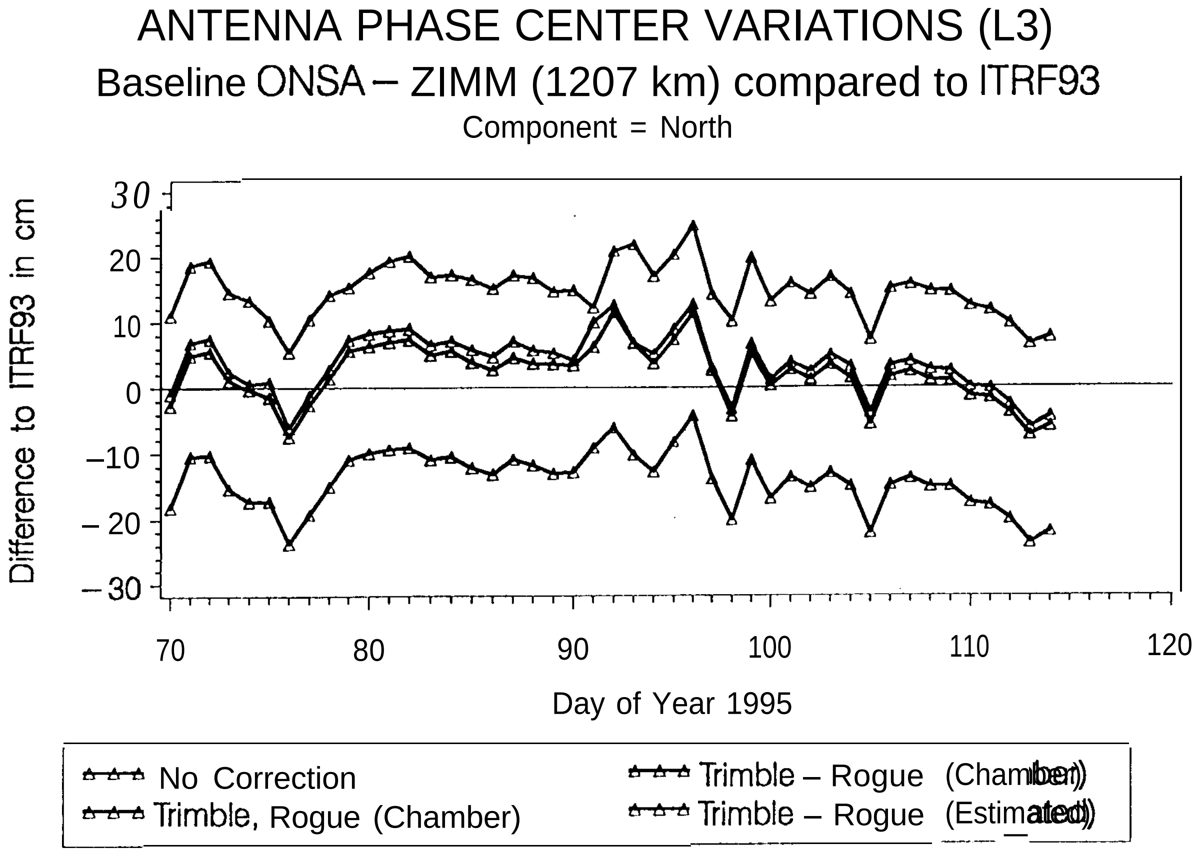


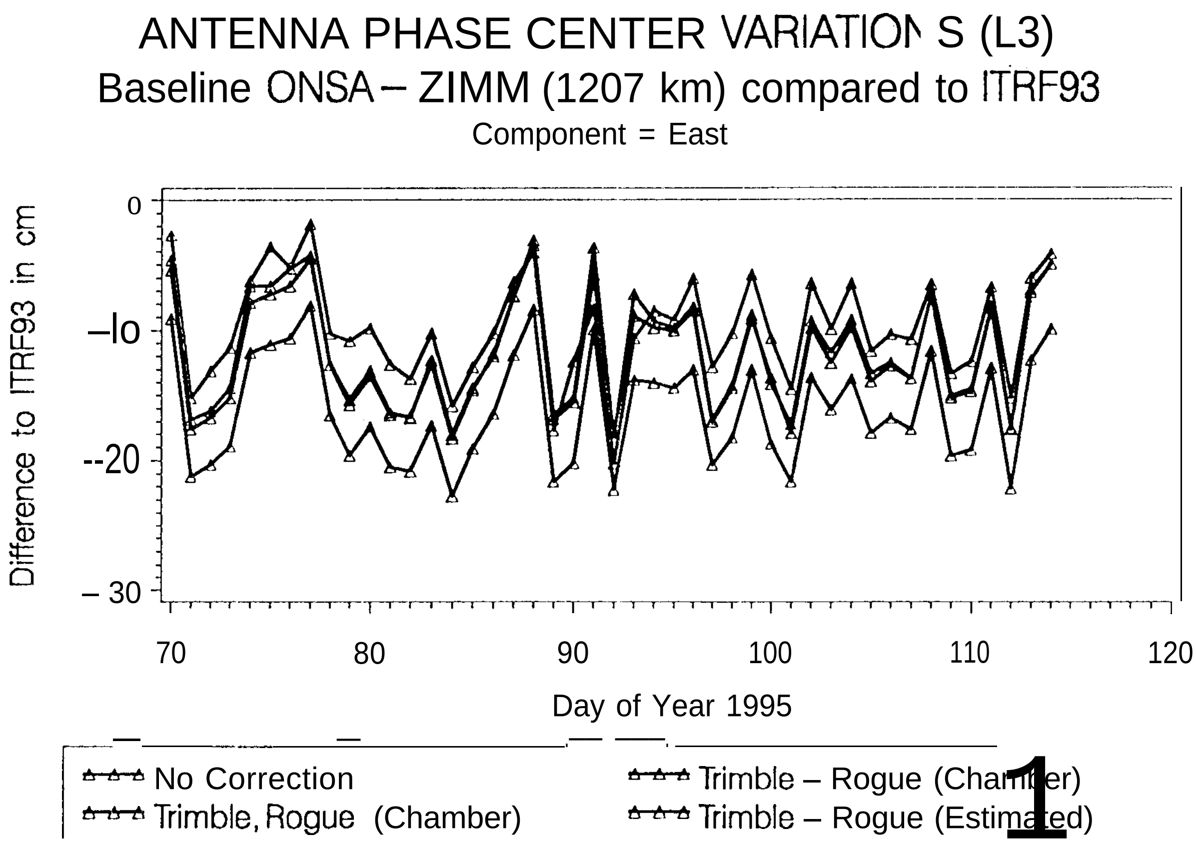
ANTENNA PHASE CENTER VARIATIONS (L3)

Baseline ONSA – ZIMM (1207 km) compared to ITRF93

Component = Length




ANTENNA PHASE CENTER VARIATIONS (L3)
Baseline ONSA – ZIMM (1207 km) compared to ITRF93
Component = North
Difference to ITRF93 in cm
30
20
10
0
–10
– 20
– 30
70
80
90
100
110
120
Day of Year 1995
No Correction
Trimble, Rogue (Chamber)
Trimble – Rogue (Chamber)
Trimble – Rogue (Estimated)


ANTENNA PHASE CENTER VARIATIONS (L3)
Baseline ONSA – ZIMM (1207 km) compared to ITRF93
Component = East
Difference to ITRF93 in cm
0
–10
–20
– 30
70
80
90
100
110
120
Day of Year 1995
No Correction
Trimble, Rogue (Chamber)
Trimble – Rogue (Chamber)
Trimble – Rogue (Estimated)

Conclusions

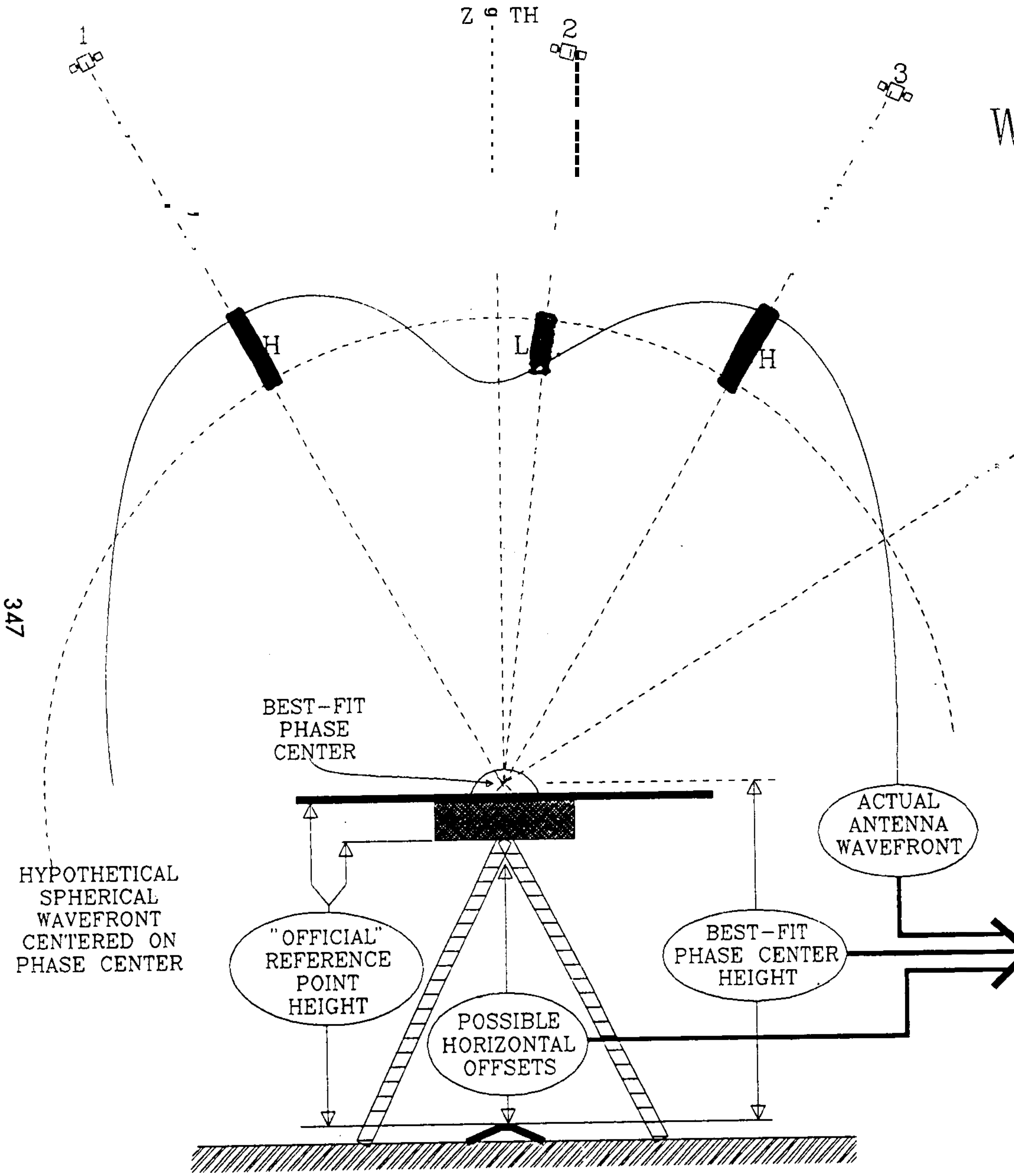
- Using GPS data it is possible to estimate the *relative* antenna phase center *offsets* and *variations* with good agreement between campaigns (different local environments).
- Comparisons with *absolute calibrations* from chamber tests still show some problems.

Recommendations

- A set of *mean antenna offsets* should be put together (for users not having the possibility to introduce elevation-dependent corrections). Cut-off angle: 15 or/and 20 degrees.
- A set of *elevation-dependent* corrections for all geodetic antenna types should be obtained from a a combination of GPS and chamber values.
- The *absolute* calibrations have to be obtained from chamber measurements in such a way, that *no scale biases* are produced in global or regional network solutions !
- Steps to reach this goal: (1) Put together all antenna results and information available. (2) Combine them *to a set of correction values* as consistent as possible. (3) Individual groups check these values before they are distributed.

WHAT ARE PHASE-CENTER VARIATIONS AND WHY SHOULD I WORRY?

T. A. Clark and B. R. Schupler



THE H – L – H VARIATIONS ARE OFTEN AS MUCH AS ± 2 cm FOR COMMON GEODETIC ANTENNAS.

VARIATIONS BETWEEN IDENTICAL ANTENNAS DO NOT CANCEL ON LONG BASELINES SINCE ZENITH ANGLES ARE SIGNIFICANTLY DIFFERENT.

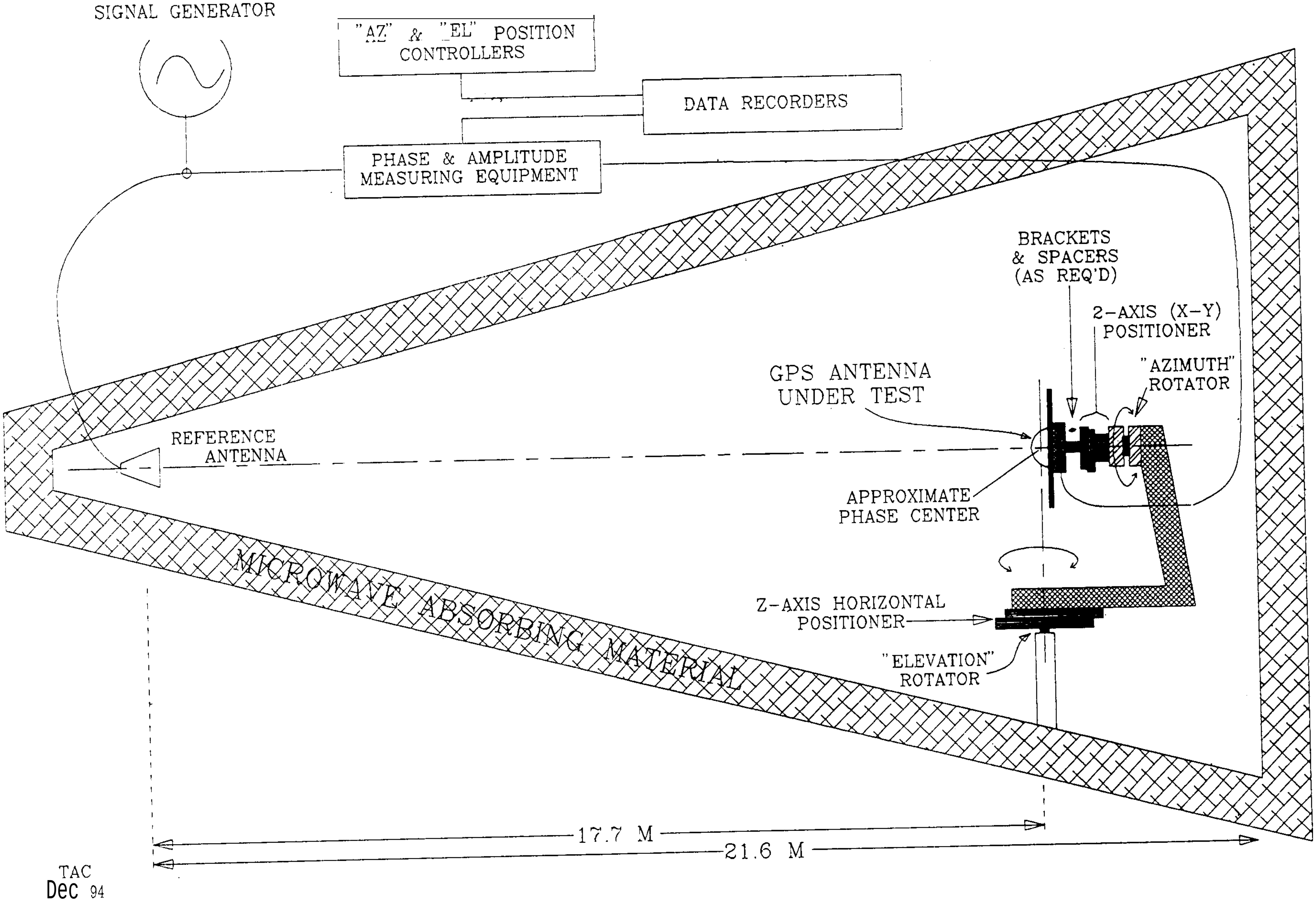
THESE ERRORS MAY BE DIFFERENT:

- BETWEEN L1 and L2
- BETWEEN DIFFERENT ANTENNAS FROM THE SAME MANUFACTURER

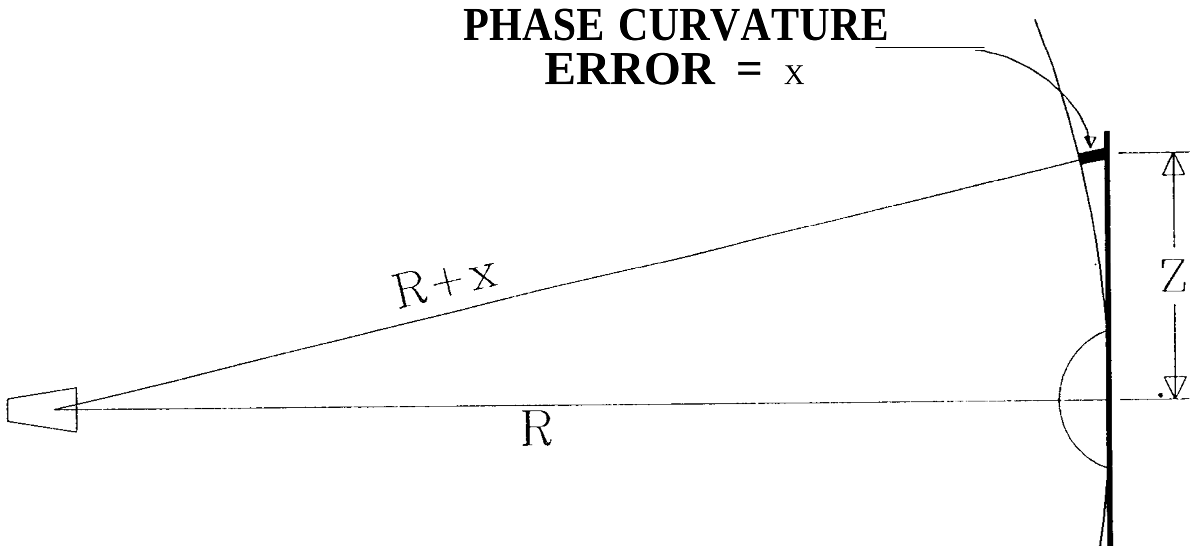
AND THEY ARE DEFINITELY DIFFERENT BETWEEN DIFFERENT MANUFACTURERS!

TAC
Dec.94

INDOOR ANECHOIC CHAMBER NASA/GSFC Bldg 19



HOW BIG SHOULD AN ANTENNA RANGE BE ?



$$(R+x)^2 = R^2 + Z^2$$

since $R >> Z >> x$

$$R^2 + 2Rx + x^2 \sim R^2 + 2Rx$$

$$\therefore 2Rx \sim Z^2$$

For $x < 2mm \sim \lambda/100$ pk-to-pk,

$$R \geq 50 * Z^2/\lambda$$

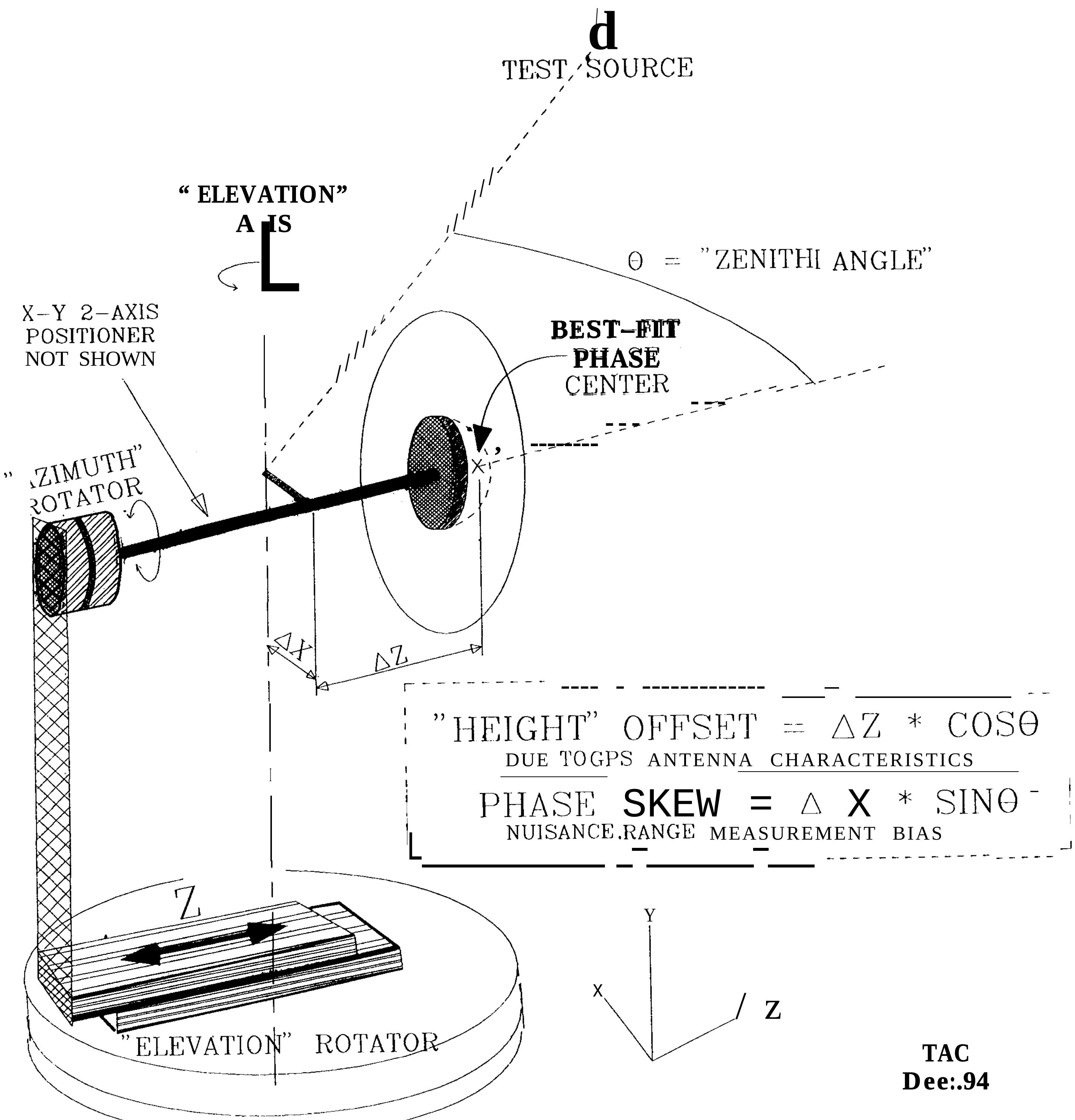
For typical GPS antennas, $Z \leq \lambda$

$\therefore R \geq 50\lambda \sim 12$ Meters

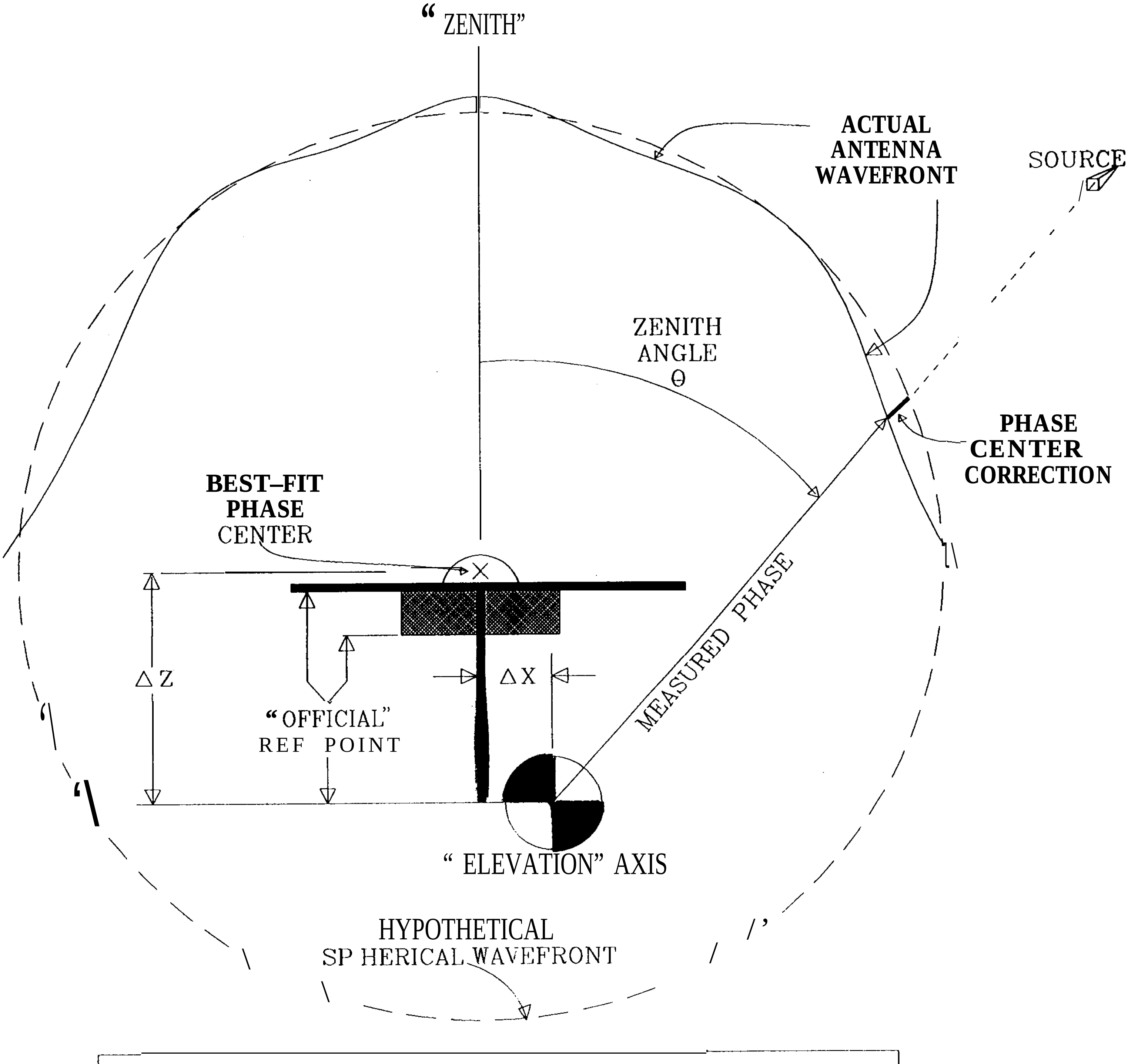
is a reasonable criterion for the size of a GPS antenna range

TAC
Dec 94

ANTENNA PATTERN MEASUREMENTS
POSITIONER GEOMETRY



MEASURING PHASE CENTER CORRECTIONS



BEST- FIT PHASE CENTER OFFSET =
MEASURED PHASE
— △ Z * COSΘ
— △ X * SINΘ
+ "OFFICIAL" REFERENCE POINT DEFINITION

[WHERE AX <c ΔY c< SOURCE DISTANCE]

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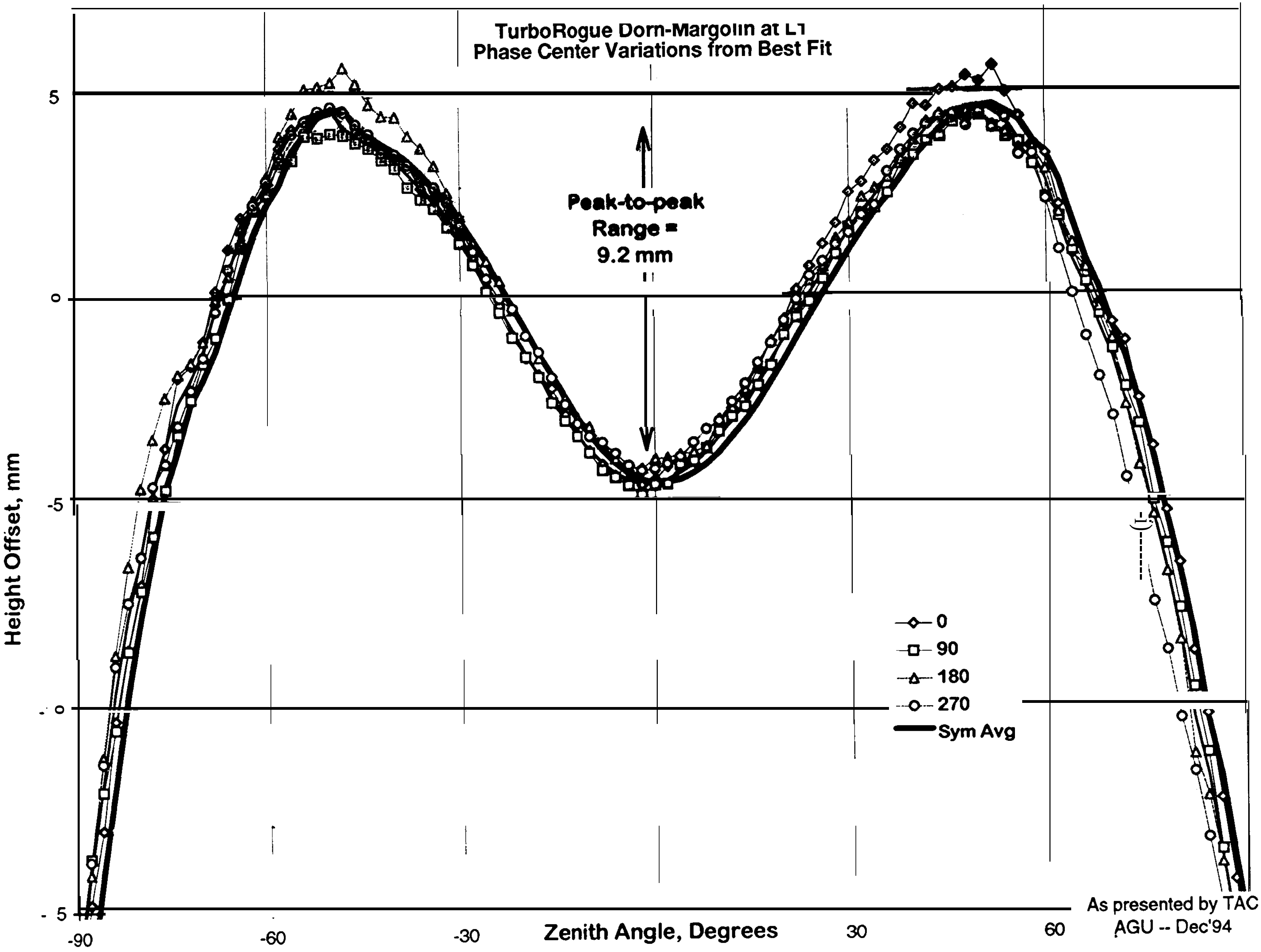
Dec.94

THE PHASE CENTER IS NOT A POINT!

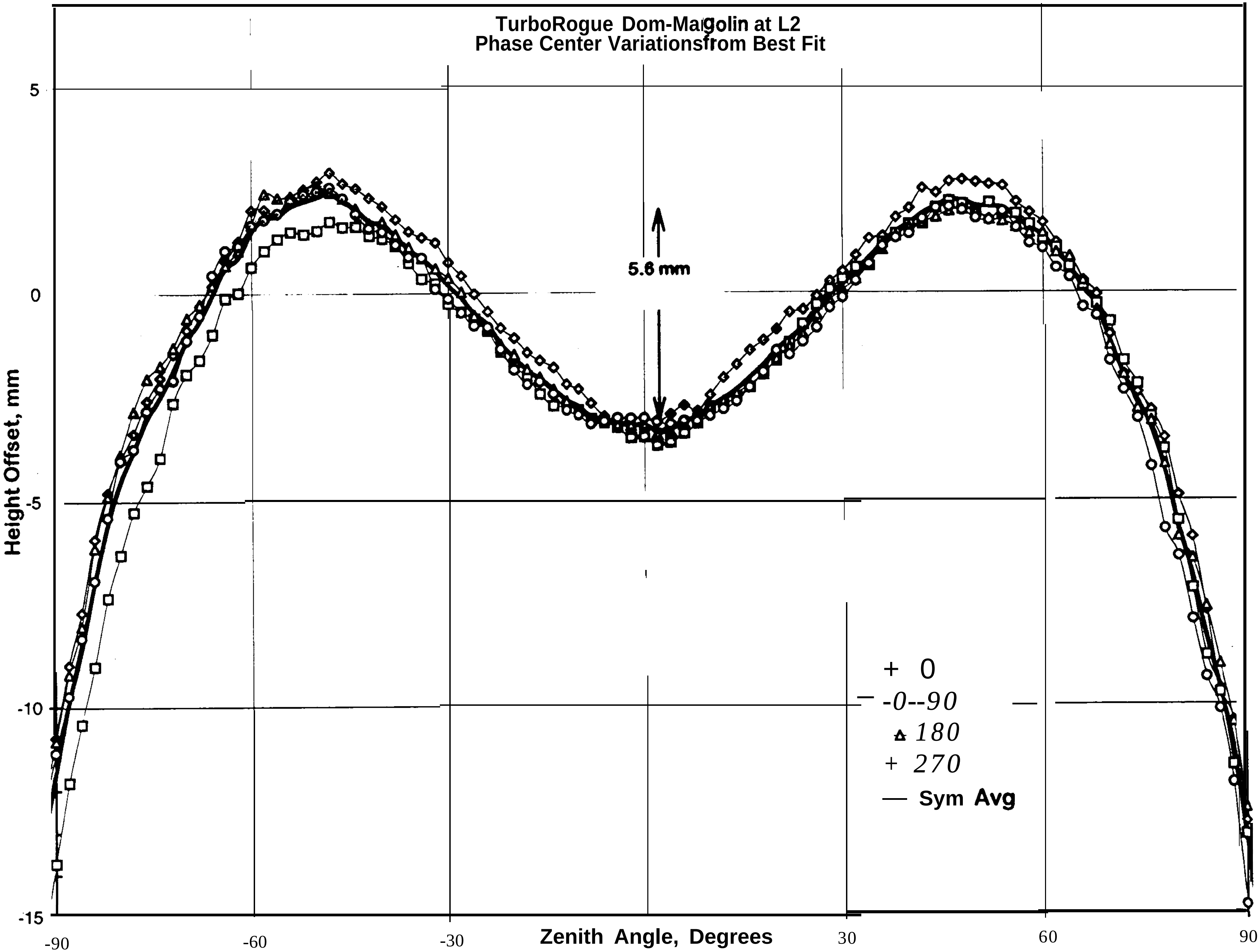
IT MOVES WITH ELEVATION.

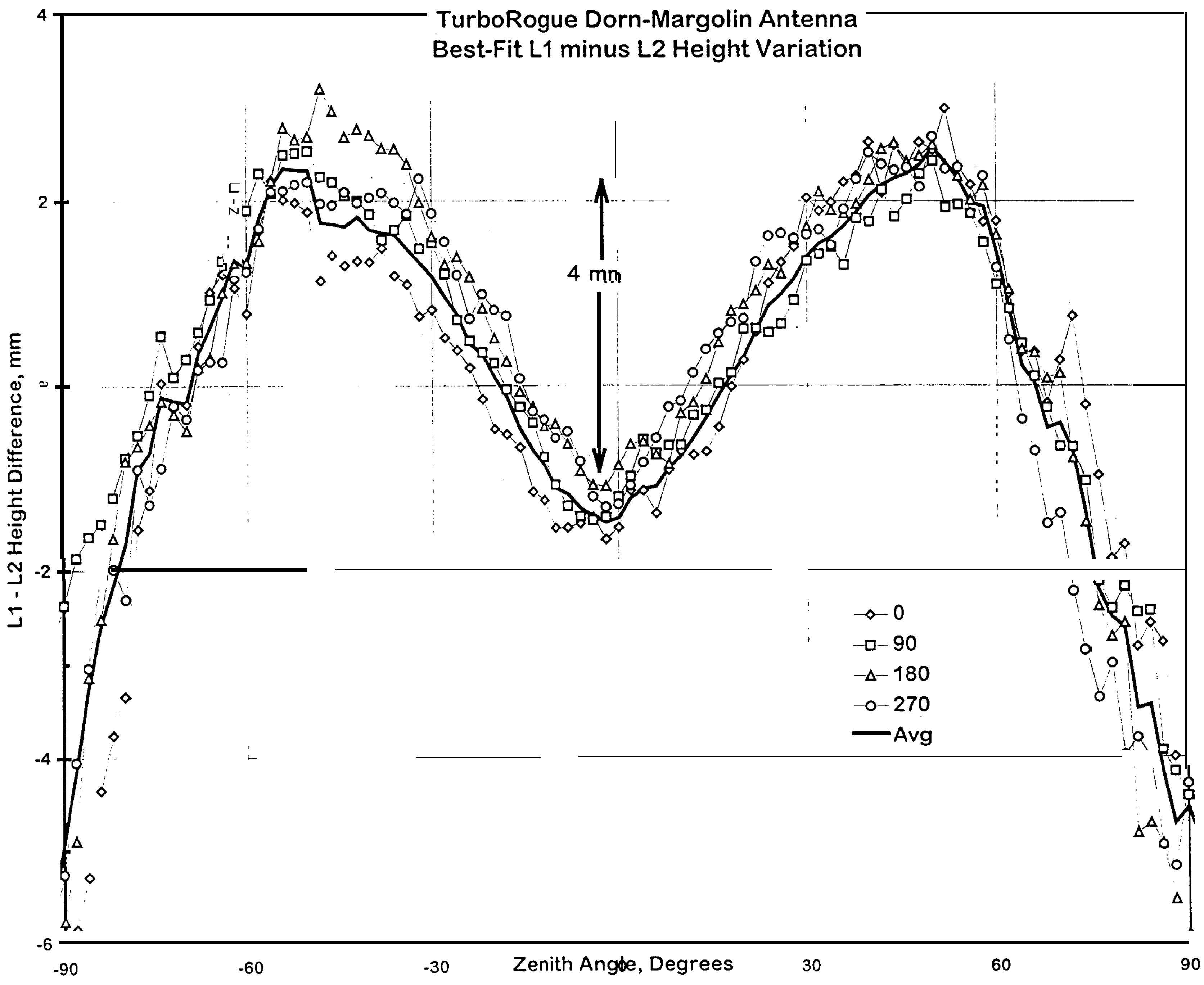
IT MOVES WITH FREQUENCY.

IT MAY NOT BE AZIMUTHALLY SYMETRIC

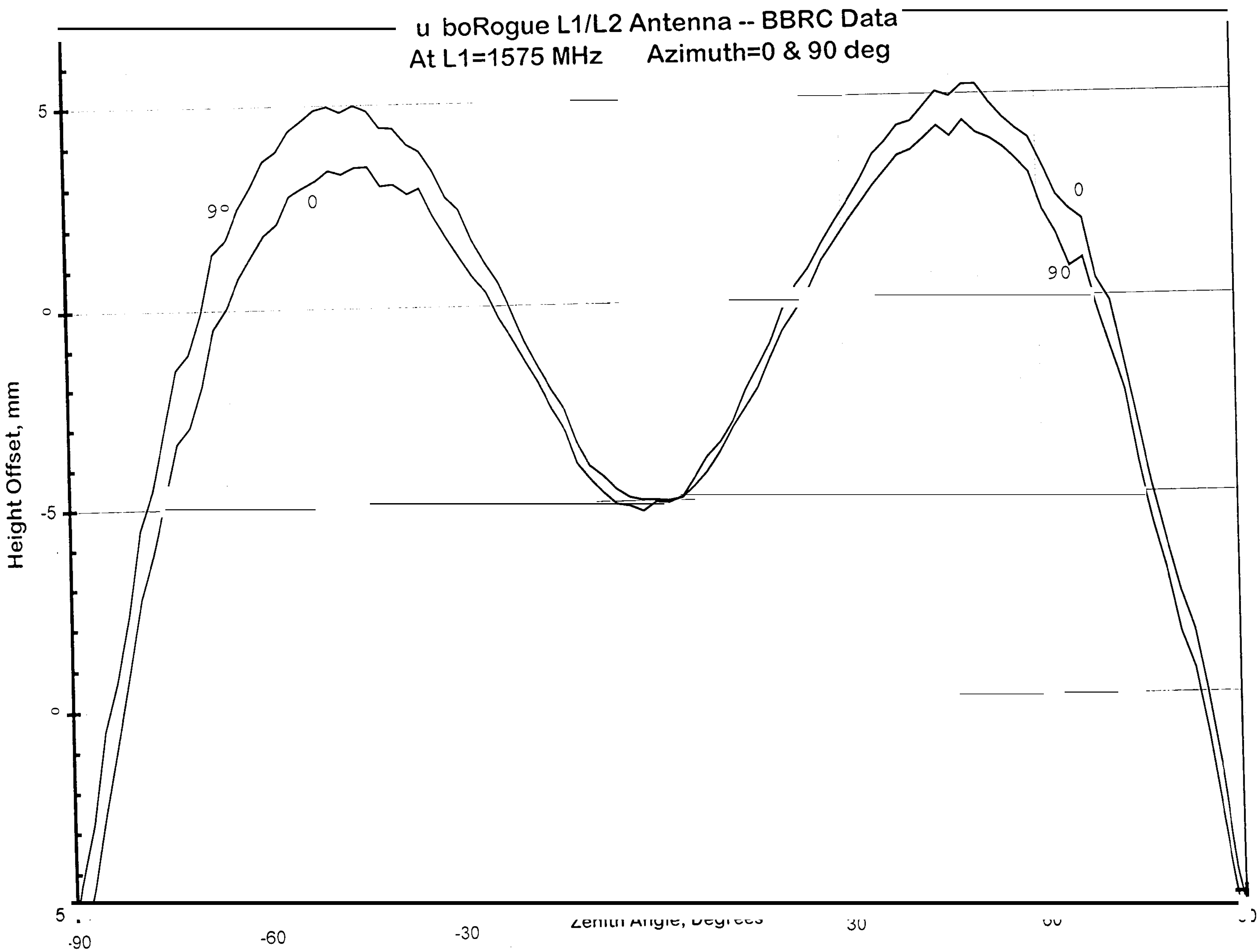


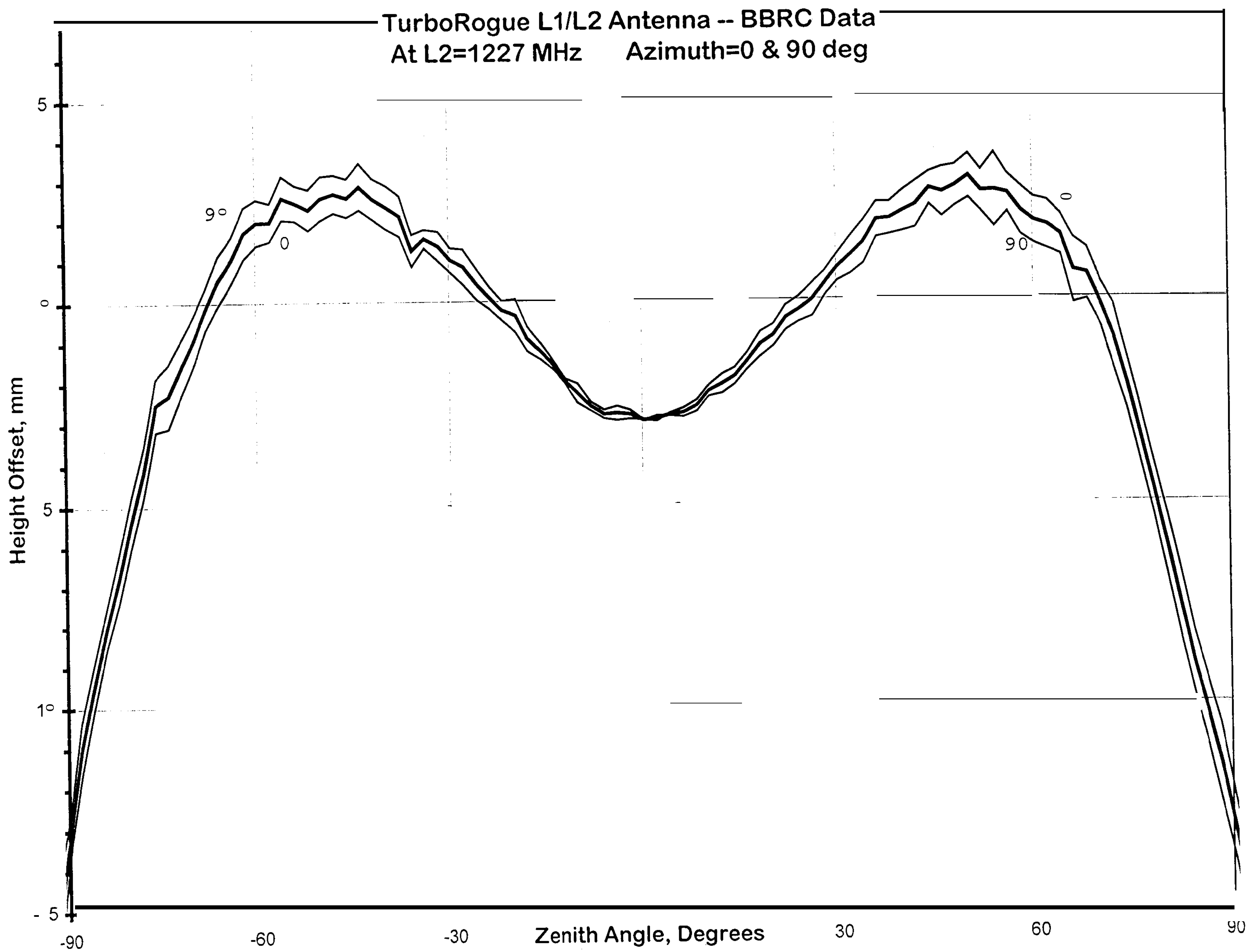
TurboRogue Dorn-Margolin at L1
Phase Center Variations from Best Fit
Peak-to-peak
Range =
9.2 mm
Height Offset, mm
Zenith Angle, Degrees
0
90
180
270
Sym Avg
As presented by TAC
AGU -- Dec'94


TurboRogue Dorn-Margolin at L2
Phase Center Variations from Best Fit
5.6 mm
Height Offset, mm
Zenith Angle, Degrees
5
0
-5
-10
-15
-90
-60
-30
30
60
90
0
90
180
270
Sym Avg



TurboRogue Dorn-Margolin Antenna
Best-Fit L1 minus L2 Height Variation
L1 - L2 Height Difference, mm
4
2
-2
-4
-6
Zenith Angle, Degrees
-90
-60
-30
30
60
90
4 mm
0
90
180
270
Avg


u boRogue L1/L2 Antenna -- BBRC Data
At L1=1575 MHz Azimuth=0 & 90 deg
Height Offset, mm
5
0
-5
-90
-60
-30
30
Zenith Angle, Degrees
9o
0
0
90


TurboRogue L1/L2 Antenna -- BBRC Data
At L2=1227 MHz
Azimuth=0 & 90 deg
Height Offset, mm
5
0
5
10
-5
Zenith Angle, Degrees
-90
-60
-30
30
60
90
90
0
0
90

NOT YET COMPARED

- OUR RECENT ASHTECH RESULTS COMPARISONS WITH OUR EARLIER DM RESULTS

- OUR RESULTS WITH **UNAVCO/BALL**

- RANGE RESULTS VS. “ON THE AIR’ RESULTS

FUTURE WORK

- **WE NOW HAVE A D-M ANTENNA TO TRY ON ALL THE RANGES "ZEBRA STRIPE"**
  - **DO THE RANGES GET THE SAME RESULTS ON THE SAME ANTENNA?**
- **WORK HARD TO RELATE THE MECHANICAL STRUCTURE TO THE ANTENNA**
- **TEST THE EFFECT OF VARIOUS RADOMES**
- **AUTOMATE THE MEASUREMENT & ANALYSIS PROCEDURE**
- **PRODUCE THE PRODUCT THE USERS REALLY NEED**

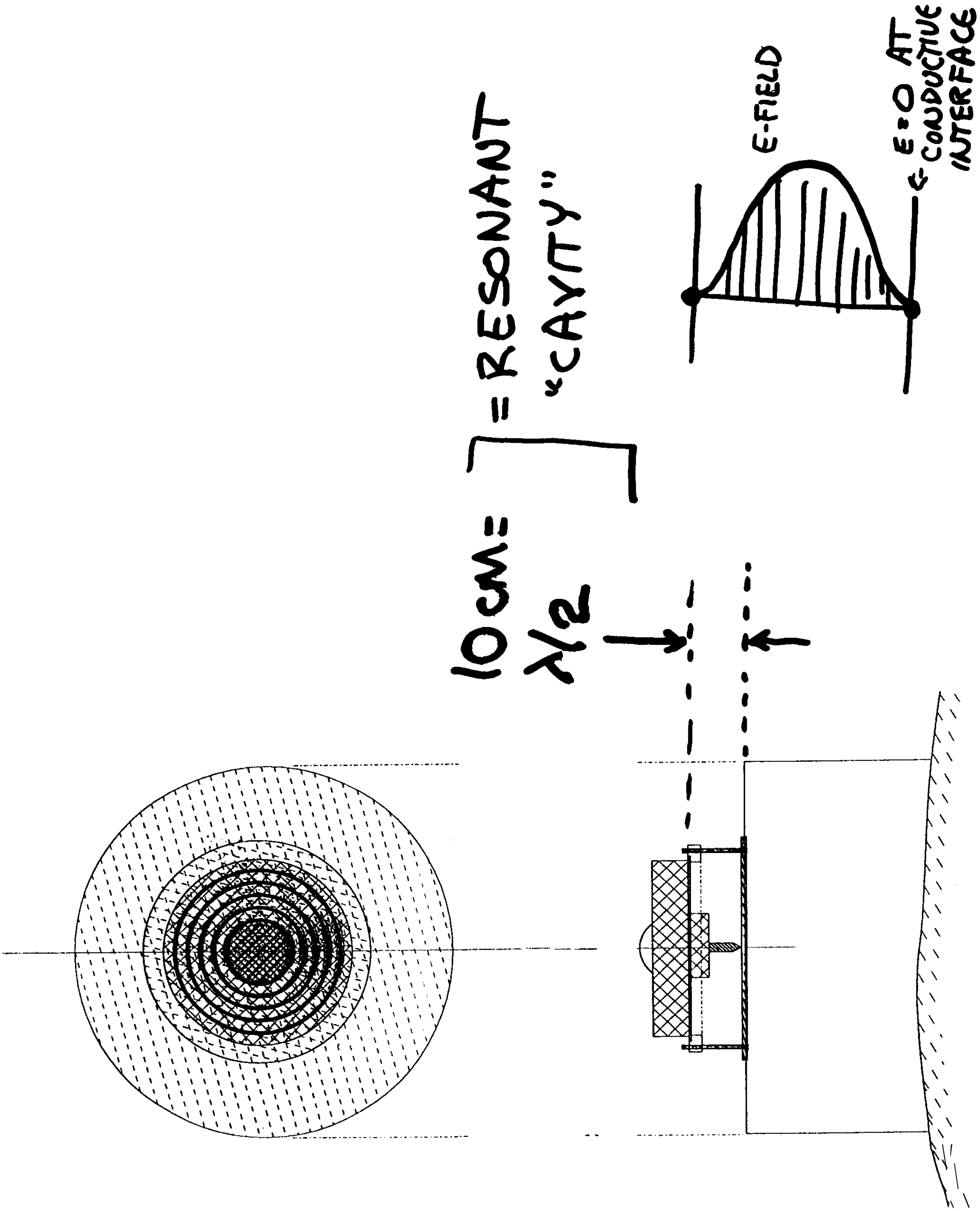
“MULTIPATH”

- NEAR FIELD

  - ANYTHING WITHIN ~λ OF THE ANTENNA PERTURBS THE PHASE & AMPLITUDE PATTERNS

- A.K.A. SCATTERING

- FAR FIELD REFLECTORS MANY λ AWAY

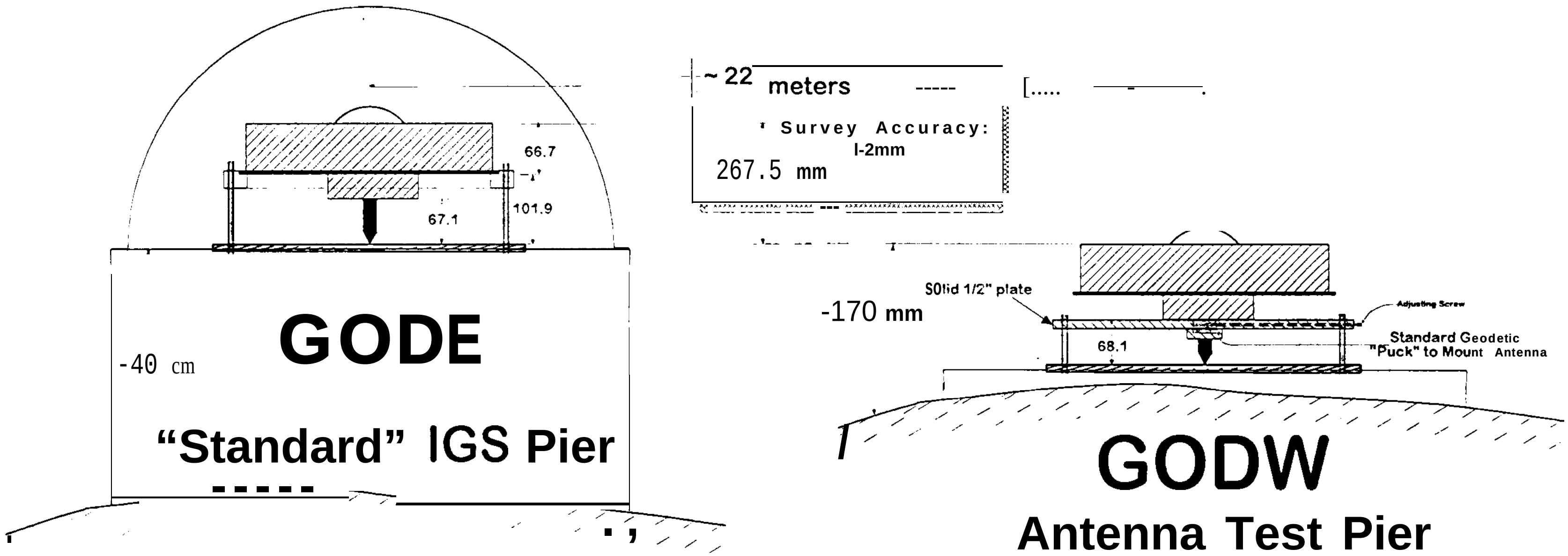

10CM = λ/2
= RESONANT
"CAVITY"
E-FIELD
E=0 AT
← CONDUCTIVE
INTERFACE

Our Testing Methodology:

- o Try several simple schemes to "kill" the cavity resonance and/or absorb the "scattered" RF energy in the antenna backplane area:
  - ■ Microwave Absorber (like Elosegui *et al*).
  - ■ Add *a* "skirt" to keep RF out.
  - ■ "Spoil" the cavity resonance.

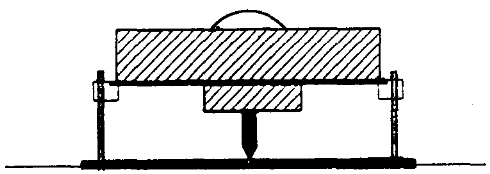
- O Take several days of data with each scheme being tried on the "operational" GODE IGS site antenna. The reference is the GODW antenna -22 meters away.
  - ■ GODE is a normal IGS operational site, using standard 8-channel TurboRogue.
  - ■ GODW using new 12-channel TurboRogue.
  - ■ GODW using new design "spike mount" (which should minimize the resonance problems).
  - ■ GODE&GODW both use identical Dorn-Margolin choke-ring antennas.
  - ■ GODW setup not changed during the tests.
  - ■ The GODE-GODW baseline has been surveyed to an accuracy -1-2 mm, so we can compare GPS results with "ground truth".

- o Process the GODE-GODW data using *GIPSY* and JPL-supplied orbit/clock for each day:
  - ■ Use common atmosphere for GODE&GODW.
  - ■ Vary Elevation Cutoff from 10° to 50°.
  - , Compare the results with ground survey "truth".

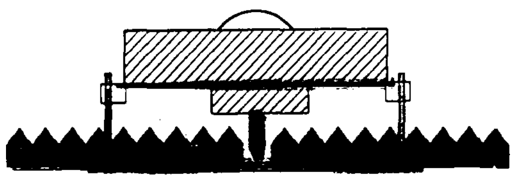


The Calibrated GPS Antenna Range at GGAO

Four different cases we tested on the normal GODE IGS antenna at GGAO*:

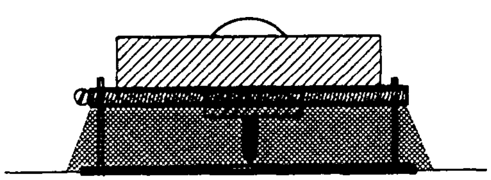


1 The "Standard" IGS Configuration



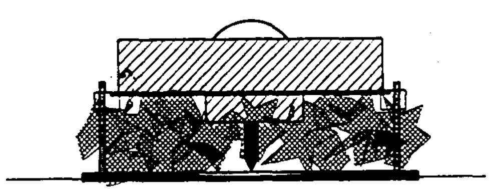
2 ABSORBER (similar to Elosegui et al): Commercial Microwave Absorbing Material (We also tried barbecue charcoal, but it did network too well)

PRICE: -$100
Special Purchase



3 Aluminum Skirt: Conical Reflecting Skirt made of ordinary aluminum window screen, held on by long hose clamp.

PRICE: -$20
@ Local Hardware Store



4 Aluminum Foil wads, filling the region behind the antenna.

PRICE: << $1
@ Local Supermarket

* GGAO = Goddard Geophysical & Astronomical Observatory
GODE = GODdard East pier, GODW = GODdard West

The Results (1):

00ur "Standard IGS" results are similar to Elosegui *et al*. They observed 45 mm height variation for elevation cutoffs from 5° to 50°, where we observe 31 mm from 10° to 50°.

❷As reported by Elosegui *et al*, the addition of microwave ABSORBER in the backplane area reduces the effect. They report a factor ~8 improvement with the absorber they used. We used a different type of absorber and see an improvement ~3. (We also tried using ordinary barbecue charcoal briquettes as an absorber but found the approach ineffective.)

❸The two new "fixes" we tried, a conductive SKIRT and filling the backplane area with household aluminum FOIL, worked as well as the microwave absorber.

❹The SKIRT shows systematic variations in the GODE-GODW height with elevation cutoffs. This is probably the result of changes in the phase pattern of the choke-ring antenna due to the addition of the skirt. (We did not attempt to measure the phase/amplitude patterns of the antenna with the added skirt).

The Results (2):

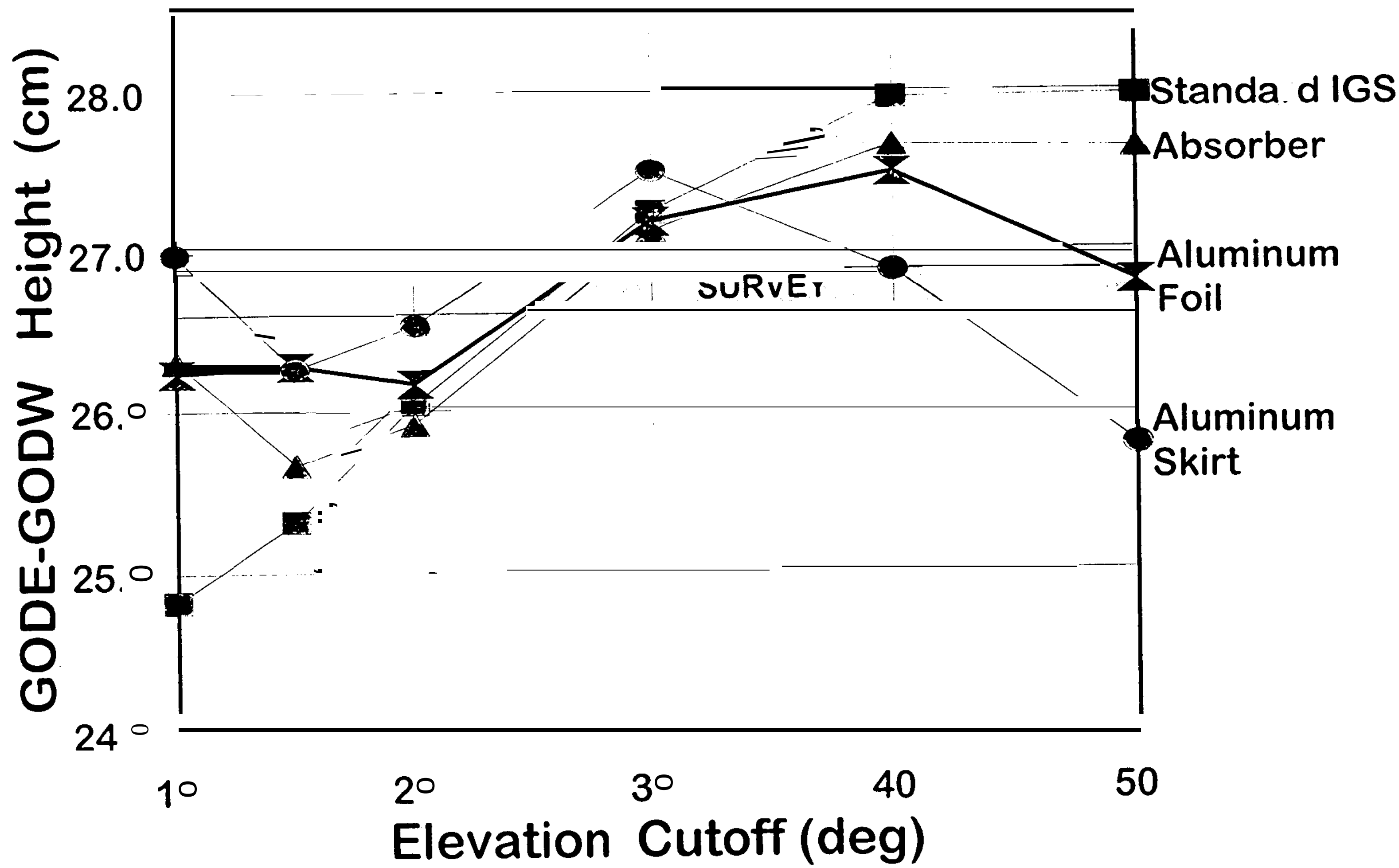
❺ The use of Aluminum FOIL in the backplane area appears to be a very effective way to suppress the "Spike" resonance! The peak-to-peak variations in recovered height with the foil were only 16 mm and the mean value agrees with ground survey "truth" to <2 mm.

❻ The FOIL "fix" is particularly attractive since the cost is very low (<$1.00), and since the material can be obtained at a local super-market *anywhere in the world'.*

❼ The ~16 mm systematic elevation angle variation is probably due to residual "ground clutter" multipath on the GODW antenna (only ~1 wavelength above ground). We plan additional tests to verify this hypothesis.

❽ There may be some small systematic biases al levels -2-3 mm due to dielectric effects in the radome used to protect GODW from the environment. Additional tests are planned to quantify radome-induced biases.

Suppressing the "Spike" Multipath



MIT T2 Analysis Report

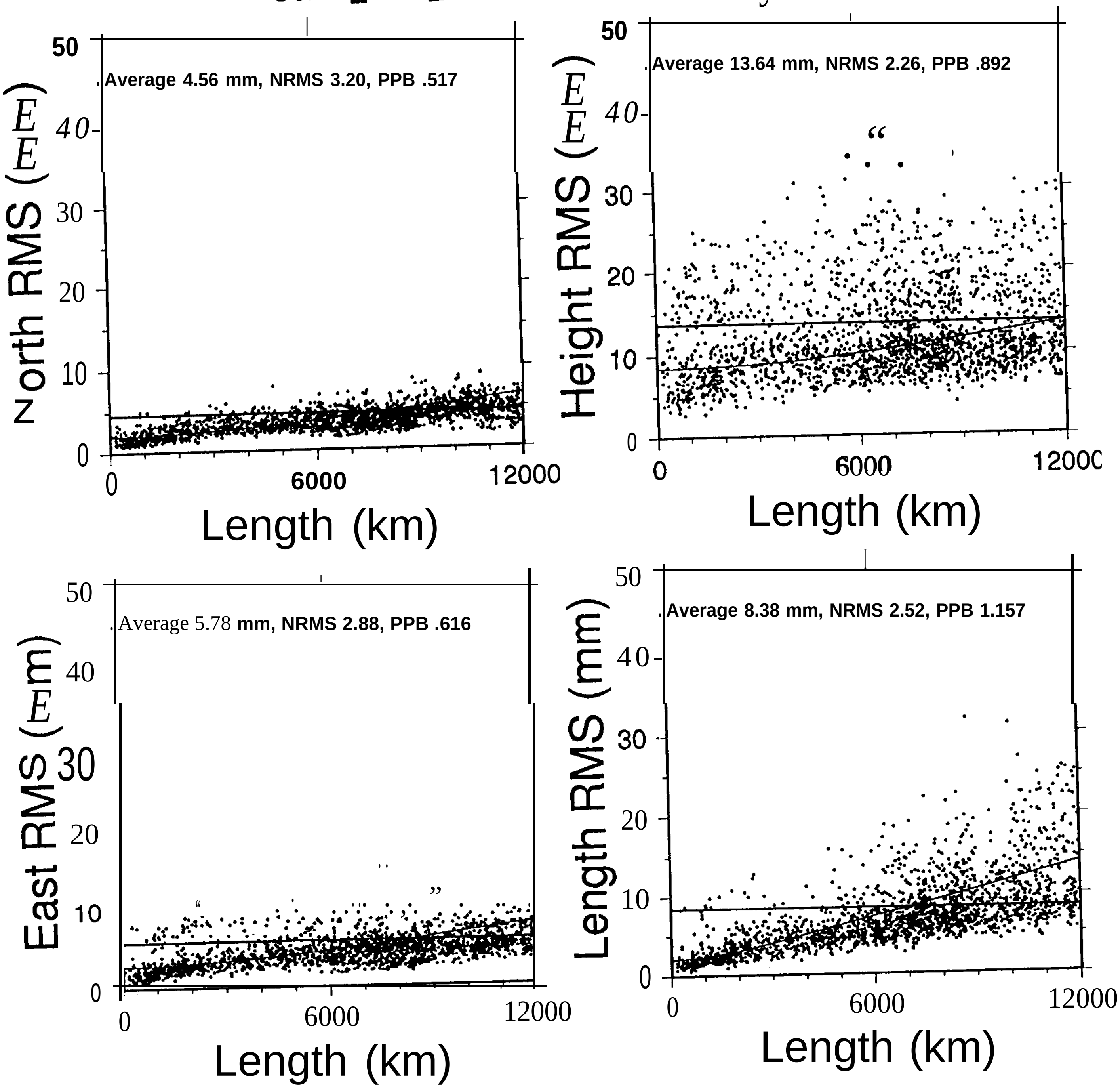
Thomas A Herring

- **Procedures:**
  - — Constraints removed for all centers except JPL and ESA
  - — Center variances based on χ^2 when "core" constrained
  - — Two analyses performed each week:
    - (a) Tight solution with core constrained
    - (b) Loose solution with translation, rotation and scale constraint applied.
  - — RMS fits to core and common sites reported for ITRF-93 and Combined solution

- **Differences from other centers**
  - — RMS fits are computed with height variance 10 times greater than horizontal
  - — Translation constraint is forced through covariance matrix (means not a simple translation).

- **Results**
  - — Repeatabilities for longest running centers
  - — Weight comparison
  - — Specific site position evolution for 6 months of data.

Comb_0819_0842 Combined Analysis



Center weights

Center	Variance	χ^2/f North	χ^2/f East	χ^2/f Height
Comb		10.2	8.3	5.1
COD	**12.3**	**88.5**	**100.4**	**35.1**
EMR	36.8	65.0	78.7	31.4
GFZ	38.6	55.5	31.2	16.0
JPL	11.8	32.8	15.4	11.0
S10	1.6	7.8	5.7	4.0

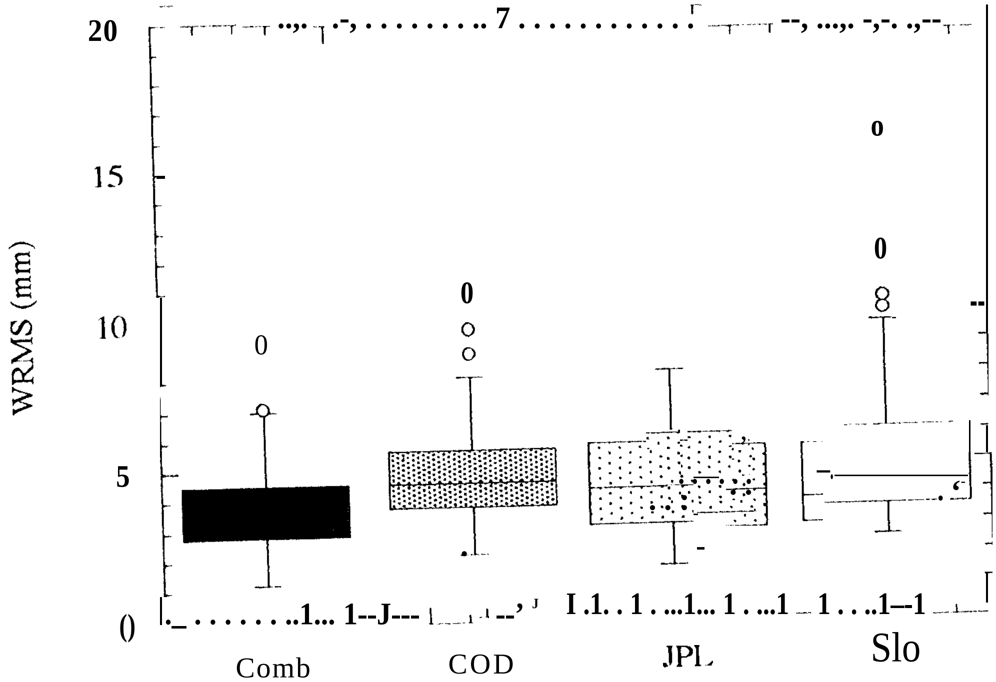
- Reasons for differences:
  - — Systematic variations in position common to many analysis centers.
  - — Stations not common so direct comparison difficult.
  - — COD/JPL and S10 produce very similar quality results and have similar weights in the combination.

- Average repeatability (about mean) for Combined solution:

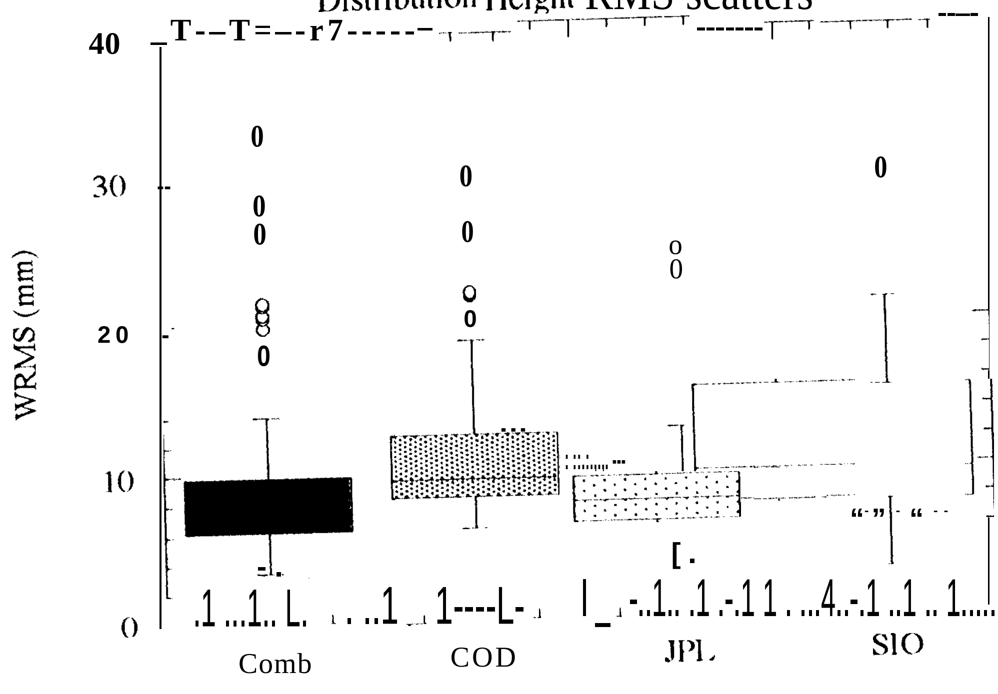
NORTH	4.5 mm
EAST	5.8 mm
HEIGHT	13.6 mm

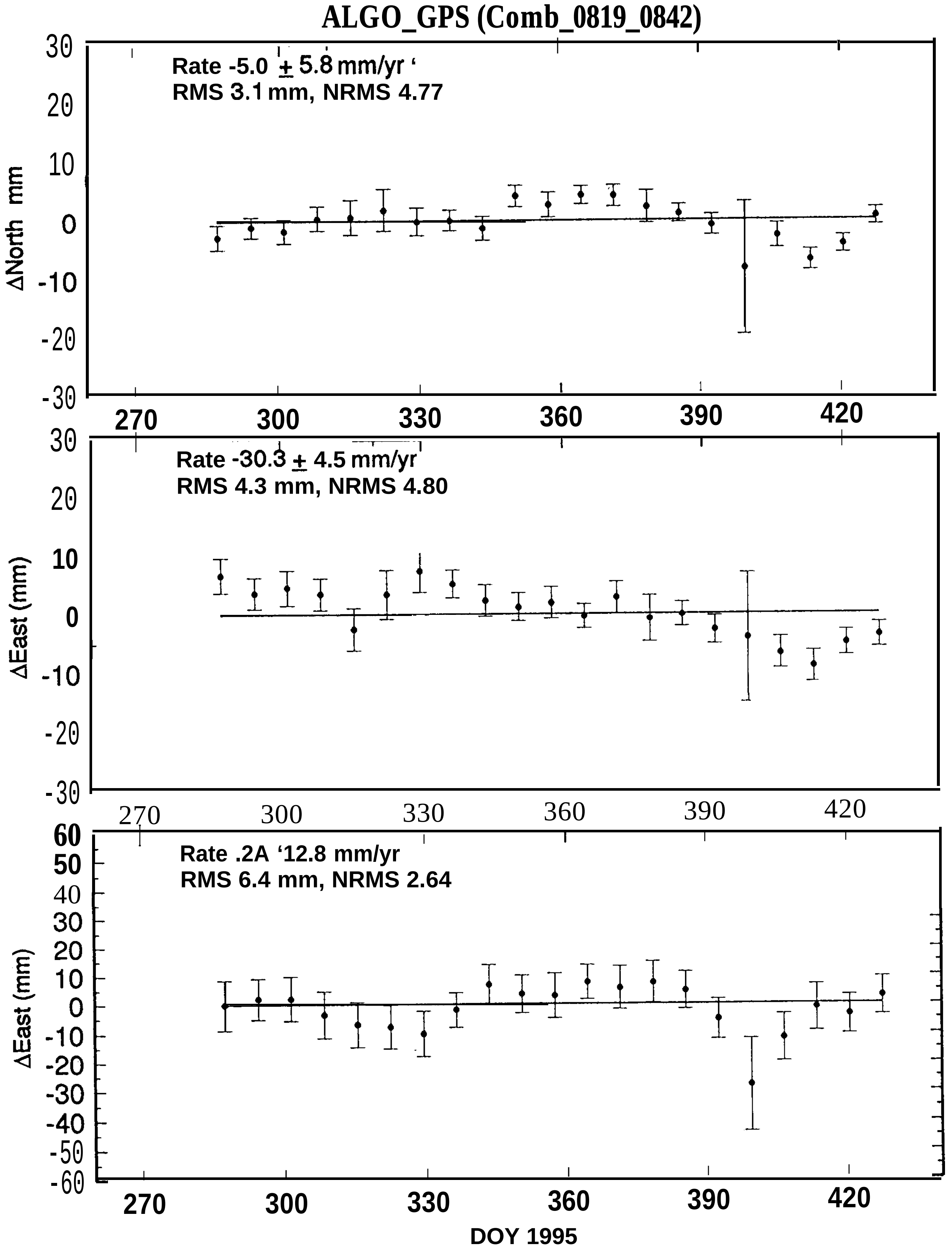
Clearly some poor performance stations.

Distribution North RMS scatters



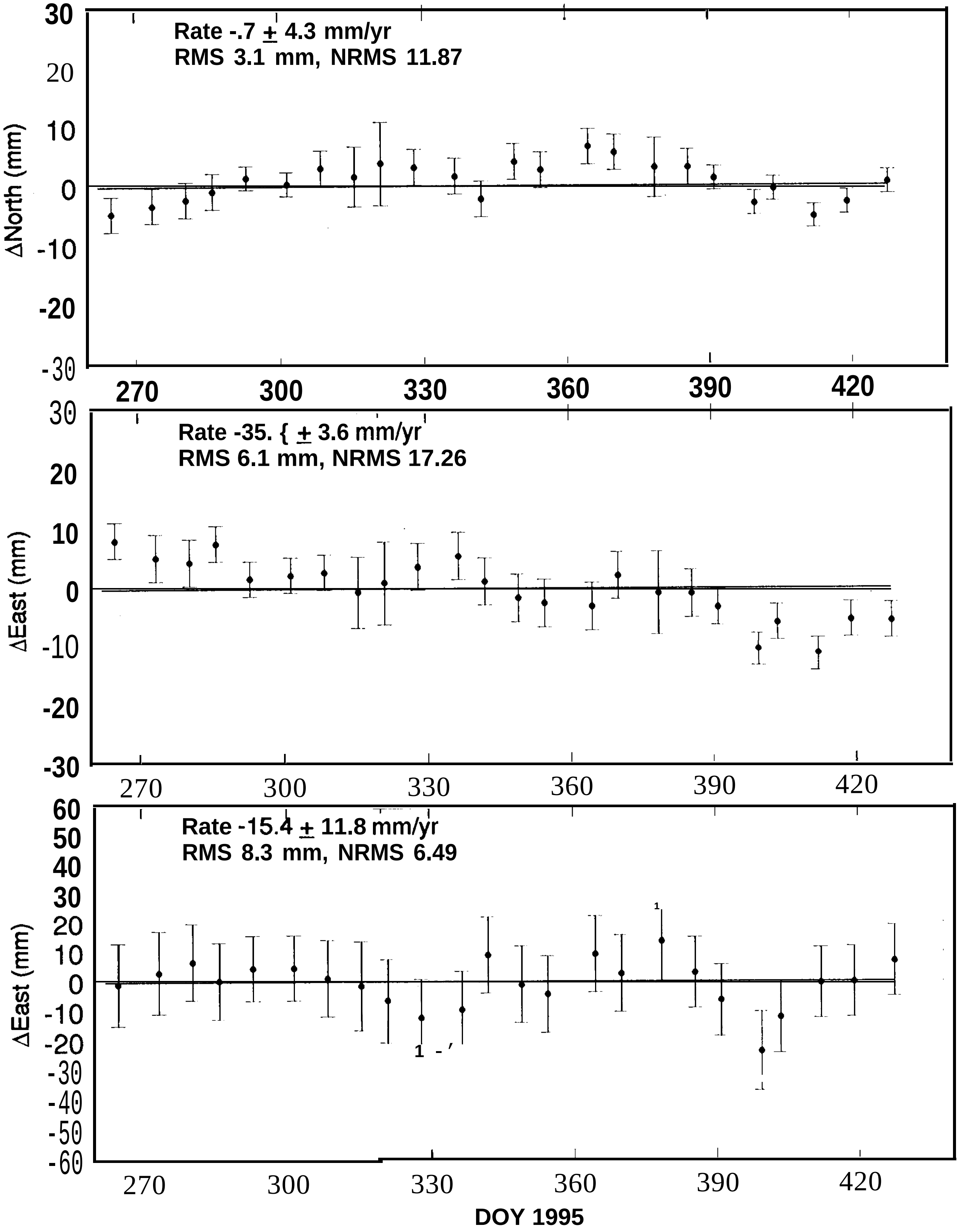
Distribution Height RMS scatters

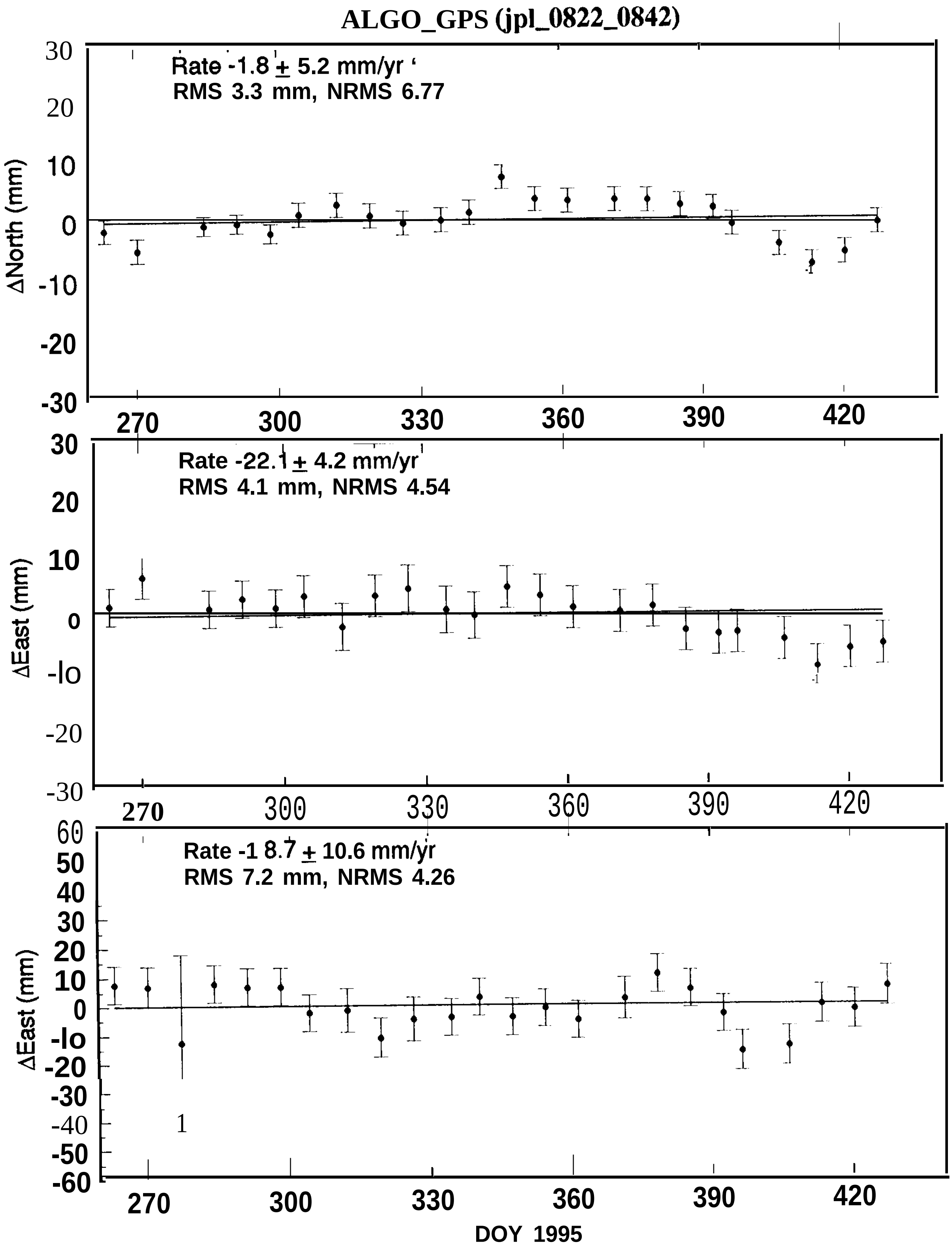




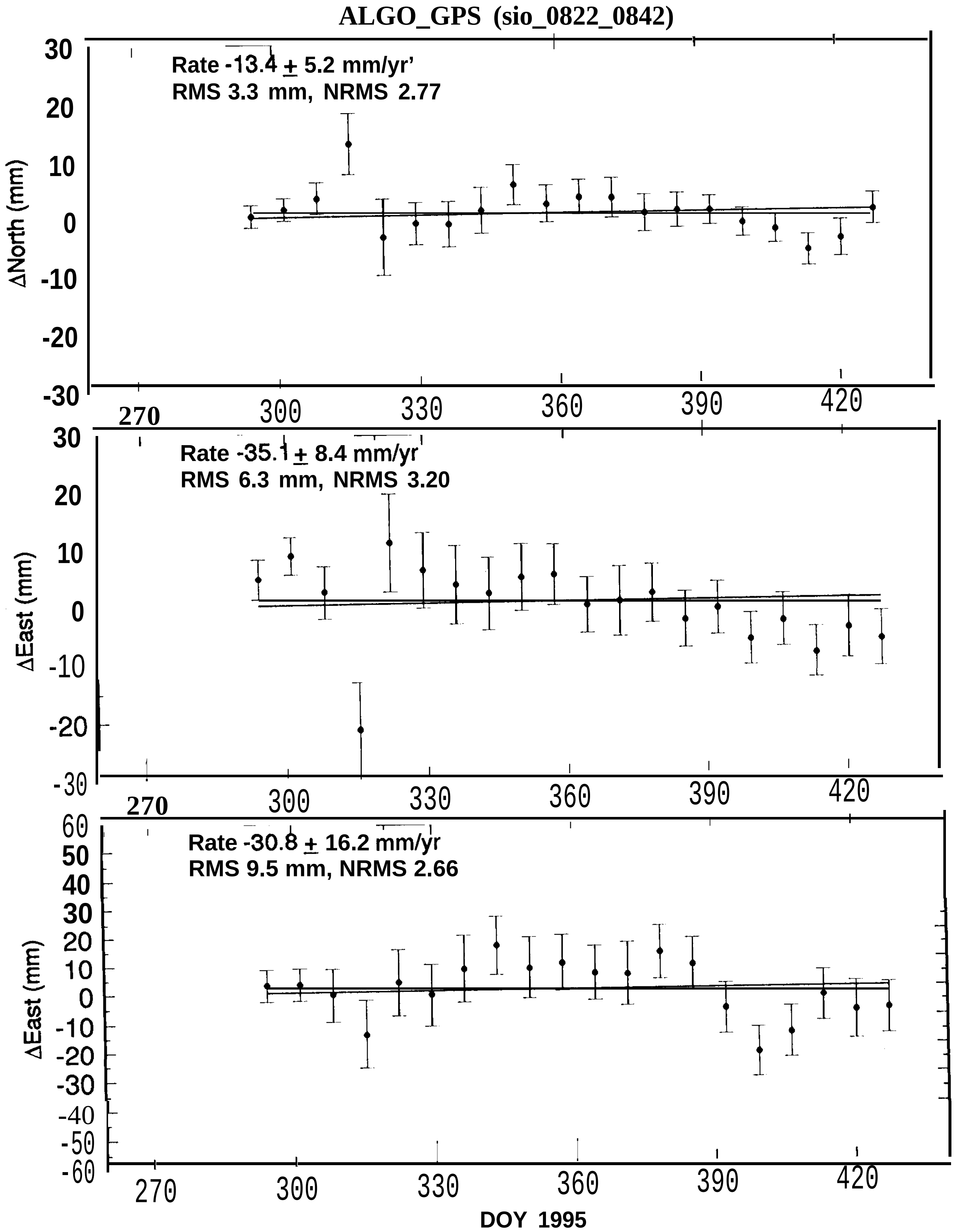
ALGO_GPS (Comb_0819_0842)
Rate -5.0 ± 5.8 mm/yr '
RMS 3.1 mm, NRMS 4.77
ΔNorth mm
30
20
10
0
-10
-20
-30
270
300
330
360
390
420
Rate -30.3 ± 4.5 mm/yr
RMS 4.3 mm, NRMS 4.80
ΔEast (mm)
30
20
10
0
-10
-20
-30
270
300
330
360
390
420
Rate .2A '12.8 mm/yr
RMS 6.4 mm, NRMS 2.64
ΔEast (mm)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
270
300
330
360
390
420
DOY 1995

ALGO_GPS (cod_0822_0842)

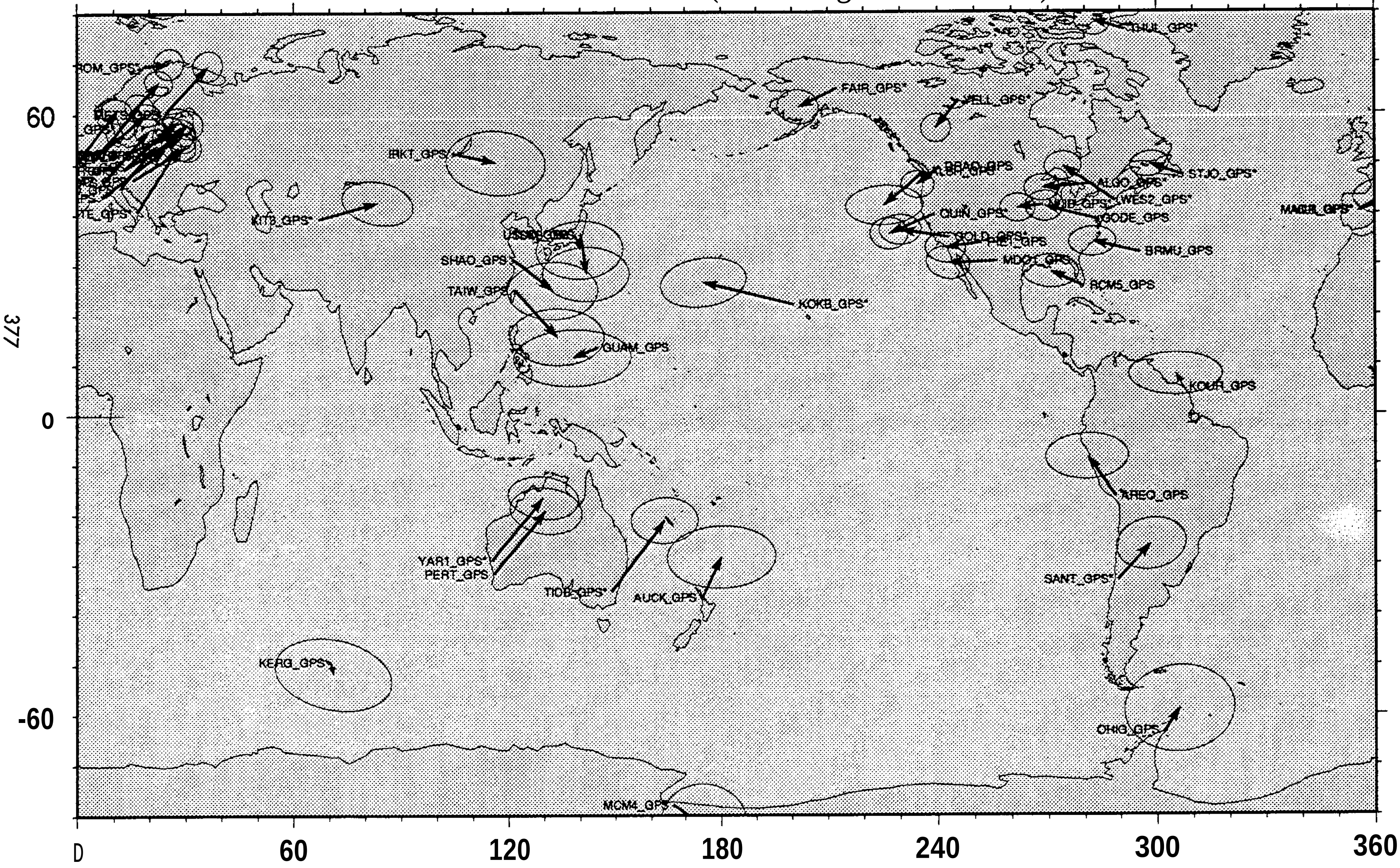




ALGO_GPS (jpl_0822_0842)
Rate -1.8 ± 5.2 mm/yr
RMS 3.3 mm, NRMS 6.77
ΔNorth (mm)
30
20
10
0
-10
-20
-30
270
300
330
360
390
420
Rate -22.1 ± 4.2 mm/yr
RMS 4.1 mm, NRMS 4.54
ΔEast (mm)
30
20
10
0
-lo
-20
-30
270
300
330
360
390
420
Rate -1 8.7 ± 10.6 mm/yr
RMS 7.2 mm, NRMS 4.26
ΔEast (mm)
60
50
40
30
20
10
0
-lo
-20
-30
-40
-50
-60
1
270
300
330
360
390
420
DOY 1995


ALGO_GPS (sio_0822_0842)
Rate -13.4 ± 5.2 mm/yr'
RMS 3.3 mm, NRMS 2.77
ΔNorth (mm)
30
20
10
0
-10
-20
-30
270
300
330
360
390
420
Rate -35.1 ± 8.4 mm/yr
RMS 6.3 mm, NRMS 3.20
ΔEast (mm)
30
20
10
0
-10
-20
-30
270
300
330
360
390
420
Rate -30.8 ± 16.2 mm/yr
RMS 9.5 mm, NRMS 2.66
ΔEast (mm)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
270
300
330
360
390
420
DOY 1995

New Global GPS sites (Excluding ITRF93 Sites)



Problems

- Analysis centers not reporting analysis changes
- Missing pieces in the SINEX files
- SINEX entries not the actual values being used in the processing.
- Bad eccentricity entries
- Weighting for centers: Need data decimation and assumed standard deviation of phase data

IONOSPHERIC PROFILING USING GPS/MET DATA

George Hajj and Larry Remans

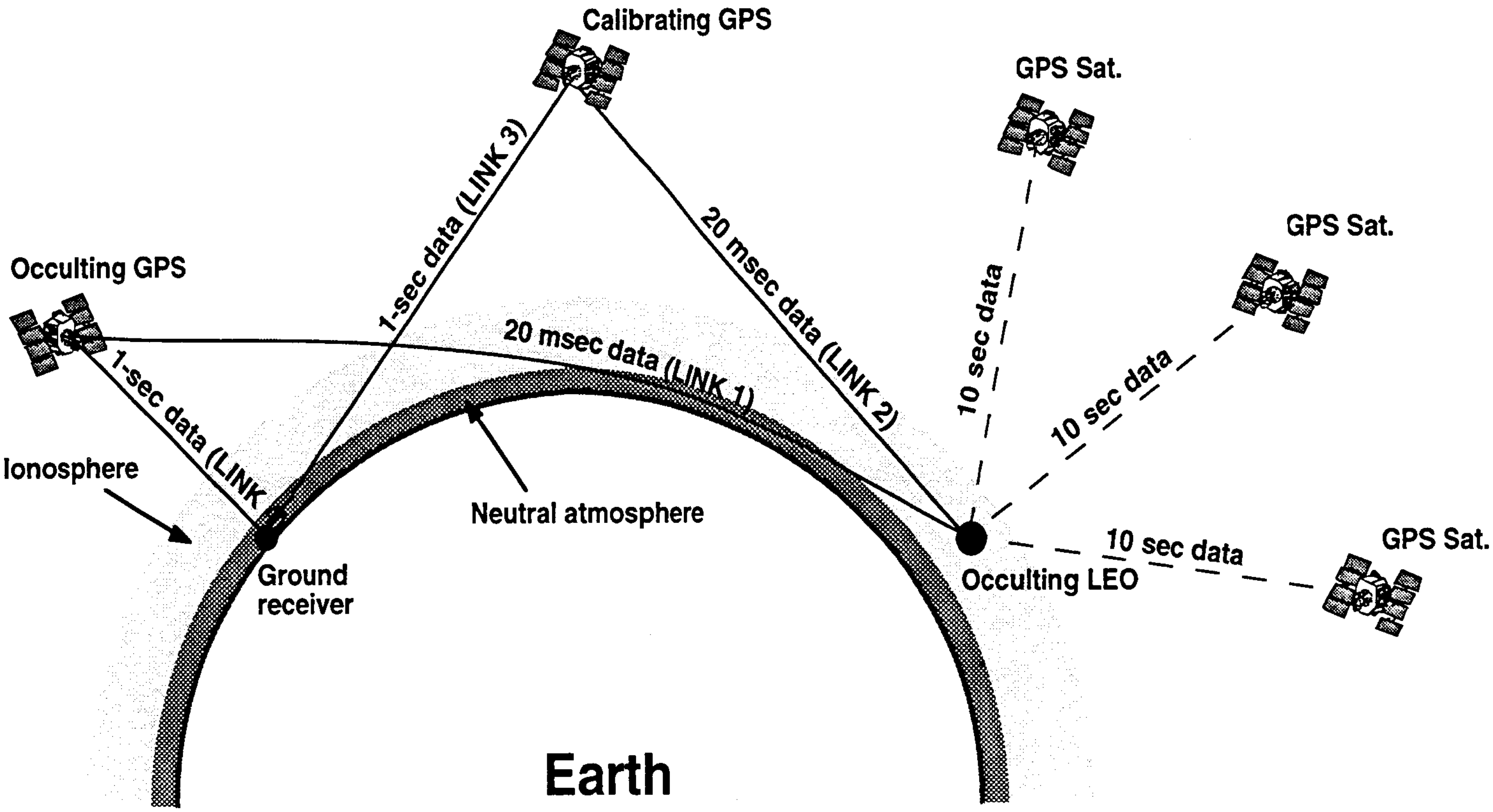
Jet Propulsion Laboratory
California Institute of Technology

IGS Workshop
Silver Spring, 19-21 March, 1996

SCOPE OF TALK

- Description of GPS occultation technique
- GPS/MET data processing system
- Example of GPS/MET data products
  - Temperature and water vapor profiles (Kursinski et al. Science, Vol. 271, pp. 1107-1110, 1996)
  - Ionospheric profiles (Hajj and Remans, *Proc. of the Institute of Navigation 52nd Annual Meeting,* Cambridge, Mass., June 19-21, 1996)
- Preliminary validation of ionospheric profiles

CALIBRATION OF GPS-LEO OCCULTATION SIGNAL



OBTAINING TEMPERATURE AND PRESSURE FROM REFRACTIVITY

Hydrostatic — Moist — Ionosphere

$$N = (n-1)\times 10^6 = 77.6\frac{P}{T} + 3.73\times 10^5\frac{P_w}{T^2} - 40.3\times 10^6\frac{n_e}{f^2}$$

$$+ \text{ higher order ionospheric terms}$$

- Equation of state

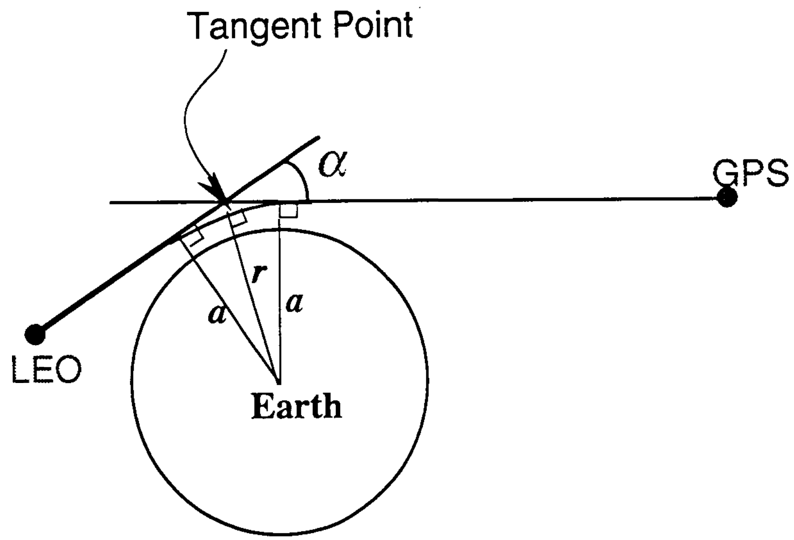
$$P = \frac{\rho R T}{m}$$

- Hydrostatic equilibrium equation

$$\frac{\partial P}{\partial h} = -g\rho$$

n = index of refraction
N = refractivity
P = total pressure
T = temperature
P_w = water vapor partial pressure
n_e = electron density
f = operating frequency
ρ = density
h = height
g = gravitational acceleration

OCCULTATION GEOMETRY AND THE ABEL TRANSFORM
LEO OBSERVING A GPS SATELLITE



- Assume spherical symmetry

Forward propagation

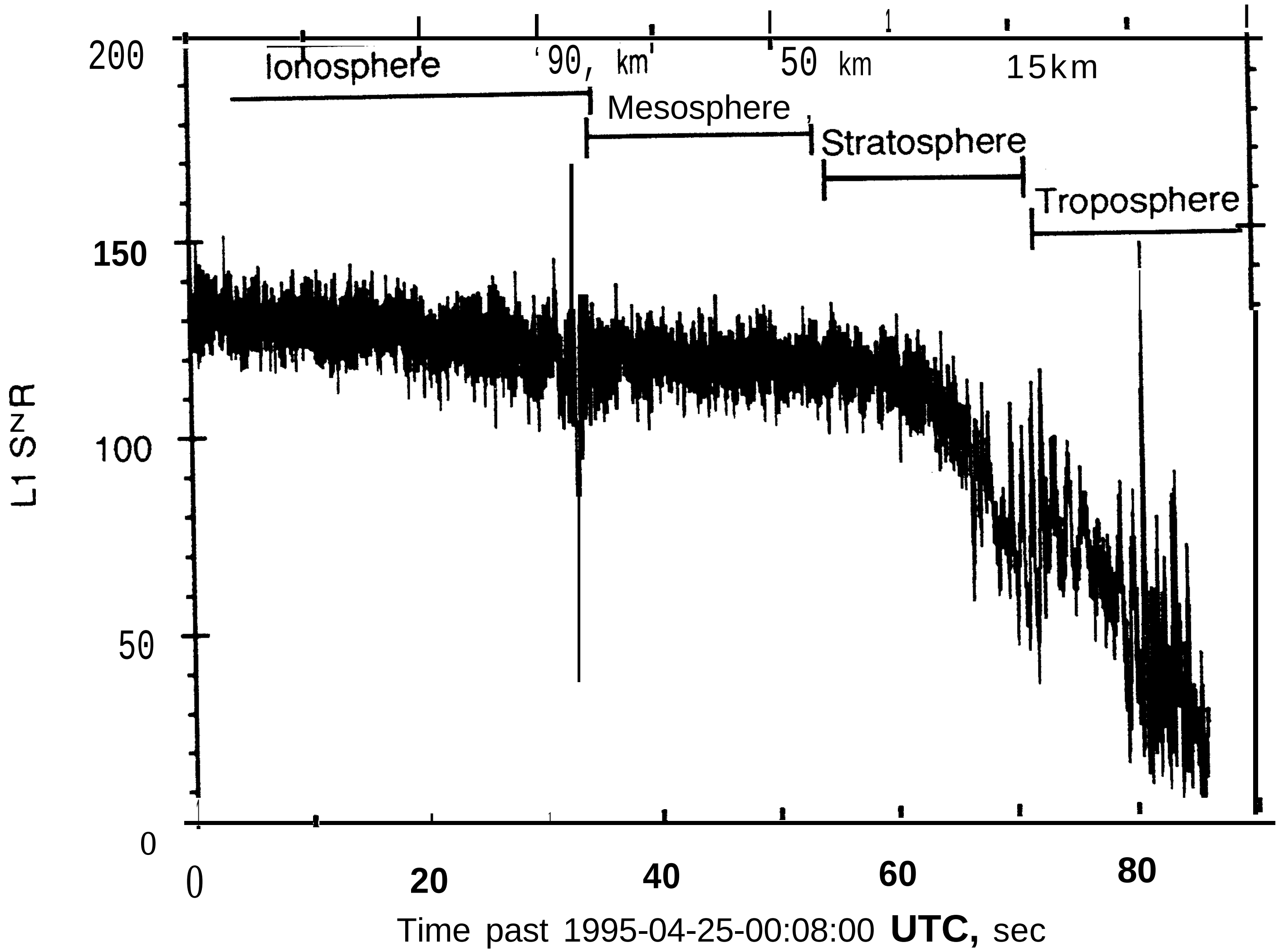
$$\alpha = -2a\int_{r_0}^{\infty} \frac{d\ln(n)/dr}{\sqrt{r^2n^2 - a^2}}dr$$

$\Rightarrow$

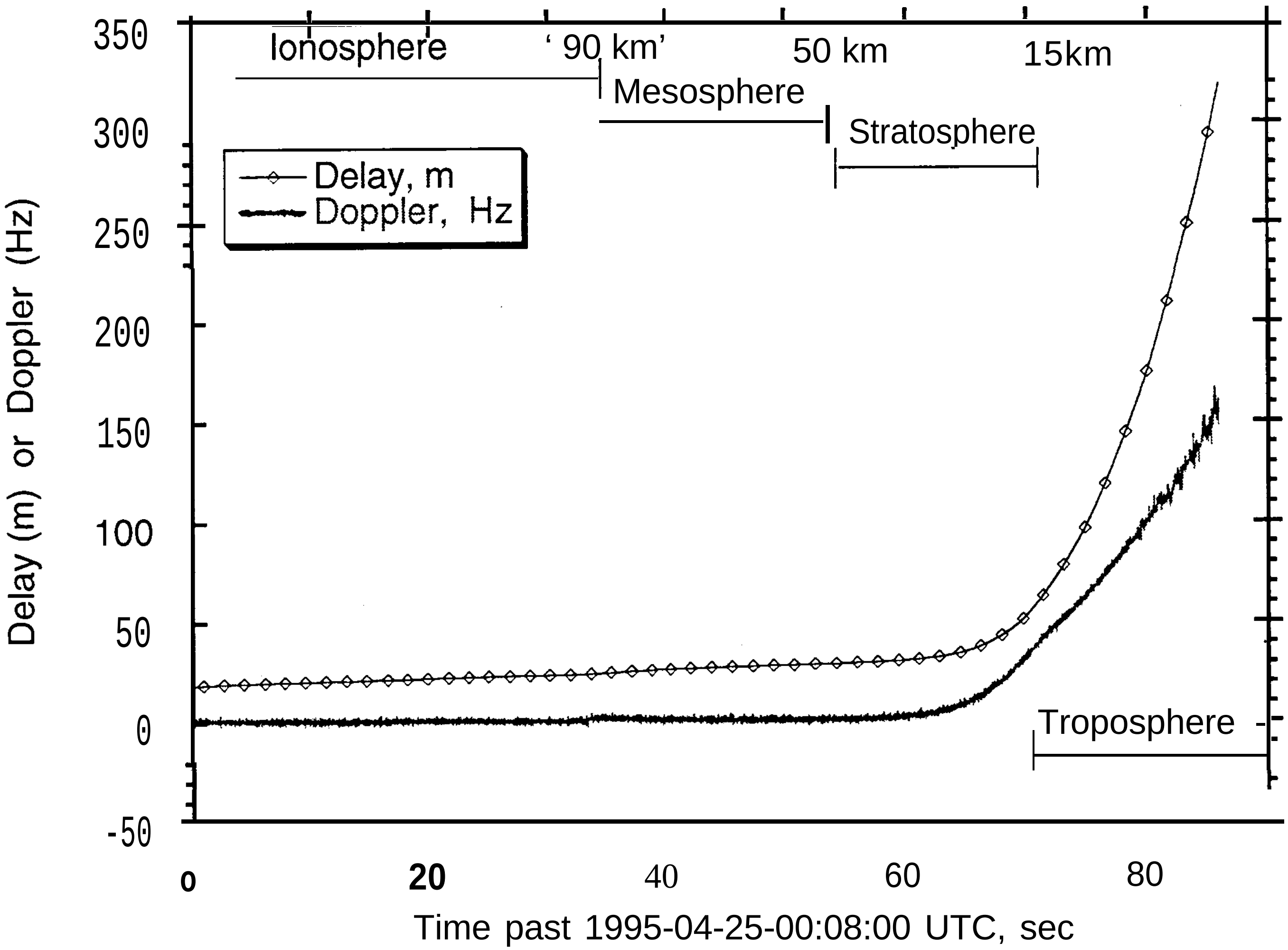
Abel inversion

$$\mathrm{n}(n(r)) = \frac{1}{\pi}\int_{nr}^{\infty} \frac{\alpha}{\sqrt{a^2 - r^2n^2}}da$$

Signal to noise ratio of occulting L1 signal

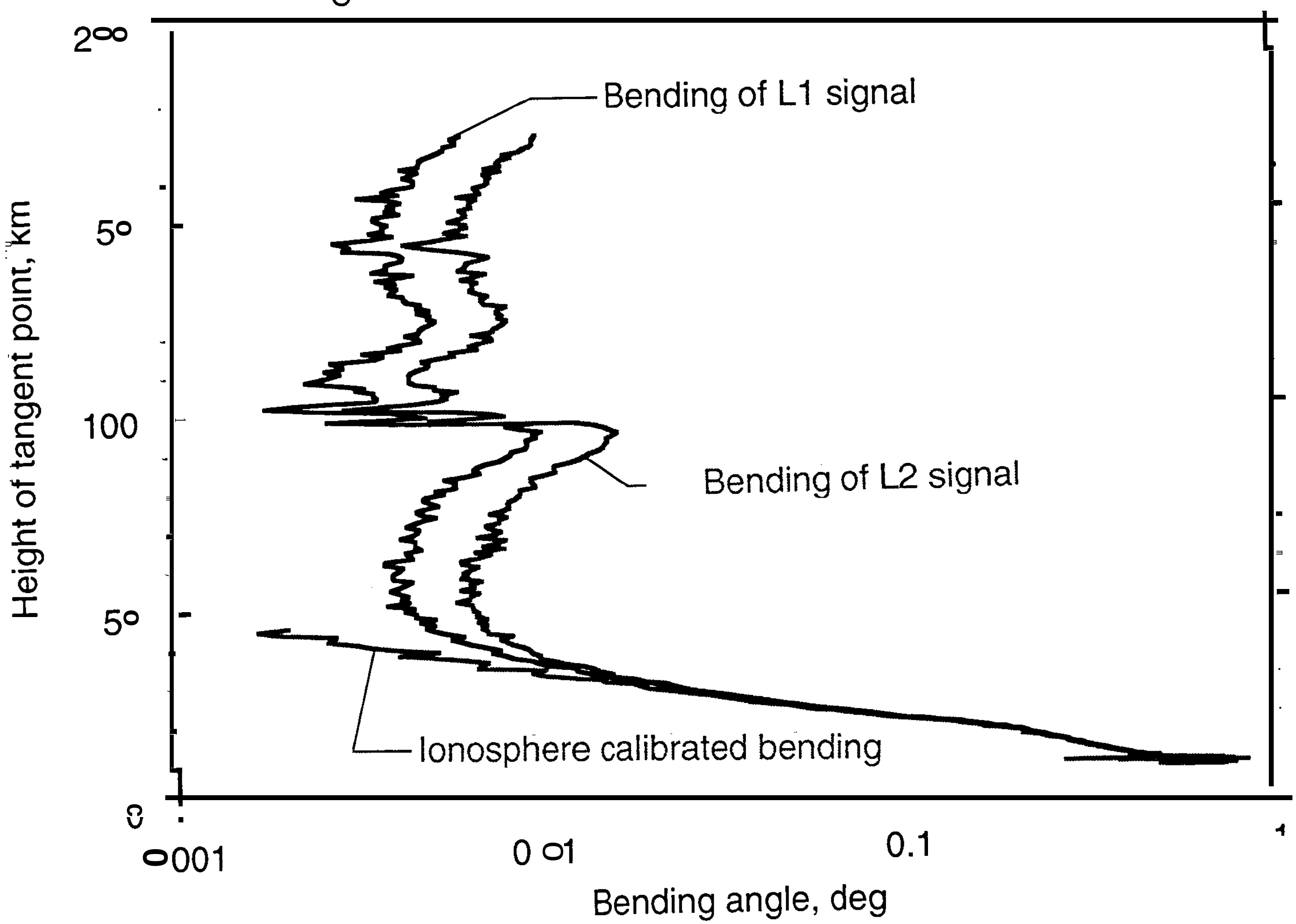


Extra delay and Doppler shift of Ll signal due to atmosphere



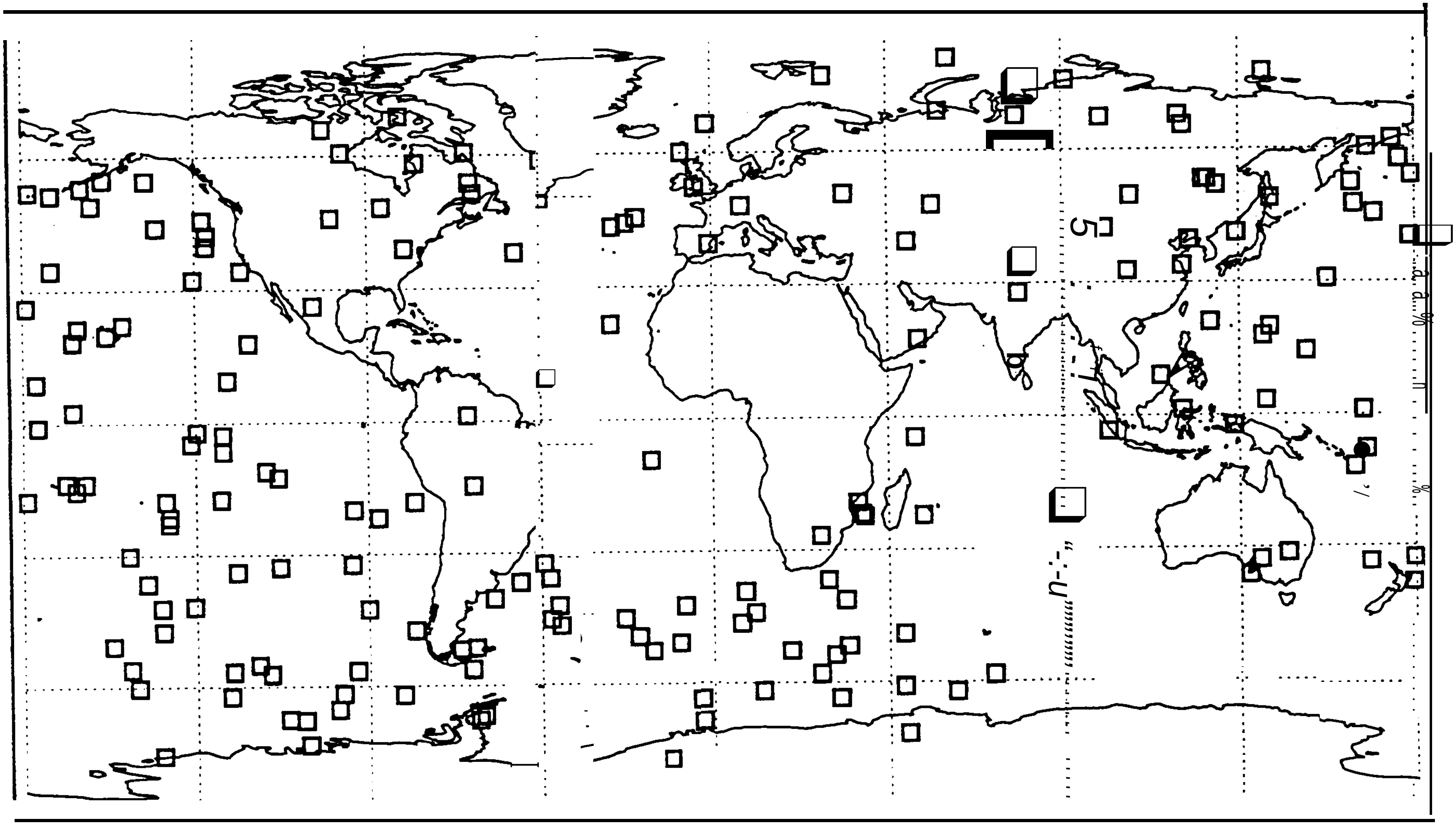
Bending of s ıal as a function of height from surface

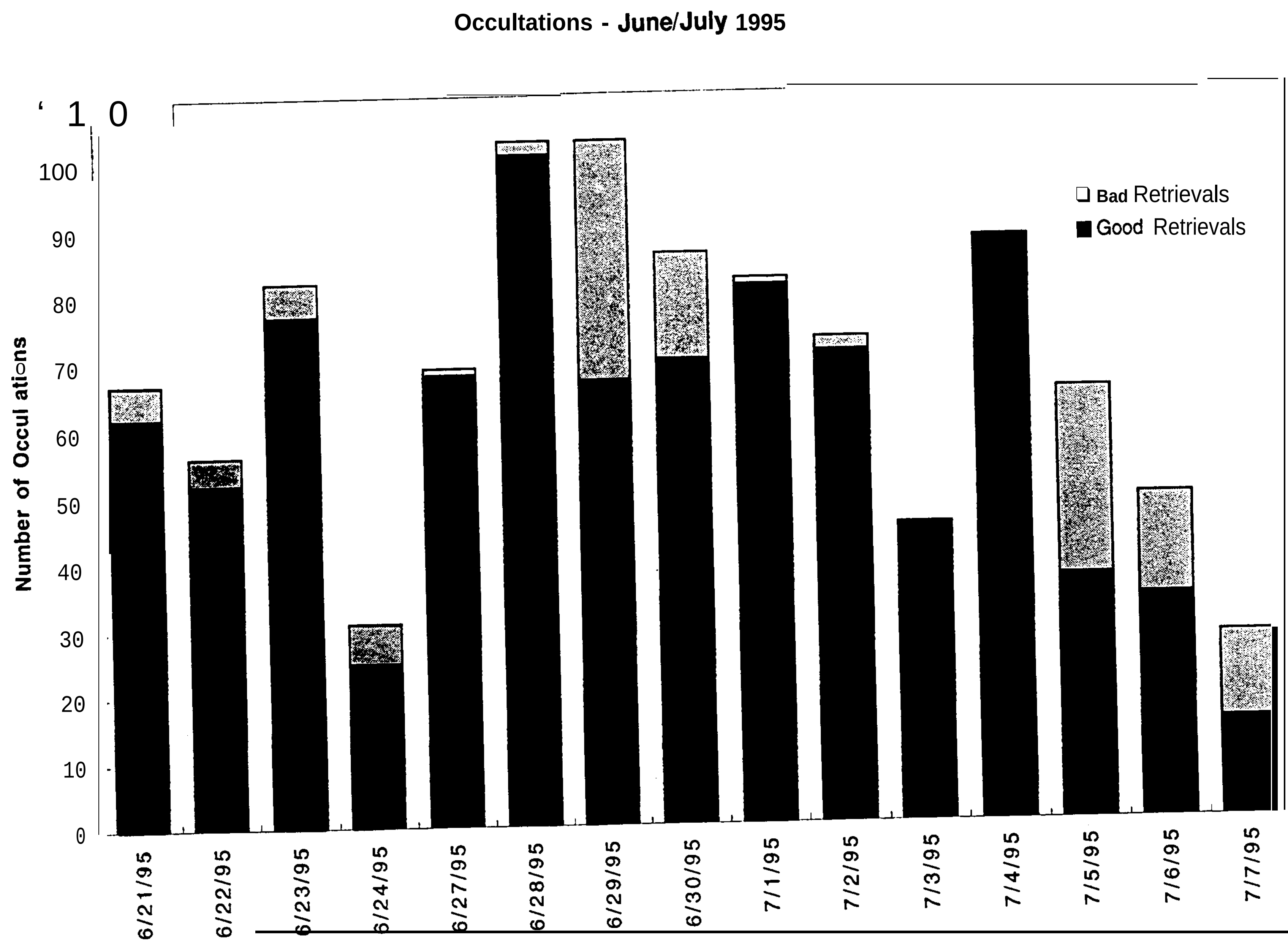
noon local time



Occultation Locations for

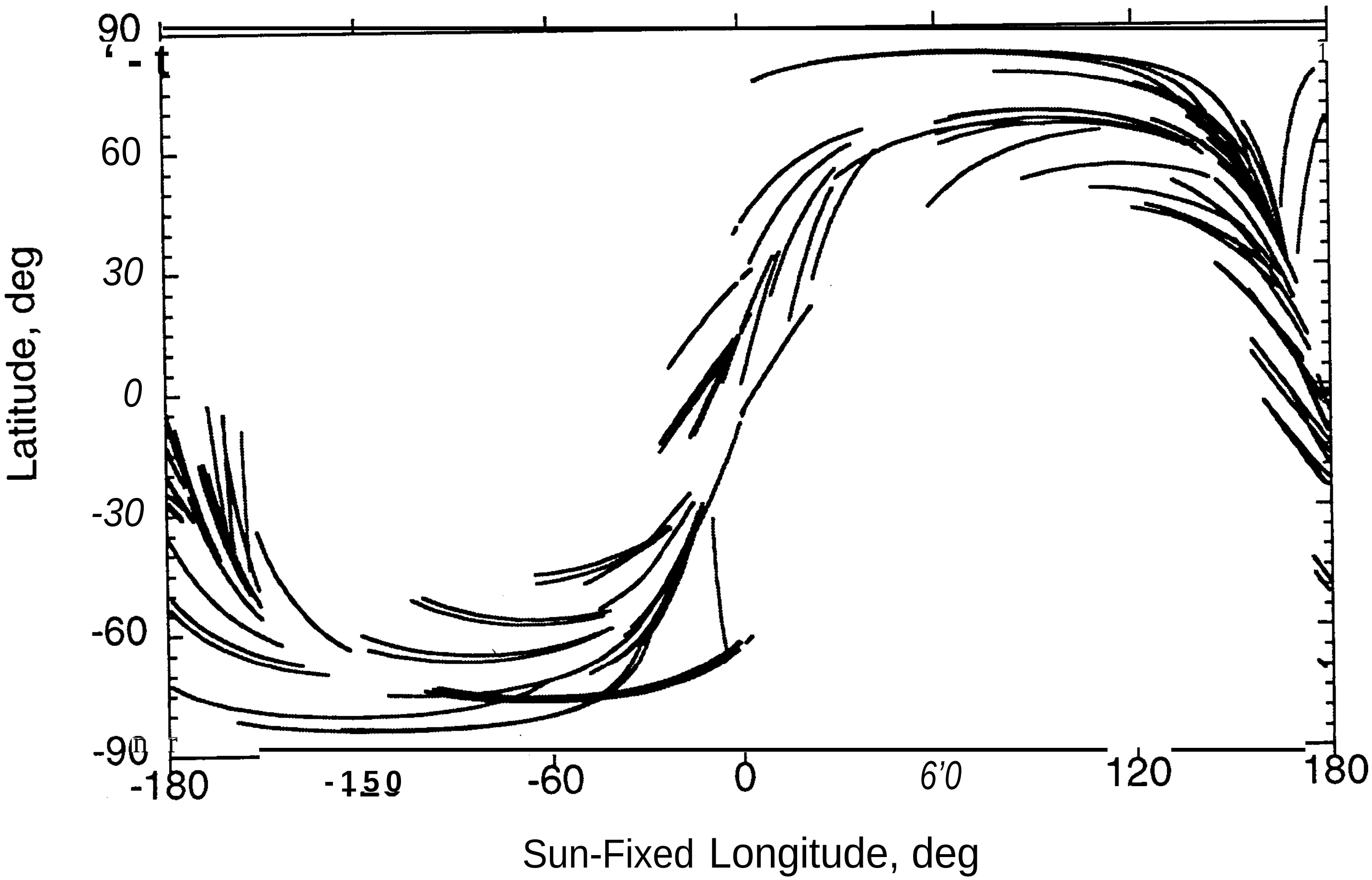
95/04/24, 95/04/25, 95/05/04 and 95/05/05



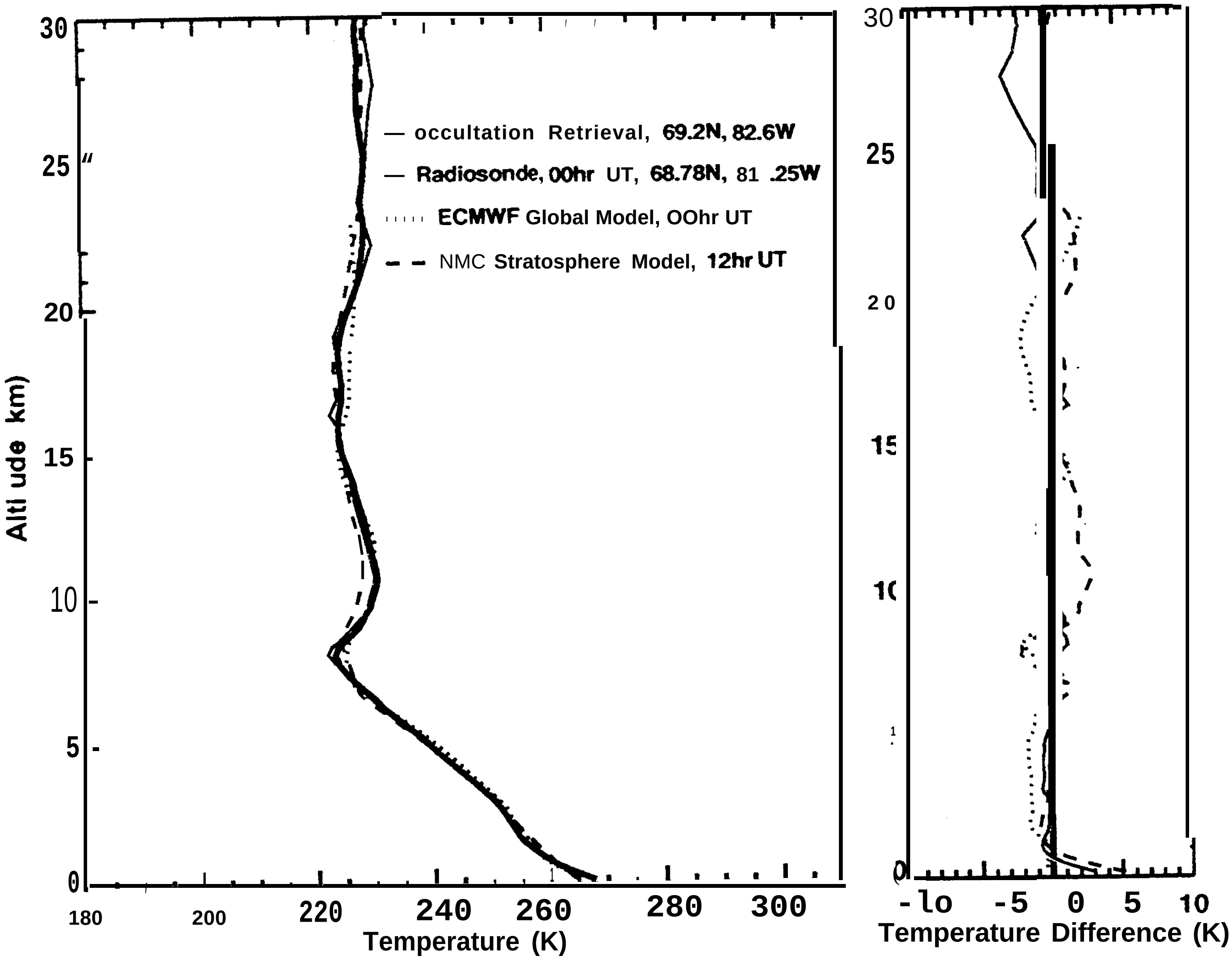


Occultations - June/July 1995
Number of Occultations
0
10
20
30
40
50
60
70
80
90
100
Bad Retrievals
Good Retrievals
6/21/95
6/22/95
6/23/95
6/24/95
6/27/95
6/28/95
6/29/95
6/30/95
7/1/95
7/2/95
7/3/95
7/4/95
7/5/95
7/6/95
7/7/95

GPS/MET COVERAGE IN SUN-FIXED COORDINATES IN 24 HOURS, MAY 4, 1995

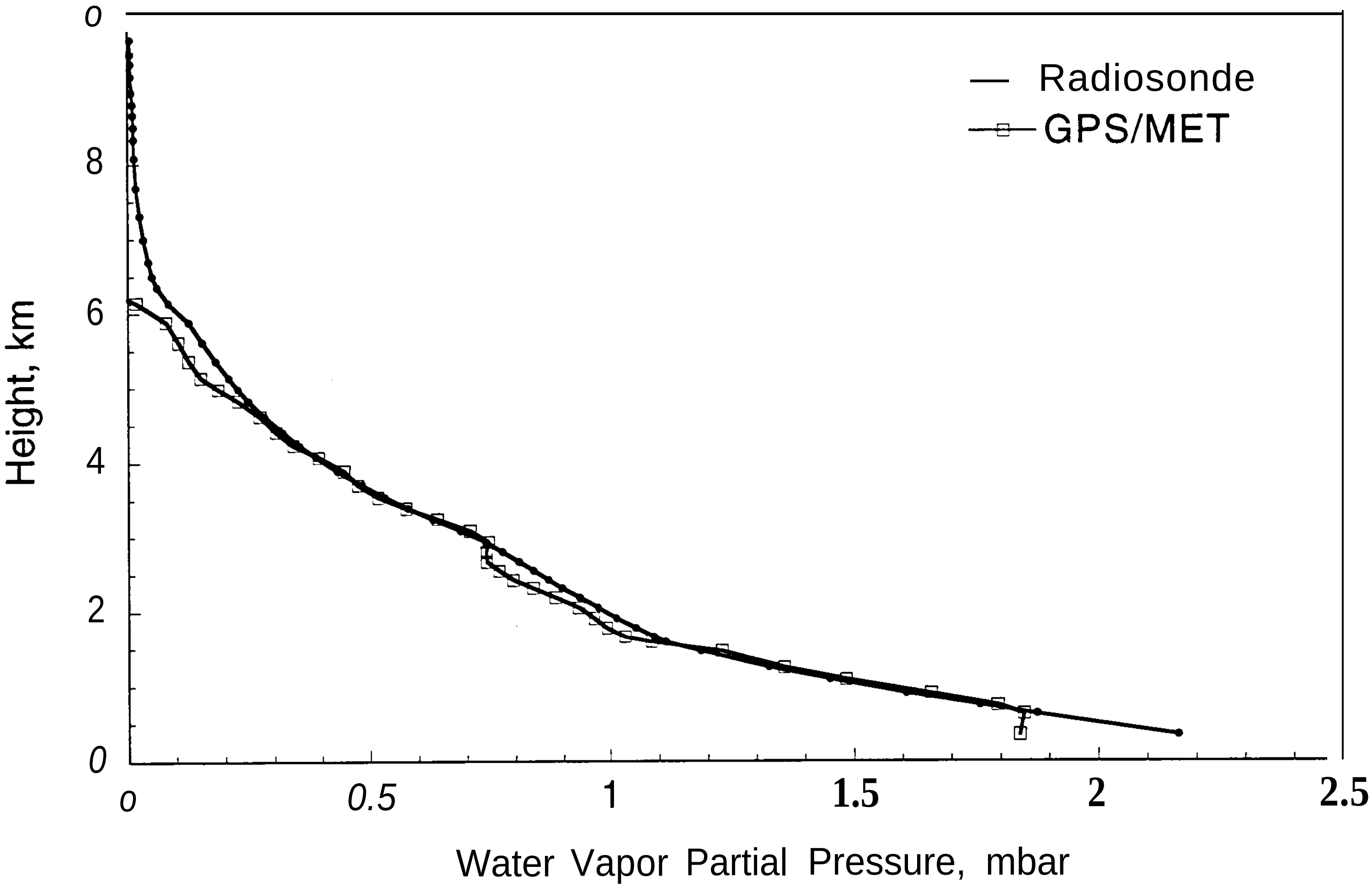


Hall Beach, Northwest Territories, 1995/05/05 at 01:33

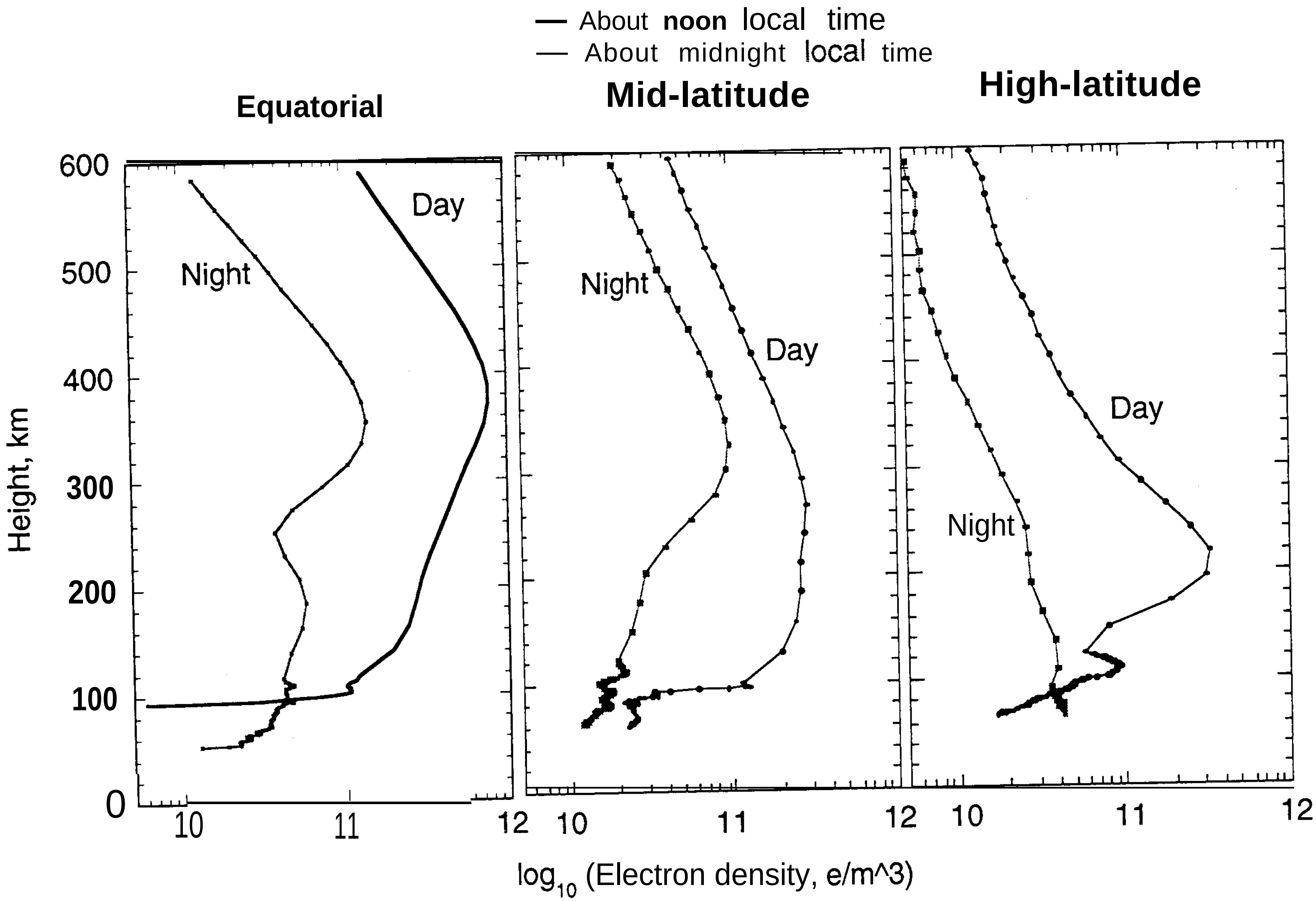


Kursinski et al., Feb 23, 1996, Science Vol. 271, pp. 1107-1110

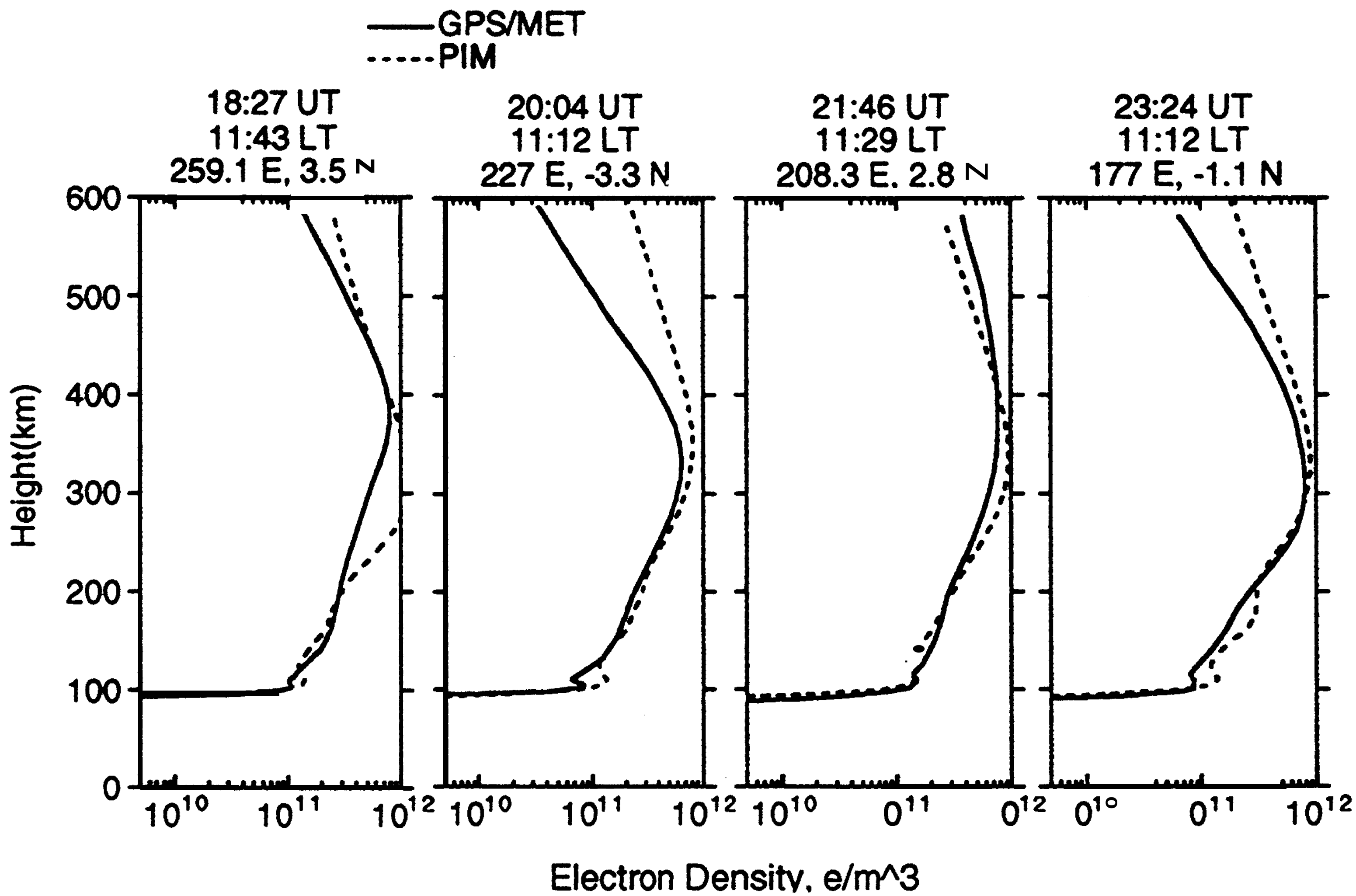
WATER VAPOR PARTIAL PRESSURE MEASUREMENTS
High Latitude Region



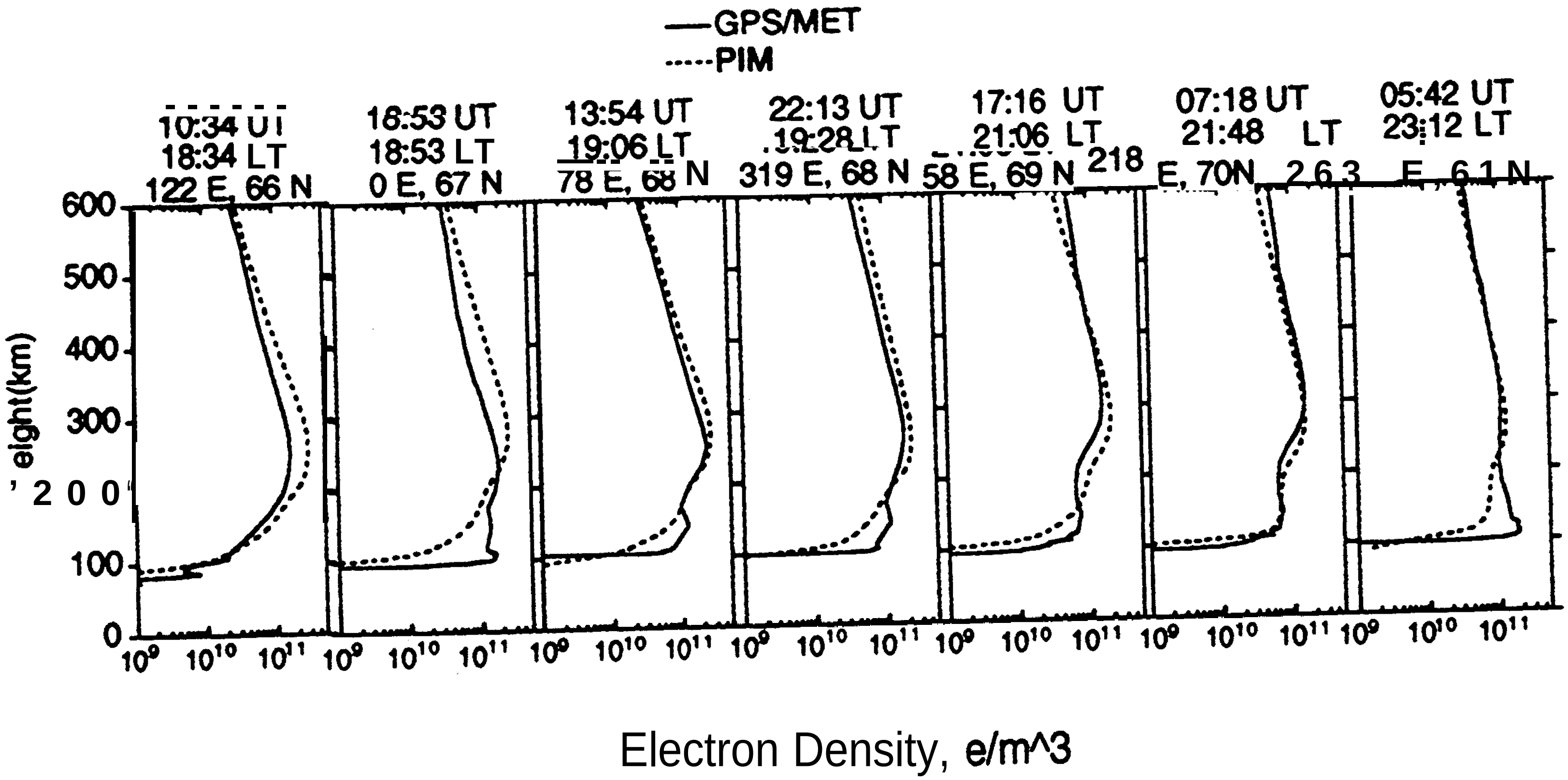
Electron density profiles from GPS/MET for May 4, 1995 (spherical symmetry assumed)



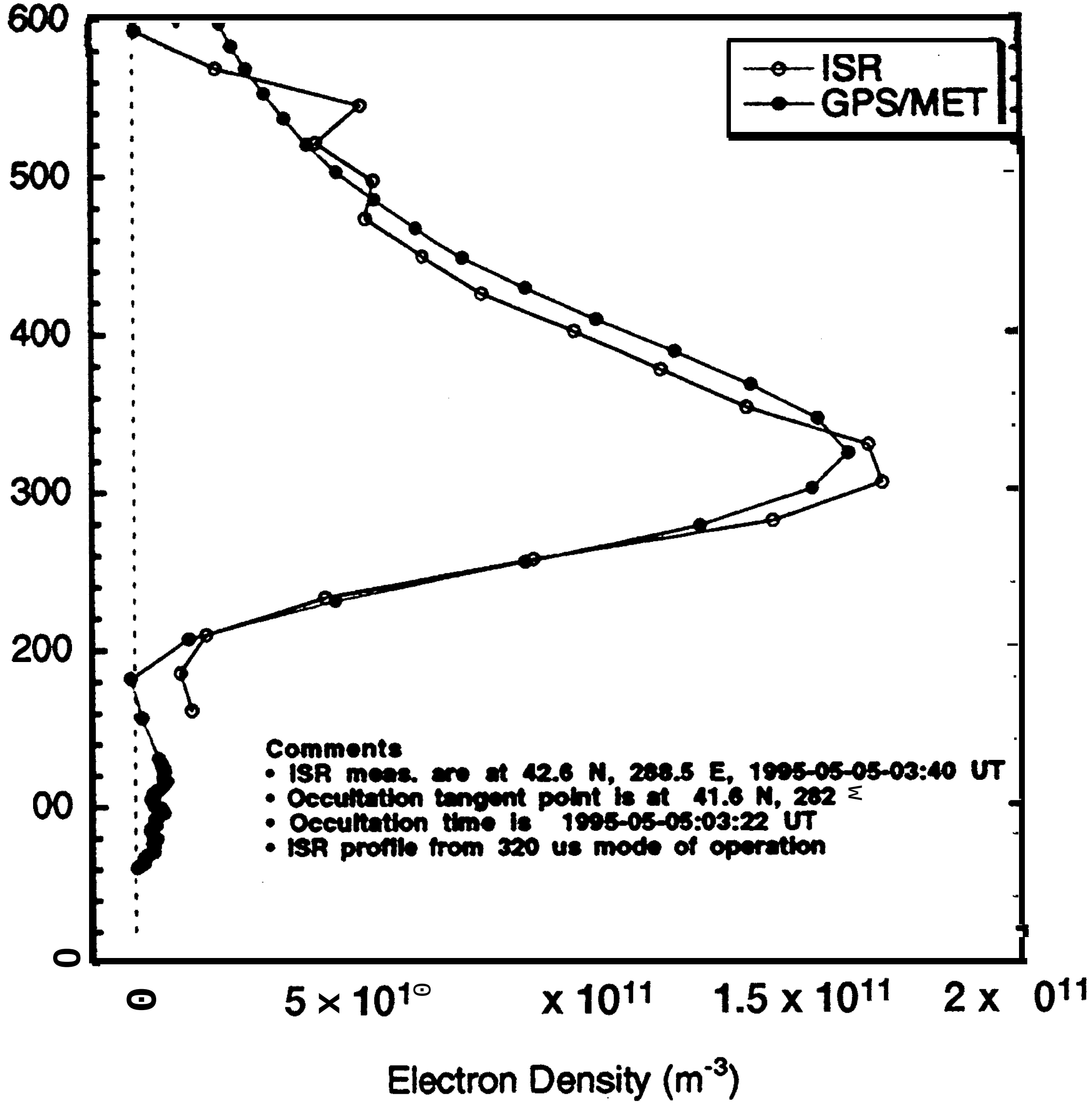
ELECTRON DENSITY PROFILES FROM GPS/MET AND THE PARAMETRIZED IONOSPHERIC MODEL OBTAINED FOR MAY 4, 1995 AT ABOUT THE SAME LATITUDE AND LOCAL TIME



ELECTRON DENSITY PROFILES FROM GPS/MET AND THE PARAMETRIZED IONOSPHERIC MODEL OBTAINED FOR MAY 4, 19% AT ABOUT THE SAME LATITUDE



Electron density profiles measured at the Millstone Hill incoherent scatter radar and derived from a nearby GPS/MET occultation



CONCLUSION

- Advantages of GPS radio occultations in the ionosphere

  - provide a simple and relatively inexpensive means of profiling the ionosphere
  - provide electron density profiles with a high vertical resolution (1 km)
  - provide a global and continuous coverage

- Disadvantages of G PS radio occultation in the ionosphere

  - The measurement is an integrated measurement over a large distance

- Spherical symmetry assumption in the ionosphere introduces an error of 0-50°/0 in determining the peak electron density

- Imposing constraints on horizontal gradient (such as from ground zenith TEC maps) can bring the error to < 20% (Hajj et al., *Int. J. Imaging Sys. and Tech.*, Vol. 5, pp. 174-184, 1994)

Global Ionospheric Mapping using GPS: Validation and Future Prospects

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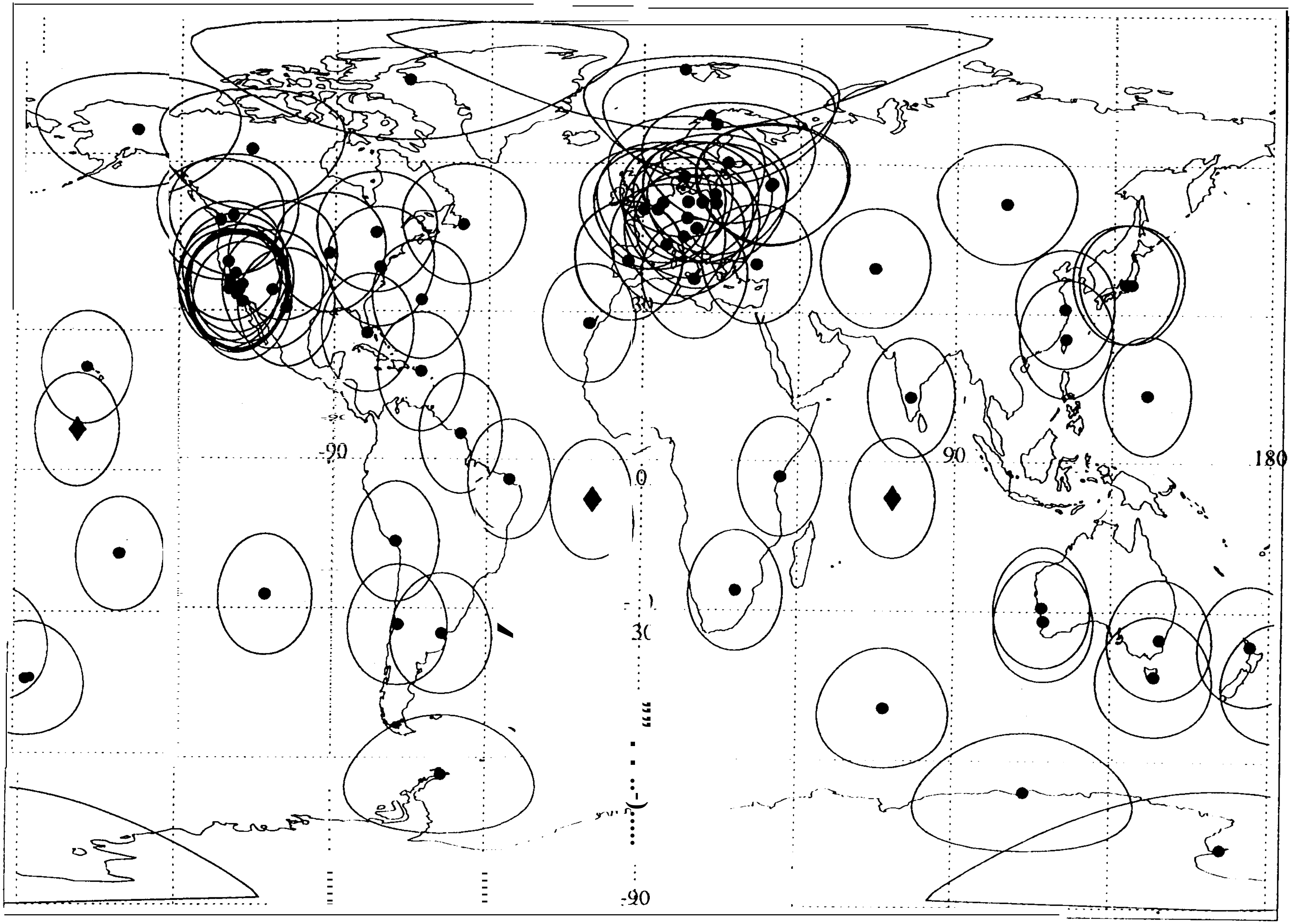
Anthony J. Mannucci
Dah-Ning Yuan
Christian Ho
Xiaoqing Pi
Tom Runge
Ulf J. Lindqwister

GPS Networks and Operations Group
Tracking Systems and Applications Section
Jet Propulsion Laboratory, California Institute of Technology

IGS Workshop, Silver Spring, MD
March 21, 1996

GPS Global Network: Coverage at Ionospheric Altitudes
February 1996



10 degree elevation mask. Effective shell height of 400km.

Ionospheric Applications

- Single-site GPS-based ionospheric calibrations for S-band tracking applications and local ionospheric studies.

- Global Ionospheric Mapping (GIM) with an accuracy of 5–10 TEC units.
  - Use GPS data from 95+ dual-frequency receiver sites.
  - Snapshot of the ionosphere every half-hour.
  - Optimal combination of model information and iono. measurements (near real-time Kalman filter).

- Ionospheric calibration for remote tracking sites without a GPS receiver.

- Global calibration of single-frequency ocean altimetry missions: ERS-1, ERS-2, and GEOSAT follow-on (GFO).

- Ionospheric correction maps for single-frequency GPS users.

- Real-time Wide Area Differential GPS (WADGPS) over the continental U. S. or the entire globe.

- Near real-time ionospheric storm monitoring/forecasting (space weather).

- Ionospheric studies: GPS signal fading, ionospheric scintillation.

Tropospheric Applications

- Single-site GPS-based tropospheric calibrations for tracking applications and local water vapor studies.
- Troposphere is too variable to interpolate a global map of water vapor, but can compute local measurements of water vapor in near real-time.
- Estimate the wet and dry zenith delays separately using temperature and pressure data from a local meteorology package.
- Convert wet delay to real-time precipitable water vapor (PWV), a primary input to weather prediction models.
- Water vapor content is the most uncertain parameter in weather prediction.

Space-borne GPS Applications

- Occultation data from a dual-frequency GPS receiver on a low-Earth orbiter (LEO).

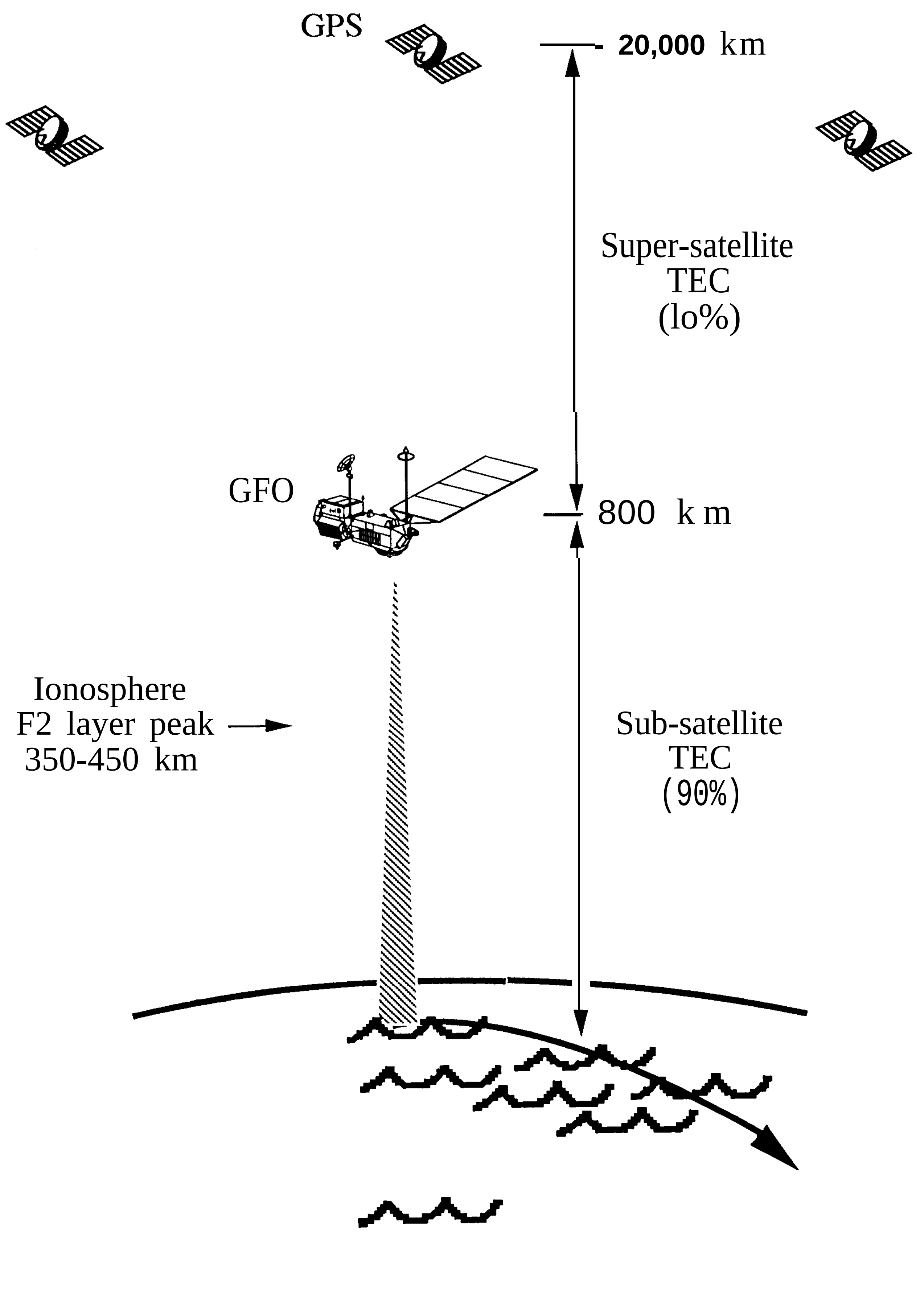
- Ionosphere: Track the non-geometric changes in phase to compute electron density profiles as a function of altitude.

- Neutral atmosphere: Invert the ray-bending data to compute the index of refraction as a function of altitude. From this, one can compute temperature or water vapor as a function of altitude.

- Proof of concept: GPS/MET mission currently flying.

- Space-borne GPS constellation: autonomous navigation and occultation science in a small micro-satellite.

- Global 3D ionospheric "tomography".



GPS
- 20,000 km
Super-satellite
TEC
(lo%)
GFO
800 km
Ionosphere
F2 layer peak
350-450 km
Sub-satellite
TEC
(90%)

Types of Global Ionosphere Models

- <u>Mathematical/Physical</u>
  first principles calculation of ion densities, temperatures and velocities
  SUPIM* (Graham Bailey et al., Univ. of Sheffield, G.B.), Schunk et al., Utah State Univ.

- <u>Climatological</u>
  month-by-month fits to data, organized by geographic location, local time, season, solar and geomagnetic activity
  Bent* (1967), IRI-90*, PIM* (Parametrized Ionosphere Model)

- <u>Semi-empirical</u>
  a database of calculated ionosphere densities, adjusted by data
  PRISM* (Parametrized Real-Time Ionosphere Model)

- <u>Data-driven</u>
  interpolated measurements of total electron content
  GIM* (Global Ionospheric Maps)

<u>Question: What approach works "best"?</u>

*Running at JPL

Global Ionospheric Maps (GIM)

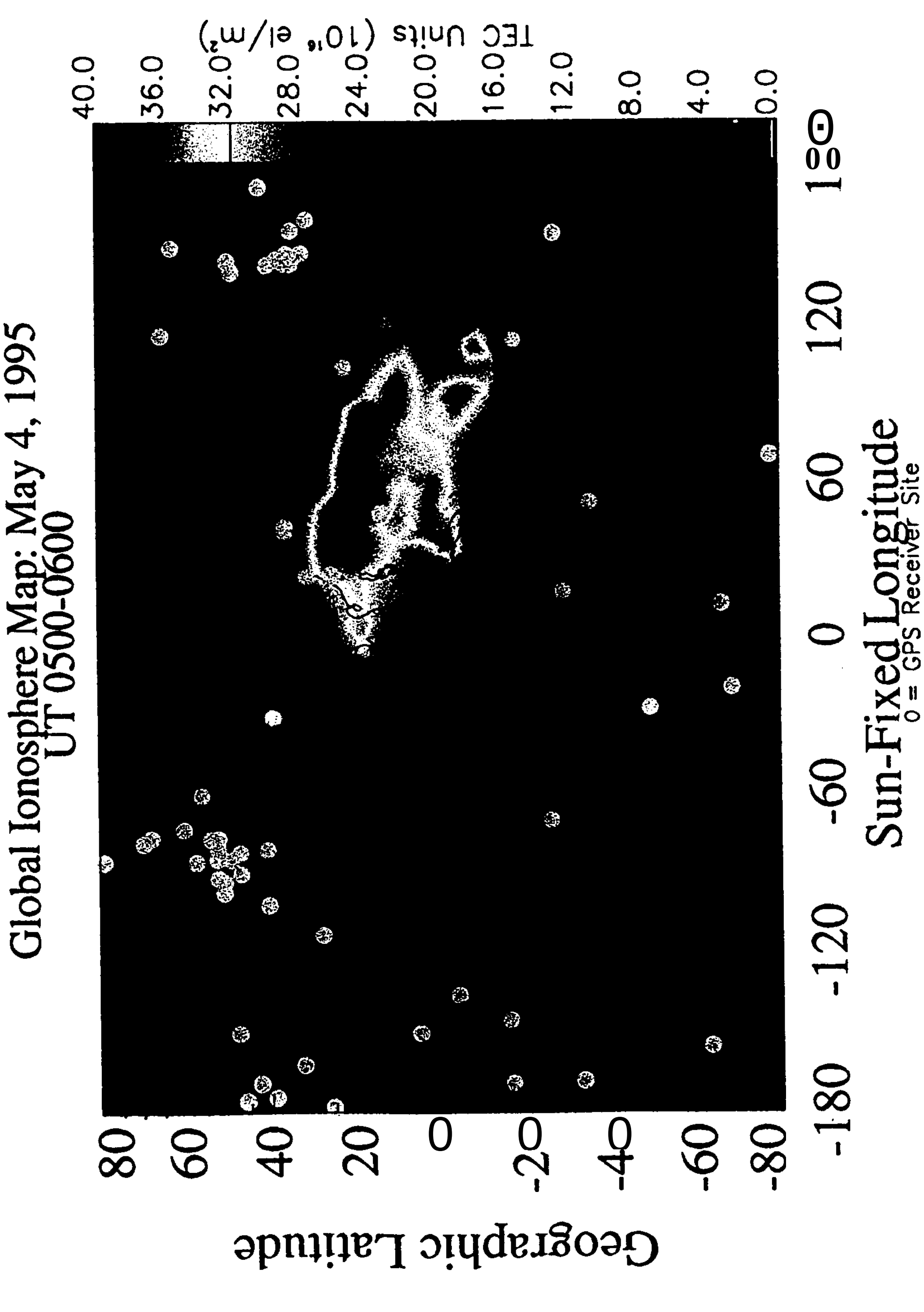
- Data-driven maps based on interpolating GPS TEC measurements on global scales.

- Maps are updated every few minutes to hourly
- Self-calibrating: simultaneously solve for inter-frequency biases
- Accuracy: 5-10 TECU globally

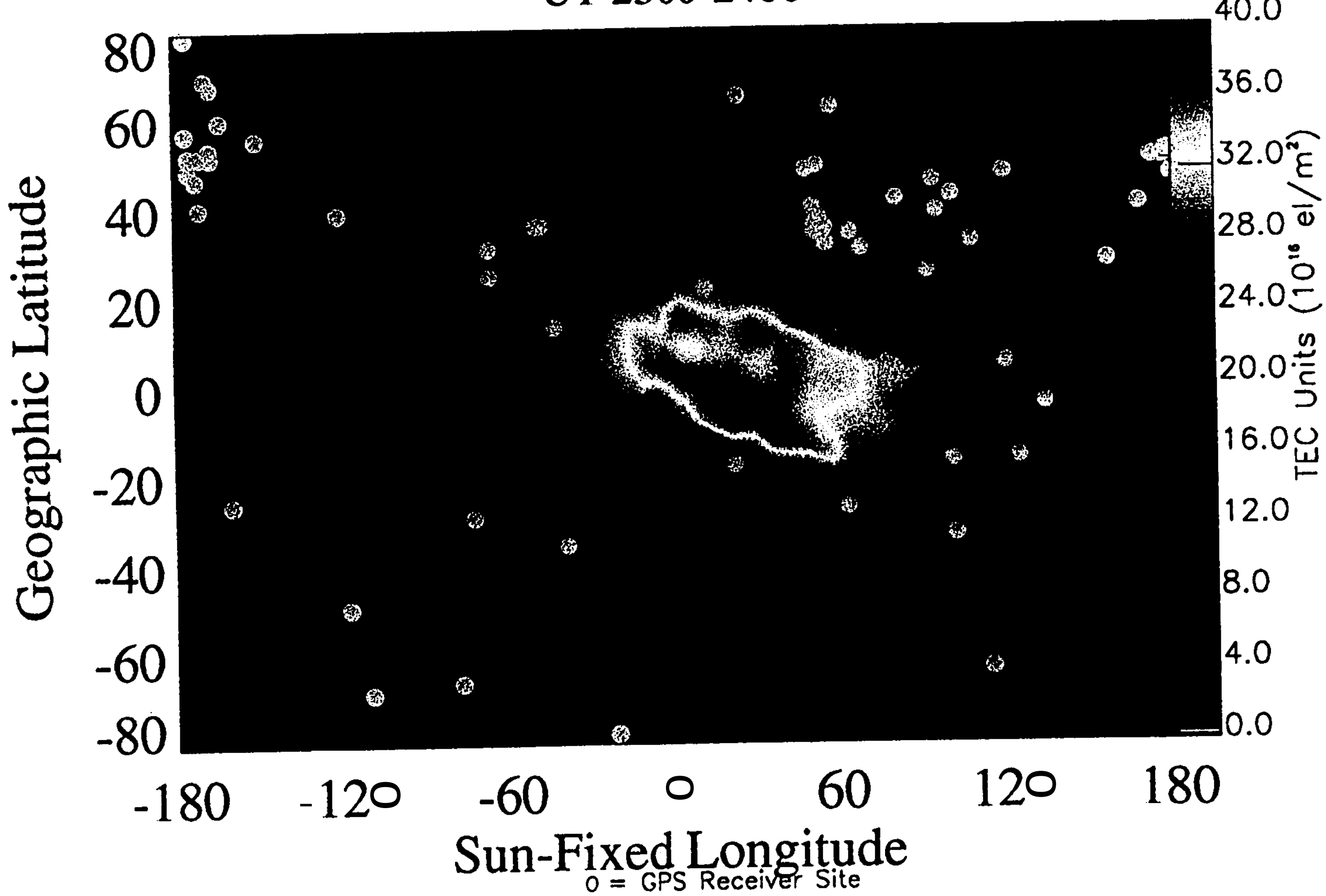
- A flexible scheme based on sequential Kalman filtering
- Grid-based approach
- Interpolation algorithm based on cubic splines (spherical geometry)
- Solar-geomagnetic reference frame

GIM combines data+ models with appropriate weighting:

- Climatological models can be used to initialize or aid the maps
- A priori model electron density profiles can be scaled to avoid scaling slant measurements to vertical


Global Ionosphere Map: May 4, 1995
UT 0500-0600
Geographic Latitude
80
60
40
20
0
-20
-40
-60
-80
-180
-120
-60
0
60
120
180
Sun-Fixed Longitude
0 = GPS Receiver Site
TEC Units (10¹⁶ el/m²)
40.0
36.0
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
0.0

Global Ionosphere Map: May 4, 1995
UT 2300-2400



Validation of Global Ionospheric Maps

<u>TEC model validation:</u>

- Extensive comparisons with vertical TEC data from the TOPEX dual-frequency altimeter.
- TOPEX (altitude 1330 km) is continuously operating and covers the latitude range 68S to 68N.”
- TOPEX accuracy is approximately 3 TECU.

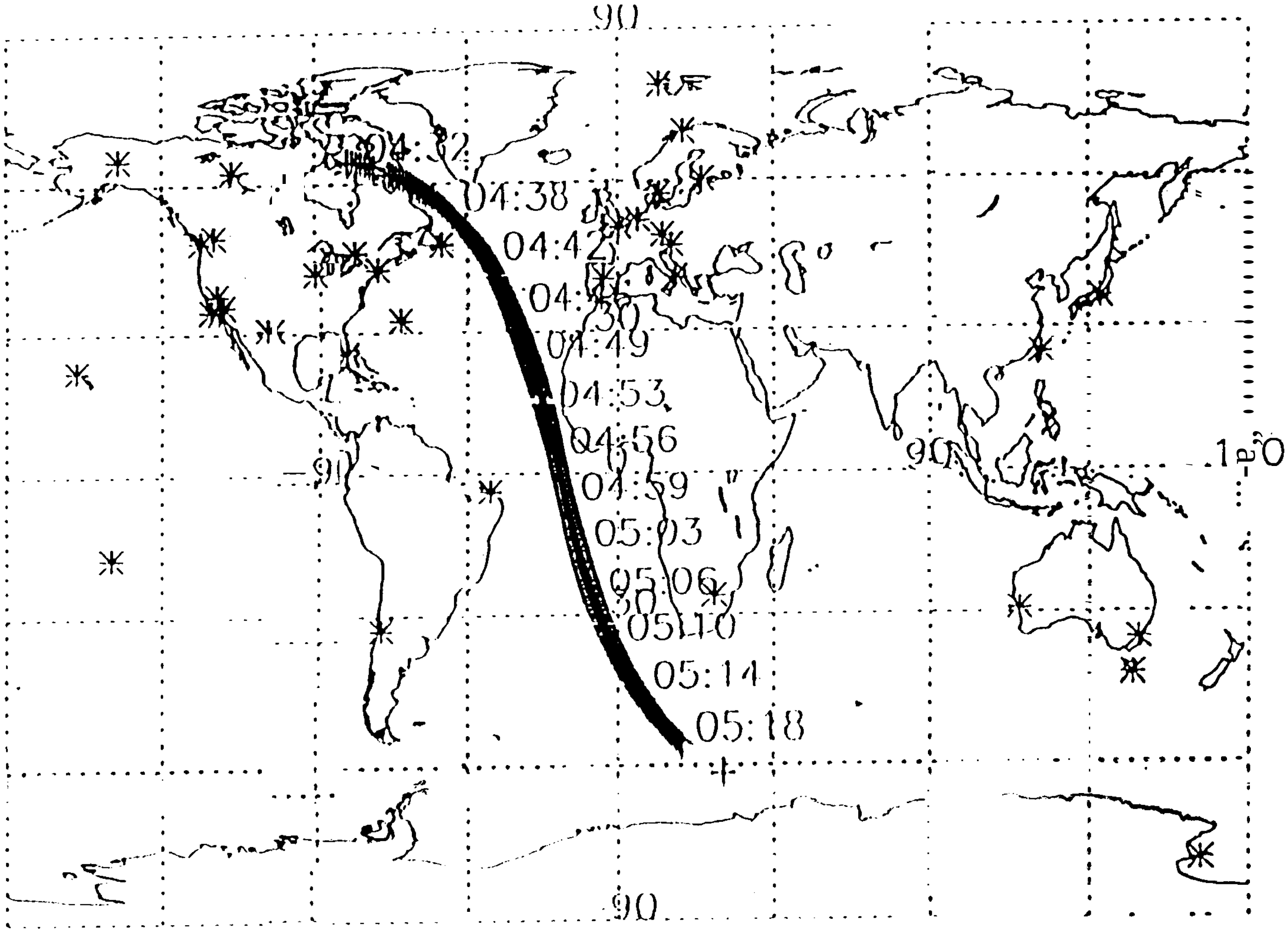
<u>Intra-ionospheric model validation:</u>

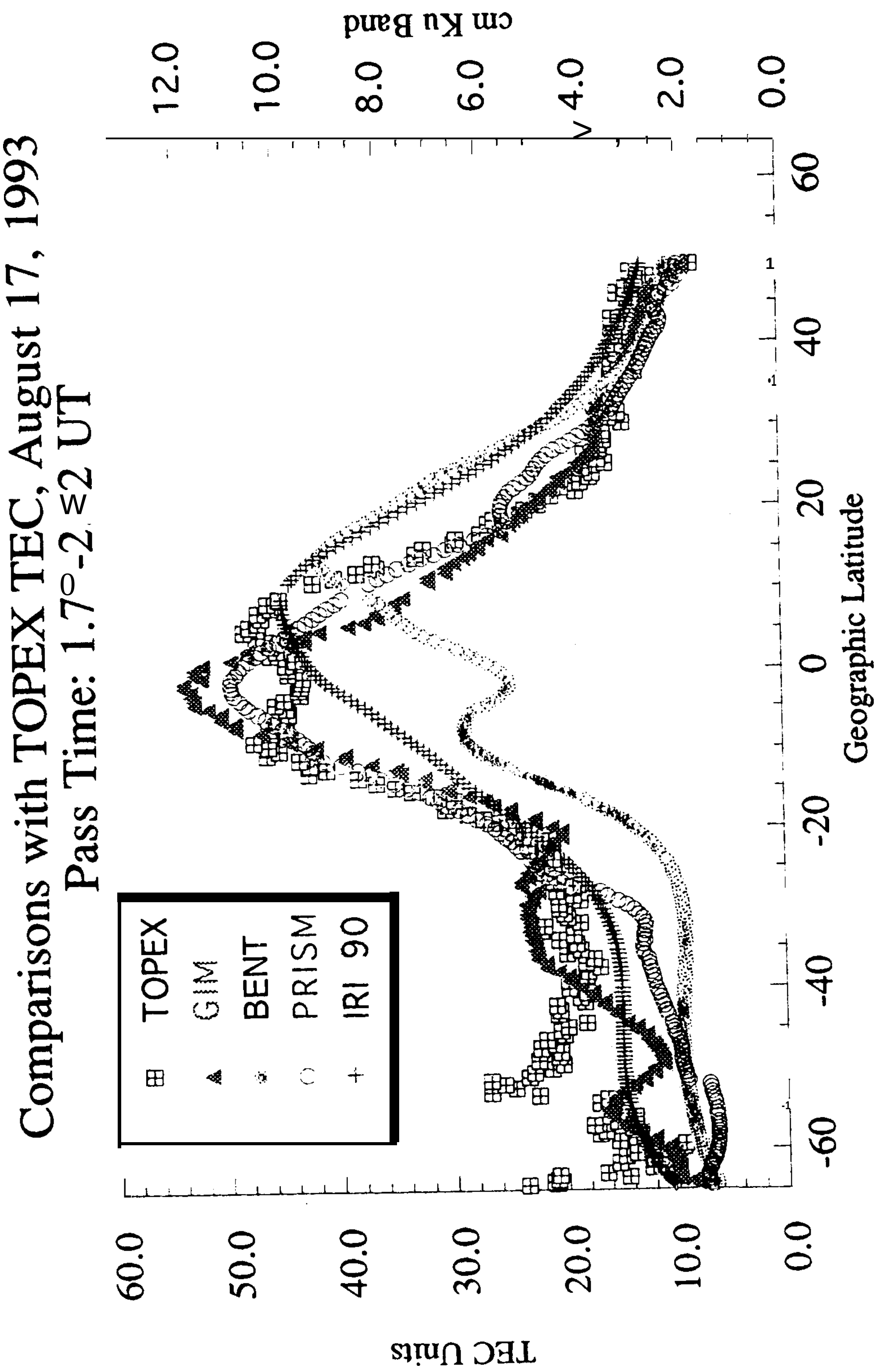
- LOS TEC from ALEXIS satellite (Los Alamos) orbiting at 800 km.
- Use GIM and Bent/IRI90 model info. to predict TEC below 800 km.
- Preliminary comparisons show 3–4 TECU agreement.

<u>Comparisons with GPS/MET:</u>

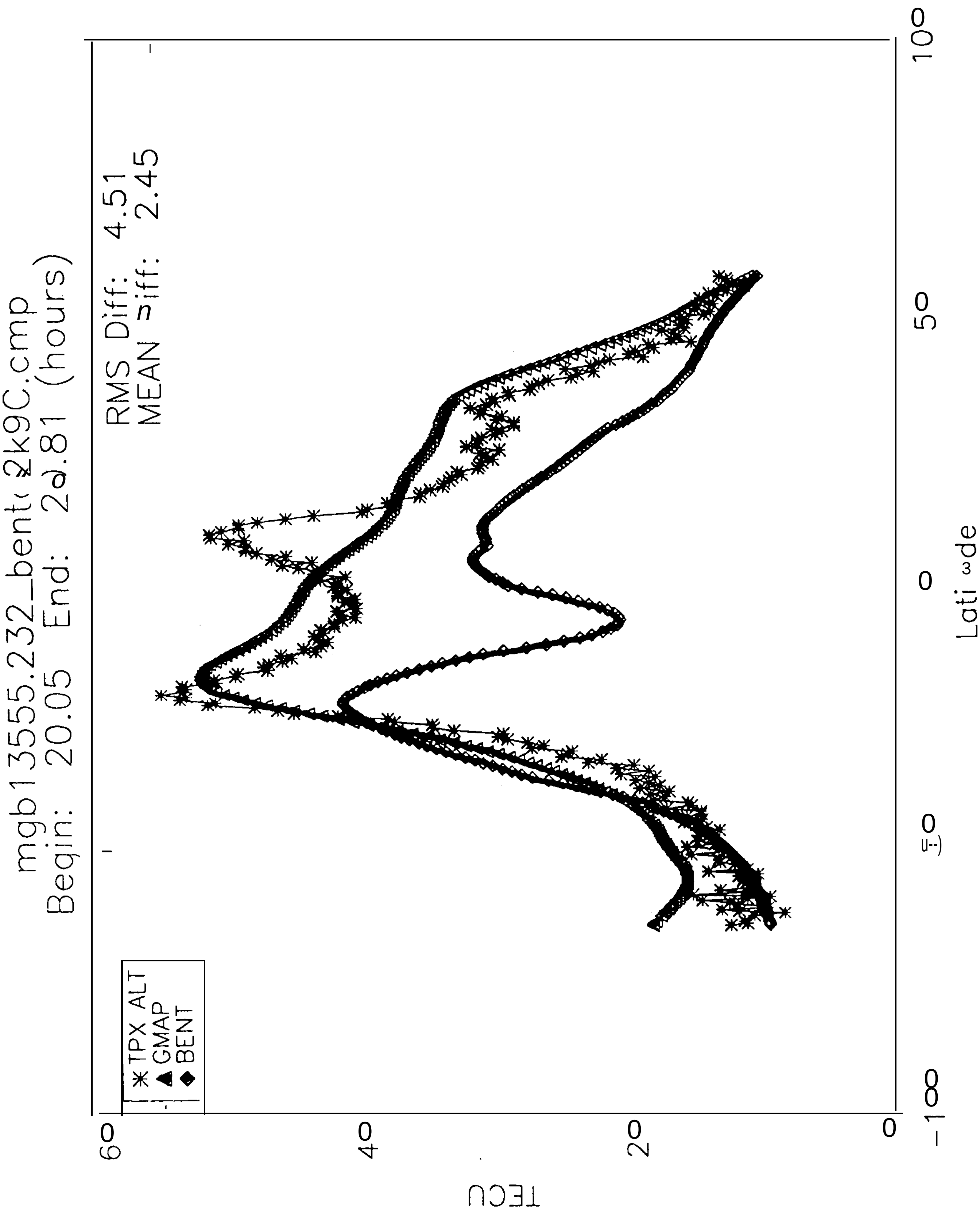
- TEC from GIM vs. integrated GPS/MET profile.
- Preliminary results show agreement to 2.3 TECU (RMS differences).

TOPEX Ground Track
August 17, 1993 — Pass 22
4.55-5.35 UT

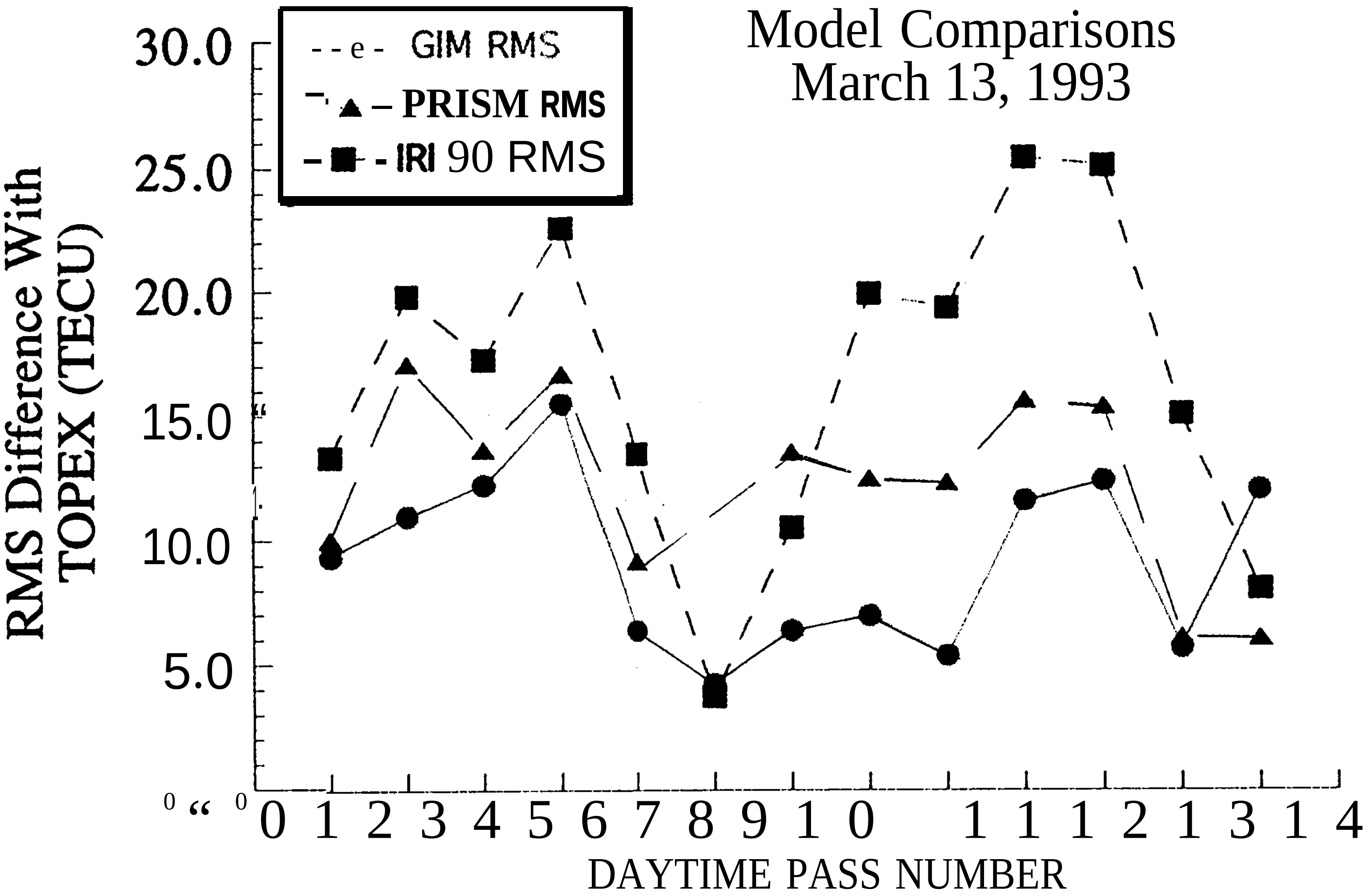




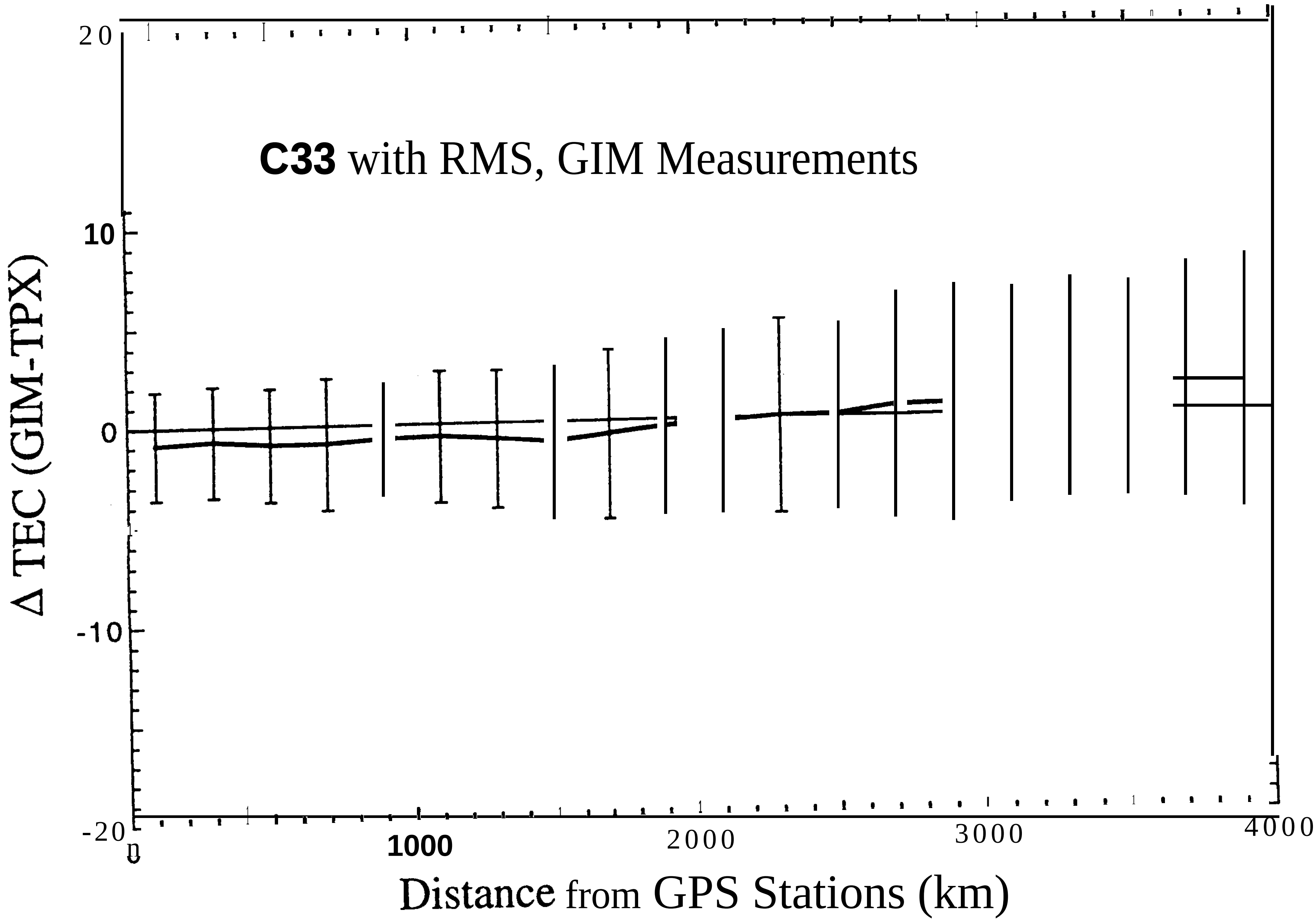
Comparisons with TOPEX TEC, August 17, 1993
Pass Time: 1.7°-2.2 UT
TOPEX
GIM
BENT
PRISM
IRI 90
TEC Units
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-60
-40
-20
0
20
40
60
Geographic Latitude
cm Ku Band
12.0
10.0
8.0
6.0
4.0
2.0
0.0

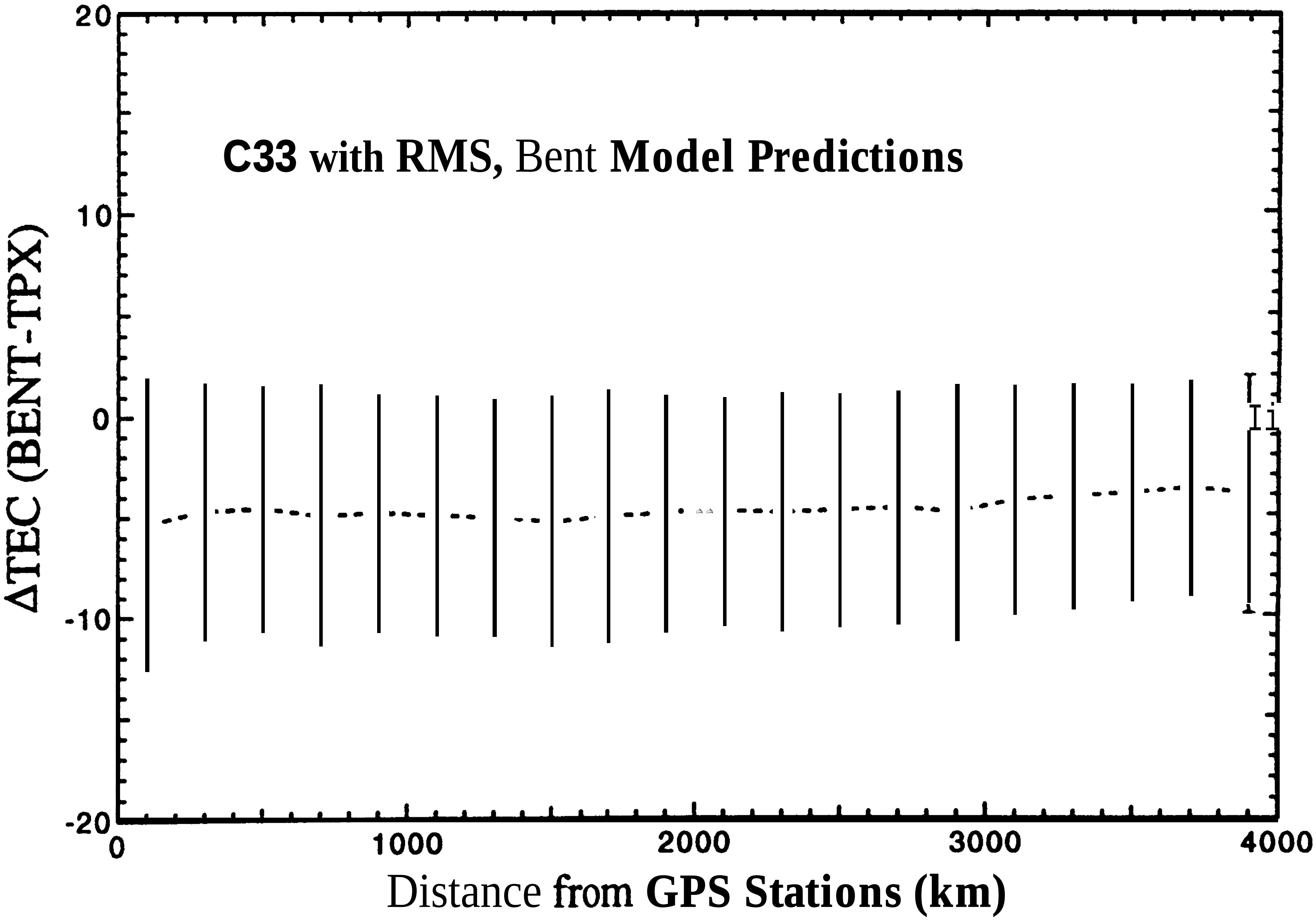


mgb13555.232_bent 2k9C.cmp
Begin: 20.05 End: 20.81 (hours)
RMS Diff: 4.51
MEAN Diff: 2.45
TPX ALT
GMAP
BENT
TECU
60
40
20
0
-100
50
0
50
100
Latitude



Model Comparisons
March 13, 1993
GIM RMS
PRISM RMS
IRI 90 RMS
RMS Difference With TOPEX (TECU)
30.0
25.0
20.0
15.0
10.0
5.0
0 1 2 3 4 5 6 7 8 9 1 0 1 1 1 2 1 3 1 4
DAYTIME PASS NUMBER


C33 with RMS, GIM Measurements
20
10
0
-10
-20
Δ TEC (GIM-TPX)
0
1000
2000
3000
4000
Distance from GPS Stations (km)

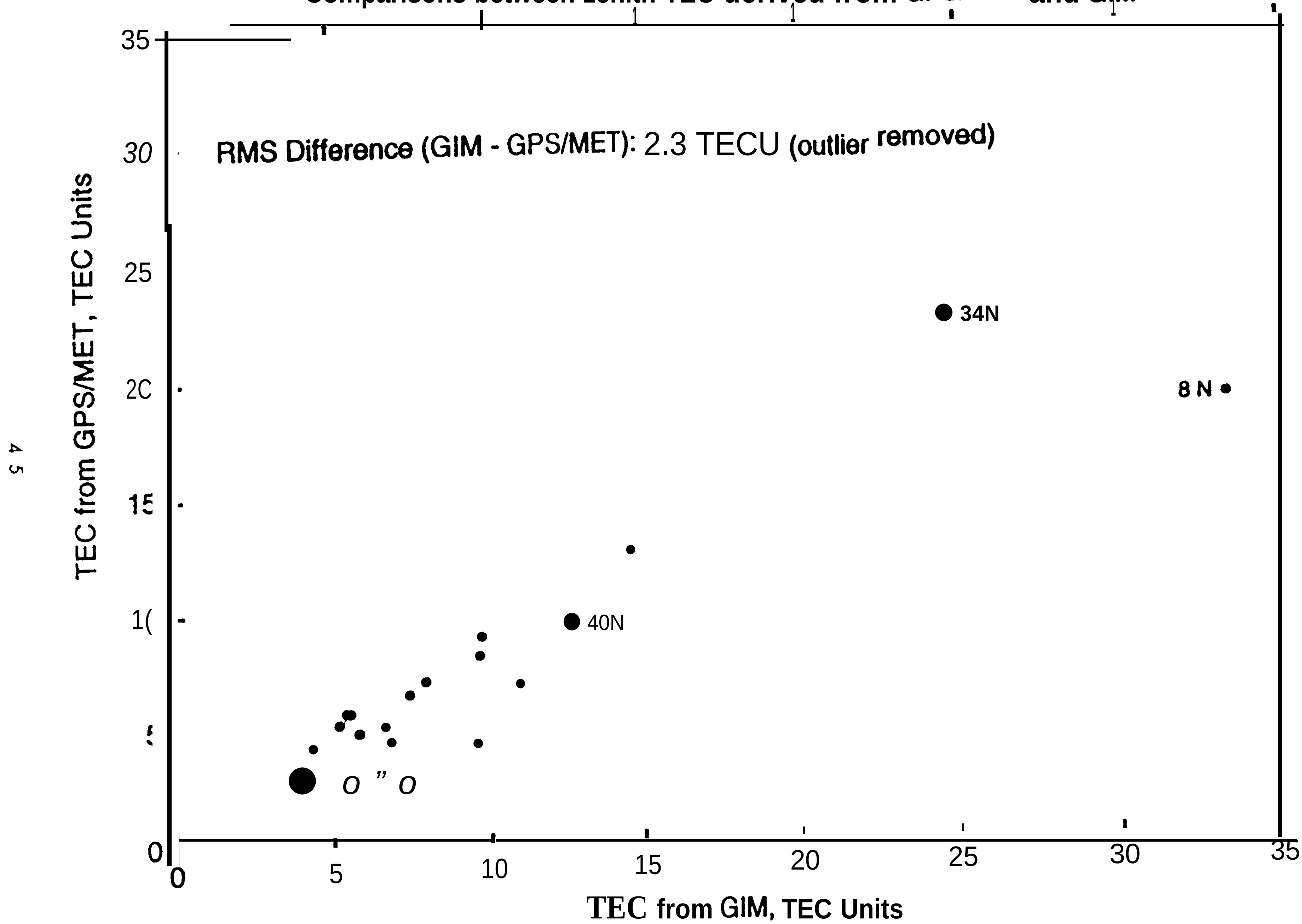

C33 with RMS, Bent Model Predictions
ΔTEC (BENT-TPX)
20
10
0
-10
-20
0
1000
2000
3000
4000
Distance from GPS Stations (km)

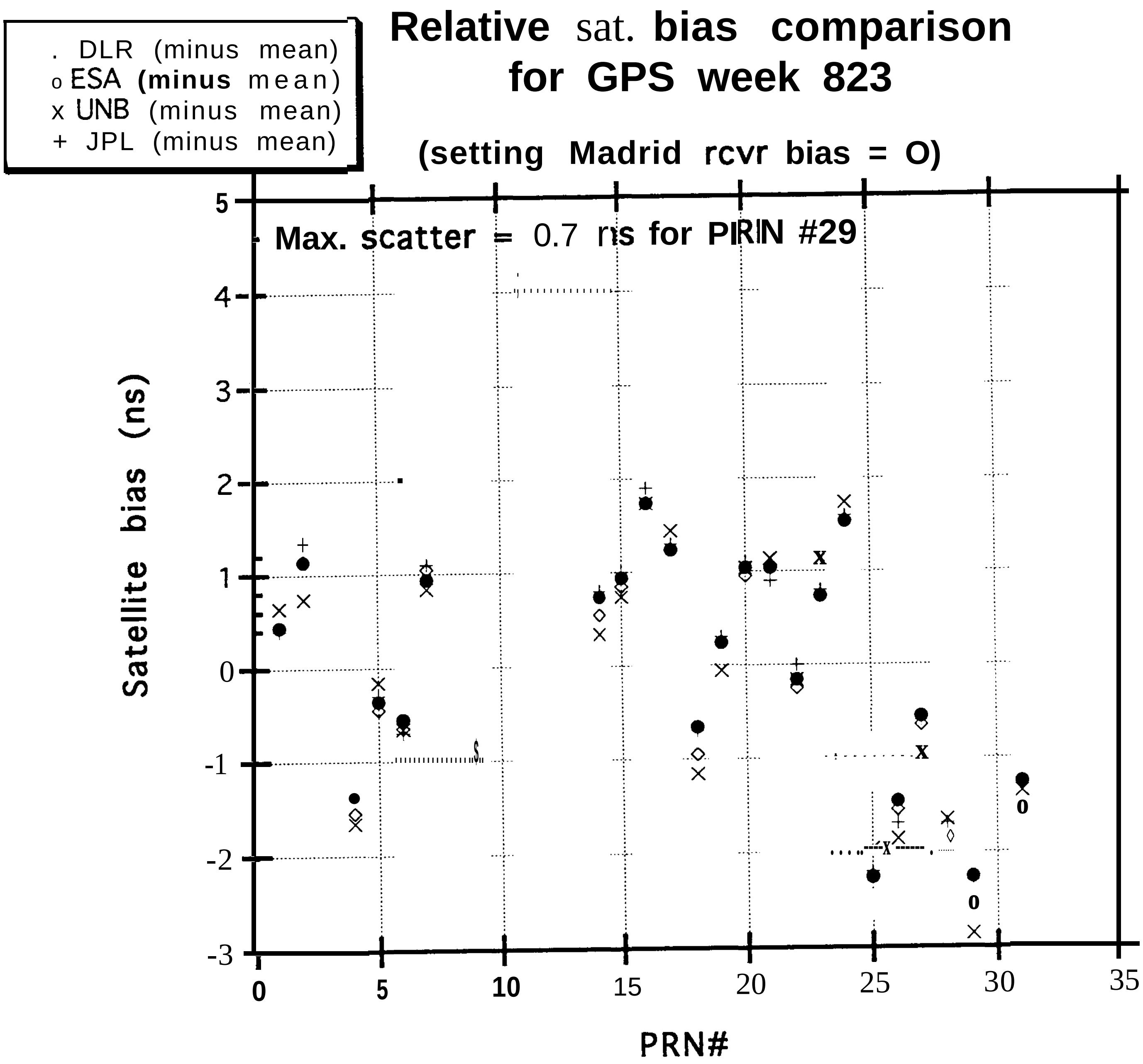
Models vs. TOPEX for NRT TEC Network

Geomagnetic Region	Model	# of Points	RMS Error (TECU)	% Improvement in Accuracy over Bent
ALL	Bent	[illegible]	8.0	—
ALL	PIM	5404	9.7	-9%
ALL	PRISM	5404	6.9	+22%
A[illegible]	GIM	[illegible]	6.1	+31%
LOW	Bent	[illegible]	[illegible]	—
LOW	PIM	[illegible]	11.7	-2%
LOW	PRISM	[illegible]	8.0	+30%
LOW	GIM	[illegible]	7.7	+33%
MID	B[illegible]	[illegible]08	6	—
MID	PIM	[illegible]	8.0	-31%
MID	PRISM	2089	6.0	+2%
MID	GIM	[illegible]	4.5	+26%
HIGH	Bent		6	—
HIGH	PIM	973	7.5	-12%
HIGH	PRISM	973	5.7	+15%
HIGH	GIM	[illegible]	4.8	+28%

- No data input: Bent & PIM.
- Global GPS input: GIM & PRISM.

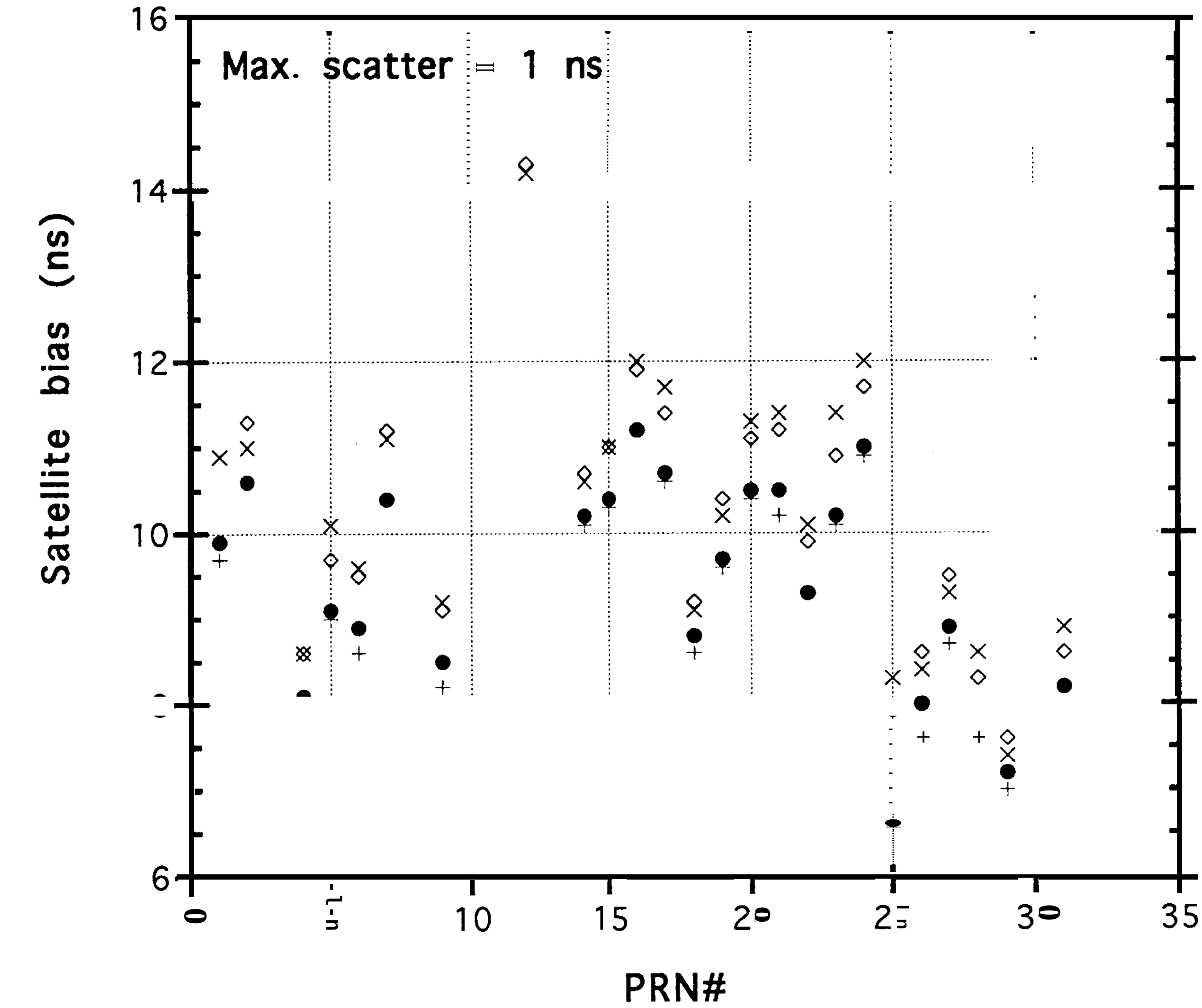
Comparisons between zenith TEC derived from GPS/MET and GIM




. DLR (minus mean)
o ESA (minus mean)
x UNB (minus mean)
+ JPL (minus mean)
Relative sat. bias comparison
for GPS week 823
(setting Madrid rcvr bias = O)
Max. scatter = 0.7 ns for PRN #29
Satellite bias (ns)
5
4
3
2
1
0
-1
-2
-3
0
5
10
15
20
25
30
35
PRN#

Satellite bias comparison for GPS week 823

(setting Madrid rcvr bias = 0)



Future Resources & Directions

- Resources:
  - Ever expanding ground-based GPS network.
  - Constellation of LEOS.

- Real-time GPS applications:
  - Real-time, globally-distributed TEC measurements.
  - Ionospheric storm monitoring/forecasting.
  - Real-time monitoring of GPS signal fading and other negative effects on GPS positioning & navigation.
  - Timely precipitable water vapor measurements => weather prediction.

- Improvements in GIM modeling:
  - Tailor fitting/parametrization strategy for specific applications.
  - Optimize use and adjustment of *a priori* electron density profiles.
  - Incorporate information from not just climatological models but also physical models into the mapping procedure.

- Ultimate goal: Recast a three-dimensional, physical ionosphere model into a form suitable for assimilating real-time ionospheric measurements from ground and space-borne GPS receivers, ionosondes, top-side sounders, DMSP, other satellites, etc.

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The Potential Use of GPS/Met in

Operational Numerical Weather prediction

Ronald D. McPherson

March 11,1996

Eugenia Kalnay

Steve Lord

Environmental Modeling Center

Outline

- Existing data base for operational NWP
  - Sources
  - Coverage
  - Gaps
- Recent advances in data assimilation
  - Direct assimilation of observed parameters
  - Use of ensembles for Adaptive Observing Systems
- Potential role for GPS/Met
  - Good news
  - Bad (?) news
  - Recommendation

Numerical Weather Prediction

The forecast skill has more than doubled since the 1970's:

- Today's 3-day forecasts are better than the 1-2 day forecasts in 1980

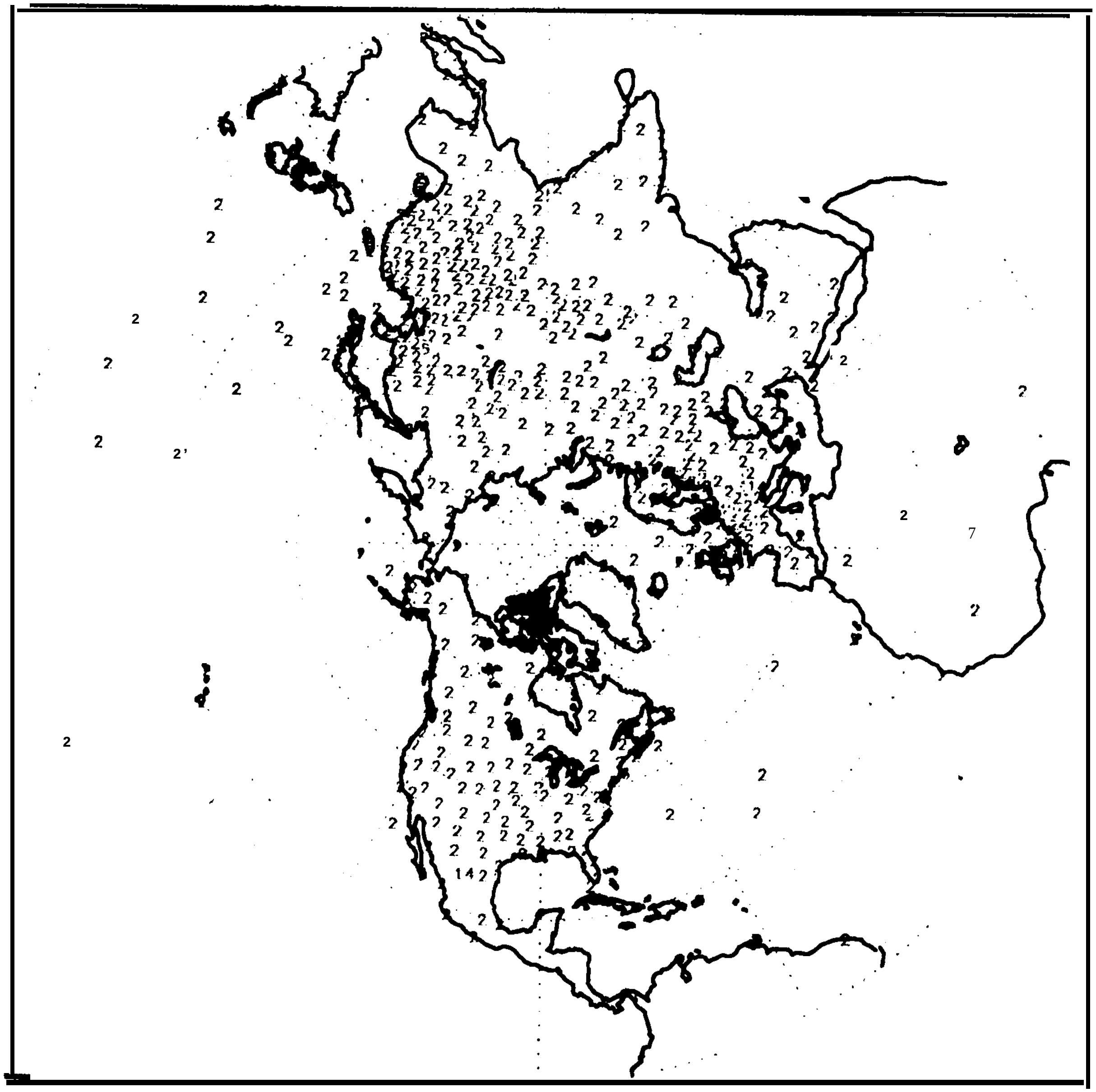
- This winter, for the first time, the 5-day forecast had an anomaly correlation with the "truth" (analysis) of 82%!

- Some winter storms are now predicted by the NWS one week in advance

Current Sources of Observations

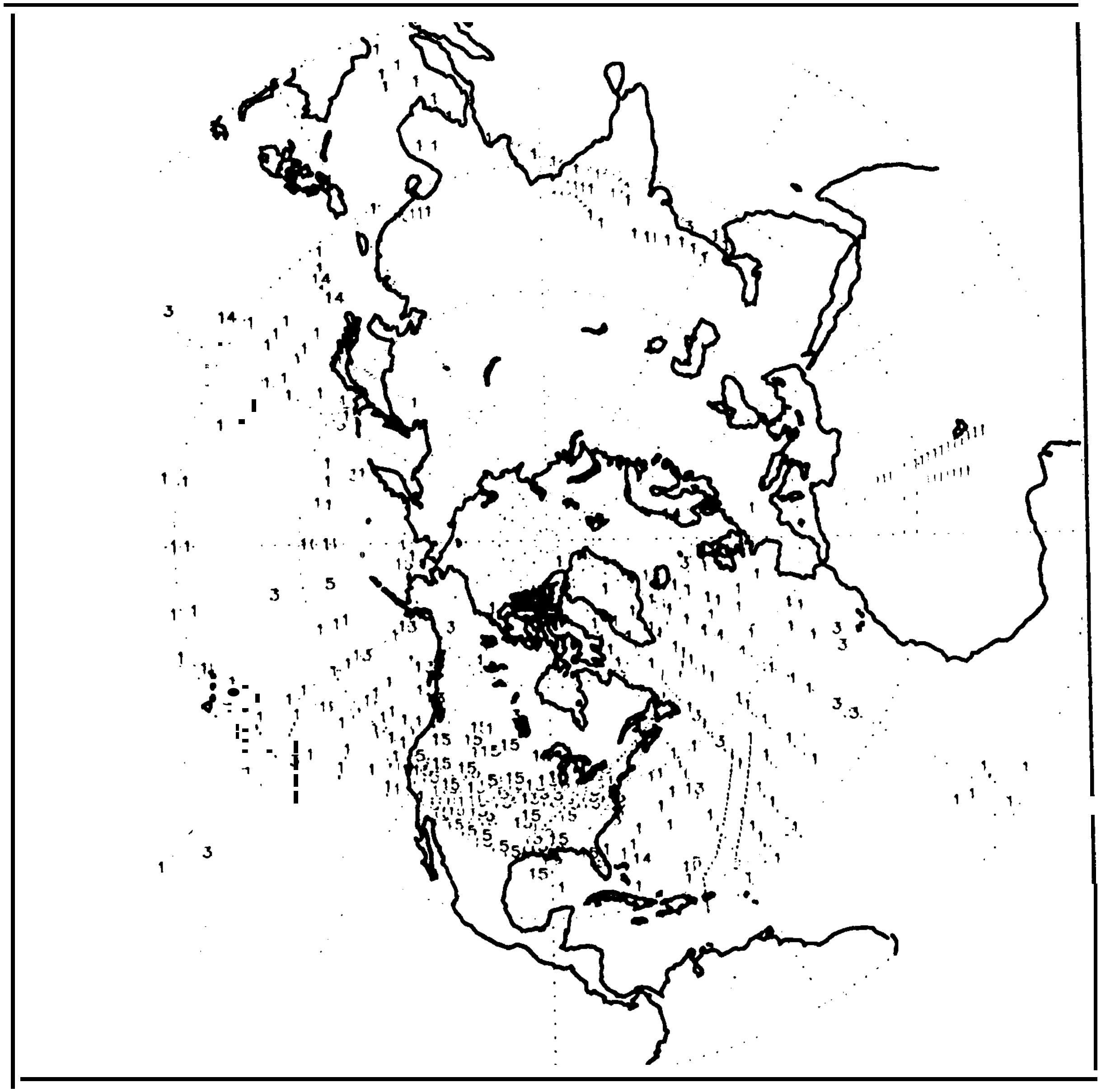
Radiosonde network
Polar orbiters
Geostationary satellites
Aircraft
Profilers
Radars
Surface stations
ships
Buoys

upa obs OOZ26FEB1996



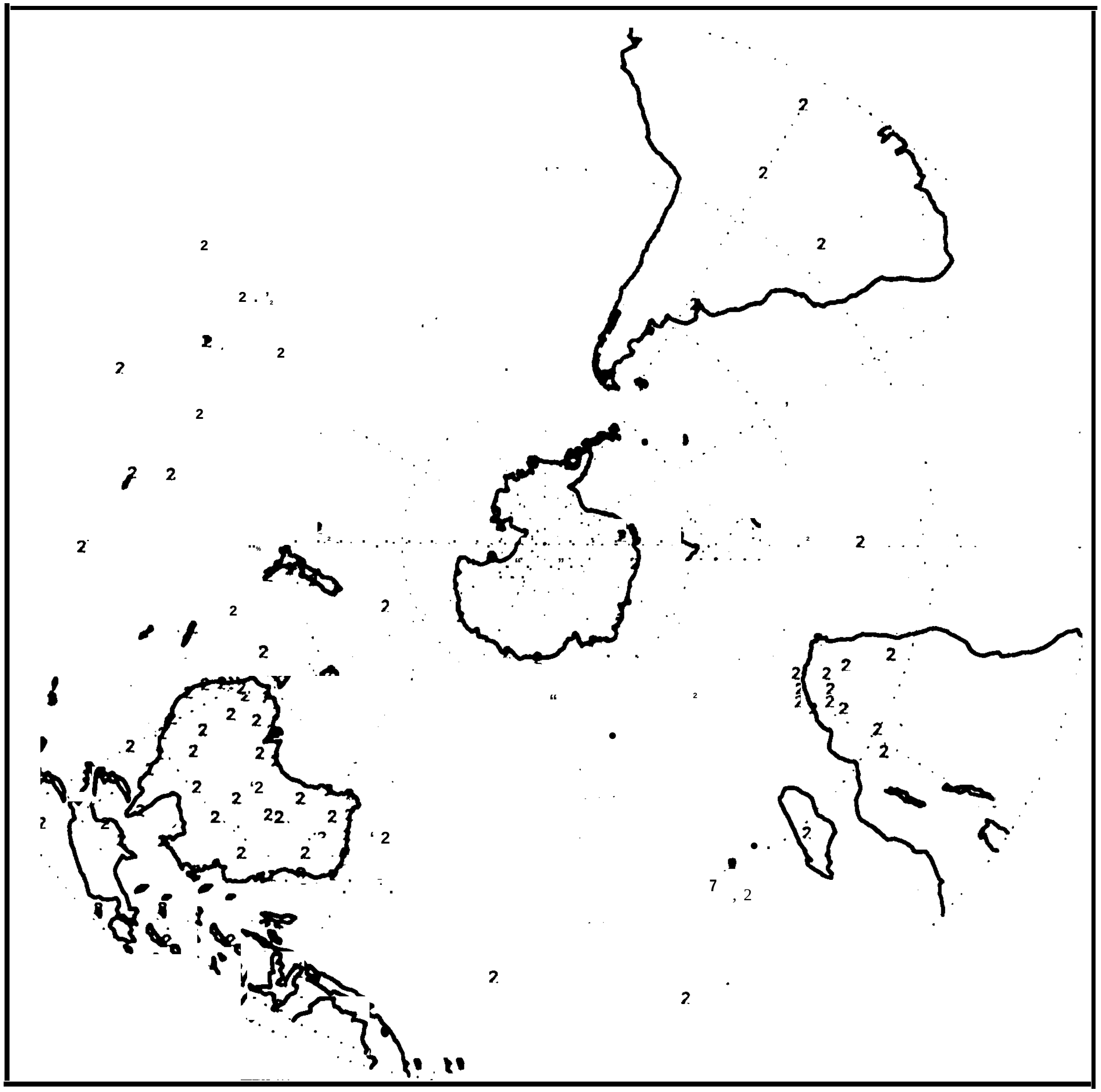
(500-500) NOBS=567 for WIND

acft obs 00Z26FEB199W

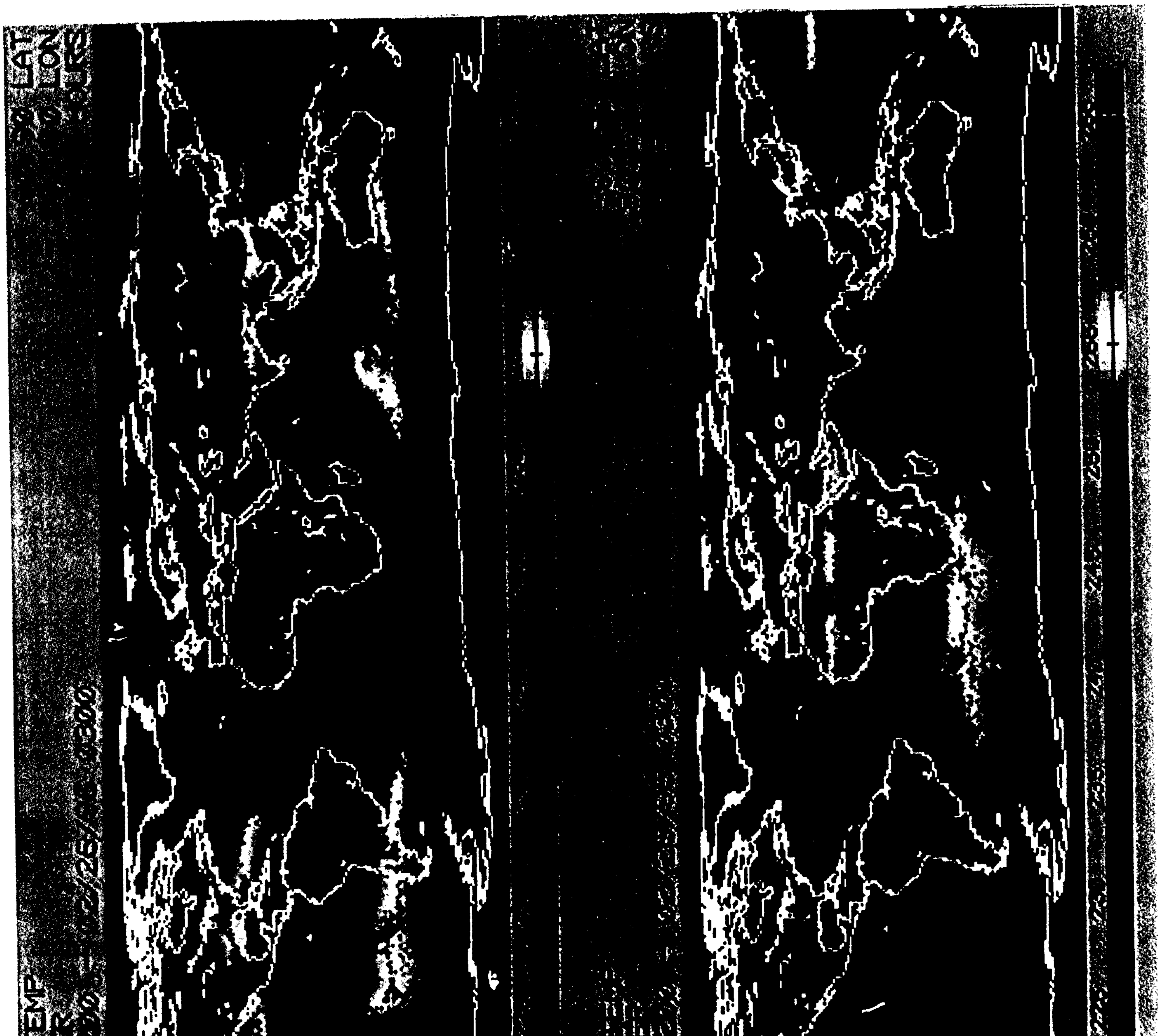


(200–350) NOBS=1175 for WIND

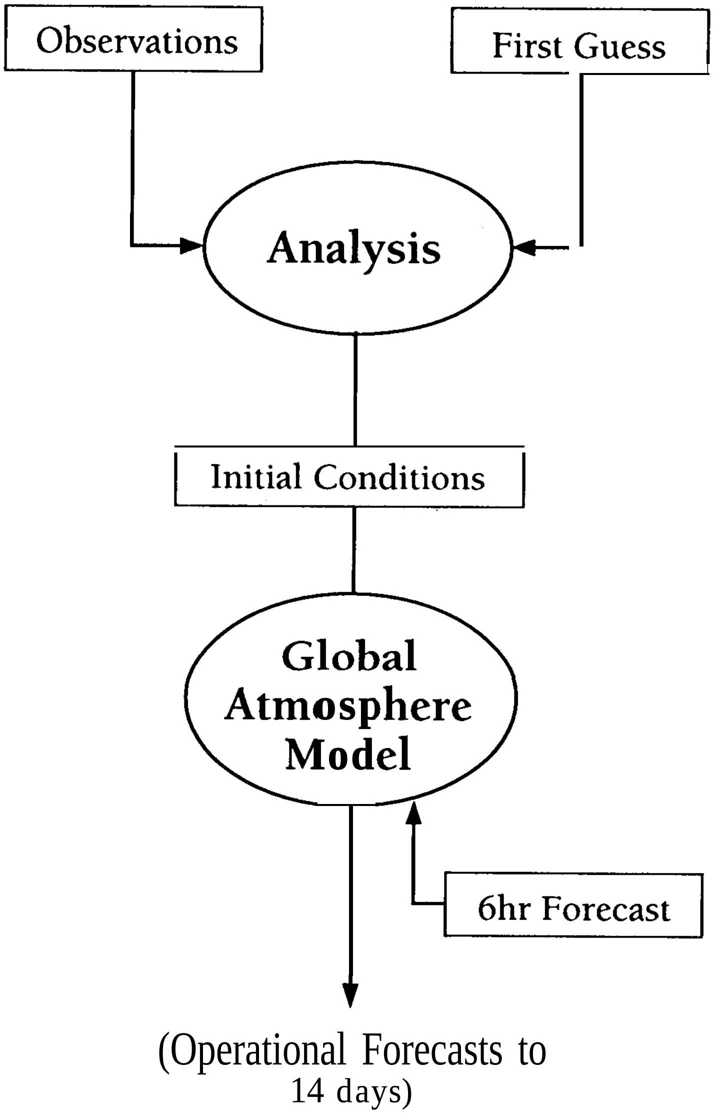
upa obs OOZ26FEB1996



(500-500) NOBS=106 for WIND


MSU CH. 2 BTEMP
NOAA-12 OPER

4-dim Data Assimilation



Analysis x has to be

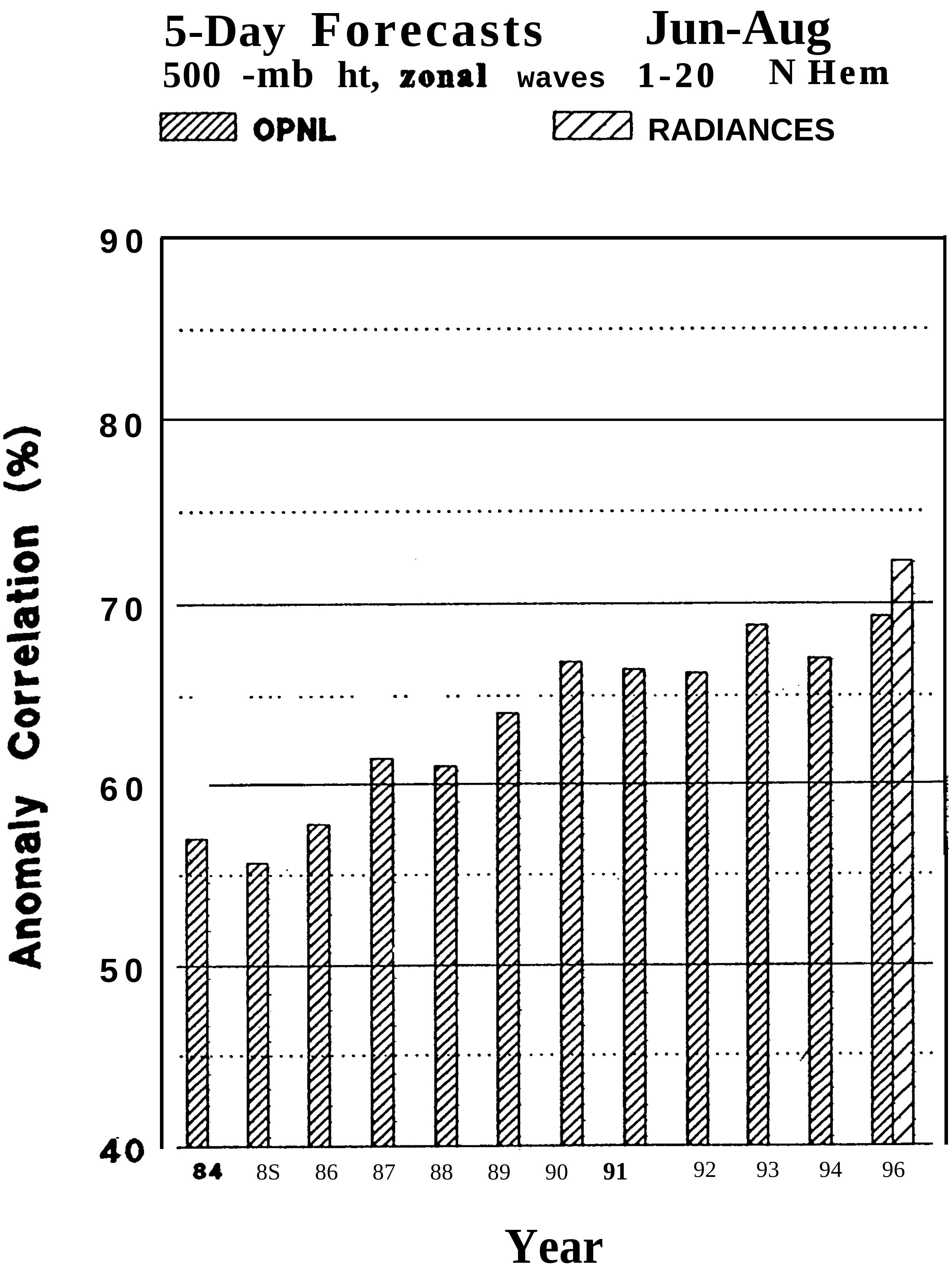
- **very close to observations y**
- **very close to 6hr forecast X_b**

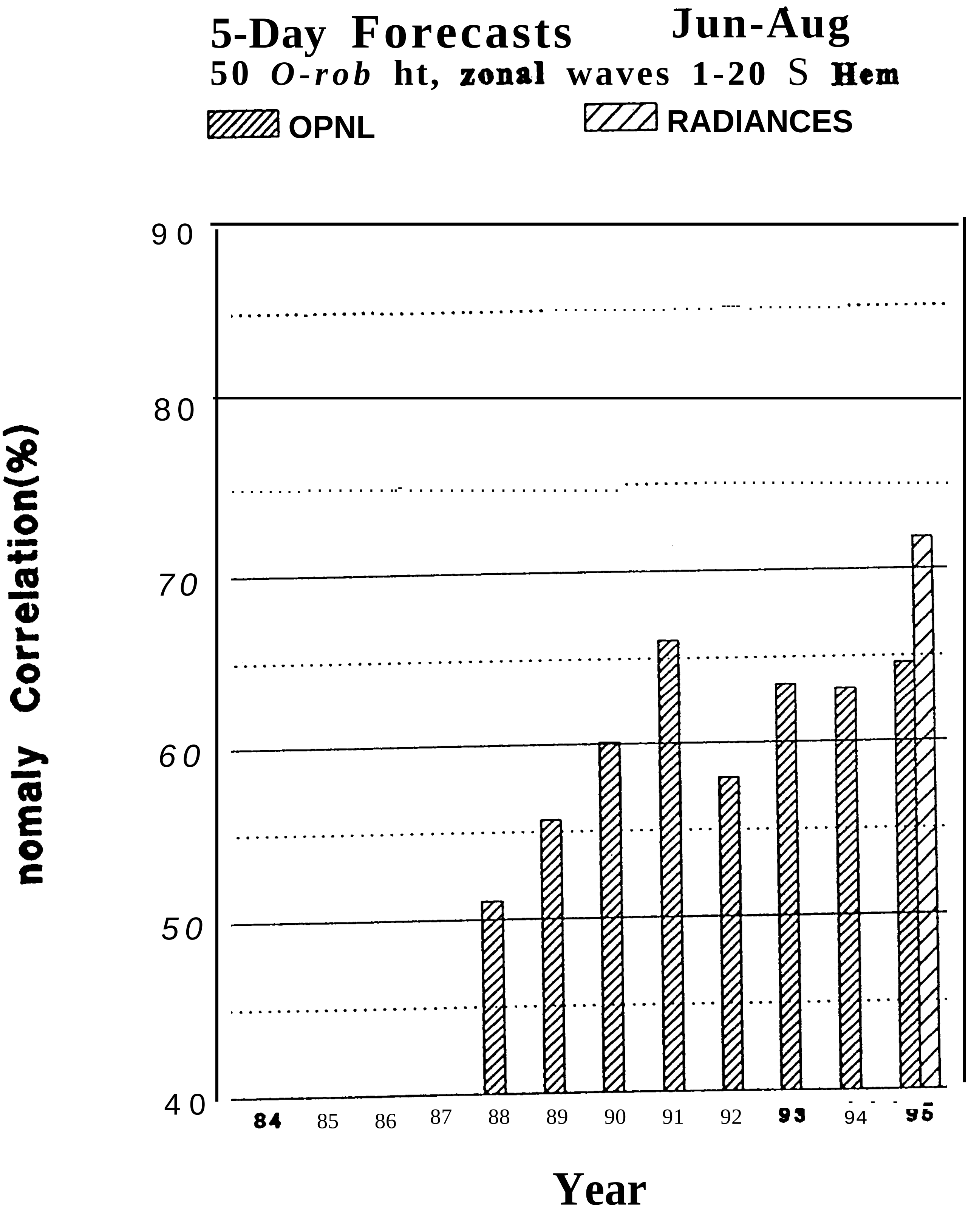
min J = distance (x,y) + distance(x,x_b)(x)

The model variables are temp t, winds, moisture q and pressure.

Remote measurements are radiances, refractivities

- **We used to convert the sat. ohs. of radiances into atm. temperature t and humidity q soundings: satellite retrievals**
- **We now convert the model t and q into satellite radiances**
- **The direct assimilation of TOVS radiances has been the largest single improvement in the last decade**
- **For the first time, satellite data are clearly improving the NH forecasts (17 years after TIROS N)**


5-Day Forecasts Jun-Aug
500 -mb ht, zonal waves 1-20 N Hem
OPNL
RADIANCES
90
80
70
60
50
40
Anomaly Correlation (%)
84
8S
86
87
88
89
90
91
92
93
94
96
Year


5-Day Forecasts Jun-Aug
50 O-rob ht, zonal waves 1-20 S Hem
OPNL
RADIANCES
nomaly Correlation(%)
90
80
70
60
50
40
84
85
86
87
88
89
90
91
92
93
94
95
Year

Analysis theory

The global analysis system produces an analysis through the minimization of an objective function given by

$$J = (x-x_b)^T B^{-1}(x - x_b) + (K(x) - y)^T O^{-1}(K(x) - y) + J_c$$

where

x is the analysis variable,

x_b is the background field (a 6 hour forecast),

B is the back ground error covariance matrix,

y is a vector of all the observations,

O is the observational error covariance matrix,

K is the transforrnation operator from the analysis variable to the form of the observation vector

J_c is a dynamical constraint term

Goal: Adjusts the analysis to fit the information in the data.

The K operator for the refractivity data represents the transformation of the analysis variables(T, q, p) to refractivity.

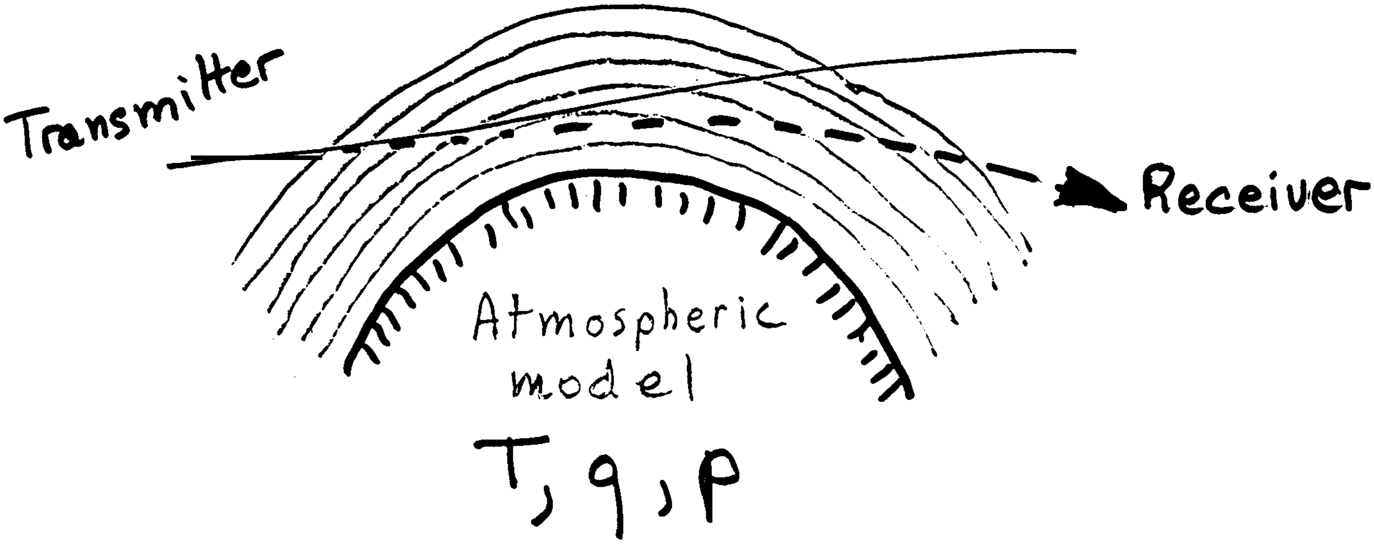
required tools for minimization:

full forward operator

tangent linear model (TGL) of the forward operator

the adjoint of TGL

For refraction angle data, forward ray-tracing its TGL and adjoint are needed



- We need a ray tracing model for GTS-MET
- Also a linear tangent (perturbation) model and its adjoint
- They need to be accurate and if possible efficient

Principal Gaps in the Existing Observing System

- Wind profiles over ocean areas
- Moisture profiles

Potential Role for GPS/Met

- Good News:

  In modem data assimilation technology, a framework exists within which GPS/Met data can be used effectively, with a relatively short learning period.

- Bad (?) News:

  Any new observing system must compete with existing observing systems, and that field is not uncrowded.

- Recommendation for GPS/Met:

  Aim at:

  Either fill a known "gap" in the current observing system.

  or

  Provide cheaper and/or better data than the current system provides.

Message-ID: <9603130956.AA17430@kora.nz.dlr.de>
Date : Wed, 13 Mar 1996 10:56:02+0100
From: Esther Sardon <sardon@NZ.DLR.DE>
Subject: DLR-Neustrelitz comments over ionospheric IGS products
To: Multiple recipients of list GPS-IONO <GPS-IONO@LISTSERV.UNB.CA>

Dear colleagues,

As I wrote two weeks ago, unfortunately nobody from DLR-Neustrelitz will take part in the next IGS meeting. But we are very interested in the collaboration with the other groups and in the discussion over ionospheric IGS products.

These are our comments to the questions that Feltens proposed at the end of his position paper:

DLR COMMENTS FOR THE DISCUSSION OVER IONOSPHERIC IGS PRODUCTS
---- ----------------------- --------- -------- ----- ---- ---- ---

0. General comment

To use "ionospheric models" for the possible IGS ionospheric products can create confusion, because we will not make a "model" like IRI, Bent, etc.. but we will provide TEC data, as a set of grid points or as a set of coefficients.
We propose to use the expresion "TEC mapping" or "ionospheric TEC information" instead of '#ionosphere models".

1. Potential users:

In general, we can distinguish two kinds of potential users for the ionospheric IGS products: single frequency users (GPS and other techniques) and scientists interested in ionospheric studies. But, dependinq on the time delay allowed by the users, we see the following groups:

- Navigation: real-time ionospheric corrections
- Radio communication: real-time ionospheric conditions
- Surveying: precise ionospheric corrections (within few days)
- Ionospheric physics: high accuracy VTEC/profiles/gradients (within weeks)
- others (radioastronomy, altimetry, etc..)

For these ionospheric products, in the near future, the navigation group can become the biggest group of users, and we should take it into account.

2. Possible products

The main IGS ionospheric product should be TEC values. They can be provided as TEC maps, but also a set of coefficients can be used to describe the ionospheric behaviour. The TEC maps are, in principle, easier to use than a set of coefficients because no knowledge about the used reference frame is needed. We propose to distribute the TEC information through maps.

Depending on the application we can think in users of global, regional and local ionospheric information. These three kind of maps should be provided, specifying in each case the level of accuracy.

In principle, the differential delays are only of interest for the people using GPS to derive TEC values. In the first step, we should not provide this information (maybe only upon request). But futher work of internal comparisons to obtain reliable sets of biases must continue.

3. Delay in providing the products

So far, using IGS data, we can only provide ionospheric products obtained in post-processing. That means 1 or 2 days of delay as minimum. This should be enough for some applications, but others (mainly navigation and radio communication) need, at least, near real-time ionospheric information. For post-processed products we propose a maximum delay of one week.

In DLR-Neustrelitz we have developed a system for real-time estimation of TEC, that could be applied to the IGS stations. For that real-time estimation, a data rate higher than 30 seconds is convenient. We propose a campaign for testing the real-time estimation of TEC with IGS data, consisting of two steps:

a) real-time simulations:
   that means to operate a reduced number (5 or 6) of IGS stations with higher data rate (10 seconds) in a certain region (for example, Europe) and to process the data at DLR-Neustrelitz using the real-time algorithms

b) real-time connections:
   that means to implement a real-time connection between such a small sub-net to demonstrate the capabilities.

4. Time intervals of update:

For the methods of TEC estimation using a Kalman filter, it is very easy to change the update rate, and mada it as high as the data rate (30 seconds). But in this case we will generate rather large files that will contain "redundant" information in case of quiet ionospheric days. In our comparisons we have used 1 hour update rate, but in this time the ionosphere can change quite a lot, mainly at low latitudes or during quite perturbed days. We propose a maximum update rate of 10 minutes.

Other methods, based on spherical harmonics or batch analysis for example, estimate a set of coefficients describing the ionosphere that are "valid" for a certain period (normally several hours) . In this case, to use a high update rate means to repeat the same information several times.

We can provide highly update (10 minutes) REGIONAL and LOCAL TEC information and keep hourly or lower updated TEC information for GLOBAL maps.

5. Which mathematical models:

Possible mathematical representaions of the ionosphere are:

- Spherical harmonics: good global representation method.

- Kalman filter: good local representations. Possibly applicable to global grids as well. The model can be auto-improved from the accumulated information over gradients or stochastic variations.

- Batch analysis with low order polynomials: subject to errors due to unaccounted variations of the ionosphere.

Based also on point 4, we propose to use Kalman filter approaches for regional and local TEC maps and spherical harmonics and tesselation into spherical trianges for global TEC maps.

6. Reference frame definition

For comparison and for users application, geographical frames are preferable.

For model development, any other frame may be chosen, but that should be probably irrelevant, except if detailed comparisons (deep to the code) are intended.

7. IGS format

We support the idea of using the IONEX format, similar to RINEX format, to provide VTEC maps in the form of grid data.

8. Next steps

Complete the comparison between different groups and evaluate the internal precision/accuracy of the work. Validation of the TEC products with independent measurements of equivalent parameters should be continued, especially in high and low latitudes.

Define requirements for each product and responsibilities for the analysis centers. Depending on experience and interests, different centers could offer different products. For example, DLR-Neustrelitz is ready to provide regional European TEC maps in the frame of IGS work, and test the extension towards real-time ionospheric products.

Best regards,

Esther Sardon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.................................  ...............................
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  DLR Fernerkundungsstation Neustrelitz        FAX:   +49 3981 480299 .
  Kalkhorstweg 53
  D-17235 Neustrelitz                       e-mail : sardon@nz.dlr.de .
  Germany
.................................................................
```


End of Message


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=================== REST OF RFC822 HEADER =============================

Received: from esoc.esa.de by VMPROFS .ESOC.ESA.DE (IBM VM SMTP V2R2) with TCP;
   Wed , 13 Mar 96 11:13:31 EWT
Received: by esoc.esa.de (8.6.12/ESARLYl.8)
 id KAA02853; Wed, 13 Mar 1996 10:14:58 GMT
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 SMTP id <14.6BB1A9FE@listserv.gmd de>; Wed, 13 Mar 1996 11:12:24 +0100
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 Sender: GPS for Ionospheric research <GPS-IONO@LISTSERV.UNB .CA>
```

GPS Orbit Determination Including Various Adjustments

G O D I V A

C. Goad, A. Mueller

HARD WARE/SOFTWARE CONFIGURA TION

***P* 90**
Windows NT
Microsoft NT Fortran

An automated procedure for generating an optimum set of linearly independent ion-free triple differences according to C. C'. Goad and A. Mueller (19SS)

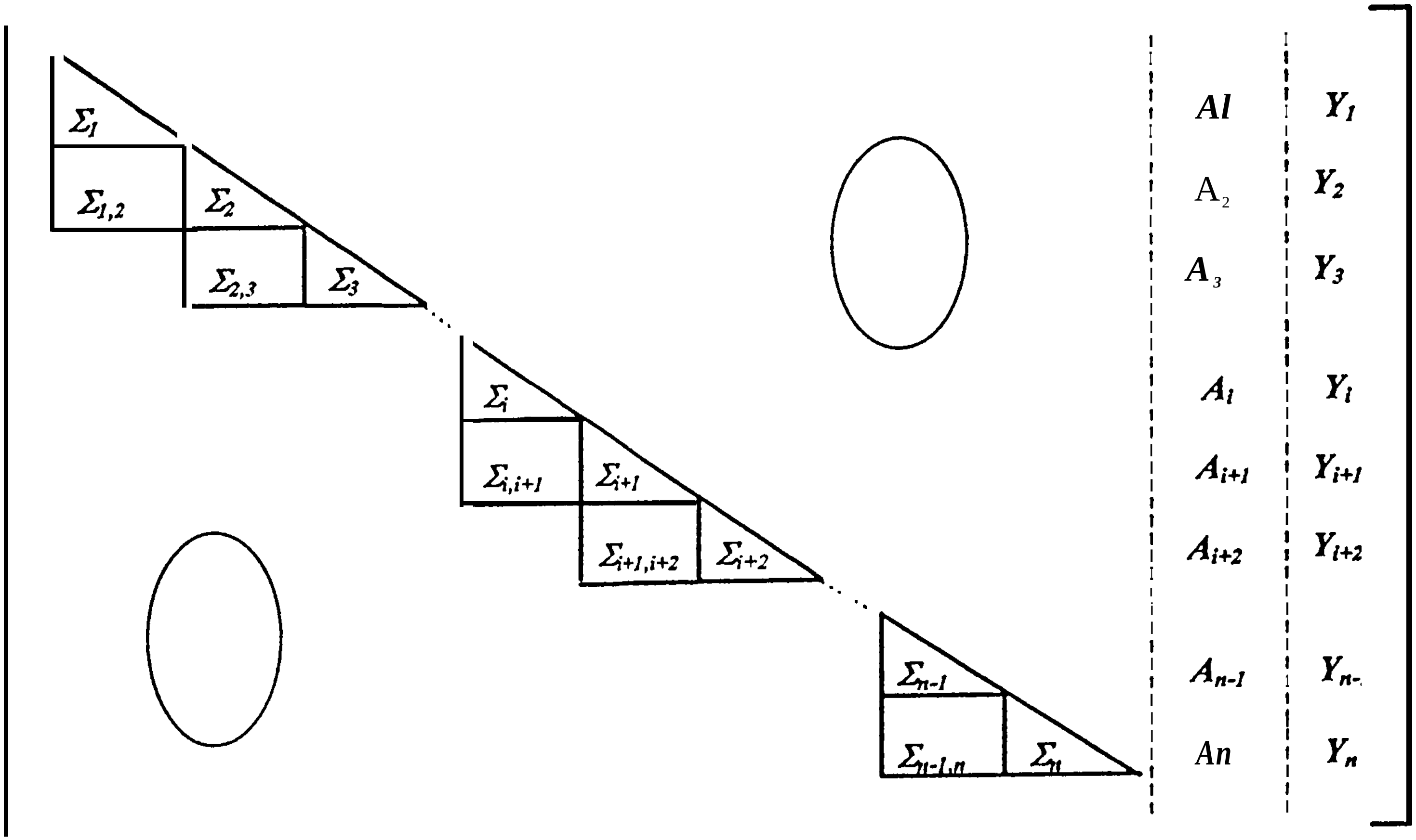
- *the Cholesky decomposition of the covariance matrix of the triple differences is performed*

- *the linear dependency between the measurements is revealed by displaying a zero diagonal element on the corresponding position in the Cholesky factor*

- *allows access to 100% of linearly independent information*

- *single precision operation is OKfor this task (fast !)*

The decorrelation scheme using Cholesky decomposition of the covariance matrix



Application of Triple Difference

Advantage: *- no separate data editing since cycle slips are treated as data outliers and are rejected during the adjustment*

- no nuisance parameters (ambiguities), thus the size of the normal matrix is significantly reduced with respect to the normal matrix for undifferenced, single or double differenced observations

Disadvantage: *correlation between epochs, thus the covariance matrix is a full or a banded matrix, depending on the differencing scheme (inverting such a matrix is not practical!)* .

Application of the Cholesky decomposition in the observation decorrelation

$$(\mathbf{A}^T\Sigma^{-1}\ \mathbf{A})\xi = \mathbf{A}^T\Sigma^{-1}\mathbf{Y} \text{ and } \Sigma = \mathbf{L}\mathbf{L}^T$$

$$\widetilde{\mathbf{A}}^T\widetilde{\mathbf{A}}\xi = \widetilde{\mathbf{A}}^T\widetilde{\mathbf{Y}}$$

$$\sim\ = \mathbf{L}^{-1}\mathbf{A} \quad \text{and} \quad \widetilde{\mathbf{Y}} = \mathbf{L}^{-1}\mathbf{Y}$$

$$\mathbf{L}\widetilde{\mathbf{A}} = \mathbf{A} \quad \text{and} \quad \mathbf{L}\widetilde{\mathbf{Y}} = \mathbf{Y}$$

Schaffrin-Grafarend Theorem

$E\{\mathbf{Y}\} = \mathbf{A}\xi + \mathbf{B}\eta, D\{\mathbf{Y}\} = \mathbf{P}^{-1}\sigma^2$

Choose transformation matrix R such that one gets:

$E\{\mathbf{R}^T\mathbf{Y}\} = \mathbf{R}^T\mathbf{A}\xi$ **and** $D\{\mathbf{R}^T\mathbf{Y}\} = \mathbf{R}^T\mathbf{P}^{-1}\mathbf{R}\sigma^2$

Solution of ξ is identical in both adjustments!

Double Differences	**Equivalent Set of Observations**
Y_1	Y_1
Y_2	Y_2-Y_1
Y_3	Y_3-Y_2
.	.
.	.
.	.
Y_{N-1}	$Y_{N-1}-Y_{N-2}$
Y_N	Y_N-Y_{N-1}

TIMING REQUIREMENTS

Automatic Data Downloading (Internet)
1 hour

Data Base Creation and Preprocessing
1.5 hours

Orbit Determination
(35 ***rein/iteration) x 5 iterations= 3 hours***

Total Processing Time = 5.5 hours

DYNAMIC MODEL

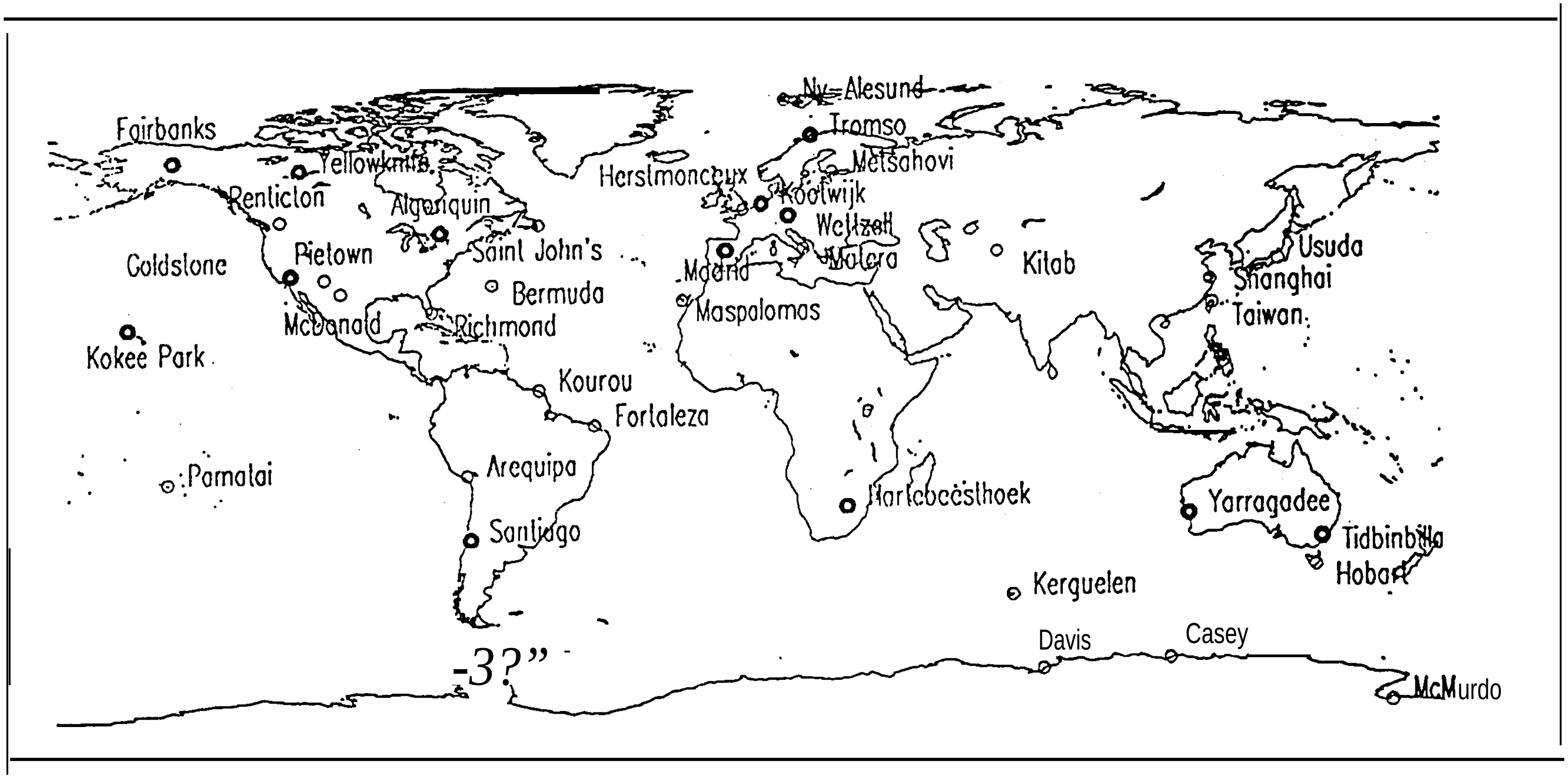
Geopotential	GEM-T3 up to degree and order 8 plus $\overline{C}_{21}$ and $\overline{S}_{21}$ according to IERS standards
	GM_E = 3. 98600436 x1014 m^3/s^2.
	a_e = 6378137 m
Third-body	Sun and Moon regarded as point masses
	Ephemeris: JPL DE-200
	GM_{sun} = 132712440000.0 km^3/s^2
	GM_{moon} = 4902.7991 km^3/s^2
Solar Radiation Pressure	ROCK4 and ROCK42 models for Block I and II satellites, respectively Satellite masses are obtained from table 3 of Fliegel and Gallini (1992) and IGS Electronic Mail (see e.g., Mail #654)
	Y-bias
	Earth shadow model: Umbra and Penumbra
Tidal Forces	Solid earth tides: Wahr model with k_2 = 0.30
	Ocean tides: Schwiderski model
Relativistic Correction	IERS Standards
Numerical Integration	Variable-order / variable-stepsize of the Adam's type Arc length: 32 hours (4+24+4)

MEASUREMENT MODEL

Basic Observable	*Triple Difference, Ionospheric-Free Linear Combination* *Sampling Rate: 15 minutes* *Weighting: Uniform, with 1cm standard deviation for the single phase* *Elevation Angle Cutoff: 16 degrees*
Ground Antenna Phase Center	*Offset - applied* *Elevation-dependent phase center correction - not applied*
Troposphere	*Modified Hopfield with mapping function developed by Goad and Goodman*
ionosphere	*Not modeled, ion-free combination used*
Plate Motion	*ITRF93 Station Velocities, fixed*
Station Tidal Displacement	*Solid Earth Tides, according to IERS Standards*
Station Displacement Due to the Dynamic Pole	*A ccording to IERS Standards*
Satellite Center of Mass Correction	*Block I: 0.211 m, 0.000 m, 0.854 m* *Block II/IIA: 0.279 m, 0.000 m, 1.023 m*

SOLUTION PARAMETERS

PRODUCT	APRIORI VALUE	APRIORI CONSTRAINT
SATELLITE POSITION	FORMER SOLUTION	1.0 m
SATELLITE VELICITY	FORMER SOLUTION	10^{-4} m
SOLAR RADIATION PRESSURE S_x, S_Z SCALING FACTORS Y-BIAS SCALING FACTOR	FORMER SOLUTION	 0.1 0.15
COORDINATES FOR 23 TRACKING STATIONS (13 FIXED IERS STATIONS)	FORMER SOLUTION IGS MAIL 819	50.0 m 3-5 mm
TROPOSPHERIC SCALING FACTORS (AT FOUR - HOUR INTERVAL)	1.0	0.1
EARTH ROTATION PARAMETERS: RATE OF (UT1-TAI) Xpole, Ypole OFFSETS	BULLETIN B	 6.5 x 10^{-3} sec / day 9.7x 10^{-2} arcsec / da
TOTAL ARC LENGTH: 32 hours (4+24+4)		

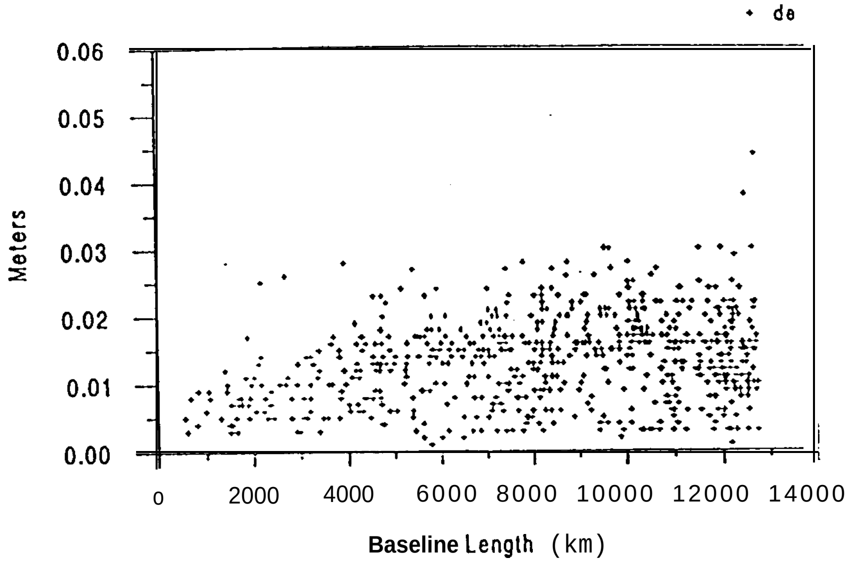


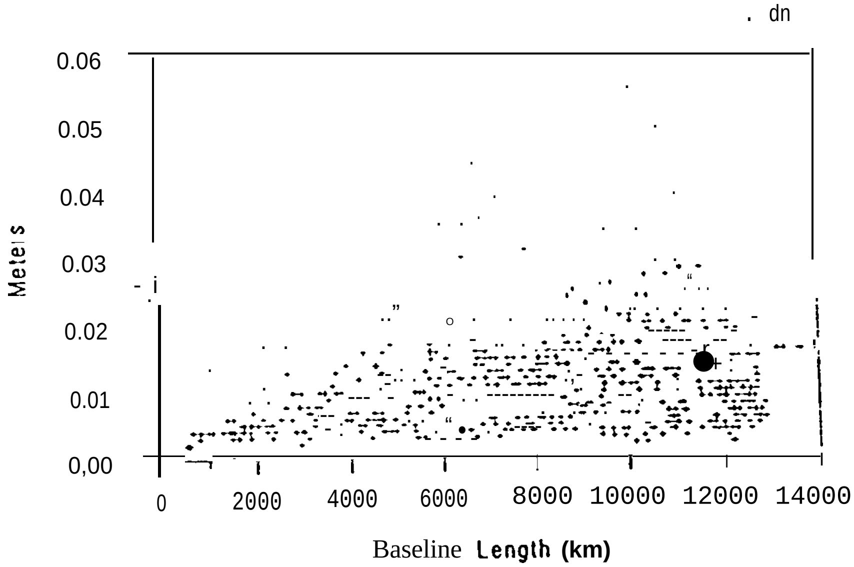
. Fiducial Stations

O Estimated Stations

	EMR	ESA	GFZ	JPL	NGS	SIO	OSU	IGS
COD	18.0	20.3	17.9	15.3	24.8	28.6	.2	0.75
EMR		22.9	18.7	17.0	25.3	27.0	19.2	2.46
ESA			21.5	22.6	28.	30.9	22.3	18.21
GFZ				6.7	26.6	2 .0	18.9	11.79
JPL					25.0	26.3	8.5	9.75
NGS						29.6	27.0	20.86
SIO							28.2	23.04
OSU								15.36

The Mean RMS of fit in [cm] of orbit comparison among the IGS centers including OSU, for GPS weeks 784-787


de
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Meters
0
2000
4000
6000
8000
10000
12000
14000
Baseline Length (km)


dn
0.06
0.05
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Meters
0
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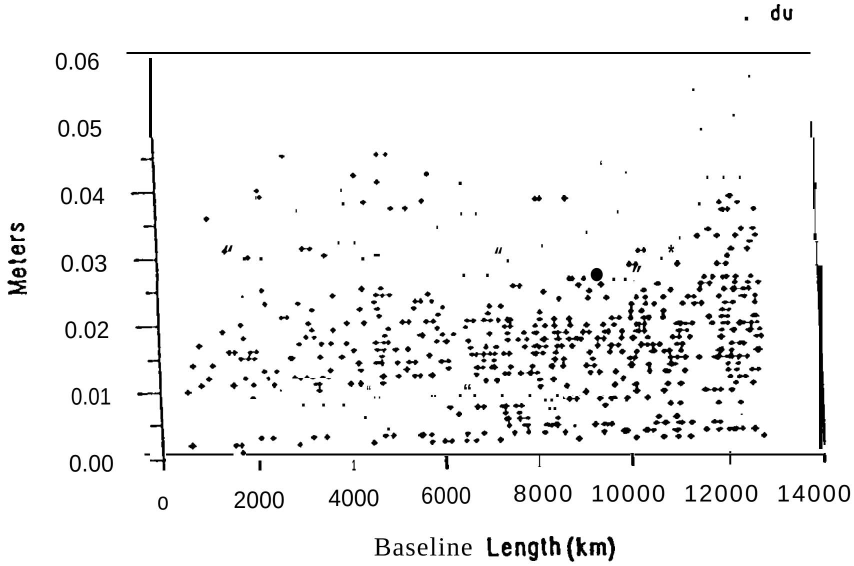
4000
6000
8000
10000
12000
14000
Baseline Length (km)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0.06
0.05
0.04
0.03
0.02
0.01
0.00
Meters
0
2000
4000
6000
8000
10000
12000
14000
Baseline Length (km)

Critical Components of our Procedure

---

1. *The choice of the procedure for generating an optimum set of linearly independent observations*

2. *Iterative solution and data editing as apart of the least squares adjustment, repeated every iteration*

Processing Times (hours)
90 MHz PC

	32 Stations	74 Stations
Predict	0.06	0.06
Generate TD's	0.05	1.20

Per Iteration

	32 Stations	74 Stations
Measurement Reduction	0.05	0.25
Cholesky	0.02	0.60
Forward Substitution	0.10	1.60
Accumulation	0.20	1.80
Solution	0.02	0.15
Total	0.41	4.40

CORS PROJECT

N. **Weston**

National Geodetic Survey
National Ocean Service
NOAA
Silver Spring, Maryland

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Deputy Project Chief	**Paul R.** Spofford **phone: 301-713-3205** **Internet:** pauls@ngs.noaa.gov
Technical staff	LT(jg) **Neil Weston, NOAA** **phone: 301-713-3234** **Internet:** nweston@ngs.noaa.gov
	Donald Haw phone: 301-713-3208 don@?ngs.noaa.gov
	James Drosdak phone: 301-713-3219 Internet: jimd@ngs.noaa.gov

CORS OBJECTIVES

- **SUPPORT NGS SURVEYING**
- **BASE STATION ACCESS TO NSRS**
- **MONITOR MOTIONS**
- **PROMOTE STANDARDIZATION**
- **PROVIDE DATA**
- **SUPPORT POSITIONING AND NON-POSITIONING APPLICATIONS**

CORS STANDARDS ACTIVITIES

- CORS **STATION STANDARDS**
  - **TO BE ISSUED JUNE/JULY 1996**

    REQUIRED AND DESIRED ACTIVITIES
- RINEX **VERSION 2 STANDARDS**

  OPTIONAL FIELDS REQUIRED FOR INCLUSION

  IN COLLABORATION WITH USERS AND HARDWARE VENDORS
- **REQUIRED ANTENNA PHASE CENTER MODELS**
  - **HARDWARE VENDORS/STANDARD NAMES**
- **METEOROLOGICAL SENSORS**

  NOAA FORECAST SYSTEMS LABORATORY

CORS COMPONENTS

- GPS **OBSERVATION STATIONS**
- **DATA TRANSMISSION**
- **CENTRAL FACILITY**
  - **- DATA FORMATTING**
  - **- QUALITY CONTROL**
  - **- DATA ARCHIVING**
- **DATA DISTRIBUTION**

MAJOR CONSIDERATIONS

- SAMPLE RATE
- **REAL TIME DATA TRANSMISSION**
- **MONUMENT STABILITY**
- DATA FORMAT
- COORDINATE SYSTEM

CORS STATION TYPES

- **TYPE A**

  MULTIPLE RECEIVERS AT STATION

  99 PERCENT RELIABILITY

  VARIABLE SAMPLE RATE (2 TO 30 SECONDS)

  IMMEDIATE DATA ACCESS VIA PACKET SERVICE (X.25)

  HOURLY DATA FILES

- **TYPE B**

  - SINGLE RECEIVER AT STATION

  - 30 SECOND SAMPLE RATE

  - DAILY DATA ACCESS VIA INTERNET/MODEM

  - DAILY DATA FILES

COAST GUARD STATIONS

RECEIVERS:

- **TWO (2) ASHTECH Z12 RECEIVERS AT EACH SITE**

SAMPLING RATE:

- **5 SECOND PLANNED (1 SECOND POSSIBLE)**

TRANSMISSION TO CENTRAL FACILITY

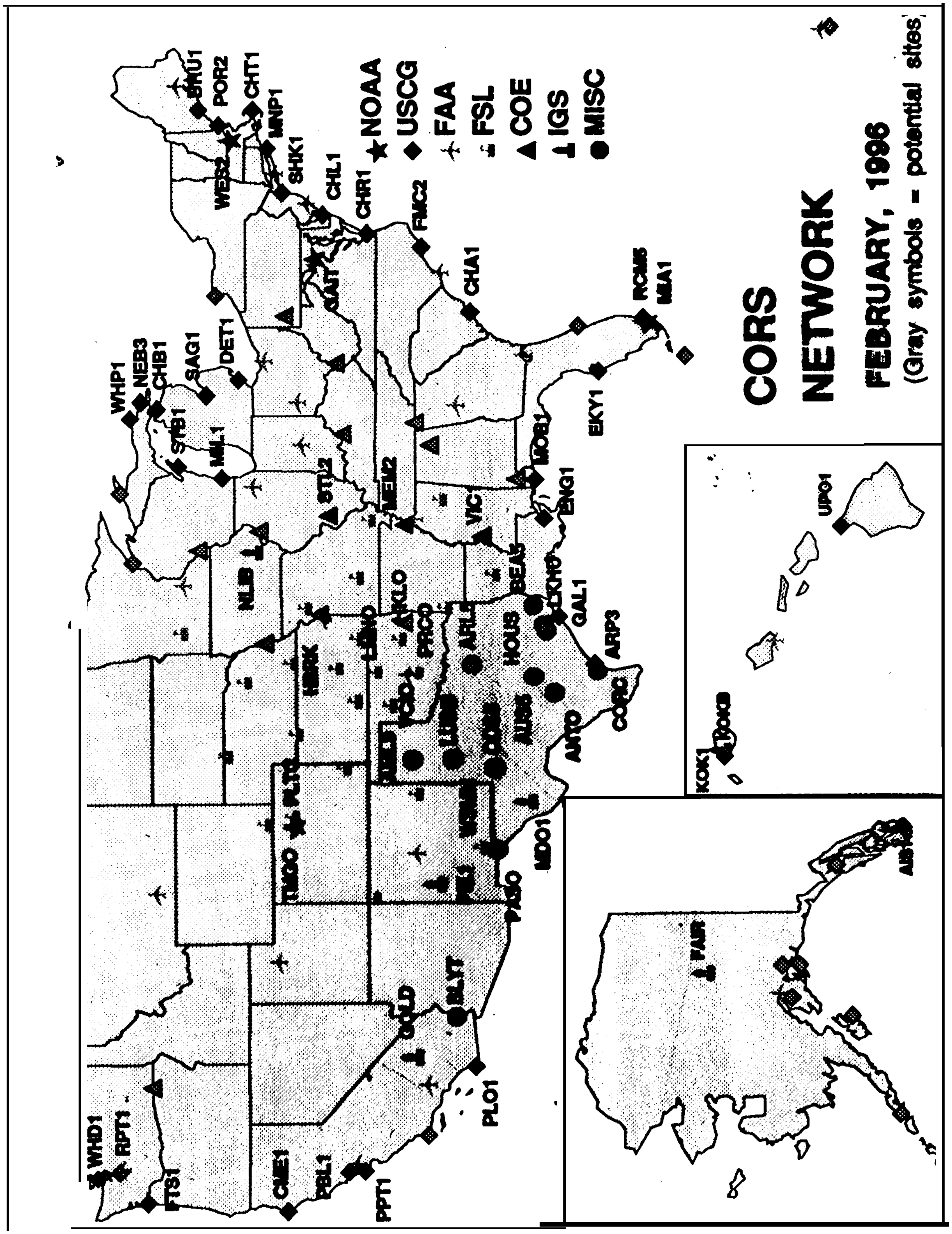
- **AT&T FTS2000, X.25 PACKET SERVICE**
- **DATA TRANSMITTED AFTER EACH SAMPLE - NO ON SITE STORAGE**

AMOUNT OF DATA TRANSFERRED:

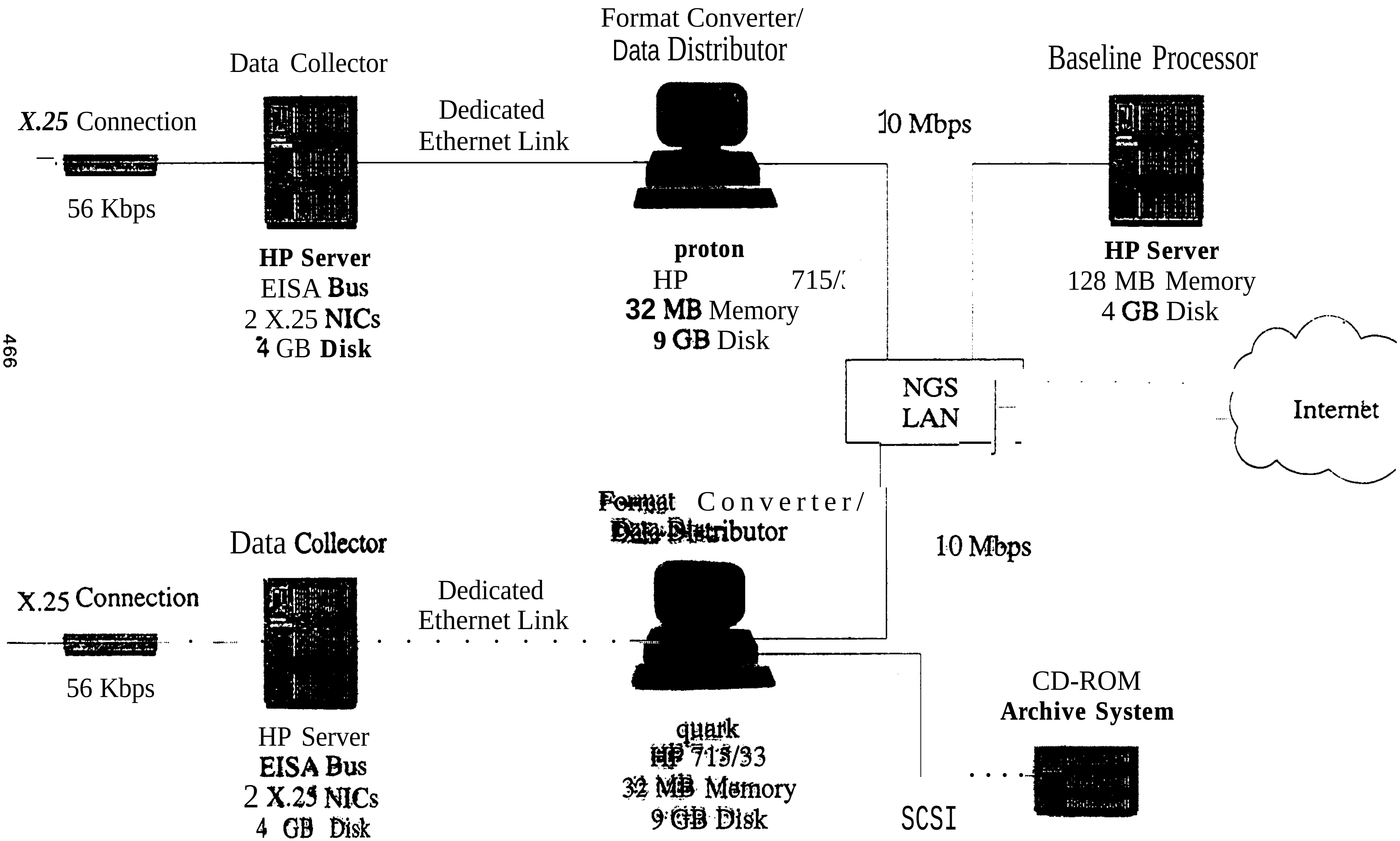
- **~5 Mbytes/DAY/STATION**

PARTICIPATING CORS OBSERVING STATIONS

- U.S. COAST GUARD/U. S. ARMY CORPS OF ENGINEERS
- NASA/JPL/IGS
- **U.S.** GEOLOGICAL SURVEY
- NOAA
- **TEXAS DEPARTMENT OF TRANSPORTATION**
- **FAA**


CORS
NETWORK
FEBRUARY, 1996
(Gray symbols = potential sites)
NOAA
USCG
FAA
FSL
COE
IGS
MISC
SHU1
POR2
CHT1
MNP1
SHK1
CHL1
CHR1
FMC2
CHA1
RCM5
MIA1
EKY1
WHP1
NEB3
CHB1
SAG1
DET1
STB1
MIL1
STL2
MEM2
MOB1
ENG1
VIC1
NLIB
BEAS
GAL1
ARP3
HOUS
CORC
ANTO
MDO1
PASO
PLTC
BLYT
PLO1
PPT1
CME1
FTS1
RPT1
WHD1
UPO1
KOK1
FAIR

CORS Data Coll[illegible]tion and Distribution
(Proposed Configuration, Phase 1.1)



ITRF94 VS CORS_ESTIMATES

RMS DISCREPANCY

North	5.6 mm
East	7.0 mm
up	12.4 mm

METEOROLOGICAL PACKAGES (GSOS)

NATIONAL DATA BUOY CENTER
STENNIS SPACE CENTER

- **NDBC developed a small meteorological sensor package (GSOS) that could be installed at the USCGD GPS sites.**

- **Will interface with the AT&T X.25 packet switching network (via a PAD).**

- **Transmit data to NGS on command (normally every 5 minutes).**

- **Merge 5 minute data epochs into an hourly file (RINEX format).**

PTB 200 SERIES DIGITAL BAROMETERS

FEATURES

- **TOTAL ACCURACY INCLUDING ONE YEAR DRIFT**

  PTB 200A +/- 0.20 mbar

  PTB 201A +/- .03 mbar

- **600 to 1100 mbar PRESSURE RANGE**
- -40∞ to +60∞ C OPERATING **TEMPERATURE RANGE**
- **RS 232C OR TTL LEVEL SERIAL INTERFACE**

APPLICATIONS

- **BAROMETRIC TRANSFER STANDARD**
- **WEATHER STATIONS**
- **ENVIRONMENTAL DATA LOGGING**
- **DATA BUOYS AND SHIPS**

HMP 233 HUMIDITY/DEWPOINT TRANSMITTER

FEATURES

- **ON-SITE ONE-POINT CALIBRATION CAN BE PERFORMED WITHIN A MATTER OF MINUTES WITHOUT DISTURBING THE UNITS OPERATION**

- **SELECTION OF OUTPUT PARAMETERS**
  - **RELATIVE HUMIDITY**
  - **DEWPOINT**
  - **TEMPERATURE**

- **SELECTION OF TEMPERATURE RANGE**

- **RELATIVE HUMIDITY**
  - **MEASUREMENT RANGE** — O TO 100%
  - **ACCURACY** — +/- 1%RH
  - **RESPONSE TIME** — 15 SECONDS

- **TEMPERATURE**
  - **MEASUREMENT RANGE** — -40∞ TO 80∞ C
  - **ACCURACY** — +/- 0.2∞ C

POTENTIAL FUTURE STATIONS

- **FEDERAL AVIATION ADMINISTRATION WAAS**
- **ADDITIONAL USGS/COE INLAND WATERWAYS STATIONS**
- **FAA LOCAL AREA DGPS SITES**
- **USCG-TYPE NATIONWIDE EXTENSION**
- **FEDERAL AGENCY SURVEYING/MAPPING REQUIREMENTS**
- **STATE AND LOCAL AGENCY COOPERATION**
- **MEXICAN NATIONAL NETWORK**

NOAA GPS Antenna-Calibration Website

G. L. Mader

http://www.grdl. noaa.gov/

GPS/PROJECTS/ANTCAU

antcal_toc.html

Average Median Data Delivery/Retreival Delay at CDDIS for 1996 (All Sites)

C. Nell

Source	Sites	Average Median Delay*
AUSLIG	CAS 1	131.50
	DAV1, HOB2, MAC1	493.55
CIGNET	BRMU, FORT, **HNPT**, KELY, RCM%;"SOii USNA, WES2	5.58
	WUHN	66.42
ESA	**KIRU, KOUR,** PERT, VILL	4.38
	MAS1	12.54
	MALI	22.30
GFZ	POTS	8.64
	LPGS	19.92
	KIT3, **ZWEN**	**41.01**
GSI	**TAIW,** TSKB	4.43
IGN	BRUS, **GRAZ,** HERS, KOSG, METS, NYAL, **OHIG,** ONSA, TROM, WETT, ZIMM	8.57
	BOR1 , GRAS, HART, KERG, MATE, REYK, **WTZR**	13.79
	JOZE, PAMA	19.72
JPL	IRKT, MDVO	37.66
	ANKR	61.20
	AOA1, CARR, CAT1 , **CIT1, LBCH, MCM4,** OAT2, SPK1 , UCLP, **WHC1,** WH1l	6.61
	CASA, CRO1 , GOLD, HARV, MADR, **MDO1, QUIN,** TIDB	9.18
	AREQ, **CICE, EISL,** FAIR, **GODE,** JPLM, KOKB, SANT, **SEY1, SNI1, USC1, THU1, USUD,** WLSN, YAR1	11.41
	AUCK, BOGT, CHAT, GUAM, **IISC,** NLIB, **PIE1,** SHAO	25.18
	MOIN	65.57
KOREA	TAEJ	2.75
NRCan""	**ALBH,** ALGO, DRAO, **STJO,** YELL	4.03
SIO	MONP, **PIN1**, PVEP, SI03, VNDP	8.86
UNAVCO	**POL2**	38.22

3/15/96

CDDIS Data Processing Schedule

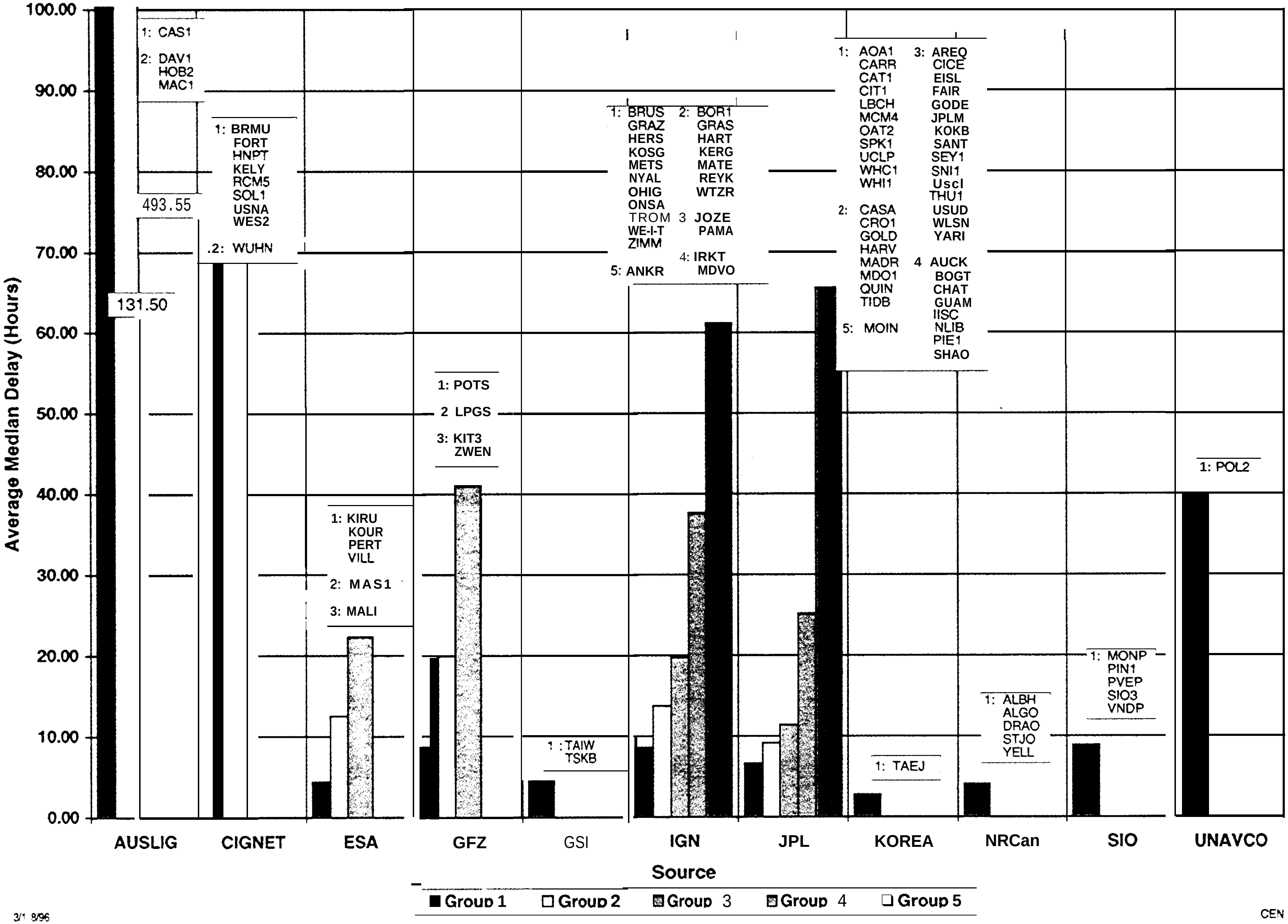
Source	Put/Get	No. Times/ Day	Put./Get Times	CDDIS Processing Times
AUSLIG	Get	1	06:30	06:30
CIGNET	Put	1	23:45	00:15,11:00 (1)
ESA	Put	1	21:00	22:00,00:30,07:30
GFZ	Put	4	02:00,08:00,14:00,20:00	03:30,08:30,15:30,20:30
GSI	Put	1	19:30	20:00,01:30
IGN	Put	4	02:00,7:30,14:00,19:00	03:00,08:00,15:00,20:00
JPL	Get/Put	1	01:30,03:30,5:00,17:00	01:30,03:30,05:30,17:00 (2)
KOREA	Put	1	19:30	21:45,01:15
NRCan	Put	1	22:45	23:00,16:00 (1)
SIO	Get	1	04:30	04:30
UNAVCO	Put	1	12:00	13:30

All times are CDDIS times (EST); adding five hours results in UTC time.

(1) Processing software is executed a second time in order to archive any late data.

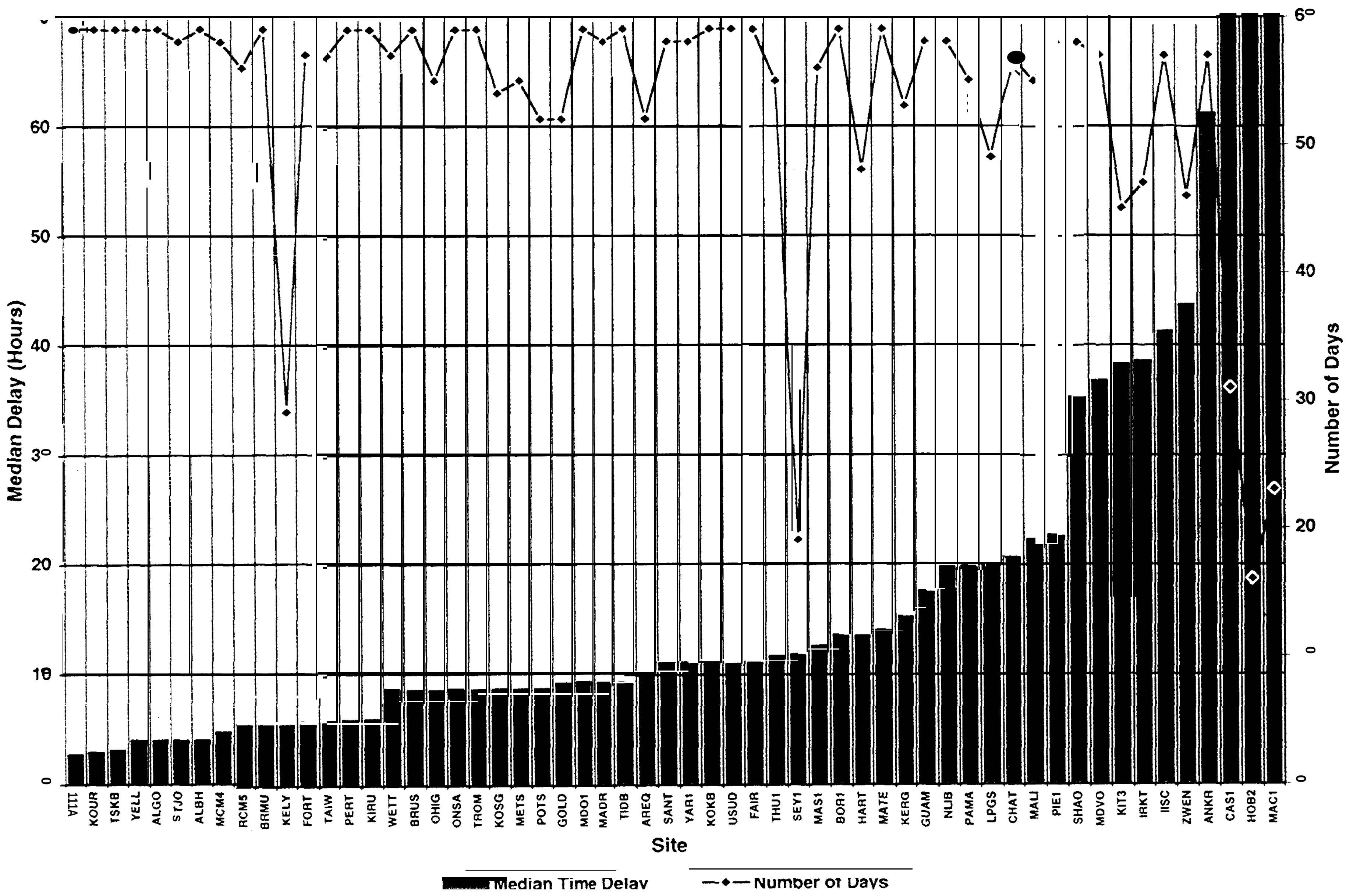
(2) JPL PUT process to CDDIS executes ~05:00; CDDIS executes GET procedures several times to retrieve data quicker.

Average Median Data Delivery Delay for 1996 (All Sites)

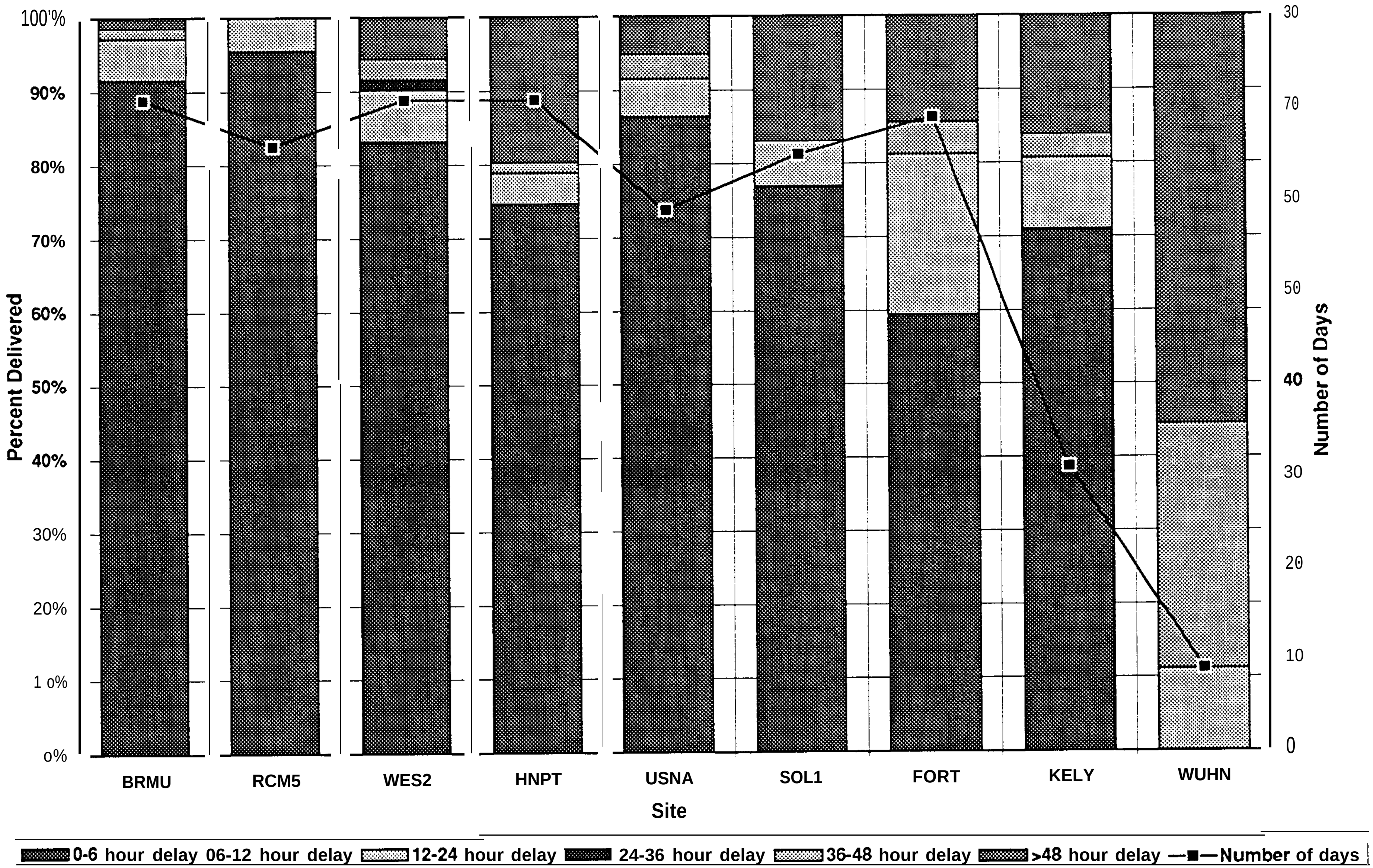


477

Median Data Delivery Delay for 1996 (Global Sites)



CIGNET Data Delivery Statistics (1996)



3/15/96

CEN

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Publication 96-23 10/96