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NASA Contractor Report 171824

FINAL REPORT — Shuttle Derived Atmospheric Density Model

Part 1: Comparisons of the Various Ambient Atmospheric Source Data with
Derived Parameters From the First Twelve STS Entry Flights — a Data
Package for AOTV Atmospheric Development

John T. Findlay
G. Mel Kelly
Patrick A. Troutman

CONTRACT NAS9-17158

December 1984



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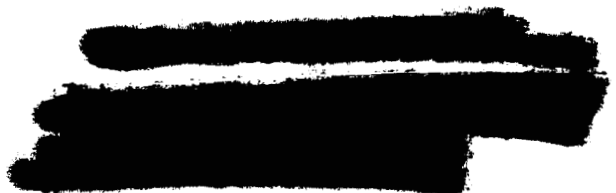
FINAL REPORT — Shuttle Derived Atmospheric Density Model

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ABSTRACT

This report, Part 1 of the final report generated under NASA Contract NAS9-17158, presents ambient atmospheric parameter comparisons versus derived values from the first twelve(12) Space Shuttle Orbiter entry flights. Available flights, flight data products, and data sources utilized are reviewed. Comparisons are presented based on remote meteorological measurements as well as two comprehensive models which incorporate latitudinal and seasonal effects. These are the Air Force 1978 Reference Atmosphere and the Marshall Space Flight Center Global Reference Model (GRAM). Atmospheric structure sensible in the Shuttle flight data is shown and discussed. Part 2 of the final report presents a model for consideration in Aero-assisted Orbital Transfer Vehicle (AOTV) trajectory analysis, proposed to modify the GRAM data to emulate Shuttle experience.

I. Introductory Background

Shuttle post-flight data reduction in support of aerodynamic and aerothermodynamic research has been ongoing throughout the aerospace community since the first mission in April, 1981. The results have been extensively published; have been utilized to evaluate and develop interim updates to the Orbiter performance, stability and control estimates; and, will ultimately evolve into a final Operational Orbiter Aerodynamic Data Base. Of significant interest during this analysis has been the apparent atmospheric structure sensed by the Orbiter in the upper reaches of the mesosphere, throughout the mesopause, and up into the thermosphere. Considerable shear structure, "potholes-in-the-sky," and generally abrupt increases/decreases in the atmospheric density have been observed. Dr. W. M. Robertson of the Charles Stark Draper Laboratories (CSDRL) has conducted extensive research in this area and has identified various meteorological mechanisms in his literature search to account for such phenomena. Proposed candidates are gravity waves, purported also by others, and Kelvin-Helmholtz instabilities. Thus, Shuttle experience is not without precedence. Though such density departures have minimal effect on the Shuttle flights per se, apart from the fact that the crew has experienced a sense of clear air turbulence in this altitude region, the effect of same on lighter, lower performance, spacecraft is of considerable interest. Specifically, AOTV trajectory analysts (Reference 1) have expressed concern re the influence of Shuttle type atmospheric structure on AOTV trajectory results. Simplified, reasonable, models to emulate similar atmospheric structure has shown large trajectory perturbations during the exit phase of the aero-assist maneuver using various guidance algorithms which utilize predictor-corrector targeting schemes. As a consequence, this task was undertaken to help establish atmospheric modelling requirements for AOTV analysts. This additional atmospheric analysis was required to provide statistical comparisons between Shuttle derived atmospheres and the National Weather Service data, and evaluate the adequacy of two available, comprehensive, models (the MSFC GRAM (Reference 2) and the Air Force 1978 Reference Model (Reference 3)), ultimately defining a perturbation model for density shears at

altitudes above 200 kft. Additionally, the results, though no mechanism was established, should provide data to assist in the development of a refined Global Atmosphere Model.

It is recognized that AOTV trajectory analysts are considering utilization of the "13th month" (average) GRAM data throughout much of the preliminary design stages. Further, design considerations presently simulate return from GEO with the aeroassist maneuver near the Equator. Consequently, latitudinal effects will be minimum. However, for the purposes of this study, the comprehensive model, to include latitudinal and seasonal effects, was utilized and an assessment of the modelled accuracy (1σ) was made. The former to establish the systematic global applicability of the GRAM, the latter to quantify the expected accuracy. This not only aids in establishing the model validity but supports the use of the MSFC error model for the various Monte Carlo analyses performed throughout the Agency.

Contractually, AMA was required to perform this analysis for the first nine(9) Shuttle flights. Since data were available from the first twelve(12) flights, it was decided to include these results as well. This part of the final report principally presents results showing comparisons of the various atmospheric sources with Shuttle derived parameters. Included herein is a background discussion of the available flights, analysis methodology, and quantification of atmospheric structure which has been encountered over the first three years of the STS Program. Part 2 of the final report presents a proposed perturbation model which can be utilized with the GRAM to emulate Shuttle experience.

II. Available STS Flights

Table I lists the twelve(12) STS flights available. Shown are the dates of entry, the approximate (local) time of landing, and the season in which each flight occurred. The landing time is for information only and would only be expected to influence the lowermost atmosphere. Actually, between entry interface (h = 400 kft) and landing, the spacecraft descends through approximately six(6) time zones, through three(3) below h = 250 kft. However, it is of interest to note that most of the landings occurred in the morning hours at Edwards Air Force Base, to include one landing just after midnight (STS-8). There were only two afternoon landings, one at EAFB and the other (STS-11) being the first historic landing at Kennedy Space Center. STS-3 landed at White Sands in the early morning. It is perhaps significant to quantify the extent of the STS atmospheric data base by season, viz:

<u>Season</u>	<u>No. of flights</u>
Spring	4
Summer	4
Fall	3
Winter	1

Schematically, the STS flights (and profile similarities) are depicted in Figures 1 and 2, respectively. Figure 1 shows the vertical profiles and ground tracks for each mission. Symbols utilized conform to the NASA Standard Set, e.g.,

<u>STS</u>	
1	○
2	□
3	◇
4	△
5	▽
6	◐
7	◑
8	◇
9	◇
11	⊕
13	⊕
14	△

The shaded region on the vertical profile emphasizes the primary altitude region of interest herein, namely, 150 kft $h < 320 < kft$. Shown on the ground

track plot are the landing sites and remote meteorological sites utilized in support of the Shuttle entries. Of interest is the one available flight (STS-9) returning from an ~60 degree orbit, a Northerly flight during the onset of winter. Also superimposed thereon is an altitude contour corresponding to the geographic location of the uppermost altitude occurrence for each flight. The shallowness of each Orbiter descent profile is quite evident in the altitude plot, at least in the region of interest. Figure 2 shows the range of Orbiter descent rate over the twelve flights. The similarity in each flight is clearly suggested, at least above $h = 180$ kft. It is noted, though not specifically evident thereon, that with the exception of STS-4 the spread in altitude rate would be considerably more narrow even below this altitude. The shallowness of the vertical descent, and the similarities in same across the twelve flights, are addressed later during the discussions of Shuttle derived atmospheres (as a possible limitation) and the sharpness (with time) of the encountered density structure.

STS	Date of Entry	Local Time of Landing (approximate)	Season
1	April 14, 1981	10:20 AM PST	Spring
2	November 14, 1981	1:25 PM PST	Fall
3	March 30, 1982	9:05 AM MST	Spring
4	July 4, 1982	9:10 AM PDT	Summer
5	November 16, 1982	6:30 AM PST	Fall
6	April 9, 1983	10:55 AM PST	Spring
7	June 24, 1983	7:00 AM PDT	Summer
8	September 5, 1983	0:40 AM PDT	Summer
9	December 8, 1983	3:45 PM PST	Fall
11 (41-B)	February 11, 1984	7:15 AM EST	Winter
13 (41-C)	April 13, 1984	5:40 AM PST	Spring
14 (41-D)	September 5, 1984	6:40 AM PDT	Summer

Table I. Shuttle flight data availability.

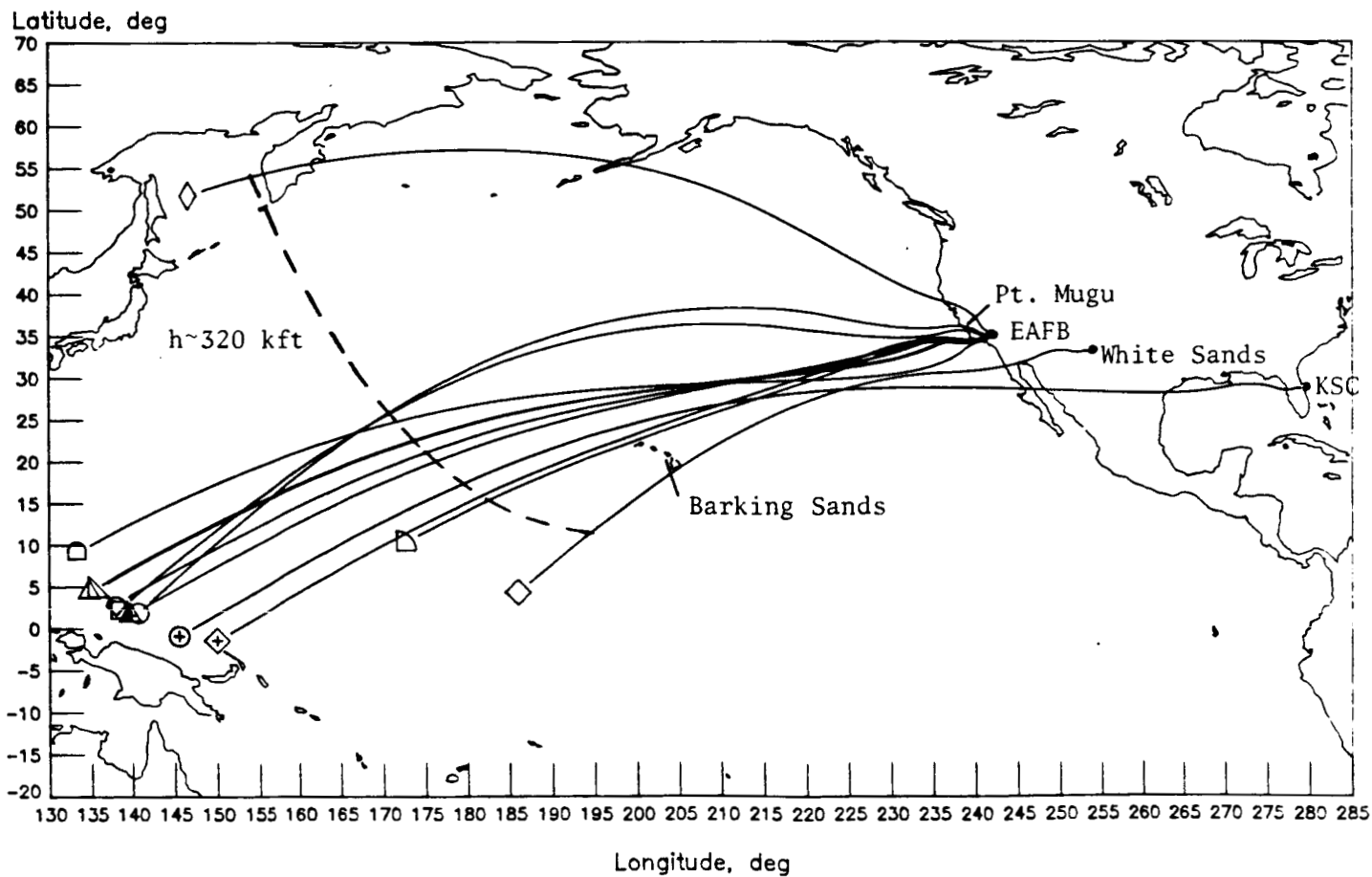
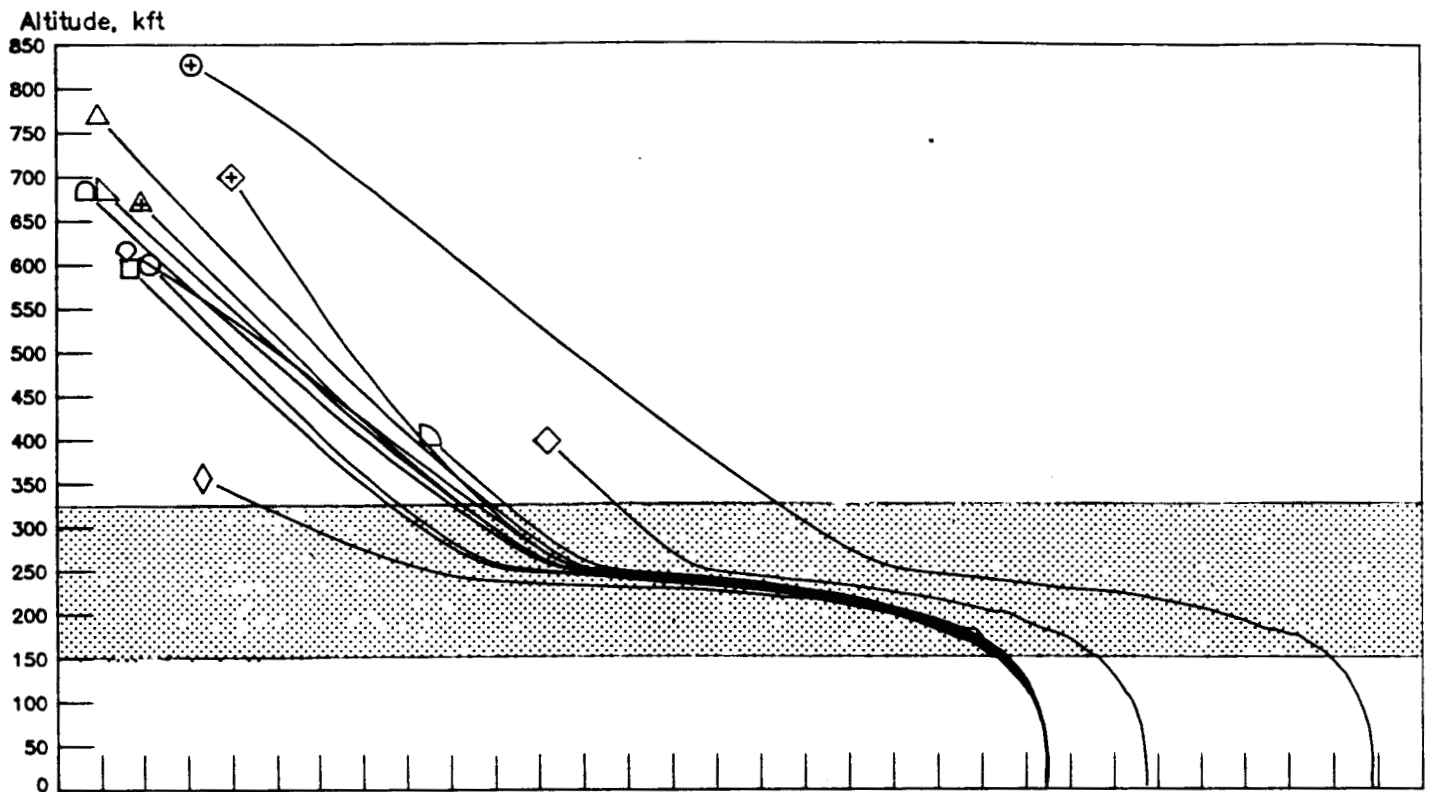


Figure 1. Ground tracks and vertical profiles for first twelve(12) STS entry flights.

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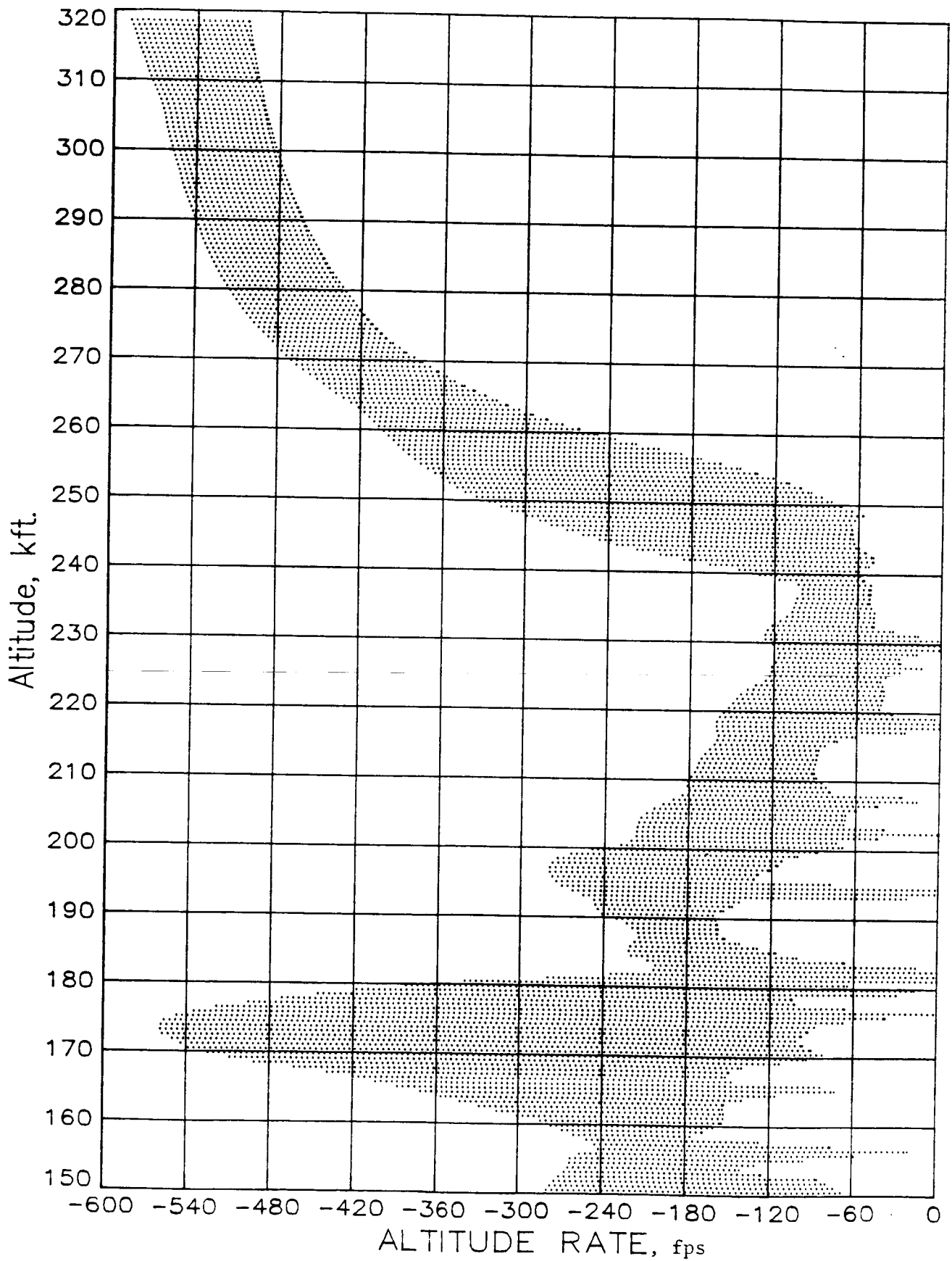


Figure 2. Range of Orbiter descent profiles for first twelve(12) entry flights.

III. Available Data, Models, and Methodology

Reader familiarity with details of the ongoing Shuttle aerodynamic research is, perhaps, presumptuous. Thus, this limited discussion is included. The concept of the Best Estimate Trajectory, as discussed by Compton, et al in Reference 4, defines the best post-flight time history of the spacecraft (inertial) state; position, velocity, and attitude, which is obtained by combining (deterministically) spacecraft dynamic measurements and (statistically) the ground based tracking information; C-band, S-band, and cine-theodolite when available. The principal source for spacecraft dynamics is the tri-redundant Inertial Measurement Unit (IMU) measurements of platform attitude quaternion and summed velocity changes in the inertial Mean of 1950 reference frame. Heck, et al, in Reference 5 presented algorithms to derive the equivalent body axes accelerations and rates from the ~ 1 Hz measurement set.¹

Given an inertial reconstructed trajectory, one needs some atmospheric information to compute the necessary air relative parameters. (The Orbiter does have an air data system which provides in situ measurements below Mach ~ 3 ($h < 100$ kft)). Obviously models can be utilized (as done herein) but, to enhance the quality of the research products, meteorological rockets and balloons have been launched in support of Shuttle entry flights. These remote measurements have been taken as time and spatially optimum as possible and yet, compilation of these measurements into a single, viable, atmosphere commensurate with the Orbiter ground track and vertical profile is still an arduous task. Two separate treatments of this process are currently performed as discussed later.

For the selected atmosphere (remote(s) or model(s)), computation of flight derived aerodynamic coefficients is straightforward. To complete the aerodynamic research, spacecraft configuration information is required to enable comparison of the flight results with that expected from ground-based facilities and/or theoretical computations. Orbiter control surface positions and reaction jet firing information are available from the Operational Instrumentation recorded data set to define the necessary

¹As part of the Orbiter Experiments Package (OEX), the High Resolution Accelerometer Package (HiRAP) is an available μg source (since STS-6) which can be utilized in the thermosphere. Results from HiRAP are presented in Part 2 of this final report.

configuration. A comprehensive Orbiter Aerodynamic Data Base is utilized to obtain predicted coefficients. The data book is based on a consensus fairing by aerodynamicists throughout the Shuttle community and was developed over a period of years and many thousands of wind tunnel operating hours. As will be shown later, the data base has, with few exceptions, been substantiated by the flights of record to be an excellent aerodynamic prediction package. Indeed, the data base has been scrutinized by the most comprehensive end-to-end flight test program ever. Project aerodynamicists have been able to develop interim Flight Assessment Deltas (FADS) in support of the Shuttle Program, ultimately geared toward development of a final Operational Orbiter Aerodynamic Data Book. For the purposes herein, a 1978 vintage data base is utilized and the FADS, small incremental changes, have not been incorporated.

With the preceding background in mind, it is apparent that the process can be reversed from one of aerodynamic performance comparison to atmospheric evaluation. The predicted aerodynamic coefficients can be utilized to derive an in situ atmosphere and said atmosphere can be compared with other sources directly to evaluate their respective adequacy, each on a common trajectory profile. This has been done herein; however, prior to presenting the results, it is worthwhile to further discuss the particulars of each atmospheric source separately.

Shuttle derived atmospheres

These atmospheric data are based, as stated, on the predicted Orbiter normal force coefficient, C_{Np} , from a vintage 1978 data base, and the measured normal acceleration, A_N , derived from the IMUs. It should be stated that an ~1 mg quantization (due to downlist limitations) in the IMU data negates use of these data above ~300 kft (due to signal-to-noise considerations) though major deviations can be detected up to ~320 kft by averaging through the noise induced signal. Density can be obtained as a direct map as follows:

$$\rho_{C_N} = \frac{A_N \cdot \text{mass}}{\frac{1}{2} V_A^2 \cdot S_{REF} C_{Np}}$$

Such a density determination is reasonably accurate. The required velocity (V_A) and altitude/latitude for the associated density profile are obtained from the BET which is, as stated, based on a statistical fit to the available tracking measurements taken during entry. Also, updated post flight mass properties are utilized. Perhaps the latent weakness of this determination, though not a major one, is the predicted aerodynamic coefficient which has been shown (see Figure 3) to be, based on the flights analyzed to date, overpredicted by some 3 to 5 percent. This overprediction reflects as a bias in the density determination, making the derived density some 3 to 5 percent less dense than actual, at least for 150 kft < h < 280 kft.

To continue, pressure is obtained from the hydrostatic equation:

$$dp = - \rho_{C_N} g dh$$

Finally, temperature is computed from the perfect gas law. Readers are reminded that the Shuttle entry flight profile is very shallow (on a relative basis) when compared to the usual sounding devices employed for atmospheric extraction. Thus, some liberties are taken in the employment of the hydrostatic equation yet, apart from this limitation (approximation) one is left with little recourse to enable determination of the "complete" ambient atmosphere. For the altitude range under consideration, no "in situ" winds are derivable from the Shuttle data.

Remote measurements

Remote soundings are taken during each Shuttle entry flight in support of the ongoing aerothermodynamic research. These soundings are as spatially and time optimum as possible. Devices such as Robin spheres (PWN-12A) and thermistors (PWN-11A) are utilized at these altitudes. Though efforts are made to obtain time optimum measurements, some analysis is required to translate these data to the Shuttle ground track and vertical profile. To that extent, there are actually two separate activities. These include (1) the development of Langley Atmospheric Information Retrieval System (LAIRS) files by J. Mac Price of the Aerothermodynamic Branch of the Space Systems Division at LaRC, and (2) development of NOAA "totem-pole" atmospheres by Mel Gelman of the Climatology Branch of the National Weather Service in Washington, D.C.

Though each treatment of the remote sounding data is equally rigorous there are some differences visible in the final products. It is not within the scope of this report to attempt to quantify the differences in the two methodologies. Suffice it to say that, by convention, the usual source for LaRC analysis is the LAIRS file (see Reference 6) and, also by convention, the JSC BET activity utilizes the "totem pole" atmospheres in conjunction with a bi-variate latitude/longitude interpolation algorithm. As part of an overall quality assessment, both atmospheres are considered prior to release of the final LaRC BET products. For the purposes herein, both remote atmospheric sources are considered. Thus, readers can review the results from each⁽²⁾, reminded that, for the most part, any differences shown reflect process differences since, in most instances, the same sounding information was utilized. What is not reflected directly is the accuracy of these soundings per se which would, of course, be subject to some error.

Models

The two models considered, namely the MSFC Global Reference Atmosphere and the Air Force 1978 Reference Atmosphere, are very comprehensive models which incorporate latitudinal and seasonal effects. A third model, the 1976 Standard Atmosphere, is only utilized to normalize the density profiles to show any signal in the various density profiles. The GRAM model, which was furnished by the government via JSC, is the most general. The Air Force model is only defined up to 90 km (55 km at the pole) and requires some extrapolation to higher altitudes. For general utility, a comprehensive upper atmosphere model would need be developed. The GRAM model already has the Jacchia-Roberts model available, and, what might prove valuable for future AOTV trajectory analyses, a spherical harmonic wind model.

(2) It is to be understood that comparisons of the two remote sources on four of the flights is not valid. The LaRC BETs utilized density profiles derived from in situ Development Flight Instrumentation pressure measurements for STS-3 and STS-5; the Air Force 1978 Model for STS-9 due to ground track considerations; and the equivalent NOAA "totem-pole" data for STS-13.

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$$\Delta C_N = \frac{(\text{flight-predicts})}{\text{flight}} \times 100$$

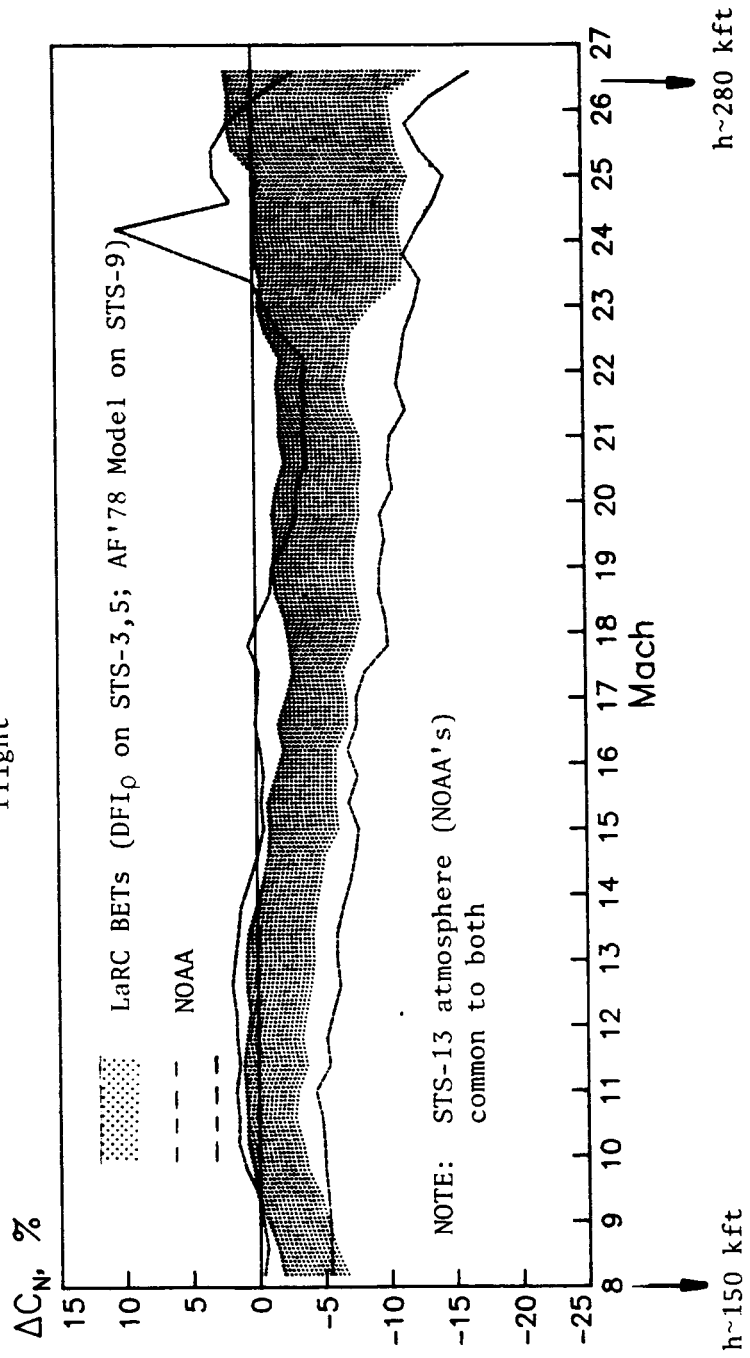


Figure 3. Pre-flight Orbiter aerodynamic data base accuracy based on actual Shuttle flight experience.

IV. Discussion of Results

Appendices A and B present density and temperature comparisons by flight for each of the available atmospheric sources. Included thereon are the Shuttle derived results. The density plots are normalized to the 1976 Standard Atmosphere to exemplify differences and permit detection of structure in the derived data. The temperature plots are included for completeness with virtually no discussion. It is density, and representative structure in same, that is of paramount importance to AOTV trajectory analysts. Readers can make specific comparisons for each flight by referring to the appropriate figure in the Appendices. Specifically, one can see the somewhat unique structure encountered during each entry. Also, any differences between the remote source data, where available, are highlighted by the shaded regions thereon. Finally, the adequacy (or lack thereof) of each of the two models and potential for improvement are readily visible. Annotation and comments as necessary are included on each chart. In this Section, a general summary of the more relevant results is presented. A measure of the range of densities sensed by the accelerometers is compared directly with the other sources. Finally, the differences between the sensed atmosphere and each source is quantified statistically.

Shuttle derived atmospheres

- Though each flight is somewhat unique, there is considerable similarity by season. Part 2 of this final report presents the derived data in this form (scaled to the GRAM values) for modelling purposes. Reference 7 also presented comparisons by season.
- Large shears (up to 15 percent on STS-4) are visible in the summer months between altitudes of 230 kft <h> 250 kft. These shears occur, in some instances, over altitude intervals on the order of 100 ft, i.e., over a period of 1 to 2 seconds, inferred from the descent rate curve (Figure 2).
- The "pothole-in-the-sky" structure observed in the STS-2 flight data is shown as a region of less density in the interval, 230 kft <h> 250 kft. In retrospect, this region,

though cause of major concern during the early aerodynamic research activity, is not so unique since similar structure can be seen in many of the flights, particularly since the results have been developed at higher altitudes for this study.

- There is typically more structure suggested in the spring months at altitudes above $h \sim 280$ kft. In particular, abrupt increases in density on the order of 15 to 20 percent over ~ 2 kft (3 to 4 seconds) are observed, e.g., at ~ 280 kft on STS-1, ~ 295 kft on STS-3.
- STS-5 results (Figure A-5) show a somewhat unique profile between 250 kft and 280 kft. This November entry implies a sharp density increase (~ 15 percent) at ~ 276 kft, decreasing as a triangular wave by ~ 10 percent, followed by two abrupt shift increases; one at ~ 266 kft and the second at ~ 252 kft. This atmosphere is perhaps the most noticeable multi-layered profile of any of the flights.
- The somewhat unique result shown for STS-9, which exhibits much less density above 230 kft, suggests some latitudinal model improvements can be made but more high inclination entry flights are certainly required. Also, STS-11 is the only winter flight available which presents a limitation in the atmospheric data base for model improvement.
- Given that the AOTV experiment is currently planned with a near Equatorial aero-assist maneuver, it is relevant to look specifically at the results from STS-3, 6, 13 and 11. These flights, ordered as indicated, are closest to the Equator during descent. Atmospheric perturbations therein are no less significant.

Though not specifically presented herein, readers can refer to the discussions in Reference 7 pertaining to potential atmospheric stability (convective overturning) in the encountered atmospheres of STS-2 and STS-4. The derived temperature profiles showed regions with super adiabatic lapse rates though, as suggested, the shallow aspects

of the STS entry profile must be considered as a possible limitation. It was recognized that the analysis was limited to implications in the vertical and, quite possibly, horizontal structure could have been encountered.

Remote measurements

Figures 4 and 5 show range of densities, as the shaded region, from the two remote sources, LAIRS and NOAA, respectively, based on the first twelve flights. Superimposed on each figure is the suggested density range (as the dashed lines) sensed by the accelerometry. Clearly the left boundary of the C_{Np} derived density spread is governed by STS-9. Therein, the LAIRS data, which utilized the AF'78 atmosphere for that flight, is somewhat misleading when represented as remote data. In any event above $h \sim 230$ kft, none of the remote sources show as broad a range of density as sensed. Other general comments are:

- Remotely measured atmospheres, due to smoothing processes at the various levels of data reduction, can never reflect the small scale atmospheric structure sensible in the Orbiter accelerometry.
- There are systematic differences between the two remote atmospheres in most instances which reflect process differences, not sounding accuracy. However, statistically each provides for essentially the same (on average) results as was shown in the ΔC_N curve of Figure 3.
- The importance of spatially (and time) optimum soundings cannot be overemphasized, in particular in view of the poor STS-9 results (Figure A-9) which required considerable translation in the latitudinal direction.
- Shuttle has had good quality sounding data for the most part. Known problems existed on STS-3 and the quality of the data for STS-11 was questionable. Fortunately, on STS-3 the DFI data were available. However, the large differences shown between the two remote sources in Figure A-10 for STS-11 certainly vindicate the need for accurate sounding information.

The above considerations are extremely relevant if an AOTV experiment is flown with planned meteorological support.

Models

Figure 6 and 7 show the range of densities over the first twelve flights suggested by the AF'78 and GRAM models, respectively, as shaded regions. Superimposed thereon are the same range of densities as sensed in the accelerometry. Both models appear to reflect the higher density boundary, albeit too dense throughout. Neither model reflects the increased spread above $h \sim 230$ kft. Again this is a latitudinal limitation. Other relevant comments are:

- Neither the GRAM nor AF'78 model can be expected to exhibit the sharp density structure evidenced in the Shuttle derived profiles.
- The GRAM density is too dense in the month of September above $h \sim 230$ kft as observed in the STS-8 and STS-14 charts (Figures A-8 and A-12, respectively). The temperature charts (Figures B-8 and B-12) would not necessarily indicate a problem in this month. The atmosphere is somewhat warmer in the region, $210 \text{ kft} < h < 280 \text{ kft}$.
- Both the GRAM and AF'78 models reflect the lower density sensed by the accelerometry for the high latitude entry flight (STS-9, Figure A-9), at least up to an altitude of $h \sim 230$ kft. However, at least for this flight, the AF'78 model would appear to be a somewhat better, though still limited, latitudinal (seasonal) representation at higher altitudes.
- Above $h \sim 250$ kft on STS-11 (Figure A-10), the only winter flight available, there are appreciable differences between the GRAM and AF'78 density profiles.
- For nine(9) of the flights, the GRAM is as good or slightly better than the AF model.

Assuming the preceding limitations are reviewed by the MSFC, the GRAM should provide AOTV analysts with a good model for future studies. It has the advantage over the AF'78 in that it contains a Jacchia-Roberts formulation for higher altitudes.

Statistical considerations

Figure 8 presents the statistical accuracy of each atmospheric source. Plotted are the computed $1\sigma(\pm)$ error about the mean difference between each source and the sensed density. The statistics for all four sources are essentially ± 5 percent (normalized to the 1976 Standard) up to $h \sim 250$ kft. Again, the overpredicted data base is substantiated in sub-Figure (b) for the remote sources. One can visually shift out the 3 to 5 percent due to the C_{Np} overprediction, at least below 280 kft. In this region, both models appear to be too dense, the GRAM model by 3 to 5 percent and the AF'78 from 5 to 7 percent. Each source shows an increase in the computed statistical spread above $h \sim 250$ kft, to approximately 10 to 12 percent (1σ), with visible shifts in the mean error noticeable for the LaRC data and the two models. This perhaps suggests a different C_{Np} prediction error at these altitudes. Blanchard, Reference 8, has made modifications to the data base bridging formula used between the free molecule flow and hypersonic continuum regimes based on his HiRAP analysis. However, based on private communications, the improved algorithm has minimal effect in the altitudes presented herein. Thus, one must assume, at least for the present analysis, that the curvature in the mean for these three sources reflect errors in the "average" atmospheres.

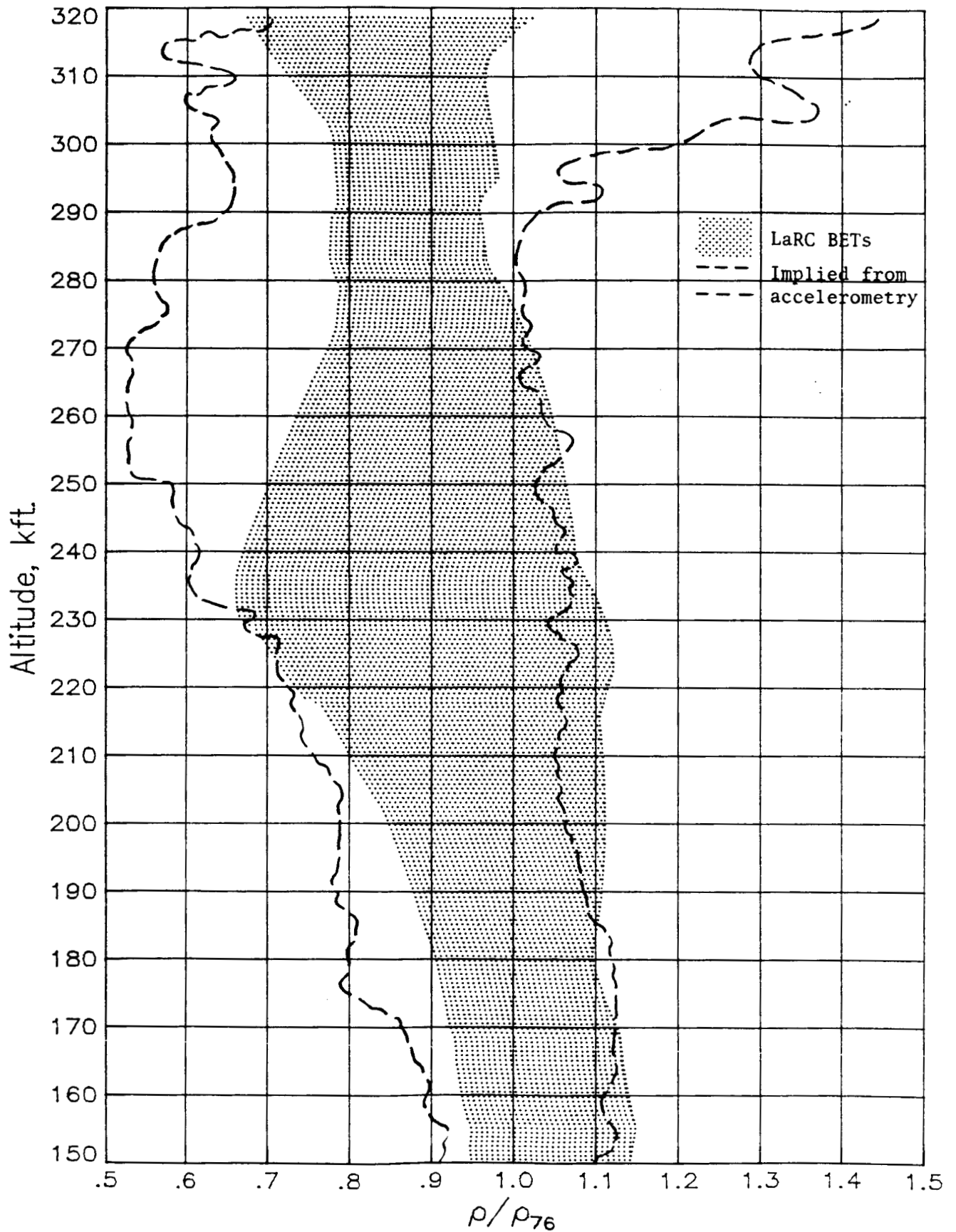


Figure 4. Comparison of density ranges (maximum and minimum values with altitude) between LaRC BET atmospheres and that implied by the accelerometry.

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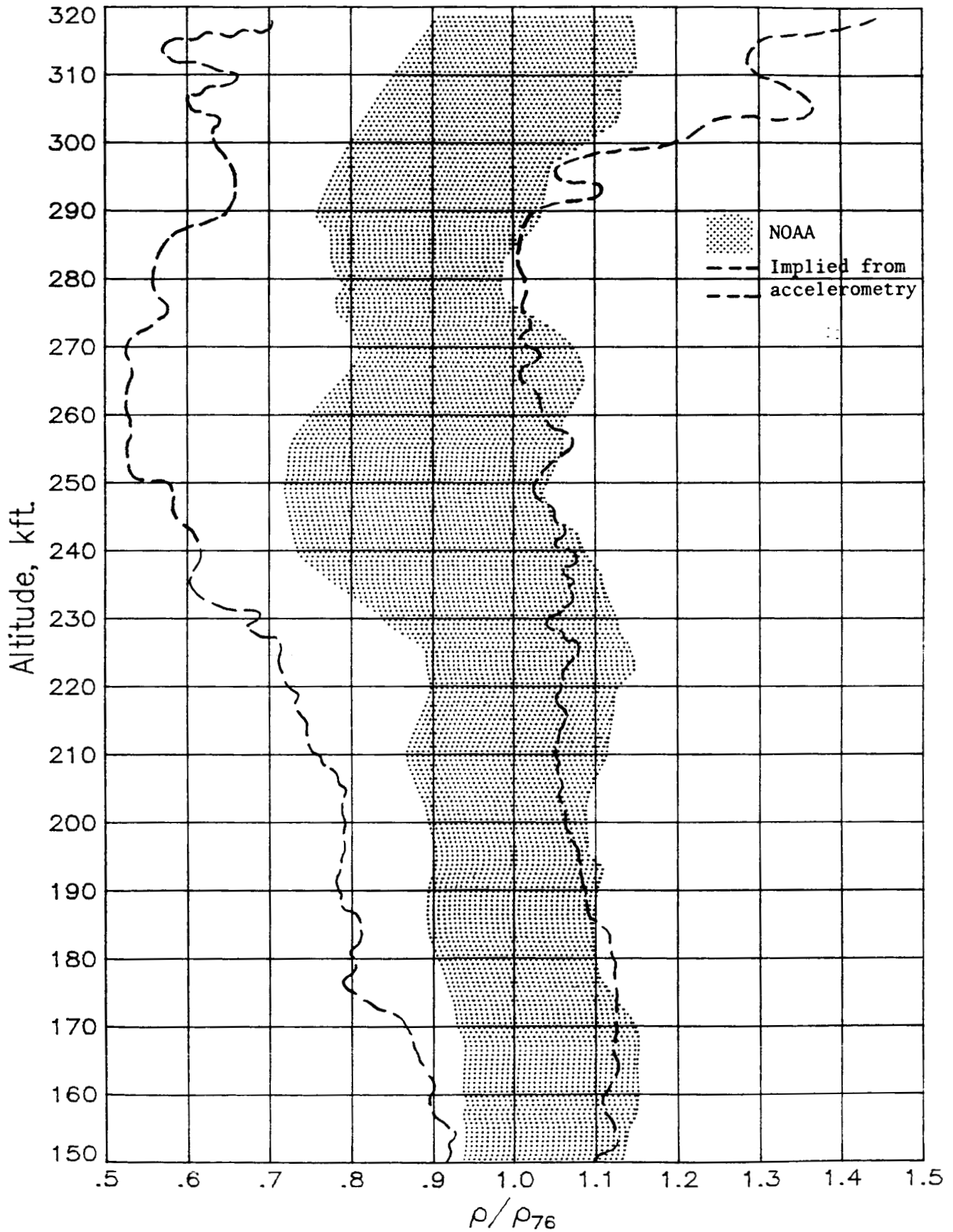


Figure 5. Comparison of density ranges (maximum and minimum values with altitude) between NOAA atmospheres and that implied by the accelerometry.

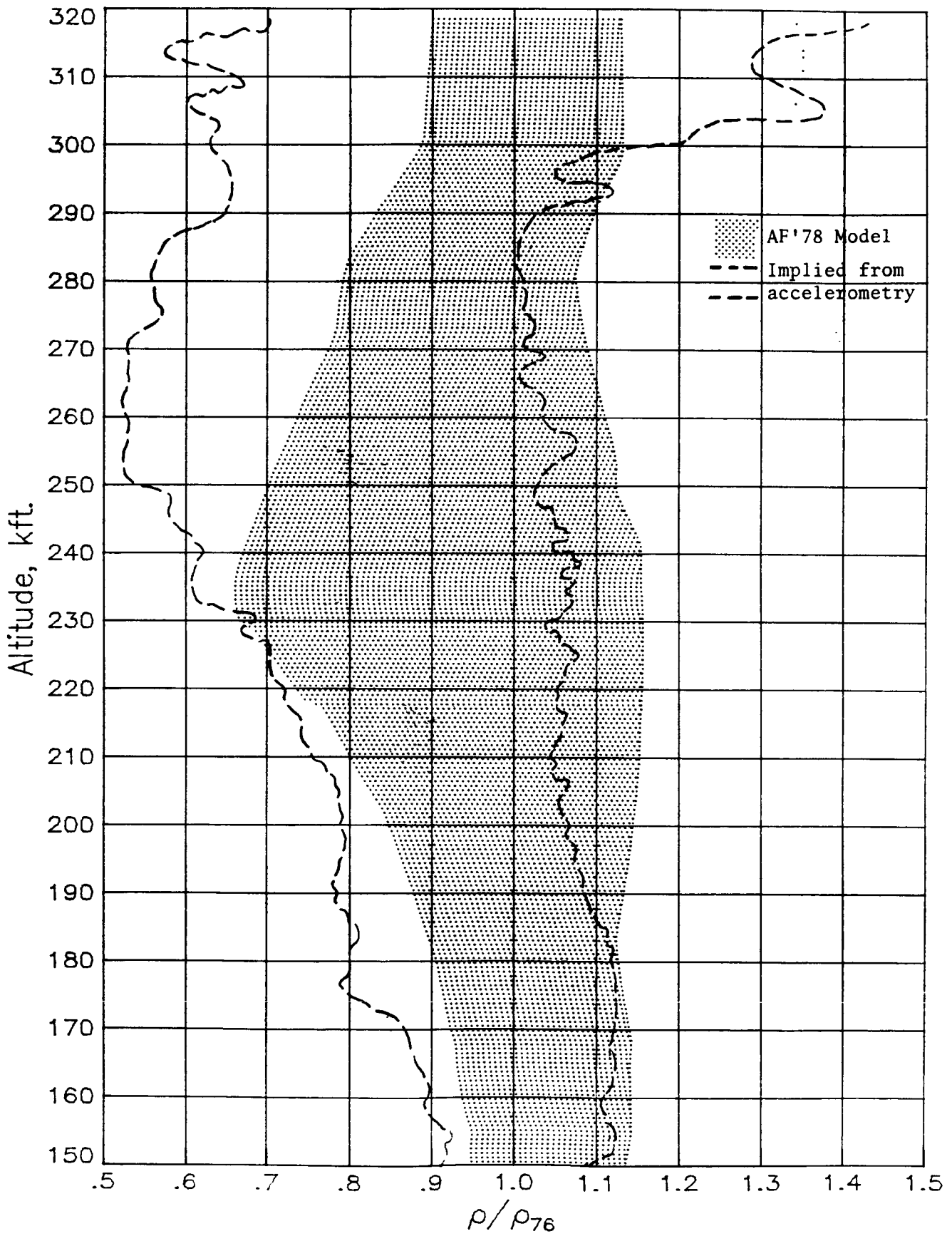


Figure 6. Comparison of density ranges (maximum and minimum values with altitude) between AF'78 atmospheres and that implied by the accelerometry. -20-

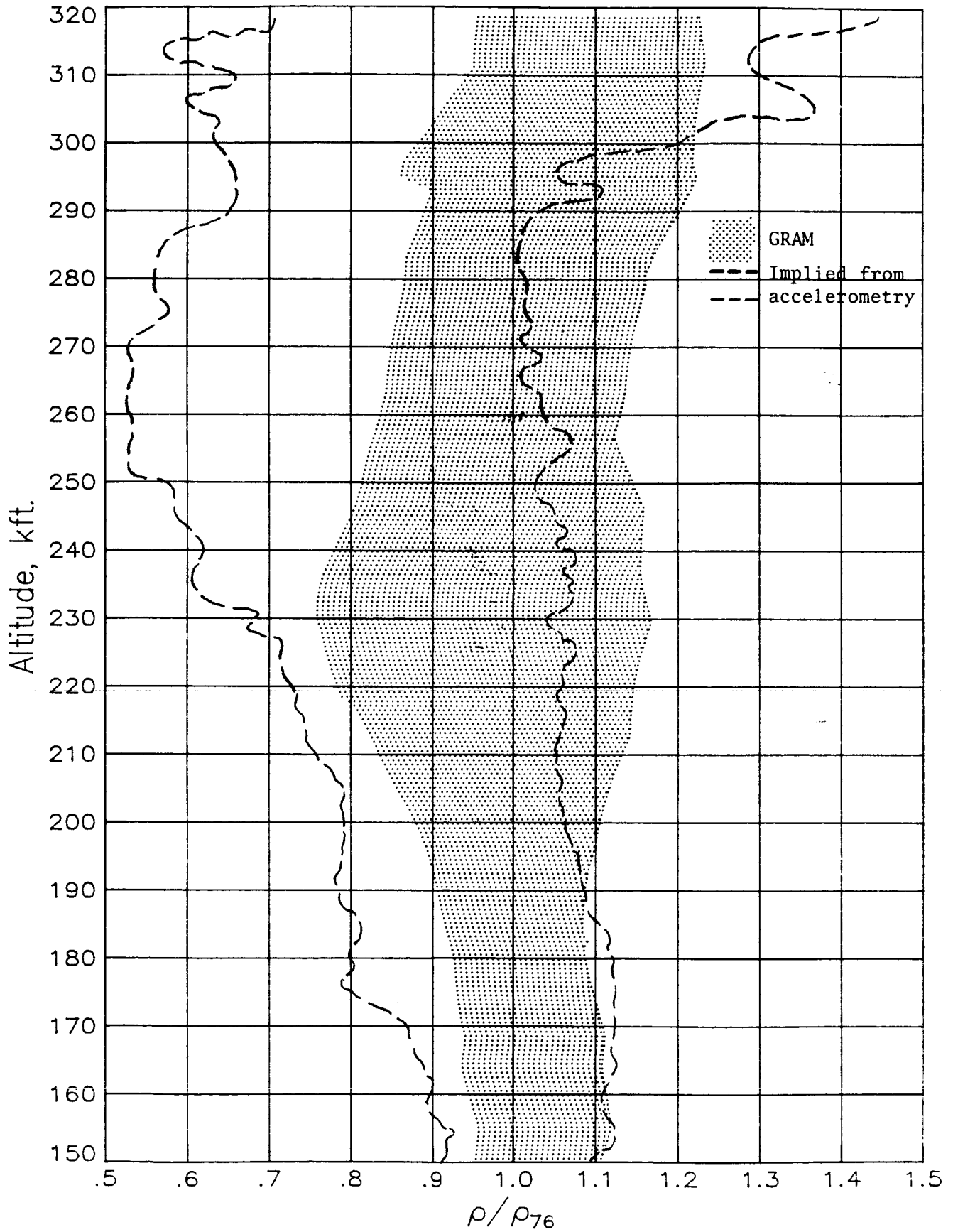


Figure 7. Comparison of density ranges (maximum and minimum values with altitude) between GRAM atmospheres and that implied by the accelerometry.

(a) Models

(b) Remote

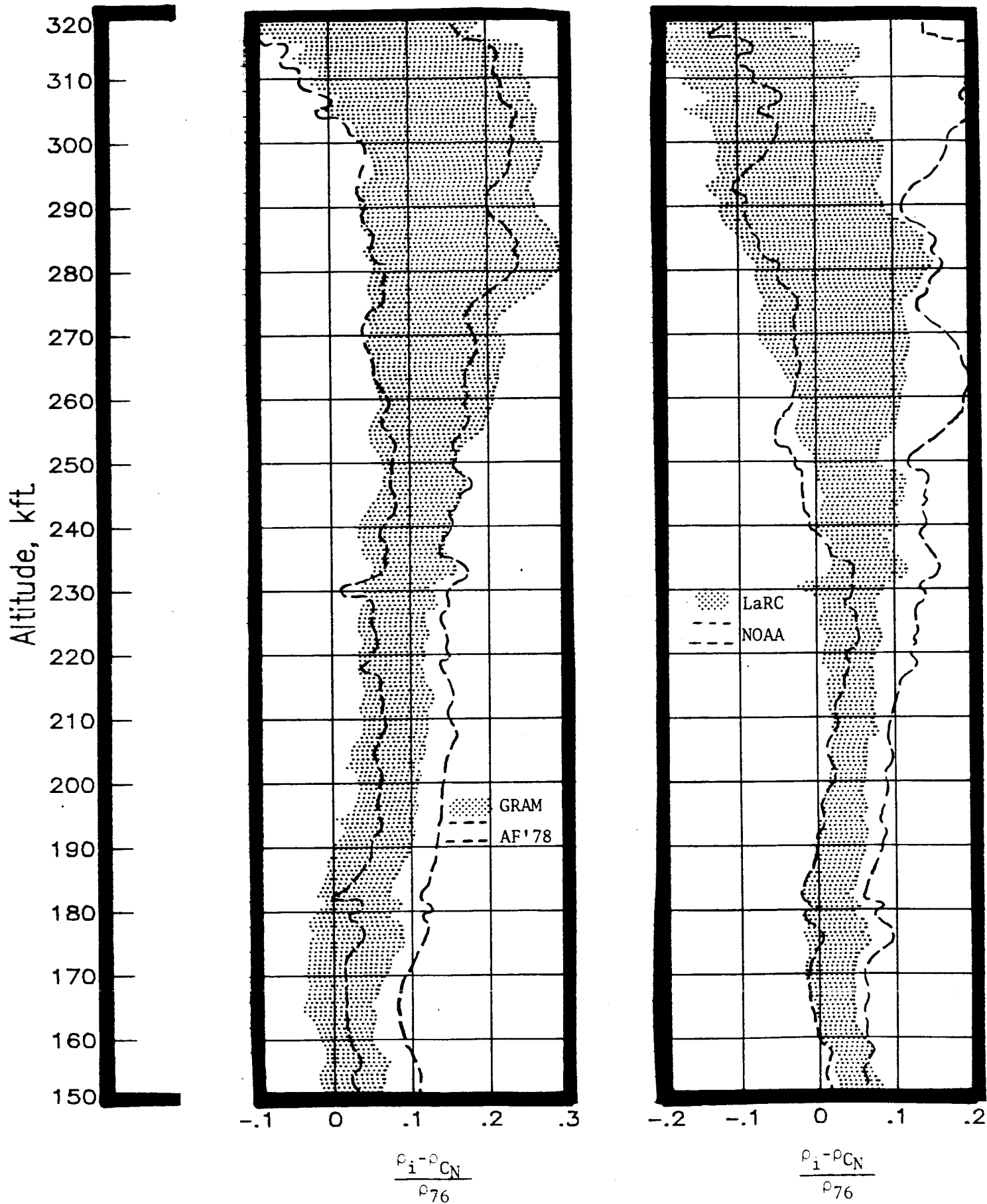


Figure 8 . Twelve flight ensemble statistical comparisons ($\pm 1\sigma$ computed error band about mean).

V. Conclusions

Atmospheres encountered during the first twelve STS flights characteristically exhibit sharp density structure, somewhat repeatable by season, which certainly must be considered significant for AOTV application. Comprehensive models and remote sounding information, the latter, though perhaps lacking locally is good on average, do not, as expected, reflect this structure. As an atmospheric data base, STS flights are limited at the higher latitudes and in the winter months. However, comprehensive coverage for three seasons in the lower Northerly latitude band ($<30^\circ$) provides a good data set for AOTV atmospheric determinations. From these flights, model adjustments can be developed to replicate Shuttle atmospheric experience.

References

1. Cerimele, C. J., Skalecki, L.M., and Gamble, J. D.; "Meteorological Accuracy Requirements for Aerobraking Orbital Transfer Vehicles"; AIAA Paper No. 84-0030; January, 1984.
2. Justus, C.G., Fletcher, G. R., Gramling, F. E., and Pace, W. B.; "The NASA/MSFC Global Reference Atmospheric Model - MOD 3 (With Spherical Harmonic Wind Model)"; NASA CR-3256; March, 1980.
3. Cole, A. E., and Kantor, A. J., "Air Force Reference Atmospheres"; AFGL-TR-78-0051; Air Force Surveys in Geophysics, No. 382; 28 February, 1978.
4. Compton, H., Findlay, J., Kelly, G., and Heck, M.; "Shuttle (STS-1) Entry Trajectory Reconstruction"; AIAA Paper No. 81-2459; November, 1981.
5. Heck, M. L., Findlay, J. T., Kelly, G. M., and Compton, H. R., "The Adaptation of a Strap Down Formulation for Processing Inertial Platform Data"; Journal of Guidance, Control, and Dynamics, Vol. 7, No. 1, pp. 15-19, January-February, 1984.
6. Price, J. M., "Atmospheric Definition for Shuttle Aerothermodynamic Investigations"; Journal of Spacecraft and Rockets, Vol. 20, pp. 133-140, March-April, 1983.
7. Findlay, J. T., Kelly, G. M., McConnell, J. G., and Compton, H. R., "Shuttle 'Challenger' Aerodynamic Performance from Flight Data - Comparisons with Predicted Values and 'Columbia' Experience"; AIAA Paper No. 84-0485; January, 1984.
8. Blanchard, R. C., and Buck, G. M.; "Determination of Rarefied-Flow Aerodynamics of the Shuttle Orbiter From Flight Measurements on STS-6 and STS-7"; AIAA Paper No. 85-0347 (to be presented at the 23rd Aerospace Sciences Meeting in January, 1985).

APPENDIX A
Atmospheric Density Comparisons
for the First Twelve Shuttle Entries

h , kft

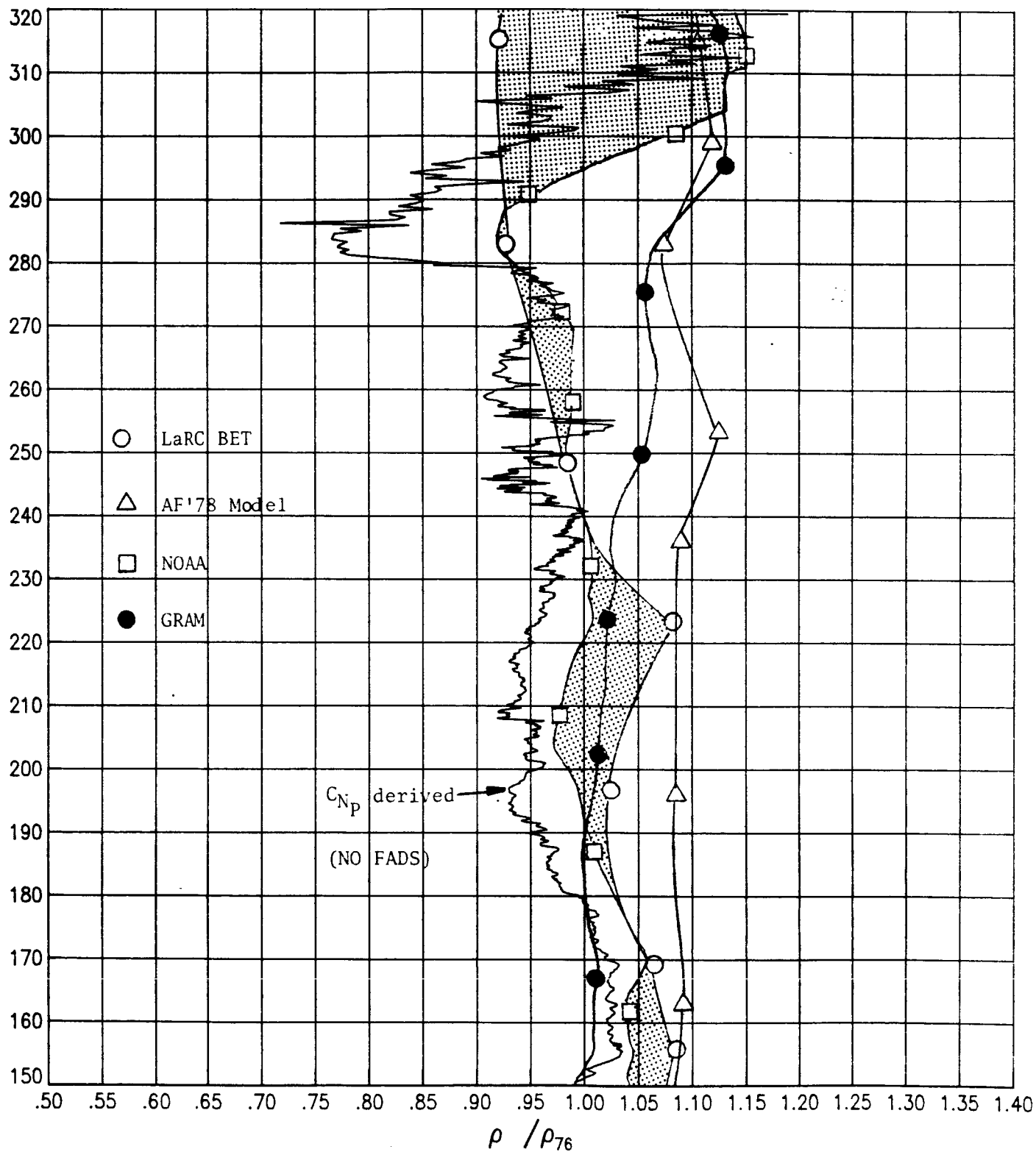


Figure A-1. STS-1 (April) density comparisons

h , kft

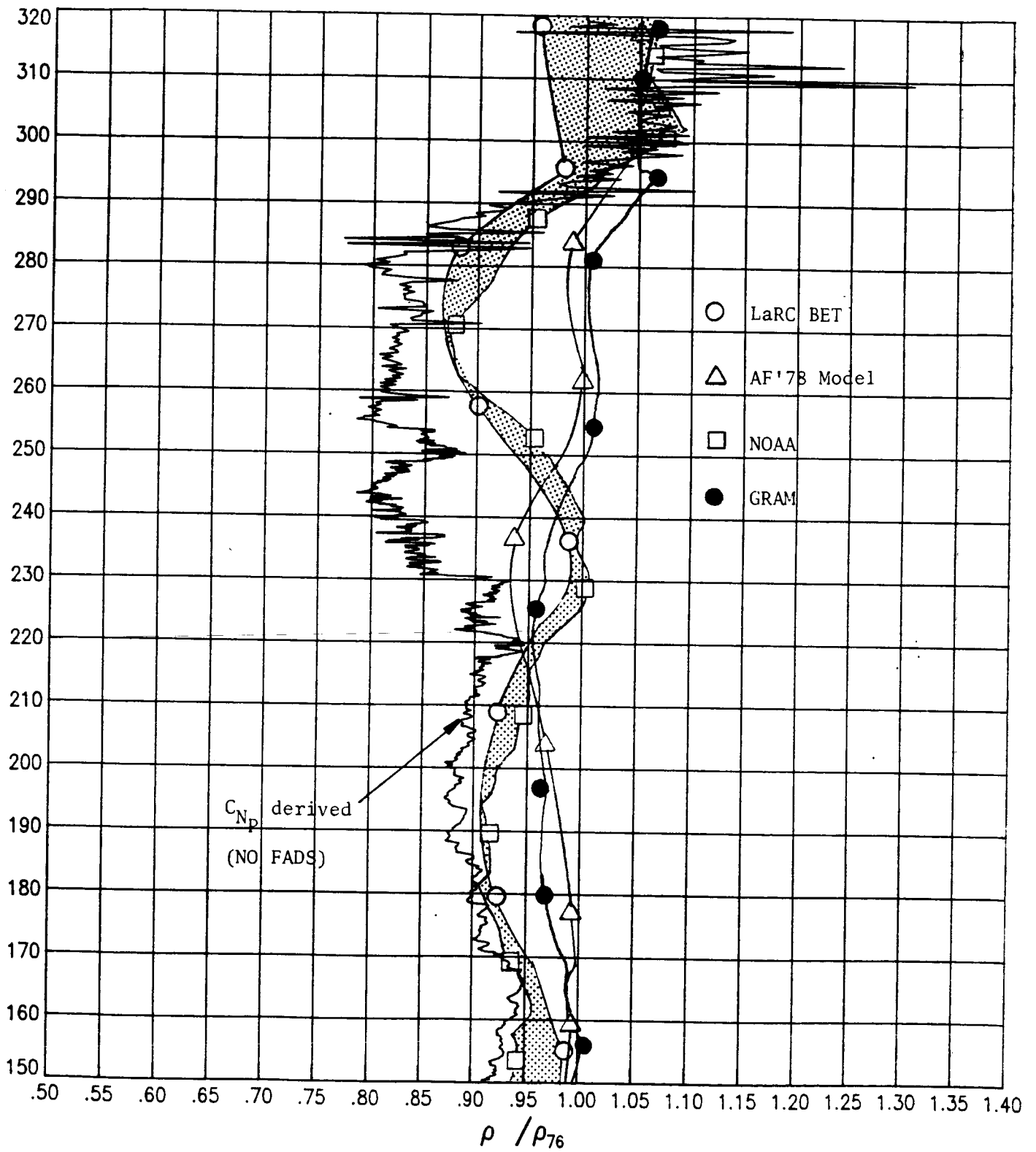


Figure A-2.STS-2 (November) density comparisons

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h , kft

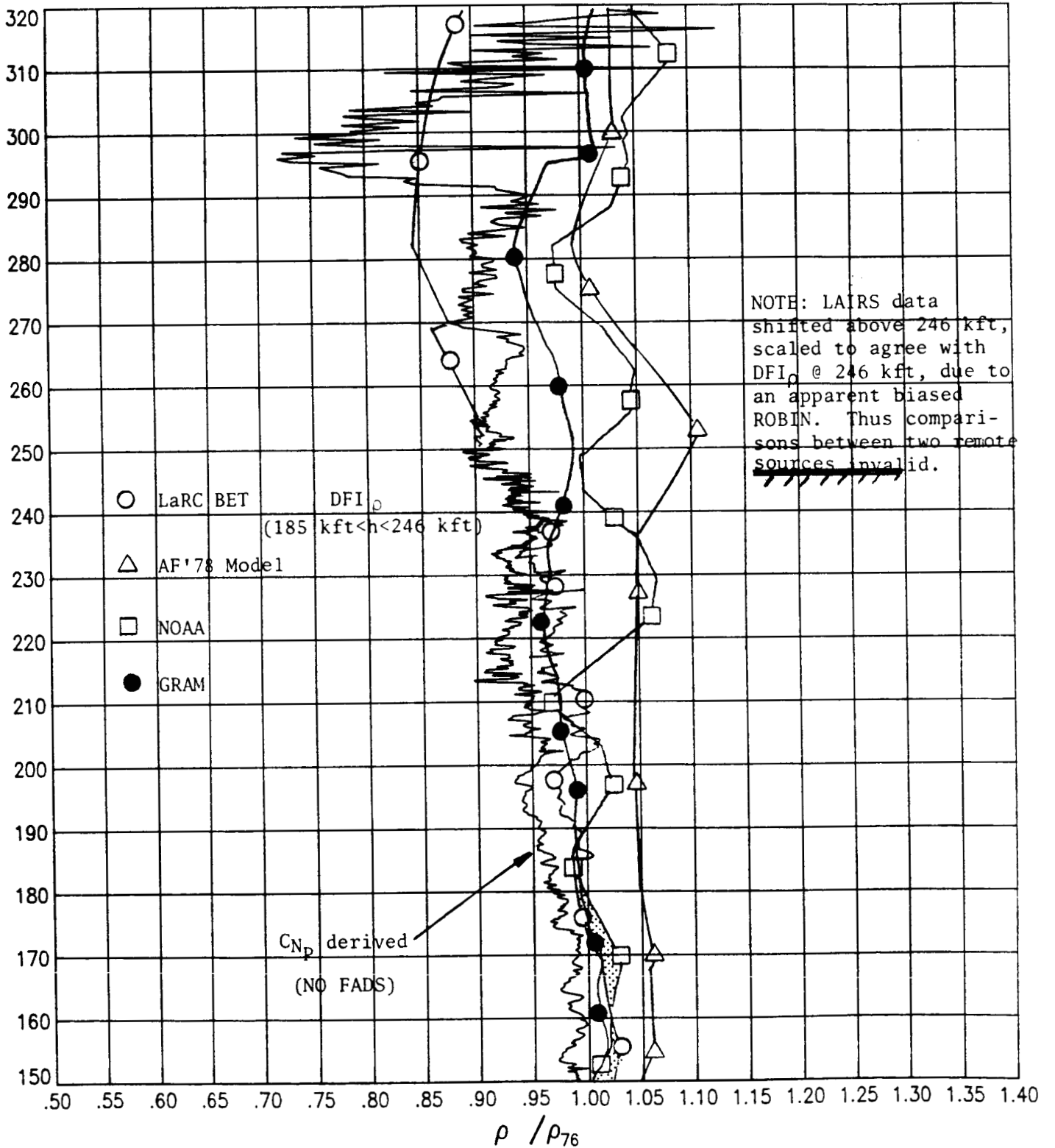


Figure A-3. STS-3 (March) density comparisons

h , kft

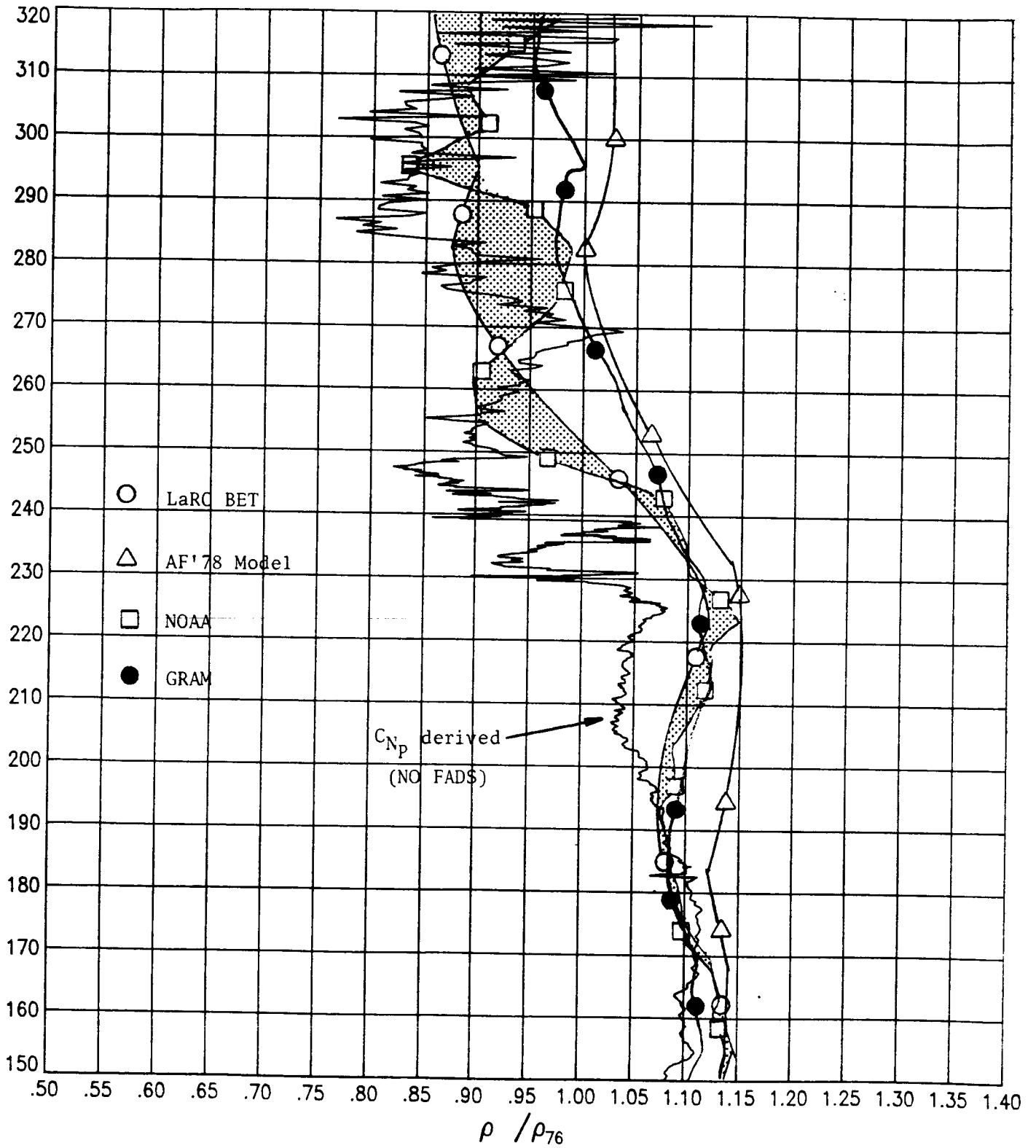


Figure A-4. STS-4 (July) density comparisons

h , kft

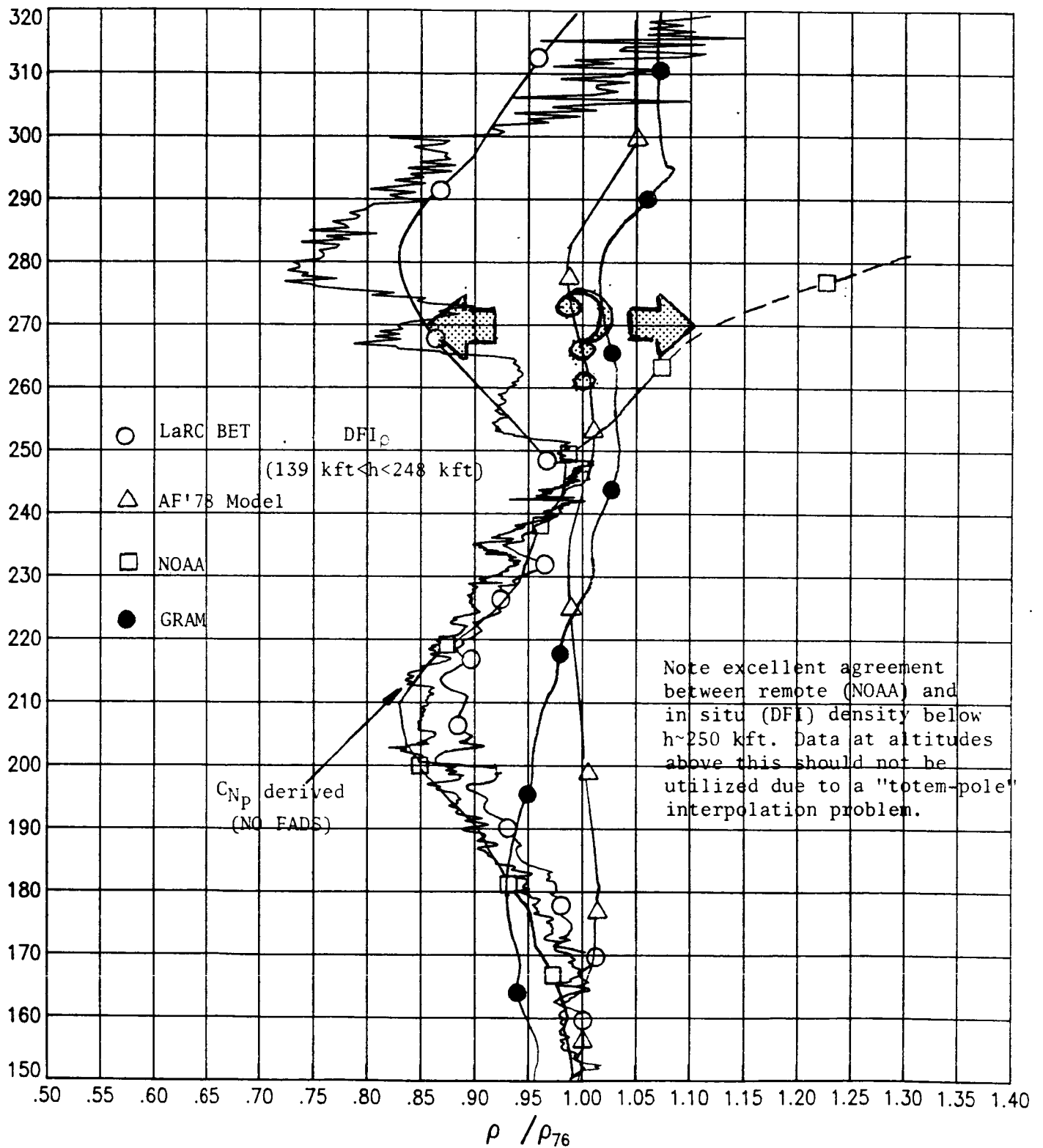


Figure A-5. STS-5 (November) density comparisons

h , kft

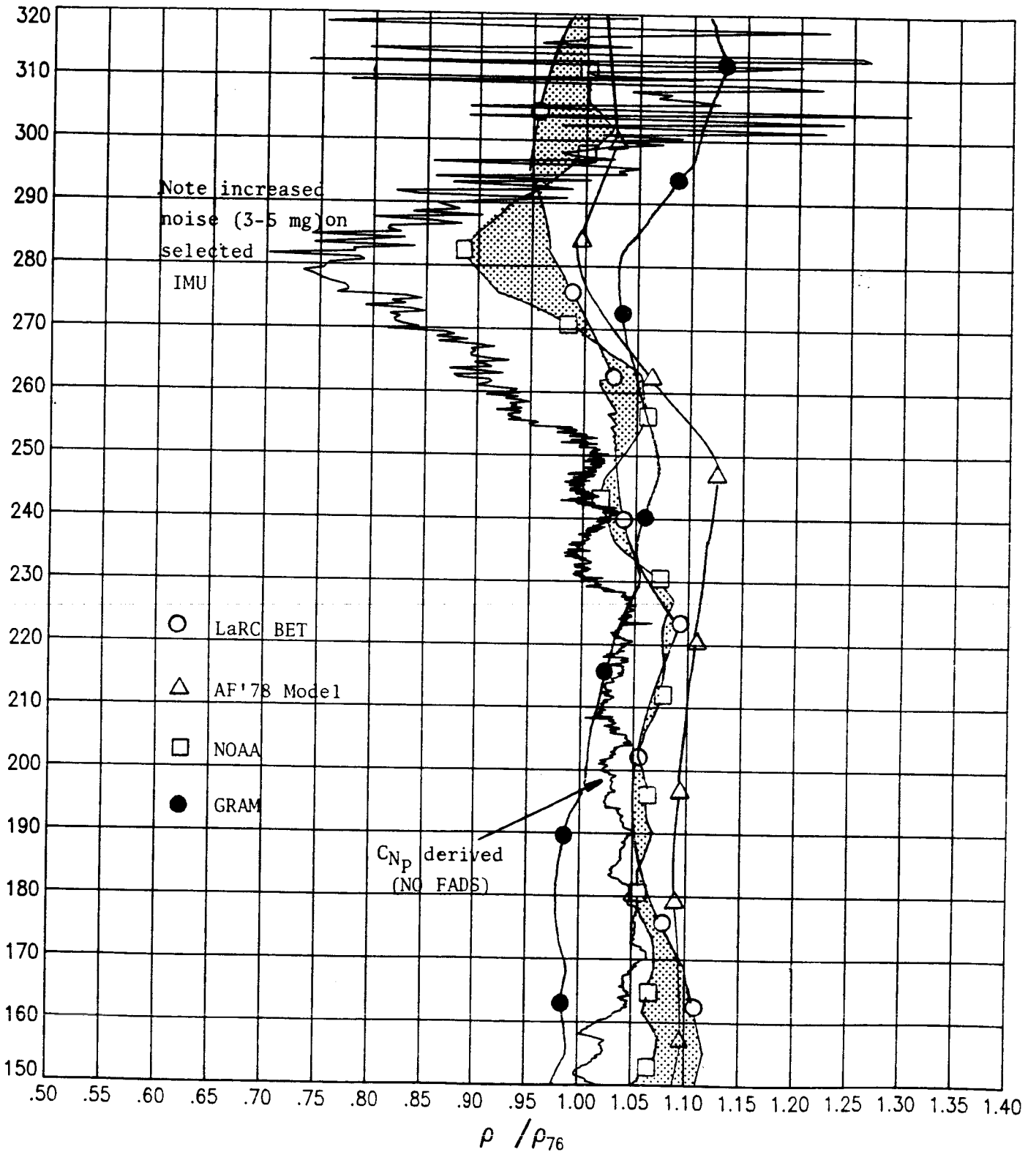


Figure A-6. STS-6 (April) density comparisons

h , kft

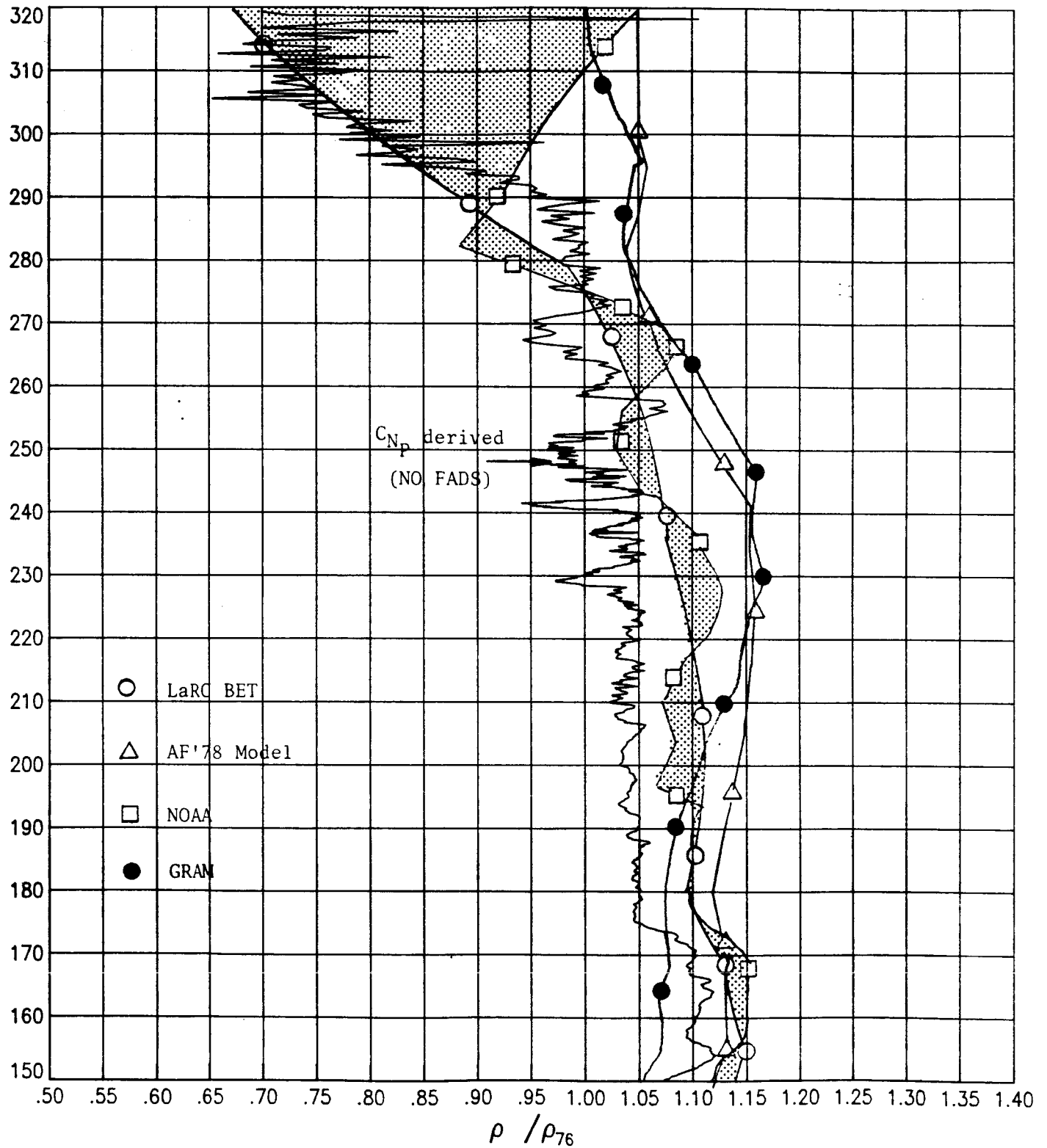


Figure A-7. STS-7 (June) density comparisons

h , kft

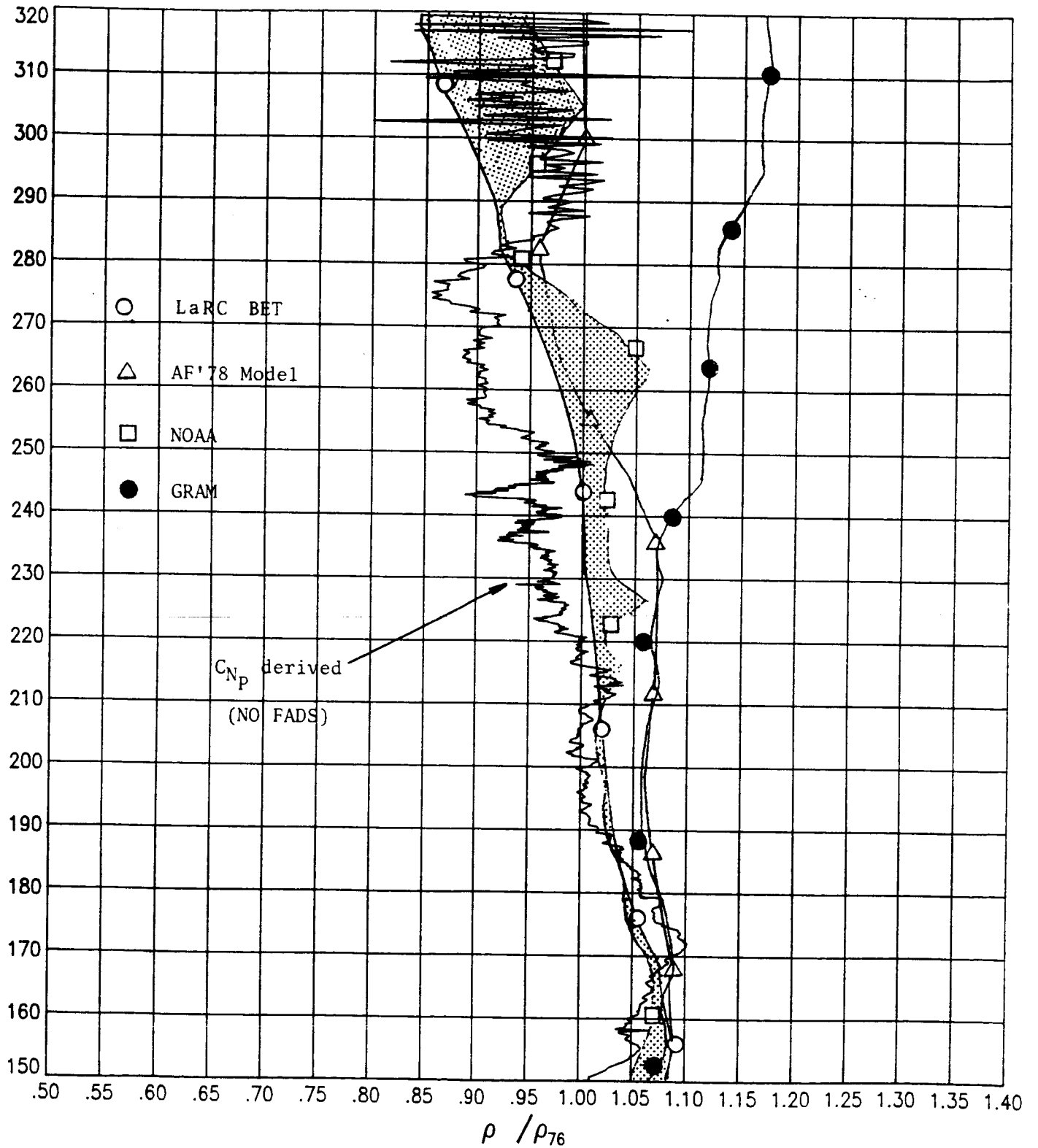


Figure A-8. STS-8 (September) density comparisons

h , kft

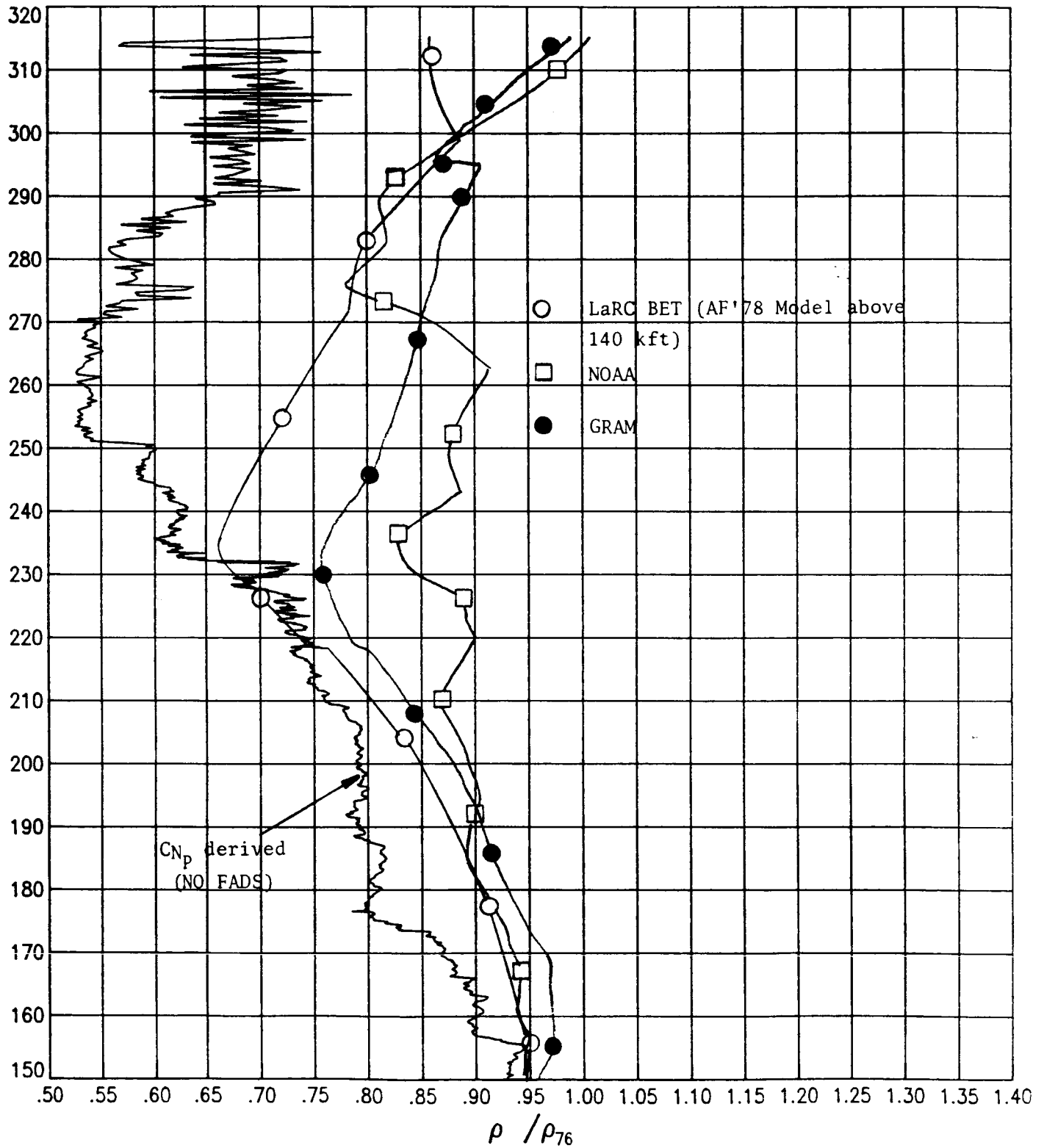


Figure A-9. STS-9 (December) density comparisons

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h , kft

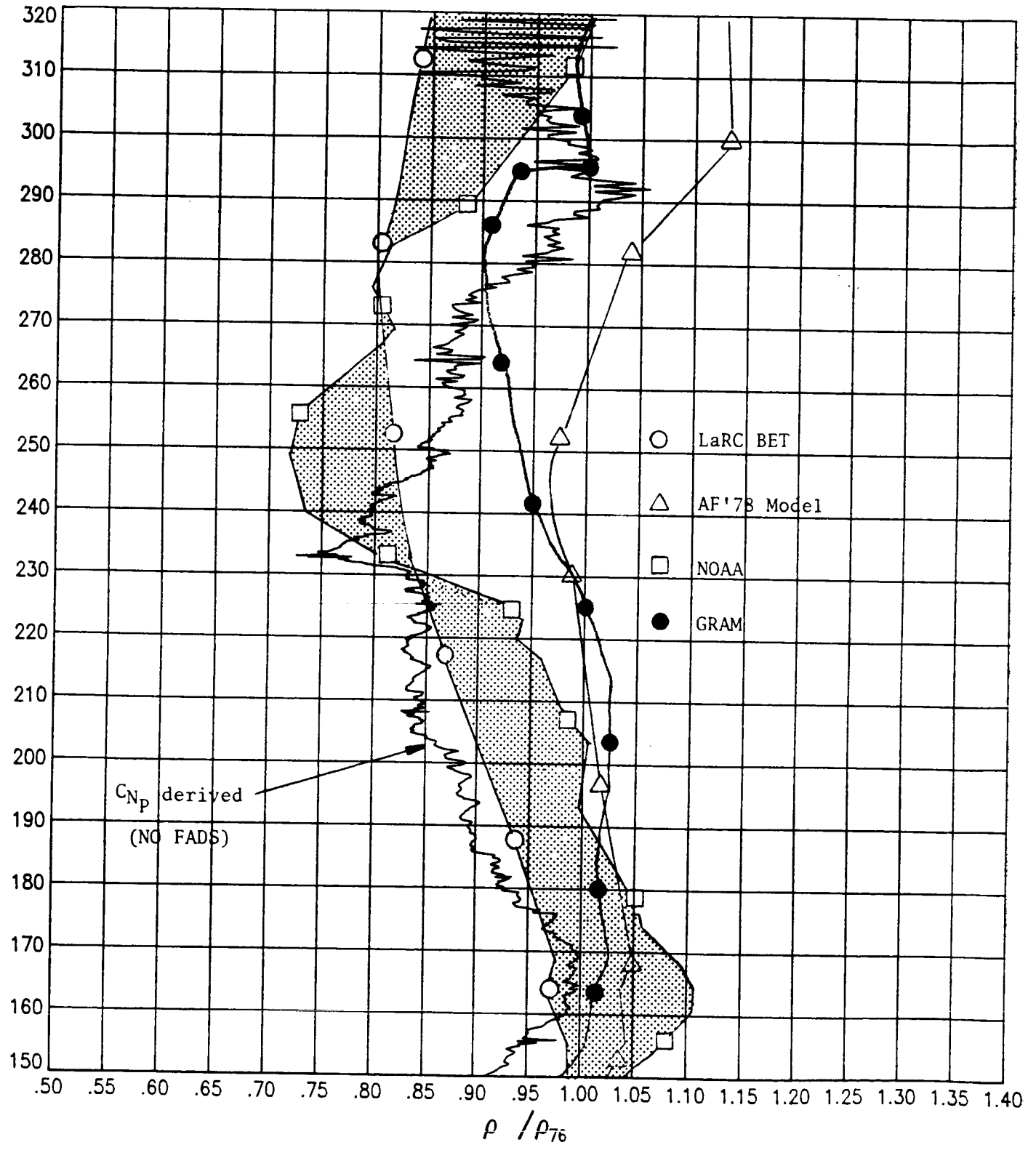


Figure A-10. STS-11 (February) density comparisons

h , kft

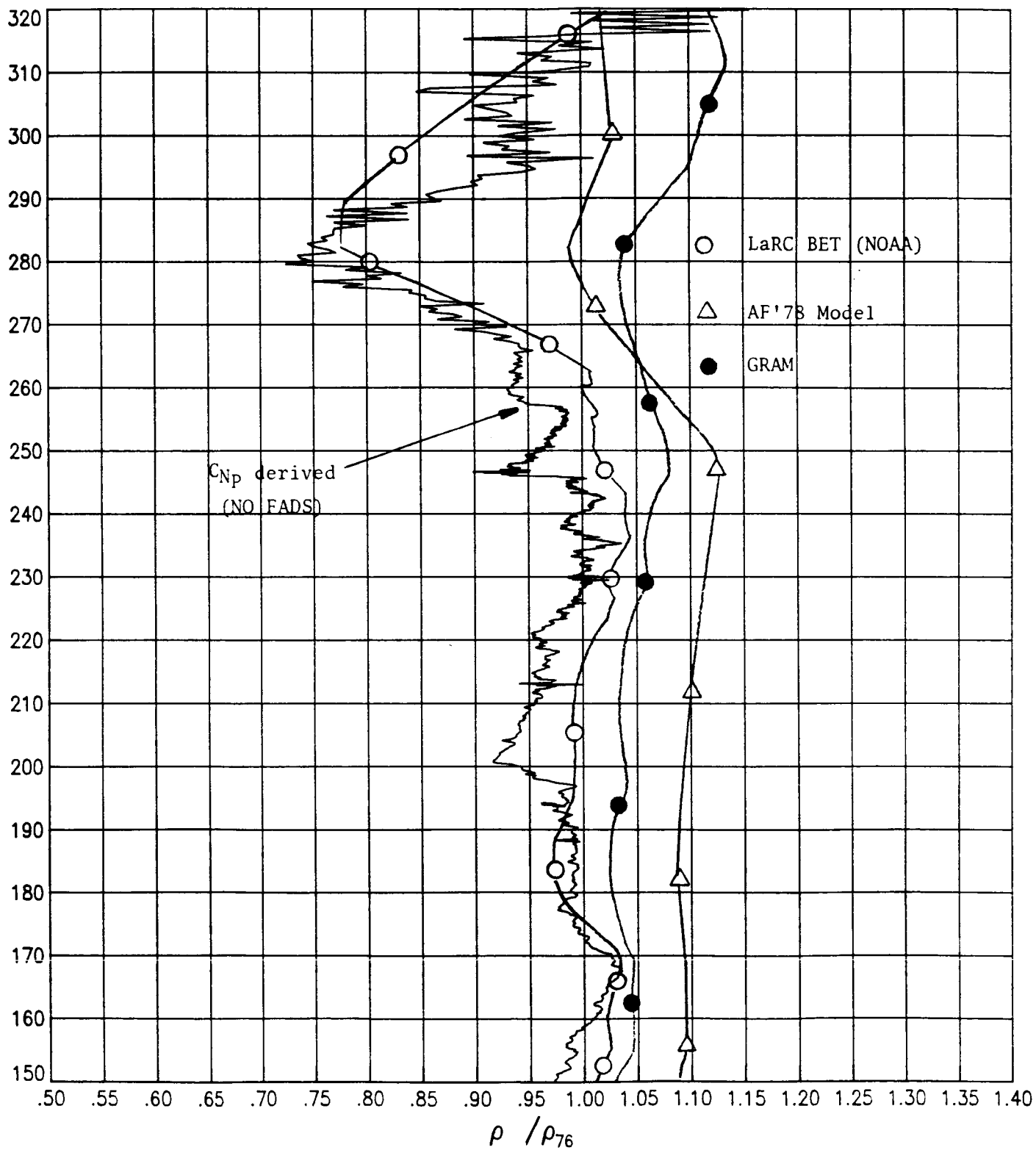


Figure A-11. STS-13 (April) density comparisons

h , kft

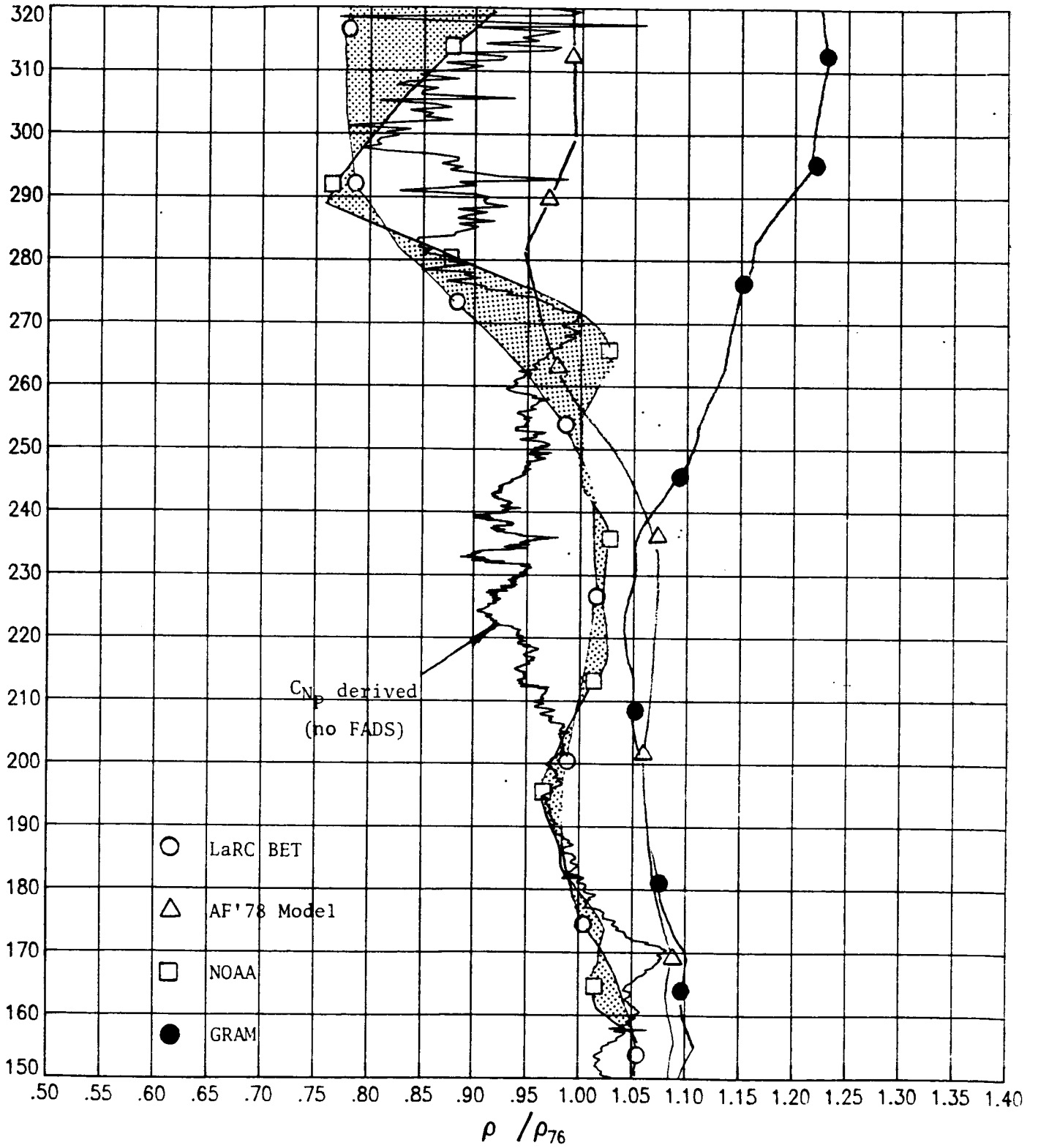


Figure A-12. STS-14 (September) density comparisons

APPENDIX B

Atmospheric Temperature Comparisons
for First Twelve Shuttle Entries

April

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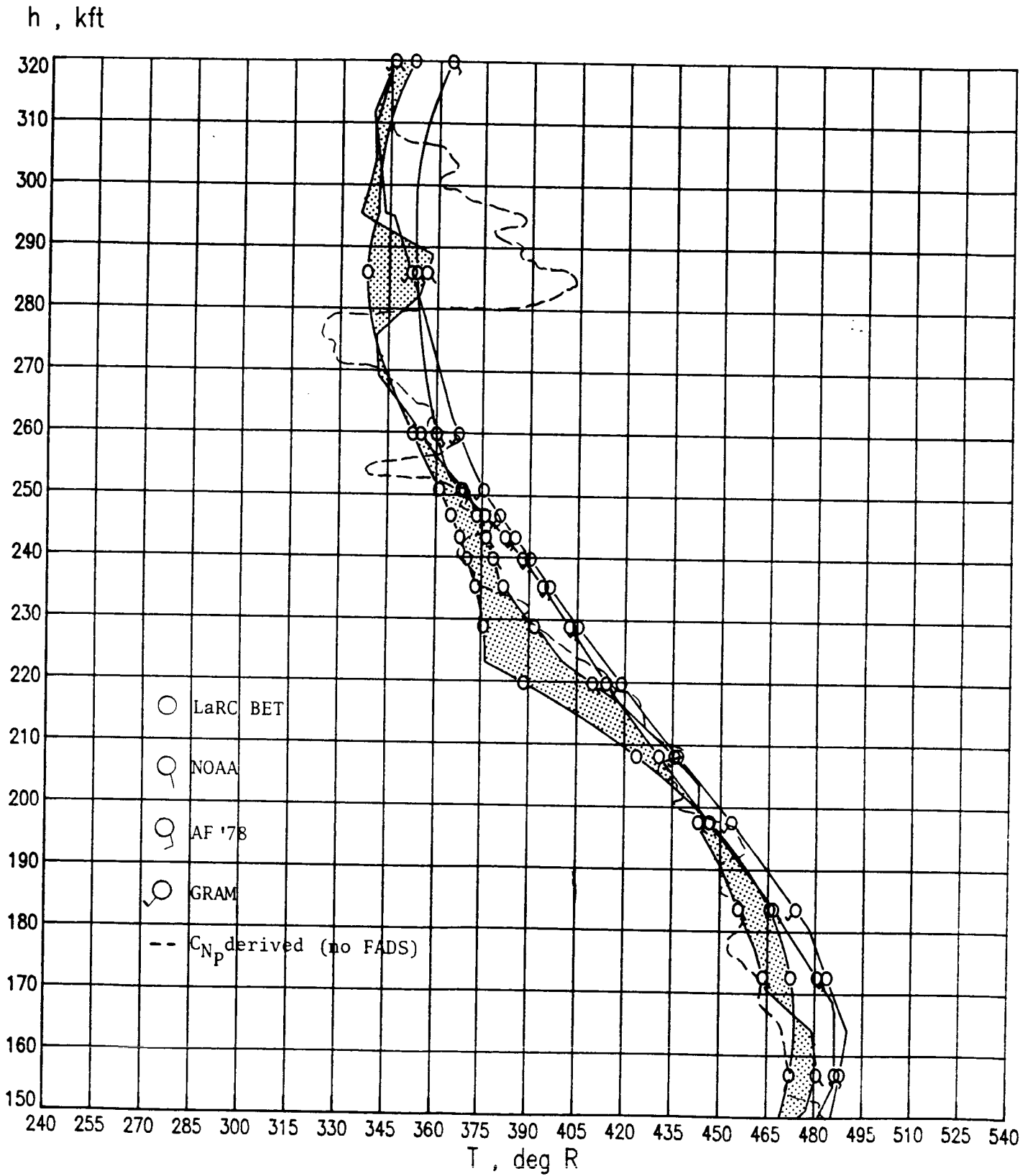


Figure B-1.STS-1 TEMPERATURE COMPARISONS

November

h , kft

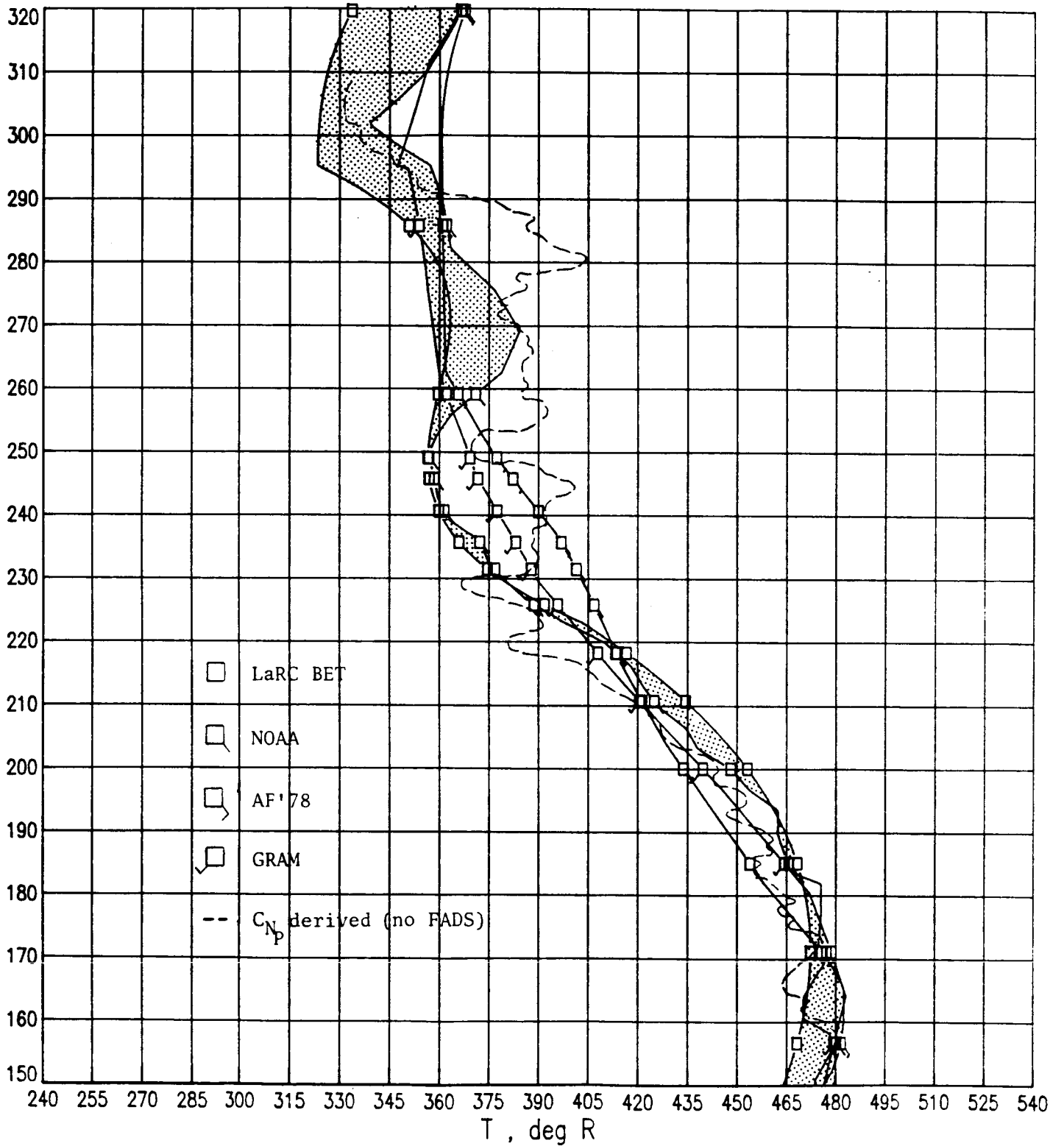


Figure B-2. STS-2 TEMPERATURE COMPARISONS

March

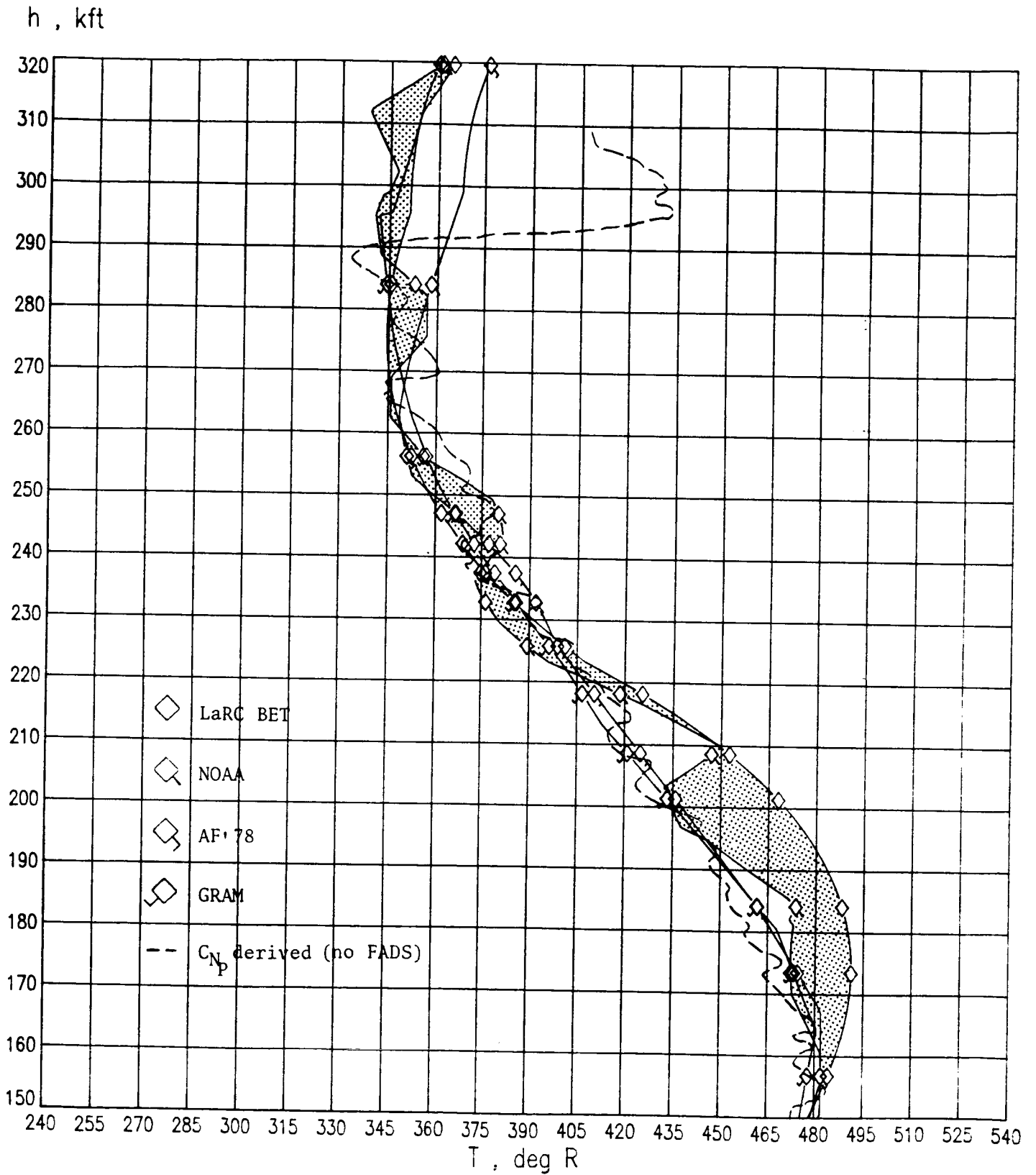


Figure B-3. STS-3 TEMPERATURE COMPARISONS

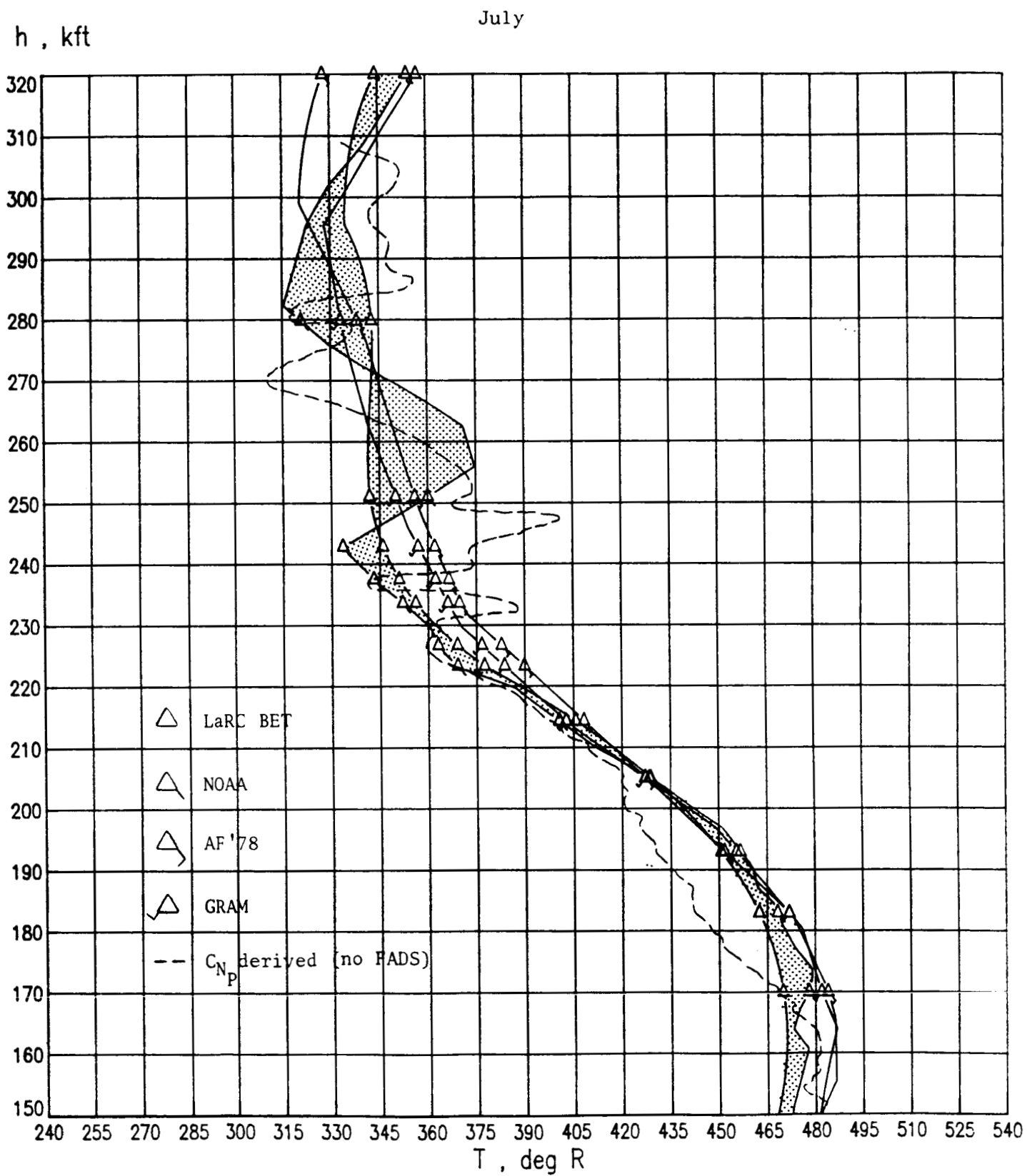


Figure B-4. STS-4 TEMPERATURE COMPARISONS

November

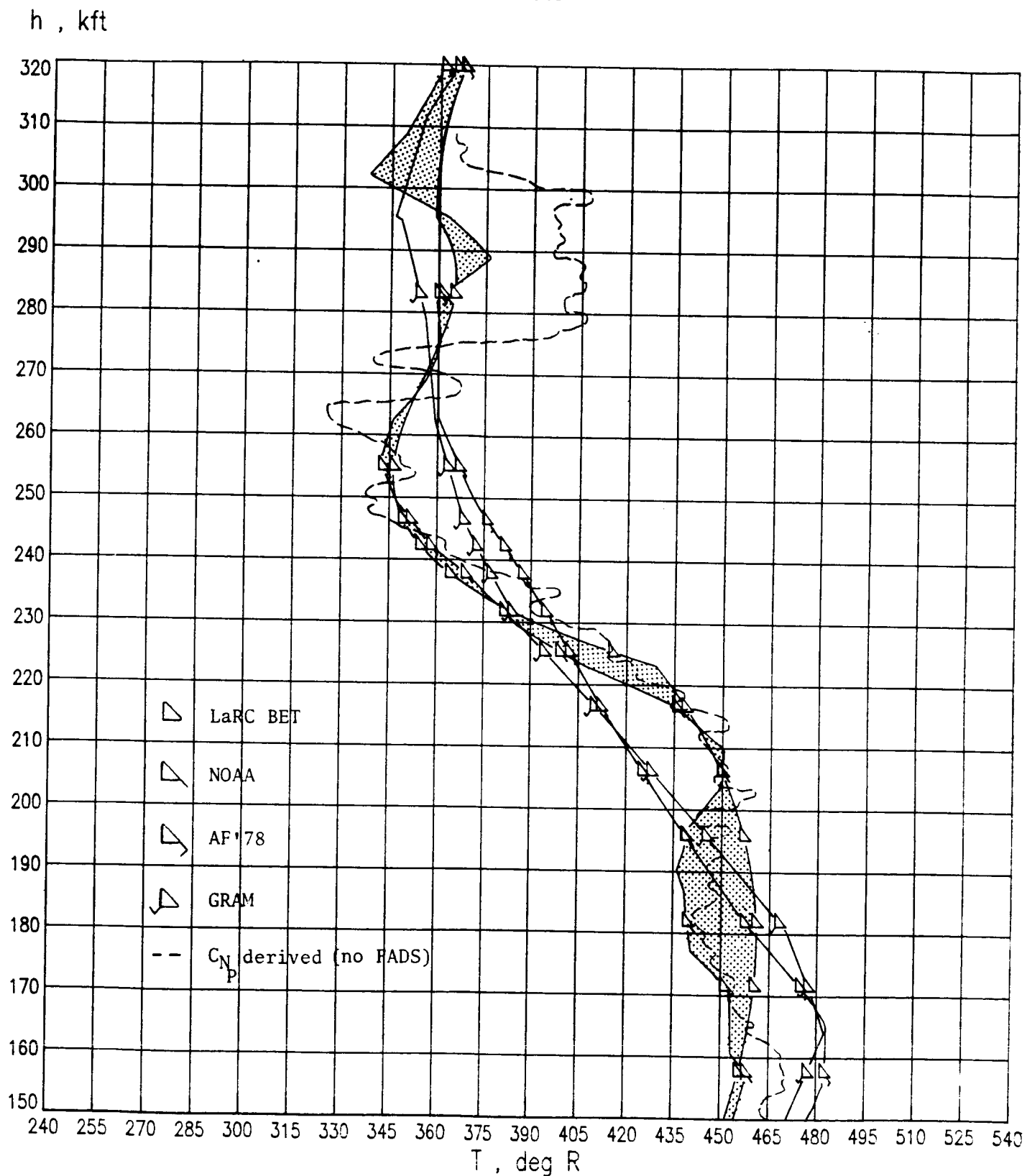


Figure B-5. STS-5 TEMPERATURE COMPARISONS

April

h , kft

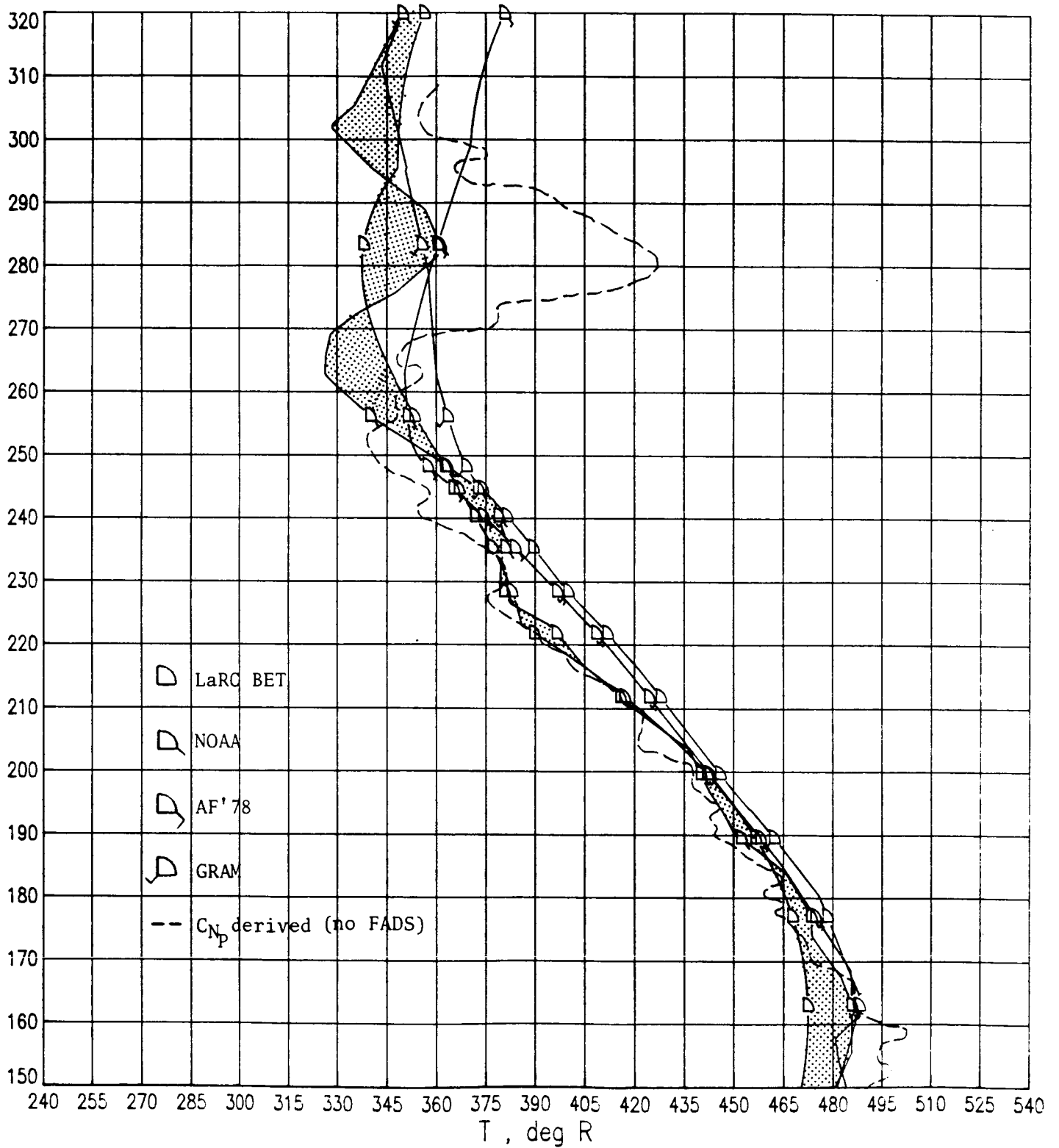


Figure B-6. STS-6 TEMPERATURE COMPARISONS

June

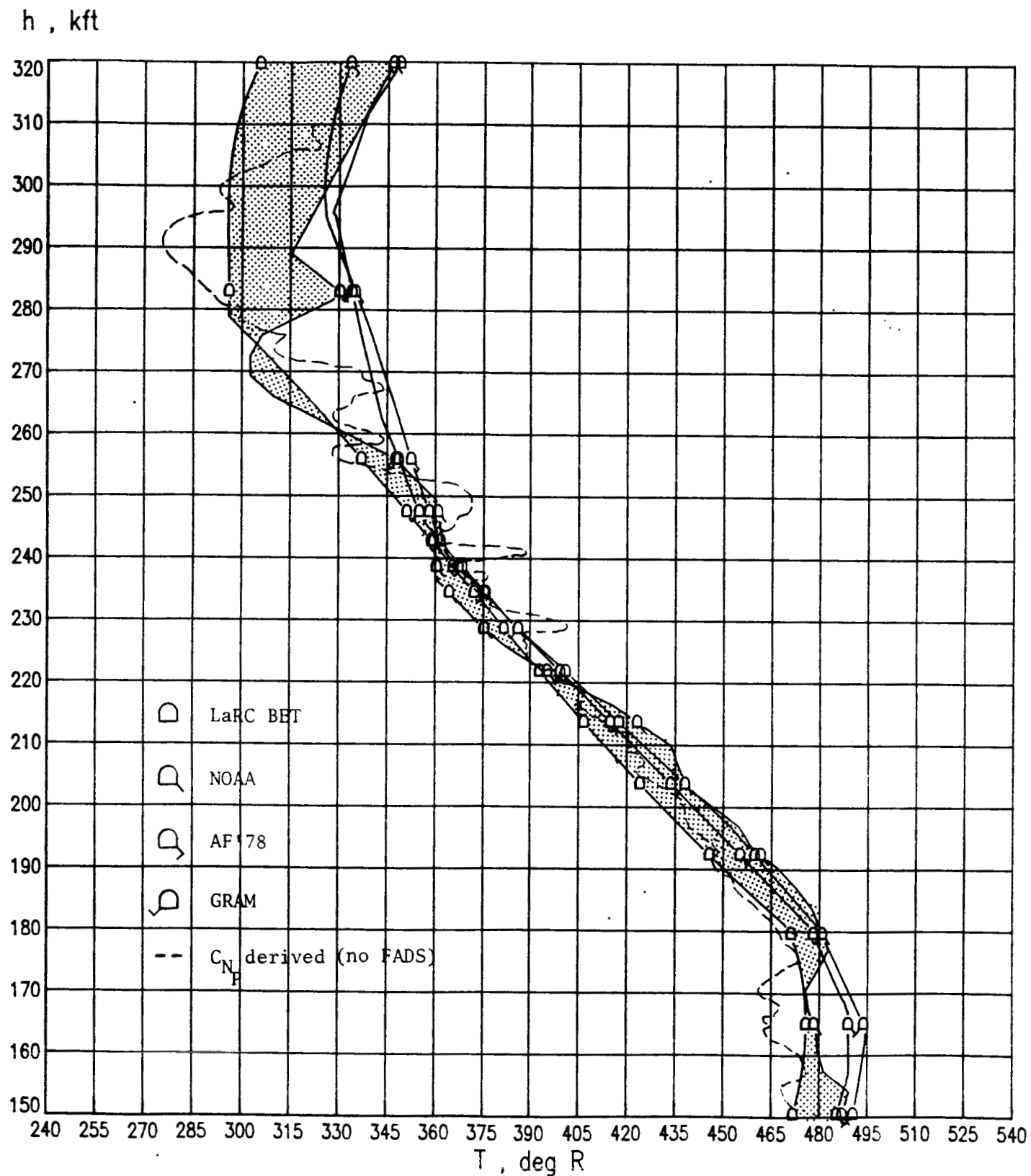


Figure B-7. STS-7 TEMPERATURE COMPARISONS

September

h , kft

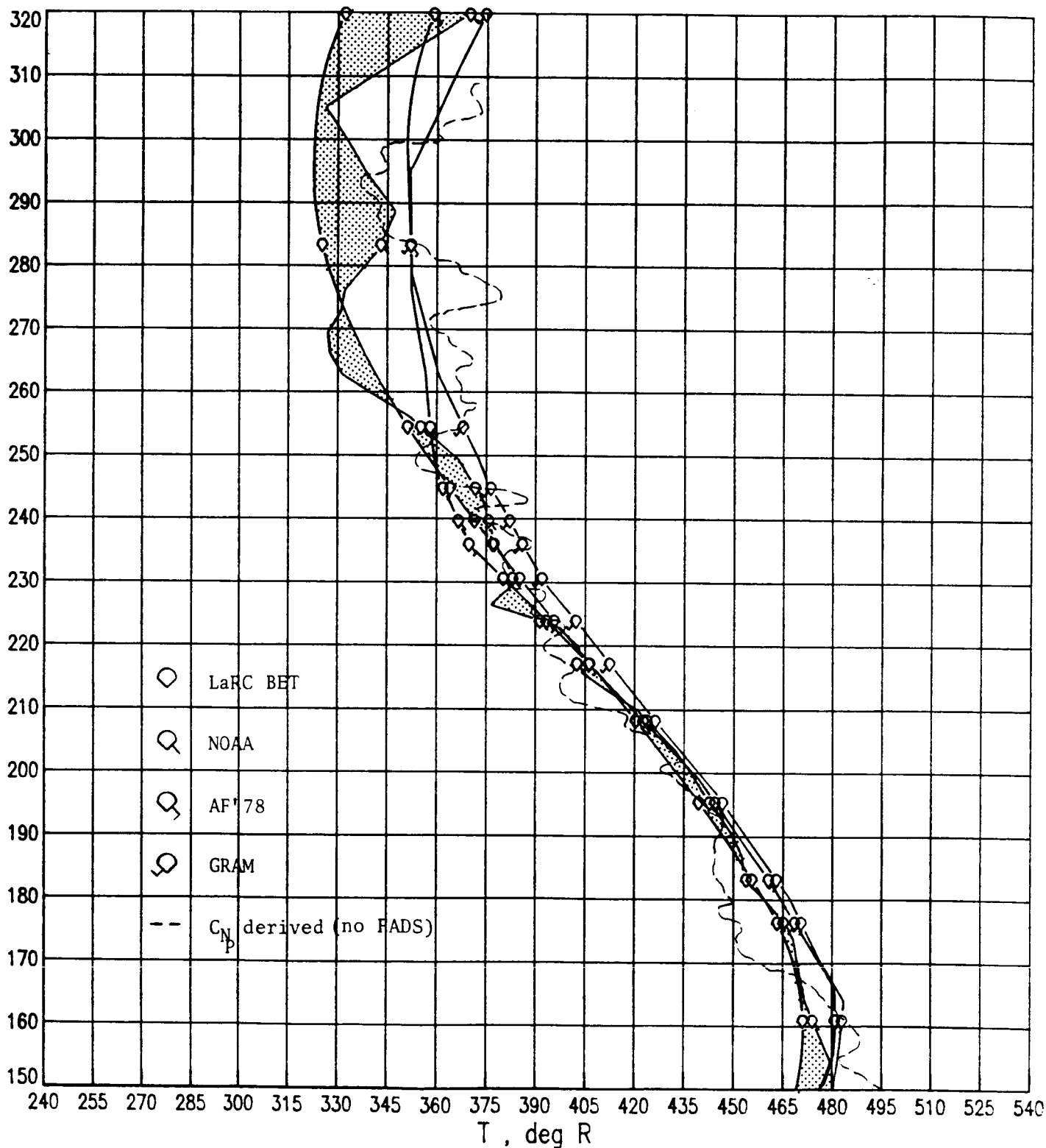


Figure B-8. STS-8 TEMPERATURE COMPARISONS

December

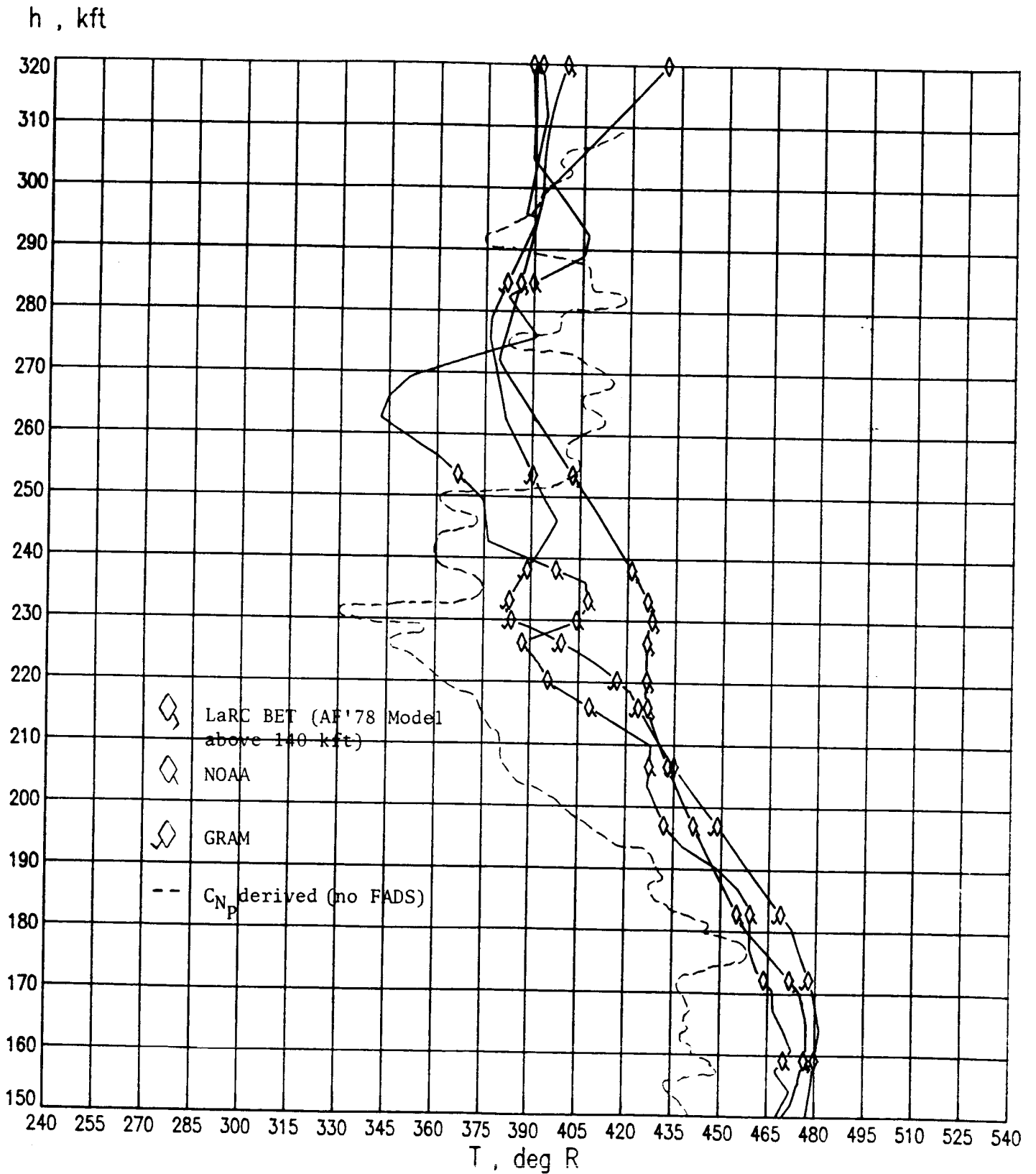


Figure B-9. STS-9 TEMPERATURE COMPARISONS

February

h , kft

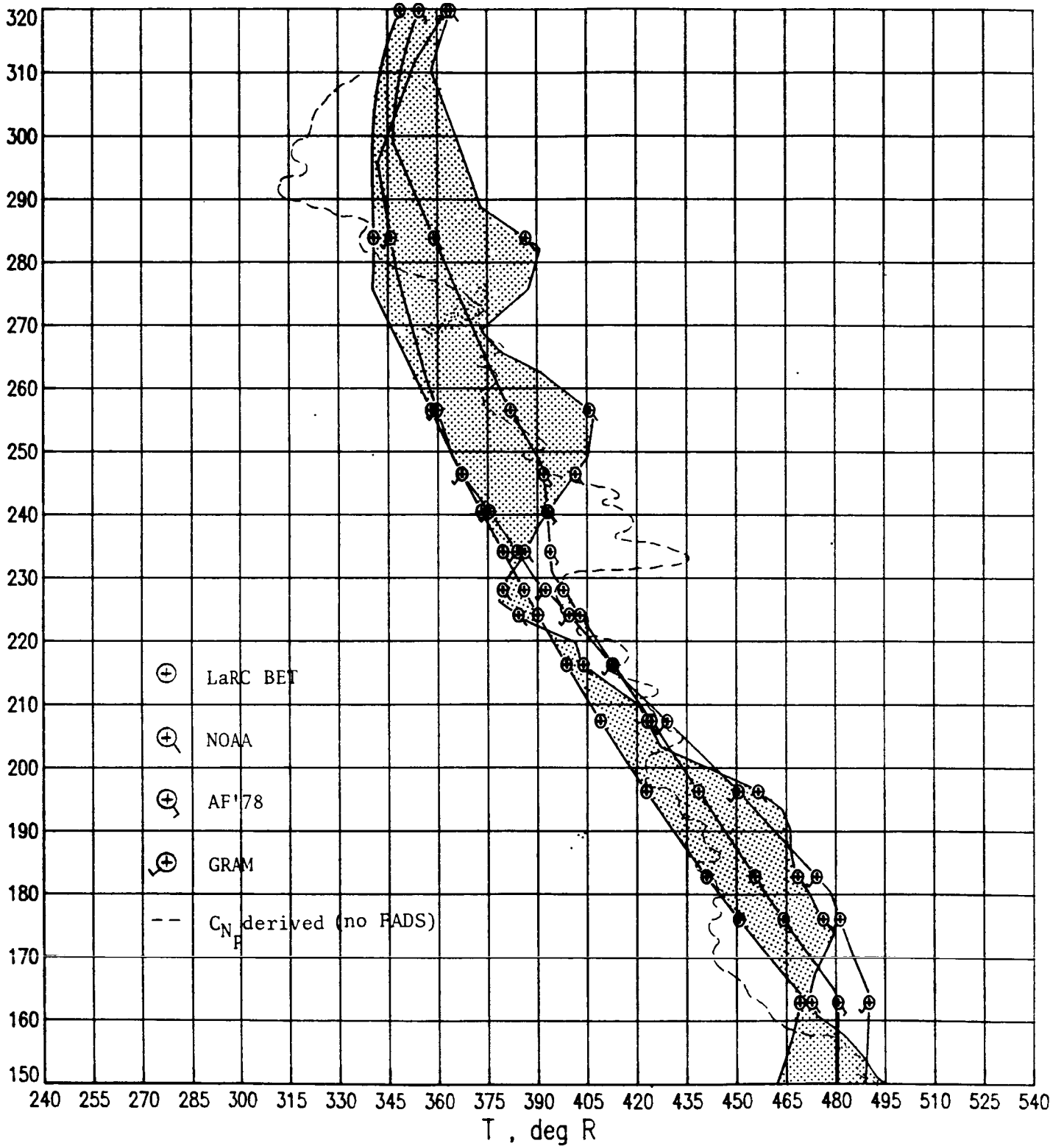


Figure B-10 STS11 TEMPERATURE COMPARISONS

April

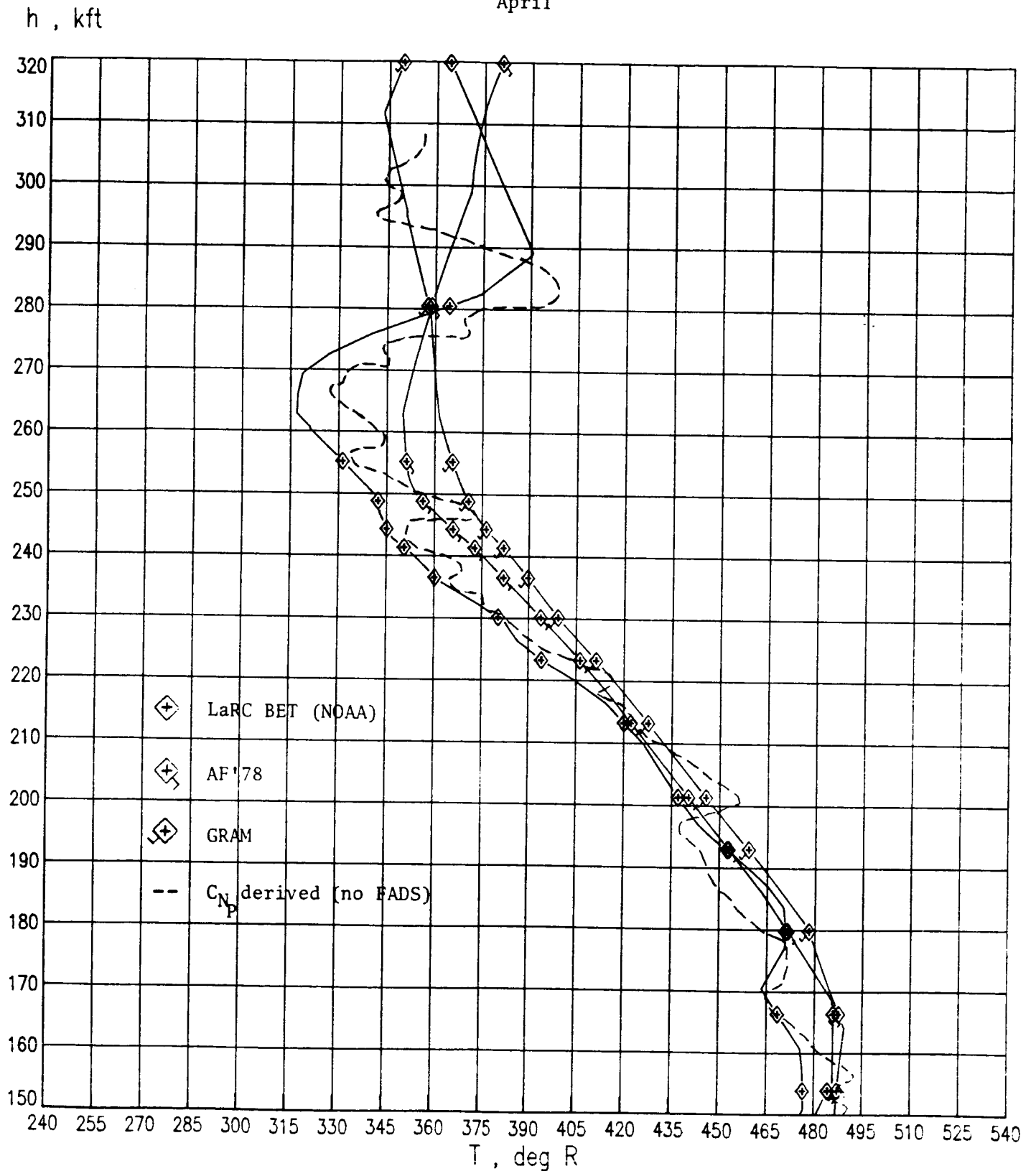


Figure B-11, STS13 TEMPERATURE COMPARISONS

September

h , kft

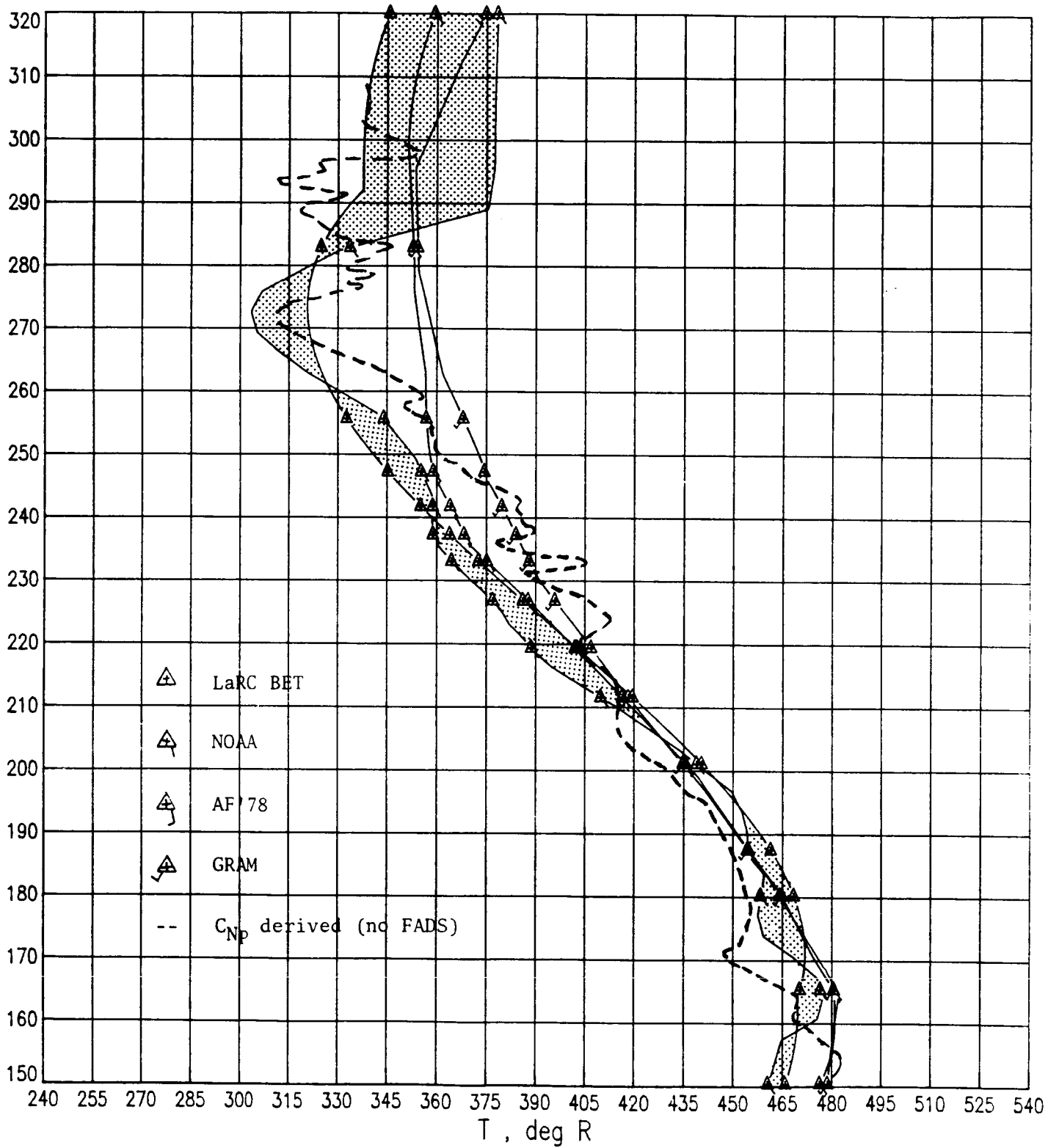



Figure B-12.STS14 TEMPERATURE COMPARISONS

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16. Abstract This report, Part 1 of the final report generated under NASA Contract NAS9-17158, presents ambient atmospheric parameter comparisons versus derived values from the first twelve (12) Space Shuttle Orbiter entry flights. Available flights, flight data products, and data sources utilized are reviewed. Comparisons are presented based on remote meteorological measurements as well as two comprehensive models which incorporate latitudinal and seasonal effects. These are the Air Force 1978 Reference Atmosphere and the Marshall Space Flight Center Global Reference Model (GRAM). Atmospheric structure sensible in the Shuttle flight data is shown and discussed. Part 2 of the final report presents a model for consideration in Aero assisted Orbital Transfer Vehicle (AOTV) trajectory analysis, proposed to modify the GRAM data to emulate Shuttle experience.					
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