30p.

NASA Contractor Report 171824

FINAL REPORT — Shuttle Derived Atmospheric Density Model

Part 2: STS Atmospheric Implications for AOTV Trajectory Analysis — a Proposed GRAM Perturbation Density Model

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

CONTRACT NAS9-17158

December 1984

[redacted]

(NASA-CR-171824) SHUTTLE DERIVED N87-10663
ATMOSPHERIC DENSITY MODEL. PART 2: STS
ATMOSPHERIC IMPLICATIONS FOR AOTV TRAJECTORY
ANALYSIS, A PROPOSED GRAM PERTURBATION Unclas
DENSITY MODEL Final Report (Analytical G3/47 44353

ANALYTICAL MECHANICS ASSOCIATES, INC.
17 Research Road
Hampton, Virginia 23666

30p

NASA Contractor Report 171824

FINAL REPORT — Shuttle Derived Atmospheric Density Model

Part 2: STS Atmospheric Implications for AOTV Trajectory Analysis — a Proposed GRAM Perturbation Density Model

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

CONTRACT NAS9-17158
December 1984

[redacted]

ANALYTICAL MECHANICS ASSOCIATES, INC.
17 Research Road
Hampton, Virginia 23666

TABLE OF CONTENTS

ABSTRACT

In this report, Part 2 of the final report, a perturbation model to the Marshall Space Flight Center (MSFC) Global Reference Atmosphere Model (GRAM) is developed for use in Aeroassist Orbital Transfer Vehicle (AOTV) trajectory analysis. The model reflects NASA Space Shuttle experience over the first twelve(12) entry flights. The GRAM was selected over the Air Force 1978 Reference Model because of its more general formulation and wider use throughout the NASA. The add-on model, a simple scaling with altitude to reflect density structure encountered by the Shuttle Orbiter (shears, waves, "potholes-in-the-sky", etc) was selected principally to simplify implementation. Perturbations, by season, can be utilized to minimize the number of required simulations, however, exact Shuttle flight history can be exercised using the same model if desired. Such a perturbation model, though not meteorologically motivated, enables inclusion of High Resolution Accelerometer Package (HiRAP) results in the thermosphere. Provision is made to incorporate differing perturbations during the AOTV entry and exit phases of the aero-assist maneuver to account for trajectory displacement (geographic) along the ground track.

I. Introductory Background

Development of a shear model for AOTV trajectory use based on Shuttle derived atmospheric data completes the requirements under the subject Contract. The model must include (at a minimum) the shear amplitude and frequency content which has already been observed in the STS accelerometry during the various entry flights. Yet, even though there is a large data base of Shuttle flights, there are no assurances that the "worse case" atmosphere has been encountered. Further, each flight exhibits (somewhat) its own unique density signature. Thus, development of a simple, all encompassing, model is nontrivial, requiring, at least, the method of omphaloskepsis to begin. However, in support of AOTV activity, a model can be developed, and taking advantage of some seasonal similarities, the number of simulations can be minimized. This Section summarizes some considerations necessary in developing such a model. Surely there are others but it would seem that the major points to consider are the following:

- utilization of STS specific atmospheres if desired,
- selection of a baseline nominal (comprehensive) atmospheric model,
- implementation,
- minimization,

and,
- interpretation.

Part 1 of this final report presented comparisons of Shuttle derived atmospheric parameters based on the first twelve STS flights. Comparisons were presented between the Shuttle derived density (and temperature) with those estimates provided by the National Weather Service remote sounding information as well as the MSFC GRAM and Air Force 1978 Reference Atmosphere models. The extent of density structure encountered during the three year STS flight history was quantified. It was stated that atmospheric perturbation models to emulate STS experience resulted in significant AOTV trajectory departures, specifically the simulations reported as Reference 1 therein. Whether or not reasonable models have been (or can be) developed requires comparisons of the simulated dispersions with those actually encountered by Shuttle.

Specific Shuttle atmospheres can, of course, be developed as was done for STS-2, 4, 6, and 7. The method utilized was to develop a scale factor (using the 1962 Standard Atmosphere as reference) to operate on the modelled atmosphere to produce the equivalent density profile. Results based on atmospheres generated in this manner were presented in Reference 1 of this report. Given the number of STS flights currently available, and considering the fact that this data base is rapidly increasing, continued evaluations of Shuttle specific atmospheres would be quite cumbersome, albeit expensive. Thus, where possible, it is advantageous to simplify the modelling requirements and still reflect the basic Shuttle environs encountered. This should not be construed as first priority but is certainly worthy of consideration. Other factors to consider, of course, are ease of implementation as well as interpretation of the resultant perturbations modelled. For these reasons, though perhaps subject to argument, it is felt that the meteorologically motivated models of Robertson (Reference 2) might prove to be cumbersome. Finally, as alluded to in Part 1, there exists acceleration data which enable extension of the results above the threshold of the Inertial Measurement Unit (IMU) measurements, i.e., the HiRAP μg source can be utilized into the thermosphere. A model developed which can readily be expanded to higher altitudes to include the HiRAP results has some merit.

Given the above considerations, a reasonable model can be developed for AOTV application. One needs to select a reference model and, to minimize the "degrees-of-freedom", reduce (reasonably) the STS atmospheric data base. Based on the results of Part 1, with the exception of the September flights and, to a certain degree on STS-9, the GRAM model appears to be the best reference data. This model has the added advantage that, unlike the AF'78 model which is only defined up to 90 km, it has a Jacchia-Roberts formulation for the uppermost altitudes. The GRAM also is more widely used throughout the NASA and, if required, has a spherical harmonic wind model available. With the GRAM as a baseline, and recalling that the STS flight derived atmospheres were (reasonably) similar by season, the limited perturbation model is next developed.

In the following Section it is assumed that AOTV requirements, due to ground track considerations during the aero-assist portion of flight, will optionally want to include different perturbations during *the entry and exit phases of the maneuver. It would be remiss not to provide for this capability in view of the apparent "local" structure sensed by the STS accelerometers. Also, perturbing the nominal density from any source will not satisfy the gas laws. One might want to resolve, say for temperature as an example, to preserve this relationship.*

II. Proposed Perturbation Model

Appendix A of this report shows Shuttle derived densities for each of the twelve(12) flights normalized to the GRAM values. Straight line segments are drawn through the curves to depict what is considered to be significant density structure.[1] As was done in Part 1, no flight updates to the predicted normal force coefficient were utilized and, as a consequence, each C_N derived density curve could be shifted (more dense) by 3 to 5 percent to reflect the current Flight Assessment Deltas (FADS). The shaded region on these twelve figures is the GRAM uncertainty ($\pm 1\sigma$) generated by the model. These are the MSFC data and not the computed statistics presented in Part 1, though reasonably comparable. These data would be those utilized by analysts when performing Monte Carlo simulations. These data are superimposed for information only but, as a side activity, could be reviewed to characterize the adequacy of the GRAM statistical model in this altitude interval. Typically, each flight shows an approximate 2σ departure from the GRAM in certain (restricted) intervals. These deviations are systematic, not random, occurrences. This might be considered adequate, however, comments would be appreciated.

Figures 1 through 3 show composite plots of the results by seasons for spring, summer, and fall, respectively. Winter results can be seen (on the basis of a single flight) in Figure A-10 for STS-11. One can detect the density similarities from these seasonal composite charts, at least in the spring and summer months. The fall data presented would also show more similarity if STS-9 were disregarded. This flight is the outlier principally due to latitudinal effects.

With caution, one could select the scaling results from a given flight for each season and, by providing for a datum shift, reasonably replicate the other flight results. This is, of course, not exact but worth considering to minimize the number of Shuttle perturbation models required, keeping in mind the (potential) factor of two to model separate

---

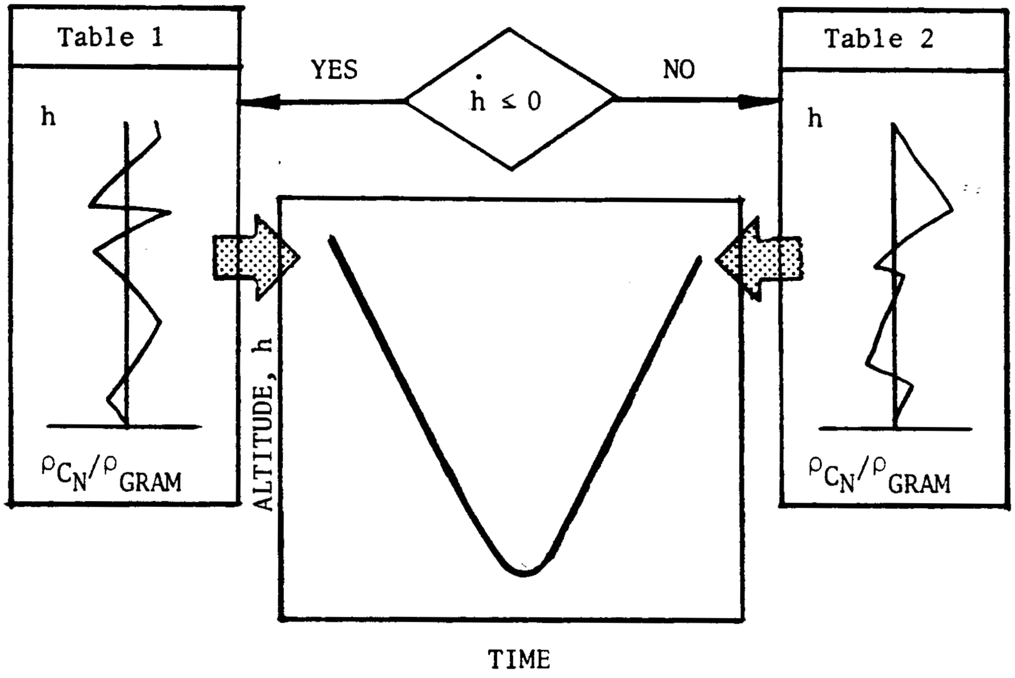
[1] Specific STS flight results can be modelled by inputting a table of scale factors versus altitude whose break-point altitudes are as shown thereon. Certainly, much less than 50 pairs [h_i, $(\rho_{C_N}/\rho_{GRAM})_i$] would be required. The resulting density would be the product of the scale factor (linearly interpolated with altitude) times the GRAM value and would thereby reflect the suggested shear structure.

entry and exit phases. Typically, in the spring months, STS-1 scaling (read directly from Figure A-1 as an example) could be utilized. By shifting these results, for example by ± 20 kft, much of the signal shown in the remaining three flights would be represented. Similarly, in the summer months, the STS-4 results (as an example) could provide the benchmark perturbation model which could be shifted to emulate the others. One should keep in mind that the two September flights (STS-8 and STS-14) can be shifted by approximately 20 percent at the top due to the fact that the GRAM is too dense in this month. In fact, the results can be essentially rotated about h~230 kft, wherein the excess model density first becomes apparent (see Part 1), peaking to ~20 percent at h~320 kft. Such an adjustment would make these two flights fall more in line with the other two summer flights. It is noted that the suggested shear structure in the narrow vicinity of 230 kft to 250 kft for the summer months is very repeatable. Shifting the STS-4 data (or the results from any of these flights) by ± 20 kft must be reviewed. If that specific structure, when displaced, creates a significant problem for AOTV analysts, the results must be carefully reviewed. Lastly, either the STS-2 or STS-5 values can be used for the fall scaling with, again, a ± 20 kft datum shift provided. This, of course, disregards the STS-9 flight results.

It is recommended that a representative flight be selected (each analyst might want to make his or her choice) and simulations be conducted in which the scaling versus altitude is shifted as suggested (±20 kft). Those simulations which show potential problems must be reviewed versus actual historical STS flight data. The charts herein in Appendix A can serve that purpose. Future flights, if more radical density structure is encountered, will need be factored into the analysis. As the AOTV design solidifies, and dependence on the various density structure (magnitude, altitude of occurrence, etc.) is better established, a further review of actual STS atmospheric phenomena might be warranted.

To implement this model a table(s) of scale factors versus altitude, a linear interpolation scheme to operate on the table(s), as well as a bias value(s) on altitude (to shift the table(s)) would be required inputs, assuming of course the GRAM is already available in the user's software.

If not, STS atmospheres scaled to the '76 Standard (see Part 1) could just as readily be utilized. One could implement a single table per season and adjust the altitude datum bias through some mechanism based on AOTV altitude rate to model differing perturbations during the entry and exit phases. In any event, trivial software modifications would be required to implement the following schematic:



Readers are reminded that the charts of Appendix A are ratioed to the comprehensive GRAM values, to include latitudinal and seasonal effects. If the 13th month "average" model is utilized the scale factors shown should still be adequate for analysis purposes during the preliminary design stages, e.g., to evaluate and quantify the effects of "representative" STS density structure on AOTV trajectories. Also, in addition to indicating structure, the scale factors reflect systematic, local, deviations from the GRAM estimates. These curves (or perhaps a smooth version of same) could therefore be utilized as a basic shift to the GRAM data in conjunction with the GRAM statistics in a Monte Carlo analysis. Thus the typical "net" zero mean error resulting from the Monte Carlo runs would actually end up describing, apart from the random signal, the baseline offset to the GRAM evidenced in the STS data.

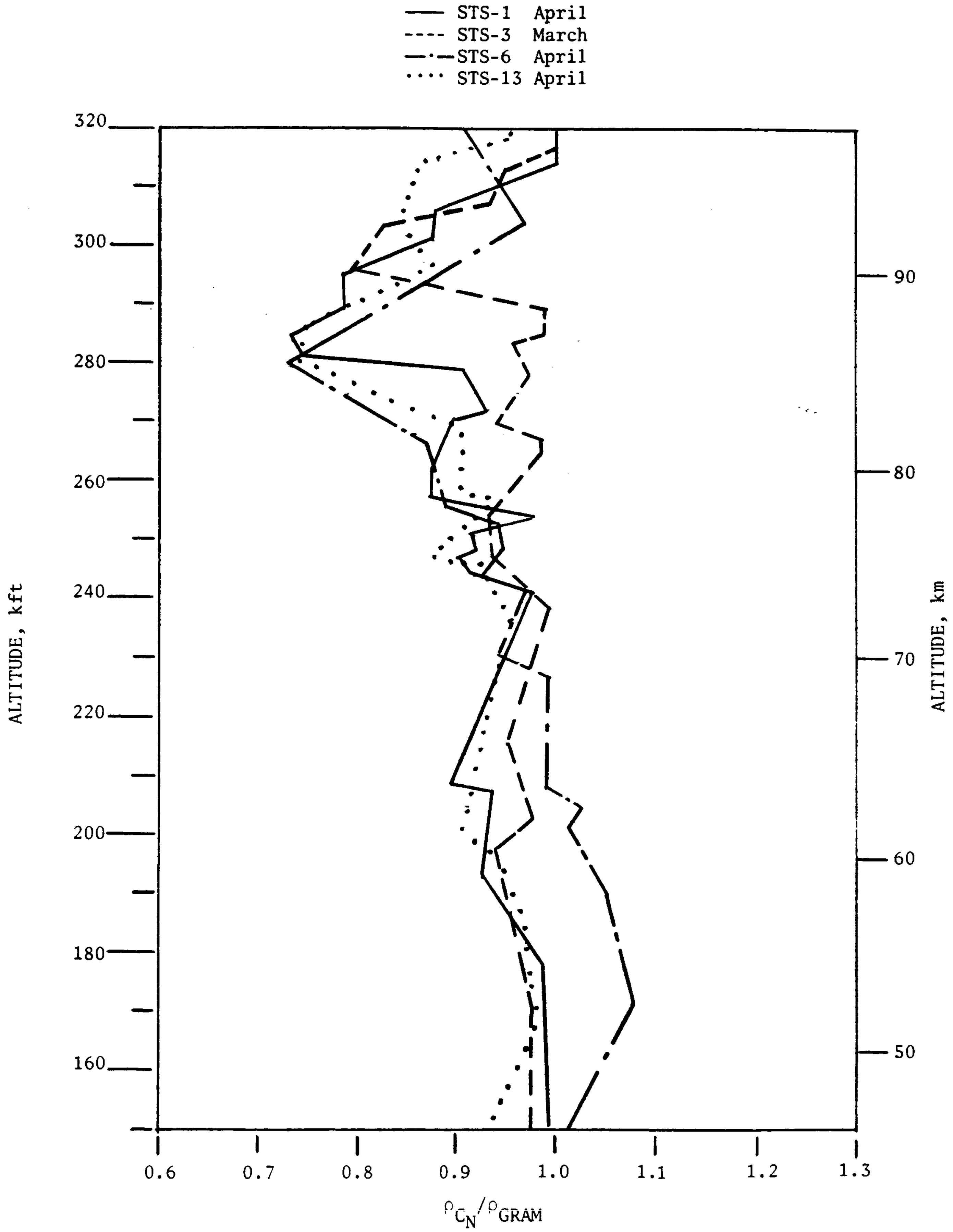


Figure 1. SPRING DENSITY COMPARISONS

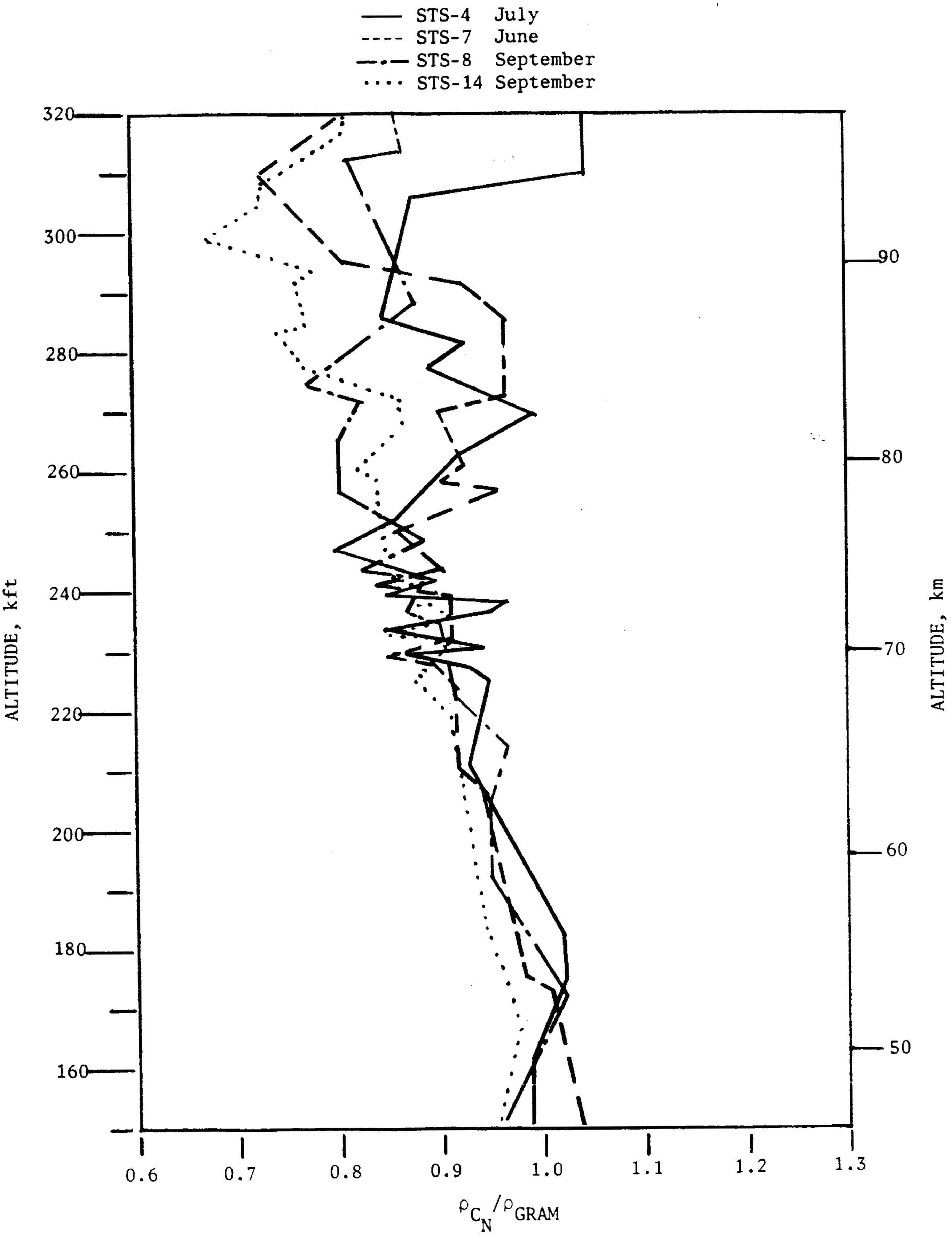


Figure 2. SUMMER DENSITY COMPARISONS

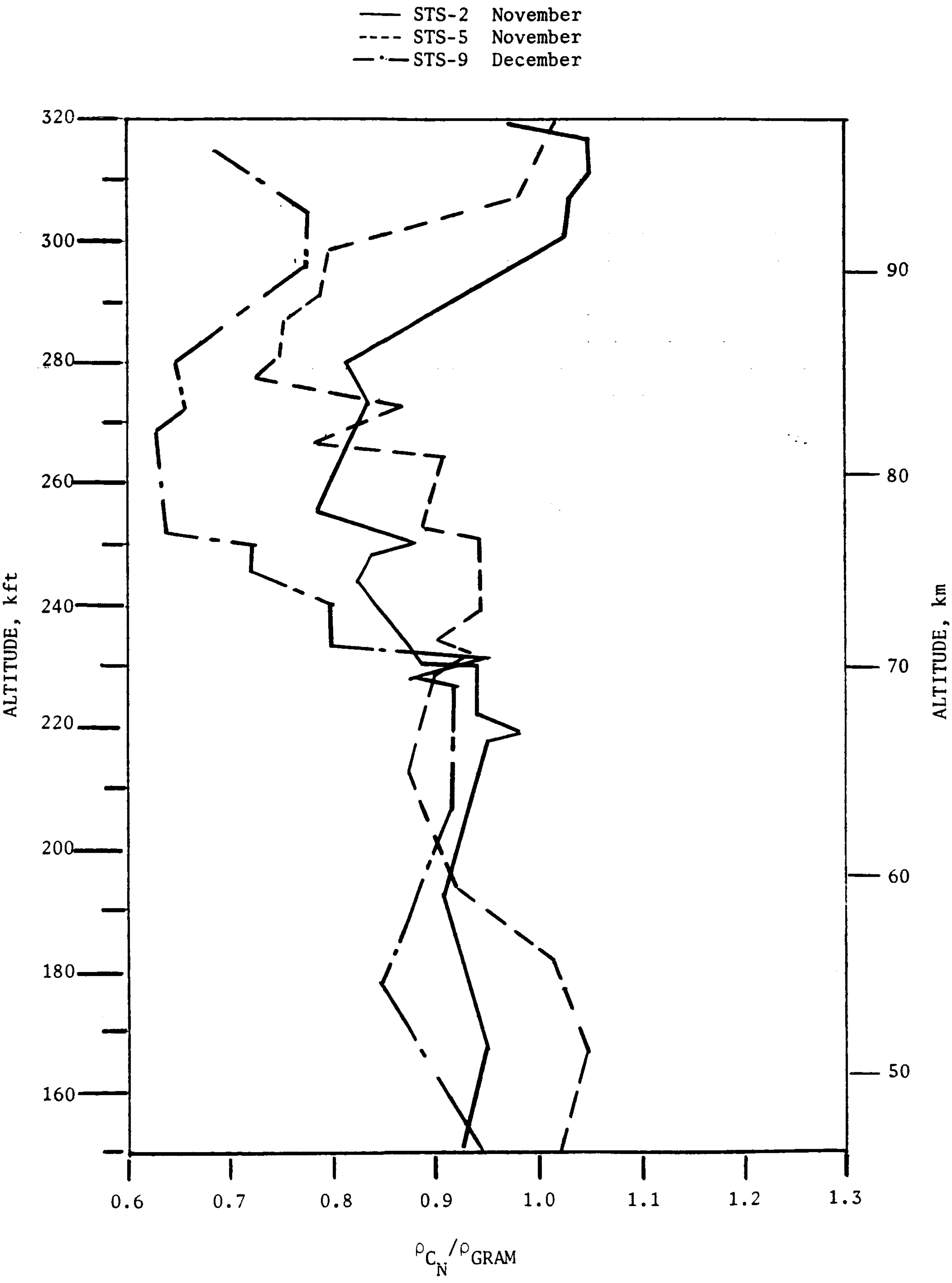


Figure 3. FALL DENSITY COMPARISONS

III. Extension to Include Perturbations in Thermosphere

Figure 4 shows STS-6 and STS-7 HiRAP results (see Reference 8 of Part 1) obtained from R. C. Blanchard of the Aerothermodynamics Branch, Space Systems Division of LaRC. With μg resolution, derived densities well up into the thermosphere are obtainable. The data, shown as a straight line segment of Blanchard's results, are contiguous with the IMU derived values as one would expect. HiRAP saturation occurs at 8 mg's wherein the IMU signal, though noisy, becomes meaningful. Shown on each sub-figure of Figure 4 are actually two curves; 1) Blanchard's results scaled to the '62 Standard, and 2) the GRAM scaled to the same Standard.[2] The HiRAP data show large waves in the thermosphere, similar in nature to that evidenced in the GRAM (perhaps substantiating in part the Jacchia-Roberts formulation) but much larger in amplitude and, in the case of STS-7, shifted by some 50 kft in altitude. Figure 5 shows the same two flights normalized to the GRAM. It is recognized that this is an extremely high altitude, low density, region but it is not inconceivable that such density departures would have some effect on AOTV trajectories, particularly during the exit phase. Thus, with virtually no a priori experience, it is recommended that consideration be given to implementing the data of Figure 5, appended to the upper end of some scaling table, as part of the AOTV trajectory analyses and design.

---

[2] Design values were utilized in the GRAM for actual and mean solar flux as well as for geomagnetic index.

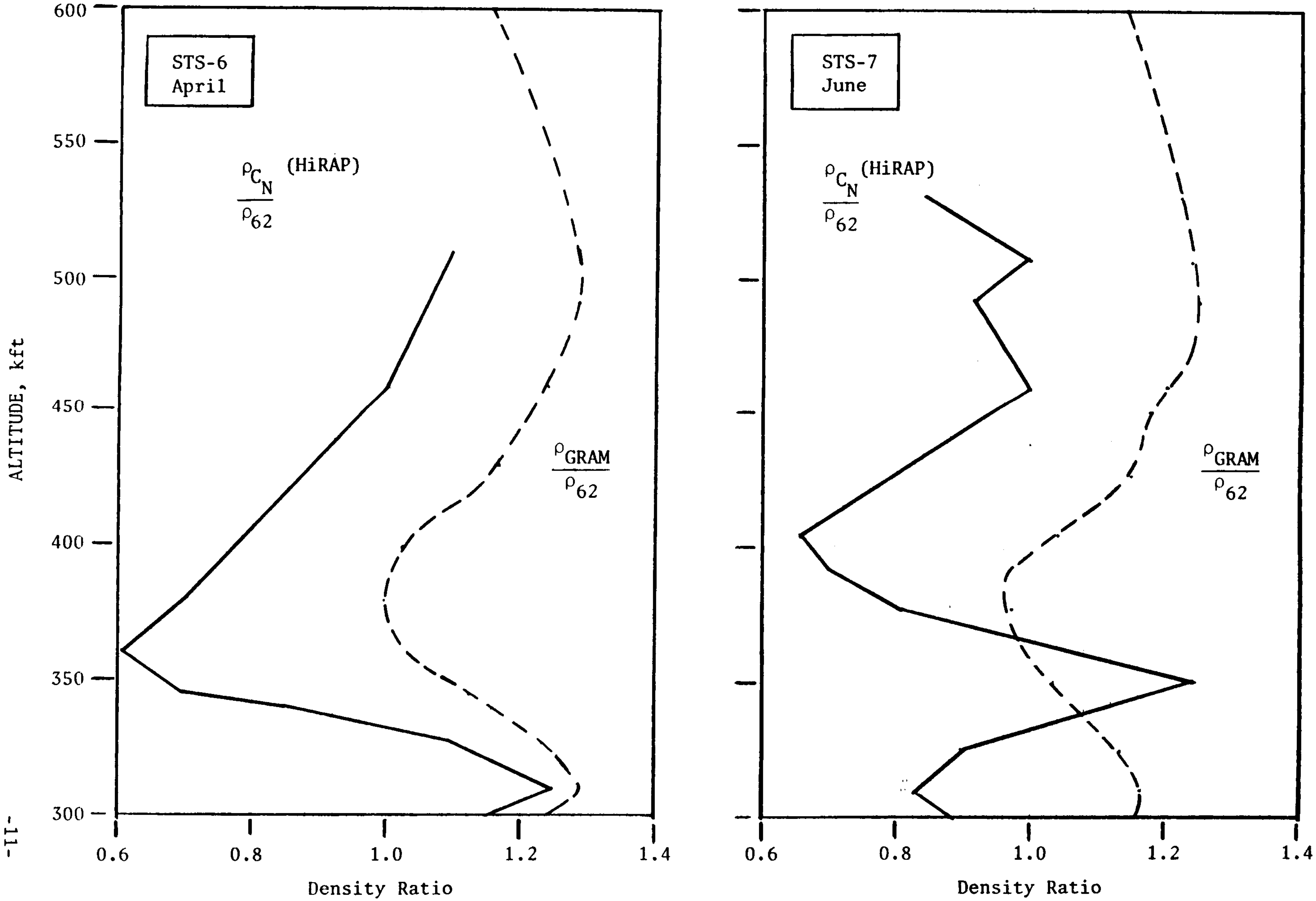


Figure 4. Density comparisons (HiRAP derived and GRAM) in the thermosphere.

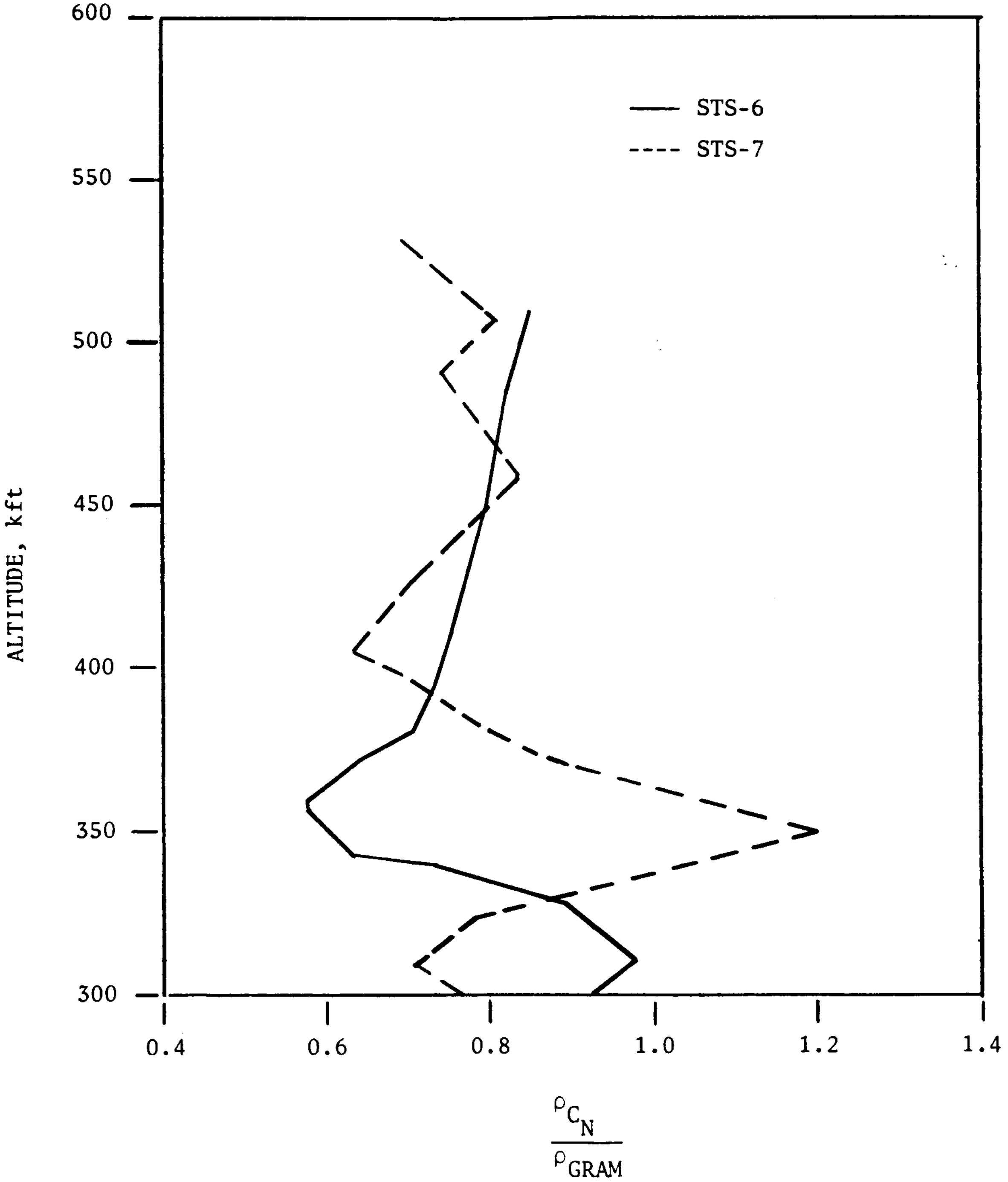


Figure 5. HiRAP results normalized to GRAM density.

IV. Conclusions

An atmospheric perturbation model for AOTV analysts has been developed to enable trajectory simulations using density profiles commensurate with those sensed during the STS Orbiter entry flights. Attempts have been made to minimize the requirements by evoking seasonal similarities observed in the Shuttle data. The proposed model, which should be readily implemented and the resultant perturbations easily interpreted, can be utilized during the entry and exit phases of the aero-assist maneuver portion of flight. Actual conclusions as to the adequacy of the model require user feedback as well as continued investigations of atmospheric structure encountered on future STS flights. For the most part, a sizeable data base of Shuttle results is available and, it is felt, the essence of the encountered atmospheric structure is adequately modelled for AOTV design studies.

References

1. Powell, R. W., Naftel, J. C., and Stone, H. W., "Performance Evaluation of the Atmospheric Phase of an Orbital Transfer Vehicle," AIAA Paper No. 84-0405, January 1984.

2. Robertson, W. M., "Parameters of Models of Gravity Waves and Kelvin-Helmholtz Instabilities," CSDRL Memo No. OTV-10E-84-11, October 18, 1984.

APPENDIX A

Comparison of Shuttle Derived Densities with MSFC GRAM Data for First Twelve Shuttle Entries

Notes:

- No FADS utilized in ρ_{C_N} derivation
- Shaded region shown is ±1σ band as defined by MSFC for their model.

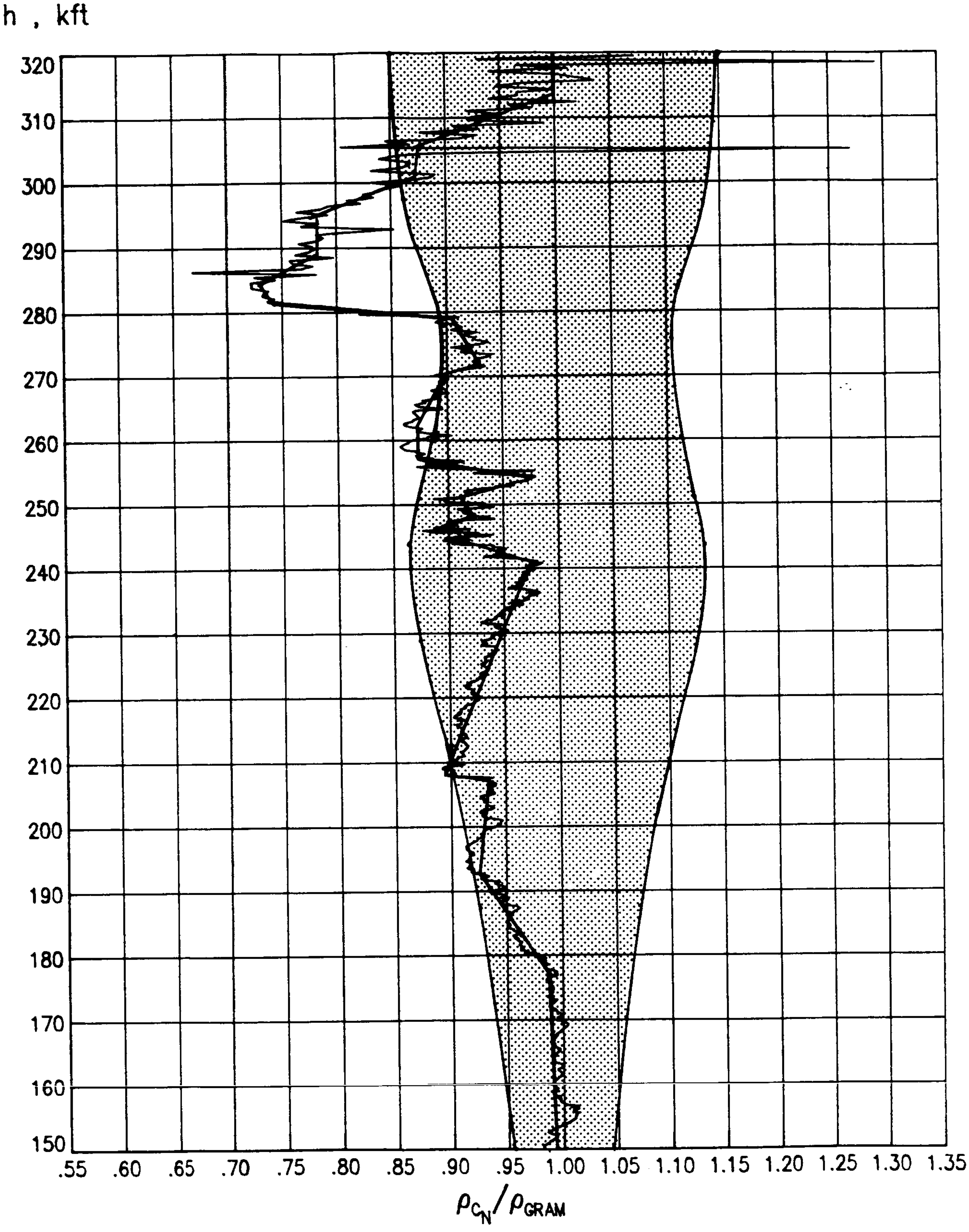


Figure A-1. STS-1 (April) GRAM density scaling

ORIGINAL PAGE IS OF POOR QUALITY

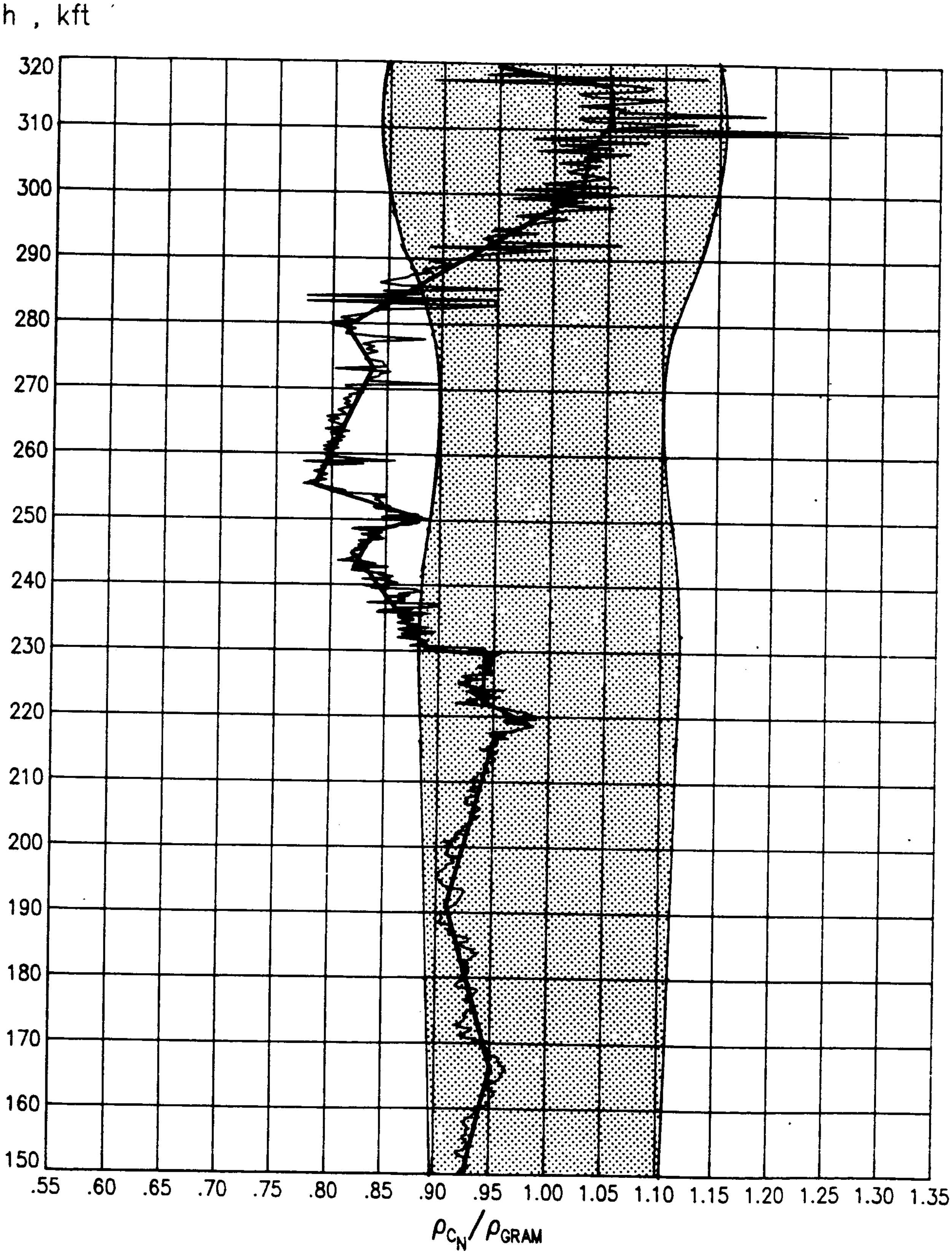


Figure A-2. STS-2 (November) GRAM density scaling

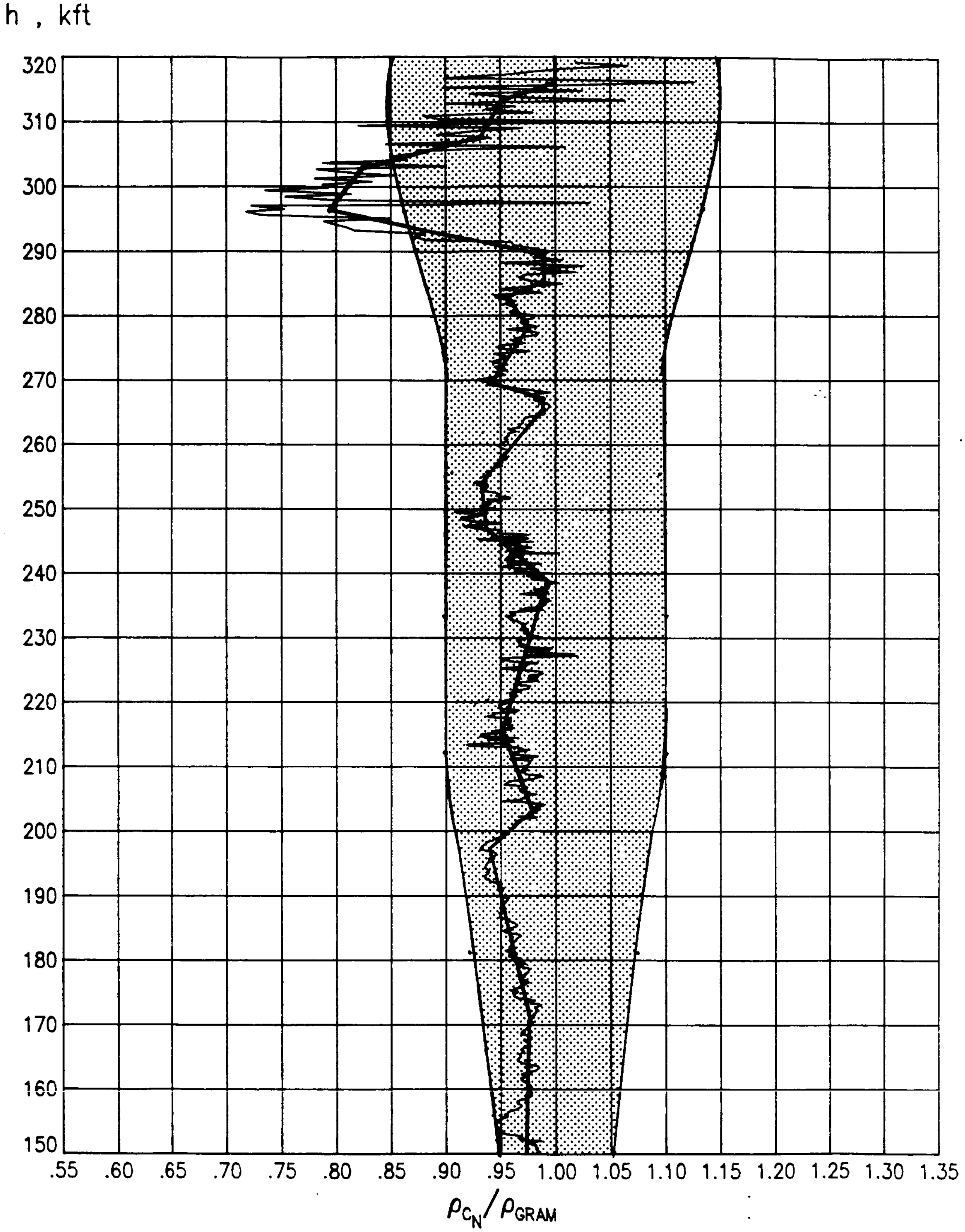


Figure A-3. STS-3 (March) GRAM density scaling

ORIGINAL PAGE IS
OF POOR QUALITY

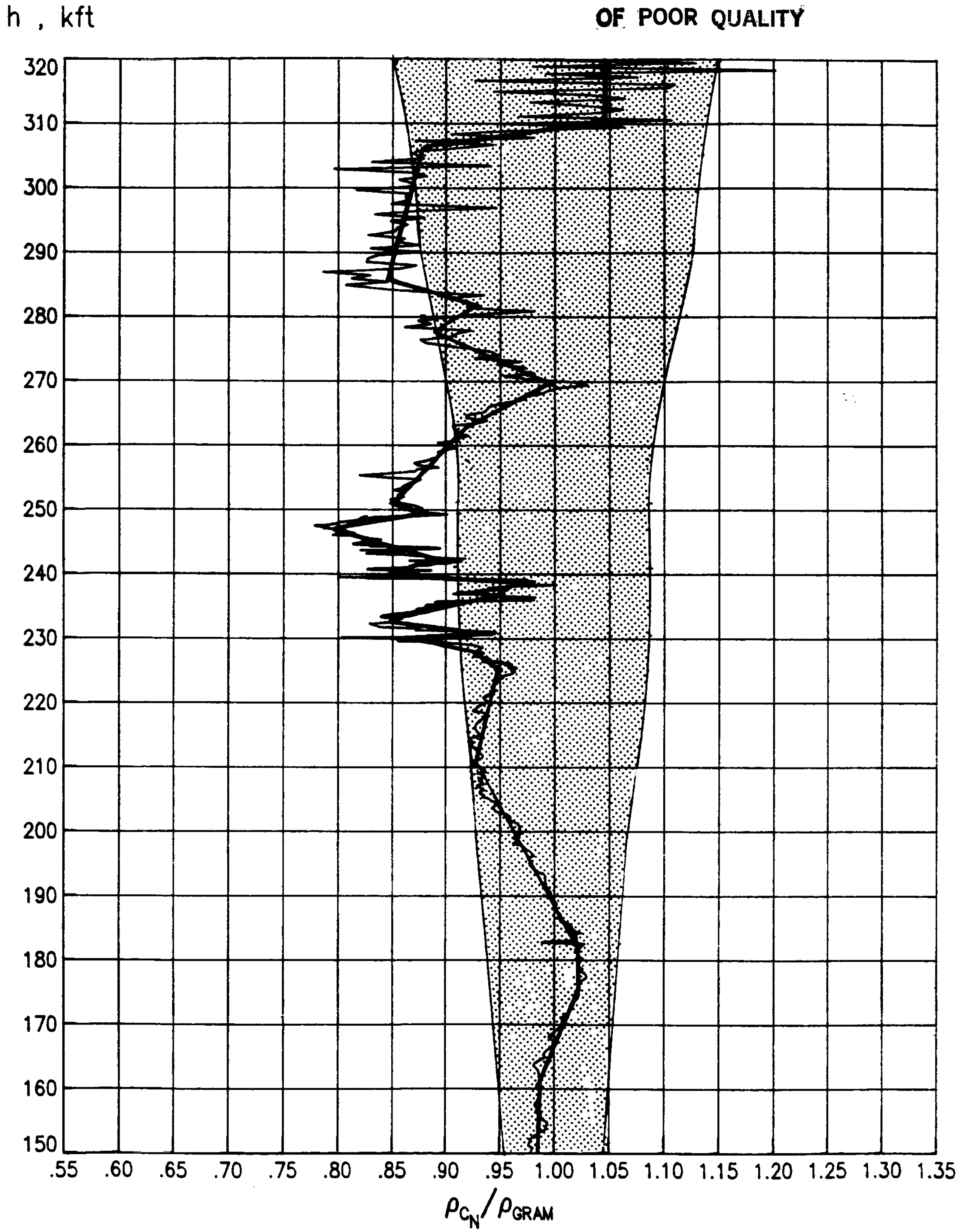


Figure A-4.STS-4 (July) GRAM density scaling

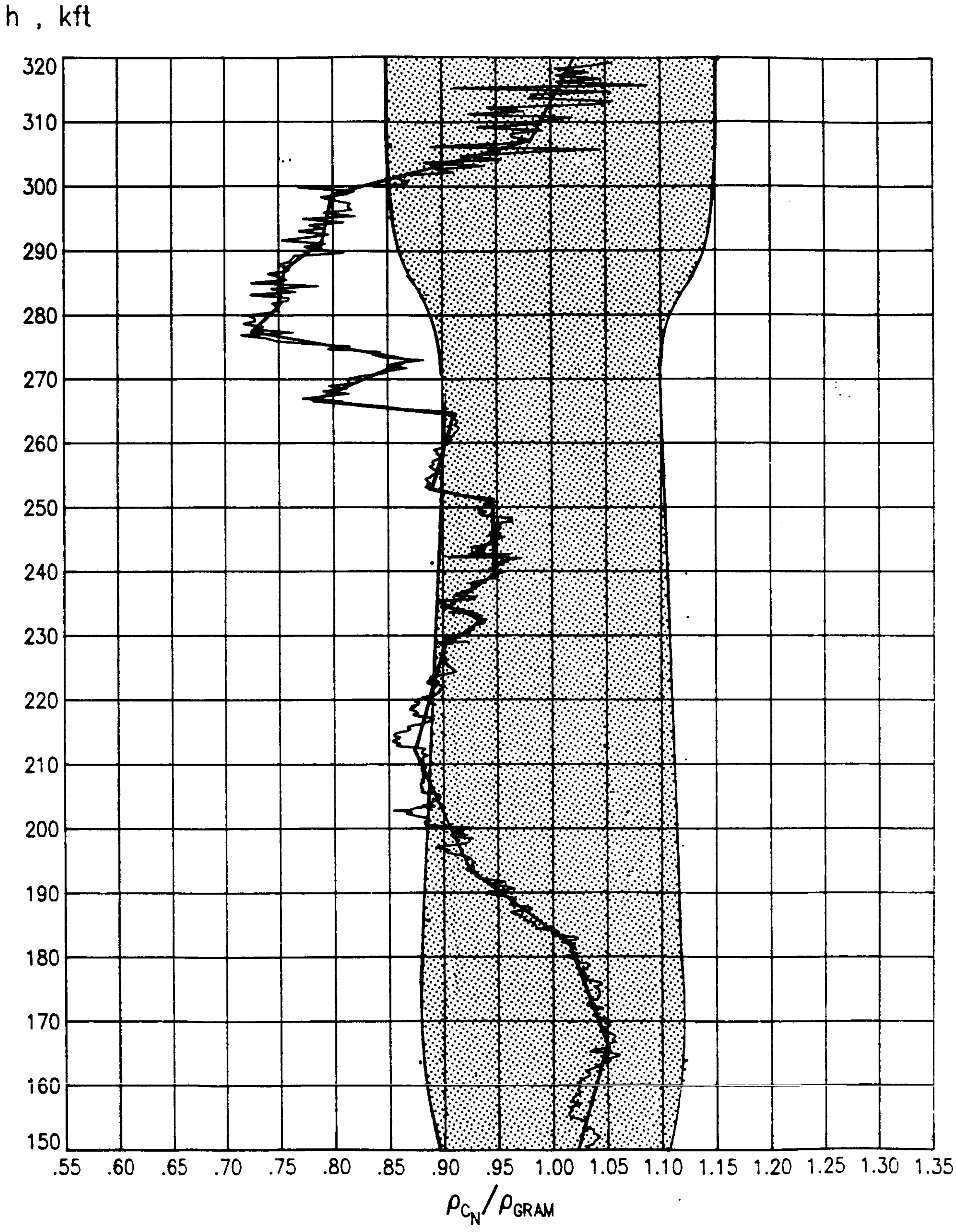
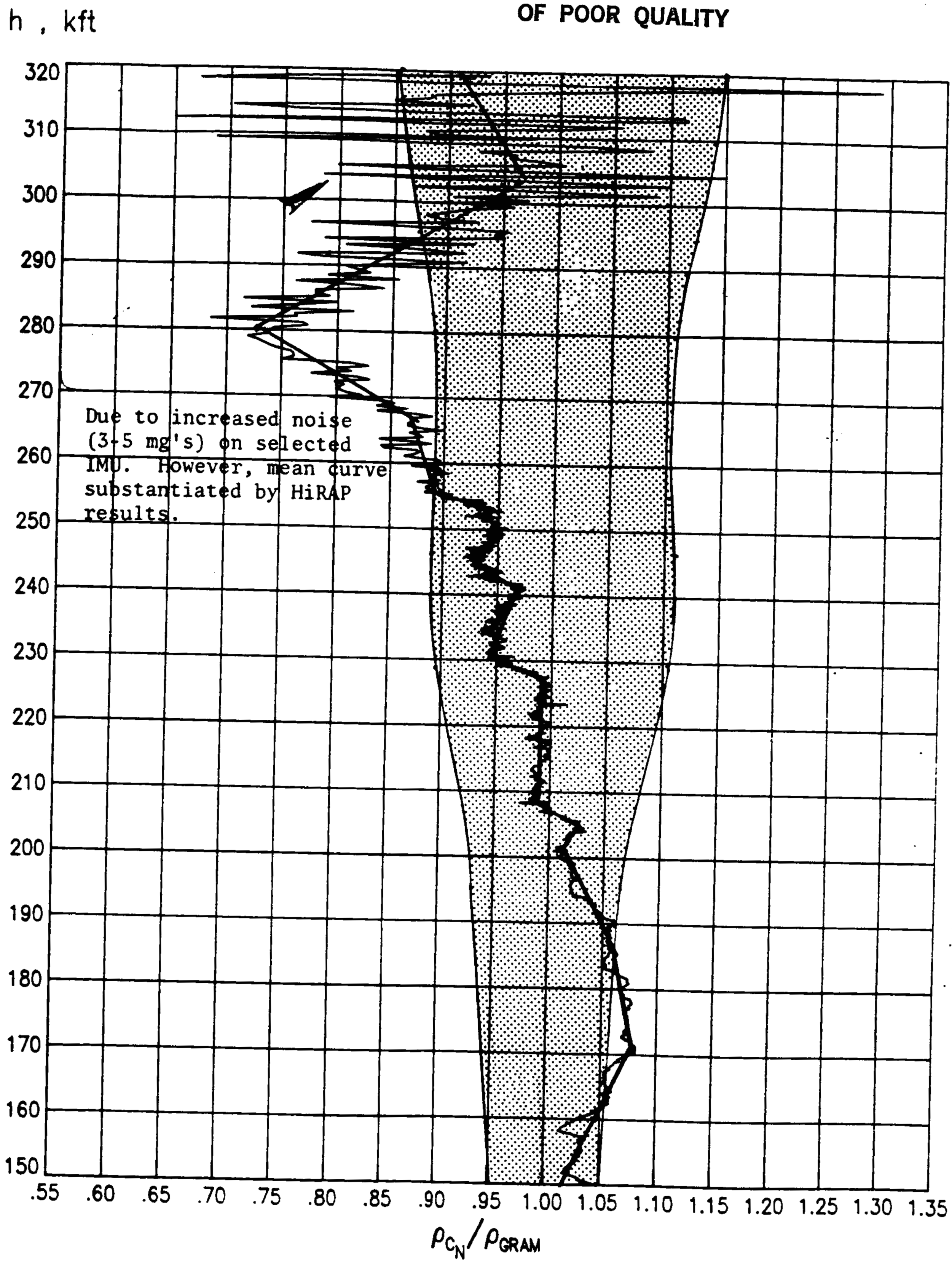


Figure A-5. STS-5 (November) GRAM density scaling

ORIGINAL PAGE IS OF POOR QUALITY



Due to increased noise (3-5 mg's) on selected IMU. However, mean curve substantiated by HiRAP results.

Figure A-6. STS-6 (April) GRAM density scaling

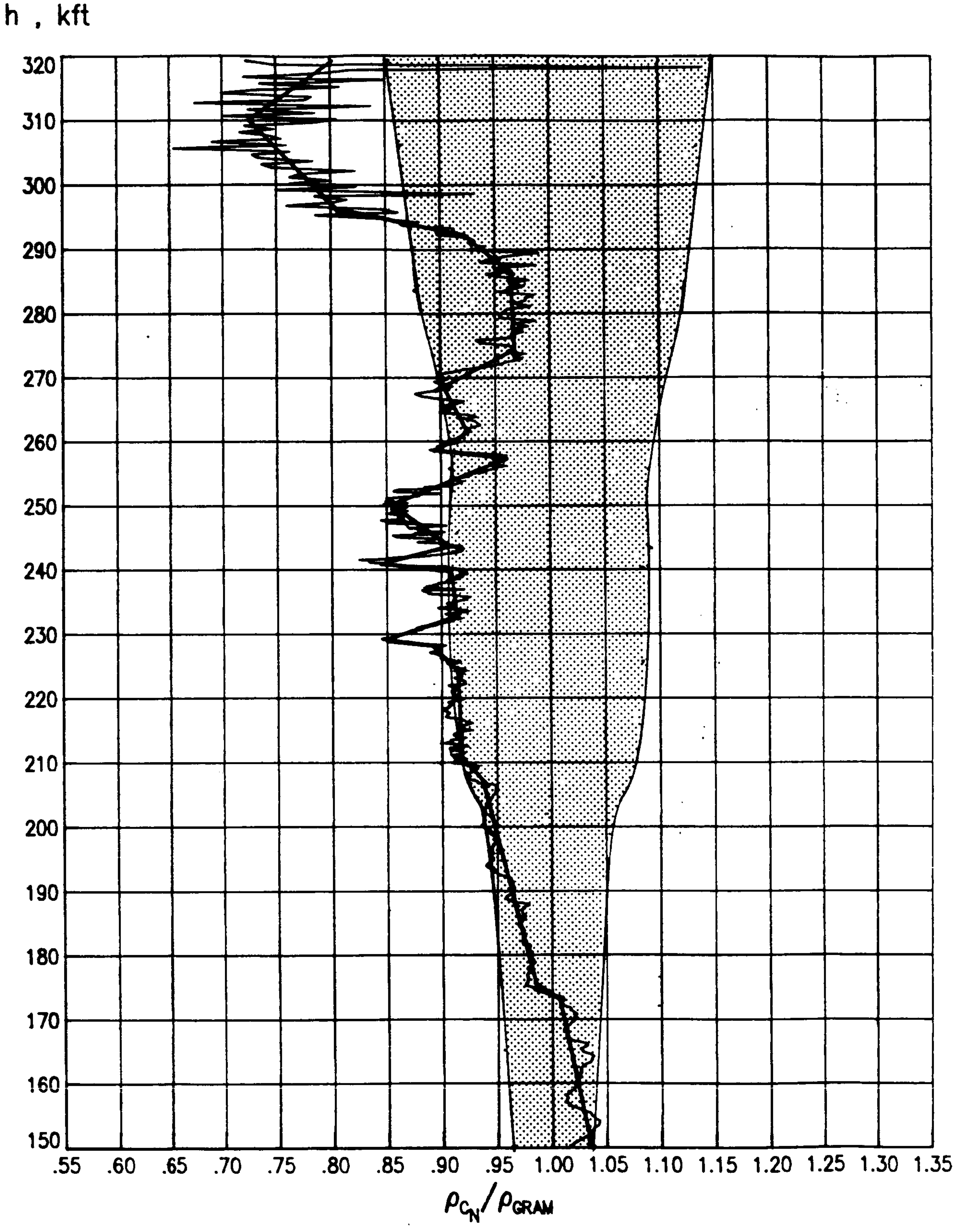


Figure A-7. STS-7 (June) GRAM density scaling

ORIGINAL PAGE IS
OF POOR QUALITY

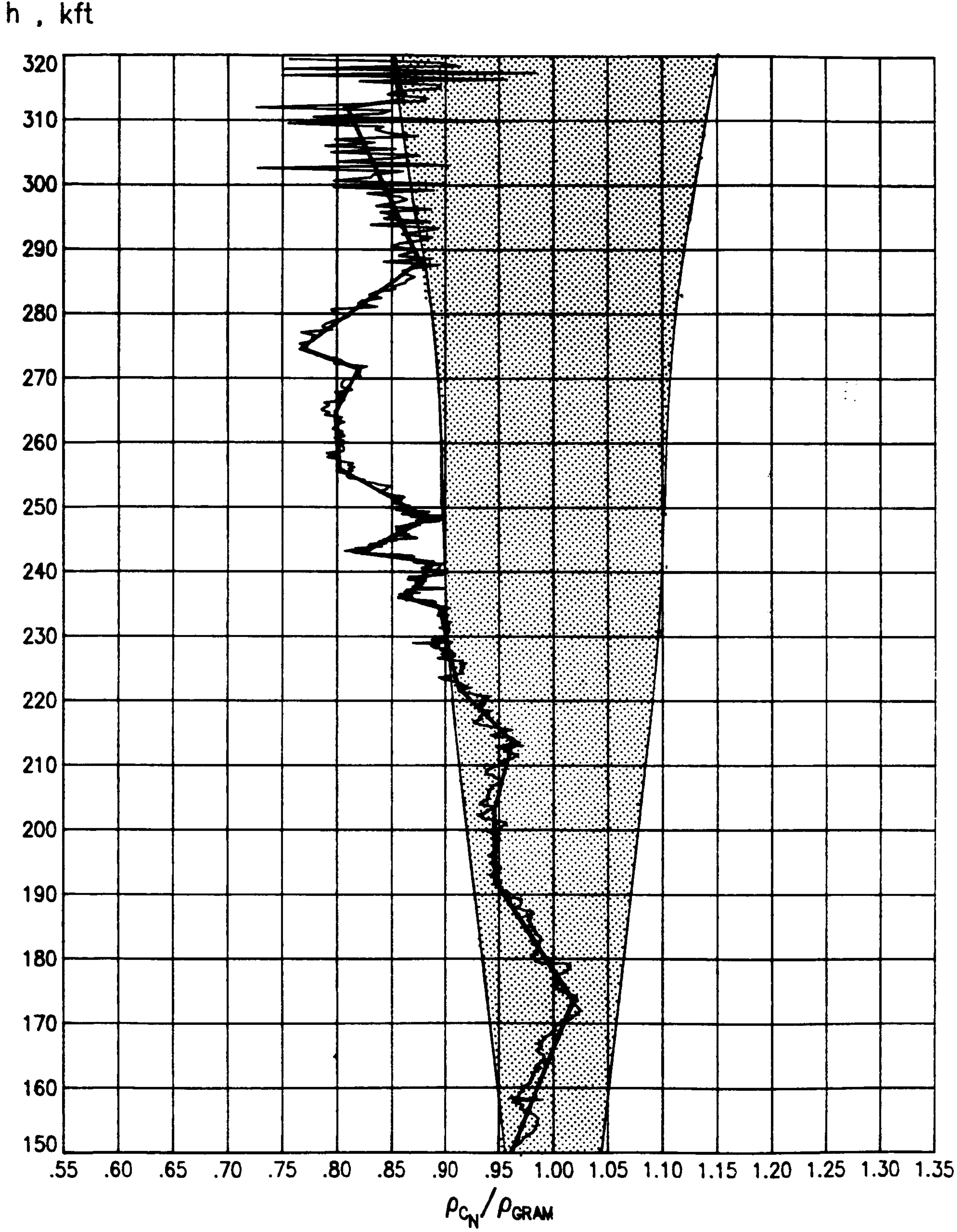


Figure A-8. STS-8 (September) GRAM density scaling

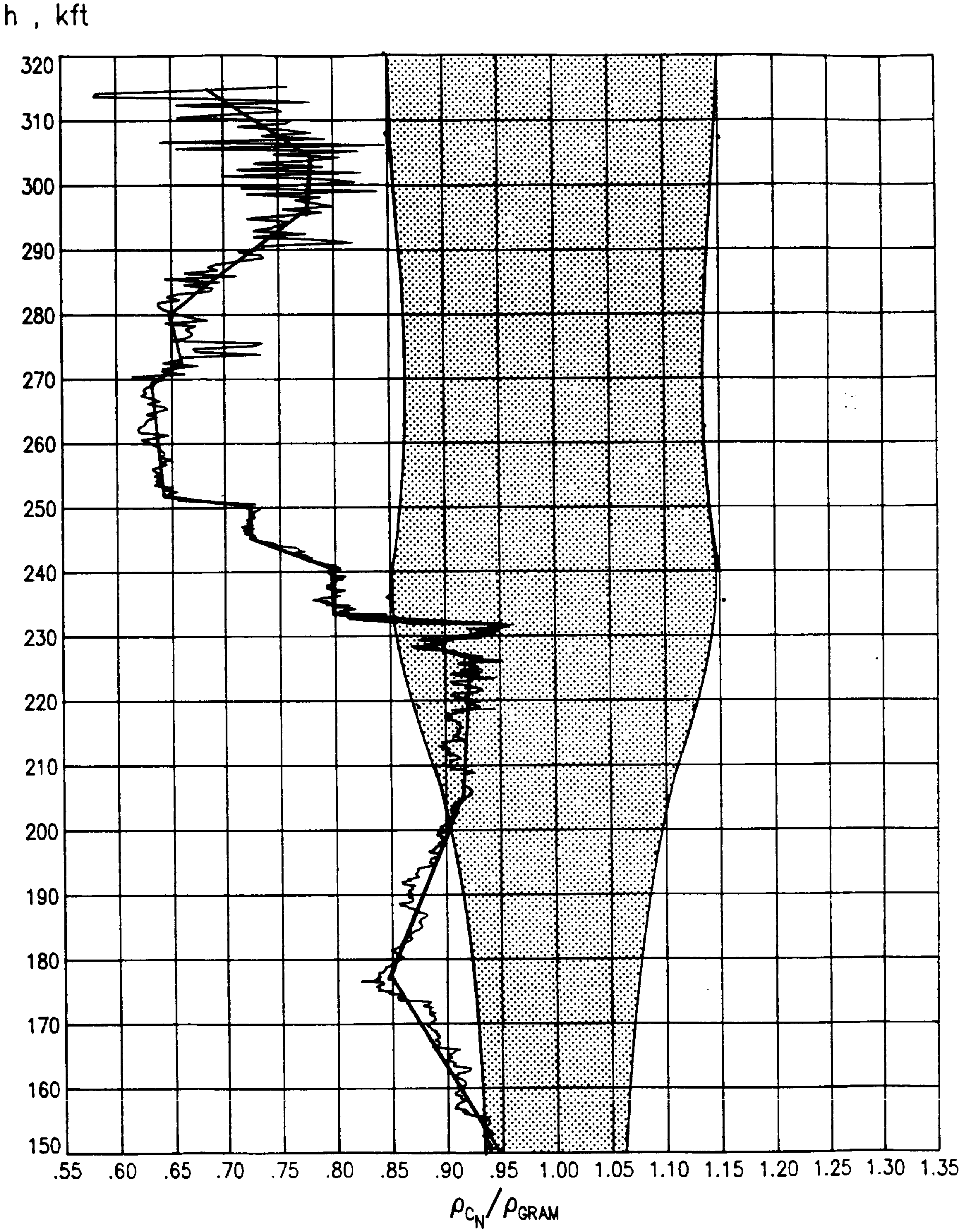


Figure A-9.STS-9 (December) GRAM density scaling

ORIGINAL PAGE IS
OF POOR QUALITY

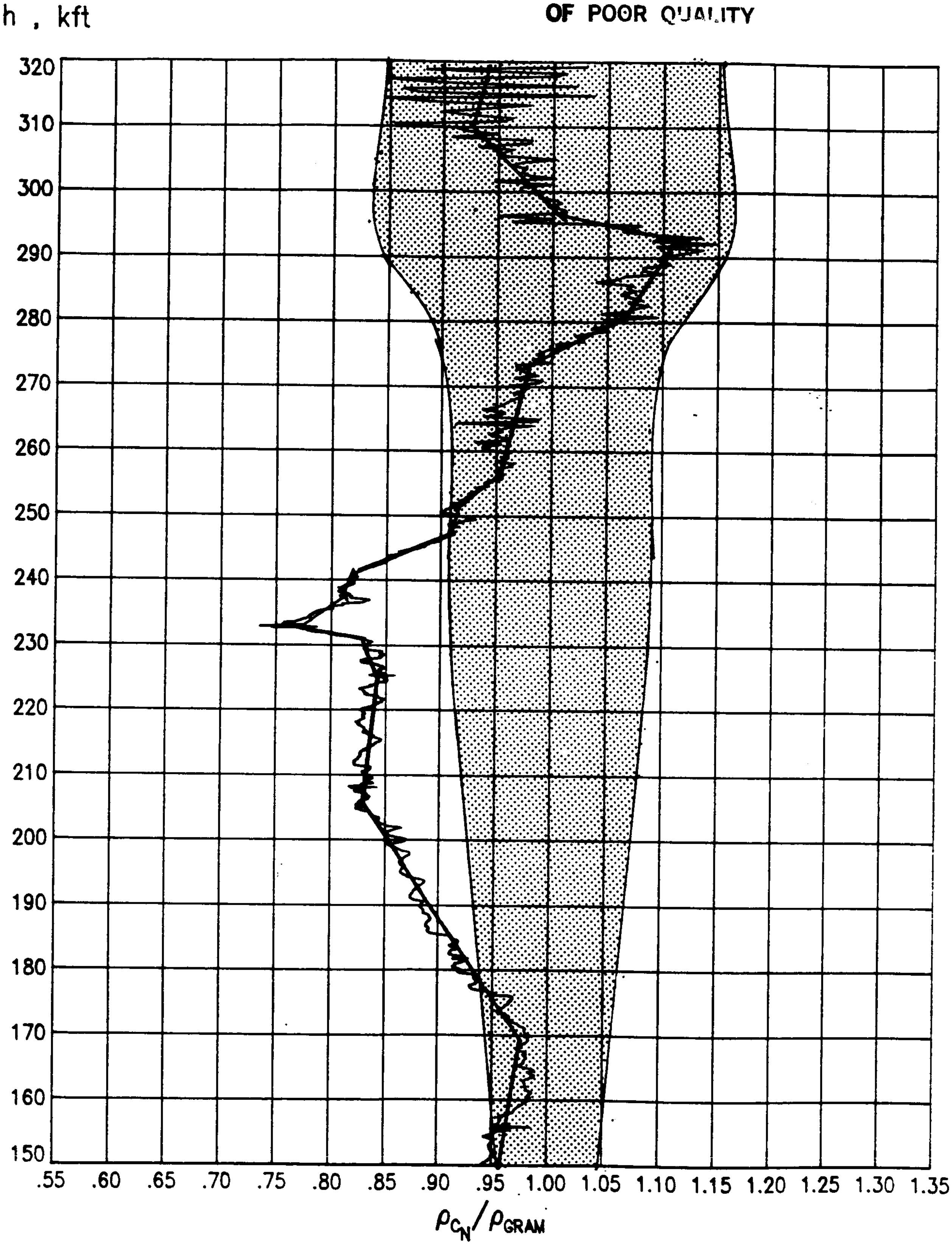


Figure A-10. STS-11 (February) GRAM density scaling

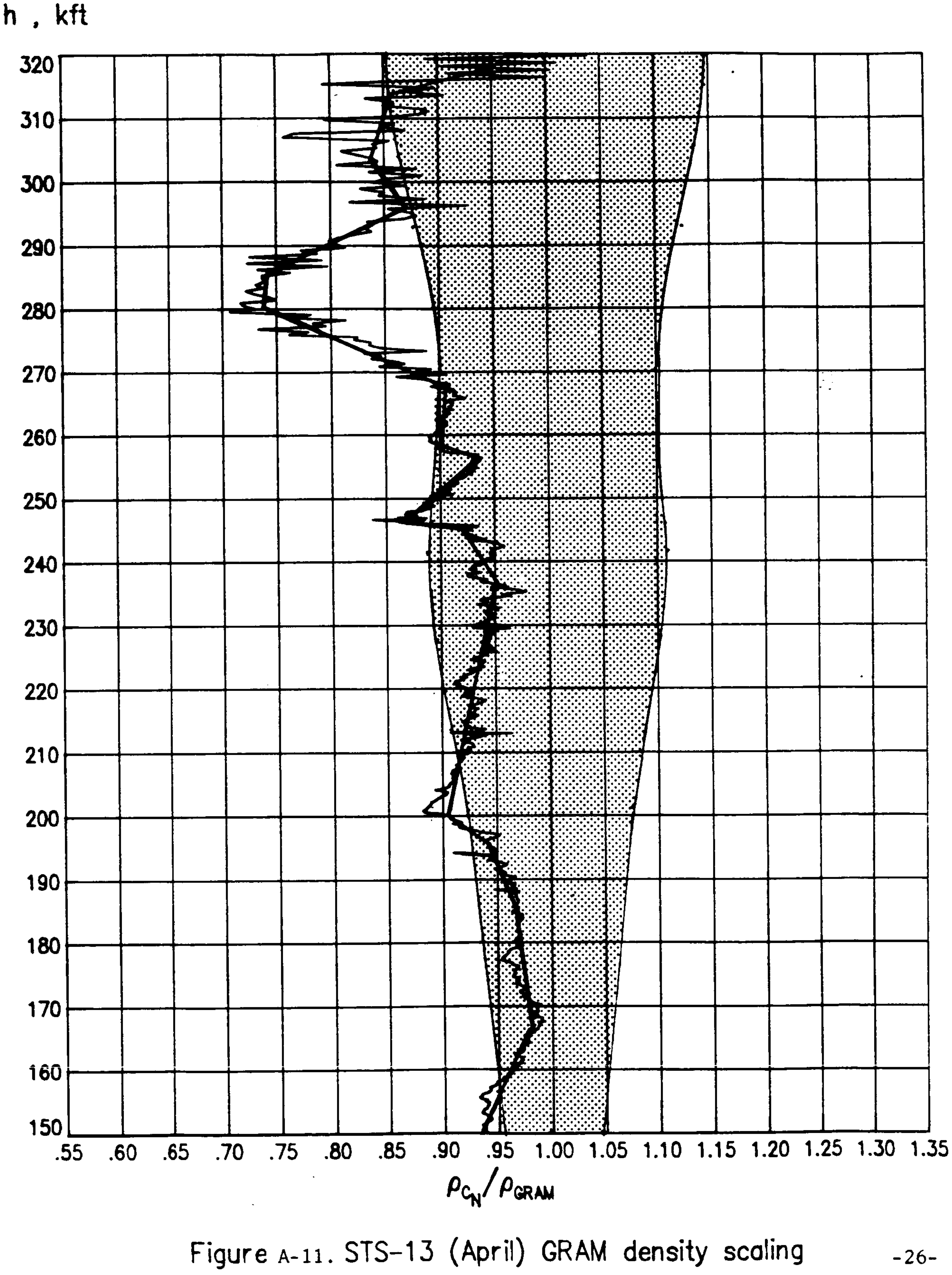


Figure A-11. STS-13 (April) GRAM density scaling

ORIGINAL PAGE IS
OF POOR QUALITY

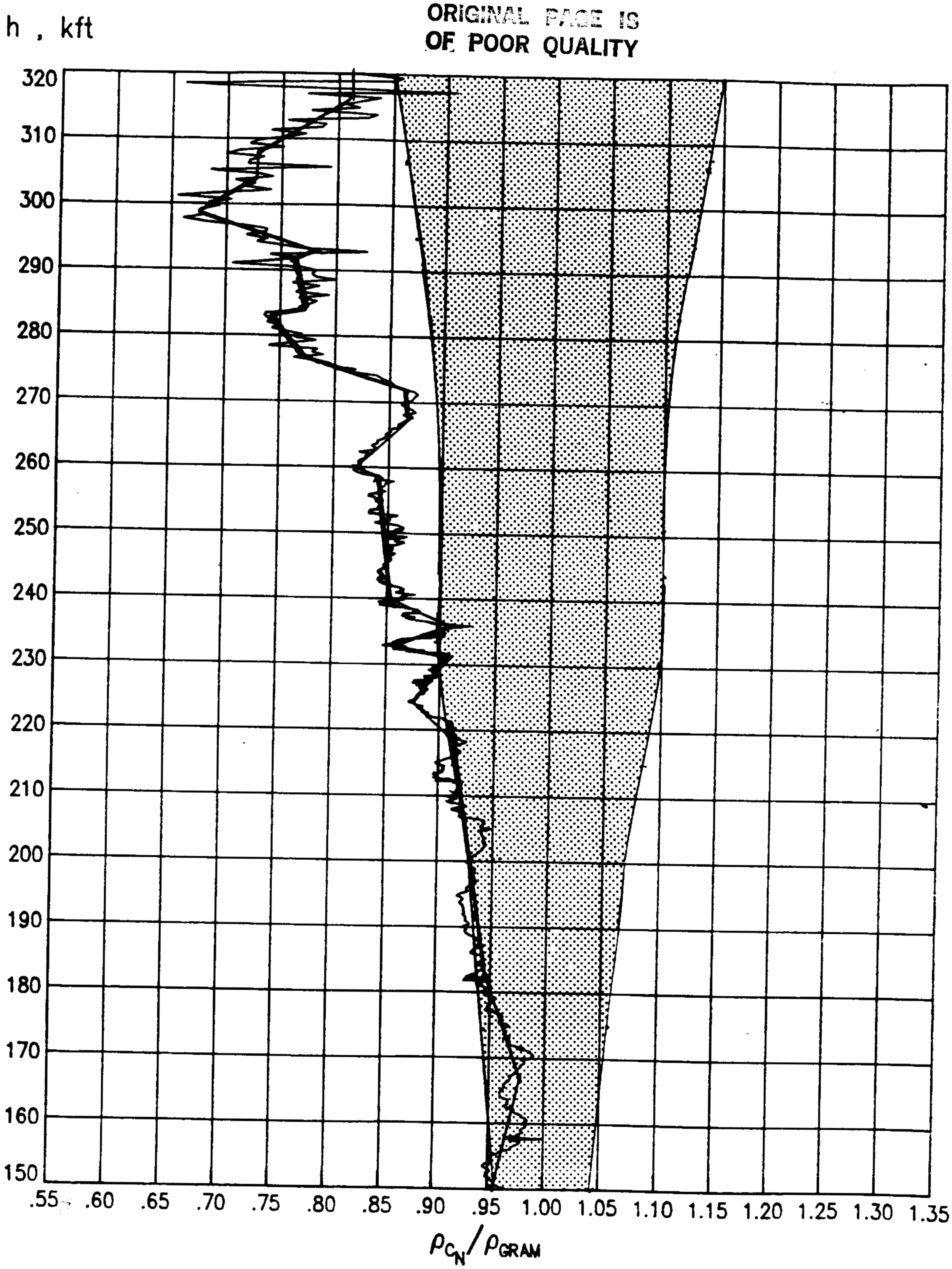


Figure A-12. STS-14 (September) GRAM density scaling

1. Report No. NASA CR- 171824	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
FINAL REPORT: Shuttle Derived Atmospheric Density Model
Part 2: STS Atmospheric Implications for AOTV Trajectory
Analysis - a Proposed GRAM Pertubation Density Model

5. Report Date
December 1984

6. Performing Organization Code

7. Author(s)
John T. Findlay
G. Mel Kelly, Patrick A. Troutman

8. Performing Organization Report No.
AMA Report No. 84-16

9. Performing Organization Name and Address
Analytical Mechanics Associates, Inc.
17 Research Road
Hampton, VA 23666

10. Work Unit No.

11. Contract or Grant No.
NAS9-17158

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code
936-15-01-01

15. Supplementary Notes
Johnson Space Center Technical Monitor: Joe D. Gamble

16. Abstract

In this report, Part 2 of the final report, a perturbation model to the Marshall Space Flight Center (MFSC) Global Reference Atmosphere Model (GRAM) is developed for use in Aeroassist Orbital Transfer Vehicle (AOTV) trajectory analysis. The model reflects NASA Space Shuttle experience over the first twelve (12) entry flights. The GRAM was selected over the Air Force 1978 Reference Model because of its more general formulation and wider throughout the NASA. The add-on model, a simple scaling with altitude to reflect density structure encountered by the Shuttle Orbiter (shears, waves, "potholes-in-the-sky", etc) was selected principally to simplify implementation. Perturbations, by season, can be utilized to minimize the number of required simulations, however, exact Shuttle flight history can be exercised using the same model if desired. Such a perturbation model, though not meteorologically motivated, enables inclusion of High Resolution Accelerometer Package (HiRAP) results in the thermosphere. Provision is made to incorporate differing perturbations during the AOTV entry and exit phases of the aero-assist maneuver to account for trajectory displacement (geographic) along the ground track.

17. Key Words (Suggested by Author(s))
Space Shuttle STS, Atmospheric Data
Atmospheric Models

18. Distribution Statement
[redacted]

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 27	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161

JSC Form 1424 (Rev Nov 75)

NASA — JSC