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Fifth Semiannual Status Report

May 1966

on the Engineering Portion of a Research Program to DEVELOP A ZERO-g, DRAG-FREE SATELLITE and to PERFORM A GYRO TEST OF GENERAL RELATIVITY IN A SATELLITE

at

Stanford University

under

Research Grant NsG-582

from the

National Aeronautics and Space Administration

(Principal investigators for the engineering portion of the program are Professor Robert H. Cannon, Jr. and Professor Benjamin O. Lange.)

CONTENTS

I. INTRODUCTION

Stanford University is engaged in a program to develop a scientific zero-g satellite, and to perform a gyro test of general relativity in a satellite. The program was conceived by Stanford in 1961 and is described in detail in a proposal for support [Ref. 1] submitted to NASA in November 1962, and in Engineering Status Report Nos. 1 to 4 [Refs. 2 to 5].

On the basis of Ref. 1, a grant, NsG-582, was awarded to Stanford by NASA on 8 May 1964, with a retroactive starting date of 1 October 1963. The present report describes research performed in the Department of Aeronautics and Astronautics during the fifth half-year of the NASA grant period, from November 1965 through April 1966, and discusses the present status of the program.

A detailed preliminary analysis of the dynamics, control and uses of the drag-free satellite and of unsupported gyroscopes, along with a trajectory error analysis and a gyro random-drift-error analysis are given in Refs. 6, 7, and 8.

During the present report period, a presentation of the flight proposal was made before the Planetary Atmospheres Subcommittee of the NASA Space Science Steering Committee. We understand the the Subcommittee is quite interested in our satellite concept and is hopeful that it may be flight-funded on one basis or another. The Subcommittee also concurred on the importance of the density data we propose to obtain. We understand the Subcommittee felt that the engineering that has been done has been thorough and very good, and that while there are important engineering problems remaining, the committee had no real doubt that we could solve them, but there is an overriding serious question as to the accuracy with which drag data can be converted to air density information at the low altitude part of the orbit. As a result, a concentrated effort was begun by Stanford in April 1966 to determine the current and projected state of knowledge and if necessary, what action would be required to improve this state so that the aeronomy experiment could be flown with the greatest confidence.

During the present report period, the engineering effort on the thrust measuring portion of the drag-free satellite was examined in detail. A thruster evaluation and calibration facility has been designed and is described in Section II.

Also during this period, a continuing engineering effort has been underway cooperatively with the Stanford Physics Department. As the feasibility of some of the relativity-experiment techniques has been established by laboratory experiment, we have worked with the Physics group to develop these concepts into engineering prototypes. Specifically, design aspects of the telescope and the attitude control system have been under detailed design study.

II. SUMMARY OF PROGRESS DURING REPORT PERIOD

A. AERONOMY EXPERIMENT SATELLITE

1. Flight Proposal

It was decided some months ago that the first engineering flights on this program should be aeronomy flights. A proposal [Ref. 9] was drafted with Prof. Gordon J. F. MacDonald of UCLA as coprincipal investigator, to construct and fly two such satellites in a polar orbit having perigee at an altitude of 120-140 km, and apogee between 400 and 1000 km, the perigee to migrate so as to cover the entire northern hemisphere, with particular emphasis on the equatorial region, during the lifetime of the satellite. The proposed first launch date was late 1969 or early 1970. (Professor MacDonald, a recognized authority on aeronomy, had prepared a similar proposal for a drag-free satellite [Ref. 10] based on work done independently at UCLA in 1962.)

These flights have two purposes. The first is to provide an instantaneous measurement of density over a range of latitude, time, and altitude (including the crucial 120-140 km regime), providing incisive knowledge of how density varies with these quantities, and thus contributing vital background for dynamic modeling of the atmosphere. The second purpose is to provide an orbital demonstration of the zero-g control technique, which has been operating in the laboratory for 20 months, and which would also be used in subsequent experiments, including the Schiff gyro test of general relativity.

The preliminary design of the orbital experiments and of the vehicle is discussed in detail in our proposal [Ref. 9] and summarized in our Fourth Semiannual Status Report [Ref. 5] .

On 28 October 1965, Professors Cannon and MacDonald met with Mr. Jesse Mitchell, Dr. Robert Fellows, and Dr. Nancy Roman at the NASA Office of Space Sciences Headquarters in Washington to review the proposal draft and discuss plans for its formal presentation to NASA. Mr. Mitchell, Dr. Fellows, and Dr. Roman made many helpful comments about the proposal. It was suggested that the next move would be to submit the proposal formally for review by Dr. Fellows' Subcommittee on Planetary Atmospheres of the NASA Space Science Steering Committee, to be followed by an oral presentation at the Subcommittees' meeting in March 1966, after which the Subcommittee would make a recommendation on it to NASA. These steps were subsequently taken, the proposal [Ref. 9] being submitted formally by Stanford University and UCLA in February 1966, and the Subcommittee Meeting taking place at Boulder, Colorado on 30 March 1966. The scientific aspects of the aeronomy flight were presented by Prof. MacDonald, and engineering design and progress to date were described by the Stanford team.

Professor MacDonald noted that the satellite would gather continous accurate drag data in an altitude range from 120-140 km at perigee to 1000 km at apogee over a period of ten or more days, with the perigee point moving naturally to cover the entire northern hemisphere. He stated that this drag data could be converted to air-density data, and that this density data, particularly that at 120-140 km altitude, would be quite crucial to our understanding of the dynamics of the atmosphere, the sun's energy being absorbed by the earth almost entirely in this narrow altitude band. He also noted that this information cannot be obtained in a continuous way by any other means.

Professor Cannon described the history of the Stanford University zero-g drag-free satellite program and its several goals: The early concentration on aeronomy flights, the interest in intermediate geodesy and other experiments, and the long-range goal of performing the Pugh-Schiff test of general relativity. He described the preliminary research and design which has been carried out over the last five years, largely under NASA Grant NsG-582, and the engineering team which has been built up under this and other sponsorship. Design tradeoffs involved in the selection of orbits, the selection of sensing techniques, and the design of the satellite vehicle, were discussed in detail and a film was shown of the air-cushion-vehicle simulator on which the control system is demonstrated in two axes. The Subcommittee raised a number of important questions, and Prof. Lange and Dr. DeBra also participated in the discussion of these.

After the presentation of our flight test proposal, we were informed that the Subcommittee was quite interested in our satellite concept and is hopeful that it may be flight-funded on one basis or another. The Subcommittee also concurred on the importance of the density data we propose to measure (particularly at low altitude), although it is not clear, they felt, that this satellite is necessarily the best way to get it. We understand the Subcommittee felt that the engineering that has been done has been thorough and very good, and that while there are important engineering problems remaining, these are of less concern than the overriding serious question as to the accuracy with which drag data can be converted to air-density information at the low-altitude part of the orbit. That is, while the committee was prepared to concede the probability of our successfully measuring drag as we had described, they felt that we had not established that we could convert this drag data to density data with "reasonable" accuracy, particularly, in the region where mean-free-path length approximately equals satellite diameter ("reasonable" being perhaps the order of 10 percent).

The Subcommittee was quoted as suggesting that perhaps even an order of magnitude in accuracy might be difficult. For this reason, as we understand it, the Subcommittee withheld endorsement of our flight proposal.

Subsequent to the Boulder Subcommittee meeting, the Stanford group consulted with Professor Daniel Bershader (Associate Head of the Department of Aeronautics and Astronautics at Stanford) whose field is high-speed ionized gas dynamics, and Professor Donald Baganoff whose field is rarefied gas physics, about the state of knowledge of the drag coefficient on a sphere under the conditions of interest. They in turn set up discussions with Professors Frank Hurlbut, F. S. Sherman, and D. R. Willis, of the University of California at Berkeley, who operate the new low-density gas dynamics tunnel at Berkeley, and whose special area of research is the theoretical and experimental study of low-density gas behavior, including specifically the effective drag coefficient in very-low-density flow. Professor Sherman produced experimental evidence from numerous sources which, in toto, indicates very convincingly that the relative drag coefficient on a sphere is known at the present time to better than 10 percent over the entire range of Knudsen numbers, including specifically the range from 0.1 to 10. Some of the key data was taken at Mach 10. Moreover, Professor Sherman is quite certain that in two years this uncertainty will be well within 2-3 percent, even at Knudsen number equal to 1.0. The group discussed the effects of different surfaces (from glass to aluminum), of small flats, of the atmospheric wake, and of the effects of the gas jets in our drag makeup system. All of these effects were considered, after substantital discussion, to be much less than 2 or 3 percent.

Preliminary agreement was reached with the University of California for a program of further study and of drag measurements in their tunnel on a scale model of our satellite in the Knudsen number range of interest and at high Mach number. (It is also planned tentatively to test our thrusters and thrust-sensing devices at extremely high vacuum in the Berkeley facilities.)

A formal report will be made on our studies of drag-to-density conversion to date, and our future plans in this regard. It is hoped that a further discussion of this question with the committee will be possible in the near future, where a thorough verbal presentation and discussion can be held.

2. Drag Sensing

Central to the success of the aeronomy experiment is the ability to measure the drag on the satellite accurately. In the drag-free satellite a proofmass is shielded by the satellite so that it follows a purely gravitational orbit. The force necessary to make the satellite track the proofmass is therefore equal to the external forces disturbing the satellite. Thus, the control forces can be measured to determine the drag force.

A preliminary design of the thrusters, with an integrated force rebalance servo for measuring the thrust, has been accomplished, and a facility for evaluating prototypes and calibrating the flight hardware is being designed.

3. Evaluation of Vacuum Facilities for Calibration

The target goal of measuring drag to 1 percent by thrust measurements make the vacuum facility for thruster testing and calibration a very important part of the overall satellite program. Therefore, design studies have been made on several types of facility in order to determine whether one should be built at Stanford, and if so, what type. Tables I and II list the various facilities considered and some of the important parameters associated with them. A price estimate is also given in the Tables (which has more value as a relative, rather than an absolute, indication of price.)

Configurations 1 or 2 of Table I are the most likely choices for the Stanford facility. These configurations do not have a capability for continuous operation of the thrusters. The remaining facilities do, with varying degrees of accuracy. The primary design goal in these vacuum chambers is to keep the ambient pressure P_a low enough so the error due to back pressure (given by P_aA_e, where A_e is the exit area of nozzle) is less than 0.2 percent of the thrust force. This is necessary to insure less than 1% error in thrust measurement in flight.)

Configuration I has the minimum volume allowable if the impulse bit does not exceed 50×10^{-3} lb sec. Configuration II has the minimum volume allowable, assuming that continuous pressure measurements are desired at an accuracy of better than 0.15 mm Hg. The two configurations can be seen in the sketch of Fig. 1. The primary differences are:

(a) The separation of the vacuum chamber into two separate chambers, one of which can be external to the laboratory, providing a considerable saving in space.

Table I

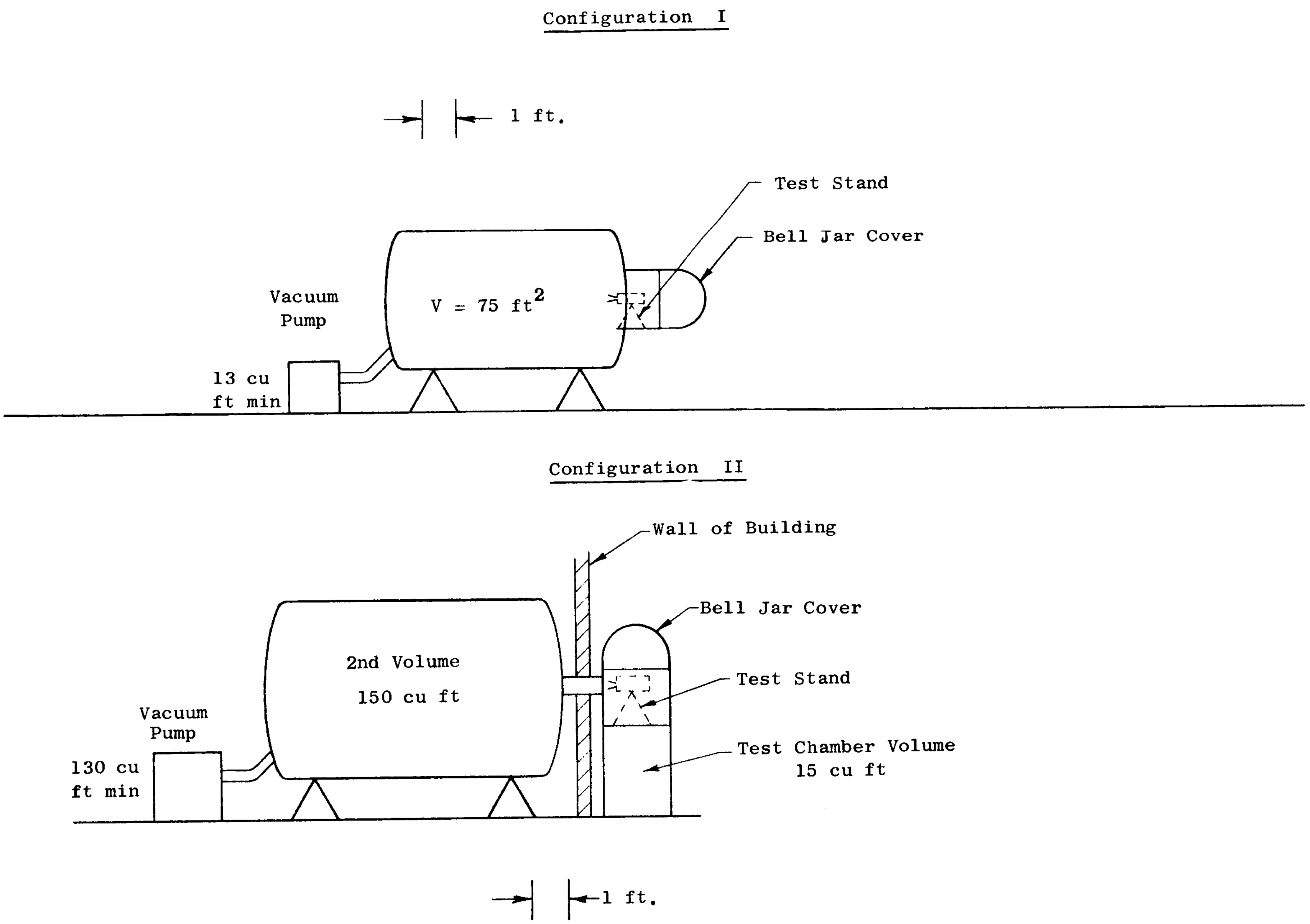
COMPARISON OF VACUUM FACILITIES - MECHANICAL PUMPS

Description of Configuration and Est Price	Vacuum Pump Speed (cfm)	Total Chamber Volume (ft^3)	Continuous Pressure Measurement	Minimum Pressure (mm Hg)	Time to Pump-Down-0.008 mm Hg (minute)	A_e/A_t Nozzle Expansion Ratio for Full Flow for $P_o = 20$ psi	Waiting Time between 1 lb x 50 ms Pulses (.2% error) (minute)	Chamber Pressure During Steady Thrust (mm Hg)
Config. No. I Single chamber, $6,750	13	75 (minimum volume)	No	0.005	66	Not possible with $P_o = 20$ psi	16.8	674
Config. No. II Separated chambers, min volume for continuous press meas to desired accuracy $12,000	130	165	Yes	0.005	22	2.5	0.715	67.4
Config No. III Single chamber + high capacity mech pump $15,500	1300	75	Yes	0.001	0.667	12.5	0.168	6.74
Config No. IV Single chamber + extra high capacity mech pump $37,000	7000	75	Yes	0.001	0.012	40	0.032	1.25

Table II

COMPARISON OF VACUUM FACILITIES - STEAM JET PUMPS

Description of Configuration and Est Price	Pump Capacity (cfm)	Total Chamber Volume (ft^3)	Continuous Pressure Measurement	Minimum Pressure (mm Hg)	Chamber Pressure During Steady Thrust (mm Hg)	A_e/A_t Nozzle Expansion Ratio for Full Flow (P_o = 20 psi)	% Error Due to Back Pressure (P_o = 20 psi & A_e/A_t = 25)	Steam Required (lbs/hr)
Config. No. V Single chamber + 2-stage steam jet $12,000	800	20	Yes	6	11	7.8	15.5%	1500
Config. No. VI Single chamber + 3-stage steam jet $17,000	2,900	20	Yes	2	3	18.5	4.2%	4100
Config No. VII Single chamber + 4-stage steam jet $23,000	17,400	20	Yes	0.3	0.5	67	0.7%	4970
Config No. VIII Single chamber + 5-stage steam jet $29,000	87,000	20	Yes	0.015	0.1	193	0.14%	5206


Configuration I

Configuration II

FIG. 1: VACUUM FACILITY CONFIGURATIONS

(b) The larger volume results in a slower rise in ambient pressure during thrusting. This allows longer test times and makes the continuous measurement of low pressures more feasible. A diaphragm-type pressure transducer has at best, a 400 millisecond time constant at 0.25 mm Hg, due to the low conductance of the gas into the transducer.

The remaining configurations are designed to provide a capability for continuous thrusting, but the expense for a facility that can provide sufficiently low pressure is quite high and does not appear justified when most of the jet operation will be in short impulses.

The types of teststands considered for thrust measurement are (a) ballistic pendulum and (b) direct force reading.

Since the primary objective of the experiment is to determine the thrust impulse and correlate it with the impulse as determined by the proposed flight hardware, a ballistic pendulum would appear to be satisfactory. However, a direct force rebalance system is being carefully investigated since it offers certain advantages over the ballistic pendulum, including the following:

- A time history of thrust is obtained which (assuming adequate frequency response) can provide some capability of detecting and correcting systematic errors associated with the vacuum system. A typical example of this would be the change in indicated thrust as the back pressure builds up.
- The nozzle will not change its orientation during or after thrusting, and thus the "core" of the jet can be directed accurately if needed, and the thrust stand can be shielded more effectively from pressure transients in the chamber.
- A more flexible test program and a faster rate of data collection is possible.

The force rebalance system is more complicated and should preferably have a natural frequency of 400 cps or higher, which is very high for a mechanical system. However, preliminary studies show this can be obtained utilizing a fast pickup (e.g., capacitive), high stiffness in all directions, and accurate alignments to eliminate cross coupling.

4. Flight Hardware for Thrust Measurement

The flight hardware proposed for measuring the impulse of the gas jets will utilize both chamber-pressure measurement and measurement of the force necessary to restrain the nozzle. The need for the force rebalance system will depend on how accurately impulse can be determined from thrust-chamber pressure and propellant temperature. The current effort is concentrated on the determination of thrust through chamber pressure measurement using the flight configuration but without the force rebalance. It is hoped that sufficient data can be taken under varying conditions to show that the thrust can be determined through pressure-temperature measurements and thus eliminate the direct measurement of force.

B. CONTROL SYSTEM ANALYSIS

The control system analysis conducted by Robert Farquhar, Dr. William Davis, and Dr. Alan Fleming is now available in the form of three SUDAAR reports (two of which are the authors' doctoral theses). These are

Farquhar, R., "Analog Studies of the Limit Cycle Fuel Consumption of a Spinning Symmetric Drag-Free Satellite," SUDAAR Report No. 276, Stanford University, Dept. of Aeronautics and Astronautics, Stanford, Calif., May 1, 1966

Davis, W. R., "Control of the Relative Motion Between Satellites in Neighboring Elliptic Orbits," SUDAAR Report No. 274, Stanford University, Dept. of Aeronautics and Astronautics, Stanford, Calif., May 1, 1966

Fleming, Alan, "Use of the Properties of Frequency Symmetry and Complex Symmetry in the Control of Linear Dynamical Systems," SUDAAR Report No. 266, Stanford University, Dept. of Aeronautics and Astronautics, Stanford, Calif., Apr 1, 1966

In summary, these results show that it is quite feasible to construct translation control systems for tumbling or freely spinning drag-free satellites which have fuel consumption rates within a factor of 2 to 1.4 of the theoretical mimimum necessary to just cancel the drag. They further show that probably the best control mechanization is the pulse-width pulse-frequency modulation (PWPF) system, although the pseudo-rate system is still being considered.

C. RESEARCH ON AIR-CUSHION VEHICLE BEHAVIOR

The term "air-cushion vehicle" pertains to a vehicle supported by a thin (1 to 4 x 10^{-3} in.) viscous gas film which is created by flowing gas at higher than ambient pressure through an orifice (or several orifices) in the center of the flat bottom surface of the vehicle. This support, therefore, is a hydrostatic gas bearing. The air-cushion-vehicle drag-free-satellite simulator is a vehicle of this type, and so is the flow research vehicle. Both have been described in previous status reports [Refs. 4 and 5].

Efforts during the present reporting period have been concentrated on obtaining quantitative experimental verification of the theoretically predicted static behavior of the gas film, and on the theoretical as well as experimental study of the self-excited vertical vibrations of a gas-supported vehicle (or bas bearing). All investigations included plane and curved (concave and convex spherical) but axisymmetric bottom surfaces of the vehicle. Experimental data for supply pressure, flow rate, tilt angle vs. mass unbalance, static side force vs. tilt angle, and the radial pressure distribution have been obtained for a wide range of relative sphericities, and for three different loads. (The parabolicity, β, is defined as the difference in gap thickness at the edge and at the center, divided by the gap thickness at the center.) Their deviation from the theoretical values is within the measuring uncertainty throughout.

The theoretical description of the eigenvibrations of the vehicle used a linearized model, the coefficients stemming from the steady-state solution of the equations for the gas film. The predicted limit of stability has been compared with the thresholds observed in experiments. The accuracy by which the latter could be determined varied from 3 to 5 percent up to hardly better than 50 percent, depending mostly on whether the flow through the orifice at the gas inlet to the actual support-flow regime is subsonic or supersonic. Within the limits of observation, the agreement with theory is better for the supersonic than for the subsonic orifice. A comparison between predicted and measured frequencies at marginal stability (i.e., of the undamped oscillations) also showed poor agreement. This is attributed to some extent to nonlinear affects which are presently being investigated.

As an illustration of the influence of bearing plate curvature, a plot of the restoring torque vs. parabolicity is shown in Fig. 2. The critical recess volume dynamic stability depends on several parameters, $\Omega_{crit.}$. Figure 3 shows the strong influence of parabolicity as well as specific load. Figure 4 illustrates the improvement in stability obtained by using subsonic orifices. The measured stability gain, however, is in poor agreement with the theoretical prediction.

It is felt that some of the disagreement between results and the linear constant-coefficient theory is because the latter neglects any explicit time-dependence of the flow field. While the explicitly time-varying problem can be formulated, it is doubtful it can be solved by any reasonable method. For this reason some effort has been expended in finding a physical system represented by the approximate equations of the air-cushion vehicle. It is hoped that by understanding the simple system and how its behavior is effected by changes in its parameters (and hence, the coefficients of the differential equation) we can get some insight into how the parameters of the air-cushion vehicle effect its behavior.

The main result of the investigation is that definite advantages can be gained by using concave plates rather than plane or convex ones. For the lateral stiffness or "restoring torque" an increase of up to 50 percent is possible compared with a plane plate. Similar improvements are possible for the static stability or "vertical bearing stiffness" and, at least for small loads per unit area, for the "dynamic stability," i.e., the tendency of the vehicle to vibrate. The optima for all these quantities lie quite close together at a relative sphericity of about -0.65.

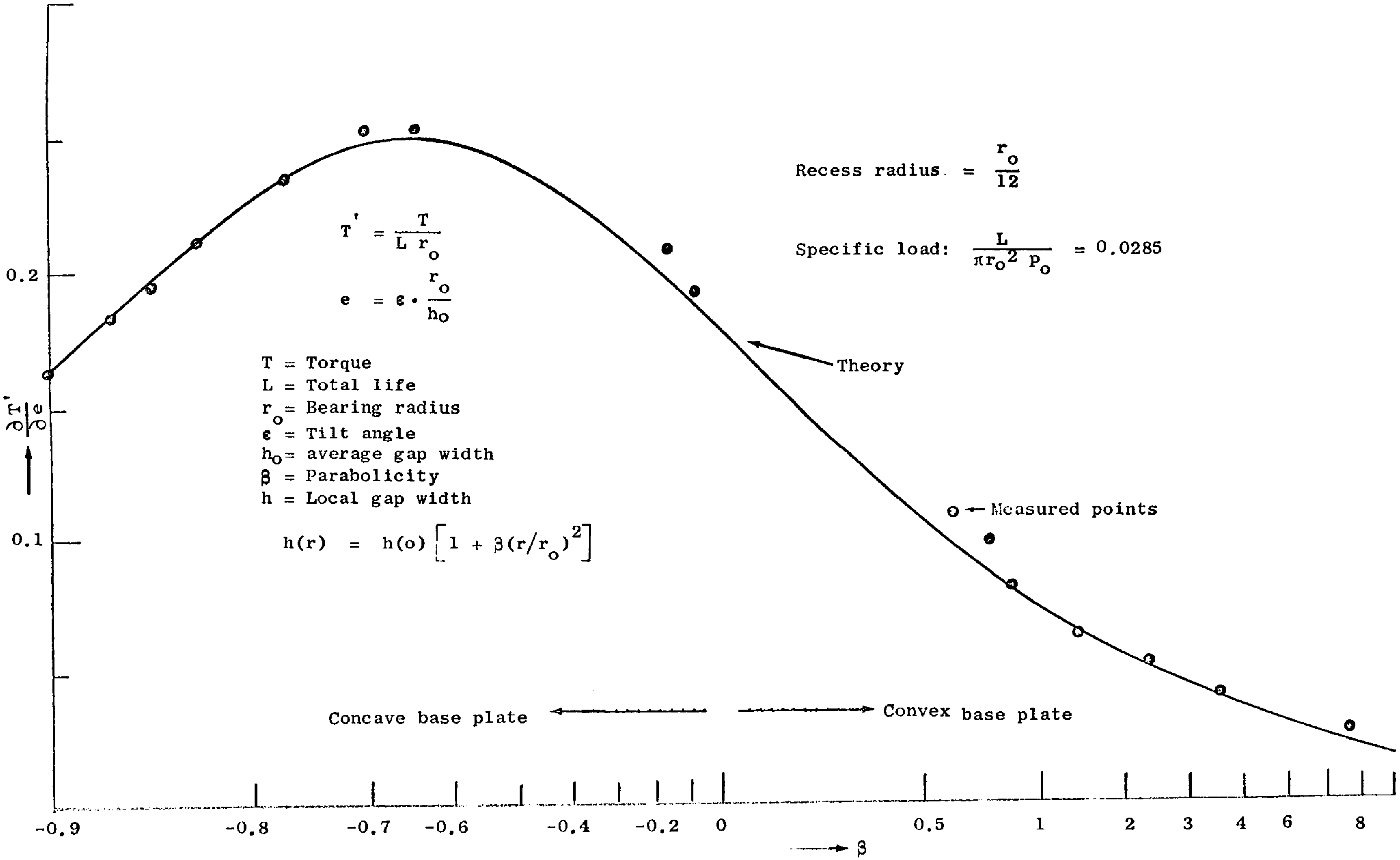


FIG. 2: RESTORING TORQUE FOR LIGHTLY LOADED THRUST GAS BEARING WITH PARABOLIC BOTTOM

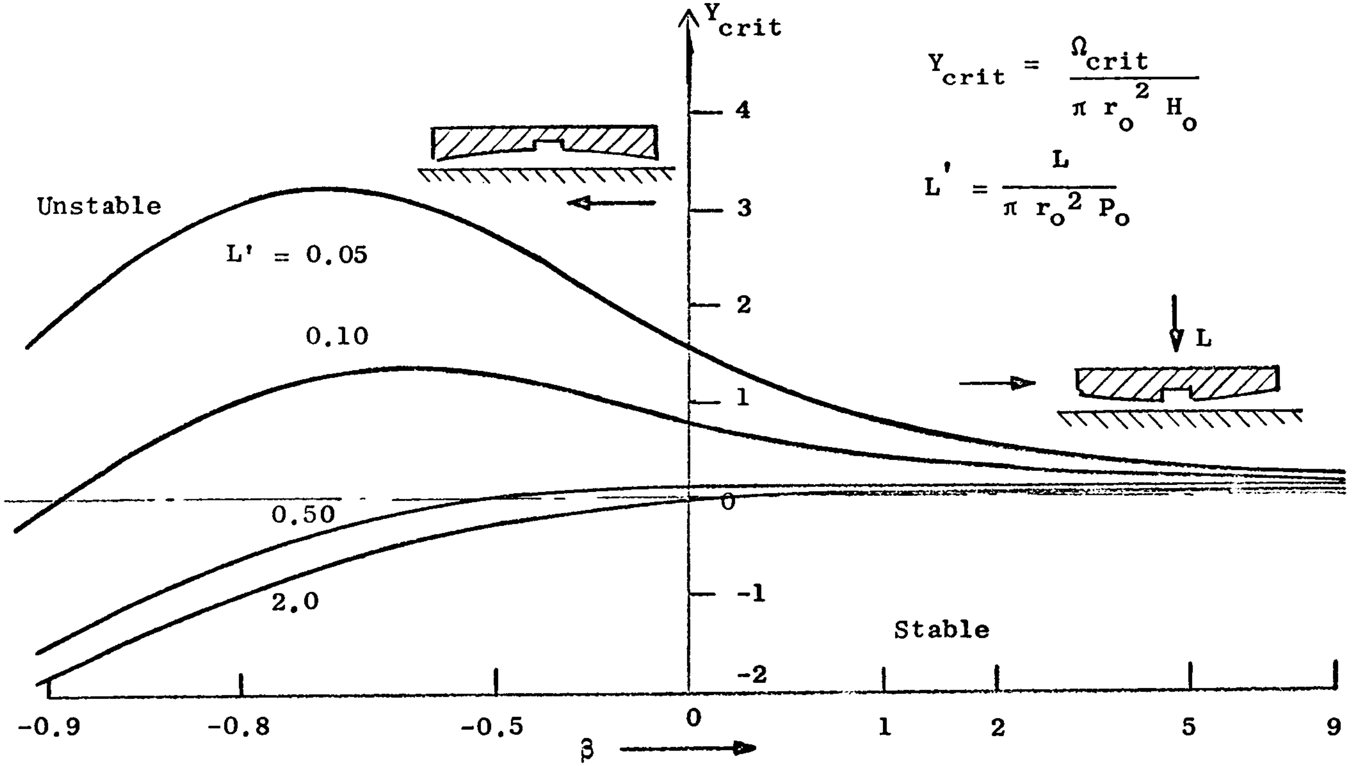


FIG. 3: LIMIT OF DYNAMIC STABILITY: CRITICAL RECESS VOLUME FOR SUPERSONIC ORIFICE

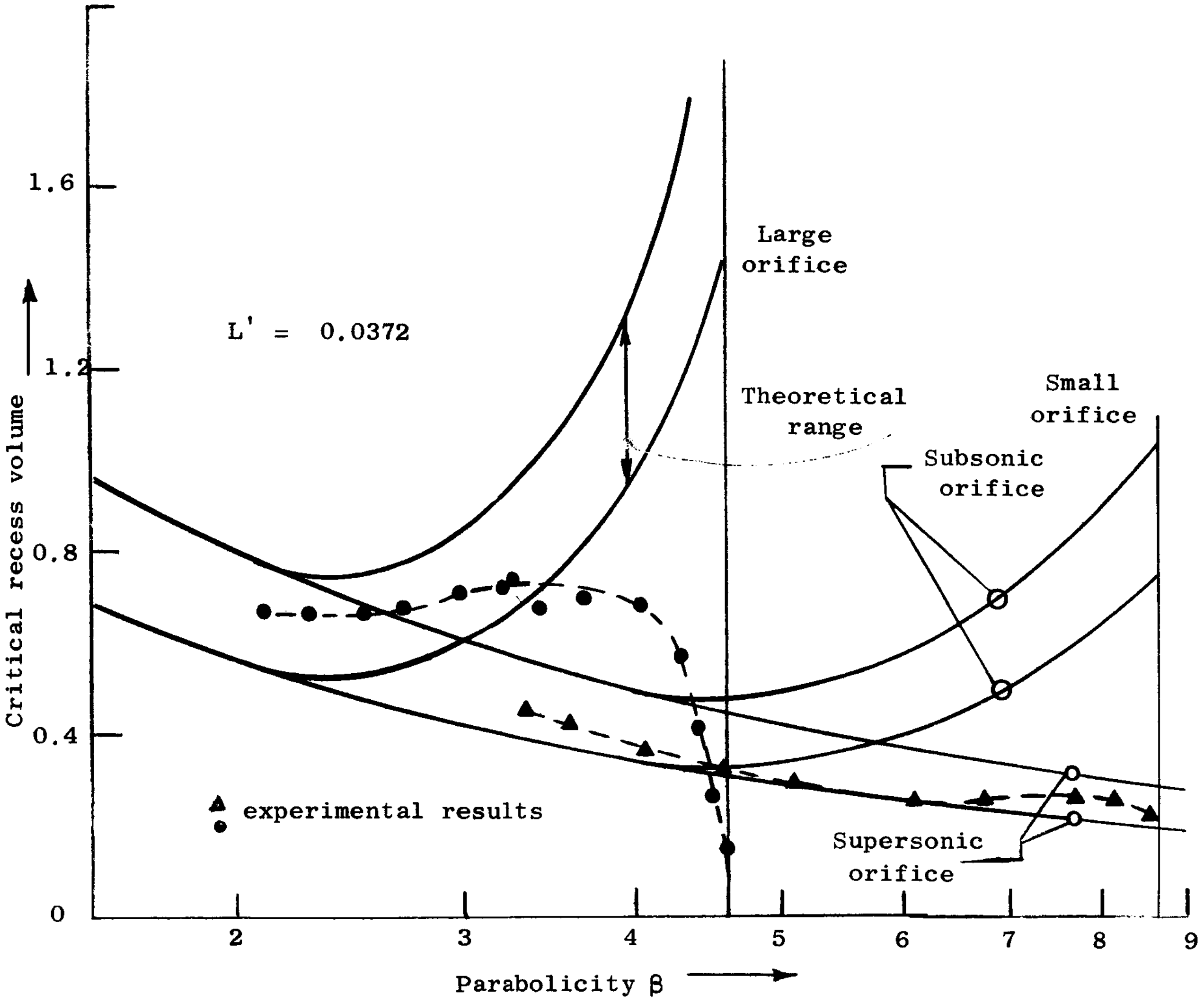


FIG 4: CRITICAL RECESS VOLUME FOR MARGINAL DYNAMIC STABILITY AS A FUNCTION OF BEARING PARABOLICITY FOR TWO DIFFERENT ORIFICE SIZES

Regarding the disturbances of the simulator by support flow anomalies, it can be shown that it is always possible--at least in theory--to keep either the static side force or the coupling between the translational viscous drag and the rotational viscous drag torque zero. Since the coupling, however, is extremely small (time constants for the development of the interaction are the order of several days), and since there is always additional coupling through the aerodynamic forces on the upper parts of the vehicle, it is advisable to build a vehicle as symmetrically as possible, balance it for zero side force and accept whatever small coupling is present.

D. EXPERIMENTAL SATELLITE CONTROL SYSTEM SIMULATION

1. Granite Table Leveling

The limitation to the accuracy of the drag-free satellite simulation due to uncertainties in table leveling has been overcome. At the present time, the small uncertainties remaining, which correspond to the equivalent of approximately 1 arc sec of table tilt, are due to the flow uncertainties in the airbearing which supports the air-cushion vehicle [Ref. 5].

The evaluation of the table leveling system has continued because its performance cannot be measured with respect to an absolute vertical reference. (If such a reference existed we would use it for control.) Comparison of the indications of level by several sensors of comparable accuracy is the only means available for evaluating its precision and stability. Data collected over the last year have been described in a paper which has been accepted for presentation in the AIAA Guidance and Control Specialist Conference scheduled in August, 1966 in Seattle, Washington [Ref. 11].

The initial performance indicated in Ref. 5 has been verified and we now feel that for periods of 12 hours or less, the table remains level within 0.5 arc sec. In half of the 12-hour periods recorded during an 8-month interval, the level stability was better than 0.1 arc sec. Furthermore, our experience in developing and operating this table leads us to believe that even greater precision can be achieved if required.

2. Granite Table Survey

A complete survey of the flatness of the granite table to an accuracy of about ± 10 μin. has been completed by Mr. S. Mohan using the autocollimator technique developed by Davidson Optronics. This consists of drawing a mirror whose surface is nominally normal to the table along the line to be surveyed with a special pull chain. The mirror rests on three legs and is directed by a special guide rail. The light from a Davidson Model D-707-101 2-axis automatic autocollimator is reflected from a porro prism onto the moving mirror and back into the autocollimator. The moving mirror tilts as the table deviates from flatness, and the signal from the autocollimator which measures this tilt is fed into a very accurate EAI analog integrator. The output of the integrator drives a recorder. Since the tilt of the moving mirror is proportional to the slope of the table surface, the integral of this tilt along the path gives a profile of the table surface on the recorder. The primary advantage of this approach is that the analog integrator smooths the noisy input signal and yields data to about ± 10 μin. A copy of the survey results are enclosed in a pocket at the end of this report.

These results will be used to interpret the precise measurements with the air-cushion vehicle simulator and to correct the table irregularities. It is hoped to be able to extend in this manner, the range of altitudes simulated.

3. Air-Cushion Vehicle

The assembly of the Jet Propulsion Laboratory surplus pneumatic parts into an improved air-cushion vehicle awaits a final indication of the orbits to be flown in the aeronomy experiment. The major development effort during this report period has been on the thrust-measuring devices and by delaying the work on the air-cushion vehicle, these thrusters can be incorporated on it, making it a more accurate representation of the flight vehicle.

III PLANS FOR THE IMMEDIATE FUTURE

A. SATELLITE FLIGHT PLANNING: DRAG-TO-DENSITY CONVERSION

As noted in Section II-A, the Subcommittee on Planetary Atmospheres has withheld a positive vote on our request for funding of a satellite flight program, for the specific reason that they are not yet convinced that the drag data we obtain can be accurately converted to atmospheric density in the crucial low-altitude regime (between 120-140 km). It should be stated that the satellite will negotiate an altidue range up to 600 or 1000 km, and there is no question about the conversion from drag to density above approximately 170 km. However, it is true that the most interesting data--data which can be obtained only with the drag-free satellite insofar as we know--will be that obtained at perigee.

In discussions with Dr. Fellows and Mr. Horowitz following the Subcommittee's vote in March, we suggested that it might be possible for us to present a strong case for the likelihood of accurate drag-to-density conversion by late summer, and inquired about the possibility of reopening the question with another presentation to the Subcommittee. Dr. Fellows has invited us to do this (cautioning us about the importance of a very carefully prepared case).

Since the meeting at Boulder, we have studied the matter carefully and discussed it with a number of experts, and we are convinced that we will be able to make accurate drag-to-density conversion on our satellite data for all altitudes. It is our plan, therefore, to request another appearance before the Subcommittee at its next meeting.

The key technical question at issue is the accuracy with which the mechanism of aerodynamic drag, and specifically the value of coefficient C_D, is understood in the vicinity of Knudsen number equals 1.0 where Knudsen number K_n is defined as the ratio of molecular mean-free path to satellite diameter. The drag mechanism is quite complicated in this regime, which is a transition between a continuum flow ($K_n << 1$) and free molecular flow ($K_n >> 1$). In our discussions with members of our own faculty who are specialists in low-density, high-speed flow, and with members of the faculty at the University of California at Berkeley, who are experts particularly in the experimental study of low-density flow, we have become convinced that the value of $C_D/C_{D_{fm}}$ in this regime is currently well known to an accuracy of better than 10 percent, and that the level of experimental effort is such that it will almost certainly be known to better than 5 percent well before our first satellite flight. (Moreover, the drag force data will be available following the satellite flight for more accurate conversion to density information as additional research in the future lowers the uncertainty in drag coefficient. Specifically, new data by Kinslow and Potter of Arnold Air Force Station, Tennessee, includes many measurements in the range of $0.1 < K_n < 2$. They report some 32 data points over this range with a standard deviation of less than 3 percent. Their measurements were made at Mach 10.7 and at a ratio of $T_w/T_\infty = 2.3$, where T_w is temperature of the surface of the sphere, and T_∞ is the free-stream temperature. The data of Kinslow and Potter will be published shortly in an Air Force report. These data fit nicely with empirical relations developed by Professors Sherman, Willis, and Maslach, of the University of California at Berkeley [Ref. 12], which also compiles many other data in approximately this regime.

While our satellite will be operating at about twice this Mach number, this should not change the value of C_D.

A theoretical question has been raised by Bird [Ref. 13] as to whether the plot of drag coefficient versus Knudsen number may overshoot the free-molecular-flow value slightly at certain Knudsen numbers for cold bodies (T_w/T_∞ of order 1.0). So far, this overshoot has not been observed experimentally; however, existing data are not inconsistent with such a possibility. Even if Professor Bird's model should prove accurate, the amount of overshoot he predicts is only 10 percent.

Professor Sherman is interested in performing experimental measurements of C_D on a scale model of our satellite in the new low-density tunnel now beginning operation at Berkeley. The range of values of K_n, Mach number, and T_w/T_∞ will be near enough those at which we will be flying so that Professor Sherman believes extrapolation will be safe.

Professor Sherman is currently making a study of the cost and time schedule in which such measurements can be made. If these turn out to be reasonable, as we expect, we propose to support from 582 funds, part of these experiments which contribute directly to drag-to-density conversion for our satellite.

Professor MacDonald has also obtained new drag data which strongly suggests that the incremental uncertainty due to operating near $K_n = 1$ is small. The uncertainty in $C_{D_{\text{free molecular}}}$ may be as large as 30% but is probably substantially smaller and will undoubtedly be improved by a factor of 2 or more in the coming two years before our launch. Our flights will, of course, contribute substantially to the improvement in knowledge of C_D by providing accurate measurements in the region of $K_n = 1$.

At this time, we are confident that the matter of conversion from drag to density will be well in hand prior to our satellite flights. As noted in the previous section, our laboratory support of the flight program--vehicle design, experiment design, and development and testing of the thruster system--are proceeding without interruption.

We hope very much that we can initiate our flight program soon after the next meeting of the Subcommittee on Planetary Atmospheres.

B. DRAG SENSING

Final decisions on the design studies described in Section II A-2 will be made and the vacuum facility will be built. It is planned to spend some time performing preliminary tests of the facility vacuum and pumping capability before starting the work on thruster evaluation.

C. DRAG-FREE SATELLITE SIMULATION

During the period reported in Ref. 4, a concentrated 3-month effort was devoted to evaluating the performance of the drag-free satellite simulator. The table operation and the performance of the airbearing on which the simulator floats occupied the greatest part of this time.

In order to determine the exact fuel consumption rates and to determine the optimum parameter settings both theoretically and experimentally, Dr. Ury Passy and Mr. Arne Folkedal will perform a complete evaluation of the two-dimensional translation control system fuel consumption using both the air-cushion vehicle simulator and the digital/analog facility. Where the purpose of the work of Farquhar and Davis was to determine which type of control mechanization to choose from the several alternatives available, it will be the job of Passy and Folkedal to determine precisely how well the air-cushion vehicle simulates the actual drag-free satellite, how much fuel will be consumed in orbit, and the optimum parameter settings for the PWPF circuitry. They will attempt to get data at rotation speeds beyond 20 radians/second and to simulate altitudes from 120 km up to 800 km. (The highest altitude which can be simulated in the laboratory is presently about 300 km, but of course the digital/analog system has no upper limit.)

D. DIRECT ENGINEERING SUPPORT TO PHYSICS GROUP

Many of the techniques to be used in performing the relativity experiment have been under development in the laboratory. As the feasibility of these techniques have been established, we have worked with the Physics group to develop these concepts into engineering prototypes. Design work on the dewar which will contain the helium necessary to create the cryogenic environment has now established the amount of helium that must be flown for a 1-year experiment. A detailed evaluation of the environmental torques that will disturb the satellite at approximately 900 km altitude indicate that the helium gas is capable of producing a momentum change much larger than the integrated effects of all other external torques. Preliminary designs of a control system utilizing the helium gas for control torques have been performed. The continuous flow removes the requirement for low leakage valves and replaces it with an easier design requirement for producing differential flows to opposing jets. Preliminary design of several devices that could be used for controlling this gas flow appear feasible and not critical.

Several detailed design evaluations of a telescope readout system with a comparator and analog storage technique have been performed. In this critical area, many factors have been considered in the tradeoffs between precision, simplicity, noise rejection, and linearity. Several concepts now appear feasible and some prototype mechanizations may be performed in the near future to assist in the final choice.

We will continue to advise and support the Physics group with the engineering aspects of their experiment as the operating parameters become available from experimental work still underway.

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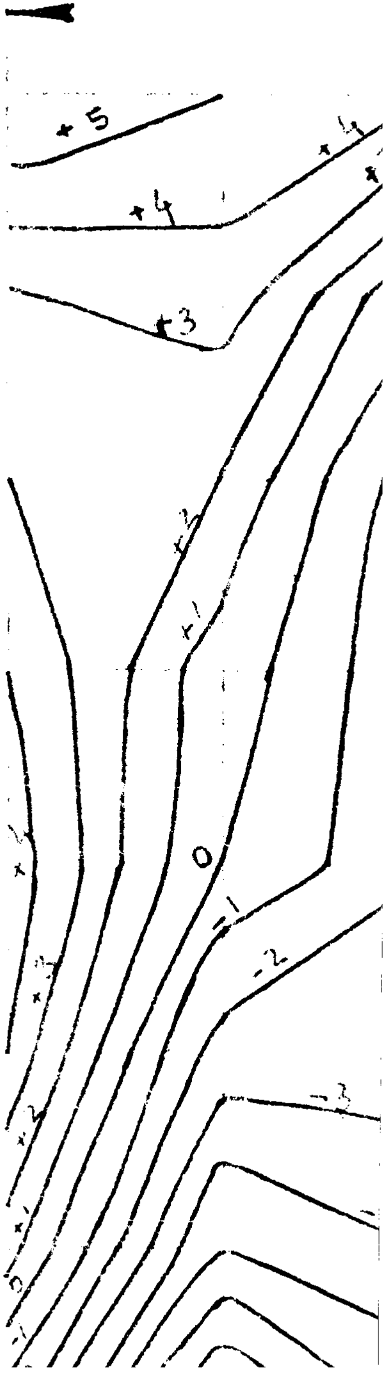
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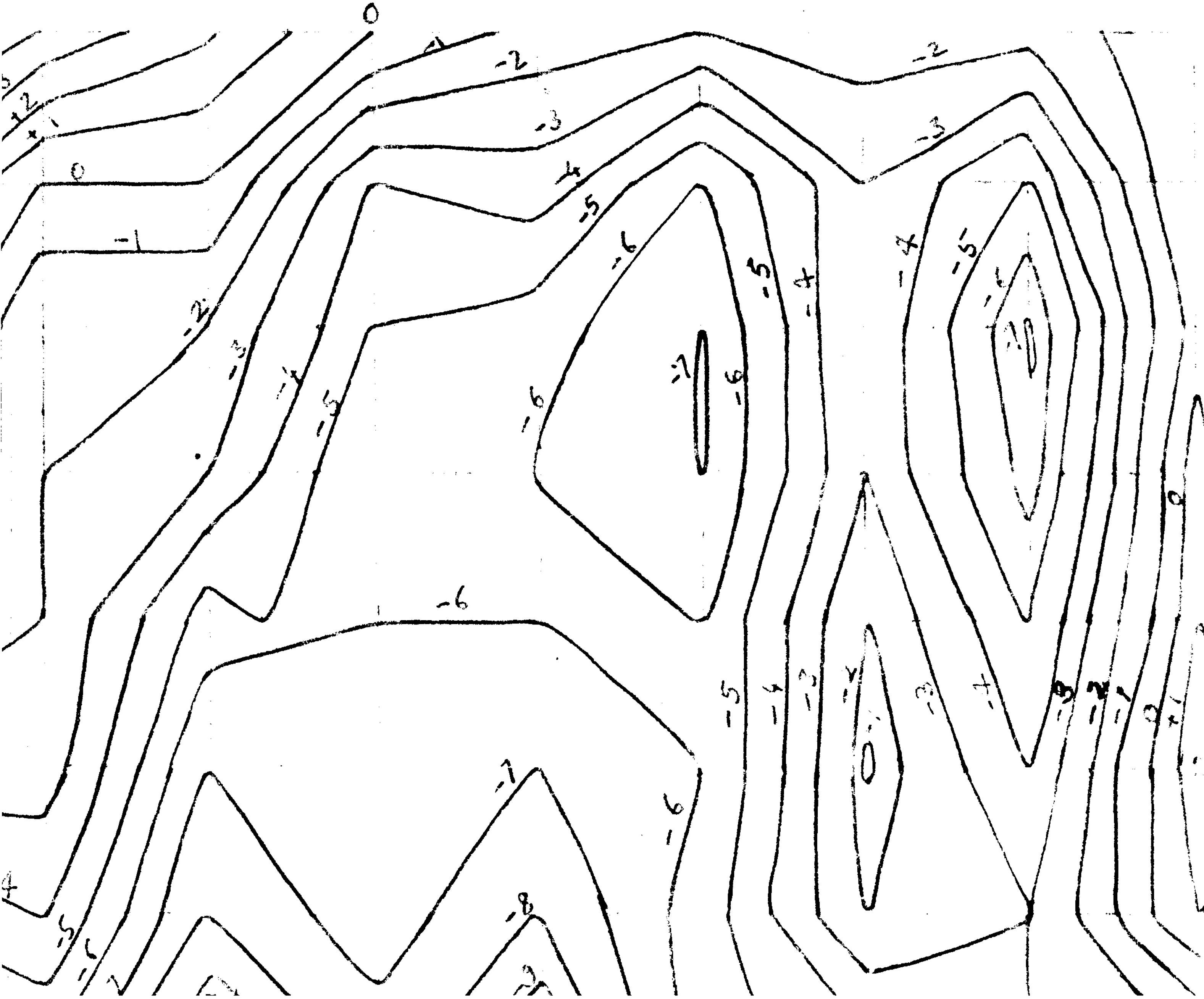

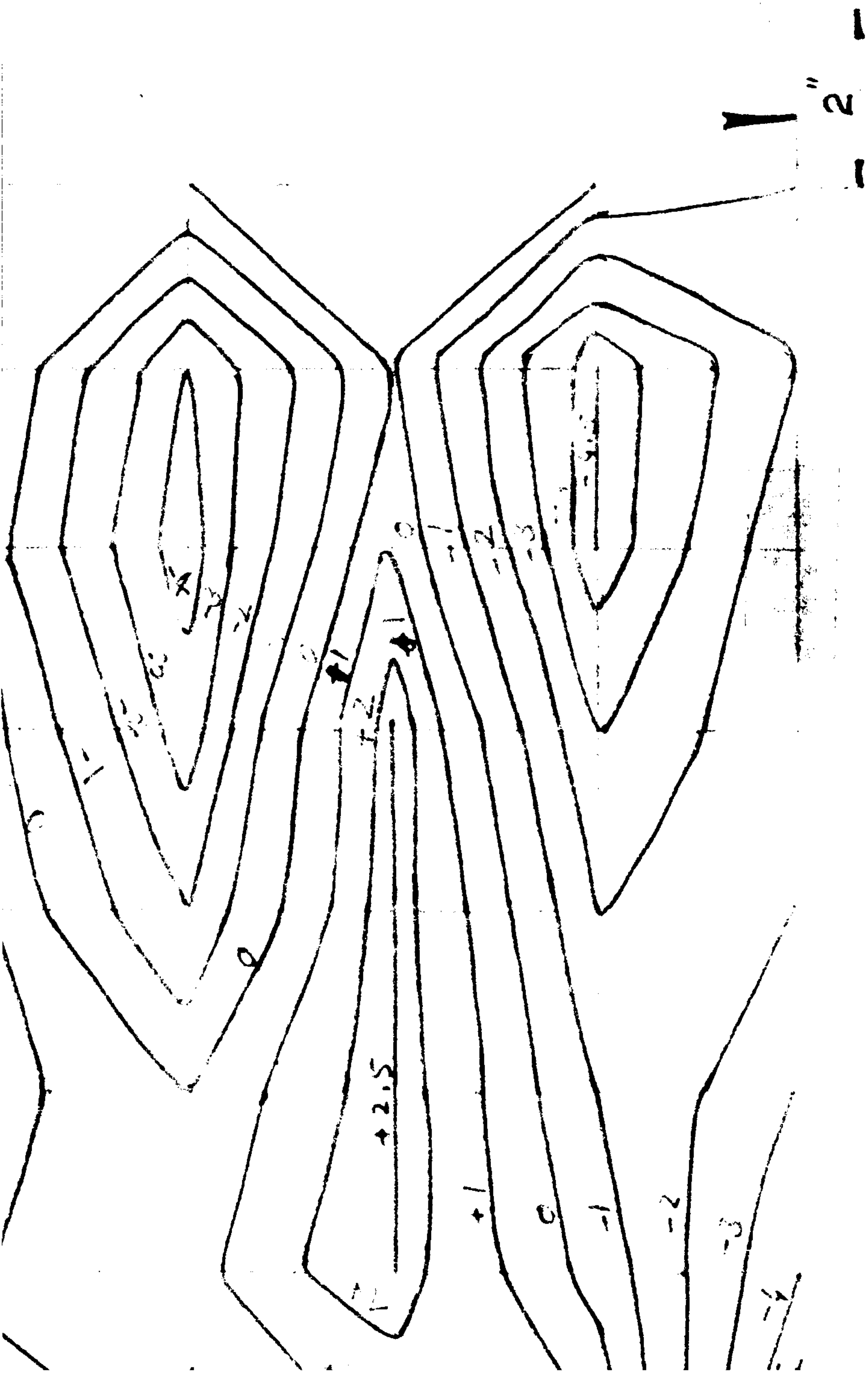
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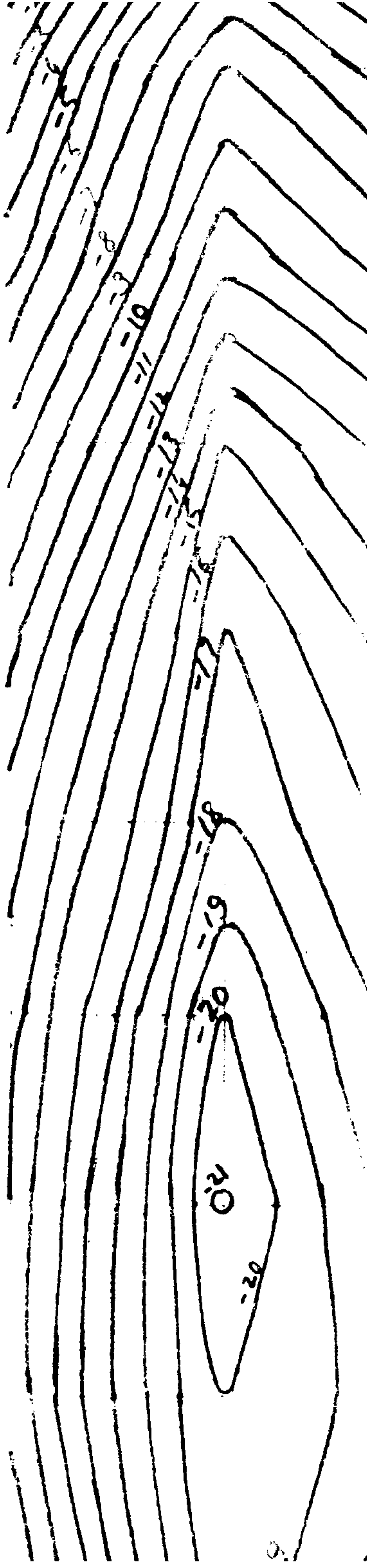

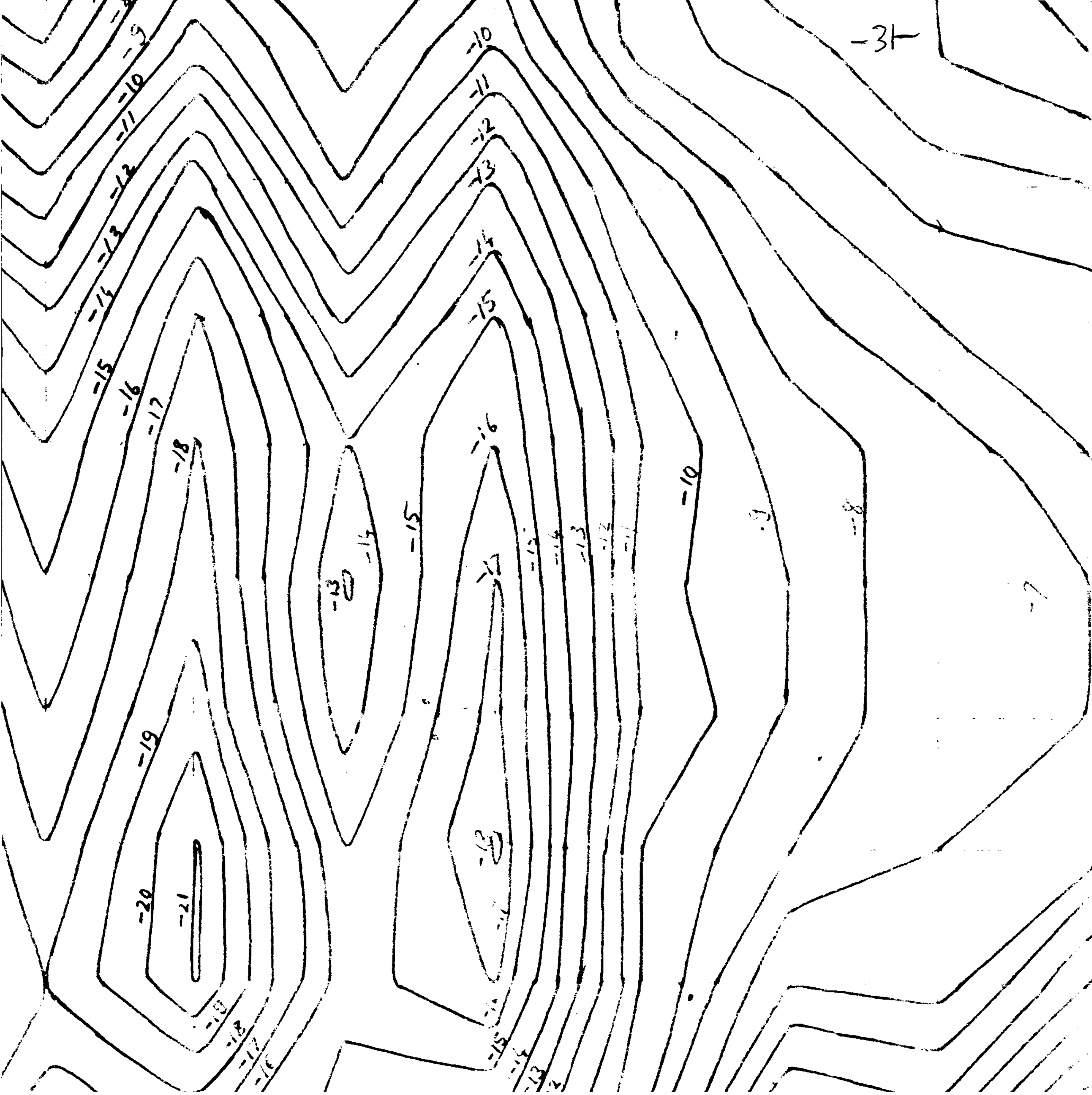
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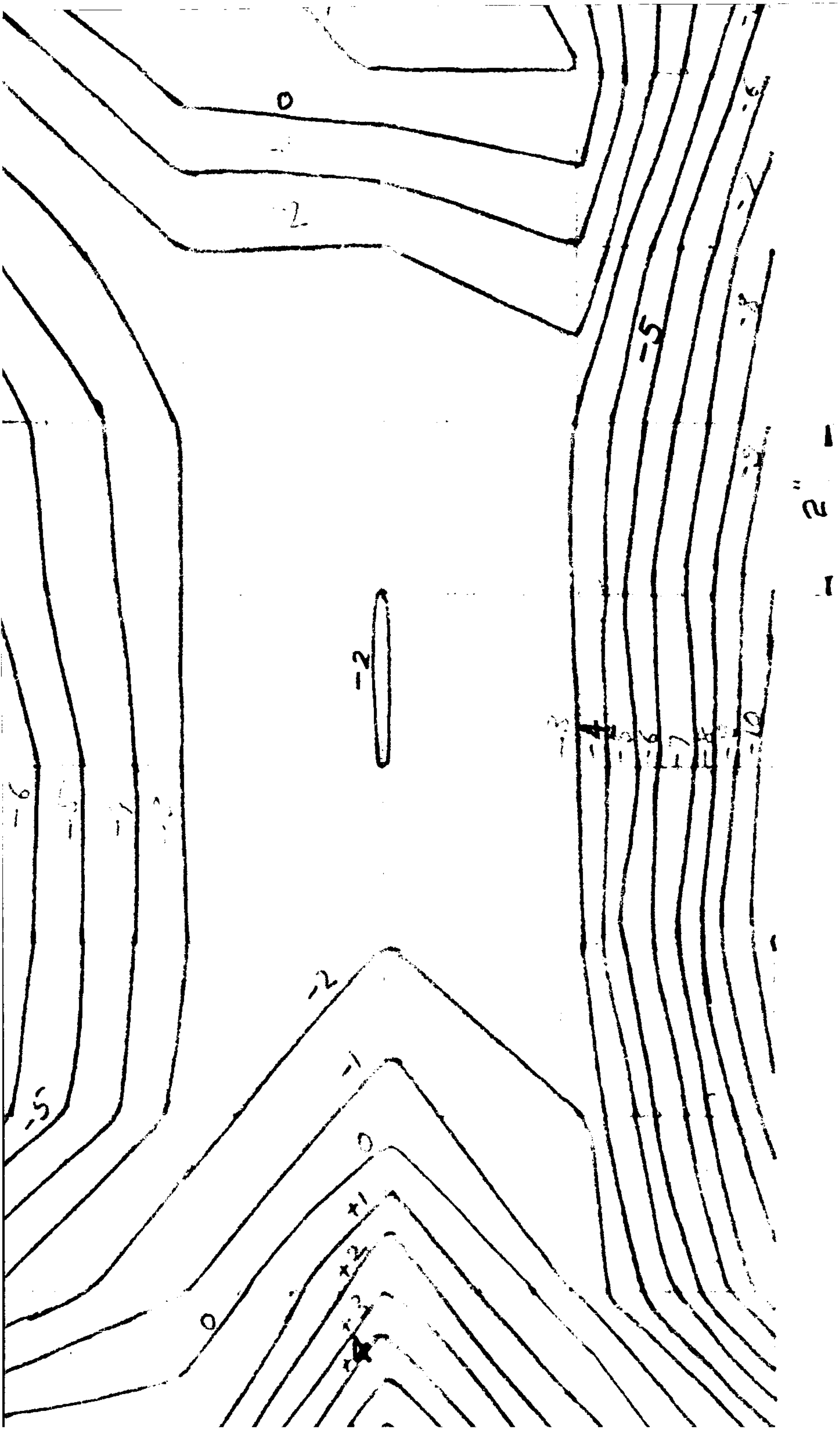
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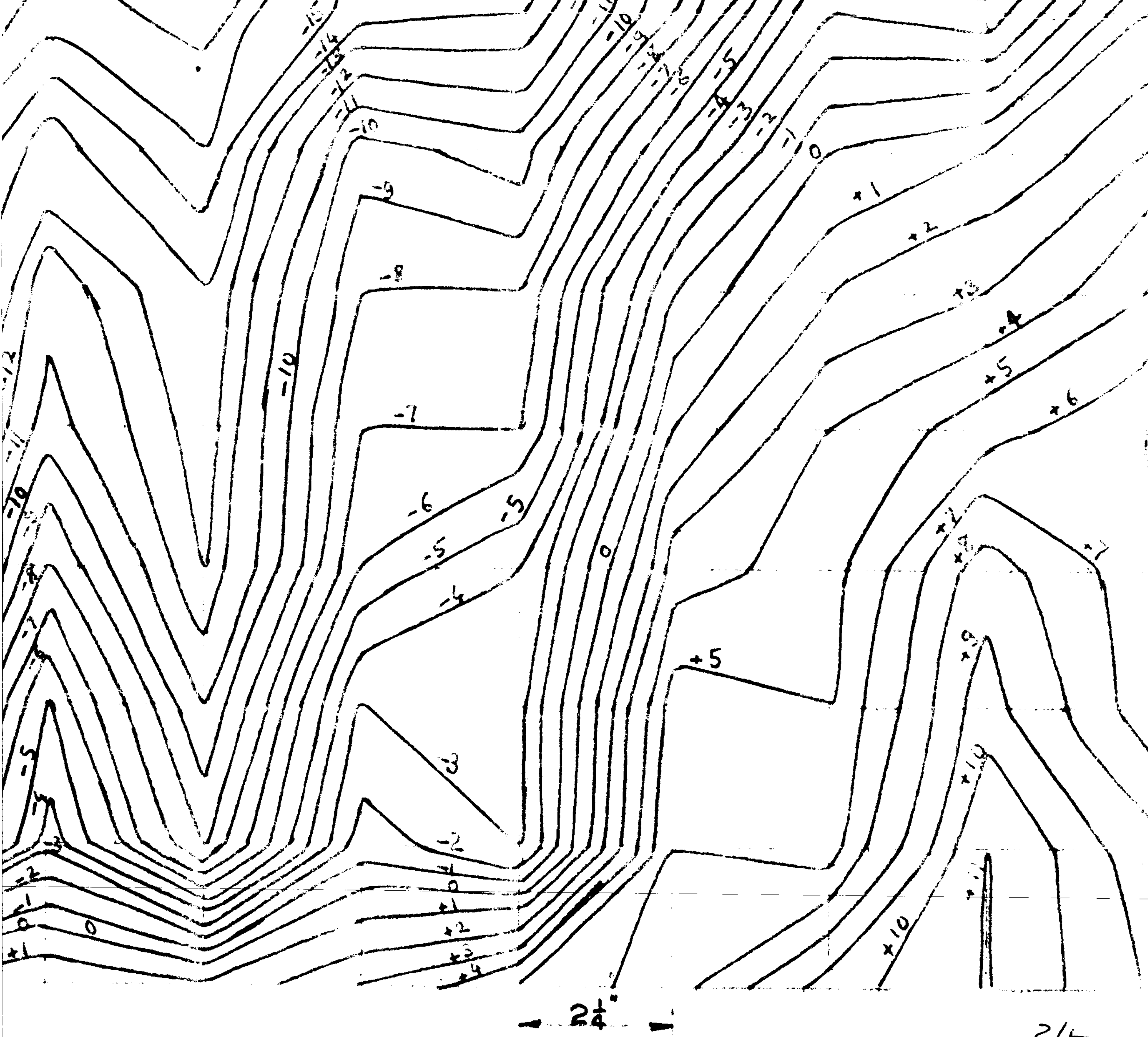
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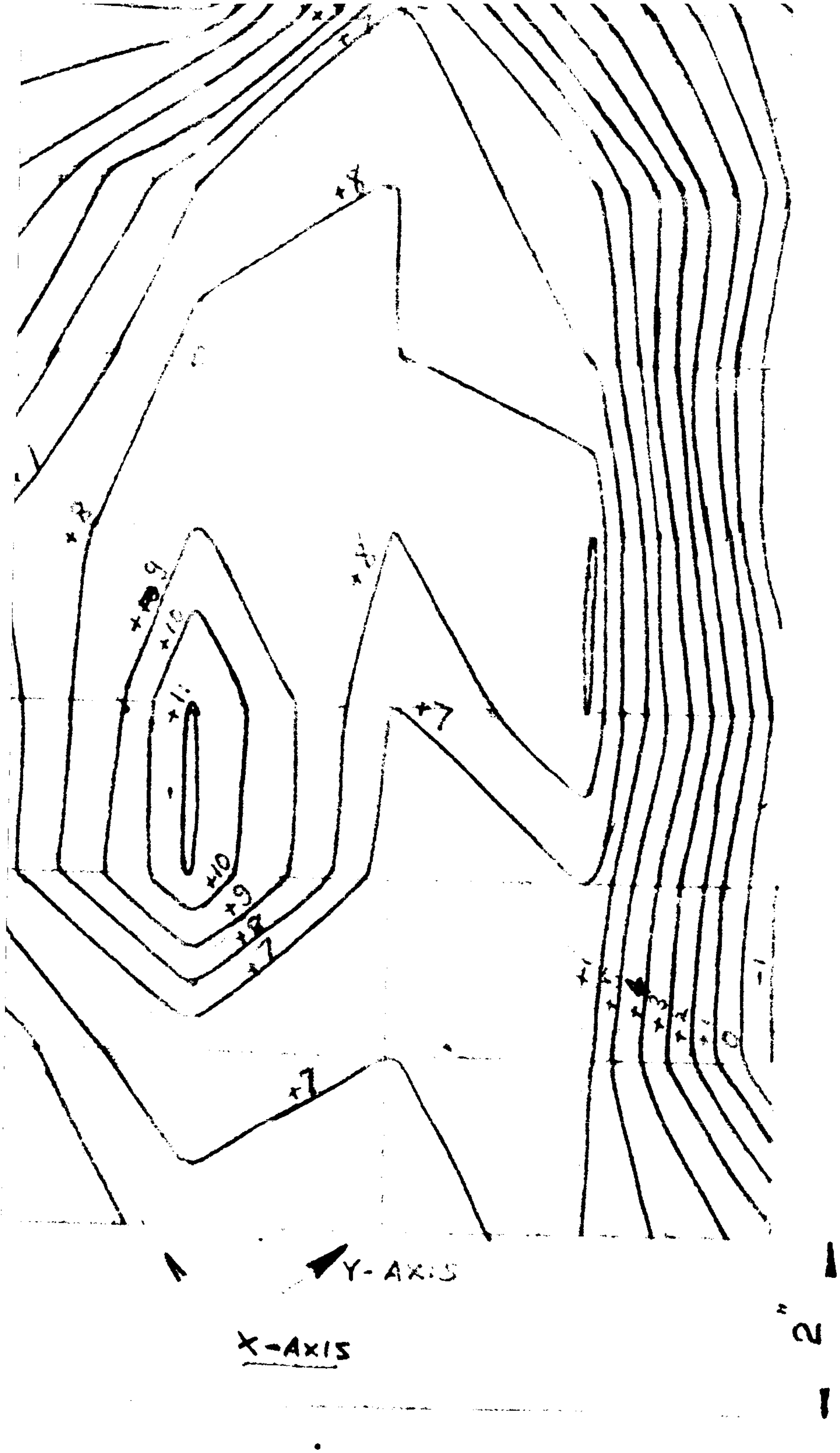
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