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Technical Report

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(U) PLANETARY EXPLORATION SYSTEM (PES) SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL EQUIPMENT

NOVEMBER 1963

TASK 6182(64)
6182(72)

AIR FORCE MISSILE DEVELOPMENT CENTER

DEPUTY FOR FOREIGN TECHNOLOGY

AIR FORCE SYSTEMS COMMAND

HOLLOMAN AIR FORCE BASE

NEW MEXICO

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FOREIGN TECHNOLOGY REPORT

AFMDC-TR-63-6

(Title Unclassified)

PLANETARY EXPLORATION SYSTEM (PES) SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL EQUIPMENT

November 1963

Tasks 6182(64)
6182(72)

Prepared by:

Captain James E. Howard

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(U) PREFACE

The information reflected in this document has been prepared for the use of Foreign Technology personnel engaged in the analysis of the Soviet space effort. This is an AFSC project, and this contribution will be of particular interest to analysts concerned with Soviet spacecraft guidance, navigation, and control equipment. This report serves as a technical support document for Tasks 6182(64 and 72) assigned to the Air Force Missile Development Center. ~~(S)~~

(U) PUBLICATION REVIEW

This Foreign Technology document has been reviewed and is approved for distribution within the Air Force Systems Command. (U)

FOR THE COMMANDER

Howard L. Conkey

HOWARD L. CONKEY
Lt Col, USAF
Deputy for Foreign Technology

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

(U) SUMMARY

Purpose

This report presents analysis initiated to satisfy Tasks 64 and 72 of the Planetary TOPS on Planetary Exploration System Spacecraft Stabilization, Control, Guidance, and Navigation. (U)

Conclusions

a. Soviet spacecraft control component design has shown a logical and dynamic progression.

b. The inclusion of a midcourse correction engine on MARS I is a significant step toward achieving the capability to perform detailed planetary exploration.

c. Improper operation of the cruise phase attitude control system led to the failure of the Mars I probe.

d. The Soviets have not demonstrated, except by inference, the capability to design control components capable of performing planetary exploration missions. (S)

Background Highlights

An examination of the data available for this task reveals an interesting fact: Soviet open source publications provide essentially the only usable information. Thus the analyst is forced to proceed knowing full well that his conclusions are completely dependent on the amount and accuracy of data released by the Soviets. If they desire to spoof, success is insured, because no choice is available but to accept their description as presented. Hopefully the Soviets are completely honest in their releases; this, apparently, has been the case in the purely scientific space ventures. Further, their approach has been to say nothing of the activities which they want to keep from us (TT Cosmos, for example), although the desire for publicity may have closed this avenue to them. In any event all conclusions arrived at from data with such a potentially unreliable validity can only be postulates no matter how well these conclusions are supported by the data. There are, however, two criteria available to lend more credence to the results: reasonability and feasibility as determined from comparable U.S. technology. Both these constraints have been constantly applied in arriving at the conclusions presented in this report. ~~(S)~~

Discussion

Basically the spacecraft control, guidance, and navigation requirements for planetary probes are the same as those enumerated in AFMDC-TR-63-2 for lunar vehicles. The spacecraft must be launched into a proper parking orbit, be precisely oriented for injection, held to the nominal flight path during injection, and controlled during the transfer orbit as required by mission objectives. The differences which exist are principally of degree: accuracy requirements are more demanding, heating loads are higher, and control in space must be maintained for longer periods. These factors increase the complexity of planetary probe design, but not to the point that lunar and planetary technology are noninterchangeable. The techniques and methods used by the Soviets in their early lunar probes unquestionably served as the basis for design of the planetary spacecraft. For this reason the previously mentioned document serves as the starting point for the analysis herein presented, and this report simply extends spacecraft control system analysis to include the interplanetary probes. (U)

SECTION I

(U) VENUS PROBE

There have been numerous Soviet articles and releases on their Venus probe launched 12 February 1961. Many of these reports give fairly detailed descriptions of systems and overall operational details. These descriptions, in conjunction with photographs and schematic drawings also released, form the major data base for this analysis. Constraints on the postulations made were determined both from available data of a classified nature and applicable U.S. technical studies. (U)

The Soviets reported that "during flight, the vehicle was positioned by an orientation system which: eliminates arbitrary rotation of the station; acquires the sun from any position of the station thus realizing station stabilization; and, near Venus, orients the parabolic antenna on the earth to insure a higher transmission rate of operational and scientific data." They further stated that the solar panels were constantly oriented toward the sun and that the parabolic antenna was unfolded only as the probe approached Venus. Few specific details of the orientation system were given; one account did note, however, that a "solar or other star sensor and an earth sensor" were included in the orientation system. These two items were also identified on the schematic drawings of the probe. (U)

By inference from the stated capabilities, examination of the available photography, and [redacted] 50X1 and 3, E.O.13526 (S)

The capability to sense and eliminate arbitrary spacecraft rotation is most simply mechanized with rate gyros. The inclusion of these components in the control system also allows specified rotations of the spacecraft to be easily commanded through torquers. Any required reorientation, either ground commanded or programmed, could be accomplished through these devices (one for each axis). Long operating times leading to breakdowns, the principal limitation of gyros, could be overcome by uncaging and running the gyros only when their operation is essential. This system has been used on almost all U.S. spacecraft requiring reorientation maneuvers. It is, therefore, postulated that a similar system is used by the Soviets for the control of both lunar and planetary probes. (S)

Because of the necessity for a mass expulsion system to stop post injection rotation and the use of cold (compressed) gas on Lunik III and Mars I, this same method is the most probable one used on the Venus probe. [redacted] 50X1 and 3, E.O.13526

Although concern has been evinced that such a system would require excessive weights for the long control periods required for planetary probes, a spacecraft properly designed to reduce perturbations coupled with control logic minimizing limit cycle operation can require extremely small fuel weights for satisfactory control. For example, Mariner II which was actively controlled throughout its 109-day flight to Venus was equipped with only 8.6 pounds of nitrogen gas. Although no control jets could be positively identified from the photography, a spherical container which could serve as the compressed gas supply was noted in two separate photographs. All these factors taken together lead to the conclusion that a compressed dry gas mass expulsion system was used for control torque generation. [8]

The schematic drawings of the probe identify a single "solar or other star sensor." Examination of this sensor in the photog-raphy shows it to be a photosensitive device which has three viewing directions: perpendicular to the plane of the solar panels, both forward and to the rear, and along the plane of the panels (see Fig. 1). This arrangement allows the system to "acquire the sun from any position of the station" with ground

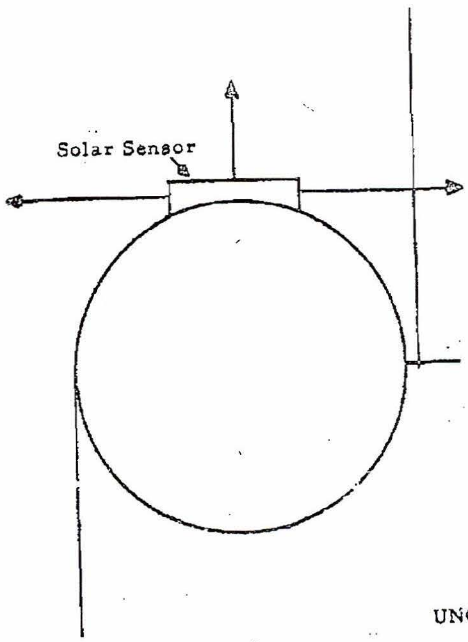

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Fig. 1 Solar Sensor Viewing Directions

command assistance. If none of the sensors had the sun in its field of view after the arbitrary injection rotation had been stopped, simple ground commanded rotations about first the longitudinal axis and then one of the other axis would insure solar acquisition. Self-contained logic could then take over to orient the spacecraft so that the sunline was perpendicular to the panels. Two-axis stability is thus accomplished and the panels can be constantly pointed at the sun. This same system could serve to reaccomplish solar acquisition at any time during the flight that the solar lock-on was lost either accidentally or through design. ~~(S)~~

With the establishment of only a sunline for orientation reference, the spacecraft is free to rotate about the sun-pointing axis. Full three-axis stability requires the sensing of another source, probably a star. The need for full three-axis orientation during the coast period of the Venus probe cannot be established. In general it is required only if some experiment necessitates this constraint. Such sensing, if required, might conceivably be accomplished by the solar viewer which points along the plane of the panels. This method seems unlikely; however, because of the strict geometrical relationship which must exist and the sensitivity range required of the sensor. ~~(S)~~

There is one other probable solar sensor located at the bottom of the forward solar panel.* This sensor, in conjunction with the apparent servo actuator attached to this panel, could be used to maintain constant solar pointing of the panel during periods when body orientation was based on a source other than the sun. These periods will be discussed subsequently. (S)

Study of photographs showing the externally mounted earth sensor and the parabolic antenna reveals an apparent operational inconsistency; both appear to be rigidly fixed to the spacecraft with a 60° misalignment. This arrangement severely complicates orientation during the cruise phase. In fact, it makes it impossible to maintain an earth and sun-lock for three-axis orientation (except for a short period) and requires a 60° rotation of the spacecraft every time it is desired to point the parabolic antenna for communications. (S)

It is very unlikely that the Soviets, given an almost free range of design, would unnecessarily complicate their control problem by such an arrangement. Therefore, it is postulated that the antenna is highly mobile and that the photographs show

*Reproduction difficulties have made it impossible to include either photographs or schematic drawings of the probe in this report. The reader is invited to use the illustrations in References 1 through 6 to locate the component described.

it in an unfolded, but retracted, position; and this accounts for the apparent physical restriction to antenna movement presented by the spacecraft body. When extended for operation, no such restriction exists and the antenna can be moved freely as required for earth pointing. Once fully deployed, the antenna is slaved to the earth sensor and is aligned with it. ~~(S)~~

The feed on the parabolic antenna (apparently four center-fed half-wave dipoles) could allow more precise alignment. By alternately connecting the probe's receiver to opposite dipole pairs, an error signal would be developed to drive the antenna to a null, thus more accurately pointing it at the ground transmitter. ~~(S)~~

Although required to insure near passage of Venus, it is estimated that no midcourse correction capability was built into the spacecraft, probably because it was beyond Soviet technical know-how in that time period. Soviet press releases substantiate this presumption by indicating that after injection, "The station traveled under the gravitational forces of the earth, sun, and planets." Navigation (position fixing) of the probe was accomplished by various ground tracking facilities and no equipment for this purpose was included on board the spacecraft. ~~(S)~~

By correlating the assessed and postulated sensor operating characteristics with the geometry of the transfer orbit, the attitude control functions up to near-Venus passage can be reconstructed. After the completion of the despin process, the spacecraft was oriented by use of the multiviewer sun sensor so that the solar panels faced the sun. This resulted in two-axis stabilization with orientation about the third (sun-pointing) axis arbitrarily established. At this time the rate gyros could be caged and turned off. Unless complete three-axis stabilization was required for some scientific experiment, this attitude would provide sufficient orientation until activation of the earth sensor. Assuming that the sensor was rigidly mounted (as it appears to be in the photographs), the approximate time of earth acquisition can be established. As shown in Fig. 2, the sensor was aligned about 30° off the sunline. This geometry matches the probe-earth-sun position which occurred approximately one month after launch. Thus, if the earth sensor were activated on about 20 April, only simple rotation about the sun-pointing axis would be required to accomplish the necessary scanning. Delay in initiating the operation of the earth sensor is not unusual; the sensitivity range possible in such a device precludes its use both near earth and near a target planet. (S)

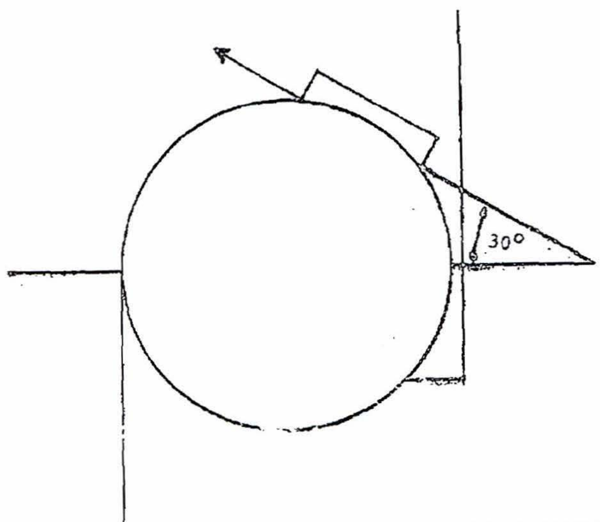

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Fig. 2 Earth Sensor Alignment

Once the sensor achieved earth lock-on, full three-axis orientation existed and information for antenna pointing was available. This condition represents optimum usage of the sensors because each performs a dual function, component pointing and body orientation. Since it appears that both the earth and sun sensors are rigidly fixed to the spacecraft, this condition cannot exist indefinitely. The sun and earth lines do not rotate at the same rate; hence, the geometry must change and both lock-ons cannot be maintained. To overcome this geometrical limitation in U.S. spacecraft, the earth sensor is usually mounted on the parabolic antenna, thus giving it the necessary freedom to rotate and maintain alignment on the earth. The Soviets probably handled this problem by transferring the sun sensing to the sensor mounted on the solar panel. This would allow orientation to be maintained on both the earth and sun, and would insure proper pointing of the panel. Perturbation sensing is slightly more complicated in this mode of operation, but it can be handled by a simple modification in the logic circuitry. (S)

This three-axis stabilization, once established, could have been used through the remainder of the flight. Any necessary reorientation as the probe passed Venus could have been accomplished either by programmed rotation from this established attitude or by sensing of the planet itself. The former is very likely the most probable from all indications. This is the method used on Mariner II. ~~(S)~~

SECTION II

(U) MARS PROBE

The Mars probe, as described by the Soviets, was considerably more sophisticated than any of the previously designed spacecraft. The thermal regulating system was more efficient, a midcourse engine was included for trajectory refinement, and provisions were made for photographing the surface of Mars during near passage. Both the midcourse correction and the necessary pointing for photography increase the requirements for control and indicate that the Mars system was necessarily more accurate than that used on the Venus probe. (S)

By examination of the physical locations of the components identified by the Soviets in both photographs and schematic drawings, certain conclusions can be drawn about control related functions of the probe. The location of the parabolic antenna on the side of the probe opposite the solar panels is inconsistent with the pointing requirements for communications with earth. Since the orbit of Mars is outside that of earth, the antenna and solar panels must point in generally the same direction. Thus it is concluded that when extended for operation, the antenna is rotated so that it can operate with approximately the same aspect as the solar panels. This is probably accomplished by antenna mounting on a cantilever arm which swings it out from the bottom of the spacecraft. Rotation about this same axis to provide the mobility necessary for the antenna to follow the earth during flight requires the long axis of the probe to lie in the trajectory plane. Therefore it can be postulated with high confidence that this was the attitude of the probe, at least during the periods that the parabolic antenna was used for communications. (S)

There is no earth sensor identified in the drawings although a "planet sensor" was listed among the components. Since the parabolic antenna feed has a device attached to it which serves no apparent purpose for communications, this attachment could be the sensor used for earth alignment. The "pickup for precise stellar and solar orientation" has a wide field of view and is probably used as the initial solar acquisition sensor. Lock-on would then be accomplished and maintained by the "pickup for permanent solar orientation" (Fig. 3). (S)

Since small spherical containers located on the periphery of the orbital compartment were identified as "tanks of the orientation system," control torque generation was undoubtedly accomplished by a compressed gas system. There is some indication, however, that precise control of the probe was not maintained

These "Flight International" drawings of the Soviet Mars probe show: 1, mid-course correction engine assembly; 2, magnetometer; 3, sensor for constant solar reorientation; 4, orbital compartment; 5, solar-cell panels; 6, omnidirectional antennas; 7, precision sensor for star and solar orientation; 8, high-pressure gas bottles for the orientation system; 9, semi-directional antennas; 10, heat-regulation radiators; 11, highly directional antenna; 12, spectro-reflexometer

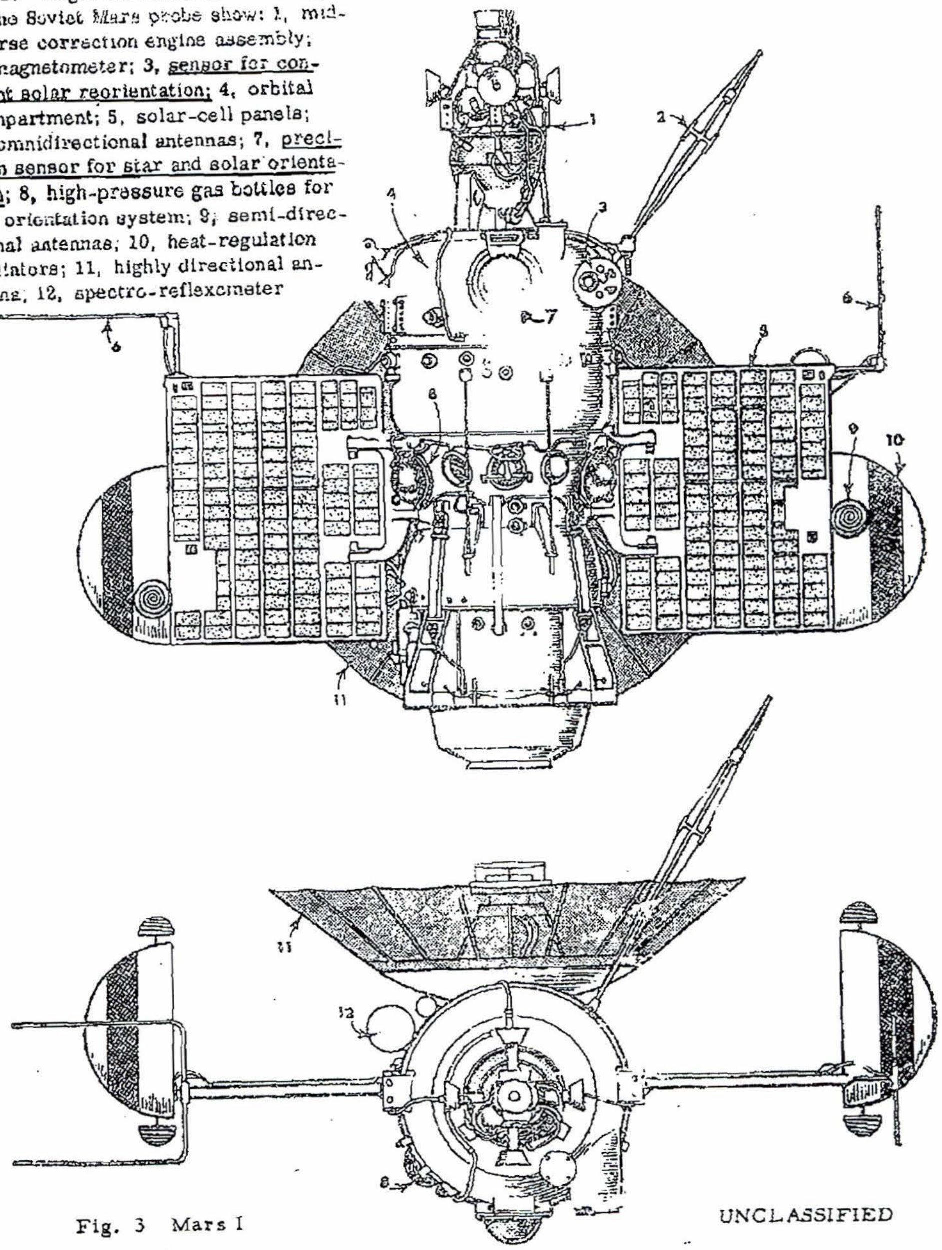

Fig. 3 Mars I

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throughout the flight. Progress reports on the operation of the spacecraft stated, "The system of orientation of the solar batteries was functioning normally." As the solar panels appear to be rigidly fixed to the body of the probe, this could be construed to mean that only solar orientation (two-axis stabilization) was maintained and will be assumed here. (S)

Although A. A. Blagonravov announced at the 6th COSPAR meeting that the probe was rotated at one-fourth rpm during cruise, little significance is attached to his statement. It was early recognized (30 November 1962) from U.S. reception of probe radio signals that it was in a complex tumbling mode. Since Blagonravov announced that the probe was a complete success in its main objectives - "long term investigations of space and testing of long range radio communications" - he would be expected to attempt to explain away the tumbling. Further, both the announcement on 14 May of the failure on 21 March, and Blagonravov's admission of control failure attempted to imply the failure had occurred in March, not in November. It is more likely that the announced rotation resulted from control system failure in November and not from a programmed profile. (S)

The most significant improvement on the Mars probe was undoubtedly the addition of the midcourse correction engine. The inclusion of this capability allows the reduction of errors accumulated during post launch orbiting and injection, and permits better scientific investigation of the target planet. The exterior appearance of this engine is quite different from those employed on U.S. spacecraft. In our design practice the fuel supply is inclosed in the body of the spacecraft and is thus afforded the same thermal protection as other components. If the fuel supply for this engine is exposed during flight as shown in the photographs, it could certainly have implications to the fuel used. The possibility exists that the shroud over the engine shown in the drawings is removed just prior to actuation of the engine, and it affords the required protection prior to that time. The other outstanding difference is the employment of four control nozzles around the main thrust nozzle. These nozzles are most probably used only during operation of the engine, and by metering out expanded gasses, provide the necessary thrust vector control during this period. (The spacecraft cold gas system cannot provide sufficient thrust to accomplish this function.) This arrangement provides no control of rotations about the thrust axis, but none is required for an autopilot-velocity meter guidance scheme (see Reference 9). The simple spherical fuel container of this system indicates that a monopropellant was most probably used. ~~(S)~~

The trajectory of the spacecraft during its flight was determined from ground measurements, both radio and optical. Upon ground command the probe transmitted beacon signals which were tracked by the parabolic antennas of the ground stations, thus providing azimuth and elevation. It is highly possible that a new doppler system was employed on this launch which allowed more accurate velocity determination than ever before possible. This system involves the transmission of frequency stabilized signals from the earth which are returned immediately from the spacecraft. The double doppler shift which thus results permits theoretical velocity determination on the order of inches per second. ~~(S)~~

No on-board navigation is deemed to have been performed, or required, on this mission. In general this function is required only when its accuracy can exceed that of the ground based tracking system. The difficulties in providing an accurate inertial reference for on-board measurements are much greater with present technology than the problem of improving tracking capabilities. ~~(S)~~

SECTION III

(U) TRENDS

The design of Soviet spacecraft has shown a very logical and dynamic progression. Their "state of the art" has moved from simple spin stabilized vehicles to highly sophisticated ones, at least theoretically capable of performing complex space missions. There have been such significant changes between each success that it is obvious Soviet designers are not tied to a static design; constant improvements are sought and achieved. This dynamic approach is indicative that the quality of the spacecraft and their ability to accomplish more intensive explorations will continue to improve. Present technological limitations will not necessarily hinder future capabilities. ~~(S)~~

The basic problem facing any designer of a component that must operate in space is how to best overcome the hostile operational environment. Theory is useful to a limited extent in this problem; the proof of the pudding is actual operation. It is apparent from the almost perfect Soviet record of failure that present design, although constantly improving, is still not up to the requirements. This is considered highly indicative of a lack of adequate simulation facilities, a problem that has also plagued

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U.S. designers. This is obviously not a permanent limitation. On the other side of the coin, the excessive failure rate during injection has denied a vast amount of necessary test information to the Soviets. Lacking adequate test facilities, the actual operation in space must serve. Without these tests, improvements must necessarily await construction of the test facilities or be based on theory. For these reasons the failures that occurred in the fall of 1962 have probably set back the Soviet interplanetary exploration program by at least 18 months. (S)

In the light of the foregoing remarks, the applicability of present control associated components to future operations is not difficult to assess. There is no evidence that they will be up to the requirements. It can definitely be stated that the attitude control system for the cruise phase is inadequate; the Mars failure proved that. The adequacy of the midcourse maneuver, both from a propulsion and a guidance and control standpoint, is unproved, probably to the Soviets as well as to us. This is also true of the planet passage orientation system. In fact, the only significant guidance and control capability firmly established is that injection can be accurately achieved; and even this conclusion is tainted by the flight of Lunik IV. (S)

Despite the lack of indicators of successful component design, the capabilities of the Soviets in this area should not be sold short. Their demonstrated abilities in areas closely allied to this field indicate that the high failure rate is an exception rather than a rule. They undoubtedly have the technological ability to perform space explorations; but this is inferred from other space operations, and is not demonstrated by the actual program. (S)

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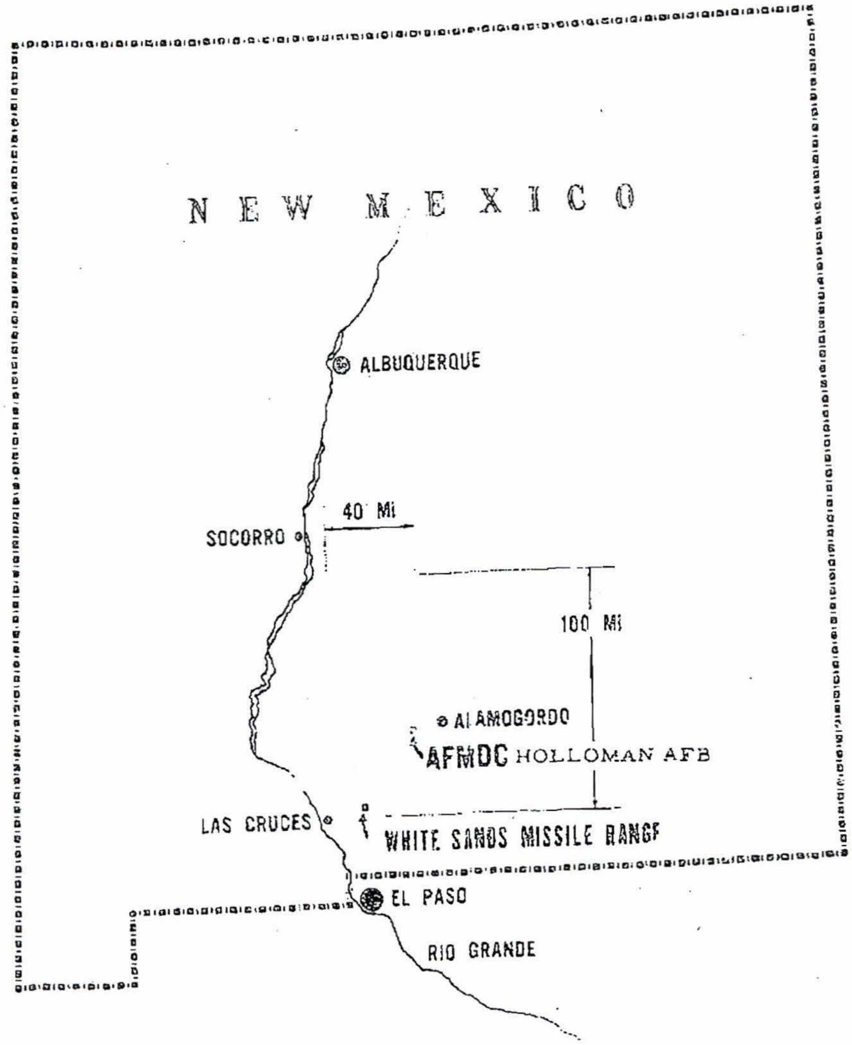

AREA MAP SHOWING LOCATION OF AFMDC

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