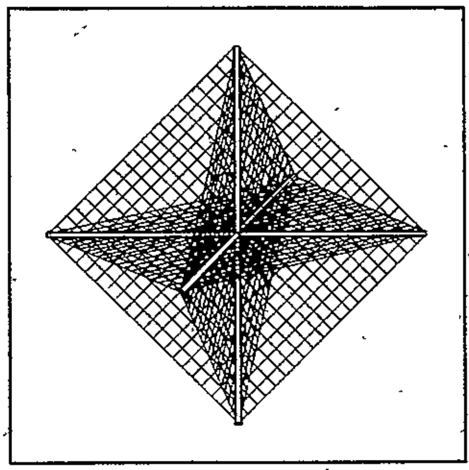
JPL PUBLICATION 78-94

Planetary Benchmarks



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National Aeronautics and
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Jet Propulsion Laboratory
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Pasadena, California

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SUBJECT: Errata

Please note the following corrections to JPL Publication 78-94, Planetary Benchmarks, by Chauncy Uphoff, et al., dated 1 December 1978:

Page 6-10, bottom of page: T = 300 K and L = 500 km

Page 6-11, top of page: Calculation should read

$$P_T \geq \frac{(1.38 \times 10^{-23})(300)(22)(10)}{(375)^2} \left[\frac{(4)(5 \times 10^5)}{2}\right]^4 = 6.48 \text{ w}$$

Very truly yours,

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JPL PUBLICATION 78-94

Planetary Benchmarks

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This report is the result of a study conducted at the Jet Propulsion Laboratory during the summer of 1978. The work was done by a small group of individuals with inputs from many sources. The idea of passive radar retroreflectors on the planetary surfaces was suggested at JPL by G. Colombo and has been discussed informally for several years by Colombo and by I. Shapiro and G. Pettengill of the Massachusetts Institute of Technology. The study was carried out under NASA Contract NAS7-100 as part of the Planetary Advance Studies program under the direction of Mr. D. Herman of NASA and Dr. A. Hibbs of JPL.

The section on science rationale was written by R. Staehle and M. Slade, the section on radar systems was written by M. Kobrick, and the section on high-temperature transponders was written by R. Jurgens. The structural analysis section was written by H. Price and the section on other applications was written by R. Staehle and D. Sonnabend. Mr. Sonnabend did the analysis of W. O'Neil's suggestion to use passive benchmarks as landing beacons. Mr. Staehle conceived the application of searching for a tenth planet based on a suggestion by C. Uphoff to use a large number of small probes to study the electromagnetic structure of the solar system. The bulk of the editing work was done by M. Buehler and R. Staehle. The study manager is particularly grateful to Mr. Staehle for his extensive contributions to this study both in the form of his ideas and technical analyses and his capable managing of the details of publication. The Introduction and Summary, Conclusions and Recommendations, and Acknowledgements were written by Mr. Uphoff.

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ABSTRACT

This report is a description of a study conducted during the summer of 1978 aimed at the establishment of design criteria and technology requirements for a system of radar reference devices to be fixed to the surfaces of the inner planets. Primary emphasis has been placed upon study of passive radar retroreflectors for the harsh environment on the surface of Venus. Science rationale includes measurement of the motion of Venus' pole, ephemeris improvement, cartographic reference points for precision mapping, and the possibility of measurement of large crustal motion if it exists.

Also discussed are some interesting offshoot applications including the use of radar corner reflectors as landing beacons on the planetary surfaces and some deep space applications that may yield a greatly enhanced knowledge of the gravitational and electromagnetic structure of the solar system.

It is shown that passive retroreflectors with dimensions of about 4 meters and weighing about 10 kg are feasible for use with orbiting radar at Venus and Mars. Earth-based observation of passive reflectors, however, would require very large and complex structures to be delivered to the surfaces. For Earth-based measurements, it is concluded that surface transponders offer a distinct advantage in accuracy over passive reflectors. A conceptual design for a high temperature transponder is presented. The design appears feasible for the Venus surface using existing electronics and power components.

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SECTION 1

INTRODUCTION AND SUMMARY

This report is a description of a recent study to evaluate the feasibility of placing long-life devices on the surfaces of planets to allow accurate tracking from Earth or from planetary orbit. Primary emphasis has been placed on conceptual design of a passive radar retroreflector capable of being fixed to the surface of Venus or Mars. Such reflectors could provide a body-fixed reference system for measurement of rotational motion, for cartography, for improvement of the ephemeris, and for the detection of tectonic activity.

Several methods of establishing such devices have been studied. They include radar (Venus) and laser corner reflectors, large quantities of super-thin needles, very long wires, and high-temperature, long-life transponders. Of these, the most promising method appears to be a function of the application. It is shown that a 2-meter octahedral corner reflector, visible to Venus orbiting radar can be built for a mass of about 10kg. Small retroreflectors can probably withstand the severe conditions of the Venusian surface for a period of the order of 20 to 50 years. Measurements from Earth-based radar, however, would require a corner reflector of from 6 to 10 meters on an edge that would necessarily weigh several hundred kilograms at best and would probably require the delivery of about one ton of mass to the surface.

This rather negative result, while not totally precluding the possibility of a large Venus benchmark, led to consideration of technology requirements for long-life, high-temperature transponders that could provide the same function for perhaps an order of magnitude less mass delivered to the surface. The severe conditions of temperature and pressure at Venus yield requirements for a very rugged device whose lifetime is difficult to predict. It is not unreasonable to expect lifetimes of several years for such transponders but the desire to make measurements over decade-long periods for comparative planetology will not be easily fulfilled by a new-technology transponder. Both the large (10-meter) retroreflector and the long-life high-temperature transponder offer exciting challenges of technology development that can lead to an enhanced capability to understand the dynamics of the solar system.

The report is the result of a short study conducted during the summer of 1978 as part of NASA's planetary advanced studies program. The fundamental idea was to examine the value and difficulty of placing a number of semi-permanent benchmarks on the planetary surfaces for use as reference points for long-term studies of planetary motion and structural dynamics. The concept was suggested by G. Colombo and has been discussed informally for several years by Shapiro, Pettingill, and Colombo.

The report begins with a major section on science rationale outlining the several types of planetological data that can be obtained from long-term, high accuracy, radar measurements of range and doppler shift. Included in a later section on transponder design are arguments showing that the direction of the Venus pole can be measured with an accuracy of one or (perhaps) two orders of magnitude improvement over current techniques. This knowledge, coupled with a similar improvement in spin rate determination, should lead to a parallel improvement in knowledge of the internal structure of Venus and its possible modes of resonance interaction with the Earth's motion.

A similarly important but not so striking improvement in knowledge of the ephemeris of Venus could have long-term implications for our knowledge of the dynamics of the inner solar system. Current ephemeris errors are about 40 km. Earth-based ranging to fixed benchmarks on the Venusian surface could improve this knowledge by a factor of two or three with most of the residual error remaining in the direction normal to Venus' orbit plane. Tracking of surface benchmarks from orbiting spacecraft could yield an even greater advantage if the spacecraft orbit can be accurately determined from Earth. Combinations of Earth-based and orbital tracking could yield an extremely accurate determination of the motion of the center of mass of Venus, perhaps to the level of tens of meters over a long observation time. Measurements of this type would provide major inputs for comparison of the predictions of several hypotheses of relativity.

Long-life, passive benchmarks fixed to the surfaces of the planets would provide a cartographic reference system that could be used for all mapping and landing missions in the next several decades. Furthermore, the data from several orbital missions could be accurately coordinated through knowledge of the locations of a few benchmarks relative to the motion of each independent spacecraft. This reference system would allow accurate compilation of data from several missions widely spaced in time and would help to provide discrimination between the temporal and spatial character of the observed phenomena.

The most rewarding application of benchmark technology is, not surprisingly, the most demanding. One of the major objectives of this study has been to evaluate the potential of a system of benchmarks to provide a base for realistic comparative planetary morphology and structural dynamics. If measurements accurate to the level of tens of centimeters are feasible on Earth, they will someday be so on Venus and Mars. It was our hope, in this study, to find a way of making such measurements on the surface of Venus but, because of power (bandwidth) limitations on available equipment, it appears that the best one can hope for in the near future is a range resolution of the order of a few meters to a few tens of meters, although these values may be improved by clever modeling and extended observation.

Nevertheless, these kinds of measurements are of such fundamental importance to a clear understanding of the roles of the several processes at work in the formation and evolution of planets that viable methods of obtaining the required accuracy are laudable goals worthy of more effort than we have been able to devote in this study. This is not to say that centimeter level accuracy is not obtainable with the techniques examined here but that we have not been able to find a clear demonstration that they are. As the methods of radio science are improved with innovations like Very Long Baseline Interferometry and sophisticated pulse compression techniques, the viability and then current usefulness of long-life benchmarks will increase proportionally.

Because of this potential usefulness, the application of benchmark technology to measurement of planetary tectonic activity is discussed in some detail. The importance of the mantle (and plate) dynamics to discrimination of formation processes is emphasized and some thought experiments are performed to estimate the number and position of benchmarks that would be required to detect the motions of the Earth's plates from orbit or from a distant planet. It is shown that six benchmarks would be sufficient to detect the gross features of terrestrial plate tectonics over an observation period of about 20 years if the measurement system is accurate to about one meter.

But there is one caveat to the arguments that such measurements are within the range of near-future capability; atmospheric turbulence may introduce errors that make centimeter level accuracy very difficult or impossible to achieve. The complexity of this problem puts it well beyond the scope of this study and it was quickly decided that such deliberations should be left to more near-term projects like VOIR where their solutions are more urgent.

With the exception of possible neutral atmospheric turbulence problems, however, it is suggested that a valuable program of comparative planetology could be started for very low cost and within the next few years by delivery of a small number of rugged passive or (shorter-lived) active benchmarks to the surface of Venus.

Section 3 of this report contains calculations of the radar system requirements for obtaining useful measurements from benchmarks. Primary emphasis is placed on estimation of the size and gain characteristics of wire mesh corner reflectors in the form of octahedral structures that tend to return a radar signal to its source no matter what direction the signal comes from.

The discussion is divided into two parts that characterize the two basic areas of study. First is the problem of distinguishing the signal returned by a distant benchmark from the inherent thermal noise in the receiver. Second is the problem of distinguishing the signal returned by a benchmark from the signal returned by the surrounding terrain (clutter) if the benchmark is on a planet. These aspects of detectability are discussed in turn and it is shown that corner reflectors on Venus of the order of 6 to 10 meters on a side should be detectable by Earth-based radar installations like Arecibo or Goldstone using observing times of one to four hours at S-band frequencies.

The reflective and focusing characteristics of radar corner reflectors are considered and it is shown that the radar cross section of these devices is proportional to the fourth power of the length of an edge and to the square of the frequency of the radar signal. From this result, one might expect that the highest attainable frequency would be used but, because of atmospheric attenuation at Venus, the highest useful frequency is S band (λ 12 cm).

Smaller benchmarks are shown to be easily detectable by orbital radar; octahedral structures forming eight corner reflectors with edges of 2 meters should appear very bright to orbital radar systems like VOIR even at L band (λ = 25 cm). Details of the reflectivity of corner reflectors and their relative brightness against backgrounds of various terrain are presented parametrically.

It was not surprising that a study of this nature led to consideration of other applications and techniques of benchmark technology. Many possible reflectors were considered for various applications. These included wire-mesh phased arrays, large groups of randomly oriented needles, and very long wires with radar dipoles spaced in phase along the wires. None of these ideas under preliminary examination seemed to offer any advantage over corner reflectors, and the concepts were shelved for possible rejuvenation in other applications.

But the broader range of thinking brought out the possibility of very long distance communication using high-powered lasers. An optical corner reflector, it was found, could return a laser beam from incredible distances. This line of thinking led to the question of whether or not it is feasible to track an array of optical corner reflectors in very deep space or to track them in orbits near the sun to determine the gravitational structure of the inner solar system. The possibility became clear that one might discriminate between the several hypotheses of general relativity through an accurate determination of the orbit of an optical benchmark and through the simultaneous determination of the quadrapole moment of the Sun.

These studies brought out yet another unexpected aspect of the benchmark problem, the problem of relative motion of benchmark and receiver. For communication with a distant corner reflector, the transmitter/receiver must be within a certain angular range of the signal path in order to receive the returned signal. In other words, if the motion of the Earth (transmitter/receiver) across the signal path is larger than a certain small fraction of the speed of light, the receiver on Earth will no longer be within the beamwidth of the reflected signal and a passive reflector is useless except during the few days per year when the Earth moves along the line of sight to the benchmark.

Thus we came to discover that for deep space applications, the original goal of long life through design of a completely passive device was extremely difficult for the distances we had begun to consider (30 to 100 A.U.). It became apparent that the passive radar retroreflector was probably untenable for very long-range applications and that the next best thing for the intended application was a very simple, very rugged, overdesigned transponder that required no antenna pointing even at the outer limits of the solar system. With the development of increased laser power potentially available in the next decade, the deep space laser retroreflector concept might become feasible. Inner solar system applications of passive laser and radar retroreflectors are probably feasible now.

The discussion of radar systems includes consideration of simple transponders that might be designed to have lifetimes of many years, perhaps many decades. The major advantage of such devices comes from the increased signal return that makes possible more precise measurements for a given level of Earth-based radar capability. The major disadvantage, of course, comes from the expected short lifetimes of such devices for use on Venus if they are built with conventional electronic technology.

The challenge of building a high-temperature, long life transponder and the possibility of realizing the scientific value of such a device led to conceptual design for a one-watt simple repeater using technology that is currently being developed at Los Alamos for subterranean applications. The conceptual design and an interesting discussion of how it might be developed is reported in Section 4.

The work at Los Alamos involved development of components called integrated thermionic circuits (ITC's) to be used at temperatures of about 500°C and expected to last for several decades. These devices, consisting of vacuum-tube components mounted on sapphire substrate, were assumed as part of the design for a Venus surface transponder.

This section includes discussions of fused salt batteries that are naturally high-temperature devices, convection cooled radioisotope thermionic generators for power, and vacuum tube cathode heating power supplied directly by a few grams of radioactive material without the need to convert the energy to electrical and then back to thermal motion of the cathode electrons.

The most difficult problem of the conceptual design is in the assurance of a stable local oscillator to control the heterodyne process required to obtain sufficient isolation of the received signal from the retransmitted radiation.

These factors are discussed in conjunction with other difficulties, and some clever possible solutions to the local oscillator stability problem are presented. It is suggested that the development of Venus surface transponders may not be so difficult as one might imagine in view of the credible design outlined here that is composed entirely of existing components. The only pervading problem with the high temperature transponder is that of making certain of a long lifetime. It is pointed out that long-life electronic components have been in use for over 20 years in the transatlantic cables and that the development of similar technology for use on the planetary surfaces represents an exciting challenge for the Laboratory that might very well yield the long-term, high accuracy results necessary to the comparative planetology experiments discussed in Section 2.

The discussion of high-temperature transponders was placed after the section on radar systems for reasons of continuity. In Section 5, we return to the problem of passive benchmark design which was one of the original goals of the study. The structural analysis shows that octahedral retroreflectors with dimensions of the order of a few meters can be built to withstand the Venusian environment using techniques currently available for deployable space antennas. Lenticular welded beams used for the Lockheed wrapped-rib antenna form the basis of a conceptual design for a 2-meter octahedral wire-mesh retroreflector that can be distinguished from the surface clutter by orbital radar systems now being designed for use at Venus.

But a Venus surface retroreflector detectable by Earth-based radar is a much more difficult problem. Estimates show that an octahedral reflector with 6-meter compression beams would be barely detectable from Earth under the best observing conditions. A very preliminary conceptual design for a 10-meter reflector showed that the strongest lenticular welded beams were incapable of self-deployment by their own stored energy.

The lenticular beam concept allows one to flatten the semicylindrical structure and roll it up like photographic film. When the bands around the rolled-up beam are released, the elastic energy in the compressed structure is released and the beam deploys as the main-spring of a mechanical watch would if released from its constraining case.

Unfortunately, there is a practical limit to the thickness of the walls of lenticular welded beams that precludes its use for sustaining Venus surface loads if the compression members are longer than a few meters.

The 10-meter design, then, seemed to require the use of astromast technology with complications of deployment and stabilization in the expected winds. Estimates of the mass of such a structure quickly reached several hundred kilograms and the difficulties of deployment were so formidable that it was decided to give up on the idea of a passive reflector of that size and complexity on the surface of Venus.

The decision to give up on the large benchmark should not be construed as a statement that it is impossible but it seems unlikely that a project of such complexity and mass requirement would have much chance of being approved. As the technology for large deployable structures improves and as the capability of Earth-based radar increases, the long-life passive Venus benchmark should be reviewed from time to time.

A possibly very low cost, cooperative venture would be possible by placement of a small (2-3 meter) retroreflector atop future Russian Venus landers. A conceptual design is presented showing that a ten kilogram benchmark could be mounted near the top of a lander and could be deployed by a timer device after the main lander mission is finished. The lander/benchmark combination would then form a semi-permanent reference point on the surface for future missions and perhaps for future improved Earth-based or Earth-orbital based radar.

Finally, in Section 5, there is a discussion of the possibility of constructing large octahedral retroreflectors for deep space and orbital tracking. The lenticular welded beam concept is at its best in deep space where the loads are minimized and, it is shown, some very large self-erecting reflectors can be built for modest mass requirements.

Section 6 contains discussions of several miscellaneous applications of benchmark technology including a promising application of passive retroreflectors as landing beacons. The benchmarks can be used as surface reference points for active radar transmitters on landers to permit accurate landing capability. The details of a conceptual lander control system have been worked out in a preliminary way and the idea looks quite promising.

Also in Section 6 is a discussion of an application that takes advantage of the low power requirements of a transmitter in the outer solar system. It was shown in Section 3 that power requirements for transponders as far away as 80 to 100 A.U. are less than one watt to be detectable by the large radio telescopes on Earth. It may be possible to launch a large number of very small, very simple, probes to the outer solar system to determine the gravitational and electromagnetic structure of the space beyond Pluto's orbit. The concept is discussed only briefly in this report as it came to mind at the end of the study and will be the subject of more thorough examination during FY 1979.

In this study we have tried to strike a balance between covering many possibilities for benchmark technology and covering some options in enough detail to allow a rational evaluation of feasibility. Because of this approach, parts of the report will appear somewhat disjoint. The reader is asked to remember the preliminary nature of the study and to bear with the authors in regions where the subject matter may appear unrelated to earlier sections. Section 7 has a brief summary of conclusions and recommendations.

SECTION 2

SCIENCE RATIONALE

2.1 SUMMARY OF SCIENCE RATIONALE

Currently our detailed knowledge of Venus is restricted primarily to upper atmospheric structure and phenomena. At the surface, only the very basic environmental parameters are known from the successful Russian landers. Pioneer Venus will again concentrate on the atmosphere but is expected to yield some surface topography data. If VOIR becomes a mission, the planet surface will be mapped morphologically, but ongoing surface dynamics will not be unambiguously revealed.

The Venus Benchmark offers the potential of answering current dynamical questions in several areas, as well as supporting some VOIR objectives. Through precise tracking of radar reflectors or transponders fixed to Venus' surface, the planet's ephemeris may be improved considerably beyond the capabilities of current radar and optical techniques. Certain aspects of internal dynamics, such as rotation rate, angular momentum vector direction (pole position), and any perturbations such as would be characteristic of Chandler wobble may be measured with high precision. With a highly accurate benchmark system, crustal motion and plate tectonic activity, if present, may be detected and the past distinguished from the present. Some lower atmospheric phenomena unmeasurable by orbiting spacecraft, such as wind direction, turbulence, and parameters like temperature, pressure and integrated density may be monitored over long time periods. In support of VOIR and later mapping missions, a small system of benchmarks may be used to establish cartographic control from a very early stage, permitting a more coordinated study of global data.

By providing a unique solution to operating in a harsh environment, the Venus Benchmark can plug some gaps in our knowledge of Earth's nearest planetary neighbor. With a long lifetime, the passive Benchmark provides the ability to monitor variable parameters over long time periods and creates an opportunity for measurement which has to date been available only on Earth. Extension of the Benchmark concept and these advantages to bodies other than Venus is almost certainly possible, though some operational and design changes are necessary to operate in different environments and farther from Earth.

2.2 CURRENT KNOWLEDGE OF VENUS (Ref. 2-1 – 2-4)

Detailed observations of Venus from spacecraft first began with the flyby of Mariner 2 in 1962. Because of its nearness, Venus was a logical choice as a first planetary target, but ever since then concrete information has been slow in coming despite active programs here and in the Soviet Union. Early data from telescopic observations consisted of measurements of albedo and the radius of Venus at the cloud-top level. It was generally believed that the surface was totally obscured. Radar measurements showed a surface not uniformly smooth at the 1962 conjunction, indicating at least that the whole planet was not ocean-covered. Microwave radiometers (3-20 cm) indicated a surface with an $\sim$700K black body temperature, but some believed this emission could result from ionospheric or lightning emissions with a cool surface. A magnetic field was presumed.

Mariner 2 had a limited scientific capability, but made two especially important measurements. Tracking data yielded Venus' mass, which in turn revealed the bulk density to be similar to Earth. Infrared radiometers measured cloud-top temperatures and showed limb darkening, indicating a thick atmosphere. Ground-based polarimetry by Clark and Kuz'min were considered consistent with a hot surface, but this hypothesis was not uniformly accepted.

Prior to 1965, only carbon dioxide had been identified as a significant constituent without question, but its percentage was quoted in the literature from 5-100%. Water was reported in small quantities. Spectroscopic observations in 1966 identified CO, HCl and HF. Surface pressures were completely uncertain, with quoted ranges from 5 to 300 bars. No ionosphere was observed and nothing about solar wind interaction was known.

Russia announced the landing of Venera-4 (on 18 October 1967), measuring a cooler atmosphere and lower pressure than anticipated.

However, the Mariner 5 flyby data (closest approach occurred on 19 October 1967, the day after the Venera-4 entry), after considerable analysis, indicated higher surface temperatures and pressures than the Venera data, forcing the eventual conclusion that Venera-4 in fact did not land prior to loss of signal, and requiring a considerable change in theories of the Venus environment.

A post-Mariner-5 synthesis of Venera and Mariner data gave quantitative credibility to the heavy atmosphere/hot surface Mariner-2 data, yielding a surface equatorial radius of 6053 km and cloud-top altitude of 67 ± 10 km, a CO_2 content exceeding 85% with upper limits on N_2, O_2 and H_2O. Temperature and pressure profiles were calculated from 25 to 90 km with further extrapolation to the surface indicating a temperature of 700 K and a pressure of 100 bars. Detailed upper atmospheric data were also compiled. A bow shock was detected and a magnetic field found virtually non-existent.

High resolution radiometry has demonstrated that there is no significant temperature variation over the disc of Venus ($\pm 5^{\circ}C$) (Ref. 2-5). Thus, the poles appear to be as hot as the equator, and the dark side is as hot as the illuminated side. This suggests that the lower atmosphere is well mixed by global convection. Direct measurements of the atmosphere have established that CO_2 represents 97% of the gasses. A surface temperature of $450^{\circ}C$ and a pressure of about 90 atmospheres seem to be consistent with both the direct and remote sensing data. The upper atmosphere also contains a number of trace gases.

Very small quantities of carbon monoxide, water vapor, hydrochloric acid, and hydrofluoric acid have been identified spectrographically. It also believed that sulfuric acid exists in the upper atmosphere at a height where the temperature is low enough to condense the acid which falls as small droplets into the hotter atmosphere where it again evaporates. Thus a perpetual rain of sulfuric acid may be occurring.

Since Mariner 5, the Soviets have enjoyed considerable success in their Venus program. Venera 7-10 all reached the surface, with the latter two making numerous detailed _in situ_ measurements on the surface as well as taking atmospheric data during descent. The surface temperature, pressure, optical and wind environments are all known for two widely separated locations over about an hour's time. However, the difficulty of characterizing the surface or meteorology of Earth with a single hour's measurements taken under similar conditions should be kept in mind.

Three important surface properties which are not as subject to the above spatial and temporal limitations were measured by Venera 9 and 10, with some supporting Venera 8 data. A gamma-ray experiment on Venera 8 measured inherent surface rock radioactivity (which can vary over a quite broad range for different rock types) indicative of siliceous rocks (like granite), while the later landers measured emissions from naturally occurring radioactive isotopes of uranium, thorium and potassium indicative of more mafic rocks (like basalts). Venera 10 performed a gamma-ray scattering experiments to measure the density of surface rocks (as opposed to the bulk density of Venus). Prior to this, ground-based radar measurements attempting to correlate density with permitivity had given a broad range of density from 1 to 4.3 $gm\text{-}cm^{-3}$ (with some confidence in the 1.5 to 2.8 $gm\text{-}cm^{-3}$ range), which tells very little. Venera 10 data narrowed the range to 2.88 ± 0.1 $gm\text{-}cm^{-3}$, consistent with the basaltic interpretation of the gamma spectrometer experiment. These data taken together very strongly indicate that Venus has undergone differentiation and even suggest different types of surface rock with at least regional variation.

Much of what is known about the surface of Venus, except for radiometric brightness, has been discovered by radar. A number of surface features having anomalous ability to backscatter microwaves were discovered by Goldstein and Carpenter in 1964 (Ref. 2-6, 2-7). These were confirmed by groups at the MIT Lincoln Laboratory and the Arecibo Observatory. Recently higher resolution radar mapping of the equatorial region has revealed that the surface of Venus has many craters, small mountains, long ridges and rilles, and a large canyon. Observations of these features have been useful in refining the measurement of the spin vector of Venus. Most recently Zohar at JPL has released new measurements which are given with prior values in Table 2-1.

Table 2-1. Rotation Period and Pole Position of Venus

Researcher	Rotation Period (days)	R.A. of Pole (degrees)	Dec. of Pole (degrees)
Shapiro (1967)	243.09±0.18	275.3±1.8	65.8±1.2
Carpenter (1970)	242.98±0.04	274.1±3.0	71.4±1.0
Jurgens (1970)	243.00±0.10	272.7±0.7	65.3±1.0
Zohar (1978)[2-8]	243.018±0.012	272.37±0.3	67.182±0.12
Synodic Resonance	243.16		
Orbital Normal		278.0	65.53
Invariable Plane Normal		273.9	67.3

Zohar's result is based on three small features that were seen in two or more of four recent conjunctions. The rotation period suggested by these determinations is just slightly off the earth-synchronous value of 243.16 days. This value would cause Venus to present the same longitude to an observer on earth at each inferior conjunction. The rotation is actually retrograde, so the spin axis is directed in the southern hemisphere. This rotation period implies a Venusian solar day of 117 days, so the subsolar point moves at a relatively slow rate of 13.54 km/hr.

Venus has no significant magnetic field and therefore has no complicated ionosphere like the Earth and Jupiter. Its upper atmosphere interacts directly with the solar wind. Radio occultations of Venus by Mariners 5 and 10 were able to measure the electron density profiles, the neutral atmosphere profile down to about 35 km, as well as fluctuations in the signal caused by turbulence in the upper atmosphere. The maximum electron density is less than 5×10^5 per cm^3 on the day side. None of the Russian Venera landers contained phase coherent repeaters, so only amplitude fluctuations of the signal demonstrate the effects of turbulence (Ref. 2-9). The percent log-amplitude fluctuations vary from about 2% at 40 km altitude to 7% at the surface. The power spectrum of the phase fluctuations can be estimated from these data if certain constants in the turbulent model are assumed (Ref. 2-10, 2-11). Unfortunately, the values of these constants are not known with any certainty.

To date, then, only a few basic facts about Venus and its environment have been unambiguously determined. With the exception of upper atmosphere data from Mariner 10, the same level of information about Earth could be summarized in a few papers. Our knowledge is especially weak in temporal data, though upper atmospheric behavior has been reasonably characterized diurnally as the result of numerous radio occultation measurements. The Pioneer Venus mission currently in flight is mainly atmosphere-oriented, while the nature of planned Russian investigations is unknown (there is a Soviet mission also underway). The Benchmark, whether an active or passive spacecraft, is the only in situ experiment proposed to date capable of making long-term temporal measurements, whether of atmospheric parameters, planetary dynamics or crustal motion. In this way it offers a substantial contribution to the data base acquired from Soviet and U.S. activities.

2.3 ATMOSPHERIC PROFILE MEASUREMENT FROM SIGNAL ALTERATION BY THE VENUS ATMOSPHERE

The ultimate resolution attainable in imaging the surface of Venus is probably set by the atmosphere. This is because the phase coherence of the illuminating signal and the return is degraded by turbulence, and some of the energy is absorbed by atmospheric carbon dioxide and clouds (especially at shorter wavelengths). If the benchmark is a strong enough source, as it would be if it were a transponder, the extent of the turbulence could be measured by detecting in some way the amount of phase demodulation of the signal. In addition, if the transponder emitted signals at two different frequencies, say X-band and S-band, the total atmospheric absorption could be determined by measuring the relative signal strength, since it has been shown by laboratory experiments that the refractive properties of CO_2 are the same at these two frequencies. By experiments such as these using long-lived benchmarks our knowledge of the Venus atmospheric parameters could be improved greatly, especially regarding their diurnal and seasonal variability. More detailed examination of atmospheric experiments using the benchmark merits further consideration.

2.4 POSSIBLE BENCHMARK ADAPTATIONS TO MEASURE SURFACE METEOROLOGICAL PHENOMENA

The harsh environment on Venus' surface precludes the operation of conventional landers for extended periods of time. However, to understand lower atmosphere meteorology, which is of interest on Venus (and Mars) for terrestrial comparisons, it is necessary to make some simple measurements repeatedly over several local days and at several locations. The phenomenon of super refraction prevents radio occultations from penetrating below a few tens of kilometers, so in situ or near vertical viewing orbital instruments must be employed. The Pioneer Venus orbiter may provide some of the latter capability for measuring surface temperature, but many other measurements are prevented by the dense cloud layers and pressure-broadened CO_2 absorption.

A possible long-term in situ capability could be provided by unconventional landers operating near ambient temperatures as discussed elsewhere in this report in the context of an active transponder on the surface. Indeed many experiments may be operated if the required electronics are within the capability of high temperature technology such as might be developed. Any serious Venus exploration program beyond the current mission should consider this technology.

There may also be an entirely passive approach to measuring wind direction by making suitable modifications to passive radar retro-reflector design. The design presented for a wire-and-strut octahedral retroreflector reflects in a roughly uniform pattern from all illumination geometries; it also does not introduce any polarization bias to the reflected signal. With some minor modifications to the baseline retro-reflector design, it is possible to introduce a polarization bias in the reflected signal at some expense to average returned signal strength.

By introducing polarization into the reflected signal, a new measurable variable becomes available which can be used as an indicator of surface phenomena. This variable is a polarization angle ϕ, indicating the direction of the plane of polarization of the returned signal. The polarization angle may be employed to measure wind direction with three modifications to the baseline retroreflector. First, the penetrator (or central mounting support employed on a smaller benchmark to secure it to a lander) is provided with a simple free-moving rotary joint whereby the reflector portion of the benchmark may rotate with respect to its support. Second, the regular octahederal shape of the reflector is distorted somewhat to create an aerodynamic center of pressure offset from the cental vertical axis of rotation. In this way, when the wind blows, the reflector structure rotates to a preferred orientation with respect to the wind. Alternatively, a small solid surface could be placed at one corner of the reflector to act as a weather vane as shown in Figure 2-1. The third modification requires that the reflective properties of the reflector be altered to introduce a polarization bias. One possible method is to use both titanium wires (reflective) and glass threads (non-reflective) in place of the all-metal wire mesh on some faces of the benchmark. Figure 2-2 illustrates one possible configuration where wires oriented in one direction on the faces in the horizontal plane are replaced with glass threads. The component of waves with their E-vectors parallel to the wires is reflected, while the perpendicular component is not. This scheme works best with near-vertical viewing, and not at all for limb viewing, but limb viewing may be difficult in any case as a result of atmospheric super-refraction. There is also a 180° ambiguity in wind direction. Atmospheric modeling might reduce this ambiguity to at least the more probable of the two directions.

While not very sophisticated by comparison with data available from the surfaces of Mars or Earth, these wind direction measurements, especially if made in a network, would greatly enhance current knowledge of Venus meteorology. Mariner 10 imaging data mapped global circulation in the upper atmosphere and discovered a very distinct pattern. The total global circulation situation must also include the lower atmosphere. Wind direction data alone would be valuable from a small number of benchmark stations scattered around the planet (as would be the case if crustal motion detection were also a goal of a Venus benchmark program). Temporal variations in any circulation pattern would be of very great interest, especially in comparison with the upper atmosphere. Such variations in the lower atmosphere are only detectable with a long-life in situ measurement system.

2.5 INTERNAL STRUCTURE AND DYNAMICS

2.5.1 Ephemeris

The ephemeris of Venus is currently determined from optical observations, spacecraft tracking data, and radar observations. Of these, the primary constraint on the orbital parameters comes from the set of radar data. The upgraded Arecibo facility allows precision on the order of 0.1 μsec. The topography of the equatorial regions of the inner planets limits, however, the usefulness of these data to accuracies of up to 10 kilometers. Venus equatorial topographic variations are on the order of ±3 km, with maximum variation around 5 km. Models for the topography introduce a large number of solve-for parameters (100) and still leave much high spatial frequency "noise". Microwave retroreflectors fixed on the surface of Venus would be a great advance over the situation outlined above. Only 3 parameters would be necessary to describe exactly each retroreflector position.

The ephemeris of Venus could be significantly improved by a few years of continuous, accurate range measurements. At present, range data for Venus exists over the past decade, but it is rather intermittent and of uncertain accuracy -- 2 km at best. Combined with the optical data, this yields an Earth-relative ephemeris uncertainty of about 50 km. The inclusion of continuous accurate (100 m) ranging over the time of one or two synodic periods (1.6 yrs) would decrease the ephemeris uncertainty by a factor of 2 or 3. The majority of this uncertainty would lie in the out-of-plane direction since the accuracy in this component is proportional to 1/sinI where I is the inclination of the orbit of Venus to the ecliptic. Furthermore, the orbit of the Earth is presently determined mainly by the preponderence of the Earth-Mars range data from Mariner 9 and Viking. Ranging to Venus would provide an independent determination of the Earth's orbital parameters and as such would greatly increase the overall integrity of the planetary ephemerides.

2.5.2 Direct Measurement of Venus Rotational Dynamics

Accurate measurements through use of the retroreflectors of the Venus rotation rate and pole orientation would be very valuable new scientific information. The state of the Venus angular velocity vector represents a major puzzle today for celestial mechanics; the rotation rate appears to be very close but measurably different from the synodic resonance of 243.16 days with the Earth. In addition the pole position is close to several stable Cassini states but again apparently measurably different from each of them. Continued conventional doppler radar measurements may not yield definitive determination of this problem, since "aspect angle" systematic effects on the order of 0.1 day appear possible in such data. Pioneer-Venus ranging accuracy will be on the order of 0.5 km, with 0.25 km sometimes possible, over a relatively short lifespan of 1-3 years. Unambiguous answers to the problems above probably can only be obtained from data with accuracy on the order of the 100 meters or better. The measurement of Venus precession, some large nutations, and the effects of atmospheric tides on the spin state are other possible scientific returns from the retroreflectors.

If advances in radar technology (e.g., reception of returns by Earth-orbiting antennas and very wide bandwidth reception) make possible the use of the retroreflectors at decimeter or even centimeter accuracy, then a much larger set of goals can be addressed. The advantages of such comparisons have been emphasized previously in such fields as planetary atmospheres, ionospheres, and magnetism.

Active systems such as radio transmitters and receivers are necessary for obtaining *in situ* planetary measurements and can be used as benchmark components. However, passive systems become desirable for measuring long time scale phenomena and/or in hostile environments such as the surface of Venus (where the necessary technology for active systems is still in a primitive development stage). The value of co-located active transmitters with passive long-lived benchmarks has been demonstrated with the lunar laser ranging retroreflectors and the Apollo Lunar Surface Experiments Package (ALSEP) transmitter.

The rotation period and pole position of Venus have been determined using radar observations of highly reflective regions on the surface. These regions are sufficiently distinctive that they can be identified from one inferior conjunction to the next. The identification is greatly aided by the (nearly) synodic resonance with the Earth, although these "features" are clearly presenting slightly different aspects to the radar due to relative orbital and spin orientation changes between the two planets. Measurement uncertainties from ten years of such radar observation are dominated by systematic errors due, in fact, to such aspect changes. These uncertainties are estimated for the period at ±0.04 (terrestrial) days (the value is at 4 standard deviations from synodic resonance), and $\sim$0.3 degrees for the pole position. The synodic lock with Earth requires a "rough" gravitational field, which appears to be also contradicted by observation. The long period and nearly 180° obliquity strongly suggest, however, that the Venus spin state is the product of an evolution to an equilibrium state. The equilibrium state which it is observed to have achieved presents difficulties for which theoretical explanations appear to lack completeness. If the Venus spin is still evolving under solar solid-body tides, then Venus is within $\sim 10^8$ years of being fully despun to solar synchronous rotation (Ref. 2-12, 2-13). The probability of our observing Venus just at this point in its evolution appears small. In addition, atmospheric tides appear capable of balancing the solar solid-body tides (Ref. 2-14) and make an equilibrium state possible.

The determination of the amplitudes of forced nutations, which can be predicted for a rigid body once its gravity field is accurately measured, could yield very important results for planetary physics. The differences from rigid-body predictions will provide valuable information about important questions on the state of the Venus interior; i.e., whether the core is fluid, and what is the amount of internal dissipation at the forcing frequencies.

The detection of free motions similar to the terrestrial "Chandler wobble" would be another case of valuable comparative planetology. The Eulerian or Chandler wobble is one of the motions of the rotation axis with respect to a reference frame fixed with respect to the (non-moving) crust of the Earth. This wobble must be distinguished from changes of the orientation of the rotation axis in inertial space, such as precession (26,000 year period for Earth), nutation, long-period variations in the obliquity ($\approx 23.^{\circ}5$), etc., (see Fig. 2-3). The detection of the Eulerian of Earth motion from variations in astronomical latitude of various observations was made by S. Chandler in 1891. The width of the spectral peak centered at the Chandler frequency implies that the motion is strongly damped, with a damping time on the order of a few decades ($\approx$20-50 years). The Chandler excitation mechanism and the location of the energy sink for its damping remain unexplained, despite much recent theoretical work. Detection on Venus of the comparable Eulerian motion would provide valuable additional clues to this puzzle. How the periods of the free motion are different from rigid body values would measure a whole body value for the effective elasticity of the Venus (interior) at those periods.

2.5.3 Measurement of Plate Tectonics on Venus and its Planetological Significance

Various global features on Earth, such as long mountain belts, island arcs, sea floor spreading and apparent matching fits of continents are currently best explained by an overall theory of plate tectonics. From Reference 2-15, "Tectonics refers to the formation and deformation of the Earth's crust resulting in large-scale structural features..." Recent ground-based radar imagery of Venus has indicated to some interpreters that such large-scale features as rift valleys might be of tectonic origin. If their interpretations are correct, it is reasonable to expect that this tectonic activity has played a significant role in the surface evolution of at least two planets, and that tectonic activity may still be present on Venus as it is on Earth.

From Reference 2-15, "Several major hypotheses stand out... in the study of tectonics: 1) the contracting Earth concept, 2) continental drift, 3) convection currents in the Earth's interior, 4) sea floor spreading, and 5) global expansion." The contracting Earth concept has been largely rejected as an explanation for terrestrial features, but is apparently analogous to the process responsible (along with rotational spin-down) for a global complex of linear scarps revealed on Mercury by Mariner 10. The expanding Earth hypothesis is disputed, but is supported by several areas of evidence. Its proof by direct measurement remains impossible at the present time, with the implied rate on the order of 0.6 mm increase in radius per year. However, groundwork laid by the National Geodetic Satellite Program (NGSP) (Ref. 2-16) and the Laser Geodynamic Satellite (LAGEOS) probably ensures confirmation or disproof of this hypothesis sometime in the future.

The bulk of evidence for terrestrial crustal motion is static and associational (i.e., fossil and rock-type correlation, glacial coverage and polar motion), rather than dynamic, however, direct measurements of drift may have been enabled by the NGSP. Since the first indications of continental drift, seismic measurements and modelling have contributed to its understanding by mapping regions of plate interaction in three dimensions. Various continental drift theories have been proposed, all based on static evidence and dating back to A. Snider in 1858. After considerable debate and several shifts in "generally accepted" geological theory, crustal motion is again generally accepted. Direct measurement may be possible on Venus, as will be addressed later.

Convection currents in the Earth's mantle were first proposed by Pekeris in 1935, and may enter as a driving mechanism for continental drift and sea floor spreading. Driven by the decay of radioactive isotopes of uranium, potassium and thorium, convection apparently does not take the form of simple cells, but may act in concert with other processes not fully understood. Plate boundaries might be modelled (as on Earth) and inferred from surface features of Venus. It should be noted that rotation rate differences on Venus and Earth could create a dynamic difference in motion of mantle materials. Also, one might expect a lower driving thermal gradient on Venus due both to its smaller size (limiting the maximum interior temperature) and its higher surface temperature. Material transport, if it exists on Venus (and crustal motion would almost certainly require its existence), would imply a pseudoviscous (plastic) mantle. This property, in turn, places certain restrictions on materials, density, temperature and pressure regimes within the mantle, besides revealing the existence of a mantle itself.

Sea floor spreading on Earth probably does not require a marine environment ("sea floor" spreading is active far above sea level in Iceland), and we might expect an analogous process on Venus. The first hypotheses of sea floor spreading were advanced in the early 1960s based on static evidence left by reversals of the Earth's magnetic field in marine basalt on either side of mid-ocean ridges. Based on positions of field reversals and radiosotope dating of the marine basalts, spreading rates have been calculated at from 2 to 12 cm per year, depending on locality. Such magnetic evidence will be unavailable on Venus until unforeseeably far in the future and perhaps was not produced at all. Inference from surface features and direct measurement remain the only potential methods for ascertaining crustal motion on Venus. Without a long lifetime seismic network on the surface, only the latter method is capable of measuring current plate tectonic activity on Venus and allowing the most useful terrestrial comparisons.

Vertical motions are also of potential interest in ascertaining tectonic activity. Several modestly sized areas on Earth exhibit marked variation in vertical movement. Some measurements have been made dynamically, while others are inferred by measuring elevations and dating vacated shorelines. Most vertical uplifts are due to isostatic rebound after glacier melting, so are of course not applicable to Venus.* Other local scale uplifts occur in volcanic areas (e.g., Tharsis Ridge, rate = ?, Palmdale Bulge, +30 mm/yr). Larger scale uplifts on Earth are associated with mountain building (as in the Himalayas), but rates are very low (perhaps of order 0.1 mm/yr).

*If short-period climate variations are the case on Mars, such uplift might be detectable there especially in polar regions.

In case rates differ from Earth, however, measurement of vertical uplift should be considered in the design of any planetary benchmark system.

Comparisons made between the inner planets (including the Moon) have lead to the terminology "live" and "dead" planets, the former referring to bodies with major interior geological processes still ongoing. Earth is unquestionably "live" and the Moon virtually "dead". Mars must be classed "controversial", with Venus and Mercury "unknown". Radar reflectors on Venus and other planets may offer the opportunity to positively class those planets with respect to interior geological activity, and to make important comparisons with Earth.

2.5.4 Feasibility of Dynamically Detecting Tectonic Motion on Venus

The first dynamic measurements on Earth which indicated tectonic activity consisted of mapping earthquake epicenters and depth. Concentration of earthquakes in narrow, linear bands of varying depths was eventually taken to indicate ongoing interaction between crustal plates (only after viewing seismic records along with a great deal of static evidence was the seismic data understood). Seismic networks are certainly feasible on Mars and Mercury, and a net has already operated on the Moon, but the environment of Venus places obvious restrictions on long term operations of any active hardware. Therefore it seems reasonable to use radar benchmarks on the surface as a yardstick to measure crustal displacement between benchmarks over the years. Now two questions remain: 1) Can we reasonably expect a high enough displacement rate between benchmarks to be measurable with a feasible benchmark design, and 2) how many benchmarks are required to determine if crustal motions exist on Venus?

2.5.4.1 Displacement Rates. Sea floor spreading rates on Earth have been calculated from 2 to 12 cm/yr, measured relative to the mid ocean ridge. Therefore, two markers placed on opposite sides of the ridge would be seen to move at a rate from 4 to 24 cm/yr relative to one another. If we assume the Earth as model (we have little choice) then with a benchmark position measurement accuracy on the order of 1 m, this suggests that detection of movement could occur after 5-20 years, and reasonably accurate rate measurements could be made over a period of 20 to 80 years. While this sounds like a long time, it has only been in the last decade that such measurements have been possible over long distances on Earth. (Improvements in accuracy afforded by benchmark position measurements from orbit might permit roughly a fivefold reduction in the times listed here.)

Without utilizing fixed landmarks on a planet surface known to high position accuracy, there is probably no method of ascertaining the presence of crustal motion on Venus and its current rate. However, based on terrestrial rates, we should note that accuracies of 1 m or better are required to conduct these experiments. Another important feature of the measurement system must be the ability to repeatedly calculate the distance between at least two widely separated benchmarks on Venus, and this accuracy must be maintained over a period of years.

2.5.4.2 Detection of Motion. While investigating crustal motion on Venus or elsewhere, we actually wish to answer several questions:

(1) Is there crustal motion on Venus?
(2) Have we made a thorough search?
(3) (If results are negative) can we be sure it does not exist (above a certain rate associated with a particular maximum surface area)?
(4) (If results are positive) what are the relative directions of motion and their rates?
(5) Can we construct an accurate map of crustal motions and boundaries by correlation with imagery of surface features?

Answering each question requires a more complex benchmark system.

Since all crustal motion on a planet surface is relative between plates, rather than to a fixed point, it is obvious that to answer question (1), we need a minimum of 2 benchmarks. However, only fortuitous placement is likely to permit detection of displacement. Lacking *a priori* knowledge, it is instructive to imagine that we are dealing with a cloud-shrouded Earth of unknown crustal structure and then examine the results we might get with different benchmark distributions. Figure 2-4 is a map of the six major and about a dozen of the more significant minor plates on the Earth. Even widely separated, two benchmarks could be moving in the same direction at similar rates, rendering relative motion undetectable.

To answer question (2) on Earth, four widely spaced benchmarks might be capable of assuring detection. Here one might see motion of one point relative to the other three, but this might also be the result of Earth's particular plate configuration. It is estimated that 6 benchmarks are required to assure detection of crustal motion or to confirm its non-existence on a significant scale (answering questions 1-3).

Six benchmarks, at the ends of 3 orthogonal axes originating at the planet center, should also provide a qualitative answer to question (4), which will reveal a pseudoviscous mantle, mantle heating and other indications of pressure, temperature and density regimes.

Question (5) will require more study but is probably beyond the scope of the proposed Venus Benchmark project. It would be sensible to not consider (5) until questions (1)-(4) are answered conclusively. Mapping could also be addressed in a much more sensible manner after some knowledge and study of global surface features at the resolution provided by the proposed Venus Orbiting Imaging Radar (VOIR) mission. If we were to map Venus crustal motions to the accuracy shown in Figure 2-4, using benchmarks alone, probably several hundred would be required. Interpretation of imagery might reduce this number somewhat below 100, but clearly this is beyond our present scope.

2.5.4.3 Possible Experiment Result Scenarios. Assuming surface radar imaging and multiple benchmark data (from perhaps 6 benchmarks) could be examined together in the future, there are several possible scenarios of the geologic picture we might get, as illustrated in Table 2-2. Without benchmarks, presumably only the imaging data are available and we have the three possible scenarios listed vertically in Table 2-2. The utility of studying crustal motion on Venus using benchmarks is illustrated by

Table 2-2. Some possible future scenarios of plate tectonic evidence on Venus. Six scenarios of general plate tectonic evidence are considered, with each combination suggesting direction of possible geological conclusions. The possible conclusions are by no means exhaustive, nor do they account for the wealth of detail and subtleties which will be present in the data. Detail in the data is likely to permit discrimination between the possibilities suggested or to introduce new possibilities.

	Benchmarks Indicate: Crustal Motion	Benchmarks Indicate: No Crustal Motion
Radar Imagery Indicates: obvious tectonic features	Plate tectonics is an active process on Venus making it structurally and chronologically similar to Earth	1) Plate tectonics was an active process on Venus, but has either ceased or is below measurement threshold, therefore: 2) Plate motion may continue as a much slower process than on Earth, or 3) Venus is now "dead" with respect to crustal activity, leaving Earth in an earlier stage of interior evolution, or 4) Crustal motion may be an intermittent process, with Venus dormant between cycles (there are suggestions that Earth is cyclic in this respect, with the current cycle starting 200-300 x 10^6 ybp), or 5) Features on Earth now regarded as tectonic in origin (they were not so regarded 25 years ago) either may not be of tectonic origin, or may not be uniquely diagnostic of tectonic activity and could have arisen through other processes.
Radar Imagery Indicates: doubtful tectonic features	Confirmation of tectonic origin for doubtful features, but tectonic surface effects are somewhat different than on Earth	1) Doubtful features not likely of tectonic origin, or 2) Plate tectonics may once have been active, but did not progress as on Earth to dominate global surface features
Radar Imagery Indicates: no recognized tectonic features	1) Tectonics manifests itself on Venus' surface differently from Earth and may exert influences of which we are unaware, or 2) Crustal motion just recently started on Venus and has yet to create surface effects, or 3) Erosion on Venus' surface destroys tectonic features as fast as they are created	1) Tectonic activity is not present on Venus and probably has not been at least for the past 10^8-10^9 years, and 2) This implies certain interior and crustal environments on Venus which would not permit recent tectonic activity.

comparing the implications listed in the first column with those in the second for each category of visible tectonic features. Discrimination between the possibilities listed in the two columns is made possible with benchmarks.

In all cases, benchmarks allow chronological distinctions between the past and present. If doubtful tectonic features exist, we may use the benchmark to interpret the origin of these features with greater certainty. If no tectonic features exist, benchmarks provide an acid test for our current theories of tectonic influence on planetary surfaces, or may indicate surface erosion rates. Taken out of the context of surface imagery and mapping, benchmarks alone can tell about the interior processes and activity on Venus, especially if crustal motion is detected. Observing all these possible scenarios together, it is apparent that a small network of benchmarks on Venus can contribute uniquely to answering some very important questions about Venus itself and evolution of all solid-surface bodies, including Earth.

2.6 CARTOGRAPHIC AND GRAVITATIONAL MAPPING APPLICATIONS

Terrestrial geodetic measurements are in the midst of a great revolution in their accuracy and the capability to interpret these data for their geodynamic information content. Three-dimensional vector differences between benchmarks which are accurate to the centimeter level over intercontinental distances are supplanting classical geodetic techniques. Satellite observations of the geoid and gravity field are also rapidly advancing in technology employed and accuracy obtained. The potential accuracy of these measurements requires the definition of more stable reference frames than those defined by the classical crust-fixed locations of a net of observatories. Several reference frames are candidates. Some examples are:

1) the frame convenient for VLBI observations which is defined by positions of extragalactic radio sources
2) inertial frames dynamically determined by the motion in space of planets, spacecraft, earth satellites, etc.

The common feature of these frames is their fundamentally extraterrestrial definition. The geodynamic information about the complex internal structure of the Earth to be extracted from these new data will require sophisticated modelling techniques, and data analysis efforts extending over many years to measure reliably tectonic plate motions, for example.

An exciting revolution is measuring the dynamics of the interior and surface of the Earth and the immediate applicability of this developing technology and analysis capability to the other terrestrial planets. The extraterrestrial nature of the defining reference frames makes this extension to other planets very natural. The largest potential payoff is the depth and breadth of understanding of geophysics that could be obtained from the comparative geodynamics between the terrestrial planets.

As each celestial body is mapped with increasingly better resolution, the difficulty of tieing different map segments acquired at different times becomes greater. Mapping uncertainties on Mars after Mariner 9 in fact resulted in a large percentage of the required size of the Viking landing target ellipses. These uncertainties, characterized by not knowing the location of a particular surface feature (a dangerous crater for example) in inertial space, placed considerable restrictions on the landing sites and eliminated sites which might have been scientifically more desirable.

Cartographic control may be established on a body by fixing a location on the surface in inertial space (at a particular time) to better than the desired mapping accuracy. From this location, all other locations are referenced by offset coordinates. In practice, more than one fixed reference location (or benchmark, as such locations are often called on Earth) is required to reduce offset errors propagating over long distances. Sophisticated techniques such as satellite geodesy may then be applied economically to interrelate a small number of benchmarks around a globe, allowing more economical (and less accurate) techniques to be applied to mapping the smaller intervening areas to a given level of accuracy determined by the quality of data and instrumentation available.

Radar mapping data acquired by a spacecraft orbiting Venus will be uncertain in position to the extent that the spacecraft's position at a particular time is uncertain with respect to the center of Venus. Tracking inaccuracies from Earth, aggravated by gravity field, atmospheric and solar perturbations to the spacecraft orbit, will limit the ability to precisely relate one set of data to another. However, if there are several sharp radar return sources (retroreflectors or transponders) scattered around the globe and appearing in radar maps, then radar returns from objects in their proximity may be located as an offset position from the radar source. Because of its small size and strong signal, more sophisticated techniques may be used to locate the reference benchmark and in determining the relative locations of several benchmarks, thereby reducing the uncertainties in knowing the relative positions of all features on the map.

Similar difficulties are encountered in gravitational mapping of a body, which is a powerful tool for studying a planet's interior. The Lunar Orbiter and first Apollo missions were plagued by unexpected deviations from anticipated positions and velocities. Analysis of the data coupled with a conceptual model of the mechanism led to the discovery and confirmation of mascons, or sub-surface regions of density higher than the normal distribution in spherical shells. Knowledge of these mascons has since been instrumental in developing theories describing the evolution of the Moon to its present state.

Other less dramatic, but perhaps more significant inhomogeneities in planetary mass distribution may be mapped by tracking a satellite's path through a planet's gravity field in inertial space and in relation to the planet center. Sub-surface intrusions of dense rock and non-spherical bulges in the surface may be detected and reveal information about past processes occurring in the planet. Comparisons may then be drawn between the terrestrial planets for which this data is available.

Gravitational mapping accuracy may be improved by having a fixed reference on the planet from which the satellite may frequently reference its position. Such a device also helps to relate the gravitational map more precisely to the planet center, which is better known by tracking a device fixed on the planet surface.

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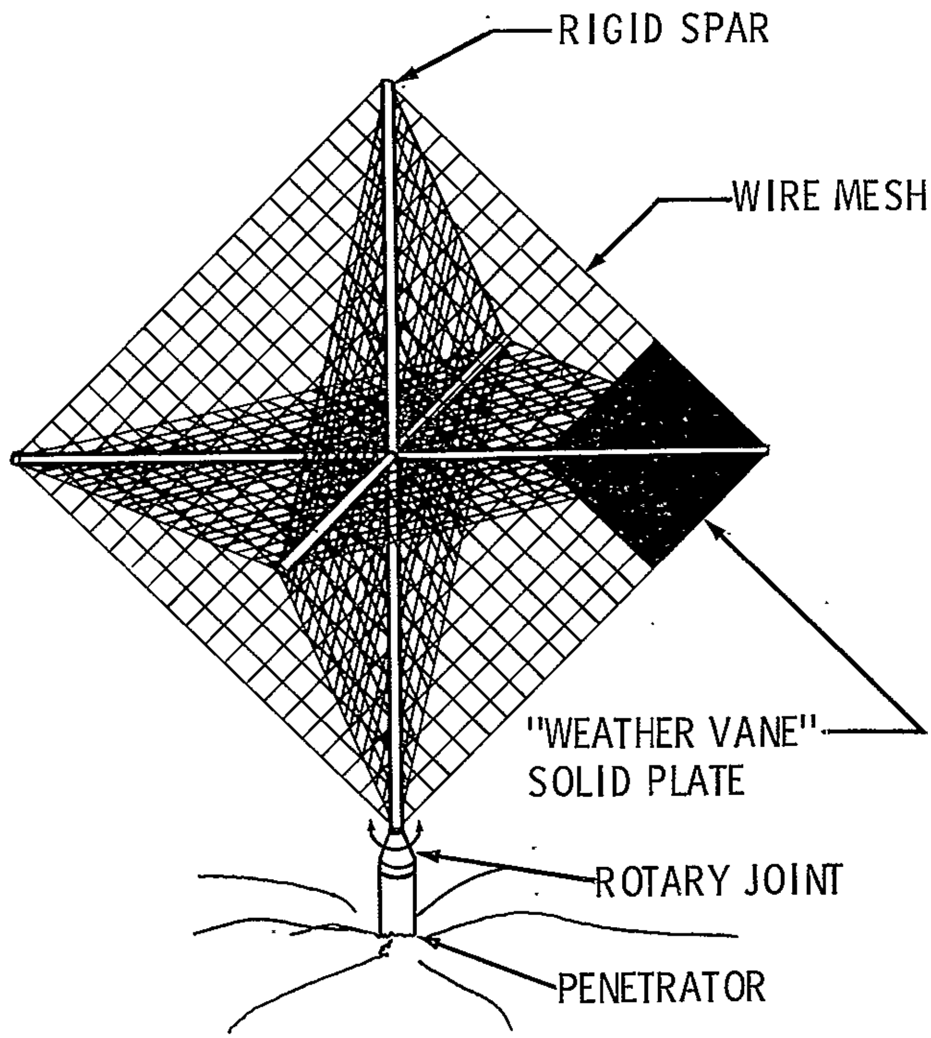

Figure 2-1. Conceptual Benchmark "Weather Vane" Configuration

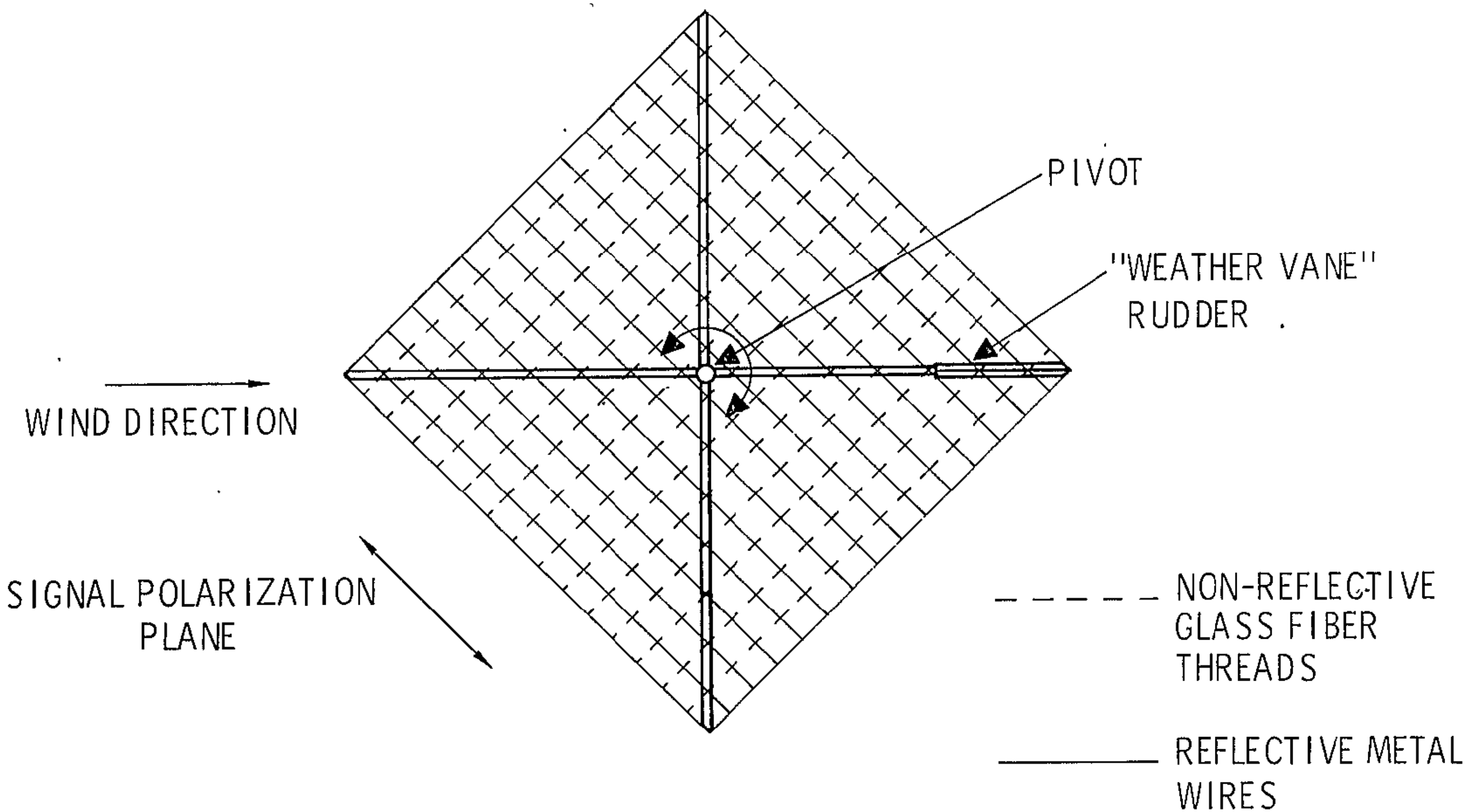

Figure 2-2. Top View of Horizontal Reflector Plane of Planetary Benchmark Showing Configuration for Detection of Wind Direction by Measuring Polarization of Returned Signal

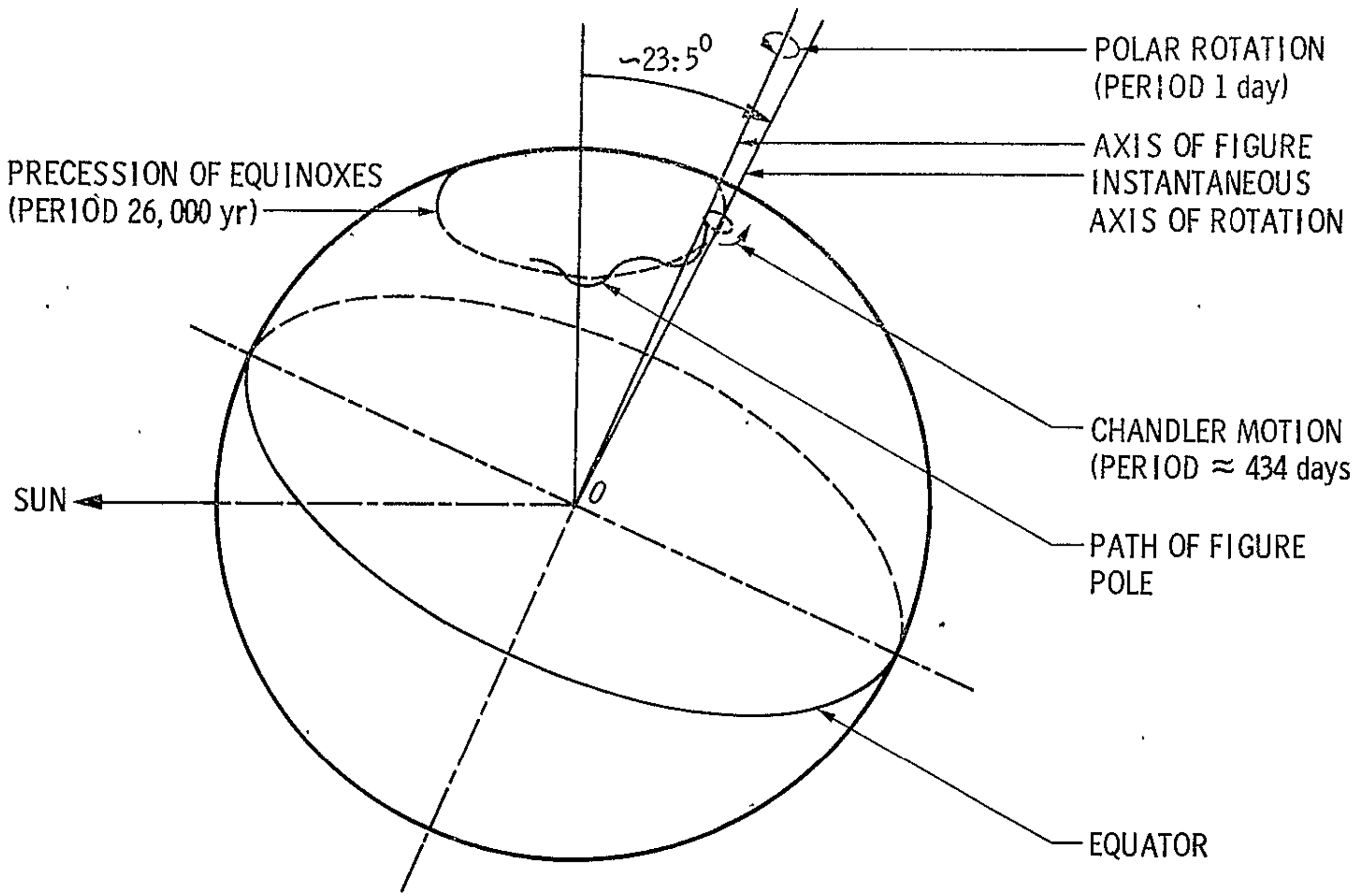

Figure 2-3. Chandler Wobble of Earth's Pole. Forced Motion of the Pole (Precession) is Manifested by a Change in Direction of the Polar Axis in Inertial Space. Chandler Wobble is Instead a Motion of the Polar Axis with Respect to the Earth's Surface. (After R. N. Arnold and L. Maunder, Gyrodynamics and Its Engineering Applications, Academic Press, 1961)

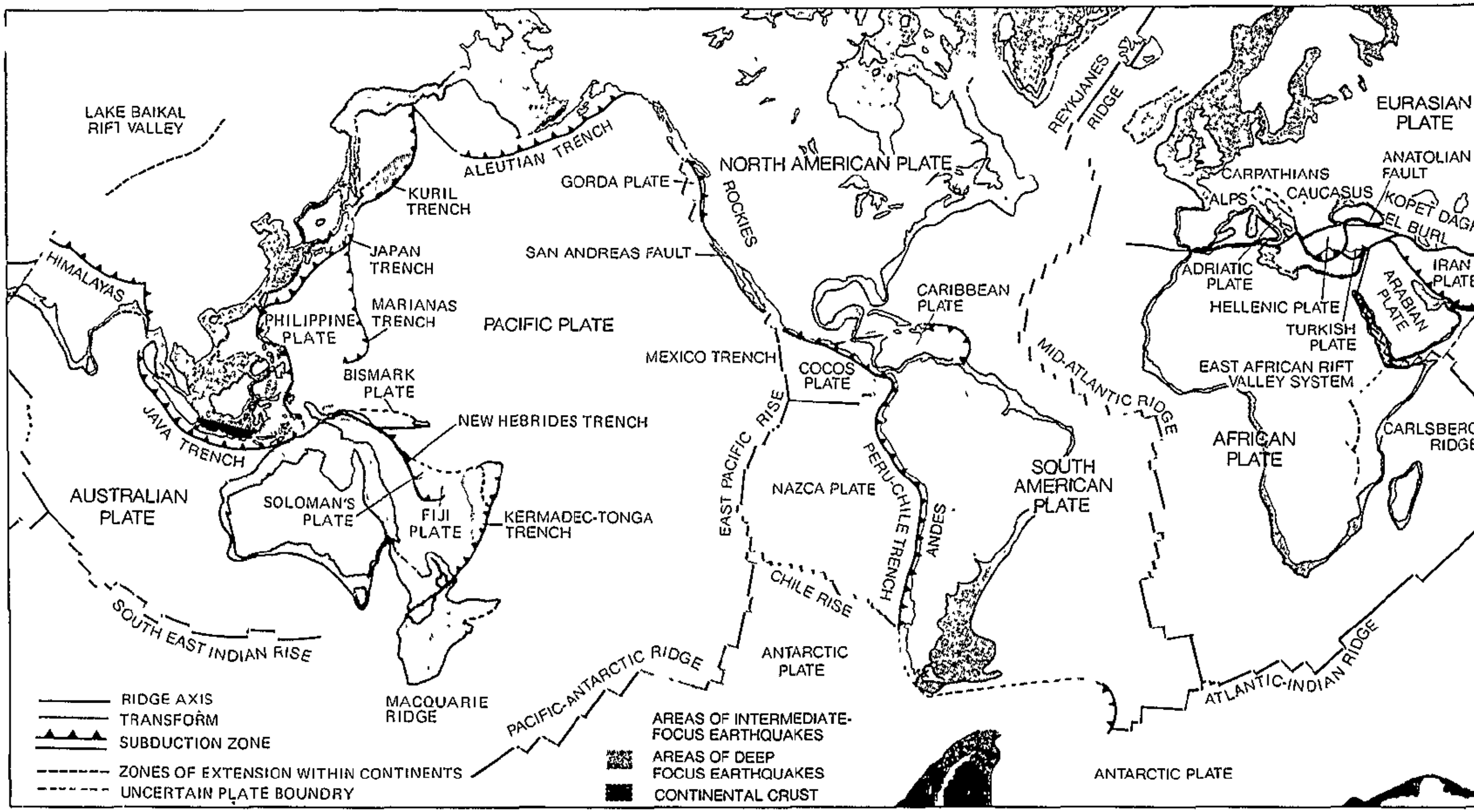

Figure 2-4. Plate Tectonic Map of Earth. Used as a Rough Model in Determining Number of Benchmarks Required to Detect Crustal Motions. [From "Plate Tectonics" by John F. Dewey. Copyright © 1972 by Scientific American, Inc. All rights reserved. (Reference 2-17)]

SECTION 3

RADAR SYSTEMS

Man-made radar reflectors and transponders have been used on Earth for years to increase the visibility of small targets such as boats and buoys and as aids to navigation. Although extending the principle to interplanetary or deep space targets might seem overly ambitious because of the tremendous distances involved, it should be remembered that modern radar astronomy and synthetic aperture imaging techniques make the detection and measurement of extremely weak signals possible. For example, the power returned from a 10 km square area on Venus to the Goldstone 64 meter antenna during a typical imaging experiment is about 10^{-22} watts! Properly designed passive reflectors or transponders of sufficient cross section or power output should be detectable by such systems.

In this section we will discuss the measurement of weak signals and the size of reflectors and transponders necessary to produce them. Radar ranging and imaging techniques will be reviewed along with the resolution attainable using currently existing and proposed systems. For Earth-based observations we will presume the use of the Goldstone 64 meter antenna operating at S or X-band, or the Arecibo observatory at S-band. Orbital radars we will consider are Seasat or VOIR type synthetic aperture imagers.

3.1 DETECTABILITY BY EARTH-BASED RADAR

There are two questions to be answered in determining the detectability of a radar target: (1) does the target return enough power to the radar for the signal to be recognizable above the system noise, and (2) can the return from the target be differentiated from those caused by nearby or background objects or terrain (clutter)?

3.2 REFLECTORS IN SPACE

To answer the first question we will assume the target is suspended in space with no nearby objects to create interference, and calculate the size necessary for its detection on Earth. The result would be applicable to a deep space mission where range information is desired to detect orbit perturbations, or to a reflector placed on a small object such as an asteroid or one of the Martian satellites. The calculation involves solving the so-called "radar equation", which relates the visibility of a target to the parameters of the radar system and the target properties.

The radar equation (which also applies to optical frequencies) can be derived in the following way. Consider an isotropic radiator transmitting power P_t and illuminating a target at distance r. The power P_r received at the transmission point (monostatic case) per unit area after being reflected by the target is

$$P_r = \frac{P_t}{4\pi r^2} \cdot \frac{\sigma}{4\pi r^2} \tag{1}$$

where σ is the cross section of the target and is the projected area of a perfectly reflecting sphere which would return the same flux to the receiver if placed in the same position. The transmitting antenna is usually not isotropic but has a gain given by

$$G = \frac{4\pi A}{\lambda^2} \tag{2}$$

where A is the transmitting antenna area and λ is the wavelength. If the receiving antenna also has area A then the radar equation is

$$P_r = \frac{P_t \sigma GA}{(4\pi r^2)^2} \tag{3}$$

To determine detectability we must compare the received power to the system noise:

$$SNR = \frac{P_r}{KT}\left(\frac{T_{obs}}{\Delta f}\right)^{1/2} \tag{4}$$

where

SNR = signal to noise ratio

K = Boltzmann constant = 1.38×10^{-23} Joules/^{o}K

T = system temperature

T_{obs} = observing time (receive mode)

Δf = spectral resolution $\approx 1/T_{RT}$

T_{RT} = round trip time = $2r/c$

In addition, the antenna area is given by

$$A = \frac{\varepsilon \pi d^2}{4} \tag{5}$$

where d = antenna diameter and ε = efficiency. Combining (2), (3), (4) and (5) and solving for σ yields

$$\sigma = \frac{64\lambda^2 \; SNR \; KT \; r^4}{P_t \; \varepsilon^2 \pi d^4 \; (T_{obs} \; T_{RT})^{1/2}} \tag{6}$$

This is the minimum cross section necessary for a point target in space to be detectable with Earth-based radar. Table 3-1 shows some values for the various parameters with present systems.

Table 3-1. Radar Parameters for Typical Systems

Parameter	Goldstone X-band	Goldstone S-band	Arecibo S-band
λ, cm	3	12.5	12.5
P_t, kW	350	350	420
ε	0.43	0.60	0.80
T, ^{o}K	25	20	40
d, m	64	64	200

Substituting these values into (6), along with $T_{RT} = 2r/c$, we get a relationship of the form

$$\sigma = \frac{c' \, r^{7/2} \, (\mathrm{AU})}{T_{obs}^{1/2} \, (\mathrm{sec})} \ \mathrm{cm} \tag{7}$$

where

$c' = 1.87 \times 10^{12}$ Goldstone X-band

$= 1.33 \times 10^{13}$ Goldstone S-band

$= 1.31 \times 10^{11}$ Arecibo S-band

3.2.1 Corner Reflectors

The device in most common use as a radar target is the triangular corner reflector (see Section 5). The peak cross section for such an object is given by

$$\sigma = \frac{4\pi a^4}{3\lambda^2} \tag{8}$$

where a is the length of one edge. Corner reflectors are generally preferred over other types of artificial target because they can be detected from almost any angle. The incoming ray undergoes a triple bounce and returns in the direction of illumination, while maintaining the phase coherence and polarization of the signal. They are not; however, truly omnidirectional. The detailed angular backscatter response has been calculated theoretically and verified experimentally many times and is plotted in Figure 3-1. Notice that there is a small range of angles where the backscatter is at least 10 dB (factor of 10) down from its peak, so if the radar happens to be located in one of these nulls detection of the reflector might be prevented. This problem would be minimized if the reflector is located on a planetary surface since, over time, observations would be made through a range of angles. If the reflector were in space it could be spun at some rate, although this would introduce a modulation that would have to be accounted for in the data processing.

Substituting (8) into (7), with the appropriate observing times (4 hours for Goldstone, 1 hour for Arecibo) we find the reflector size necessary for detection to be

$$a = C_{cr} \, r^{7/8} \text{ (AU) meters} \tag{9}$$

where

$$\begin{aligned} C_{cr} &= 42.78 \text{ Goldstone X-band} \\ &= 142.59 \text{ Goldstone S-band} \\ &= 53.42 \text{ Arecibo S-band} \end{aligned}$$

a is plotted as a function of r in Figure 3-2.

If the reflector is located in space an additional complication is provided by the relative motion of the radar and target. The change in range during the observation can be eliminated during the data processing since it will be known approximately, but the difference in velocities perpendicular to the line of sight might carry the Earth out of the reflector beam during the round trip transit time of the signal. For the receiver to remain in the beam of a reflector in the outer solar system for the round trip time the Earth's projected velocity time T_{RT} must be less than half the beamwidth times the distance:

$$V_p \frac{2r}{c} \leq \frac{\lambda r}{2a}$$

or,

$$a \leq \frac{\lambda c}{4V_p}$$

where c = the speed of light, and V_p is the orbital speed V_e of the Earth (30 km/sec) projected onto a perpendicular to the Sun-reflector line. If we let

$$V_p = V_e \cos \theta$$

where θ = the angle reflector-Sun-Earth, and substitute the appropriate values, we get

$$a \leq \frac{2500\ \lambda}{\cos \theta} \qquad (10)$$

For example, Figure 3-2 shows that at S-band at 40 AU a 1400 meter reflector is necessary. From (10) this implies $\theta \approx 77.1^{\circ}$, or about 26 days every 6 months when observations can be made. For X-band this decreases to 9 days.

3.2.2 Other Reflectors

In addition to trihedral corners, several other suggestions for passive reflectors in space have been investigated. These include arrays of resonant dipoles printed on wires and stabilized by rotation, and large sheets of reflective material stabilized and oriented toward the Earth or Sun by various combinations of rotation and radiation pressure. In all cases these proved to be necessarily too large (the corner reflector is apparently the brightest passive target for a given amount of payload), and as a result suffered from even more stringent beamwidth restrictions.

Since the cross section of the corner reflector is inversely proportional to the square of the wavelength, the use of optical systems was also considered. Equations (1) through (3) apply to visible wavelengths, so the power output of a laser necessary to illuminate a Lageos-type array of large optical cubes was calculated assuming that the return signal was being observed with a 2.4 meter telescope and the most sensitive currently available photometer. The results indicated that a pulsed laser with peak power output of several tens of megawatts would be sufficient for a reflector at 50 AU, if the considerable atmospheric problems could be eliminated. These power levels are not out of the question for weapon-type lasers that will probably be built in the near future. The relative motion problem, however, remains. The same size-to-wavelength factor responsible for the large cross section of optical reflectors also implies an extremely narrow beamwidth. The Earth rapidly moves out of the return beam even at moderate distance and there is apparently no solution to this dilemma. Slight defocusing of the reflectors was considered but this lowered the cross section and therefore increased the laser power necessary to unacceptably high levels.

3.2.3 Transponders

One way to keep the size and weight of a radar benchmark down is to relax slightly the requirement that it be totally passive. A transponder that repeats a code transmitted from the Earth, or even a simple transmitter that generates its own code has several advantages over totally passive reflectors. First of all, the radar equation for an isotropically radiating transmitter in space being detected from the Earth is

$$P_r = \frac{P_t A}{4\pi r^2} \tag{11}$$

where the terms are all defined as previously. In this case P_t is the power transmitted by the transponder, not from the Earth. It should be apparent that the r^{-2} instead of r^{-4} distance dependence will lessen the power requirements considerably.

If we assume that the device is generating its own phase coded continuous wave (CW) signal (or that it is keying it to one previously received from the Earth), the round trip time is not a factor and the signal-to-noise ratio can be written

$$\mathrm{SNR} = \frac{P_r\, T_{obs}}{KT} \tag{12}$$

where T_{obs} is now about 8 hours for Goldstone and 2 hours for Arecibo, and T must now include the noise temperature of the transmitter ($\approx 300^{\circ}$K). Combining (11) and (12) along with (5), we find the power necessary for the benchmark to transmit:

$$P_t = \frac{16 r^2\, KT\, \mathrm{SNR}}{\varepsilon d^2\, T_{obs}} \tag{13}$$

Substituting from Table 3-1, we find, for SNR = 10:

$$P_t = C_{tr}\, r^2(\mathrm{AU}) \text{ watts} \tag{14}$$

where

$$\begin{aligned} C_{tr} &= 2.94 \times 10^{-4} \text{ Goldstone X-band} \\ &= 2.11 \times 10^{-4} \text{ Goldstone S-band} \\ &= 6.47 \times 10^{-5} \text{ Arecibo S-band} \end{aligned}$$

P_t is plotted as a function of r in Figure 3-3. Note that the Arecibo figure implies that the benchmark need only transmit 0.16 watt to be detectable from 50 AU!

The only drawback to this method is that the range accuracy is ultimately a function of the stability of the oscillator, both over the transmission time and over the length of the mission. The first of these is probably not a problem since oscillators are commercially available today that are stable to one part in 10^{11} over periods of tens of hours. This is sufficient to allow range measurements with accuracies of kilometers or even hundreds of meters, adequate for detecting gravitational perturbations in the outer solar system. The second problem can be solved by having the transponder perform the same sort of process we would on the Earth, i.e., cross correlate the incoming signal (let us say a very long pseudo-random code) with a code generated internally thereby synthesizing a very narrow pulse, and beginning transmission of its own signal with some preset time following the reception of this pulse.

This type of transponder can be a quite simple device. It requires a very small antenna (a wire of some sort of simple array) and need not be oriented so no control system is necessary. The transmitted power required is so low (<1 watt) that currently available long-life power sources like RTGs could keep them operating for the scores of years necessary for a deep-space mission.

3.3 REFLECTORS ON PLANETARY SURFACES

For a benchmark located on a planetary surface the problem of differentiating the radar echo from the reflector from those caused by nearby objects and surrounding terrain becomes dominant. To be detectable the cross section of the reflector must be some factor f larger than the cross section σ_{cell} of neighboring cells:

$$f = \frac{\sigma}{\sigma_{cell}} . \tag{15}$$

Thus, detectability is determined only by the resolution of the radar, whether it be orbital or Earth-based.

The reflectivity of terrain is usually described by a "normalized cross section" σ_0, or radar cross section per unit area. This quantity varies widely with terrain type and incidence angle (angle between a ray from the radar and the normal to the surface). Figure 3-4 shows σ_0 in dB as a function of incidence angle for several terrain types measured on the Earth, and two curves derived for the average returns from Venus. Since the reflectivity of terrain has a strong angular dependence and that of a corner reflector has very little, it is clearly best to try to observe at as high an incidence angle as possible.

From the definition above, cross section of a resolution cell is σ_0 for the appropriate terrain type times the area of a cell:

$$\sigma_{cell} = \sigma_0 L^2 \tag{16}$$

where L = surface radar resolution.

3.3.1 Corner Reflector

Combining (15), (16) and equation (8) for the cross section of a corner reflector and solving for a yields

$$a^4 = \frac{3\lambda^2 fL^2 \sigma_0}{4\pi} \tag{17}$$

Current design plans for VOIR call for λ = 25 cm (L-band) and L $\approx$ 300 meters. For Goldstone λ = 12.5 cm (S-band) and the best resolution images we have obtained so far have L $\approx$ 10 km. a is plotted in Figures 3-5 and 3-6 as a function of resolution for these two wavelengths for several values of f. For these plots σ_0 has been assumed equal to -15 dB, an average value for Venus at an incidence angle of about 40°. If the reflector is placed into a "radar dark" area, determined for example from previous Earth-based images, σ_0 could be as much as -30 dB.

Figure 3-7 shows a synthetic aperture radar image of a number of corner reflectors set out in a cross pattern on Goldstone Dry Lake in the Mojave Desert. The image was obtained with the JPL L-band imaging radar, which is flown on board the NASA Convair 990. This instrument operates at a wavelength of 25 cm with a resolution of 25 meters, and the reflectors have a equal to about 1.83 meters. Therefore, from Equation (17), they should appear about 15.8 dB brighter than the background if it has σ_0 = -15 dB, a typical value for desert at these incidence angles. The reflectors do not appear quite that bright in the image, so it is suspected that either (1) the radar was operating at reduced resolution, or (2) subsurface moisture created a dielectrically rough interface several tens of cm below the playa surface, which raised σ_0 to approximately 10 dB (the image was obtained during the summer following an unusually rainy spring). This reiterates the importance of the background scattering in detection of a benchmark.

3.3.2 Transponders

The problem of differentiating the benchmark from background reflections can be solved quite nicely by use of a transponder radiating a signal at a slightly different wavelength than the illuminating radar. In this case the background is very low and the transmitted power necessary is the same as that given in Figure 3-3. A more detailed treatment of the operation of a transponder in the harsh Venus environment is given in Section 4.

3.4 SUMMARY

The main conclusion to be drawn from this analysis is that for most applications totally passive radar reflectors are unsatisfactory as benchmarks for Earth-based observations. For deep space missions, reflectors with dimensions of several hundred meters are required (Figure 3-2), while for planetary surfaces 10 meters would just suffice to make the benchmark visible against the background (Figures 3-5 and 3-6). Smaller passive benchmarks, visible to orbiting radar, appear to be viable in the near future.

Great savings in weight and complexity can be realized, however, by the use of simple transponders. Figure 3-3 shows that the transmitted power required from the transponders is extremely modest in all cases, well within the capabilities of modern equipment. In addition, no orientation or antenna pointing is required, eliminating the need for a control system. It is concluded here from detectability and accuracy considerations that if they can be constructed to withstand the expected severe environmental conditions and to have lifetimes sufficient for measurements of planetological significance, transponders are greatly preferred over any kind of passive reflector.

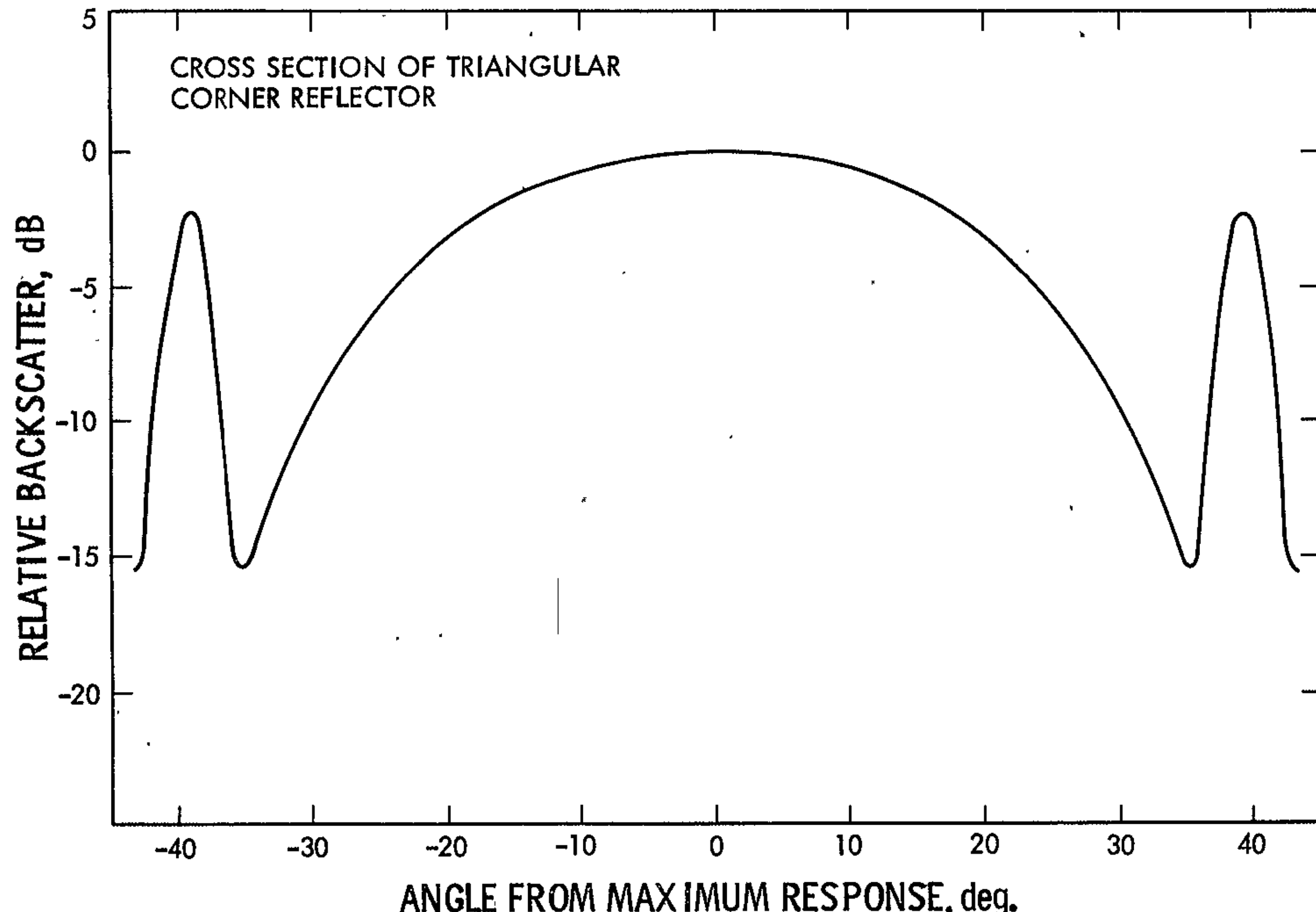

Figure 3-1. Relative Cross Section of a Corner Reflector as a Function of Angle From Boresight. There is a small range of angles (∿10°) where the cross section is reduced by an order of magnitude.

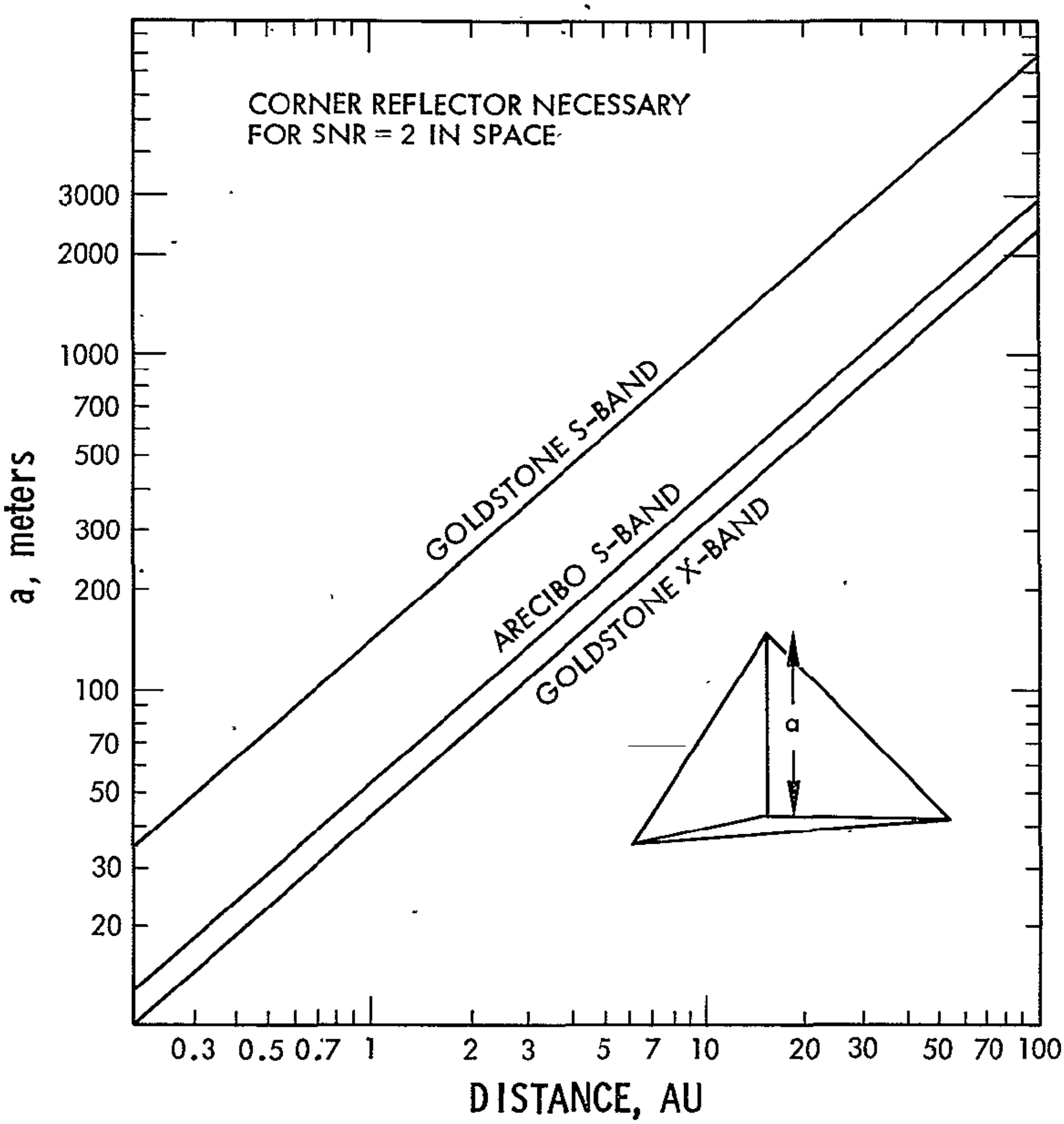

Figure 3-2. Size of Corner Reflector Necessary for Absolute Minimum Detectability in Space

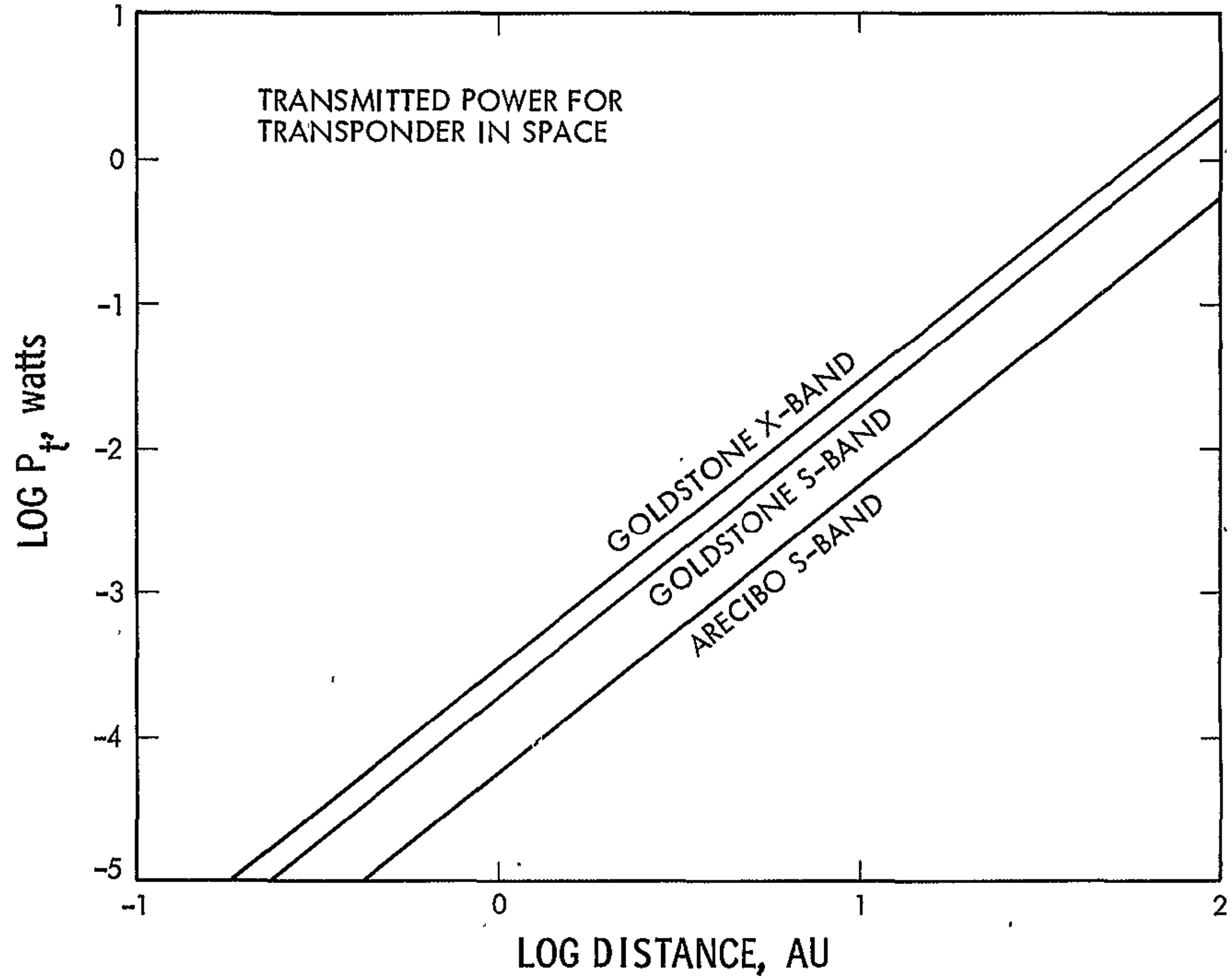

Figure 3-3. Average Power Output Necessary for a Transmitter To Be Detectable in Space

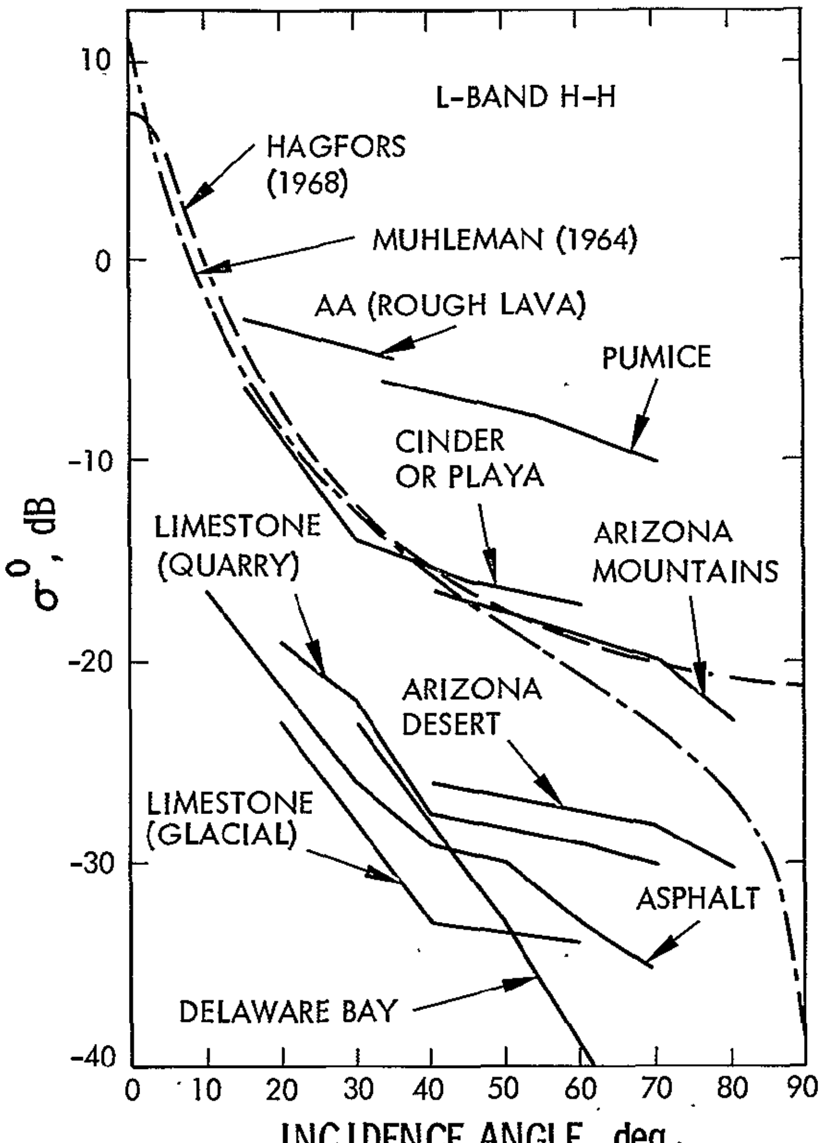

Figure 3-4. Backscatter Cross Section per Unit Angle as a Function of Incidence Angle. Solid lines are experimentally determined from terrestrial targets, and broken lines are scattering laws fit to averaged Venus backscatter data.

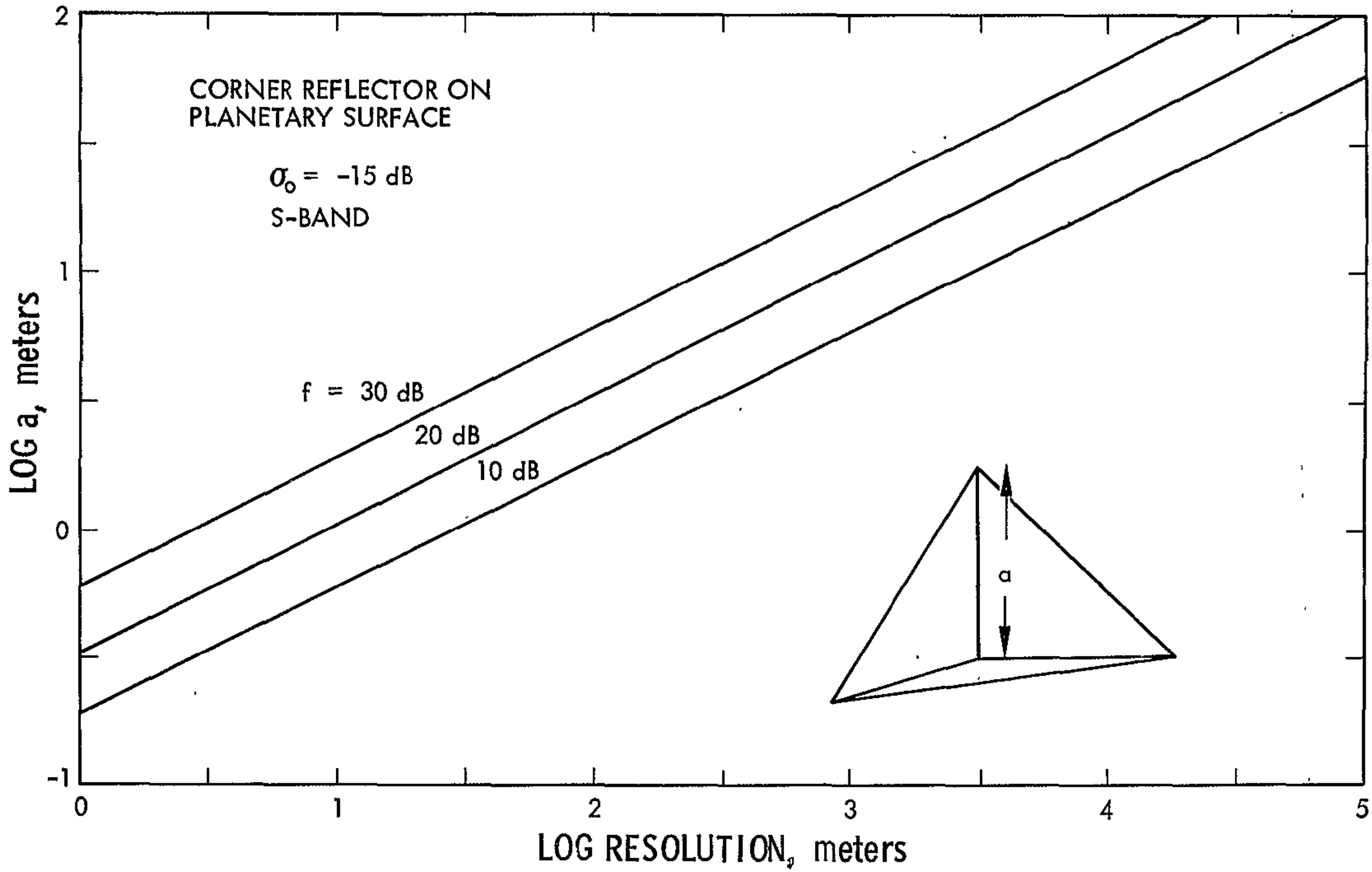

Figure 3-5. Corner Reflector Necessary for Visibility With Signal to Clutter Ratio f on Planetary Surface at S-Band (λ= 12.5 cm)

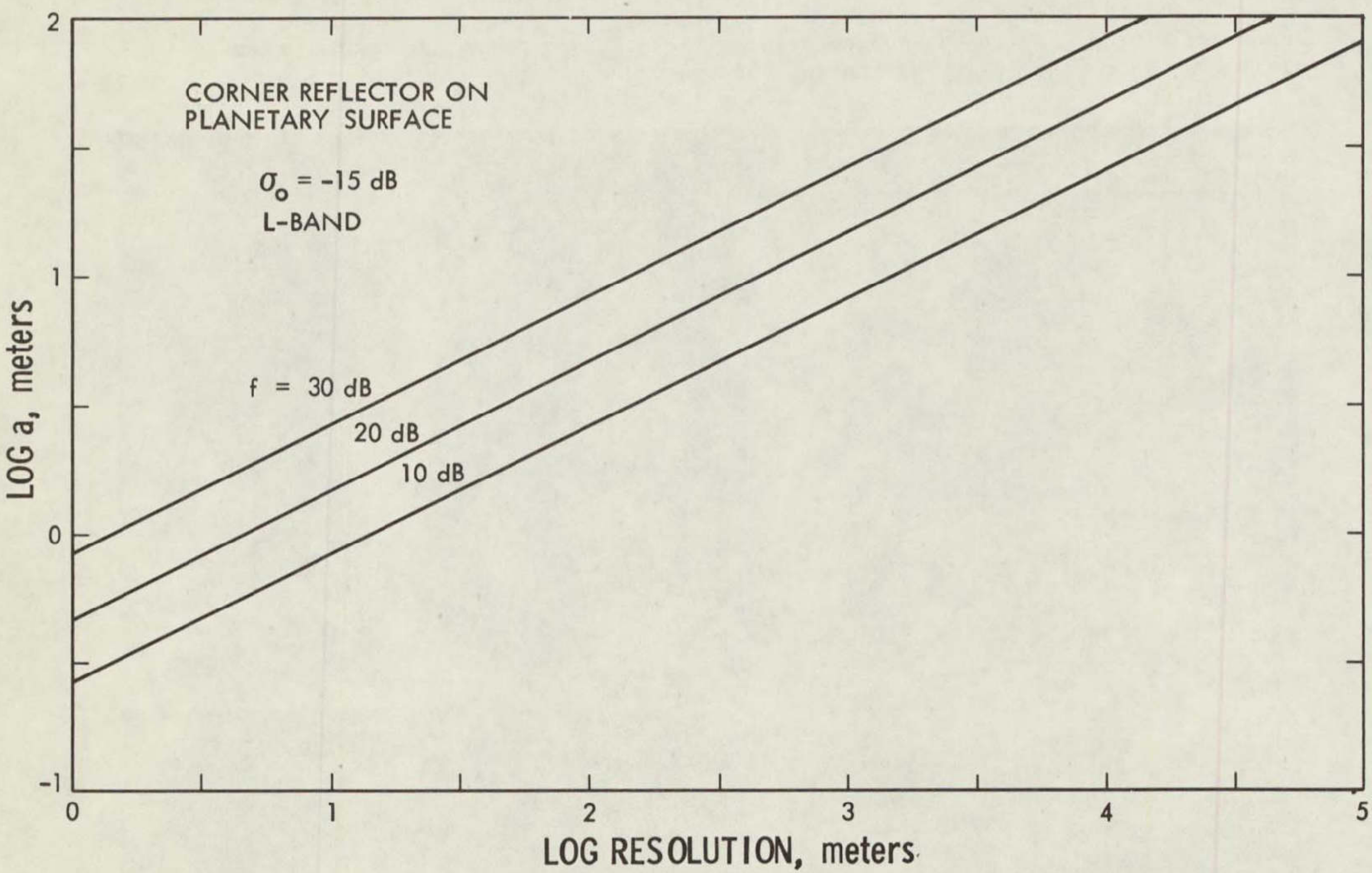

Figure 3-6. Corner Reflector Necessary for Visibility With Signal to Clutter Ratio f on Planetary Surface at L-Band (λ= 25 cm)

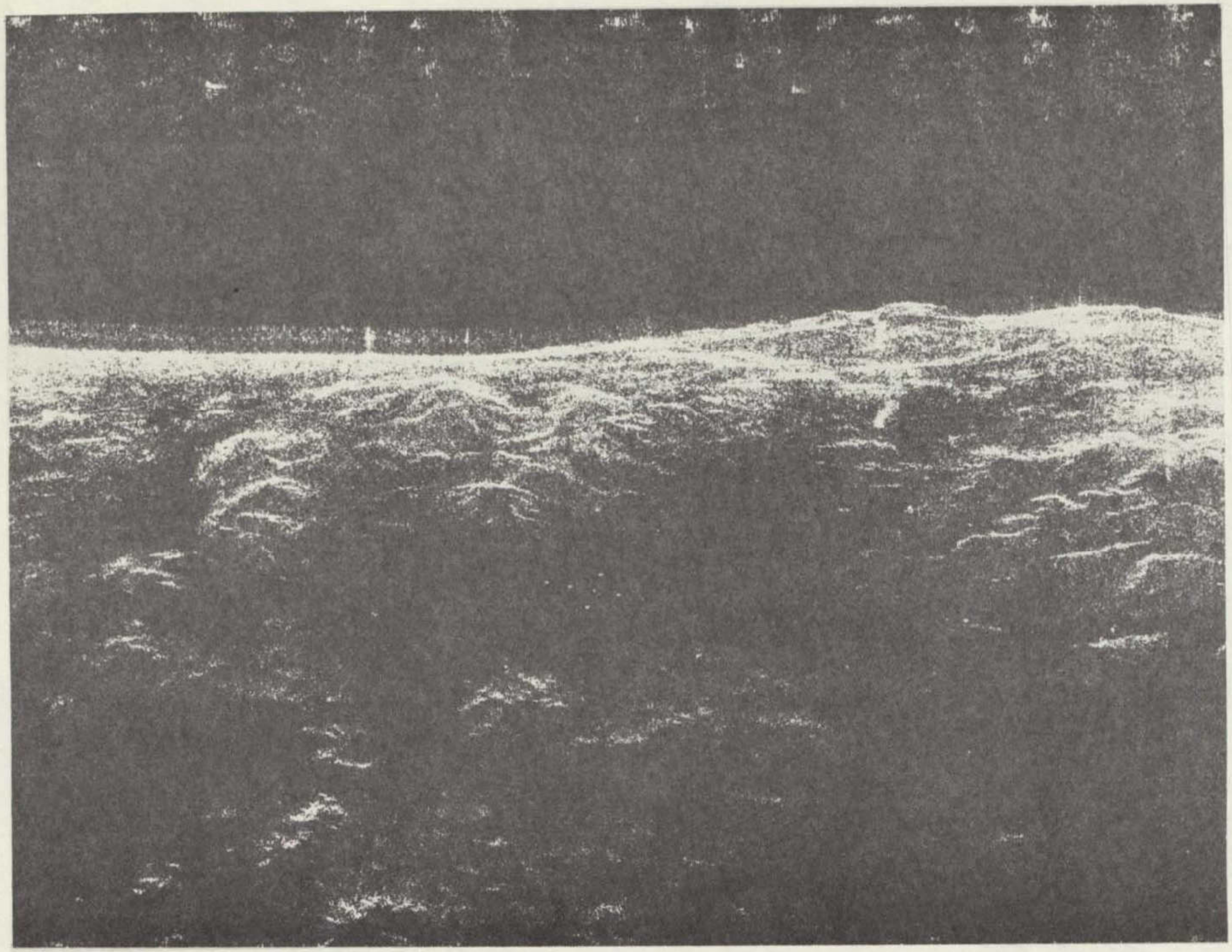

Figure 3-7. Synthetic Aperture Radar Image of Corner Reflectors (Arrayed in a Cross Pattern) on Goldstone Dry Lake, California, Which Is Surrounded by Low Hills. The radar was operating at L-band (λ= 25 cm) with a resolution of 25 meters, while the corner reflectors had edges of 2.4 and 1.8 meters. This image demonstrates the importance of placing passive reflectors in "radar dark" surroundings.

Occultation data from Mariners 5 and 10 give information on the turbulence in the Venusian atmosphere above 40 km. Unfortunately more than 90% of the atmosphere lies below this level, and its effect is unknown except to the extent that ground based radar astronomy has successfully achieved lineal resolutions on the order of 4 km.

Also not so obvious is the use of a simple radio repeater to determine the rotation rate and spin axis of the planet. The procedure for such a determination is well known and has been applied to delay-Doppler signatures of a number of small radar features presumed to be fixed to the surface of the planet. The repeater simply acts as a point feature permitting delay and Doppler signatures to be measured several orders of magnitude more accurately than possible with the intrinsic features. Even a short span of data (a few months) from two or three properly placed repeaters can yield a determination of the pole and rotation rate between two and three orders of magnitude better than presently possible from the totality of ground-based radar data if high resolution ranging can be incorporated. The point source repeaters also avoid certain systematic errors that are introduced in the radar feature data caused by the apparent shift of the location of the maximum reflection as the angle of incidence changes. The accurate measurement of the rotation rate and direction of the Venusian pole seems to have diverse implications with respect to everything from the planet's internal structure to the mass of Pluto. The atmospheric turbulence, on the other hand, places limits on a number of scientific experiments including the measurement of the pole direction and rotation rate and the ultimate resolution of synthetic aperture radars (SAR's).

4.2 SCOPE OF STUDY

This study is primarily concerned with the state of technology applicable to electronics and support systems that could operate at the environmental temperature of Venus. Also considered are the ground based station capability and a highly preliminary design for a simple continuous wave (C.W.) repeater. The designs of telemetry systems and other atmospheric measuring devices are not considered. Areas where certain technological advances are required or where critical design data are unknown are isolated and discussed. The remainder of the section is broken into major system subsections and supporting technological subsections.

4.3 UP-LINK REQUIREMENTS

The complexity or simplicity of a radio repeater is primarily controlled by the signal strength that can be delivered to its receiving antenna. In its simplest form the repeater is a passive reflector, but because the signal strength returned to the observer decreases by the reciprocal of the 4th power of distance, it is often impractical to use such a simple repeater. An active radio repeater, on the other hand, is broken into two independent paths such that the path loss increases only as the 2nd power of distance, and active amplification is introduced in the center of the link. The up-link portion of the system turns out to be the most demanding half of the loop for a simple C.W. repeater.

The up-link difficulties are partially caused by a strong desire to keep the system simple. The electronics and servomotors required in pointing a high gain antenna system seem unnecessarily complicated; therefore, a simple omnidirectional antenna appears to be the only choice. Also, the up-link receiver cannot be designed with the low noise technology used in the ground stations. The effective receiver temperature may be as high as $10,000^{\circ}K$. A further limitation is imposed by the stability of any local oscillator that may be required in the receiver. That is, wider bandwidths may be required in the receiver system in order to tolerate the long term drifts of the local oscillators.

The feasibility of the repeater and its ability to meet the science objectives are highly dependent upon the signal to noise ratio that can be achieved prior to the final frequency conversion. The spectral purity of the retransmitted signal depends upon the signal to noise ratio, and this is ultimately dependent upon the stability of the various local oscillators. Therefore, we approach the problem in reverse and ask what signal to noise ratio is required and what stability does it imply.

The receiving antenna of the repeater is assumed to be a simple crossed dipole device with gain between 1 and 2 depending upon its orientation. The power received by such an antenna is given by Eq. (1),

$$P_R = \frac{P_T\ G_T\ A_R}{4\pi\ D^2} \quad \text{watts,} \tag{1}$$

where

P_T is the power transmitted in watts;

G_T is the antenna gain of the transmitting antenna relative to an isotropic radiator;

A_R is the effective collecting area of the receiving antenna in meters squared;

D is the path distance in meters.

D varies from 0.3 to 1.7 A.U. for Venus. Since it might be desirable to use the repeater at all times, both limits are considered in Table 4-1. Table 4-1 shows the critical parameters of the up-link transmission path for several ground based transmitting facilities. The Arecibo radar at S-Band can deliver the largest flux density to the surface of Venus and would be ideal for Doppler frequency measurements if the tracking time were not so short. The Goldstone radar at X-Band is next best, however, the collecting area of an omnidirectional receiving antenna is very small, and an X-Band receiver is more difficult to design. Also, atmospheric absorption will decrease the signal strength greatly as the path length through the atmosphere increases. The power density of the Goldstone S-Band system is only a factor of 10 smaller than the Arecibo system and if the receiver bandwidth can be reduced, either system could be used.

Table 4-1 also contains a few parameters not shown explicitly in Eq. (1). These are A_L and η. A_L is the atmospheric absorption loss which is about 4 db at X-Band for a direct path through the atmosphere. η is a transmitter efficiency factor which is near unity except for the B-Band radar at Arecibo.

Table 4-1 also shows the effective receiving area for a 1/2 wave dipole antenna at each wavelength. W_{R1} and W_{R2} are the power densities deliverable to the surface of Venus from each transmitter system for the nearest and farthest distance respectively. P_1 and P_2 are the

Table 4-1. Up-link Power Densities, Received Power, and Signal to Noise Ratios f
Station Configurations. The receiver antenna is a one hemisphere omn
with gain of a halfwave dipole.

Uplink Band	Arecibo (S-Band)	Arecibo (B-Band)	Goldstone (S-Band)
P_t, watts	400×10^{3}	125×10^{3}	400×10^{3}
G_t, dB	72.0	61.2	62.1
A_L, dB	0.0	0.0	0.0
η	1.0	0.7	1.0
W_{R1}, watts/m^2	2.5×10^{-10}	4.5×10^{-12}	2.5×10^{-11}
W_{R2}, watts/m^2	7.8×10^{-12}	1.4×10^{-13}	7.8×10^{-13}
A_R, m^2	2.0×10^{-3}	6.4×10^{-2}	2.0×10^{-3}
P_1, watts	5.1×10^{-13}	2.9×10^{-13}	5.0×10^{-14}
P_2, watts	1.6×10^{-14}	8.9×10^{-15}	1.6×10^{-15}
G_R	halfwave dipole		

actual power received by the dipole antenna assuming W_{R1} and W_{R2} for power densities. The values of P show that the Arecibo B-Band system is not much worse than the S-Band system in this application. A B-Band receiver would be much easier to design, and therefore this route should not be overlooked. The Arecibo B-Band system operates at 430 MHz (λ = 70 cm) and is ideal for the vacuum tube technology being considered for the receiver.

The signal to noise ratio at the receiver depends upon the effective noise temperature of the receiver and the bandwidth that may be required to handle unknowns in location of the probe and various drifts in the local oscillators. The maximum Doppler drift as a function of planet position is 1/2 the usual limb to limb Doppler dispersion encountered in the radar broadening. This is less than 150 Hz at S-Band and would suggest a passband of $\pm$75 Hz from the center frequency. The long term drift of a crystal oscillator is probably greater than this, although little is known about the long term stability of quartz crystals at such elevated temperatures. At room temperature the long term stability of good quartz crystal oscillators is in the order of a few parts in 10^{10} per day. This would correspond to a few tenths of a Hertz per day at S-Band. Here again only a fairly small bandwidth is required if the operational life-time is on the order of a year or two. It is not expected that a quartz crystal operating at 450°C will have a stability that comes close to those of crystals operating near room temperature. Therefore, the signal to noise ratio that may be achieved depends upon the receiver design and any tricks that can be used to provide immunity to drifts in the local oscillators. The next section considers a few simple receivers that are immune to drifts in the local oscillators.

In order to get some feel for the P_1 and P_2 values of Table 4-1, one may consider a typical vacuum tube receiver having an expective input temperature of 10,000°K and a bandwidth of 10^4 Hertz. The effective noise power is given by P_N = k TB where k is Boltzmann's constant (1.38 x 10^{-23} watts/°K). The noise power is then about 1.38 x 10^{-15} watts and provides reasonable signal to noise ratios for some of the received powers shown in Table 4-1.

If the repeater is not to expend its transmitting power on noise, it is clear that some improvement is necessary if the repeater is to be used at the greatest distance with the Goldstone Antenna System at S-Band.

4.4 DOWN-LINK REQUIREMENTS

The basic downlink requirement is only that an adequate signal to noise ratio be present at the ground station to permit high resolution spectral analysis. Since the broadening of the spectral line is known to be less than 0.01 Hz from previous radar observations, we can presume that the predetection bandwidth of 0.01 Hz is entirely possible and design the transmitter for adequate detectability. Again the power received by the ground station is given by Eq. (1) where P_T is the transmitted power from the lander, G_T its antenna gain, and A_R is the collecting area of the ground station. If we presume a 1 watt transmitter and the receiver temperatures as tabulated, the resulting signal to noise ratios are shown for inferior and superior conjunctions of the planet for each receiving station. Obviously there is no problem in detecting the signal, and transmitter power requirement could be relaxed. Bistatic operation is clearly possible, for example, it would be desirable for the Arecibo radar to transmit and Goldstone radar to receive in order to obtain a continuous 2.5 hour C.W. data span for high spectral resolution. Larger continuous time spans are possible if the Goldstone antennas are used in a bistatic system. A smaller antenna (26 m diameter) would be adequate on the downlink.

4.5 HIGH RESOLUTION RANGING

The previous section considered the design of a simple CW repeater or transponder. Although valuable scientific objectives can be met with such a device, the ability to repeat a wideband signal has a definite advantage in that high resolution ranging becomes possible. Present day transponders designed for deep space ranging utilize bandwidths as large as several megahertz. Therefore, consider a modified transponder for Venus having a bandwidth of about 2 MHz. The wider bandwidth has the advantage that it simplifies the design of the I.F. amplifiers and relaxes the stability required of the passive components.

In the simple C.W. repeater, the design was such as to attempt to maintain a sufficiently high signal to noise ratio so as to devote most of the transmitter's power to sending the signal rather than the noise. This was accomplished by making the IF bandwidth narrow enough to reject most of the noise power; however, it is not necessary to do so. The signal to noise ratio is so good on the down link that the transmitter power could be reduced by a factor of 10^3, therefore, the transmitter could just as well transmit 0.999 watts of noise and 1 milliwatt of signal (see Table 4-2). Calculation of the uplink signal to noise ratio for a bandwidth of 2 MHz, and a receiver temperature of 10^4 degrees K can be found by using the parameters in Table 4-1. The noise power, kTB, is 2.76×10^{-13} watts. Thus the noise power is about one half of the signal power obtained by using the Arecibo system at S-Band when Venus is close. The worst case to be considered might be to use the Goldstone system at S-Band with Venus at the greatest distance. The signal to noise ratio would be 0.0058, and would mean that about 5.8 milliwatts of signal power would be radiated. The question of which part of the loop controls the final signal to noise density can now be determined. Since both paths contain the same distance, the only consideration is the quantity $(P_T\ G_T\ A_R)/T_R$ for each path. In this case, because the narrow bandwidth of the ground station is not being considered, the up link signal to noise density is much greater than that of the downlink. Then, from the standpoint of analysis, it is only necessary to consider the experiment as a 5 milliwatt transmitter sending to the ground station, i,e., the uplink noise density contribution can be ignored.

At this point it is necessary to consider the range encoding and decoding process. Whatever system is used, it is essential that it does not eliminate all of the carrier component. Some part of the carrier is required to operate the phase-locked-loop in order to effect

Table 4-2. Downlink Detectability for a 1 watt Transmitter with a 0.01 Hz Bandwidth for Distances of 0.3 and 1.7 AU and Four Different Receiving Configurations on Earth

Uplink Band	Arecibo (S-Band)	Arecibo (B-Band)	Goldstone (S-Band)	Goldstone (X-Band)
P_T, watts	1	1	1	1
G_T	2	2	2	2
A_R, m^2	1.97×10^4	3.8×10^4	2.0×10^3	1.8×10^3
A_L	0.0	0.0	0.0	2.5 (4.0 dB)
P_1, watts	1.55×10^{-18}	2.99×10^{-18}	1.57×10^{-19}	5.66×10^{-20}
P_2, watts	4.82×10^{-20}	9.93×10^{-20}	4.89×10^{-21}	1.76×10^{-21}
T_R, °K	60	100	25	50
S/N1	1.87×10^5	2.17×10^5	4.55×10^4	8.20×10^3
S/N2	5.82×10^3	7.20×10^3	1.42×10^3	2.55×10^2

the phase coherent frequency translation. Carrier can be assured by maintaining the shift less than $\pm 90°$ for code sequence. A pseudo random code or a sequence of square wave codes can be used to resolve the range ambiguity associated with a periodic code sequence. The original C.W. carrier is re-established at the ground station by multiplying the incoming signal by its complex conjugate delayed by incremental time steps. Spectral analysis of samples from each range or time gate establishes the doppler frequency. Since this process is a matched filter, no signal energy is lost, and the detectability is no different than that of the C.W. case except that the transponder sends only a small portion of its total power as signal. The choice of Doppler resolution can be made after-the-fact if the time series data are recorded. Therefore, an observing period T_0 seconds long can be divided into a set of coherent spans T_B seconds long where $T_0 \geq N\ T_B$. The reciprocal of T_B defines the Doppler resolution, B, in Hertz. The signal to noise ratio can be found from the signal power ratio to noise fluctuation ratio for N experiments as follows.

$$P_R = \frac{P_T\ G_T\ A_R}{4\pi\ D_p^2} \tag{2}$$

$$\Delta P_N = k\ T_R\ B/\sqrt{N} = k\ T_R/\sqrt{T_B\ T_0} \tag{3}$$

$$\frac{S}{\Delta N} = \frac{P_R}{\Delta P_N} = \frac{P_T\ G_T\ A_R\ \sqrt{T_B\ T_0}}{4\pi\ D_p^2\ k\ T_R} \tag{4}$$

where

P_R is the power received at the ground station

P_T is the signal power transmitted by the transponder

A_R is the effective collecting area of the ground station

D_P is the distance to Venus

k is Boltzmann's constant

T_R is the effective temperature of the ground station receiver system

T_0 is the total observation time span

T_B is the coherent time span for frequency analysis

The signal to noise fluctuation ratio, $S/\Delta N$, can be computed assuming the worst case situation where 5 milliwatts of transmitting power is sent to the 64 m Goldstone antenna at S-Band with Venus at its greatest distance. This gives

$$\frac{S}{\Delta N} = \frac{5 \times 10^{-3}\ 1.61\ 2 \times 10^{3}}{4\pi\ (2.55 \times 10^{11})^{2}\ 1.38 \times 10^{-23}\ 20} \sqrt{T_B\ T_0}$$

$$= 7.138 \times 10^{-2} \sqrt{T_B\ T_0}$$

If T_0 equals T_B, one spectrum of length T_0 yields the largest signal to noise ratio. If T_0 is 100 seconds a signal to noise ratio of 7.138 will result. It is already known that a 0.01 Hz resolution bandwidth is possible on Venus, so no difficulty exists in obtaining this signal to noise ratio. The 2 MHz bandwidth assumed in calculating the signal portion of transponder power permits a range baud in the order of a microsecond. If the range gate decoders are spaced at smaller intervals than the baud (over sampling), model fitting can be used to determine the range to higher resolution. In practice a factor of ten is not too difficult to obtain if the signal to noise ratio is greater than 10 to 20. Similar transponders achieve accuracies on the order of 20 to 30 nanoseconds by model fitting. This corresponds to about 3 or 4 meters in distance. As a result, both high resolution range and Doppler measurements are possible. It would appear that if no atmospheric limitations are found, ranging accuracies on the order of 20 nanoseconds and Doppler accuracies on the order of 5×10^{-5} Hz are possible. This range accuracy is on the order of 20 to 50 times better than what is presently done by ground based radar. The Doppler resolution is about a factor of 200 to 600 better than present ground based resolution on Venus.

4.6 SIMPLE RADIO REPEATERS

An ideal radio repeater would produce an exact phase coherent copy of the incoming signal translated in frequency. The design of such a repeater is generally not possible due to frequency drifts and phase fluctuations of various local oscillators used in the heterodyne process required to effect the frequency translation. Phase coherence can be achieved by phase locking the master oscillator or clock to the incoming signal. The frequency translation is then in an exact ratio of the incoming signal, but phase jitter will remain and appears as a spectral broadening of the repeated frequency. In a properly designed phase lock receiver the phase noise or jitter can generally be held approximately to that inherent in the master oscillator or clock. The master oscillator is presumed to be voltage controllable such that a feedback signal from a phase comparator can force the frequency to be exactly that required to maintain phase lock. Such systems are called phase locked loops (PLL's). Under conditions of high signal to noise ratio, an ideal first order PLL has a variance of the phase noise given by

$$\sigma_\phi^2 = \frac{N_0 \, B_L}{A^2} \tag{5}$$

where N_0 is the spectral density of the assumed white noise, B_L is the loop bandwidth, and A is the amplitude of the sinusoidal input signal (Ref. 4-2). If both the incoming signal and the oscillator being locked are stable, B_L may be made as narrow as desired, however, phase noise on either the incoming signal or the local oscillator require B_L to be on the order of the bandwidth of the incoming signal or the bandwidth of the local oscillator whichever is the largest.

Phase jitter in the incoming signal may be caused by the atmospheric turbulence and is one of the quantities to be measured. Phase noise inherent in the master oscillator can be thought of as a contamination signal applied to an ideal master oscillator. The design goal hopefully would be to make the phase noise of the master oscillator significantly smaller than that produced by the turbulence. The loop bandwidth, B_L, would have to be determined automatically, since the spectral spreading caused by the turbulence is an a priori unknown and presumably variable. The signal to noise ratio is also variable.

The question of whether or not an adequate master oscillator or clock can be designed to operate at 750°K is perhaps one of the least well answered questions of this study and is one of the primary areas requiring research. It would seem unlikely that any of the complicated atomic frequency references could be made to operate at 750°K without a massive research effort. Simplicity of design is also a paramount factor for any system exposed to new and difficult environments. The simplicity of the quartz crystal oscillator seems ideally suited to this application if adequate stability can be achieved. Unfortunately, little is known about the operation of quartz crystal oscillators at high temperatures. Quartz crystals change from α to β quartz at 543°C; this is sufficiently above the Venusian ambient temperature that no problem is expected. Another property of quartz called "twinning" also renders the crystal inoperative if the rate of temperature increase is greater than about 50°C per minute. Again such rapid temperature changes are not expected. The question of what long term stability and what short term phase noise may be expected at 750°K is not known. The temperature sensitivity is expected to be in the order of 1 part in 10^5 per degree centigrade. This is sufficiently poor that the bandwidth of the receiver may have to be as broad as 50 kHz just to contain the drifts due to temperature. Fortunately, the temperature variation at the surface of Venus is believed to be fairly stable, perhaps as small as a few degrees centigrade. This still would cause rather large drifts in frequency, and if the local oscillator can be made no better than this, severe difficulties exist in designing phase locked loops capable of frequency tracking while maintaining high spectral purity.

Receivers can be designed to be relatively immune to the drifts in the local oscillators. There are certain drawbacks to each design, however, the use of a combination of several techniques may give an adequate design.

Figure 4-1a shows a simple superheterodyne receiver which converts the incoming signal to a lower intermediate frequency where it is filtered. The signal is then converted up to the original signal frequency by the same local oscillator. The major difficulty of this design is obtaining adequate isolation from the input to output so as to prevent feedback. An oscillation path exists through the local oscillator as well. The main advantage of this procedure is that all drifts and phase noise inherent in the local oscillator are cancelled out in the second conversion mixer as long as the bandwidth of the first IF amplifier is wide enough to pass the spectrum of the local oscillator. This procedure can be applied to double and triple conversion systems.

A simple repeater can be formed by following the amplifier with a frequency multiplier, as shown in Figure 4-1b. A square law device followed by an amplifier tuned to two times f_1 is all that is required. The signal to noise ratio of the output signal remains the same as the input signal in the high signal to noise case. Thus, there is no significant reduction of the signal to noise ratio in such a transponder, and its main drawback is the large isolation required to prevent feedback.

In order to prevent internal feedback it is advantageous to obtain the required amplification at several different frequencies and not convert up to the original signal frequency. This can be accomplished by a phase locked offset oscillator that generates an apparent local oscillator at a frequency of $f_0 + f_1/n$ as shown in Figure 4-2. As n is made large the output frequency, f_3, approaches f_1 making it more difficult for the R.F. amplifiers to separate the upper and lower sidebands following mixers 2 and 3. The advantage is that the spectral width of the offset oscillator decreases as 1/n at the VCO. If phase lock is obtained, the phase differences at the comparator must be less than $\pm 90°$. The phase variation of the VCO must be less by a ratio of 1/n, and that phase noise is reflected directly at the output. The system shown in Figure 4-2 is also immune to variations in the free-running local oscillator provided that the heterodyned signal from Mixer 1 does not drift out of the IF amplifier passband.

Given an adequately stable local oscillator, it should be possible to design a full phase locked receiver. In such a receiver a voltage controlled master oscillator is used to drive a phase locked frequency synthesizer which generates all local oscillator frequencies and the offset reference frequency. The analysis of such a system is beyond the scope of this initial study, but most likely is the form of repeater that will be required. Again it is possible to design all conversion stages such that the phase noise cancels except where offset frequencies are generated.

4.7 THERMIONIC ACTIVE DEVICES

The need for high temperature electronic devices has been apparent ever since the first germanium transistors appeared on the market in the late 1950's. The thermal instability of these devices completely changed electronic design procedures in a few short years. The wider energy band gap of silicon soon offered a solution to operation up to about 200°C, however, applications in space and geophysics existed for devices operating at even higher environmental temperature. Attempts to produce semiconductors with higher band gap energies than silicon have not been very successful, and the amount of effort required to advance this technology appears to be fairly large.

Because of the difficulties in the area of high temperature semiconductors, one is soon driven to consider what can be done with the highly developed thermionic devices of the late 1950's. In particular specification sheets appeared from General Electric Company advertising small ceramic triodes designed to operate at the cathode temperature of 750°C. These devices have been used in industry to handle a number of high temperature instrumentation applications. The original intent of the manufacturer was directed more toward UHF radio applications where very close spaced planar elements were required to reach frequencies up to X-Band.

The only major drawback of these triodes is the energy required to increase the cathode temperature from the Venusian ambient of 750°K to the temperature required for proper operation of the thermionic cathode which is near 1000°K. Lower cathode temperatures greatly reduce the cathode current density. The current density generated by a thermionic cathode is given by

$$J = 120 \times 10^4 \, T^2 \, \ell^{-11,600 \, Ew/T} \; \text{amps/m}^2 \qquad (6)$$

where Ew is the work function of the cathode (Ref. 4-3). These ceramic triodes employ an oxide cathode having a work function of about 1.0 e.v. Operation of the cathode at 750°K would reduce the available current density by nearly a factor of 100, and proper space charge limited operation would not be possible. The power required to raise the cathode to 1000°K from room temperature is about 1.5 watt. Approximately 1.03 watts would be required to raise the temperature from 750°K to 1000°K if the heat losses are primarily radiative. The high ambient temperature of the surface of Venus is not a great help unless a cathode of lower work function can be manufactured.

More recently, McCormick and others at Los Alamos Laboratory have developed integrated thermionic circuits, ITC's, by extending earlier work by Geppert, Dore, and Mueller at Stanford which was reported in 1969 and 1971 (Refs. 4-4 ... 4-6). These circuits are produced by a photolithographic process much in the same manner as the semiconductor integrated circuits. A cathode and grid structure is deposited on a sapphire substrate in an interlaced zig-zag geometry. A second anode structure is supported above the cathode-grid structure by separators, and the region between is evacuated. The sapphire substrate is operated at a temperature between 650° and 750°C. Experimental line drivers and thermocouple amplifiers have been designed using this technology for applications in geothermal energy exploration. The present research is aimed at developing an adequate package and socket system for the ITC's. It appears these devices will be very useful for low frequency applications such as phase-locked-loops and active filter elements that may be required in the repeaters or especially for instrumentation associated with weather sensors and telemetry amplifiers.

4.8 LANDER POWER SYSTEM

The design of a high temperature power system is not without some problems, however, it is presently believed that adequate information is available to design a power system that could remain operative for several years. The heart of the system is a small fused-salt battery pack designed to supply the plate supply voltage for the ceramic button triodes, integrated thermionic circuits, and heater power if necessary. The batteries can be fairly small in weight as experimental versions of many fused-salt batteries have provided in excess of 200 watt-hours/kg. Most of these batteries act as secondary cells and are rechargeable several thousand times. It is conceivable that a precharged pack of adequate size could run a repeater for several months without recharging, however, a much smaller battery pack would be possible if a recharging system were available.

4.8.1 Wind Power

The only natural power source on Venus that may be capable of providing adequate power is a windmill. The wind velocity near the surface of Venus is known to be small (less than a few meters per second). A fairly large windmill would be required to generate more than a few watts. The windmill could be coupled to a generator which has multiple windings to permit generation of both plate voltages and heater voltage if required. The problems of designing a high temperature dc to dc power converter is avoided in this way. No serious problem is expected in designing a high temperature generator. General Electric Company has had motors in operation inside the cores of nuclear reactors for at least ten years. These motors operate at temperatures in excess of 500°C. The only problem is the wind or lack of it.

4.8.2 RTG Power Sources

An alternate possibility for an electrical power source is to use radio isotopes to generate a temperature higher than the Venusian ambient temperature. Radioisotope thermoelectric generators (RTG's) have been built in the 25 watt size for use in a room temperature environment. These generators require a temperature difference between a pair of electrical junctions and have a theoretical efficiency limited by some percentage of the Carnot efficiency. A device designed to operate at room temperature would be less efficient with the low temperature sink operating in the Venusian environment. Thermal generators have a distinct advantage, however, if the high temperature heat source can be coupled directly to the thermionic devices used in the radio repeater. This would reduce the electric power requirement to that needed only by plate supply which is expected to require less than 30% of the total power requirement. It may be that radioisotope heaters can be designed separately for each of the thermionic cathode sources rather than attempting to share the heat from the master power source.

Presently the high temperature side of the RTG's operates near 1000°C. This temperature is a little high for thermionic emission with the low work function cathodes but may be too low for efficient electric power generation in the Venusian atmosphere at 750°K. The design of an efficient power system for the repeater represents an area where some research will be required to optimize the use and forms of energy with respect to mass and size.

4.8.3 Fused Salt Batteries

The fused-salt battery technology is somewhat newer with major research beginning in the late 1960's. Many combinations of materials have been tested, and some operate in the temperature range of interest. Unfortunately the majority of the research and development has been concerned with the lower temperature batteries, but many of the techniques for keeping the liquid electrodes in place and solidifying the electrolite appear to be applicable to the higher temperature cells. One of the most well developed types of fused-salt batteries employs lithium-sulphur or the sodium-sulphur electrodes operating near 300°C. Experimental batteries of the same composition have been reported operating to temperatures of 470°C by workers at General Electric Company (Ref. 4-7). These batteries are reported to have energy densities over 200 wh/kg making them very attractive with respect to weight. It is not clear that the developmental batteries can be operated at higher temperatures. Increased temperature causes greater activity of the highly corrosive electrodes which could cause deterioration of the separators and seals.

The next most promising battery has a lower energy density (79 wh/kg) and employs a lithium-silicon negative electrode and an iron sulfide positive electrode (Ref. 4-7). This cell operates between 400°C to 450°C making it ideal for this application (Ref. 4-8, 4-9). Developmental batteries are being tested by Atomic International Division of Rockwell International. These batteries are of the 150 to 200 wh capacity and have been cycled 200 times from full charge to discharge. The major limitation in lifetime is caused by corrosion of the negative electrode and the hermetically sealed can. This corrosion can be almost entirely eliminated by use of more expensive materials such as molybdenum or titanium (Ref. 4-10). The lifetime of these modified batteries is unknown and no testing program has been started. Earlier experimental batteries which have been reported by Sudar, Heredy, Hall, and McCoy have survived 2500 discharge cycles with less than 20% loss in capacity. The use of the more exotic metals in the negative electrode and enclosure would most likely yield cells that could approach the life of the experimental cells and might easily operate for several years in the Venusian environment.

4.9 ENERGY BUDGET

The total energy budget of a simple repeater based on thermionic devices heated directly by radioisotope sources and electrically powered by an RTG can be estimated by considering the number of active components that may be required to realize a simple repeater. The total weight of the repeater is also of interest but is more difficult to estimate accurately. The data presented here are only intended as a rough guess based on crude ideas about the energy requirements of presently available components.

For most applications at radio frequencies and intermediate amplifier frequencies two triode devices connected in a cascode configuration may be required to eliminate the need of neutralization of plate

Table 4-3. Power Budget for a Quadra-Conversion Phase-Locked Receiver Using Standard Ceramic Triodes and ITC's

Section	Stages	Triodes	Heater Power, W	Plate Power, W
RF Amplifier	2	4	4	2.0
Mixer 1	1	2	2	0.5
IF Amplifier 1	1	2	2	1.0
Mixer 2	1	2	2	0.5
IF Amplifier 2	1	2	2	1.0
Mixer 3	1	2	2	0.5
IF Amplifier 3	1	2	2	1.0
Mixer 4	1	2	2	0.5
IF Amplifier 4	2	4	4	2.0
Mixer 5	1	2	2	0.5
IF Amplifier 5	1	2	2	1.0
Mixer 6	1	2	2	0.5
IF Amplifier 6	1	2	2	1.0
Mixer 7	1	2	2	0.5
IF Amplifier 7	1	2	2	1.0
Mixer 8	1	2	2	0.5
IF Amplifier 8	1	2	2	1.0
Offset Mixer	1	2	2	0.5
AGC Amplifier ITC	Multi	Multi	10	2.0
PLL - ITC	Multi	Multi	10	2.0
PLL Mixer	1	2	2	0.5
L.O. Synthesizer	20	20	20	10.0
Transmitter Driver	1	2	2	1.0
Transmitter P.A.	1	2	2	2.5
Totals			86	33.5

to grid feedback. The receiver is assumed to have four stages of frequency conversion both down and back up with a phase locked offset. The local oscillators are synthesized from a single crystal clock that is locked to the incoming signal.

The power totals give 86 w of heat required for the cathodes. If this is supplied by Plutonium 238 about 172 grams are required. The 33.5 watts of plate supply must be delivered at electrical power and suffers from the conversion efficiency of the RTG's which may be on the order of 8%. A 150 watt RTG on Voyager weighed about 83 lbs. A rough estimate of the weight of the plate power unit would be found from a proportional scaling. This gives about 18.5 lbs.

The initial hope was to be able to constrain the entire package to 10 kg. The simple approach taken here indicates that this will require some careful design to lower the energy requirements. Several possibilities exist. First the triode amplifiers could be designed much smaller as they do not have to operate at the power levels of the ones available. Second, the inner stages of the intermediate amplifiers and mixers could be designed as an ITC. The standard ITC heater package requiring 10 watts should be redesigned to be more efficient. These changes could easily reduce the power requirements by a factor of ten and thereby reduce the weight requirement almost proportionally.

4.10 LANDER ANTENNA SYSTEM

In order to be able to track the lander over a full semi-rotation of Venus as viewed from the earth, a broad pattern antenna is desirable. An antenna with uniform gain in one hemisphere would be ideal, however, since the orientation of the polarization vector would be unknown it is desirable that the antenna be circularly polarized. Such an antenna is not physically realizable, so some compromise will have to be made. A pair of crossed dipoles above a suitable ground plane can be designed to give an adequate pattern, however, the polarization characteristic off-axis becomes linear. Also the ground plane cannot be infinite in size, so a uniform coverage to low angles is not possible.

Certain slot radiators on a metallic surface are also possible and may have mechanical advantages, however, electrically they should not be greatly different in pattern if the size is kept restricted to a wavelength or less. For the purposes of this study we have assumed that an adequate compromise is possible and that the on axis gain is 2. As the polarization changes to linear going off-axis, only half of the transmitted circularly polarized wave is coupled, and the apparent gain approaches one.

The design of an adequate antenna system for this lander involves the determination of the required ground plane size and location to obtain low angle coverage for both the receiving and transmitting antennas. These most likely will be stacked vertically unless the slot type radiator is found to be desirable.

4.11 CONCLUSIONS

The advances in technology in the areas of high temperature electronics and power systems have progressed to the level that the design of a survivable lander for Venus should be considered. Progress in fused-salt batteries and RTG power sources capable of operating at 450°C has been such that the required power sources could be designed now. Adequate high frequency vacuum tube technology presently exists, and the addition of radioisotope heaters to these devices does not appear to be a particularly difficult problem. Integrated thermionic circuits have been developed to the point that the details of adequate packaging are under study, and the designs for specific devices are being simulated. Commercial ITC's will most likely be available in two years. Passive components for use with ITC's are presently being tested and appear to have stabilities of about 1 part in 10^4. This stability is adequate for most applications except for very narrow band filter designs. The major unknown presently is the stability that can be achieved by various local oscillators that are required to effect the frequency translation. Variable reactance controlled quartz crystal oscillators appear to be the simplest type of design for use as VCOs in phase locked loops. Unfortunately, little is known about the stability and phase noise of quartz controlled oscillators at 450°C. This then is an area requiring immediate investigation.

The power requirements for a simple repeater are not very large. The addition of other instrumentation could increase the power requirements significantly unless most of the instrumentation amplifiers, multiplexers, encoders, and modulators utilize specially designed ITCs. The power requirements for thermionic devices are significantly larger then those of present day transistor devices, and every effort should be made to keep the electronics as simple as possible and the energy budget as small as possible.

Although technology adequate to implement a survivable lander for Venus either exists or is under development, few components can be purchased off the shelf that are adequate for a final design. For example, the vacuum tubes having externally heated cathodes are no longer manufactured. The coupling of radioisotope heaters to these devices quite possibly has never been tried, and information concerning the lifetime of irradiated cathodes is unknown. Therefore, several years of testing the various components will be required to gain experience related to the efficient design and measurement of reliability of many of the components.

Information that such a radio repeater and environmental monitoring system can provide is needed now for the design of future radio science experiments for Venus. Unfortunately it is already late for this system to provide data for missions that are already planned or in the design phase. Irrespective of this, the design of a simple radio repeater for Venus will provide the engineering and technological data base required for more ambitious projects in the future. Data from the repeater will provide vital information pertaining to the ultimate radio "seeing" through the dense atmosphere as well as more refined measurements of the rotation rate and direction of the pole. Ultimately, if the seeing is adequate and the stability of the radio repeater adequate, the measurement of crustal motion may be possible if a number of repeaters are placed on the surface.

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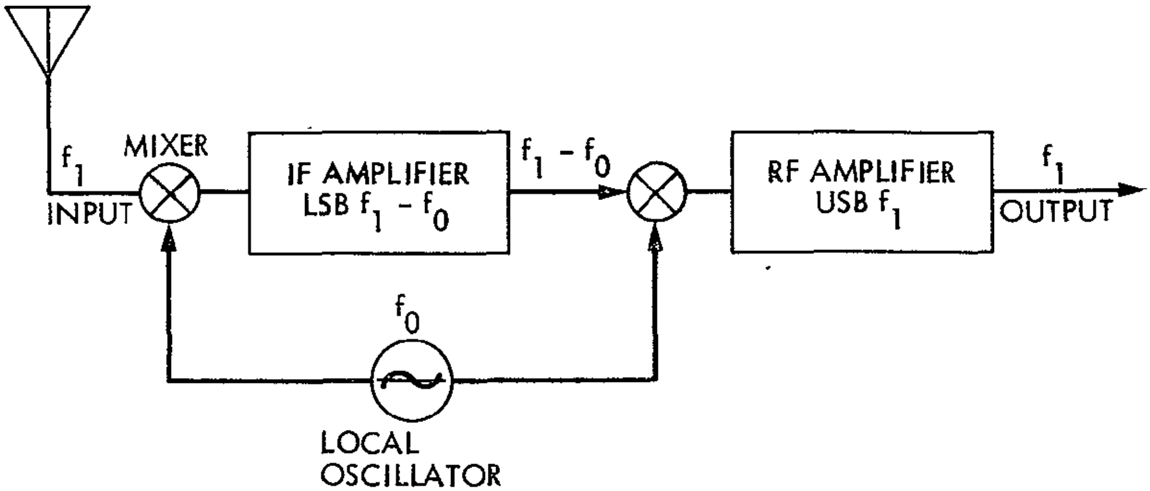

Figure 4-1a. Narrow Band Amplifier That Is Independent of Drifts and Phase Noise in the Local Oscillator.

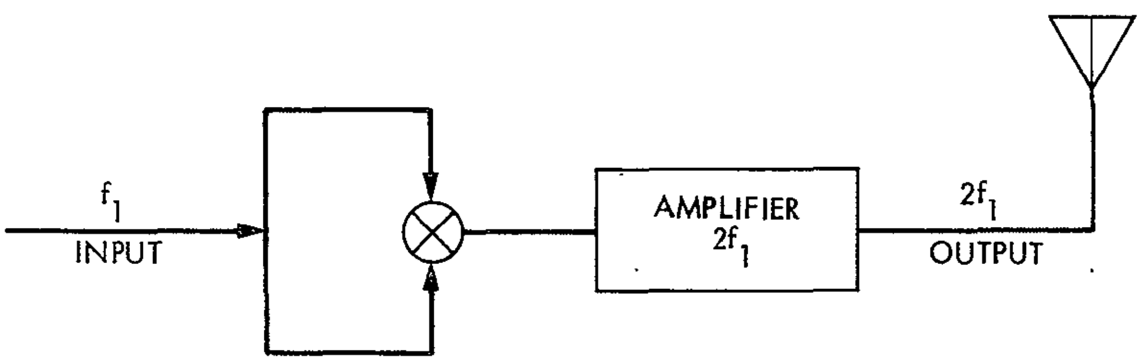

Figure 4-1b. Simple Frequency Doubler To Follow the Amplifier of Figure 4-1a. Note that modulating processes are modified by this system.

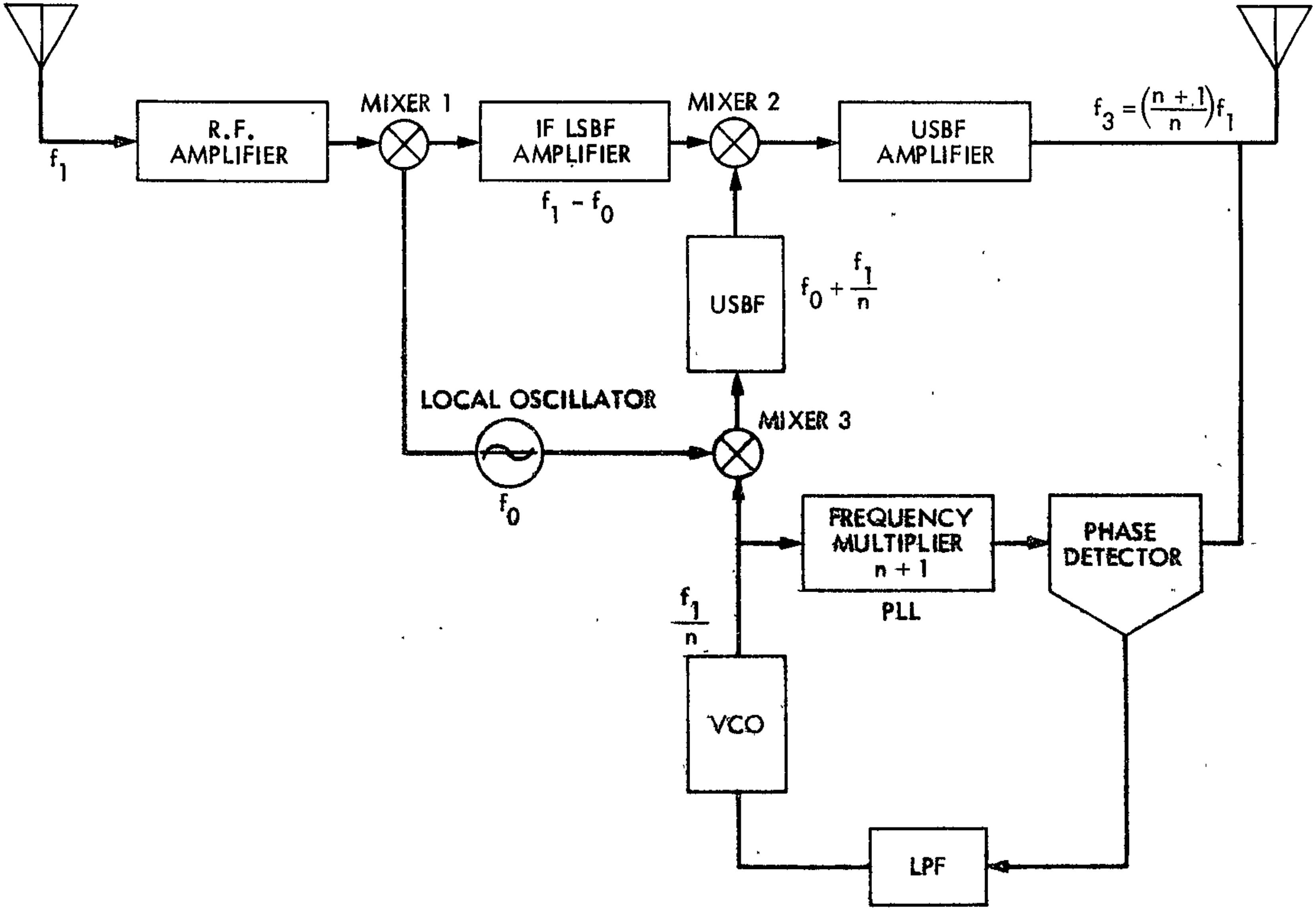

Figure 4-2. Phase Locked Repeater That Generates an Offset Frequency $\frac{n+1}{n} f_1$ with Immunity to the Phase Noise of the Local Oscillator

SECTION 5

STRUCTURAL ANALYSIS

5.1 INTRODUCTION

This section is a description of several possible configurations for octahedral benchmarks for various applications. Lenticular welded beams are used in a preliminary design for a deployable 2-meter benchmark weighing about 10 kg and estimates of entry and deployment equipment are obtained. It was found that a 10-meter benchmark for Venus will weigh a minimum of about 200 kg without accounting for delivery and anchoring equipment. A minimum estimate for a delivered 10-meter reflector is about 300 to 500 kg. Furthermore, such a device would require development of astromast and deployment equipment technology similar to that required for square solar sail deployment. A technique of fixing a 2-meter benchmark to the top of a lander has been worked out and estimates of the mass of very large (100-200 meter) retroreflectors have been obtained for possible deep-space applications.

Configurations were developed for a 2-meter and 10-meter corner radar retroreflectors to be deployed on the surface of Venus. The basic concept is an eight cell array of tetrahedral corner reflectors arranged such that incoming radar from any direction will be reflected toward its source. This arrangement is achieved with twelve 45° right triangular wire mesh planes stretched between six compression members as depicted in Figure 5-1. The maximum deflection of the planes allowable from wind forces and gravity is 2° from being at right angles to each other. The Venusian environment assumed for design and analysis has the following parameters (Reference 5-1):

Temperature	755°K
Atmospheric density	65 kg/m^3
Atmospheric composition	CO_2
Maximum wind velocity	3.5 m/sec

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Drag coefficient of round wire normal to wind	1.2
Gravity field	Earth normal, 1 g

5.2 2 METER VENUS BENCHMARK

The 2 meter Venus Benchmark is fairly simple in design and deployment (see Figure 5-2). The compression members are lenticular welded beams which can be flattened and rolled up. When released, they will deploy under their own stored tension and unroll to become rigid beams (see Figure 5-3). In the Benchmark's collapsed configuration, the lenticular welded beams are flattened and rolled up in a spiral with the mesh accordion folded in between them. The rolled up beams and mesh are constrained in this shape by two ring shaped bands. At the desired time of deployment, the two bands are released in sequence (perhaps by pyrotechnic devices set to detonate at a preset atmospheric pressure or temperature) allowing the beams to deploy somewhat violently under their own stored tension. The deployment is very similar to the Lockhead Wrapped Rib Parabolic Antenna.

In the structural analysis, the equation for deflection of each wire in the mesh is (Reference 5-2):

$$\delta = \ell\left(\frac{3\omega\ell}{64\ EA}\right)^{1/3}$$

where

ℓ = wire length

ω = loading on wire

E = modulus of elasticity of wire

A = cross-sectional area of wire

The horizontal component of tension in the wire is (Reference 5-2):

$$H = \frac{1}{8}\,\frac{\omega\ell^2}{\delta}$$

where δ = deflection.

The wire mesh is composed of square cells of 1.27 cm to the side. The wire mesh and the compression members are assumed to be composed of titanium 6Al-4V with the following material properties at 755°K (Reference 5-1):

$$E = 7.53 \times 10^6 \text{ newtons/cm}^2$$

$$\sigma_{allowable} = 4.14 \times 10^4 \text{ newtons/cm}^2$$

The structural wire mesh elements which take out the bending moments in the lenticular welded beam compression members were sized 0.23 mm in diameter in order to meet the 2° deflection criteria. The non-structural cross wire elements of the mesh were sized 0.025 mm in diameter. In sizing the lenticular welded beam compression members, it was found that the most severe loading was generated by impacting the Venusian surface at an assumed 3 meters/sec during touch-down. Sized for this impact load, the beams are 4.128 cm in diameter with a wall thickness of 0.89 mm. The component weights were estimated as follows:

6 lenticular welded beams (titanium)	7.3 kg + 20%; - 10%
Titanium mesh	0.45 kg ± 20%
Welding, fittings, etc.	2.25 kg ± 30%
∴ mass of corner reflector ≈ 10 kg	
Deployment mechanisms	2.3 kg ± 50%
Heatshield (Pioneer Venus Small Probe) (Reference 5-3)	11.2 kg ± 5%
Aeroshell structure (PVSP) (Reference 5-3)	13.3 kg ± 5%
Separation/despin sub-system (PVSP) (Reference 5-3)	4.2 kg ± 5%
∴ mass of entry capsule ≈ 31 kg	

Total mass of package ≈ 41 kg

The wind drag on the structure was calculated to be approximately 236 newtons giving an over-turning moment of 332 newton-meters. The weight of the benchmark is insufficient to overcome this over-turning moment, and it will tumble across the planet's surface unless anchored. An 8.6 kg weight would be sufficient for anchoring; therefore, one solution would be to keep the benchmark attached to the entry capsule's heat shield which would serve as the anchoring weight.

5.3 10 METER VENUS BENCHMARK

A 10 meter benchmark (Figure 5-4) is too large to allow the use of lenticular welded beams for the compression members, given the forces it would be subjected to on the Venusian surface. For larger structures, lenticular welded beams become inefficient due to the wall thinness required to have them be collapsible and rollable. Large, thin-walled tubes are more susceptible to local buckling.

Astromasts were considered for these large corner reflectors since they are generally the lightest and most compactly stowed deployable booms. If the structure was not heavy enough to keep it anchored in the Venusian wind, then the corner reflector could be deployed from a platform which had been anchored to the soil with some sort of active penetration device (Figure 5-5).

Complications arise in the deployment of these structures. To have the masts deploy straight out of the can instead of the usual rotating fashion requires a more complex storage cannister than typically used for astromasts (Figure 5-6). Since the reflective mesh cannot be pre-attached to the astromast while stowed, the mesh will have to attach to the deploying astromast through transfer rings (Figure 5-7) in a manner similar to that devised for the square sail. A scheme for stowage and controlled deployment of the mesh would have to be devised. The guy wires for the configuration in Figure 5-5 could be stored on ejectable reels (Figure 5-8).

A rough "order-of-magnitude" type sizing of the astromasts for an assumed 669 newton compressive force is as follows (Reference 5-4):

Astromast Diameter	--	41 cm
Astromast Weight	--	(0.75 kg/m)(10 m) = 7.5 kg
Cannister Length	--	127 cm
Cannister Diameter	--	48 cm
Cannister Weight	--	18 kg

The weight of the wire mesh would be negligible compared to the astromasts. Obtaining a weight estimate for deployment mechanisms and transfer rings is very difficult since systems like these have not been developed. Doubts arise as to the reliability of the involved deployment schemes required for large collapsible structures such as the 10 Meter Venus Benchmark.

5.4 2 METER VENERA LANDER BENCHMARK

The 2 meter benchmark using lenticular welded beams could probably be adapted as a 10 kg experiment to be deployed from a Soviet Venera class lander. The Venera would provide a massive stable platform from which to deploy a radar retroreflector (see Figure 5-9). The package could be located atop the science instrument housing cylinder which is atop the aerodynamic braking device (Reference 5-5). The benchmark package would be exposed when the parachute was jettisoned. The reflector would be deployed after the vehicle's data transmission had ceased so as not to interfere with the transmission antenna which is helically wound around the science instrument housing. A four-cell corner reflector array is depicted in Figure 5-9 in which the horizontal lenticular welded beams are stabilized on the lower end by guy wires running to the science instrument housing.

5.5 LARGE SPACE BENCHMARKS

Large space benchmarks similar in design to the 2 Meter Venus Benchmark (Figure 5-1) could conceivably be constructed. With no wind, gravity, or impact forces, lenticular welded beams hundreds of meters long might be feasible. The most severe forces on the structure would be those encountered in deployment. It is felt by Lockheed that they could build 100 meter Wrapped Rib Antennas and perhaps even larger. The surface accuracy requirements for the benchmark are not as severe as those for the parabolic antenna, so benchmarks larger than 100 meters are probably not unreasonable. A rough curve for estimating the mass of large space benchmarks is provided in Figure 5-10. This is based on estimated weight curves for deployable mesh parabolic antennas such as the Lockheed Wrapped Rib Antenna which are similar in concept to the benchmark (Reference 5-6).

REFERENCES

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5-5 Avduevskii, et al., "Automatic Stations Venera 9 and Venera 10 — Functioning of Descent Vehicles and Measurement of Atmospheric Parameters," Kosmicheskie Issledovania, Vol. 14, No. 5, pp. 655-666, September-October 1976.

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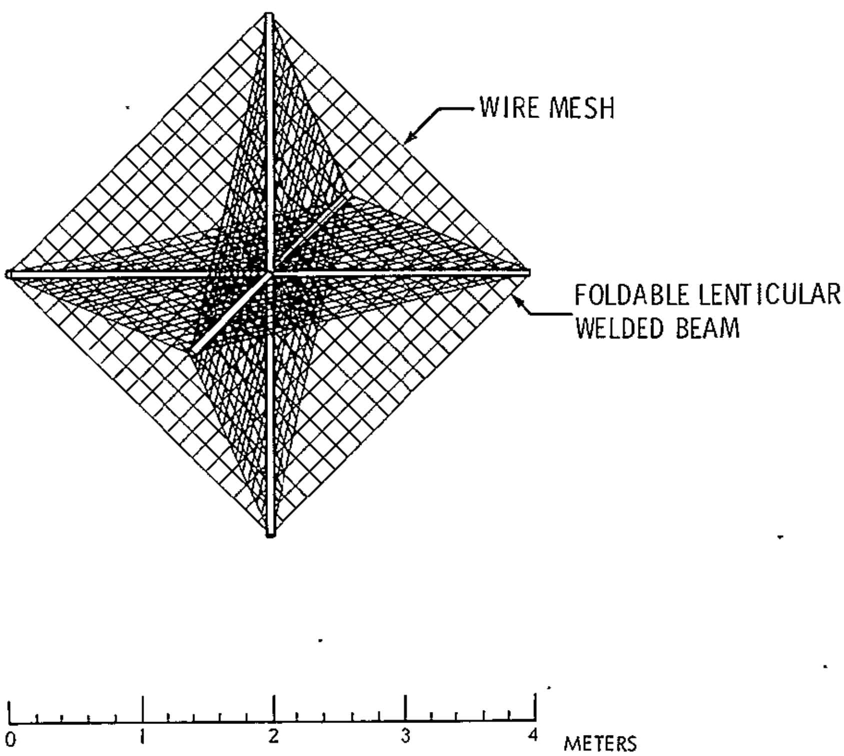


Figure 5-1. 2 Meter Venus Benchmark

C-2

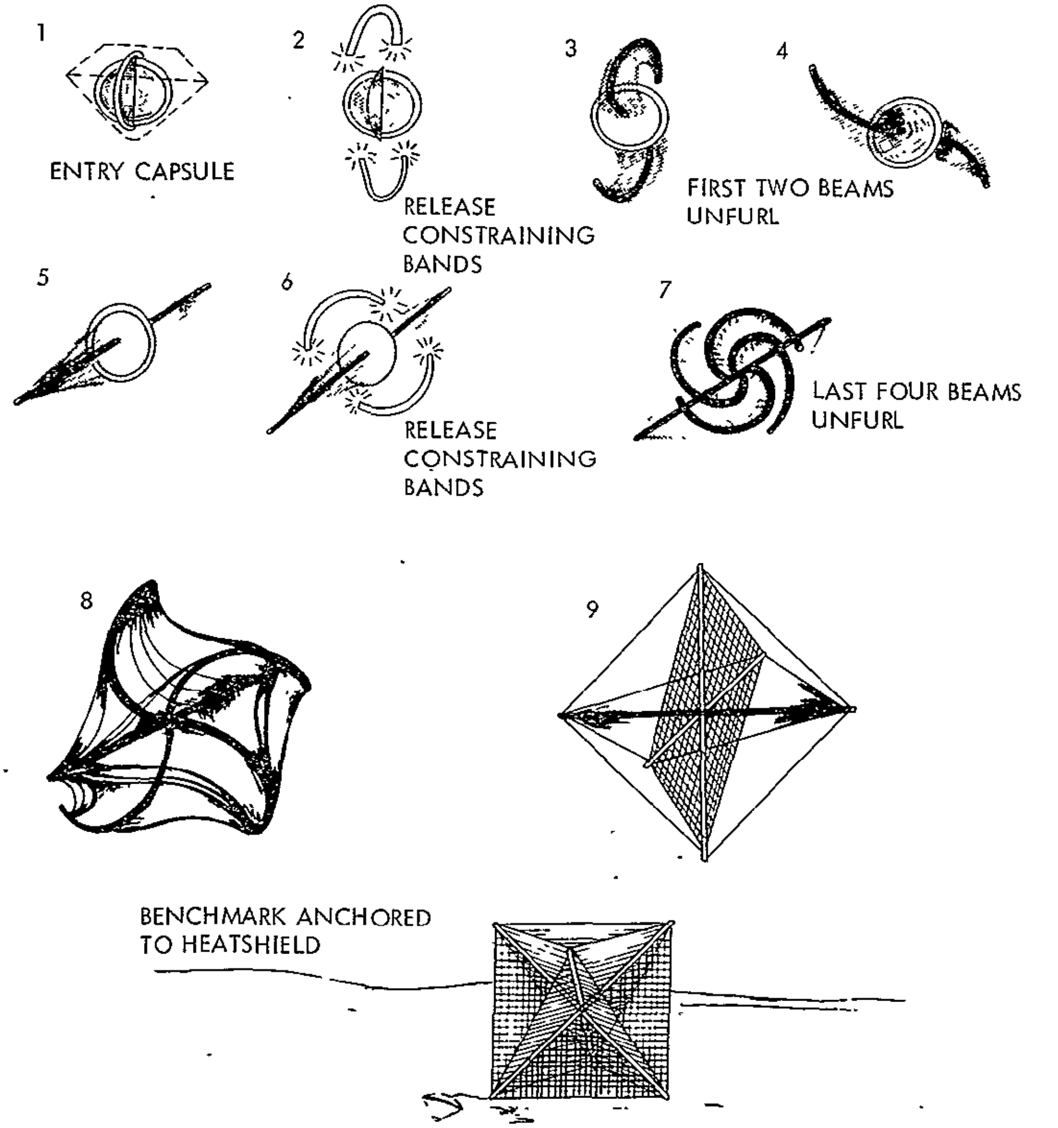


Figure 5-2. Deployment of 2 Meter Venus Benchmark

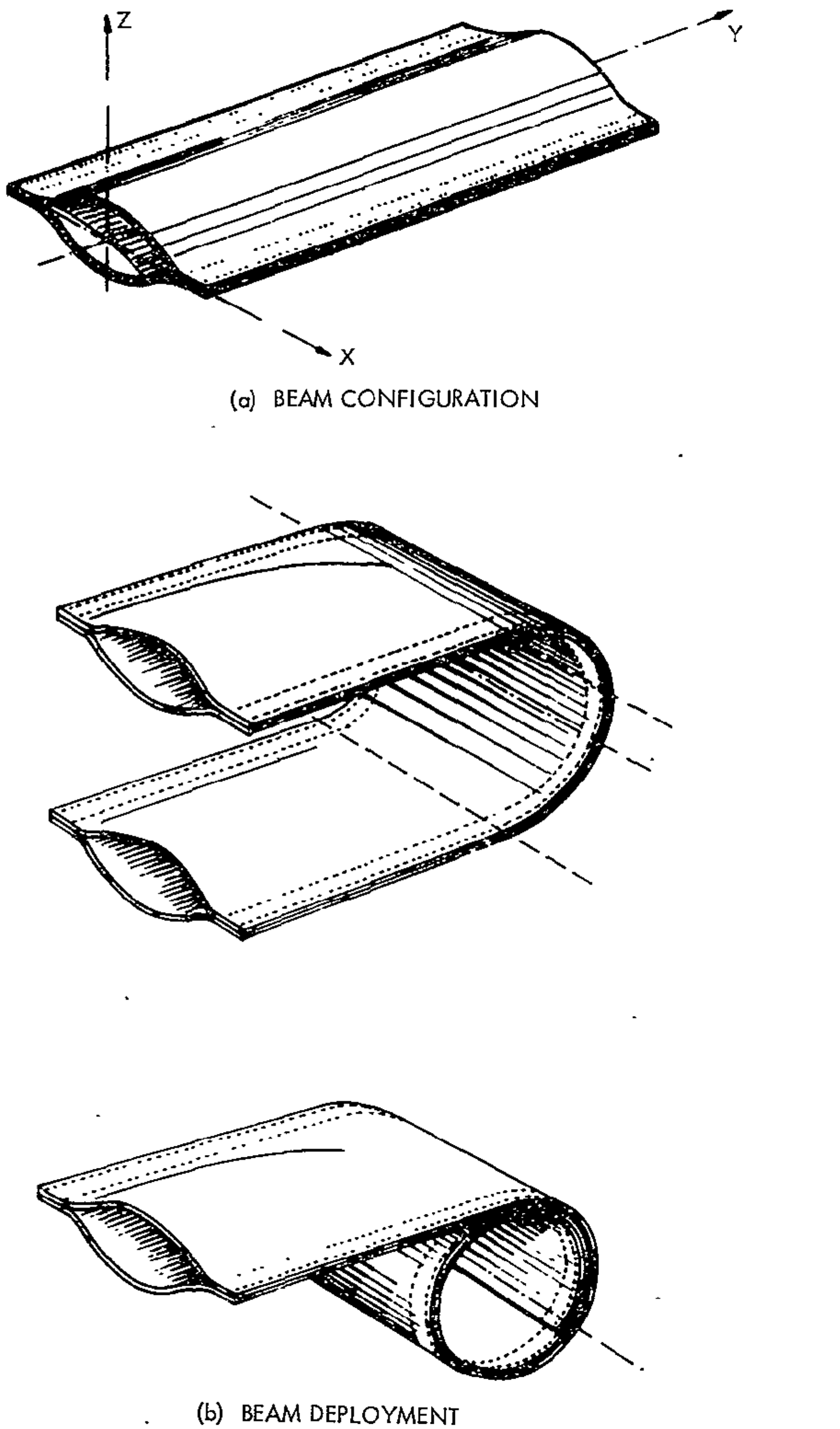


Figure 5-3. Lenticular Welded Beam (from J. Fernández-Sintes and J. C. Cristos, Foldable Elastic Tubes for Hinges on Satellites, Final Report, CR-65, European Space Research Organization, 1973)

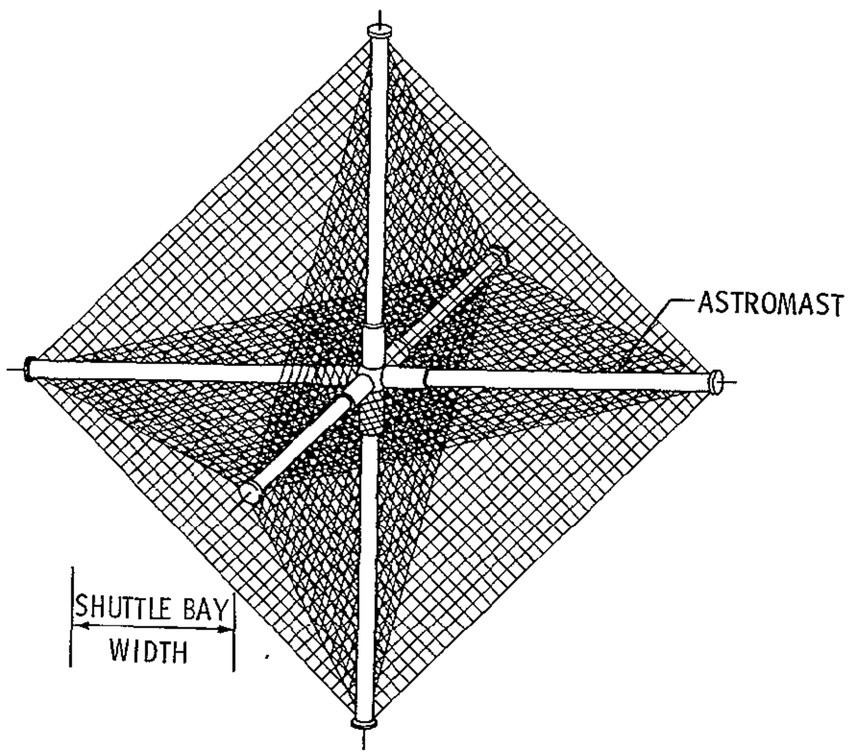


Figure 5-4. 10 Meter Venus Benchmark

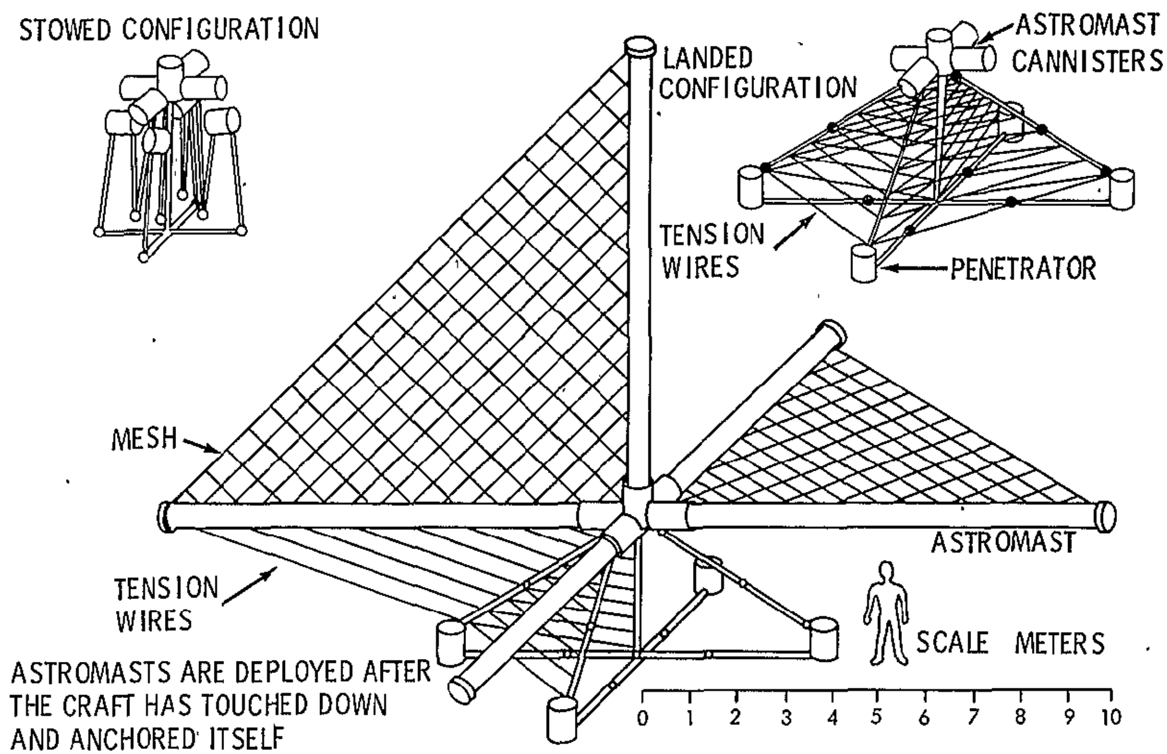


Figure 5-5. 10 Meter Venus Benchmark With Penetrator Anchoring System

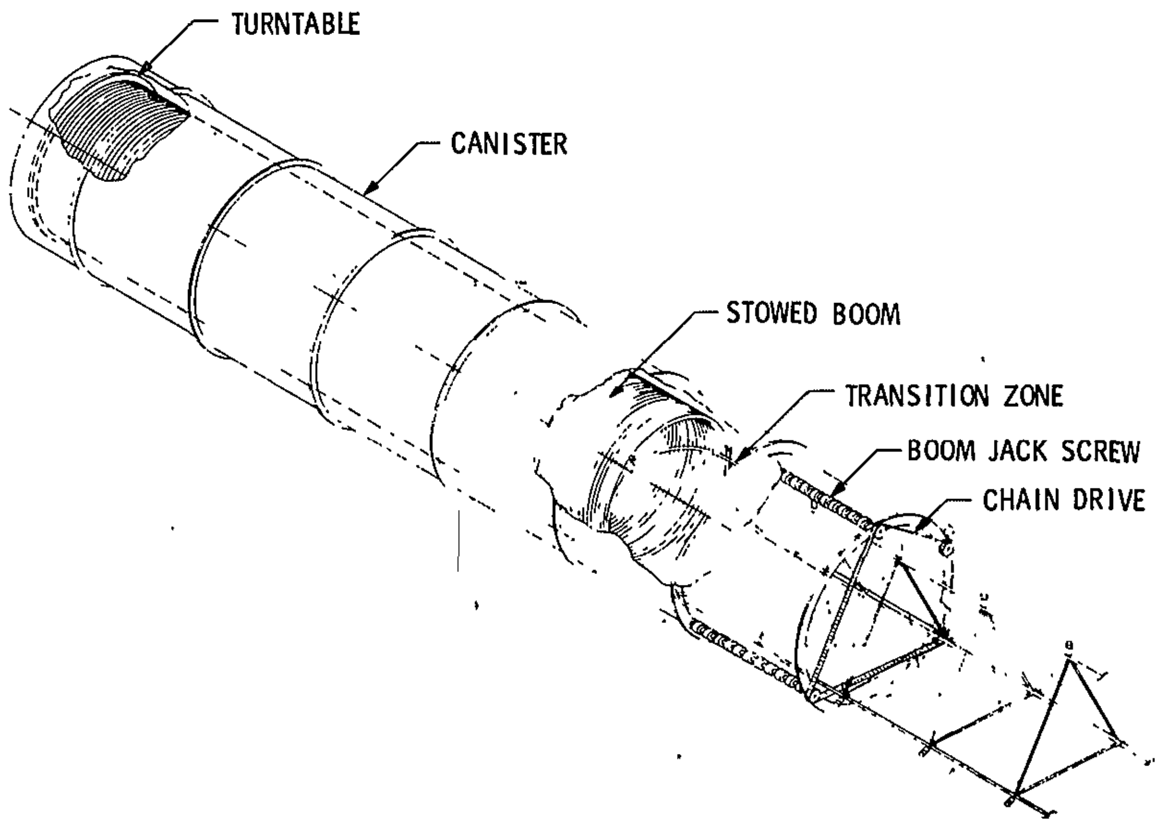


Figure 5-6. Square Solar Sail Boom Canister and Deployment Mechanism for Nonrotating Mast

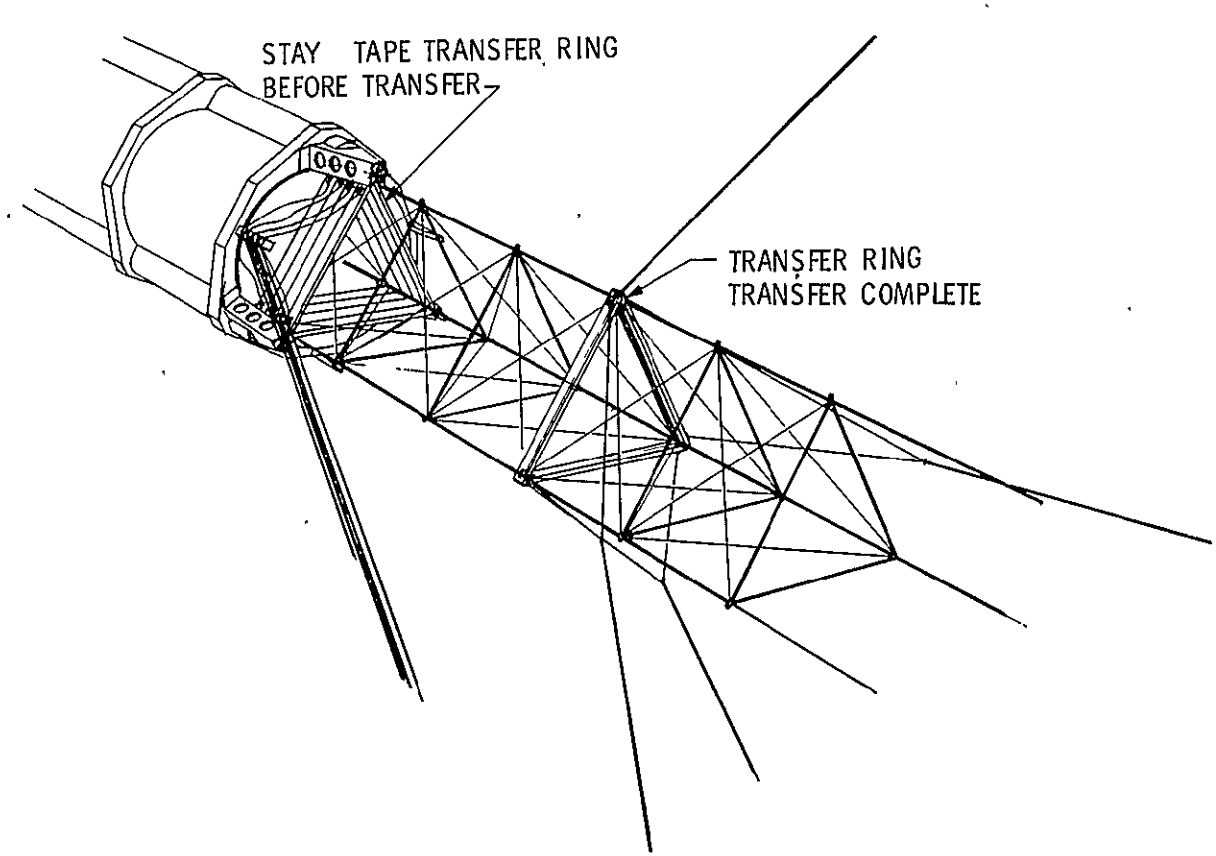


Figure 5-7. Square Solar Sail Transfer Ring Mechanism for Attachment to Deploying Mast

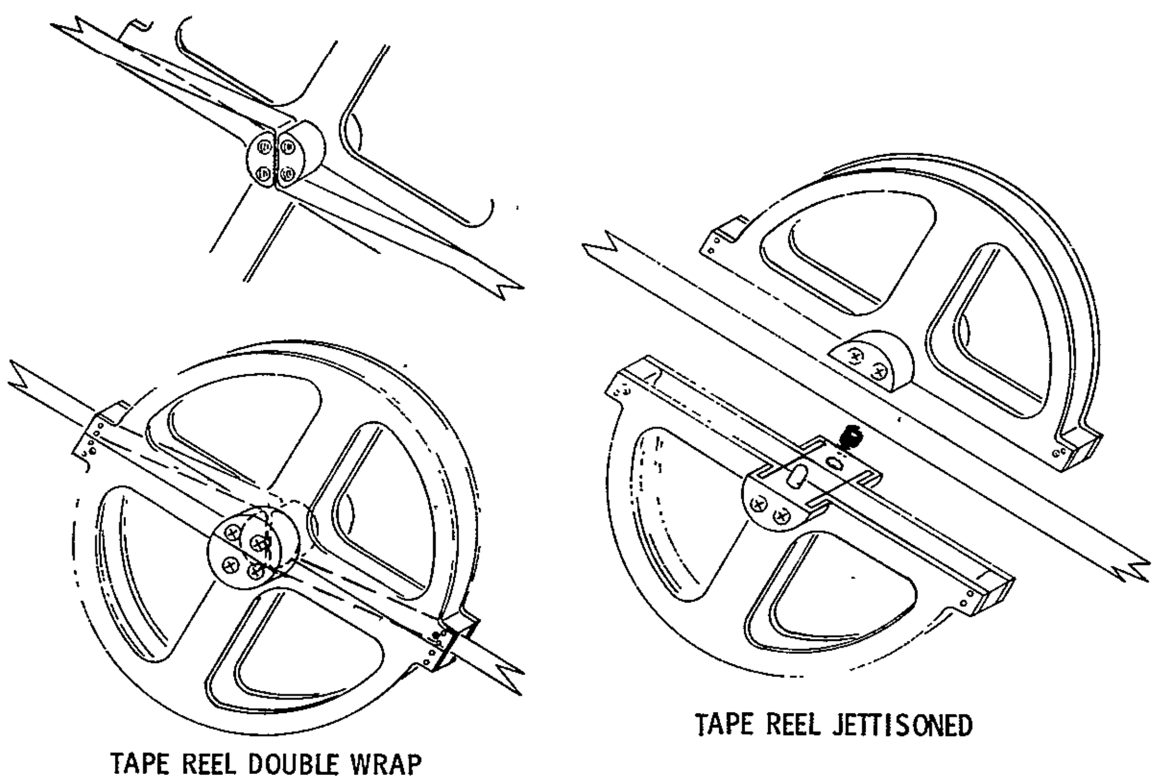


Figure 5-8. Square Solar Sail Ejectable Reel

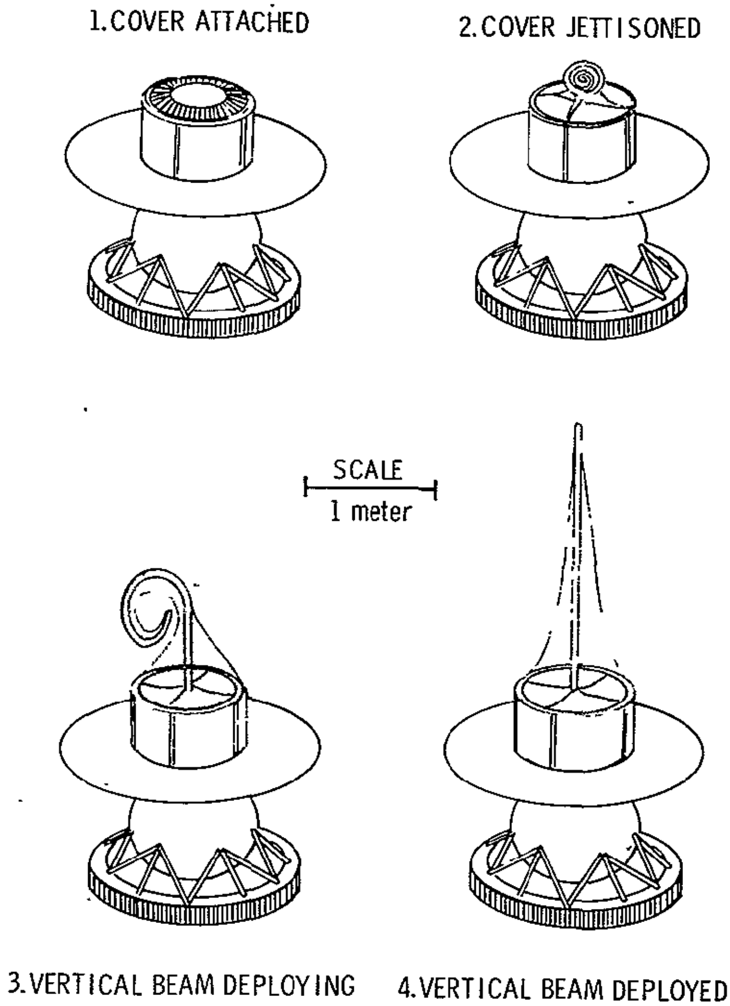
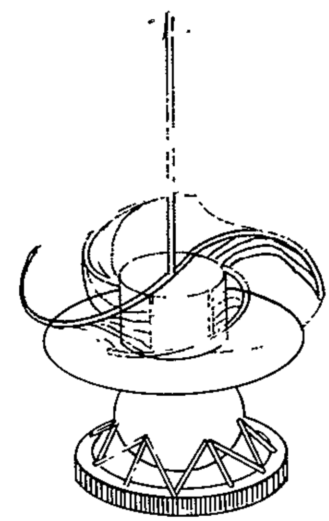
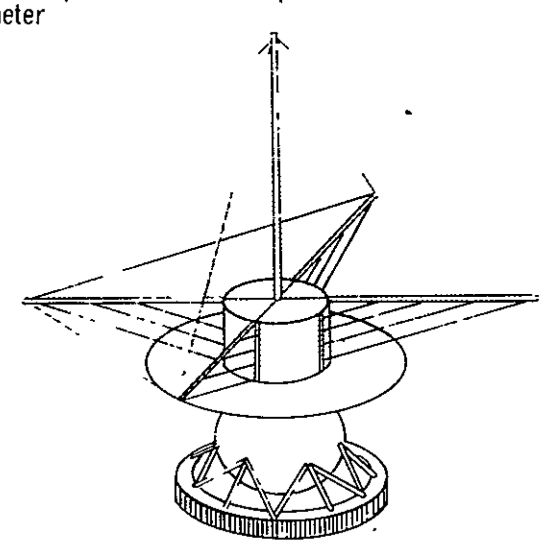


Figure 5-9. 2 Meter Benchmark for Venera Lander

5. HORIZONTAL BEAMS DEPLOYING



SCALE
1 meter



6. CORNER REFLECTOR FULLY DEPLOYED

Figure 5-9. (Continued)

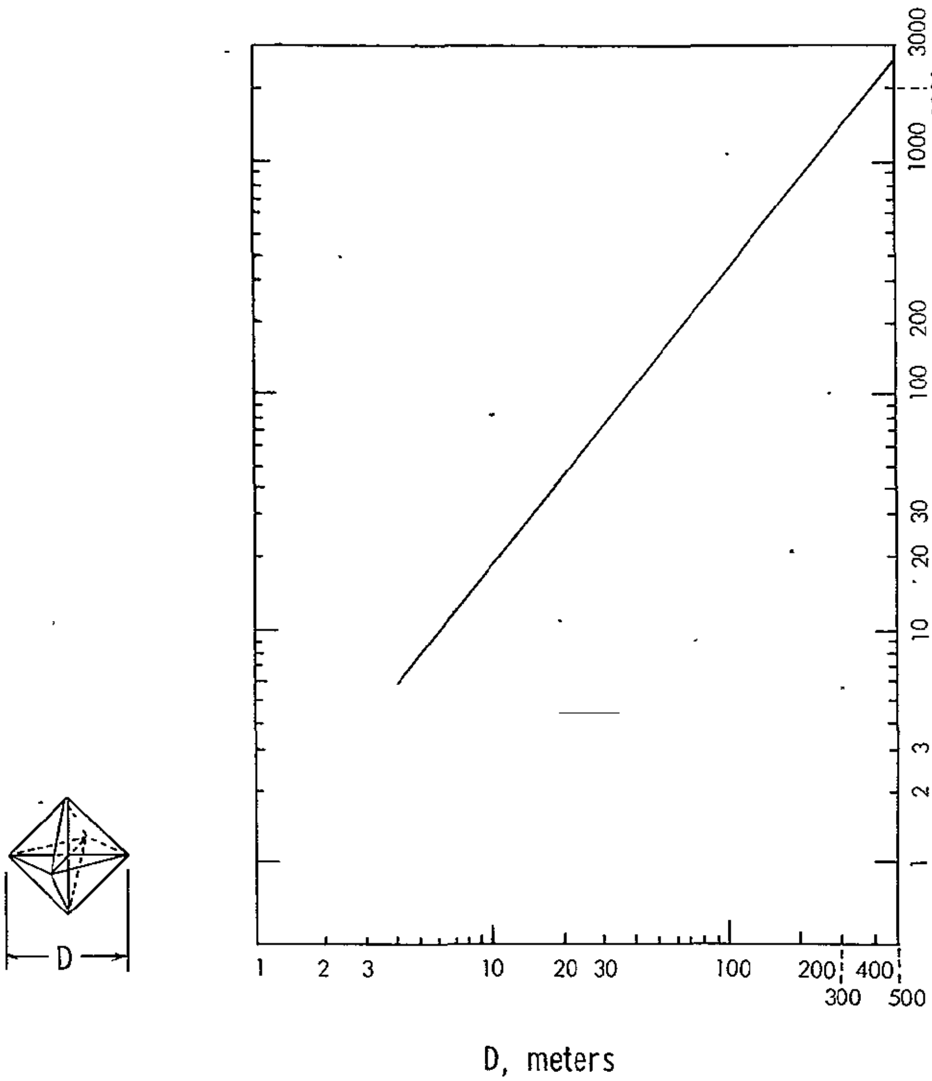


Figure 5-10. Mass Estimation Curve for Large Space Benchmark

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SECTION 6

OTHER APPLICATIONS

6.1 DEEP SPACE APPLICATIONS

Several deep space applications of the benchmark concept have been suggested. Because these suggestions were made close to the end of the study, there has not been time for detailed analysis of their utility or feasibility. Where available, preliminary results are presented here. Each potential application is presented and followed by the results of whatever analysis is available. Further analysis in FY 1979 is anticipated for the more promising concepts.

6.1.1 Extra-Plutonian Planet Search

There is considerable observational evidence that the nine major planets known today do not constitute all those in the solar system. Unexplained residuals exist in the motions of the outer planets which are best accounted for by assuming the existence of a tenth planet (or perhaps more), but observations to date based on several calculations have failed to show another body. Telescopic searches suffer two serious drawbacks; first, small planets at the required distance from the Sun ($\gtrsim$ 50 a.u.) are too dim to be easily detected, and second, there is too much sky, even near the ecliptic, to search in a reasonable time with the required telescope.

This study recommends an entirely different approach to a planet search (Reference 6-1). A set of small tracking beacons or retroreflectors are placed into very high eccentricity heliocentric orbits near the ecliptic, with eccentricity vectors pointing in equal increments around the solar system, as shown in Figure 6-1. The set consists of a number of identical lightweight and simple spacecraft, perhaps from 8 to 24, depending on available tracking accuracy. Each one is tracked periodically with its actual position compared with a prediction based upon known bodies in the solar system and any systematic perturbations such as light pressure which act equally on all spacecraft. Deviations in the path of one or two spacecraft may then be solved for both the location (orbit) and mass of any planetary body passed by the probes. A low level of perturbations on all spacecraft would conclusively set an upper limit on the mass of any body within the search region which could blanket the ecliptic plane out to ≈100 a.u., or more than twice Pluto's aphelion. The mass upper limit could be set by design to some arbitrary value, such as the mass of Mercury. A strong case has been made against major planets out of the ecliptic based on solar system dynamic stability (Reference 6-2).

A number of possible spacecraft configurations have been considered to date; the best probably has yet to be proposed. Some of these concepts are discussed in greater detail in Section 3.2. Very large radar reflectors deployed by inflation or folded lenticular welded beams needed to be too large for reasonable mass constraints (see Section 5.5). Long strings of phased reradiating dipoles (Reference 6-3) suffered from pointing problems. Other large reflectors not based on corner cubes also suffered from the inability to reliably point at Earth for long periods. Corner cube laser reflectors (Reference 6-4) were considered, but very large lasers are needed at Earth. All retroreflector arrangements with a narrow enough return beam to achieve the required signal suffered from the fact that the Earth and the sending sites are not in the same place when the return signal arrives as when the incident signal was sent, because of Earth's rotation and its motion around the Sun. With advancing technology and schemes involving airborne lasers, the laser technique may merit further consideration since mean motion effects of the Earth around the Sun are minimized every six months when Earth is at maximum elongation as seen from the spacecraft. Transponders were considered, but apparently a large receiving antenna at the spacecraft must be precisely pointed at Earth to receive the interrogation signal. Several spinning spacecraft schemes were considered to alleviate the problem, but they apparently preclude the required integration time.

Near the close of this year's study, the use of an external clock such as a pulsar (Reference 6-5) observable by the spacecraft and Earth was suggested to key the spacecraft signals without requiring an

Earth-originated signal. Pulsars are probably too dim and introduce pointing problems, while signals from the Sun (Reference 6-6) and Jupiter (Reference 6-6) may not carry sharp enough time variations and may suffer serious differential atmospheric distortions. The most recent suggestion involves flying a clock on the spacecraft which, rather than controlling a simple train of signals with fixed time intervals (this scheme suffers from long-term clock drift), simply broadcasts the time it senses (Reference 6-7). This time is tracked through the mission to determine the onboard clock rate, which in turn allows accurate ranging measurements. Work will continue examining this option.

6.1.2 Determination of Outer Planet Masses

In order to make accurate predictions of the trajectories of extra-plutonian planet probes for comparison with actual orbits, it is necessary to know precisely the mass and position of the outer planets (Jupiter and beyond) so a gravitational map of the known solar system may be constructed. Positions are determinable from Earth measurements, and masses may be determined by other spacecraft flybys (though not as accurately if the spacecraft expells propellant) or by measuring the periods and orbit sizes of the moons. Beyond Saturn, however, optical inaccuracies may limit mass determination. It is planned that at least one probe then be flown past each of the outer planets so their mass may be determined for use in the gravitational model and as valuable information in itself. Flybys of Jupiter and Saturn may be used to calibrate the techniques for undiscovered planet use.

6.1.3 Measurement of the Solar Gravity Field

A simple mission with near-term promise arose from discussions of laser reflectors for outer solar system applications. Apparently through narrow-band filtering, using a laser at the appropriate wavelength, an optical retroreflector may be tracked even in transit across the solar disc. The very high accuracies available from laser tracking allow precise mapping of the solar gravitational field (Reference 6-7), which may then permit the determination of non-spherical shell distributions in the solar interior.

Gravitational mapping data is best obtained with a fairly massive (in relation to its size) laser reflector in a low solar orbit of high inclination. This sort of data will prove most complementary to the Solar Polar data obtained regarding the surface and solar upper atmosphere environment at high solar latitudes. Only a close-orbiting spacecraft making a number of orbits can provide the refined data which is desirable. Because of its low mass and available tracking precision, the laser corner reflector is very well suited to this solar physics experiment.

6.1.4 Other Applications

A number of other applications were also suggested for which there was not time to conduct any serious analysis. Some of those are listed here, with the originator referenced where known.

During passes through the outer solar system, ephemerides could perhaps be improved for the outer planets by determining their positions from probe perturbations (Reference 6-8). Because of their indefinite lifetime, long-term residence in the solar system, and the ability to track a retroreflector at virtually any time in the future, retroreflectors would be an ideal location to place materials samples which would provide most valuable exposure effects data for future generations (Reference 6-8). Very long baseline and precise tracking might permit a variety of gravity wave and relativity experiments to be conducted (Reference 6-8). By mounting magnets on the retroreflector and making their reflection and polarization change with orientation, it might be possible to track a retroreflector's long-term alignment with the interplanetary magnetic field (Reference 6-1). Examining time and phase variations (scintillations) in returned signals caused by the intra-solar system plasma environment could provide a passive data source for many widely-spaced locations in the solar system (Reference 6-9).

Reflectors or transponders orbiting the outer planets could be used both to yield very precise ephemerides and as navigation beacons to guide spacecraft into orbit around those planets (Reference 6-8). A spacecraft on a fast escape trajectory alternatively could provide the

Deep Space Network and its follow-on systems with an extreme distance test (Reference 6-8), providing useful experience prior to such long distance missions as the Interstellar Precursor already studied (Reference 6-10).

6.2 LANDER OFFSET TERMINAL GUIDANCE USING RADAR REFLECTORS

6.2.1 Introduction

In connection with studies of the uses of radar retroreflectors, located on planetary surfaces, it has been suggested by W. O'Neil that they may be used as terminal landing aids for other programs, such as sample return missions. Here this concept is examined, a specific implementation is proposed, and a few preliminary feasiblity calculations are furnished. To anticipate, the idea looks promising.

Suppose a microwave retroreflector is deployed on a planet, and that its location is known, both absolutely, and relative to nearby features of interest. This could be accomplished directly by a side looking radar from orbit, or indirectly by multiple doppler ranging coupled with photographs, also from orbit. Then suppose that a landing site is chosen in a precise location relative to the retroreflector. The idea is that by augmenting the usual landing altimeter with a doppler measurement from the reflector, it is possible to observe three axis position and velocity variations from the nominal landing trajectory. From this, variations in thrust vector or aerodynamic controls can be computed to return to a desirable landing trajectory.

As for the hardware, the doppler system needs about 3 w of output power at X-band, using a steerable antenna of about 0.37 m aperture. A conventional receiver and phase-locked doppler extractor completes the doppler electronics. Most of this will probably be needed anyway by the command and telemetry systems. The control system electronics includes a digital memory to store altitude, doppler, and control variables for the nominal trajectory; a linear state estimator, to extract the position and velocity variations from the measurements; and actuator amplifiers that would exist even without the doppler measurement.

6.2.2 Discussion of Controls

In the absence of the doppler measurement, thrust (and possibly lift) controls u_0 would be programmed from memory, with corrections δu supplied by the altimeter in the terminal phase. With the addition of the doppler system, it is possible in principal to observe the entire state x (position and velocity in some appropriate coordinates). If $x_0(t)$ is the state along the nominal (optimal) trajectory, then the observed difference $\delta\hat{x} = \hat{x} - x_0$ can be used to generate an incremental control $\delta u = u - u_0$.

Imagine that the original optimal control problem was satisfied by a field of extremals, for which the associated control vectors are given by $u = G(x, t)$. Since explicit functions G are rarely available, a full table of potentially useful u values requires that m 6-dimensional arrays of numbers be stored on board at each t, where m is the number of controls. This is almost surely unfeasible.

To avoid this, u may be linearized about the nominal:

$$\delta u \doteq \partial_x G(x_0, t)\delta\hat{x} \equiv C(t)\delta\hat{x}$$

Here, the actual δx has been replaced by the available estimate $\delta\hat{x}$ to produce a viable control law. The storage of $C(t)$ and $u_0(t)$ requires only 7 m numbers at each t. This approach is assumed hereafter.

Optimal controls are often saturated; e.g., zero or maximum thrust. This can be enforced either by programming u_0 well beyond the commandable limits, or by zero elements in $C(t)$, or both.

6.2.3 State Error Estimator

Suppose the landing vehicle dynamics can be described by a set of state equations:

$$\dot{x} = F(x, u, t) + w(x, t)$$

where $w(x, t)$ is an unmodellable disturbance. At the same time, a set of measurements y can be modelled as:

$$y = H(x, t) + v(x, t)$$

where $v(x, t)$ is measurement noise.

In principle, a state estimator can be constructed directly from these equations and the control law. In practice it is much easier to linearize about the nominal trajectory, just as with the control law. Thus:

$$\dot{x} \doteq \dot{x}_0 + \partial_x F_0(t)(x - x_0) + \partial_u F_0(t)(u - u_0) + w(x, t)$$

$$y \doteq H_0(t) + \partial_x H_0(t)(x - x_0) + v(x, t)$$

where

$$F_0(t) \equiv F(x_0, u_0, t); \quad H_0(t) = H(x_0, t)$$

An estimator based on these has the structure:

$$\delta\dot{\hat{x}} = \dot{\hat{x}} - \dot{x}_0 = \partial_x F_0(t)\partial\hat{x} + \partial_u F_0(t)\delta u + K(t)\varepsilon_y$$

in which ε_y is the difference between the actual and estimated measurements:

$$\varepsilon_y \equiv y - \hat{y} = y - H_0(t) - \partial_x H_0(t)\delta\hat{x}$$

and in which $K(t)$ is the Kalman gain matrix, which is derivable from the (presumably) given statistics of w and v.

As for the storage requirements, if k is the number of measurements, then at each t, 36 numbers are needed for $\partial_x F_0(t)$, 6 m for $\partial_u F_0(t)$, 6 k for $K(t)$, k for $H_0(t)$, and 6 k for $\partial_x H_0(t)$, for a total of 13 k + 6m + 36. Overall, after adding the controls requirements this becomes 13(k + m) + 36. For example, if there are 3 engine controls and 3 measurements, 114 numbers are needed at each time step. At, say, 100 time steps and 16 bits per number plus 2 parity bits, a total of 2.052×10^5 bits are needed. This will conveniently fit on one magnetic bubble memory chip.

There are several questions on the performance of this estimator that will need to be explored. First, will this system actually converge to an accurate estimate $\delta\hat{x}$? This can be answered directly by simulation on a general purpose computer. Another way is to examine the rank of the observability matrix, which is constructed from $\partial_x F_0(t)$ and $\partial_x H_0(t)$. This test is sure to fail in the case that the retroreflector is in the plane of the descent orbit, as then lateral displacements from the path are unobservable. There is actually a finite band about the surface track of the orbit that should be avoided, as the closer to this track that the retroreflector is placed, the worse the crosstrack estimation errors.

Another problem is that the retroreflector should not be too far from the landing point, as then the doppler system will lose lock too early due to horizon effects. This is not normally disastrous, as the final portion of the trajectory is nearly vertical, and the estimator will not diverge rapidly just from the loss of the doppler signal. A similar effect occurs if the altimeter will not function at the initial orbit altitude, or if the initial position is too far from, or below the horizon of the retroreflector. If there are no inputs to the estimator, it becomes a dead reckoning device, and navigates optimally based on the initial state information.

If the retroreflector distance and cross-track restrictions are considered together a plot of favorable landing sites from the navigational standpoint, can be made up. By plotting contours of constant expected navigational error, something like Figure 6-2 should emerge. The line from the right is the desired ground track, terminating at the desired landing point. "Best", "good", and "poor" then refer to possible locations of the retroreflector.

6.2.4 Doppler Tracker

A fairly conventional implementation of a doppler tracker is shown in Figure 6-3. In the RF section, an oscillator signal f_1 is converted to X-band (or higher) $f_1 + f_2$, and transmitted. The return is doppler shifted by amount f_D, and heterodyned down to $f_1 + f_D$. A phase lock loop recovers the phase error between this and an equivalent signal constructed from the estimated doppler shift. When the loop locks up, this phase error is a measure of the error in the estimated doppler frequency $\varepsilon_D = D - \hat{D}$. These quantities are the doppler components of the ε_y, y, and $\hat{y}$ vectors in the estimator theory of the last section.

A useful feature of phase lock systems is that the effective noise bandwidth is twice the width of the low pass filter in the phase lock loop. The smaller this is, the less power will be needed. In a free phase lock system (no $\hat{D}$ input), the minimum filter width is set by the requirement to track a variable f_D. Here, the minimum is lowered by "guiding" the loop with the estimated doppler shift $\hat{D}$. Using the estimator definitions in the last section this is:

$$\hat{D} = D_0(t) + \partial_x D_0(t)\delta\hat{x}$$

where $D_0(t)$ is the doppler component of $H_0(t)$.

If the loop is accurately guided, minimum bandwidth tends to depend on acquisition requirements. Consider a Mars landing. Circular orbit speed at the surface is 3.55 km/sec. Allowing a bit for Mars rotation, a reasonable closing speed might be 3.2 km/sec. Then using a transmitter frequency $f_1 + f_2 = 10$ GHz, we get $f_D = (2)(10^{10})(3.2)/(3 \times 10^5) = 213$ khz. Assuming a deboost from orbit of 500 m/sec, and, say, a 2% execution error, the uncertainty in f_D is 667 Hz. If 1 minute is permitted to find f_D, something like 11 Hz is needed in the filter, for a 22 Hz noise bandwidth.

The other major design determinant is the antenna. While an articulated paraboloid would be needed for communications in any case, a tracking loop must be regarded as highly undesirable. Thus beamwidths must be large enough to accommodate position and attitude errors without too much gain loss. Assuming an overall error of 3° will degrade the antenna gain by 50%, and that the system will then operate, the forward antenna gain is limited to

$$G \leq \frac{6750}{\Theta_{HH}^2} = 750$$

However, the actual gain at 3° error is only $G_T = 375$. For a 50% efficient aperture, this is a 0.37 m diameter dish.

Next consider the corner cube. In this study, a cubic edge dimension of $a = 2$ m has been assumed. This gives an effective area of approximately $A_e = \pi a^2/4$ an effective retransmission gain of $G_c = (\pi a/\lambda)^2$, neglecting reflection losses. The illumination at the reflector is $I_c = P_T G_T/(4\pi L^2)$, where P_T is the transmitted power and L is the distance from the lander to the reflector. Thus the retransmitted power is

$$P_c = I_c A_e = P_T G_T \left(\frac{a}{4L}\right)^2$$

and the illumination back at the lander is:

$$I_L = \frac{P_c G_c}{4\pi L^2} = \frac{\pi P_T G_T a^4}{64\lambda^2 L^4}$$

Now, the effective receiving area is $A_R = G_T \lambda^2/(4\pi)$, so the received power is:

$$P_R = I_L A_R = P_T G_T^2 \left(\frac{a}{4L}\right)^4$$

To compute the required transmitter power P_T, we must compare this to the noise power $P_N = kTB$, where B is the noise bandwidth, T is the receiver noise temperature, and $k = 1.38 \times 10^{-23}$ j/K = Boltzmann's constant. Thus to achieve a given minimum signal to noise ratio $(S/N)_{min}$:

$$P_T \geq \frac{kTB}{G_T^2}\left(\frac{4L}{a}\right)^4 \left(\frac{S}{N}\right)_{min}$$

Letting $(S/N)_{min} = 10$ for fast acquisition T - 300 K, and assuming initial acquisition at L = 300 km gives

$$P_T \leq \frac{(1.38 \times 10^{-23})(300)(22)(10)}{(375)^2} \left[\frac{(4)(5 \times 10^5)}{2}\right]^2 = 6.48 \text{ w}$$

At, say, 15% efficiency, 43.2 w of electrical power is needed; however, as a variety of RF losses have been neglected, 100 w seems more realistic. While this is probably feasible, a substantial reduction could be achieved by adding an accelerometer along the thrust axis. This would permit a big reduction in the effect of the deboost execution error on the initial doppler uncertainty. Thus, the bandwidth B could be lowered to perhaps 5 Hz; so that $P_T \geq 1.47$ w, and the required electrical power is now 23 w. The accelerometer is assumed in what follows, and in fact was the reason for supposing 3 measurements in the last section.

Some additional comments on the doppler tracker are in order. First, Figure 6-3 shows antenna pointing commands taken from a stored program in the digital memory. This is simplest, in that it requires no on board computation, but it does not make full use of the available information. Other possibilities are that pointing commands be computed directly from the estimated state, or that corrections are computed from the estimated state variations, using stored partial derivatives. The former requires substantial calculation, but no memory; while the latter has very little calculation, but substantial additonal memory. It is possible that gyro information could reduce the effect of attitude errors. The benefit of this is that a higher gain G_T could be employed, thus reducing power.

Another possible improvement is an all digital phase lock loop. In this case, a relatively low f_1 would be chosen, and the signal from the IF amplifier would be pre-filtered, sampled at about 5 f_1, and digitized. Then the detector, modulator, and filters would all be digital; and the D/A and A/D converters would be deleted. The requirement for very low frequency filters makes this especially attractive.

Finally it should be noted that most of the design parameters have been chosen rather arbitrarily. A few weeks of preliminary design effort would serve to clarify the power-weight-performance tradeoffs needed for a full landing system design.

6.2.5 Altimeter

Since a lander would carry some sort of altimeter in any case, no special study of it will be made here. Only a few comments are offered on the present application. First, any kind of radar or laser altimeter, suitable for vertical landing, can be employed here. Second, a fairly high maximum altitude is desirable, since the sooner the estimator gets reliable altitude data, the better the system performance. On the other hand, once a full state estimator is used, it may be possible to relax the minimum altitude requirement. That is, many altimeters will not work when too close to the ground; but here, the estimator's dead reckoning should be adequate in the last few hundred meters.

Finally, one altimeter configuration could have a big impact on the design. If a 3 or 4 beam "JANUS" configuration is used, information on the local vertical is available, and could be combined with gyro and accelerometer data to yield a better estimate of the state. In addition, some of these instruments can do 3 axis doppler measurements as well as range, thus yielding relative ground velocity. If this information were available to the estimator, much tighter control would be possible; and if it were available early in the trajectory, the accelerometer could be dispensed with as an aid in acquiring phase lock in the doppler tracker.

6.2.6 Overall Landing System

The complete system is pictured in Figure 6-4. The configuration is the simplest variation discussed above, except that an accelerometer has been added to reduce the initial dopper error. The oscillator on the left is the system's basic timing reference, and should have very good stability, especially over the range of round trip travel times (up to a few milliseconds). The clock is needed to synchronize all the system's digital operations, and as shown, merely counts down f_1 from the oscillator. In the case of a digital phase lock loop, a higher frequency would be needed for sampling; but this might come from the f_2 multiplier in the doppler system.

Little has been said about what the controls control. A vertical lander must have a throttle. Side vector control is also required, and can be provided by side jets, engine gimbals, rotating the whole vehicle, or some combination. Also, for Mars at least, aerodynamic lift and braking might be employed to reduce the thrust requirements. The memory and estimator could then be regarded as an autopilot, controlling rudder, elevators, ailerons, or whatever. The additional memory and logic are insignificant, compared to the hardware of the added controls.

To sum up, the use of a benchmark retroreflector as a navigator aid for a planetary lander seems quite feasible from the standpoint of the necessary extra lander weight, power, and complexity. As only a few days have been available for this study, it has not been possible to synthesize the estimator, and thus find the tradeoff between weight, power, and performance. A few man-months should be sufficient to do this, and get good estimates on achievable maximum levels of terminal position and velocity errors.

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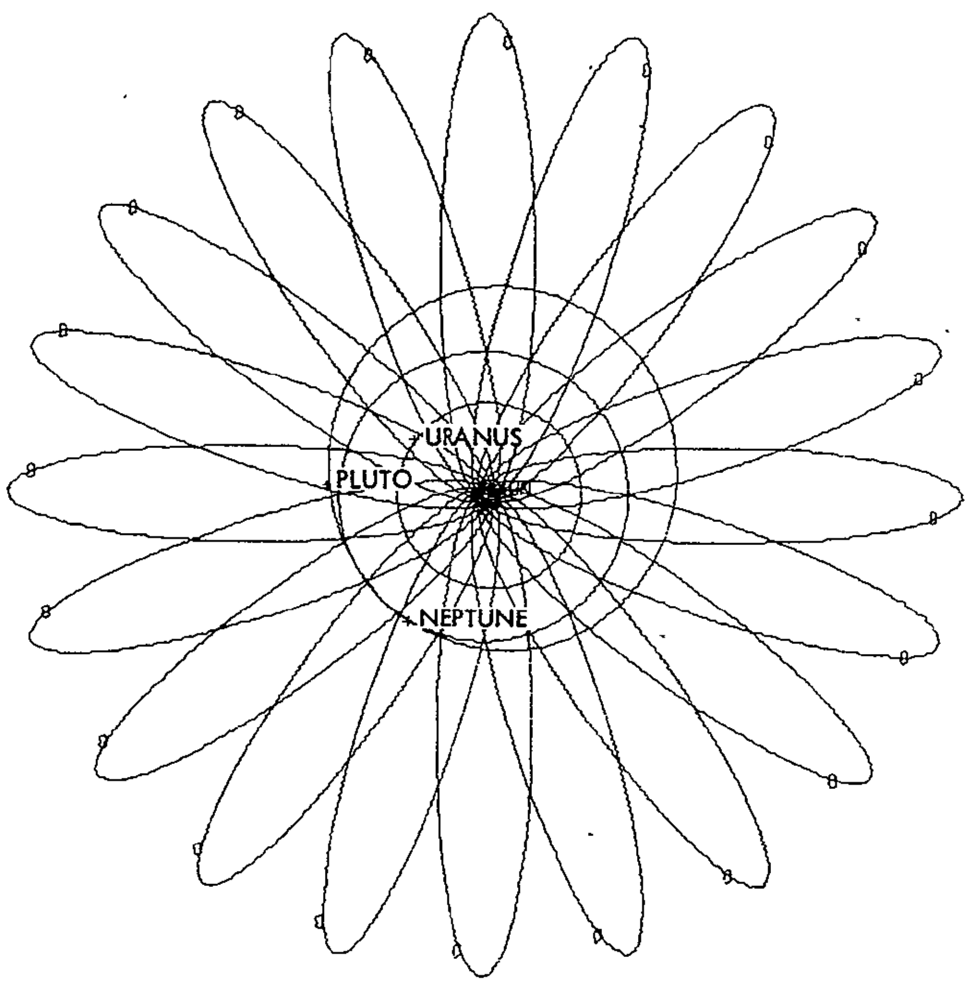

Figure 6-1. Planet Probes Near Aphelion

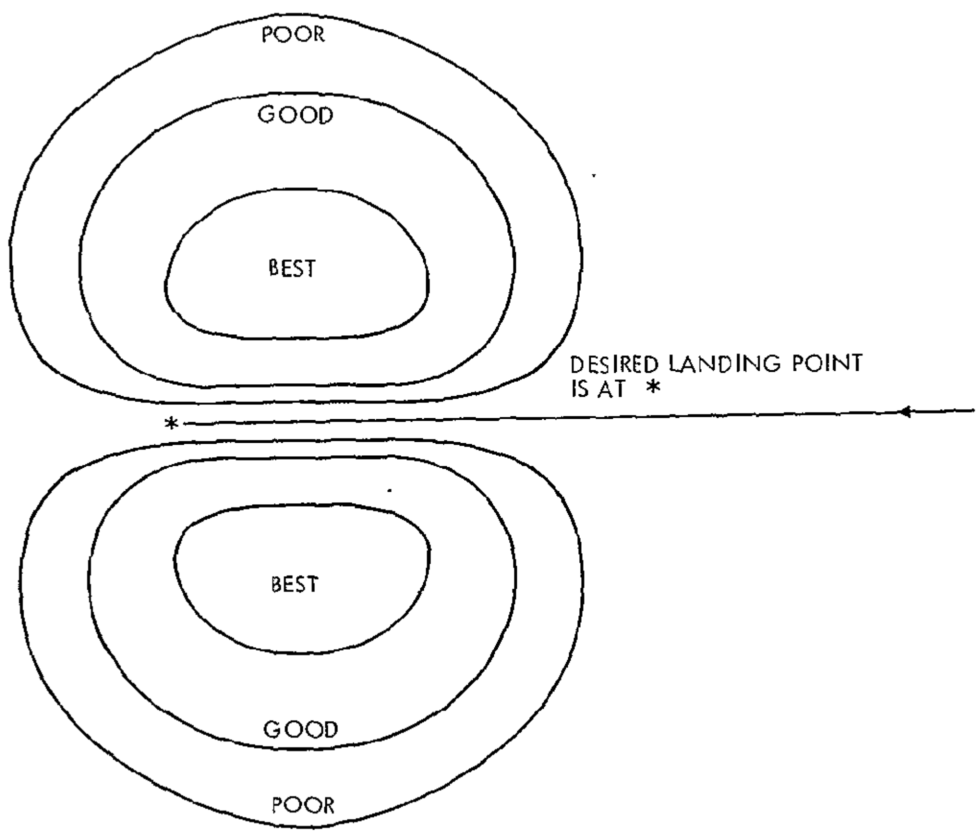

Figure 6-2. A Qualitative Picture of Relative Retroreflector Locations

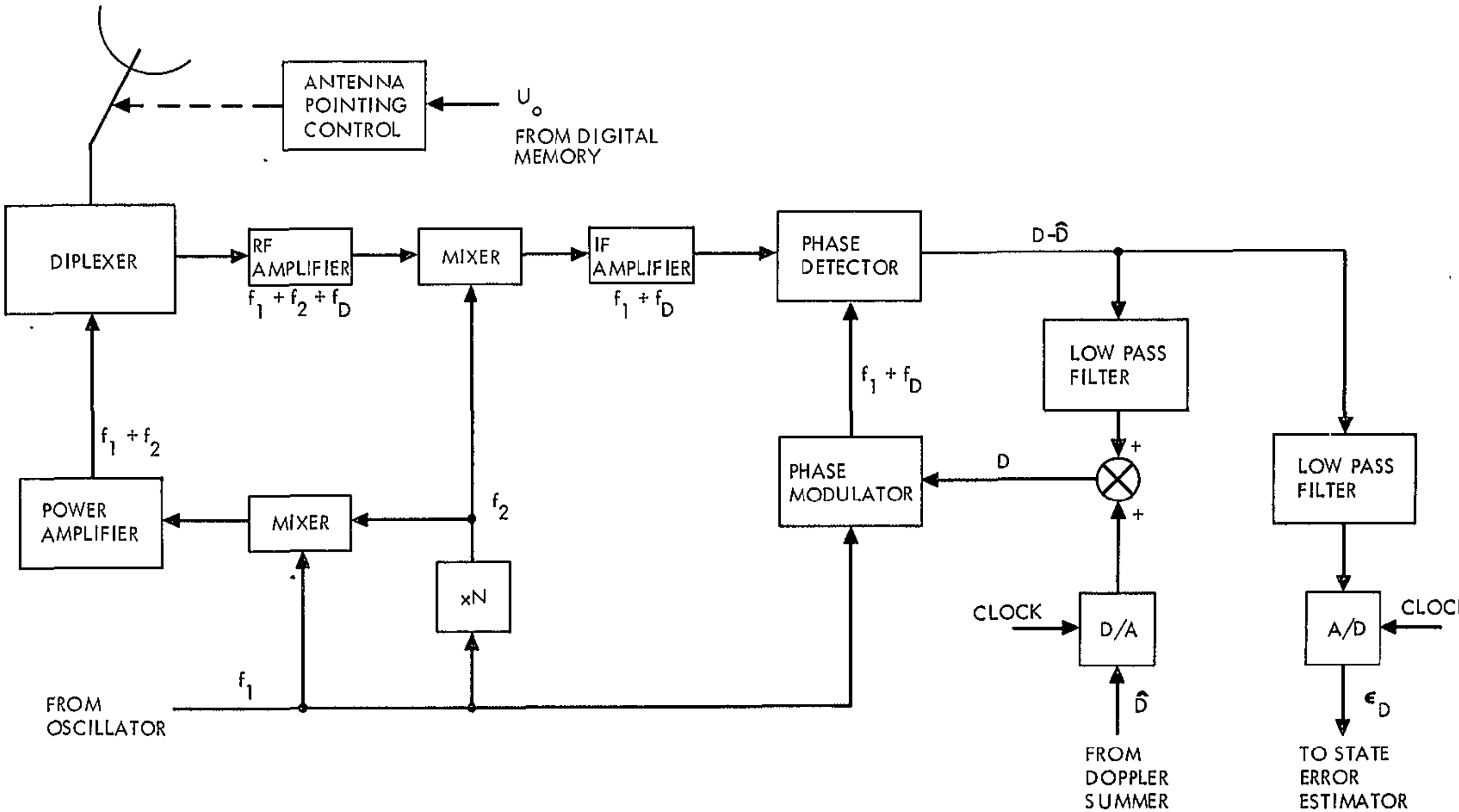

Figure 6-3. Doppler System Acquisition Loop Deleted For Simplicity

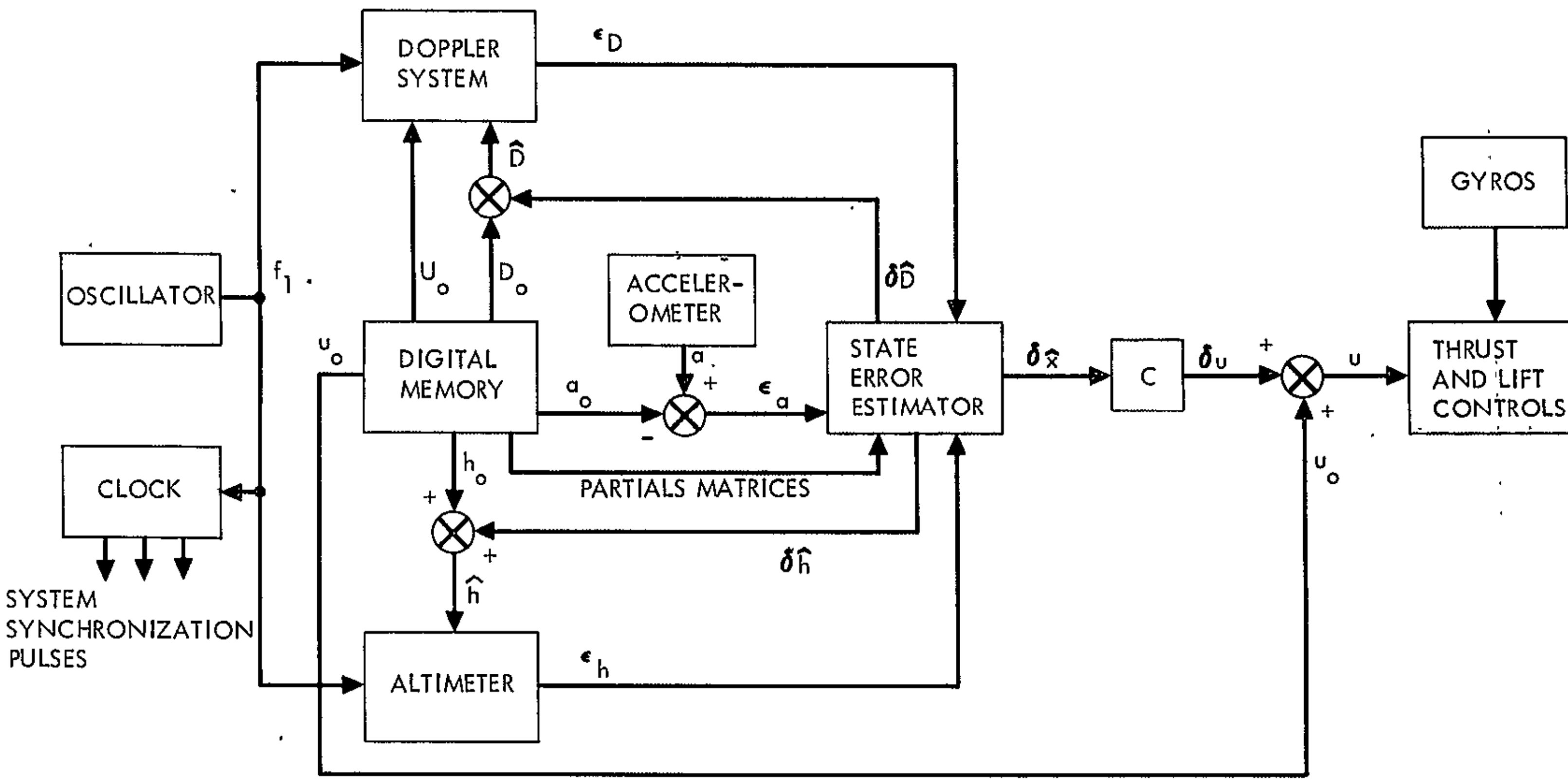

Figure 6-4. Overall Landing System

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

An exploratory study of the feasibility of a system of planetary or deep-space benchmarks has been performed and the results were presented above. The study was performed by a small group of individuals with inputs from a larger number of consultants. The conclusions and recommendations are not unanimous nor do they necessarily represent a majority opinion. What follows are the general conclusions drawn by the study manager based upon inputs from the contributors and consultants.

It has been shown that long-term tracking of a number of passive or active radar reflectors offers great potential for improvement of our understanding of planetary structure and dynamics. Earth-based Doppler tracking with ranging to the level of several tens of meters could provide an order of magnitude improvement in our knowledge of the spin state of Venus. Long-term (decades) observation of the motion of several benchmarks could yield another order of magnitude of improvement in our knowledge. Substantial improvements in knowledge of the in-plane components of the Venus ephemeris could be obtained by Earth-based benchmark tracking over one Earth-Venus synodic period but residuals of the order of 20 km would remain in the direction normal to the Venus orbit plane.

A conceptual design has been completed for a 2 meter, 10 kg octahedral corner reflector suitable for deployment on the Venus surface and visible to orbital radar but not visible to Earth-based radar. Ranging accuracy to the benchmark would be limited only by the characteristics of the orbital radar. For the proposed VOIR mission the resolution would be about 50 meters. Attempts to design a 10 meter passive benchmark for Earth-based observation showed that such a device would weigh several hundred kilograms at least and would require a complex deployment and anchoring system. Ranging accuracy to a large Venus benchmark would be of the order of 100 m using our largest radio telescopes on Earth. It is suggested that this idea be shelved for possible application as Earth-based radar capability improves. The concept should definitely be reexamined if a large Earth-orbital radio telescope becomes available.

A design for a high-temperature transponder for use on the surface of Venus has been worked out and appears to be feasible. Mass estimates for the device are in the 20 to 30 kilogram range. The only drawback is the difficulty of guaranteeing a lifetime sufficiently long for measurements of planetological significance. It has been suggested that this concept be pursued as a promising means of achieving the scientific goals discussed in Section 2.

Several offshoot applications of benchmark technology have been studied briefly and appear to offer exciting possibilities. High powered lasers of the type being built by the military are probably adequate for tracking LAGEOS-type corner reflectors throughout the inner solar system for a number of relativity and planetary dynamics applications. The small passive benchmark was also shown to serve well as a landing reference for Martian or Venusian landers having moderate steerable radar capability. It is shown that the benchmark enables a straightforward implementation of offset guidance technology. The application is probably adequate for landing systems under consideration now for Mars.

Investigation of several deep space applications of the benchmark concept led to the realization that a very low power transmitter is detectable on Earth even when the transmitter if as far away as 100 A.U. This rather remarkable fact led to consideration of a number of very simple, over-designed spacecraft to be launched from Earth orbit into trajectories with aphelia beyond 100 A.U. As the spacecraft spread out in all directions, they form an expanding circle that passes Uranus' orbit in only 7.7 years. In addition to providing a full map of the electromagnetic environment, the probes would yield an accurate mass determination for each outer planet, and, after they pass Pluto's orbit 20 years after launch, some of them would be assured of being perturbed by a tenth planet if it exists and has a mass greater than about one-third the Earth's mass. The concept is under further investigation as part of the FY 1979 Advanced Concepts Study.

Specific recommendations are as follows:

(1) Continue study of small (2-3 m) benchmarks.

(2) Intensify study of simple, high temperatures, long-life transponders.

(3) Shelve the concept of a large passive retroreflector on the planetary surfaces for Earth-based observations. Reexamine if Earth-orbital radio telescope is built.

(4) Continue study of interplanetary and deep space benchmarks.

(5) Investigate use of high-power laser technology for inner solar system tracking.

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