# Seismic Holography for Underground Viewing

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13. ABSTRACT

The potential benefits to be gained from the development of an underground viewing system are many. For the first time, a method would be available to look into the ground and "see" targets, thereby defining such anomalies as tunnels, mines, bunkers, and other voids or water filled cavities. It would be a valuable tool for surveying the earth ahead of, or prior to, excavations to determine potential hazards. It would also have applications in defining certain rubble zones in the earth such as might exist after a nuclear underground explosion, and for the military, in locating underground bunkers and supply stores.

The objective of this research program is to define a preliminary underground viewing system based on acoustic holography principles that is capable of detecting and imaging anomalies associated with a selected field test site. Tasks associated with the program include the selection of a field test site, a theoretical analysis, a preliminary system design specifying the required equipment and techniques to carry out a field test. In addition, holographic image enhancement techniques capable of resolving weak target signals in the presence of strong undesired signals will be studied.

In this report, covering the work during the first six months of the program, emphasis will be given to the selection of a field test site and studies relating to weak signal enhancement techniques.

## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

# SECTION 1

# TECHNICAL REPORT SUMMARY

The purpose of this project is to define a preliminary underground viewing system based on acoustic holography principles capable of detecting and imaging underground anomalies associated with a selected field test site. System requirements and equipment specifications based on the geology of the selected site will be designated. In addition, studies to develop a holographic weak-signal-enhancement technique will be made.

One of the program tasks was to select a suitable field test site at which a future field test experiment could be performed. Some of the criteria used for the site selection included the degree of surface weathering, the type of earth material at the site ("hard" or crystalline rock specified in contract), targets (tunnels, caves, bunkers, etc.) associated with the site, surface topography, and access to the area. Potential sites evaluated included:

- Climax Stock, U.S.A.E.C. Nevada Test Range, Nye County, Nevada
- Batholith of Southern California
- Pikes Peak area, Colorado
- Guadalupe Mountains area, New Mexico and Texas
- Victoria Peak area, Texas
- Big Bend area, Texas and Mexico
- Winnfield Salt Dome, Winn Parish, Louisiana

A brief description of these sites is given in Section 3 of this report.

The site selected was the "Piledriver" site in the Climax Stock on the U.S.A.E.C. test range in Nevada. Tenative selection was made in a meeting on September 13, 1971, with Bendix scientists and consultants and the Contracting Agent's Project Engineer. The site was then visited and inspected on September 14, 1971. During this visit, A.E.C. personnel indicated that there would be no problem in arranging to use the site for a future experiment. They also indicated they are very interested in this project as it may provide a means to resolve fracture zones caused by nuclear explosions.

The geology of the "Piledriver" site is well documented. The earth material consists of two petrological types, granodiorite and quartz monzonite. Both types are similar physically and in acoustic properties. Velocity logs made at drill holes in the area are also documented. Targets associated with the site include a vertical shaft extending down to a tunnel complex at a depth of 1400 feet and the chimney (fracture zone) caused by the Piledriver explosion. Information still desirable prior to a test is near surface velocity measurements, depth of the overburden (estimated between 10 and 25 feet), and acoustic attenuation in the medium. It is recommended that a shallow refraction survey be made at the site to determine some of these parameters prior to final specifications of field test equipment. An analysis of the geology at this site will be used to specify the requirements for a seismic holography system.

Computer simulation studies have been made for the purpose of developing a holographic weak-signal-enhancement technique (WSET). A two-layered earth model was chosen for this study. In the initial work, lossless media are assumed. When a weak scattering target is buried below the reflecting layer separating the layers, WSET provides good image enhancement and resolution. For the case when a weak scattering target (or an extended scattering target) is located above the reflecting layer and only scattered compressional (P) waves are allowed, good image enhancement is again achieved, even if random scatterers (noise) are included in the model. When both scattered P and S (shear) waves are allowed and the scatterer is above the reflecting layer, however, the S-waves interfere to the extent that the image resolution is substantially degraded. Ways to reduce the influence of the S-wave interference are now being investigated.

# SECTION 2

# INTRODUCTION

The potential benefits to be gained from the development of an underground viewing system are many. For the first time, a method would be available to look into the ground and "see" targets, thereby defining such anomalies as tunnels, mines, bunkers, and other voids or water filled cavities. It would be a valuable tool for surveying the earth ahead of, or prior to, excavations to determine potential hazards. It would also have applications in defining certain rubble zones in the earth such as might exist after a nuclear underground explosion, and for the military, in locating underground bunkers and supply stores.

The objective of this research program is to define a preliminary underground viewing system based on acoustic holography principles that is capable of detecting and imaging anomalies associated with a selected field test site. Tasks associated with the program include the selection of a field test site, a theoretical analysis to determine the requirements of a holographic system, and based on the analysis, a preliminary system design specifying the required equipment and techniques to carry out a field test. In addition, holographic image enhancement techniques capable of resolving weak target signals in the presence of strong undesired signals will be studied.

In this report, covering the work during the first six months of the program, emphasis will be given to the selection of a field test site and studies relating to weak signal enhancement techniques.

# SECTION 3

# SELECTION OF FIELD TEST SITE

The selection of a specific field test site is a deviation from the original program plan. Initially, Bendix scientists and the Contracting Agent's Project Engineer (CAPE) were to jointly identify the types of targets (tunnels, mines, bunkers, etc.) of greatest interest to the government. The types of hard rock in which the targets might exist along with typical target depths were also to be specified. However, in the first meeting between Bendix personnel and the CAPE on June 18, 1971, it became apparent that a far better approach would be to identify a specific test site at which known and well-defined targets exist and where the geologic conditions of the area are known and documented. With this modification of the program plan, a search for a potential site was begun.

Criteria used for site selection included the following:

(1) The area should have little or no soil overburden or weathering. This restraint will permit a higher operating frequency to be used for a field test without the need of planting seismic detectors and sources below the surface.

(2) The earth material at the site should be of a suitable rock type (i.e., igneous rock or crystalline limestone) to conform with the contrast requirement that the principal geologic medium of interest is hard or crystalline rock.

(3) A suitable subsurface target must be present at the site.

(4) The area should preferably have a reasonably flat topography so that excessive phase compensations to correct for surface elevation differences are not required in an initial field experiment.

(5) Access to the site should be reasonable and there should be no restrictions to the use of explosives as a seismic energy source.

Several potential field test sites were considered. The preliminary evaluation of the site was mainly accomplished by accumulating and analyzing published geologic data. When possible, persons familiar with each site were contacted for additional information. A brief description of the sites considered is given in the following subsections for completeness. The area finally selected (in a joint meeting with Bendix personnel and consultants and the CAPE on September 13, 1971) was the "Piledriver" site in the Climax Stock on the U.S.A.E.C. test range in Nye County, Nevada. A more detailed description of this site is given in Section 4.

## 3.1 CLIMAX STOCK, U.S.A.E.C. NEVADA TEST RANGE, NYE COUNTY, NEVADA

The Climax Stock is an intrusive igneous body located in the north-central portion of the Oak Spring Quadrangle, Nye County, Nevada. This is in the northeastern portion of the Nevada Test Site and is immediately north of Yucca Flat.

The area of exposure of the stock is approximately 4 square kilometers and the rock types are granodiorite and quartz monzonite. The two rock types have been differentiated in field mapping, but there is a good possibility that the two rocks will have essentially similar physical and acoustic properties. Both tend toward a granitic-type composition.

The general geology of the Nevada Test Site is treated in a publication of Eckel, et al.[1] The engineering and fracture properties of the rock of the Climax Stock has been studied by Ege.[2]

According to Ege, and on the map by Houser and Poole,[3] a vertical shaft of 385 feet, 450 feet of drifts, and a 70-foot-diameter unsupported hemispherical chamber were to be excavated in the rock of the Climax stock. The vertical entry shaft was sunk in the proximity of the contact between the granodiorite and the quartz monzonite, and the horizontal drift extended in the quartz monzonite toward the contact. Houser and Poole show the vertical shaft as labeled Station 1500 and the horizontal drift on their cross section F-F'. A number of drill holes are shown on the maps, and a more extensive system of underground openings may exist. (More details are given in Section 4.)

There is approximately 1000 feet of topographic relief at the surface over the Climax stock. Slopes are steeper in the northern portion and more gentle to the south and southeast. Access to the area should be good because of the numerous roads and trails put in by the Atomic Energy Commission.

## 3.2 BATHOLITH OF SOUTHERN CALIFORNIA

Portions of Orange, Riverside, and San Diego Counties, California, are underlain by a complex of igneous rocks, mostly of Cretaceous age, which are known collectively as the Southern California batholith. The northwestern portion of the batholith has been described by Larsen,[4] and other areas have been reported upon by a number of different authors. Two areas within the batholith seem to be of prime interest: the Cajalco area and the Cuyamaca Peak area.

### Cajalco Area

This potential site is located in Sections 1 and 2, T. 4 S., R. 6 W., Riverside County, California. In addition to the publication by Larsen, a U.S. Geological Survey open-file report by Page and Thayer[5] should be available for examination at the Menlo Park, California office of the Geological Survey. A considerable amount of geologic mapping related to water projects has also been done for the Metropolitan Water District of Southern California, and it should be possible to obtain access to these maps.

The principal rock of the Cajalco area is the Woodson Mountain Granodiorite. The rock is typically white to pale brownish gray with scattered black grains and is rather coarse grained. It averages 33 percent quartz, 60 percent feldspar, 5 percent biotite, and small amounts of other minerals.

Potential targets in the area include the old workings of the Cajalco tin mine (this is also referred to as the Temescal mine or Temescal district in some reports) and the Cajalco water tunnel. Larsen (1948) quotes older reports (esp. Fairbanks, 1983) to the effect that the mine in the 1890's had two 180-foot vertical shafts and 300 feet of horizontal workings. I do not know the present state of these workings. From the topographic map the Cajalco tunnel appears to reach depths of 100 feet or so below the surface.

Topographic relief in the area is 200 feet or less, and access appears to be good. Proximity to the Lake Mathews reservoir and to facilities of the water district might restrict the use of dynamite in testing. Orchards now occupy an area adjacent to the tin mine property, and this might imply unfavorable soil conditions.

### Cuyamaca Peak Area

The Cuyamaca Peak area has been described by Everhart.[6] This potential site is a rather large area which includes several more restricted locations of interest within the 15-minute Cuyamaca Peak quadrangle. The more important localities are the Boulder Creek district, the Stonewall Mine, the Oriflamme Mine, and the Descanso Mine.

The Boulder Creek district and the Stonewall Mine are located in areas where the country rock is a "mixed" rock of Stonewall Granodiorite and Julian Schist. The Julian Schist is an older, metamorphic rock, possibly of Triassic age, which has been invaded by the granitic igneous rocks of the Stonewall Granodiorite which is possibly of Jurassic age. This "mixed" rock might create problems because of lack of homogeneity, but if the invasion and assimilation of the metamorphic rock by the igneous rock is thorough, the resultant might be a fairly homogeneous rock. This would need further investigation. Many of the mines in the Boulder Creek district were being worked at the time of Everhart's paper or during earlier field work in the 1940's. Several of the mines have workings which extend through a vertical distance of some 200 feet and a lateral distance of several hundred feet. The workings of the Stonewall Mine extended through 600 feet vertically and 400 to 500 feet laterally. The Stonewall property has been largely inactive since 1895. There is about 1000 feet of topographic relief in the Boulder Creek district, but rather large areas of moderate relief are present in the district. The Stonewall Mine is in an area of low relief. The Boulder Creek district would apparently be accessible for work and for the use of dynamite. The Stonewall Mine might not be feasible because it lies within a state park, is along the shore of Cuyamaca Reservoir, and is near developed recreational facilities.

The Oriflamme Mine is located in the Julian Schist. There may be sufficient inhomogenities within this rock to preclude its use. There were originally 1000 feet of underground workings, but the mine is long abandoned, and may be caved in large part. Access to the mine area would also be difficult due to lack of developed roads.

The Descanso Mine is located in the Bonsall Tonalite. This rock is light gray, medium- to coarse-gray, and consists of predominant feldspar, up to 25 percent quartz, biotite and hornblende. This is probably the most favorable rock type in the Cuyamaca Peak area for the proposed experiment. The mine originally had a 230-foot inclined shaft and three levels with about 80 feet of workings on each level. Access to the mine area should not be difficult, but the workings may be caved.

## 3.3 PIKES PEAK AREA, COLORADO

Some sites in the Pikes Peak region of south-central Colorado should possibly be considered. These are the NORAD site in Cheyenne Mountain near Colorado Springs and the Cripple Creek area of Teller County, Colorado.

Both sites are located in granitic-type rocks of the Pikes Peak batholitic complex, but the Cripple Creek area has been further subjected to volcanic activity and mineralization related to the formation of the volcanic Cripple Creek caldera. The rocks of the NORAD site thus tend to be rather homogeneous while those at Cripple Creek are complex.

A number of geologic reports dealing with portions of the Pikes Peak area have been published, and Dr. R. M. Hutchinson of the Colorado School of Mines geology faculty is completing an extensive study of the entire Pikes Peak batholith. Dr. Hutchinson's maps are available in manuscript form and will soon be published.

The principal disadvantage to utilization of the NORAD site would be the steep surface topography. Topography would not be a significant factor in the Cripple Creek area. Extensive study of the records of the mines in the Cripple Creek district would be necessary to determine the best site for experimentation. Most of the mines are currently shut down; many of them are also deep and probably out of the desired depth range.

Should the NORAD site be considered for further investigation, a large volume of geologic, engineering and mining data was obtained during the planning and excavation of the underground facilities. It would be desirable to obtain access to this information.

## 3.4 GUADALUPE MOUNTAINS AREA, NEW MEXICO AND TEXAS

The area at the southern end of the Guadalupe Mountains in New Mexico and adjacent Texas is a classic region for reef limestone development and the formation of cave systems, such as Carlsbad Caverns. Topographic maps of the Carlsbad Caverns East, Carlsbad Caverns West, and El Paso Gap quadrangles, and geologic maps for two of the quadrangles, Carlsbad Caverns East and Carlsbad Caverns West have been obtained.

A considerable thickness of massive, reef limestone is developed in the general area indicated between the dashed purple lines on the topographic sheets. These limestones are of Permian age and include the Capitan Limestone and associated beds and the Goat Seep Limestone and associated beds. Extensive cave systems are developed in the limestones, and some of these caves have been well studied and surveyed.

Access to the area for the experiment may be hampered by the fact that a large portion of the area is included within Carlsbad Caverns National Park. Because of the high volume of visitors and the delicate nature of the cave formations, the National Park Service may be very reluctant to permit the use of explosives. However, there are locations away from high visitor use and outside the Park where experimentation might take place.

The topography of the reef front is very rugged, and access to the front itself would be virtually impossible for vehicles. The reef-top area is accessible through some of the canyons, and once the top area is reached the topography is not too rugged. A number of roads from the north permit access also.

## 3.5 VICTORIO PEAK AREA, TEXAS

The Victorio Peak area is located in westernmost Texas in Hudspeth and Culberson Counties and south of the Guadalupe Mountains. The larger region around Victorio Peak is known as Sierra Diablo and is described by King.[7]

In the vicinity of Victorio Peak there is as much as 1500 to 2000 feet of Permaian limestone of the Bone Spring and Victorio Peak formations. Cave systems in these limestones are not well documented, but there are vague indications on the maps of the presence of some caves. Some mining has also been done in the vicinity of small igneous intrusions which cut the limestones.

The principal drawback to the Victorio Peak area is the topography. Along the east-facing slope of the Sierra Diablo there is a steep escarpment. The limestones also form cliffs. The topographic and geologic maps do show areas of relatively moderate relief along the crest of the Sierra Diablo escarpment, and if one of these areas could be located in conjunction with a cave, the site might be suitable. There may also be some difficulty with vehicular access because the road system is not well developed.

## 3.6 BIG BEND AREA, TEXAS AND MEXICO

Within Big Bend National Park in west Texas and in adjacent portions of Mexico, thick limestone of Early Cretaceous age are developed. The geology of the region is well described by Maxwell, et al.[8] The best areas of exposure are in the Sierra del Carmen and its extensions on the eastern side of the Park (Boquillas Canyon area) and the Mesa de Anguila along the western side of the Park (Santa Elena Canyon area). Similar rocks are also exposed in the Mariscal Mountains in the south-central Park.

Cave systems do exist within the limestones and there have been mining activities in the Mariscal Mountains. Information on the cave systems is probably available in speleological references.

The topography of the region is rugged, but the tops of the limestone mesas are relatively flat. Vehicular access may be difficult, but there are some primitive roads in the area. Access to localities on the Mexican side may well be impossible except in the vicinity of Boquillas, Mexico which does have a road connection to the United States.

Since the areas are within a National Park for the most part, it might be difficult to obtain permission for the proposed experiments. However, the desirable areas are remote and visitor use is low, so permission might be granted with less difficulty than in other National Parks. There is a slight possibility that a suitable site might be located outside the Park boundary, but the best locations appear to be within the Park.

## 3.7 WINNFIELD SALT DOME, WINN PARISH, LOUISIANA

Although salt is not a hard rock material, its acoustic properties (high velocity) are similar. For this reason, salt bearing areas were not excluded from the survey.

The Winnfield salt dome is located in Winn Parish, Louisiana, approximately midway between Shreveport and Alexandria. The salt, which extends within 300 feet of the surface, has been mined at a single level at a depth of about 800 feet. Maps are available of the mine workings. The cap rock on the salt has been quarried, leaving a layer of gypsum and anhydrite (which have physical properties similar to rock salt) between the surface and the salt.

Unfortunately, the tunnels and mine workings have been flooded with water in the past few years and the mine is no longer accessible. In addition, the area quarried over the salt is probably smaller than would be desired for a field test.

# SECTION 4

## DESCRIPTION OF PROPOSED FIELD TEST SITE

As stated in Section 3, the "Piledriver" site in the Climax Stock, located on the U.S.A.E.C. test range, Nye County, Nevada, has been selected as the proposed field test site. Subsequent to this selection, the site was visited and inspected by Bendix personnel and consultants on September 14, 1971. During this visit, A.E.C. personnel indicated there would be no problem in arranging to use the site for a future field test, especially since the project is supported by ARPA. A.E.C. personnel are particularly interested in this project as it may provide a means to resolve fracture zones caused by nuclear explosions.

The proposed site for the seismic holography experiment lies at the northern boundary of the Nevada test site within N901000 to N903000 and E676000 to E679000 of the Nevada grid system.

The surface geology and overall geologic setting can be obtained from the Preliminary Geologic Map of the Climax Stock and Vicinity, Nye County, Nevada, U.S. Geologic Survey Map I-328. The Climax Stock at the proposed site consists of two petrological types: granodiorite to the north and a younger porphyritic quartz monzonite to the south. Figure 4-1 shows the indurated, nearly vertical, contact between the two. There is general agreement that the differences between the quartz monzonite and the granodiorite of the stock are insignificant with regard to transmission of seismic energy. The measured physical properties at depth of the two rock types does not show significant differences, and the bulk chemical compositions are essentially the same.

Of greater consideration are the joints and faults in the area. There are three prominent sets of joints.

(a) Strike N30° to 40°W dip 15° to 35° NE

(b) Strike generally NW, steep dip

(c) Strike generally NE, steep dip

The joints with low dip angle all seem to be firmly healed with secondary minerals. The joints with nearly vertical dip are less well healed and are generally filled with clay and calcite. Velocity surveys run from shot points 1000 feet away from the U-15a drill hole (see Figure 4-1) indicate average horizontal velocities slightly higher than average vertical velocities, indicating that open or loosely filled vertical joints are probably not an important factor at depth.

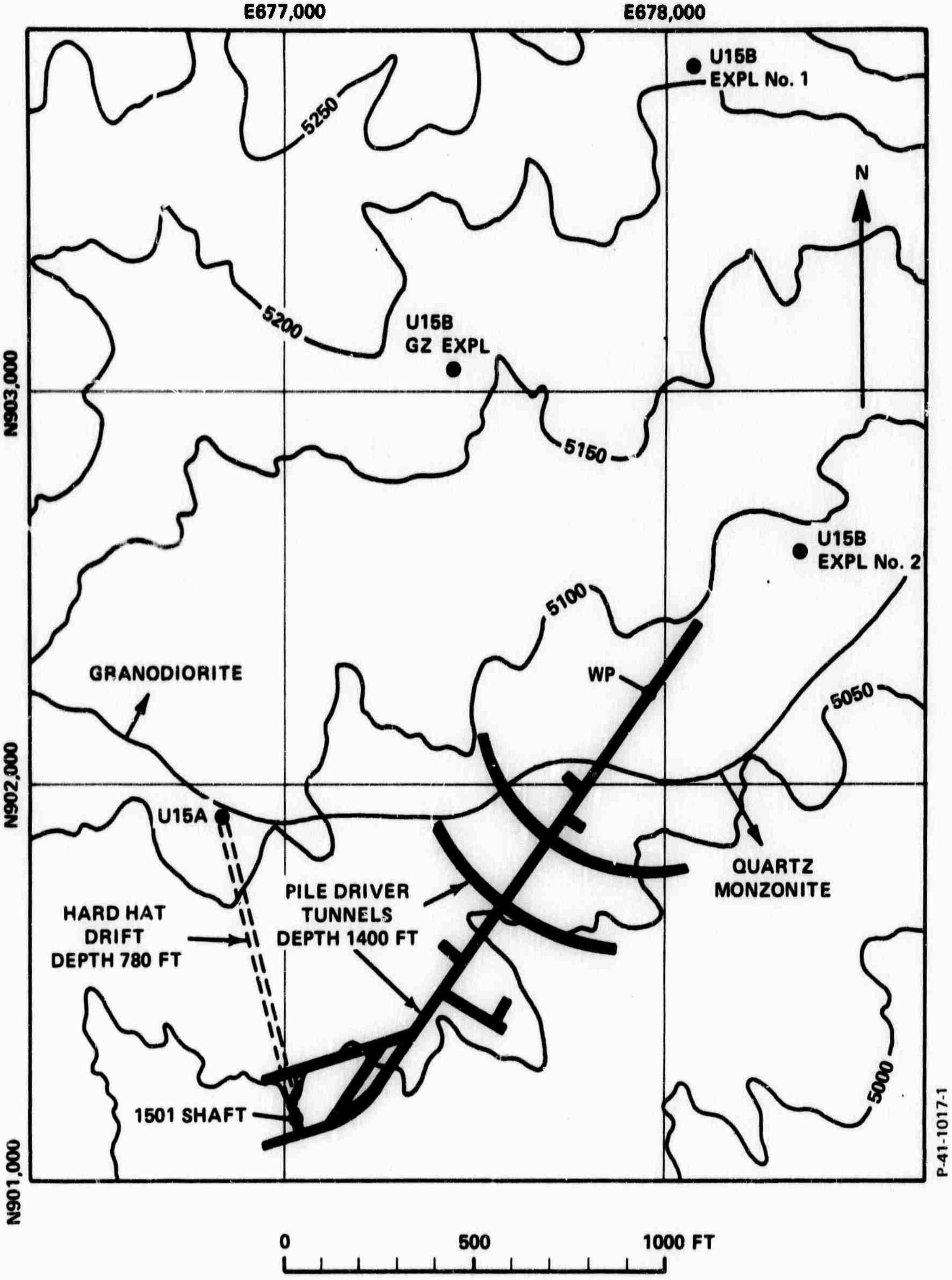

Figure 4-1 - Map Showing Location of Pile Driver Tunnels Area 15, Nevada Test Site, Nevada (from Technical Letter, Pile Driver - 1)

Little precise information can be determined about faults in the area from information at hand. Several intervals in the drill holes have been suggested as possible fault zones. It is the consensus that faults do exist and that they probably dip very steeply and strike more or less parallel to joints. It is the steep dip which makes it difficult to correlate fault zones with adjacent drill doles.

Surface and near-surface weathering in the area will have a profound effect on the proposed seismic holography experiment. No core recovery from depths above 20 feet is reported from any of the core holes described in these reports. Apparently, the combination of fracturing and weathering of rocks near the surface and drilling considerations have combined to prevent core recovery at these shallow depths. In addition, weathering effects can extend to as much as 360 feet in the drill holes studied. In the upper portions of the drill holes, there is both oxidation and alteration of the minerals. This suggests that to the depth of the Piledriver tunnel (1400 feet), there are at least three different seismic zones to be considered. The properties of the surface and the near-surface zones are poorly known. The percent porosity of weathered surface samples of both the quartz monzonite and the granodiorite is higher than that of the unweathered rock. The grain density of both weathered and unweathered material is essentially the same, and the dry bulk density of both is nearly the same.

A review of the series of reports on the Hardhat (an earlier event near Piledriver in the Climax Stock) and Piledriver explosions indicates that the explosions have had no significant effect on the properties of the surface or near-surface zones. For the Piledriver event, the maximum vertical extent of increased permeability is 1032 ± 36 feet about shot level or approximately 500 feet from the surface. In the weaker Hardhat event, explosion-produced fractures extend a maximum radial distance of approximately 520 feet from the shot point.

At depth in the distressed zone surrounding each shot point, the velocities of compressional and shear waves has undoubtedly been reduced. The attenuation of the higher frequencies (250 Hz and above) will be most critical to the purposes of the proposed experiment. An estimate of the decreased velocity to be expected can be obtained from data taken in the distressed zone surrounding the Piledriver tunnel. The opening of the tunnel produced a distressed zone of 0 to 8 feet thickness. Seismic velocities in the distressed zone are lower than those measured in the rock beyond the distressed zone.

(a) Distressed zone velocities 10,000 - 15,000 ft/sec.

(b) Beyond distressed zone velocities 17,000 - 23,000 ft/sec.

The lithologic information on the proposed site is relatively complete. However, for a seismic holography experiment, other types of information are desired. Primarily, this will be near surface velocity and attenuation data of the in situ rock. If an assumed model consisting of two layers over a half space is sufficiently accurate for the experiment, then velocity and attenuation data for the three zones should be specified. In addition to the usual compressional wave data, the method of seismic holography (see weak-signal-enhancement technique) requires information on shear wave transmission in the three zones.

The interference between returning compressional and shear waves is known to be a factor in all seismic exploration techniques and, in the early stages of the seismic holography program, interference must be monitored and modeled accurately. Some of the factors which determine the amplitudes and phase of the returning compressional and shear waves are outlined below.

(a) Acoustic impedances (product of density and velocity) vary with depth. An increase in acoustic impedance yields a decrease in amplitude and vice versa.

(b) In near-surface weathered layers, observed ratios of shear-wave to compressional-wave velocity ($V_S/V_P$ ratios) can be as low as 1/7. The result is that the shear wave velocity contrast at the base of the layer can be several times greater than the corresponding compressional wave velocity contrast. This results in a larger proportion of the shear source energy being trapped in the surface layer.

(c) The weathered zone can be an effective high frequency filter. Experiments in weathered sediments have shown the average amplitude of shear wave frequencies within the 40 - 60 Hz band was down about 10 to 1 with respect to the spectrum peak at 14Hz. If the upward propagating shear energy is similarly filtered by the near-surface, the decay of high frequency relative to low is of the order of 100 to 1. This reduces shear wave interference at the hologram plane.

(d) When low $V_S/V_P$ ratios occur in a weathered layer, the shorter wavelength shear wave is influenced to a greater extent by horizontal variations in the thickness of the layer. Multiple reflections may occur which can effect the seismic hologram.

Determination of parameters to model the proposed site can be obtained in part by a seismic refraction survey of the area. Velocities and seismic depths of the near-surface and weathered layers should be readily obtainable. In addition, it may be possible to determine indications of existing fault zones. The survey lines would be spaced to give maximum detail on the thickness variation of the weathered layers. At present, an investigation is being made to optimize the refraction survey to obtain attenuation data at depth.

# SECTION 5

# HOLOGRAPHIC WEAK-SIGNAL-ENHANCEMENT TECHNIQUES STUDY

The Bendix-developed Holographic Weak-Signal-Enhancement Technique (WSET) was described in Section 2.4.1 of Bendix Proposal No. 4425, "Seismic Holography for Underground Viewing." This technique, which lends itself to computer simulation, has shown promise in defining images of targets that have signal strengths too weak to be seen by conventional holographic imaging (reconstruction) methods, as is often the case when a scattering target is located either above or below a strong signal reflecting layer.

Enhancement results, using a simple model of the earth, were reported in both the First Monthly Letter Progress Report and the First Quarterly Management Report. Those results were obtained using a two-layer earth model, the two layers being separated by a reflecting layer with a scatterer located below the reflector. Using conventional reconstruction methods, the scatterer could not be seen, but with WSET, the scattering target was imaged with good resolution.

The original computer model has subsequently been modified to simulate another situation which can arise, that of a scattering target located above the reflecting layer separating two earth media (see Figure 5-1). In addition, an extended scattering target (simulating a tunnel) can be studied and random scattering targets (noise) is allowed in the model.

In the computer simulation, lossless media are assumed. (Lossy media will be treated later). Further, the scattered fields in the holographic plane are based upon the theoretical analysis of Knopoff[9] who has derived expressions for the scattering coefficients for the problem of incidence of a plane P-wave on a perfectly rigid spherical obstacle. The sphere is assumed small compared to the incident wavelength. Knopoff's analysis finds that the scattered P-wave spatial distribution is doubly circular, equal in the forward and back directions with nulls normal to the direction of propagation. The scattered S-wave distribution is also doubly circular, with a maximum amplitude about three times greater than the scattered P-waves, but rotated in space through 90 degrees so the null lies in the direction of propagation.

Figure 5-2 shows a conventional reconstruction using the model of Figure 5-1 for the case of a single scattering target. The reconstruction is in the plane of the scatterer (hereafter called $S_2$). Only the out-of-focus image due to the reflecting layer (hereafter called $S_1$) can be seen, $S_2$ cannot be resolved. Figure 5-3 shows the result for the same case when WSET is used and only scattered P-waves are allowed. The image $S_2$ is now well resolved. Figure 5-4 is the result for the same case as Figure 5-3 except that random scattering targets (noise) are now included in the model. Again, good image resolution is obtained. Figure 5-5 again gives

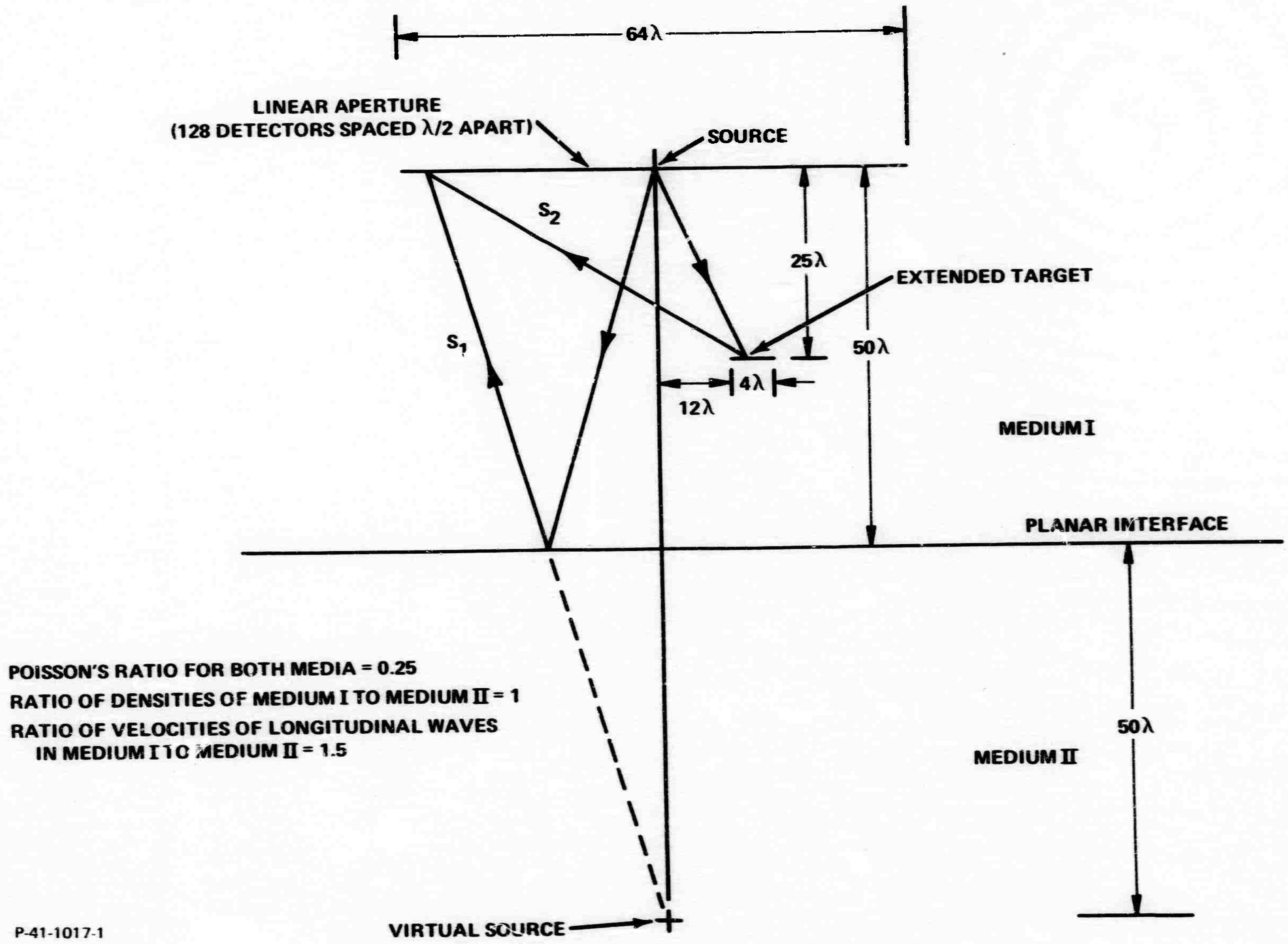

Figure 5-1 - Computer Simulation Model

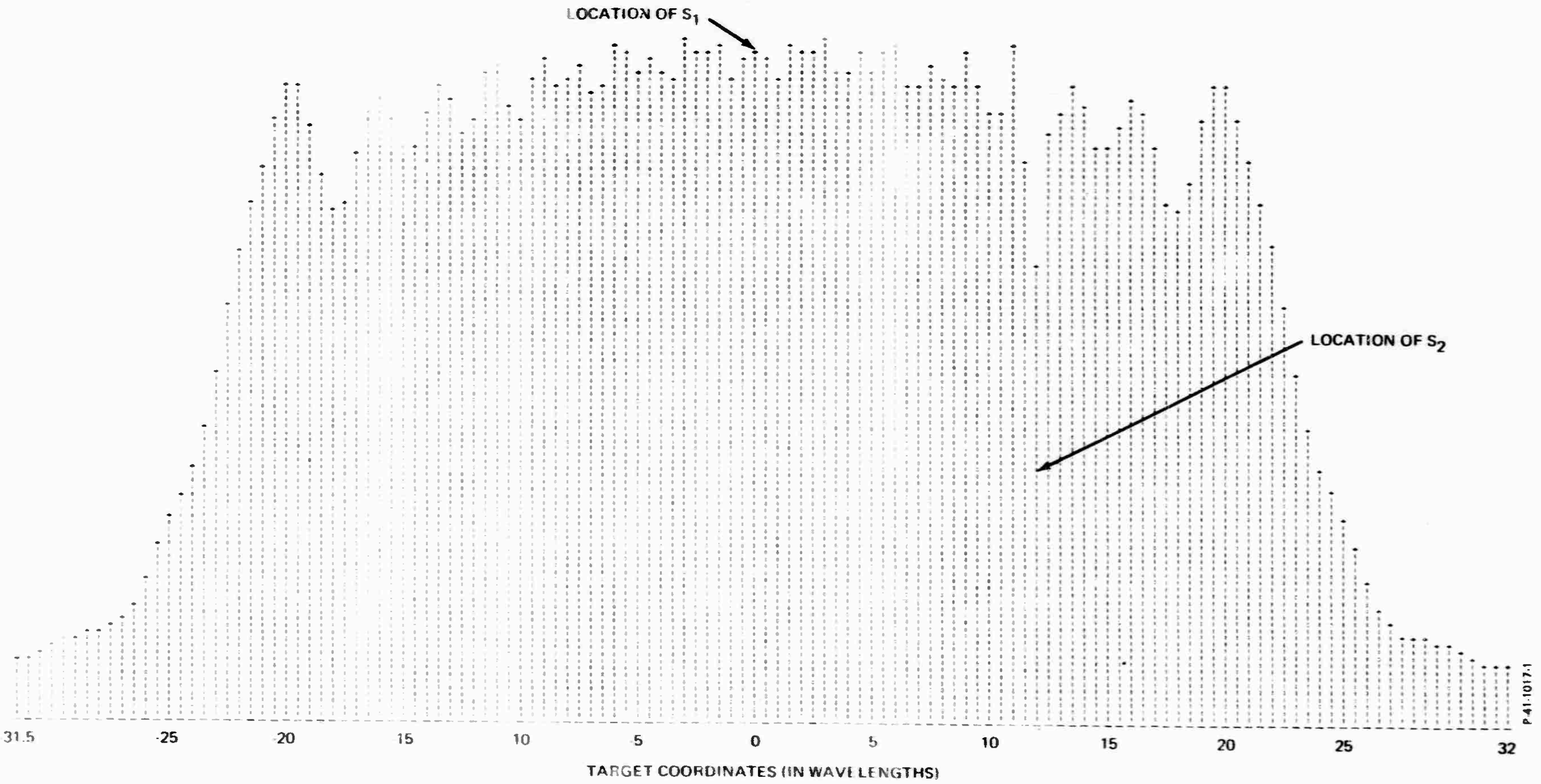

Figure 5-2 - Conventional Holographic Reconstruction of $(S_1 + S_2)$ in the Image Plane of $S_2$ . $S_2$ is not Visible

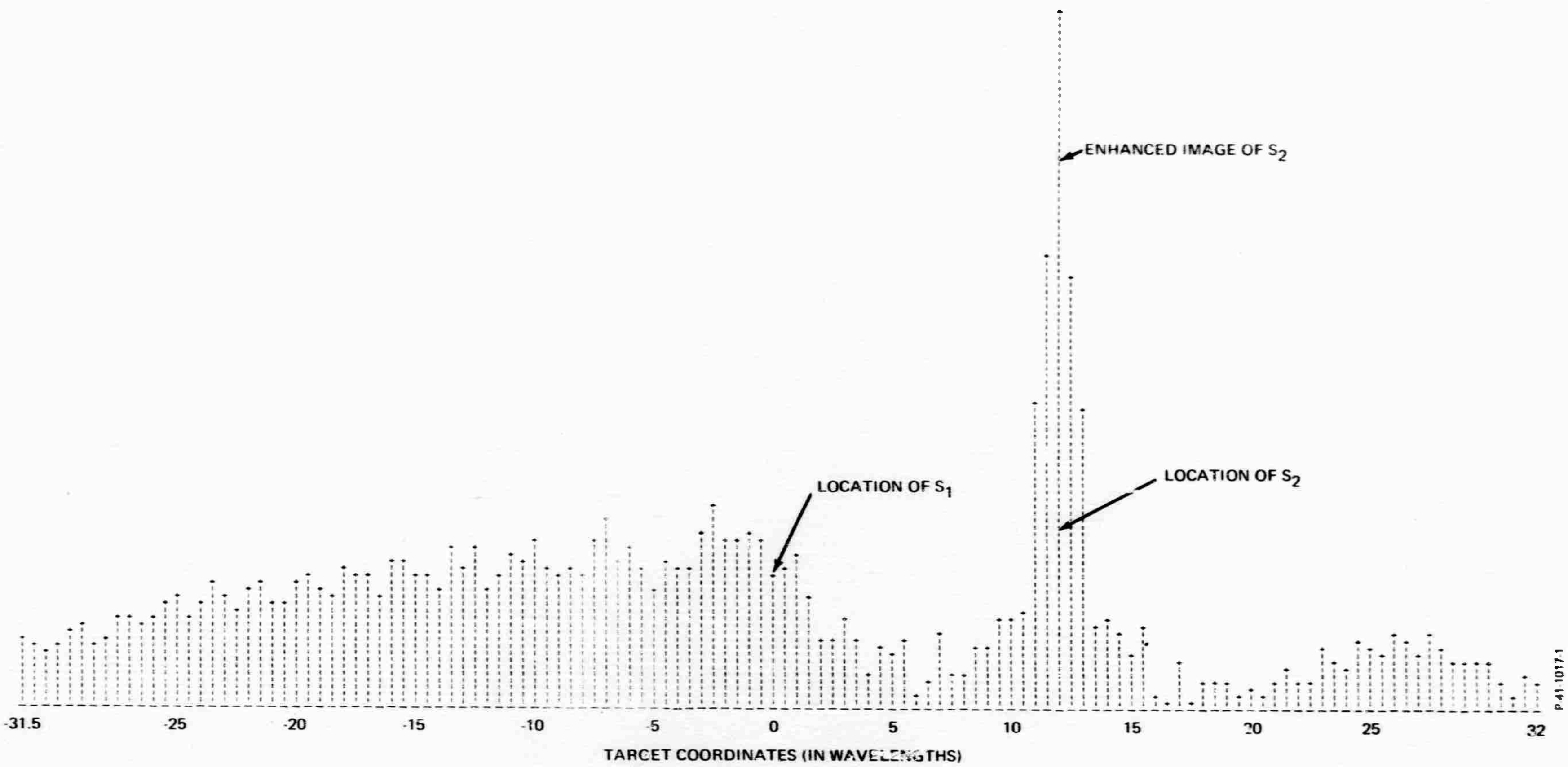

Figure 5-3 - Weak Signal Enhancement Reconstruction of a Single Scatterer in the Image Plane of $S_2$. Only scattered P-waves are allowed.

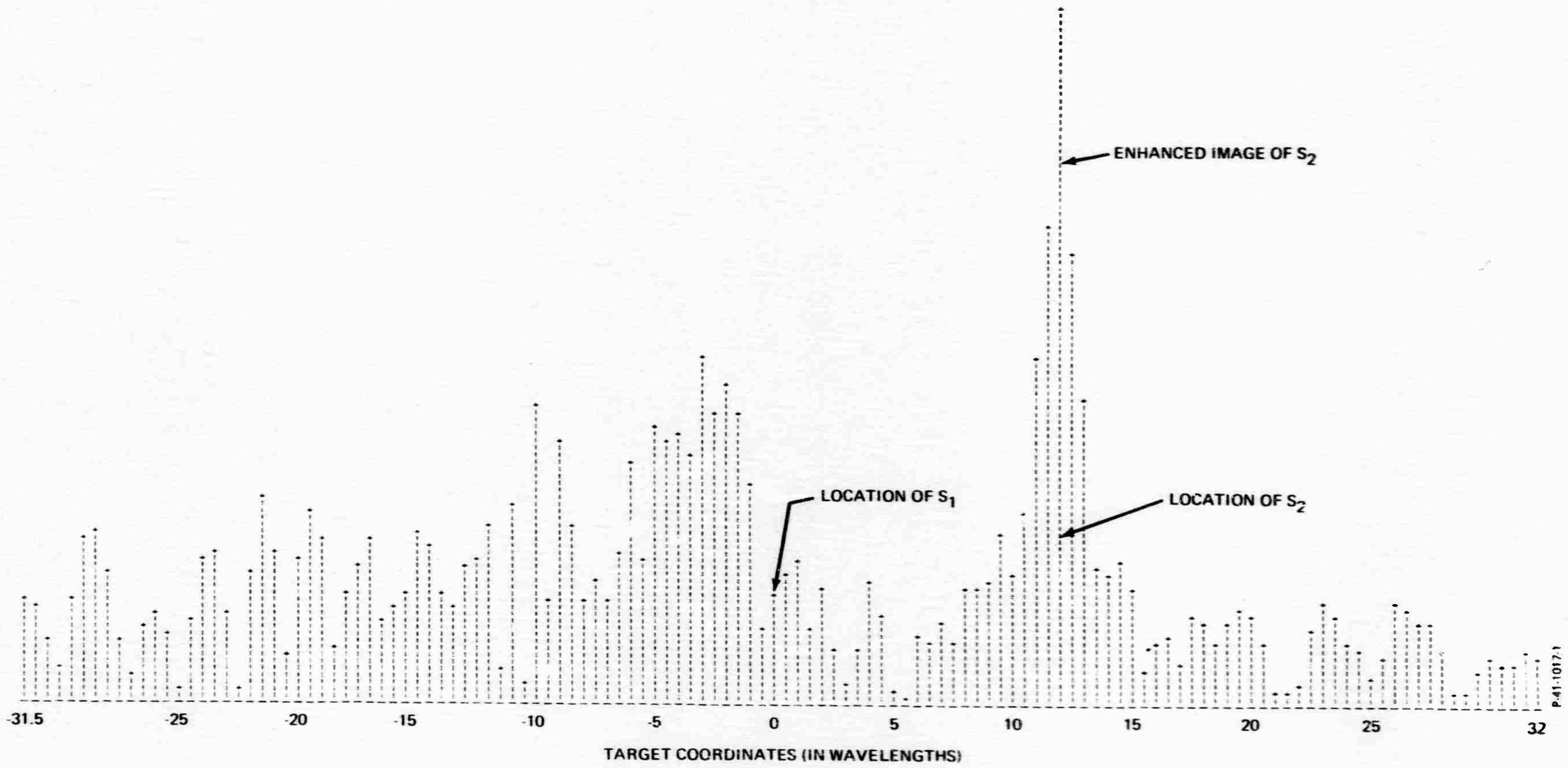

Figure 5-4 - Weak Signal Enhancement Reconstruction of a Single Scatterer in the Image Plane of $S_2$. Random scattering targets are included in the model.

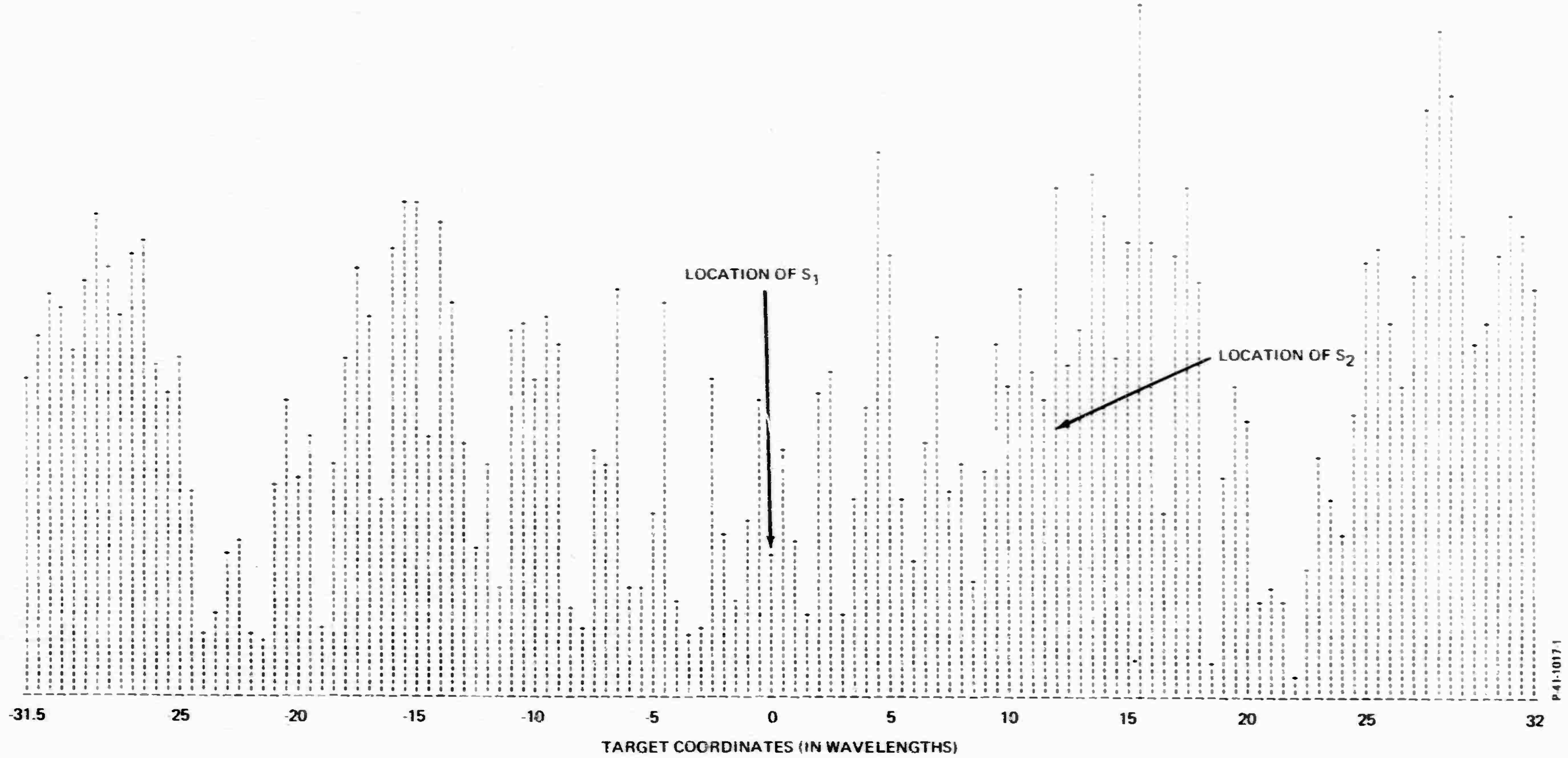

Figure 5-5 - Weak Signal Enhancement Reconstruction of a Single Scatterer in the Image Plane of S2. Both scattered P- and S-waves are allowed.

the results for a single scatterer ($S_2$), but here both scattered P- and S-waves are allowed. In this case, interference between S and P-wave greatly reduce the resolution of the reconstructed image.

When an extended scatterer ($S_2$) is used instead of a single scatterer, the results are as follows. The conventional reconstructor is essentially the same as shown in Figure 5-2 for a single scatterer, i.e., $S_2$ cannot be resolved. Figure 5-6 shows the results when only scattered P-waves are allowed and with no random scatterers. Figure 5-7 is for the same case, except random scatterers are included in the model. In both cases $S_2$ is again well resolved. Figure 5-8 gives the results when both scattered P- and S-waves are allowed. The S-wave interference is again apparent in that it greatly reduces the $S_2$ image resolution.

The results given above indicate that, at least for the model shown, interference due to scattered S-waves influence the resolution of the desired image to a greater extent than does the presence of random noise sources. Because of this, ways in which the shear wave interference can be reduced, and to what extent it needs to be reduced, will be investigated. One computer test, for example, has shown that if the shear wave amplitude is reduced by a factor of ten there is no noticeable interference.

The computer model used, in which a lossless medium is assumed, is actually a worse case condition with respect to S-wave interference. In a lossy medium, S-waves typically attenuate more than P-waves, which should result in less S-wave interference at the hologram plane.

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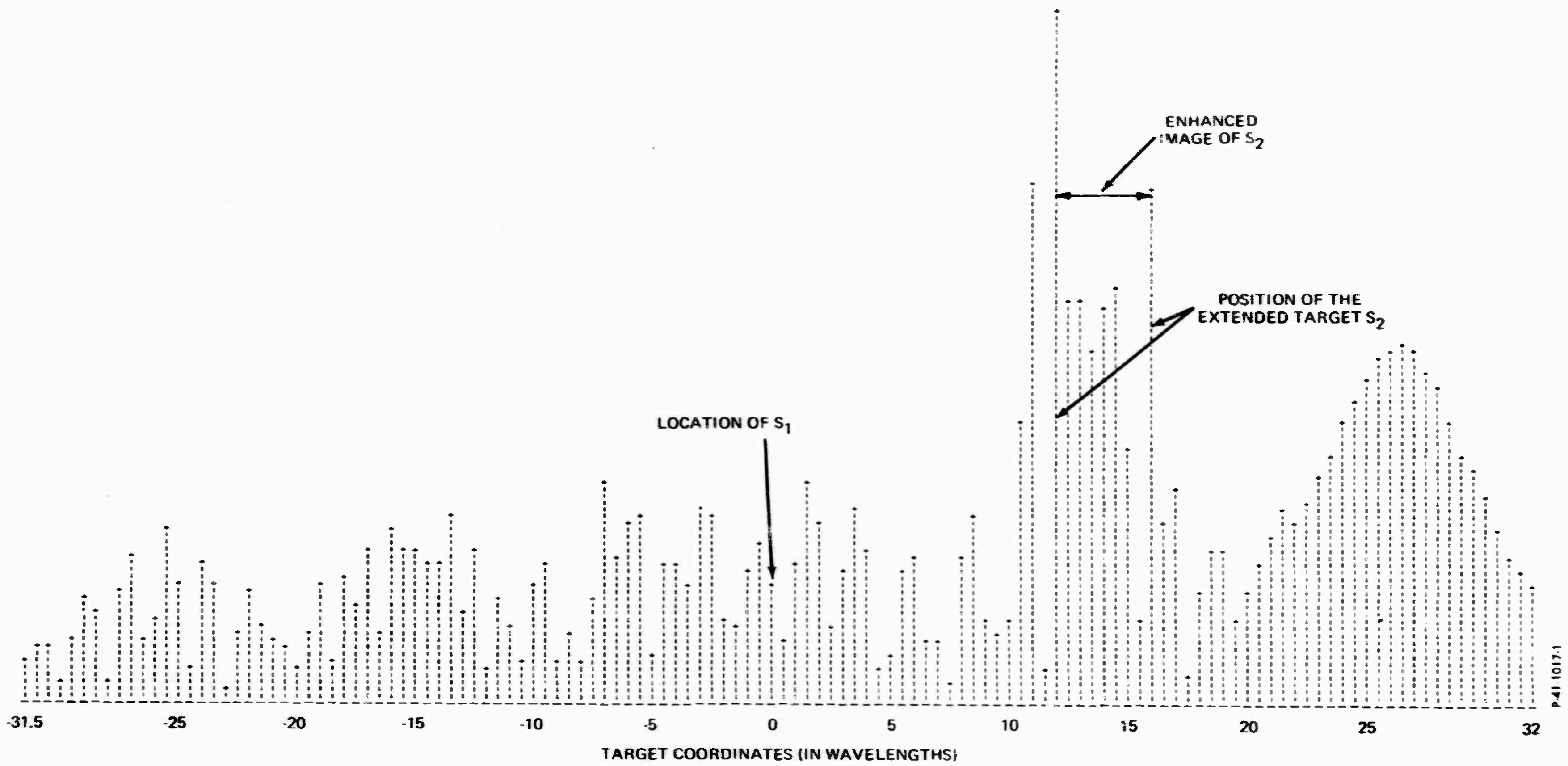

Figure 5-6 - Weak Signal Enhancement Reconstruction of Extended Scatterers in the Image Plane of $S_2$. Only scattered P-waves are allowed.

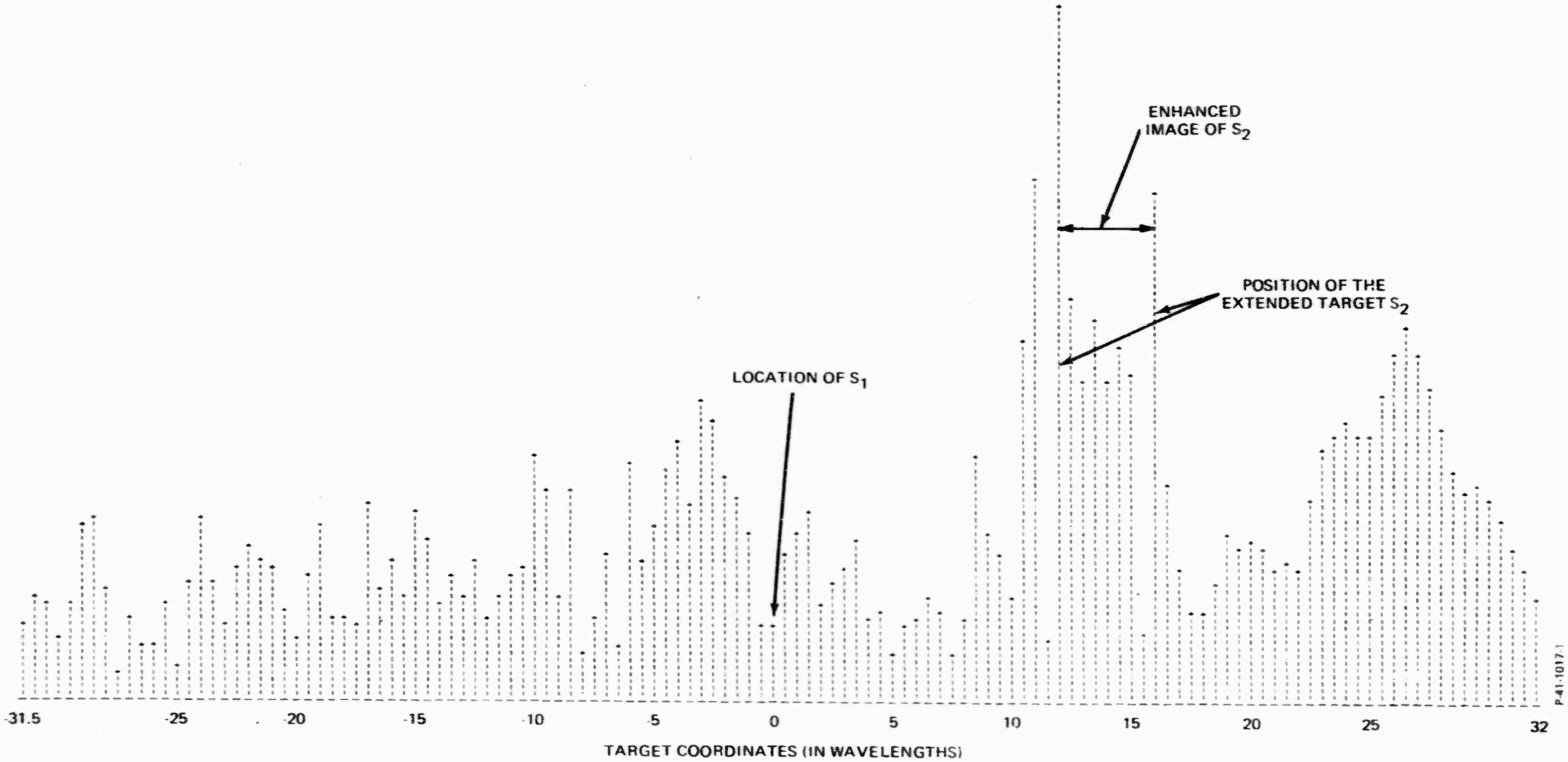

Figure 5-7 - Weak Signal Enhancement Reconstruction of Extended Scatterers in the Image Plane of $S_2$. Random scattering targets are included in the model.

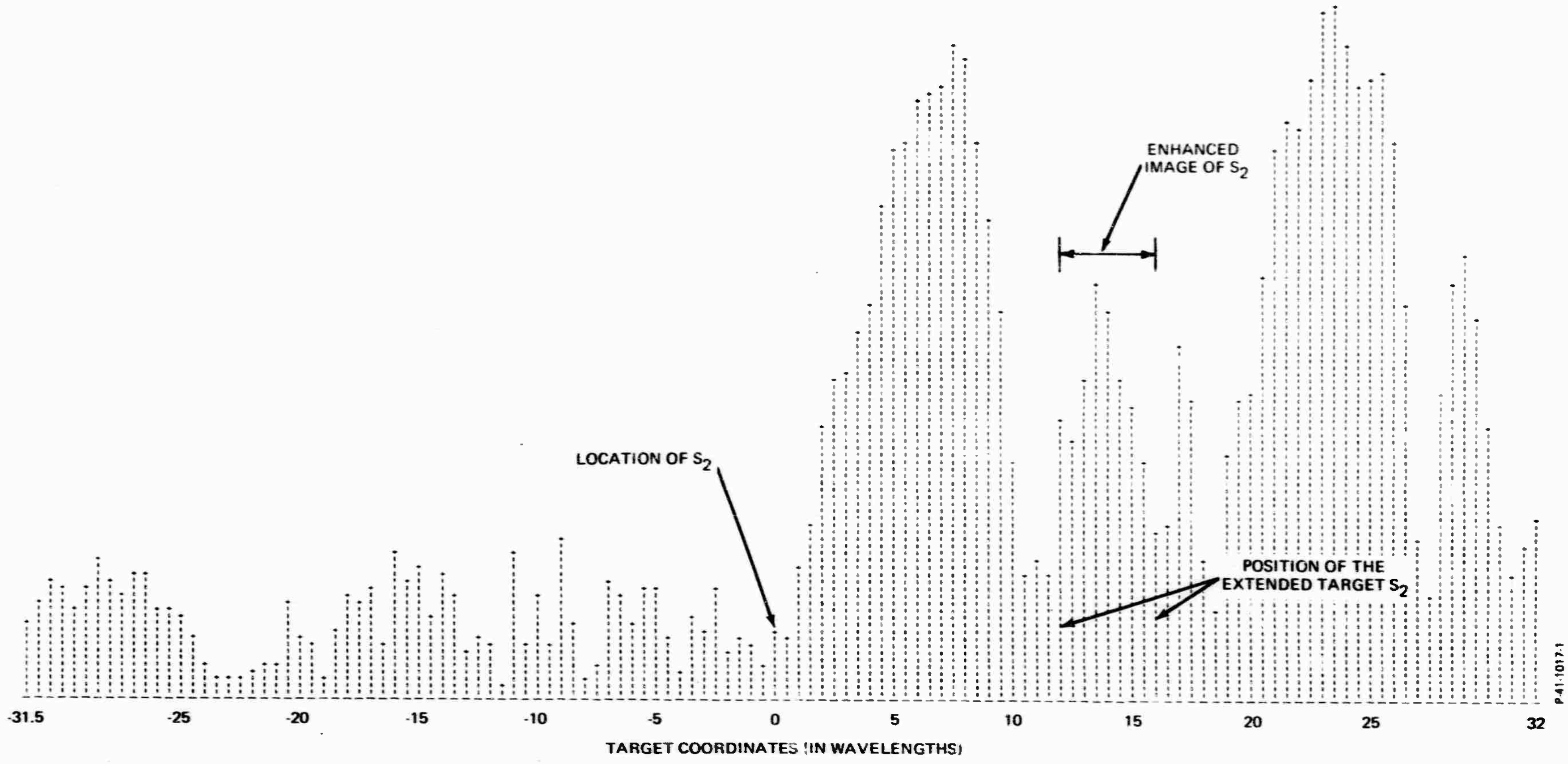

Figure 5-8 - Weak Signal Enhancement of Extended Scatterers in the Image Plane of $S_2$. Both scattered P- and S-waves are allowed.

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